

ABSTRACT

MEASURING THE DIPHOTON PRODUCTION FROM HIGGS BOSON DECAYS AND IN ASSOCIATION WITH HEAVY FLAVOR JETS

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In this dissertation, two important measurements are presented related to diphoton production, the differential cross-section measurement of the Higgs boson in the diphoton decay channel as well as a measurement on inclusive diphoton production with associated heavy-flavor jets. Selections between the two analyses are complimentary, making them a natural pairing in the context of this dissertation. The cross-section measurement is performed in a fiducial region of phase space to closely matches experimental selections. This allows for a largely model-independent measurement, providing a meticulous test of the Standard Model as well as other theoretical predictions. The production of diphoton + heavy-flavor jets has never before been measured and initial sensitivity estimates are presented here. This measurement is important as a probe of quantum chromodynamics due to the heavy-flavor jet production, but also as a contributor to other analyses' backgrounds that probe Higgs boson properties. The results presented here were obtained using proton-proton collision data collected by the ATLAS detector using the full Run 2 dataset with a center-of-mass energy of $\sqrt{s} = 13$ TeV at the Large Hadron Collider.



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**MEASURING THE DIPHOTON PRODUCTION FROM HIGGS BOSON
DECAYS AND IN ASSOCIATION WITH HEAVY FLAVOR JETS**

BY

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It is strange¹ to think that only a few years ago I was an undeclared freshman at the University of Oregon and now I'm leaving Northern Illinois University with a Ph.D. in physics. I could double the length of this dissertation in an attempt to mention every single person I met along the way who helped professionally and personally. As it is already quite long though, I will keep things brief and only mention a few. First, I have to thank Dr. Liza Brost, who helped introduce me to the field as an undergrad, was a wonderful mentor and friend throughout my physics career, and who convinced me to apply to the graduate program at NIU in the first place. Alongside Liza's encouragement, the deciding factor to attend Northern Illinois came down to Professor Jahred Adelman. His immediate friendliness, patience, and humor made the decision to spend the next 5 years as a member of his research group easy. Thank you, Jahred, for always responding quickly to my Skype questions while I was at CERN and didn't realize that it was 5am in Chicago. Thank you for your patience while I had the same sum of weights bug over and over again in my codes. Thank you for the perspective on things when I felt like I had no idea what I was doing. And importantly, thank you for giving me an opportunity to show off my clip art skills during presentations (which ranged from adding ghosts and snowmen depending on the time of year, to incorporating Paw Patrol characters to make sure your son wasn't too bored during my progress reviews). Truly, thank you for everything.

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¹“Strange” the adjective, not ”strange” the quark.

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DEDICATION

To my cat, Lacy, who did everything in her power to draw my attention to her instead of
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CHAPTER 1

INTRODUCTION

Particle physicists seek knowledge about the fundamental constituents of the universe and how they interact. This knowledge is encapsulated in the Standard Model theory. In science lessons around the world, students are taught that the universe is made of matter and that combinations of electrons, protons, and neutrons create atomic elements. The study of particle physics considers matter at a more fundamental level to describe how elementary particles coalesce to form those protons and neutrons, as well as the forces of nature that bring - and keep - them together.

The Large Hadron Collider was built collaboratively at CERN by various countries around the world to test the Standard Model and Beyond the Standard Model theories with the hope of answering some of the open fundamental questions about the universe. These questions range from “What happened during and right after the Big Bang?” to “How do the fundamental particles and forces interact?”. To answer these big questions, the world’s largest machine was built to study the smallest constituents of the cosmos. While most physicists will say that answering these questions is a good enough reason to build such a machine, the technologies developed at CERN and other research facilities for the LHC have many applications to everyday life. The most famous technology invented at CERN is the World Wide Web, which was created to make sharing data between scientists easier. Now, the web has evolved in a way that it can be used by anyone to find information on anything!

The analyses in this dissertation focus on understanding and testing the predictions made by the Standard Model by looking at the production of two particles of light (photons). By making precision measurements that test all properties of the particles, we hope to gain

knowledge on the interactions that produced them. So far, no deviation from the Standard Model has been found in these processes.

This dissertation presents studies that are the outcome of a joint effort by myself and other members of the ATLAS Collaboration. My personal contribution for the $H \rightarrow \gamma\gamma$ cross-section analysis was determining the reducible background in a data-driven way (see Chapter 6.2.2) and through studies for and the implementation of the $N_{\text{b-jets}}$ differential measurement. In the diphoton + heavy flavor analysis, I was the sole analyzer for most of the analysis and was responsible for obtaining the sensitivity and uncertainty estimates using Asimov data.

This dissertation is laid out in a way such that aspects common to both analyses are presented first, beginning with the Standard Model theory in Chapter 2 and the LHC and ATLAS detector presented in Chapter 3. The common data and simulation samples and how objects are reconstructed is detailed in Chapter 4 and 5. The individual analyses are then separated, beginning with the Higgs boson differential and fiducial cross-section measurements which starts in Chapter 6, followed by the diphoton + heavy flavor jet production measurement beginning in Chapter 11.

CHAPTER 2

THEORETICAL FRAMEWORK

The Standard Model describes the fundamental constituents of matter and how they interact. In this chapter, the basics of the Standard Model are described and the motivation for studying it will be explained.

2.1 The Standard Model

The Standard Model (SM) [1] is a hugely successful theory that has yet to be disproved despite rigorous testing. An overview of the model is presented in Chapter 2.1.1. The mathematical framework behind the theory is detailed in Chapter 2.1.2. The Standard Model is splendidly successful, but as with most things, it is not without flaws. While the topics in this dissertation are not directly related to the shortcomings in this otherwise accurate theory, for completeness they must be mentioned and are concisely addressed in Chapter 2.1.3.

2.1.1 Model Overview

The model breaks down the universe into elementary particles, and sorts them into two main categories, fermions and bosons, while also describing the interactions between them (the forces in nature).

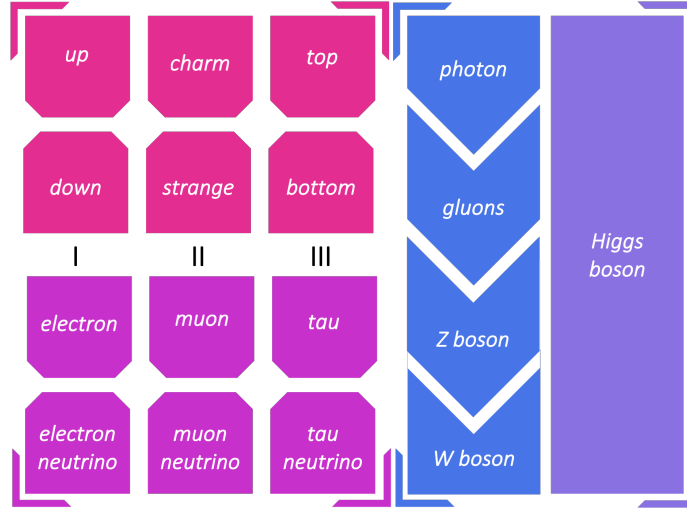


Figure 2.1: The Standard Model particles with fermions on the left and bosons on the right.

Bosons come in two types, gauge bosons, which are spin-1 particles¹, and scalar bosons that carry spin-0. There is only one scalar boson in the theory, the Higgs boson, which plays a central role in the first analysis presented in this dissertation. The SM gauge bosons are gluons (g) which mediate the strong force, the $W^\pm$ and Z^0 bosons which mediate the weak nuclear force, and the photon (γ) which mediates the electromagnetic force. All bosons are neutral and are their own antiparticles except the W^+ with electric charge +1 and W^- with charge -1 that act as the antiparticles to each other.

Fermions, like bosons, are broken down into two sub-categories that all carry spin- $\frac{1}{2}$ called leptons and quarks, both of which have three generations of particles. Leptons can be electrically charged or neutral and differ from quarks in that as they do not carry QCD color, they do not interact with the strong force. The charged leptons are electrons (e), muons (μ), and taus (τ), where each is more massive than the previous generation and each carry a negative charge of -1. Generally, charge is defined in term of the electron charged, so a charge of -1 refers to $1e = -1.602 \times 10^{-19}$ Coulombs. Electrons are the lightest charged leptons and are the only generation that stably exists to build atoms and matter. The anti-particles (e^+ ,

¹All known gauge bosons are spin-1, but there are theoretical predictions for the existence of spin-2 bosons.

μ^+ , and τ^+) to these leptons are all positively charged (+1), but have the same mass and spin as the negatively charged version. The neutral leptons are neutrinos which are very light and rarely interact with matter. They also come in three flavors, corresponding to each of the charged leptons, called the electron neutrino (ν_e), muon neutrino (ν_μ), and tau neutrino (ν_τ) with corresponding antiparticles $\bar{\nu}_e$, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$. The last elementary particle type is the quark, which comes in six flavors and has six antiparticles with the same mass and spin, but opposite color and charge. The up and down quark are in the first generation and, like the electron, are the ones that make up matter. Specifically, the up and down quark are bound together via gluons to create protons and neutrons. The second generation contains the charm and strange quarks, and the heaviest generation contains the top and bottom quark. The quark first in each generation pair carries a charge of $-\frac{1}{3}$ while the second carries charge $+\frac{2}{3}$. The charm and bottom quark are the focus of the second analysis presented in this dissertation as we define heavy-flavor to be either of those two. The top quark is the heaviest fundamental particle in the Standard Model and decays quickly in the detector to other final states therefore excluding it from the heavy-flavor definition. However, as the top quark often decays to a W boson and a bottom quark, it is still included in the analysis via its decay products.

These particles interact with each other via forces. The fundamental forces in order of decreasing strength are the strong nuclear force, the weak nuclear force, the electromagnetic force, and the gravitational force. The strong and weak forces interact over extremely short distances and are responsible for the interactions between the sub-atomic particles. The electromagnetic force acts between charged particles and the gravitational force can act over extremely long distances on massive objects. In this dissertation, the role of the first three forces are considered, leaving out gravity. While it is the most familiar to us as it plays a large role in peoples' day-to-day lives, the gravitational interaction is often neglected when considering elementary particles as it has little impact at the mass scales considered.

Table 2.1: Properties of the elementary particles in the Standard Model [2] including the Higgs mass reported as the averaged mass value from ATLAS and CMS Collaborations used in the Higgs to diphoton fiducial and inclusive cross-section measurement [3].

Particle	Symbol	Charge	Spin	Mass
Quarks				
Up	u	$+2/3$	$+1/2$	2.16 MeV
Charm	c	$+2/3$	$+1/2$	1.27 GeV
Top	t	$+2/3$	$+1/2$	172.69 GeV
Down	d	$-1/3$	$+1/2$	4.67 MeV
Strange	s	$-1/3$	$+1/2$	93.4 MeV
Bottom	b	$-1/3$	$+1/2$	4.18 GeV
Leptons				
Electron	e	-1	$+1/2$	0.511 MeV
Muon	μ	-1	$+1/2$	105.66 MeV
Tau	τ	-1	$+1/2$	1.776 GeV
Electron Neutrino	ν_e	0	$+1/2$	< 1.1 eV
Muon Neutrino	ν_μ	0	$+1/2$	< 0.19 eV
Tau Neutrino	ν_μ	0	$+1/2$	< 18.2 eV
Bosons				
Gluon	g	0	+1	0
Photon	γ	0	+1	0
W Boson	$W^\pm$	± 1	+1	80.37 GeV
Z Boson	Z^0	0	+1	91.19 GeV
Higgs	H	0	0	125.09 GeV

2.1.2 Phenomenology

The Standard Model [4] is a quantum field theory (QFT) that combines special relativity and quantum mechanics and is represented by $SU(3)_c \times SU(2)_L \times U(1)_Y$ symmetries, where each symmetry has a corresponding conserved quantity according to Noether's theorem [5]. The SM theory establishes the 12 gauge bosons (photon, three weak bosons, and eight gluons), one scalar boson (the Higgs boson), and 12 fermions (quarks and leptons). Quantum

chromodynamics (QCD) is an $SU(3)$ symmetry group dealing with interactions of the strong force and describes color interactions. quantum electrodynamics (QED) is a gauge theory with $U(1)$ symmetry that describes the electromagnetic interactions. Electroweak theory unifies the electromagnetic and weak interactions as a $SU(2)_L \times U(1)_Y$ gauge group which deals with spontaneous symmetry breaking and requires the Higgs mechanism.

The SM can be described by a Lagrangian density (referred to as just the Lagrangian) that dictates particle masses, how they interact with each other, and encodes symmetries. In these treatments, natural units are used so that $c = \hbar = 1$.

First we start with Equation 2.1 as it is the basic Lagrangian for a Dirac field that describes a free spin- $\frac{1}{2}$ particle. Here, Ψ is the fermion field (known as a Dirac spinor) with $\bar{\Psi} = \Psi^\dagger \gamma^0$, m is the particle's mass, γ^μ are the gamma matrices, and $\partial_\mu = \partial/\partial x^\mu$. Here the μ index ranges from 0 to 3.

$$\mathcal{L}_{\text{Dirac}} = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi \quad (2.1)$$

Charged fermions interact with the electromagnetic field which has a Lagrangian that can be expressed as shown in Equation 2.2. The kinematic term is given by $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $A_\mu = (V, \vec{A})$ is the electromagnetic field using the electric and magnetic potentials.

$$\mathcal{L}_{\text{EM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (2.2)$$

Equation 2.2 doesn't include the effects of the 4-current density from interacting with the charged fermion. For this, an additional correction is made where $\mathcal{L}_{\text{current}} = -eJ^\mu A_\mu$. The current density and local charge density are included in $J^\mu = (\rho, \vec{J})$. This gives the last portion of the fermion Lagrangian (the potential term) in Equation 2.3.

$$\mathcal{L}_{\text{int}} = -Qe\bar{\Psi}\gamma^\mu\Psi A_\mu \quad (2.3)$$

Putting all of the pieces together in Equation 2.4 we get the full QED Lagrangian for fermions to be:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\Psi}(i\gamma^\mu\partial_\mu - m)\Psi - eQ\bar{\Psi}\gamma^\mu\Psi A_\mu \quad (2.4)$$

One can then define the covariant derivative to make the Lagrangian gauge-invariant:

$$D_\mu \equiv \partial_\mu + ieA_\mu \quad (2.5)$$

Using this in Equation 2.4, the full Lagrangian is then rewritten as:

$$\mathcal{L}_{\text{QED}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu\Psi - m\bar{\Psi}\Psi \quad (2.6)$$

Taking this completed form and applying a $U(1)$ phase transformation where $\Psi \rightarrow e^{iQ\theta(x)}\Psi$ with $\theta(x)$ as an arbitrary function of spacetime, and transforming $A_\mu \rightarrow A_\mu - \partial_\mu\theta(x)$, the Lagrangian $\mathcal{L}_{\text{QED}}$ is unchanged [6]. From these transformations, two very important things are established that are 1) charge is conserved and 2) the vector field A_μ represents a massless photon (as adding a mass term would not be gauge invariant). All of quantum electrodynamics can be derived by requiring $U(1)$ gauge symmetry.

Moving from the electromagnetic interactions to the strong interactions, we will next talk about quantum chromodynamics [1]. As stated above, QCD is invariant under $SU(3)$ gauge symmetry. The Lagrangian is shown in Equation 2.7, where $a = 1, \dots, 8$ and T^a are eight 3×3 matrices that are the generators of the group:

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + \bar{\Psi}(i(\partial_\mu - igA_\mu^a T^a)\gamma^\mu - m)\Psi \quad (2.7)$$

To be invariant under these non-Abelian gauge transformations, the eight generators are all massless, defining the eight massless gluons in the SM. Additionally, the QCD $SU(3)_c$ symmetry group is an absolute symmetry that describes color charge invariance. Each quark carries one of three colors (red, blue, green) that must be conserved and gluons carry a color + anticolor combination. Colored particles cannot exist on their own but must combine into colorless bound states called hadrons, commonly mesons and baryons². Baryons are a combination of three quarks (or antiquarks) where each carries one of the three colors (e.g. RBG). A meson is a quark and antiquark pair with a color + anticolor (e.g. $R\bar{R}$). Mesons have integer spin and can have electric charge +1, 0, or -1. Baryons also have integer charge but are half-integer spin particles.

The weak interactions are based on $SU(2)$ gauge symmetry which applies an arbitrary local phase rotation. The $SU(2)_L$ group describes weak isospin which is a symmetry of the strong interactions and tells us that left-handed fermions are doublets and right-handed fermions are singlets. This right-handed and left-handedness is known as chirality. Following the method for QED, $U(1)_Y$ symmetry is imposed which describes weak hypercharge Y that differs for right- vs. left-handed fermions, but is still conserved. Using this combination of $SU(2)_L \times U(1)_Y$, four gauge fields are required for electroweak interactions to remain invariant, that arise from linear combinations of W_μ^a with $a = 1, 2, 3$ and B_μ . Equation 2.8 is the pure gauge part of the electroweak Lagrangian and also describes $W_{\mu\nu}^a$ self-interactions

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4}B_{\mu\nu}^a B^{a\mu\nu} \quad (2.8)$$

In terms of the SM vector bosons, $W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \pm W_\mu^2)$ represents the charged $W^\pm$ bosons while the electrically neutral fields of W_μ^3 and $B_{\mu\nu}^a$ mix as a result of spontaneous symmetry breaking. The Z^0 and photon are linear combinations of these fields and are related by the

²There has also been evidence for exotic four-quark hadrons (tetraquarks) [7] and four-quark + one antiquark hadrons (pentaquarks) [8].

weak mixing angle θ_W which is related to the coupling constant via $\tan \theta_W \equiv \frac{g'}{g}$, and as shown in Equation 2.9.

$$\begin{pmatrix} W_\mu^3 \\ B_{\mu\nu}^a \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} \quad (2.9)$$

Two important things must be mentioned on this outcome regarding the boson fields. First: no mass terms are included. While the actual photon and gluons particles *are* massless, we know from experiment that the weak bosons have masses of 91.1876 GeV for the Z boson and 80.379 GeV for the W boson. If these particles are massive, they should then couple to the particles in the same way regardless of left- and right-handed chirality. Instead, experiment [9] has shown this last part to also not be true. So, now a modification needs to be made to the theory to include an explanation for why the $W^\pm$ bosons couple to only left-handed fermions (and right-handed antifermions), while the Z_0 couples differently to left- vs right-handed fermions, and the photon couples the both at the same strength. This parity violation means that there is a distinction between right- and left-handed fermions. To account for this, spontaneous symmetry breaking is introduced that generates mass for these particles and is called the Higgs mechanism [10–14].

The Higgs mechanism introduces a new scalar potential field in the Lagrangian which is shown in Equation 2.10 and is illustrated in Figure 2.2 where Ψ is a complex scalar field.

$$V_{\text{Higgs}} = -\mu^2 \Psi^\dagger \Psi + \lambda (\Psi^\dagger \Psi)^2 \quad (2.10)$$

The minima of this potential is given by $\Psi^\dagger \Psi = v^2/2$ where $v = \sqrt{\mu^2/\lambda}$ is the vacuum expectation value. Since the photon must remain massless, this value must be nonzero. The real scalar field $h(x)$ is defined and used in the covariant derivative to obtain the interactions with the vector bosons for the Lagrangian $\mathcal{L} = D^\mu \Psi^\dagger D_\mu \Psi - V_{\text{Higgs}}$. In the $SU(2)_L \times U(1)_Y$

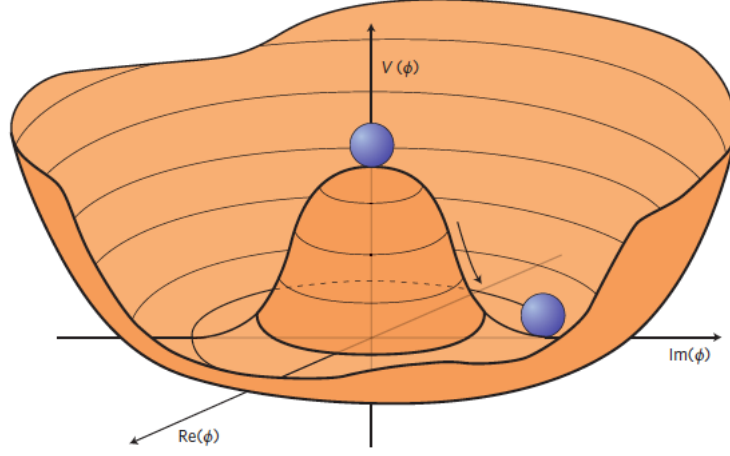


Figure 2.2: Illustration of the Higgs potential showing where $\mu^2 < 0$ is the minimum [15].

gauge symmetries, the transformation on this field then yields the Lagrangian shown in Equation 2.11 where again, $\mu = 1, 2, 3$.

$$\mathcal{L} = \frac{1}{2} \partial_\mu h \partial^\mu h + \frac{(v+h)^2}{4} (g^2 W_\mu^+ W^{-\mu} + \frac{1}{2} (g^2 + g'^2) B_\mu B^\mu) \quad (2.11)$$

As stated before, the $W^\pm$ bosons are linear combinations of W^1 and W^2 . The photon and Z^0 boson are linear combinations of B_μ and W_μ and are related via Equation 2.9. The newly appearing Higgs boson is represented by h . The predicted masses for the gauge bosons is shown in Equation 2.12 where g is the coupling constant that comes from experiment, and the vacuum expectation value which is approximately 246 GeV [16]. The Higgs boson mass is not directly predicted from the Standard Model, and is instead given as $m_h = \sqrt{-2\mu^2}$ [4].

$$M_W = \frac{1}{2} g v, \quad M_Z = \frac{g v}{\cos \theta_W}, \quad M_\gamma = 0 \quad (2.12)$$

The last part of the theory to consider is that earlier, we treated fermions as massless, which is not true as we know quarks and the electron-like leptons are all massive³. This

³Experiments studying neutrino oscillations have proven that neutrinos have mass, however the means by which they obtain their mass is unknown and is currently under study [17, 18].

requires the Yukawa interaction which describes the coupling between the Higgs field and the quark and lepton fields which, through the spontaneous symmetry breaking of these fields, acquire mass. Their interaction Lagrangian for these fermion fields (f) is shown in Equation 2.13 and the masses are $m_f = \frac{1}{\sqrt{2}}y_f v$ where y_f is the coupling strength.

$$\mathcal{L}_{\text{Yukawa}} = -\frac{y_f}{\sqrt{2}}(v + h)\bar{f}f \quad (2.13)$$

The Standard Model under $SU(3)_c \times SU(2)_L \times U(1)_Y$ group symmetries correctly predicts most interactions however, as mentioned, some aspects are not predicted by the model and need to be accounted for. While current experimental values fit well into the model, there are still open questions about why certain values are chosen or if the Higgs boson that was discovered in 2012 [19, 20] with $m_h \approx 125$ GeV has the same properties as the SM Higgs boson. More complex theories than the theory described here exist which propose multiple physical Higgs bosons, though no conclusive evidence for this has been discovered yet. Measurements have been obtained for several Higgs boson production mechanisms and decay modes [21–43]. The pursuit of validating the Standard Model provides the motivation for the two analyses presented in this dissertation, which study SM predictions.

2.1.3 Standard Model Inconsistencies

While the Standard Model has predictions for most aspects of nature, there are some it offers no explanation to or tweaks that need to be made based purely on experimental findings.

The most famous unexplained mysteries of the universe is the origin and composition of dark matter [44] and dark energy [45]. There is ample cosmological evidence that the matter we know about (the particles described in the SM) only make up about 5% of the contents of the universe. The remaining space as far as we can tell is made of unknown substances we

call "dark" (naturally, as we can't see it). While we cannot detect it directly, we know it's there via indirect means. Evidence of dark matter (roughly 20% of the universe) and dark energy (roughly 70%) comes from many experimental sources like the gravitational effect dark matter has on the visible matter around it, the Cosmic Microwave Background, the expansion of the universe, galaxy rotation, etc. This evidence leads the belief that there exists an unknown massive particle (or particles) that is weakly interacting. The SM, however, offers no dark matter candidate particle. When considering both the visible and dark matter of the universe then, it was previously assumed that the expansion of the universe will continuously slow down due to gravitational attraction. Conversely, it was found that it was actually accelerating instead due to some new force that is now believed to make up the remaining 75% of the universe called dark energy. Again, the SM offers no explanation of this.

Another problem related to the composition of the universe that is unacknowledged by the SM is the asymmetry between matter and antimatter [46]. We know symmetry plays a central role in the SM, so it is postulated that matter and antimatter should have been created in equal amounts in the early universe. Nevertheless, as far as can be detected, most antimatter was annihilated leaving only matter. This means that the symmetry is broken though there is no explanation as to how so much matter is left as matter/antimatter annihilation would have only left pure energy behind.

The Higgs boson plays a vital role in the theory as it is the only scalar boson predicted and is thought to give mass to the $W^\pm$ and Z^0 bosons. But, despite it's predominance, the model offers no direct prediction for its mass. This also leads us to the hierarchy problem. This questions why the weak force is 10^{24} times stronger than gravity and the scale of the electroweak and Higgs bosons compared to the Plank scale (defined by the speed of light, the gravitational constant, and the Plank and Boltzmann constants).

The SM has also been called into question when it comes to neutrinos. The model predicts massless neutrinos, however it was experimentally proven that neutrinos can oscillate between the three generation [17, 18]. For this to occur, neutrinos must have non-zero mass.

These questions, among others, require careful study of the Standard Model to see what pieces are missing from the puzzle.

2.2 Hadron Physics

Protons and neutrons are held together by the strong force, specifically the interaction and exchange of gluons between quarks. The internal structure of a proton is illustrated in Figure 2.3. These point-like constituents are generally referred to as partons. The proton

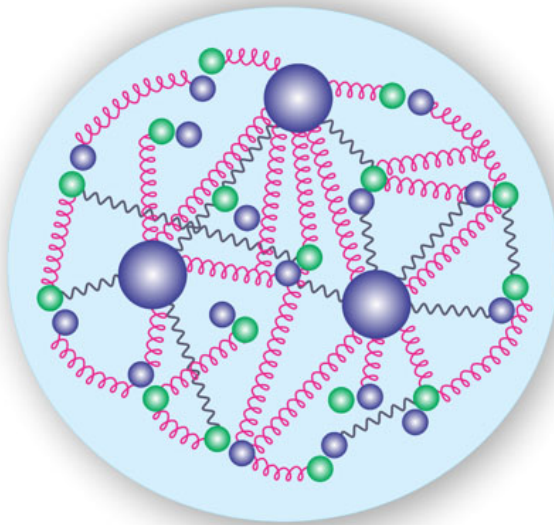


Figure 2.3: Illustration of the internal structure of a proton [47].

is a bound state of three quarks, specifically uud , which are called valence quarks, that are continuously interacting and exchanging gluons within the proton. During such interactions, short-lived quark pairs ($q\bar{q}$) can be produced and are called sea quarks. When proton

beams are collided, two types of processes can happen, hard scatter and soft QCD processes. Hard-scattering occurs when partons collide directly between the two protons, while in soft events, only exchanges and radiation of low-energy gluons occur. Both valence quarks and virtual sea quarks can participate in scattering along with the gluons. The dynamics of these parton interactions are expressed by Parton Distribution Functions (PDFs). These functions determine the probability of finding a parton with a particular fraction of the hadron's momentum the parton is within. The functional forms depend on the dynamics of the proton and reflect the underlying event structure, but cannot be calculated from first-principles, meaning they are obtained from experiment.

The probability that an interaction will occur is given by the cross-section (dimensions of area) and is specific to a process. The calculation is done by integrating over the matrix elements as well as additional phase space variables. The first analysis in this dissertation measures the cross-section of the Higgs boson when it decays to two photons. The second analysis in this dissertation aims to measure diphoton production with associated b - and/or c -hadrons.

2.3 Higgs Boson Production

When performing a measurement on the Higgs boson, the process that produced the Higgs boson particle is taken into consideration. As mentioned earlier, during collisions, the gluons and quarks (virtual or valence) within the proton can be involved in the interaction and those interactions initiate various processes. For the Higgs boson at the LHC, the main production mode is gluon-gluon fusion (ggF) where the gluons emit and absorb a loop of heavy virtual quarks (typically top or bottom quarks) which then emit the Higgs boson. The next dominant production mode is vector boson fusion (VBF) which occurs when two

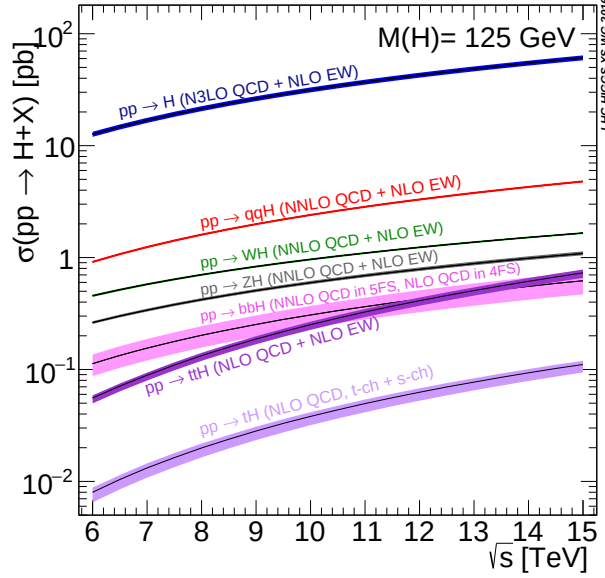


Figure 2.4: The Higgs boson cross-sections for each production mode as a function of the center-of-mass energy [2].

quarks exchange a virtual $W^\pm$ or Z^0 boson that produce a Higgs boson. The Higgs boson can also be produced in association with a vector boson (VH) and is often referred to as Higgs-strahlung. Here, a quark/antiquark pair produce an off-shell boson that then radiates a Higgs boson. The last production mode considered is association production with heavy quarks ($t\bar{t}H$ or $b\bar{b}H$), where a quark/antiquark pair are produced from gluon interactions and emit a Higgs boson. Figure 2.4 shows the cross-section values for the various Higgs boson production modes and the leading-order diagrams of each are shown in Figure 2.5.

The cross-section measurement can be taken a step further by calculating the differential cross-section. Here, the cross-section is calculated in bins of some selected observable variable. A differential cross-section measurement allows for probing of the kinematics of the Higgs boson and of the charge conjugation and parity properties to compare to the SM predictions. For example, in the first analysis in this dissertation, one of the differential cross-section measurements is calculated when the event has one b -tagged jet along with the $\gamma\gamma$ decay

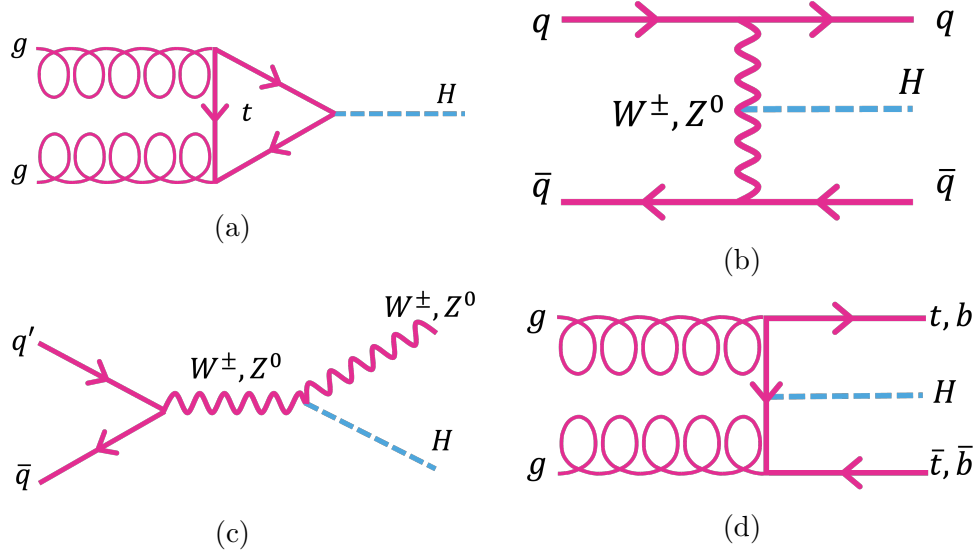


Figure 2.5: The Higgs boson leading-order production Feynman diagrams for (a) gluon-gluon fusion, (b) vector-boson fusion, (c) Higgs-strahlung, and (d) associated production with a heavy quark pair.

products in the final state. This is a more intricate test of the Standard Model and allows more precision testing.

It should be noted that there are multiple ways to obtain b quarks in the final state with the Higgs boson decay products. One common method is through the $t\bar{t}H$ and $b\bar{b}H$ production modes as shown in Figure 2.5(d). For $b\bar{b}H$, the b quarks can be in the final state and for $t\bar{t}H$ production, the top quarks will decay almost 100% of the time to a W boson and a b quark [2]. Another production mode for Higgs + b is through vector boson fusion as shown in Figure 2.5(b). Here the W or Z bosons decay to a quark-antiquark pair approximately 70% of the time for the Z boson and 67% for the W boson.

Probing Higgs Boson Properties Through Production

Two important properties of the Higgs boson that are a focus in future ATLAS analyses is the shape of the Higgs boson scalar field potential and the coupling of the Higgs boson

to the top quark. As the top quark is the heaviest particle in the SM, the coupling of the Higgs boson to it should be quite large as the Yukawa coupling is directly proportional to the masses. The $t\bar{t}H$ production mode of the Higgs boson is a great way to study this directly. The top quark is often produced in pairs at the LHC as pair production occurs via strong interactions while single-top production occurs via weak interactions. The shape of the Higgs scalar field potential is related directly to the Higgs boson self-coupling which impacts the diHiggs production cross-section. Higgs boson pair production can occur at leading-order via gluon-gluon fusion with a trilinear Higgs self-coupling interaction. While neither of these targeted analyses are the topic of this dissertation, the analyses that are presented are related to them either via the $t\bar{t}H$ fiducial cross-section measurement or due to $\gamma\gamma$ + heavy flavor jets being a previously unmeasured background to them.

2.4 Higgs Boson Decays

The diphoton decay channel of the Higgs boson is chosen for the Higgs cross-section measurement as it has a clean final state of two photons that we can reconstruct and an invariant mass peak of the diphoton system around the Higgs boson mass. It is not, however, a dominant decay channel for the Higgs boson, as its branching ratio is smaller compared to others. A branching ratio tells how much each final state contributes to the total decay width. The Higgs boson couples to both fermions and bosons and the strength of the coupling is proportional to the mass of each particle. The higher the mass/coupling, the more likely it is for the Higgs boson to decay to the particle. The Higgs boson branching ratio is shown in Figure 2.7, where $H \rightarrow b\bar{b}$ has a much higher branching fraction than the diphoton channel. This means that $H \rightarrow \gamma\gamma$ will occur less often compared to the $b\bar{b}$ final state, but it is still a measurable process. The Higgs boson does not couple directly to the photon as it is

electrically neutral, therefore the decay is mediated by massive charged particles. The leading order contributions to this decay process is through a top quark loop and a W boson loop as shown in Figure 2.6.

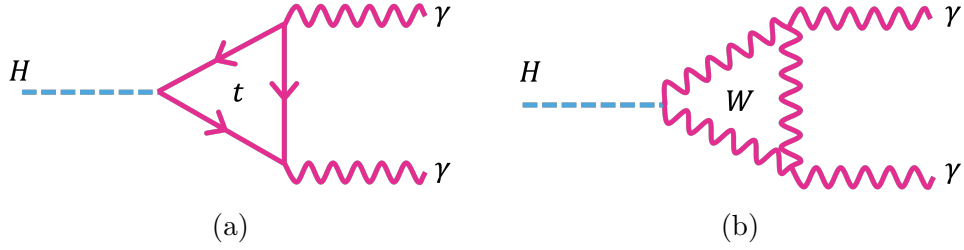


Figure 2.6: Feynman diagrams of the Higgs boson decay to two photons using (a) a top quark loop or (b) a W boson loop.

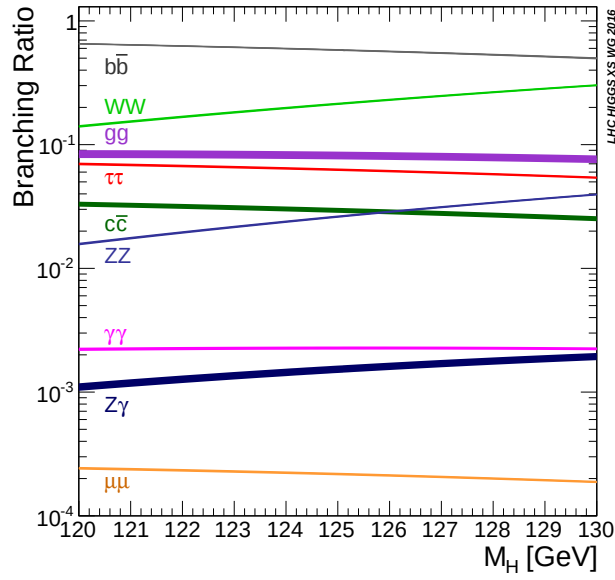


Figure 2.7: The Higgs boson branching ratios and related uncertainties for m_H near 125 GeV [48].

2.5 Diphoton Production

The most abundant source of diphoton pairs that the LHC is from the decay of the neutral pion, which is a hadron containing a pair of up or down quarks ($u\bar{u}$, $d\bar{d}$) as shown in Figure 2.8. Two photons can also be produced independently as any charged particle interaction can emit a photon. However, both analyses in this dissertation target prompt photons, i.e. those not produced in hadron decays, that are from the same interaction. Besides the Higgs boson decay as mentioned above, diphoton pairs can be produced via gluon interactions and quark-antiquark interactions at leading order [49, 50]. Jets can be emitted in during this process via gluon emissions. Figure 2.8 also shows examples of diphoton production with associated jets via direct $q\bar{q}$ production and single-fragmentation gluon interactions.

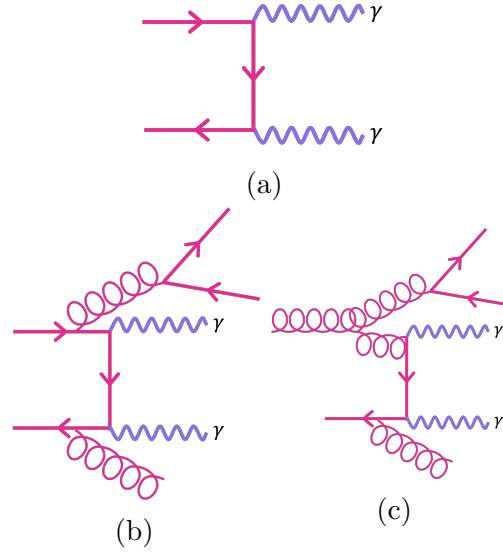


Figure 2.8: Example Feynman diagrams for diphoton production via (a) neutral pion decay, (b) direct production of $\gamma\gamma$ + jets, and (c) single-fragmentation [49].

CHAPTER 3

THE LARGE HADRON COLLIDER AND THE ATLAS DETECTOR

In order to study the smallest constituents of the universe, the largest machine ever built was needed. The European Council for Nuclear Research, referred to as CERN (as in French the name is Conseil Européen pour la Recherche Nucléaire) operates an international laboratory housing many physics experiments and the Large Hadron Collider. The facilities at CERN are used by more than 600 universities and institutes globally and host experiments covering all aspects of fundamental physics including nuclear and high-energy physics.

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [51] is a particle accelerator sitting on the border of France and Switzerland. The project was conceived in the early 1980's, approved by the CERN Council in the mid 1990's, and first produced data in the mid 2000's. The LHC is a synchrotron that accelerates two beams of hadrons in opposite directions around a 27 km ring. The mean depth of the LHC is 100 meters below the ground and it uses electromagnets to accelerate and orbit beams of charged particles. As electromagnetic fields are used to influence the particles, the beams must consist of charged particles. Also, the particles in the beams must be stable, which limits the choice to electrons, ions, and protons. Therefore the LHC is equipped to accelerate both proton bunches and heavy ions. Electron beams are not currently used in the LHC as the radiation energy losses would be much more significant

than for protons at this energy, meaning that proton beams can be accelerated to higher energies than electrons. The pp beams are collided once they've reached a Run 2 peak energy of 6.5 TeV per beam to produce a center-of-mass energy of 13 TeV. The particles travel inside a vacuum tube and are manipulated via magnets and accelerating cavities. To get up to the required speed, an accelerator complex is used with multiple machines in a sequence to accelerate the beams as shown in Figure 3.1.

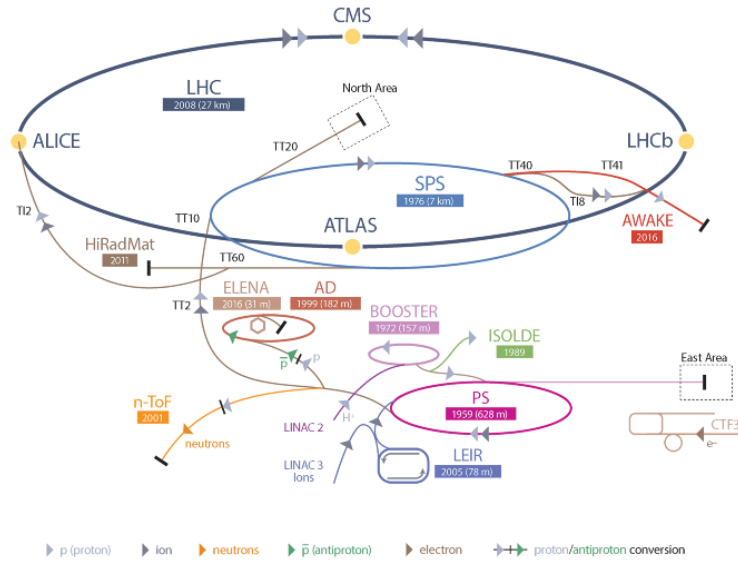


Figure 3.1: The LHC Accelerator complex where the protons start at LINAC 2 and go next to the BOOSTER, PS, SPS then arrive at the LHC [52].

At the beginning of the accelerator chain, electrons are stripped from hydrogen ions leaving behind protons that are then fed through a linear accelerator (LINAC) and boosters to incrementally accelerate them. Once they reach the Proton Synchrotron (PS) bunch trains are formed spaced at an approximate 7.5 m distance. The last step before reaching the LHC is the Super Proton Synchrotron (SPS) which accelerates the bunches to 450 GeV and then divides the protons into two beams that will circulate the LHC in opposite directions. After about 20 minutes in the LHC, the beams of particles are moving at nearly the speed of light

(0.999997828x the speed of light to be exact) with an energy of 6.5 TeV at its peak per beam for Run 2. The two beams contain 100,000 million protons per bunch with 2808 bunches per beam. When it's time to collide the protons, beams are brought together (referred to as a bunch crossing) every 25 ns.

3.1.1 LHC Components

In order to completely control the particles and collisions, two main aspects are needed in the machine: magnets to modify the particle trajectory and cavities to accelerate and maintain the proton bunches.

The LHC has 9,593 magnets [53] of various types. The main ones used are dipoles, of which there are 1232 and they are the largest magnets, and 392 quadrupoles. The dipole magnets utilize the idea of superconductivity, which states that when cooling a material down to extremely low temperatures, electrical current resistance drops to zero. A lack of electrical resistance allows current to flow freely without heating up the magnets. This means that the current can be stronger than if non-superconducting magnets were used, which leads to higher energy particles being accelerated. The magnets are cooled using helium which, at the LHC operational temperatures of 1.9 K, becomes a super-fluid. Each dipole is 15 meters long and produces a magnetic field of 8.3 T which bends the beams. This field has to be large as the maximum energy of each beam is proportional to this strength. While all magnets in the LHC are important, the other type to specifically mention are the quadrupole magnets. These magnets are responsible for focusing the beams in two directions to compress the bunches to the smallest possible size. This is necessary as during collision we want to maximize the likelihood of protons colliding head-on instead of either missing each other or just glancing off one another.

The cavities of the LHC are highly important as within them are where the particles are actually accelerated. Radio frequency (r.f.) electric fields are maintained within each cavity to boost the charged particles as they enter. Additionally, each r.f. cavity oscillates so that protons are accelerated or decelerated depending on when they enter. This sorts the beam into the desired bunches. To achieve these desired effects, the cavities are long, straight sections of the LHC connected by arcs that contain the dipole magnets, which is shown in Figure 3.2. Also shown in the figure are the four main collision points: CMS, ATLAS, LHCb, and ALICE. ATLAS and CMS are the two general purpose detectors that focus on proton-proton collisions but both are able to utilize heavy ion data as well. The LHCb experiment is specialized to study flavor physics with aims to understand the matter/antimatter asymmetry and investigate other symmetry violations. The ALICE experiment is the only dedicated heavy-ion experiment of the four main large experiments on the main LHC ring. A main interest of the ALICE experiment is to study quark-gluon plasma.

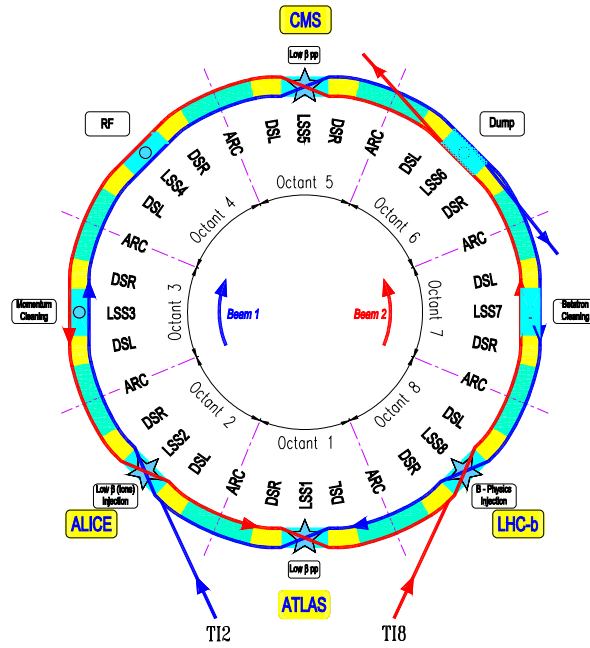


Figure 3.2: Schematic layout of the LHC showing arcs and straight sections and the beam rotations [51].

3.1.2 LHC Data Delivery

The LHC delivers collisions to all detectors on the ring and the amount of data collected is measured in terms of integrated luminosity, which is given by taking an integral over time of the instantaneous luminosity $\mathcal{L} = \int L_i dt$. The instantaneous luminosity L_i for a Gaussian beam is proportional to the number of particles per bunch (squared), the number of bunches, and the frequency of revolution around the accelerator, and is inversely proportional to the beam size [51]. It is measured in units of $area^{-2}$, specifically in units of inverse femto-barns (fb^{-1}) where $1b = 10^{-23} m^2$. Figure 3.3 shows the amount of data collected during Run 2 by the ATLAS detector.

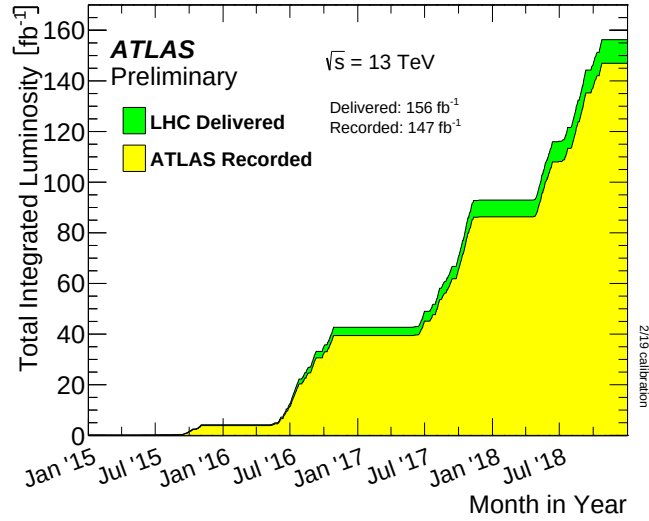


Figure 3.3: Graph of the total integrated luminosity over time during Run 2 of the LHC [54].

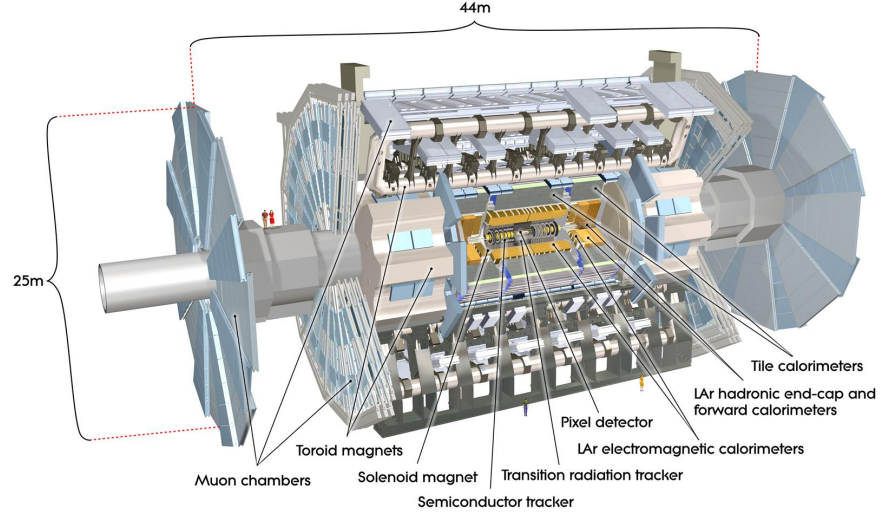


Figure 3.4: Representation of the ATLAS detector with 2 people outside the left muon chamber for scale [55].

3.2 The ATLAS Detector

The ATLAS (**A Toroidal LHC ApparatuS**) experiment [56] is the largest volume particle detector and sits on the LHC ring opposite of CMS. The detector itself, represented in Figure 3.4, is 25 m high, 25 m wide, and roughly 45 m long, sitting 100 m underground. The main detector subsystems are the inner tracking detector, calorimeters, magnets, and a muon spectrometer. These systems are forward-backward symmetric and provide full solid angle coverage for each collision.

Each of these subsystems come together to give a full picture of the interactions occurring within the ATLAS detector. Each system is designed to target the reconstruction of certain particles. A representation of the main particle types and how they interact with the detector is shown in Figure 3.5.

ATLAS uses a right-handed coordinate system and places the origin at the interaction point. The z -axis is placed along the beamline, the x -axis point from the origin to the

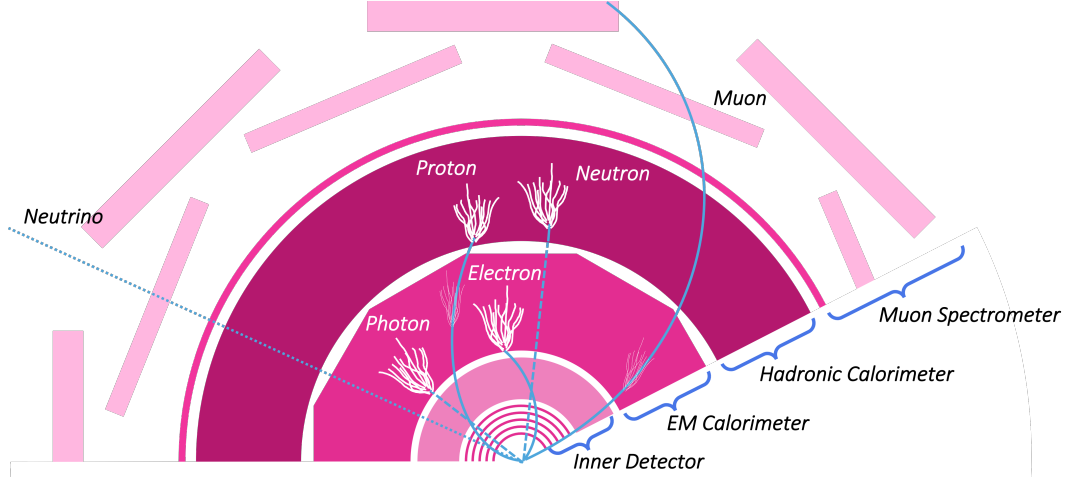


Figure 3.5: Representation how each particle interacts with the main subdetectors. Dashed lines represent no interaction and particle showers and pictured in white in the respective calorimeter.

center of the LHC ring, and the y-axis points upwards towards the surface. More often however, the coordinates referred to will be ϕ and something related to θ . The coordinate ϕ is the azimuthal angle which measures radially outwards in the x-y plane around the z-axis. Rapidity y is measured as $\frac{1}{2} \ln\left(\frac{E+p_z}{E-p_z}\right)$ where p_z is the component of the particle's momentum along the beamline. Typically the pseudo-rapidity coordinate η is used along with ϕ as η is approximately equal to rapidity in the limit of $m \ll \vec{p}$ and is related to θ by $\eta = -\ln(\tan(\frac{\theta}{2}))$ which is measured along the beamline as shown in Figure 3.6.

Other quantities measured within the detector are ΔR between two objects which is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Two impact parameters are defined to measure displacement from the interaction point. The transverse impact parameter d_0 is the distance of closest approach to the primary interaction in the x-y plane, while the longitudinal impact parameter z_0 is the distance along the beamline between a particle track and the interaction point.

In this dissertation, all energy and momentum quantities are usually measured and reported in terms of their transverse components as E_T and p_T , respectively. This transverse portion is perpendicular to the beamline (as the detector is built radially outwards from the

beamline). For massless particles, the transverse energy and transverse momentum are used interchangeably¹.

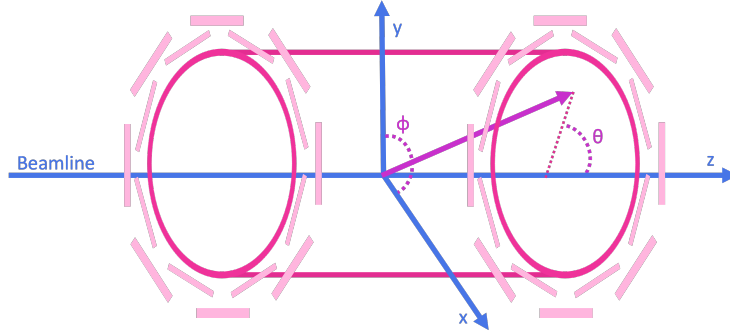


Figure 3.6: Representation of the coordinate system within ATLAS.

Magnet System

Immediately after collision, any charged particles are influenced by a magnetic field. A solenoid magnet surrounds the inner detector along the beamline with a field strength of 2 T using 1173 turns per coil. The purpose of this central magnet is to bend the trajectories of charged particles within the inner detector which, based on the radius of curvature of the path, helps determine the particle's charge and momentum. This system is also surrounded by three air-core toroid magnets (a distinguishing feature of ATLAS and its namesake), each using a series of eight coils arranged symmetrically around the beam pipe to produce a magnetic field of 3.5 T. Two are at the end-caps of the detector with 116 turns per coil on each and one larger toroidal magnet is at the center of the detector with 120 turns. The purpose of these iconic magnets is to aid in measuring the momentum of muons specifically. A sketch of this magnet system within ATLAS is shown in Figure 3.7.

¹This is obvious when considering the energy-momentum relation which states $E^2 = (pc)^2 + (mc^2)^2$ since the mass is negligible at the energies considered and $c = 1$ in natural units, we are left with the relation $E^2 = p^2$.

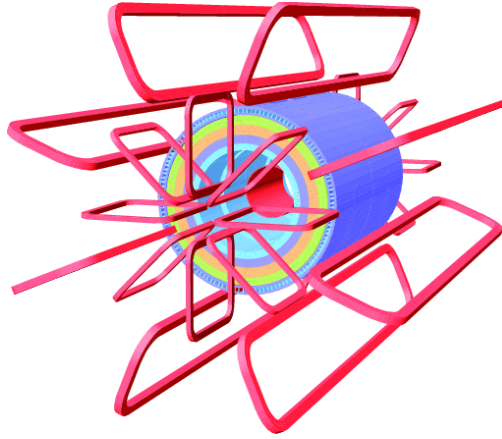


Figure 3.7: Illustration of the magnet systems in ATLAS showing the central solenoid and three toroidal magnets [57].

Inner Detector

The inner detector (ID) [58] consists of three main systems with the Pixel detector being the closest to the beam, the Semiconductor Tracker (SCT) as the next layer, and the Transition Radiation Tracker (TRT) surrounding the other two as shown in Figure 3.8. Typically, as a particle traverses the inner detector with $\eta < 2.0$, the path of a particle (its “track”) would have 3 pixel cluster hits, 8 SCT strip cluster hits, and more than 30 TRT straw hits.

Pixel Detector The Pixel detector [59] is a fine-granularity detector which uses layers of silicon pixel modules to measure energy deposited by charged particles. Silicon is used as it is a semiconductor that is p- or n-doped and has a reverse-bias. The doping creates impurities that introduces electron holes or extra electron carriers respectively. As a charged particles passes though a module, an electron is knocked out of place to create or replace a hole producing an electric signal that is recorded. The reverse-bias on the silicon is from an external voltage that creates an electric field which helps move those freed up electrons to where they can be read out. The pixels have good spatial resolution

allowing for precision measurements to determine the impact parameters and aid in the identification and reconstruction of primary and secondary vertices. The Pixel detector is the main source for identifying objects originating from or containing b -quarks (b -tagging is discussed further in Chapter 5). The Insertable B-Layer (IBL) was later added to the Pixel detector to improve b -tagging performance and to mitigate the impact of degradation on the pixels due to radiation effects [60]. In total, there are 1456 modules in the barrel region of the detector and another 144 modules per endcap giving a total of 1744 pixel modules. All modules are identical and contain 46,080 pixel electronics channels. For the entire detector, this amounts to approximately 80 million pixels which, with a size of 50 microns in the ϕ direction and 400 microns in z , they cover a total active area of about $1.7m^2$.

Semiconductor Tracker The SCT [61] uses silicon microstrips to get eight precision measurements per track. The strips are arranged in four concentric barrels containing 2112 of these silicon strip detector modules and two end-caps with 9 disks containing 988 modules per end-cap. Each module is parallel to the magnetic field of the detector and contains four silicon-strip sensors that are approximately 12 cm long and contain 768 readout strips. In total, the detector contains $61m^2$ of silicon detectors with just over 6 million readout channels.

Transition Radiation Tracker Charged particles pass through the pixels and silicon strips then next through the TRT, which is a straw detector. The TRT [62] is made up of long tubes filled with a gas mixture of Ar , CO_2 , and O_2 with a gold-plated tungsten wire down the center of the tube. As a charged particle passes through the tube, the gas inside ionizes producing an electronic signal as free electrons drift towards the wire. The TRT takes things a step further by surrounding the tubes with polymer fibers and foils in the barrel and end-caps which creates transition radiation as a particle moves between materials. This radiation is absorbed by the argon atoms which produces a signal as additional energy is deposited. Specifically, as a relativistic particle with Lorentz factor $\gamma = E/mc^2$ traverses

through at a given energy, the amount of radiation is dependent on the mass of the particle. More transition radiation occurs with electrons than other less massive objects, like pions, which helps reject these potential electron-fakes passing through the tubes. The ID covers tracks left by charged particles out to $|\eta| < 2.0$. The barrel region of the detector is covered by 52,544 straw tubes parallel to the beamline while the endcaps use 122,880 each that are perpendicular. Each tube is 1.5 m long and 4.4 cm in diameter.

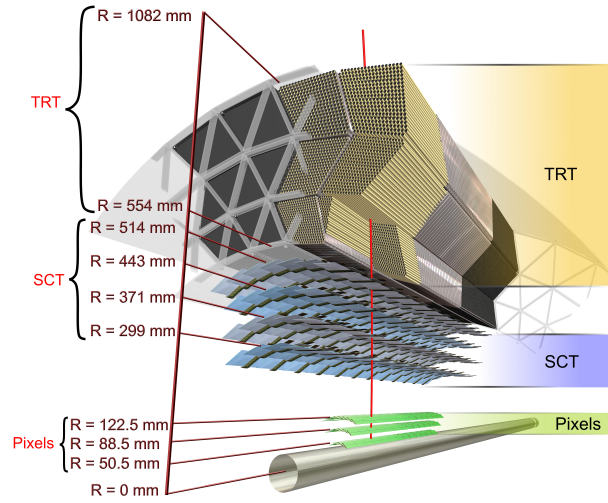


Figure 3.8: Schematic of the Inner Detector, separating out the Pixels, SCT, and TRT and showing the IBL around the beam pipe [63].

Calorimeters

There are two types of calorimeters in the ATLAS detector, an electromagnetic (EM) and a hadronic calorimeter. Each calorimeter is designed with the intention of forcing a certain type of particle to deposit all of its energy as it travels through the material. The EM calorimeter [64] is a lead and liquid-argon (LAr) detector that has an accordion geometry.

Electrons and photons are the target particles as when they pass through the structure, they get stopped by the lead plates which causes them to create a “shower” of lower energy particles. As the electron can emit photons then photons can convert into e^+e^- pairs. A shower is this continuous cascade of particles decrease in energy until they are too low in energy to repeat the process. A signal is produced by the electric current that is generated when those new, lower energy particles ionize the liquid-argon. The LAr electromagnetic calorimeter consists of a barrel section that surrounds the inner detector with a coverage of $|\eta| < 1.47$ and two end-caps covering the range cover $1.37 < |\eta| < 3.2$. There is a crack region when transitioning between the barrel and end-caps meaning a lot of material for particles to traverse though and the potential interactions are not well understood, so the region of $1.37 < |\eta| < 1.52$ is not used for precision physics. In both analyses presented in this dissertation, photons within this region are rejected. The hadronic calorimeters surround the LAr calorimeter and cover ranges up to $|\eta| < 4.9$. Around the barrel is the Tile calorimeter which uses iron plates and plastic scintillating tiles. It is split into one barrel and two extended barrels with coverage of $|\eta| < 1.0$ and $0.8 < |\eta| < 1.7$, respectively. The Tile calorimeter operates with the same general idea as the EM calorimeter with an iron absorber and using the plastic scintillating tiles as the active material that measures the energy. Though, the hadronic calorimeter aims instead to measure the energy of composite particles (hadrons). Beyond the barrel there is a LAr hadronic calorimeter wheel at each end-cap made with copper plates which covers $1.5 < |\eta| < 3.2$ and the Forward Calorimeter covering the remaining $3.1 < |\eta| < 4.9$ space made with copper and tungsten as the absorbing materials along with the liquid-argon as the active medium. All calorimeters are shown graphically in Figure 3.9. The radiation length within the LAr calorimeter is more than 25 [65] and the interaction length of around 10 for the hadronic calorimeter [66].

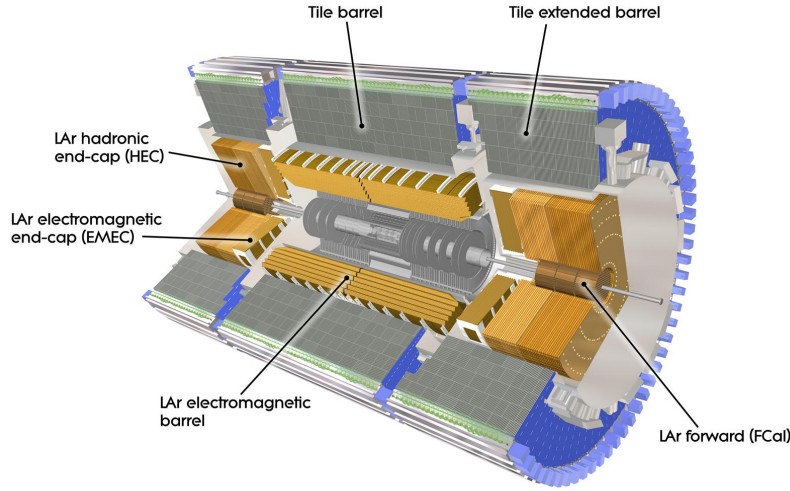


Figure 3.9: Graphical representation of the ATLAS calorimeter system [55].

Muon Spectrometers

Most particles will decay or be absorbed by the calorimeters as they traverse the detector. However, some particles like muons and neutrinos², interact very minimally with those materials meaning they are hard to detect and have a long lifetime before they decay. A special muon spectrometer is constructed to reconstruct muons as their trajectories are altered by the aforementioned air-core toroid magnets as they electrically charged. Four detector technologies are used: Monitored Drift Tubes (MDTs), Cathode Strip Chambers (CSCs), Resistive Plate Chambers (RPCs), and Thin Gap Chambers (TGCs) as shown in Figure 3.10 [67]. Each muon, when influenced by the various toroid magnets, should pass through three chambers depositing energy along the way. Each subsystem of the muon spectrometer is meant to provide a complimentary measurement that, when put all together, gives the full reconstruction of the particle. The TGCs and RPCs are for triggering and obtaining coordinate information at the endcaps or in the central region of the detector, respectively.

²Neutrinos do not interact with the detector so are instead identified through the missing energy calculations.

The CSCs provide a precise coordinate measurement at the ends of the detector and the MDTs are used to measure the curves of tracks.

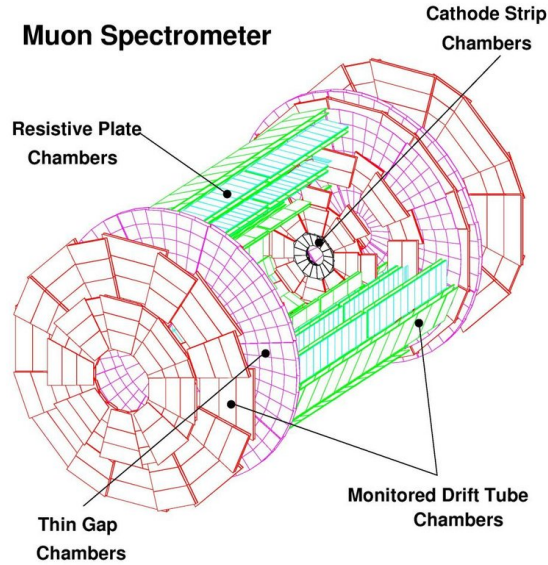


Figure 3.10: Schematic of the ATLAS muon system [67].

Trigger System

All components of the ATLAS detector provide each particle's track and energy deposition information to the trigger system for readout and recording. An event is a bunch crossing that occurs every 25 ns. Within each event, many interactions can occur, lighting up the detector with signal hits. However, limitations on modern technology prevent all of this information to be recorded every 25 ns for a prolonged period of time. In addition to it just being too much, not all bunch crossings result in head-on proton collisions producing interesting interactions. Therefore, a trigger system is required that runs over the data as it is collected to decide which events to record and which to throw away. The trigger has two main systems that process information, the Level-1 (L1) trigger and the High Level Trigger (HLT). The L1

system is hardware-based and has a separate system for the calorimeters (L1Calo) and muon system (L1Muon). This system uses basic information like energy deposits, multiplicity, or topological requirements to select events. Decisions from the L1 trigger system are made within 2.5 ms after the event occurs. From here, these events are sent to the software-based HLT and its subsystems where pattern recognition, and track-finding algorithms are run to identify an event based on various trigger criteria. The HLT decision occurs within 200 ms and can send 1000 events per second to be recorded. For example, for the diphoton triggers used in this analysis, there must be tracks reconstructed that is consistent with two isolated photons of a certain minimum energy. Another factor to consider when designing the trigger is mitigating pileup. Each bunch crossing contains up to 10^{11} protons, meaning that more than one interaction is likely per collision. These additional interactions are considered pileup. The ATLAS trigger system has to sift through the pileup to try to trigger on only interesting hard-scatter processes, which can entail correctly identifying the main collision, the primary vertex, and the interaction that follows. For each run, a list of specific triggers are decided on by experts and the collaboration to decide which processes are considered “interesting”.

CHAPTER 4

DATA AND SIMULATION

To measure the Higgs boson cross-section and diphoton + heavy flavor jet production the data are compared to predictions from Monte Carlo (MC) simulations. The following chapter gives an overview of the data collected by the ATLAS detector that is used and how simulation samples are generated.

4.1 Monte Carlo Simulation

To simulate event information (collisions, interactions, decays, etc.), a MC method is used. During event generation, the initial and final state is specified along with a few additional kinematic constraints, leaving all other physics processes unspecified. For example, one can generate $pp \rightarrow H \rightarrow \gamma\gamma$, specifying the initial energies of the incoming protons and the final decay products, but the momentum of each photon can be a range of values allowed by the physics of the decay. Else, constraints can be set on the photons so that each photon carries a momentum value > 20 GeV, on the angular separation between the photons, etc. The Monte Carlo method relies on random sampling to choose values for all of the remaining free parameters. To start, a calculation is done to determine how likely a certain initial-to-final-state transition is to occur using the Parton Distribution Functions mentioned in Chapter 2.2. These calculations are performed to a given order in perturbation theory: Leading-Order (LO), Next-to-Leading Order, Next-to-Next-to Leading order, etc. (NLO, NNLO, N³LO, ...). Higher order calculations give a more accurate prediction, though may be too computationally

intensive for some interactions. When generating events, parton showering, which models each parton splitting into two new partons, is performed. This splitting is continued until no further momentum transfer is possible. Additional underlying event information is produced to account for multi-parton interactions and additional scattering which can be due to initial or final state radiation. With these partonic processes simulated, a hadronization step is performed. This step transforms the showers into the colorless bound states that are required for all particles carrying color charge. Jets, which are collimated sprays of particles, are formed during parton-parton showering. An example of these processes is shown in Figure 4.1 showing the interaction of two particles and ending with two final state jets.

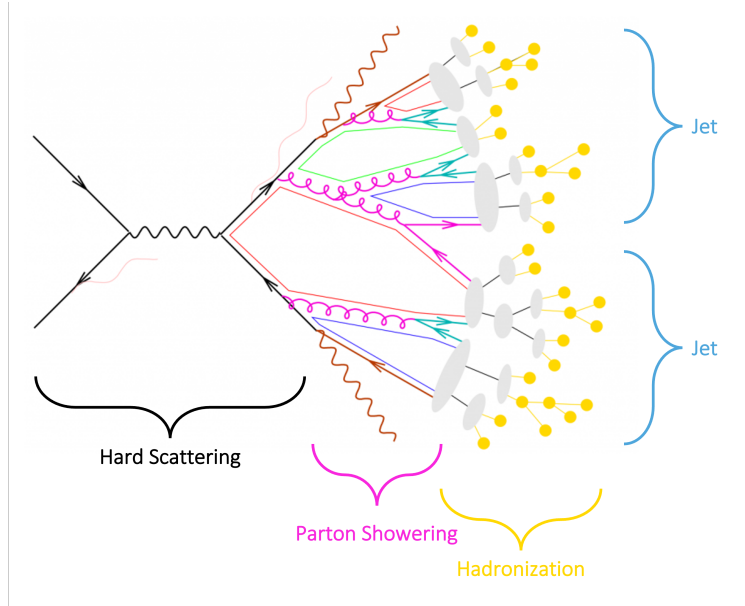


Figure 4.1: Example illustration of hard scattering, showering, and hadronization that occurs during event simulation of two jets. [68].

The main generators used for simulation samples in this dissertation are SHERPA [69], MADGRAPH5_aMC@NLO [70], and POWHEG [71]. The parton showering was either performed after generation in SHERPA directly, or else using PYTHIA8 [72] or HERWIG7 [73]. The software used for each simulation sample used is shown in Table 4.1.

Table 4.1: List of all simulation samples and the generator + parton showering software used.

Process	Generator + PS
$t\bar{t}$	SHERPA (ME@NLO+PS)
$t\bar{t}\gamma$	MG5_aMC@NLO+PYTHIA
$t\bar{t}\gamma\gamma$	MG5_aMC@NLO+PYTHIA
$Z\gamma\gamma$	SHERPA (ME@NLO+PS)
$HH \rightarrow bb\gamma\gamma$	POWHEG + PYTHIA
Diphoton + Jets Production	
$\gamma\gamma$	SHERPA (ME@NLO+PS)
$\gamma\gamma + 2 \text{ jets}$	MG5_aMC@NLO+PYTHIA
$\gamma\gamma + bb$	SHERPA (ME@NLO+PS)
Higgs Samples (by Production Mode)	
ggF	POWHEG + PYTHIA
VBF	POWHEG + PYTHIA
$W^\pm H$	POWHEG + PYTHIA
ZH	POWHEG + PYTHIA
$t\bar{t}H$	POWHEG + PYTHIA
$b\bar{b}H$	POWHEG + PYTHIA
$tHjb$	AMC@NLO + HERWIG
tWH	AMC@NLO + HERWIG

A Dalitz decay [74] occurs when forcing diphoton decays of the Higgs boson. The process has a final state of any two fermions f , excluding the top quark, and one photon $H \rightarrow \gamma\gamma^* \rightarrow \gamma f\bar{f}$. Though as these events do not have a stable diphoton final state, they are not considered to be part of the fiducial volume. However, these types of events are generated by PYTHIA during showering and need to be accounted for and removed. This process makes up roughly 6% of generated events and most are identified and removed. The remaining Dalitz events that pass selections make up roughly 0.4% of all reconstructed events. When they are removed, the simulation needs to be reweighted to account for the change to maintain the correct normalization.

The MC samples are split up to match beam and detector conditions for each data-taking period during Run 2. For the 2015 period, a dedicated simulation is created, denoted as mc16a. The 2016 and 2017 runs had similar enough conditions that only one set of simulation

was needed, denoted as mc16d. The final data-taking year, 2018, is modeled by mc16e simulation.

4.1.1 Detector Reconstruction

Generated particles are passed through detector simulation based on GEANT4 [75] which models how the particles will interact with various materials in the ATLAS detector producing measurable signals. These signals are then reconstructed with the same software as the data using the requirements detailed in the following chapter. As this detector simulation process can be very CPU intensive, a fast simulation is developed which replaces the calorimeter response with a parameterization [76]. For samples with a large number of generated events, it is preferable to use this method instead of the full response. Fast simulation is used for the SHERPA diphoton sample as well as for the $t\bar{t}\gamma$ and $t\bar{t}\gamma\gamma$ samples. All simulation samples are overlaid with minimum bias events which are inelastic hadron-hadron events unrelated to the hard-scattering process. These events are weighted to match the distributions of the number of pileup interactions in data.

4.2 Data

All data analyzed was collected by the ATLAS detector during Run 2 which lasted from 2015 to 2018 [77]. The data recorded by the detector is divided up into runs, which are periods of continuous recording. These runs are divided into luminosity blocks, which mark a group of collisions as being under the same trigger configurations, instantaneous luminosity, detector, and data quality conditions [78]. To ensure data quality, a Good Run List (GRL) is used as a reference for each data-taking period. The GRL uses the luminosity blocks to list

which runs are certified for physics analysis and only data during those periods are considered by physics analyses. The total size of the dataset is given by the integrated luminosity which, for the full Run 2 dataset, was 139 fb^{-1} . During Run 2, the average number of interactions per bunch-crossing was calculated as shown in Figure 4.2. As the luminosity increased, so did the number of pileup interactions.

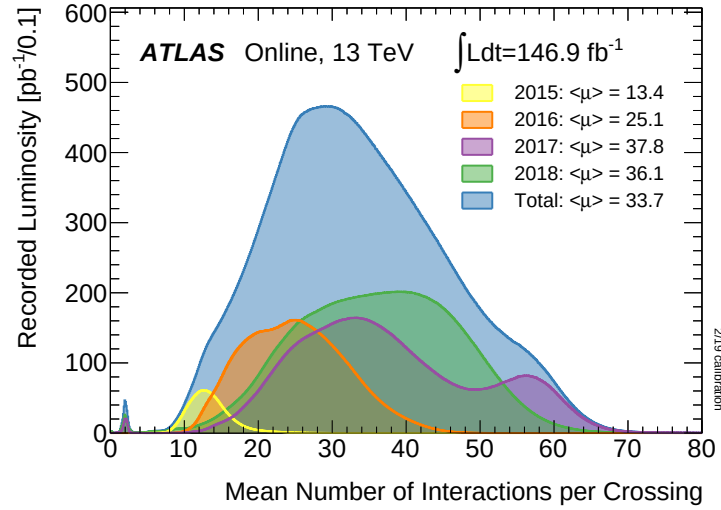


Figure 4.2: Average number of interactions per proton bunch crossing at the LHC per year and as a total for the full Run 2 dataset [54].

4.2.1 Triggers

As mentioned in Chapter 3.2, during data-taking a trigger system is used to decide which events to record. For this dissertation, events were required to pass specific diphoton triggers that were based on shape of the showering in the electromagnetic calorimeter and energy deposit thresholds. These shower shape requirements are less strict than those required in later selections as detailed in Chapter 5. The triggers require checks based on the L1 trigger information, as well as the High Level Trigger. The main trigger for 2015-2016

data (`HLT_g35_loose_g25_loose`) requires energy deposits consistent with photons to be greater than 15 GeV at Level-1 and the HLT must identify two energy signatures from photons at a minimum of 35 and 25 GeV respectively. An additional trigger on the HLT only is used for 2015 and for part of 2016 (`HLT_2g20_tight`) which has an E_T threshold of 20 GeV. For the rest of the 2016 data run the trigger threshold was raised from 20 to 22 GeV. For 2017-2018, to cope with pileup slightly tighter requirements on the shower shape were implemented along with higher baseline E_T thresholds. The 2-part trigger used (`HLT_g35_medium_g25_medium_L12EM20VH`) had a minimum L1 energy threshold of 20 GeV, but the same HLT leading and subleading energies of 35 and 25 GeV as 2015-2016 data. The HLT-only trigger for 2017-2018 requires the 22 GeV threshold to match with the later half of the 2016 run. These requirements are summarized in Table 4.2. The trigger efficiency was studied for $H \rightarrow \gamma\gamma$ selections is taken to be more than 98%.

Table 4.2: Breakdown of the L1 and HLT trigger requirements per data-taking period.

Trigger	Period Used	L1 Requirements	HLT Requirements
<code>HLT_g35_loose_g25_loose</code>	2015, 2016	$2 \times E_T > 15 \text{ GeV}$	$E_T^{\gamma 1} > 35 \text{ GeV}$ $E_T^{\gamma 2} > 25 \text{ GeV}$
<code>HLT_2g20_tight</code>	2015, 2016	-	$E_T^{\gamma 1,2} > 20 \text{ GeV}$
<code>HLT_g35_medium_g25_medium_L12EM20VH</code>	2015, 2016	$2 \times E_T > 25 \text{ GeV}$	$E_T^{\gamma 1} > 35 \text{ GeV}$ $E_T^{\gamma 2} > 25 \text{ GeV}$
<code>HLT_2g22_tight</code>	2016-2018	-	$E_T^{\gamma 1,2} > 22 \text{ GeV}$

CHAPTER 5

OBJECT RECONSTRUCTION AND IDENTIFICATION

As detailed in Chapter 3.2, there are multiple regions in the ATLAS detector. These include the tracker, calorimeters, and muon spectrometers. As a particle traverses the detector interactions can occur that create a measurable signal. The information from the regions can be combined to recreate the object’s path and kinematic properties. The detector was designed so that each particle type can create a fairly unique signature to help with identification (see Figure 3.5), though this is not foolproof. As objects in the detector are only “seen” via the interactions and signals they create within the detector, it is possible to incorrectly identify an object as something similar. In the analyses presented in this dissertation, the most commonly confused objects are jets and electrons misidentified as photons. Additional steps are taken to reduce these mistake based on the properties of each object. The treatments described below are performed identically on both data and simulation.

5.1 Photons

For an object to be considered a photon, there are identification and isolation requirements that go into the event preselections.

In general, photons in the detector are either prompt or background and can be converted or unconverted. Prompt photons are those that arise during the collision as a result of hard scattering and are produced before hadronization. These are classified differently than

background photons which originate from hadronic decays or radiation. In both analyses in this dissertation target prompt photons. Any photon can remain unconverted or convert into an electron-positron pair. To identify converted photons, a conversion vertex must be identified that tracks back to an electromagnetic cluster. To distinguish from electrons that are not from a converted photon, conversion vertices with only one track must not have any hits in the inner-most layers of the tracker while vertices that contain two tracks must be of opposite sign and have an invariant mass of zero. Both converted and unconverted photons are considered in the analyses. Roughly 70% of the photons passing selections will be unconverted.

The trigger thresholds set the baseline scale for the photon energy where candidates must have a minimum $E_T > 22$ GeV. A check must also be done to ensure that the leading and subleading photons (the two highest E_T candidates) match the original diphoton trigger objects mentioned in Chapter 4.2 using a distancing algorithm. As a further part in identification, a sliding-window algorithm creates clusters based on seeds in the EM calorimeter [79]. These clusters cover the region $|\eta| < 2.5$ and have a size of $\Delta\eta \times \Delta\phi = 0.075 \times 0.1213$ with a minimum transverse momentum of 2.5 GeV. These seeds are loosely matched to tracks in the inner detector and then an interaction vertex is defined. From here, there are four main types of variables used in photon identification which are related to detector acceptance, hadronic leakage, and the electromagnetic middle and strip layers of the reconstructed photon cluster [80]. All photons must fall within the a detector acceptance of $|\eta| < 2.37$ but exclude the crack region $1.37 < |\eta| < 1.52$ to continue in the selections. The discriminating variables for all photon candidates are as follows and are represented pictorially in Figure 5.1:

- $R_{\text{had}} = E_{\text{T}}^{\text{Had}}/E_{\text{T}}$: The ratio of energy behind the photon in the hadronic calorimeter cluster to the energy of the photon cluster in the EM calorimeter

- $R_{\text{had}_1} = E_{\text{T}}^{\text{Had}_1}/E_{\text{T}}$: The ratio of energy in the first sampling layer of the hadronic calorimeter to the energy of the photon cluster in the EM calorimeter
- $R_{\eta} = E_{3 \times 7}^{S2}/E_{7 \times 7}^{S2}$: Ratio of cell energies between $\Delta\eta \times \Delta\phi = 3 \times 7$ set and a 7×7 set of cells with variation only in the η direction that are centered on the photon cluster in the second layer of the EM calorimeter
- $R_{\phi} = E_{3 \times 3}^{S2}/E_{3 \times 7}^{S2}$: Similar to R_{η} but with the variation in the ϕ direction
- ω_{η_2} : Lateral shower width in a $\Delta\eta \times \Delta\phi = 3 \times 5$ cell region in the second layer of the EM calorimeter that is centered around the photon cluster
- ω_{s_3} : Shower width calculated by identifying the strip in the first layer of the EM calorimeter with the maximum energy deposit and considering the preceding and succeeding strips
- $\omega_{s_{\text{tot}}}$: Total lateral shower width using all strips
- $F_{\text{side}} = (E_{7 \times 1}^{S1} - E_{3 \times 1}^{S1})/E_{3 \times 1}^{S1}$: Fraction of energy deposited outside of the three core strips but within seven strips divided by the energy within the three core strips
- $\Delta E = E_{\text{max},2}^{S1} - E_{\text{min}}^{S1}$: Difference in energy between the second maximum deposit in the strip layer and the minimum value between the first and second maxima
- E_{ratio} : Ratio of the energy difference of the two largest energy deposits in strip layers to the sum of these energies

Based on the above variables, various levels of identification are defined ranging from loose to tight. Unless otherwise stated (like when determining jets-faking-photons), both photon candidates are required to pass tight identification requirements. The variables for each level are reported in Table 5.1 which also includes LoosePrimeN definitions which are used in

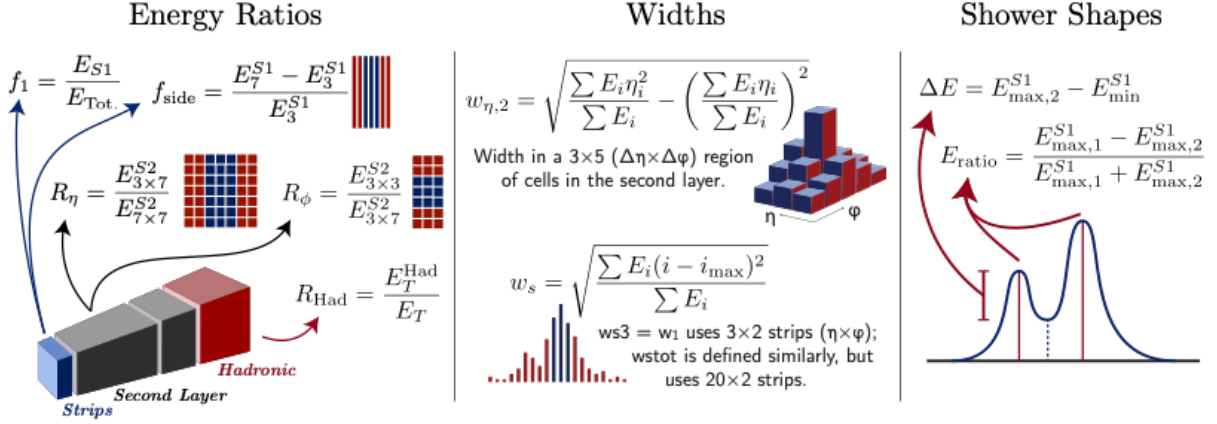


Figure 5.1: Representation of the photon identification discriminating variables [80].

background studies and removes N number of requirements from the Tight ID. The definitions used are LoosePrime2, LoosePrime3, and LoosePrime5. The definition that corresponds to LoosePrime4 removed the ω_{stot} requirement compared to the previous cut, however due to some tightening of the trigger, this definition was then equivalent to LoosePrime3, though the naming conventions are kept, so it was dropped from consideration.

Table 5.1: The variables used to determine the definitions of the Loose, Tight, and LoosePrime selections.

Category	Variable	Loose	LoosePrime2	LoosePrime3	LoosePrime5	Tight
Hadronic Leakage	R_{had}	✗	✗	✗	✗	✗
	R_{had1}	✗	✗	✗	✗	✗
EM Middle Layer	R_η	✗	✗	✗	✗	✗
	R_ϕ		✗	✗	✗	✗
	$\omega_{\eta 2}$	✗	✗	✗	✗	✗
EM Strip Layer	E_{ratio}		✗	✗		✗
	ω_{stot}		✗	✗		✗
	ΔE		✗			✗
	F_{side}					✗
	ω_{s3}					✗

Photon candidates must be isolated from significant activity of other objects in an effort to further reject photons emitted by hadronic jets (e.g. $\pi^0 \rightarrow \gamma\gamma$). These isolation requirements

are track and calorimeter-based within a ΔR requirement around the photon with a cut on the transverse energy within the ΔR cone. The calorimeter based cut is calculated using the Σp_T of the topoclusters within $\Delta R = 0.2$ which must be $< 6.5\%$ of E_T^γ . For track-based isolation, the Σp_T must be $< 5\% E_T^\gamma$ when considering tracks within $\Delta R = 0.2$ with $p_T > 1$ GeV and originating from the same diphoton vertex.

Once the two photons with the highest momentum in an event are identified, an additional check is made to ensure that both photons came from the same interaction point (the diphoton vertex). Any particles that cannot be traced back to the identified primary diphoton vertex will be considered as coming from a pileup interaction. Each vertex candidate is considered and the diphoton production vertex is chosen using a neural network. The algorithm is trained on $H \rightarrow \gamma\gamma$ events through gluon-gluon fusion for the Higgs boson production [81], which is the dominant production mode at the LHC. The position along the beamline of all photon objects, the summed transverse momenta of tracks (Σp_t and Σp_t^2), and the azimuthal angle between the diphoton system and all tracks are inputs to the algorithm. The efficiency to select the correct production vertex is studied in $Z \rightarrow ee$ events where the electron tracks are removed. Agreement was found between the efficiency values in both data and simulation. Once the primary vertex is identified, each photon candidate's trajectory is recalculated to take this origin into account to improve the inclusive diphoton invariant mass resolution.

5.2 Jets

As quarks hadronize to form colorless bound states, QCD interactions occur and the particles emitted will be bunched in a way that allows them to be reconstructed as a single object called a jet. These objects are reconstructed using the anti- k_T algorithm [82] which identifies a cone of space with radius of $R = 0.4$ in the detector around the final state object

to capture the full energy deposited. Information from the tracker and calorimeters is also fed into a particle-flow algorithm [83] to further identify jet kinematics. This particle-flow algorithm creates a topological cluster from the calorimeter cell signals which contain shape and location information. Overlap between the momentum of tracks from charged hadrons in the inner detector and the topoclusters is removed via a subtraction process. If the particles in the cluster are not associated with the diphoton primary vertex selected by the neural network, the energy deposited by the particle in the calorimeter is subtracted from the cluster. This is then replaced by the momentum of any tracks that can be matched to the cluster. This removal of energy deposits of charged hadrons and instead using their momenta results in an increase in the measurement accuracy. Quality cuts are established to suppress noise in the calorimeter or pileup by requiring jets to have $|y| < 4.4$ and $p_T > 25$ GeV. A jet-vertex tagger (JVT) [84] is employed on jets with $|\eta| < 2.5$ to suppress pileup based on a k-nearest neighbor (kNN) algorithm using track momentum information to discriminate. The requirements on the JVT multivariate discriminant are only applied to jets with $20 < p_T < 60$. Any jets with $|\eta| > 2.5$, which are outside of the tracker acceptance, pass through an additional forward JVT (fJVT) algorithm [85].

5.2.1 *b*-tagging

These algorithms exploit the long lifetime, high mass and high decay multiplicity of *b*-hadrons as well as the properties of the *b*-quark fragmentation

Of particular interest are jets originating from hadrons containing *b* quarks. Jet flavor labeling is done for *b*- and *c*-hadrons, where a jet is labeled as one of these if the hadron is within $\Delta R < 0.3$ mm of the jet axis. If more than one jet matches to the hadron, the jet closest in ΔR is labeled with the flavor. A specialized algorithm, DL1r, is used to identify

these jets originating from bottom, charm, or other light quarks based on a deep-learning neural-network [86]. As the lifetime of the bottom quark is longer than that of lighter flavors, the hadronization chain will be displaced compared to the primary vertex (meaning a larger d_0). The DL1r algorithm exploits this long life-time along with the high mass and high decay multiplicity of b -hadrons to distinguish them. This identification of b -jets relies on track information from the inner detector, primary vertex identification, and hadronic jet reconstruction and track-jet matching. The algorithm was trained on a hybrid sample with $t\bar{t}$ and Z' simulated events to get a full p_T range for the considered jets. The output discriminant is based on the probabilities that a jet can be one of the three flavors (b , c , or light). These discriminant distributions are divided into five pseudo-continuous bins and are delimited at values of 85%, 77%, 70%, and 60% efficiency. The higher the efficiency point the more b -jets are accepted by the algorithm, however the contamination of c - and light-flavor jets also increases. The 60% efficiency working point (WP) is considered the tightest as it has the highest purity of true b -jets.

5.3 Charged Leptons

In general, events with electrons or muons in the final state are not considered in either analysis presented in this dissertation, with the exception of a specific lepton region when computing the Higgs boson fiducial cross-section. Electrons, like photons, are reconstructed from clusters in the EM calorimeter and tracks from the inner detector [87]. Muons, however, use information from the muon spectrometers along with inner detector tracks [88]. Both objects must have a $p_T > 10$ GeV and have $|\eta| < 2.47$ or $|\eta| < 2.7$ for electron and muons respectively. Both objects must also pass vertex association requirements for the tracks with respect to the diphoton primary vertex as shown in Table 5.2. The requirements on the

impact parameter helps reduce the effect of cosmic muons or electrons from other interactions. Electrons are also required to be isolated within a cone of $R = 0.2$ centered around the electron track. This requirement helps separate electrons from QCD multi-jet backgrounds. An overlap removal process is done between photons, leptons, and jets using a ΔR cut in the following order of priority:

- Remove electrons within $\Delta R = 0.4$ of any photon
- Remove muons within $\Delta R = 0.4$ of any photon
- Remove jets within $\Delta R = 0.4$ of any photon
- Remove jets within $\Delta R = 0.2$ of any electron
- Remove electrons within $\Delta R = 0.4$ of any jet
- Remove muons within $\Delta R = 0.4$ of any jet

Table 5.2: Electron and muon selection criteria.

Selection Criteria	Electron	Muon
Pseudorapidity range	$ \eta < 2.47$ excluding $1.37 < \eta < 1.52$	$ \eta < 2.7$
Track to vertex association	$ d_0/\sigma(d_0) < 5$ $ z_0 \times \sin \theta < 0.5 \text{ mm}$	$ d_0/\sigma(d_0) < 3$ $ z_0 \times \sin \theta < 0.5 \text{ mm}$

5.4 Missing Transverse Energy

As events occur in the z-axis along the beamline, conservation of momentum principles can be applied to determine if any particles were not reconstructed by the detector. As interactions occur and particles enter the x-y (or η - ϕ) plane, the 4-vectors of all objects

depositing energy in the detector is summed. The negative magnitude of this vector sum is the E_T^{miss} of the event. If there are no missed objects, then this sum would be zero as there would be no directional imbalance. This imbalance is commonly caused by non-interacting Standard Model neutrinos that pass through ATLAS undetected¹.

¹This can also be caused by mismeasurements in the detector, however due to requirements on the amount of E_T^{miss} in an event in the analyses presented in this dissertation, this is extremely unlikely to be the source .

CHAPTER 6

HIGGS DIFFERENTIAL AND FIDUCIAL CROSS SECTION MEASUREMENTS IN THE DIPHOTON CHANNEL

This chapter details the measurement of the inclusive and differential fiducial cross-section of the Higgs boson in the diphoton decay channel [89]. Since the Higgs boson discovery in 2012, a large effort within the ATLAS Collaboration has been placed towards testing all predictions from the Standard Model related to this particle. This analysis looks specifically at the diphoton decay channel of the Higgs as it has a very clean final state in the detector and a precise invariant mass peak for reconstructing the Higgs mass. The analysis was conducted using a blinded approach, meaning all fits and optimizations were done before looking at the data in the signal region. The discriminating value defining this region is the diphoton invariant mass ($m_{\gamma\gamma}$). A narrow window is placed around the Higgs mass ($m_{\gamma\gamma} \in 121\text{--}129$ GeV) to determine the signal region. In order to minimize the number of assumptions made, the final state particles are limited to a volume of phase space, called the fiducial volume, that is defined by detector acceptance.

The procedure for the fiducial inclusive and differential analysis is as follows:

- Using the data and simulation samples listed in Chapter 6.1.1, an event selection is applied that defines the inclusive fiducial region in Chapter 6.1.2
- Events are split into additional fiducial regions and the inclusive fiducial volume is further divided into several bins for each of the variables as detailed in Chapter 6.1.3
- The diphoton invariant mass distribution in each bin is analyzed for the signal and background in Chapter 6.2

- The signal yield is extracted for each bin and the distributions are unfolded to the particle-level yields and corrected for detector effects in Chapter 6.3
- The cross-sections are obtained and compared to theoretical models in Chapter 6.5
- The obtained results are interpreted to probe additional aspects of the SM and beyond the SM physics (BSM) in Chapter 6.5.4

6.1 Event Selections and Fiducial Definitions

6.1.1 Data and Simulation Samples

The data used in this analysis is the 2015-2018 Run 2 ATLAS dataset discussed in Chapter 4.2 and the simulation samples described in Chapter 4.1. The signal samples are split by production mode and are listed, along with the background sample used, in Table 6.1 with the corresponding cross-section values and the number of events generated for the analysis [90–95]. The mass of the Higgs in all simulation samples is set to 125.09 GeV [96].

6.1.2 Event Selection

The measurement is performed in the fiducial volume which requires only minimal assumptions and produces a largely model-independent measurement.

The baseline selections are built upon the object prerequisites mentioned in Chapter 5 though now with tighter selections and targeted more towards $H \rightarrow \gamma\gamma$ decays. All selections applied to simulation are also applied to data events are performed as follows:

1. The data must pass initial run quality checks

Table 6.1: List of all signal and background simulation samples used in the Higgs cross-section measurement showing the cross-section of each process given in [fb].

Process	Cross-Section [fb]
Signal	
ggF	110.1404
VBF	8.57833
W^+H	1.90226
W^-H	1.20605
$q\bar{q} \rightarrow ZH$	1.724519
$gg \rightarrow ZH$	0.278529
$t\bar{t}H$	1.149755
$b\bar{b}H$	1.10390
$tHbj$	0.16857
tWH	0.034436
Background	
$\gamma\gamma + \text{jets}, m_{\gamma\gamma} \in 90\text{--}175 \text{ GeV}$	5.1823×10^4

2. Both data and simulation must then pass the diphoton triggers mentioned in Chapter 4.2.1
3. The data has an additional quality check to ensure each event record contains the full detector information
4. The event must have at least one primary vertex candidate
5. There must be at least two photons candidates that pass the loose identification requirements
6. Another quality check is done only for 2016 data and the corresponding MC simulation to remove photons that are in the region where some calorimeter cells were dead during that data-taking period

7. The two photon candidates with the highest transverse momentum (referred to as the hardest) are checked to ensure that they match the photon objects that were triggered on via a distance matching tool
8. Photons must pass asymmetric thresholds of 35 and 25 GeV on the transverse momentum on the leading and subleading photon
9. The two hardest photons are rechecked to pass tight identification and isolation requirements along with an η acceptance check
10. The diphoton system must pass a relative cut $p_T/m_{\gamma\gamma} > 35\%$ and 25% for the leading and subleading photon, respectively
11. Finally, the mass of the combined diphoton system must be within the range $m_{\gamma\gamma} \in [105 - 160]$ to target the 125.09 GeV Higgs mass

For data, the selections are shown in the cutflow listed in Table 6.2 for each data-taking period, detailing the number of events passing each cut and the relative efficiency of the cut between each step. For simulation, the number of events passing each selection cut is shown for ggF simulated events in Table 6.3. The efficiency for an event to pass the full selection in each of the production mode samples is listed in Table 6.4. The mc16a simulation corresponds to the 2016 data, mc16d matches the 2016-2017 data-taking period, and mc16e equates to the 2018 data. The 2015 run had the lowest average number of interactions per bunch-crossing, with the number increasing with each year (see Figure 4.2). This is reflected in a higher efficiency in mc16a compared to mc16d and mc16e. Between different simulated processes, the efficiency can vary due to the kinematics of the events that may impact the individual selections. For example, the efficiency of the photon identification cut increases with the energy of the photon and was optimized on $\gamma + \text{jet}$ events. A larger impact may

also be from the primary vertex selection as it has a strong dependence on the presence of jets or leptons in the event.

Table 6.2: Event selections in data and their relative efficiency compared to the previous cut.

Selection step	2015		2016		2017		2018	
	Events	rel. eff.	Events	rel. eff.	Events	rel. eff.	Events	rel. eff.
GRL	12452692	-	124681288	-	97223552	-	123107840	-
Pass trigger	12200404	98.0%	122364544	98.1%	74409536	76.5%	95320480	77.4%
Detector DQ	12199222	100.0%	122360960	100.0%	74398584	100.0%	95315520	100.0%
Has PV	12199201	100.0%	122360944	100.0%	74398584	100.0%	95315520	100.0%
2 loose photons	3544612	29.1%	36088752	29.5%	20394948	27.4%	26479374	27.8%
dead HV cell veto	3544612	100.0%	36003392	99.8%	20394948	100.0%	26479374	100.0%
Trigger match	2597350	73.3%	26987652	75.0%	11926558	58.5%	16802010	63.5%
tight ID	373747	14.4%	3668597	13.6%	4590772	38.5%	6371438	37.9%
isolation	150788	40.3%	1460976	39.8%	1845892	40.2%	2477688	38.9%
photon $p_T/m_{\gamma\gamma}$ cuts	131211	87.0%	1270606	87.0%	1604111	86.9%	2154394	87.0%
$m_{\gamma\gamma} \in [105, 160]$ GeV	28739	21.9%	283184	22.3%	370229	23.1%	496739	23.1%
Events per fb ⁻¹	8925 $\pm$ 94		8576 $\pm$ 93		8355 $\pm$ 91		8499 $\pm$ 92	

Table 6.3: Event selections in simulated ggF signal events.

Selection step	mc16a		mc16d		mc16e	
	Events	rel. eff.	Events	rel. eff.	Events	rel. eff.
Simulated events	206565168	-	206558544	-	342535104	-
No duplicates	206565168	100.0%	206558544	100.0%	342535104	100.0%
Pass trigger	133940928	64.8%	133238920	64.5%	221122080	64.6%
Has PV	133940928	100.0%	133238920	100.0%	221122080	100.0%
2 loose photons	111583656	83.3%	109957496	82.5%	182221840	82.4%
dead HV cell veto	111352680	99.8%	109957496	100.0%	182221840	100.0%
Trigger match	107462544	95.5%	99091160	90.1%	164492016	90.3%
tight ID	92439592	86.0%	88826752	89.6%	147848288	90.0%
isolation	83112568	89.9%	77150184	86.9%	129633992	87.7%
photon $p_T/m_{\gamma\gamma}$ cuts	77047216	92.7%	72065168	93.4%	120928016	93.3%
$m_{\gamma\gamma} \in [105, 160]$ GeV	77029432	99.9%	72048592	99.9%	120897128	99.9%
Efficiency (%)	37.3		34.9		35.3	

The inclusive fiducial region is defined at the particle level, meaning the selections are based on generation information using only stable final-state particles. No particles included in the region definition can come from GEANT4 simulation of the detector response. Each particle type is represented by a PDGID as defined by the Particle Data Group which is a number used to identify Monte Carlo generated particles [16] and is stored in the truth record for each event. The selection criteria for the inclusive fiducial volume is defined by

Table 6.4: Simulation selection efficiency for each simulation periods and Higgs production mode.

Production Mode	Efficiency (%)		
	mc16a	mc16d	mc16e
ggF	37.3	34.9	35.3
VBF	37.5	35.3	35.6
W^+H	31.0	29.2	29.6
W^-H	34.5	32.4	32.7
$q\bar{q} \rightarrow ZH$	33.2	30.8	31.3
$gg \rightarrow ZH$	40.9	38.8	39.4
$t\bar{t}H$	37.9	35.8	36.2
$b\bar{b}H$	40.5	37.6	37.9
$tHb\bar{j}$	34.7	31.7	32.2
tWH	41.2	38.6	39.5
$\gamma\gamma + \text{jets}, m_{\gamma\gamma} \in 90\text{--}175 \text{ GeV}$	20.9	19.2	18.5

requirements on the truth-level information of photons, leptons, and jets which closely match the requirements for the detector-level particles during reconstruction and are detailed below.

Photons Photons are selected at the particle-level if they have a $PDGID = 22$ and are not produced during hadronization. All photons must have $p_T > 25 \text{ GeV}$ and $|\eta| < 2.37$ excluding the crack region between $1.37 < |\eta| < 1.52$. A particle-level isolation requirement is applied to photons determined by the four-vector sum of all charged particles within a cone of $\Delta R = 0.2$ around the photon with $p_T > 1 \text{ GeV}$. This value must be less than 5% of the p_T of the photon. The two photons with the highest transverse momentum define the diphoton system and their combined invariant mass must fall within the range $m_{\gamma\gamma} \in [105 - 160] \text{ GeV}$. Finally, the photons must pass a relative cut such that $p_T/m_{\gamma\gamma} > 35(25)\%$ for the leading (subleading) photon.

Charged Leptons Particle-level electrons and muons must have $|PDGID| = 11$ or $|PDGID| = 13$, respectively, including the antiparticles and cannot be produced during hadronization. All particle-level leptons must have $p_T > 15 \text{ GeV}$. Electrons must have $|\eta| < 2.47$ excluding the crack region and $|\eta| < 2.7$ for muons. For electrons only, an overlap removal procedure is followed to remove any electron within $\Delta R < 0.4$ of a selected photon.

Jets Particle-level jets are reconstructed using the same anti- k_T algorithm employed at the detector-level using a cone of radius $R = 0.4$ to cluster all stable particles except prompt leptons and prompt photons from the Higgs boson decay. These jets must pass kinematic cuts of $p_T > 30$ GeV and $|y| < 4.4$ and are rejected if they lie within $\Delta R < 0.4$ of a selected photon or $\Delta R < 0.2$ of a selected electron. A b -jet is defined if there is a b -hadron within $\Delta R < 0.4$ around the jet with $p_T > 5$ GeV. All b -jets must be central within the detector ($|\eta| < 2.5$) to match the detector acceptance of the Inner Detector.

Missing Energy The missing energy (E_T^{miss}) is the negative vector sum of the transverse momenta of all particle-level neutrinos that are not produced as a decay of a hadron.

The number of events at the particle level can be calculated as the product of the theoretical fiducial cross-section σ_{fid} and the dataset luminosity $\mathcal{L}$. Table 6.5 gives the expected number of events in the dataset that will fall within the inclusive fiducial volume.

Table 6.5: For each data-taking period in Run 2, the luminosity and expected numbers of particle-level signal events are given.

Dataset	Luminosity, $\mathcal{L}$	Particle-Level Yield
2015+2016	$36.24 \text{ fb}^{-1} \pm 2.1\%$	2307
2017	$44.31 \text{ fb}^{-1} \pm 2.4\%$	2825
2018	$58.45 \text{ fb}^{-1} \pm 2.0\%$	3723
Total	$139.0 \text{ fb}^{-1} \pm 1.7\%$	8855

6.1.3 Additional Fiducial Regions

Within the inclusive fiducial region, four fiducial volume are defined: a single-lepton enriched region to enhance the contribution from VH production (Higgs boson production with associated vector boson), a region requiring missing energy to also target VH production

as well as events that may produce associated dark matter particles, a region targeting $t\bar{t}H$ production (quarks emit a Higgs boson) by requiring b -jets, and lastly a targeted VBF production region (when quarks exchange vector bosons that emit a Higgs boson). These four regions are defined as follows and are summarized in Table 6.6. They are referred to as fiducial regions as they are regions of phase space within the inclusive fiducial volume, though they can also be thought of as targeted signal production regions.

- A single-lepton region targets VH , $t\bar{t}H$, and tH production modes by selecting events with at least one charged lepton with $p_T > 15$ GeV passing $|\eta| < 2.47$ for electrons or $|\eta| < 2.7$ for muons.
- A high- E_T^{miss} region targets VH and $t\bar{t}H$ production as well as Higgs boson production with associated dark matter particles by requiring a large missing transverse momentum ($E_T^{\text{miss}} > 80$ GeV) and diphoton invariant mass $p_T^{\gamma\gamma} > 80$ GeV.
- A VBF-enhanced region that considers ggF production as background by selecting events with at least two jets with $p_T > 30$ GeV where the leading two jets have a large invariant mass ($m_{jj} > 600$ GeV) and a large rapidity separation $|\Delta y_{jj}| > 3.5$.
- A $t\bar{t}H$ -enhanced region which is also enhanced in tH production by requiring events to contain at least one b -jet and at least four jets in events with no leptons or at least three jets if one lepton is present.

Table 6.6: Summary of the fiducial regions.

Region	Definition
Inclusive	≥ 2 isolated prompt photons, $ \eta < 1.37$ or $1.52 < \eta < 2.37$, $p_T/m_{\gamma\gamma} > 0.35$ and 0.25
Lepton	≥ 1 e (μ) with $p_T > 15$ GeV and $ \eta < 2.47(2.7)$
High- E_T^{miss}	$E_T^{\text{miss}} > 80$ GeV and $p_T^{\gamma\gamma} > 80$ GeV
VBF	≥ 2 jets, $m_{jj} > 600$ GeV, $ \Delta y_{jj} > 3.5$
$t\bar{t}H$	≥ 1 b -jet AND (≥ 1 lepton, ≥ 3 jets) OR (0 leptons, ≥ 4 jets)

These fiducial regions are not orthogonal and there may be overlap between the Lepton, $t\bar{t}H$ -enhanced, and High- E_T^{miss} regions. The largest overlap is between High- E_T^{miss} and the Lepton region due to the likelihood of neutrinos produced with the leptons where 42% of events in the High- E_T^{miss} are also in the Lepton region. Table 6.7 details the expected number of events in each of the overlapping regions.

Table 6.7: Overlap between fiducial regions.

Overlapping Regions		Number of Events	Fraction of Events	
Region 1	Region 2		In Region 1	In Region 2
VBF	Lepton	1.3	0.6%	1.6%
VBF	High- E_T^{miss}	0.7	0.3%	1.6%
VBF	$t\bar{t}H$	3.1	1.4%	3.7%
Lepton	High- E_T^{miss}	17.43	21%	42%
Lepton	$t\bar{t}H$	26.04	32%	31%
High- E_T^{miss}	$t\bar{t}H$	10.88	26%	13%

In 139 fb^{-1} of data, 8855 events are expected at the particle-level in the inclusive fiducial region, 212 in the VBF-enhanced, 82 in the single-lepton, 42 in the E_T^{miss} , and 84 events in the $t\bar{t}H$ -enhanced region. Figure 6.1 shows the composition of each fiducial region definition, comparing the relative particle-level contribution of each Higgs boson production mechanism. In the inclusive diphoton fiducial region, the production is dominated by gluon-gluon fusion, while VBF dominates in the VBF-enhanced region (as intended), then VH production dominates in the lepton and High- E_T^{miss} regions, and finally $t\bar{t}H$ production dominates (again, as intended), in the $t\bar{t}H$ -enhanced region.

6.1.4 Differential Binning

In addition to measuring the Higgs boson production cross-section in the various fiducial volumes, it is also measured differentially. This is done by splitting the fiducial volume into several bins of a particular kinematic variable. For the inclusive volume, this measurement was done for 17 kinematic variables and 4 two-dimensional variables to obtain doubly-differential

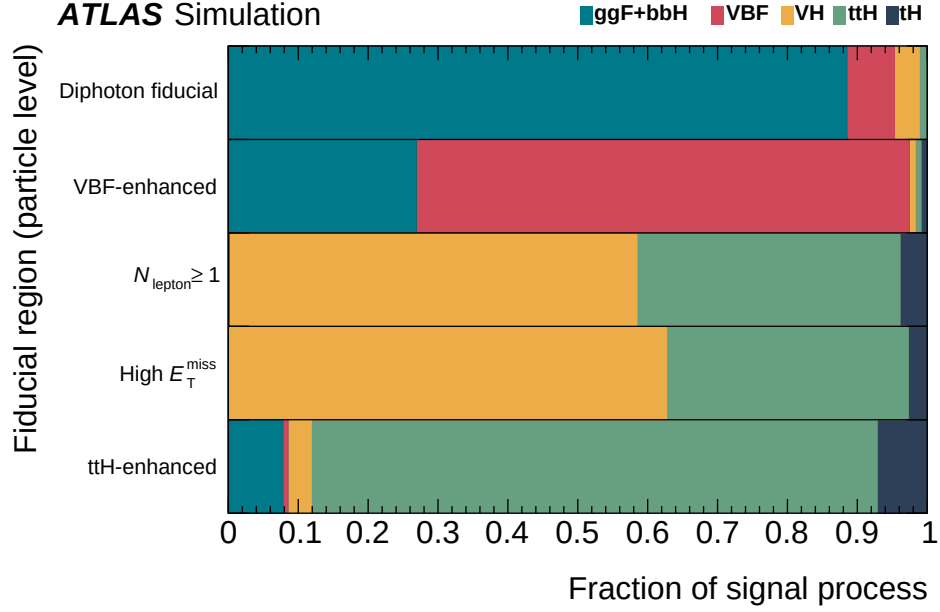


Figure 6.1: The relative contribution of each Higgs production mode at the particle-level to each fiducial region.

cross-sections. The VBF-enhanced region is also split differentially in an effort to better probe the VBF production. The distributions can be categorized as variables related to Higgs boson/diphoton kinematics or to jet activity, variables that are sensitive to spin-CP or VBF production, else in a miscellaneous category. As Higgs boson production is dominated by gluon-gluon fusion at the LHC, there is a large emission of soft gluons and quarks, therefore many of the differential variables probe QCD modeling or coupling between the quarks and Higgs boson [29].

The variables are defined as follows:

- $p_T^{\gamma\gamma}$: The transverse momentum of the inclusive diphoton system (i.e. $(\vec{p}_{\gamma_1} + \vec{p}_{\gamma_2})_T$) is sensitive to the Yukawa couplings of the b and c quarks as well as the Higgs boson coupling to the top quark or other new physics in the production loop

- $|y_{\gamma\gamma}|$: The absolute value of the rapidity of the inclusive diphoton system is sensitive to the Parton Distribution Functions and light-quark Yukawa couplings
- $p_T^{\gamma\gamma, \text{jet-veto}}$: The transverse momentum of the diphoton system when at least one associated jet is present, vetoing any event if the jet p_T^j is greater than 30, 40 50, 60 GeV (as 4 separate variables: $p_T^{\gamma\gamma, \text{jet veto } 30}$, $p_T^{\gamma\gamma, \text{jet veto } 40}$, $p_T^{\gamma\gamma, \text{jet veto } 50}$, $p_T^{\gamma\gamma, \text{jet veto } 60}$) which provides insights into jet-veto resummation [97]
- $p_T^{\gamma 1}/m_{\gamma\gamma}$ and $p_T^{\gamma 2}/m_{\gamma\gamma}$: The relative transverse momentum of the leading and subleading photon to probe Higgs boson decay kinematics
- N_{jets} : The number of jets with $p_T^j > 30$ GeV as the multiplicity is sensitive to the production mode and to QCD modeling
- $N_{\text{b-jets}}$: The number of central¹ ($|\eta| < 2.5$) jets tagged by a b -tagging algorithm at the 70% efficiency working point with $p_T^j > 30$ GeV in an event without muons or electrons² to probe the production of Higgs bosons with association heavy-flavor particles
- p_T^{j1} : The transverse momentum of the leading jet with $p_T^j > 30$ GeV which probes perturbative QCD modeling
- H_T : The scalar sum of of transverse momentum of all jets with $p_T^j > 30$ GeV which probes perturbative QCD modeling
- $p_T^{\gamma\gamma j}$: The transverse momentum of the diphoton-jet system (i.e. $(\vec{p}_{\gamma 1} + \vec{p}_{\gamma 2} + \vec{p}_{j1})_T$) where the leading jet has $p_T^j > 30$ GeV as this is sensitive to resummation effects [1207.4207]

¹The jets are required to be central to match the inner detector acceptance to benefit from tracking which is necessary for b -tagging.

²The lepton veto helps suppress the contribution of $t\bar{t}H$ production which has its own targeted fiducial region.

- $m_{\gamma\gamma j}$: The invariant mass of the diphoton-jet system which is sensitive to resummation effects
- τ_{C,j_1} : The maximum value of $\tau_i = \frac{m_T}{2 \cosh(y^*)}$ where $y^* = y_{j_i} - y_{\gamma\gamma}$ and $m_T = \sqrt{p_{T,j_i}^2 + m_{j_i}^2}$ which is a beam-thrust variable for a given jet, i , with $p_T^j > 30$ GeV
- $\Sigma\tau_{C,j}$: The scalar sum of τ_{C,j_i} for all jets with a minimum of $\tau_{j_i} > 5$ and $p_T^j > 30$ GeV
- m_{jj} : The invariant mass of the dijet system (i.e. $m(\vec{p}_{j_1} + \vec{p}_{j_2})$) for jets with $p_T^j > 30$ GeV
- $\Delta\phi_{jj}$: The azimuthal angle difference between the two leading jets with $p_T^j > 30$ GeV
- $p_T^{\gamma\gamma jj}$: The transverse momentum of the diphoton + dijet system (i.e. $(\vec{p}_{\gamma_1} + \vec{p}_{\gamma_2} + \vec{p}_{j_1} + \vec{p}_{j_2})_T$)
- $|\Delta\phi_{\gamma\gamma jj}|$: The absolute value of the azimuthal difference between the diphoton and dijet systems

A double-differential cross-sections are also computed in the inclusive fiducial volume. These variables compare the rapidity and transverse momentum of the diphoton system ($p_T^{\gamma\gamma}$ vs. $|y_{\gamma\gamma}|$), the relative p_T of the leading and subleading jet ($(p_T^{\gamma_1} + p_T^{\gamma_2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma_1} - p_T^{\gamma_2})/m_{\gamma\gamma}$), the p_T of the diphoton vs diphoton + jets systems ($p_T^{\gamma\gamma}$ vs. $p_T^{\gamma\gamma j}$), and the transverse momentum of the diphotons vs the beam thrust τ variable ($p_T^{\gamma\gamma}$ vs. τ_{C,j_1}).

For the VBF-enhanced region, the kinematic variables chosen for the differential cross-section measurement are sensitive to the features of the VBF mechanism and aim to disentangle ggF from VBF production. These observable variables are (i) the transverse momentum of the leading jet $p_T^{j_1}$, (ii) the azimuthal angle separation of the dijets $\Delta\phi_{jj}$, (iii) the pseudorapidity difference between the diphoton and dijet systems $|\eta^*|$, and (iv) the transverse momentum of the diphoton and dijet combined system $p_T^{\gamma\gamma jj}$.

The binning of each differential variable was studied and optimized for events falling in the signal region to increase the migration purity and boost the expected signal significance. The significance is then calculated using Equation 6.1. The parameter n^{sig} is the number of events in the signal region while n^{bkg} is the number of background events expected to be in the signal region. The value n^{bkg} is estimated by a linear extrapolation of the events that are outside the signal region, falling into the $m_{\gamma\gamma}$ side-bands between 105-121 GeV and 129-160 GeV.

$$\sqrt{2 \cdot \left((n^{\text{sig}} + n^{\text{bkg}}) \cdot \ln\left(1 + \frac{n^{\text{sig}}}{n^{\text{bkg}}}\right) - n^{\text{sig}} \right)} \quad (6.1)$$

For each bin, the significance should be close to or greater than 2σ though the binning is not optimized with respect to the significance. The other requirement for determining binning of a kinematic variable is on the migration purity. This requires that 50% of the particle-level values to fall into the corresponding detector-level bin. The particle-level values for each detector-level bin should sum to 100%. Another way to think about this, is that for each variable the truth vs. reconstructed distributions in the signal region are plotted together as a 2D distribution where 50% of the events must fall along the diagonal of that plot. An example of these requirements are shown for the variable N_{jets} where the significance is calculated in Table 6.8 and the purity values are shown in Figure 6.2. The migration purity matrix demonstrates how the majority of events fall along the diagonal as intended to ensure the reconstructed and truth values align.

Table 6.8: The binning choice for N_{jets} showing the calculated significant for each bin.

N_{jets} Bin	n^{sig}	n^{bkg}	Signal Significance
0 - 1	3070.77	95856.6	9.87
1 - 2	1673.17	44879.9	7.85
2 - 3	776.81	17728.4	5.79
3 - 10	355.91	8650.72	3.8

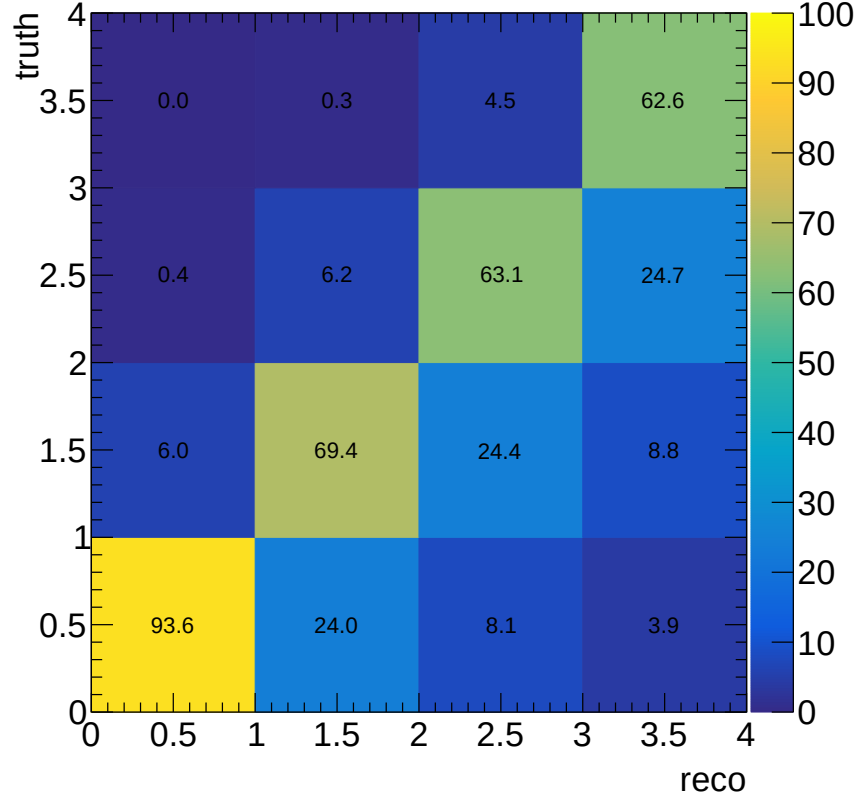


Figure 6.2: Migration purity for variable N_{jets} plotting the particle-level (truth) vs. detector-level (reco) values for each bin. Here, bin 0 represents $N_{\text{jets}} = 0$, bin 1 represents $N_{\text{jets}} = 1$, bin 2 represents $N_{\text{jets}} = 2$, and bin 3 represents $N_{\text{jets}} \geq 3$.

The chosen binning for each variable is summarized in Table 6.9 for the main differential variables and in Table 6.10 for the double-differential variables.

It is worth noting that for the category variables (e.g. jet multiplicities, fiducial regions), an extra bin is included that contains events that fail the category definition. This is done to help reduce uncertainties in the fit and unfolding and as a cross-check for consistency with the inclusive cross-section measurement.

The binning table and migration matrix for all other variables is given in Appendix A.1.

Table 6.9: Bin ranges for each variable of the different cross-section analysis. The transverse momenta, invariant masses and the H_T and τ variables are given in GeV while for the jet multiplicity variables, the number of jets correspond to the number of bins.

Variable	Bin Edges	N_{bins}
$p_T^{\gamma\gamma}$	0, 5, 10, 15, 20, 25, 30, 35, 45, 60, 80, 100, 120, 140, 170, 200, 250, 300, 450, 650, 13000	20
$ y_{\gamma\gamma} $	0, 0.15, 0.3, 0.45, 0.6, 0.75, 0.9, 1.2, 1.6, 2.0, 2.5	10
$p_T^{\gamma 1}/m_{\gamma\gamma}$	0.35, 0.45, 0.5, 0.55, 0.6, 0.65, 0.75, 0.85, 0.95, 10	9
$p_T^{\gamma 2}/m_{\gamma\gamma}$	0.25, 0.35, 0.4, 0.45, 0.5, 0.55, 0.65, 0.75, 0.85, 10	9
N_{jets}	0, 1, 2, ≥ 3	4
$N_{b\text{-jets}}$	$N_{\text{jets}}^{\text{central}} = 0$ or $N_{\text{lep}} > 0$, $N_{b\text{-jets}} = 0, \geq 1$	3
p_T^{j1}	30, 60, 90, 120, 350, 13000	5
H_T	30, 60, 140, 200, 500, 13000	5
$p_T^{\gamma j}$	0, 30, 60, 120, 13000	4
$m_{\gamma\gamma j}$	120, 220, 300, 400, 600, 900, 13000	6
$\tau_{C,j1}$	0, 5, 15, 25, 40, 13000	5
$\Sigma\tau_{C,j}$	5, 15, 25, 40, 80, 13000	5
$p_T^{\gamma\gamma, \text{jet veto } 30}$	0, 5, 10, 15, 20, 30, 40, 50, 100, 13000	9
$p_T^{\gamma\gamma, \text{jet veto } 40}$	0, 5, 10, 15, 20, 30, 40, 50, 60, 100, 13000	10
$p_T^{\gamma\gamma, \text{jet veto } 50}$	0, 5, 10, 15, 20, 30, 40, 50, 60, 70, 100, 13000	11
$p_T^{\gamma\gamma, \text{jet veto } 60}$	0, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 13000	12
m_{jj}	0, 120, 450, 3000, 13000	4
$\Delta\phi_{jj}$	$-\pi, -\frac{\pi}{2}, 0, \frac{\pi}{2}, \pi$	4
$\pi - \Delta\phi_{\gamma\gamma,jj} $	0, 0.15, 0.65, π	3
$p_T^{\gamma jj}$	0, 30, 60, 120, 13000	4
VBF-enhanced: p_T^{j1}	30, 120, 13000	2
VBF-enhanced: $\Delta\phi_{jj}$	$-\pi, -\frac{\pi}{2}, 0, \frac{\pi}{2}, \pi$	4
VBF-enhanced: $ \eta^* $	0, 1, 2, 10	3
VBF-enhanced: $p_T^{\gamma jj}$	0, 30, 13000	2

6.2 Signal and Background Models

6.2.1 Signal Invariant Mass Modeling

The yield of Higgs boson signal events is determined using an unbinned maximum-likelihood fit to the diphoton invariant mass spectrum. This is performed on the full diphoton mass range $105 < m_{\gamma\gamma} < 160$ GeV for each fiducial region and in each bin of the differential distributions. The signal and background components are fit independently using analytical functions which are summed together to get a full fit model. The likelihood function that

Table 6.10: Bin ranges for each variable of the double-differential cross-section. The transverse momenta and τ variables are given in GeV.

Variable	Bin Edges		N_{bins}
$p_T^{\gamma\gamma}$ vs $ y_{\gamma\gamma} $	$0.0 < y_{\gamma\gamma} < 0.5$	$p_T^{\gamma\gamma}: 0, 45, 120, 350$	12
	$0.5 < y_{\gamma\gamma} < 1.0$	$p_T^{\gamma\gamma}: 0, 45, 120, 350$	
	$1.0 < y_{\gamma\gamma} < 1.5$	$p_T^{\gamma\gamma}: 0, 45, 120, 350$	
	$1.5 < y_{\gamma\gamma} < 2.5$	$p_T^{\gamma\gamma}: 0, 45, 120, 350$	
$(p_T^{\gamma_1} + p_T^{\gamma_2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma_1} - p_T^{\gamma_2})/m_{\gamma\gamma}$	$0.6 < (p_T^{\gamma_1} + p_T^{\gamma_2})/m_{\gamma\gamma} \leq 0.8$	$(p_T^{\gamma_1} - p_T^{\gamma_2})/m_{\gamma\gamma}: 0, 0.3$	8
	$0.8 < (p_T^{\gamma_1} + p_T^{\gamma_2})/m_{\gamma\gamma} \leq 1.1$	$(p_T^{\gamma_1} - p_T^{\gamma_2})/m_{\gamma\gamma}: 0, 0.05, 0.1, 0.2, 0.8$	
	$1.1 < (p_T^{\gamma_1} + p_T^{\gamma_2})/m_{\gamma\gamma} \leq 4$	$(p_T^{\gamma_1} - p_T^{\gamma_2})/m_{\gamma\gamma}: 0, 0.3, 0.6, 4$	
$p_T^{\gamma\gamma}$ vs $p_T^{\gamma\gamma j}$	$N_{\text{jets}} = 0$	$p_T^{\gamma\gamma}: 0, 350$	9
	$0 < p_T^{\gamma\gamma j} \leq 30$	$p_T^{\gamma\gamma}: 0, 100, 350$	
	$30 < p_T^{\gamma\gamma j} \leq 60$	$p_T^{\gamma\gamma}: 0, 45, 120, 350$	
	$60 < p_T^{\gamma\gamma j} \leq 350$	$p_T^{\gamma\gamma}: 0, 80, 250, 450$	
$p_T^{\gamma\gamma}$ vs $\tau_{C,j1}$	$N_{\text{jets}} = 0$	$p_T^{\gamma\gamma}: 0, 350$	9
	$0 < \tau_{C,j1} \leq 15$	$p_T^{\gamma\gamma}: 0, 100, 350$	
	$15 < \tau_{C,j1} \leq 25$	$p_T^{\gamma\gamma}: 0, 120, 350$	
	$25 < \tau_{C,j1} \leq 40$	$p_T^{\gamma\gamma}: 0, 200, 350$	
	$40 < \tau_{C,j1} \leq 400$	$p_T^{\gamma\gamma}: 0, 250, 650$	
VBF-enhanced: p_T^{j1} vs $\Delta\phi_{jj}$	$-\pi < \Delta\phi_{jj} < 0$	$p_T^{j1}: 30, 120, 500$	4
	$0 < \Delta\phi_{jj} < \pi$	$p_T^{j1}: 30, 120, 500$	

is built for each min and maximized is shown in Equation 6.2. It uses the fitted number of signal and background events, ν^{sig} and ν^{bkg} , as well as $v = \nu^{\text{sig}} + \nu^{\text{bkg}}$ which is the mean value of the Poisson distribution for n events. The value $m_{\gamma\gamma}^j$ is the diphoton invariant mass for each event j , and the parameters $\mathcal{S}(m_{\gamma\gamma}^j; \theta_k)$ and $\mathcal{B}(m_{\gamma\gamma}^j)$ are the signal and background probability density functions, receptively. Nuisance parameters are represented by θ_k and are parameters that affect the distributions of our observables and must be accounted for. Examples of this are the signal and background shape parameters which are impacted by systematic uncertainties.

$$\mathcal{L}(m_{\gamma\gamma}; \nu^{\text{sig}}, \nu^{\text{bkg}}) = \frac{e^{-\nu}}{n!} \prod_j^n \left[\nu^{\text{sig}} \mathcal{S}(m_{\gamma\gamma}^j; \theta_k) + \nu^{\text{bkg}} \mathcal{B}(m_{\gamma\gamma}^j) \right] \quad (6.2)$$

The invariant mass distribution for Higgs boson decays to diphotons is a resonant distribution that is expected to follow a Breit-Wigner curve with the peak at the Higgs boson mass

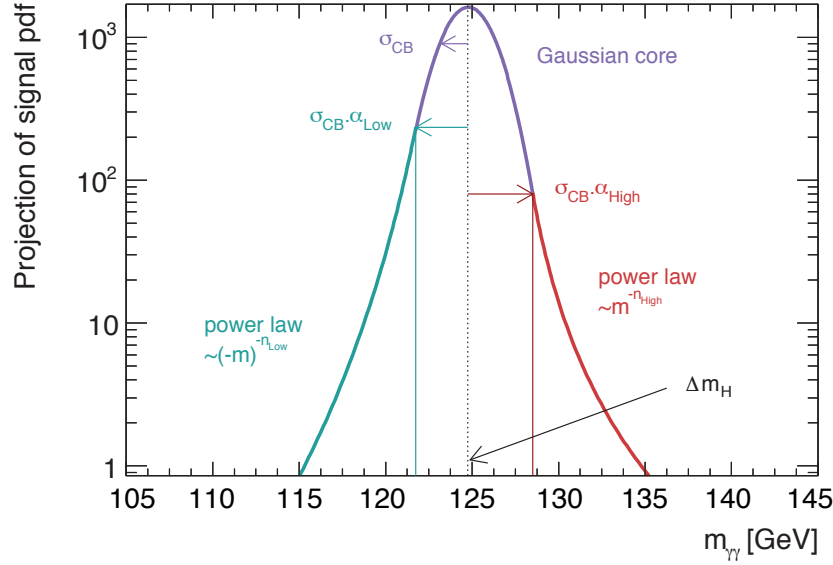


Figure 6.3: Illustration of a double-sided Crystal Ball function around the Higgs boson mass [98].

m_H . The $pp \rightarrow H \rightarrow \gamma\gamma$ process has a narrow width of a few MeV [99] which is much smaller than the reconstructed photon energy resolution which is around a GeV causing smearing around the peak. The diphoton invariant mass peak is modeled with a double-sided Crystal Ball (DSCB) function [100] which has a Gaussian core and exponential tails on the low and high mass sides as shown in Figure 6.3. The analytical form the function is presented in Equation 6.3 where $t = (m_{\gamma\gamma} - \mu_{CB})/\sigma_{CB}$, $R_{\text{low}} = \frac{\alpha_{\text{low}}}{n_{\text{low}}}$, and $R_{\text{high}} = \frac{\alpha_{\text{high}}}{n_{\text{high}}}$.

Here, N is a normalization parameter, μ_{CB} and σ_{CB} are parameters of the Gaussian distribution giving the mean and width respectively, α_{low} and α_{high} determine where the transition from the Gaussian core to the exponential tails on the low and high mass sides occurs, and n_{low} and n_{high} are the exponents of the low and high mass tails. The peak position is given by $m_H + \Delta\mu_{CB}$.

$$CB(m_{\gamma\gamma}) = N \times \begin{cases} e^{-t^2/2}, & \text{if } -\alpha_{\text{low}} \leq t \leq \alpha_{\text{high}} \\ e^{-\frac{1}{2}\alpha_{\text{low}}^2} \left[\frac{1}{R_{\text{low}}} (R_{\text{low}} - \alpha_{\text{low}} - t) \right]^{-n_{\text{low}}}, & \text{if } t < -\alpha_{\text{low}} \\ e^{-\frac{1}{2}\alpha_{\text{high}}^2} \left[\frac{1}{R_{\text{high}}} (R_{\text{high}} - \alpha_{\text{high}} - t) \right]^{-n_{\text{high}}}, & \text{if } t > \alpha_{\text{high}} \end{cases} \quad (6.3)$$

As the simulation uses a Higgs boson mass of 125 GeV, the μ_{CB} value is shifted by 90 MeV to fit for a mass of 125.09 GeV. This value is fixed in the signal extraction though slight shifts in the mean of the distribution are allowed when fitting to each bin via uncertainties. To obtain the shape parameters for the DSCB function, excluding the normalization, a fit is done to the $H \rightarrow \gamma\gamma$ simulated signal samples using all Higgs boson production modes weighted by their SM cross-section values. They are derived separately in each fiducial region and in each bin of the differential distributions. For example, the signal parameterization for the inclusive fiducial region and the N_{jets} differential variable for the bin where there is one jet is shown in Figure 6.4. The shape parameters are impacted by photon energy scale and resolution uncertainties to change the width or peak position. These shifts, as well as the relative composition of the Higgs boson production modes are treated as nuisance parameters which are discussed further in Chapter 6.4.

The signal parameterization for all other variables is given in Appendix A.2.

6.2.2 Background Invariant Mass Modeling

Background events of the $H \rightarrow \gamma\gamma$ signal process comes from either real photon pairs ($\gamma\gamma$) or from misidentifying a jet as a photon ($\gamma j, jj$). The two backgrounds are expected to have a smoothly falling diphoton invariant mass distribution for the range $105 < m_{\gamma\gamma} < 160$ GeV and are therefore described by empirically chosen analytical functions. The real photon

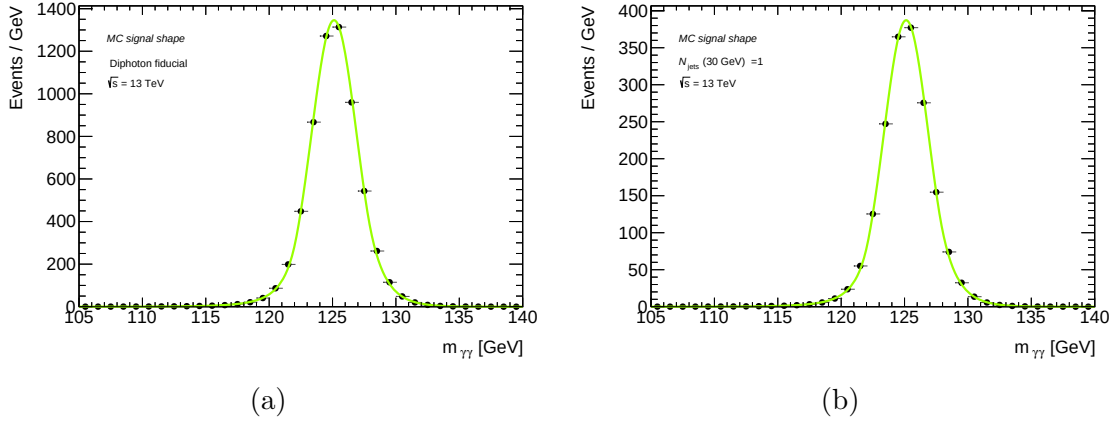


Figure 6.4: Signal parameterizations normalized to 139 fb^{-1} for the (a) inclusive fiducial volume and (b) N_{jets} differential variable in the bin where $N_{\text{jets}} = 1$.

background process is an irreducible component as it is very difficult to distinguish real photon pairs produced by other mechanisms from photon pairs originating from a Higgs boson decay. These photons are produced during hard-scattering by QCD interactions and form a non-resonant continuum background of two prompt, isolated photons. An estimation of the contribution of these events is obtained using the SHERPA diphoton simulation sample. The reducible background for our signal process is from mistaking one or two hadronic jets as photons. Unfortunately, the Monte Carlo simulations poorly model jets-faking-photons so the data side-bands ($105 < m_{\gamma\gamma} < 121$ GeV and $129 < m_{\gamma\gamma} < 160$ GeV) are used in conjunction with the simulation to estimate this background.

To model the contribution of $\gamma\gamma$, γj , and jj events, a two-dimensional double-sideband (2x2D sideband) method is employed [101]. The method statistically separates each component using the discriminating power of photon identification and isolation by counting the number of photons and jets that pass or fail the requirements. It is a data-driven method which uses a system of 16 equations to extrapolate the background in the side-bands of the identification and isolation variables. The process starts with a sample of photons passing a LoosePrime

definition (see Table 5.1) where the total number of events is a sum of each type as shown by Equation 6.4.

$$N_{TOTAL} = W_{\gamma\gamma}^{LP} + W_{\gamma j}^{LP} + W_{j\gamma}^{LP} + W_{jj}^{LP} \quad (6.4)$$

Here, the indices refer to the true type of the leading and subleading photon candidates, whether it is a true photon or a jet. Next, additional criteria is checked to see if the photon candidate passed the tight identification cut and the isolation cut (see Chapter 5.1). Each photon candidate falls into a category A, B, C, or D based on if it passes the identification and isolation cuts. The photons are considered sequentially, where the 2x2D sideband is applied first to extract the signal yield for the leading photon, then applied again for the subleading photon. Because of this, we obtain 16 orthogonal categories, labeled AA to DD, as shown in Figure 6.5 denoting which category each photon falls in to.

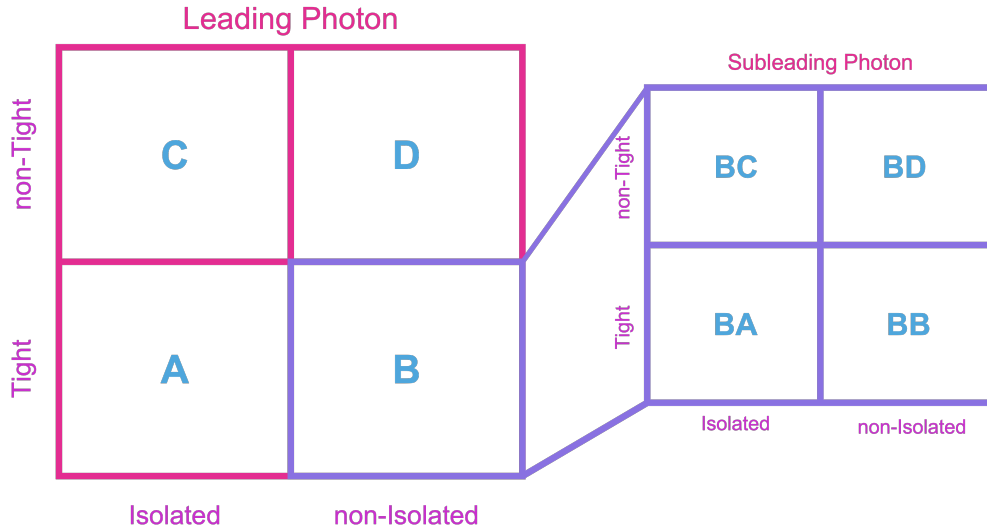


Figure 6.5: A schematic representation of the 2x2D sideband method for two photon candidates. Shown is an example where the leading photon passes tight identification but fails the isolation cut, falling into the B category. The figure then shows the four possible combinations with the subleading photon depending on which cuts it passes. The lower left A region is the signal region where the photon is both tight and isolated.

The following inputs are used to solve the system of equations describing the number of events in each category:

- The tight identification efficiencies for the leading and subleading signal photon which are obtained from Monte Carlo
- The isolation efficiencies for the leading and subleading signal photon which are obtained from Monte Carlo
- The correlation between identification and isolation fake rates for the leading and subleading fake photons from jets
- The number of events falling into the $\gamma\gamma$, γj , $j\gamma$, and jj categories once a photon passes the LoosePrime selection
- The tight identification fake rates in γj and $j\gamma$ events for the leading and subleading jets
- The tight identification fake rates in jj events for the leading and subleading jets
- The isolation fake rates in γj and $j\gamma$ events for the leading and subleading jets
- The isolation fake rates in jj events for the leading and subleading jets
- The correlation between the isolation of jets in jj events

Of these 19 inputs, six are known (identification and isolation efficiencies and the correlations for the leading and subleading jets), allowing the set of 16 equations to be solved. In the end, the fraction of events passing the LoosePrime definitions is obtained from Monte Carlo while the overall normalizations are obtained from data. For the inclusive fiducial region, the relative fraction of each component including the statistical uncertainty is $76.0\% \pm 0.1$ for $\gamma\gamma$ events, $21.0\% \pm 0.1$ for γj events, and $3.0\% \pm 0.0$ for jj events when using the LoosePrime3

definition. The values for the differential variables $p_T^{\gamma\gamma}$ and N_{jets} is shown in Figure 6.6. As shown, the jj component contributes as only a small fraction of the total events and was found to have a negligible impact on the results so is not included from here on. The breakdown of values in each bin for all categories and differential variables is given in Appendix B.

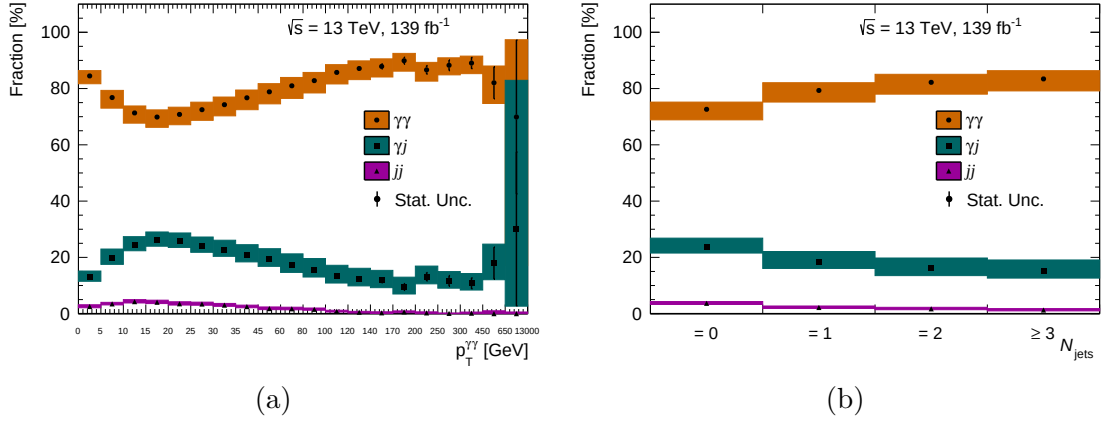


Figure 6.6: Fractional contributions for $\gamma\gamma$, γj , and jj events in the (a) $p_T^{\gamma\gamma}$ and (b) N_{jets} differential bins.

Once the estimations on the $\gamma\gamma$ and γj relative fractions are obtained, a background template is built of the diphoton invariant mass using the weighted reducible $\gamma\gamma$ background from simulation and the irreducible γj background from data. The summed templates are normalized to data yields in the diphoton mass sidebands excluding the region $123 < m_{\gamma\gamma} < 127 \text{ GeV}$. The background template is then smoothed using GPR (Gaussian Process Regression) smoothing techniques to remove statistical fluctuations.

The GPR process is used to smooth out fluctuations in low-statistics bins without removing any real features of the background. A prior distribution is defined in a Gibbs kernel and an additional custom error kernel to account for noise. The Gibbs kernel is motivated for a spectra that falls smoothly, like our reducible + irreducible background, with a length scale that increases linearly. The two hyperparameters of this kernel are the length scale λ and the slope of this length scale b_λ which need to be optimized. The custom error kernel allows for

an error magnitude to decrease linearly with two highly constrained hyperparameters ϵ and b_ϵ . To define and optimize the criteria for all hyperparameters, an artificial bump is injected into a background template. The magnitude of the injections is set to be only 1% of the total background integral with a narrow bump on the order of the bin width or wide bump on the order of the expected signal width. In the case of a narrow bump, the hyperparameter selections should allow for at least 33% of the features to be smoothed out. For the wide bump, less than 25% of the features should be smoothed out. These two widths are set to mimic statistical fluctuations or signal-like shape.

An example of the obtained background template is shown in Figure 6.7 which shows the background template, smoothed template, and the portion of the background that comes from the reducible γj component in the $N_{b\text{-jets}}$ differential variable where there is at least 1 b -tagged jet. The impact of the smoothed background is seen in this example as there is some fluctuation, the biggest impact of the GPR smoothing is in these more statistically limited bins compared to, for example, the total inclusive fiducial region.

The background template for all other variables, including the fiducial inclusive region, is given in Appendix A.3.

Several functional forms were then considered for the parameterization of the diphoton mass spectrum:

- Exponential functions of first through fourth degree polynomials
- Bernstein polynomials of degree three, four, and five
- First and second degree power law functions

The choice of function was determined for each bin based on the spurious signal and goodness of fit.

Spurious signal is the potential bias caused by over- or under-estimating the background which impacts the measured number of signal events in the fit. For each potential fit function,

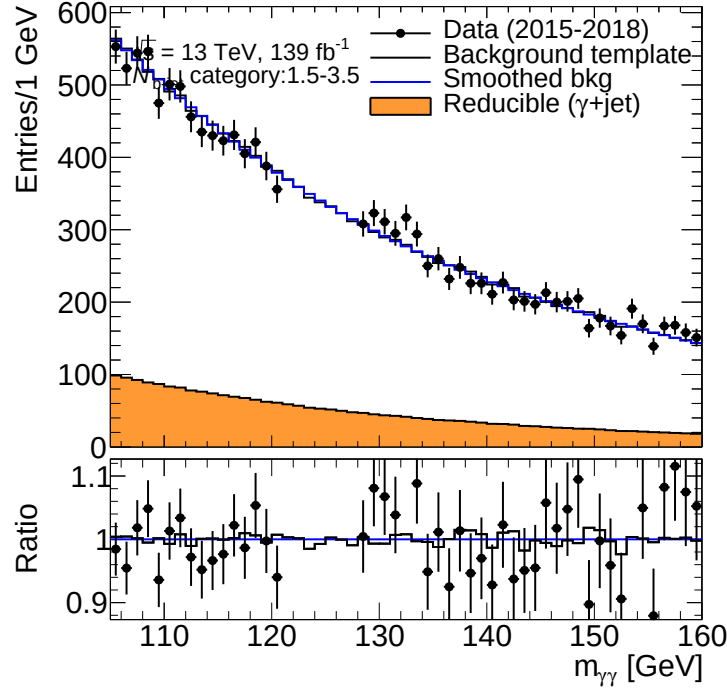


Figure 6.7: The background template for the $N_{b\text{-jets}}$ differential variable when there is at least 1 b -tagged jet. It shows the reducible component in orange that contributes to the full template in black. The smoothed template is represented by the blue line. The bottom ratio compares both the data and the unsmoothed template to the smoothed one.

the signal yield is fit to the smoothed background templates of the mass spectrum using a signal model in the range $123 < m_{\gamma\gamma} < 127$ GeV. The maximum absolute value is called the spurious signal. If the chosen background function is ideal and matches very well to the background template, we expect very low spurious signal. The spurious signal plus its statistical uncertainty must be less than 20% of the background uncertainty or less than 10% of the number of expected signal events. The background uncertainty here is calculated as an estimate on the statistical uncertainty of the signal. If more than one functional form satisfies this condition, then the one with the lowest number of degrees of freedom is selected. Figure 6.8 shows the spurious signal for each function in the inclusive fiducial region. Here, the ExpPoly2 (exponential function of a 2nd degree polynomial) was chosen with a spurious signal value of -3.8%. In bins with low statistics, an exponential function is used by default.

These bins are identified as “low-stat” bins if less than 150 data sideband events are expected. No GPR smoothing is applied in this case and the exponential function is validated using the Wald test described below.

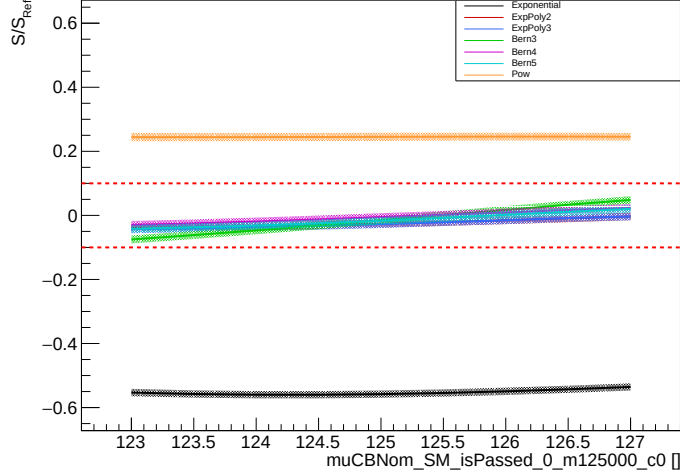


Figure 6.8: The spurious signal obtained for each evaluated function for the inclusive fiducial region.

A goodness of fit χ^2 probability is also used to evaluate the choice of function. To ensure that sidebands are well described by the templates, the p -value (which gives the probability for deviations) must be larger than 1% when evaluated on the unsmoothed templates.

Once a function is selected by the spurious signal and χ^2 tests, a check is performed on the function against the data sidebands. As data may have features not seen in simulations, this check is performed to see if higher order functions are needed to more accurately model data. A Wald test (or F-test) is performed which computes the test statistic shown in Equation 6.5.

$$\lambda_{(1,2)} = -2 \ln(L_1/L_2) \quad (6.5)$$

This test uses the likelihood values of the fit for the nominal background templates as L_1 and L_2 is the value when the background template has an additional degree of freedom to

obtain a statistical value $\lambda_{(1,2)}$. Then, if the probability of obtaining a higher $\lambda_{(1,2)}$ compared to the observed one $\lambda_{(1,2)}^{\text{obs}}$ is less than or equal to 5%, i.e. $P(\lambda_{(1,2)} \geq \lambda_{(1,2)}^{\text{obs}}) < 0.05$, then the higher degree of freedom function is chosen. This test is continued with higher orders until this probability exceeds 5%. The final functions selected for each category and differential variable bin is summarized in Table 6.11.

Table 6.11: Selected function to model the background of each category and differential variable per bin. Here, B = Bernstein Polynomial, EP = exponentiated polynomial, and P = power law.

Variable	Bin																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Inclusive	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Lepton	EP2	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
High- E_T^{miss}	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$t\bar{t}$ -enhanced	EP2	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VBF-enhanced	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$p_T^{\gamma\gamma}/m_{\gamma\gamma}$	EP2	EP2	EP3	EP3	B3	EP3	EP2	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-
$p_T^{\gamma\gamma}/m_{\gamma\gamma}$	B4	EP2	EP2	EP3	EP3	P	P	P	P	-	-	-	-	-	-	-	-	-	-	-
$p_T^{\gamma\gamma}$	B4	EP2	EP2	EP3	EP2	EP2	EP2	EP2	EP2	B4	B3	EP2	P	EP1	EP1	EP1	EP2	EP1	EP1	EP1
$ y_{\gamma\gamma} $	EP2	EP2	EP2	EP2	EP2	EP3	EP2	EP2	EP2	EP2	-	-	-	-	-	-	-	-	-	-
N_{jets}	EP2	EP2	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$N_{\text{b-jets}}$	EP2	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$p_T^{\Delta\phi_{jj}}$	EP2	EP2	EP1	EP1	EP2	P	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$p_T^{\gamma j}$	EP2	EP2	EP2	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$m_{\gamma\gamma j}$	EP2	EP3	B3	P	EP2	EP1	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-
$\tau_{C,j1}$	EP2	EP2	EP2	EP2	EP1	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$\Sigma\tau_{C,j}$	EP2	EP2	EP2	EP2	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
H_T	EP2	EP2	EP3	EP2	EP2	P	-	-	-	-	-	-	-	-	-	-	-	-	-	-
m_{jj}	EP2	EP2	EP2	EP2	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$\Delta\phi_{jj}$	EP2	EP3	EP2	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$ \Delta\phi_{\gamma jj} $	EP2	EP3	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$p_T^{\gamma jj}$	EP2	EP2	EP2	EP2	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$p_T^{\gamma\gamma, \text{jet veto } 30}$	EP2	B4	EP2	EP2	B4	EP2	EP2	EP2	EP2	B3	-	-	-	-	-	-	-	-	-	-
$p_T^{\gamma\gamma, \text{jet veto } 40}$	EP2	B4	EP2	EP2	EP3	EP2	EP2	EP2	EP2	EP2	EP2	-	-	-	-	-	-	-	-	-
$p_T^{\gamma\gamma, \text{jet veto } 50}$	EP2	B4	EP2	EP2	EP3	EP2	EP2	EP2	EP2	EP2	EP3	EP2	-	-	-	-	-	-	-	-
$p_T^{\gamma\gamma, \text{jet veto } 60}$	EP2	B4	EP2	EP2	EP3	EP2	EP2	EP2	EP2	EP2	B4	B3	P	-	-	-	-	-	-	-
$p_T^{\gamma\gamma} \text{ vs } y_{\gamma\gamma} $	EP2	EP1	EP1	EP3	EP2	EP1	EP2	EP2	EP1	EP2	EP1	P	-	-	-	-	-	-	-	-
$p_T^{\gamma\gamma} \text{ vs } p_T^{\gamma j}$	EP2	EP2	EP2	EP2	EP1	EP1	EP1	EP1	EP1	-	-	-	-	-	-	-	-	-	-	-
$p_T^{\gamma\gamma} \text{ vs } \tau_{C,j1}$	EP2	EP2	EP1	EP2	EP2	P	EP2	EP2	EP1	-	-	-	-	-	-	-	-	-	-	-
$(p_T^{\gamma\gamma} + p_T^{\gamma j})/m_{\gamma\gamma} \text{ vs } (p_T^{\gamma\gamma} - p_T^{\gamma j})/m_{\gamma\gamma}$	B5	EP2	EP2	EP2	EP2	P2	EP2	EP2	-	-	-	-	-	-	-	-	-	-	-	-
VBF $ y_{\gamma\gamma} $	EP2	EP1	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VBF $\Delta\phi_{jj}$	EP1	EP1	EP1	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VBF $p_T^{\gamma j}$	EP1	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VBF $p_T^{\gamma jj}$	P	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VBF $p_T^{\gamma j} \text{ vs } \Delta\phi_{jj}$	EP1	EP1	EP1	EP1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

6.3 Unfolding

When making a measurement, the underlying physics process needs to be disentangled from the detector response. All observables from the detector will have some level of statistical

fluctuation and distortion because of experimental limitations. This smearing causes the migration of some events between particular defined regions of phase space (or bins). The procedure of correcting for this migration because of detector response effects is called unfolding.

For a given measurement, the probability density function for a measured value x is $f_{\text{meas}}(x)$ as shown in Equation 6.6. Here, $R(x|y)$ represents the detector response function and $f_{\text{true}}(y)$ is the PDF of the physics process we're trying to measure with unknown values y .

$$f_{\text{meas}}(x) = \int R(x|y)f_{\text{true}}(y)dy \quad (6.6)$$

Unfortunately, this is a bit idealized. In practice, we consider binned histograms of distributions, so the detector response function becomes a conditional probability matrix R_{ij} . This matrix gives the probability for an event with true value in bin i to have reconstructed value in bin j which can be split into an efficiency term and migration term. For these binned observables, the reconstructed distribution x_i is given by Equation 6.7 where N is the number of bins for the true distribution y .

$$x_i = \sum_{j=1}^N R_{ij}y_j \quad (6.7)$$

Unfolding then inverts Equation 6.7 to obtain the true value y_j from the measured x_i value.

In this analysis specifically, the obtained cross-section is measured as a function of the true particle-level observable. This is done by performing a simultaneous fit to the diphoton mass spectrum in all the bins for the corresponding detector-level observable. For each fiducial bin r , the signal yield ν_r is parameterized using Equation 6.8.

$$\nu_r = \frac{1}{C_r^{\text{fid}}} \sum_t R_{rt} \sigma_t B_{\gamma\gamma} \mathcal{L}_{\text{int}} \quad (6.8)$$

In this equation, $\mathcal{L}_{\text{int}}$ is the integrated luminosity, $\sigma_t B_{\gamma\gamma}$ is the fiducial cross-section in truth-bin t (from the MC generator information) multiplied by the branching ratio for the Higgs boson to decay to two photons. The response matrix is represented as R_{rt} and C_r^{fid} is a correction factor that is determined from the simulation to subtract events outside of the fiducial volume and Dalitz events. Figure 6.9 shows the response matrix for two differential variables, $p_T^{\gamma\gamma}$ and N_{jets} . In this example, it is easier to get numbers close to 1 along the diagonal for $p_T^{\gamma\gamma}$ vs N_{jets} due to the resolution of the detector. If the true value is off by even a few GeV, the truth and reconstructed value can still be in the same bin, however with N_{jets} , being off by even 1 causes migration. Additionally, the higher $p_T^{\gamma\gamma}$ bins have values closer to 1 as the bin ranges are larger, allowing more events to fall into the bin. The response matrices for all other variables are given in Appendix A.4. As a cross-check, a closure test was performed. This compared the particle-level cross-sections from simulated samples to unfolded cross-sections in a dataset that was built using signal parameters from simulation and background parameters from the data sidebands. No bias was observed resulting in good closure.

To obtain the final cross-section measurement, the diphoton invariant mass distribution is modeled via a combination of the signal and background models, then a simultaneous maximum-likelihood fit is performed in all bins of the observable. The final results are reported in Chapter 6.5.

6.4 Systematic Uncertainties

In any obtained result, all sources of systematic uncertainties need to be taken into consideration.

The main types are:



Figure 6.9: Response matrices using MC simulation for the (a) $p_{\text{T}}^{\gamma\gamma}$ and (b) N_{jets} differential distributions. Values smaller than 1% are suppressed.

- Uncertainties related to the signal and background modeling
- Uncertainties affecting the luminosity
- Uncertainties affecting the branching ratios
- Theoretical and experimental uncertainties on the response matrices

As the cross-sections are obtained by fitting the diphoton invariant mass spectrum, the uncertainties on the shape modeling of signal and background are important. When modeling the signal shape, the main source of uncertainties arise from the photon energy scale and resolution. The uncertainties on the photon energy scale affect μ_{CB} which shifts the peak position in the double-sided Crystal Ball function. The photon energy resolution affects the σ_{CB} parameter of the DSCB by modifying the width of the peak. As with the energy scale, this is treated as a nuisance parameter and the impact is calculated during the signal model fit using the recalculated diphoton mass with the modified photon energies. When evaluating

a nuisance parameter, all other parameter values are fixed to the nominal fit values. For the photon energy scale uncertainties, the final impact was small as the peak position only varied between 0.2% and 0.5% per bin. The photon energy resolution modified the width of the signal peak between 5% and 27% with a larger impact on photons with higher transverse momentum. An additional systematic uncertainty on the peak position is included to account for the uncertainty on the Higgs boson mass $m_H = 125.09 \pm 0.24$ GeV. The spurious signal is assigned to be the systematic uncertainty from the choice of background function. It is estimated using the GPR smoothed template to reduce the statistical fluctuations and, since each function is chosen empirically for each bin, the uncertainties are considered to be uncorrelated between the various differential distribution bins.

Any uncertainty on the luminosity affects the cross-section measurement as it is used directly in Equation 6.8. The uncertainty is derived from calibration of the beams using van der Meer scans (x - y beam-separation scans) [102]. For the combined 2015-2018 dataset, the uncertainty on the integrated luminosity is 1.7%.

For inclusive measurements where the branching ratio is considered, an uncertainty of 2.9% on the $H \rightarrow \gamma\gamma$ branching ratio is used [96]. For samples produced with PYTHIA, Dalitz decays are subtracted out during the unfolding process as they are not considered to be a part of the fiducial volume. As the branching ratio of Higgs boson to these types of decays is unknown, a 100% uncertainty is applied which results in a 0.4% uncertainty in the measured fiducial inclusive cross-section.

Experimental Uncertainties on Response Matrices

The purpose of conducting the measurement in a fiducial volume is to minimize the number of assumptions made in order to produce a largely model-independent measurement.

However, slight model dependence will be introduced during the unfolding process when corrections from simulation are applied to a distribution. For example, the particle-level vs detector-level phase space may vary slightly. When the response matrices R_{ij} are calculated, SM expectations are used to extrapolate between the two. The following details the various experimental uncertainties that affect the response matrix and therefore impact the signal yield and migration matrices. For each efficiency uncertainty, the scale factors are varied by $\pm$ their uncertainties then the unfolding procedure is re-performed. The difference in the unfolded cross-section is taken as the systematic uncertainty.

Diphoton trigger efficiency The efficiency of the diphoton triggers are calculated using a bootstrap method [103]. This method calculates the efficiency of a higher trigger threshold by comparing to a trigger with a lowered E_T threshold which results in an uncertainty of approximately 1%.

Vertex selection efficiency The primary vertex in an event is identified using a neural-network algorithm as the vertex with the highest summed transverse momentum (the default vertex chosen by the inner detector) may not be correct, particularly with ggF production of the Higgs boson. The efficiency of the algorithm is estimated by running over $Z \rightarrow e^+e^-$ events with the electron tracks removed to imitate unconverted photons. The resulting uncertainty was found to be less than 0.3%.

Photon identification efficiency Photons are required to pass the tight identification requirement. The efficiency, of this cut is measured in three data-driven ways: radiative Z decays, electron extrapolation, and with inclusive photons [104]. The uncertainty is then derived by varying the efficiency scale factors between data and simulation. The radiative Z decay method uses low-energy photons from $Z \rightarrow \ell\ell\gamma$ where ℓ is an electron or muon, which provides an efficiency ϵ_{ID} for photon energies between 10 and approximately 100 GeV. The

electron extrapolation method uses $Z \rightarrow e^+e^-$ decays where the electromagnetic showers are modified to look like photon showers. This allows a measurement of ϵ_{ID} in the region $25 < E_{\text{T}} < 150$ GeV. The third method uses inclusive photons with a single-photon trigger and track-based isolation criteria to derive ϵ_{ID} in the region $25 \text{ GeV} < E_{\text{T}} < 1.5 \text{ TeV}$. In the inclusive fiducial region, the uncertainty is estimated to be 1.8% and to decrease with higher photon transverse momentum to 1%.

Photon isolation efficiency The isolation efficiency of photons is also measured with radiative Z decays along with inclusive photon samples [87] with the uncertainty being derived from modifying the isolation factors. The overall photon isolation efficiency uncertainty is estimated to be 1.6% in the inclusive fiducial region and increases with photon energy up to 2%.

Photon energy scale and resolution In addition to the impact on the signal modeling parameters, the photon energy scale and resolution impact the response matrices through bin migrations. This effect was found to be very small, reaching a maximum uncertainty impact of 0.2% in the very high photon momentum bins.

Pileup Jet variables are impacted by pileup uncertainties due to fake jets from other vertices in the event. These jet selection uncertainties arise from JVT and fJVT efficiencies though overall are very small, maxing out at 0.3%. A larger overall impact comes from reweighting the simulation to match the pileup in data. The number of interactions per bunch crossing is varied to account for the uncertainty in the ratio between predicted and measured inelastic cross-section. In the inclusive fiducial region, the uncertainty is 1.5% and increases with p_{T} and jet multiplicity up to 6%.

Jet energy calibration In measurements related to jets, the jet energy scale and resolution carry their own uncertainties, similar to photons. These calibration uncertainties

are estimated using Z +jets, γ +jets and dijet events using a transverse momentum balance technique [105]. The combined jet-related uncertainties range from roughly 5% to 24%, and increases with jet multiplicity.

Charged lepton uncertainties As leptons are not necessary in the inclusive fiducial volume, the uncertainties arising from electron [87] and muon [106] reconstruction, identification, and isolation has the biggest impact in the single-lepton fiducial cross-section measurement. They are measured using dilepton decays from the Z boson and J/Ψ mesons and the uncertainty is 0.6% and 0.5% for electrons and muons, respectively.

E_T^{miss} **uncertainties** The uncertainties of the photon, jet, and lepton energy scales and resolutions are all propagated through to the E_T^{miss} uncertainty as any or all of these objects can be used to determine the value of missing energy. Uncertainties related to unassociated charged particle tracks are included as well to give a resulting uncertainty of 13% in the E_T^{miss} -enhanced fiducial cross-section measurement.

b -tagging uncertainties The b -tagging efficiencies are determined using $t\bar{t}$ events [107]. The 70% efficiency working point was used to identify b -jets, and corresponds to an uncertainty of 4% in the highest $N_{b\text{-jets}}$ bin.

Theoretical Uncertainties on Response Matrices

Signal composition uncertainty Simulation of the Higgs boson diphoton decays is split by production mode then combined assuming SM cross-sections, which introduces model dependence. To obtain the uncertainty associated with assuming a certain composition of Higgs boson production mechanisms, the cross-section of each production mode is varied within its own uncertainty [108]. The variations for each production mode cross-section are

given in Table 6.12. The resulting uncertainties from the above variations are very small,

Table 6.12: Relative variations applied to each Higgs boson production mode.

Production Mode	Variation
ggH	$\Delta\sigma^{+8.7\%}_{-8.7\%}$
VBF	$\Delta\sigma^{+20\%}_{-18\%}$
WH	$\Delta\sigma^{+31\%}_{-29\%}$
ZH	$\Delta\sigma^{+30\%}_{-28\%}$
$t\bar{t}H$	$\Delta\sigma^{+18\%}_{-17\%}$
bbH	$\Delta\sigma^{+20\%}_{-24\%}$
tWH	$\Delta\sigma^{+9\%}_{-8\%}$
$tHjb$	$\Delta\sigma^{+7\%}_{-15\%}$

maxing out at 1% in bins with high jet multiplicities.

Modeling of the matrix element generator The uncertainty due to the choice of matrix element is derived by simulating events with MADGRAPH5 instead of the nominal matrix element generator, POWHEG. Both this sample and the nominal sample are showered with PYTHIA and the response matrices are calculated. Each matrix element is compared and the relative difference between the two generators is incorporated in the likelihood fit as a nuisance parameter. The relative difference in signal yield is roughly 0.1% between the two samples for all production mechanisms. The resulting uncertainty on our measurement is small, varying between 1% and 2% in the high p_T and jet multiplicity bins.

Modeling of the parton shower, underlying event, and hadronization The response matrices are generated using signal samples with PYTHIA and HERWIG showering. The relative differences were incorporated into the likelihood nuisance parameters producing an uncertainty that peaked at 1.6% in high multiplicity jet bins.

Figure 6.10 shows the breakdown of uncertainties on the cross-section measurement in each bin of the $p_T^{\gamma\gamma}$ and N_{jets} differential distributions. Only the top five leading sources

of uncertainty are shown, with the rest being grouped up as “other” via a quadrature summation. The sources are grouped as being from (i) statistical uncertainties, (ii) photon efficiency uncertainties, (iii) photon energy calibration (scale, resolution) uncertainties, (iv) jet uncertainties, (v) lepton and E_T^{miss} uncertainties, (vi) flavor tagging uncertainties, (vii) spurious signal, (viii) trigger efficiency uncertainties, (ix) pileup uncertainties, (x) modeling uncertainties, and (xi) luminosity uncertainties.

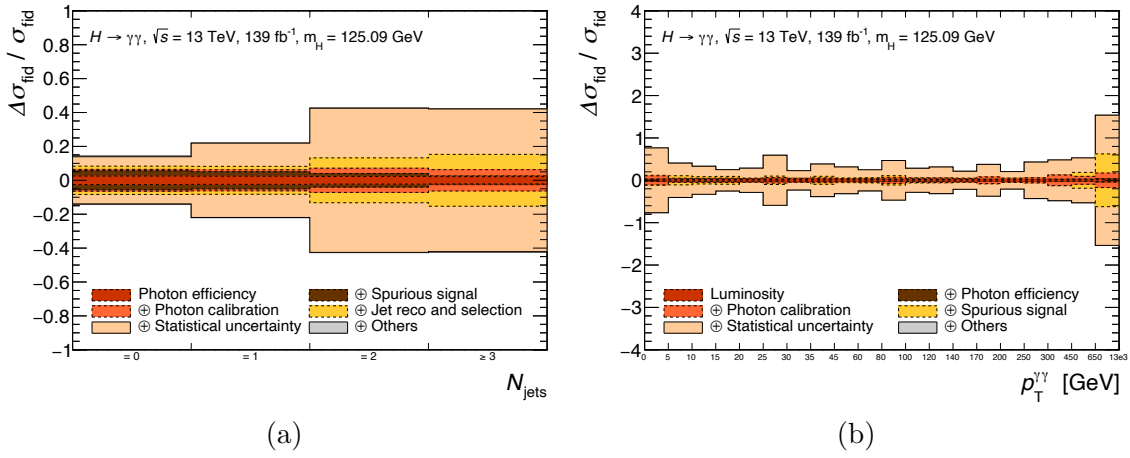


Figure 6.10: Breakdown of the sources of uncertainty per bin for (a) $p_T^{\gamma\gamma}$ and (b) N_{jets} differential distributions.

In each plot, the order of the contributions represents the order in the ranked list of leading sources. For example, the $p_T^{\gamma\gamma}$ variable in Figure 6.10 is dominated by statistical uncertainties, followed by the spurious signal, the photon calibration, the photon efficiency, and then luminosity. They are shown starting from the smallest one (the luminosity) and then each is added in quadrature one-by-one in reverse order. For N_{jets} , the ranked order is statistical uncertainties, jet reconstruction and selection uncertainties, followed by the photon calibration, the spurious signal, then the photon efficiency, with all others being included in “other”.

The uncertainty plots for all other variables is given in Appendix A.5.

6.5 Results

All measured cross-sections are compared to theoretical predictions. Chapter 6.5.1 details the theoretical models that are examined and Chapter 6.5.2 shows the final results.

6.5.1 Theoretical Predictions

The nominal theoretical predictions come from the default POWHEG+PYTHIA SM simulation which are scaled to their latest cross-section calculations. In these predictions, additional uncertainties are applied related to the choice of PDF, the Higgs boson branching ratio, and additional perturbative uncertainties are applied to the production modes using the simplified template cross-sections (STXS) stage 1.2 uncertainty scheme [96] and scale variations available in POWHEGBOX. The predictions for each fiducial region are shown in Table 6.13.

Table 6.13: Nominal cross-sections in each fiducial region using the default theoretical predictions. Here the inclusive fiducial cross-section is $\sigma_{\text{SM}}^{\text{fid}}$, the VBF-enhanced region is $\sigma_{\text{SM}}^{\text{VBF}}$, the single-lepton region is $\sigma_{\text{SM}}^{\text{lep}}$, the $E_{\text{T}}^{\text{miss}}$ -enhanced region is $\sigma_{\text{SM}}^{\text{MET}}$ and the $t\bar{t}H$ -enhanced region is $\sigma_{\text{SM}}^{\text{ttH}}$.

Fiducial Region	Predicted Cross-Section
$\sigma_{\text{SM}}^{\text{fid}}$	$64 \pm 4 \text{ fb}$
$\sigma_{\text{SM}}^{\text{VBF}}$	$1.53 \pm 0.09 \text{ fb}$
$\sigma_{\text{SM}}^{\text{lep}}$	$0.59 \pm 0.04 \text{ fb}$
$\sigma_{\text{SM}}^{\text{MET}}$	$0.302 \pm 0.021 \text{ fb}$
$\sigma_{\text{SM}}^{\text{ttH}}$	$0.60 \pm 0.09 \text{ fb}$

Several other theoretical predictions are also compared to the measured results in addition to the default SM predictions and are summarized below.

- **MATRIX+RadISH** [109]: Combines fully differential cross-sections for color-singlet production processes at NNLO accuracy in QCD using MATRIX [110, 111] and all-order resummation with RADISH [112, 113]
- **RadISH+NNLOjet**: Predicts the $p_T^{\gamma\gamma}$ distribution with RADISH [112, 113] and matches it to high- p_T^H distribution for Higgs + jets from NNLOJET [114, 115]
- **Sherpa+MCFM+OpenLoops**: Higgs + ≥ 2 -jets matrix elements from MCFM [116] and Higgs + ≥ 3 -jets with OPENLOOPS [117–119] matched with the SHERPA parton shower
- **ResBos2** [120, 121]: Predictions for inclusive Higgs boson production via gluon–gluon fusion
- **SCETlib::qT** [122–126]: Predictions that include resummation of logarithms at small $p_T < m_H$
- **SCETlib::pTj1** [122, 127, 128]: Predictions are for $gg \rightarrow H$ in the narrow-width limit
- **SCET+MG5 (NNLL'+NNLO)** [122]: Predictions for the 0-jet ggF cross-section using τ_{C,j_1}
- **STWZ, BLPTW** [127, 129]: Perturbative predictions using resummation in QCD for the p_T of the leading and subleading jet
- **proVBF NNLO** [130]: Calculates fully differential next-to-next-to-leading order corrections for the VBF Higgs boson production mechanism
- **GoSam** [131, 132]: Predictions using fixed-order loop contributions for the inclusive Higgs + 0, 1, 2, 3 jets regions

6.5.2 Measured Cross-Sections

For each fiducial region and differential bin, an unbinned signal-plus-background fit to the diphoton invariant mass distribution is performed. Figure 6.11 shows the distribution including the fitted signal-plus-background model for the measurement of the fiducial cross-section. Figure 6.12 shows the diphoton invariant mass distribution for the other four fiducial volumes, VBF-enhanced, single-lepton, E_T^{miss} -enhanced, and $t\bar{t}H$ -enhanced. In the VBF-enhanced, lepton, and inclusive regions, the distributions have an obvious peak around the Higgs boson mass when looking at the residual between the data and the background component of the total model. The peaks in the E_T^{miss} -enhanced and $t\bar{t}H$ -enhanced regions are less significant though present.

The fitted diphoton invariant mass distributions for all other variables is given in Appendix A.6.

The particle-level cross-sections for the $pp \rightarrow H \rightarrow \gamma\gamma$ process are then obtained by unfolding the detector-level yields from the signal fits and each measurement is compared to selected theoretical predictions described earlier. The measured total fiducial cross-section is $\sigma_{\text{fid}} = 67 \pm 5 \text{ (stat.)} \pm 4 \text{ (sys.) fb} = 67 \pm 6 \text{ fb}$. This can be compared to a predicted value from SCETLIB::qT of $64.2 \pm 3.4 \text{ fb}$. The measured values compared to predictions for each of the five fiducial regions are shown in Figure 6.13. Using the CL_s procedure [133], for the fiducial inclusive cross-section, upper limits at the 95% confidence level (CL) were set with an observed significance below 3σ . Good agreement between the predictions and data is observed. The lepton-enhanced region is the furthest away from the predicted value, however is still within the total uncertainty on the measurement. In each measured cross-section, the uncertainty is dominated by the statistical component, however this is expected due to the relatively small branching ratio of the Higgs boson to diphoton decay. In the future, the

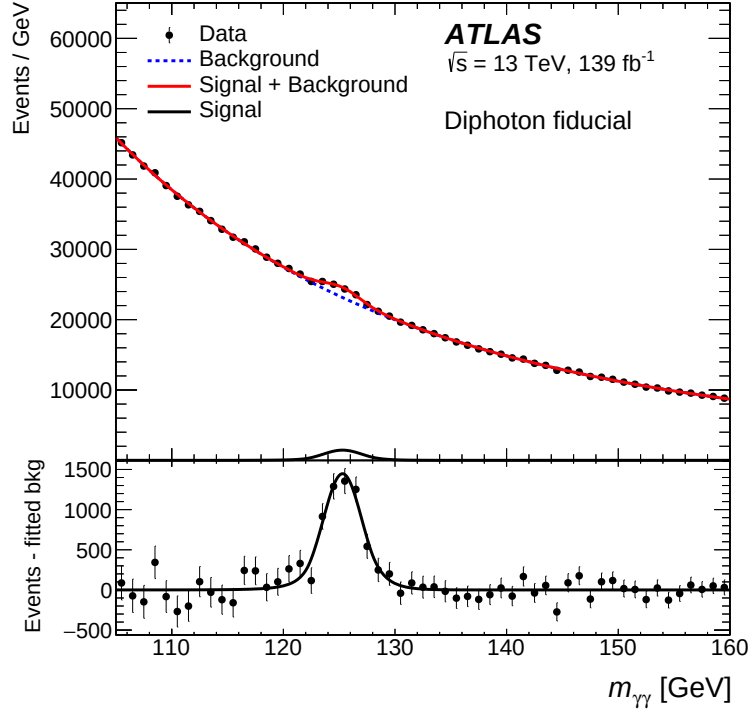


Figure 6.11: The diphoton invariant mass spectrum for events passing the inclusive fiducial selections. The fitted signal-plus-background model for this region is shown in red. The plot on the bottom shows the residual events between the data and background with a peak at the Higgs boson mass $m_H = 125.09 \pm 0.24$ GeV.

LHC Run 3 dataset will be at a higher luminosity meaning more data which will improve the precision of this measurement.

Table 6.14 shows the measured cross-section value compared to the SM value for each of the fiducial regions along with the relative uncertainty. The sources are grouped as being from statistical sources (stat.), from the photon energy scale and resolution (PES+PER), the luminosity (Lumi), trigger efficiency (Trigger), photon identification and isolation efficiency (Photon eff.), pileup modeling (PRW), then uncertainties related to jet (Jet), flavor-tagging (Flavor), or lepton and E_T^{miss} , then modeling, and spurious signal uncertainties from background modeling followed by the total error with all uncertainties summed in quadrature.

To test the compatibility of each measured cross-section with the SM value, a χ^2 test is employed to compute the p -value considering all uncertainties. Table 6.15 gives the final

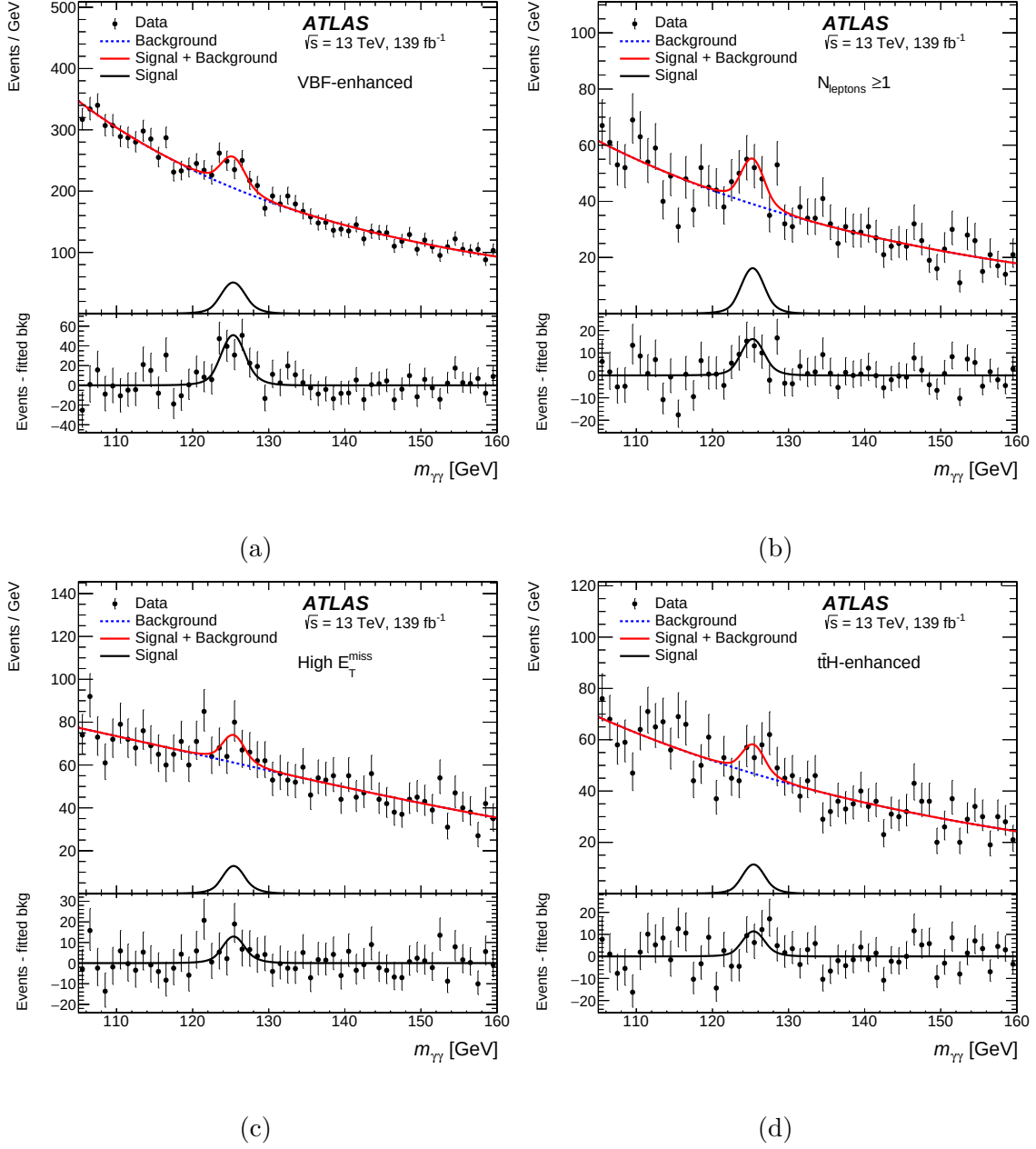


Figure 6.12: The diphoton invariant mass spectrum for events passing each of the fiducial volume selections for the (a) VBF-enhanced, (b) single-lepton, (c) E_T^{miss} -enhanced, and (d) $t\bar{t}H$ -enhanced regions. In each, the bottom plot shows the residuals between the data and the background fit.

measured cross-section value, along with the related systematic and statistical uncertainties,

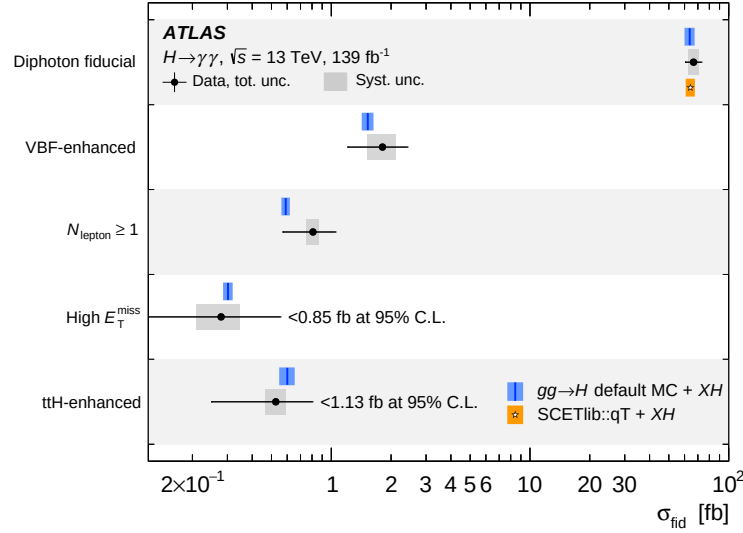


Figure 6.13: The particle-level cross-sections times the branching ratio for each of the fiducial regions. The measured values are shown in black with the corresponding uncertainties as compared to the predicted values from the default simulation in blue and SCETLIB::qT in orange. The +XH for each prediction indicates all the Higgs boson production modes except for ggF.

to compare to the SM prediction. In the table, the p -value is reported as well showing good compatibility between the fitted cross-sections and the prediction.

Table 6.14: Observed cross-sections compared to the predicted Standard Model value σ/σ_{SM} for each fiducial region and the associated uncertainties.

Bin	σ/σ_{SM}	stat.	PES+PER	Lumi	Trigger	Photon eff.	PRW	Jet	Flavor	Lep+MET	modeling	SS	tot. err.
Inclusive	1.046	± 0.075	± 0.036	± 0.018	± 0.010	± 0.026	± 0.014	± 0.000	± 0.000	± 0.000	± 0.004	± 0.038	± 0.098
E_T^{miss}	0.923	± 0.882	± 0.090	± 0.016	± 0.009	± 0.020	± 0.050	± 0.031	± 0.000	± 0.117	± 0.050	± 0.144	± 0.911
VBF	1.186	± 0.345	± 0.064	± 0.020	± 0.011	± 0.026	± 0.027	± 0.169	± 0.000	± 0.000	± 0.041	± 0.026	± 0.396
Lepton	1.370	± 0.394	± 0.053	± 0.023	± 0.013	± 0.031	± 0.020	± 0.000	± 0.000	± 0.010	± 0.014	± 0.064	± 0.406
$t\bar{t}H$	0.875	± 0.449	± 0.081	± 0.015	± 0.008	± 0.018	± 0.005	± 0.048	± 0.011	± 0.002	± 0.026	± 0.006	± 0.461

Along with the fiducial cross-section, the total cross-section for the full phase space is calculated. This is performed using the same methodology using a fit to the inclusive sample of all selected Higgs boson to diphoton candidates using the full acceptances. All uncertainties evaluated for the fiducial cross-section are included in the total cross-section measurement. As a result, the final total measured cross-section divided by the branching

Table 6.15: Particle-level cross-sections times branching ratio in the five fiducial regions and the total combined cross-section times branching ratio with the associated statistical and systematic uncertainties. The last column shows the probabilities from a χ^2 compatibility test.

Fiducial region	Measured [fb]			SM prediction [fb]		p -value
	$\pm$ stat	$\pm$ sys		$\pm$ tot err		
Inclusive	67	5	4	64	4	69%
VBF-enhanced	1.80	0.5	0.3	1.53	0.10	64%
Lepton	0.81	0.23	0.06	0.59	0.03	36%
High E_T^{miss}	0.28	0.27	0.07	0.302	0.017	93%
$t\bar{t}H$ -enhanced	0.53	0.27	0.06	0.60	0.05	79%
Total	132	10	8	126	7	69%

ratio is $\sigma_{\text{tot}} = 58 \pm 4$ (stat.) ± 4 (sys.) pb = 58 ± 6 pb which is in agreement with the SM prediction of 55.6 ± 2.7 pb [123].

In Figure 6.14, the $p_T^{\gamma\gamma}$ differential cross-section is shown compared to multiple theoretical predictions. Various predictions for ggF are shown along with the combination of the other considered production mechanisms are denoted as XH . The ratio of the combined ggF prediction + XH is shown at the bottom of each plot. The boosted region with $p_T^{\gamma\gamma} > 350$ GeV is newly presented which is sensitive to BSM effects. Though it is very statistically limited, 95% CL upper limits of 3.1 and 5.8 were set on the ratio of the cross-section compared to the SM prediction for $450 < p_T^{\gamma\gamma} < 650$ GeV and $p_T^{\gamma\gamma} > 650$ GeV respectively which is a significant improvement from previous limits set.

Figure 6.15 includes the Higgs + heavy flavor contribution in the last bin of the $N_{b\text{-jets}}$ measured cross-section. This measurement has one of the larger deviations from the SM with $\sigma/\sigma_{SM} = 1.848 \pm 0.651$ for the bin with at least 1 b -tagged jet. As with many of these measurements, it is statistically limited in that bin (± 0.624) but hopefully with future

datasets, this measurement will be more precise as this process is not well understood in the ggF production mode.

For the remaining obtained cross-sections, good agreement is observed between the data and the various theoretical predictions, including the Standard Model predictions. Some bins of these distributions have a very large systematic uncertainty and have predictions that are off the scale of the ratio plot. In these cases, it is indicated with an arrow. The double-differential measurements are shown in Figures 6.19.

The differential measurements in the VBF-enhanced fiducial region are shown in Figure 6.20. In these bins, the predictions are on VBF production instead of ggF as with the ones above, therefore the remaining predictions here is a different sum XH , and is shown in pink. The systematic uncertainties in these bins are somewhat smaller than those seen in some other distributions, including uncertainties for the predictions themselves, though the data are still statistically limited.

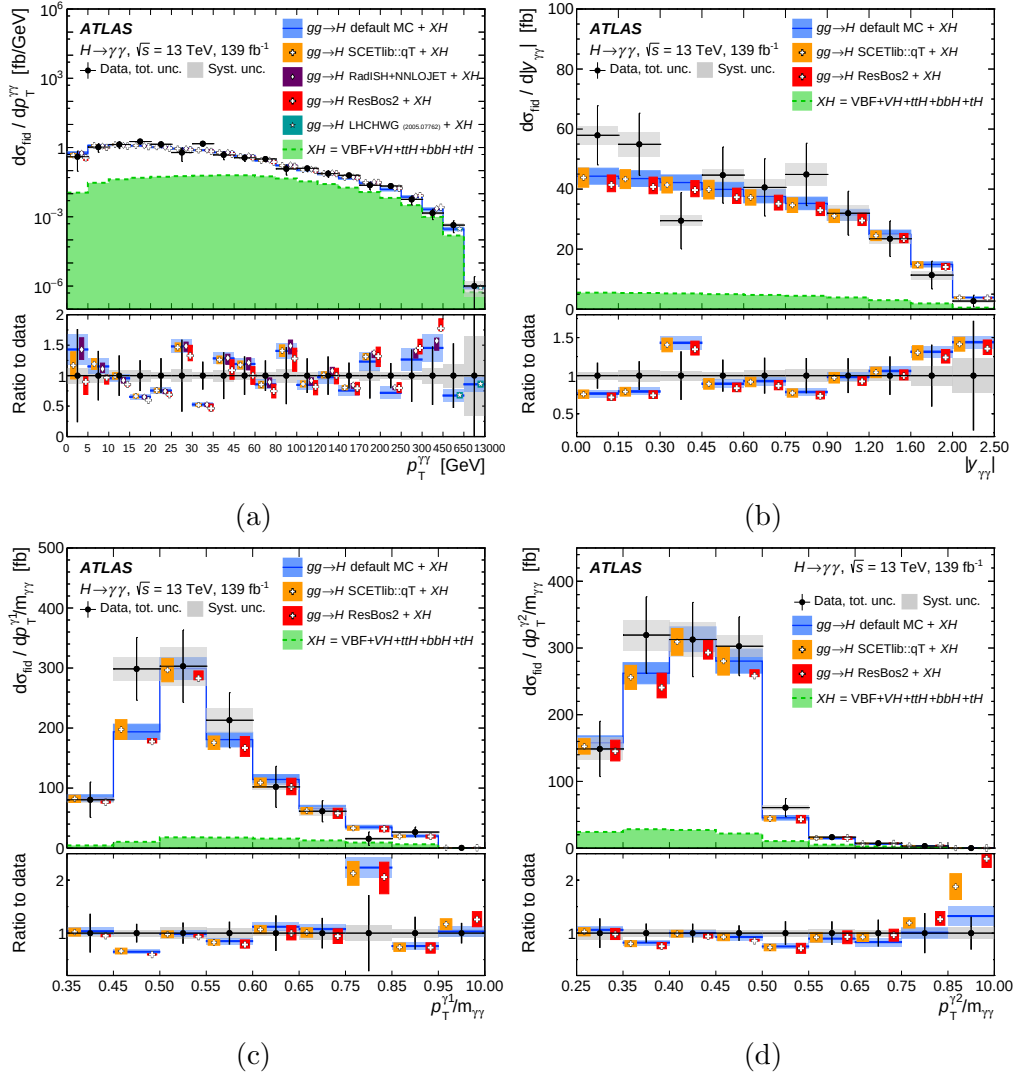


Figure 6.14: Particle-level fiducial differential cross-sections times branching ratio for (a) $p_T^{\gamma\gamma}$, (b) $|y^{\gamma\gamma}|$, (c) $p_T^{\gamma\gamma}/m_{\gamma\gamma}$, and (d) $p_T^{\gamma\gamma^2}/m_{\gamma\gamma}^2$ differential distributions compared to theoretical predictions.

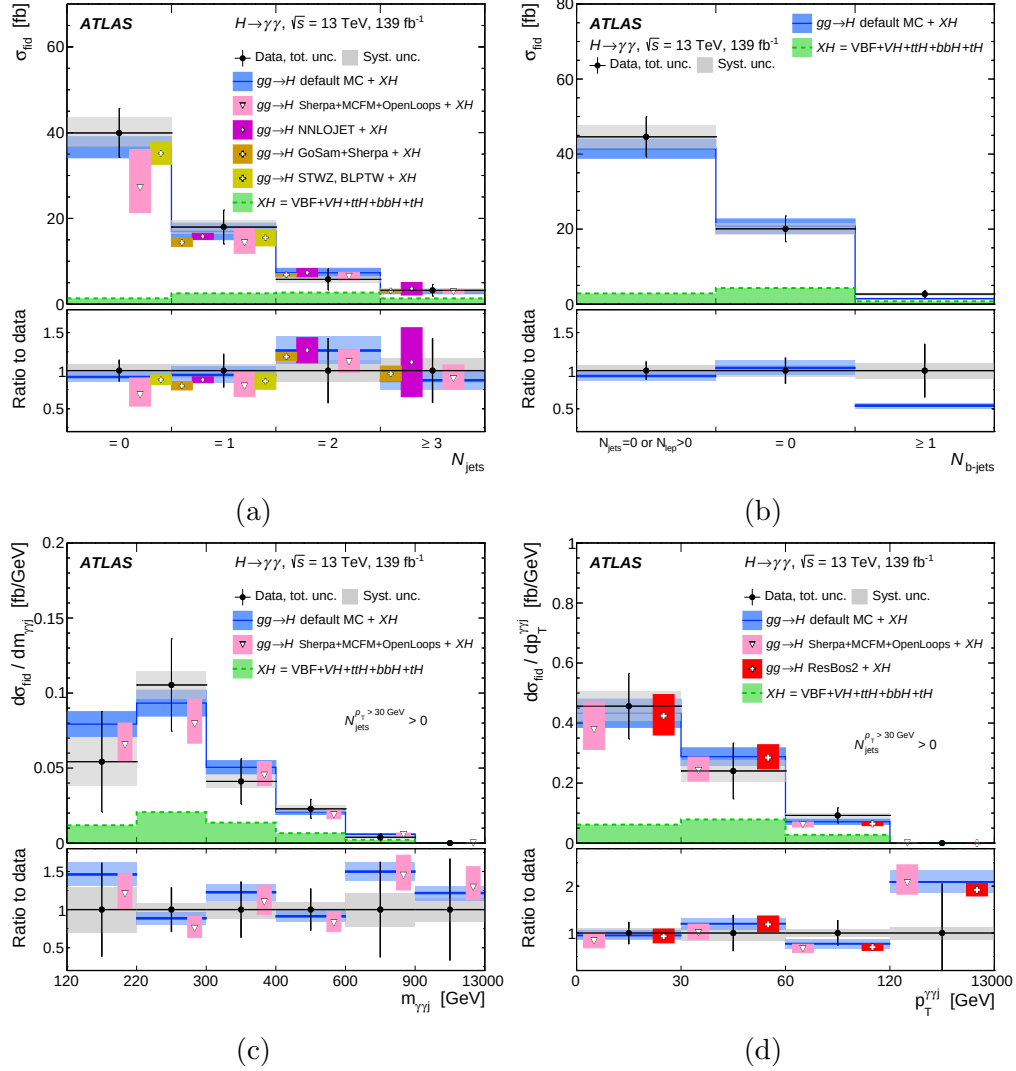


Figure 6.15: Particle-level fiducial differential cross-sections times branching ratio for (a) N_{jets} , (b) $N_{\text{b-jets}}$, (c) $m_{\gamma\gamma j}$, and (d) $p_{\text{T}}^{\gamma\gamma j}$ differential distributions compared to theoretical predictions.

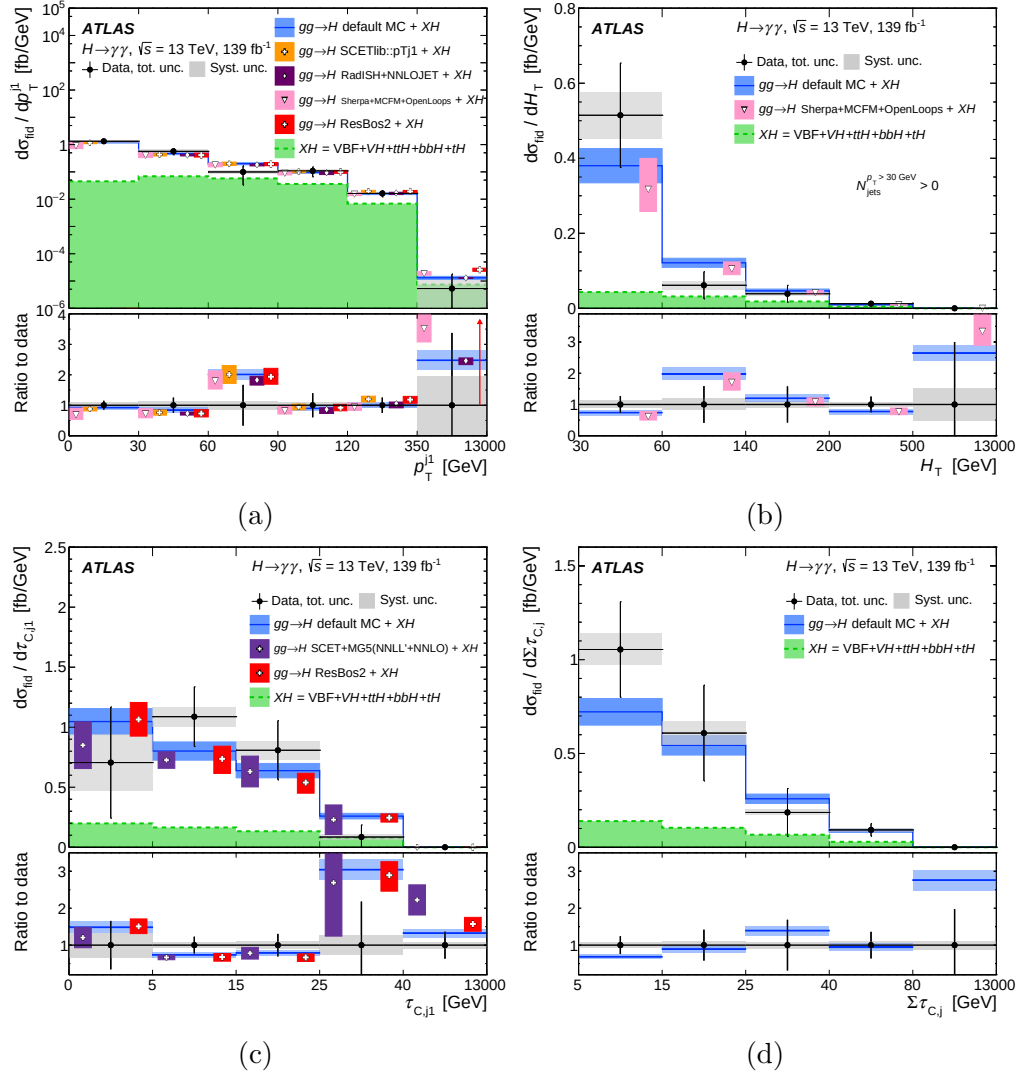


Figure 6.16: Particle-level fiducial differential cross-sections times branching ratio for (a) p_T^{j1} , (b) H_T , (c) $\tau_{C,j1}$, and (d) $\Sigma \tau_{C,j}$ differential distributions compared to theoretical predictions.

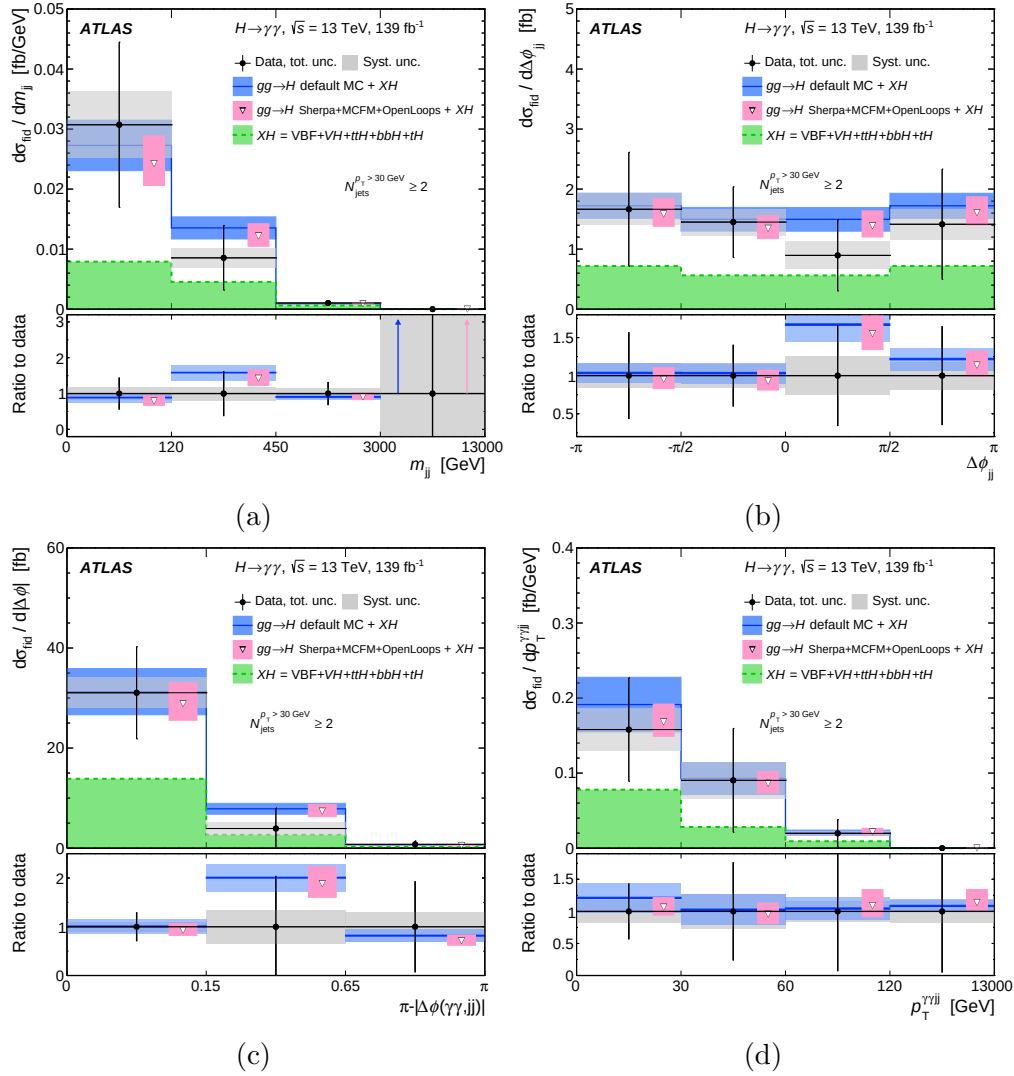


Figure 6.17: Particle-level fiducial differential cross-sections times branching ratio for (a) m_{jj} , (b) $\Delta\phi_{jj}$, (c) $|\Delta\phi_{\gamma\gamma,jj}|$, and (d) $p_T^{\gamma\gamma jj}$ differential distributions compared to theoretical predictions.

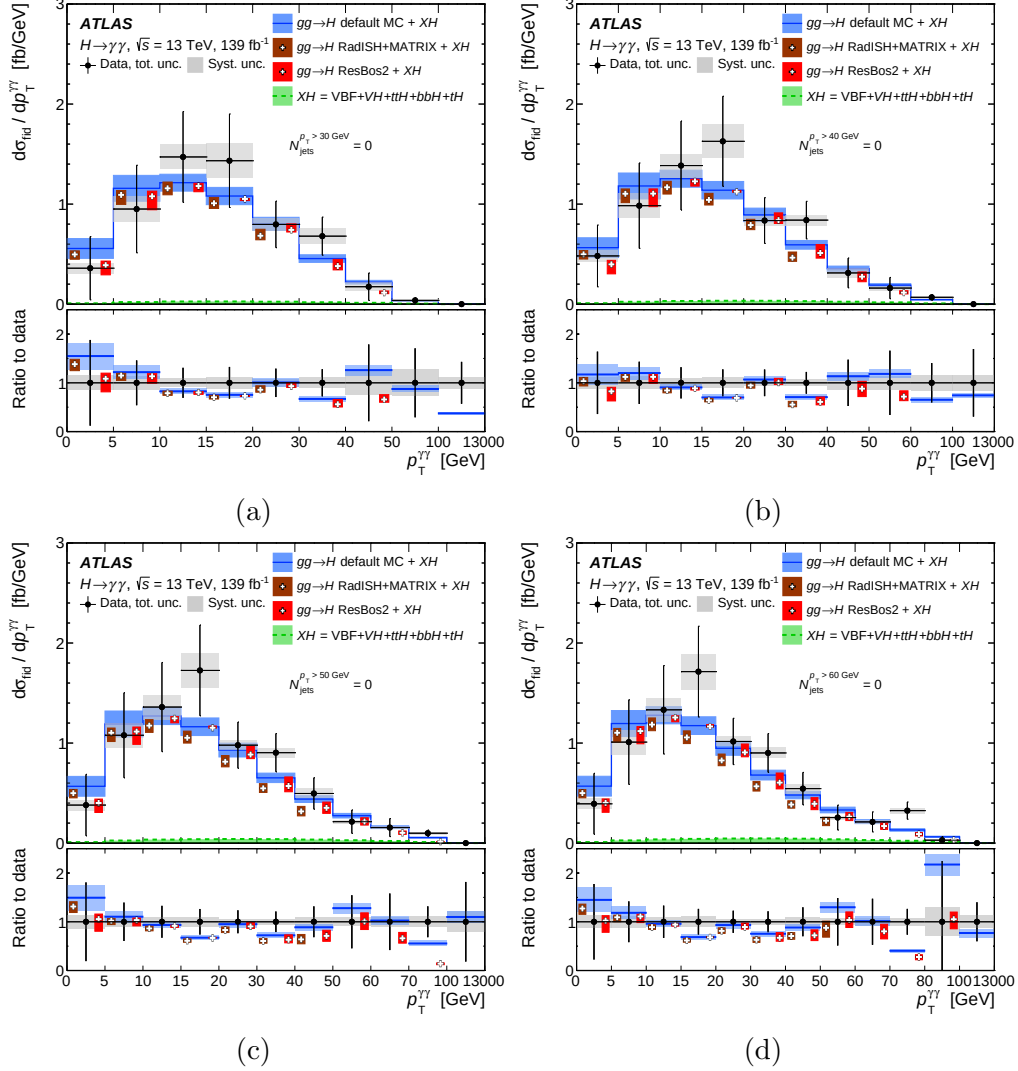


Figure 6.18: Particle-level fiducial differential cross-sections times branching ratio compared to theoretical predictions for $p_T^{\gamma\gamma}$ differential variables with a jet-veto, i.e. no jets with p_T above a certain threshold equal to (a) 30, (b) 40, (c) 50, and (d) 60 GeV.

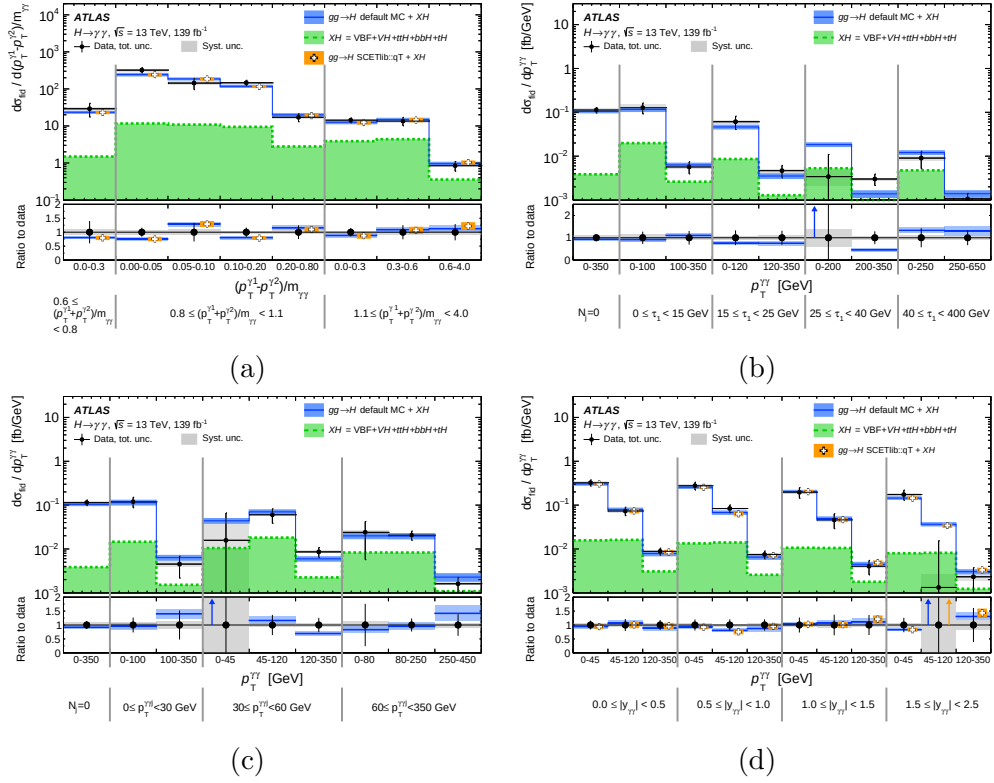


Figure 6.19: Particle-level fiducial differential cross-sections times branching ratio for (a) $(p_T^{\gamma 1} + p_T^{\gamma 2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma 1} - p_T^{\gamma 2})/m_{\gamma\gamma}$, (b) $p_T^{\gamma\gamma}$ vs. $\tau_{C,j1}$, (c) $p_T^{\gamma\gamma}$ vs. $p_T^{\gamma j}$, and (d) $p_T^{\gamma\gamma}$ vs. $|y^{\gamma\gamma}|$ double-differential distributions compared to theoretical predictions.

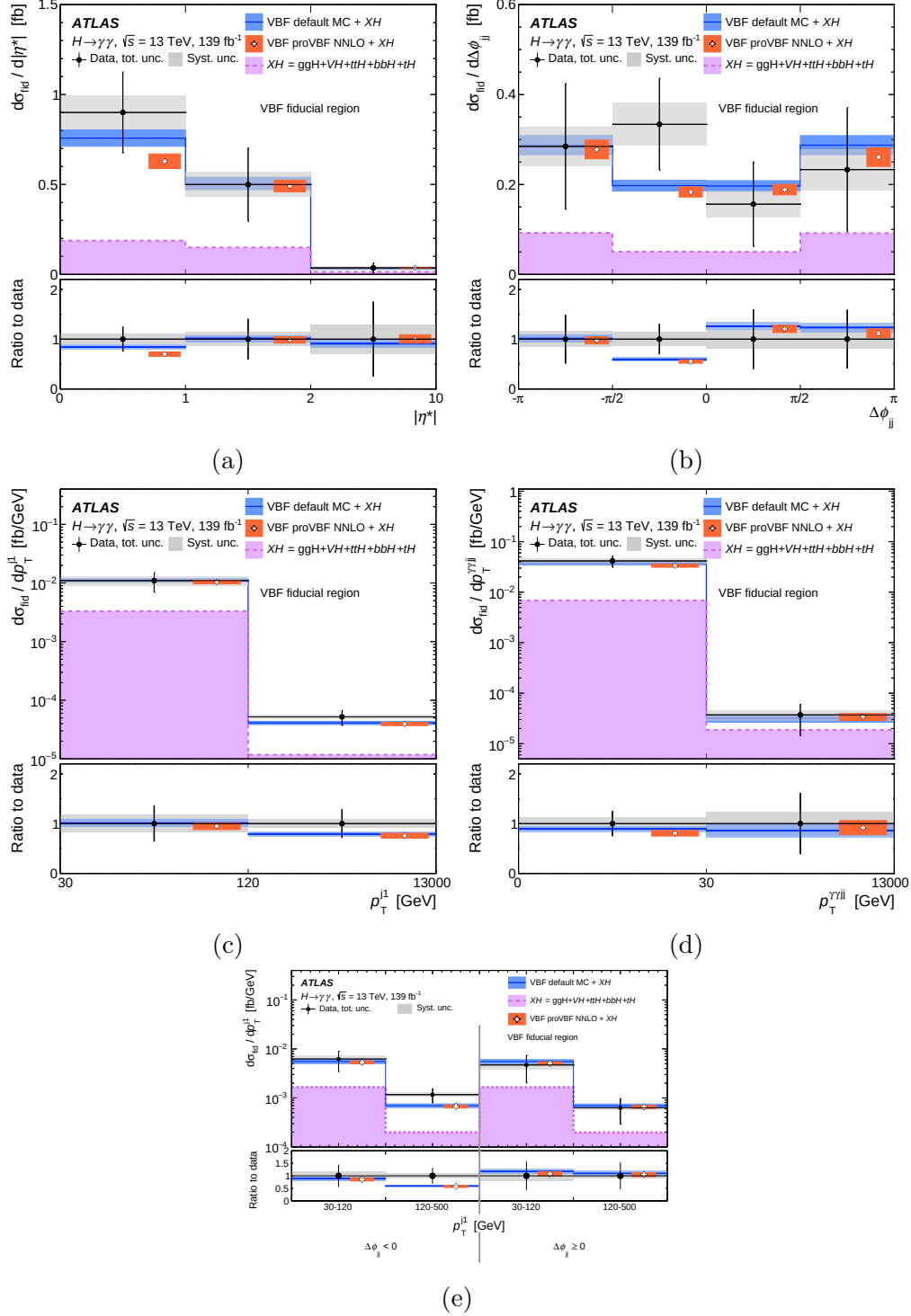


Figure 6.20: Particle-level fiducial differential cross-sections times branching ratio for (a) $|\eta^*|$, (b) $\Delta\phi_{jj}$, (c) p_T^{j1} , (d) $p_T^{\gamma\gamma jj}$, and (e) p_T^{j1} vs $\Delta\phi_{jj}$ differential variables in the VBF-enhanced fiducial volume compared to theoretical predictions.

6.5.3 Nuisance Parameters

For all nuisance parameters, a check is performed on the pre-fit and post-fit values to determine if any of them are over-constrained or pulled significantly away from its initial best-fit value during fitting. A pre-fit impact is determined by shifting a nuisance value away from their initial value by 1σ then performing the fit and allowing other parameters to drift. The variation in the final fitted signal yield is the pre-fit impact. The post-fit impact is determined with all nuisance parameters set to their best fit values. Figure 6.21 shows the top 20 nuisance parameters impacting the fit in the inclusive fiducial region in order. Those ranked highest are the nuisance parameters related to spurious signal (bkgbias_c0), photon identification and isolation efficiency (PH_EFF_ID_Uncertainty, PH_EFF_ISO_Uncertainty), the luminosity uncertainty (ATLAS_LUMI), and the e/γ resolution uncertainties (EG_RESOLUTION*)

6.5.4 Interpretations

The cross-section results obtained are interpreted in two ways to further test SM predictions. First, the measured results are used to constrain the Yukawa coupling modifiers for the b and c quark as presented in Chapter 6.5.4.1. Next, BSM interactions are probed using an effective field theory (EFT) approach as presented in Chapter 6.5.4.2.

6.5.4.1 Yukawa Coupling Interpretation

The b and c quarks contribute to the quark-initiated and loop induced gluon-gluon fusion production of the Higgs boson as shown in Figure 6.22.

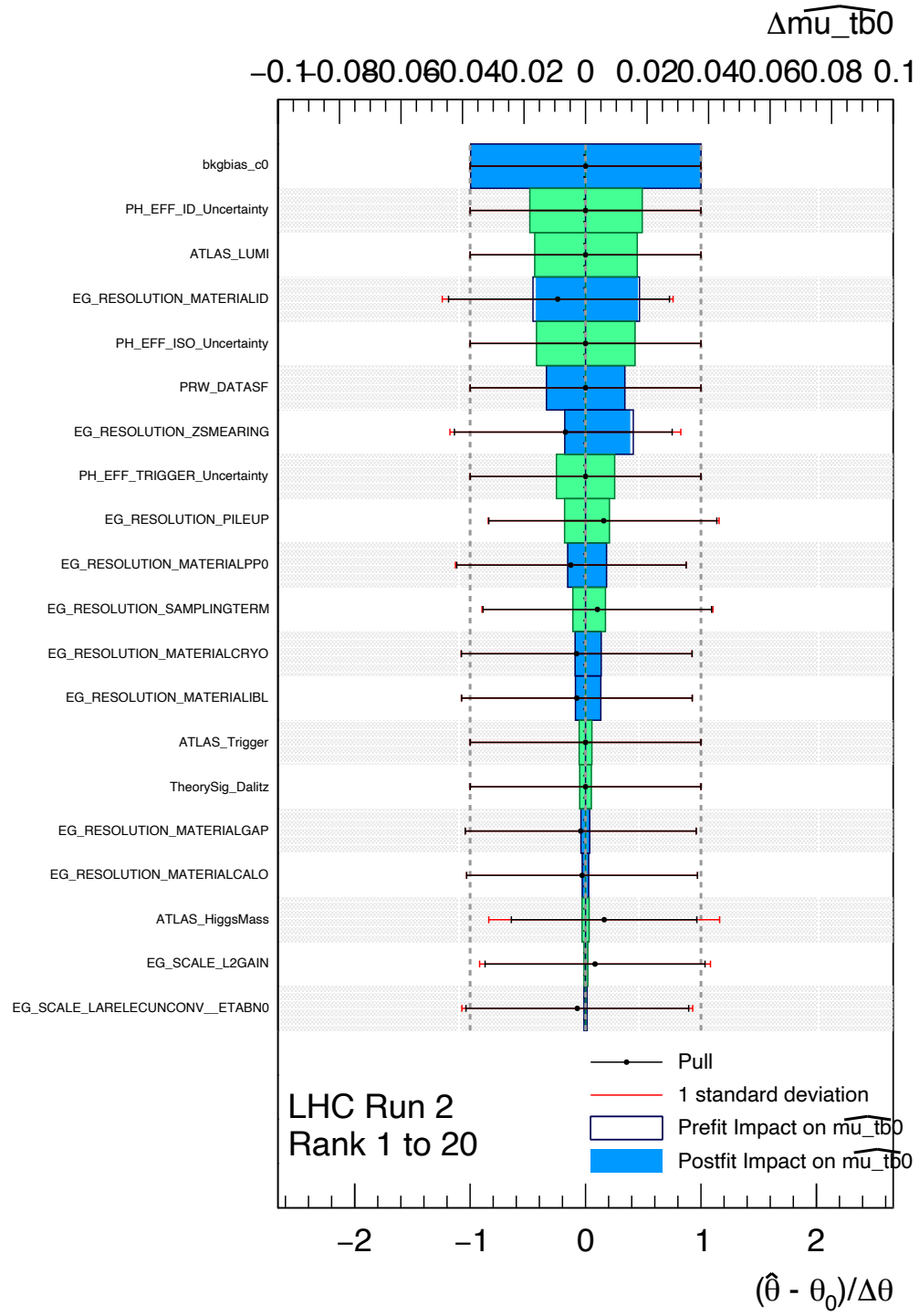


Figure 6.21: The rankings of the top 20 nuisance parameters impacted the fit in the inclusive fiducial region.

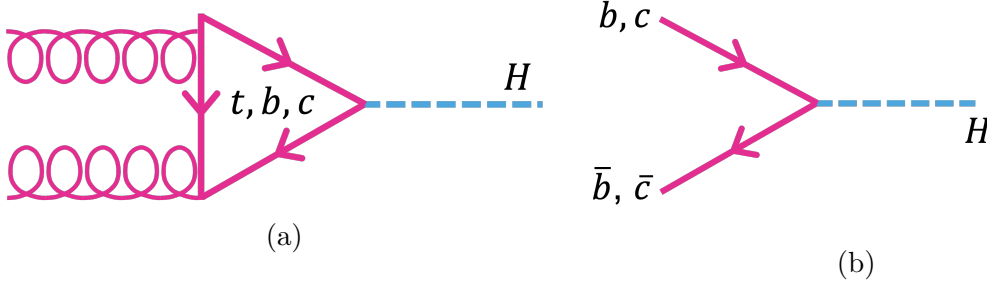


Figure 6.22: Leading order Feynman diagrams for the Higgs boson production processes that are sensitive to a modification in the Yukawa coupling via (a) gluon-gluon fusion and (b) quark-initiated production.

Changes in the Yukawa coupling modifiers κ_c and κ_b would change these two production modes which would in turn modify the shape and the normalization of the Higgs boson transverse momentum spectrum. Additionally, the branching ratio for $H \rightarrow \gamma\gamma$ would be impacted, changing the $H \rightarrow \gamma\gamma$ decay width as well as the total Higgs boson decay width. Therefore, we can probe κ_c and κ_b indirectly through the measured $p_T^{\gamma\gamma}$ spectrum. An advantage of the indirect probe is that the analysis is not limited by the tagging efficiency of b - or c -jets.

For this measurement, the cross-section is parameterized as a function of the b and c quark Yukawa coupling modifiers κ_b and κ_c . The parameters and corresponding uncertainties, θ , are included in a likelihood fit along with the measured cross-section to obtain limits. Equation 6.9 gives this likelihood function used where σ_{obs} is the vector of the measured cross-sections times branching ratio, V is the covariance matrix, $\sigma_H(\kappa_b, \kappa_c, \theta)$ is the parameterized cross-section times branching ratio and $\mathcal{C}(\theta)$ is the constraint term of the nuisance parameters in the parameterized cross-section.

$$L = \exp \left[-\frac{1}{2} (\sigma_{\text{obs}} - \sigma_H(\kappa_b, \kappa_c, \theta))^T V^{-1} (\sigma_{\text{obs}} - \sigma_H(\kappa_b, \kappa_c, \theta)) \right] \times \mathcal{C}(\theta), \quad (6.9)$$

Limits are set on the Yukawa coupling modifiers when considering only shape effects on the $p_T^{\gamma\gamma}$ spectrum as well as when including normalization considerations and the dependence on the branching ratio and cross-section. These limits are set using a test statistic that is based on the ratio of the profiled likelihoods using the measured differential cross-section with $p_T^{\gamma\gamma} < 200$ GeV. In the fit, all other Higgs boson couplings were set to SM values $\kappa = 1$ and each of the Yukawa couplings under study for b and c were done so independently where the other value was fixed to the SM value of 1. The 95% CL limits are shown in Table 6.16 with the upper and lower limits for the measured and predicted values for fits considering shape-only effects and fits including normalization and branching ratio modifications.

Table 6.16: Observed and expected 95% CL limits on the allowed ranges of modifications of the b - and c -quark Yukawa couplings to the Higgs boson, κ_b and κ_c .

Fit set-up	κ	Observed 95% CL	Expected 95% CL
Shape-only	κ_c	$[-12.6, 18.3]$	$[-10.1, 17.3]$
	κ_b	$[-3.5, 10.3]$	$[-2.5, 8.1]$
Shape+XS+BR	κ_c	$[-2.5, 2.3]$	$[-3.0, 3.1]$
	κ_b	$[-1.1, -0.8] \cup [0.8, 1.1]$	$[-1.2, -0.9] \cup [0.8, 1.2]$

The upper and lower limit for each coupling modifier was then used to obtain the fiducial differential cross-section times branching ratio measurement for $p_T^{\gamma\gamma}$. The measured values compared to the SM prediction is shown in Figure 6.23 when using the shape-only fit and in Figure 6.24 when including modifications to the normalization, cross-section, and branching ratio in the fit.

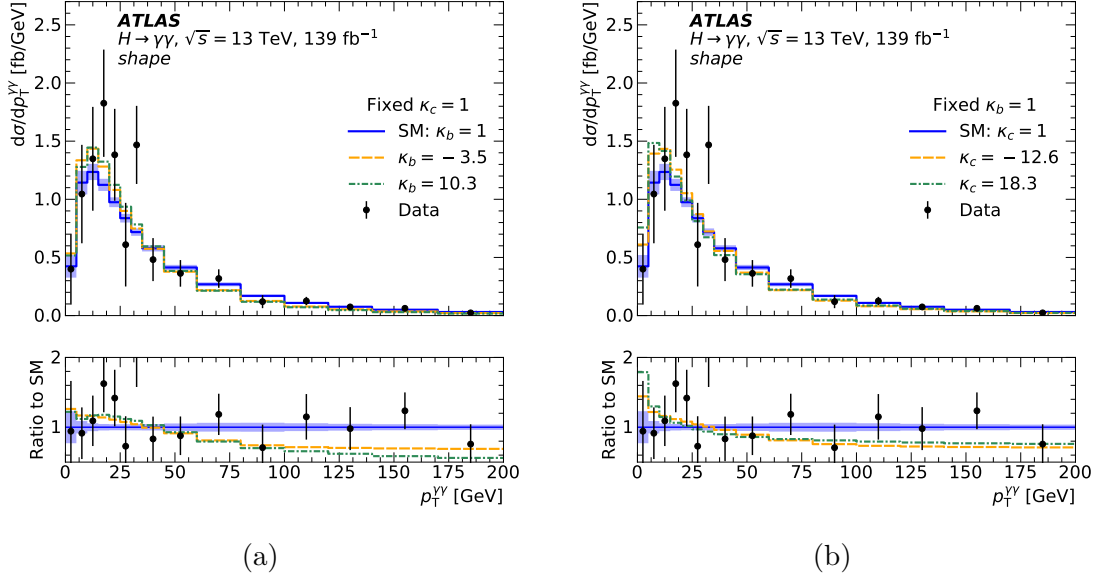


Figure 6.23: The fiducial differential cross-section times branching ratio measurement of the diphoton transverse momentum with modification to the Yukawa couplings for the (a) b and (b) c quark to the Higgs boson for the shape-only fit.

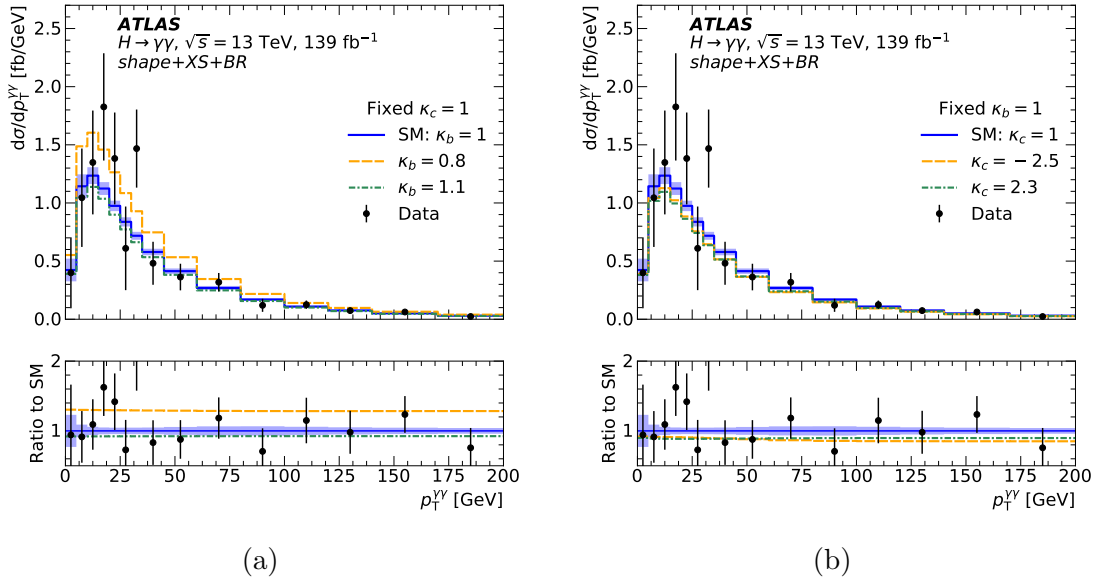


Figure 6.24: The fiducial differential cross-section times branching ratio measurement of the diphoton transverse momentum with modification to the Yukawa couplings for the (a) b and (b) c quark to the Higgs boson for the shape-only fit.

6.5.4.2 EFT Interpretation

An effective field theory approach is used here to probe deviations from the SM by modifying its Lagrangian. In this approach, additional dimension-6 operators $\mathcal{O}_i^{(6)}$ are added to the SM Lagrangian as shown in Equation 6.10.

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} \quad (6.10)$$

The parameter c_i is a non-zero Wilson coefficient which specifies the strength of the interaction and Λ is the scale of the new beyond the Standard Model (BSM) physics. Cross-sections are the obtained, including differential cross-sections binned by $p_T^{\gamma\gamma}$, N_{jets} , m_{jj} , $\Delta\phi_{jj}$ and p_T^{j1} . The modifications impact the $H \rightarrow \gamma\gamma$ branching ratio and cross-section which leads to the following expansion to calculate the product as shown in Equation 6.11.

$$\sigma \times B = \sigma_{\text{SM}} B_{\text{SM}} + (\sigma_{\text{SM}} B_{\text{INT}} + \sigma_{\text{INT}} B_{\text{SM}}) + (\sigma_{\text{SM}} B_{\text{BSM}} + \sigma_{\text{BSM}} B_{\text{SM}}) + \mathcal{O}(c_i^3/\Lambda^6), \quad (6.11)$$

The first term is purely from the SM while the second term will be linear in c_i and accounts for the interactions (denoted as INT) between the SM and the new BSM theory. The third term is quadratic in c_i and is the product between the SM and BSM values without additional interactions.

For these calculations, the operators are parameterized using the Warsaw basis of the Standard Model EFT (SMEFT) Lagrangian [134, 135] which gives two classifications of coefficients:

- Coefficients c_{HG} and its CP-odd counterpoint $c_{H\tilde{G}}$ affect the gluon-gluon fusion production mode and may impact the Higgs boson total width

- Coefficients c_{HW} , c_{HB} , and c_{HWB} and their CP-odd counterparts $c_{H\tilde{W}}$, $c_{H\tilde{B}}$, and $c_{H\tilde{W}B}$, affect the partial decay width of $H \rightarrow \gamma\gamma$ and the VBF and VH production cross-sections

Limits on the Wilson coefficients are set via the likelihood function computed at the scaled $\Lambda = 1$ TeV and the results are reported in Table 6.17. When studying each coefficient, all others are set to zero. Two scenarios are shown, using only the interference terms or using both the interference term and quadratic term. Strict limits are set all CP-even operators. These results are comparable to previously obtained results by ATLAS [136, 137] and CMS [138].

Table 6.17: The 95% CL observed limits on the Wilson coefficients of the SMEFT basis

Coefficient	95% CL, interference-only terms	95% CL, interference and quadratic terms
c_{HG}	$[-6.1, 11.0] \times 10^{-3}$	$[-6.5, 10.2] \times 10^{-3}$
$c_{H\tilde{G}}$	$[-0.12, 0.23]$	$[-3.1, 3.5] \times 10^{-2}$
c_{HW}	$[-1.9, 0.9] \times 10^{-2}$	$[-1.8, 1.0] \times 10^{-2} \cup [0.28, 0.30]$
$c_{H\tilde{W}}$	$[-10.2, 5.2]$	$[-7.3, 7.3] \times 10^{-2}$
c_{HB}	$[-5.8, 2.8] \times 10^{-3}$	$[-5.5, 3.0] \times 10^{-3} \cup [8.4, 9.3] \times 10^{-2}$
$c_{H\tilde{B}}$	$[-21.8, 5.7] \times 10^2$	$[-2.3, 2.3] \times 10^{-2}$
c_{HWB}	$[-5.2, 10.7] \times 10^{-3}$	$[-0.17, -0.15] \cup [-5.5, 9.8] \times 10^{-3}$
$c_{H\tilde{W}B}$	$[-2.5, 4.0] \times 10^2$	$[-4.0, 4.0] \times 10^{-2}$

CHAPTER 7

DIPHOTON PRODUCTION IN ASSOCIATION WITH HEAVY FLAVOR JETS

Diphoton production with associated jets that contain b - or c - hadrons (referred to as heavy flavor jets) is an important Standard Model process that has never been measured nor is there a direct prediction for it anywhere in the literature. This process is especially crucial going forward as it is a dominant background for many interesting physics analyses, including $HH \rightarrow \gamma\gamma bb$ and $t\bar{t}H(\gamma\gamma)$. The diHiggs analysis is important for studying the trilinear coupling of the Higgs boson, which is one of the free parameters of the Higgs potential. The $\gamma\gamma bb$ decay channel specifically is predicted to be one of the leading discovery channels in Run 3 [138–141]. The $t\bar{t}H$ process is also a focus for current and future LHC analyses. It is a great channel for studying the top quark Yukawa coupling and it can potentially help disentangle the small CP-odd components of the Higgs boson. The diphoton decay channel is one of two leading observation channels for $t\bar{t}H$ [142]. In these processes and many others, having accurate modeling of the background is essential, especially when using advanced multivariate analysis tools, therefore prediction for the heavy flavor (HF) content of diphoton + jets production is important. In addition to the role $\gamma\gamma$ + one or two HF jets plays in other measurements and searches, HF jet production in proton-proton collisions is dominated by mechanisms governed by quantum chromodynamics, and in turn by the structure of the proton, thus $\gamma\gamma$ + HF can be used to probe QCD in the perturbative realm.

The analysis presented here aims to measure diphoton production with either one or two associated HF jets in the final state. Events are categorized by the jet flavor combinations

denoted as just b -, c -, or light-flavor (l) for the highest p_T jet or bb , bc , bl , cc , cl , and ll referring to the leading and subleading jet flavors. To extract the HF signal, a template fit to the neural-network jet flavor-tagging discriminant is used. There are two types of backgrounds that need to be accounted for, either from an electron mistakenly reconstructed as a photon or a jet faking a photon. In both cases, Monte Carlo simulation is unreliable for modeling the misconstructions, therefore other techniques are utilized. For the electron case, an electron-photon fake rate will be calculated which gives the probability of an electron to be reconstructed as a photon. This rate is then used to measure the number of electron faking photons in our signal. For jets, the 2x2D sideband method used by the $H \rightarrow \gamma\gamma$ fiducial and differential cross-section measurement in Chapter 6.2 is adapted to be used here.

The diphoton + HF analysis is described in the following chapters: Chapter 7.1 discussed the specific data and simulation samples used and the selections applied. Chapter 7.2 and Chapter 7.3 describe the creation of signal and background templates used to extract the signal. The associated uncertainties are discussed in Chapter 7.4 and the expected results (using Asimov data) are shown in Chapter 7.5.

7.1 Data and Simulation Event Selections

While this measurement does not target Higgs to diphoton decays, the analysis framework used is the same as in the $H \rightarrow \gamma\gamma$ cross-section measurement. Since we are still looking for two photons and the framework has the mechanisms in place to identify heavy flavor jets, it was the most logical choice to build upon what already existed. As the cross-section measurement was completed before the diphoton + HF measurement, the framework has since been updated to account for new calculations of the efficiency of the tight photon identification and scale factors as well as updates on uncertainties for the E_T^{miss} calculations.

The b -tagging algorithm is the same as was used in the previous analysis, however all efficiency working points are used. The DL1r deep feed-forward neural network [143] reports efficiency values as measured on $t\bar{t}$ events at values of 85%, 77%, 70%, and 60%, where the 60% and 85% are considered the tightest and loosest b -tag, respectively.

7.1.1 Data and Simulation Samples

The data used in this analysis is the 2015-2018 Run 2 ATLAS dataset discussed in Chapter 4.2 and the simulation samples described in Chapter 4.1. The specific simulation signal and background samples used are listed in Table 7.1 with the corresponding cross-section values and the number of events generated.

Table 7.1: List of all signal and background simulation samples used in the diphoton + heavy flavor jet measurement showing the cross-section $\times$ branching ratio of each process given in [fb].

Process	Cross-Section $\times$ BR [fb]
Signal	
$\gamma\gamma$ +jets, $m_{\gamma\gamma} \in 90\text{--}175$ GeV	5.1823×10^4
$\gamma\gamma$ +jets, $m_{\gamma\gamma} \in 175\text{--}2000$ GeV	1.0999×10^4
$\gamma\gamma$ +jets, $m_{\gamma\gamma} > 2000$ GeV	0.70335
$t\bar{t}\gamma\gamma$ (hadronic decays)	4.0761
$t\bar{t}\gamma\gamma$ (leptonic decays)	6.4820
$Z(\rightarrow q\bar{q})\gamma\gamma$	0.53803
$Z(\rightarrow b\bar{b})\gamma\gamma$	0.15137
Background	
$t\bar{t}\gamma$	4.6233×10^3
$t\bar{t}$	7.6277×10^4

Two alternative signal samples were used in this analysis to help determine uncertainties. The first is generated and showered with SHERPA, like the nominal diphoton + jets samples,

however a heavy flavor filter is applied to generated events for a $\gamma\gamma bb$ final state. This alternative sample has a diphoton invariant mass of 90 GeV or greater and uses a slightly newer version of SHERPA. This sample was only produced using the conditions matching the 2015 dataset (mc16a) however so can only be compared to the corresponding 2015/mc16a nominal diphoton + jets sample. Additionally, a diphoton + 2 jets sample was produced using MADGRAPH5_aMC@NLO for generation and PYTHIA showering.

Table 7.2 shows the breakdown of the truth content per signal sample after the full events selection is applied and the number of weighted events passing the selections. Each category is the fraction of passing events regardless of the b -tagging. For the nominal diphoton+jets and $Z\gamma\gamma$ simulation samples, the majority of the events (83.9% and 70.6%, respectively) are light-flavor when only considering the leading jet. Though it should be noted that the Z boson sample only has roughly 5 events passing selections when scaled to the dataset luminosity. As the top quarks in the $t\bar{t}\gamma\gamma$ process often decay to b -hadrons, this fraction is smaller and only 42.5% of the events has a light-flavor leading jet, meaning the remainder of events contain heavy flavor.

Table 7.2: Fraction of simulated events falling into each truth jet-flavor combination bin for dijet events and the total number events passing the selection, inclusive of flavor.

Signal Sample	Fraction of Simulated Events						Total Events
	bb	bc	bl	cc	cl	ll	
$\gamma\gamma$ +jets	0.4%	0.4%	3.0%	3.4%	18.1%	74.6%	244262.83
$t\bar{t}\gamma\gamma$	17.7%	11.1%	42.3%	0.9%	9.8%	18.2%	128.5
$Z\gamma\gamma$	6.1%	1.3%	11.0 %	6.4%	14.2%	60.9%	4.9

7.1.2 Event Selection

The selections in the diphoton + HF jet analysis closely follow the selections made in the Higgs boson cross-section measurement as detailed in Chapter 6.1.2. The only modifications are on the jet requirements and the inclusion of a lepton veto. The relative cut of $p_T/m_{\gamma\gamma} > 35\%$ and 25% for the leading and subleading photon, respectively, has a relative efficiency of roughly 85% in the nominal diphoton signal sample compared to the preceding selection (isolation). There is a requirement on the diphoton system of $m_{\gamma\gamma} \in [105-160]$ GeV¹. As we are targeting diphoton with associated HF jets, each event must have at least one reconstructed, central jet with $p_T^j > 25$ GeV and $\eta < 2.5$. The jet is required to be central to follow the acceptance of the inner detector and for b -tagging. When measuring diphoton + dijet HF production, both jets must pass these checks. The last requirement that is different from the Higgs boson cross-section analysis is a lepton veto. The $t\bar{t}$ will decay to two b quarks and two W bosons, then the bosons can decay to leptons and their associated neutrinos. To reduce the impact of background events where the two photons could come from jet fakes, electron fakes, or unassociated photons, we reject all events with an isolated electron or muon with $p_T^\ell \geq 10$ GeV². The updated total event selection is summarized as follows:

- The two photon candidates with highest transverse momentum have to be matched to the photon trigger objects
- The two selected photons should pass tight identification requirements
- Photons must have an absolute pseudorapidity less than 2.37, excluding the transition region between the barrel and endcap sections of the calorimeter ($1.37 < |\eta| < 1.52$)

¹This is a feature of the framework that was designed for $H \rightarrow \gamma\gamma$ measurements and the cap at 160 GeV will be removed in the future.

²By requiring these leptons to be isolated, we reduce the likelihood of vetoing a heavy-flavor event where the hadron decays leptonically.

- The two selected photons are required to pass isolation requirements
- The leading and subleading photons are required to have $p_T/m_{\gamma\gamma}$ larger than 0.35 and 0.25, respectively, while also having $E_T^\gamma > 25$ GeV.
- The invariant mass of the diphoton system must be larger than 105 GeV and less than 160 GeV
- The event must have at least one reconstructed jet with $p_T > 25$ GeV and be central in the detector (meaning $|\eta| > 2.5$)
- The event cannot have any reconstructed electrons or muons with $p_T \geq 10$ GeV

For all simulation samples, the particle-level jet content is saved for each jet so that they can be categorized as originating from hadrons containing b quarks or c quarks. A b - or c -jet is identified if there is a least one b - or c -hadron within $\Delta R < 0.3$ around the jet with $p_T > 5$ GeV. Else, all other jet origins are referred to as having "light" flavor (likely from hadrons containing only up or down quarks). This information is saved for each of the two leading jets so that dijet events can be categorized as bb , bc , bl , cc , cl , or ll or single jet events can be categorized based on the leading jet flavor. For both data and simulation, the b -tagging efficiency working point each jet is tagged (or untagged) at is saved for template creation.

7.1.3 Duplicate Event Removal

It is expected that there will be an overlapping region of phase space where events could be duplicated in multiple samples when generating events with similar final states and kinematics. This occurs between simulated $t\bar{t}$ +jets and $t\bar{t}\gamma$ +jets, and between $t\bar{t}\gamma$ +jets and

$t\bar{t}\gamma\gamma$ +jets due to QED final state radiation by the parton shower modeling which produces additional photons. A simple procedure was used to identify these overlapping events in simulation based on the particle-level kinematic and origin information. To do this, a dedicated tool identifies an “overlap region” based on photons and leptons and only allows events from one of the samples to populate events there. In each event, the leptons considered are required to have originated from the hard-scatter process based on the particle-level truth information from the generator. The photons must also not originate from particle decays and must have $p_T^\gamma > 25$ GeV. The region is then defined as containing events falling outside the $\Delta R(\gamma, l) > 0.2$ range. For $t\bar{t}$ +jets, events with the leading photon candidate meeting these requirements (i.e. having no close leptons) is vetoed as to not overlap with $t\bar{t}\gamma$ +jets. Then, for $t\bar{t}\gamma$ +jets, events with the two leading photons candidates falling into the region are vetoed and are considered only in $t\bar{t}\gamma\gamma$ +jets. Figures 7.1 and 7.2 show the p_T and $\Delta R(\gamma, l)$ distributions in the overlap region compared to the broader event selections in the $t\bar{t}\gamma$ +jets sample. The only noticeable difference is seen in Figure 7.2 for the leading photon, where outside the overlap region, there is more of a peak around $\Delta R = \pi$.

7.2 Signal Templates

For diphoton + HF jet production, a template fit is performed using Monte Carlo simulation that is then fit to the data to obtain a measurement. With this method, the shape of the template remains intact during the fit, but the normalization of the individual templates is shifted to best match the data. To extract the HF signal, the template is fit to the four b -tagging working points. These templates are obtained from events passing the full event selection in simulation, separated by jet flavor, then a binned template profile likelihood fit is performed.

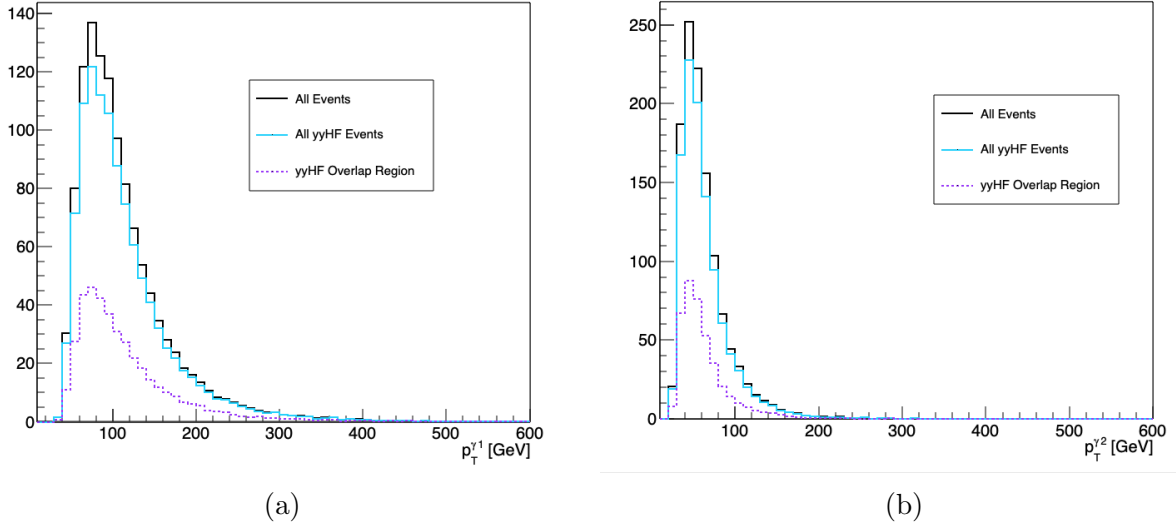


Figure 7.1: Plots show the distributions of the reconstructed (a) leading and (b) subleading photon p_T for all events passing the nominal preselections in black, the subset passing all selections inclusively in flavor in blue, and then which of those events fall into the above defined overlap region in purple.

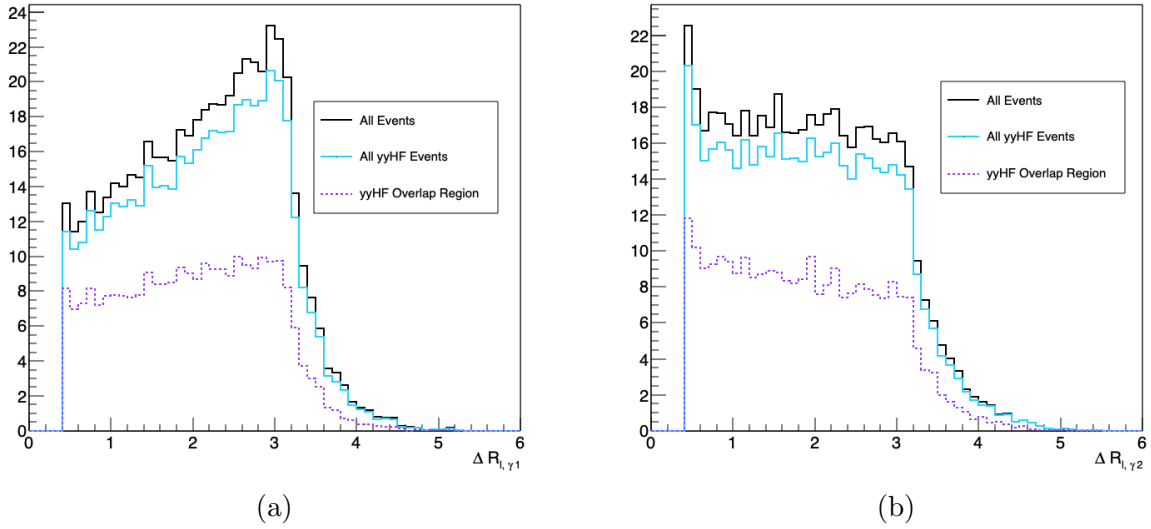


Figure 7.2: Plots show the distributions of the ΔR between the reconstructed (a) leading and (b) subleading photon and any reconstructed lepton for all events passing the nominal preselections in black, the subset passing all selections inclusively in flavor in blue, and then which of those events fall into the above defined overlap region in purple.

To create the templates, the b -tagging score of a jet is binned with the corresponding efficiency working point (WP). For the diphoton + 2 HF jets (referred to as dijet events), the leading and subleading jet score is considered. For diphoton + 1 HF jet (referred to as monojet), only the leading jet is studied. Each jet is assigned to a bin with the following method:

- If a jet is passing the DL1 algorithm 60% WP, it is assigned to bin 4
- Else if a jet is passing the 70% WP, it is assigned to bin 3
- Else if a jet is passing the 77% WP, it is assigned to bin 2
- Else if a jet is passing the 85% WP, it is assigned to bin 1
- Else if a jet is passing no WP, it is assigned to bin 0

Jets passing the algorithm's tightest 60% WP will also pass the looser working points, but each jet is checked in order of tightest to loosest b -tag score, making each bin exclusive.

In events with two passing jets, the above method gives a 5x5 matrix that can be used in a one-dimensional fit by taking

$$(\text{leading jet } b - \text{tag bin}) \times 5 + \text{subleading jet } b - \text{tag bin}$$

Figure 7.3 shows the fit axis using the signal diphoton simulation with each particle-level flavor combination separated out. As expected events with two untagged jets (bin 0) is dominated by light flavor, with the majority of the light-light events falling into this category. On the other end, an event with two jets tagged at the tightest (60%) working point (bin 24) is dominated by two truth b -jets. The bc and cl combinations do not particularly dominate anywhere, which means they may be trickier than the others to measure on their own. Then, bl dominates in bins with one untagged jet and one b -tagged at the 60% WP (with a slight

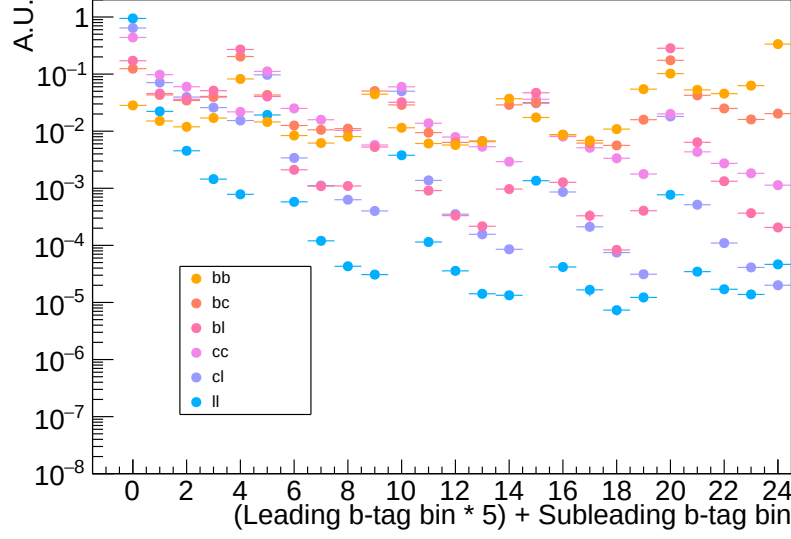


Figure 7.3: The normalized distribution of nominal diphoton simulation events split by truth flavor combinations.

dominance in bins where the jet is tagged at the 70% WP), as expected, corresponding to bins 4 and 20 (and slight dominance in bins 3 and 15). The cc flavor combination dominates a few bins, but most notably in bins where the leading jet is untagged or b -tagged at the looser levels, with a subleading jet that does *not* pass the tightest WP (meaning is either untagged if the leading jet is loosely tagged or the subleading jet is also loosely tagged). A separate template for each jet flavor or flavor combination is created for all simulated signal samples using the particle-level flavor content. Figure 7.4 shows the relative contribution from each input sample to the overall signal yield in each jet flavor combination bin for dijet and monojet events extremely zoomed in to show the contributions making up less than 0.2% of the monojet events and less than 2% of the dijet events. The yields are dominated by the nominal diphoton + jets signal sample, with small $< 0.1\%$ and $< 2\%$ contributions from $t\bar{t}\gamma\gamma$ for diphoton + monojet and dijets respectively. The contribution from $Z\gamma\gamma$ processes is extremely small due to the small cross-section but is still included for completeness.

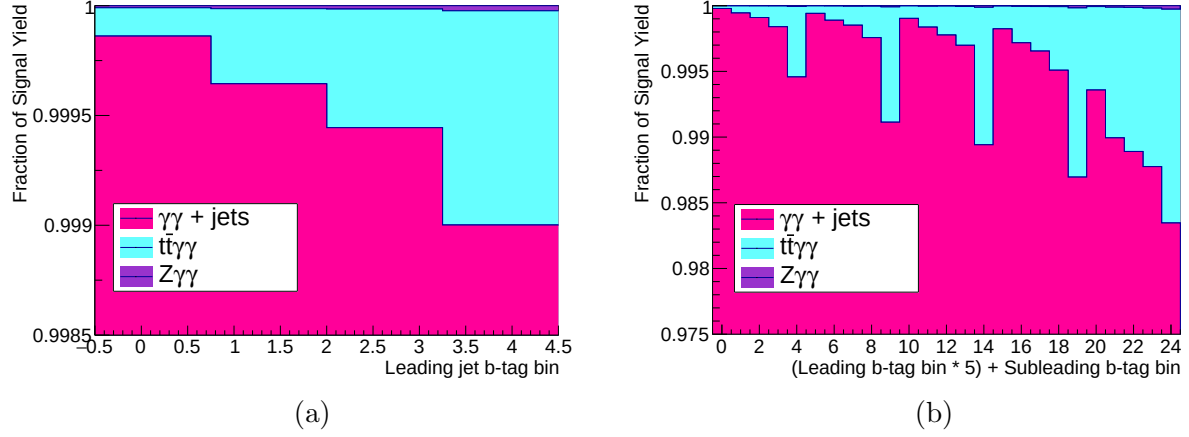


Figure 7.4: The relative contribution of diphoton + jets signal, $t\bar{t}\gamma\gamma$, and $Z\gamma\gamma$ samples to each flavor combination bin for (a) diphoton + 1 HF jet and (b) diphoton + 2 HF jets .

As a comparison, the nominal diphoton + jets sample was compared with the alternative diphoton + 2 jet MADGRAPH5_aMC@NLO sample for each truth flavor combination as shown in Figure 7.5. The ratio is shown at below each distribution to directly compare the shape. In the bl , cc , cl , and ll flavor categories, the two generators are comparable, though with slight variation in the bins where the leading jet is light-flavor, where the MADGRAPH generates more of these types of events, though is much more statistically limited.

The alternative SHERPA sample with the heavy flavor filter applied to target $\gamma\gamma b\bar{b}$ events is compared to the nominal SHERPA sample in Figure 7.6. Only the mc16a simulation sample is compared between the two and differences in shape are observed. Additional generation rounds are underway to improve selection efficiency in the sample, however the discrepancies will be accounted for in the future as an additional uncertainty on the $b\bar{b}$ template shape.

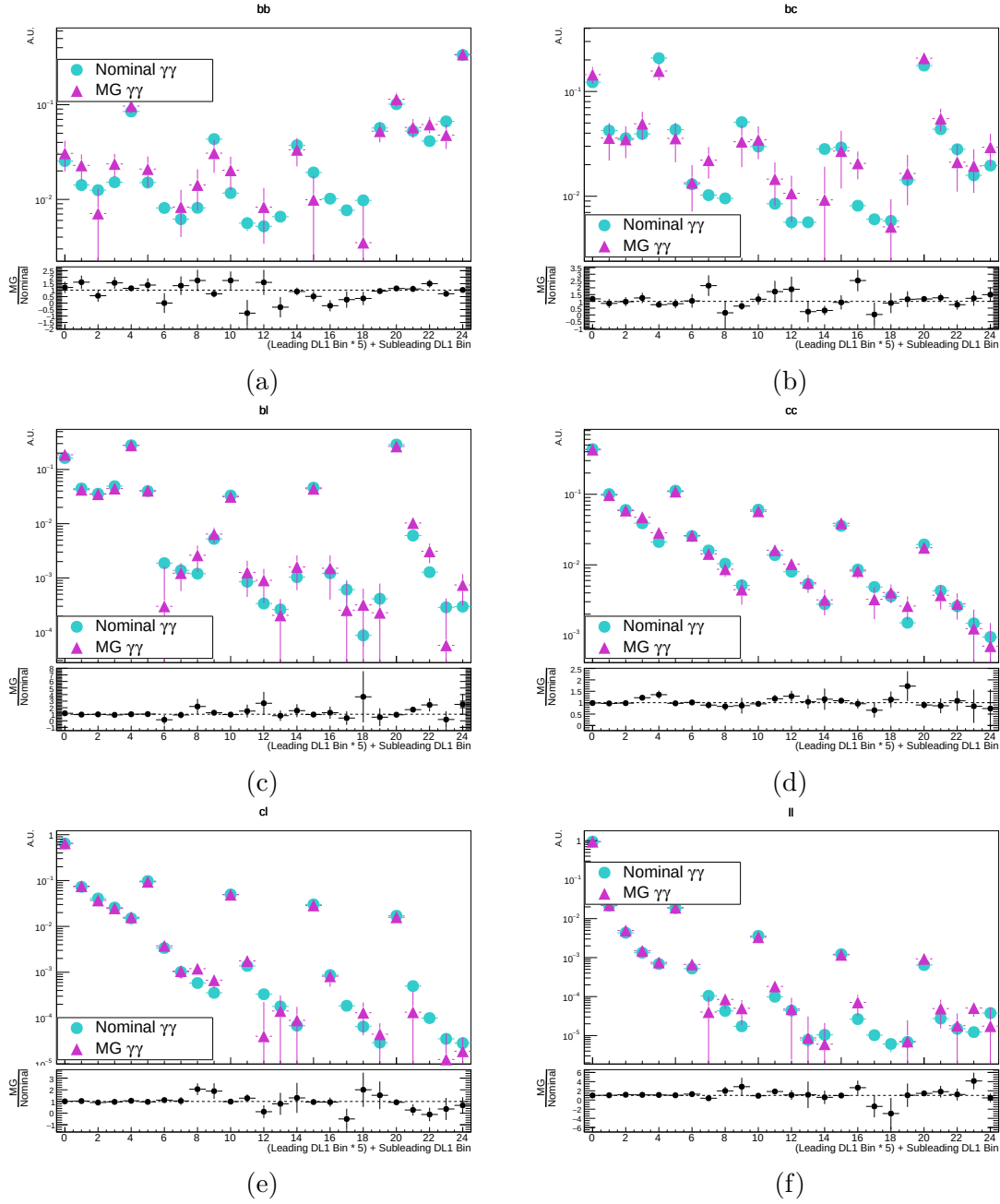


Figure 7.5: Normalized template comparison between the nominal SHERPA diphoton + jets compared to MADGRAPH for truth (a) bb, (b) bc, (c) bl, (d) cc, (e) cl, and (f) ll, flavor combinations.

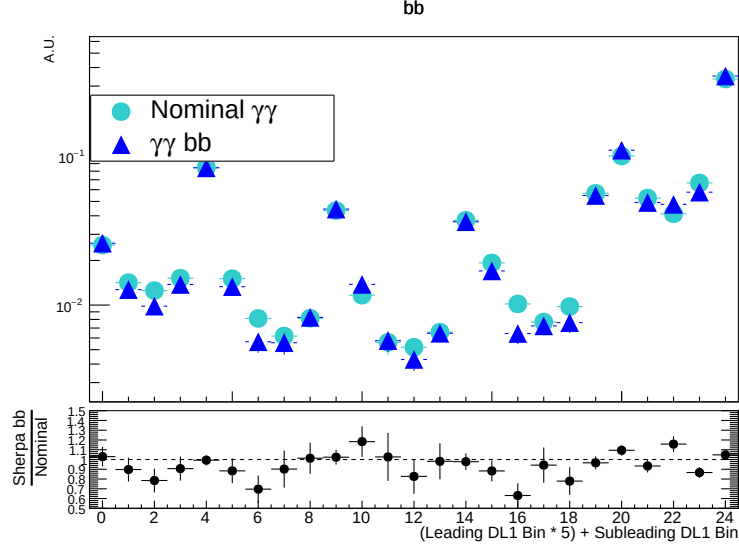


Figure 7.6: Normalized template comparison between the nominal diphoton + jets compared to the bb filtered sample.

7.3 Background Templates

Templates are created for both background input samples, $t\bar{t}\gamma$ and $t\bar{t}$. The same requirements on the signal are made on the background and the template are created inclusively in all truth-flavor combinations.

Additional templates are also made to correct for the jets faking photons background. This is done in two steps. First, $\gamma - jet$ and $jet - jet$ templates are created by running over data. The former template requires one photon passing the tight isolation requirements while the other photon candidate fails tight but passes one of the LoosePrime isolation definitions. For $jet - jet$, both photons are required to fail tight but pass LoosePrime. A separate template is made for each LoosePrime definition. Next, as there is expected to be some $\gamma\gamma$ leakage in these fake templates, another template is created by running over the nominal signal simulation with the same isolation and identification requirements used for $\gamma - jet$ and $jet - jet$. The templates created from simulation are subtracted from the data templates

leaving us with a corrected $\gamma - jet$ and $jet - jet$ fake template. For diphoton + dijet events, the nominal data-derived fake templates use the LoosePrime3 definition. Each fake template is given to the fitting tool as a symmetric variation to be mirrored up and down. These fake templates are scaled by the purity values for the respective fake type compared to $\gamma\gamma$ as output by the 2x2D sideband method as detailed in Chapter 6.2.2. A comparison of the simulation to the data is shown in Figure 7.7 showing their agreement when the jet faking photon component for one or both photons is included along with the nominal diphoton simulation in the leading and subleading p_T distributions.

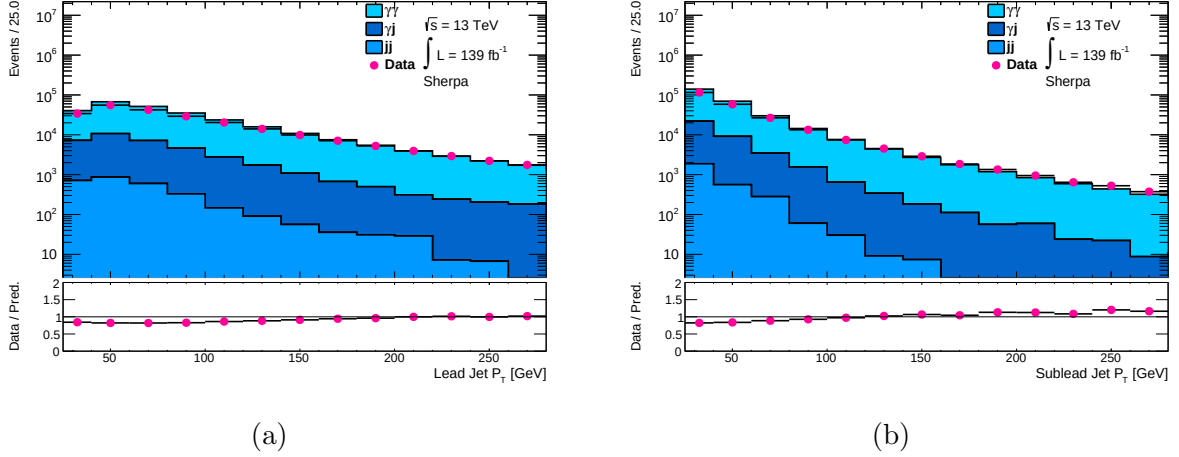


Figure 7.7: (a) Leading and (b) subleading jet transverse momentum distributions comparing data and simulation broken down into the $\gamma\gamma$, γ -jet, and jet-jet components.

No estimation on electrons fakes has been obtained yet for diphoton + HF events, however studies are currently underway. The method to be used is described here. To estimate the impact of electrons faking photons, an electron-photon fake rate is to be derived using $Z \rightarrow ee$ simulated events [144]. As the Z boson cannot decay directly into an electron+photon, any events reconstructed as such in the the Z boson mass peak means an electron was likely

misidentified as a photon. The fake factor is then defined as the ratio of probabilities for the electron to be misidentified over it being correctly identified and is shown in Equation 7.1.

$$F_{e \rightarrow \gamma} = \frac{N(Z \rightarrow e\gamma)}{2 \times N(Z \rightarrow ee)} \quad (7.1)$$

Here, the factor of 2 in the denominator represents events where both electrons are misidentified as photons. The $F_{e \rightarrow \gamma}$ fake factor is calculated in both data and MC simulation to obtain a scale factor (SF) that can be applied to the simulation as shown in Equation 7.2

$$\text{SF} = \frac{F_{e \rightarrow \gamma}^{\text{Data}}}{F_{e \rightarrow \gamma}^{\text{MC}}} \quad (7.2)$$

To obtain these scale factors, a fit is performed to the invariant mass peak of the decay products in the following control regions (CRs):

- $\text{CR}_{Z \rightarrow ee}$: events with two electrons with opposite electric charge, $E_{\text{T}}^{\text{miss}} < 40$ GeV and $70 < m_{ee} < 110$ GeV
- $\text{CR}_{Z \rightarrow e\gamma}$: events with one tight, isolated photon and one electron, $E_{\text{T}}^{\text{miss}} < 40$ GeV and $70 < m_{ee} < 110$ GeV

The inclusion of the $E_{\text{T}}^{\text{miss}}$ requirement is to avoid selecting events where the electron comes from the W decay instead of the Z .

In addition to the fake-rates, to estimate the relative contribution of the two top-pair background samples in our signal regions, two additional bins are created to control the impact of $t\bar{t}$ and $t\bar{t}\gamma$ that will be included in the fit. In these control regions, an event is required to have a lepton with $p_T > 10$ GeV and pass the b -tagging algorithm at either the 60 or 70 WP for the two leading jets. Then, if the lepton is an electron the event will fall in bin 25, if the lepton is a muon it is in bin 26. Previously, studies have been done that include

a cut on the allowed amount of E_T^{miss} in events in these lepton bins. However, it was found that this requirement has very little impact and it was not worth the added uncertainties that would arise from the additional cut.

7.4 Systematic Uncertainties

To evaluate the systematic uncertainties impacting the final fit, a parameter of the analysis is altered and its impact on the template is considered. Two templates are created for each systematic source (up and down) using the altered parameter in the nominal diphoton signal sample. Systematic uncertainties on efficiencies are calculated in the same way as was done in the Higgs boson cross-section analysis in Chapter 6.4. The uncertainty sources in this analysis impacting the templates are as follows:

- Diphoton trigger efficiency
- Vertex selection efficiency
- Photon identification efficiency
- Photon isolation efficiency
- Photon energy scale and resolution
- Pileup reweighting
- Luminosity and branching ratios
- Jet energy calibration
- b -tagging uncertainties

The b -tagging systematics are expected to have a bigger impact compared to the cross-section analysis as b -tagging plays a large role in this analysis. The efficiencies for the DL1 algorithm with the neural-network chosen primary vertex were again checked with the diphoton + HF events selections as shown in Appendix C. It was found that the same efficiency targets were reached, therefore no additional uncertainties related to b -tagging and the diphoton vertex were needed. To obtain the uncertainties on b -tagging in general, the tagging scale factors that are derived from calibration analyses were varied through the use of eigenvectors. Covariance matrices of the uncertainties are built by varying each source of uncertainty in b -tagging by 1σ (i.e. statistical uncertainties, and those related to MC modeling and jet calibrations). These matrices are summed into one final covariance matrix that is symmetric and positive-definite, which can be diagonalized to produce a set of orthogonal eigenvectors. These eigenvectors are the uncorrelated systematic uncertainty components that can then be used to determine the uncertainties on the b -tagging algorithms in our analysis and is done for b -jet, c -jet, and light-jet scale factors [107, 145].

Additional sources related to the physics modeling (i.e. PDFs, renormalization scale, etc.) are not yet included but will be in the future. Uncertainties due the signal modeling will also be considered by comparing the templates from various MC generators.

In addition to these sources, an overall normalization uncertainty of 100% was imposed on $Z\gamma\gamma$ events to be conservative in estimations as the process is not well studied. To compensate for uncertainties related to generation overlap, an uncertainty of 30% and 50% were applied to $t\bar{t}\gamma$ and $t\bar{t}$, respectively.

A separate parameter of interest, $\Delta\mu$ was set for each flavor combination. The impact on each parameter of interest (POI) by a nuisance parameter θ is ranked in decreasing order of their impact in Figures 7.8-7.13 for dijet events and Figures 7.14-7.16 for monojet. If a parameter is under-constrained, as shown in 7.14 for the JET_JER_EffectiveNP_2 nuisance parameter, this could indicate issues with the systematic template that needs to be investigated

further. The value $\hat{\theta}$ is the maximum likelihood estimator of the nuisance parameter. The bottom x-axis of each figure shows the nuisance parameter pulls which compare the best-fit value to the nominal pre-fit value divided by the pre-fit uncertainty. For bb , the highest ranked nuisance parameters are the uncertainties related to flavor and the $t\bar{t}$ and $t\bar{t}\gamma$ fixed normalization. For the single-jet rankings, the jets-faking photons (specifically γj) has a larger impact than dijet events. The uncertainty in the jet composition between quarks and gluons (JET_Flavor_Composition) [146] is consistently ranked high in dijet categories and in the light-single jet rankings. Studies are underway to modify the quark/gluon content from 50/50 to favor quark initiated jets to try to reduce this.

The statistical uncertainties from the MC are visualized in Figure 7.17 for the dijet categories. The largest impact of $\pm 10\%$ is in the CR bins and in events with 60/70 WP b -tags for the leading/subleading jet (bin 23). As the monojet categories only require one additional jet instead of two, all categories are much less statistically limited.

7.5 Asimov Results

As this analysis is still on-going at the time of this dissertation, only estimates of its sensitivity can be determined. These are obtained using an Asimov dataset [147] which fixes the parameters of interest to their expected Standard Model values. The pre-fit dataset also fixes the nuisance parameters to their expected values while the post-fit dataset fixes them to their best-fit value in the likelihood.

In this chapter, results are shown using an Asimov dataset corresponding to the luminosity of the full Run 2 dataset. Estimations on the signal strength in each flavor category is shown in Figure 7.18. Strong constraints are shown on all 6 dijet final states with the highest uncertainty is on the bc final state with roughly 16%. The monojet uncertainties are estimated

to be even lower leading to a stronger signal. All uncertainties on template shapes, statistical and systematic uncertainties on jet fakes, and systematic uncertainties related to jets, flavor, and photons are accounted for.

The profile likelihood fit to Asimov data is shown in Figure 7.19 and 7.20 showing the pre-fit and post-fit constraints. The post-fit plot uses best-fit results for all nuisance parameters including the post-fit effect of gammas.

Nuisance parameter pull plots showing the uncertainties relative to the pre-fit values for the SM expectation are shown in Figures 7.21-7.25. No additional constraints on photon-related uncertainties were found nor for most jet-related uncertainties. The uncertainty related to the light-jet scale factors in b -tagging was further constrained as shown in Figure 7.22. Additionally, some constraints on the $t\bar{t}$, $t\bar{t}\gamma$, and $t\bar{t}\gamma\gamma$ is shown in Figure 7.25.

As the analysis continues, further studies will be done to obtain the electron-photon fake rate as well as to optimize the control region definitions for $t\bar{t}\gamma$ and $t\bar{t}$. The studies presented here using the Asimov data to obtain sensitivities indicates that a measurement will be possible in all flavor combinations for both both diphoton + 2 HF jets and diphoton + 1 HF jet.

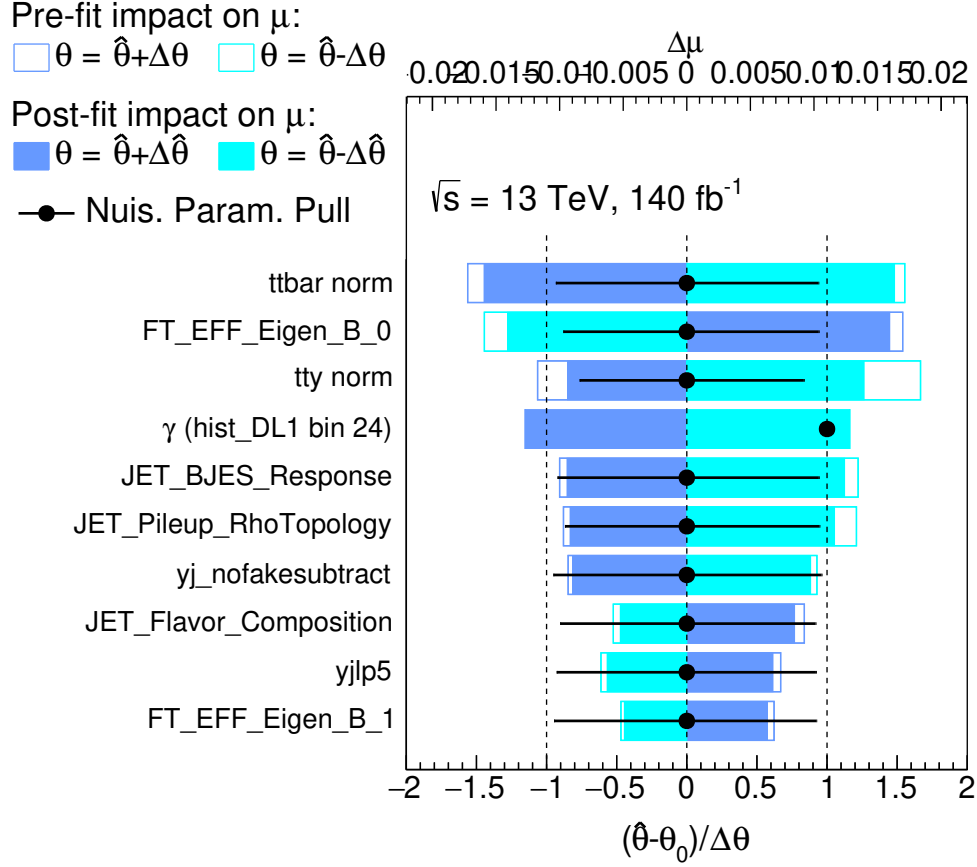


Figure 7.8: Impact of the top ranking nuisance parameters for the $b\bar{b}$ flavor category where ttbar norm and tty norm is the fixed uncertainties set on the normalization of $t\bar{t}$ and $t\bar{t}\gamma$, FT_EFF_Eigen_B_0,1 are uncertainties on the b -tagging calibration, γ uncertainties are the statistical uncertainties in a listed bin, yj_nofakesubtract is the uncertainty on the MC subtraction from the γj fake template and yjlp5 is the uncertainty from varying the LoosePrime definition from LP3 to LP5, JET_BJES_Response is the jet energy calibration uncertainty for b -jets, JET_Pileup_RhoTopology is the uncertainty of the per-event p_T density modeling in MC simulation (ρ) and JET_Flavor_Composition is the uncertainty in the jet composition between quarks and gluons.

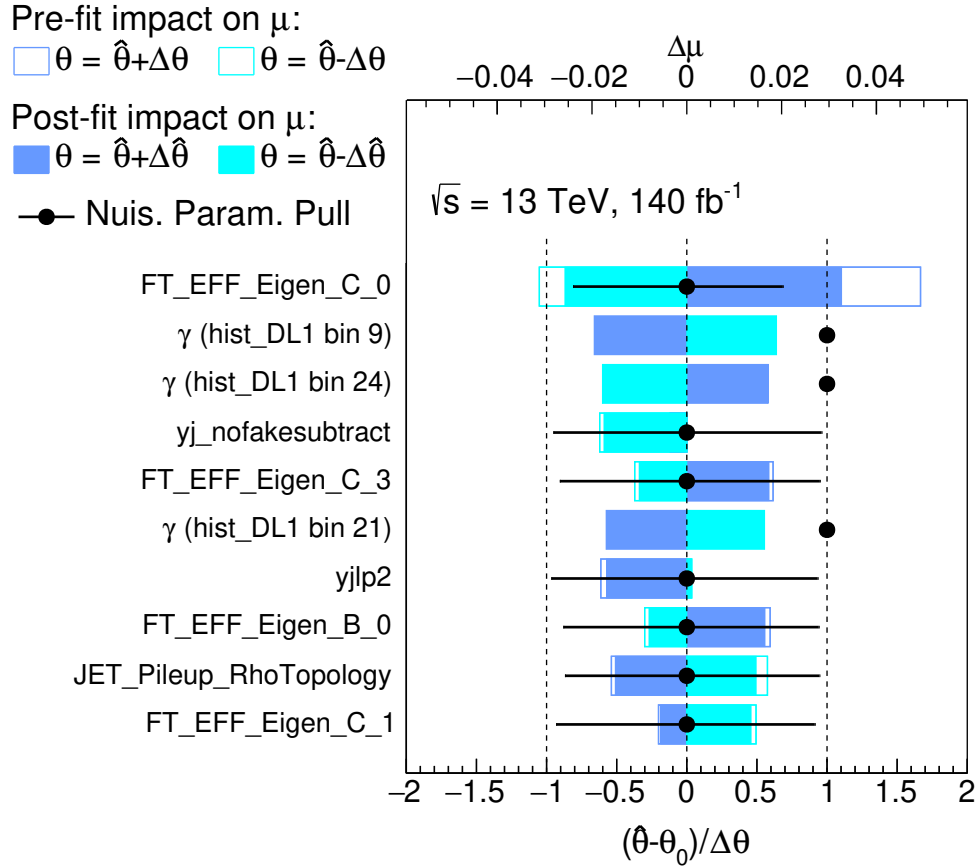


Figure 7.9: Impact of the top ranking nuisance parameters for the bb flavor category where FT_EFF_Eigen_C_0,1,3 are uncertainties on the c -tagging calibration, FT_EFF_Eigen_B_0 are uncertainties on the b -tagging calibration, γ uncertainties are the statistical uncertainties in a listed bin, yj_nofakesubtract is the uncertainty on the MC subtraction from the γj fake template and yjlp5 is the uncertainty from varying the LoosePrime definition from LP3 to LP2, and JET_Pileup_RhoTopology is the uncertainty of the per-event p_T density modeling in MC simulation (ρ).

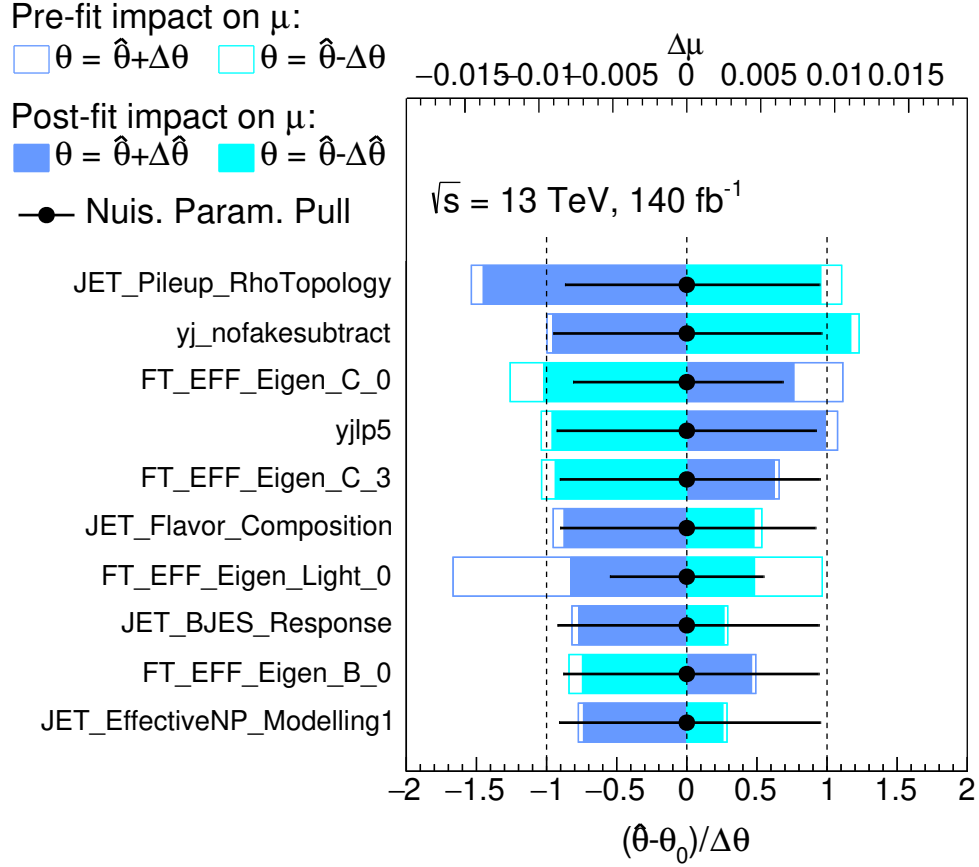


Figure 7.10: Impact of the top ranking nuisance parameters for the bb flavor category where JET_Pileup_RhoTopology is the uncertainty of the per-event p_T density modeling in MC simulation (ρ), yj_nofakesubtract is the uncertainty on the MC subtraction from the γj fake template, FT_EFF_Eigen_C_0,3 are uncertainties on the c -tagging calibration, yjlp5 is the uncertainty from varying the LoosePrime definition from LP3 to LP5, JET_Flavor_Composition is the uncertainty in the jet composition between quarks and gluons, FT_EFF_Eigen_L_0 are uncertainties on the light-jet tagging calibration, JET_BJES_Response is the jet energy calibration uncertainty for b -jets, FT_EFF_Eigen_B_0 are uncertainties on the b -tagging calibration, and JET_EffectiveNP_Modelling1 is the uncertainty in modeling the effective jet energy scale.

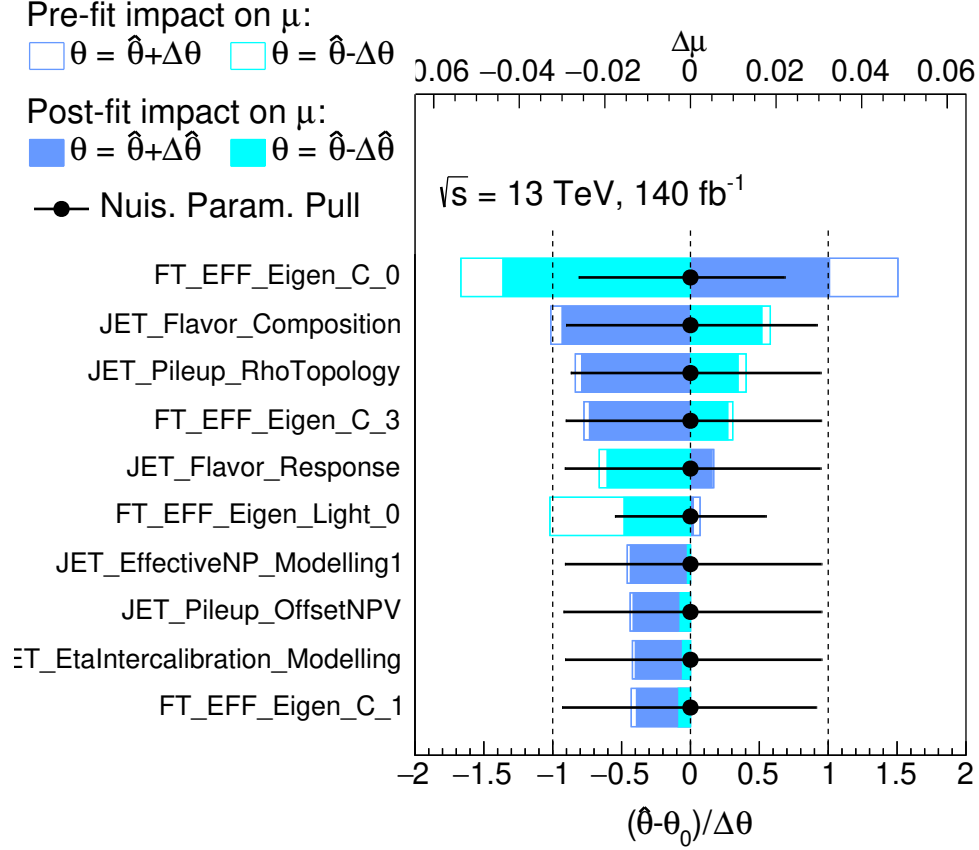


Figure 7.11: Impact of the top ranking nuisance parameters for the bb flavor category where FT_EFF_Eigen_C_0,1,3 are uncertainties on the c -tagging calibration, JET_Flavor_Composition is the uncertainty in the jet composition between quarks and gluons, JET_Pileup_RhoTopology is the uncertainty of the per-event p_T density modeling in MC simulation (ρ), JET_Flavor_Response is the uncertainty related to the differing responses of gluon initiated jets, FT_EFF_Eigen_L_0 are uncertainties on the light-jet tagging calibration, JET_EffectiveNP_Modelling1 is the uncertainty in modeling the effective jet energy scale, JET_Pileup_OffsetNPV is the uncertainty related to the modeling of the number of primary vertices in simulation, and JET_EtaIntercalibration_Modelling is the uncertainties related to the mismodeling of the physics of the jets.

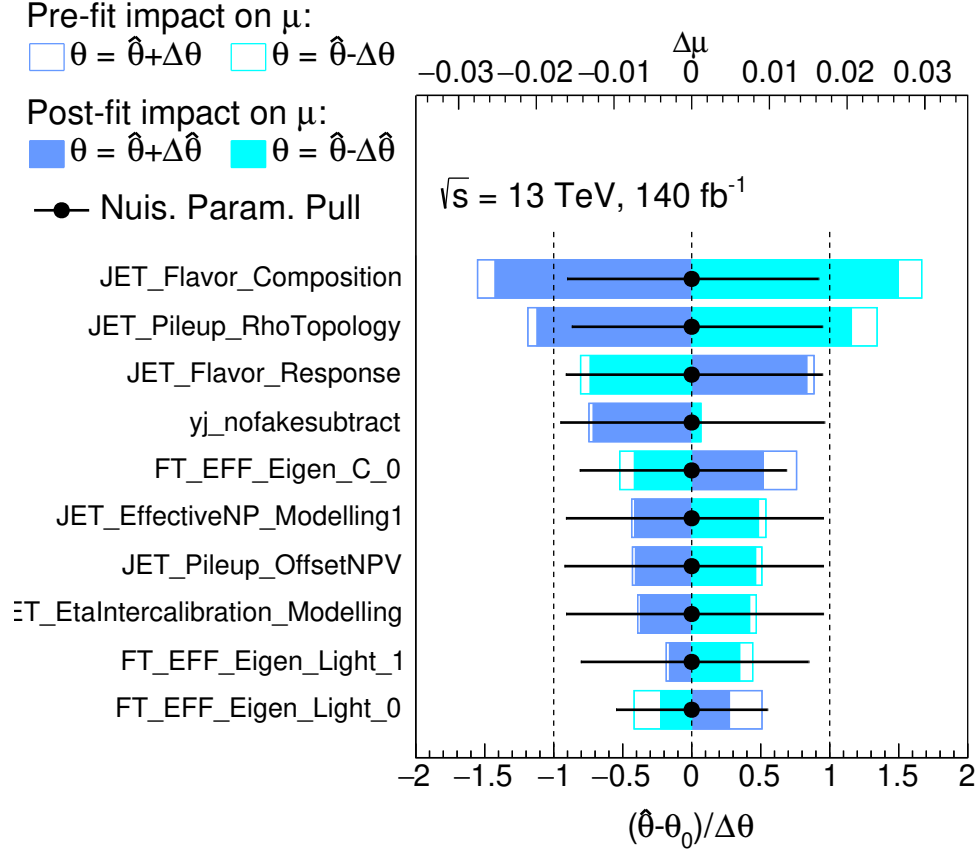


Figure 7.12: Impact of the top ranking nuisance parameters for the bb flavor category where JET_Flavor_Composition is the uncertainty in the jet composition between quarks and gluons, JET_Pileup_RhoTopology is the uncertainty of the per-event p_T density modeling in MC simulation (ρ), JET_Flavor_Response is the uncertainty related to the differing responses of gluon initiated jets, yj_nofakesubtract is the uncertainty on the MC subtraction from the γj fake template, FT_EFF_Eigen_C_0 are uncertainties on the c -tagging calibration, JET_EffectiveNP_Modelling1 is the uncertainty in modeling the effective jet energy scale, JET_Pileup_OffsetNPV is the uncertainty related to the modeling of the number of primary vertices in simulation, JET_EtaIntercalibration_Modelling is the uncertainties related to the mismodeling of the physics of the jets, and FT_EFF_Eigen_L_0 are uncertainties on the light-jet tagging calibration.

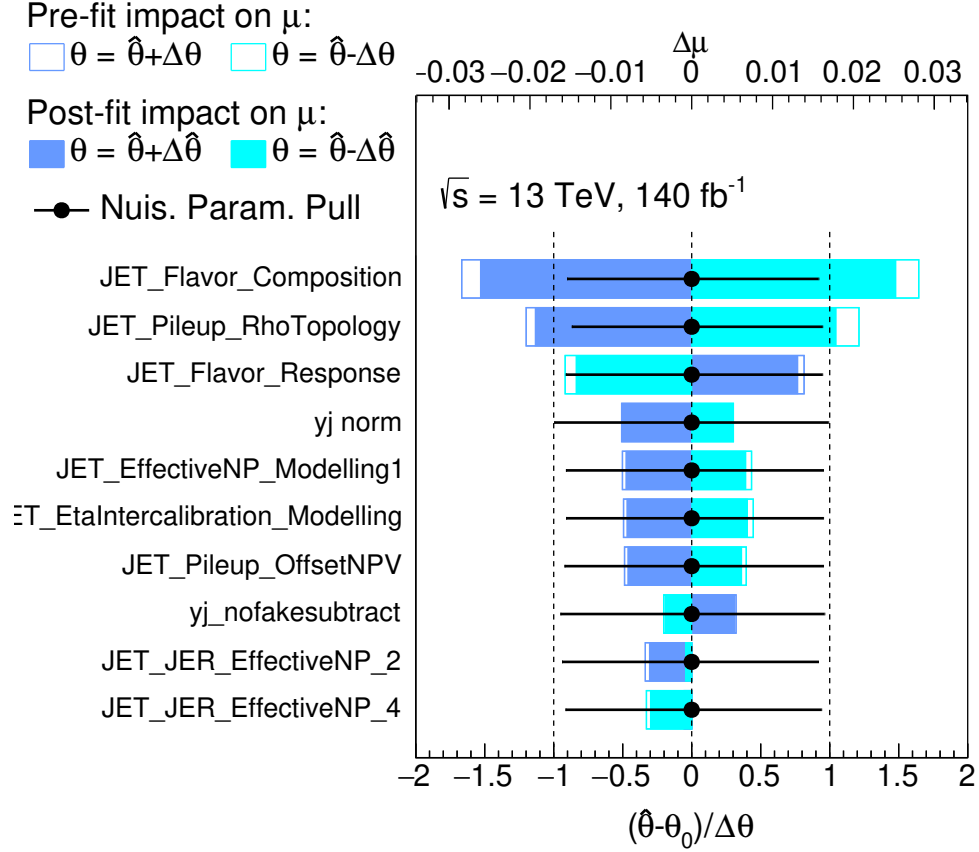


Figure 7.13: Impact of the top ranking nuisance parameters for the ll flavor category where JET_Flavor_Composition is the uncertainty in the jet composition between quarks and gluons, JET_Pileup_RhoTopology is the uncertainty of the per-event p_T density modeling in MC simulation (ρ), JET_Flavor_Response is the uncertainty related to the differing responses of gluon initiated jets, yj norm is the uncertainty related to the normalization of the γj fake template, JET_EffectiveNP_Modelling1 is the uncertainty in modeling the effective jet energy scale, JET_EtaIntercalibration_Modelling is the uncertainties related to the mismodeling of the physics of the jets, JET_Pileup_OffsetNPV is the uncertainty related to the modeling of the number of primary vertices in simulation, yj_nofakesubtract is the uncertainty on the MC subtraction from the γj fake template, and JET_JER_EffectiveNP_2,4 is the uncertainty related to the effective jet energy resolution.

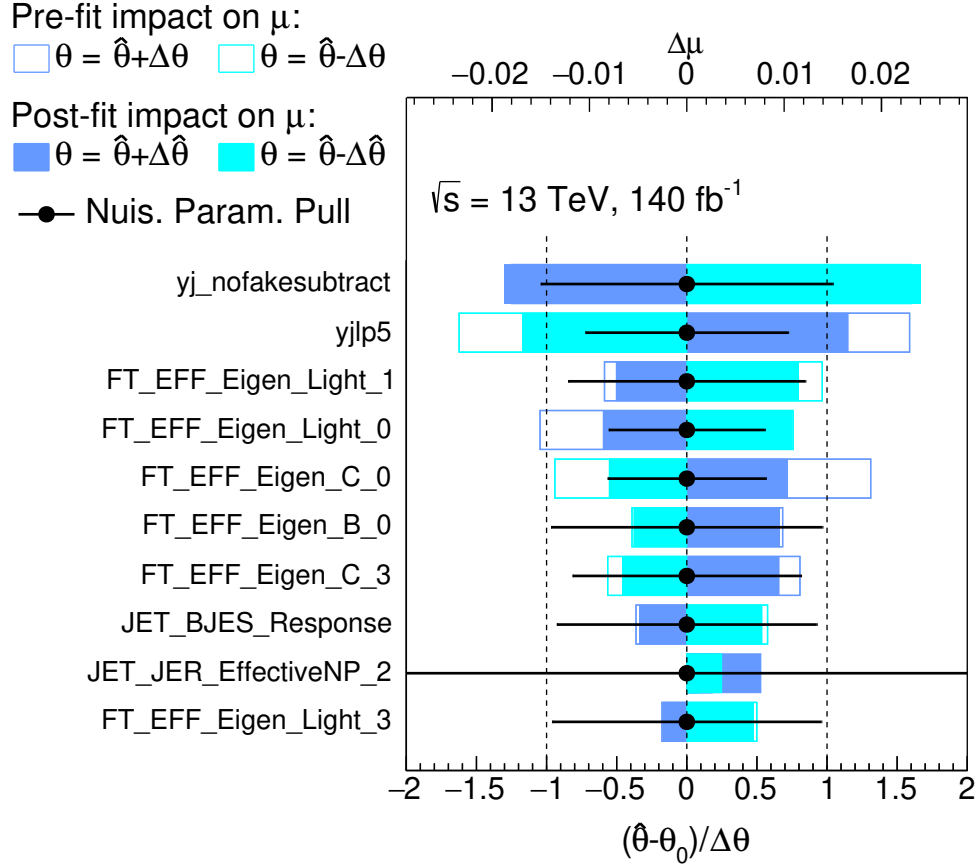


Figure 7.14: Impact of the top ranking nuisance parameters for monojet categories with b -jet flavor where yj_nofakesubtract is the uncertainty on the MC subtraction from the γj fake template, FT_EFF_Eigen_L_0,1 are uncertainties on the light-jet tagging calibration, FT_EFF_Eigen_C_0,1,3 are uncertainties on the c -tagging calibration, FT_EFF_Eigen_B_0 are uncertainties on the b -tagging calibration, JET_BJES_Response is the jet energy calibration uncertainty for b -jets, JET_JER_EffectiveNP_2 is the uncertainty related to the effective jet energy resolution, yjlp2,5 is the uncertainty from varying the LoosePrime definition from LP3 to LP2 or LP5, EG_SCALE_ALL is the uncertainty in the photon energy scale, JET_Pileup_RhoTopology is the uncertainty of the per-event p_T density modeling in MC simulation (ρ), yj norm is the uncertainty related to the normalization of the γj fake template, JET_Flavor_Composition is the uncertainty in the jet composition between quarks and gluons, and JET_EtaIntercalibration_Modelling is the uncertainties related to the mismodeling of the physics of the jets.

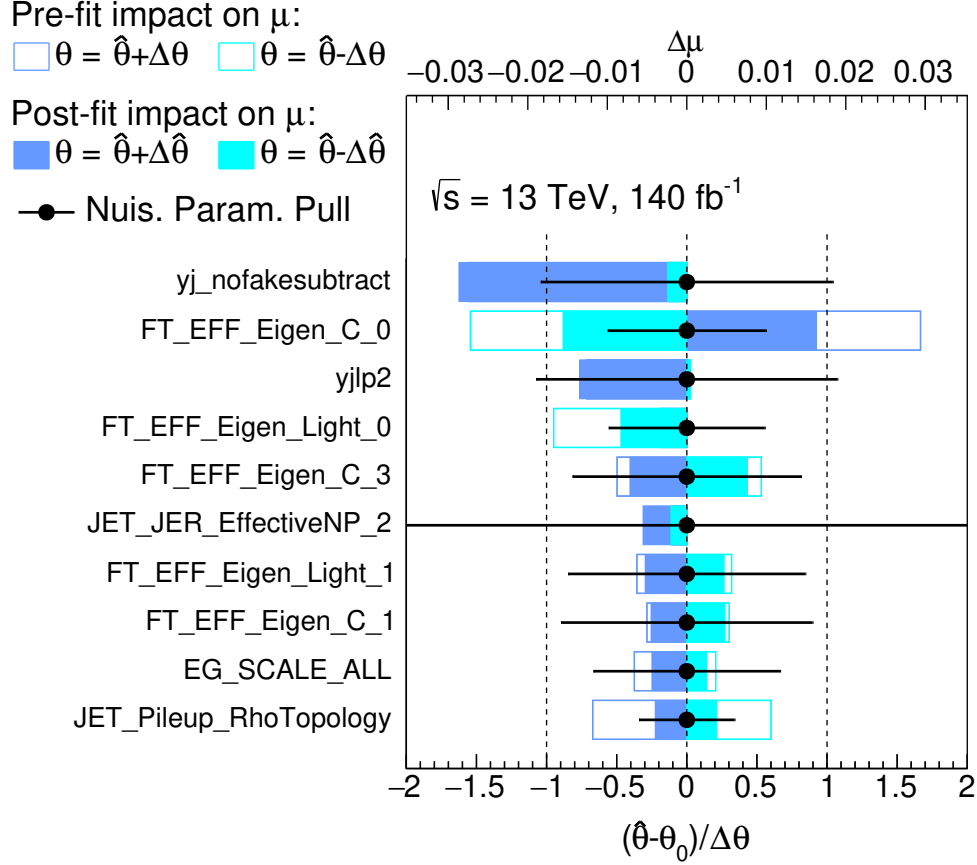


Figure 7.15: Impact of the top ranking nuisance parameters for monojet categories with c -jet flavor where yj_nofakesubtract is the uncertainty on the MC subtraction from the γj fake template, FT_EFF_Eigen_L_0,1 are uncertainties on the light-jet tagging calibration, FT_EFF_Eigen_C_0,1,3 are uncertainties on the c -tagging calibration, FT_EFF_Eigen_B_0 are uncertainties on the b -tagging calibration, JET_BJES_Response is the jet energy calibration uncertainty for b -jets, JET_JER_EffectiveNP_2 is the uncertainty related to the effective jet energy resolution, yjlp2,5 is the uncertainty from varying the LoosePrime definition from LP3 to LP2 or LP5, EG_SCALE_ALL is the uncertainty in the photon energy scale, JET_Pileup_RhoTopology is the uncertainty of the per-event p_T density modeling in MC simulation (ρ), yj norm is the uncertainty related to the normalization of the γj fake template, JET_Flavor_Composition is the uncertainty in the jet composition between quarks and gluons, and JET_EtaIntercalibration_Modelling is the uncertainties related to the mismodeling of the physics of the jets.

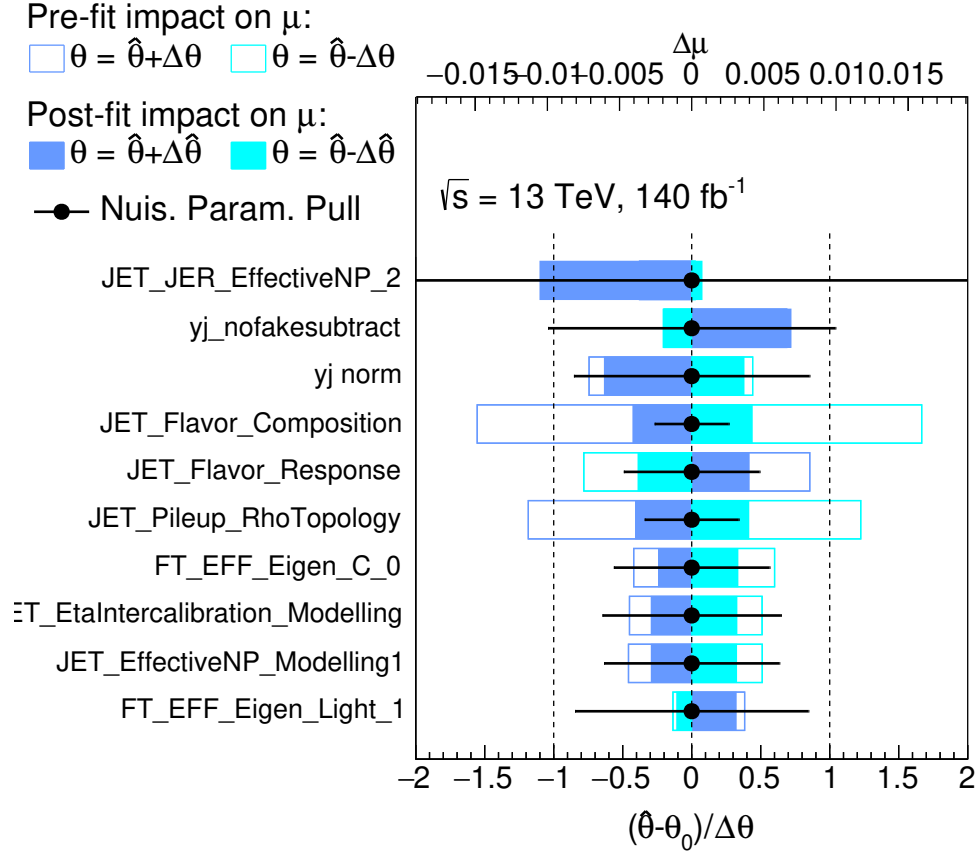


Figure 7.16: Impact of the top ranking nuisance parameters for monojet categories with light-jet flavor where $yj_nofakesubtract$ is the uncertainty on the MC subtraction from the γj fake template, $FT_EFF_Eigen_L_0,1$ are uncertainties on the light-jet tagging calibration, $FT_EFF_Eigen_C_0,1,3$ are uncertainties on the c -tagging calibration, $FT_EFF_Eigen_B_0$ are uncertainties on the b -tagging calibration, $JET_BJES_Response$ is the jet energy calibration uncertainty for b -jets, $JET_JER_EffectiveNP_2$ is the uncertainty related to the effective jet energy resolution, $yjlp2,5$ is the uncertainty from varying the LoosePrime definition from LP3 to LP2 or LP5, EG_SCALE_ALL is the uncertainty in the photon energy scale, $JET_Pileup_RhoTopology$ is the uncertainty of the per-event p_T density modeling in MC simulation (ρ), yj norm is the uncertainty related to the normalization of the γj fake template, $JET_Flavor_Composition$ is the uncertainty in the jet composition between quarks and gluons, and $JET_EtaIntercalibration_Modelling$ is the uncertainties related to the mismodeling of the physics of the jets.

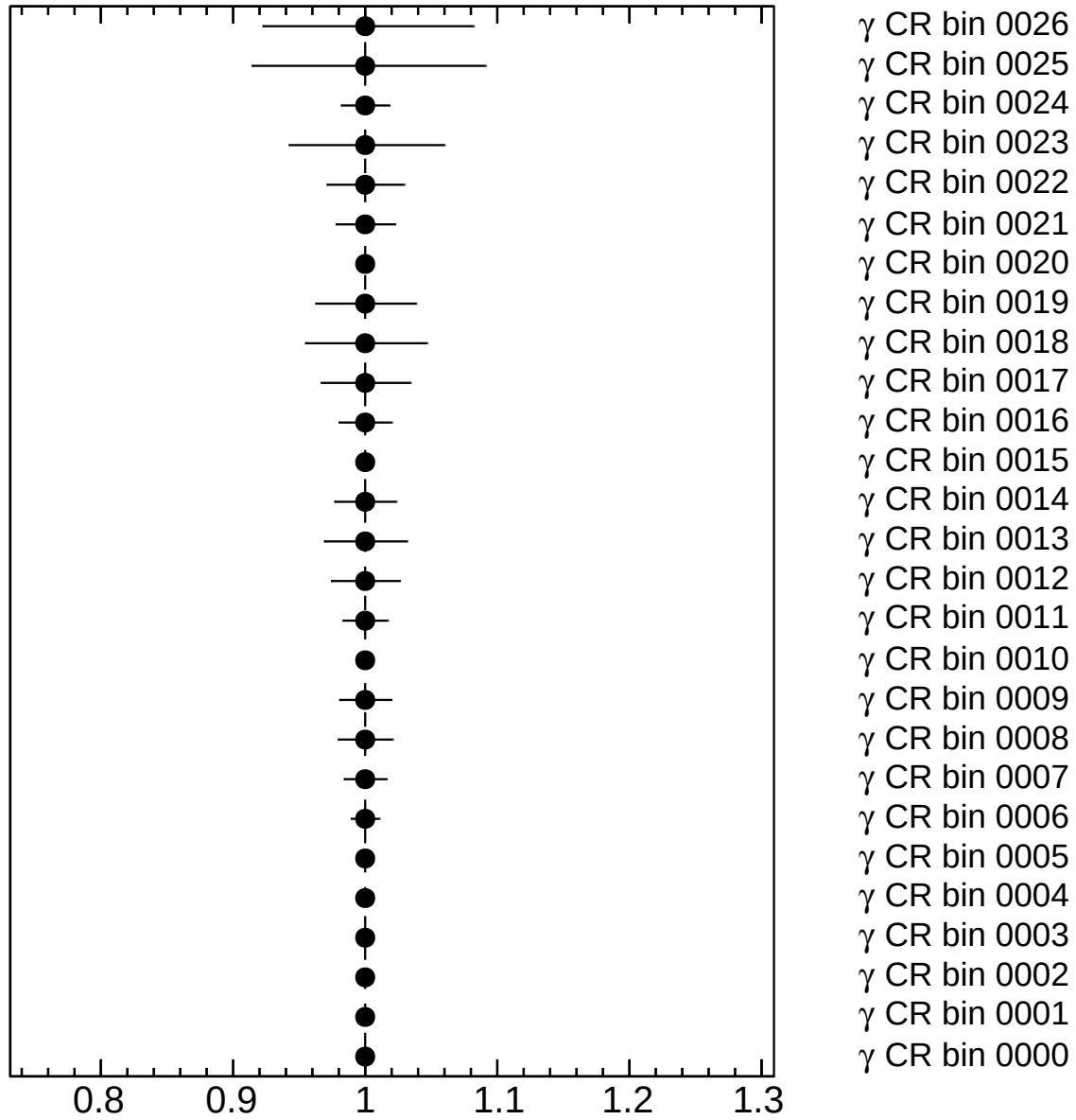


Figure 7.17: Effect of limited MC statistics per bin in dijet events.

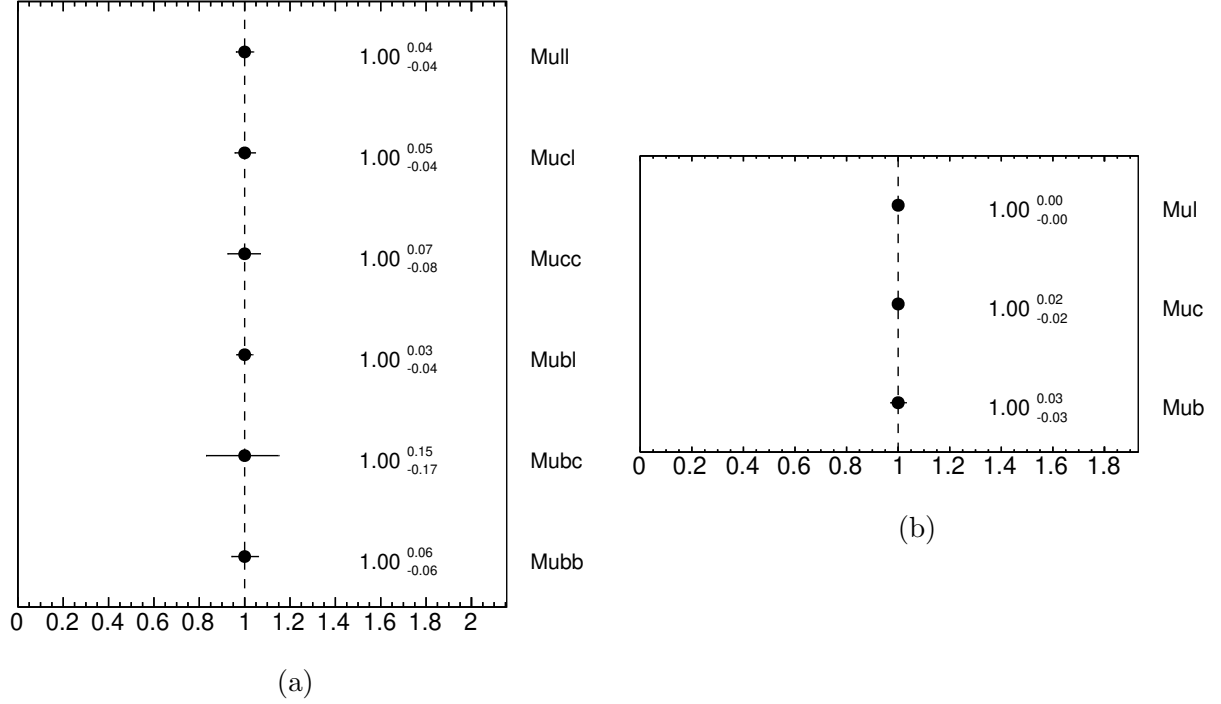


Figure 7.18: Signal sensitivities in each of the flavor categories.

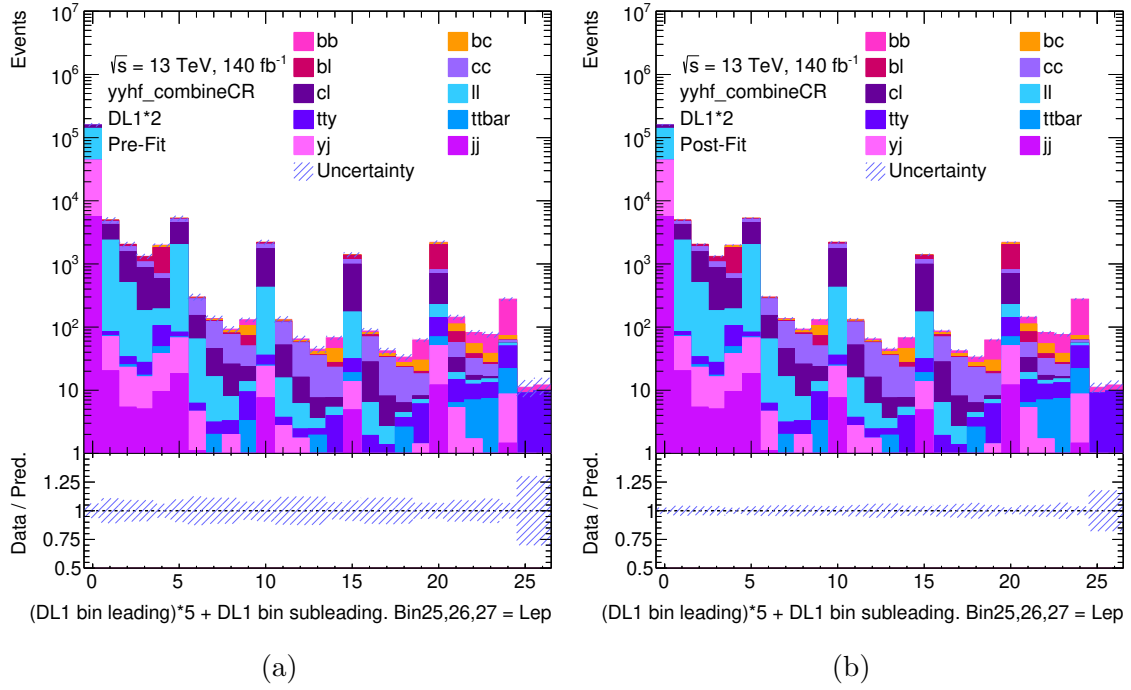


Figure 7.19: The (a) pre-fit and (b) post-fit plots to Asimov data for diphoton + 2 HF jets.

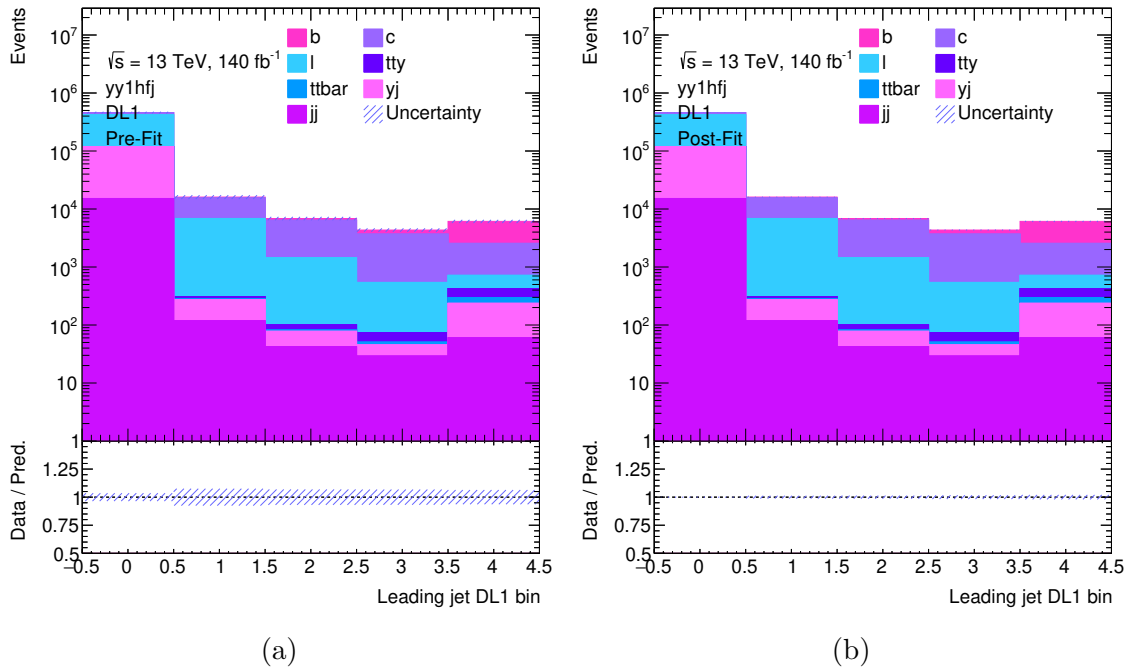
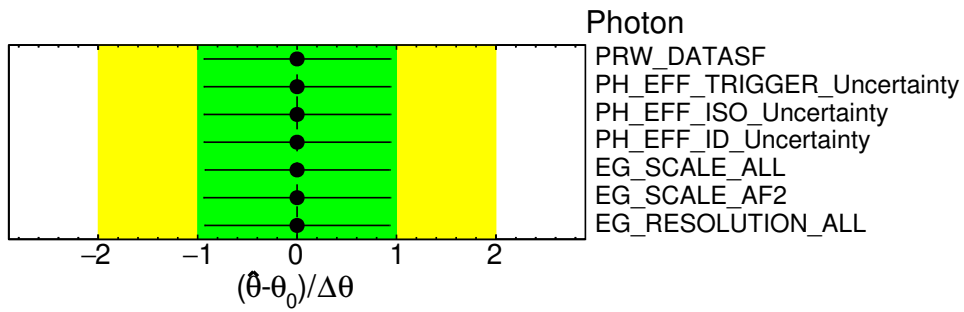
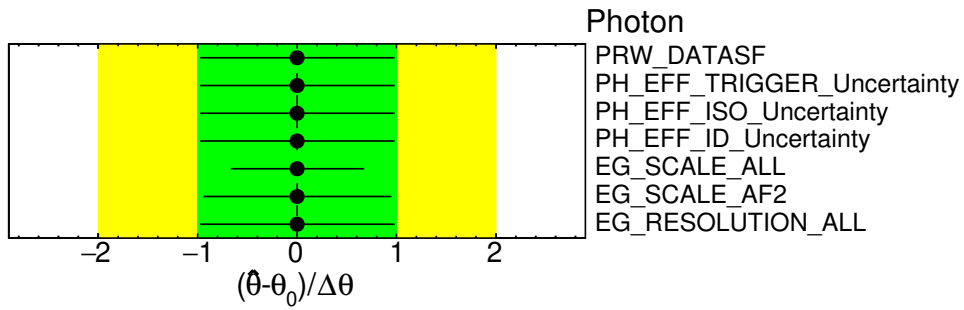


Figure 7.20: The (a) pre-fit and (b) post-fit plots to Asimov data for diphoton + 1 HF jet.

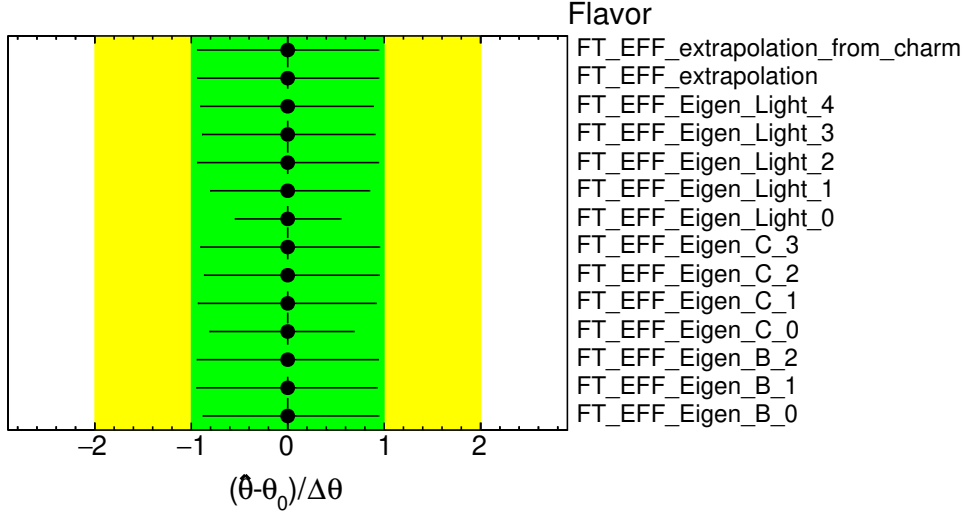


(a)

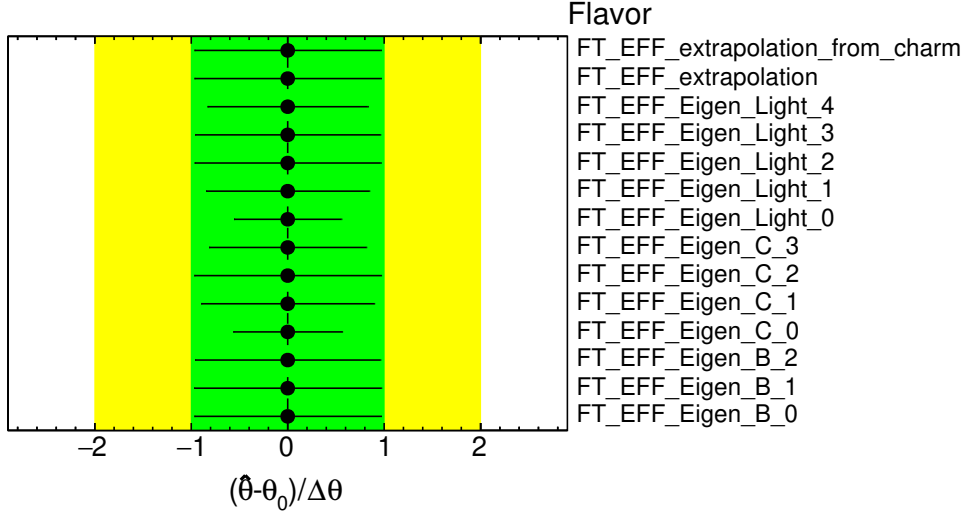


(b)

Figure 7.21: Constraints on photon-related nuisance parameters in (a) dijet and (b) monojet events for uncertainties on pileup reweighting scale factors, trigger efficiency, isolation and identification efficiency and photon energy scale and resolution.



(a)



(b)

Figure 7.22: Constraints on flavor tagging-related nuisance parameters in (a) dijet and (b) monojet events for uncertainties on high- p_T extrapolation of the flavor-tagging uncertainty and on the b -, c -, and light-flavor calibrations.

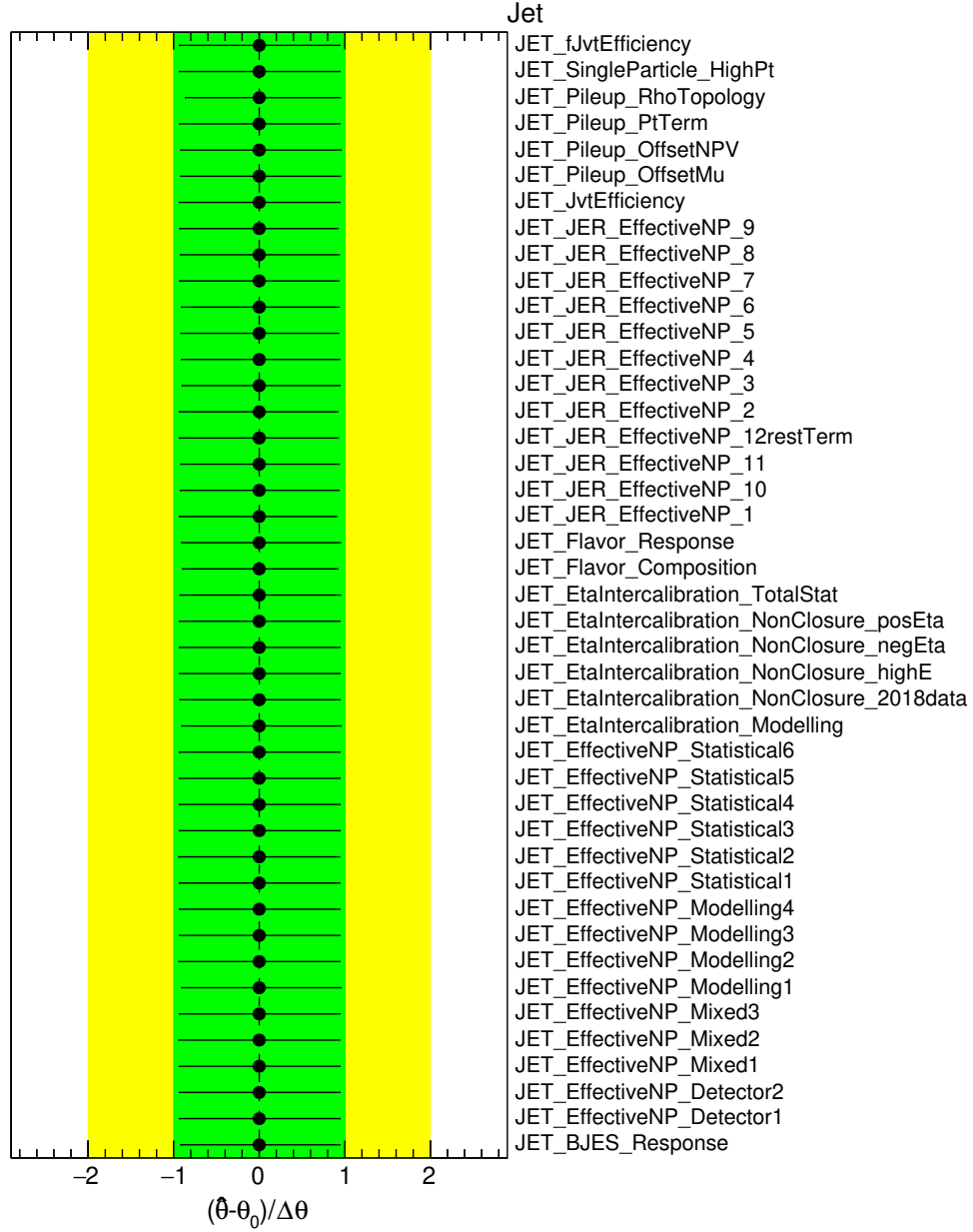


Figure 7.23: Constraints to jet-related nuisance parameters in dijet events for uncertainties on fJVT, high- p_T jets, per-event p_T density modeling, pileup, JVT, effective jet energy resolution, flavor composition and response, jet physics, effective jet energy scale, and related to b -jets.

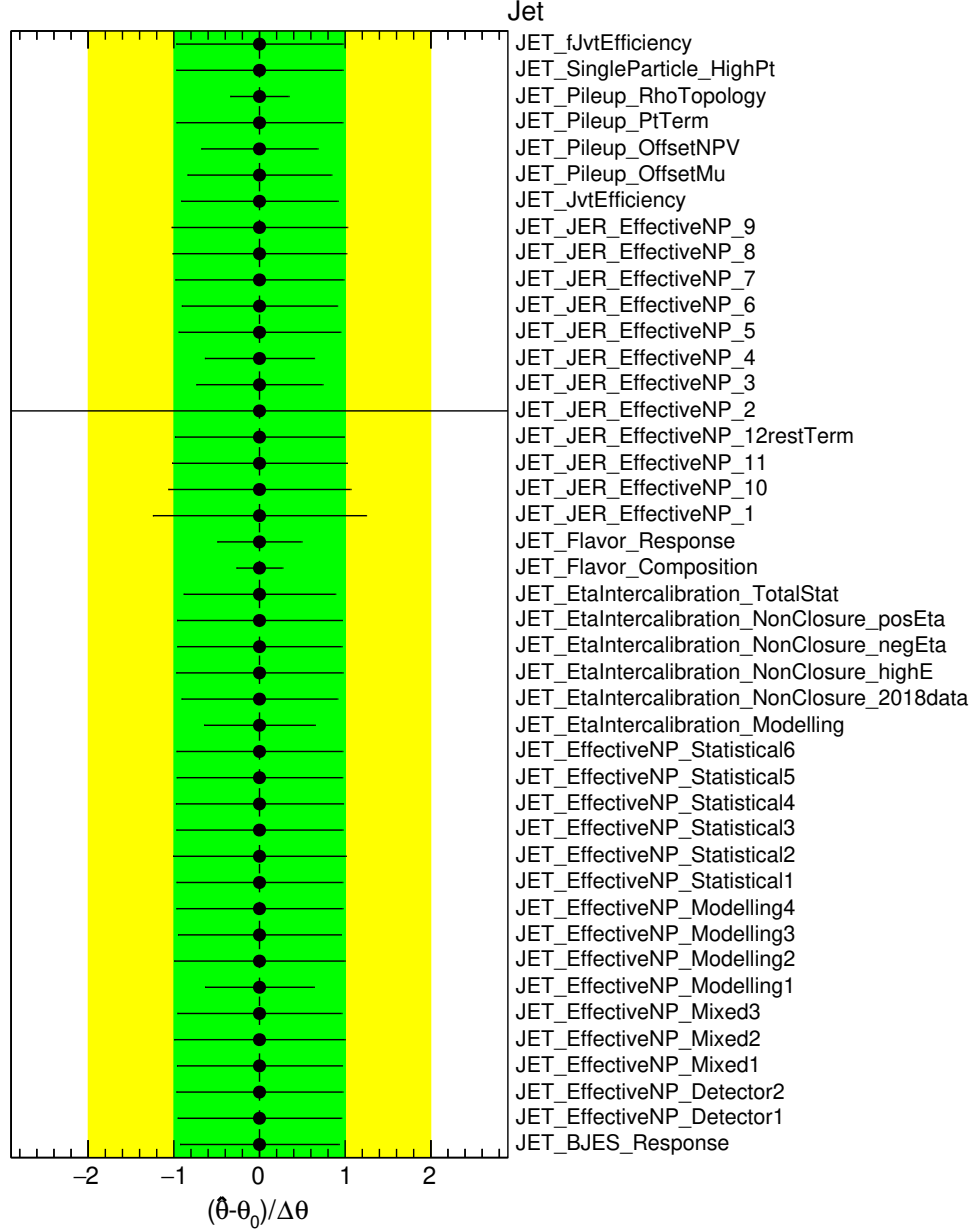


Figure 7.24: Constraints on jet-related nuisance parameters in monojet events for uncertainties on fJVT, high- p_T jets, per-event p_T density modeling, pileup, JVT, effective jet energy resolution, flavor composition and response, jet physics, effective jet energy scale, and related to b -jets.

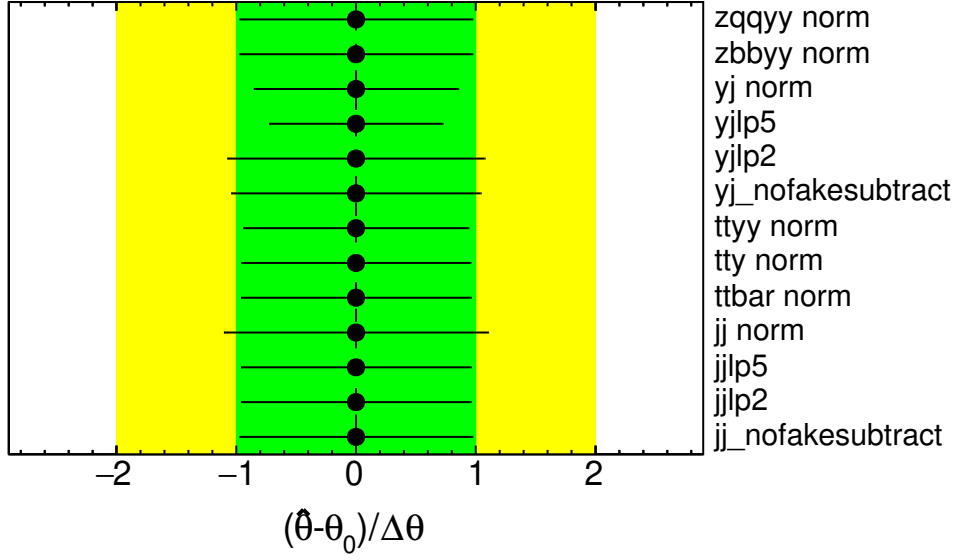
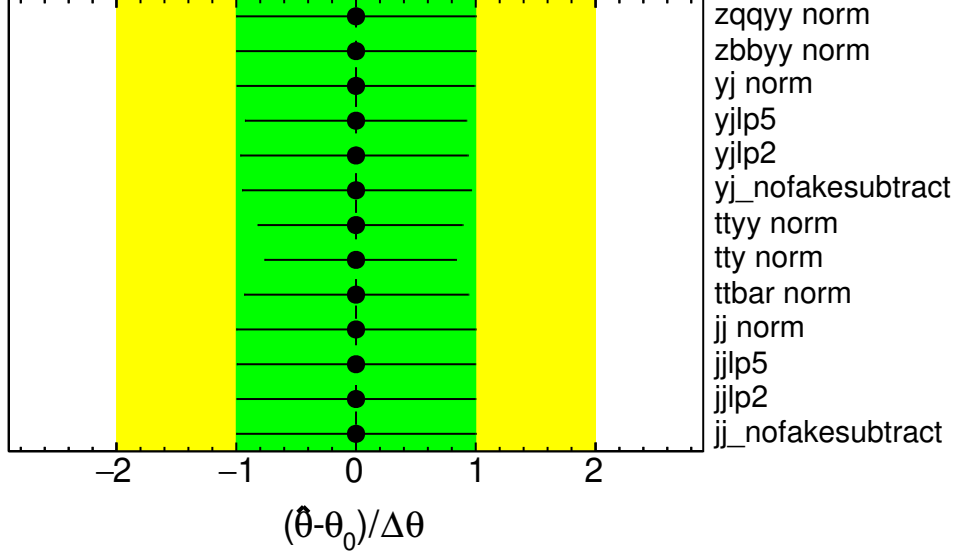


Figure 7.25: Constraints on all other nuisance parameters in (a) dijet and (b) monojet events for uncertainties related to the normalization of $Z(qq) \rightarrow \gamma\gamma$ and $Z(bb) \rightarrow \gamma\gamma$, $t\bar{t}\gamma\gamma$, $t\bar{t}\gamma$, and $t\bar{t}$, as well as those related to jets faking photons template normalization and the LoosePrime definition used.

CHAPTER 8

CONCLUSIONS

In this dissertation, measurements of the Higgs boson inclusive and differential fiducial cross-sections in the diphoton decay channel are presented along with two interpretations of the results. The data were gathered during proton-proton collisions at the LHC during 2015-2018 at a center-of-mass energy of $\sqrt{s} = 13$ TeV with an integrated luminosity of 139 fb^{-1} .

The cross-section measurements were performed in a fiducial region defined by detector acceptance which required two prompt isolated photons with transverse momentum greater than 35% and 25% of the diphoton invariant mass and a spatial requirement of $|\eta| < 2.37$, excluding the region of $1.37 < |\eta| < 1.52$ for each. The final measured fiducial cross-section times branching ratio for the inclusive volume for $H \rightarrow \gamma\gamma$ events is

$$\sigma_{\text{fid}} = 67 \pm 5 \text{ (stat.)} \pm 4 \text{ (sys.) fb},$$

which agrees with the Standard Model prediction of $64 \pm 4 \text{ fb}$. The cross-sections were also measured in four other fiducial regions, each targeting specific aspects of Higgs boson production. They include a region targeting Higgs bosons produced via vector-boson fusion as well as Higgs boson production in association with a top-quark pair. An additional measurement was done in a fiducial region with high- $E_{\text{T}}^{\text{miss}}$ to target Higgs boson production with associated vector bosons (VH) or a top-quark pair ($t\bar{t}H$). The last region requires at

least one lepton to target VH , $t\bar{t}H$, as well as tH production. The final measured cross-section times branching ratio in each volume was measured to be

$$\begin{aligned}\sigma_{\text{VBF-enhanced}} &= 1.8 \pm 0.5 \text{ (stat.)} \pm 0.3 \text{ (sys.) fb,} \\ \sigma_{N_{\text{lepton}} \geq 1} &= 0.81 \pm 0.23 \text{ (stat.)} \pm 0.06 \text{ (sys.) fb,} \\ \sigma_{\text{High-}E_{\text{T}}^{\text{miss}}} &= 0.28 \pm 0.27 \text{ (stat.)} \pm 0.07 \text{ (sys.) fb,} \\ \sigma_{t\bar{t}H\text{-enhanced}} &= 0.53 \pm 0.27 \text{ (stat.)} \pm 0.06 \text{ (sys.) fb,}\end{aligned}$$

which all agree with Standard Model predictions as shown in Table 6.15.

A total cross-section was extrapolated to the full phase space resulting in a total Higgs boson production cross-section of $58 \pm 4 \text{ (stat.)} \pm 4 \text{ (sys.) pb}$ which agrees with the Standard Model prediction of $55.6 \pm 2.7 \text{ pb}$.

Seventeen differential cross-sections and four double-differential cross-sections were also measured within the inclusive fiducial volume and compared with Standard Model predictions with no deviations observed. The differential variables chosen target specific aspects of the Higgs boson like jet kinematics, spin, and CP quantum numbers as well as production kinematics. Included as a differential measurement is the production of Higgs + HF in the form of the number of b -tagged jets ($N_{b\text{-jets}}$). Additionally, four differential cross-sections and one double-differential cross-section in the VBF-enhanced fiducial region were measured to probe VBF kinematics and CP properties.

The measured cross-sections were used in two interpretations for beyond the Standard Model Yukawa couplings and additional dimension-6 operators using an effective field theory approach.

A measurement of the production of diphotons with associated heavy flavor jets is also presented using an Asimov dataset scaled to an integrated luminosity of 139 fb^{-1} . This measurement plays an important role in multiple other ATLAS analyses and has never before been measured. As an Asimov dataset was used in conjunction with the Monte Carlo simulation, only an estimation on the sensitivity and expected uncertainties was presented. It can be concluded from these measurements that a measurement is feasible in all dijet and monojet combinations of b -, c -, and light-flavor jets.

The two analyses in this dissertation were presented together as the diphoton final state is common to both, either as a Higgs boson decay product or as hard-scatter independent from the Higgs boson. Specific measurements of heavy and inclusive jet flavor were studied in each as well. This was studied in the diphoton + HF measurement by looking explicitly at the jet flavor and in the cross-section measurement via $N_{b\text{-jets}}$ and the flavor-inclusive N_{jets} differential measurements. The diphoton + HF measurement is intended to be used in future analyses targeting Higgs bosons in the diphoton decay channel as a way to improve simulation and predictions of background processes that include both heavy- and light-flavor.

In the future, the diphoton + HF analysis will continue on to obtain a measurement in data and could be extended as a differential measurement binned by various jet kinematic variables. Another potential application of the analysis beyond the scope of background in Higgs boson processes, is via a search. This measurement could be extended to search for a new particle that decays into heavy-flavor quarks produced in association with photons. An example of this was searched for previously targeting single production of a vector-like B -quark that decays into a Higgs boson and a b quark where the Higgs boson then decays via photons [148]. The Higgs boson differential cross-section will be repeated using the upcoming Run 3 ATLAS dataset. The new data has a record center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$ with an increased collision rate. This will allow for greater precision measurements as well as a higher discovery potential, which means new discoveries may be right around the corner.

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APPENDIX A

ADDITIONAL HIGGS CROSS-SECTION DISTRIBUTIONS

A.1 Binning and Migration Purities

Table A.1: Binning choice for $p_T^{\gamma\gamma}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$p_T^{\gamma\gamma}$ [GeV]	0.0 - 5.0	256.2	9650.41	2.6		0.39
$p_T^{\gamma\gamma}$ [GeV]	5.0 - 10.0	545.39	18243	4.02		0.25
$p_T^{\gamma\gamma}$ [GeV]	10.0 - 15.0	585.59	19733.2	4.15		0.24
$p_T^{\gamma\gamma}$ [GeV]	15.0 - 20.0	538.64	18196.5	3.97		0.25
$p_T^{\gamma\gamma}$ [GeV]	20.0 - 25.0	471.9	15756.5	3.74		0.27
$p_T^{\gamma\gamma}$ [GeV]	25.0 - 30.0	407.37	13228.7	3.52		0.29
$p_T^{\gamma\gamma}$ [GeV]	30.0 - 35.0	348.76	11064.6	3.3		0.31
$p_T^{\gamma\gamma}$ [GeV]	35.0 - 45.0	556.53	17197.2	4.22		0.24
$p_T^{\gamma\gamma}$ [GeV]	45.0 - 60.0	583.87	16957.3	4.46		0.23
$p_T^{\gamma\gamma}$ [GeV]	60.0 - 80.0	493.29	13057.7	4.29		0.24
$p_T^{\gamma\gamma}$ [GeV]	80.0 - 100.0	307.69	6718.11	3.73		0.27
$p_T^{\gamma\gamma}$ [GeV]	100.0 - 120.0	200.7	3376.34	3.42		0.3
$p_T^{\gamma\gamma}$ [GeV]	120.0 - 140.0	140.13	1784.51	3.28		0.31
$p_T^{\gamma\gamma}$ [GeV]	140.0 - 170.0	140.2	1343.15	3.76		0.27
$p_T^{\gamma\gamma}$ [GeV]	170.0 - 200.0	86.9	632	3.38		0.31
$p_T^{\gamma\gamma}$ [GeV]	200.0 - 250.0	79.58	446.81	3.66		0.29
$p_T^{\gamma\gamma}$ [GeV]	250.0 - 300.0	37.68	172.94	2.77		0.39
$p_T^{\gamma\gamma}$ [GeV]	300.0 - 450.0	33.97	124.43	2.92		0.37
$p_T^{\gamma\gamma}$ [GeV]	450.0 - 650.0	6.36	18.72	1.4		0.79
$p_T^{\gamma\gamma}$ [GeV]	650.0 - 1000.0	1.05	2.55	0.62		1.81

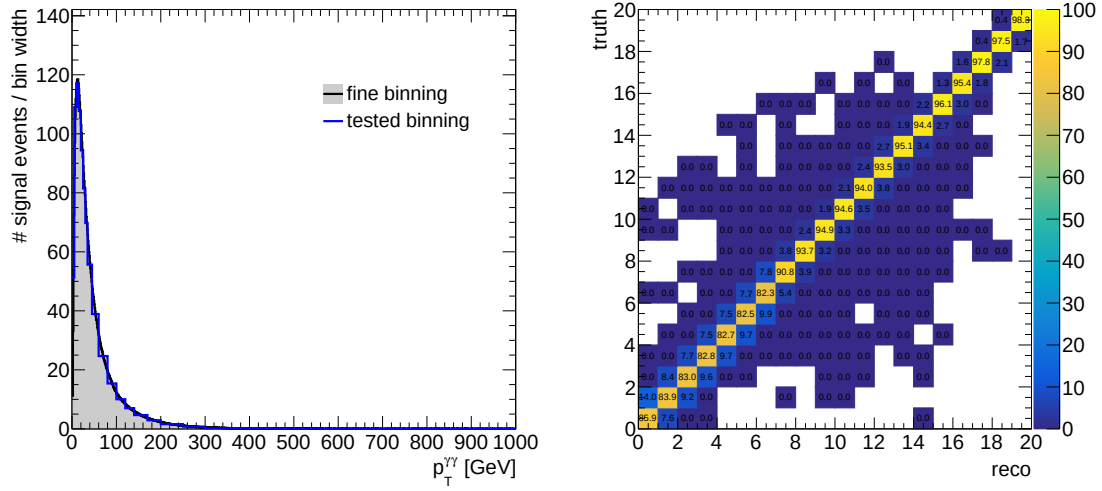


Figure A.1: Signal distribution and purity for variable $p_T^{\gamma\gamma}$.

Table A.2: Binning choice for $|y_{\gamma\gamma}|$.

Variable	Bin	Signal	Data	Sig.	Stat. Error
$ y_{\gamma\gamma} $	0.0 - 0.15	637.03	16324	4.95	0.2
$ y_{\gamma\gamma} $	0.15 - 0.3	626.39	15993.8	4.92	0.21
$ y_{\gamma\gamma} $	0.3 - 0.45	607.39	15362	4.87	0.21
$ y_{\gamma\gamma} $	0.45 - 0.6	572.18	14257.2	4.76	0.21
$ y_{\gamma\gamma} $	0.6 - 0.75	534.51	13660.9	4.54	0.22
$ y_{\gamma\gamma} $	0.75 - 0.9	492.38	13366.4	4.23	0.24
$ y_{\gamma\gamma} $	0.9 - 1.2	852.11	25991.1	5.26	0.19
$ y_{\gamma\gamma} $	1.2 - 1.6	872.49	29753.7	5.03	0.2
$ y_{\gamma\gamma} $	1.6 - 2.0	513.23	16896.7	3.93	0.26
$ y_{\gamma\gamma} $	2.0 - 2.5	169.73	5556.26	2.27	0.45

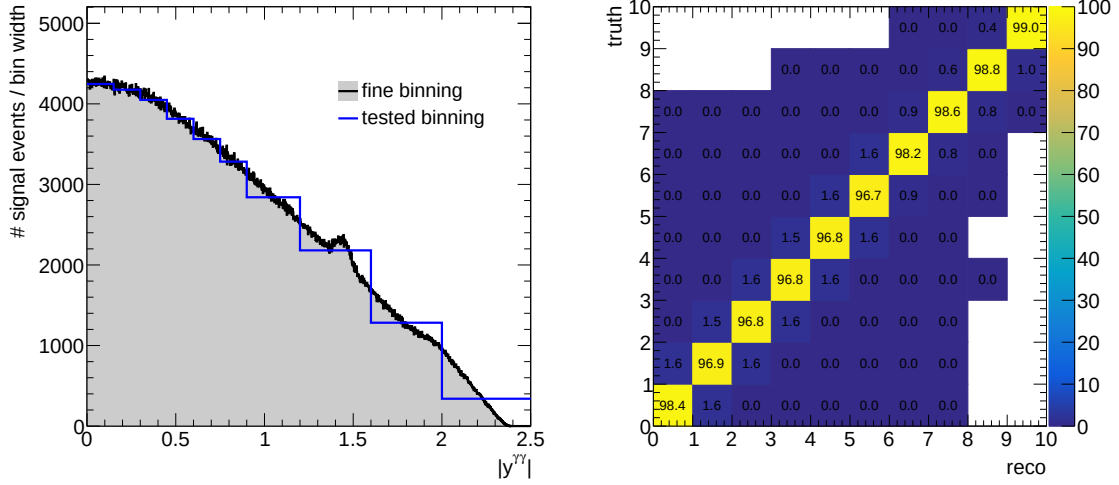
Figure A.2: Signal distribution and purity for variable $|y_{\gamma\gamma}|$.

Table A.3: Binning choice for N_{jets} . Here, bin 0 represents $N_{\text{jets}} = 0$, bin 1 represents $N_{\text{jets}} = 1$, bin 2 represents $N_{\text{jets}} = 2$, and bin 3 represents $N_{\text{jets}} \geq 3$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
N_{jets}	0.0 - 1.0	3070.77	95856.6	9.87		0.1
N_{jets}	1.0 - 2.0	1673.17	44879.9	7.85		0.13
N_{jets}	2.0 - 3.0	776.81	17728.4	5.79		0.18
N_{jets}	3.0 - 10.0	355.91	8650.72	3.8		0.27

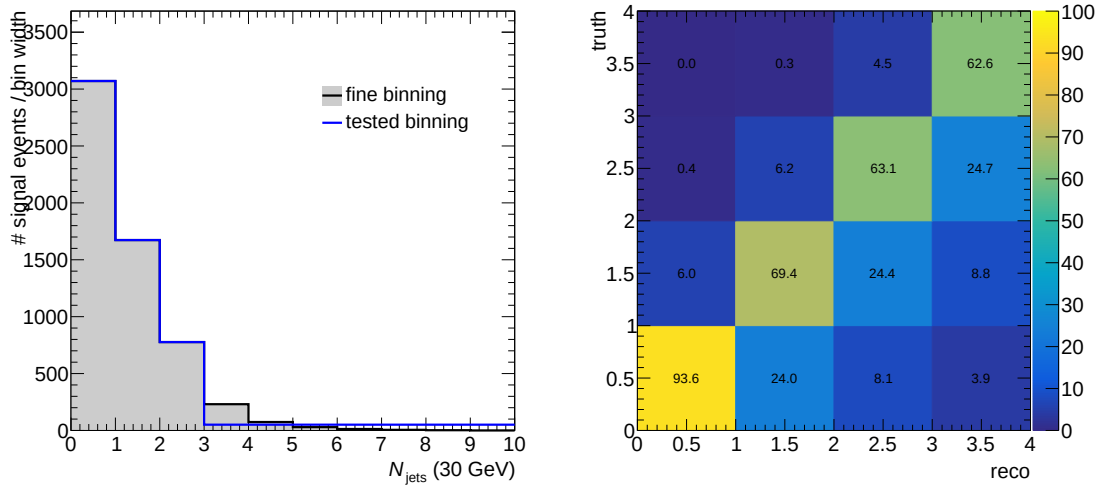


Figure A.3: Signal distribution and purity for variable N_{jets} . Here, bin 0 represents $N_{\text{jets}} = 0$, bin 1 represents $N_{\text{jets}} = 1$, bin 2 represents $N_{\text{jets}} = 2$, and bin 3 represents $N_{\text{jets}} \geq 3$.

Table A.4: Binning choice for $N_{b\text{-jets}}$. Here, bin 0 represents $N_{\text{jets}}^{\text{central}} = 0$ or $N_{\text{leptons}} > 0$, bin 1 represents passing the central jet and lepton requirement, but $N_{b\text{-jets}} = 0$, and bin 2 represents $N_{b\text{-jets}} \geq 1$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
N_{jets}	0.0 - 1.0	3657.17	109032	11.01		0.09
N_{jets}	1.0 - 2.0	2032.62	56271.7	8.52		0.12
N_{jets}	2.0 - 3.0	108.9	2388.55	2.21		0.46

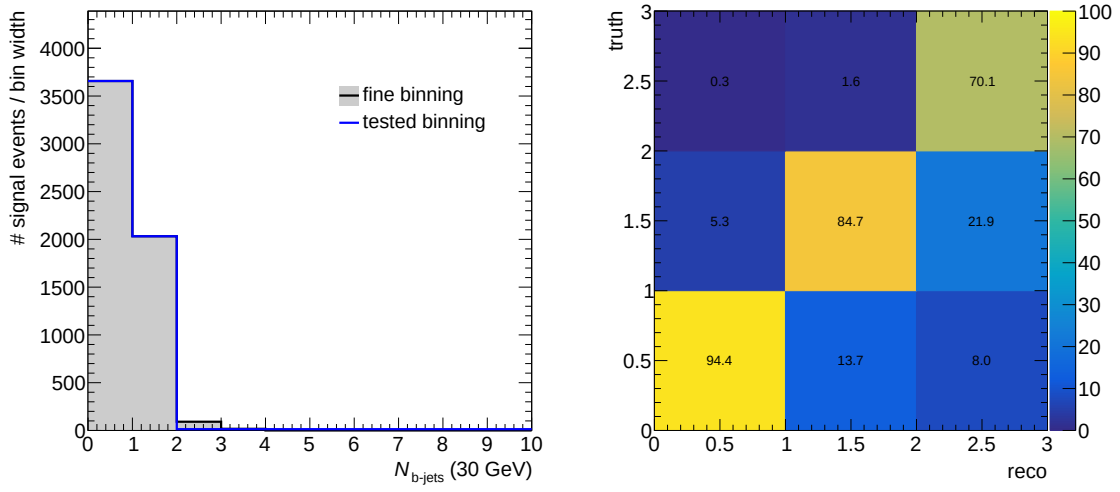


Figure A.4: Signal distribution and purity for variable $N_{b\text{-jets}}$. Here, bin 0 represents $N_{\text{jets}}^{\text{central}} = 0$ or $N_{\text{leptons}} > 0$, bin 1 represents passing the central jet and lepton requirement, but $N_{b\text{-jets}} = 0$, and bin 2 represents $N_{b\text{-jets}} \geq 1$.

Table A.5: Binning choice for $p_T^{\gamma_1}/m_{\gamma\gamma}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$p_T^{\gamma_1}/m_{\gamma\gamma}$	0.35 - 0.45	687.98	39026.8	3.47		0.29
$p_T^{\gamma_1}/m_{\gamma\gamma}$	0.45 - 0.5	880.46	28587.8	5.18		0.19
$p_T^{\gamma_1}/m_{\gamma\gamma}$	0.5 - 0.55	1413.44	34972.4	7.51		0.13
$p_T^{\gamma_1}/m_{\gamma\gamma}$	0.55 - 0.6	856.2	21219.2	5.84		0.17
$p_T^{\gamma_1}/m_{\gamma\gamma}$	0.6 - 0.65	537.2	13403.5	4.61		0.22
$p_T^{\gamma_1}/m_{\gamma\gamma}$	0.65 - 0.75	614.31	14982.7	4.99		0.2
$p_T^{\gamma_1}/m_{\gamma\gamma}$	0.75 - 0.85	324.21	7386.92	3.75		0.27
$p_T^{\gamma_1}/m_{\gamma\gamma}$	0.85 - 0.95	187.19	3726.63	3.04		0.33
$p_T^{\gamma_1}/m_{\gamma\gamma}$	0.95 - 4.0	375.31	3843.74	5.96		0.17

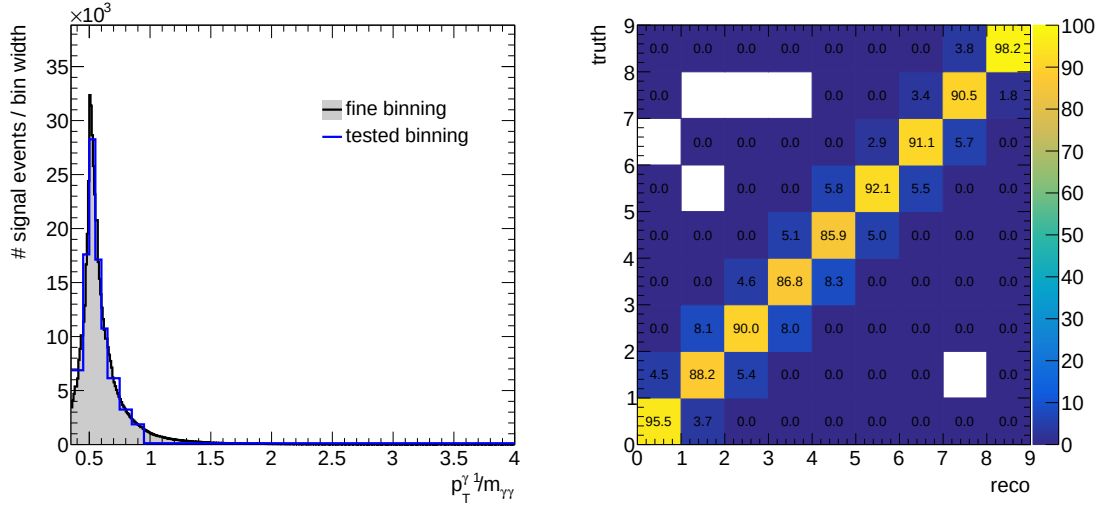
Figure A.5: Signal distribution and purity for variable $p_T^{\gamma_1}/m_{\gamma\gamma}$.

Table A.6: Binning choice for $p_T^{\gamma^2}/m_{\gamma\gamma}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$p_T^{\gamma^2}/m_{\gamma\gamma}$	0.25 - 0.35	1306.9	63231.9	5.18		0.19
$p_T^{\gamma^2}/m_{\gamma\gamma}$	0.35 - 0.4	1197.27	37742.7	6.13		0.16
$p_T^{\gamma^2}/m_{\gamma\gamma}$	0.4 - 0.45	1487.27	35564.4	7.83		0.13
$p_T^{\gamma^2}/m_{\gamma\gamma}$	0.45 - 0.5	1354.83	26362.6	8.27		0.12
$p_T^{\gamma^2}/m_{\gamma\gamma}$	0.5 - 0.55	228.32	2614.48	4.4		0.23
$p_T^{\gamma^2}/m_{\gamma\gamma}$	0.55 - 0.65	153.66	1079.49	4.57		0.23
$p_T^{\gamma^2}/m_{\gamma\gamma}$	0.65 - 0.75	64.83	304.51	3.59		0.3
$p_T^{\gamma^2}/m_{\gamma\gamma}$	0.75 - 0.85	33.6	126.13	2.87		0.38
$p_T^{\gamma^2}/m_{\gamma\gamma}$	0.85 - 4.0	50.73	117.11	4.4		0.26

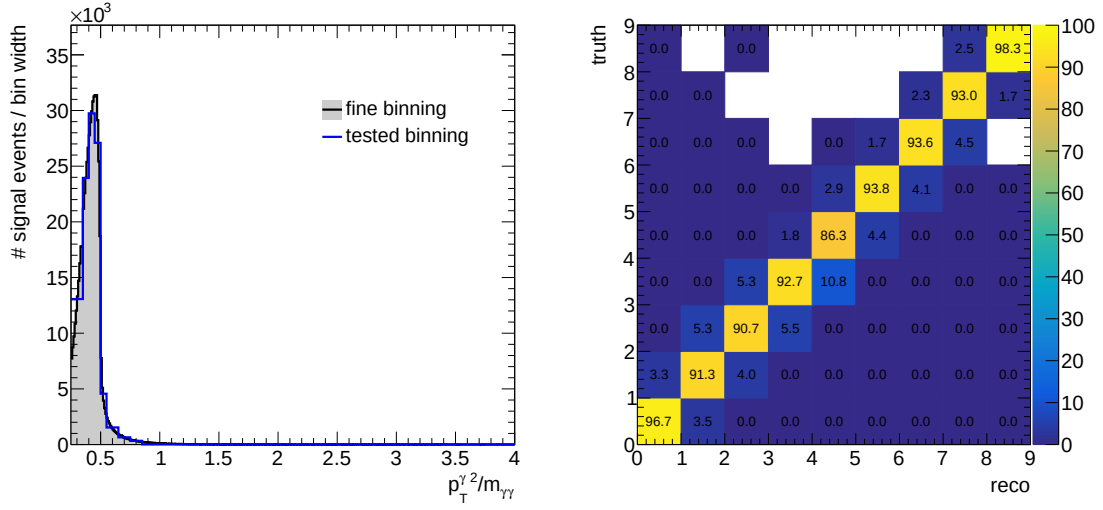
Figure A.6: Signal distribution and purity for variable $p_T^{\gamma^2}/m_{\gamma\gamma}$.

Table A.7: Binning choice for $p_T^{j_1}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$p_T^{j_1}$ [GeV]	30.0 - 60.0	1554.68	43444.2	7.42		0.14
$p_T^{j_1}$ [GeV]	60.0 - 90.0	584.04	15227.9	4.7		0.22
$p_T^{j_1}$ [GeV]	90.0 - 120.0	283.14	6152.5	3.58		0.28
$p_T^{j_1}$ [GeV]	120.0 - 350.0	367.68	6193.37	4.63		0.22
$p_T^{j_1}$ [GeV]	350.0 - 999.0	16.91	261.62	1.03		0.99

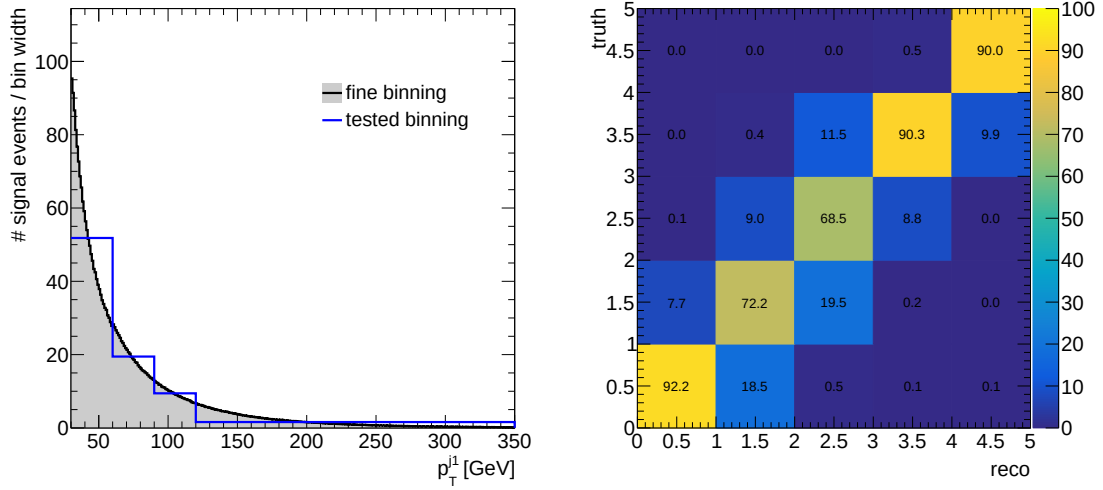
Figure A.7: Signal distribution and purity for variable $p_T^{j_1}$.

Table A.8: Binning choice for $p_T^{\gamma\gamma}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$p_T^{\gamma\gamma}$ [GeV]	0.0 - 30.0	1216.13	32902.1	6.66		0.15
$p_T^{\gamma\gamma}$ [GeV]	30.0 - 60.0	976.34	24532.2	6.19		0.16
$p_T^{\gamma\gamma}$ [GeV]	60.0 - 120.0	487.38	11044.8	4.6		0.22
$p_T^{\gamma\gamma}$ [GeV]	120.0 - 350.0	122.1	2677.28	2.34		0.43

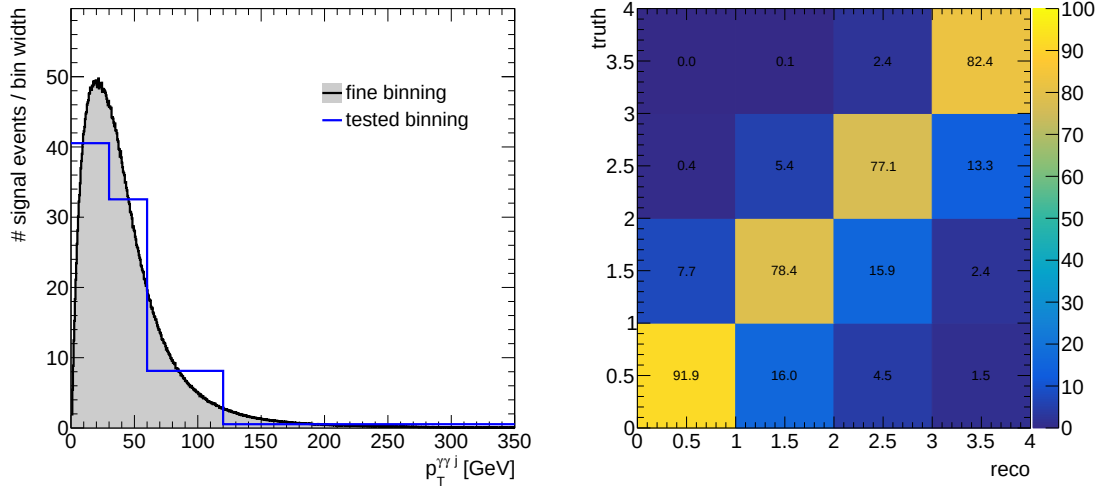
Figure A.8: Signal distribution and purity for variable $p_T^{\gamma\gamma}$.

Table A.9: Binning choice for H_T .

Variable	Bin	Signal	Data	Sig.	Stat.	Error
H_T [GeV]	30.0 - 60.0	1164.7	33184.7	6.36		0.16
H_T [GeV]	60.0 - 140.0	999.69	25954.1	6.17		0.16
H_T [GeV]	140.0 - 200.0	290.4	6068.09	3.7		0.27
H_T [GeV]	200.0 - 500.0	300.22	5693.45	3.94		0.26
H_T [GeV]	500.0 - 999.0	29.62	550.3	1.25		0.81

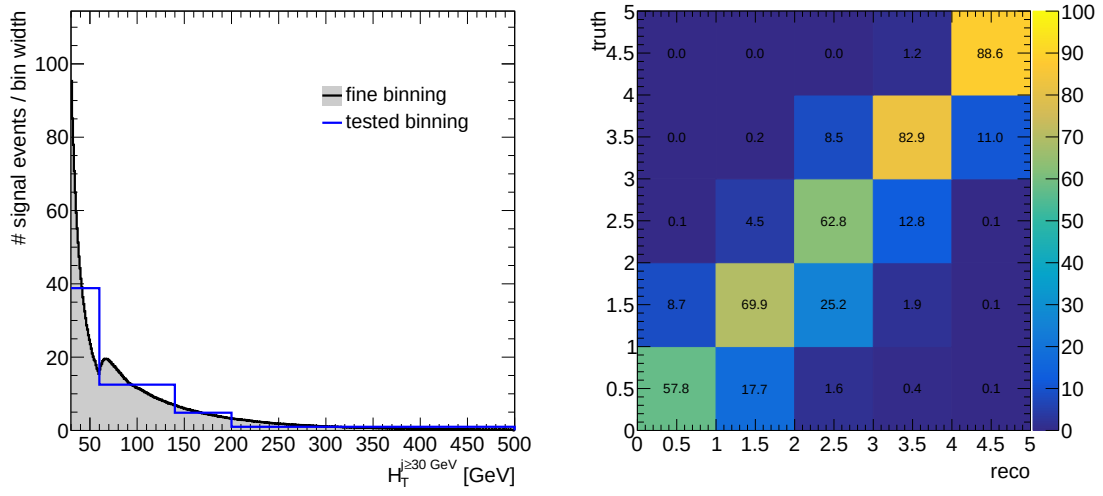
Figure A.9: Signal distribution and purity for variable H_T .

Table A.10: Binning choice for τ_{C,j_1} .

Variable	Bin	Signal	Data	Sig.	Stat.	Error
τ_{C,j_1} [GeV]	0.0 - 5.0	3737.2	109799	11.22		0.09
τ_{C,j_1} [GeV]	5.0 - 15.0	784.89	19403.4	5.6		0.18
τ_{C,j_1} [GeV]	15.0 - 25.0	632.48	19290.5	4.53		0.22
τ_{C,j_1} [GeV]	25.0 - 40.0	373.87	11068.6	3.53		0.29
τ_{C,j_1} [GeV]	40.0 - 400.0	348.71	7575.15	3.98		0.26

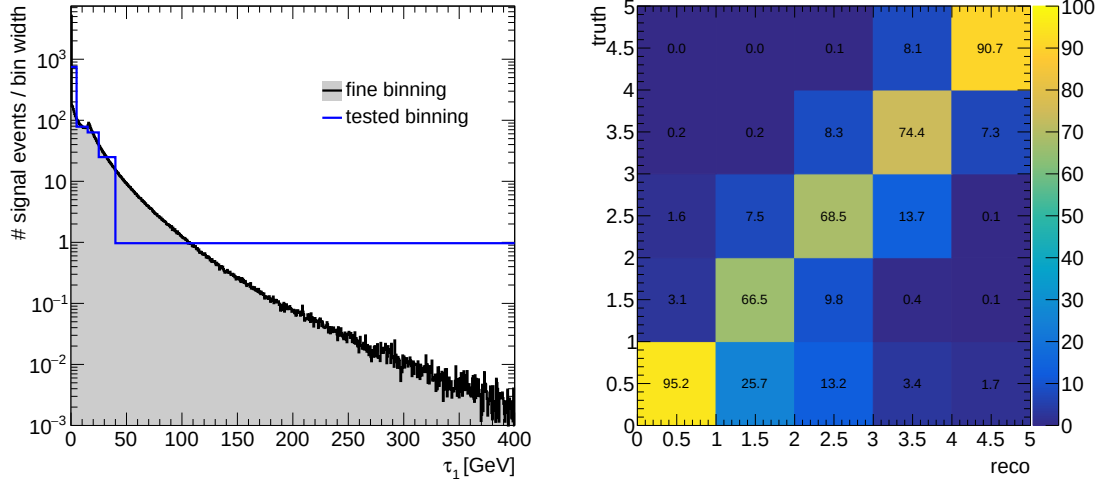
Figure A.10: Signal distribution and purity for variable τ_{C,j_1} .

Table A.11: Binning choice for $\Sigma\tau_{C,j}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$\Sigma\tau_{C,j}$ [GeV]	5.0 - 15.0	728.73	18274.4	5.36		0.19
$\Sigma\tau_{C,j}$ [GeV]	15.0 - 25.0	516.22	15507.2	4.12		0.25
$\Sigma\tau_{C,j}$ [GeV]	25.0 - 40.0	374.33	11053.1	3.54		0.29
$\Sigma\tau_{C,j}$ [GeV]	40.0 - 80.0	345.22	9025.7	3.61		0.28
$\Sigma\tau_{C,j}$ [GeV]	80.0 - 400.0	174.14	3446.3	2.94		0.35

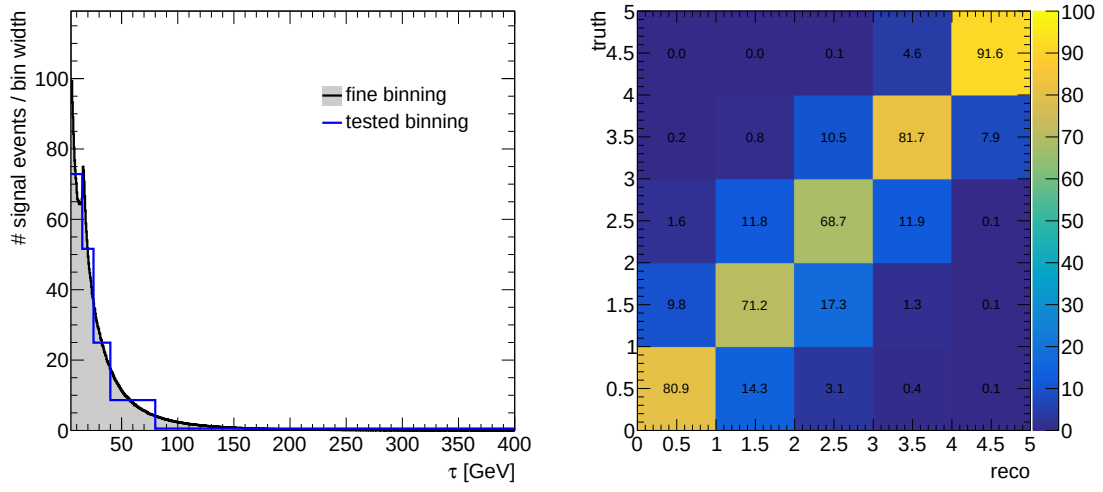
Figure A.11: Signal distribution and purity for variable $\Sigma\tau_{C,j}$.

Table A.12: Binning choice for $m_{\gamma\gamma j}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$m_{\gamma\gamma j}$ [GeV]	120.0 - 220.0	784,33	27729.5	4.69		0.22
$m_{\gamma\gamma j}$ [GeV]	220.0 - 300.0	744.3	20680.8	5.15		0.2
$m_{\gamma\gamma j}$ [GeV]	300.0 - 400.0	525.82	10801	5.02		0.2
$m_{\gamma\gamma j}$ [GeV]	400.0 - 600.0	458.49	7657.7	5.19		0.2
$m_{\gamma\gamma j}$ [GeV]	600.0 - 900.0	206.67	3171.58	3.63		0.28
$m_{\gamma\gamma j}$ [GeV]	900.0 - 2000.0	84.79	1222.47	2.4		0.43

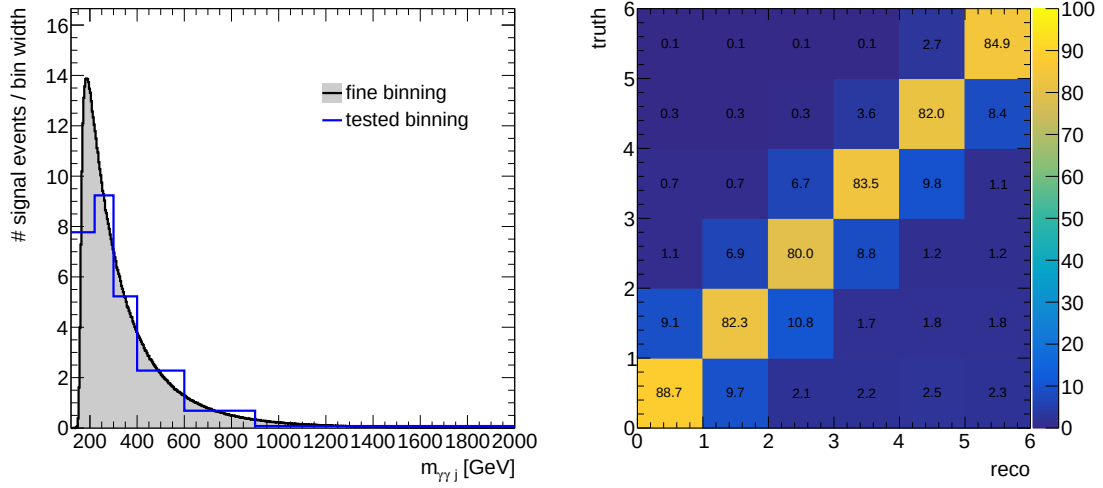
Figure A.12: Signal distribution and purity for variable $m_{\gamma\gamma j}$.

Table A.13: Binning choice for m_{jj} .

Variable	Bin	Signal	Data	Sig.	Stat.	Error
m_{jj} [GeV]	0.0 - 120.0	382.96	9088.14	3.99		0.25
m_{jj} [GeV]	120.0 - 450.0	478.44	14057.9	4.01		0.25
m_{jj} [GeV]	450.0 - 3000.0	267.4	3224.17	4.65		0.22
m_{jj} [GeV]	3000.0 - 9999.0	3.26	5.96	1.23		0.93

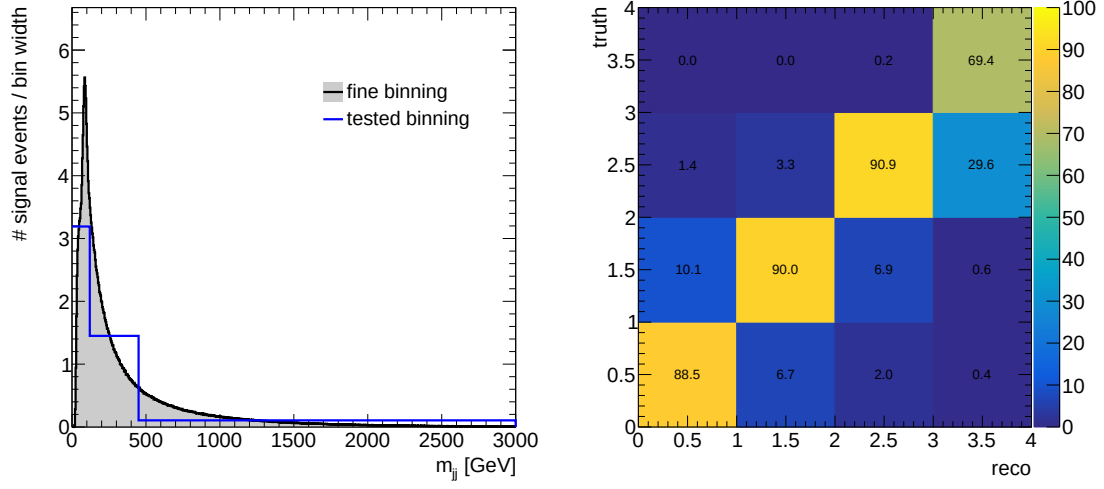
Figure A.13: Signal distribution and purity for variable m_{jj} .

Table A.14: Binning choice for $\Delta\phi_{jj}$.

Variable	Bin	Signal	Data	Sig.	Stat. Error
$\Delta\phi_{jj}$	-3.15 - -1.5708	296.07	9116.94	3.08	0.33
$\Delta\phi_{jj}$	-1.5708 - 0.0	270.13	4094.47	4.18	0.24
$\Delta\phi_{jj}$	0.0 - 1.5708	269.66	4070.13	4.18	0.24
$\Delta\phi_{jj}$	1.5708 - 3.15	297.04	9096.34	3.1	0.33

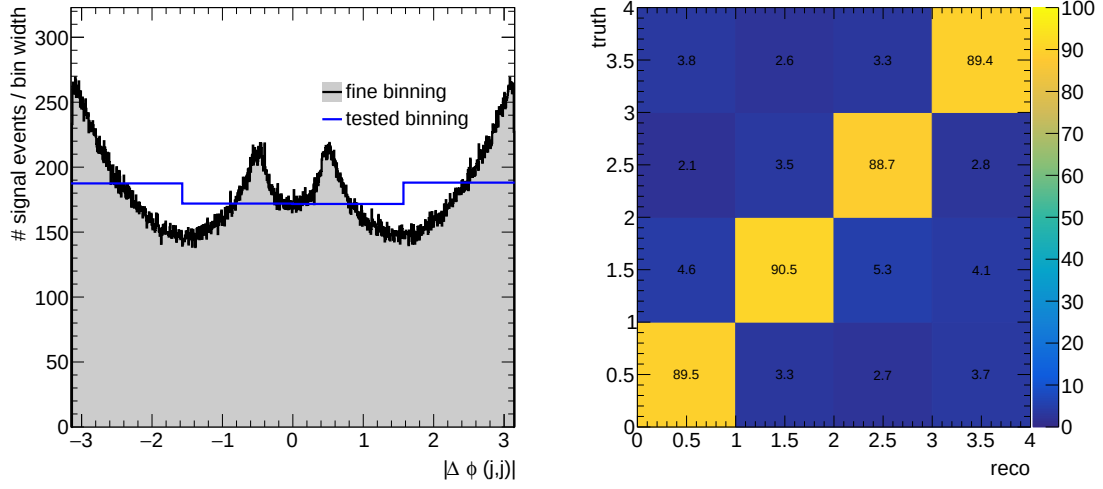
Figure A.14: Signal distribution and purity for variable $\Delta\phi_{jj}$.

Table A.15: Binning choice for $p_T^{\gamma\gamma jj}$.

Variable	Bin	Signal	Data	Sig.	Stat. Error
$p_T^{\gamma\gamma jj}$ [GeV]	0.0 - 30.0	543.7	11391.8	5.05	0.2
$p_T^{\gamma\gamma jj}$ [GeV]	30.0 - 60.0	371.55	9683.88	3.75	0.27
$p_T^{\gamma\gamma jj}$ [GeV]	60.0 - 120.0	175.39	4528.68	2.59	0.39
$p_T^{\gamma\gamma jj}$ [GeV]	120.0 - 350.0	40.79	754.04	1.47	0.69

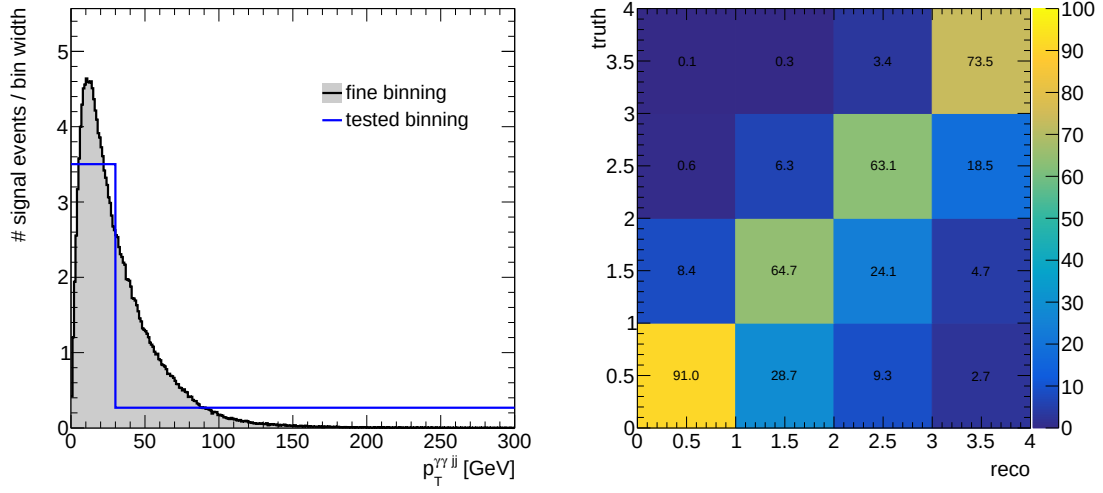
Figure A.15: Signal distribution and purity for variable $p_T^{\gamma\gamma jj}$.

Table A.16: Binning choice for $|\Delta\phi_{\gamma\gamma,jj}|$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$ \Delta\phi_{\gamma\gamma,jj} $	0.0 - 2.5	239.42	8657.53	2.56		0.39
$ \Delta\phi_{\gamma\gamma,jj} $	2.5 - 3.0	447.27	11209.5	4.2		0.24
$ \Delta\phi_{\gamma\gamma,jj} $	3.0 - 3.15	446.21	6510.81	5.47		0.19

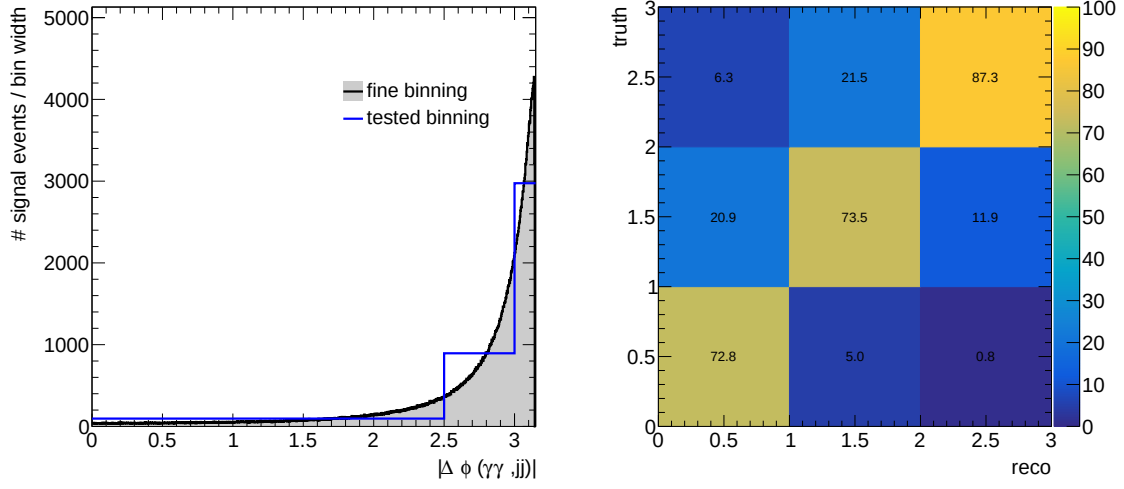
Figure A.16: Signal distribution and purity for variable $|\Delta\phi_{\gamma\gamma,jj}|$.

Table A.17: Binning choice for $p_T^{\gamma\gamma, \text{jet veto } 30}$.

Variable	Bin	Signal	Data	Sig.	Stat. Error
$p_T^{\gamma\gamma, \text{jet veto } 30}$	0.0 - 5.0	227.17	7758.13	2.57	0.39
$p_T^{\gamma\gamma, \text{jet veto } 30}$	5.0 - 10.0	478.16	14155.5	4	0.25
$p_T^{\gamma\gamma, \text{jet veto } 30}$	10.0 - 15.0	500.22	14440.1	4.14	0.24
$p_T^{\gamma\gamma, \text{jet veto } 30}$	15.0 - 20.0	441.19	12207.6	3.97	0.25
$p_T^{\gamma\gamma, \text{jet veto } 30}$	20.0 - 30.0	647.26	15942.4	5.09	0.2
$p_T^{\gamma\gamma, \text{jet veto } 30}$	30.0 - 40.0	372.64	7657.75	4.22	0.24
$p_T^{\gamma\gamma, \text{jet veto } 30}$	40.0 - 50.0	189.55	3385.52	3.23	0.32
$p_T^{\gamma\gamma, \text{jet veto } 30}$	50.0 - 100.0	164.79	2691.4	3.14	0.32
$p_T^{\gamma\gamma, \text{jet veto } 30}$	100.0 - 200.0	11.48	60.6	1.43	0.74

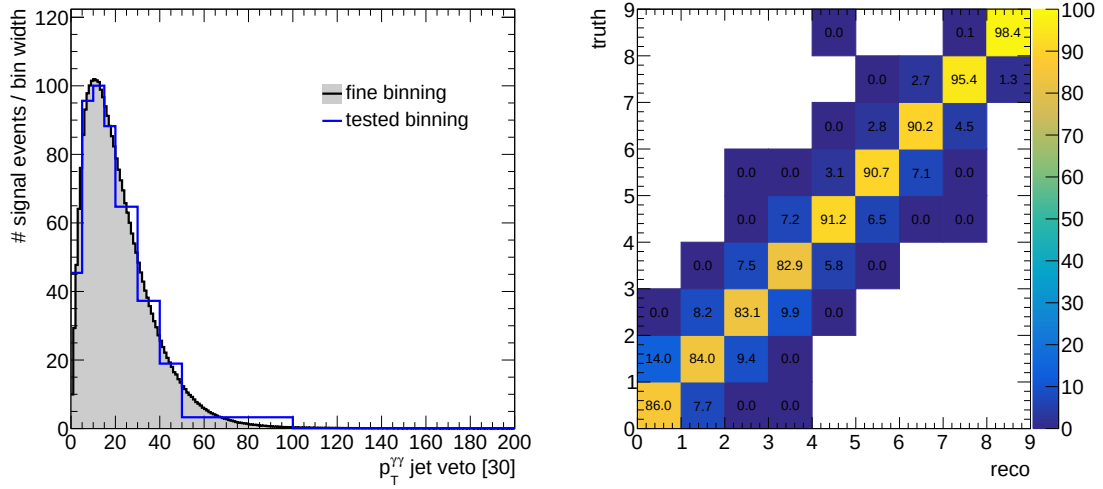
Figure A.17: Signal distribution and purity for variable $p_T^{\gamma\gamma, \text{jet veto } 30}$.

Table A.18: Binning choice for $p_T^{\gamma\gamma, \text{jet veto } 40}$.

Variable	Bin	Signal	Data	Sig.	Stat. Error
$p_T^{\gamma\gamma, \text{jet veto } 40}$	0.0 - 5.0	246.16	9264.55	2.55	0.4
$p_T^{\gamma\gamma, \text{jet veto } 40}$	5.0 - 10.0	521.12	17351	3.94	0.26
$p_T^{\gamma\gamma, \text{jet veto } 40}$	10.0 - 15.0	553.08	18400	4.06	0.25
$p_T^{\gamma\gamma, \text{jet veto } 40}$	15.0 - 20.0	499.36	16527.1	3.87	0.26
$p_T^{\gamma\gamma, \text{jet veto } 40}$	20.0 - 30.0	777.77	24671.4	4.93	0.21
$p_T^{\gamma\gamma, \text{jet veto } 40}$	30.0 - 40.0	511.44	14913.9	4.16	0.24
$p_T^{\gamma\gamma, \text{jet veto } 40}$	40.0 - 50.0	308.07	8202.96	3.38	0.3
$p_T^{\gamma\gamma, \text{jet veto } 40}$	50.0 - 60.0	172.6	4201.18	2.64	0.38
$p_T^{\gamma\gamma, \text{jet veto } 40}$	60.0 - 100.0	176.05	3861.1	2.81	0.36
$p_T^{\gamma\gamma, \text{jet veto } 40}$	100.0 - 200.0	20	182.64	1.45	0.71

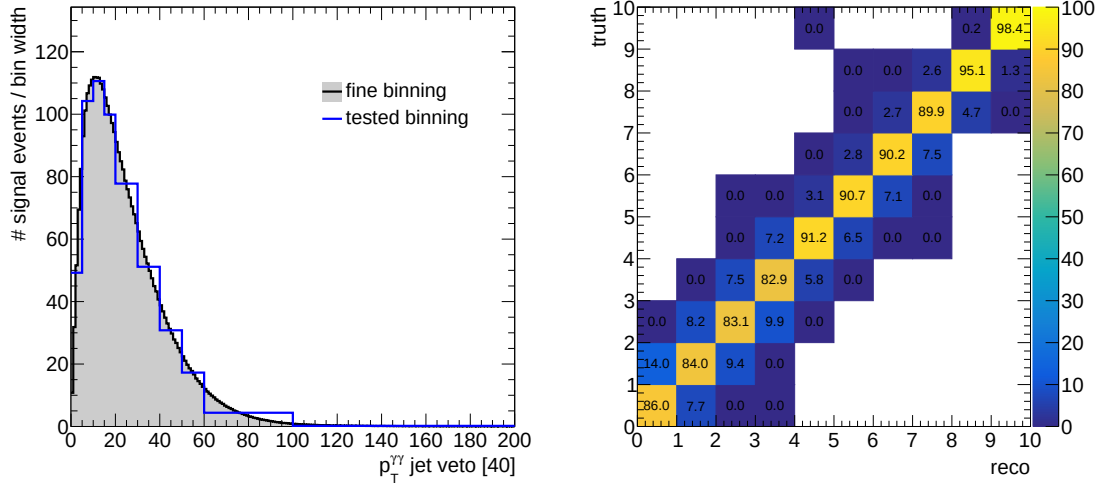
Figure A.18: Signal distribution and purity for variable $p_T^{\gamma\gamma, \text{jet veto } 40}$.

Table A.19: Binning choice for $p_T^{\gamma\gamma, \text{ jet veto } 50}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	0.0 - 5.0	251.59	9466.58	2.57		0.39
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	5.0 - 10.0	534.11	17779.5	3.99		0.25
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	10.0 - 15.0	569.94	19027.5	4.11		0.25
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	15.0 - 20.0	519.16	17273.2	3.93		0.26
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	20.0 - 30.0	827.91	26570.2	5.05		0.2
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	30.0 - 40.0	577.85	17283.5	4.37		0.23
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	40.0 - 50.0	385.09	10581.5	3.72		0.27
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	50.0 - 60.0	242.71	6036.76	3.1		0.33
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	60.0 - 70.0	145.27	3311.31	2.51		0.4
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	70.0 - 100.0	159.02	3040.34	2.86		0.36
$p_T^{\gamma\gamma, \text{ jet veto } 50}$	100.0 - 200.0	38.41	380.09	1.94		0.53

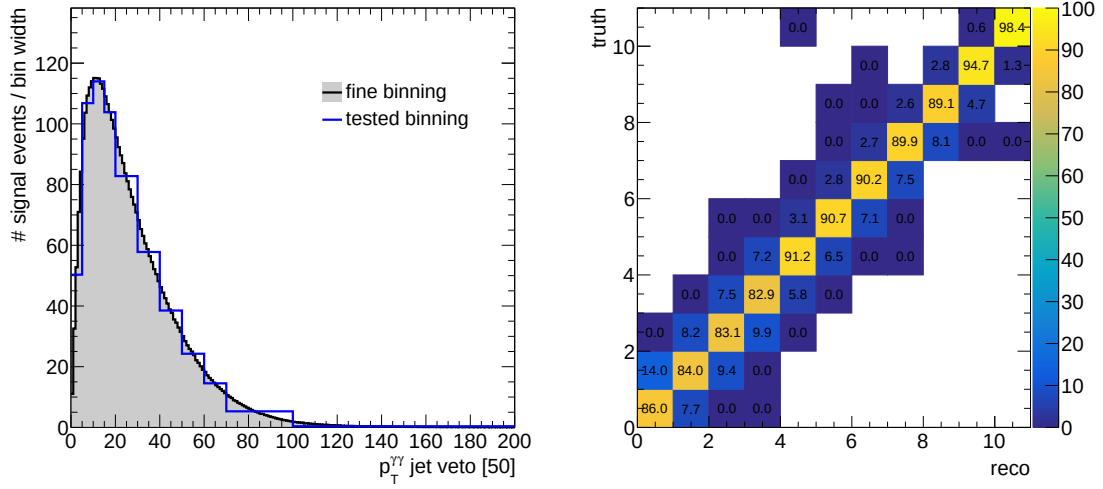
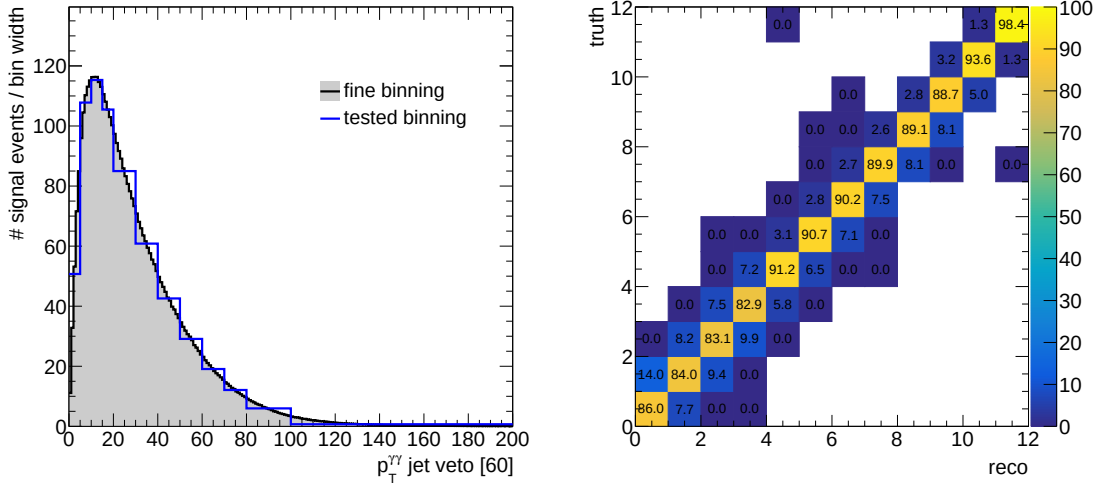
Figure A.19: Signal distribution and purity for variable $p_T^{\gamma\gamma, \text{ jet veto } 50}$.

Table A.20: Binning choice for $p_T^{\gamma\gamma, \text{jet veto } 60}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$p_T^{\gamma\gamma, \text{jet veto } 60}$	0.0 - 5.0	253.62	9542.67	2.58		0.39
$p_T^{\gamma\gamma, \text{jet veto } 60}$	5.0 - 10.0	538.99	17966.4	4		0.25
$p_T^{\gamma\gamma, \text{jet veto } 60}$	10.0 - 15.0	576.6	19305.7	4.13		0.24
$p_T^{\gamma\gamma, \text{jet veto } 60}$	15.0 - 20.0	527.37	17615.1	3.95		0.26
$p_T^{\gamma\gamma, \text{jet veto } 60}$	20.0 - 30.0	849.87	27479.8	5.1		0.2
$p_T^{\gamma\gamma, \text{jet veto } 60}$	30.0 - 40.0	608.4	18477	4.45		0.23
$p_T^{\gamma\gamma, \text{jet veto } 60}$	40.0 - 50.0	425.82	12108.1	3.85		0.26
$p_T^{\gamma\gamma, \text{jet veto } 60}$	50.0 - 60.0	291.1	7561.39	3.33		0.3
$p_T^{\gamma\gamma, \text{jet veto } 60}$	60.0 - 70.0	190.84	4482.54	2.83		0.36
$p_T^{\gamma\gamma, \text{jet veto } 60}$	70.0 - 80.0	121.02	2512.84	2.4		0.42
$p_T^{\gamma\gamma, \text{jet veto } 60}$	80.0 - 100.0	119.54	2058.21	2.61		0.39
$p_T^{\gamma\gamma, \text{jet veto } 60}$	100.0 - 200.0	69.95	707.23	2.59		0.4

Figure A.20: Signal distribution and purity for variable $p_T^{\gamma\gamma, \text{jet veto } 60}$.

A.1.1 VBF Variables

Table A.21: Binning choice for VBF $p_T^{j_1}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$p_T^{j_1}$ [GeV]	30.0 - 120.0	120.5	1179.4	3.45		0.3
$p_T^{j_1}$ [GeV]	120.0 - 500.0	56.76	293.62	3.21		0.33

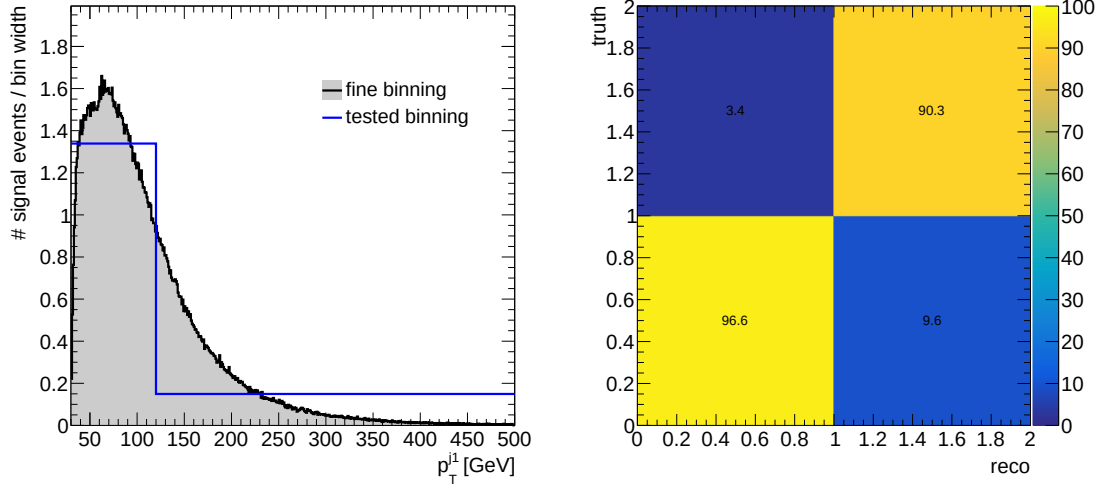
Figure A.21: Signal distribution and purity for variable VBF $p_T^{j_1}$.

Table A.22: Binning choice for VBF $\Delta\phi_{jj}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$\Delta\phi_{jj}$	-3.15 - -1.5708	50.04	479.83	2.25		0.46
$\Delta\phi_{jj}$	-1.5708 - 0.0	38.84	259.57	2.35		0.44
$\Delta\phi_{jj}$	0.0 - 1.5708	38.32	266.72	2.29		0.46
$\Delta\phi_{jj}$	1.5708 - 3.15	50.43	468.43	2.29		0.45

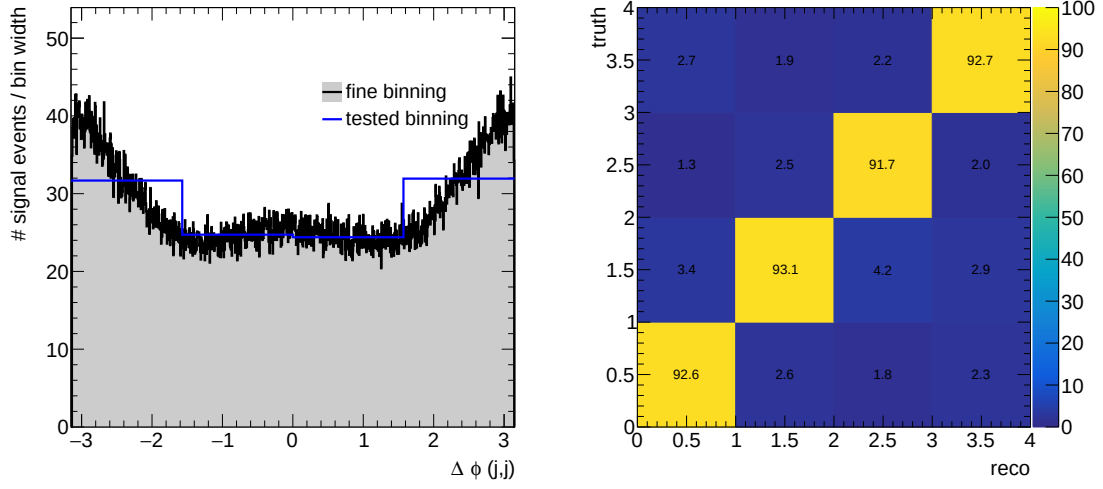
Figure A.22: Signal distribution and purity for variable VBF $\Delta\phi_{jj}$.

Table A.23: Binning choice for VBF $|\eta^*|$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$ \eta^* $	0.0 - 1.0	83.21	381.28	4.12		0.26
$ \eta^* $	1.0 - 2.0	57.7	418.21	2.76		0.38
$ \eta^* $	2.0 - 6.0	36.67	672.85	1.4		0.73

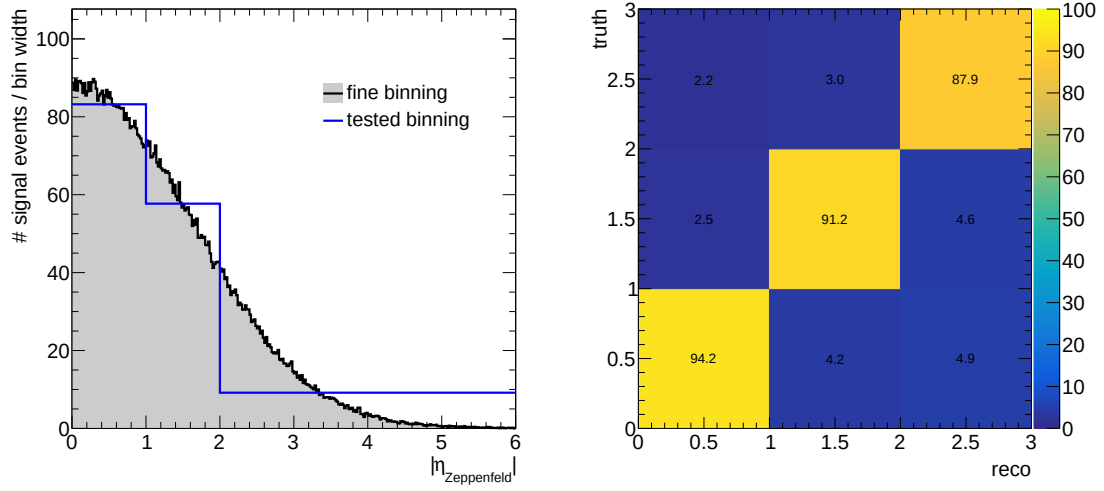
Figure A.23: Signal distribution and purity for variable VBF $|\eta^*|$

Table A.24: Binning choice for VBF $p_T^{\gamma\gamma jj}$.

Variable	Bin	Signal	Data	Sig.	Stat.	Error
$p_T^{\gamma\gamma jj}$ [GeV]	0.0 - 30.0	105.08	454.98	4.75		0.23
$p_T^{\gamma\gamma jj}$ [GeV]	30.0 - 999.0	72.56	1019.57	2.25		0.46

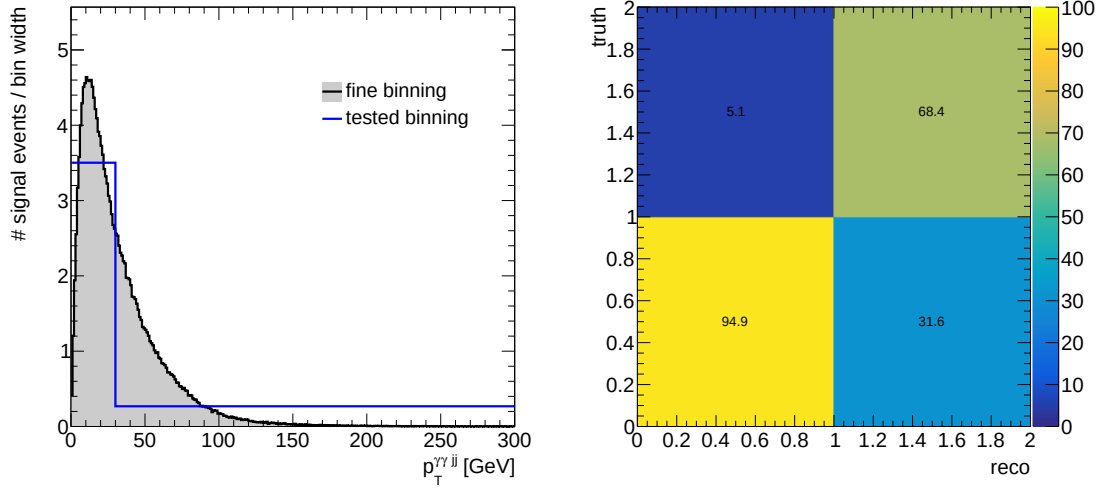
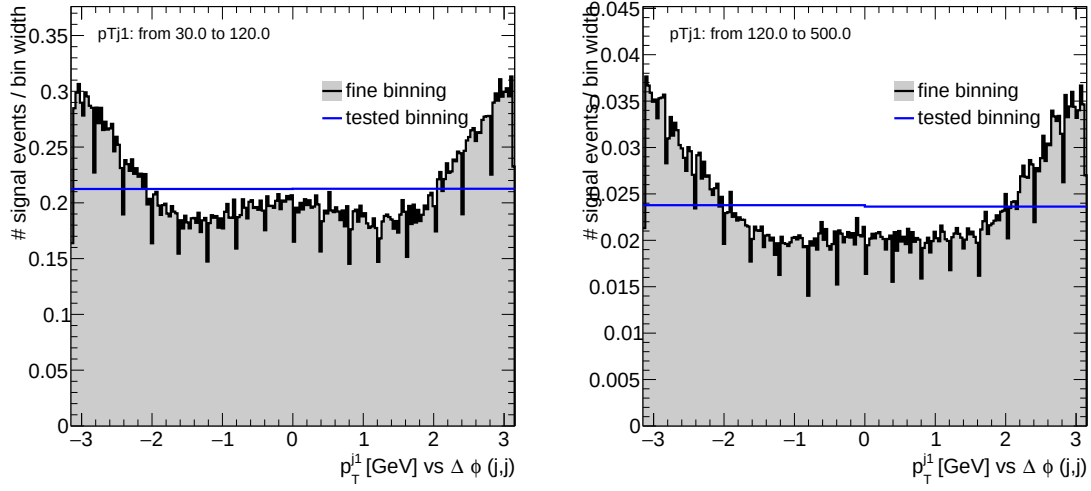
Figure A.24: Signal distribution and purity for variable VBF $p_T^{\gamma\gamma jj}$.

Table A.25: Binning choice for VBF $p_T^{j_1}$ vs $\Delta\phi_{jj}$.

Variable	BinX	BinY	Signal	Data	Sig.	Stat.	Error
$p_T^{j_1}$ [GeV] vs $\Delta\phi_{jj}$	30.0 - 120.0	-3.15 - 0	60.22	592	2.43		0.42
$p_T^{j_1}$ [GeV] vs $\Delta\phi_{jj}$	30.0 - 120.0	0 - 3.15	60.28	587.4	2.45		0.42
$p_T^{j_1}$ [GeV] vs $\Delta\phi_{jj}$	120.0 - 500.0	-3.15 - 0	28.47	146.89	2.28		0.47
$p_T^{j_1}$ [GeV] vs $\Delta\phi_{jj}$	120.0 - 500.0	0 - 3.15	28.29	146.72	2.27		0.47

Figure A.25: 2D binning for variable VBF $p_T^{j_1}$ vs $\Delta\phi_{jj}$.

A.1.2 Double-Differential Variables

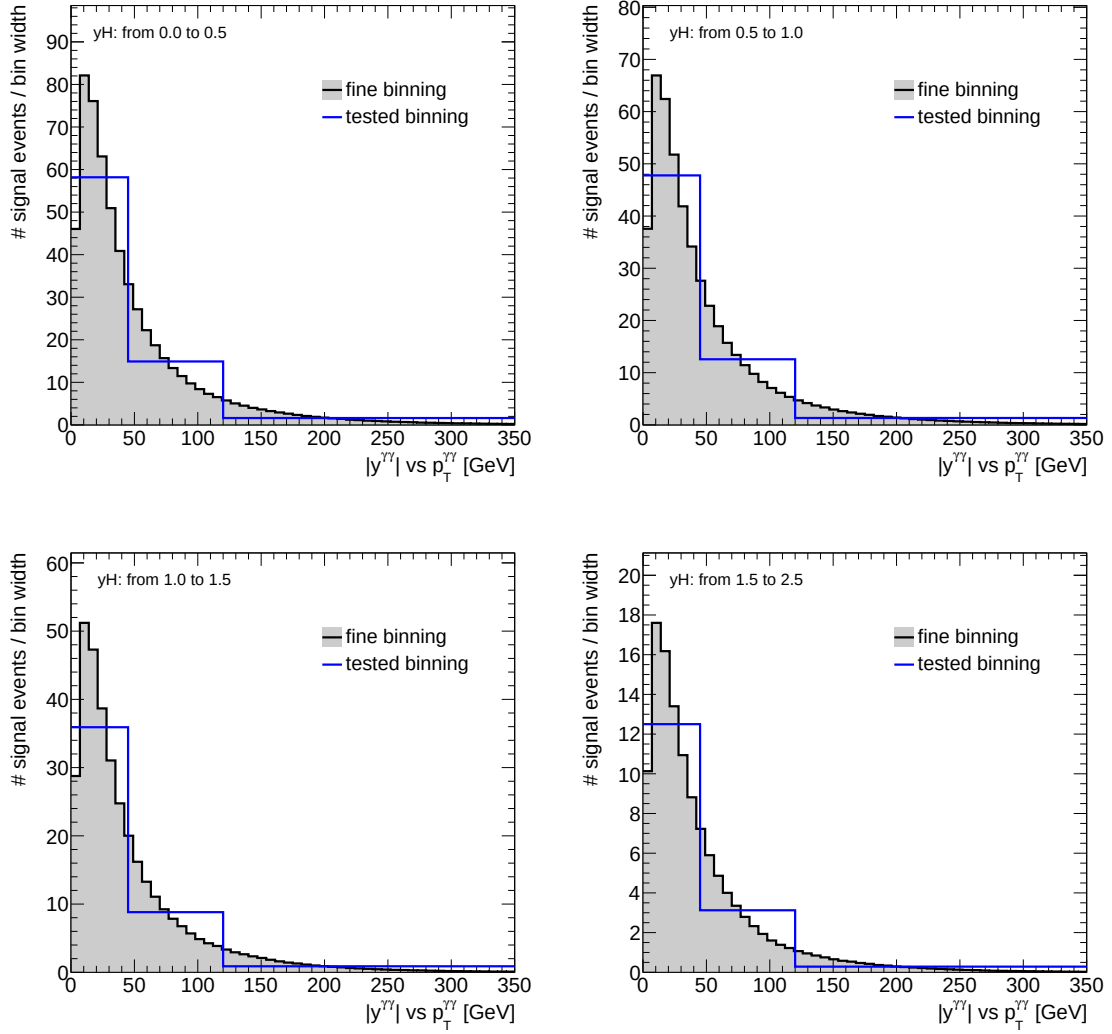


Figure A.26: 2D binning for variable $|y_{\gamma\gamma}|$ vs $p_T^{\gamma\gamma}$.

Table A.26: Binning choice for $p_T^{\gamma\gamma}$ vs $|y_{\gamma\gamma}|$.

Variable	Bin X	Bin Y	Signal	Data	Sig.	Stat.	Error
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	0.0 - 0.5	0 - 45	1309.1	38927.7	6.6		0.15
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	0.0 - 0.5	45 - 120	558.89	12227.1	5.02		0.2
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	0.0 - 0.5	120 - 350	185.45	1309.96	5.01		0.21
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	0.5 - 1.0	0 - 45	1075.1	32887	5.9		0.17
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	0.5 - 1.0	45 - 120	471.29	11109.6	4.44		0.23
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	0.5 - 1.0	120 - 350	152.15	1188.77	4.32		0.24
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	1.0 - 1.5	0 - 45	808.13	30452.8	4.61		0.22
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	1.0 - 1.5	45 - 120	330.54	9204.43	3.42		0.3
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	1.0 - 1.5	120 - 350	101.52	1052.6	3.08		0.33
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	1.5 - 2.5	0 - 45	562.52	20408.2	3.92		0.26
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	1.5 - 2.5	45 - 120	234.38	7434.04	2.7		0.37
$ y_{\gamma\gamma} $ vs $p_T^{\gamma\gamma}$	1.5 - 2.5	120 - 350	65.67	887.15	2.18		0.47

Table A.27: Binning choice for $(p_T^{\gamma_1} + p_T^{\gamma_2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma_1} - p_T^{\gamma_2})/m_{\gamma\gamma}$.

Variable	Bin X	Bin Y	Signal	Data	Sig.	Stat. Error
Rel. Sum vs. Difference	0.6 - 0.8	0 - 0.3	558.4	37235.4	2.89	0.35
Rel. Sum vs. Difference	0.8 - 1.1	0 - 0.05	1144.4	27954	6.8	0.15
Rel. Sum vs. Difference	0.8 - 1.1	0.05 - 0.1	884.02	21363.7	6.01	0.17
Rel. Sum vs. Difference	0.8 - 1.1	0.1 - 0.2	1108.84	29495	6.42	0.16
Rel. Sum vs. Difference	0.8 - 1.1	0.2 - 0.8	1065.56	35616.2	5.62	0.18
Rel. Sum vs. Difference	1.1 - 4.0	0 - 0.3	388.29	3451.57	6.49	0.16
Rel. Sum vs. Difference	1.1 - 4.0	0.3 - 0.6	424.23	7109.11	4.98	0.2
Rel. Sum vs. Difference	1.1 - 4.0	0.6 - 4	298.8	4926.47	4.22	0.24

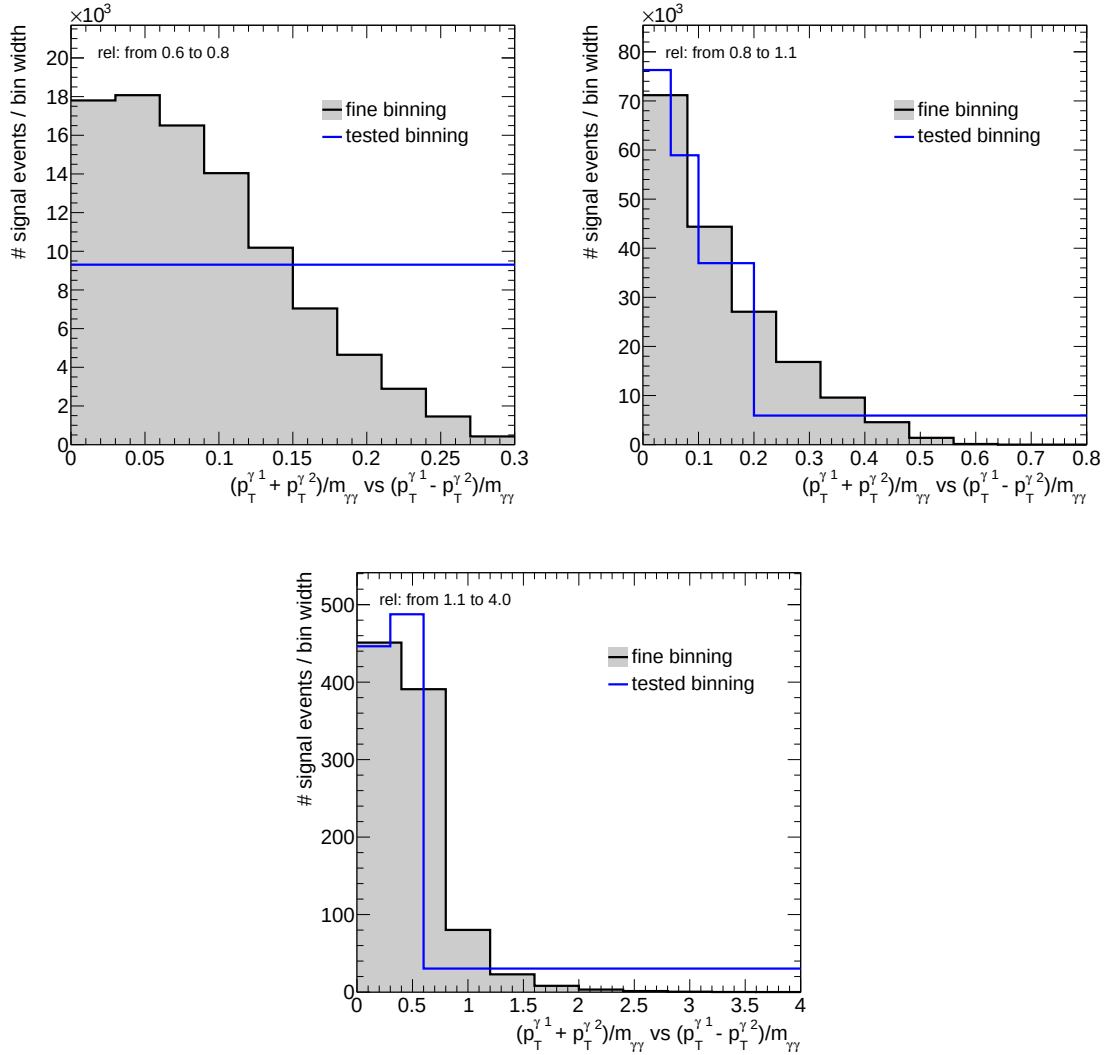
Figure A.27: 2D binning for variable $(p_T^{\gamma_1} + p_T^{\gamma_2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma_1} - p_T^{\gamma_2})/m_{\gamma\gamma}$.

Table A.28: Binning choice for $p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$.

Variable	Bin X	Bin Y	Signal	Data	Sig.	Stat.	Error
$p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$	0.0 - 30.0	0 - 100	1061.46	30983.8	6		0.17
$p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$	0.0 - 30.0	100 - 350	143.21	2014.47	3.15		0.32
$p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$	30.0 - 60.0	0 - 45	349.92	12573.3	3.11		0.32
$p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$	30.0 - 60.0	45 - 120	478.49	10743.5	4.58		0.22
$p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$	30.0 - 60.0	120 - 350	137.61	1281.19	3.78		0.27
$p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$	60.0 - 350.0	0 - 80	213.81	9073.53	2.24		0.45
$p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$	60.0 - 350.0	80 - 250	338.16	4484.09	4.99		0.21
$p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$	60.0 - 350.0	250 - 450	49.6	188.6	3.47		0.31

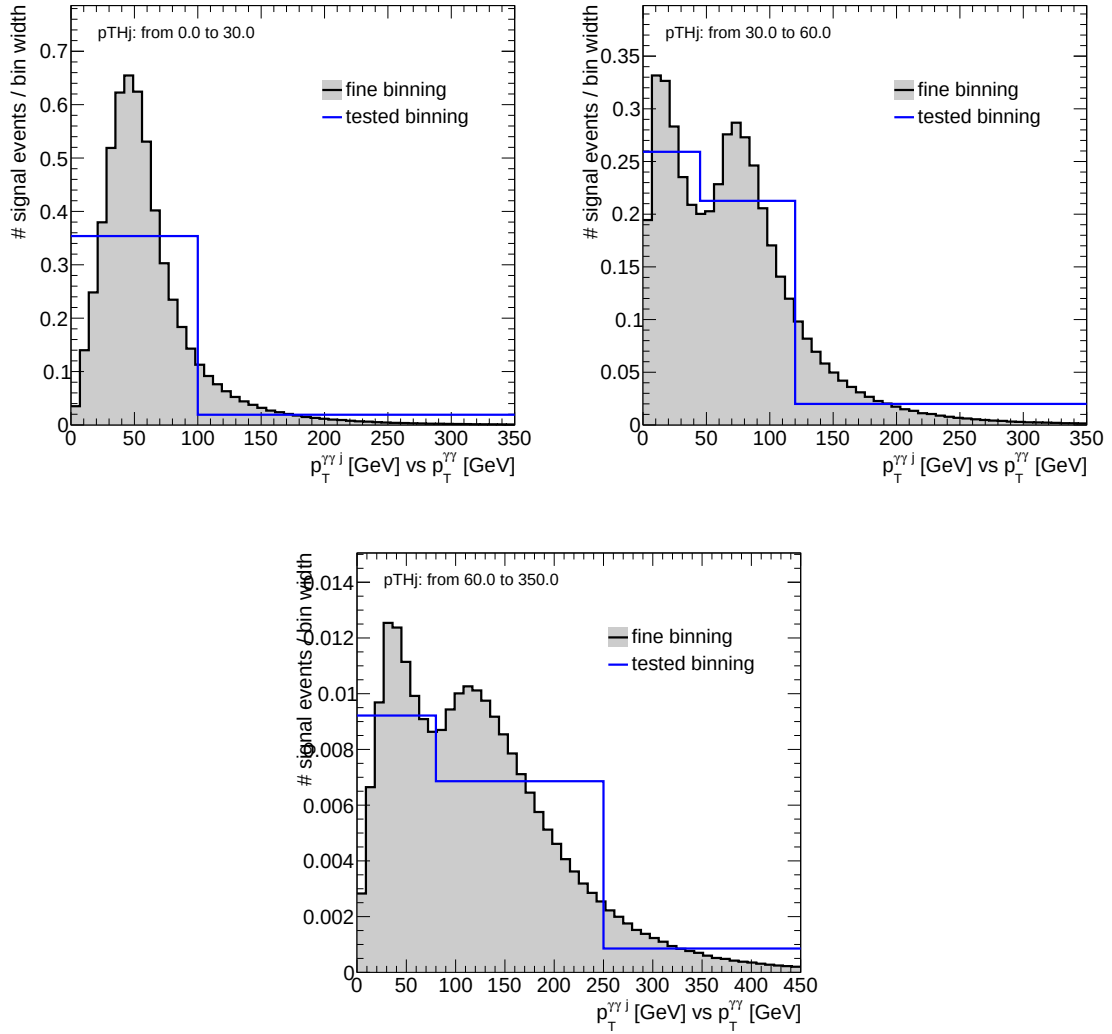
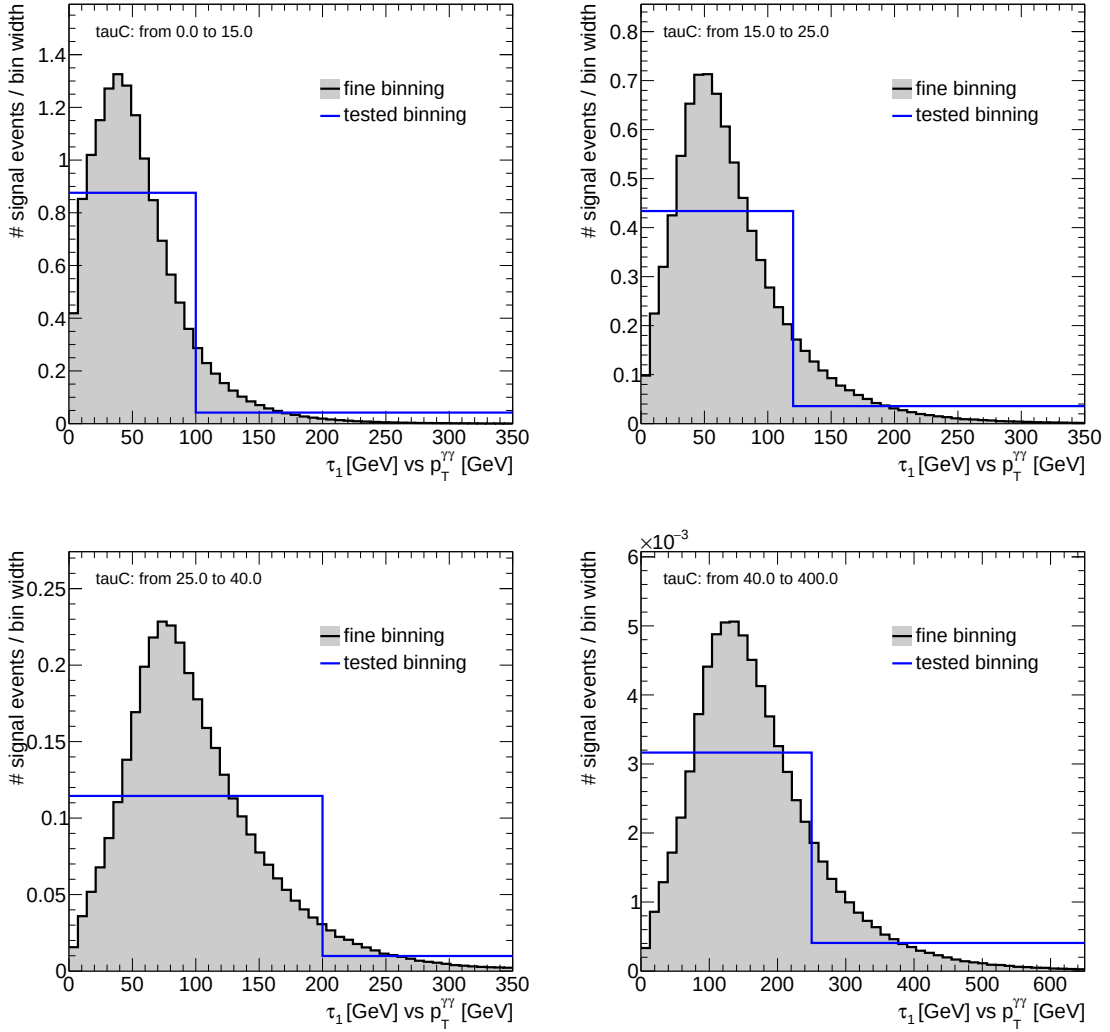
Figure A.28: 2D binning for variable $p_T^{\gamma j}$ vs $p_T^{\gamma\gamma}$.

Table A.29: Binning choice for $\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$.

Variable	Bin X	Bin Y	Signal	Data	Sig.	Stat. Error
$\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$	0.0 - 15.0	0 - 100	1313.9	33132.8	7.17	0.14
$\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$	0.0 - 15.0	100 - 350	157.21	1246.13	4.36	0.24
$\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$	15.0 - 25.0	0 - 120	520.61	17993.7	3.86	0.26
$\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$	15.0 - 25.0	120 - 350	82.19	654.64	3.15	0.33
$\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$	25.0 - 40.0	0 - 200	343.45	10848.7	3.28	0.31
$\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$	25.0 - 40.0	200 - 350	22.14	96.17	2.18	0.49
$\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$	40.0 - 400.0	0 - 250	284.83	7256.85	3.32	0.3
$\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$	40.0 - 400.0	250 - 650	58.62	261.11	3.5	0.31

Figure A.29: 2D binning for variable $\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$.

A.2 Signal Parameters

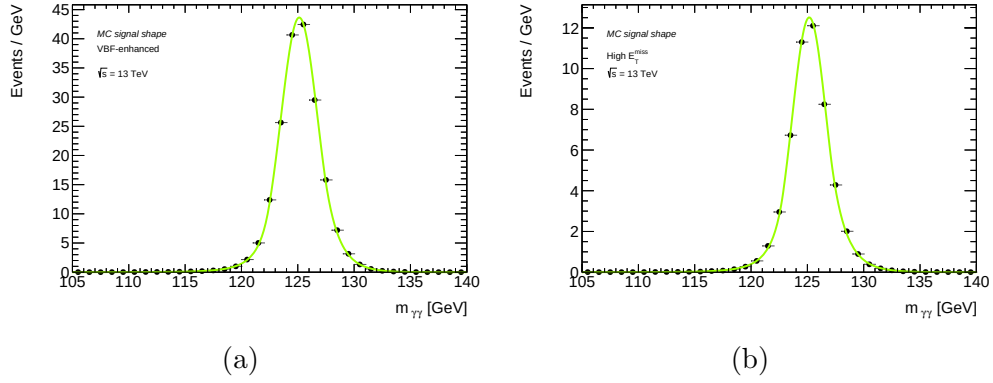


Figure A.30: Signal parameterization for the (a) VBF-enhanced and (b) High- E_T^{miss} fiducial volume.

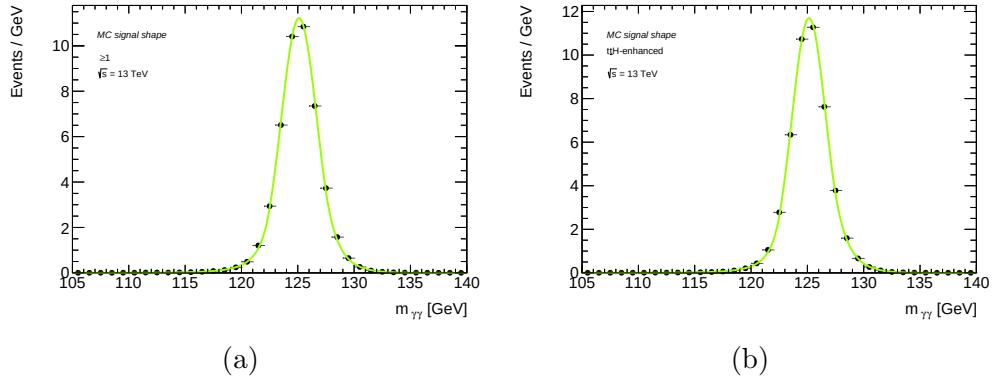


Figure A.31: Signal parameterization for the (a) lepton-enhanced and (b) $t\bar{t}H$ -enhanced fiducial volume.

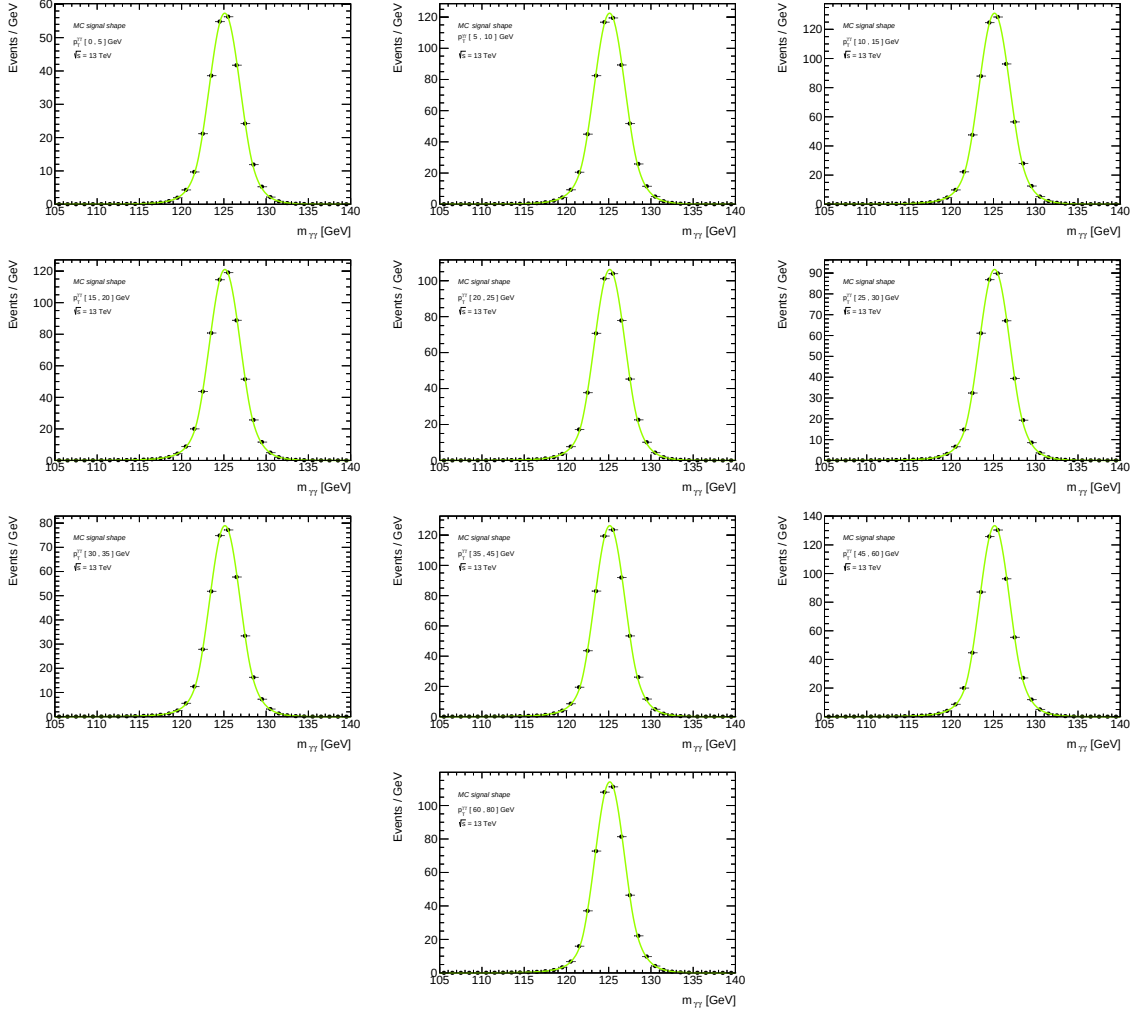


Figure A.32: Signal parameterization in each of the $p_T^{\gamma\gamma}$ bins. (Continued on next page.)

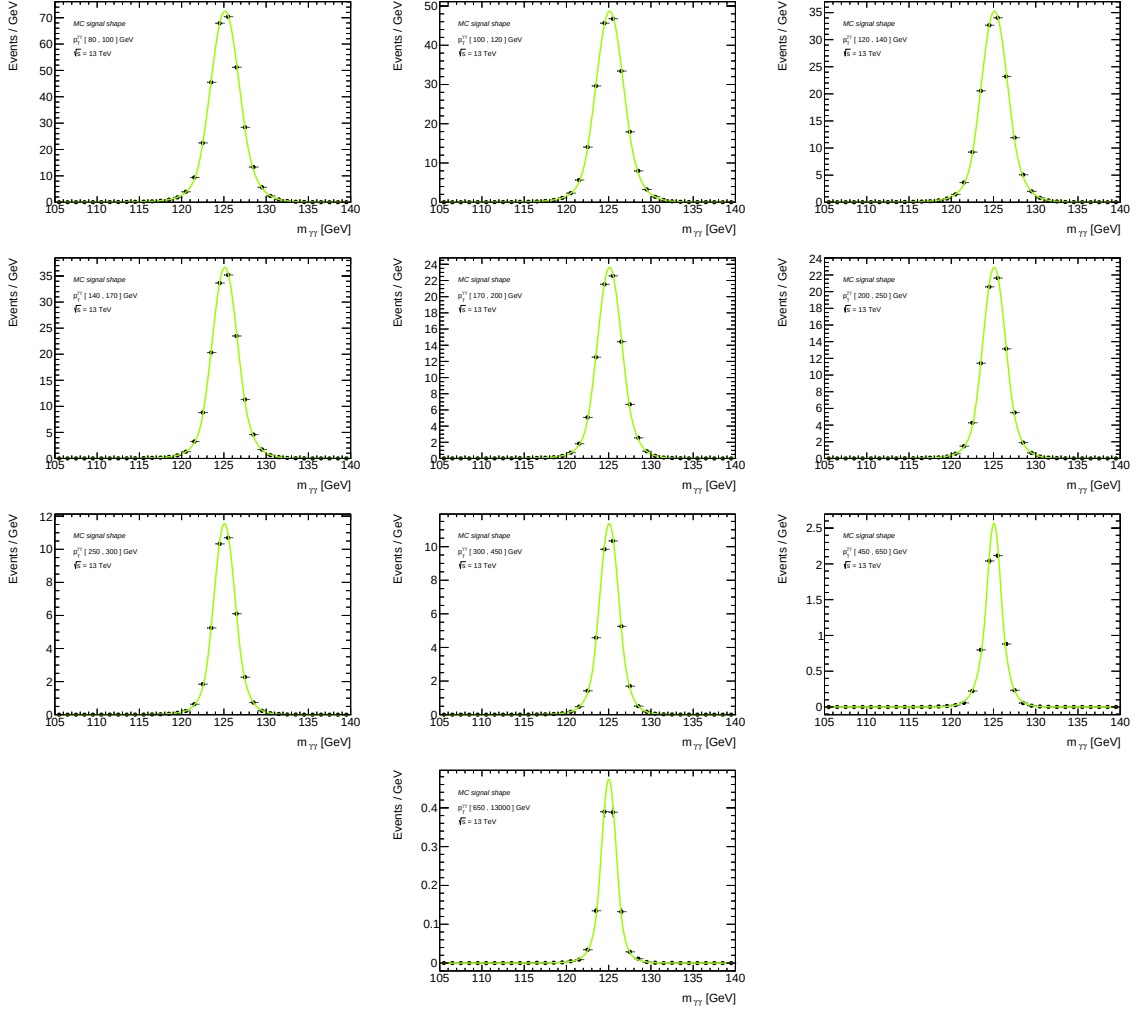


Figure A.33: Continuation of the signal parameterization in each of the $p_T^{\gamma\gamma}$ bins.

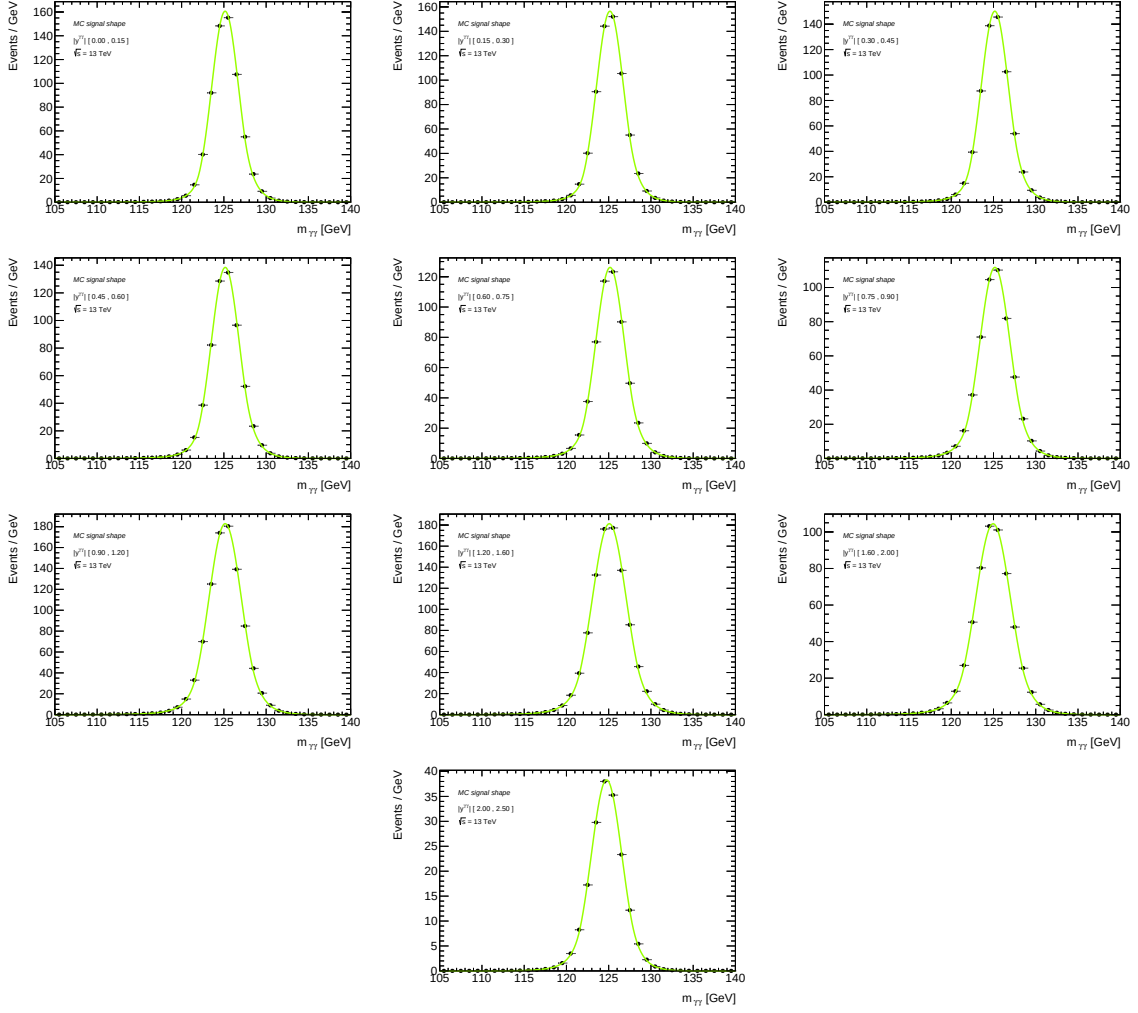


Figure A.34: Signal parameterization in each of the $|y^\gamma|$ bins.

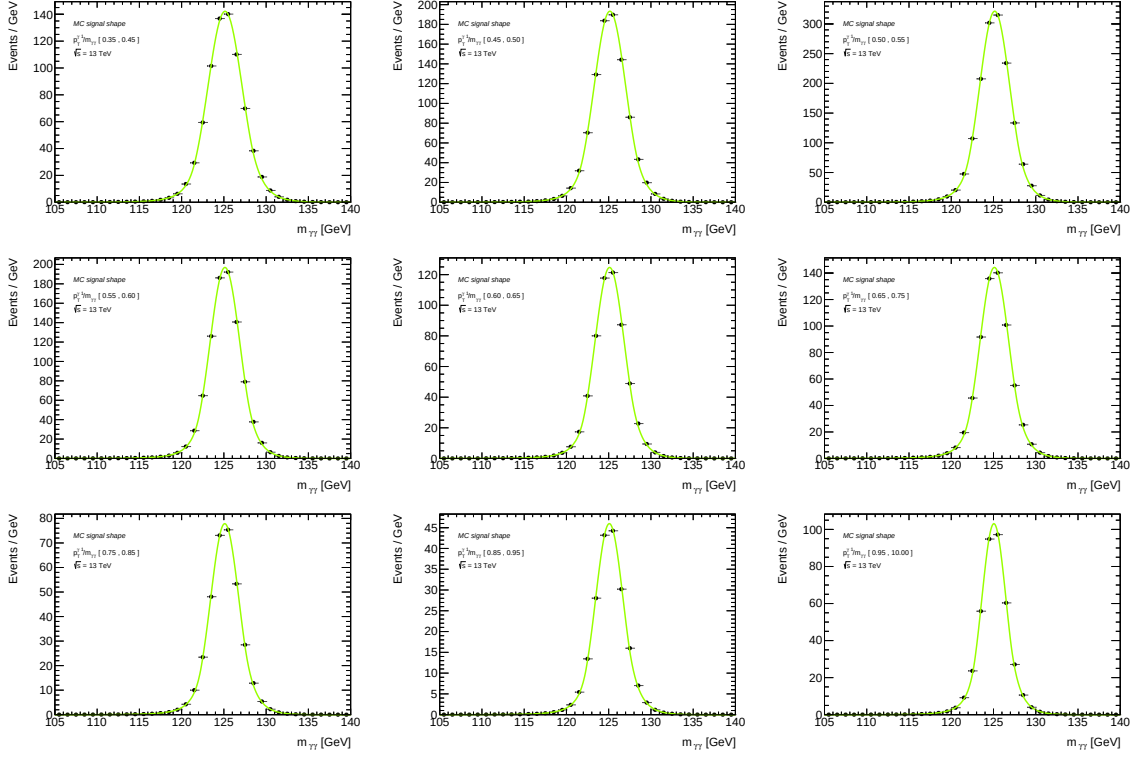


Figure A.35: Signal parameterization in each of the $p_T^{\gamma_1}/m_{\gamma\gamma}$ bins.

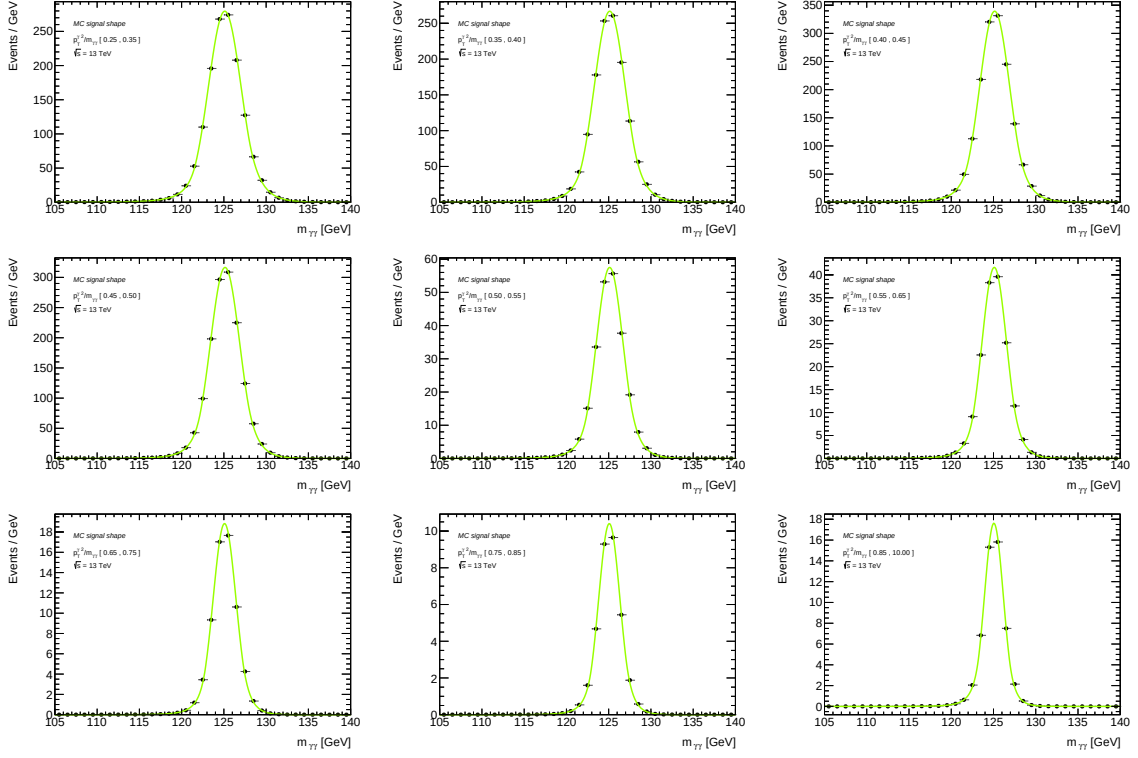


Figure A.36: Signal parameterization in each of the $p_T^2/m_{\gamma\gamma}$ bins.

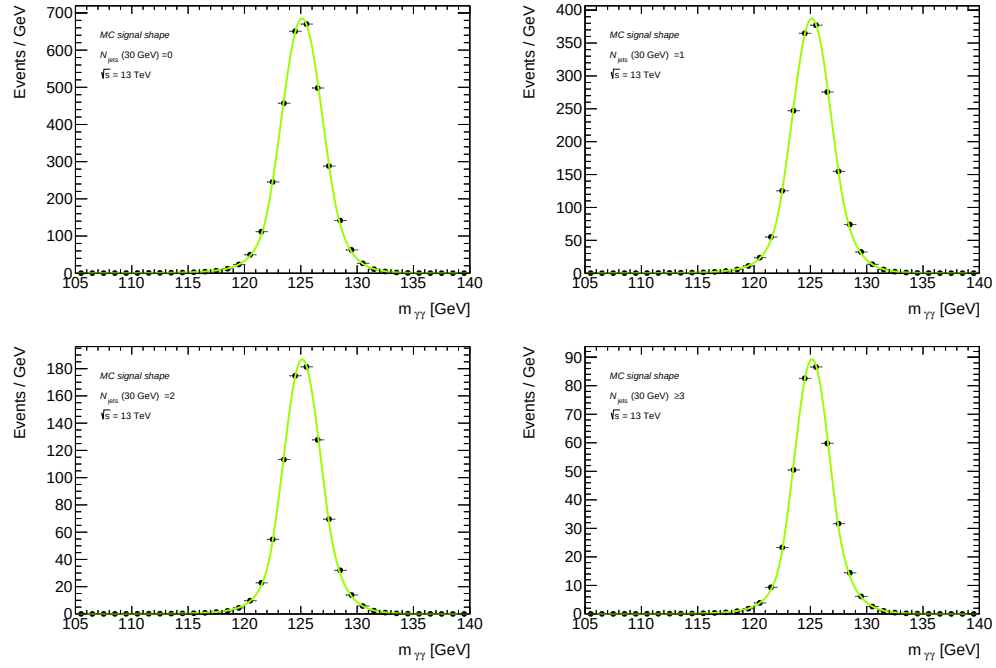


Figure A.37: Signal parameterization in each of the N_{jets} bins.

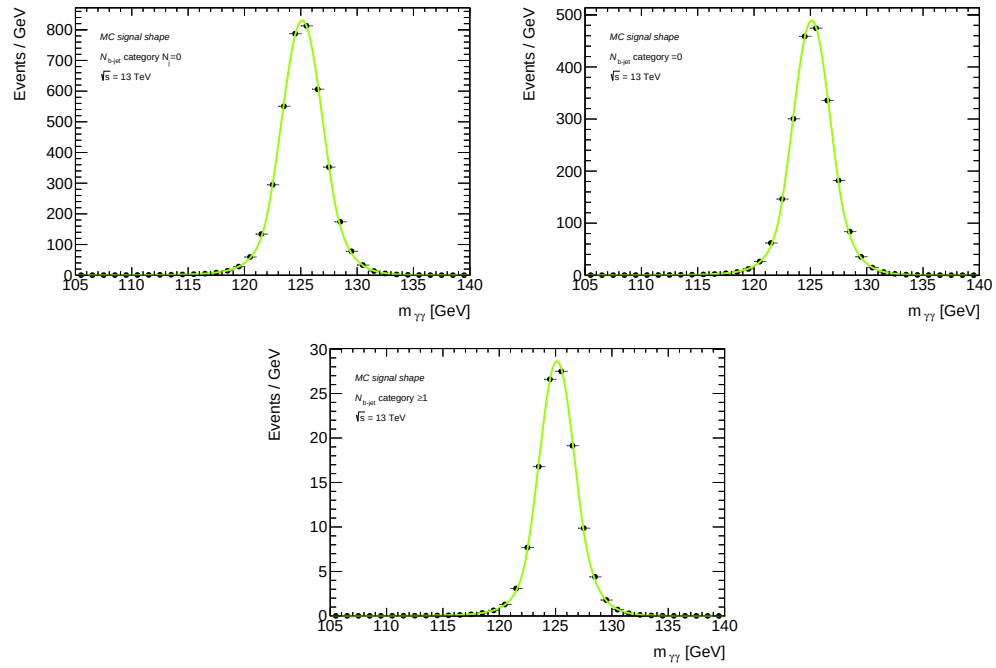


Figure A.38: Signal parameterization in each of the $N_{b\text{-jets}}$ bins.

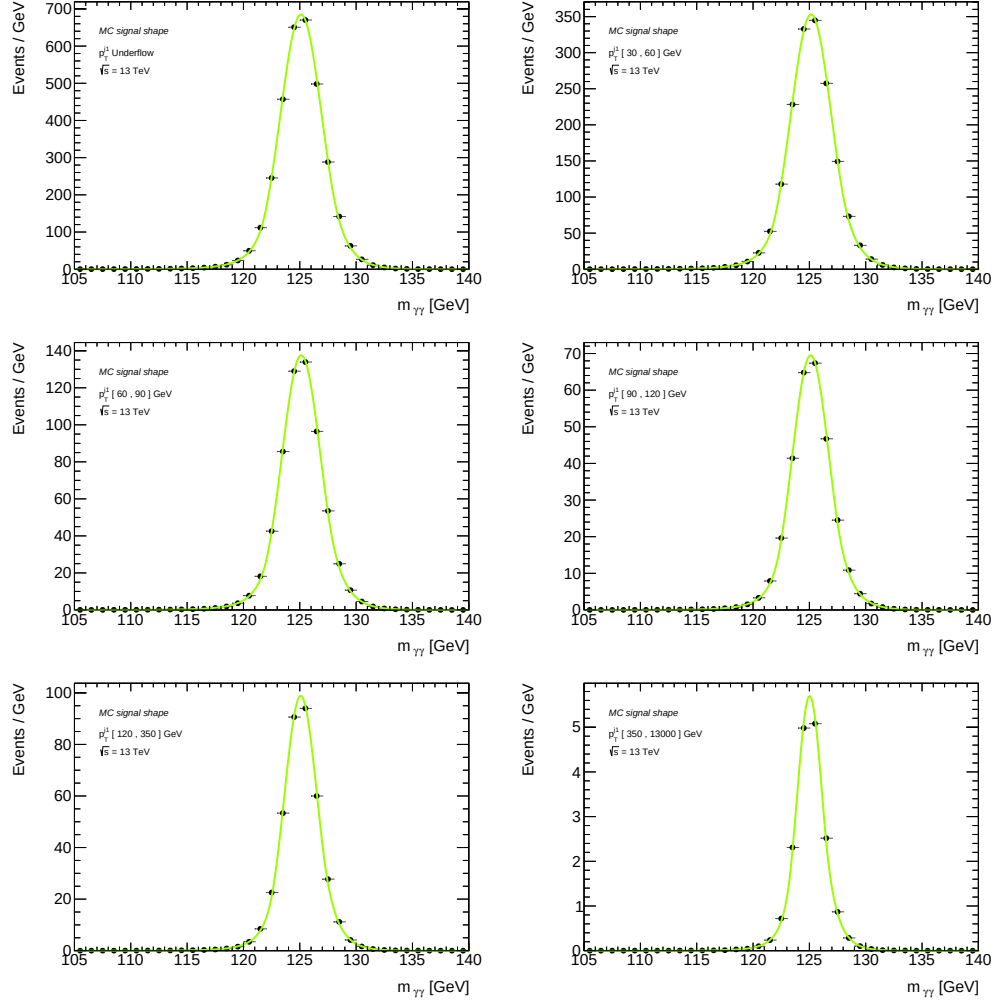


Figure A.39: Signal parameterization in each of the p_T^{j1} bins.

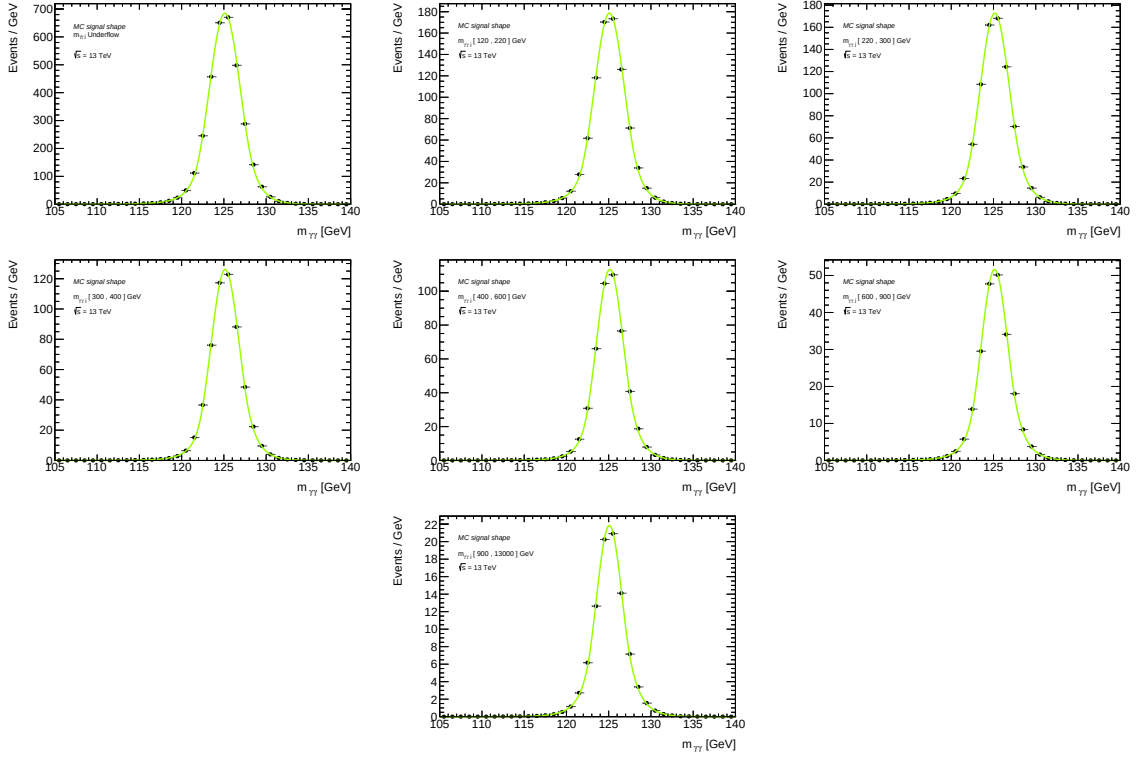


Figure A.40: Signal parameterization in each of the $m_{\gamma\gamma j}$ bins.

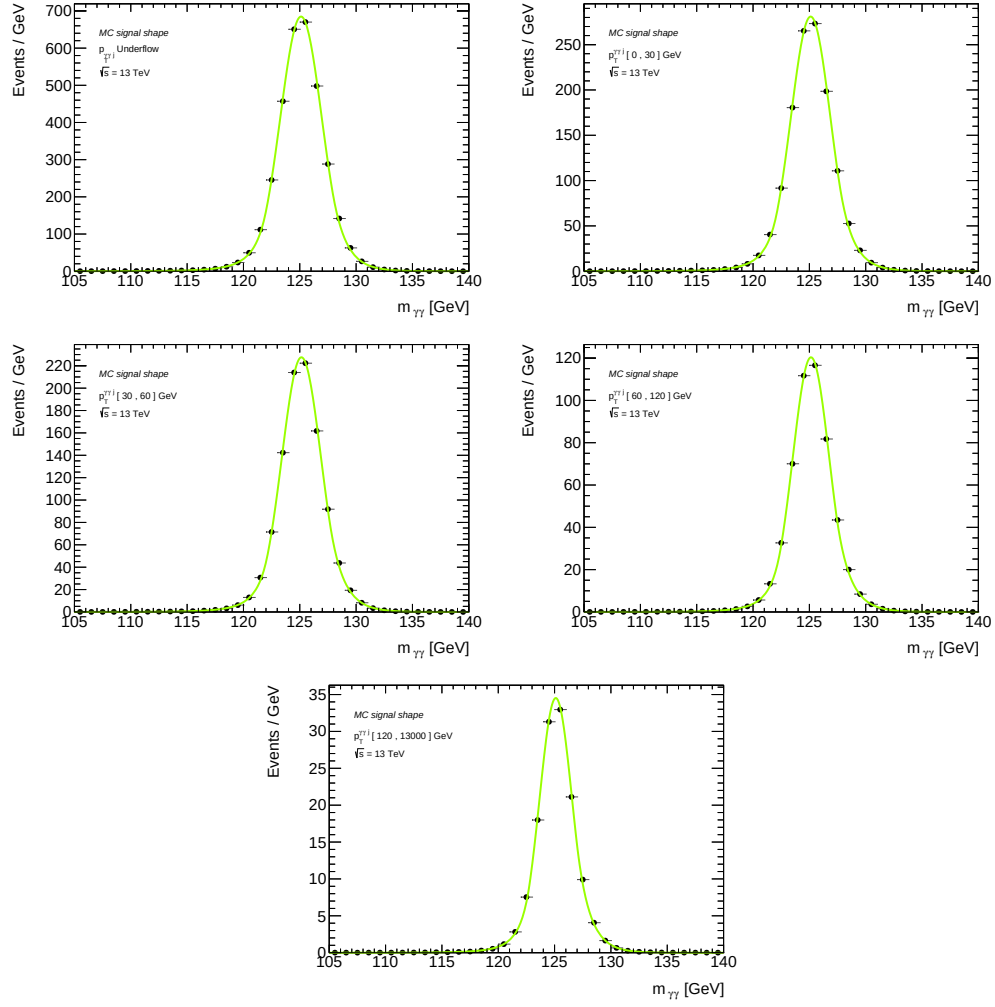


Figure A.41: Signal parameterization in each of the $p_T^{\gamma\gamma}$ bins.

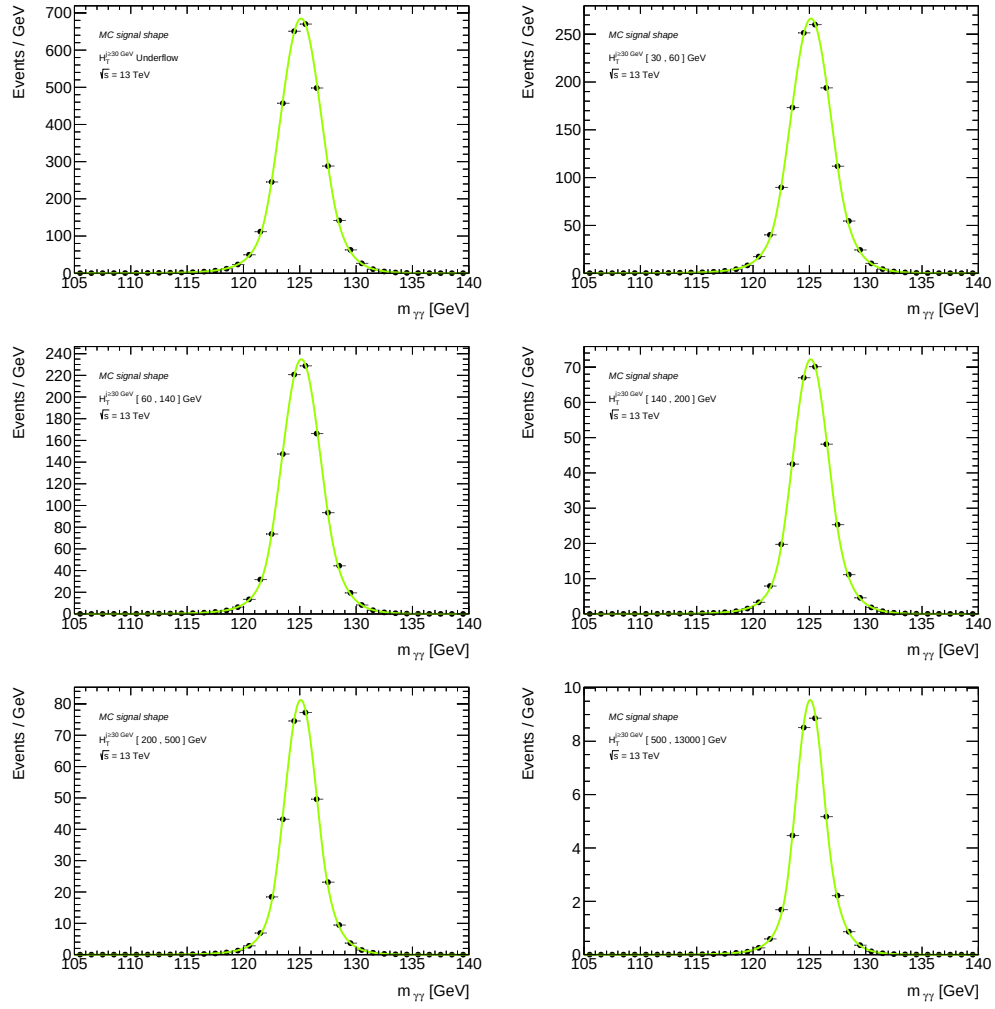


Figure A.42: Signal parameterization in each of the H_T bins.

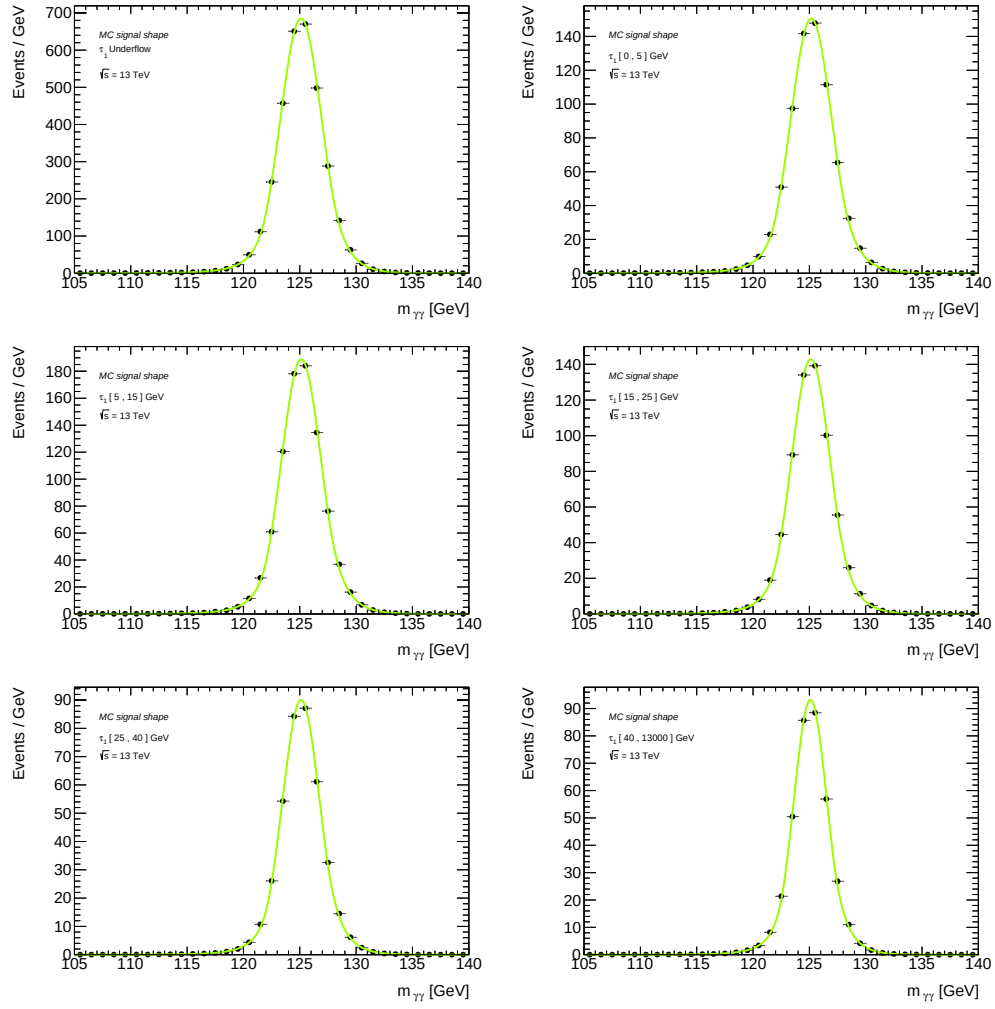


Figure A.43: Signal parameterization in each of the τ_{C,j_1} bins.

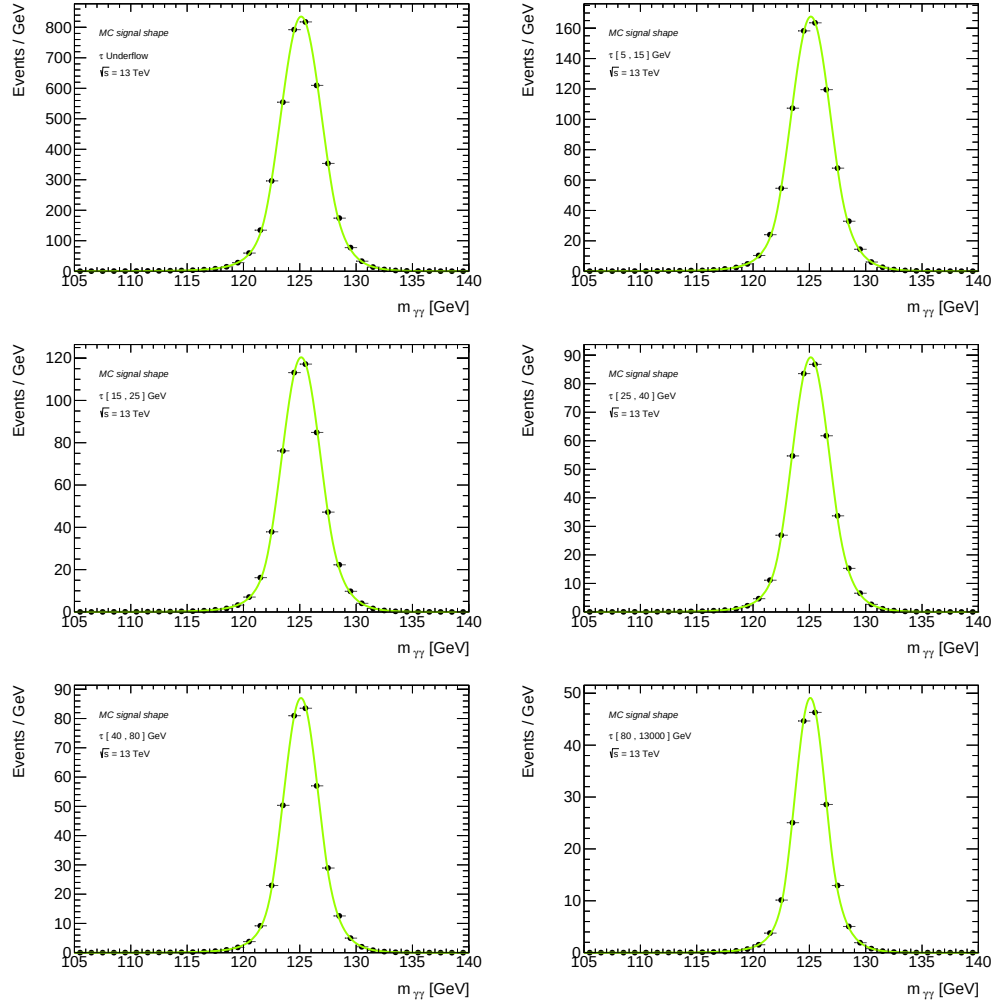


Figure A.44: Signal parameterization in each of the $\Sigma\tau_{C,j}$ bins.

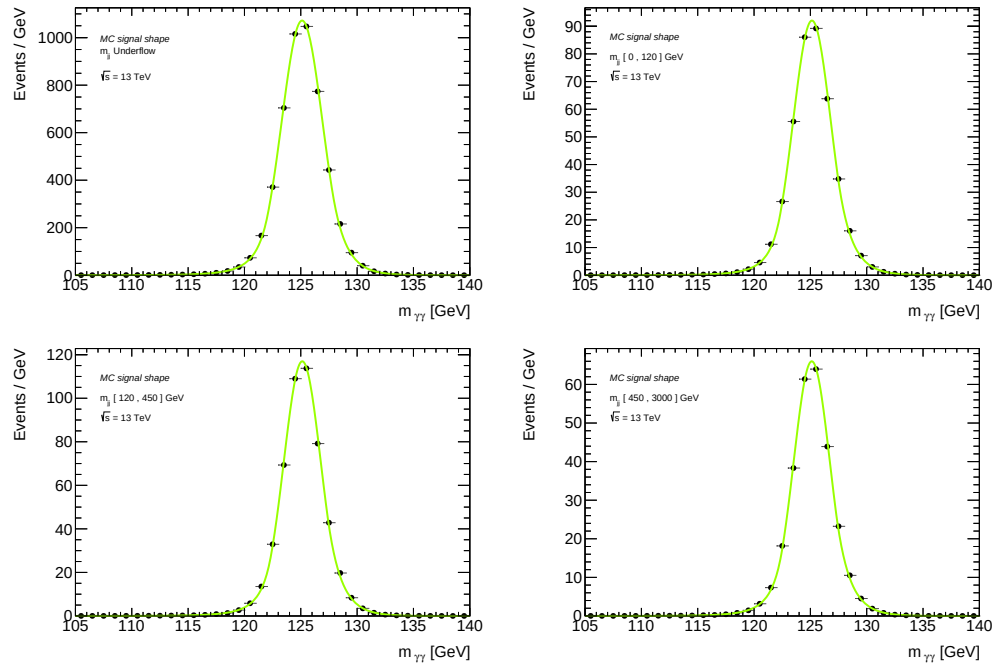


Figure A.45: Signal parameterization in each of the m_{jj} bins.

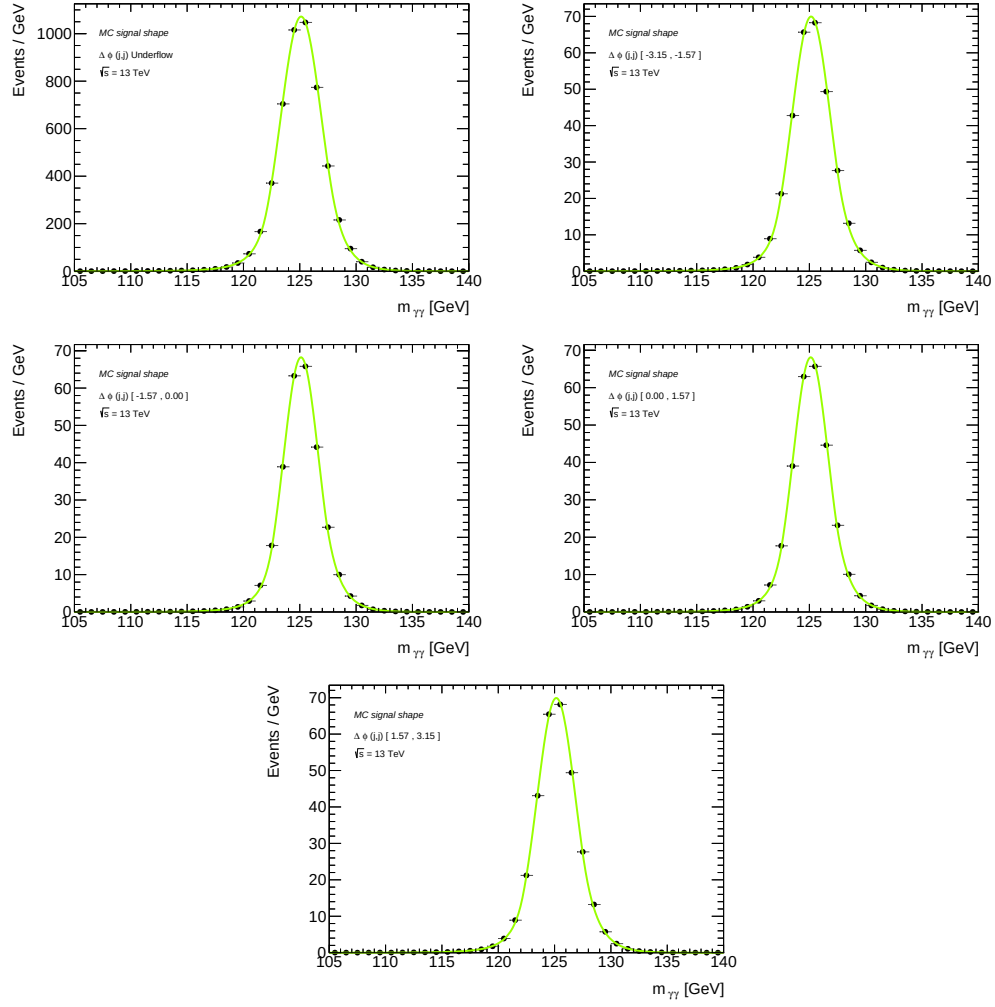


Figure A.46: Signal parameterization in each of the $\Delta\phi_{jj}$ bins.

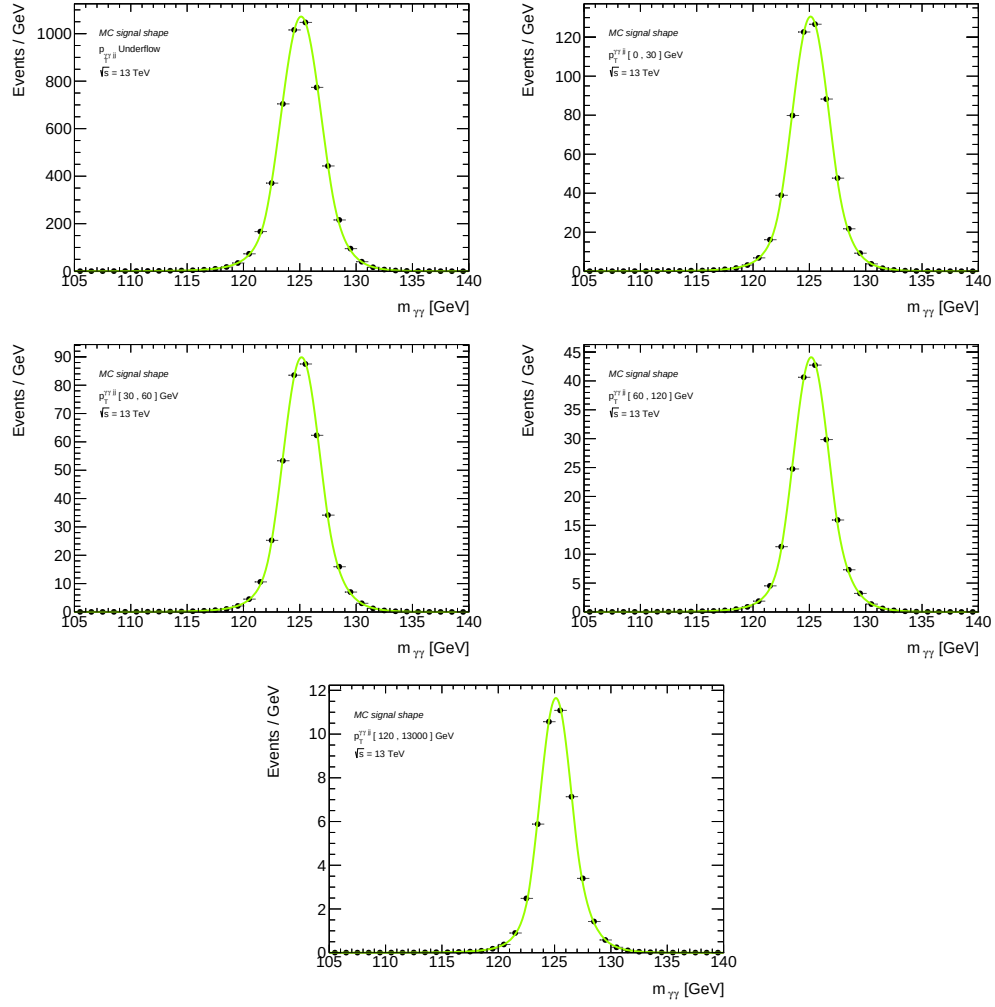


Figure A.47: Signal parameterization in each of the $p_T^{\gamma\gamma jj}$ bins.

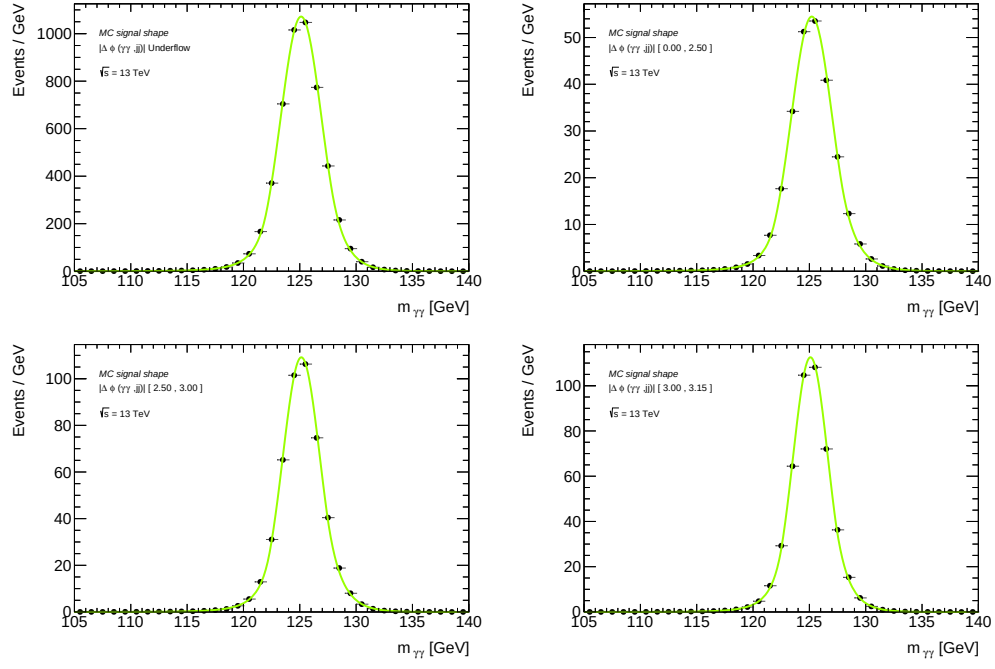


Figure A.48: Signal parameterization in each of the $|\Delta\phi_{\gamma\gamma,jj}|$ bins.

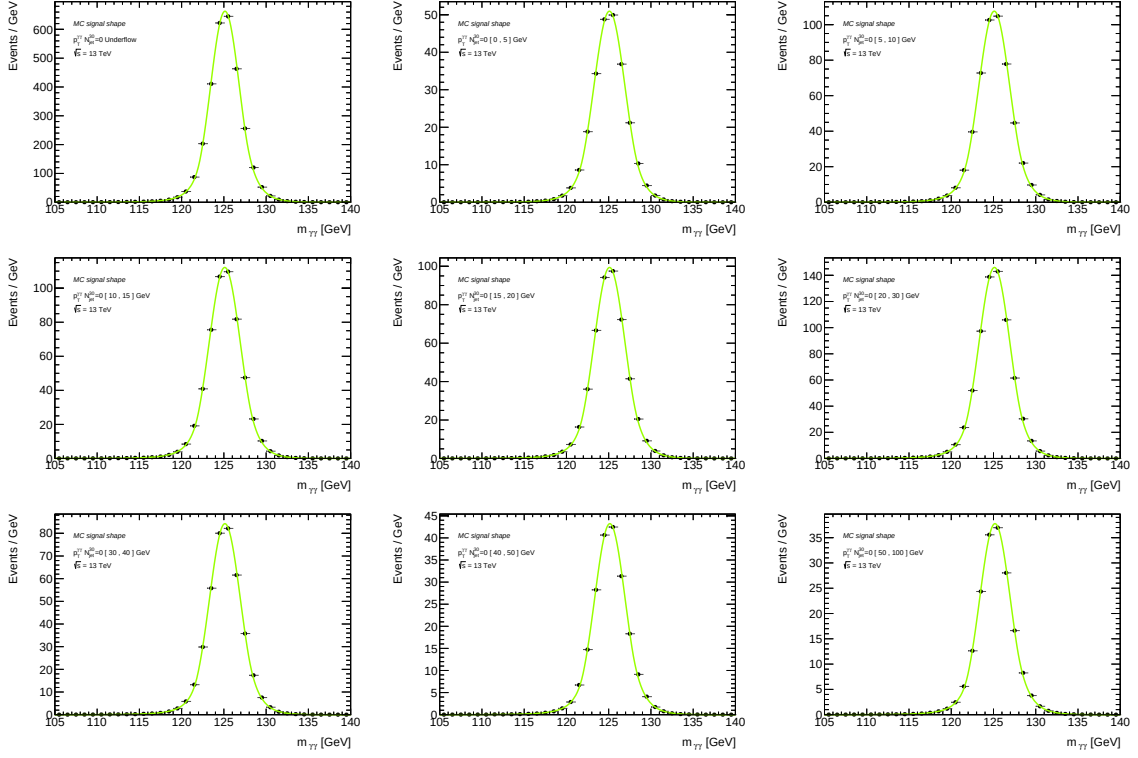


Figure A.49: Signal parameterization in each of the $p_T^{\gamma, \text{jet veto}}$ bins.

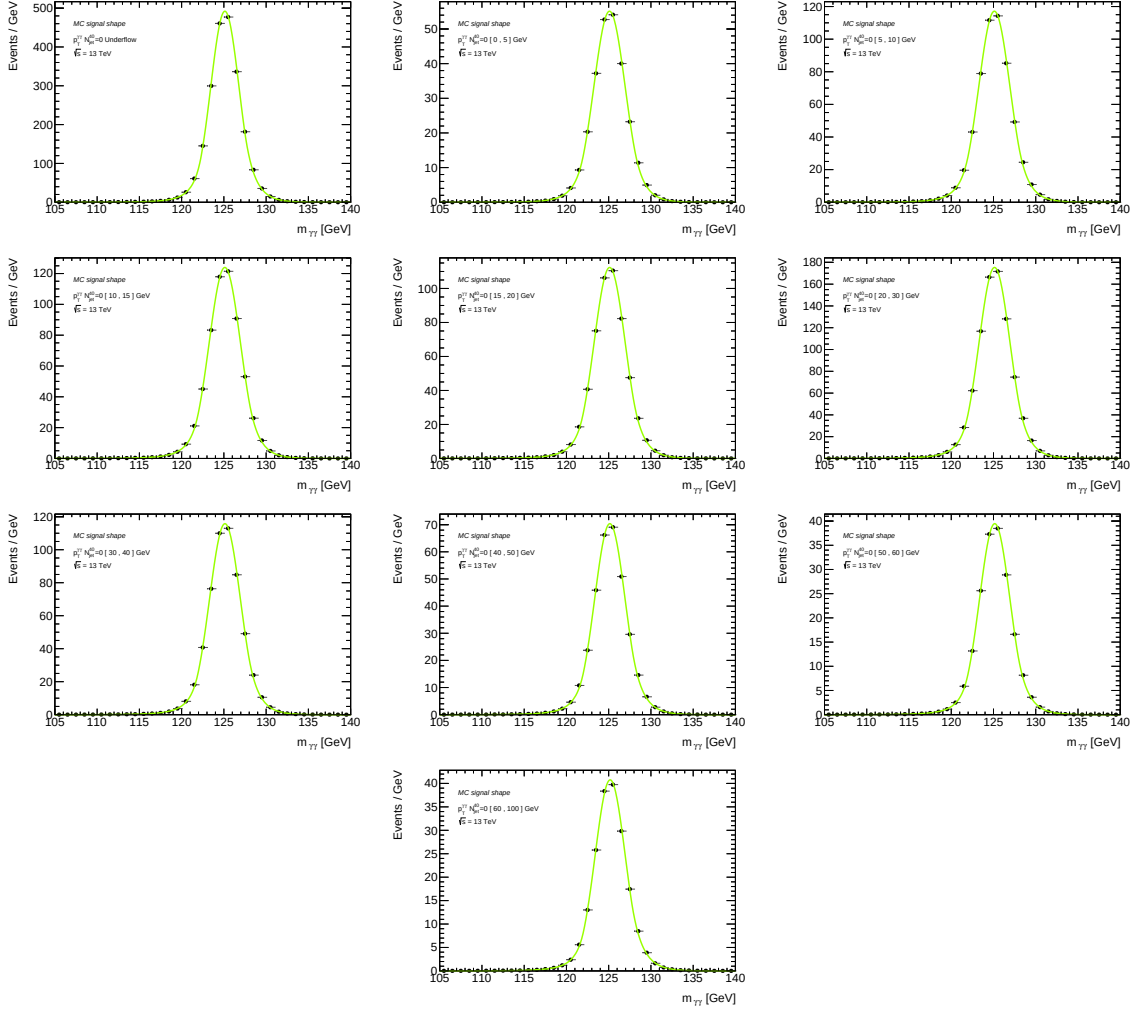


Figure A.50: Signal parameterization in each of the $p_T^{\gamma\gamma}$, jet veto 40 bins.

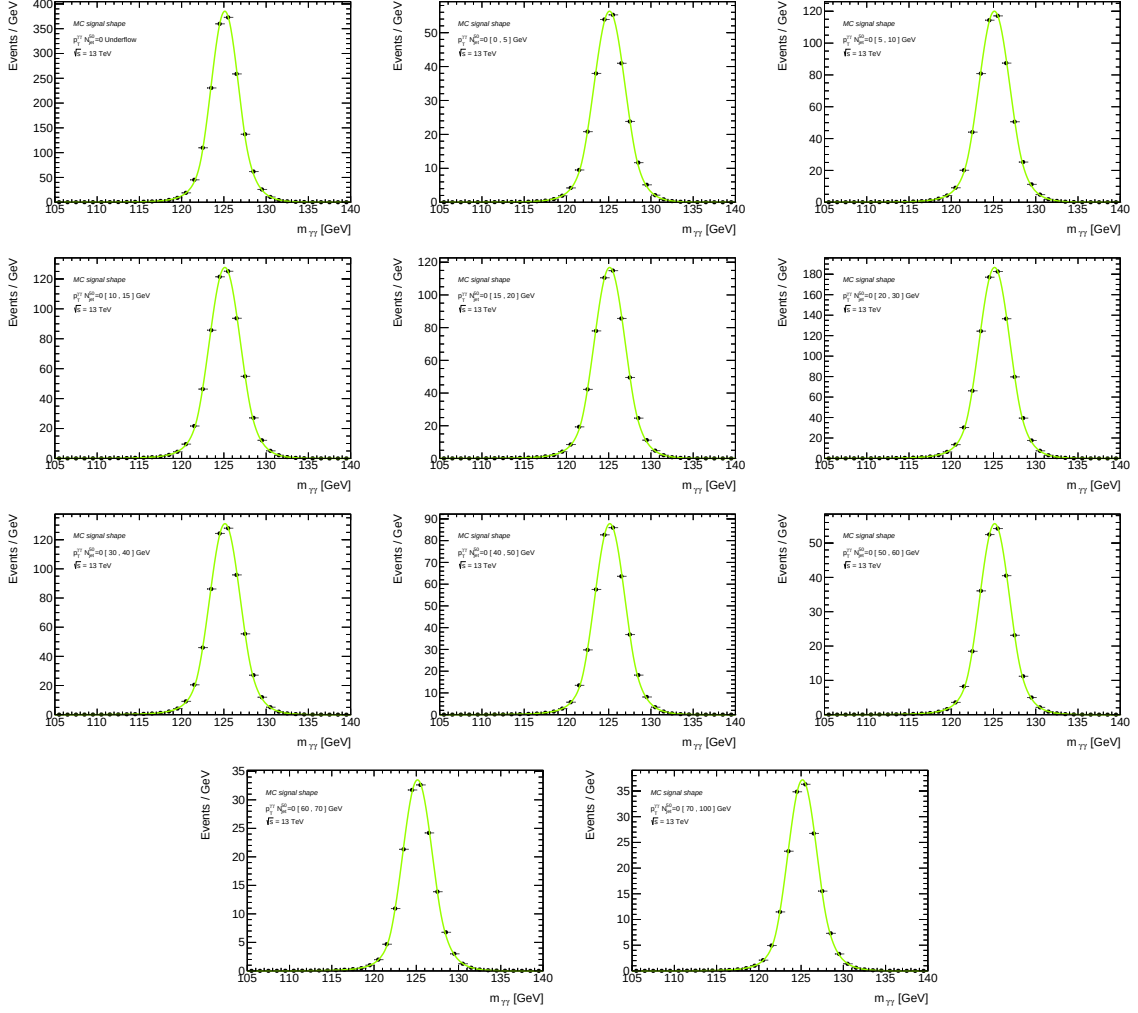


Figure A.51: Signal parameterization in each of the $p_T^{\gamma, \text{jet veto}}$ 50 bins.

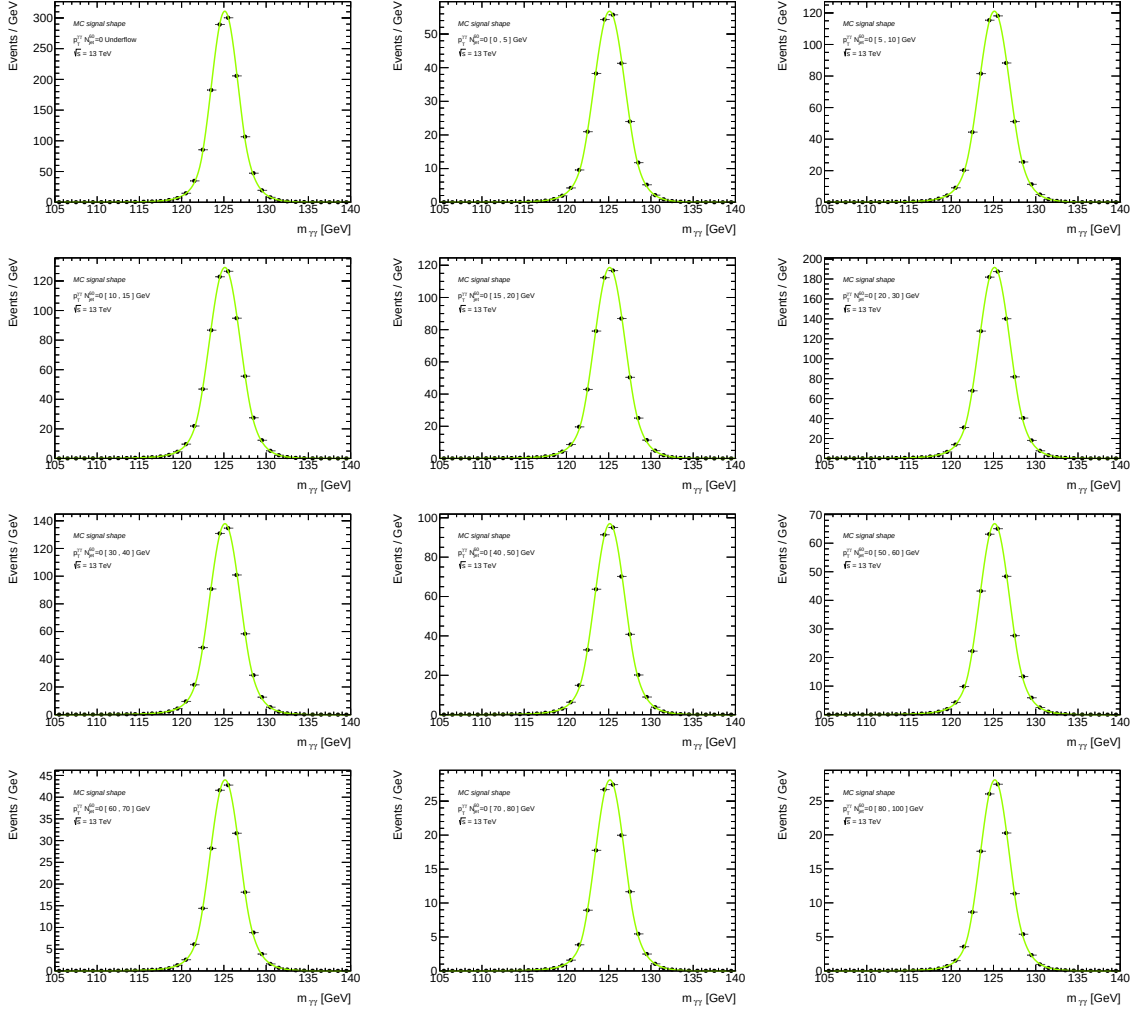


Figure A.52: Signal parameterization in each of the $p_T^{\gamma, \text{jet veto}}$ 60 bins.

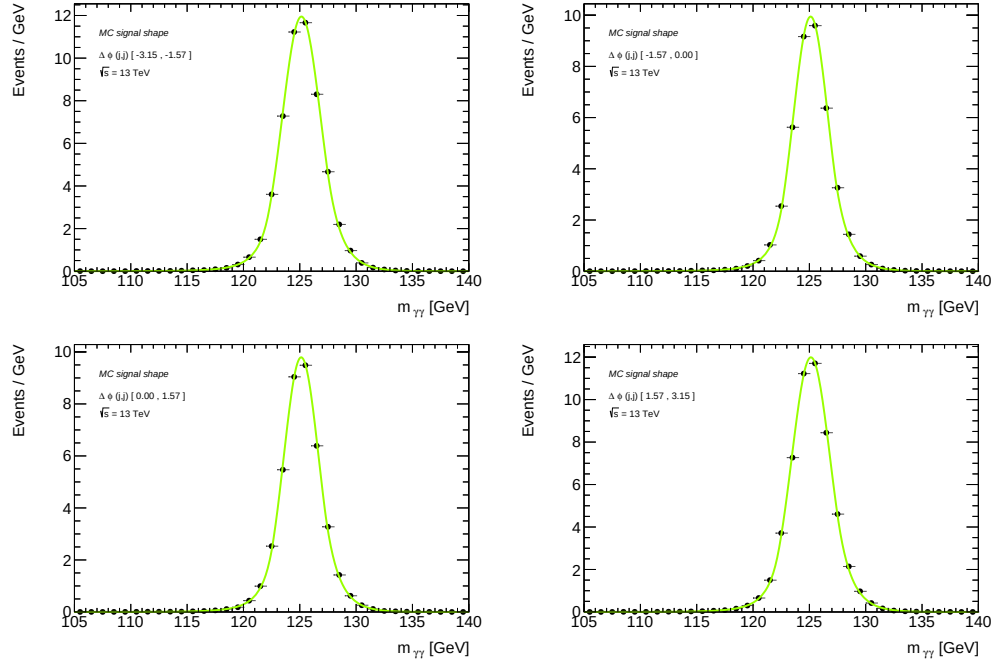


Figure A.53: Signal parameterization in each of the $\Delta\phi_{jj}$ bins in the VBF-enhanced fiducial volume.

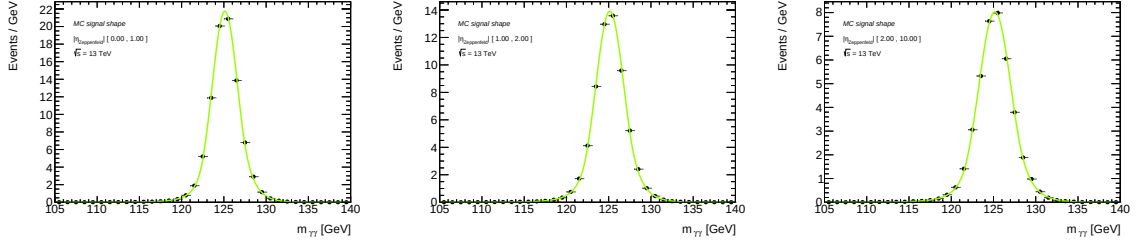


Figure A.54: Signal parameterization in each of the $|\eta^*|$ bins in the VBF-enhanced fiducial volume.

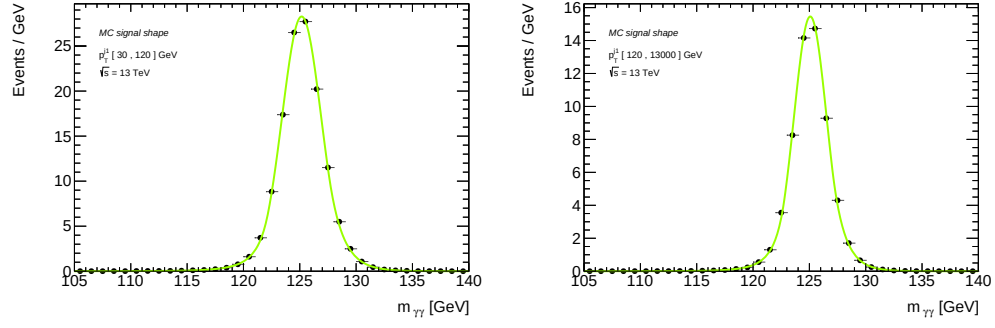


Figure A.55: Signal parameterization in each of the p_T^{j1} bins in the VBF-enhanced fiducial volume.

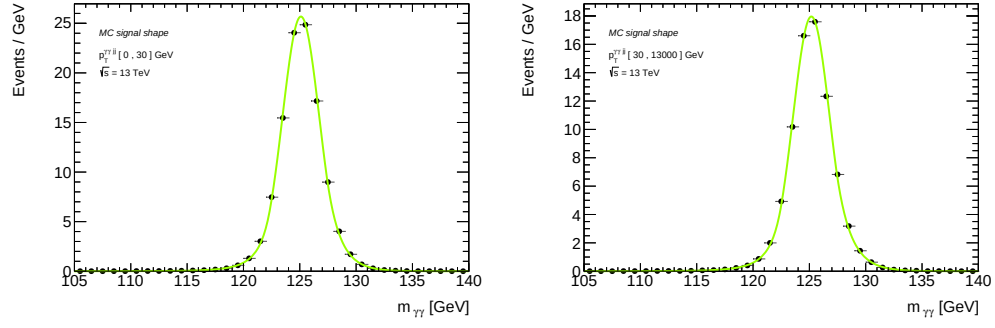


Figure A.56: Signal parameterization in each of the $p_T^{\gamma\gamma jj}$ bins in the VBF-enhanced fiducial volume.

A.2.1 Double-differential variables

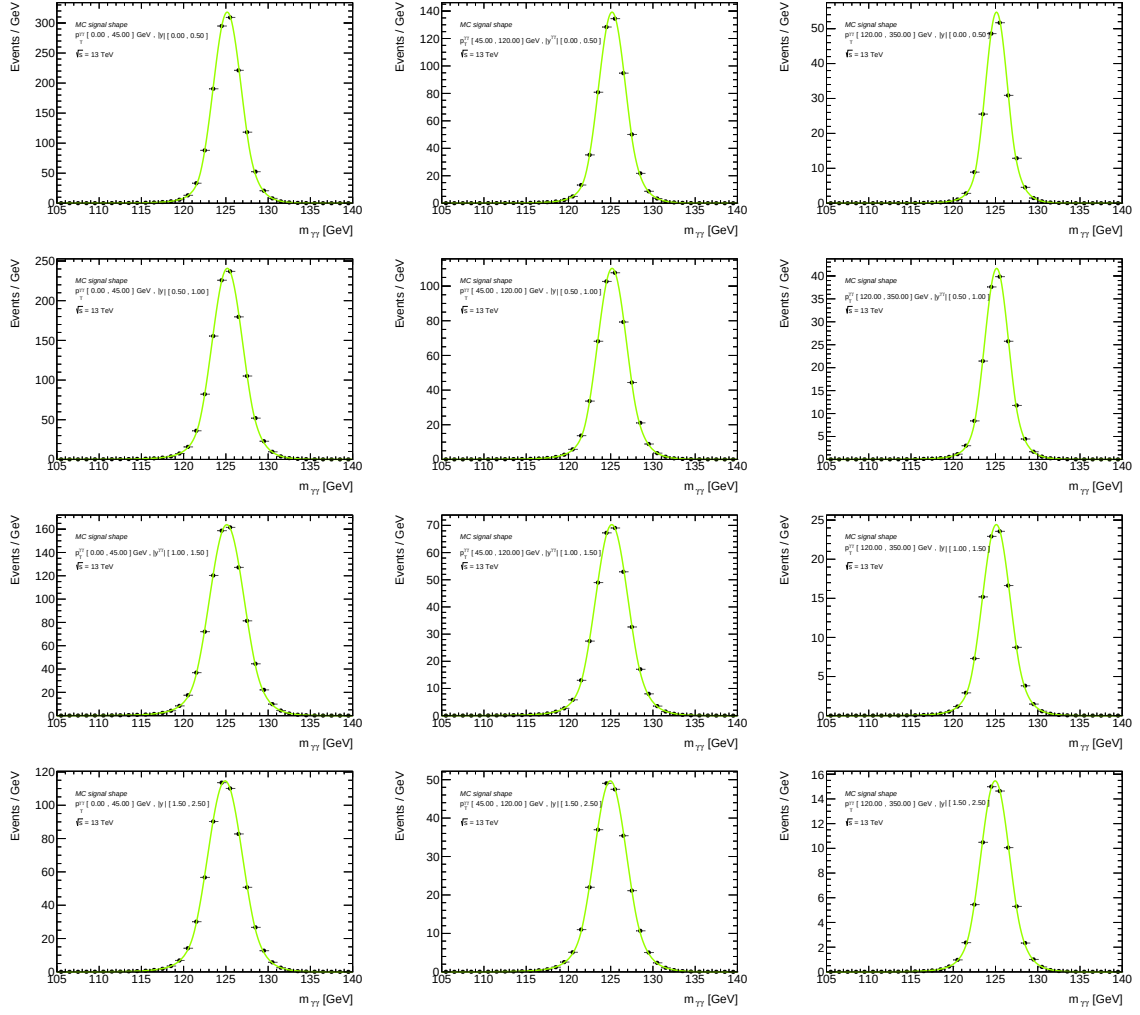


Figure A.57: Signal parameterization in each of the $p_T^{\gamma\gamma}$ vs $|y_{\gamma\gamma}|$ bins.

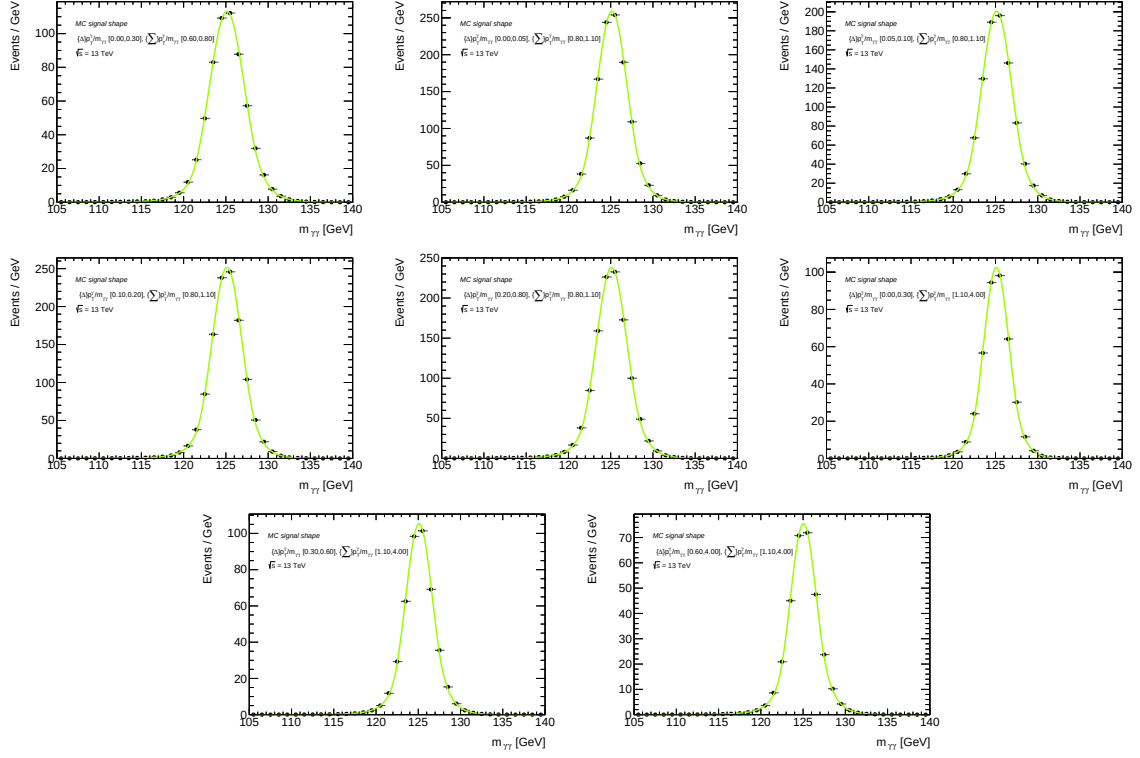


Figure A.58: Signal parameterization in each of the $(p_T^{\gamma_1} + p_T^{\gamma_2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma_1} - p_T^{\gamma_2})/m_{\gamma\gamma}$ bins.

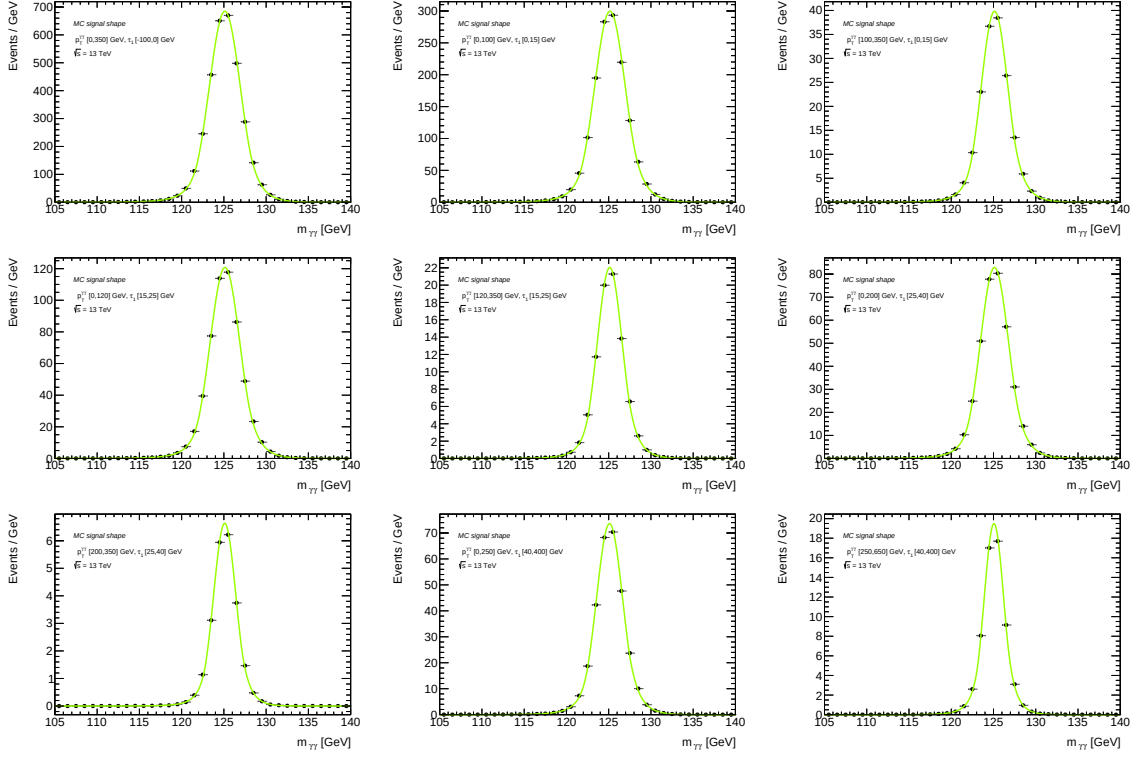


Figure A.59: Signal parameterization in each of the $\tau_{C,j1}$ vs $p_T^{\gamma\gamma}$ bins.

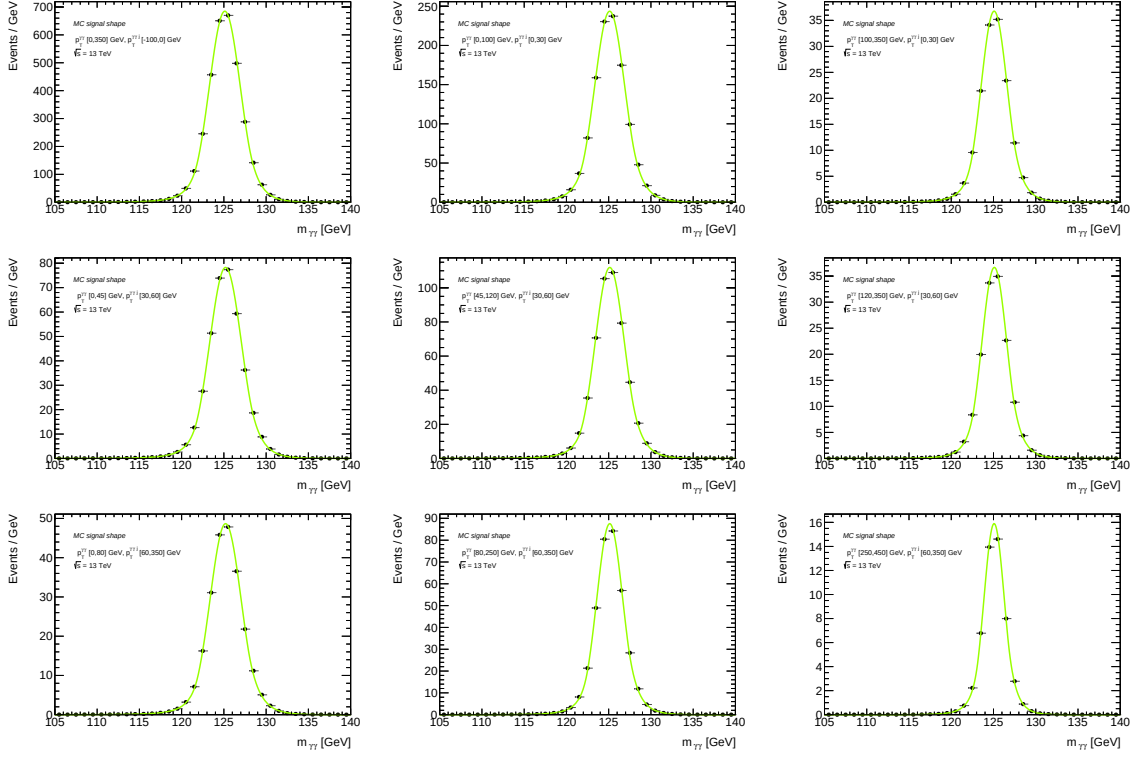


Figure A.60: Signal parameterization in each of the $p_T^{\gamma\gamma}$ vs $p_T^{\gamma\gamma}$ bins.

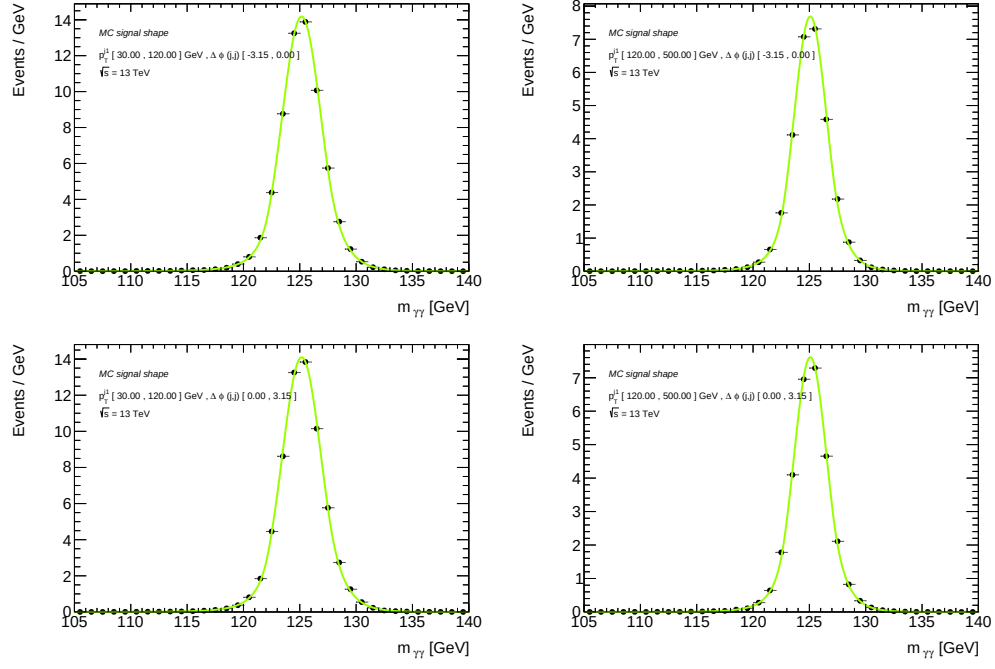


Figure A.61: Signal parameterization in each of the p_T^{j1} vs $\Delta\phi_{jj}$ bins in the VBF-enhanced fiducial volume.

A.3 Background Templates

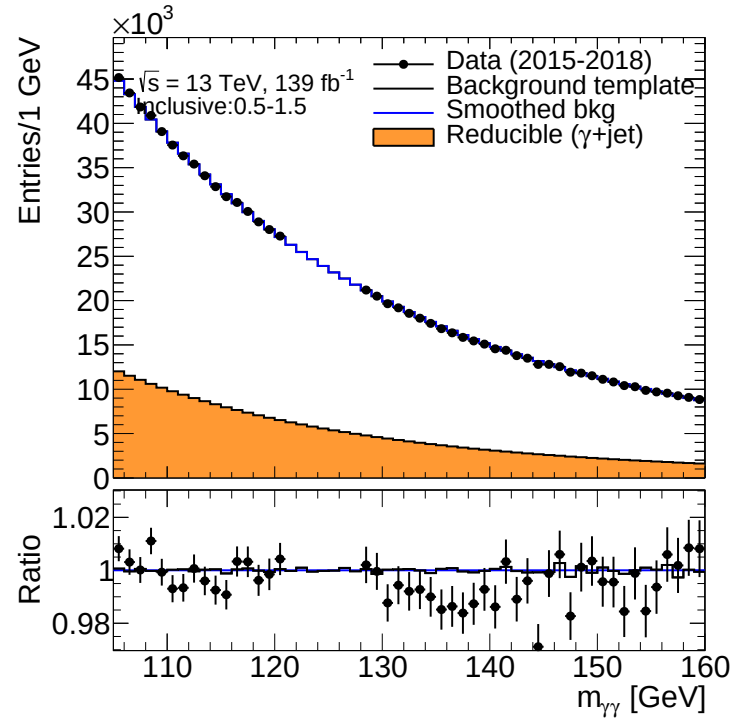


Figure A.62: The background template for the inclusive fiducial region.

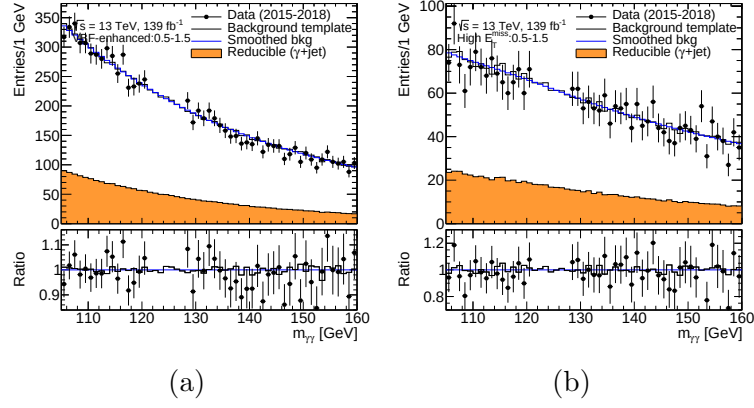


Figure A.63: Background template for the (a) VBF-enhanced and (b) High- E_T^{miss} fiducial volume.

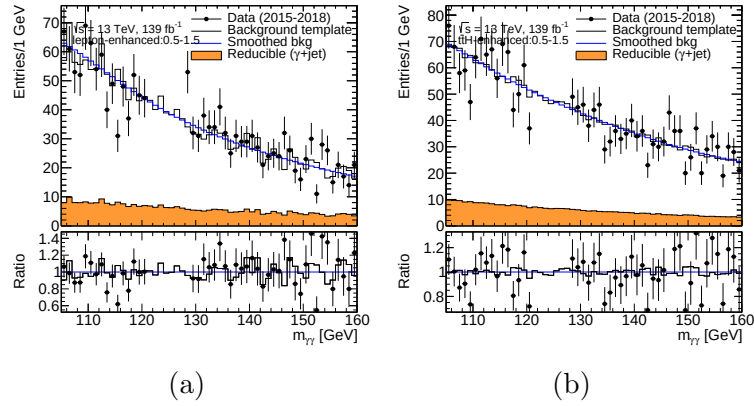


Figure A.64: Background template for the (a) lepton-enhanced and (b) $t\bar{t}H$ -enhanced fiducial volume.

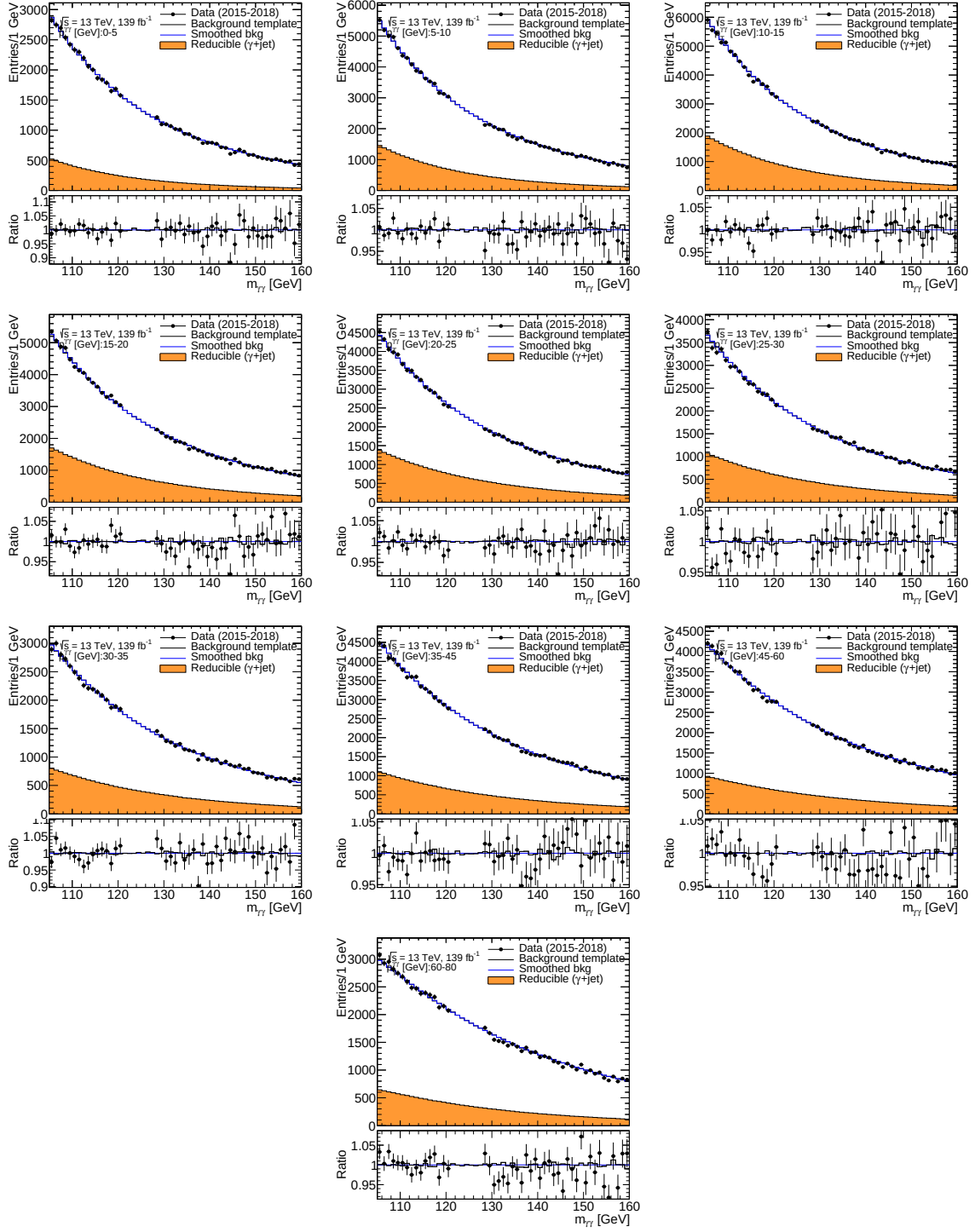


Figure A.65: Background template in each of the $p_T^{\gamma\gamma}$ bins.

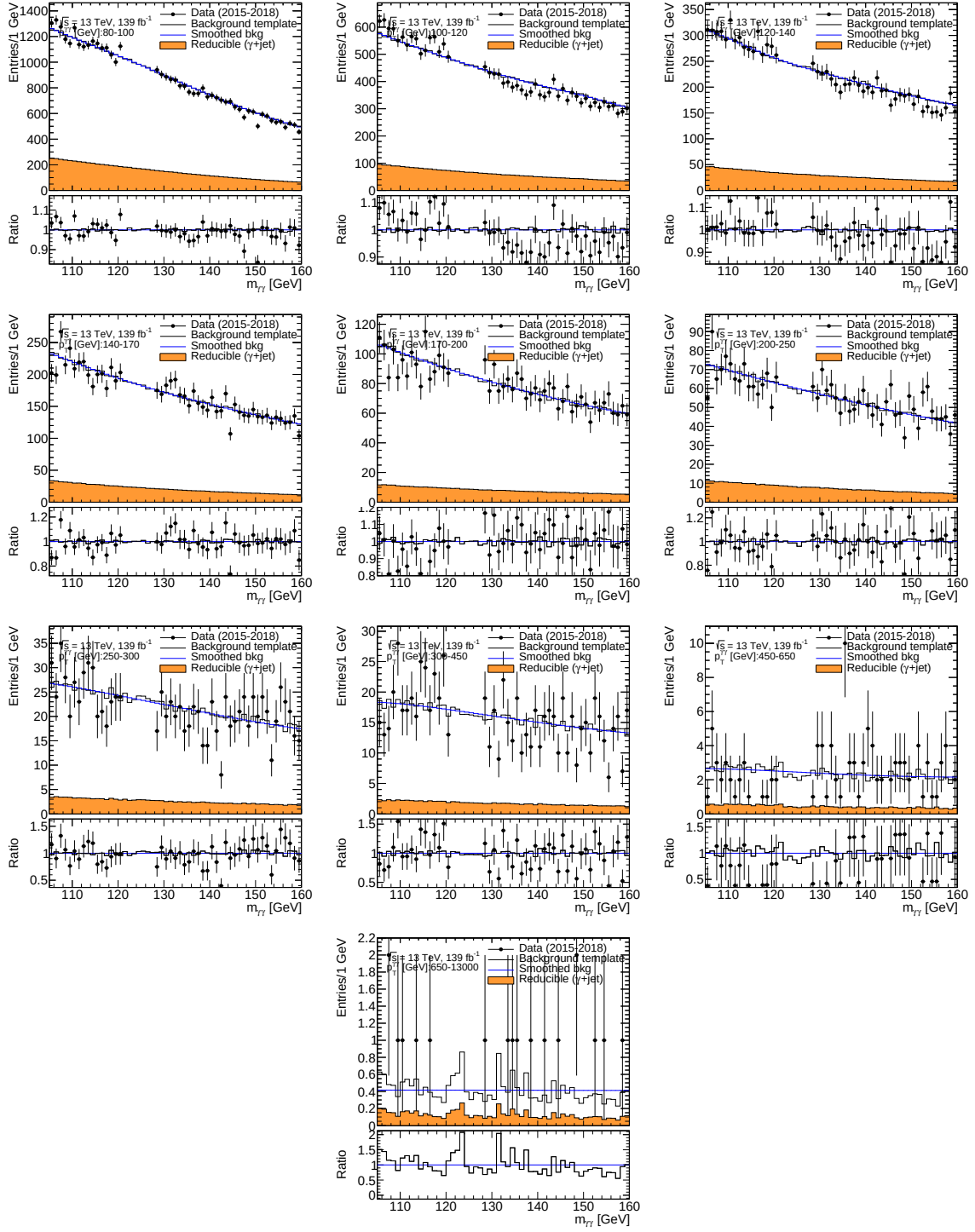
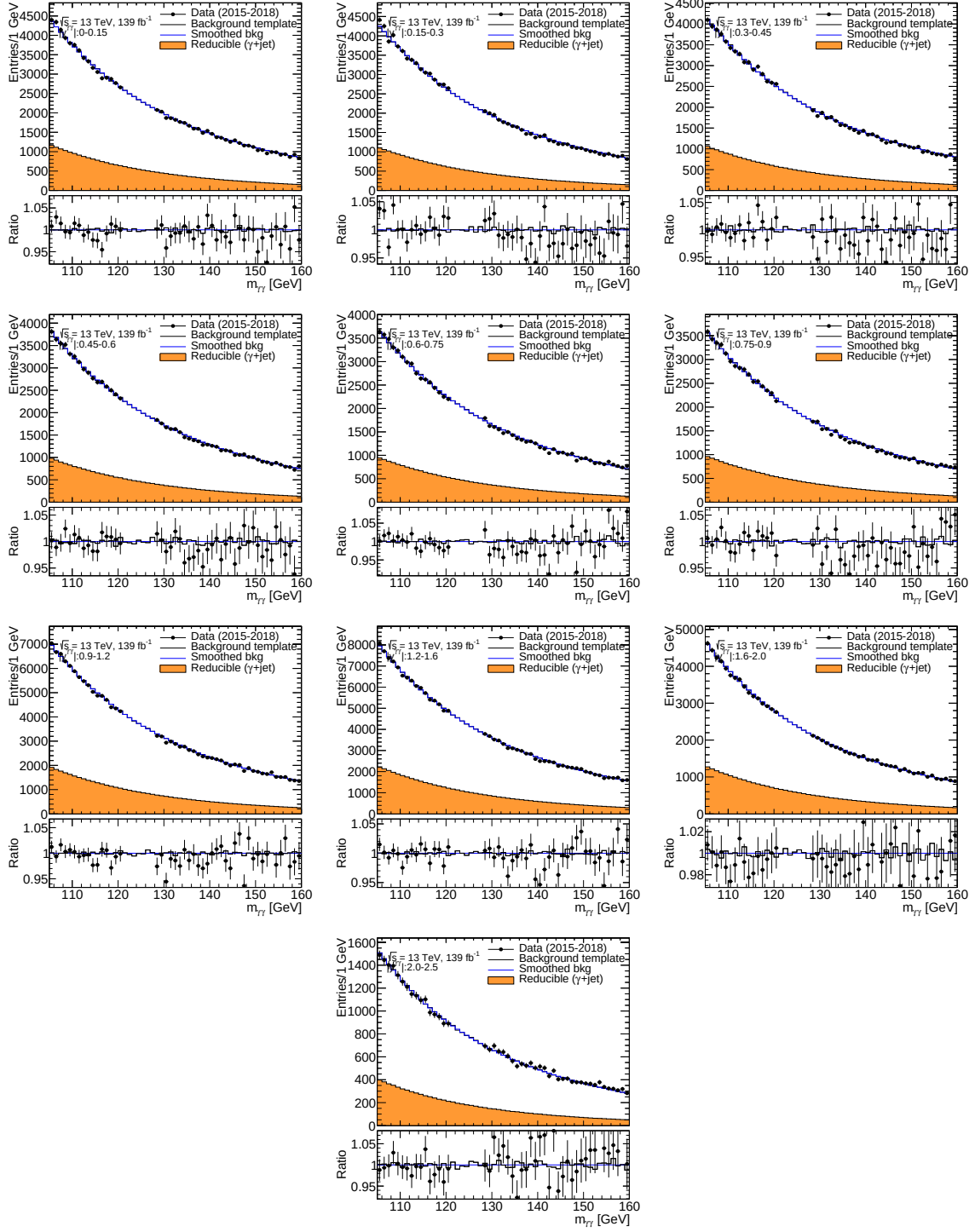


Figure A.66: Background template in each of the $p_T^{\gamma\gamma}$ bins.

Figure A.67: Background template in each of the $|\gamma\gamma|$ bins.

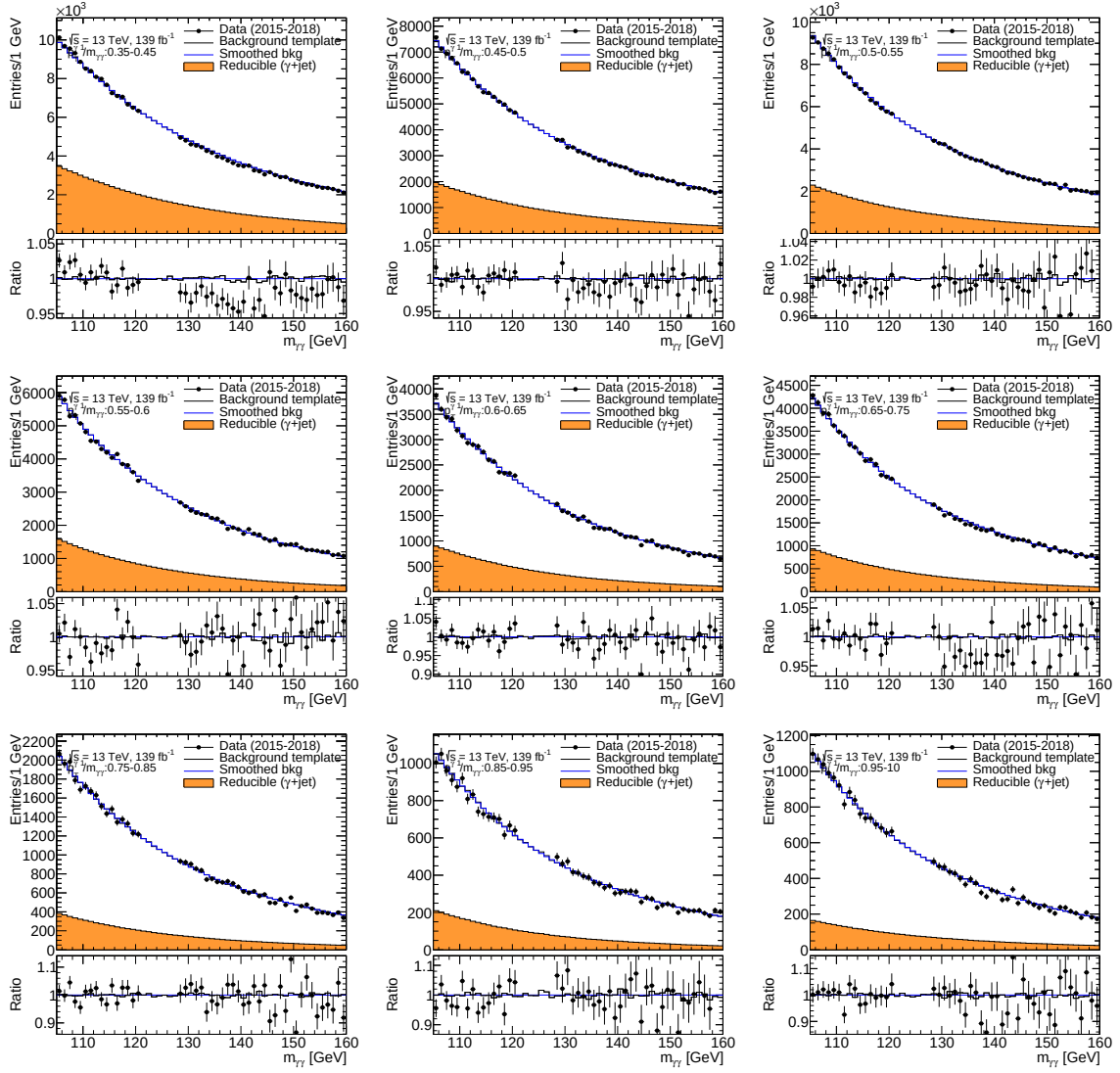


Figure A.68: Background template in each of the $p_T^{\gamma_1}/m_{\gamma\gamma}$ bins.

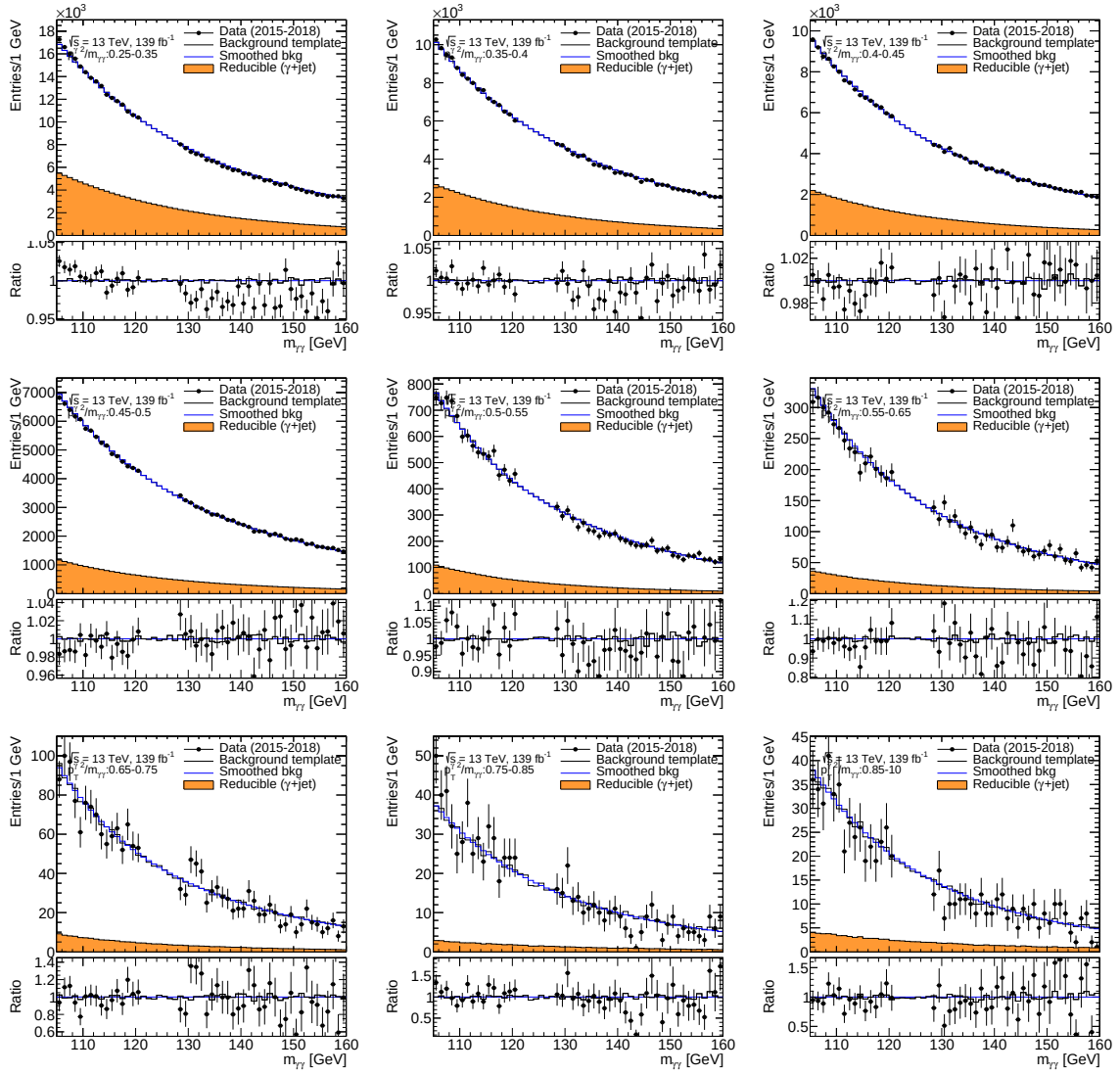


Figure A.69: Background template in each of the $p_T^{\gamma^2}/m_{\gamma\gamma}$ bins.

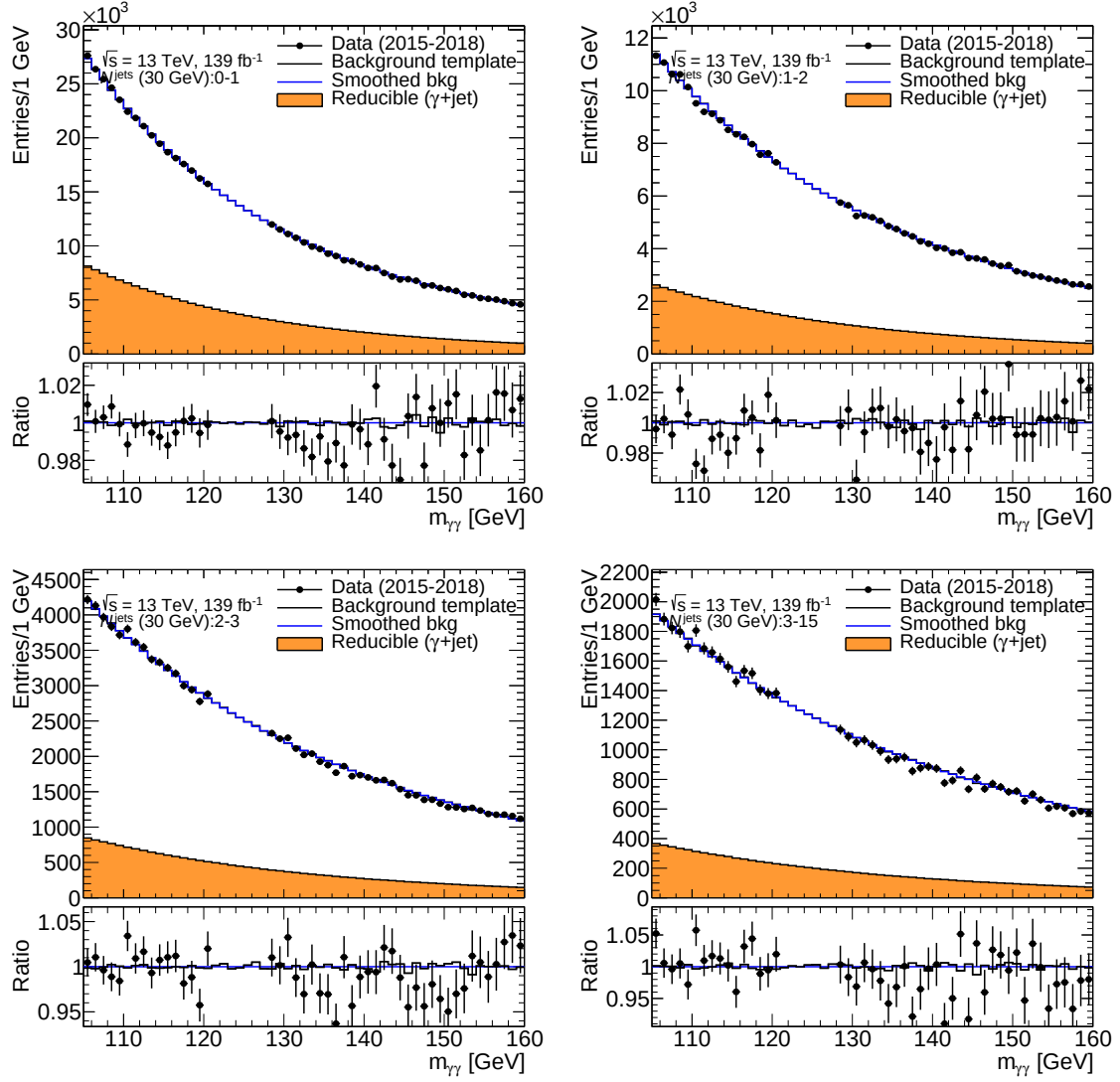


Figure A.70: Background template in each of the N_{jets} bins.

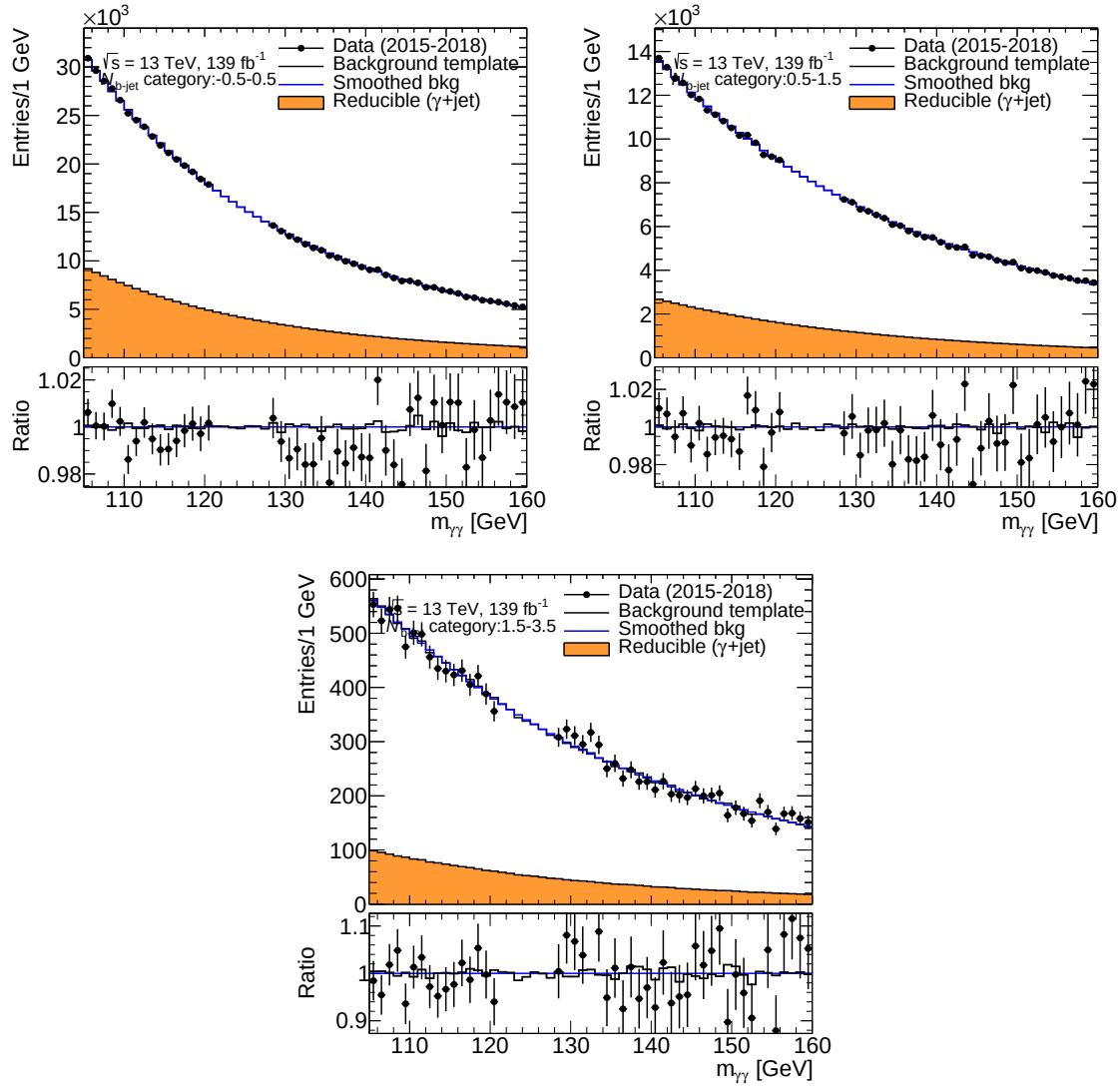


Figure A.71: Background template in each of the $N_{b\text{-jets}}$ bins.

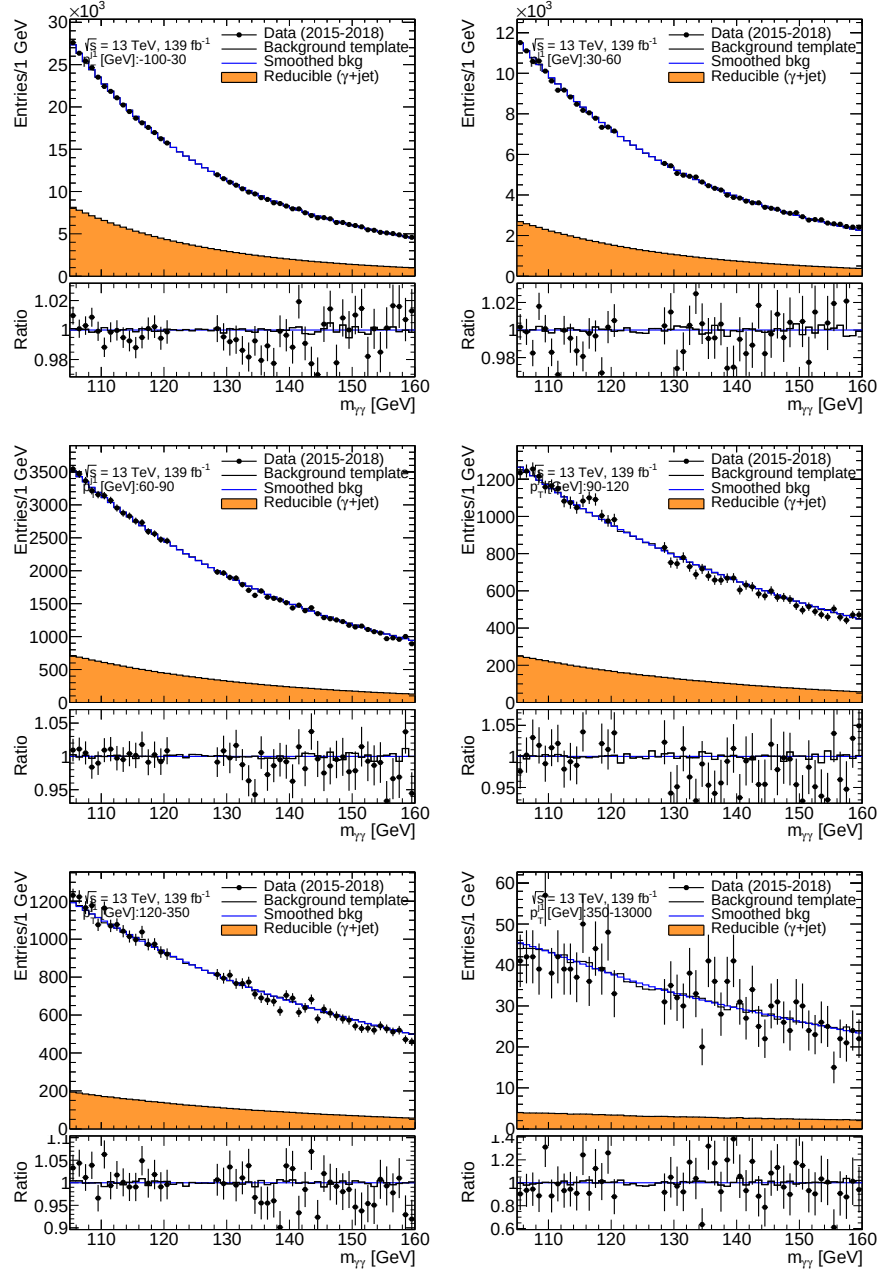


Figure A.72: Background template in each of the p_T^{j1} bins.

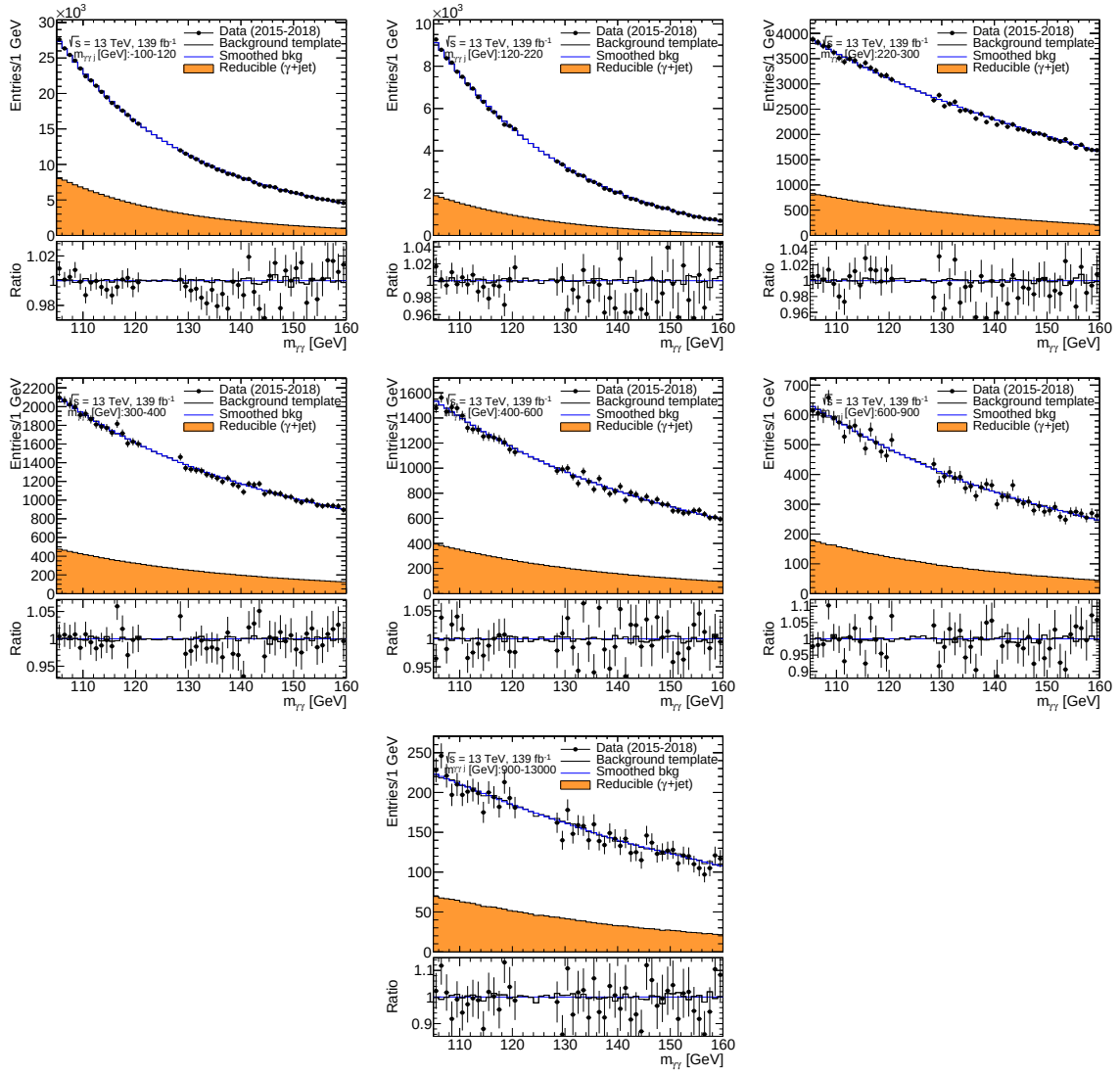


Figure A.73: Background template in each of the $m_{\gamma\gamma j}$ bins.

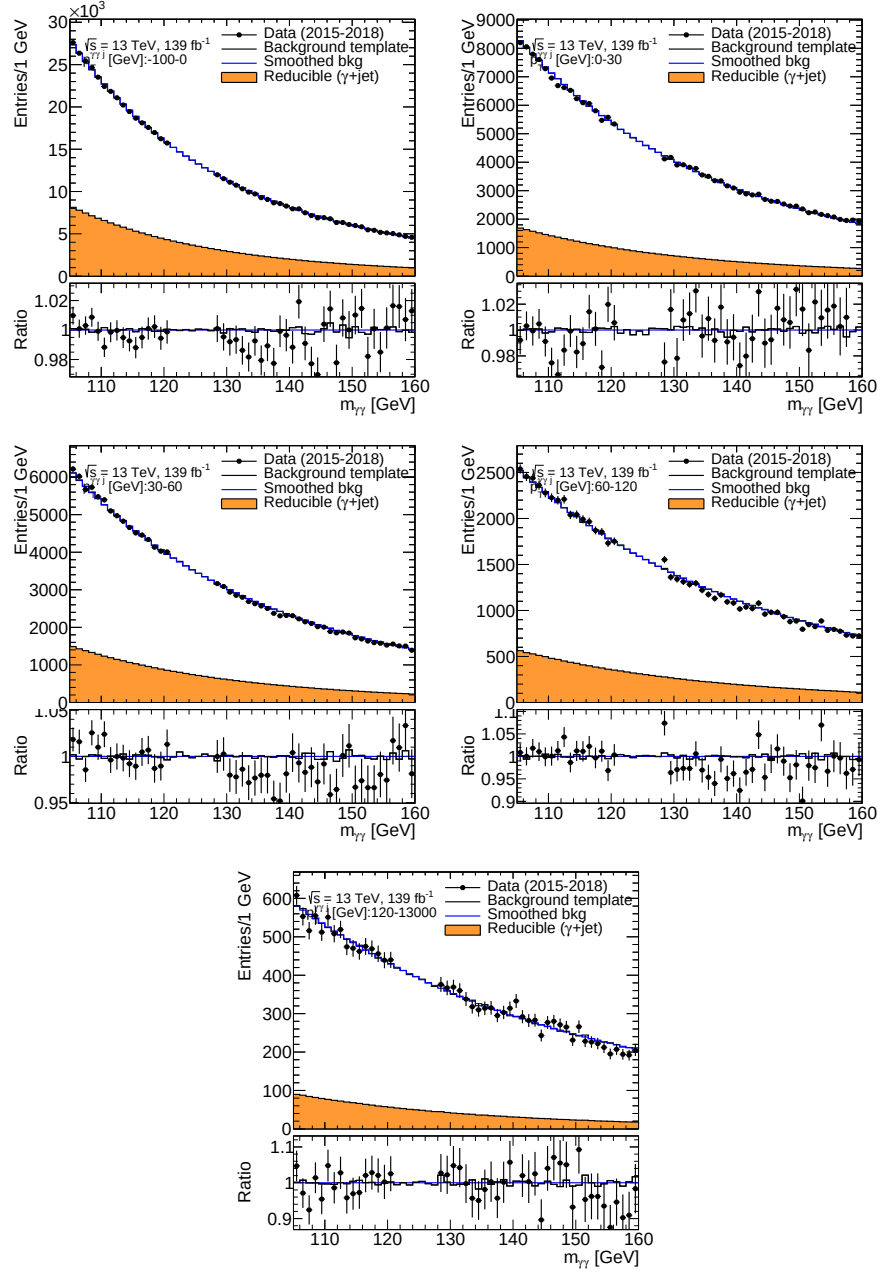
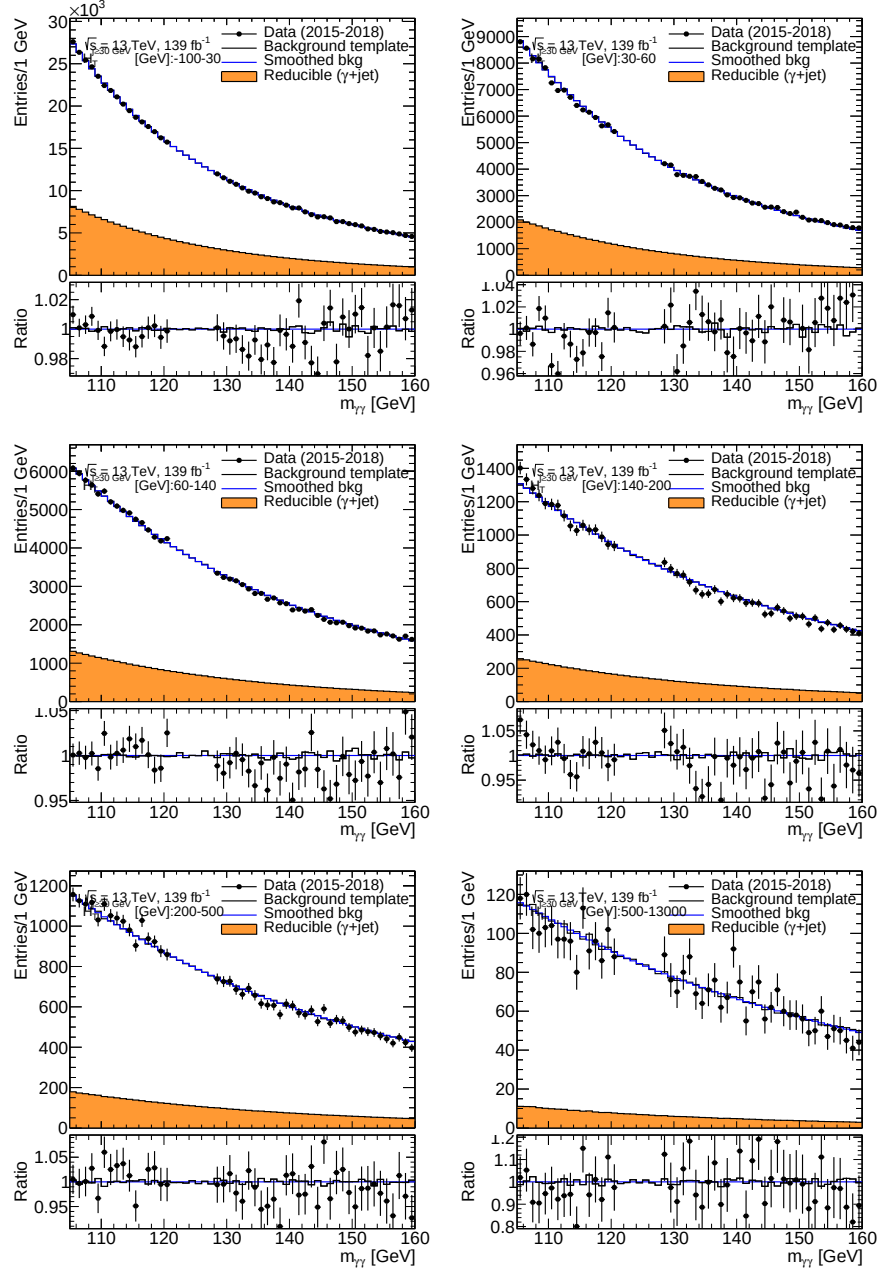


Figure A.74: Background template in each of the $p_T^{\gamma\gamma j}$ bins.

Figure A.75: Background template in each of the H_T bins.

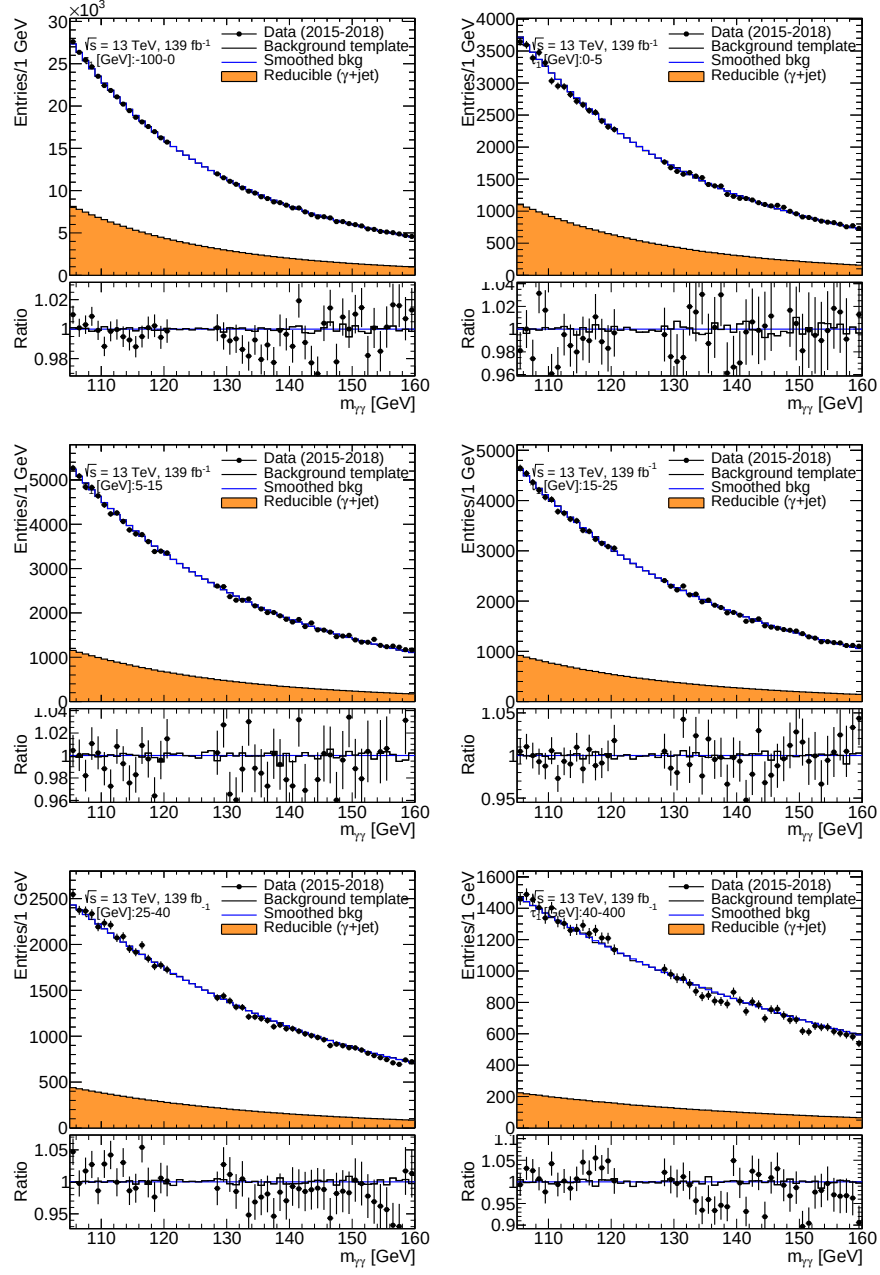


Figure A.76: Background template in each of the τ_{C,j_1} bins.

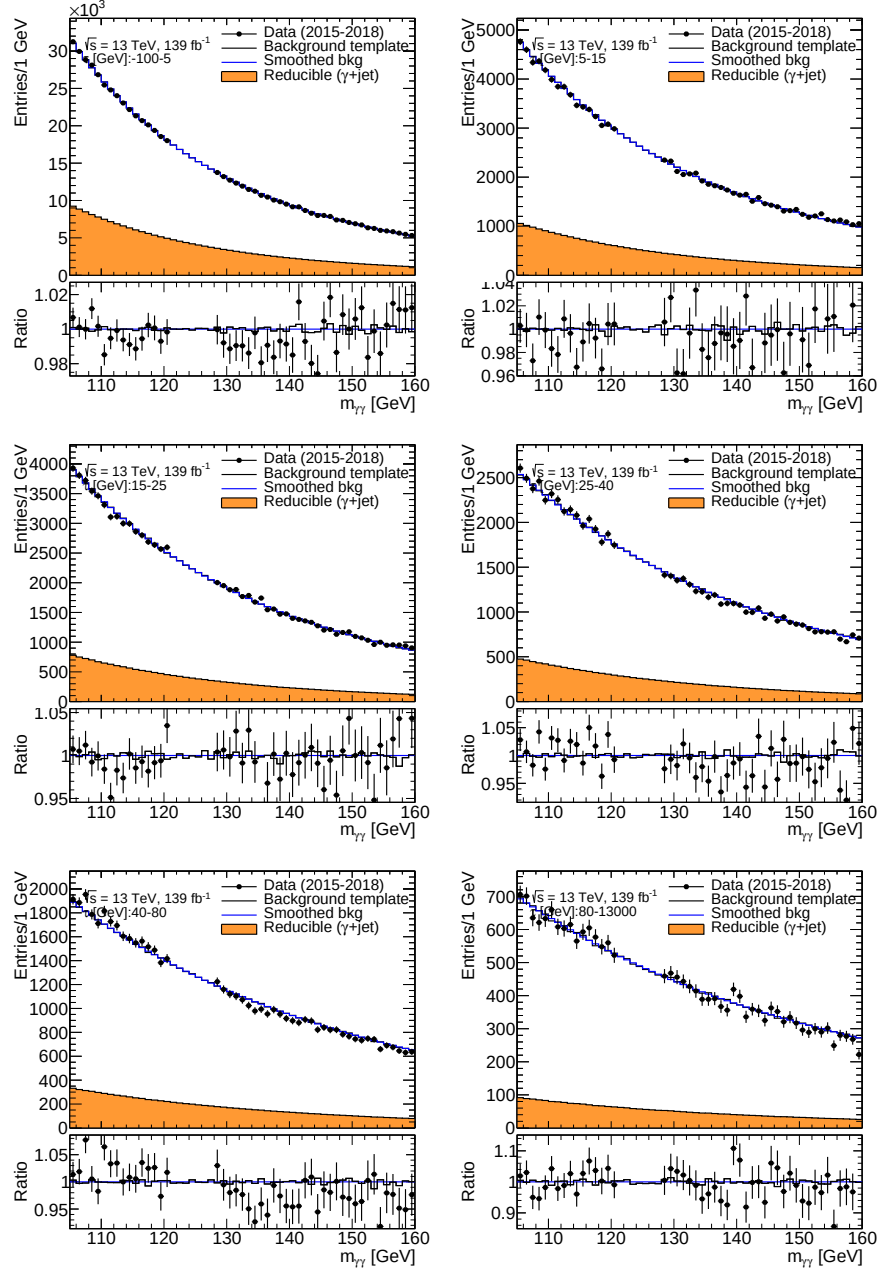
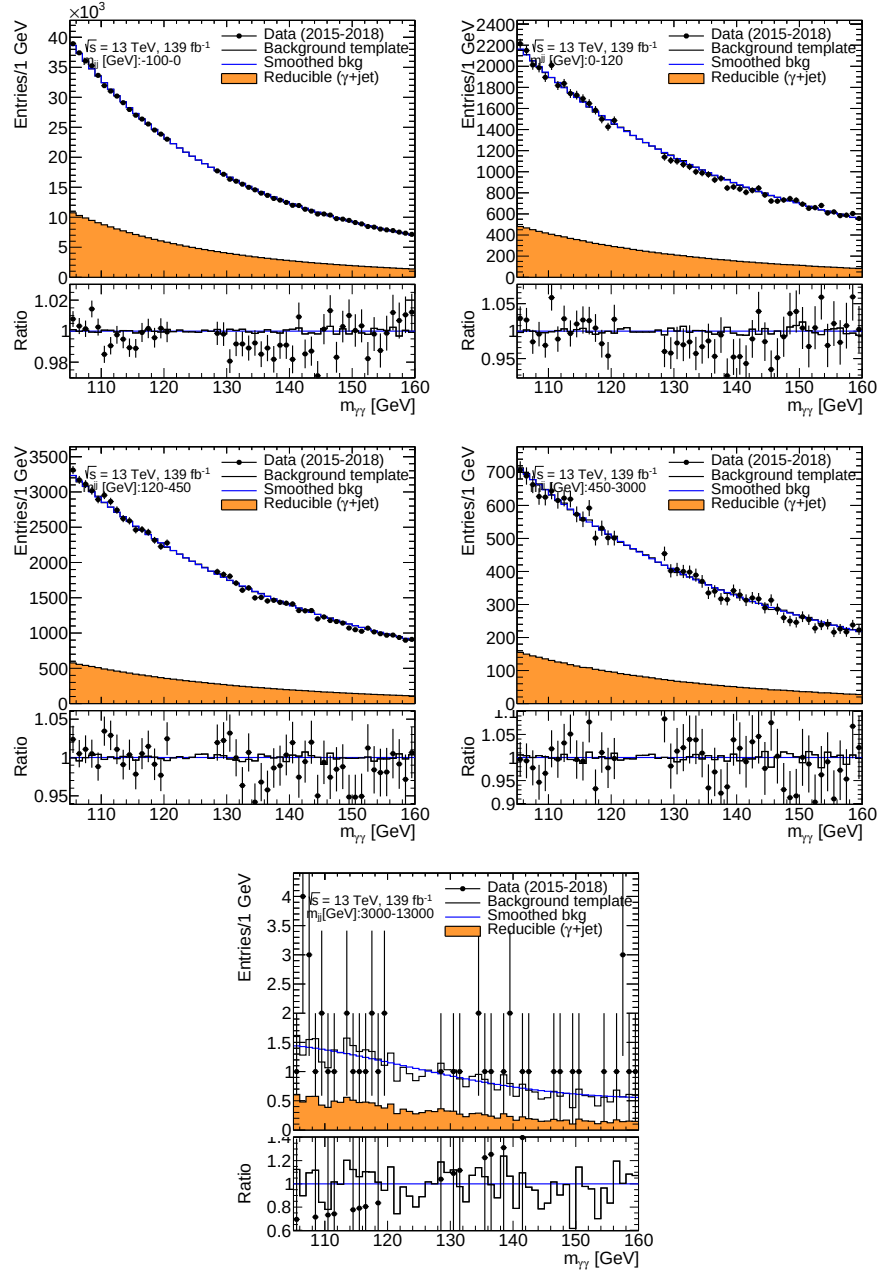


Figure A.77: Background template in each of the $\Sigma\tau_{C,j}$ bins.

Figure A.78: Background template in each of the m_{jj} bins.

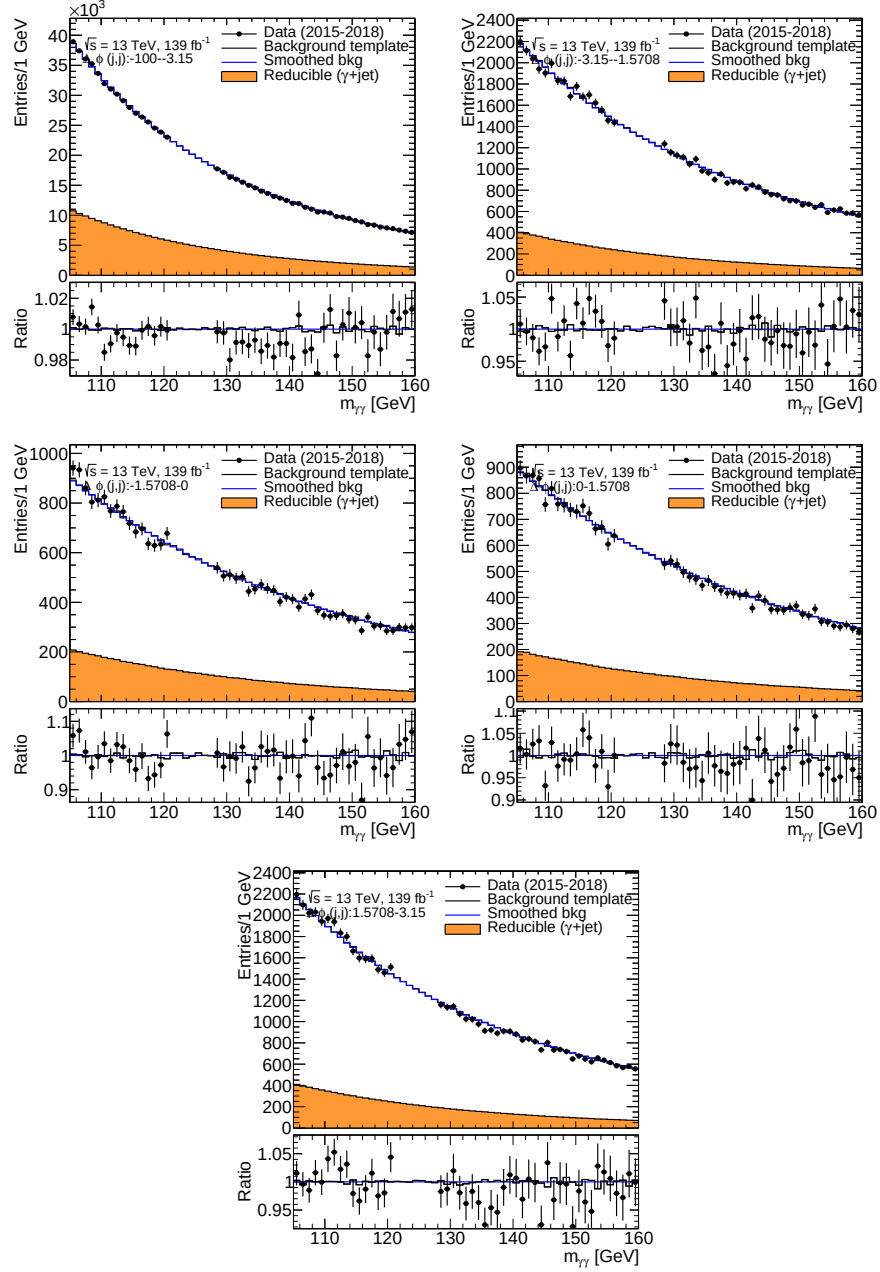


Figure A.79: Background template in each of the $\Delta\phi_{jj}$ bins.

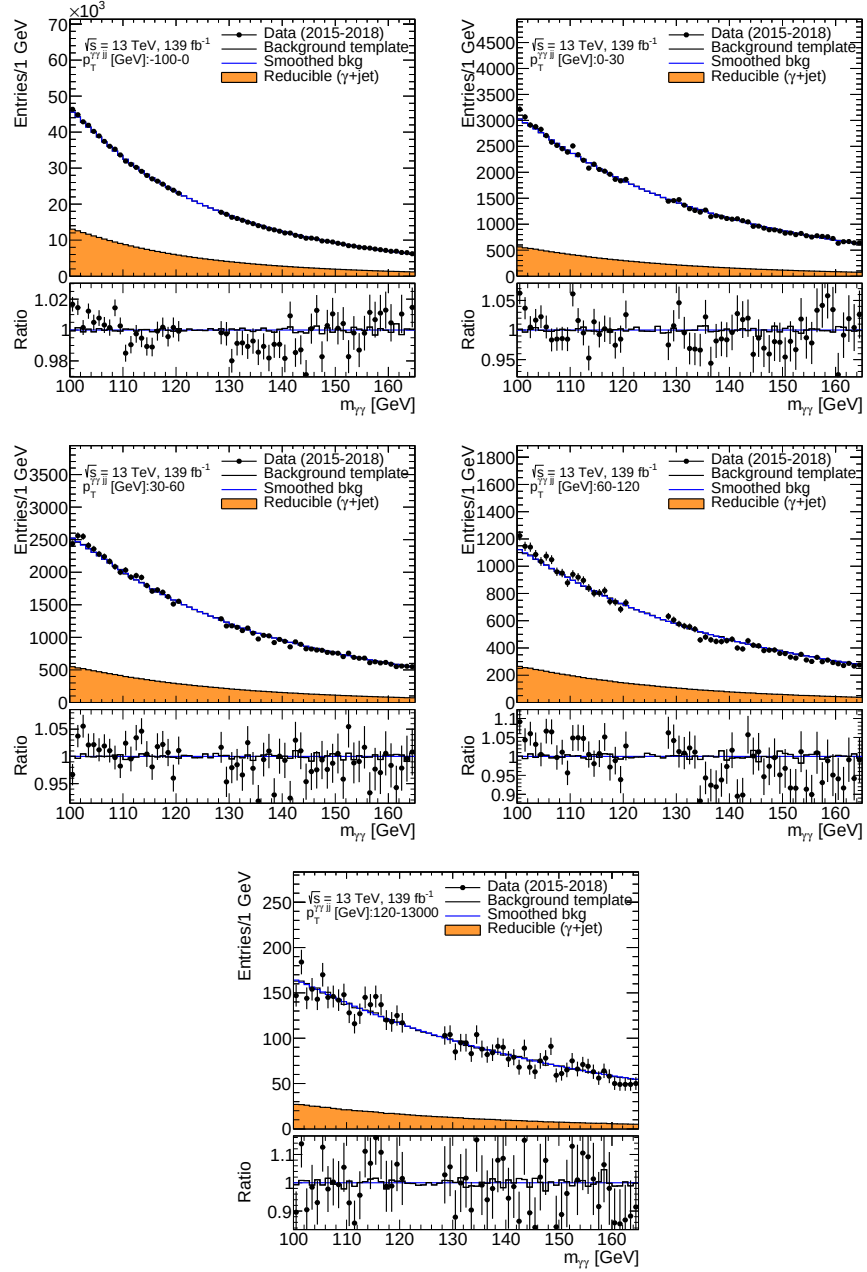


Figure A.80: Background template in each of the $p_T^{\gamma\gamma jj}$ bins.

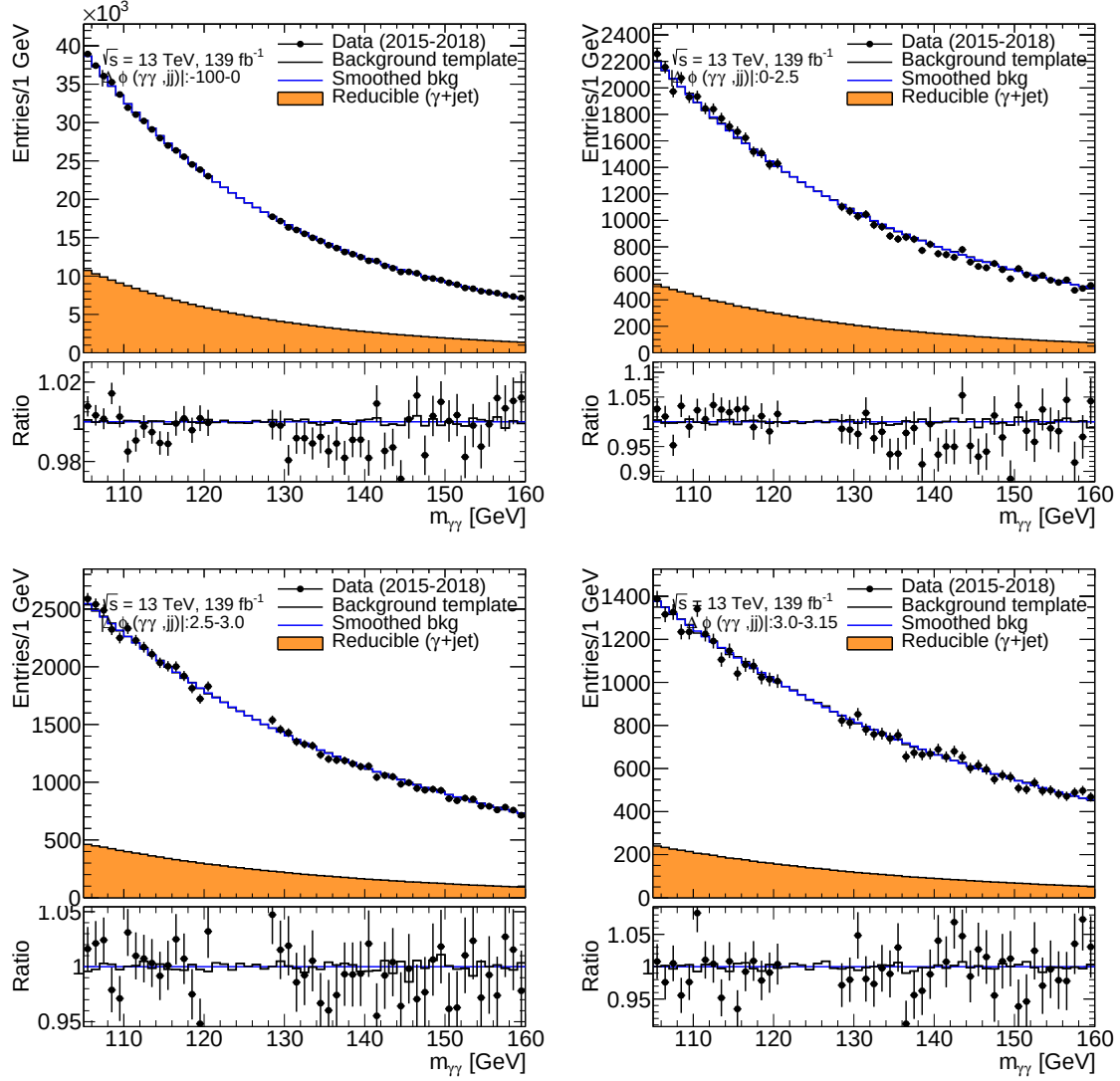


Figure A.81: Background template in each of the $|\Delta\phi_{\gamma\gamma,jj}|$ bins.

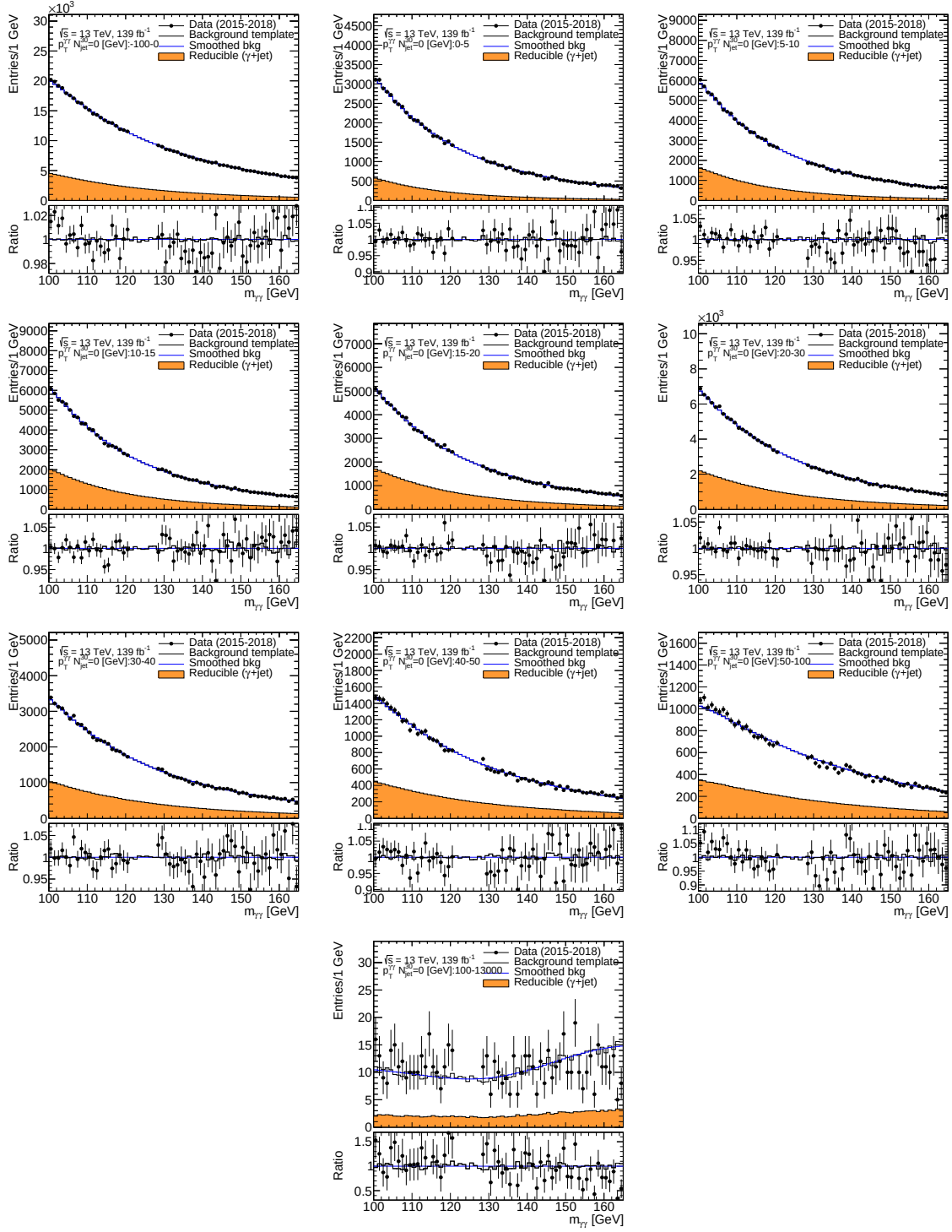


Figure A.82: Background template in each of the $p_T^{\gamma, \text{jet veto } 30}$ bins.

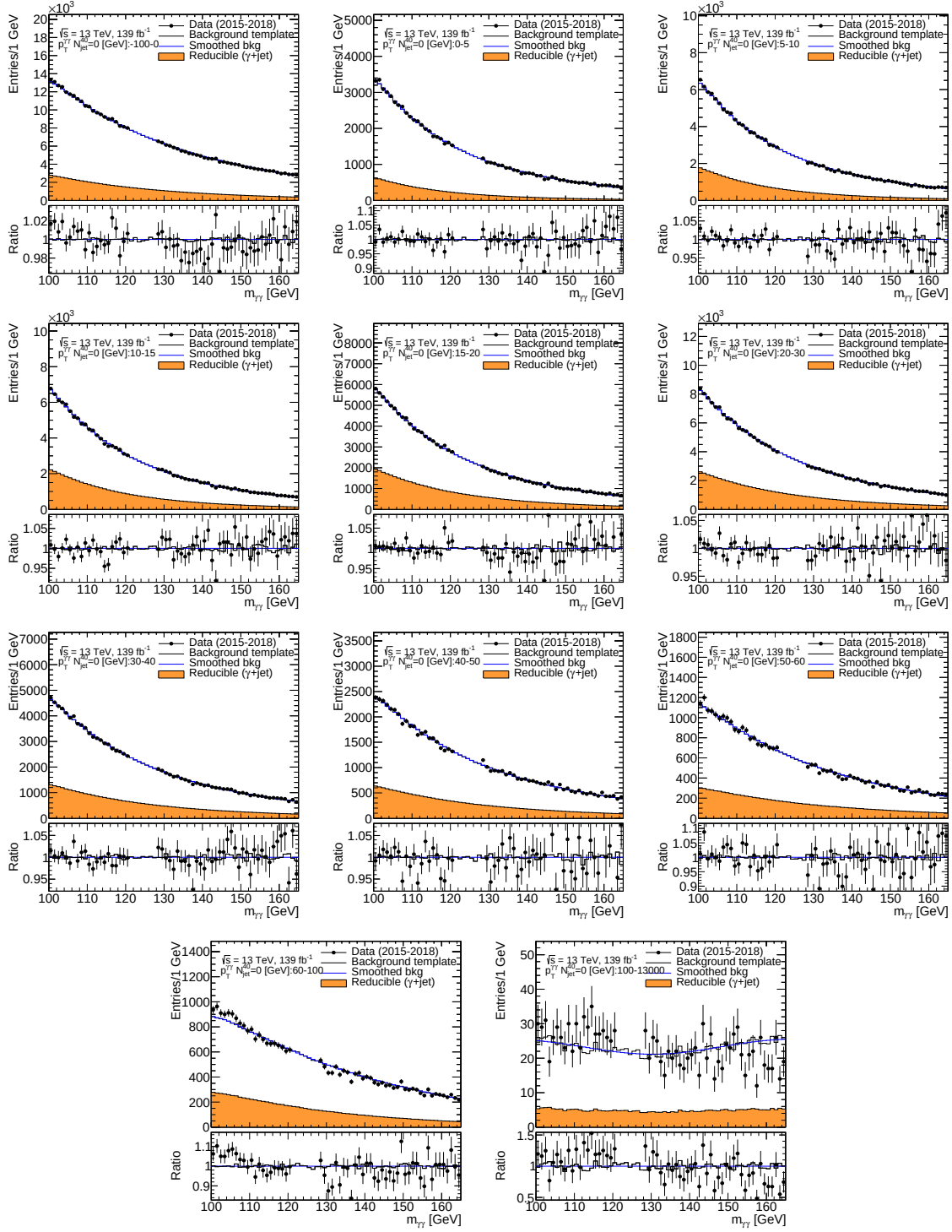


Figure A.83: Background template in each of the $p_T^{\gamma, \text{jet veto}}$ bins.

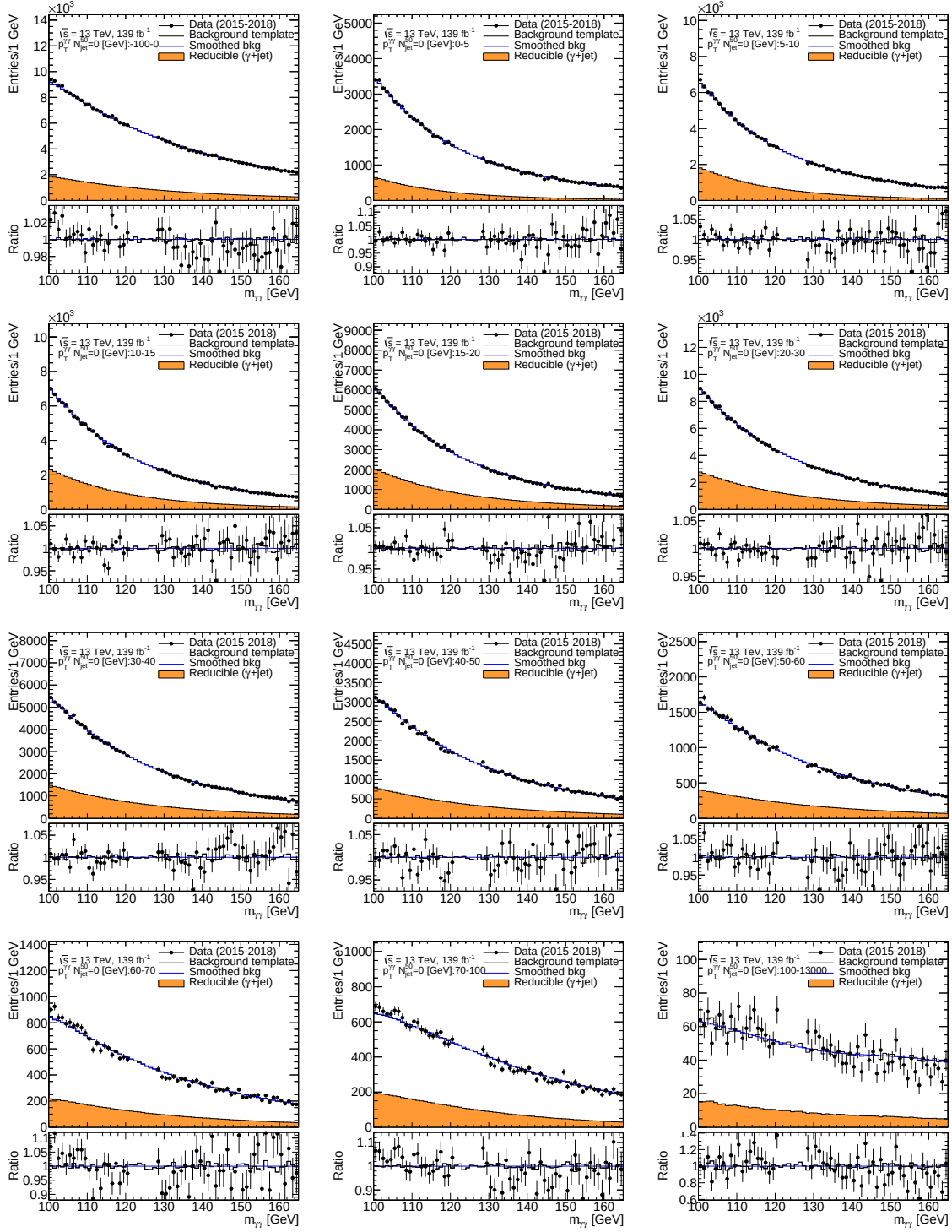


Figure A.84: Background template in each of the $p_T^{\gamma, \text{jet veto}}$ bins.

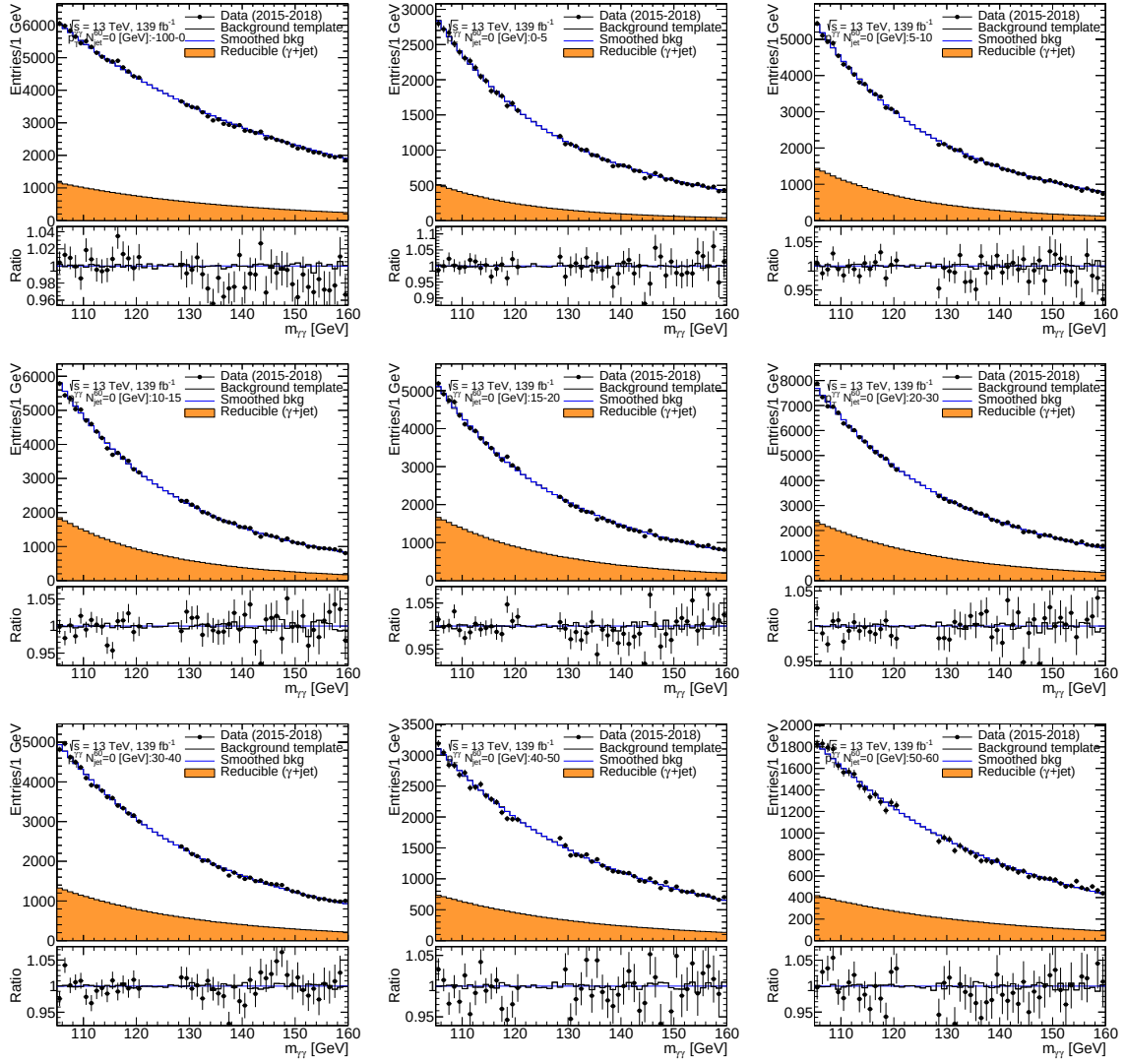


Figure A.85: Background template in each of the $p_T^{\gamma\gamma, \text{jet veto}}$ bins. (Continued on next page.)

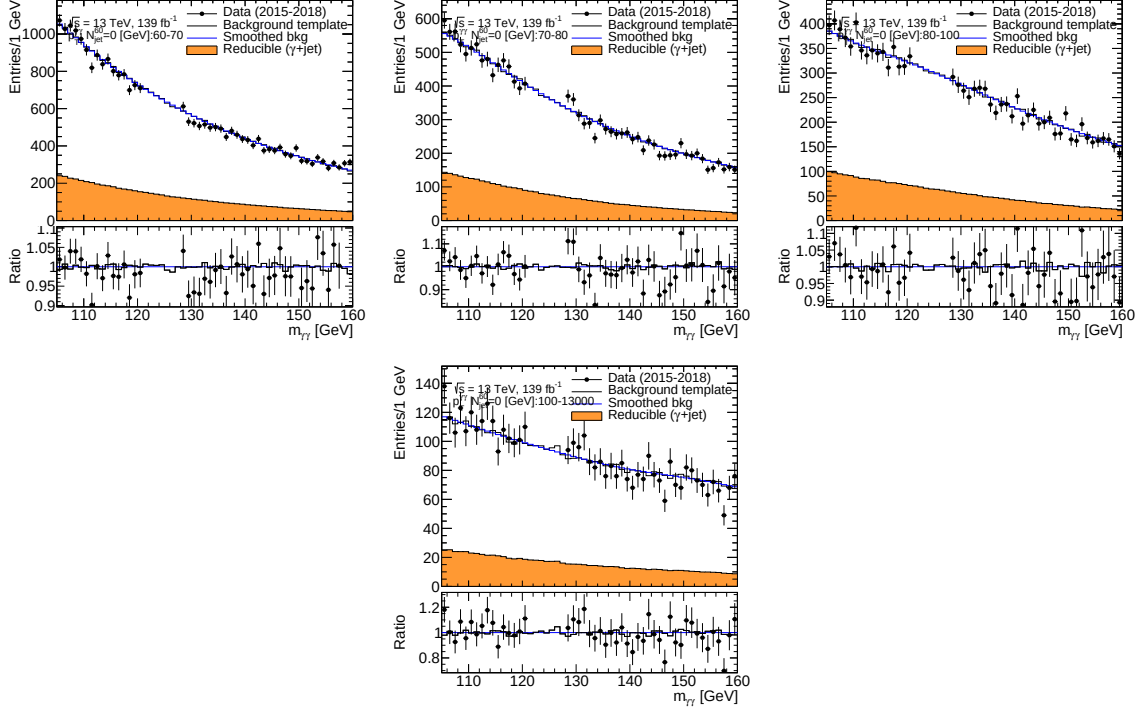


Figure A.86: Continuation of background template in each of the $p_T^{\gamma\gamma, \text{jet veto } 60}$ bins.

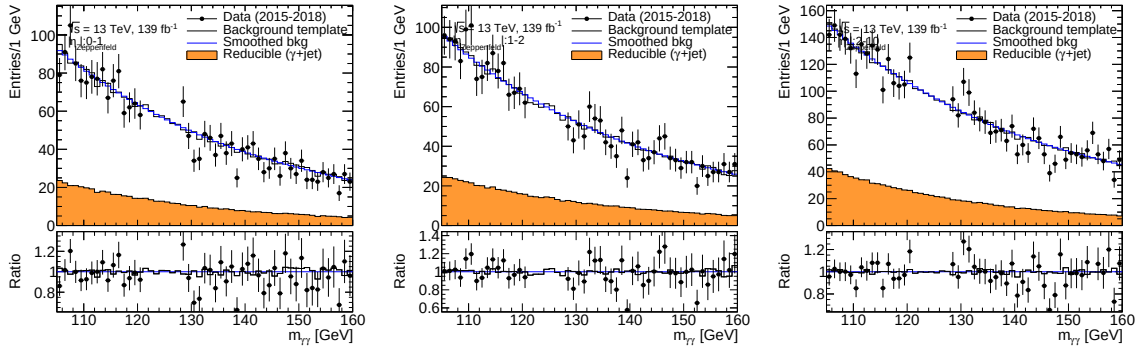


Figure A.87: Background template in each of the $|\eta^*|$ bins in the VBF-enhanced fiducial volume.

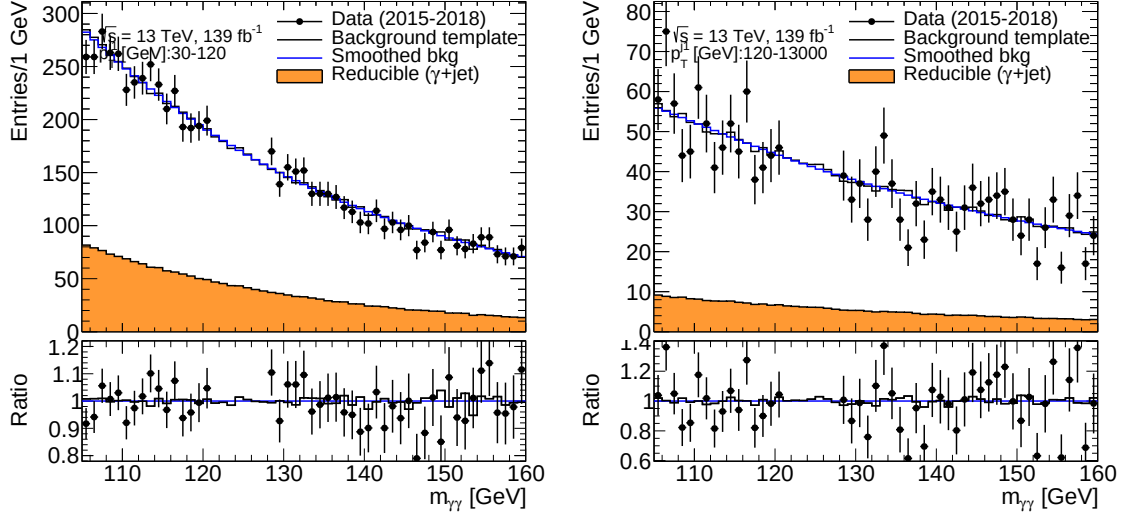


Figure A.88: Background template in each of the p_T^{j1} bins in the VBF-enhanced fiducial volume.

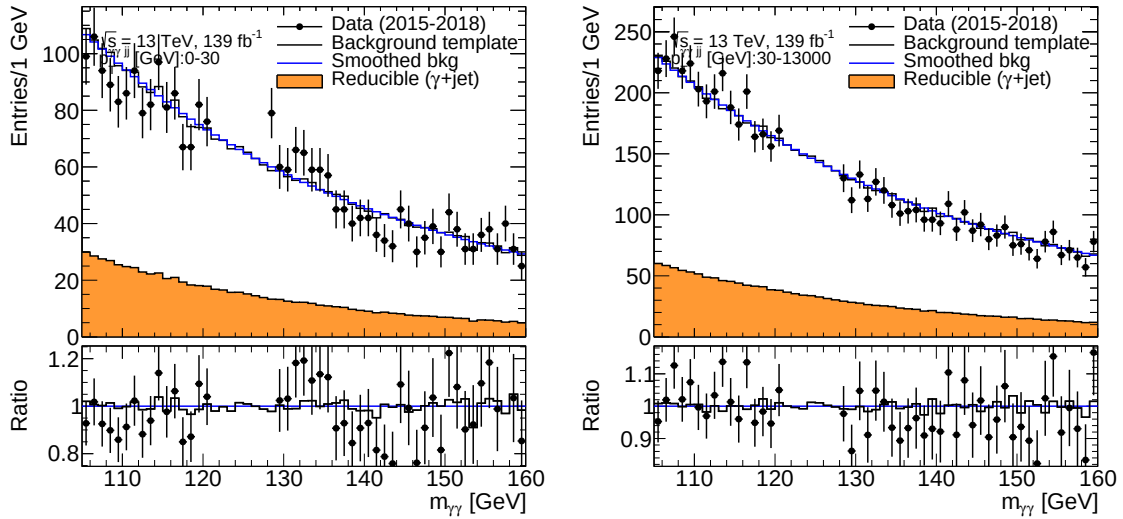


Figure A.89: Background template in each of the $p_T^{\gamma\gamma jj}$ bins in the VBF-enhanced fiducial volume.

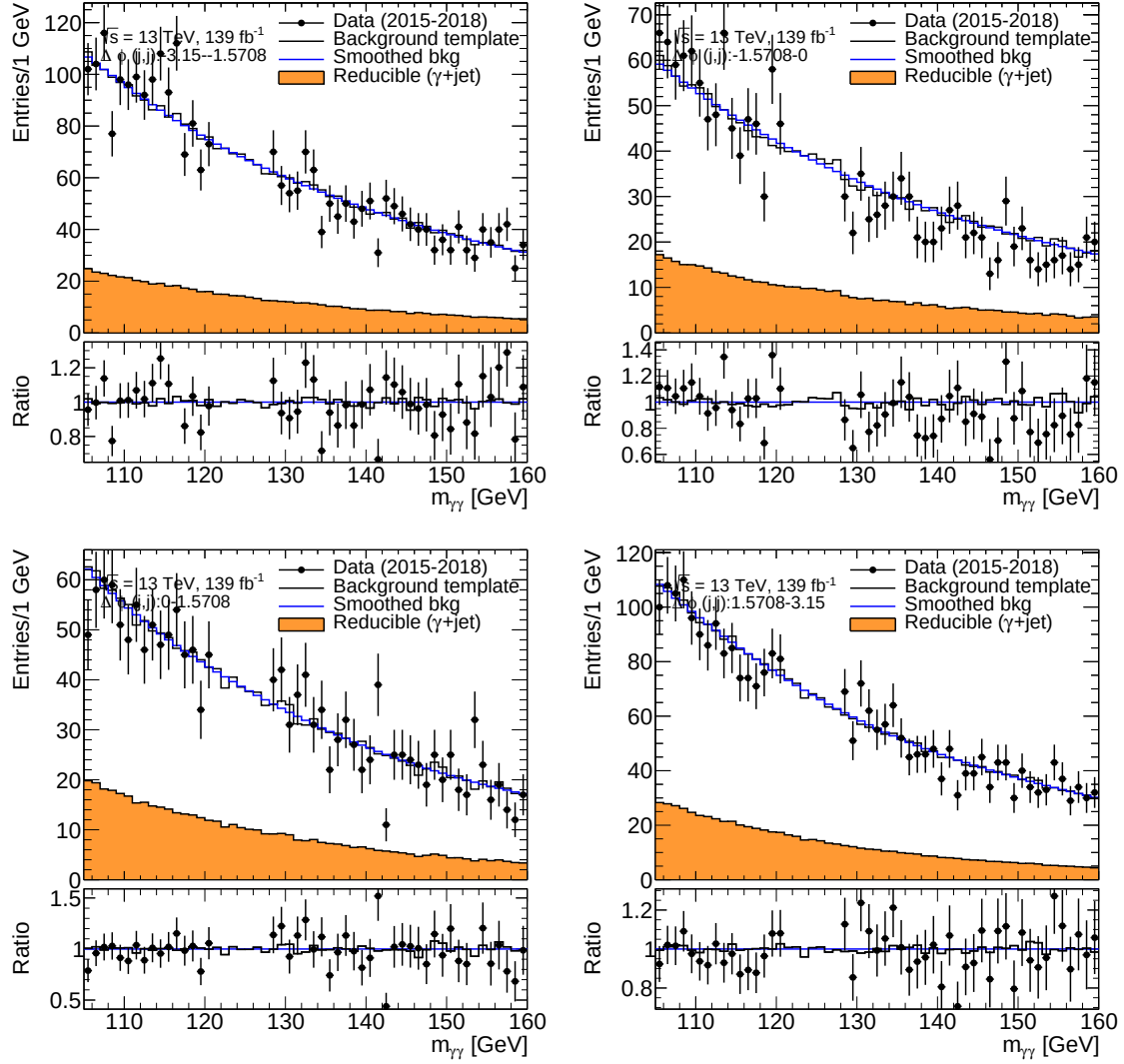


Figure A.90: Background template in each of the $\Delta\phi_{jj}$ bins in the VBF-enhanced fiducial volume.

A.3.1 Double-differential variables

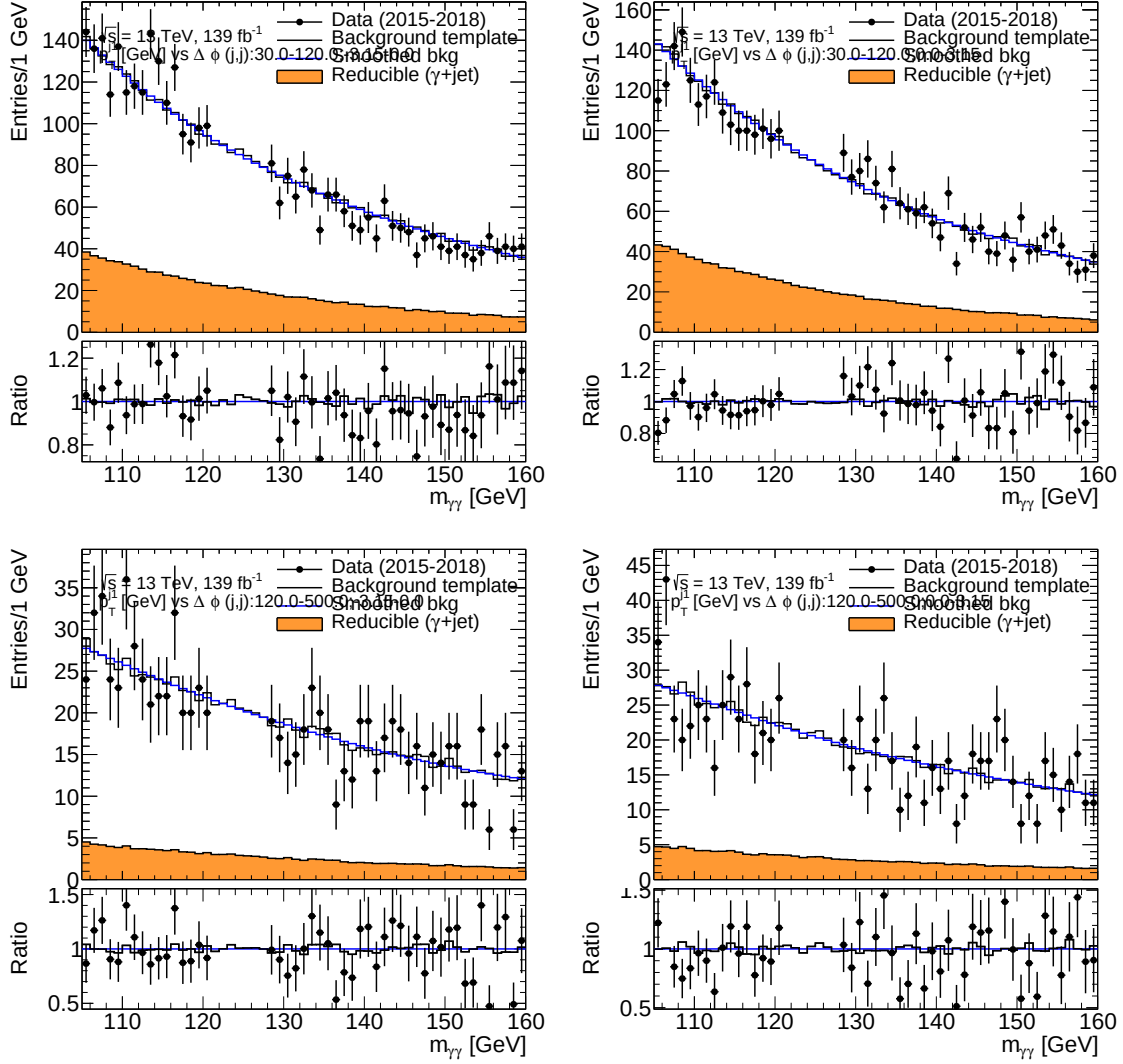


Figure A.91: Background template in each of the p_T^{j1} vs $\Delta\phi_{jj}$ bins in the VBF-enhanced fiducial volume.

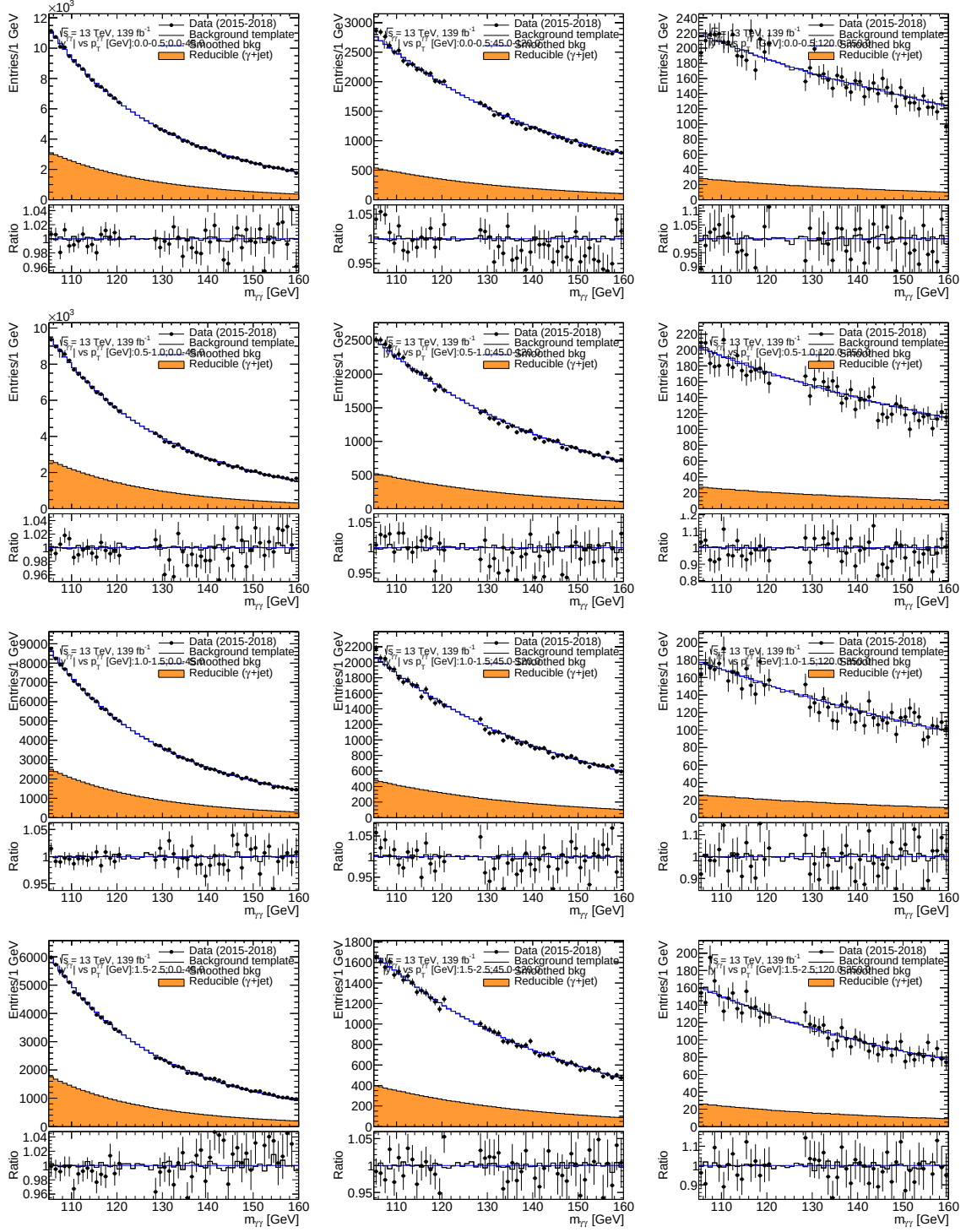


Figure A.92: Background template in each of the $p_T^{\gamma\gamma}$ vs $|y^{\gamma\gamma}|$ bins.

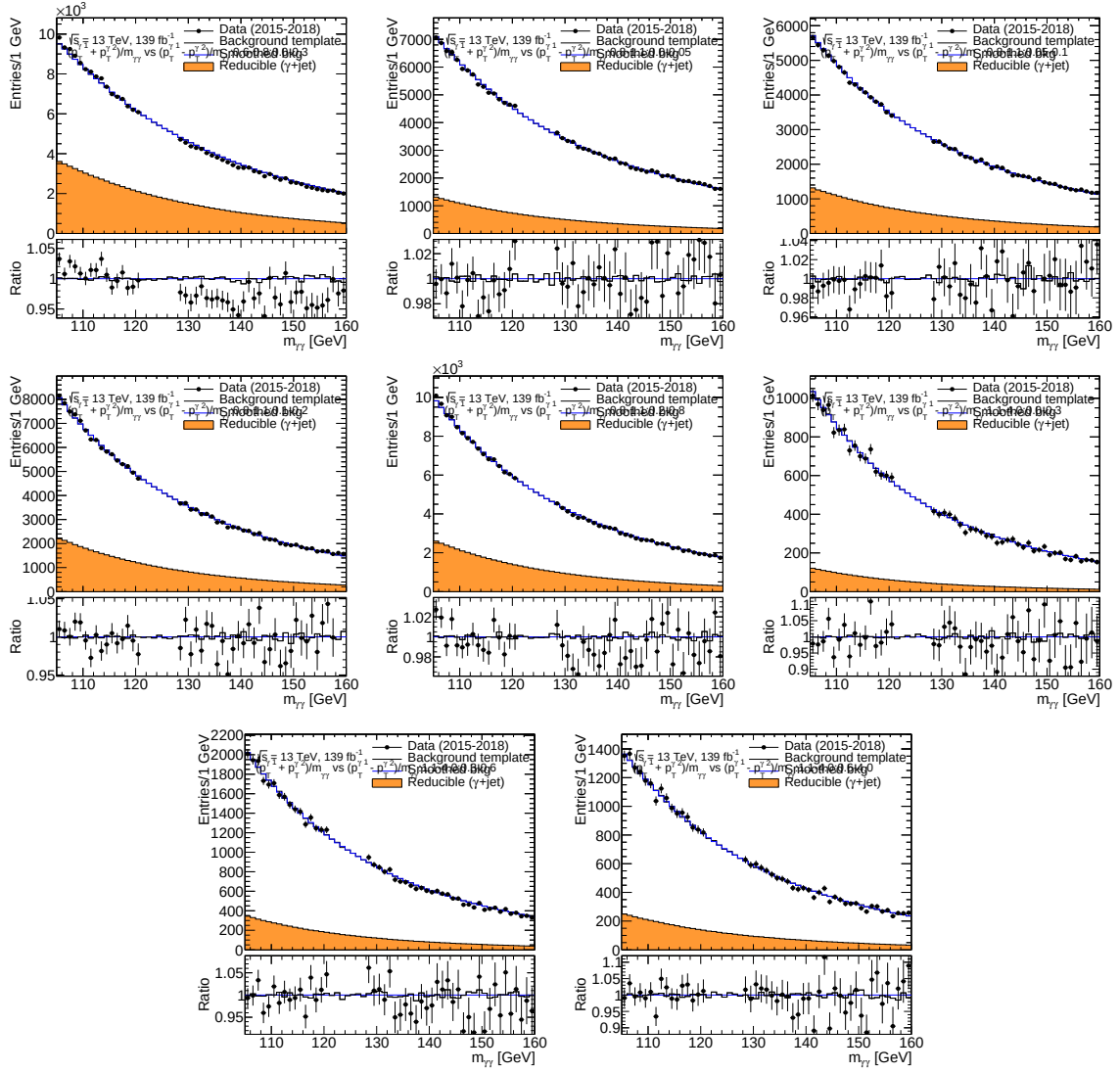


Figure A.93: Background template in each of the $(p_T^{\gamma 1} + p_T^{\gamma 2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma 1} - p_T^{\gamma 2})/m_{\gamma\gamma}$ bins.

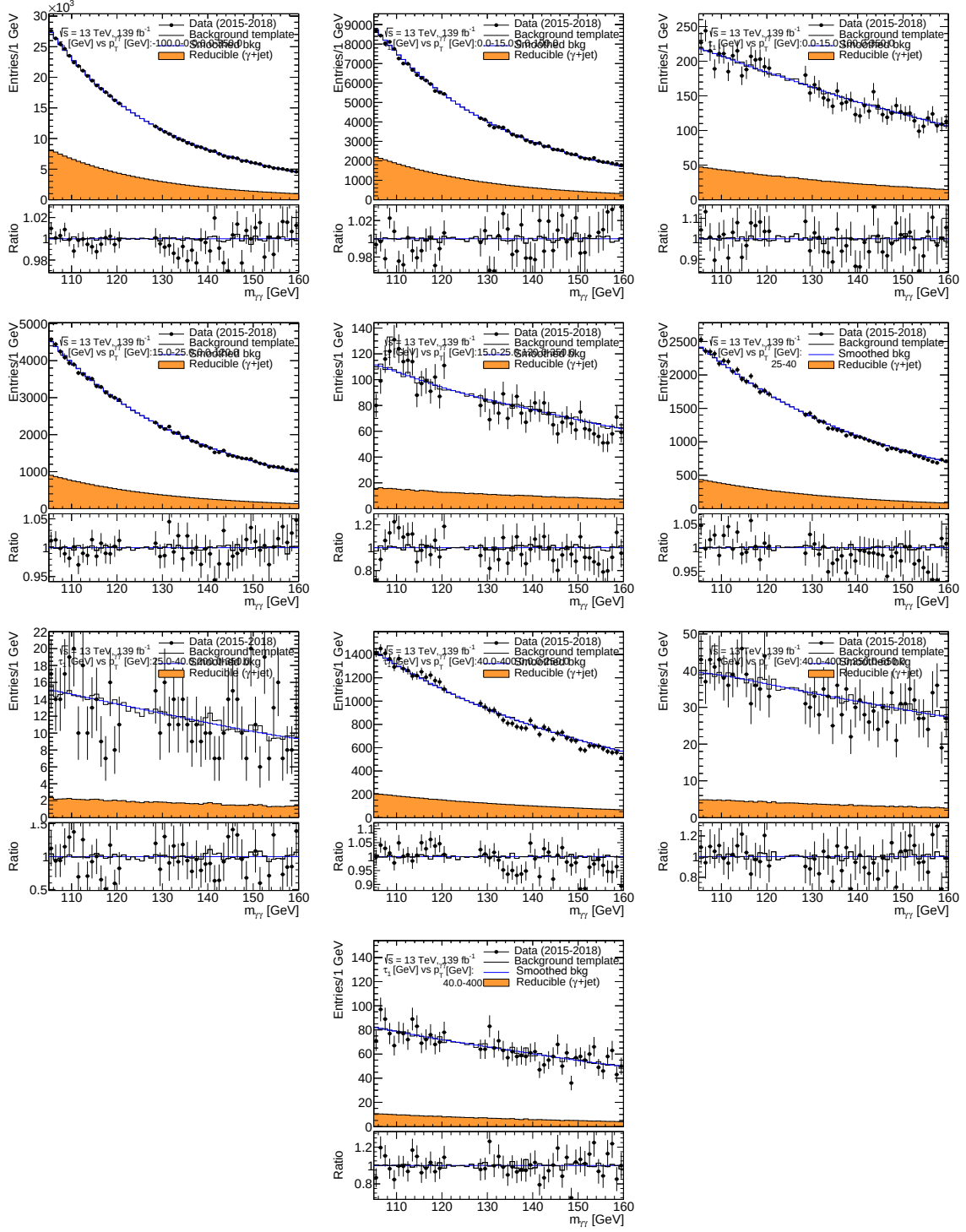


Figure A.94: Background template in each of the $p_T^{\gamma\gamma}$ vs $\tau_{C,j1}$ bins.

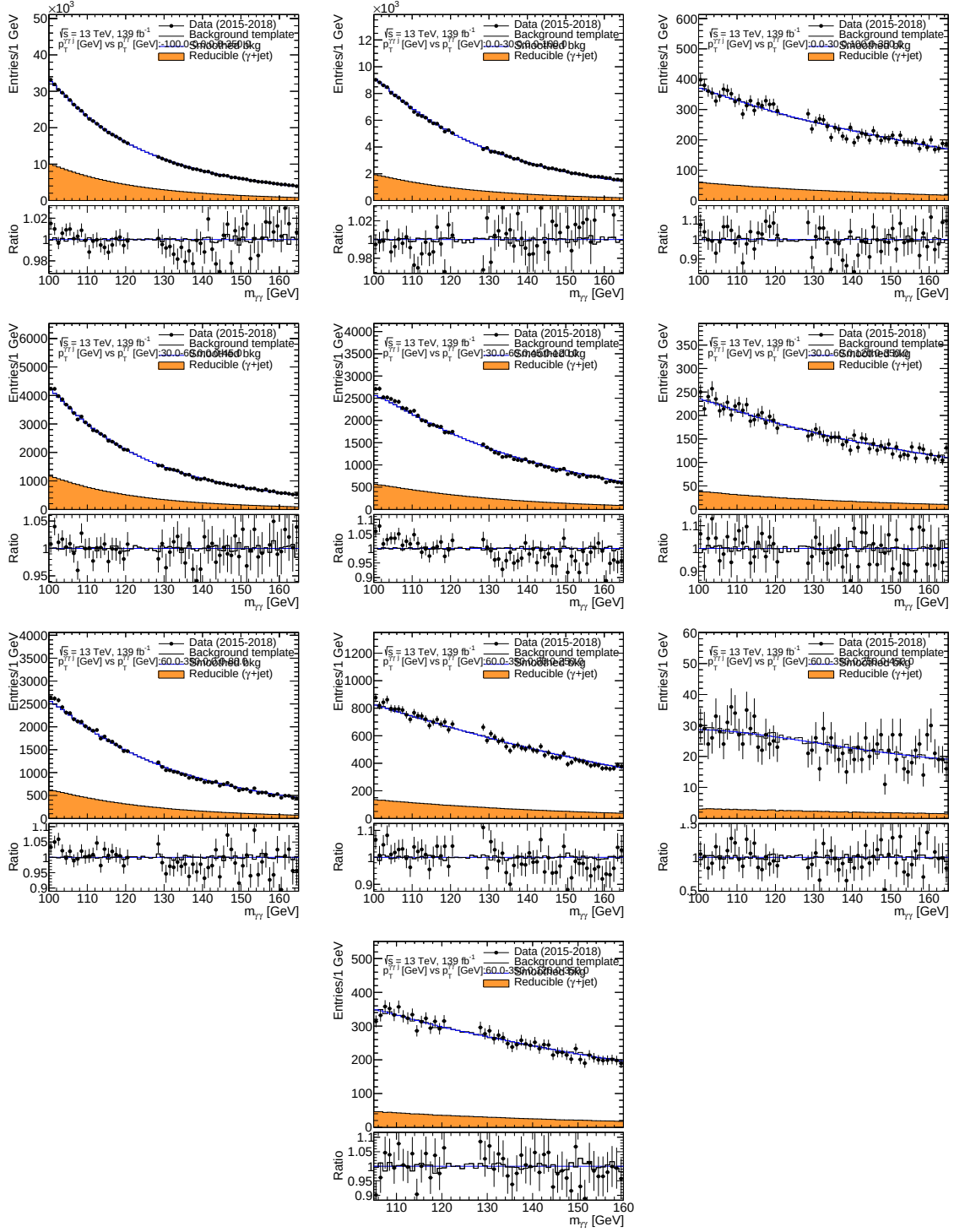


Figure A.95: Background template in each of the p_T^γ vs $p_T^{\gamma,j}$ bins.

A.4 Response Matrices

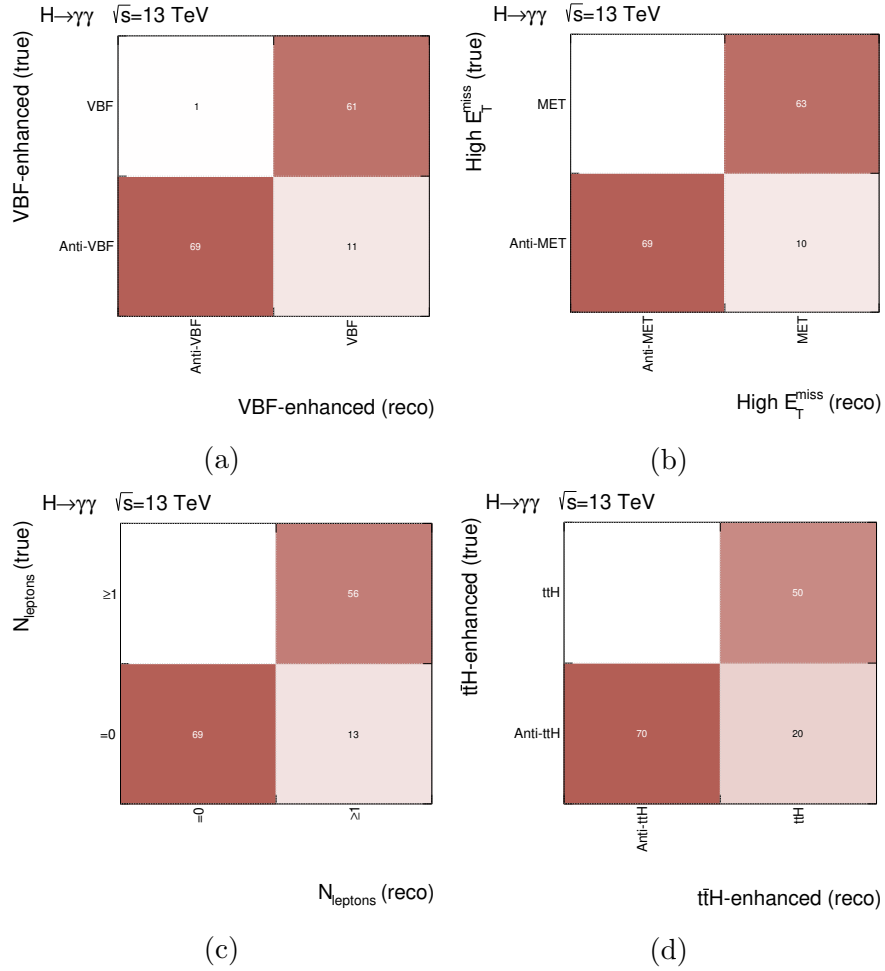


Figure A.96: Response matrices for the (a) VBF-enhanced, (b) High- E_T^{miss} , (c) lepton-enhanced region, and (d) $t\bar{t}H$ -enhanced fiducial regions. Bins with content less than 0.01 are not shown.

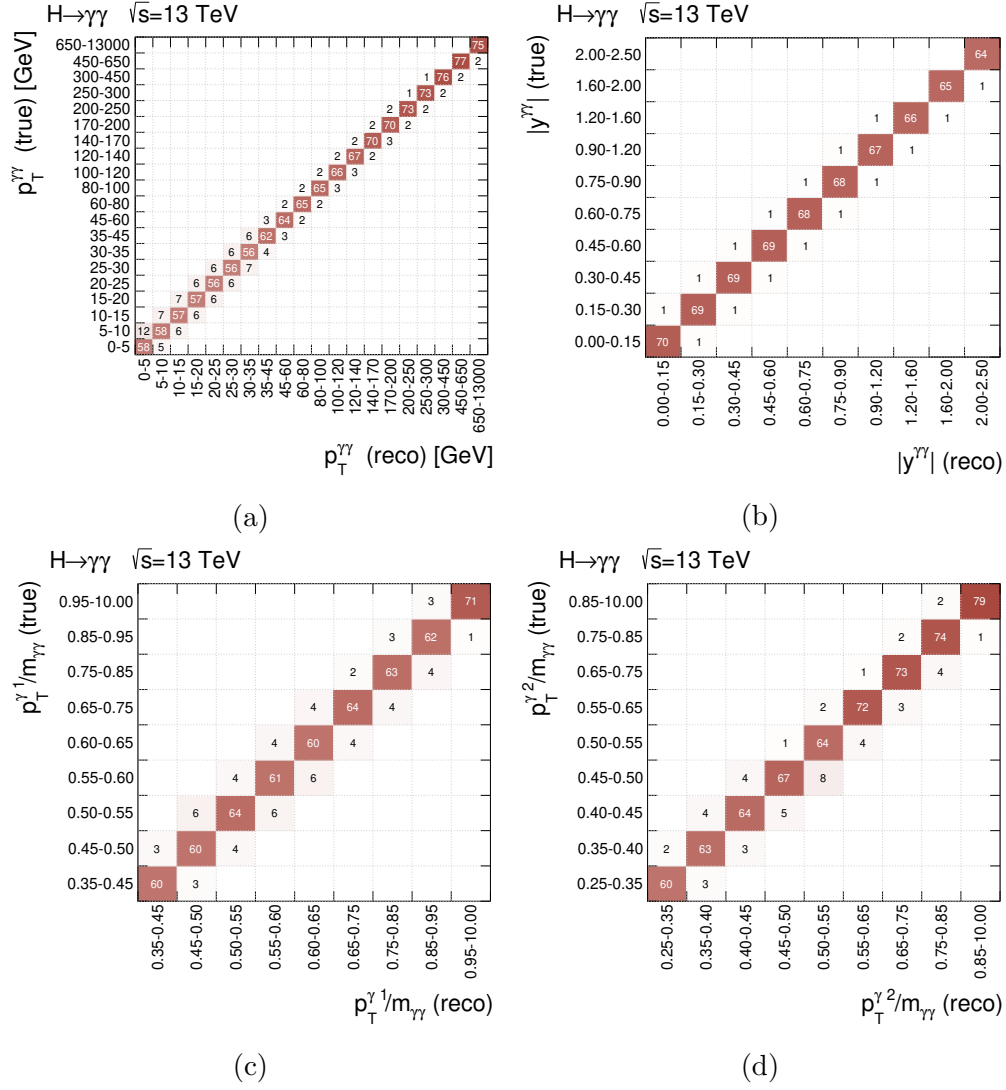


Figure A.97: Response matrices for (a) $p_T^{\gamma\gamma}$, (b) $|y^{\gamma\gamma}|$, (c) $p_T^{\gamma 1}/m_{\gamma\gamma}$, and (d) $p_T^{\gamma 2}/m_{\gamma\gamma}$ differential variables. Bins with content less than 0.01 are not shown.

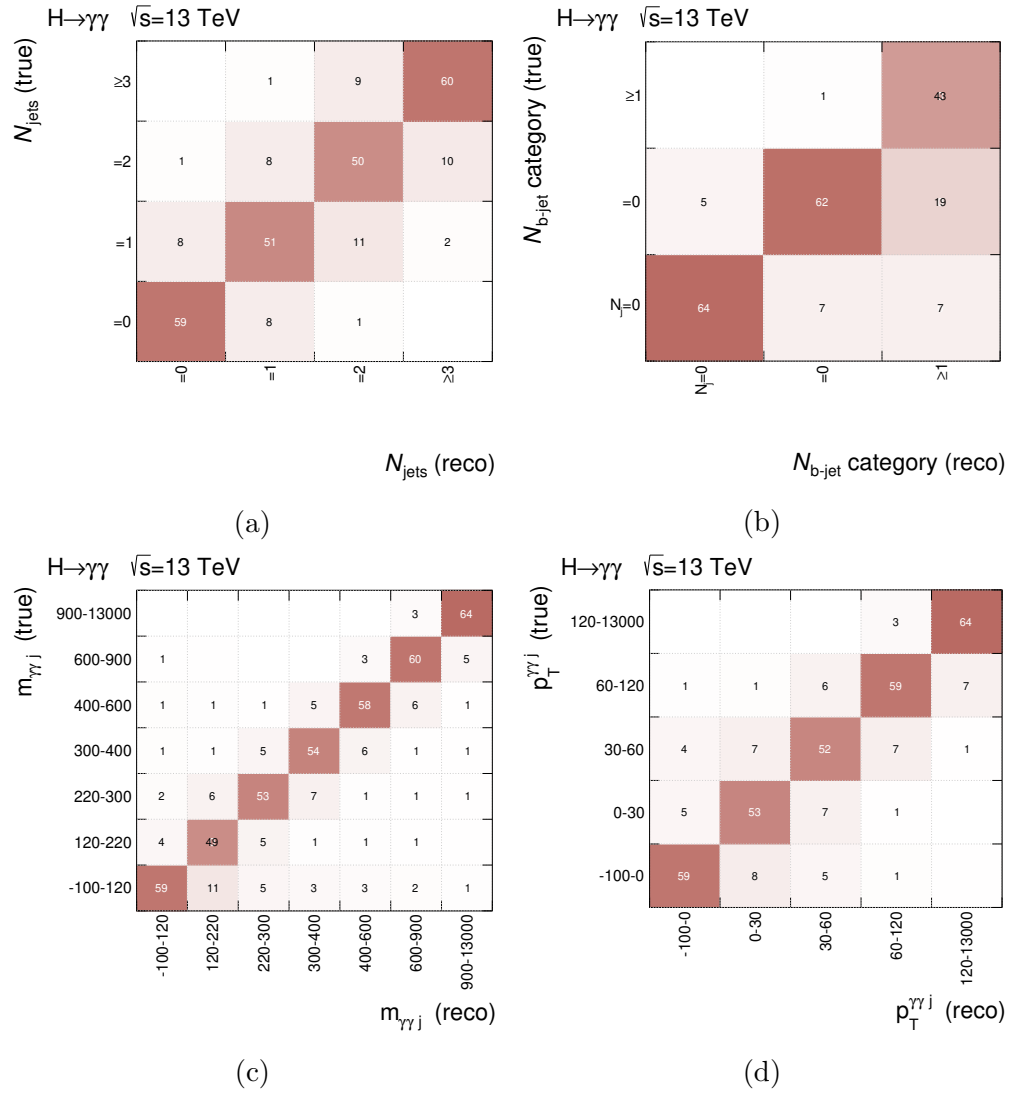


Figure A.98: Response matrices for (a) N_{jets} , (b) $N_{\text{b-jets}}$, (c) $m_{\gamma\gamma j}$, and (d) $p_T^{\gamma\gamma j}$ differential variables. Bins with content less than 0.01 are not shown.

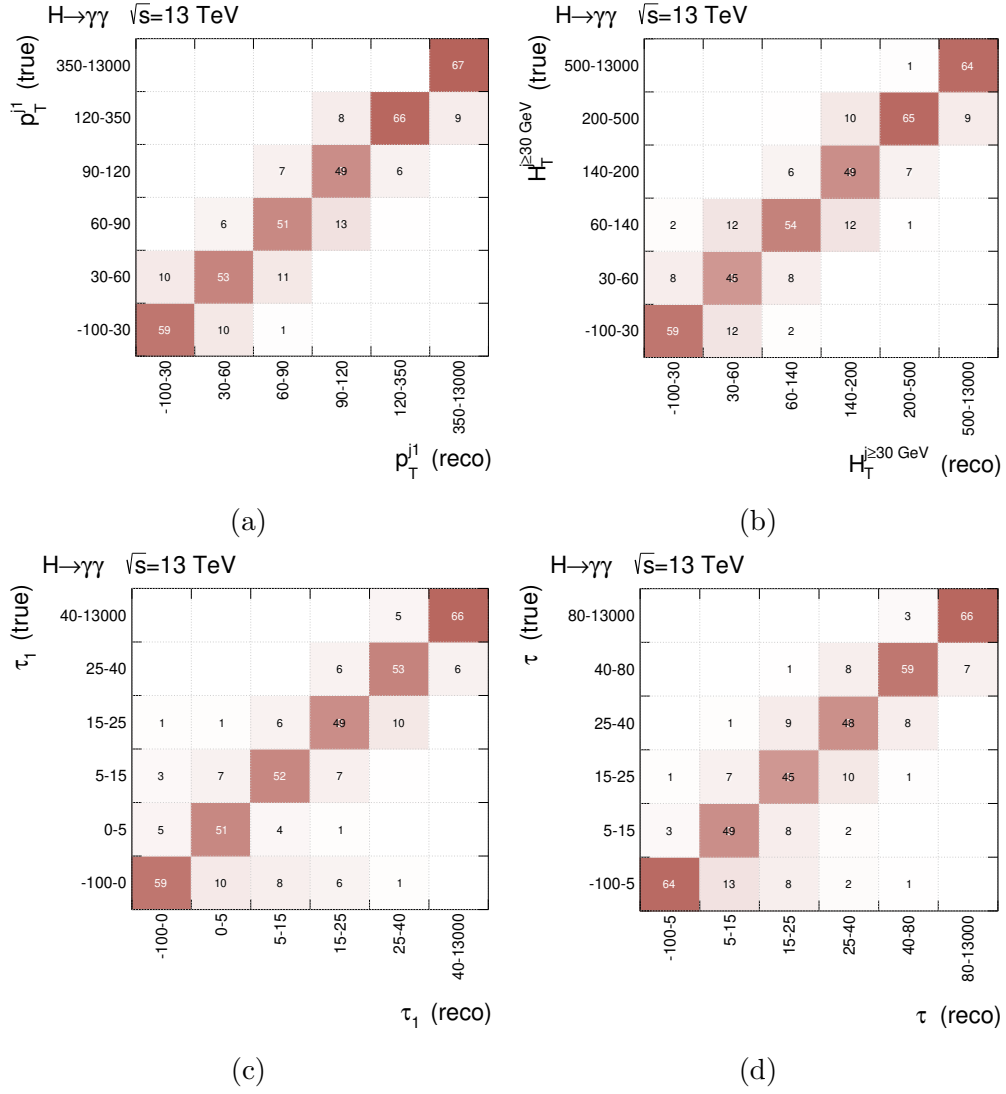


Figure A.99: Response matrices for (a) p_T^{j1} , (b) H_T , (c) $\tau_{C,j1}$, and (d) $\Sigma\tau_{C,j}$ differential variables. Bins with content less than 0.01 are not shown.

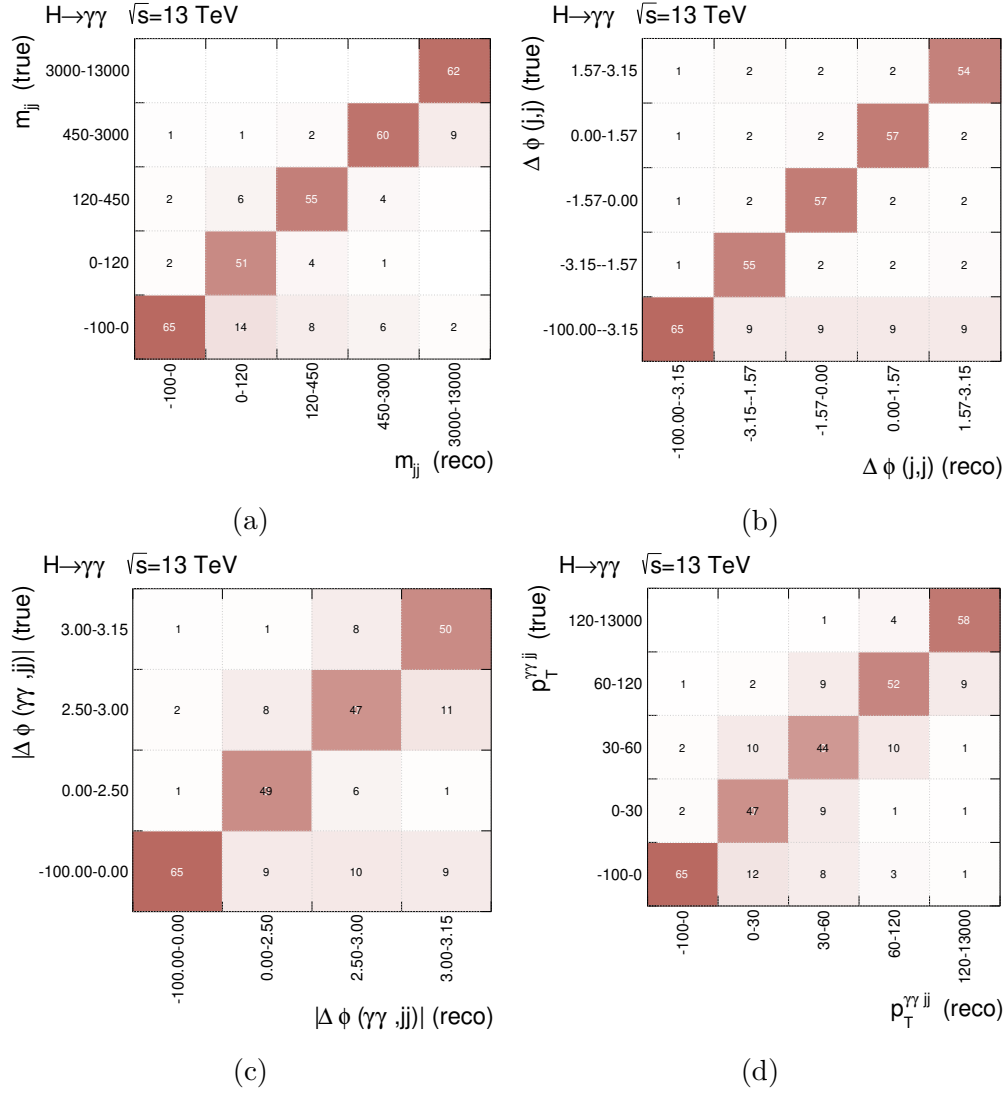


Figure A.100: Response matrices for (a) m_{jj} , (b) $\Delta\phi_{jj}$, (c) $|\Delta\phi_{\gamma\gamma,jj}|$, and (d) $p_T^{\gamma\gamma jj}$ differential variables. Bins with content less than 0.01 are not shown.

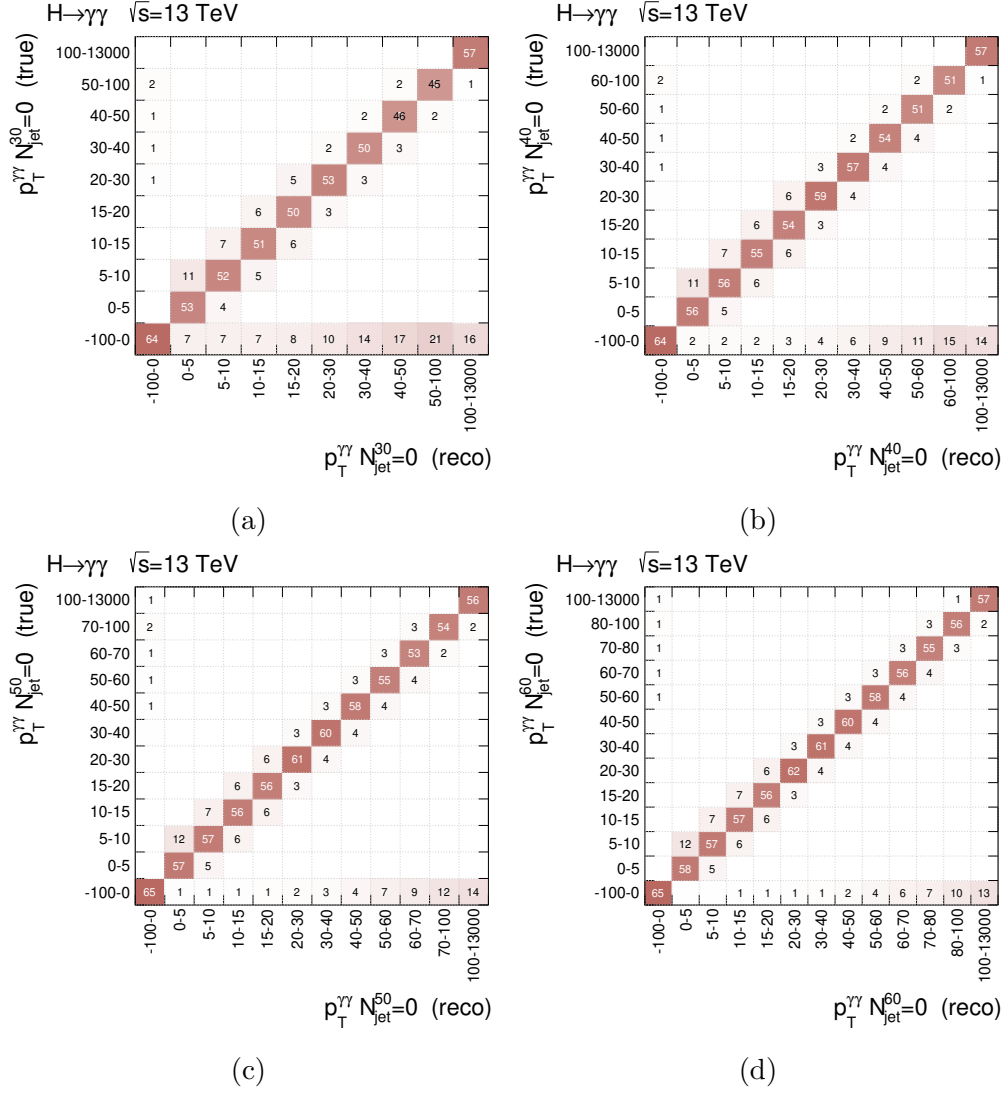


Figure A.101: Response matrices for the 1D $p_T^{\gamma\gamma}$ differential variables with a jet-veto, i.e. no jets with p_T above a certain threshold equal to (a) 30, (b) 40, (c) 50, and (d) 60 GeV. Bins with content less than 0.01 are not shown.

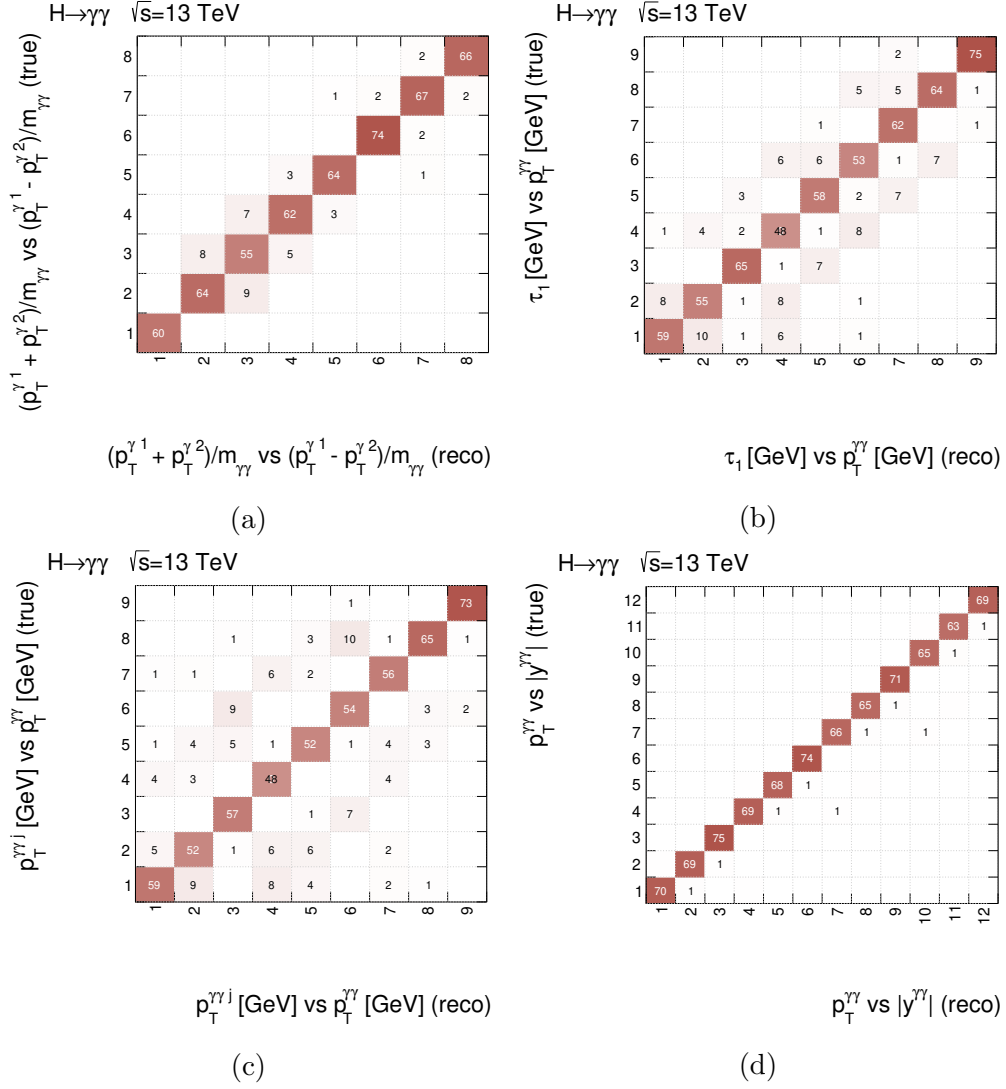


Figure A.102: Response matrices for (a) $(p_T^{\gamma 1} + p_T^{\gamma 2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma 1} - p_T^{\gamma 2})/m_{\gamma\gamma}$, (b) $p_T^{\gamma\gamma}$ vs $\tau_{C,j1}$, (c) $p_T^{\gamma\gamma j}$ vs $p_T^{\gamma\gamma}$, and (d) $p_T^{\gamma\gamma}$ vs $|y^{\gamma\gamma}|$ double differential variables. Bins with content less than 0.01 are not shown.

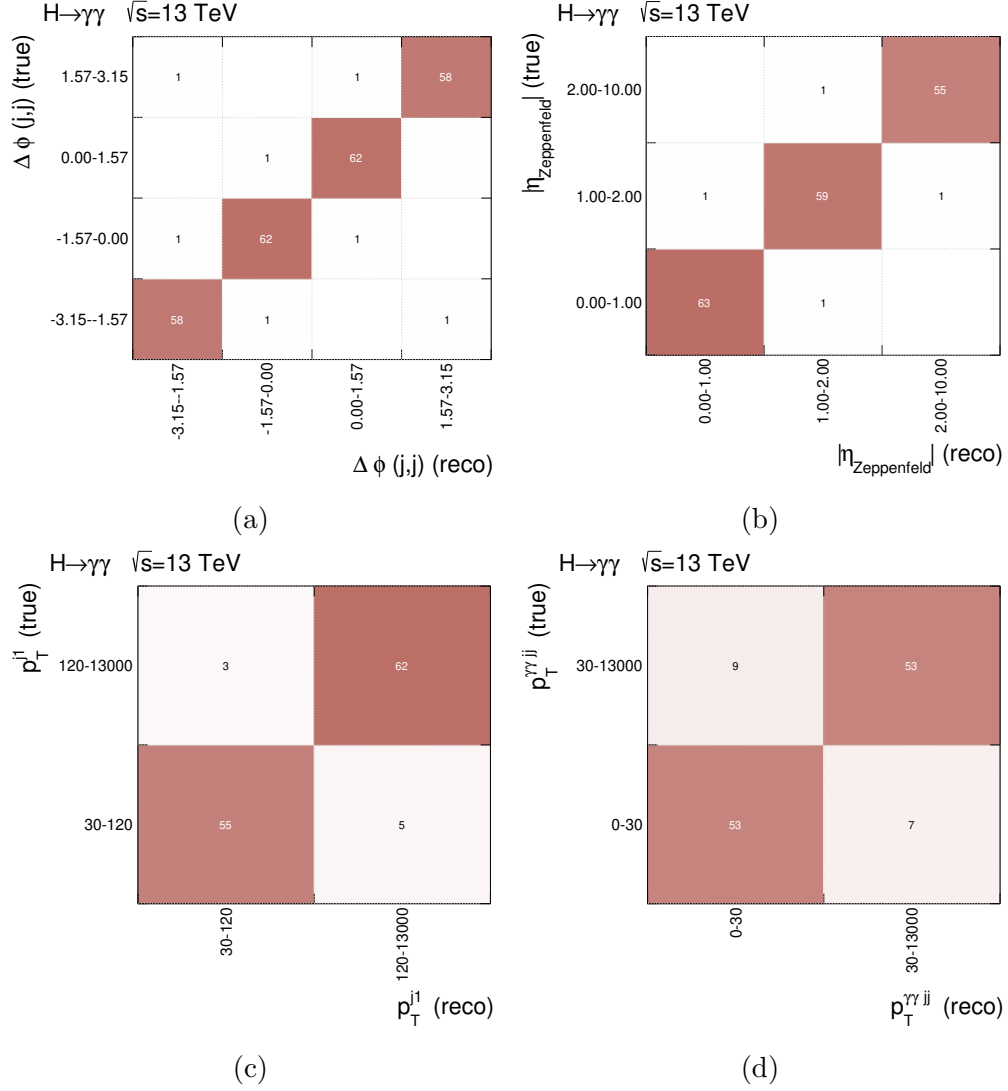


Figure A.103: Response matrices for the (a) $\Delta\phi_{jj}$, (b) $|\eta^*|$, (c) p_T^{j1} , and (d) $p_T^{\gamma\gamma jj}$ differential variables in the VBF-enhanced fiducial volume. Bins with content less than 0.01 are not shown.

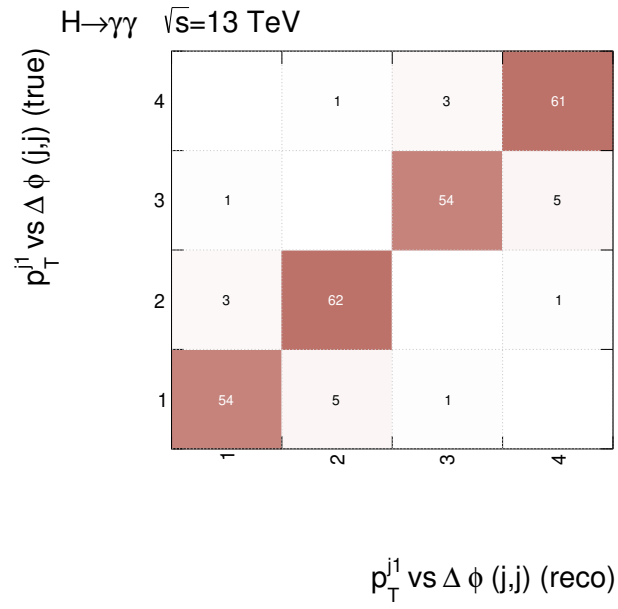


Figure A.104: Response matrices for the p_T^{j1} vs $\Delta\phi_{jj}$ double-differential variable in the VBF-enhanced fiducial volume. Bins with content less than 0.01 are not shown.

A.5 Uncertainty Sources

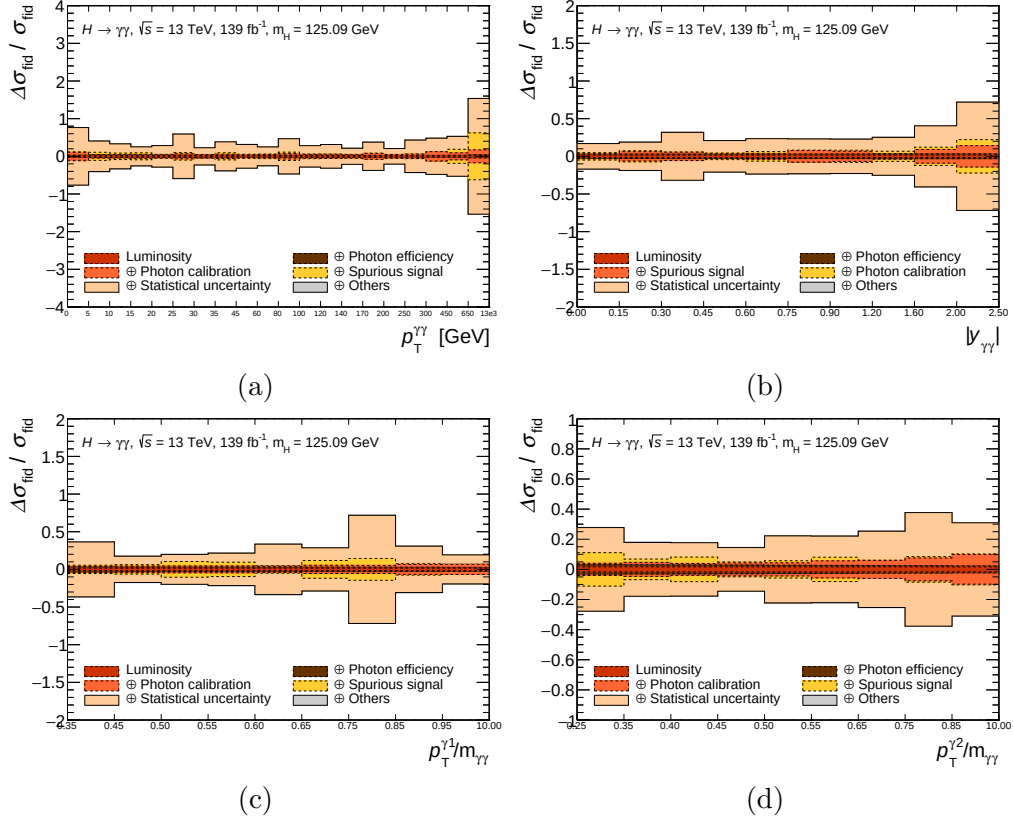


Figure A.105: Summary of the cross section uncertainties for (a) $p_T^{\gamma\gamma}$, (b) $|y^{\gamma\gamma}|$, (c) $p_T^{\gamma 1}/m_{\gamma\gamma}$, and (d) $p_T^{\gamma 2}/m_{\gamma\gamma}$ differential variables.

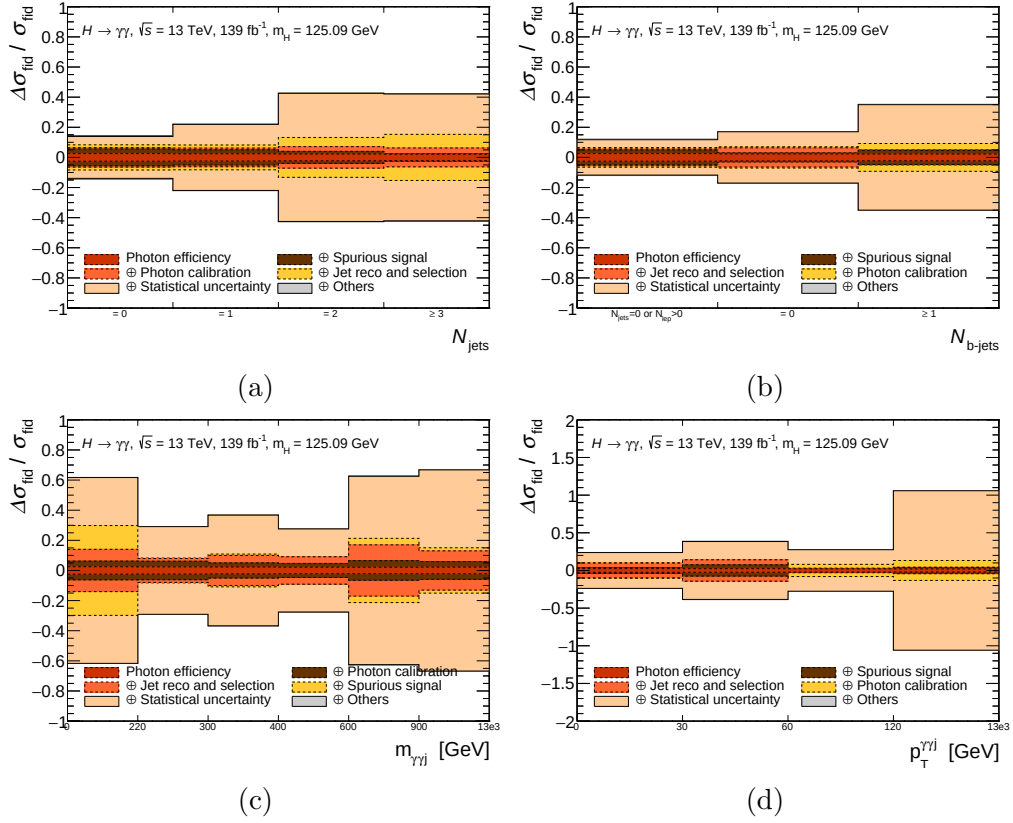


Figure A.106: Summary of the cross section uncertainties for (a) N_{jets} , (b) $N_{\text{b-jets}}$, (c) $m_{\gamma\gamma j}$, and (d) $p_T^{\gamma j}$ differential variables.

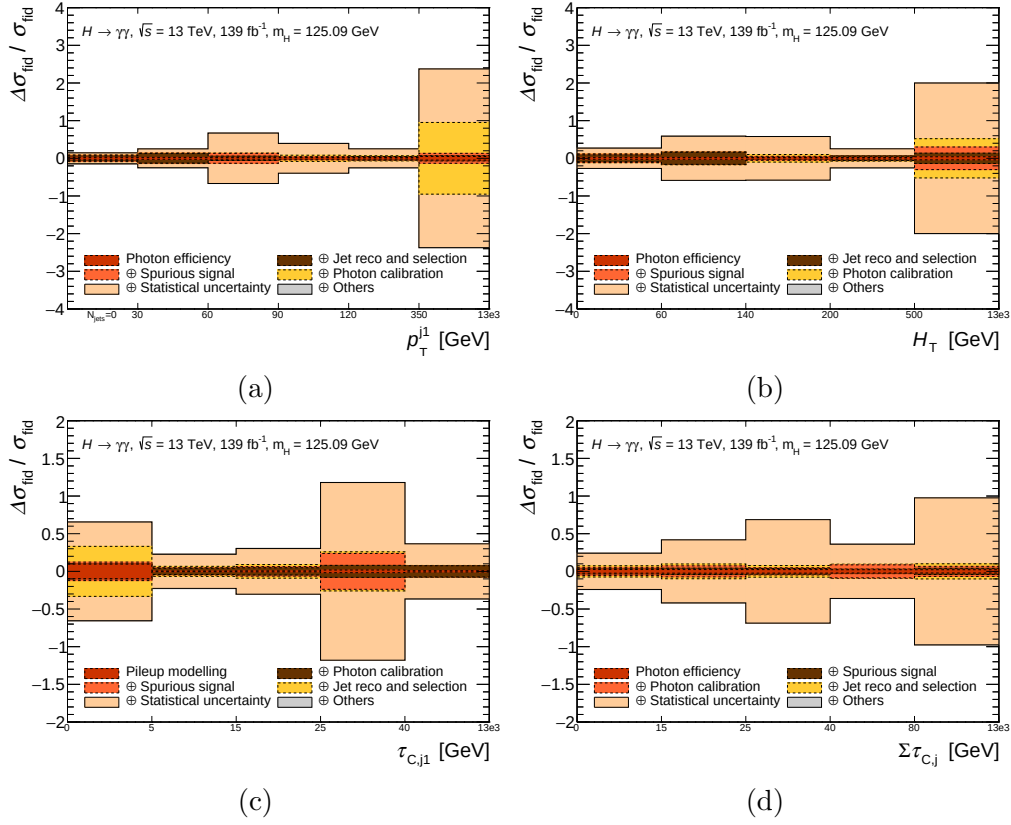


Figure A.107: Summary of the cross section uncertainties for (a) p_T^{j1} , (b) H_T , (c) $\tau_{C,j1}$, and (d) $\Sigma \tau_{C,j}$ differential variables.

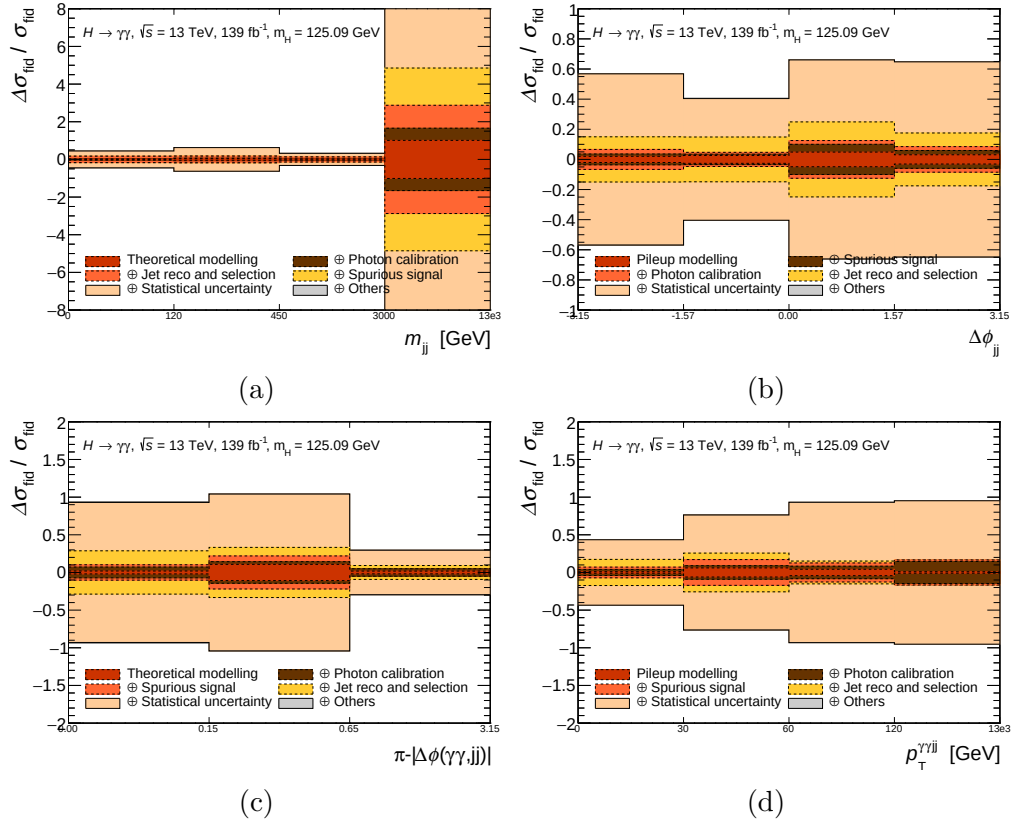


Figure A.108: Summary of the cross section uncertainties for (a) m_{jj} , (b) $\Delta\phi_{jj}$, (c) $|\Delta\phi_{\gamma\gamma,jj}|$, and (d) $p_T^{\gamma\gamma jj}$ differential variables.

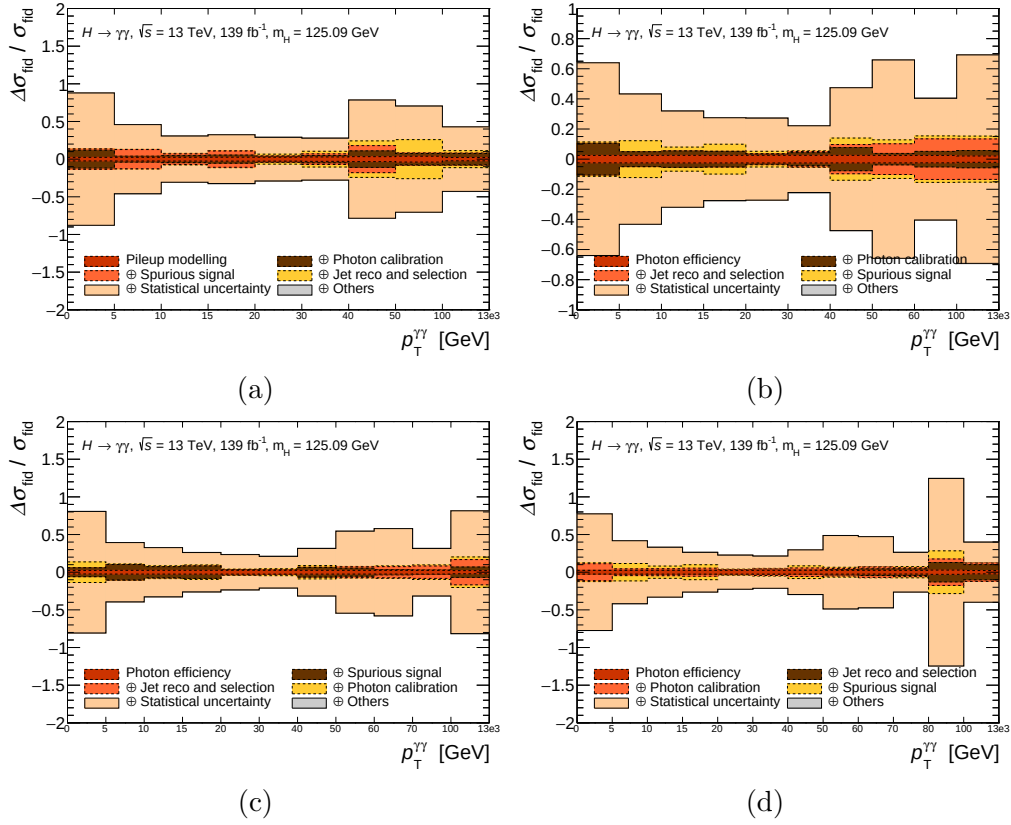


Figure A.109: Summary of the cross section uncertainties for the $p_T^{\gamma\gamma}$ differential variables with a jet-veto, i.e. no jets with p_T above a certain threshold equal to (a) 30, (b) 40, (c) 50, and (d) 60 GeV.

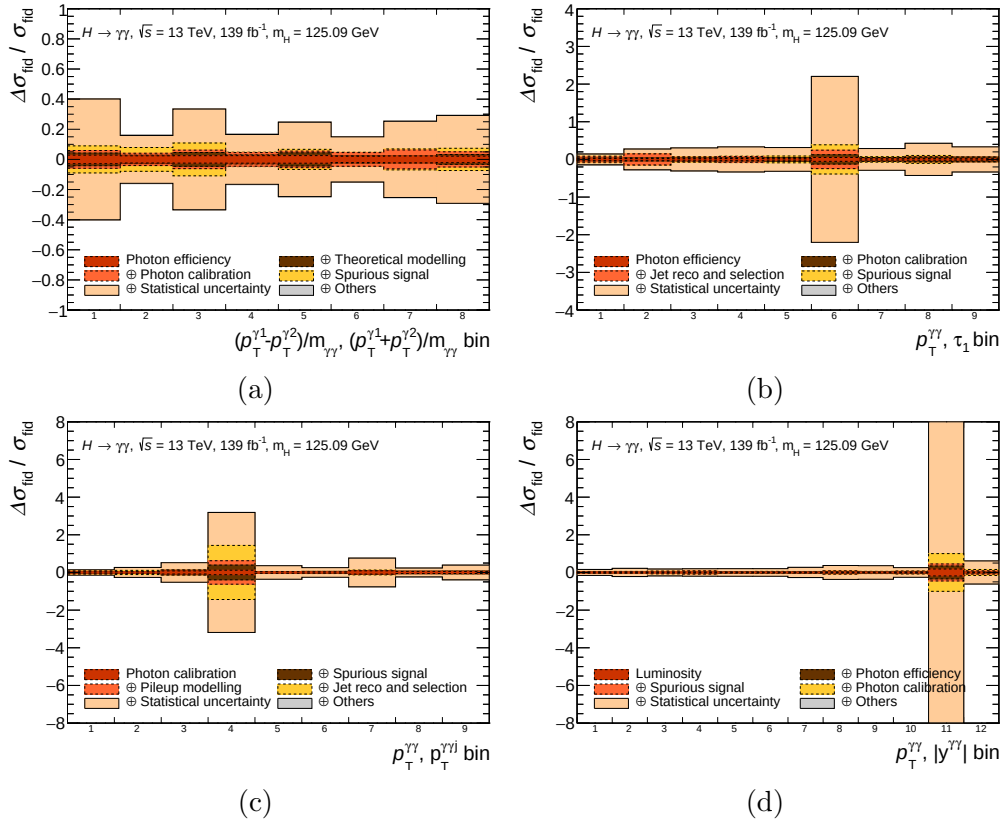


Figure A.110: Summary of the cross section uncertainties for (a) $(p_T^{\gamma 1} + p_T^{\gamma 2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma 1} - p_T^{\gamma 2})/m_{\gamma\gamma}$, (b) $p_T^{\gamma\gamma}$ vs $\tau_{C,j1}$, (c) $p_T^{\gamma\gamma}$ vs $p_T^{\gamma j}$, and (d) $p_T^{\gamma\gamma}$ vs $|y^{\gamma\gamma}|$ double differential variables.

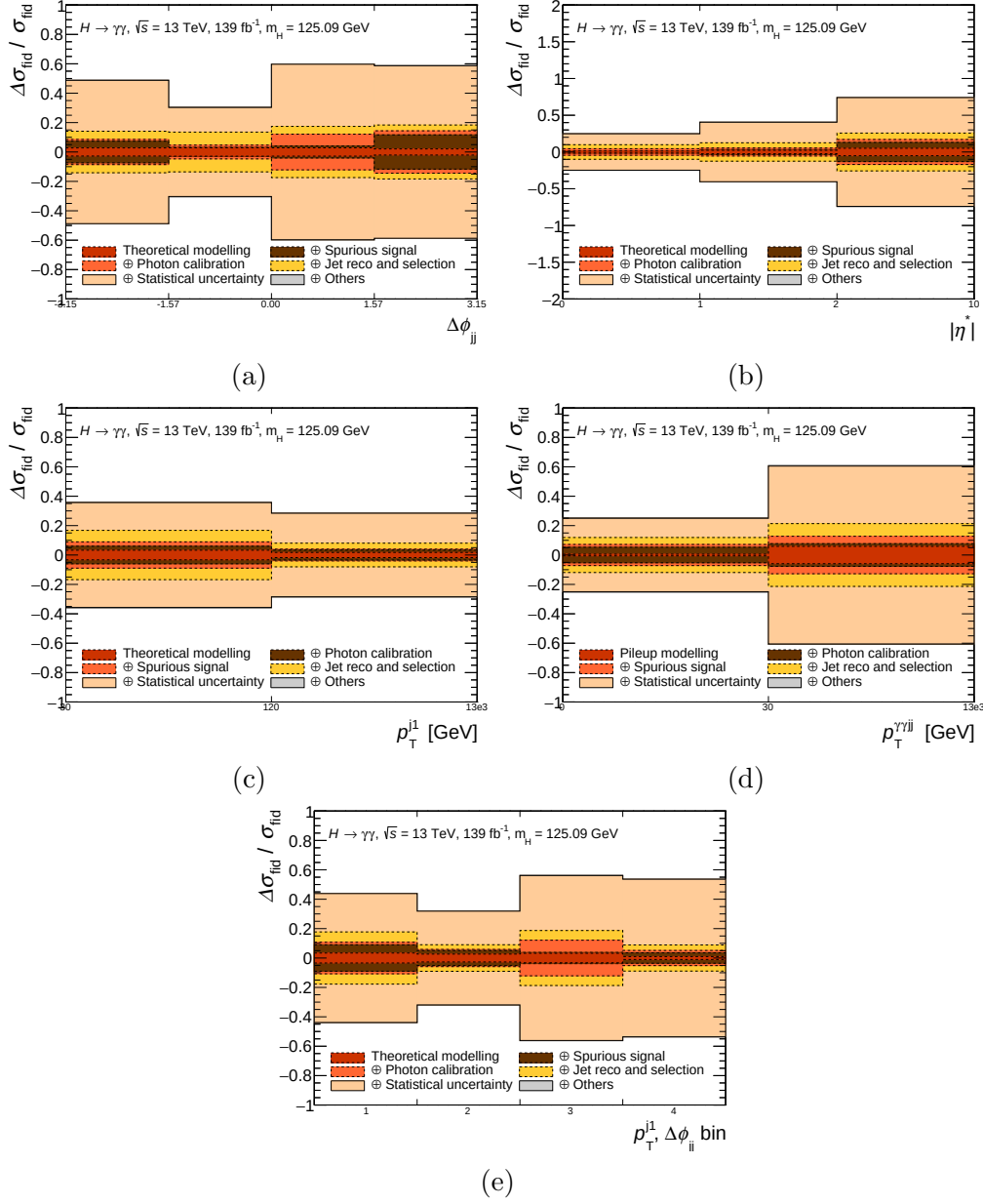


Figure A.111: Summary of the cross section uncertainties for the (a) $\Delta\phi_{jj}$, (b) $|\eta^*|$, (c) p_T^{j1} , (d) $p_T^{\gamma\gamma jj}$, and (e) p_T^{j1} vs $\Delta\phi_{jj}$ differential variables in the VBF-enhanced fiducial volume.

A.6 Data Yield Fits

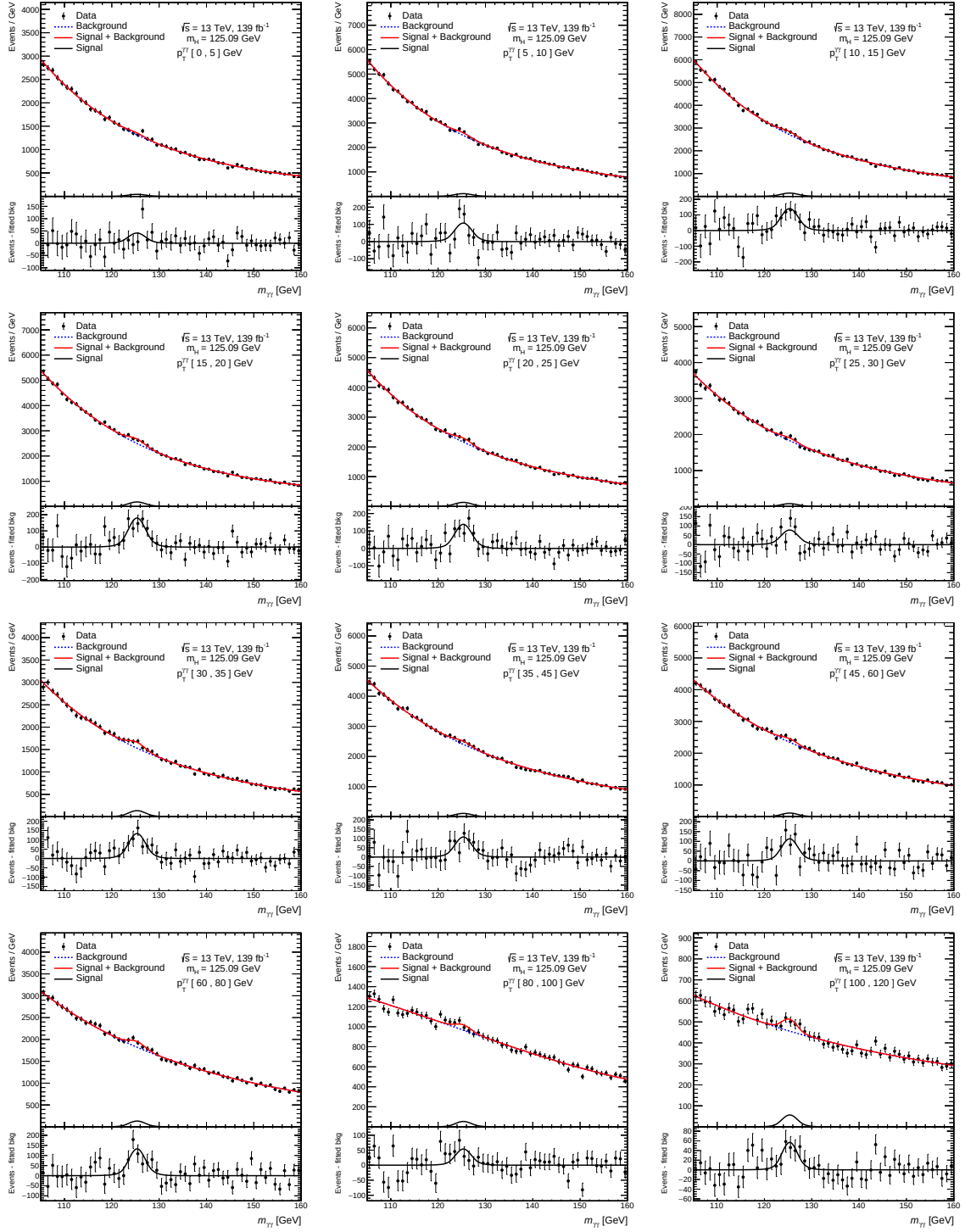


Figure A.112: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma}$ bins. (Continued on next page.)

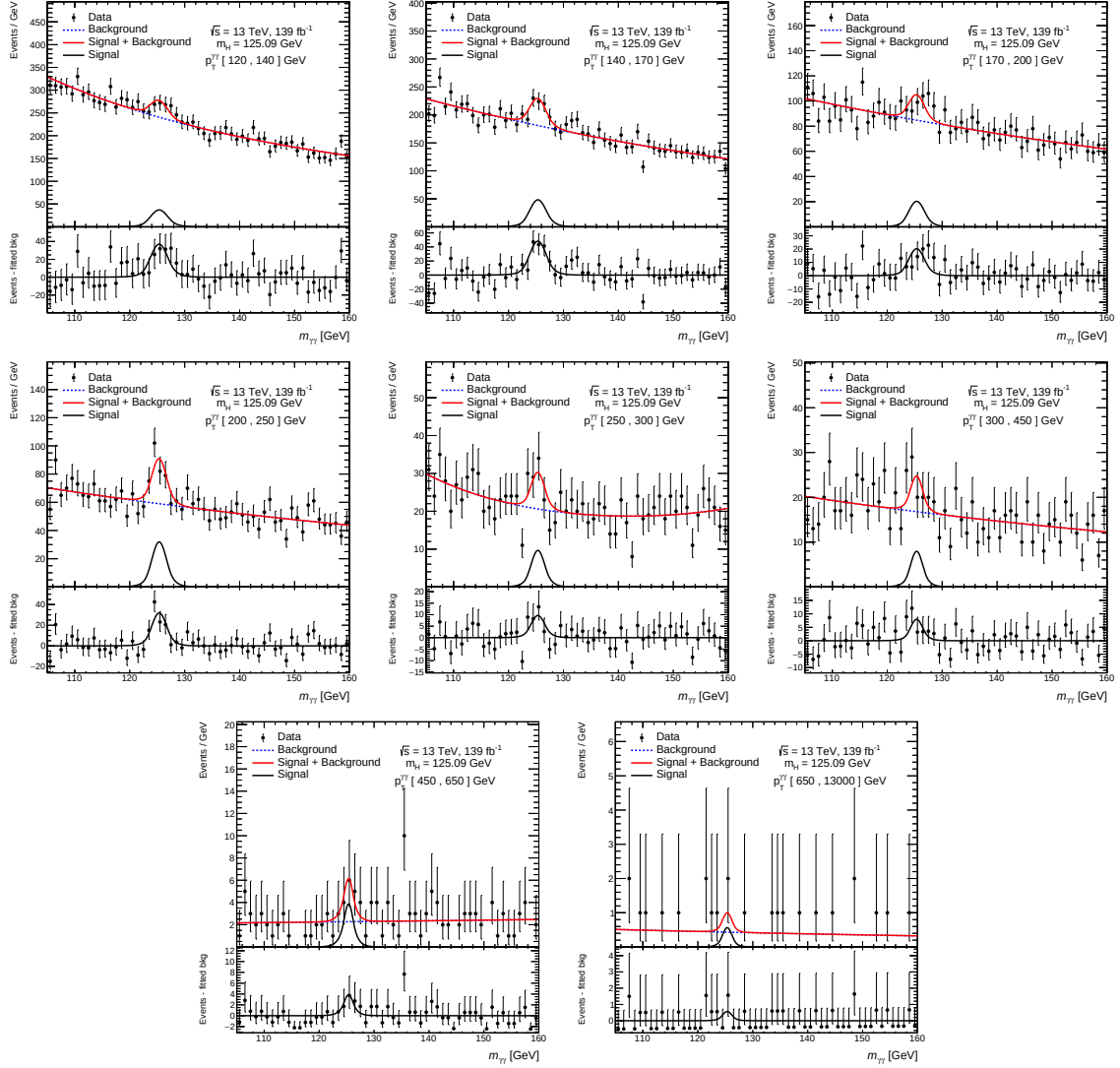
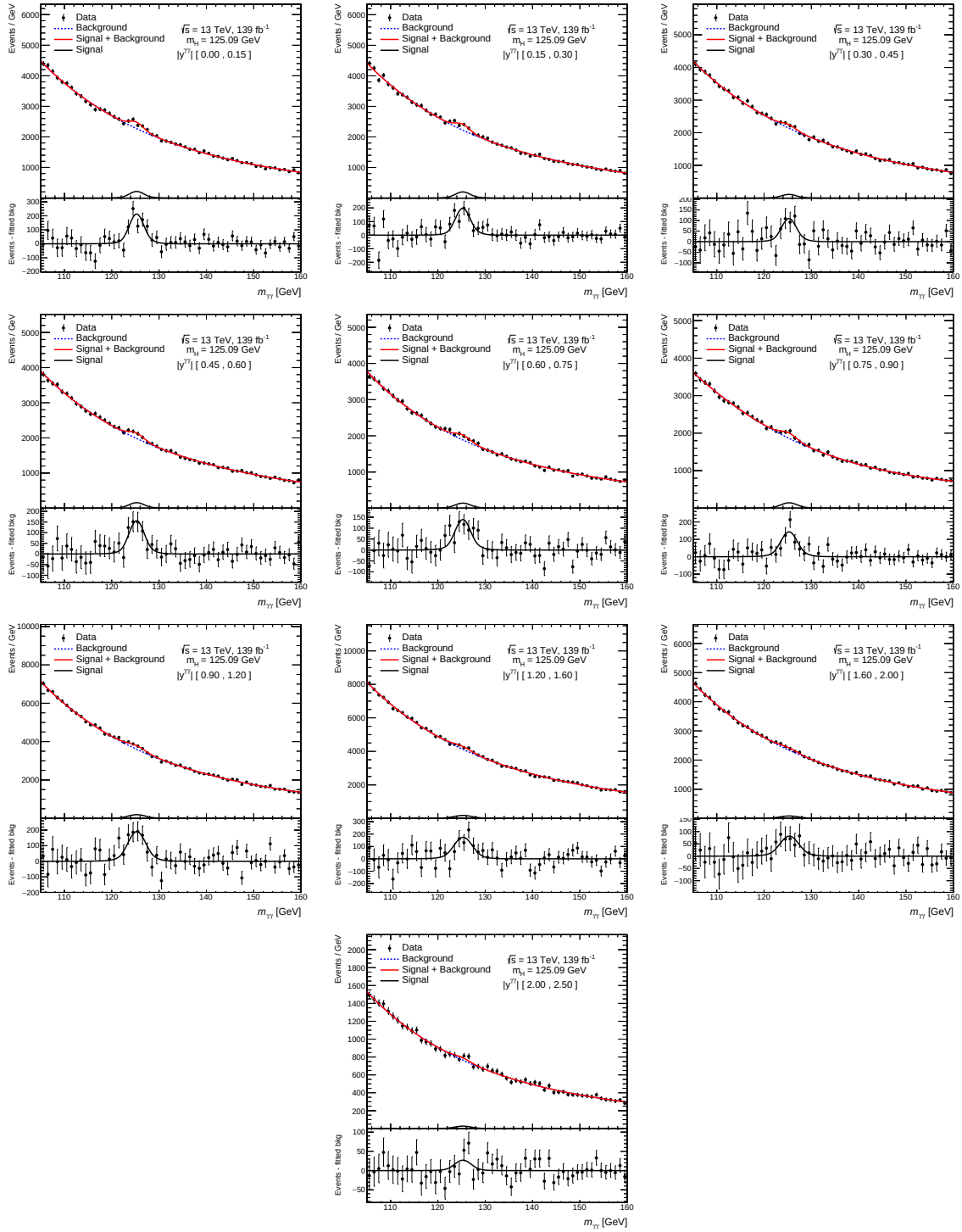


Figure A.113: Continuation of the diphoton invariant mass fits in each of the p_T^γ bins.

Figure A.114: Diphoton invariant mass fits in each of the $|y^{\gamma\gamma}|$ bins.

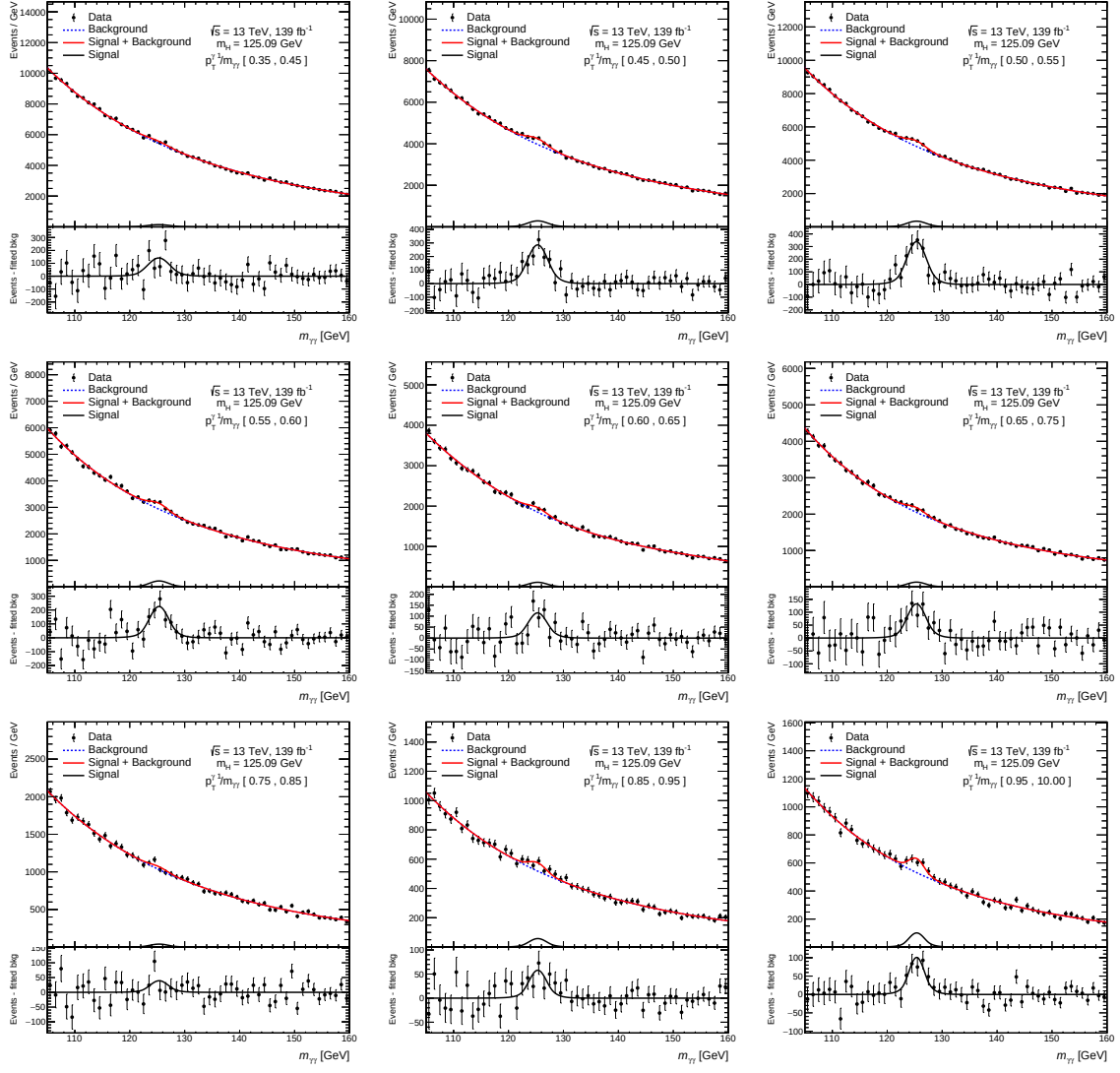


Figure A.115: Diphoton invariant mass fits in each of the $p_T^\gamma/m_{\gamma\gamma}$ bins.

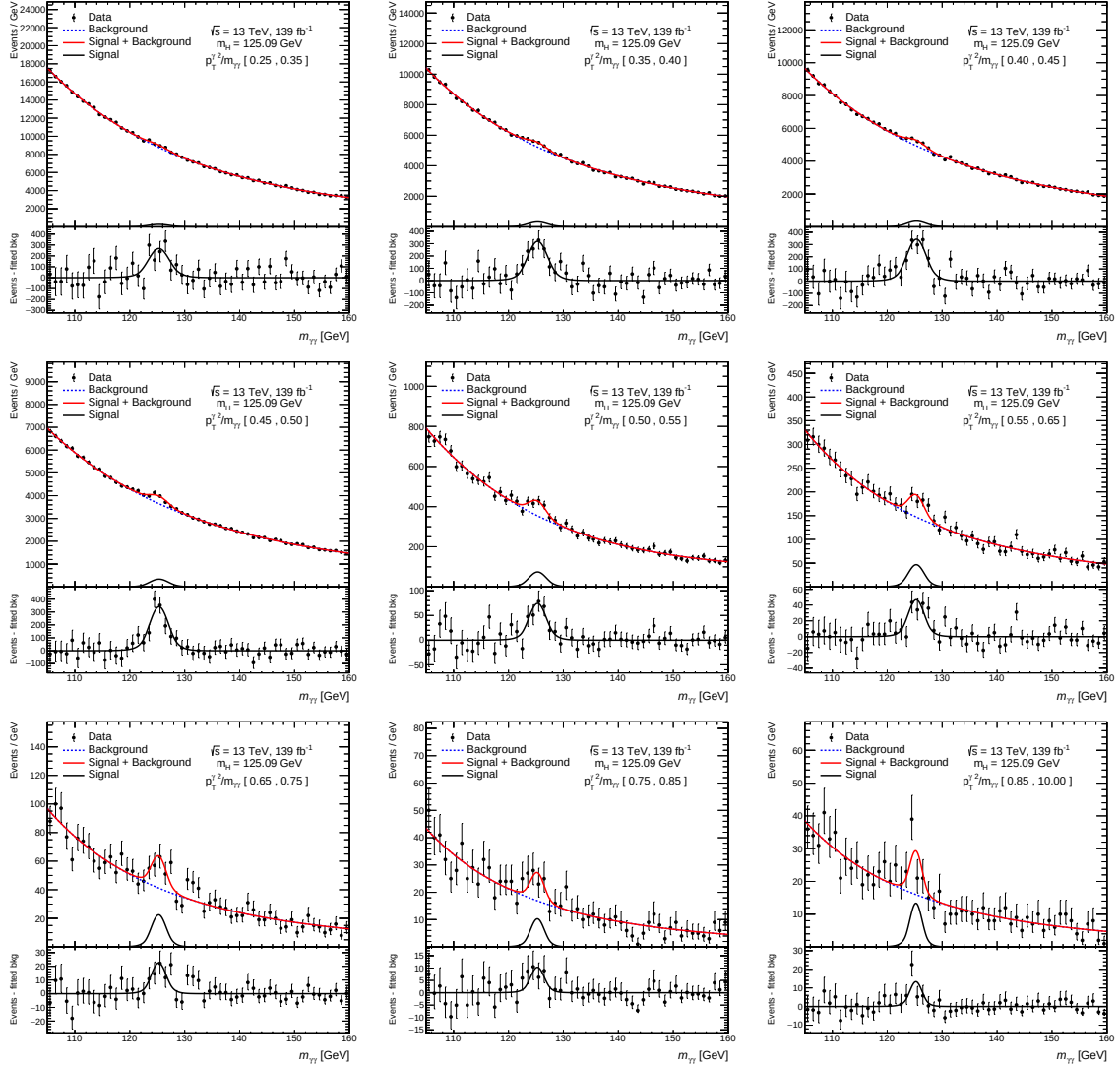


Figure A.116: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma}/m_{\gamma\gamma}$ bins.

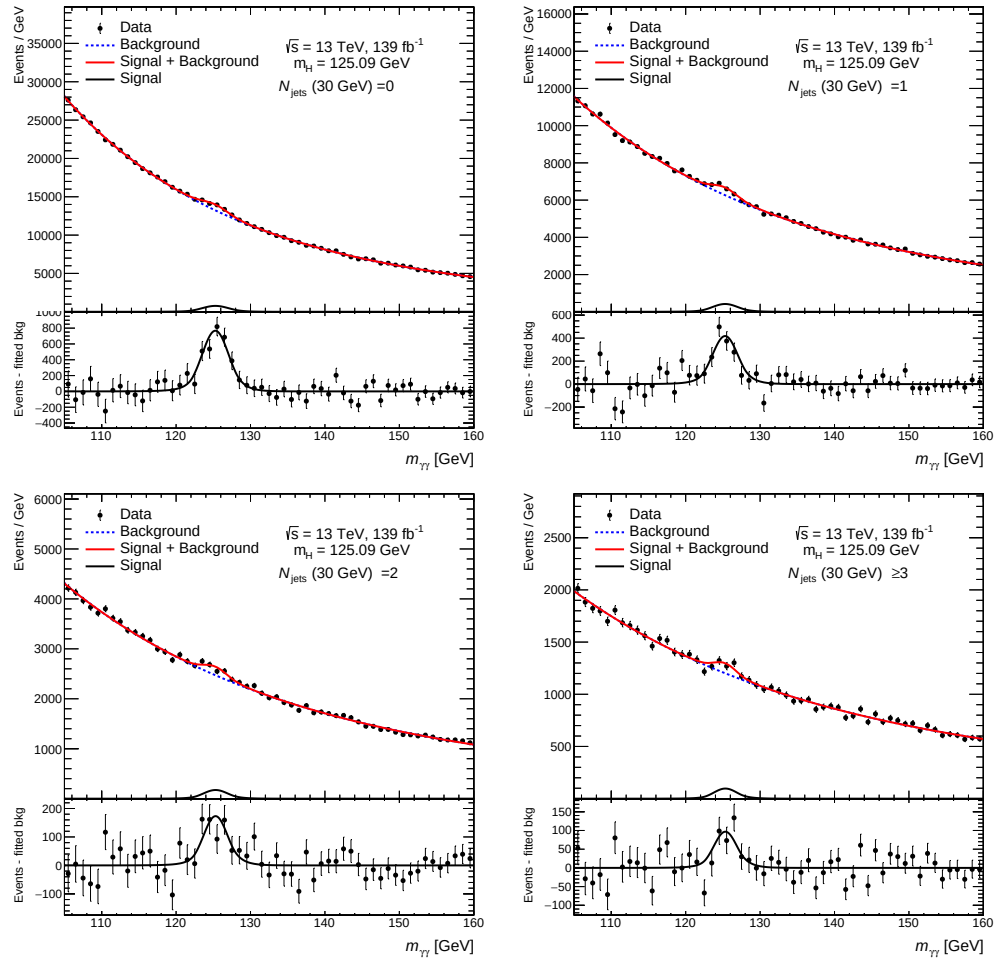


Figure A.117: Diphoton invariant mass fits in each of the N_{jets} bins.

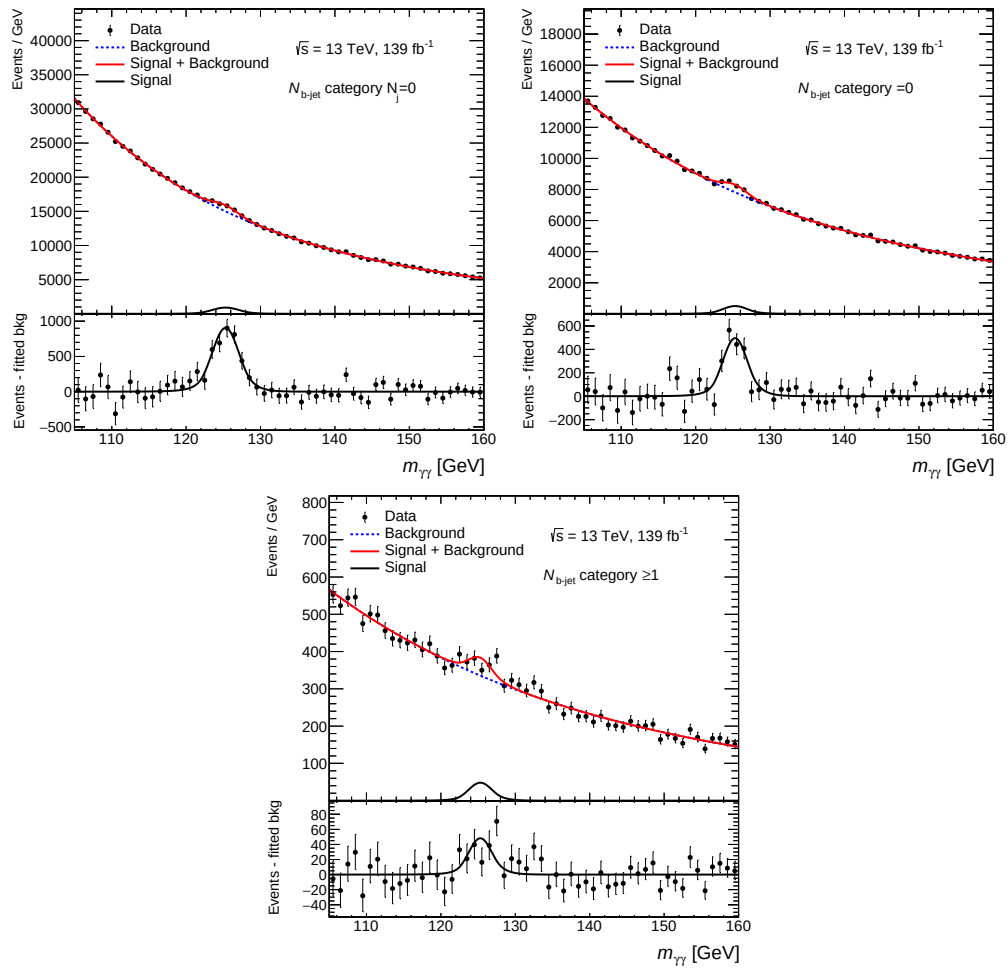


Figure A.118: Diphoton invariant mass fits in each of the $N_{b\text{-jets}}$ bins.

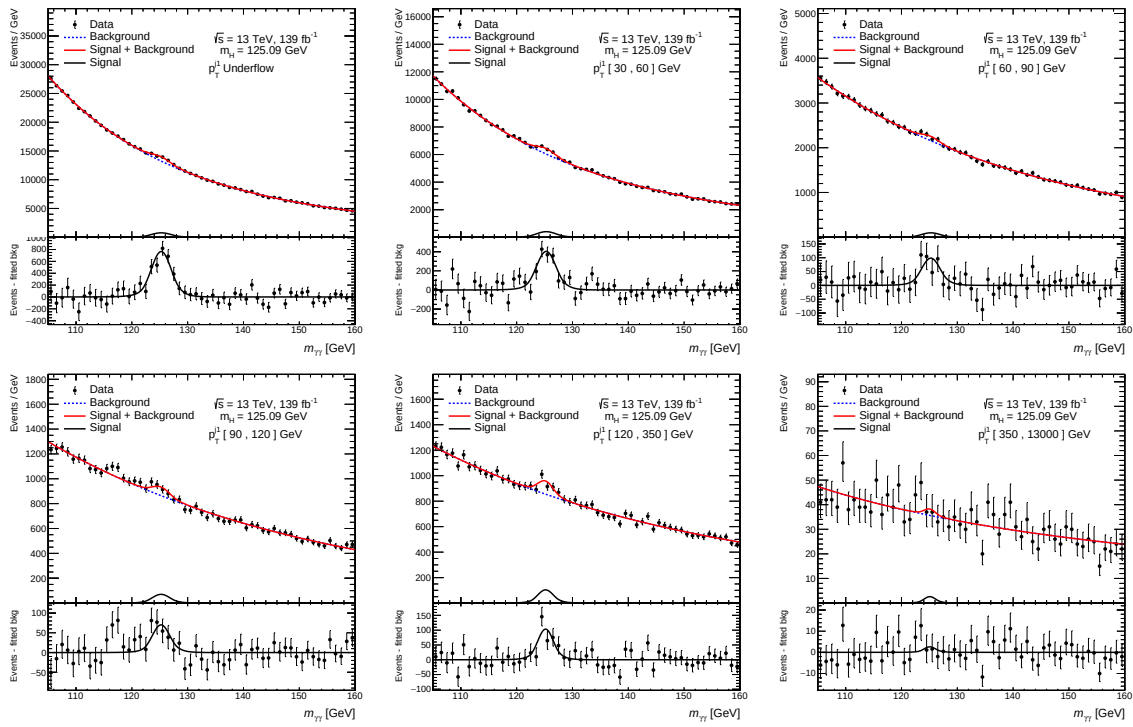


Figure A.119: Diphoton invariant mass fits in each of the p_T^{j1} bins.

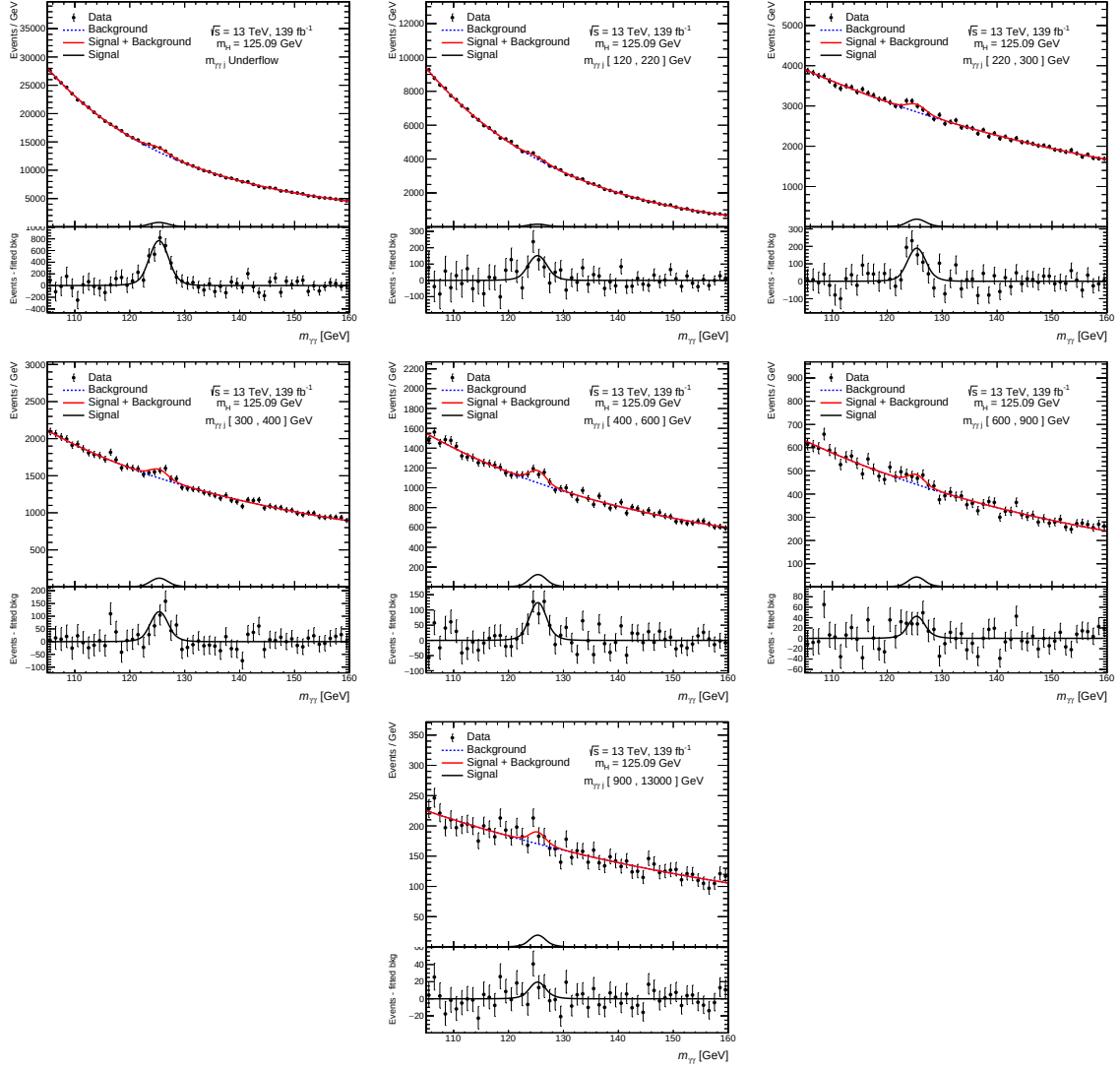


Figure A.120: Diphoton invariant mass fits in each of the $m_{\gamma\gamma}$ bins.

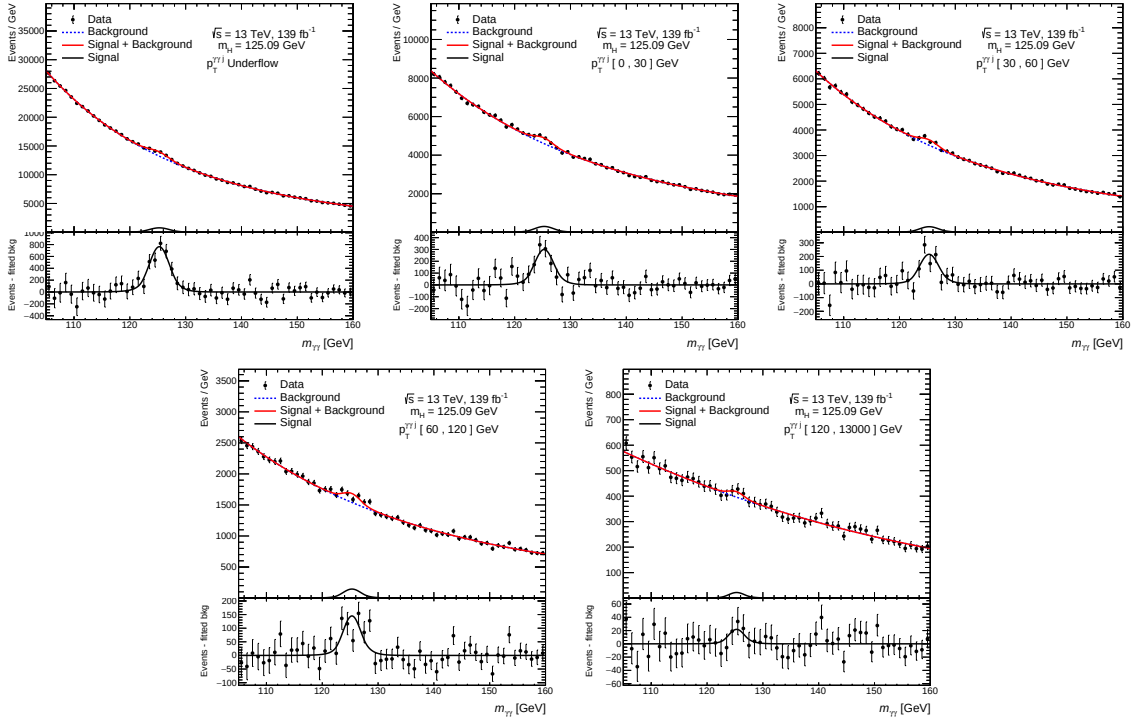


Figure A.121: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma}$ bins.

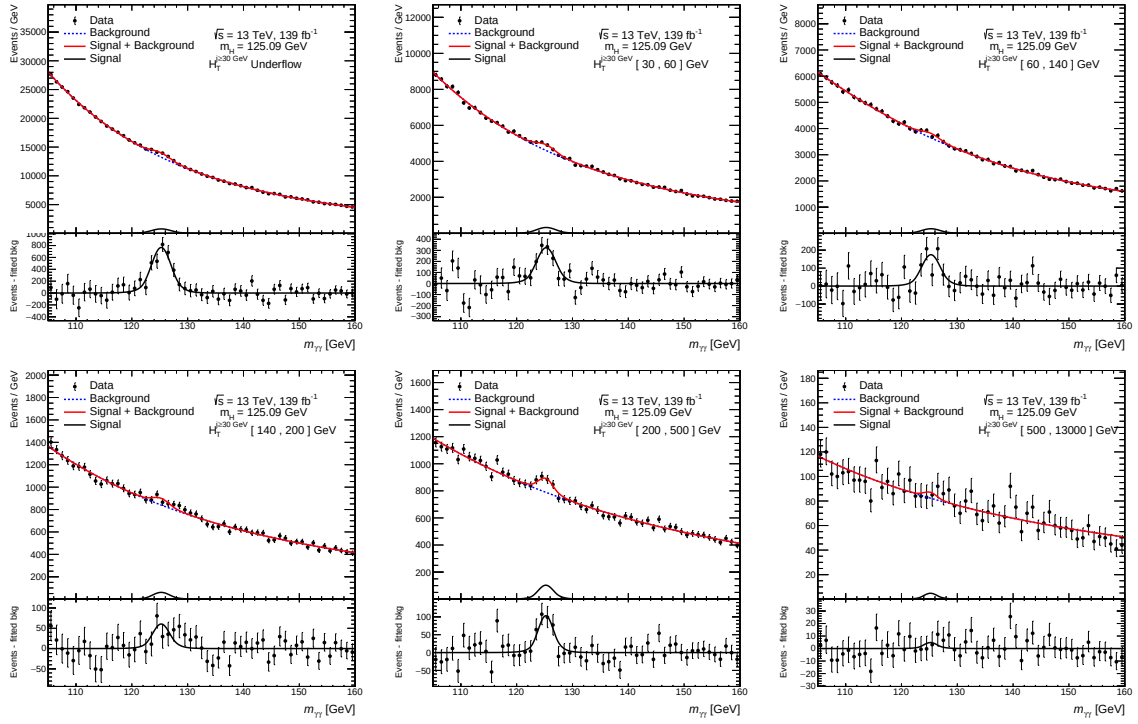


Figure A.122: Diphoton invariant mass fits in each of the H_T bins.

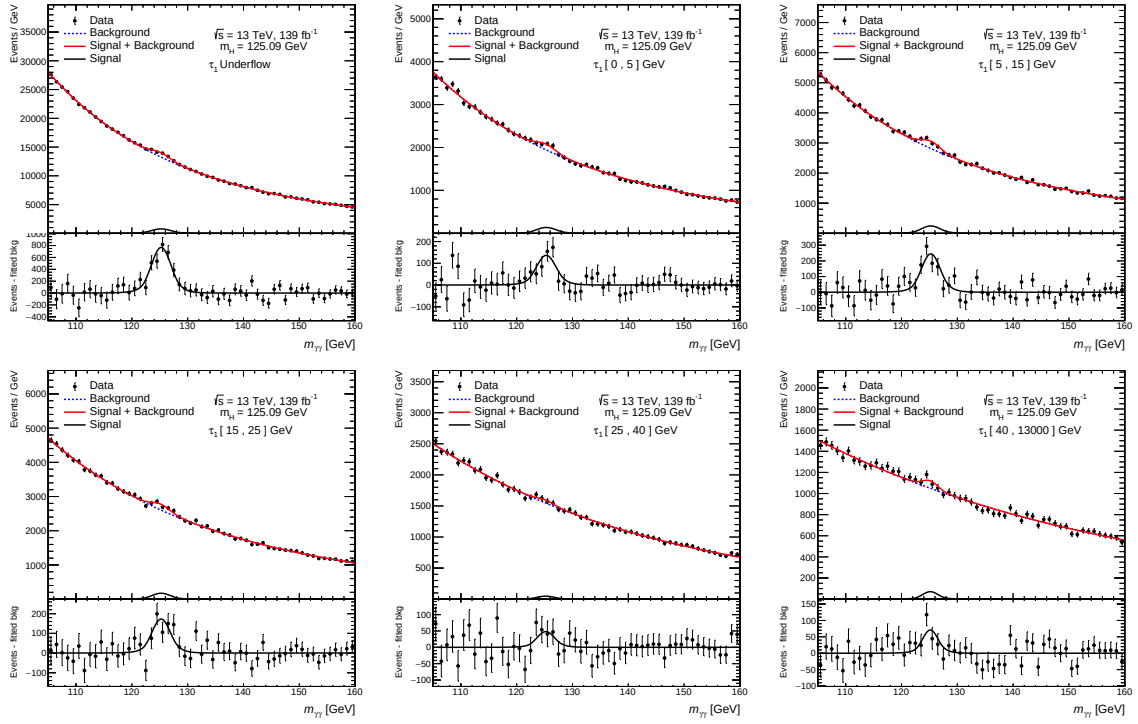


Figure A.123: Diphoton invariant mass fits in each of the τ_{C,j_1} bins.

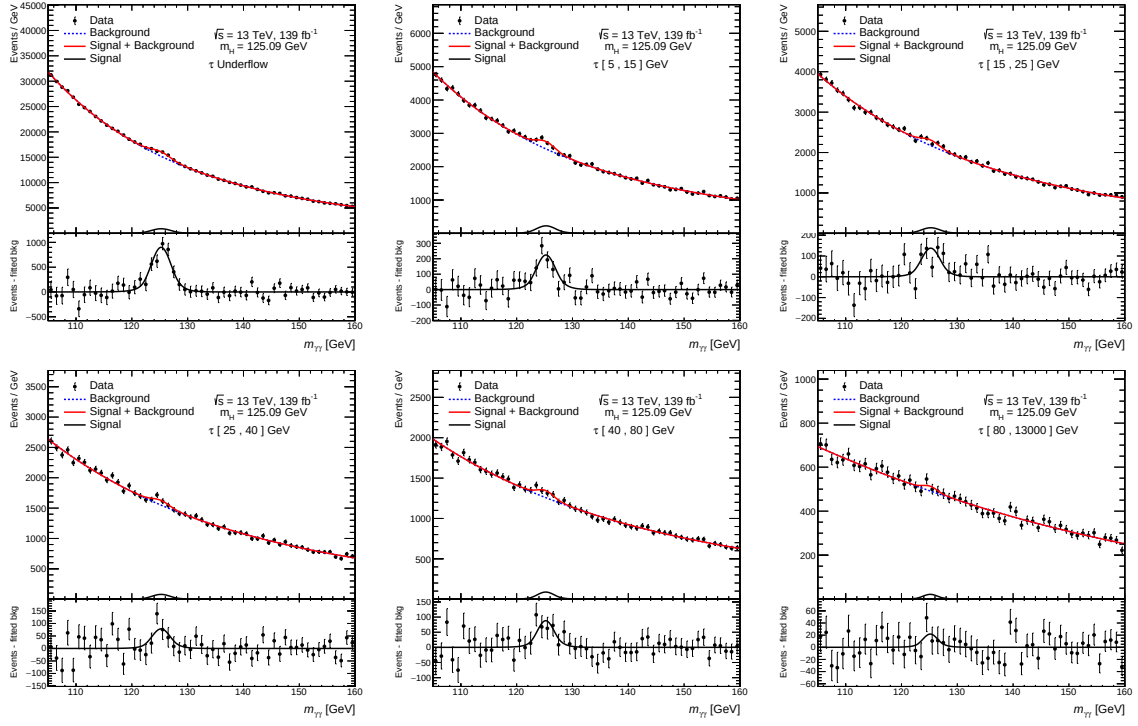


Figure A.124: Diphoton invariant mass fits in each of the $\Sigma\tau_{C,j}$ bins.

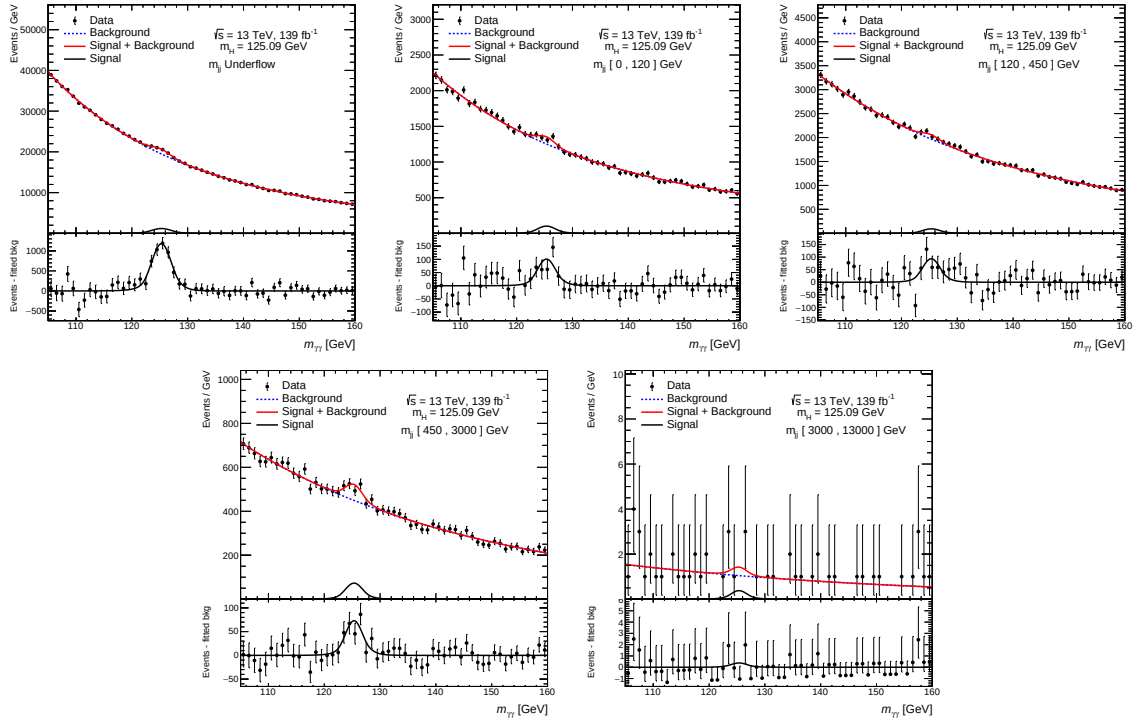


Figure A.125: Diphoton invariant mass fits in each of the m_{jj} bins.

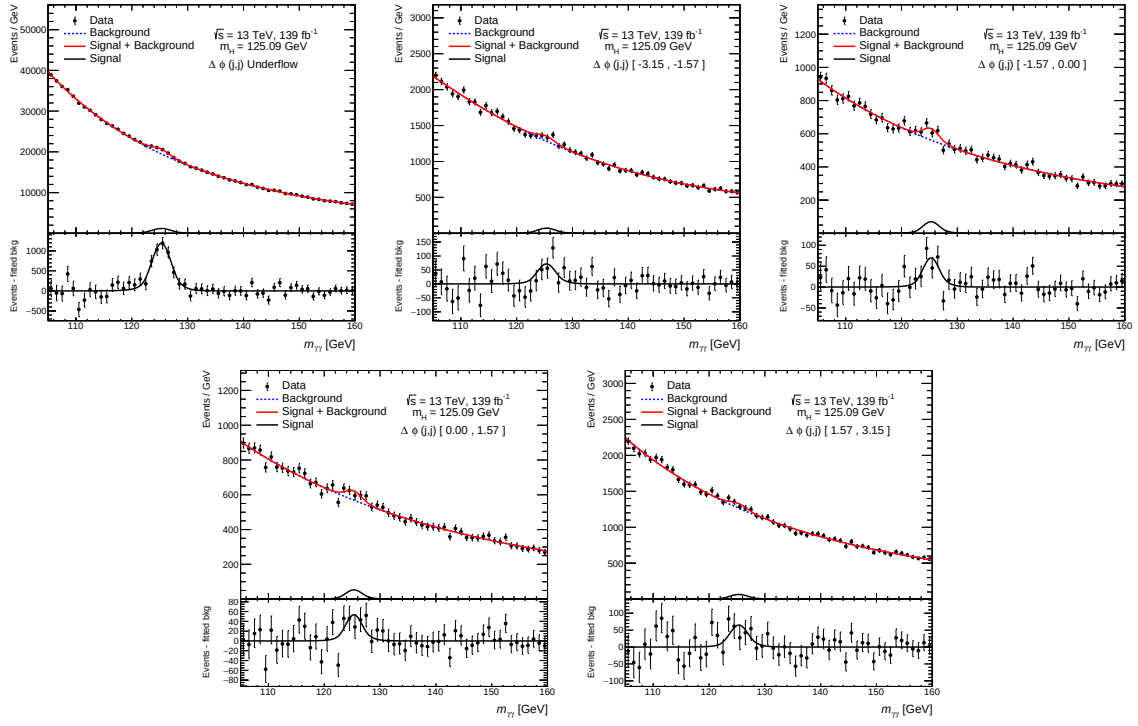


Figure A.126: Diphoton invariant mass fits in each of the $\Delta\phi_{jj}$ bins.

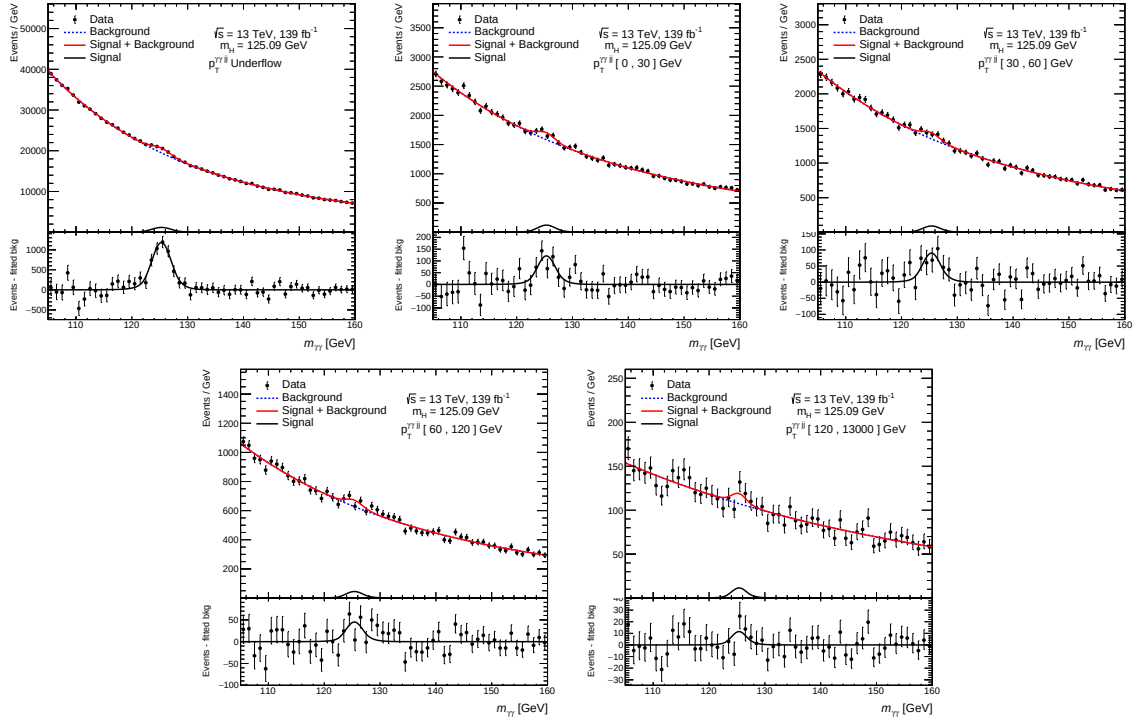


Figure A.127: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma jj}$ bins.

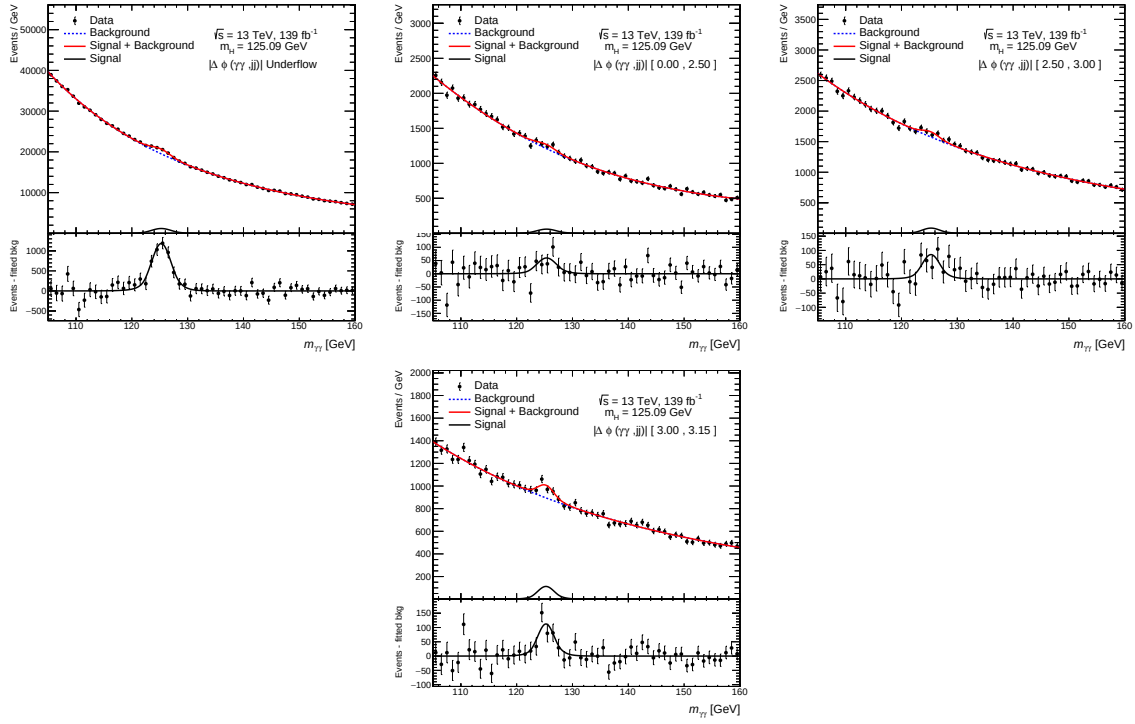


Figure A.128: Diphoton invariant mass fits in each of the $|\Delta\phi_{\gamma\gamma,jj}|$ bins.

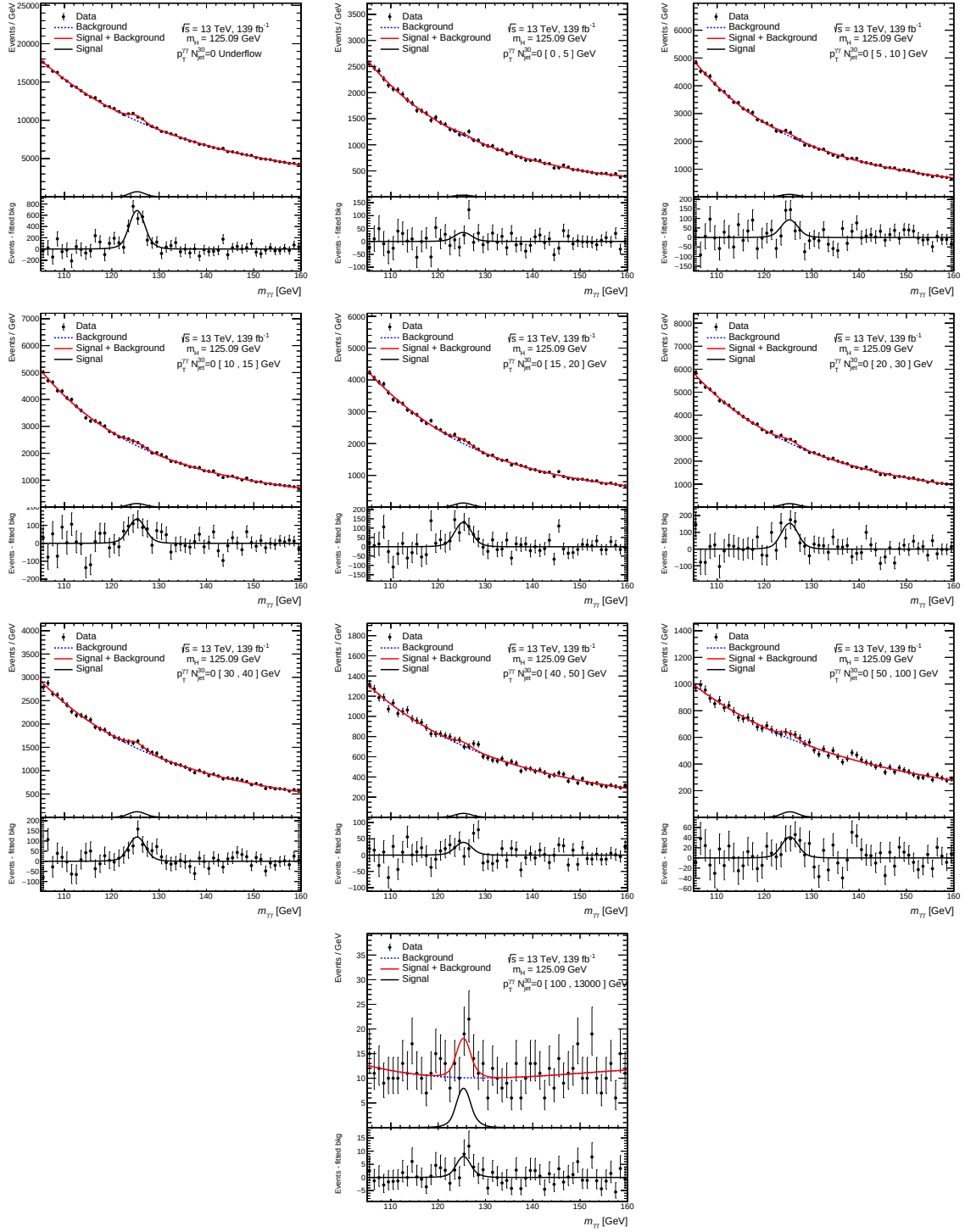


Figure A.129: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma}$, jet veto 30 bins.

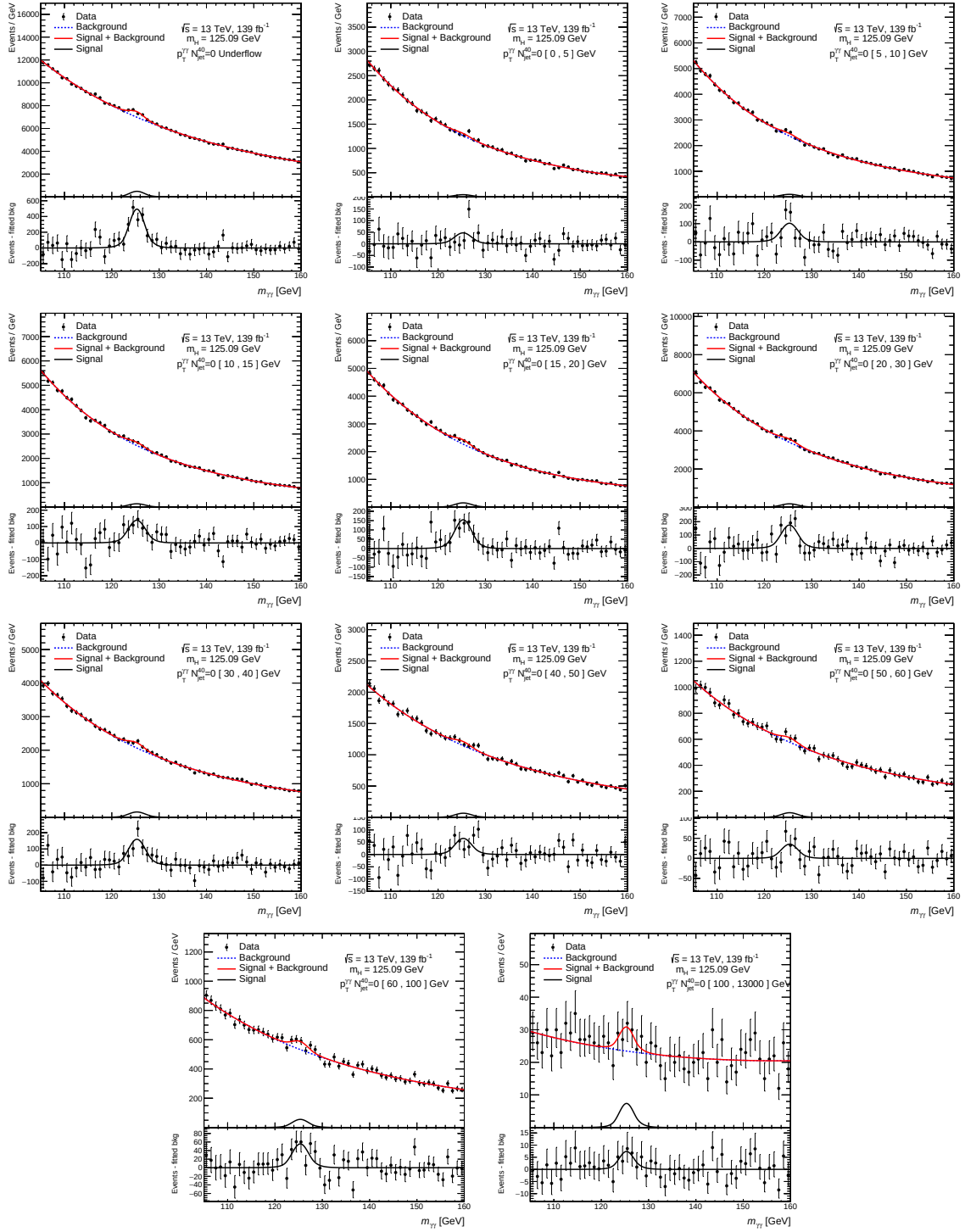


Figure A.130: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma}$, jet veto 40 bins.

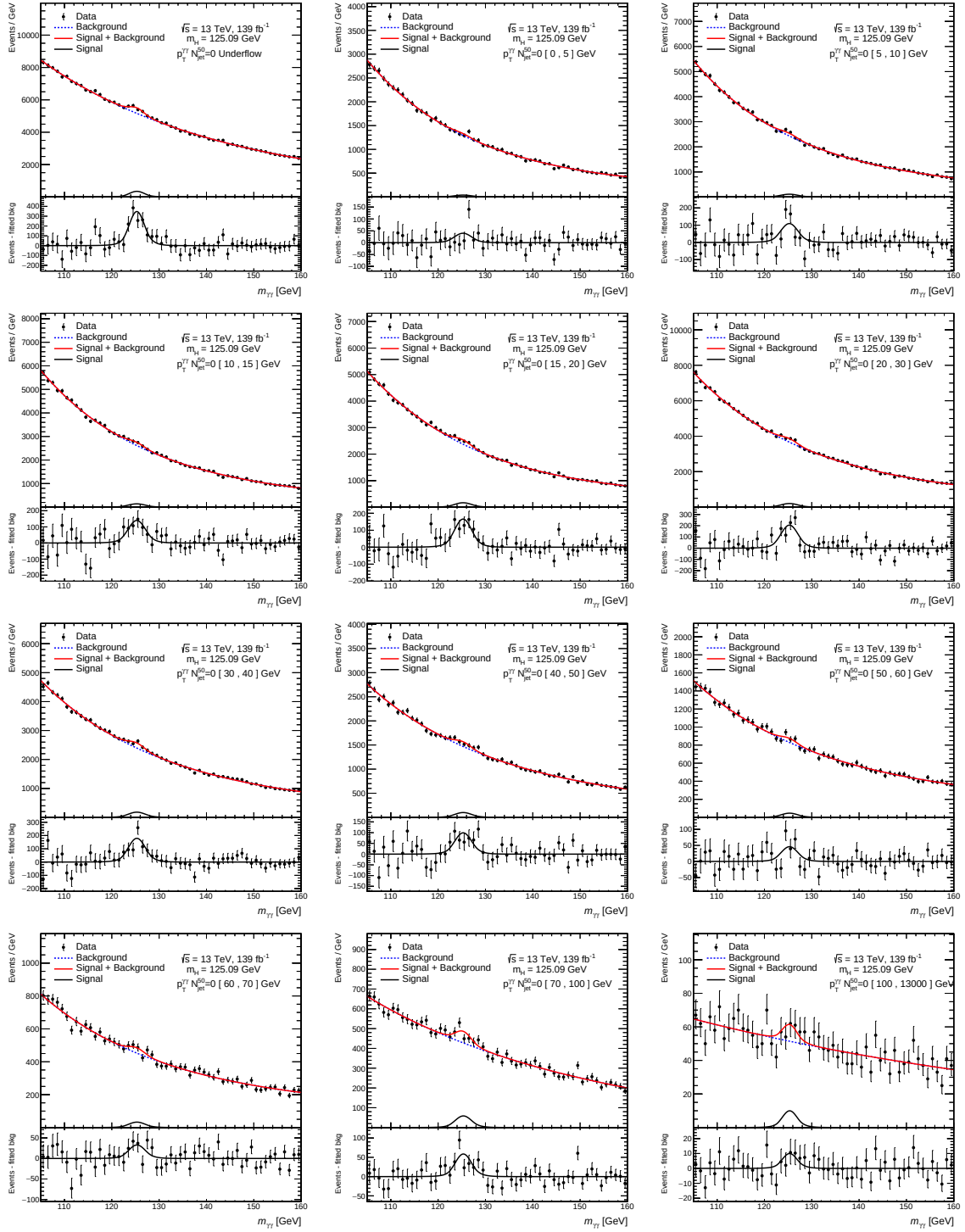


Figure A.131: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma, \text{jet veto } 50}$ bins.

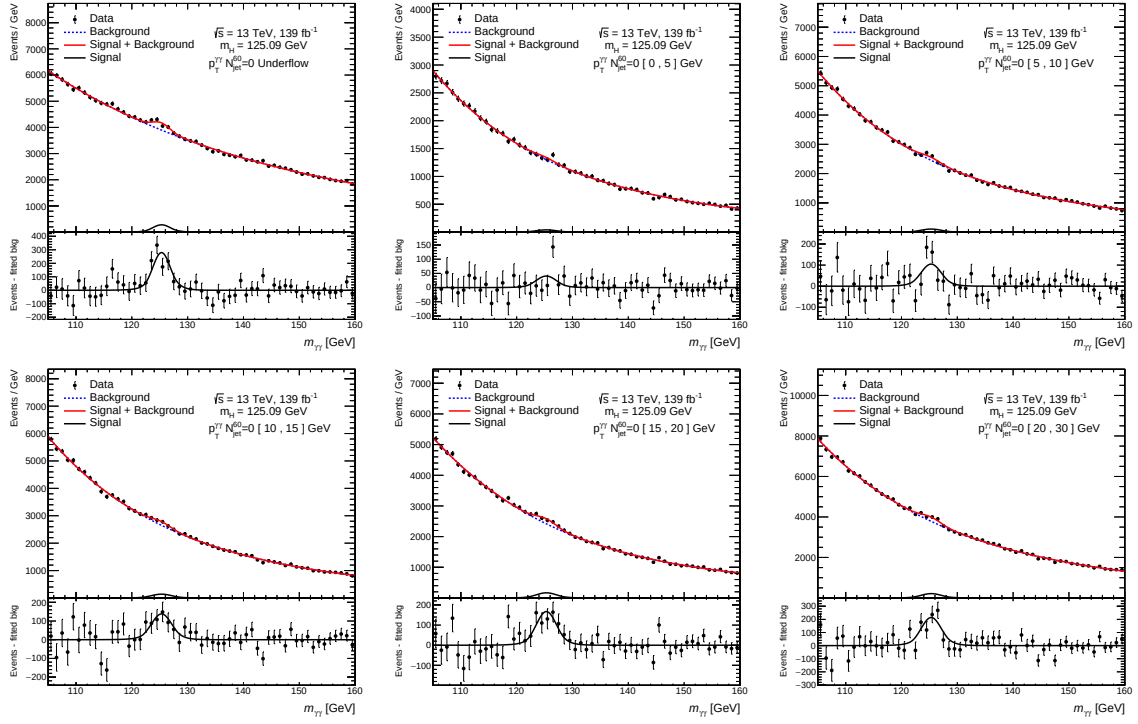


Figure A.132: Diphoton invariant mass fits in the first six $p_T^{\gamma\gamma}$, jet veto 60 bins.

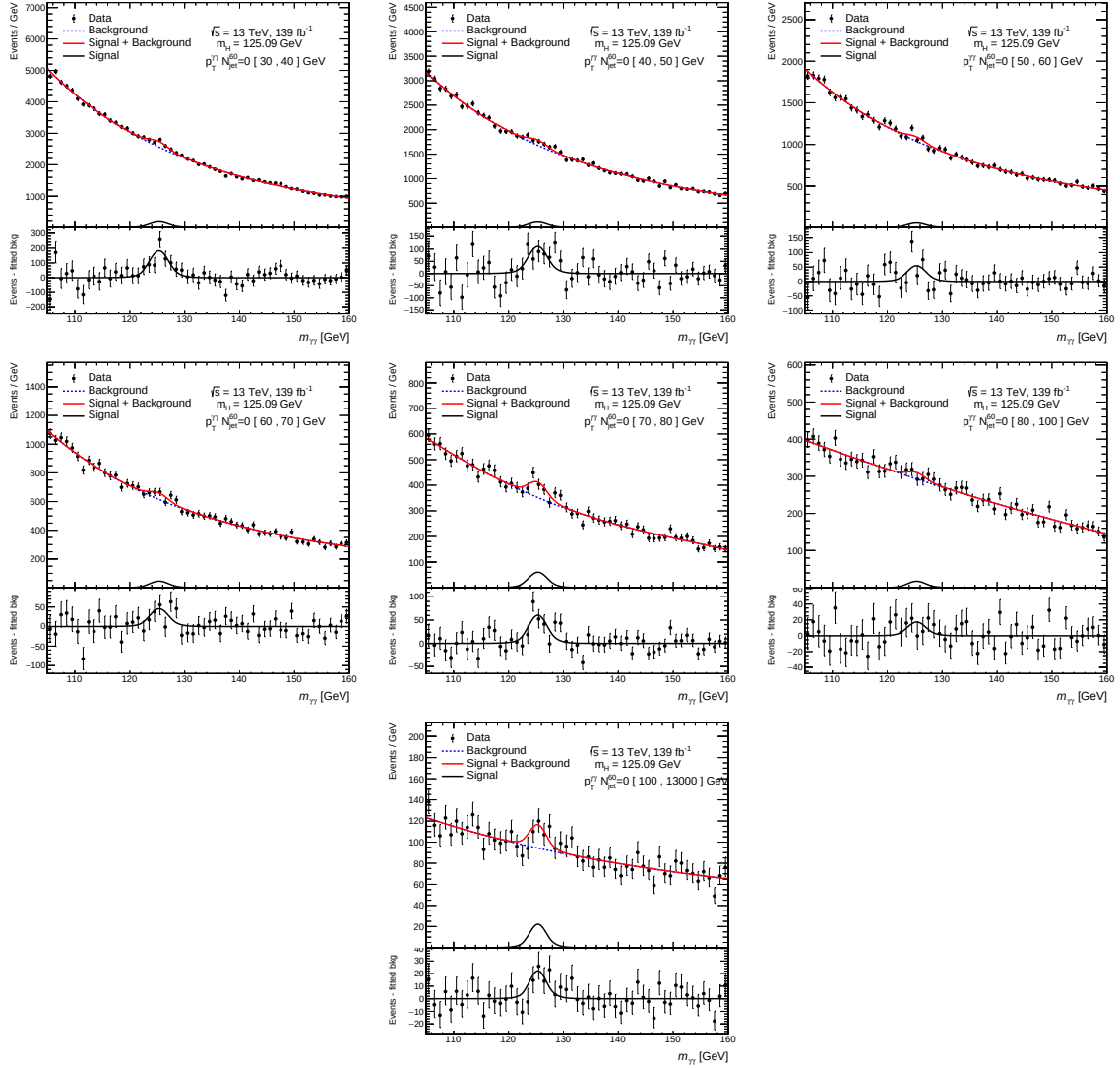


Figure A.133: Diphoton invariant mass fits in the remaining $p_T^{\gamma, \text{jet veto } 60}$ bins.

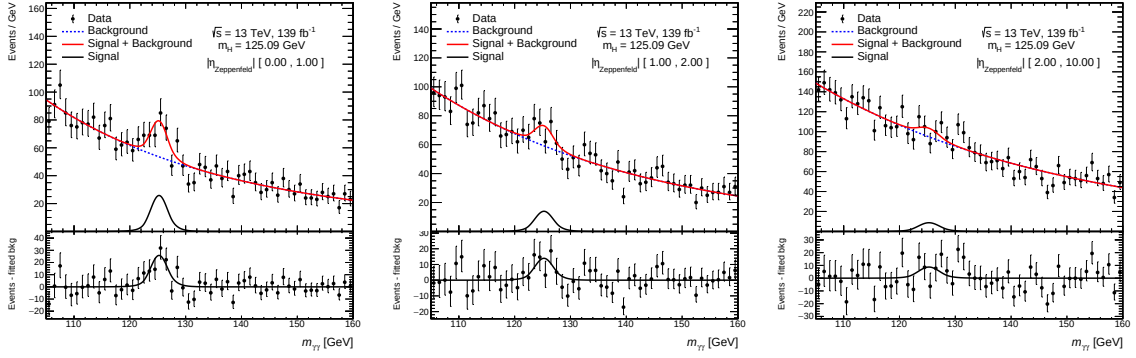


Figure A.134: Diphoton invariant mass fits in each of the $|\eta^*|$ bins in VBF-enhanced region.

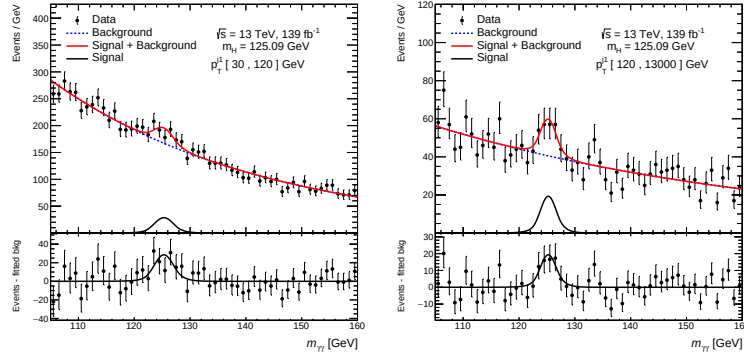


Figure A.135: Diphoton invariant mass fits in each of the p_T^{j1} bins in VBF-enhanced region.

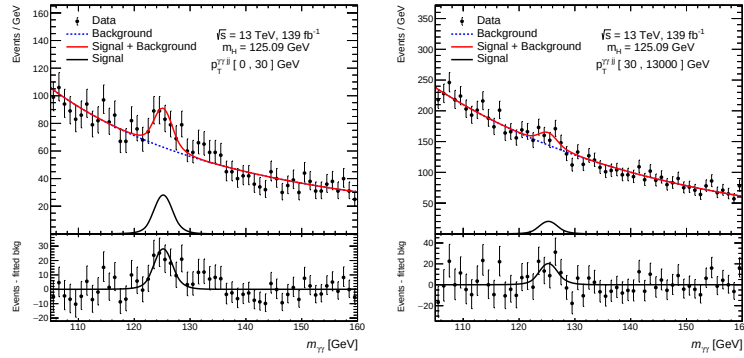


Figure A.136: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma jj}$ bins in VBF-enhanced region.

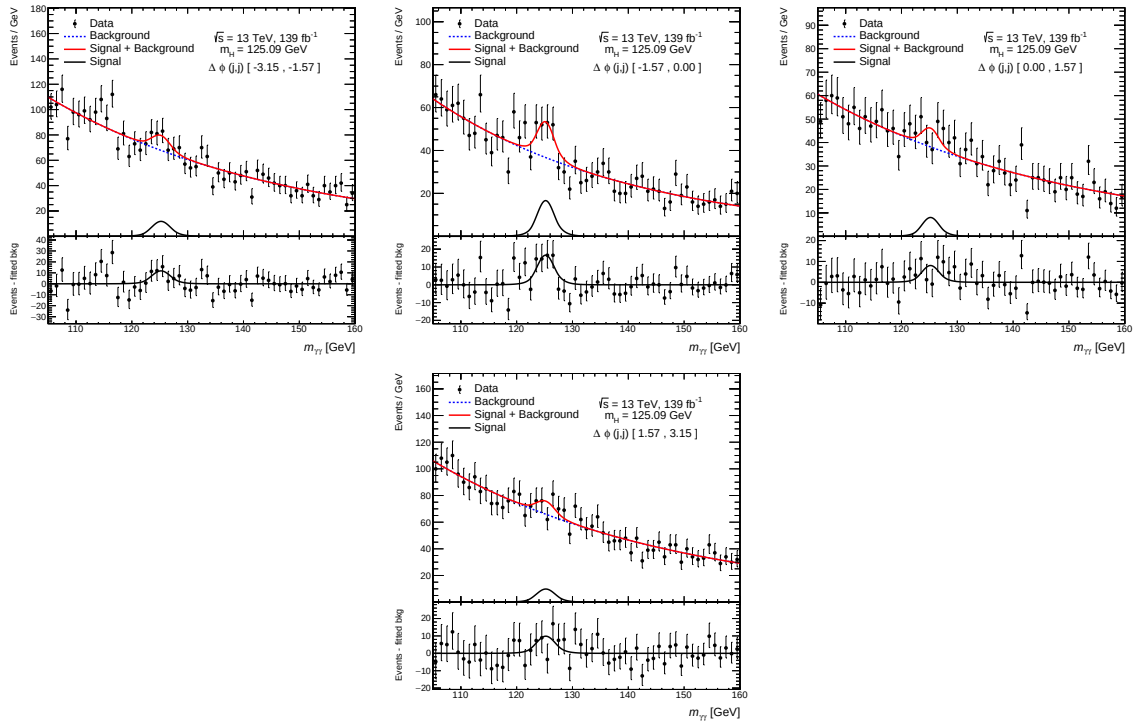


Figure A.137: Diphoton invariant mass fits in each of the $\Delta\phi_{jj}$ bins in VBF-enhanced region.

A.6.1 Double-differential variables

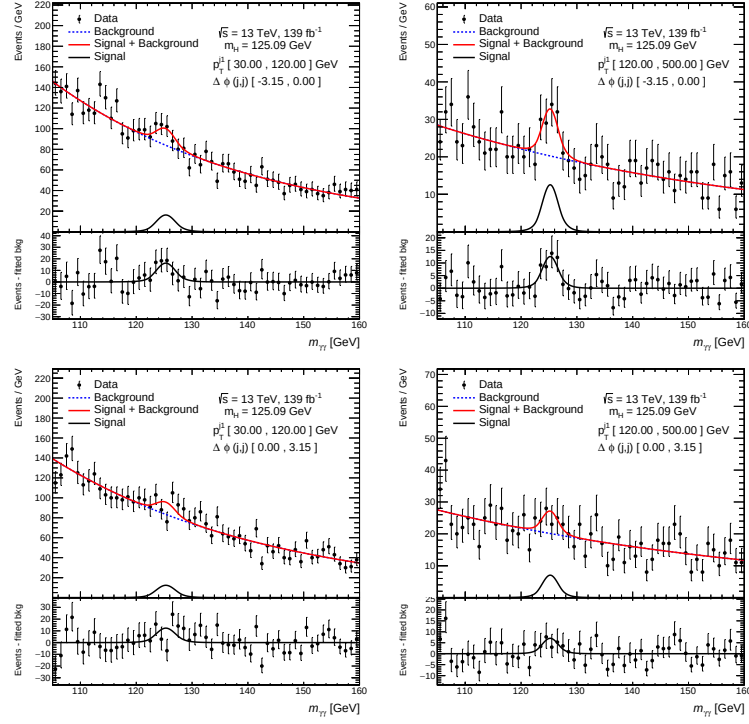


Figure A.138: Diphoton invariant mass fits in each of the p_T^{j1} vs $\Delta\phi_{jj}$ bins in the VBF-enhanced fiducial volume.

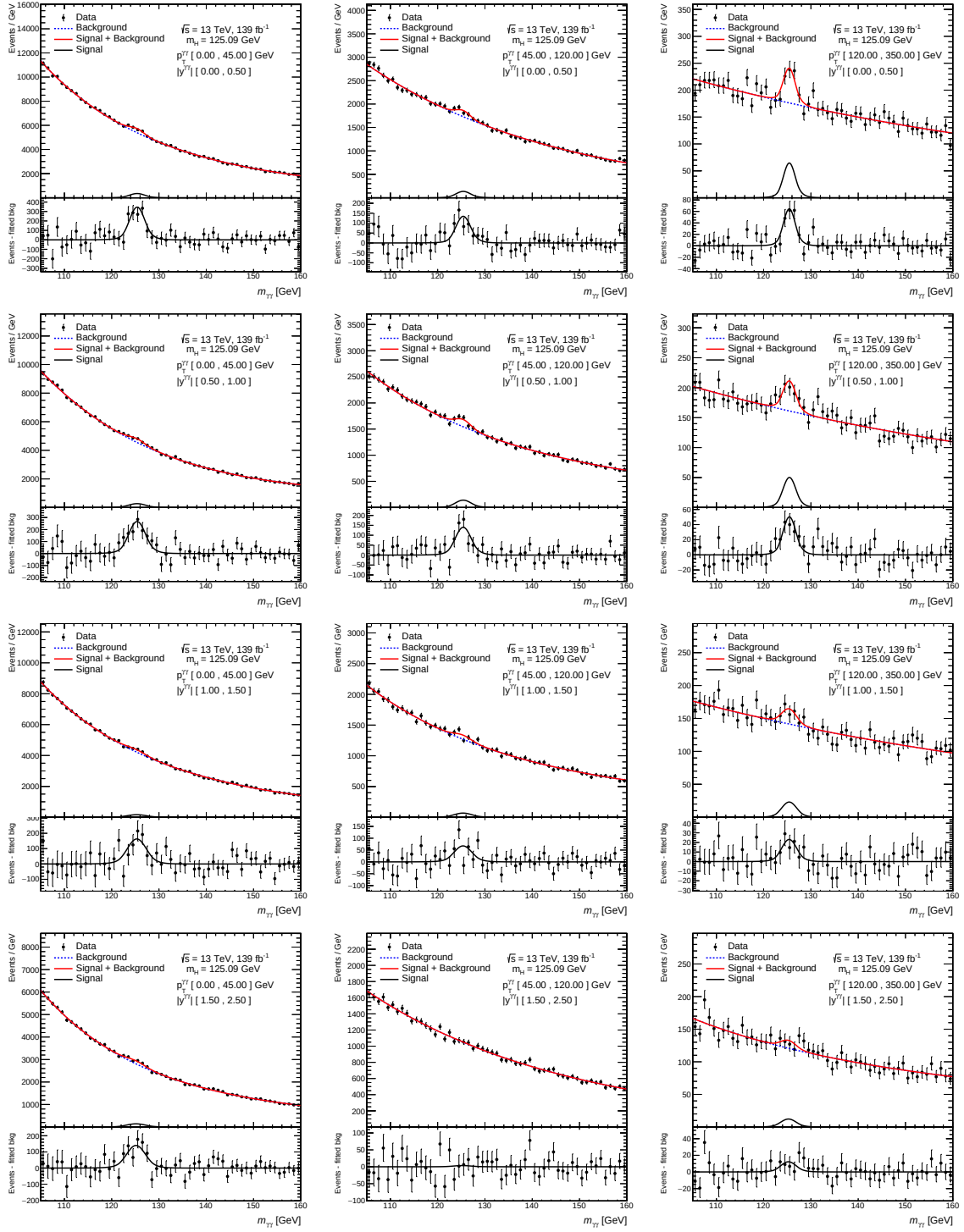


Figure A.139: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma}$ vs $|y^{\gamma\gamma}|$ bins.

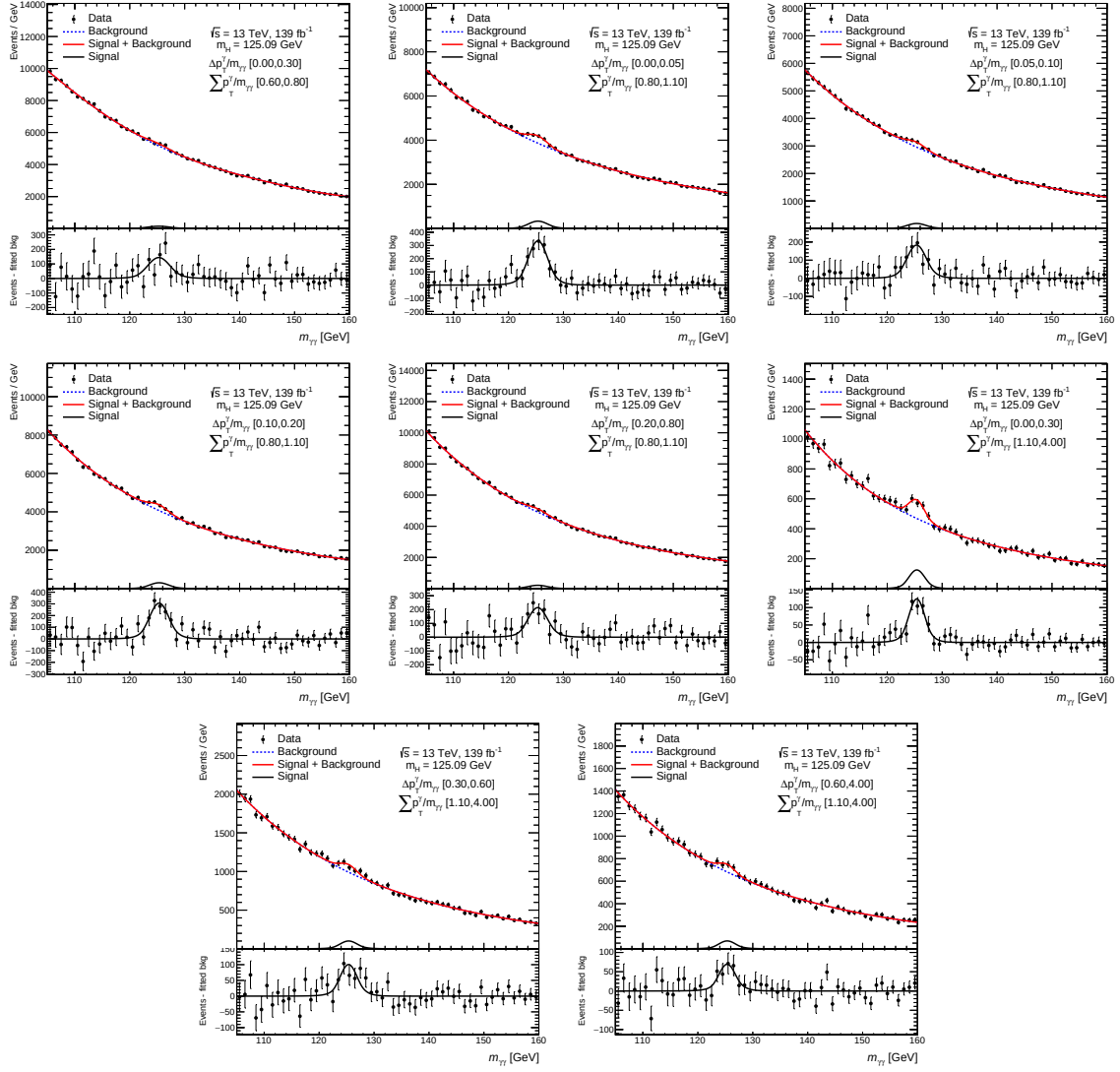


Figure A.140: Diphoton invariant mass fits in each of the $(p_T^{\gamma 1} + p_T^{\gamma 2})/m_{\gamma\gamma}$ vs. $(p_T^{\gamma 1} - p_T^{\gamma 2})/m_{\gamma\gamma}$ bins.

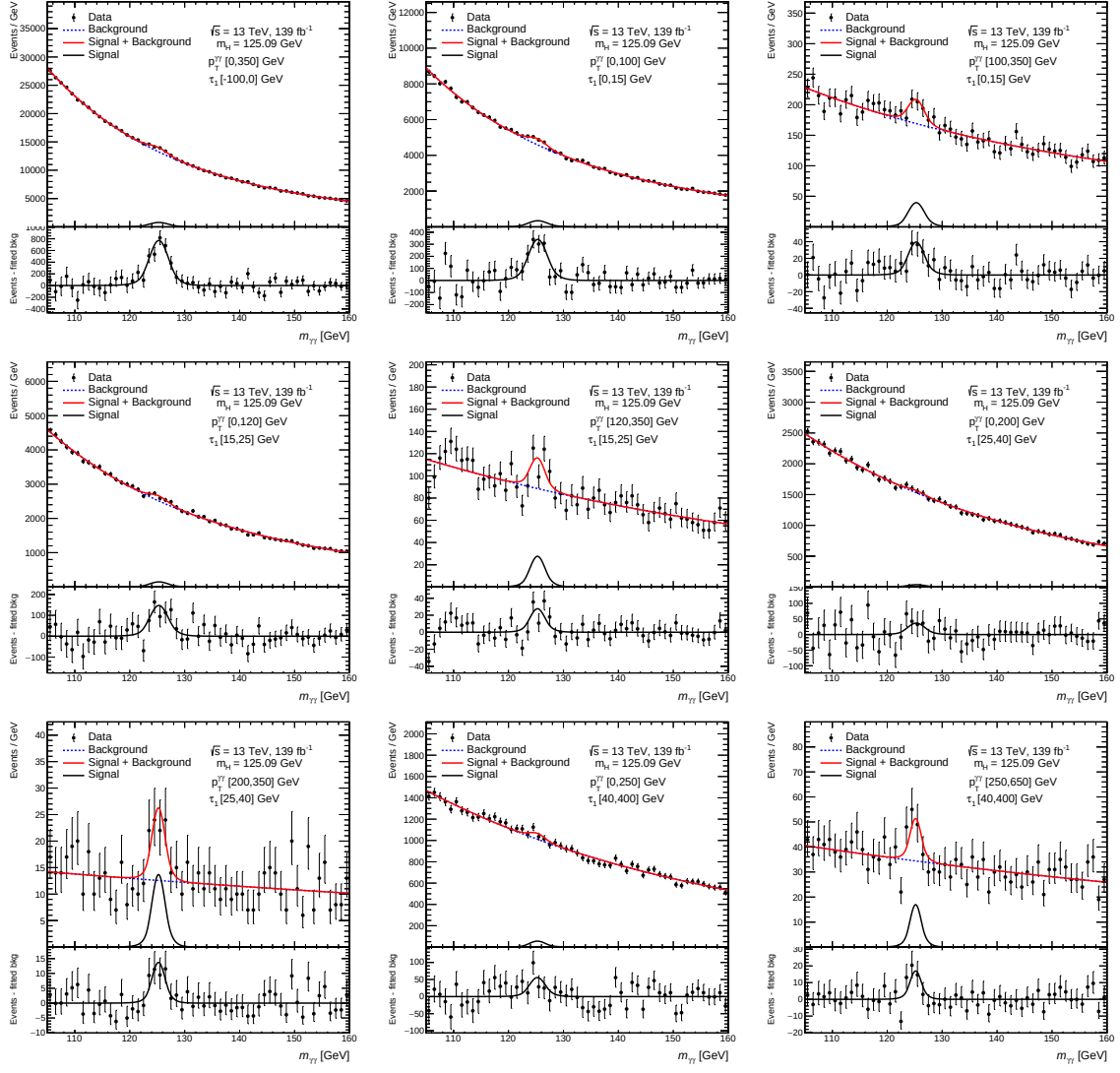


Figure A.141: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma}$ vs $\tau_{C,j1}$ bins.

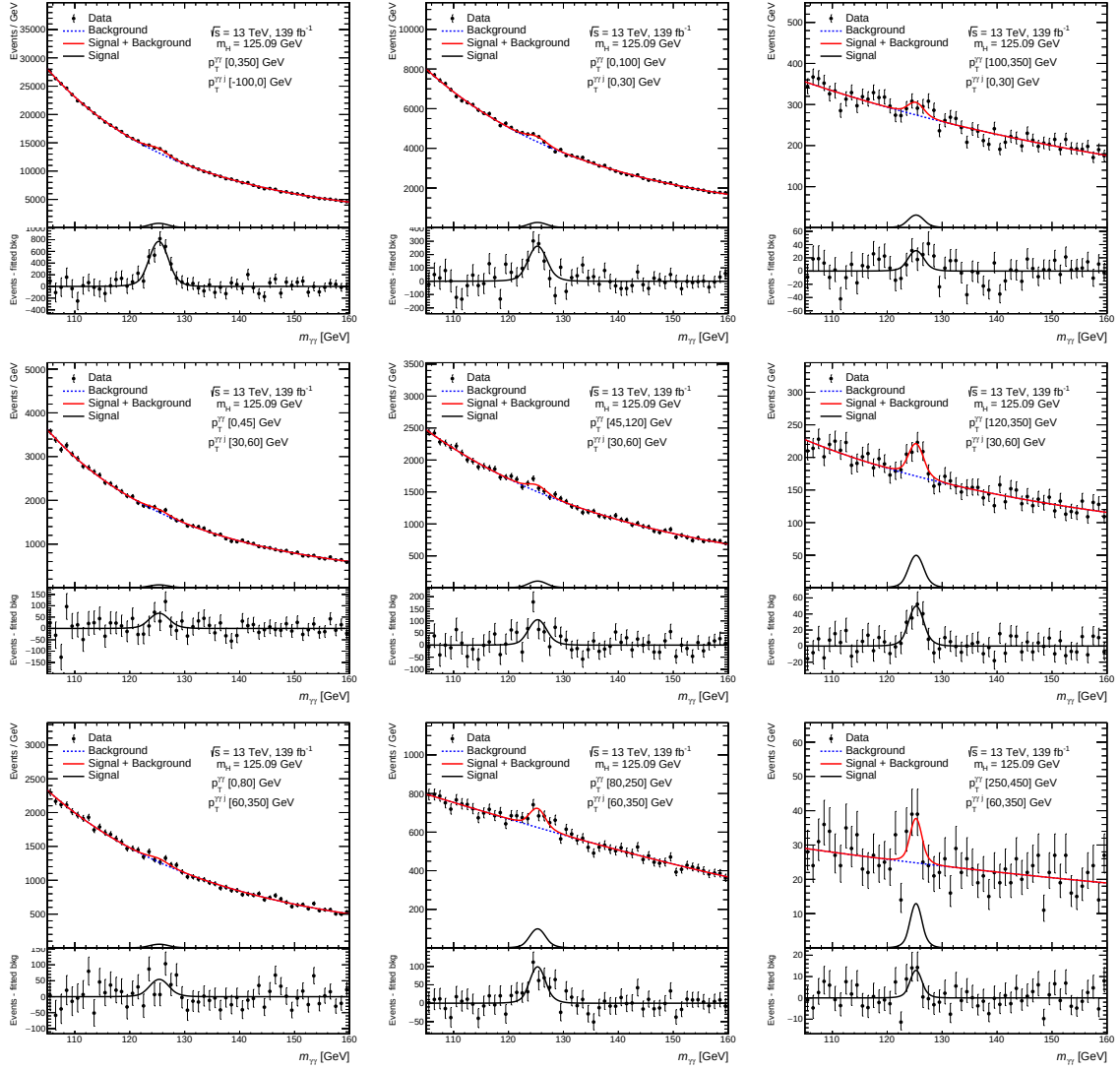


Figure A.142: Diphoton invariant mass fits in each of the $p_T^{\gamma\gamma}$ vs $p_T^{\gamma\gamma j}$ bins.

APPENDIX B

2X2D SIDEBAND OUTPUT TABLES

This appendix details the output of the 2x2D sideband method for obtaining the relative contribution of $\gamma\gamma$, γj and jj events. This method was applied in each bin for all differential variables as well as in each fiducial category.

Each bin gives a yield for the default LoosePrime definition of LoosePrime3, however the variation if LoosePrime2 or LoosePrime5 is given below.

B.0.1 Higgs Cross-Section Measurement Outputs

Table B.1: Yield and purity outputs from the 2x2D Sideband Method for the fiducial regions.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
Inclusive						
105 - 160	895061 $\pm$ 1617 $^{+31281}_{-46115}$	247677 $\pm$ 1489 $^{+39234}_{-26819}$	34944 $\pm$ 464 $^{+7046}_{-4367}$	76.0 $\pm$ 0.1 $^{+2.6}_{-3.9}$	21.0 $\pm$ 0.1 $^{+3.3}_{-2.3}$	3.0 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -13476	+10604 -0	+3044 -0	+0.00 -1.16	+0.90 -0.00	+0.26 -0.00
LP5	+6956 -0	+0 -5569	+0 -1325	+0.59 -0.00	+0.00 -0.47	+0.00 -0.11
High E_T^{miss}						
-0.5 - 0.5	892812 $\pm$ 1595 $^{+31206}_{-46020}$	246962 $\pm$ 1425 $^{+39145}_{-26751}$	34789 $\pm$ 453 $^{+7041}_{-4361}$	76.0 $\pm$ 0.1 $^{+2.6}_{-3.9}$	21.0 $\pm$ 0.1 $^{+3.3}_{-2.3}$	3.0 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -13465	+10579 -0	+3052 -0	+0.00 -1.16	+0.90 -0.00	+0.26 -0.00
LP5	+6936 -0	+0 -5541	+0 -1331	+0.59 -0.00	+0.00 -0.47	+0.00 -0.11
0.5 - 1.5	2283 $\pm$ 86 $^{+77}_{-116}$	698 $\pm$ 81 $^{+103}_{-70}$	143 $\pm$ 26 $^{+16}_{-10}$	73.1 $\pm$ 2.7 $^{+2.5}_{-3.8}$	22.3 $\pm$ 2.7 $^{+3.3}_{-2.2}$	4.6 $\pm$ 1.0 $^{+0.5}_{-0.3}$
LP2	+0 -42	+40 -0	+4 -0	+0.00 -1.39	+1.27 -0.00	+0.12 -0.00
LP5	+21 -0	+0 -25	+1 -0	+0.73 -0.00	+0.00 -0.78	+0.05 -0.00
VBF-enhanced						
-0.5 - 0.5	886997 $\pm$ 1643 $^{+31025}_{-45714}$	245456 $\pm$ 1481 $^{+38892}_{-26605}$	34684 $\pm$ 449 $^{+6984}_{-4322}$	76.0 $\pm$ 0.1 $^{+2.6}_{-3.9}$	21.0 $\pm$ 0.1 $^{+3.3}_{-2.3}$	3.0 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -13364	+10509 -0	+3022 -0	+0.00 -1.16	+0.90 -0.00	+0.26 -0.00
LP5	+6937 -0	+0 -5565	+0 -1309	+0.59 -0.00	+0.00 -0.48	+0.00 -0.11
0.5 - 1.5	8106 $\pm$ 153 $^{+275}_{-432}$	2190 $\pm$ 135 $^{+374}_{-235}$	251 $\pm$ 40 $^{+59}_{-45}$	76.9 $\pm$ 1.4 $^{+2.6}_{-4.1}$	20.8 $\pm$ 1.3 $^{+3.5}_{-2.2}$	2.4 $\pm$ 0.4 $^{+0.6}_{-0.4}$
LP2	+0 -136	+122 -0	+17 -0	+0.00 -1.31	+1.15 -0.00	+0.16 -0.00
LP5	+21 -0	+0 -6	+0 -16	+0.21 -0.00	+0.00 -0.05	+0.00 -0.15
Single Lepton						
-0.5 - 0.5	893347 $\pm$ 1631 $^{+31217}_{-46019}$	247400 $\pm$ 1482 $^{+39150}_{-26762}$	34922 $\pm$ 461 $^{+7033}_{-4360}$	76.0 $\pm$ 0.1 $^{+2.6}_{-3.9}$	21.0 $\pm$ 0.1 $^{+3.3}_{-2.3}$	3.0 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -13446	+10582 -0	+3036 -0	+0.00 -1.15	+0.90 -0.00	+0.26 -0.00
LP5	+6943 -0	+0 -5559	+0 -1323	+0.59 -0.00	+0.00 -0.47	+0.00 -0.11
0.5 - 1.5	1680 $\pm$ 69 $^{+72}_{-108}$	316 $\pm$ 60 $^{+93}_{-64}$	10 $\pm$ 17 $^{+16}_{-8}$	83.7 $\pm$ 3.2 $^{+3.6}_{-5.4}$	15.8 $\pm$ 3.1 $^{+4.6}_{-3.2}$	0.5 $\pm$ 0.8 $^{+0.8}_{-0.4}$
LP2	+0 -34	+25 -0	+9 -0	+0.00 -1.68	+1.26 -0.00	+0.43 -0.00
LP5	+16 -0	+0 -14	+0 -2	+0.77 -0.00	+0.00 -0.69	+0.00 -0.08
$t\bar{t}H$ -enhanced						
-0.5 - 0.5	893046 $\pm$ 1617 $^{+31218}_{-46030}$	247352 $\pm$ 1434 $^{+39162}_{-26765}$	34886 $\pm$ 453 $^{+7032}_{-4357}$	76.0 $\pm$ 0.1 $^{+2.6}_{-3.9}$	21.0 $\pm$ 0.1 $^{+3.3}_{-2.3}$	3.0 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -13464	+10598 -0	+3037 -0	+0.00 -1.16	+0.90 -0.00	+0.26 -0.00
LP5	+6943 -0	+0 -5562	+0 -1320	+0.59 -0.00	+0.00 -0.47	+0.00 -0.11
0.5 - 1.5	2059 $\pm$ 69 $^{+76}_{-111}$	284 $\pm$ 58 $^{+101}_{-69}$	51 $\pm$ 19 $^{+11}_{-11}$	86.0 $\pm$ 2.6 $^{+3.2}_{-4.6}$	11.9 $\pm$ 2.5 $^{+4.2}_{-2.9}$	2.1 $\pm$ 0.8 $^{+0.5}_{-0.4}$
LP2	+0 -25	+20 -0	+6 -0	+0.00 -1.07	+0.83 -0.00	+0.24 -0.00
LP5	+12 -0	+0 -5	+0 -6	+0.48 -0.00	+0.00 -0.21	+0.00 -0.26

Table B.2: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma}$. (Continued on next page.)

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma} [GeV]$						
0 - 5	56028 $\pm$ 330 $^{+1353}_{-2002}$	8610 $\pm$ 232 $^{+1385}_{-929}$	1683 $\pm$ 81 $^{+400}_{-277}$	84.5 $\pm$ 0.4 $^{+1.9}_{-2.7}$	13.0 $\pm$ 0.4 $^{+2.1}_{-1.4}$	2.5 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -558	+402 -0	+131 -0	+0.00 -0.81	+0.61 -0.00	+0.20 -0.00
LP5	+263 -0	+0 -181	+0 -82	+0.40 -0.00	+0.00 -0.27	+0.00 -0.12
5 - 10	97368 $\pm$ 524 $^{+3240}_{-4780}$	25022 $\pm$ 468 $^{+4059}_{-2760}$	4401 $\pm$ 149 $^{+677}_{-430}$	76.8 $\pm$ 0.4 $^{+2.5}_{-3.7}$	19.7 $\pm$ 0.4 $^{+3.2}_{-2.2}$	3.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1463	+1201 -0	+281 -0	+0.00 -1.17	+0.94 -0.00	+0.22 -0.00
LP5	+780 -0	+0 -641	+0 -132	+0.61 -0.00	+0.00 -0.51	+0.00 -0.10
10 - 15	98479 $\pm$ 581 $^{+3398}_{-4995}$	33696 $\pm$ 549 $^{+4039}_{-2774}$	5890 $\pm$ 178 $^{+973}_{-610}$	71.3 $\pm$ 0.4 $^{+2.4}_{-3.6}$	24.4 $\pm$ 0.4 $^{+2.9}_{-2.0}$	4.3 $\pm$ 0.1 $^{+0.7}_{-0.4}$
LP2	+0 -1481	+1045 -0	+450 -0	+0.00 -1.08	+0.75 -0.00	+0.33 -0.00
LP5	+794 -0	+0 -560	+0 -224	+0.57 -0.00	+0.00 -0.41	+0.00 -0.16
15 - 20	89253 $\pm$ 556 $^{+3224}_{-4648}$	33304 $\pm$ 526 $^{+3735}_{-2630}$	5181 $\pm$ 175 $^{+919}_{-573}$	69.9 $\pm$ 0.4 $^{+2.5}_{-3.6}$	26.1 $\pm$ 0.4 $^{+2.9}_{-2.1}$	4.1 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -1408	+1023 -0	+392 -0	+0.00 -1.11	+0.80 -0.00	+0.31 -0.00
LP5	+887 -0	+0 -704	+0 -173	+0.69 -0.00	+0.00 -0.55	+0.00 -0.14
20 - 25	78301 $\pm$ 508 $^{+2810}_{-4038}$	28405 $\pm$ 467 $^{+3270}_{-2330}$	3878 $\pm$ 152 $^{+777}_{-464}$	70.8 $\pm$ 0.4 $^{+2.5}_{-3.6}$	25.7 $\pm$ 0.4 $^{+3.0}_{-2.1}$	3.5 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -1177	+845 -0	+330 -0	+0.00 -1.06	+0.76 -0.00	+0.30 -0.00
LP5	+751 -0	+0 -631	+0 -107	+0.67 -0.00	+0.00 -0.57	+0.00 -0.10
25 - 30	67230 $\pm$ 461 $^{+2447}_{-3482}$	22343 $\pm$ 428 $^{+2890}_{-2073}$	3178 $\pm$ 135 $^{+598}_{-367}$	72.5 $\pm$ 0.5 $^{+2.6}_{-3.7}$	24.1 $\pm$ 0.5 $^{+3.1}_{-2.2}$	3.4 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -975	+746 -0	+234 -0	+0.00 -1.06	+0.80 -0.00	+0.25 -0.00
LP5	+662 -0	+0 -583	+0 -75	+0.71 -0.00	+0.00 -0.63	+0.00 -0.08
30 - 35	57946 $\pm$ 428 $^{+2092}_{-3080}$	17716 $\pm$ 388 $^{+2617}_{-1776}$	2366 $\pm$ 118 $^{+453}_{-308}$	74.3 $\pm$ 0.5 $^{+2.7}_{-3.9}$	22.7 $\pm$ 0.5 $^{+3.4}_{-2.3}$	3.0 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -937	+764 -0	+160 -0	+0.00 -1.19	+0.98 -0.00	+0.21 -0.00
LP5	+505 -0	+0 -397	+0 -95	+0.63 -0.00	+0.00 -0.51	+0.00 -0.12
35 - 45	92865 $\pm$ 525 $^{+3316}_{-5109}$	25161 $\pm$ 465 $^{+4483}_{-2857}$	3027 $\pm$ 139 $^{+621}_{-464}$	76.7 $\pm$ 0.4 $^{+2.7}_{-4.2}$	20.8 $\pm$ 0.4 $^{+3.7}_{-2.4}$	2.5 $\pm$ 0.1 $^{+0.5}_{-0.4}$
LP2	+0 -1673	+1514 -0	+148 -0	+0.00 -1.38	+1.25 -0.00	+0.12 -0.00
LP5	+610 -0	+0 -451	+0 -149	+0.50 -0.00	+0.00 -0.37	+0.00 -0.12
45 - 60	93886 $\pm$ 513 $^{+3427}_{-5084}$	23062 $\pm$ 441 $^{+4410}_{-3006}$	2143 $\pm$ 124 $^{+682}_{-417}$	78.8 $\pm$ 0.4 $^{+2.9}_{-4.3}$	19.4 $\pm$ 0.4 $^{+3.7}_{-2.5}$	1.8 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -1444	+1150 -0	+282 -0	+0.00 -1.21	+0.97 -0.00	+0.24 -0.00
LP5	+672 -0	+0 -564	+0 -102	+0.56 -0.00	+0.00 -0.47	+0.00 -0.09
60 - 80	74539 $\pm$ 446 $^{+2707}_{-4109}$	15933 $\pm$ 376 $^{+3609}_{-2408}$	1585 $\pm$ 105 $^{+515}_{-303}$	81.0 $\pm$ 0.4 $^{+2.9}_{-4.5}$	17.3 $\pm$ 0.4 $^{+3.9}_{-2.6}$	1.7 $\pm$ 0.1 $^{+0.6}_{-0.3}$
LP2	+0 -1236	+987 -0	+238 -0	+0.00 -1.33	+1.07 -0.00	+0.26 -0.00
LP5	+452 -0	+0 -363	+0 -89	+0.49 -0.00	+0.00 -0.39	+0.00 -0.10
80 - 100	39357 $\pm$ 305 $^{+1361}_{-2060}$	7438 $\pm$ 252 $^{+1854}_{-1224}$	734 $\pm$ 69 $^{+208}_{-139}$	82.8 $\pm$ 0.6 $^{+2.9}_{-4.3}$	15.7 $\pm$ 0.6 $^{+3.9}_{-2.6}$	1.5 $\pm$ 0.2 $^{+0.4}_{-0.3}$
LP2	+0 -600	+531 -0	+73 -0	+0.00 -1.27	+1.12 -0.00	+0.15 -0.00
LP5	+213 -0	+0 -175	+0 -39	+0.45 -0.00	+0.00 -0.37	+0.00 -0.08
100 - 120	20396 $\pm$ 207 $^{+636}_{-961}$	3192 $\pm$ 151 $^{+883}_{-583}$	201 $\pm$ 36 $^{+79}_{-53}$	85.7 $\pm$ 0.7 $^{+2.7}_{-4.0}$	13.4 $\pm$ 0.7 $^{+3.7}_{-2.4}$	0.8 $\pm$ 0.2 $^{+0.3}_{-0.2}$
LP2	+0 -280	+262 -0	+20 -0	+0.00 -1.19	+1.10 -0.00	+0.09 -0.00
LP5	+103 -0	+0 -94	+0 -8	+0.43 -0.00	+0.00 -0.40	+0.00 -0.03
120 - 140	10984 $\pm$ 146 $^{+326}_{-486}$	1560 $\pm$ 99 $^{+462}_{-298}$	64 $\pm$ 21 $^{+35}_{-28}$	87.1 $\pm$ 0.9 $^{+2.6}_{-3.9}$	12.4 $\pm$ 0.8 $^{+3.7}_{-2.4}$	0.5 $\pm$ 0.2 $^{+0.3}_{-0.2}$
LP2	+0 -150	+160 -0	+0 -8	+0.00 -1.20	+1.27 -0.00	+0.00 -0.07
LP5	+73 -0	+0 -61	+0 -8	+0.55 -0.00	+0.00 -0.49	+0.00 -0.06
140 - 170	8375 $\pm$ 125 $^{+241}_{-347}$	1129 $\pm$ 81 $^{+326}_{-233}$	28 $\pm$ 15 $^{+31}_{-18}$	87.9 $\pm$ 0.9 $^{+2.5}_{-3.6}$	11.8 $\pm$ 0.9 $^{+3.4}_{-2.4}$	0.3 $\pm$ 0.2 $^{+0.3}_{-0.2}$
LP2	+0 -100	+101 -0	+0 -2	+0.00 -1.04	+1.06 -0.00	+0.00 -0.02
LP5	+63 -0	+0 -76	+14 -0	+0.65 -0.00	+0.00 -0.79	+0.14 -0.00

Table B.3: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma}$ continued.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma} [GeV]$						
170 - 200	4031 ± 83 $^{+103}_{-156}$	425 ± 50 $^{+147}_{-98}$	28 ± 11 $^{+11}_{-6}$	89.9 ± 1.2 $^{+2.3}_{-3.5}$	9.5 ± 1.2 $^{+3.3}_{-2.2}$	0.6 ± 0.3 $^{+0.2}_{-0.1}$
LP2	+0 -42	+40 -0	+4 -0	+0.00 -0.98	+0.89 -0.00	+0.09 -0.00
LP5	+11 -0	+0 -14	+3 -0	+0.25 -0.00	+0.00 -0.32	+0.07 -0.00
200 - 250	2765 ± 71 $^{+71}_{-119}$	418 ± 44 $^{+112}_{-64}$	9 ± 8 $^{+9}_{-6}$	86.6 ± 1.5 $^{+2.2}_{-3.7}$	13.1 ± 1.5 $^{+3.5}_{-2.0}$	0.3 ± 0.2 $^{+0.3}_{-0.2}$
LP2	+0 -51	+51 -0	+0 -1	+0.00 -1.56	+1.60 -0.00	+0.00 -0.03
LP5	+17 -0	+0 -14	+0 -1	+0.48 -0.00	+0.00 -0.45	+0.00 -0.03
250 - 300	1068 ± 41 $^{+23}_{-35}$	141 ± 20 $^{+33}_{-22}$	1 ± 1 $^{+2}_{-1}$	88.3 ± 1.9 $^{+1.9}_{-2.8}$	11.6 ± 1.9 $^{+2.7}_{-1.8}$	0.1 ± 0.1 $^{+0.1}_{-0.1}$
LP2	+0 -14	+13 -0	+0 -0	+0.00 -1.08	+1.09 -0.00	+0.00 -0.01
LP5	+7 -0	+0 -7	+0 -0	+0.58 -0.00	+0.00 -0.56	+0.00 -0.02
300 - 450	808 ± 34 $^{+13}_{-31}$	98 ± 16 $^{+26}_{-12}$	2 ± 2 $^{+3}_{-1}$	89.1 ± 2.0 $^{+1.5}_{-3.2}$	10.8 ± 2.0 $^{+2.9}_{-1.4}$	0.2 ± 0.2 $^{+0.3}_{-0.1}$
LP2	+0 -18	+14 -0	+2 -0	+0.00 -1.75	+1.54 -0.00	+0.20 -0.00
LP5	+2 -0	+0 -2	+0 -0	+0.25 -0.00	+0.00 -0.20	+0.00 -0.05
450 - 650	113 ± 13 $^{+3}_{-7}$	25 ± 7 $^{+5}_{-2}$	0 ± 0 $^{+1}_{-0}$	82.1 ± 5.7 $^{+1.7}_{-4.7}$	17.9 ± 5.7 $^{+3.7}_{-1.5}$	0.0 ± 0.0 $^{+1.0}_{-0.3}$
LP2	+0 -4	+3 -0	+1 -0	+0.00 -2.84	+2.17 -0.00	+0.67 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.31 -0.00	+0.00 -0.32	+0.00 -0.00
650 - 13000	17 ± 8 $^{+1}_{-11}$	7 ± 6 $^{+11}_{-1}$	0 ± 0 $^{+0}_{-0}$	69.9 ± 27.4 $^{+2.4}_{-45.2}$	30.1 ± 27.4 $^{+45.2}_{-2.4}$	0.0 ± 0.6 $^{+0.0}_{-0.0}$
LP2	+0 -8	+8 -0	+0 -0	+0.00 -31.87	+31.87 -0.00	+0.00 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.65 -0.00	+0.00 -0.65	+0.00 -0.00

Table B.4: Yield and purity outputs from the 2x2D Sideband Method for p_T^{j1} .

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{j1} [GeV]$						
-100 - 30	489942 ± 1269 $^{+17348}_{-25388}$	159881 ± 1186 $^{+21129}_{-14526}$	24809 ± 374 $^{+4198}_{-2735}$	72.6 ± 0.2 $^{+2.6}_{-3.7}$	23.7 ± 0.2 $^{+3.1}_{-2.2}$	3.7 ± 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -7755	+5970 -0	+1749 -0	+0.00 -1.15	+0.89 -0.00	+0.26 -0.00
LP5	+4405 -0	+0 -3424	+0 -930	+0.65 -0.00	+0.00 -0.51	+0.00 -0.14
30 - 60	241417 ± 790 $^{+8469}_{-12605}$	58013 ± 706 $^{+10933}_{-7398}$	7132 ± 211 $^{+1656}_{-1041}$	78.7 ± 0.2 $^{+2.8}_{-4.1}$	18.9 ± 0.2 $^{+3.6}_{-2.4}$	2.3 ± 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -3599	+2981 -0	+618 -0	+0.00 -1.17	+0.97 -0.00	+0.20 -0.00
LP5	+1619 -0	+0 -1388	+0 -217	+0.52 -0.00	+0.00 -0.45	+0.00 -0.07
60 - 90	88216 ± 464 $^{+3035}_{-4540}$	17189 ± 382 $^{+4010}_{-2689}$	1916 ± 110 $^{+538}_{-343}$	82.2 ± 0.4 $^{+2.8}_{-4.2}$	16.0 ± 0.4 $^{+3.7}_{-2.5}$	1.8 ± 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1280	+1065 -0	+223 -0	+0.00 -1.20	+0.99 -0.00	+0.21 -0.00
LP5	+521 -0	+0 -403	+0 -107	+0.48 -0.00	+0.00 -0.38	+0.00 -0.10
90 - 120	36100 ± 291 $^{+1226}_{-1826}$	6818 ± 232 $^{+1624}_{-1091}$	556 ± 63 $^{+208}_{-135}$	83.0 ± 0.6 $^{+2.8}_{-4.2}$	15.7 ± 0.6 $^{+3.7}_{-2.5}$	1.3 ± 0.2 $^{+0.5}_{-0.3}$
LP2	+0 -477	+413 -0	+76 -0	+0.00 -1.12	+0.95 -0.00	+0.18 -0.00
LP5	+180 -0	+0 -145	+0 -34	+0.41 -0.00	+0.00 -0.33	+0.00 -0.08
120 - 350	37459 ± 279 $^{+1235}_{-1800}$	5814 ± 206 $^{+1652}_{-1137}$	367 ± 51 $^{+157}_{-106}$	85.8 ± 0.5 $^{+2.8}_{-4.1}$	13.3 ± 0.5 $^{+3.8}_{-2.6}$	0.8 ± 0.1 $^{+0.4}_{-0.2}$
LP2	+0 -447	+434 -0	+32 -0	+0.00 -1.06	+0.99 -0.00	+0.07 -0.00
LP5	+229 -0	+0 -241	+11 -0	+0.53 -0.00	+0.00 -0.55	+0.03 -0.00
350 - 13000	1681 ± 51 $^{+46}_{-74}$	163 ± 27 $^{+68}_{-43}$	2 ± 1 $^{+4}_{-2}$	91.1 ± 1.6 $^{+2.5}_{-3.9}$	8.8 ± 1.6 $^{+3.7}_{-2.3}$	0.1 ± 0.1 $^{+0.2}_{-0.1}$
LP2	+0 -25	+21 -0	+2 -0	+0.00 -1.23	+1.14 -0.00	+0.09 -0.00
LP5	+0 -1	+2 -0	+0 -0	+0.00 -0.10	+0.11 -0.00	+0.00 -0.01

Table B.5: Yield and purity outputs from the 2x2D Sideband Method for $max\tau^{\gamma\gamma,j}$ and $\Sigma\tau^{\gamma\gamma,jj}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$max\tau^{\gamma\gamma,j}[GeV]$						
-100 - 0	489942 $\pm$ 1265 $^{+17347}_{-25387}$	159881 $\pm$ 1179 $^{+21129}_{-14526}$	24809 $\pm$ 372 $^{+4198}_{-2736}$	72.6 $\pm$ 0.2 $^{+2.6}_{-3.7}$	23.7 $\pm$ 0.2 $^{+3.1}_{-2.2}$	3.7 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -7755	+5970 -0	+1749 -0	+0.00 -1.15	+0.89 -0.00	+0.26 -0.00
LP5	+4405 -0	+0 -3424	+0 -930	+0.65 -0.00	+0.00 -0.51	+0.00 -0.14
0 - 5	71566 $\pm$ 487 $^{+2522}_{-3716}$	23485 $\pm$ 452 $^{+3118}_{-2108}$	3385 $\pm$ 141 $^{+589}_{-406}$	72.7 $\pm$ 0.5 $^{+2.6}_{-3.8}$	23.9 $\pm$ 0.5 $^{+3.2}_{-2.1}$	3.4 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -1089	+931 -0	+155 -0	+0.00 -1.10	+0.95 -0.00	+0.16 -0.00
LP5	+568 -0	+0 -475	+0 -87	+0.57 -0.00	+0.00 -0.48	+0.00 -0.09
5 - 15	114926 $\pm$ 538 $^{+3991}_{-5973}$	25508 $\pm$ 450 $^{+5180}_{-3510}$	3105 $\pm$ 137 $^{+817}_{-472}$	80.1 $\pm$ 0.3 $^{+2.8}_{-4.2}$	17.8 $\pm$ 0.3 $^{+3.6}_{-2.4}$	2.2 $\pm$ 0.1 $^{+0.6}_{-0.3}$
LP2	+0 -1692	+1333 -0	+366 -0	+0.00 -1.18	+0.93 -0.00	+0.25 -0.00
LP5	+688 -0	+0 -582	+0 -107	+0.48 -0.00	+0.00 -0.41	+0.00 -0.07
15 - 25	107956 $\pm$ 512 $^{+3752}_{-5568}$	21134 $\pm$ 419 $^{+4932}_{-3331}$	2062 $\pm$ 117 $^{+643}_{-412}$	82.3 $\pm$ 0.3 $^{+2.9}_{-4.2}$	16.1 $\pm$ 0.3 $^{+3.8}_{-2.5}$	1.6 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1497	+1261 -0	+253 -0	+0.00 -1.15	+0.96 -0.00	+0.19 -0.00
LP5	+640 -0	+0 -511	+0 -116	+0.48 -0.00	+0.00 -0.39	+0.00 -0.09
25 - 40	64670 $\pm$ 384 $^{+2255}_{-3367}$	11127 $\pm$ 303 $^{+3026}_{-2034}$	995 $\pm$ 83 $^{+346}_{-214}$	84.2 $\pm$ 0.4 $^{+2.9}_{-4.4}$	14.5 $\pm$ 0.4 $^{+3.9}_{-2.7}$	1.3 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -987	+867 -0	+136 -0	+0.00 -1.30	+1.13 -0.00	+0.18 -0.00
LP5	+443 -0	+0 -396	+0 -45	+0.58 -0.00	+0.00 -0.52	+0.00 -0.06
40 - 13000	45799 $\pm$ 307 $^{+1496}_{-2209}$	6729 $\pm$ 224 $^{+2023}_{-1376}$	396 $\pm$ 54 $^{+194}_{-123}$	86.5 $\pm$ 0.5 $^{+2.8}_{-4.2}$	12.7 $\pm$ 0.4 $^{+3.8}_{-2.6}$	0.7 $\pm$ 0.1 $^{+0.4}_{-0.2}$
LP2	+0 -538	+494 -0	+61 -0	+0.00 -1.04	+0.93 -0.00	+0.11 -0.00
LP5	+209 -0	+0 -214	+7 -0	+0.39 -0.00	+0.00 -0.41	+0.01 -0.00
$\Sigma\tau^{\gamma\gamma,jj}[GeV]$						
-100 - 5	561644 $\pm$ 1348 $^{+19865}_{-29091}$	183287 $\pm$ 1266 $^{+24237}_{-16633}$	28223 $\pm$ 401 $^{+4786}_{-3139}$	72.6 $\pm$ 0.2 $^{+2.6}_{-3.7}$	23.7 $\pm$ 0.2 $^{+3.1}_{-2.2}$	3.7 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -8825	+6876 -0	+1921 -0	+0.00 -1.14	+0.89 -0.00	+0.25 -0.00
LP5	+4968 -0	+0 -3889	+0 -1022	+0.64 -0.00	+0.00 -0.50	+0.00 -0.13
5 - 15	103092 $\pm$ 522 $^{+3579}_{-5352}$	23092 $\pm$ 447 $^{+4642}_{-3144}$	2844 $\pm$ 133 $^{+725}_{-427}$	79.9 $\pm$ 0.4 $^{+2.8}_{-4.1}$	17.9 $\pm$ 0.4 $^{+3.6}_{-2.4}$	2.2 $\pm$ 0.1 $^{+0.6}_{-0.3}$
LP2	+0 -1514	+1202 -0	+316 -0	+0.00 -1.18	+0.93 -0.00	+0.24 -0.00
LP5	+625 -0	+0 -526	+0 -98	+0.48 -0.00	+0.00 -0.41	+0.00 -0.08
15 - 25	89730 $\pm$ 468 $^{+3110}_{-4674}$	17960 $\pm$ 383 $^{+4147}_{-2754}$	1695 $\pm$ 107 $^{+525}_{-349}$	82.0 $\pm$ 0.4 $^{+2.8}_{-4.3}$	16.4 $\pm$ 0.4 $^{+3.8}_{-2.5}$	1.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1357	+1180 -0	+190 -0	+0.00 -1.25	+1.08 -0.00	+0.17 -0.00
LP5	+545 -0	+0 -436	+0 -99	+0.49 -0.00	+0.00 -0.40	+0.00 -0.09
25 - 40	64989 $\pm$ 391 $^{+2265}_{-3346}$	11612 $\pm$ 315 $^{+2975}_{-2034}$	1192 $\pm$ 89 $^{+384}_{-225}$	83.5 $\pm$ 0.4 $^{+2.9}_{-4.3}$	14.9 $\pm$ 0.4 $^{+3.8}_{-2.6}$	1.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -882	+723 -0	+169 -0	+0.00 -1.14	+0.93 -0.00	+0.22 -0.00
LP5	+395 -0	+0 -343	+0 -52	+0.51 -0.00	+0.00 -0.44	+0.00 -0.07
40 - 80	53872 $\pm$ 347 $^{+1840}_{-2744}$	9130 $\pm$ 268 $^{+2478}_{-1666}$	675 $\pm$ 70 $^{+275}_{-169}$	84.6 $\pm$ 0.5 $^{+2.9}_{-4.3}$	14.3 $\pm$ 0.4 $^{+3.9}_{-2.6}$	1.1 $\pm$ 0.1 $^{+0.4}_{-0.3}$
LP2	+0 -752	+674 -0	+100 -0	+0.00 -1.21	+1.05 -0.00	+0.16 -0.00
LP5	+307 -0	+0 -283	+0 -21	+0.48 -0.00	+0.00 -0.44	+0.00 -0.03
80 - 13000	21660 $\pm$ 204 $^{+696}_{-1001}$	2710 $\pm$ 141 $^{+921}_{-650}$	149 $\pm$ 33 $^{+90}_{-49}$	88.3 $\pm$ 0.6 $^{+2.8}_{-4.1}$	11.1 $\pm$ 0.6 $^{+3.8}_{-2.7}$	0.6 $\pm$ 0.1 $^{+0.4}_{-0.2}$
LP2	+0 -194	+166 -0	+39 -0	+0.00 -0.83	+0.67 -0.00	+0.16 -0.00
LP5	+104 -0	+0 -114	+10 -0	+0.42 -0.00	+0.00 -0.46	+0.04 -0.00

Table B.6: Yield and purity outputs from the 2x2D Sideband Method for m_{jj} and $m_{\gamma\gamma j}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$m_{jj} [GeV]$						
-100 - 0	741485 $\pm$ 1486 $^{+26011}_{-38352}$	218249 $\pm$ 1355 $^{+32424}_{-22106}$	31913 $\pm$ 426 $^{+5968}_{-3815}$	74.8 $\pm$ 0.1 $^{+2.6}_{-3.9}$	22.0 $\pm$ 0.1 $^{+3.3}_{-2.2}$	3.2 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -11505	+9107 -0	+2480 -0	+0.00 -1.17	+0.92 -0.00	+0.25 -0.00
LP5	+6062 -0	+0 -4793	+0 -1203	+0.61 -0.00	+0.00 -0.48	+0.00 -0.12
0 - 120	51440 $\pm$ 366 $^{+1818}_{-2618}$	11307 $\pm$ 311 $^{+2264}_{-1607}$	1289 $\pm$ 91 $^{+400}_{-205}$	80.3 $\pm$ 0.5 $^{+2.8}_{-4.1}$	17.7 $\pm$ 0.5 $^{+3.5}_{-2.5}$	2.0 $\pm$ 0.2 $^{+0.6}_{-0.3}$
LP2	+0 -606	+422 -0	+199 -0	+0.00 -0.96	+0.65 -0.00	+0.31 -0.00
LP5	+349 -0	+0 -314	+0 -31	+0.54 -0.00	+0.00 -0.49	+0.00 -0.05
120 - 450	83559 $\pm$ 436 $^{+2877}_{-4240}$	14356 $\pm$ 343 $^{+3797}_{-2599}$	1241 $\pm$ 92 $^{+456}_{-270}$	84.3 $\pm$ 0.4 $^{+2.9}_{-4.3}$	14.5 $\pm$ 0.4 $^{+3.8}_{-2.6}$	1.3 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1099	+927 -0	+191 -0	+0.00 -1.12	+0.93 -0.00	+0.19 -0.00
LP5	+499 -0	+0 -448	+0 -51	+0.50 -0.00	+0.00 -0.45	+0.00 -0.05
450 - 3000	18604 $\pm$ 214 $^{+623}_{-951}$	3737 $\pm$ 176 $^{+846}_{-553}$	403 $\pm$ 50 $^{+108}_{-72}$	81.8 $\pm$ 0.8 $^{+2.7}_{-4.2}$	16.4 $\pm$ 0.8 $^{+3.7}_{-2.4}$	1.8 $\pm$ 0.2 $^{+0.5}_{-0.3}$
LP2	+0 -262	+232 -0	+38 -0	+0.00 -1.18	+1.01 -0.00	+0.17 -0.00
LP5	+46 -0	+0 -29	+0 -21	+0.22 -0.00	+0.00 -0.13	+0.00 -0.09
3000 - 13000	37 $\pm$ 13 $^{+2}_{-6}$	14 $\pm$ 14 $^{+4}_{-2}$	4 $\pm$ 5 $^{+3}_{-1}$	67.3 $\pm$ 26.3 $^{+2.8}_{-10.7}$	25.6 $\pm$ 25.7 $^{+6.6}_{-2.9}$	7.1 $\pm$ 11.7 $^{+5.2}_{-1.5}$
LP2	+0 -4	+2 -0	+2 -0	+0.00 -6.94	+3.27 -0.00	+3.67 -0.00
LP5	+0 -1	+1 -0	+0 -1	+0.00 -1.21	+2.29 -0.00	+0.00 -1.09
$m_{\gamma\gamma j} [GeV]$						
-100 - 120	489942 $\pm$ 1279 $^{+17348}_{-25388}$	159881 $\pm$ 1192 $^{+21129}_{-14526}$	24809 $\pm$ 365 $^{+4198}_{-2736}$	72.6 $\pm$ 0.2 $^{+2.6}_{-3.7}$	23.7 $\pm$ 0.2 $^{+3.1}_{-2.2}$	3.7 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -7755	+5970 -0	+1749 -0	+0.00 -1.15	+0.89 -0.00	+0.26 -0.00
LP5	+4405 -0	+0 -3424	+0 -930	+0.65 -0.00	+0.00 -0.51	+0.00 -0.14
120 - 220	158345 $\pm$ 643 $^{+5668}_{-8476}$	34283 $\pm$ 545 $^{+7435}_{-5014}$	3701 $\pm$ 158 $^{+1036}_{-638}$	80.7 $\pm$ 0.3 $^{+2.9}_{-4.3}$	17.5 $\pm$ 0.3 $^{+3.8}_{-2.6}$	1.9 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -2472	+2072 -0	+402 -0	+0.00 -1.26	+1.06 -0.00	+0.20 -0.00
LP5	+1075 -0	+0 -947	+0 -126	+0.55 -0.00	+0.00 -0.48	+0.00 -0.06
220 - 300	119616 $\pm$ 540 $^{+4087}_{-6062}$	23169 $\pm$ 444 $^{+5328}_{-3634}$	2614 $\pm$ 128 $^{+173}_{-442}$	82.3 $\pm$ 0.3 $^{+2.8}_{-4.2}$	15.9 $\pm$ 0.3 $^{+3.7}_{-2.5}$	1.8 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1622	+1265 -0	+365 -0	+0.00 -1.12	+0.87 -0.00	+0.25 -0.00
LP5	+692 -0	+0 -552	+0 -122	+0.47 -0.00	+0.00 -0.38	+0.00 -0.08
300 - 400	61485 $\pm$ 391 $^{+2054}_{-3101}$	12974 $\pm$ 323 $^{+2732}_{-1828}$	1481 $\pm$ 93 $^{+381}_{-223}$	81.0 $\pm$ 0.5 $^{+2.7}_{-4.1}$	17.1 $\pm$ 0.4 $^{+3.6}_{-2.4}$	2.0 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -934	+800 -0	+154 -0	+0.00 -1.25	+1.05 -0.00	+0.20 -0.00
LP5	+376 -0	+0 -353	+0 -20	+0.49 -0.00	+0.00 -0.47	+0.00 -0.03
400 - 600	42183 $\pm$ 336 $^{+1404}_{-2092}$	10624 $\pm$ 286 $^{+1846}_{-1216}$	1197 $\pm$ 82 $^{+259}_{-184}$	78.1 $\pm$ 0.6 $^{+2.6}_{-3.9}$	19.7 $\pm$ 0.6 $^{+3.4}_{-2.3}$	2.2 $\pm$ 0.2 $^{+0.5}_{-0.3}$
LP2	+0 -615	+583 -0	+54 -0	+0.00 -1.17	+1.07 -0.00	+0.10 -0.00
LP5	+282 -0	+0 -241	+0 -40	+0.52 -0.00	+0.00 -0.45	+0.00 -0.07
600 - 900	16988 $\pm$ 225 $^{+573}_{-874}$	4773 $\pm$ 202 $^{+725}_{-484}$	646 $\pm$ 62 $^{+168}_{-94}$	75.8 $\pm$ 1.0 $^{+2.6}_{-3.9}$	21.3 $\pm$ 0.9 $^{+3.2}_{-2.2}$	2.9 $\pm$ 0.3 $^{+0.7}_{-0.4}$
LP2	+0 -250	+175 -0	+86 -0	+0.00 -1.15	+0.77 -0.00	+0.38 -0.00
LP5	+66 -0	+0 -36	+0 -33	+0.30 -0.00	+0.00 -0.16	+0.00 -0.15
900 - 13000	6460 $\pm$ 144 $^{+244}_{-320}$	2096 $\pm$ 130 $^{+267}_{-205}$	204 $\pm$ 37 $^{+57}_{-39}$	73.8 $\pm$ 1.6 $^{+2.8}_{-3.7}$	23.9 $\pm$ 1.5 $^{+3.0}_{-2.3}$	2.3 $\pm$ 0.5 $^{+0.6}_{-0.4}$
LP2	+0 -56	+45 -0	+18 -0	+0.00 -0.70	+0.50 -0.00	+0.20 -0.00
LP5	+76 -0	+0 -65	+0 -11	+0.87 -0.00	+0.00 -0.74	+0.00 -0.13

Table B.7: Yield and purity outputs from the 2x2D Sideband Method for VBF $|\Delta\phi(j, j)|$, $|\eta_{Zeppenfeld}|$, p_T^{j1} , and $p_T^{\gamma\gamma, jj}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
VBF $ \Delta\phi(j, j) [rad]$						
-3.1 - -1.6	2711 ± 85 $^{+89}_{-130}$	626 ± 72 $^{+112}_{-78}$	83 ± 22 $^{+20}_{-15}$	79.3 ± 2.3 $^{+2.6}_{-3.8}$	18.3 ± 2.2 $^{+3.3}_{-2.3}$	2.4 ± 0.7 $^{+0.6}_{-0.4}$
LP2	+0 -24	+14 -0	+9 -0	+0.00 -0.68	+0.42 -0.00	+0.26 -0.00
LP5	+0 -1	+8 -0	+0 -7	+0.00 -0.01	+0.23 -0.00	+0.00 -0.22
-1.6 - 0.0	1412 ± 64 $^{+51}_{-91}$	415 ± 52 $^{+82}_{-45}$	55 ± 8 $^{+10}_{-9}$	75.0 ± 2.9 $^{+2.7}_{-4.8}$	22.1 ± 2.9 $^{+4.4}_{-2.4}$	2.9 ± 0.5 $^{+0.5}_{-0.5}$
LP2	+0 -39	+36 -0	+3 -0	+0.00 -2.07	+1.93 -0.00	+0.14 -0.00
LP5	+0 -6	+10 -0	+0 -4	+0.00 -0.32	+0.52 -0.00	+0.00 -0.21
0.0 - 1.6	1401 ± 67 $^{+50}_{-68}$	487 ± 61 $^{+55}_{-42}$	40 ± 17 $^{+22}_{-9}$	72.7 ± 3.3 $^{+2.6}_{-3.5}$	25.2 ± 3.3 $^{+2.9}_{-2.2}$	2.1 ± 1.0 $^{+1.1}_{-0.5}$
LP2	+0 -5	+0 -5	+13 -0	+0.00 -0.38	+0.00 -0.29	+0.67 -0.00
LP5	+12 -0	+0 -10	+0 -2	+0.62 -0.00	+0.00 -0.53	+0.00 -0.08
1.6 - 3.1	2588 ± 85 $^{+92}_{-149}$	647 ± 75 $^{+134}_{-82}$	83 ± 23 $^{+16}_{-11}$	78.0 ± 2.4 $^{+2.8}_{-4.5}$	19.5 ± 2.3 $^{+4.0}_{-2.5}$	2.5 ± 0.8 $^{+0.5}_{-0.3}$
LP2	+0 -59	+56 -0	+3 -0	+0.00 -1.78	+1.69 -0.00	+0.09 -0.00
LP5	+20 -0	+0 -20	+0 -1	+0.62 -0.00	+0.00 -0.60	+0.00 -0.02
VBF $ \eta_{Zeppenfeld} $						
0 - 1	2165 ± 79 $^{+74}_{-124}$	533 ± 70 $^{+113}_{-64}$	90 ± 23 $^{+13}_{-17}$	77.7 ± 2.7 $^{+2.6}_{-4.5}$	19.1 ± 2.6 $^{+4.1}_{-2.3}$	3.2 ± 0.9 $^{+0.5}_{-0.6}$
LP2	+0 -49	+48 -0	+2 -0	+0.00 -1.79	+1.71 -0.00	+0.08 -0.00
LP5	+4 -0	+6 -0	+0 -10	+0.15 -0.00	+0.20 -0.00	+0.00 -0.35
1 - 2	2287 ± 80 $^{+74}_{-118}$	647 ± 68 $^{+101}_{-63}$	59 ± 18 $^{+17}_{-11}$	76.4 ± 2.4 $^{+2.5}_{-3.9}$	21.6 ± 2.4 $^{+3.4}_{-2.1}$	2.0 ± 0.7 $^{+0.6}_{-0.4}$
LP2	+0 -38	+34 -0	+4 -0	+0.00 -1.27	+1.14 -0.00	+0.13 -0.00
LP5	+0 -5	+0 -0	+4 -0	+0.00 -0.15	+0.01 -0.00	+0.14 -0.00
2 - 10	3647 ± 105 $^{+131}_{-192}$	1016 ± 94 $^{+160}_{-109}$	104 ± 28 $^{+34}_{-25}$	76.5 ± 2.1 $^{+2.8}_{-4.0}$	21.3 ± 2.0 $^{+3.3}_{-2.3}$	2.2 ± 0.6 $^{+0.7}_{-0.5}$
LP2	+0 -46	+32 -0	+15 -0	+0.00 -0.99	+0.67 -0.00	+0.32 -0.00
LP5	+23 -0	+0 -11	+0 -12	+0.48 -0.00	+0.00 -0.23	+0.00 -0.25
VBF $p_T^{j1}[GeV]$						
30 - 120	6294 ± 140 $^{+216}_{-351}$	1874 ± 128 $^{+302}_{-182}$	253 ± 40 $^{+50}_{-40}$	74.7 ± 1.6 $^{+2.6}_{-4.2}$	22.3 ± 1.6 $^{+3.6}_{-2.2}$	3.0 ± 0.5 $^{+0.6}_{-0.5}$
LP2	+0 -124	+111 -0	+14 -0	+0.00 -1.48	+1.32 -0.00	+0.16 -0.00
LP5	+15 -0	+1 -0	+0 -16	+0.18 -0.00	+0.01 -0.00	+0.00 -0.20
120 - 13000	1819 ± 60 $^{+62}_{-89}$	290 ± 41 $^{+82}_{-58}$	18 ± 3 $^{+6}_{-4}$	85.5 ± 2.1 $^{+2.9}_{-4.2}$	13.6 ± 2.1 $^{+3.9}_{-2.7}$	0.8 ± 0.2 $^{+0.3}_{-0.2}$
LP2	+0 -8	+7 -0	+2 -0	+0.00 -0.39	+0.31 -0.00	+0.08 -0.00
LP5	+3 -0	+0 -2	+0 -1	+0.13 -0.00	+0.00 -0.09	+0.00 -0.04
VBF $p_T^{\gamma\gamma, jj}[GeV]$						
0 - 30	2516 ± 86 $^{+83}_{-136}$	700 ± 76 $^{+106}_{-71}$	82 ± 23 $^{+37}_{-13}$	76.3 ± 2.5 $^{+2.5}_{-4.1}$	21.2 ± 2.4 $^{+3.2}_{-2.1}$	2.5 ± 0.8 $^{+1.1}_{-0.4}$
LP2	+0 -48	+26 -0	+23 -0	+0.00 -1.47	+0.77 -0.00	+0.70 -0.00
LP5	+0 -0	+3 -0	+0 -3	+0.01 -0.00	+0.09 -0.00	+0.00 -0.10
30 - 13000	5586 ± 127 $^{+192}_{-296}$	1491 ± 111 $^{+269}_{-164}$	169 ± 33 $^{+37}_{-32}$	77.1 ± 1.6 $^{+2.6}_{-4.1}$	20.6 ± 1.6 $^{+3.7}_{-2.3}$	2.3 ± 0.5 $^{+0.5}_{-0.4}$
LP2	+0 -89	+97 -0	+0 -6	+0.00 -1.25	+1.33 -0.00	+0.00 -0.08
LP5	+20 -0	+0 -7	+0 -13	+0.28 -0.00	+0.00 -0.10	+0.00 -0.18

Table B.8: Yield and purity outputs from the 2x2D Sideband Method for N_{jets} and $N_{\text{b-jets}}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
N_{jets}						
$N_{\text{jets}} = 0$	489942 $\pm$ 1220 $^{+17348}_{-25388}$	159881 $\pm$ 1134 $^{+21129}_{-14527}$	24809 $\pm$ 377 $^{+4199}_{-2736}$	72.6 $\pm$ 0.2 $^{+2.6}_{-3.7}$	23.7 $\pm$ 0.2 $^{+3.1}_{-2.2}$	3.7 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -7754	+5970 -0	+1749 -0	+0.00 -1.15	+0.89 -0.00	+0.26 -0.00
LP5	+4405 -0	+0 -3424	+0 -930	+0.65 -0.00	+0.00 -0.51	+0.00 -0.14
$N_{\text{jets}} = 1$	251319 $\pm$ 792 $^{+8707}_{-13043}$	58561 $\pm$ 702 $^{+11388}_{-7614}$	6952 $\pm$ 206 $^{+1661}_{-1067}$	79.3 $\pm$ 0.2 $^{+2.7}_{-4.1}$	18.5 $\pm$ 0.2 $^{+3.6}_{-2.4}$	2.2 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -3840	+3281 -0	+601 -0	+0.00 -1.22	+1.03 -0.00	+0.19 -0.00
LP5	+1660 -0	+0 -1395	+0 -245	+0.52 -0.00	+0.00 -0.44	+0.00 -0.08
$N_{\text{jets}} = 2$	102769 $\pm$ 502 $^{+3551}_{-5236}$	20096 $\pm$ 413 $^{+4609}_{-3169}$	2144 $\pm$ 118 $^{+662}_{-373}$	82.2 $\pm$ 0.4 $^{+2.8}_{-4.2}$	16.1 $\pm$ 0.3 $^{+3.7}_{-2.5}$	1.7 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1337	+1056 -0	+300 -0	+0.00 -1.08	+0.84 -0.00	+0.24 -0.00
LP5	+587 -0	+0 -518	+0 -71	+0.47 -0.00	+0.00 -0.41	+0.00 -0.06
$N_{\text{jets}} \geq 3$	50871 $\pm$ 345 $^{+1765}_{-2579}$	9319 $\pm$ 274 $^{+2300}_{-1586}$	791 $\pm$ 74 $^{+297}_{-174}$	83.4 $\pm$ 0.5 $^{+2.9}_{-4.2}$	15.3 $\pm$ 0.5 $^{+3.8}_{-2.6}$	1.3 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -630	+525 -0	+126 -0	+0.00 -1.06	+0.86 -0.00	+0.21 -0.00
LP5	+305 -0	+0 -272	+0 -33	+0.50 -0.00	+0.00 -0.45	+0.00 -0.05
$N_{\text{b-jets}}$						
$N_{\text{b-jets}} = 0$	554566 $\pm$ 1349 $^{+19598}_{-28718}$	182139 $\pm$ 1250 $^{+23894}_{-16392}$	28281 $\pm$ 396 $^{+4769}_{-3113}$	72.5 $\pm$ 0.2 $^{+2.6}_{-3.7}$	23.8 $\pm$ 0.2 $^{+3.1}_{-2.1}$	3.7 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -8717	+6774 -0	+1932 -0	+0.00 -1.14	+0.89 -0.00	+0.25 -0.00
LP5	+4883 -0	+0 -3817	+0 -1012	+0.63 -0.00	+0.00 -0.50	+0.00 -0.13
$N_{\text{b-jets}} = 1$	326114 $\pm$ 889 $^{+11230}_{-16671}$	63241 $\pm$ 726 $^{+14764}_{-10018}$	6228 $\pm$ 202 $^{+1963}_{-1180}$	82.4 $\pm$ 0.2 $^{+2.8}_{-4.2}$	16.0 $\pm$ 0.2 $^{+3.7}_{-2.5}$	1.6 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -4542	+3799 -0	+815 -0	+0.00 -1.16	+0.96 -0.00	+0.21 -0.00
LP5	+1972 -0	+0 -1705	+0 -256	+0.50 -0.00	+0.00 -0.43	+0.00 -0.06
$N_{\text{b-jets}} \geq 1$	14276 $\pm$ 183 $^{+517}_{-786}$	2457 $\pm$ 148 $^{+711}_{-464}$	217 $\pm$ 41 $^{+75}_{-53}$	84.2 $\pm$ 0.9 $^{+3.0}_{-4.6}$	14.5 $\pm$ 0.9 $^{+4.2}_{-2.7}$	1.3 $\pm$ 0.3 $^{+0.4}_{-0.3}$
LP2	+0 -235	+215 -0	+24 -0	+0.00 -1.40	+1.27 -0.00	+0.14 -0.00
LP5	+84 -0	+0 -67	+0 -16	+0.49 -0.00	+0.00 -0.40	+0.00 -0.10

Table B.9: Yield and purity outputs from the 2x2D Sideband Method for $H_T^{j \geq 30 \text{ GeV}}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$H_T^{j \geq 30 \text{ GeV}} [\text{GeV}]$						
-100 - 30	489922 $\pm$ 1281 $^{+17341}_{-25372}$	159899 $\pm$ 1189 $^{+21114}_{-14520}$	24811 $\pm$ 372 $^{+4197}_{-2736}$	72.6 $\pm$ 0.2 $^{+2.6}_{-3.7}$	23.7 $\pm$ 0.2 $^{+3.1}_{-2.2}$	3.7 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -7743	+5960 -0	+1748 -0	+0.00 -1.14	+0.88 -0.00	+0.26 -0.00
LP5	+4404 -0	+0 -3423	+0 -930	+0.65 -0.00	+0.00 -0.51	+0.00 -0.14
30 - 60	183391 $\pm$ 712 $^{+6406}_{-9586}$	44363 $\pm$ 619 $^{+8343}_{-5588}$	5627 $\pm$ 185 $^{+1218}_{-793}$	78.6 $\pm$ 0.3 $^{+2.7}_{-4.1}$	19.0 $\pm$ 0.3 $^{+3.6}_{-2.4}$	2.4 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -2829	+2408 -0	+416 -0	+0.00 -1.21	+1.03 -0.00	+0.18 -0.00
LP5	+1244 -0	+0 -1053	+0 -175	+0.53 -0.00	+0.00 -0.45	+0.00 -0.08
60 - 140	147461 $\pm$ 614 $^{+5103}_{-7584}$	31635 $\pm$ 515 $^{+6619}_{-4489}$	3339 $\pm$ 147 $^{+900}_{-604}$	80.8 $\pm$ 0.3 $^{+2.8}_{-4.2}$	17.3 $\pm$ 0.3 $^{+3.6}_{-2.5}$	1.8 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -2052	+1660 -0	+412 -0	+0.00 -1.13	+0.91 -0.00	+0.23 -0.00
LP5	+866 -0	+0 -707	+0 -149	+0.47 -0.00	+0.00 -0.39	+0.00 -0.08
140 - 200	35485 $\pm$ 288 $^{+1228}_{-1824}$	6631 $\pm$ 229 $^{+1638}_{-1106}$	566 $\pm$ 62 $^{+190}_{-121}$	83.1 $\pm$ 0.6 $^{+2.9}_{-4.3}$	15.5 $\pm$ 0.6 $^{+3.8}_{-2.6}$	1.3 $\pm$ 0.2 $^{+0.4}_{-0.3}$
LP2	+0 -522	+473 -0	+60 -0	+0.00 -1.24	+1.10 -0.00	+0.14 -0.00
LP5	+241 -0	+0 -230	+0 -11	+0.57 -0.00	+0.00 -0.54	+0.00 -0.03
200 - 500	34644 $\pm$ 268 $^{+1155}_{-1652}$	5076 $\pm$ 198 $^{+1505}_{-1060}$	383 $\pm$ 51 $^{+165}_{-94}$	86.4 $\pm$ 0.5 $^{+2.9}_{-4.1}$	12.7 $\pm$ 0.5 $^{+3.8}_{-2.6}$	1.0 $\pm$ 0.1 $^{+0.4}_{-0.2}$
LP2	+0 -328	+286 -0	+70 -0	+0.00 -0.88	+0.70 -0.00	+0.17 -0.00
LP5	+196 -0	+0 -191	+0 -8	+0.49 -0.00	+0.00 -0.47	+0.00 -0.02
500 - 13000	3890 $\pm$ 80 $^{+114}_{-181}$	324 $\pm$ 49 $^{+164}_{-108}$	19 $\pm$ 11 $^{+18}_{-6}$	91.9 $\pm$ 1.2 $^{+2.7}_{-4.2}$	7.6 $\pm$ 1.2 $^{+3.9}_{-2.5}$	0.4 $\pm$ 0.3 $^{+0.4}_{-0.1}$
LP2	+0 -58	+43 -0	+12 -0	+0.00 -1.30	+1.03 -0.00	+0.28 -0.00
LP5	+3 -0	+0 -2	+0 -2	+0.09 -0.00	+0.00 -0.05	+0.00 -0.04

Table B.10: Yield and purity outputs from the 2x2D Sideband Method for $\Delta\phi(j, j)$ and $|\Delta\Phi_{\gamma\gamma, jj}|$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$\Delta\phi(j, j)[rad]$						
-100.0 - -3.1	741485 $\pm$ 1512 $^{+26011}_{-38353}$	218249 $\pm$ 1389 $^{+32424}_{-22106}$	31913 $\pm$ 427 $^{+5968}_{-3815}$	74.8 $\pm$ 0.1 $^{+2.6}_{-3.9}$	22.0 $\pm$ 0.1 $^{+3.3}_{-2.2}$	3.2 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -11505	+9107 -0	+2480 -0	+0.00 -1.17	+0.92 -0.00	+0.25 -0.00
LP5	+6062 -0	+0 -4793	+0 -1204	+0.61 -0.00	+0.00 -0.48	+0.00 -0.12
-3.1 - -1.6	53978 $\pm$ 354 $^{+1866}_{-2758}$	9429 $\pm$ 283 $^{+2455}_{-1685}$	947 $\pm$ 79 $^{+312}_{-174}$	83.9 $\pm$ 0.5 $^{+2.9}_{-4.3}$	14.7 $\pm$ 0.5 $^{+3.8}_{-2.6}$	1.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -717	+576 -0	+142 -0	+0.00 -1.12	+0.89 -0.00	+0.22 -0.00
LP5	+310 -0	+0 -280	+0 -31	+0.48 -0.00	+0.00 -0.44	+0.00 -0.05
-1.6 - 0.0	23039 $\pm$ 244 $^{+791}_{-1185}$	5305 $\pm$ 204 $^{+1049}_{-688}$	479 $\pm$ 57 $^{+141}_{-107}$	79.9 $\pm$ 0.8 $^{+2.7}_{-4.1}$	18.4 $\pm$ 0.7 $^{+3.6}_{-2.4}$	1.7 $\pm$ 0.2 $^{+0.5}_{-0.4}$
LP2	+0 -316	+297 -0	+29 -0	+0.00 -1.12	+1.02 -0.00	+0.10 -0.00
LP5	+107 -0	+0 -73	+0 -35	+0.37 -0.00	+0.00 -0.25	+0.00 -0.12
0.0 - 1.6	23309 $\pm$ 242 $^{+811}_{-1161}$	4974 $\pm$ 202 $^{+1003}_{-713}$	540 $\pm$ 59 $^{+190}_{-97}$	80.9 $\pm$ 0.8 $^{+2.8}_{-4.0}$	17.3 $\pm$ 0.7 $^{+3.5}_{-2.5}$	1.9 $\pm$ 0.2 $^{+0.7}_{-0.3}$
LP2	+0 -257	+170 -0	+100 -0	+0.00 -0.93	+0.58 -0.00	+0.34 -0.00
LP5	+157 -0	+0 -131	+0 -26	+0.54 -0.00	+0.00 -0.45	+0.00 -0.09
1.6 - 3.2	53300 $\pm$ 356 $^{+1853}_{-2718}$	9714 $\pm$ 287 $^{+2411}_{-1673}$	970 $\pm$ 80 $^{+327}_{-175}$	83.3 $\pm$ 0.5 $^{+2.9}_{-4.2}$	15.2 $\pm$ 0.5 $^{+3.8}_{-2.6}$	1.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -683	+542 -0	+153 -0	+0.00 -1.08	+0.84 -0.00	+0.24 -0.00
LP5	+319 -0	+0 -307	+0 -12	+0.50 -0.00	+0.00 -0.48	+0.00 -0.02
$ \Delta\Phi_{\gamma\gamma, jj} [rad]$						
-100 - 0	741485 $\pm$ 1492 $^{+26011}_{-38352}$	218249 $\pm$ 1388 $^{+32423}_{-22106}$	31913 $\pm$ 427 $^{+5968}_{-3815}$	74.8 $\pm$ 0.1 $^{+2.6}_{-3.9}$	22.0 $\pm$ 0.1 $^{+3.3}_{-2.2}$	3.2 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -11505	+9106 -0	+2480 -0	+0.00 -1.17	+0.92 -0.00	+0.25 -0.00
LP5	+6062 -0	+0 -4793	+0 -1204	+0.61 -0.00	+0.00 -0.48	+0.00 -0.12
0.0 - 2.5	48386 $\pm$ 364 $^{+1740}_{-2551}$	11487 $\pm$ 314 $^{+2211}_{-1528}$	1221 $\pm$ 92 $^{+344}_{-210}$	79.2 $\pm$ 0.5 $^{+2.8}_{-4.2}$	18.8 $\pm$ 0.5 $^{+3.6}_{-2.5}$	2.0 $\pm$ 0.2 $^{+0.6}_{-0.3}$
LP2	+0 -641	+500 -0	+136 -0	+0.00 -1.04	+0.82 -0.00	+0.22 -0.00
LP5	+304 -0	+0 -266	+0 -41	+0.50 -0.00	+0.00 -0.43	+0.00 -0.07
2.5 - 3.0	66602 $\pm$ 392 $^{+2267}_{-3358}$	11582 $\pm$ 313 $^{+2958}_{-2038}$	1225 $\pm$ 88 $^{+459}_{-224}$	83.9 $\pm$ 0.4 $^{+2.8}_{-4.2}$	14.6 $\pm$ 0.4 $^{+3.7}_{-2.6}$	1.5 $\pm$ 0.1 $^{+0.6}_{-0.3}$
LP2	+0 -856	+617 -0	+248 -0	+0.00 -1.09	+0.77 -0.00	+0.31 -0.00
LP5	+341 -0	+0 -283	+0 -57	+0.43 -0.00	+0.00 -0.36	+0.00 -0.07
3.0 - 3.2	38531 $\pm$ 288 $^{+1284}_{-1862}$	6369 $\pm$ 219 $^{+1701}_{-1161}$	496 $\pm$ 57 $^{+168}_{-114}$	84.9 $\pm$ 0.5 $^{+2.8}_{-4.1}$	14.0 $\pm$ 0.5 $^{+3.7}_{-2.6}$	1.1 $\pm$ 0.1 $^{+0.4}_{-0.3}$
LP2	+0 -457	+461 -0	+33 -0	+0.00 -1.08	+1.00 -0.00	+0.07 -0.00
LP5	+248 -0	+0 -239	+0 -6	+0.54 -0.00	+0.00 -0.53	+0.00 -0.01

Table B.11: Yield and purity outputs from the 2x2D Sideband Method for p_T^{γ} jet veto[30].

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
p_T^{γ} jet veto [30]						
-100 - 0	404953 $\pm$ 990 $^{+14019}_{-20862}$	87979 $\pm$ 861 $^{+18284}_{-12365}$	9892 $\pm$ 250 $^{+2629}_{-1614}$	80.5 $\pm$ 0.2 $^{+2.8}_{-4.1}$	17.5 $\pm$ 0.2 $^{+3.6}_{-2.5}$	2.0 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -5839	+4879 -0	+1047 -0	+0.00 -1.17	+0.97 -0.00	+0.21 -0.00
LP5	+2553 -0	+0 -2184	+0 -351	+0.50 -0.00	+0.00 -0.43	+0.00 -0.07
0 - 5	50450 $\pm$ 306 $^{+1219}_{-1854}$	7203 $\pm$ 209 $^{+1285}_{-818}$	1542 $\pm$ 75 $^{+331}_{-251}$	85.2 $\pm$ 0.4 $^{+1.8}_{-2.8}$	12.2 $\pm$ 0.4 $^{+2.2}_{-1.4}$	2.6 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -544	+409 -0	+105 -0	+0.00 -0.88	+0.70 -0.00	+0.18 -0.00
LP5	+181 -0	+0 -72	+0 -98	+0.29 -0.00	+0.00 -0.12	+0.00 -0.17
5 - 10	85402 $\pm$ 483 $^{+2830}_{-4168}$	21795 $\pm$ 430 $^{+3548}_{-2407}$	3845 $\pm$ 138 $^{+577}_{-371}$	76.9 $\pm$ 0.4 $^{+2.5}_{-3.7}$	19.6 $\pm$ 0.4 $^{+3.2}_{-2.2}$	3.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1268	+1057 -0	+237 -0	+0.00 -1.16	+0.95 -0.00	+0.21 -0.00
LP5	+683 -0	+0 -553	+0 -117	+0.61 -0.00	+0.00 -0.50	+0.00 -0.11
10 - 15	82657 $\pm$ 534 $^{+2864}_{-4219}$	28611 $\pm$ 501 $^{+3415}_{-2332}$	5042 $\pm$ 163 $^{+802}_{-515}$	71.1 $\pm$ 0.5 $^{+2.4}_{-3.6}$	24.6 $\pm$ 0.4 $^{+2.9}_{-2.0}$	4.3 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -1316	+953 -0	+368 -0	+0.00 -1.14	+0.82 -0.00	+0.32 -0.00
LP5	+718 -0	+0 -508	+0 -199	+0.61 -0.00	+0.00 -0.44	+0.00 -0.17
15 - 20	70655 $\pm$ 502 $^{+2519}_{-3678}$	27117 $\pm$ 466 $^{+2952}_{-2053}$	4195 $\pm$ 153 $^{+719}_{-446}$	69.3 $\pm$ 0.5 $^{+2.5}_{-3.6}$	26.6 $\pm$ 0.5 $^{+2.9}_{-2.0}$	4.1 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -1139	+834 -0	+303 -0	+0.00 -1.12	+0.82 -0.00	+0.30 -0.00
LP5	+661 -0	+0 -525	+0 -126	+0.64 -0.00	+0.00 -0.52	+0.00 -0.12
20 - 30	98866 $\pm$ 592 $^{+3538}_{-5107}$	37931 $\pm$ 557 $^{+4135}_{-2916}$	5206 $\pm$ 171 $^{+968}_{-600}$	69.6 $\pm$ 0.4 $^{+2.5}_{-3.6}$	26.7 $\pm$ 0.4 $^{+2.9}_{-2.1}$	3.7 $\pm$ 0.1 $^{+0.7}_{-0.4}$
LP2	+0 -1522	+1111 -0	+404 -0	+0.00 -1.07	+0.78 -0.00	+0.28 -0.00
LP5	+947 -0	+0 -770	+0 -164	+0.66 -0.00	+0.00 -0.54	+0.00 -0.12
30 - 40	52937 $\pm$ 436 $^{+1967}_{-2792}$	19834 $\pm$ 397 $^{+2346}_{-1639}$	2461 $\pm$ 119 $^{+430}_{-318}$	70.4 $\pm$ 0.6 $^{+2.6}_{-3.7}$	26.4 $\pm$ 0.5 $^{+3.1}_{-2.2}$	3.3 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -820	+677 -0	+130 -0	+0.00 -1.08	+0.90 -0.00	+0.17 -0.00
LP5	+567 -0	+0 -444	+0 -113	+0.74 -0.00	+0.00 -0.59	+0.00 -0.15
40 - 50	25557 $\pm$ 296 $^{+962}_{-1460}$	9417 $\pm$ 271 $^{+1215}_{-812}$	895 $\pm$ 76 $^{+241}_{-148}$	71.2 $\pm$ 0.8 $^{+2.7}_{-4.1}$	26.3 $\pm$ 0.8 $^{+3.4}_{-2.3}$	2.5 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -511	+404 -0	+102 -0	+0.00 -1.42	+1.13 -0.00	+0.29 -0.00
LP5	+247 -0	+0 -206	+0 -41	+0.69 -0.00	+0.00 -0.57	+0.00 -0.11
50 - 100	20932 $\pm$ 281 $^{+865}_{-1195}$	8260 $\pm$ 260 $^{+987}_{-739}$	858 $\pm$ 73 $^{+217}_{-126}$	69.7 $\pm$ 0.9 $^{+2.9}_{-4.0}$	27.5 $\pm$ 0.9 $^{+3.3}_{-2.5}$	2.9 $\pm$ 0.3 $^{+0.7}_{-0.4}$
LP2	+0 -335	+226 -0	+102 -0	+0.00 -1.10	+0.76 -0.00	+0.34 -0.00
LP5	+271 -0	+0 -235	+0 -38	+0.90 -0.00	+0.00 -0.78	+0.00 -0.13
100 - 13000	495 $\pm$ 37 $^{+15}_{-34}$	114 $\pm$ 32 $^{+35}_{-14}$	19 $\pm$ 9 $^{+2}_{-6}$	78.8 $\pm$ 5.4 $^{+2.4}_{-5.3}$	18.2 $\pm$ 5.2 $^{+5.6}_{-2.2}$	2.9 $\pm$ 1.6 $^{+0.3}_{-1.0}$
LP2	+0 -19	+21 -0	+0 -3	+0.00 -2.84	+3.35 -0.00	+0.00 -0.50
LP5	+2 -0	+2 -0	+0 -4	+0.32 -0.00	+0.28 -0.00	+0.00 -0.60

Table B.12: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma}$ jet veto[40].

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma}$ jet veto [40]						
-100 - 0	289001 $\pm$ 843 $^{+9926}_{-14746}$	57863 $\pm$ 693 $^{+13041}_{-8821}$	5844 $\pm$ 195 $^{+1741}_{-1076}$	81.9 $\pm$ 0.2 $^{+2.8}_{-4.2}$	16.4 $\pm$ 0.2 $^{+3.7}_{-2.5}$	1.7 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -4049	+3448 -0	+673 -0	+0.00 -1.16	+0.97 -0.00	+0.19 -0.00
LP5	+1760 -0	+0 -1528	+0 -218	+0.50 -0.00	+0.00 -0.43	+0.00 -0.06
0 - 5	53960 $\pm$ 322 $^{+1294}_{-1963}$	7955 $\pm$ 224 $^{+1358}_{-872}$	1668 $\pm$ 80 $^{+371}_{-273}$	84.9 $\pm$ 0.4 $^{+1.8}_{-2.8}$	12.5 $\pm$ 0.4 $^{+2.2}_{-1.4}$	2.6 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -568	+418 -0	+119 -0	+0.00 -0.85	+0.66 -0.00	+0.19 -0.00
LP5	+187 -0	+0 -76	+0 -99	+0.28 -0.00	+0.00 -0.12	+0.00 -0.16
5 - 10	92627 $\pm$ 506 $^{+3071}_{-4541}$	23733 $\pm$ 454 $^{+3864}_{-2614}$	4166 $\pm$ 144 $^{+633}_{-404}$	76.9 $\pm$ 0.4 $^{+2.5}_{-3.7}$	19.7 $\pm$ 0.4 $^{+3.2}_{-2.2}$	3.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1397	+1159 -0	+260 -0	+0.00 -1.17	+0.96 -0.00	+0.22 -0.00
LP5	+732 -0	+0 -598	+0 -124	+0.60 -0.00	+0.00 -0.50	+0.00 -0.10
10 - 15	91655 $\pm$ 562 $^{+3162}_{-4669}$	31511 $\pm$ 513 $^{+3776}_{-2582}$	5568 $\pm$ 172 $^{+901}_{-562}$	71.2 $\pm$ 0.4 $^{+2.4}_{-3.6}$	24.5 $\pm$ 0.4 $^{+2.9}_{-2.0}$	4.3 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -1424	+1015 -0	+418 -0	+0.00 -1.11	+0.79 -0.00	+0.32 -0.00
LP5	+750 -0	+0 -533	+0 -205	+0.58 -0.00	+0.00 -0.42	+0.00 -0.16
15 - 20	80529 $\pm$ 541 $^{+2896}_{-4206}$	30678 $\pm$ 514 $^{+3375}_{-2366}$	4747 $\pm$ 163 $^{+825}_{-507}$	69.4 $\pm$ 0.5 $^{+2.5}_{-3.6}$	26.5 $\pm$ 0.5 $^{+2.9}_{-2.0}$	4.1 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -1309	+960 -0	+348 -0	+0.00 -1.13	+0.83 -0.00	+0.30 -0.00
LP5	+792 -0	+0 -643	+0 -138	+0.68 -0.00	+0.00 -0.56	+0.00 -0.12
20 - 30	122131 $\pm$ 642 $^{+4387}_{-6323}$	44584 $\pm$ 606 $^{+5166}_{-3645}$	6182 $\pm$ 192 $^{+1158}_{-716}$	70.6 $\pm$ 0.4 $^{+2.5}_{-3.6}$	25.8 $\pm$ 0.4 $^{+3.0}_{-2.1}$	3.6 $\pm$ 0.1 $^{+0.7}_{-0.4}$
LP2	+0 -1873	+1401 -0	+474 -0	+0.00 -1.08	+0.81 -0.00	+0.27 -0.00
LP5	+1176 -0	+0 -976	+0 -183	+0.67 -0.00	+0.00 -0.57	+0.00 -0.11
30 - 40	76633 $\pm$ 499 $^{+2785}_{-4088}$	25138 $\pm$ 457 $^{+3500}_{-2355}$	3202 $\pm$ 138 $^{+568}_{-421}$	73.0 $\pm$ 0.5 $^{+2.6}_{-3.9}$	23.9 $\pm$ 0.4 $^{+3.3}_{-2.2}$	3.1 $\pm$ 0.1 $^{+0.5}_{-0.4}$
LP2	+0 -1260	+1082 -0	+159 -0	+0.00 -1.19	+1.04 -0.00	+0.15 -0.00
LP5	+703 -0	+0 -544	+0 -144	+0.66 -0.00	+0.00 -0.52	+0.00 -0.14
40 - 50	43245 $\pm$ 359 $^{+1575}_{-2395}$	13284 $\pm$ 321 $^{+2044}_{-1352}$	1296 $\pm$ 92 $^{+344}_{-222}$	74.8 $\pm$ 0.6 $^{+2.7}_{-4.1}$	23.0 $\pm$ 0.6 $^{+3.5}_{-2.3}$	2.2 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -769	+625 -0	+135 -0	+0.00 -1.32	+1.08 -0.00	+0.23 -0.00
LP5	+319 -0	+0 -255	+0 -65	+0.55 -0.00	+0.00 -0.44	+0.00 -0.11
50 - 60	21826 $\pm$ 266 $^{+831}_{-1210}$	6982 $\pm$ 236 $^{+1017}_{-712}$	622 $\pm$ 67 $^{+204}_{-117}$	74.2 $\pm$ 0.9 $^{+2.8}_{-4.1}$	23.7 $\pm$ 0.8 $^{+3.5}_{-2.4}$	2.1 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -344	+244 -0	+99 -0	+0.00 -1.17	+0.83 -0.00	+0.34 -0.00
LP5	+196 -0	+0 -156	+0 -37	+0.66 -0.00	+0.00 -0.53	+0.00 -0.12
60 - 100	20028 $\pm$ 266 $^{+813}_{-1176}$	6580 $\pm$ 243 $^{+995}_{-703}$	659 $\pm$ 68 $^{+180}_{-111}$	73.5 $\pm$ 0.9 $^{+3.0}_{-4.3}$	24.1 $\pm$ 0.9 $^{+3.7}_{-2.6}$	2.4 $\pm$ 0.3 $^{+0.7}_{-0.4}$
LP2	+0 -358	+262 -0	+83 -0	+0.00 -1.28	+0.97 -0.00	+0.31 -0.00
LP5	+221 -0	+0 -185	+0 -39	+0.82 -0.00	+0.00 -0.67	+0.00 -0.14
100 - 13000	1028 $\pm$ 52 $^{+30}_{-54}$	254 $\pm$ 42 $^{+52}_{-26}$	22 $\pm$ 10 $^{+5}_{-6}$	78.8 $\pm$ 3.4 $^{+2.3}_{-4.1}$	19.5 $\pm$ 3.4 $^{+4.0}_{-2.0}$	1.7 $\pm$ 0.8 $^{+0.4}_{-0.4}$
LP2	+0 -24	+26 -0	+0 -3	+0.00 -1.77	+1.98 -0.00	+0.00 -0.22
LP5	+4 -0	+0 -3	+0 -2	+0.34 -0.00	+0.00 -0.19	+0.00 -0.16

Table B.13: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma}$ jet veto[50].

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma}$ jet veto [50]						
-100 - 0	215230 $\pm$ 716 $^{+7350}_{-10914}$	40776 $\pm$ 578 $^{+9735}_{-6568}$	3985 $\pm$ 161 $^{+1202}_{-762}$	82.8 $\pm$ 0.2 $^{+2.8}_{-4.2}$	15.7 $\pm$ 0.2 $^{+3.7}_{-2.5}$	1.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -2995	+2624 -0	+433 -0	+0.00 -1.17	+1.01 -0.00	+0.17 -0.00
LP5	+1311 -0	+0 -1150	+0 -151	+0.50 -0.00	+0.00 -0.44	+0.00 -0.06
0 - 5	55079 $\pm$ 326 $^{+1315}_{-1985}$	8215 $\pm$ 228 $^{+1369}_{-888}$	1696 $\pm$ 81 $^{+389}_{-282}$	84.8 $\pm$ 0.4 $^{+1.8}_{-2.8}$	12.6 $\pm$ 0.4 $^{+2.2}_{-1.4}$	2.6 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -559	+399 -0	+131 -0	+0.00 -0.82	+0.62 -0.00	+0.20 -0.00
LP5	+186 -0	+0 -72	+0 -103	+0.27 -0.00	+0.00 -0.11	+0.00 -0.16
5 - 10	94873 $\pm$ 515 $^{+3148}_{-4662}$	24377 $\pm$ 457 $^{+3961}_{-2681}$	4292 $\pm$ 145 $^{+657}_{-416}$	76.8 $\pm$ 0.4 $^{+2.5}_{-3.7}$	19.7 $\pm$ 0.4 $^{+3.2}_{-2.2}$	3.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1434	+1182 -0	+273 -0	+0.00 -1.17	+0.95 -0.00	+0.22 -0.00
LP5	+741 -0	+0 -608	+0 -126	+0.60 -0.00	+0.00 -0.49	+0.00 -0.10
10 - 15	94833 $\pm$ 570 $^{+3267}_{-4800}$	32581 $\pm$ 539 $^{+3883}_{-2669}$	5710 $\pm$ 175 $^{+929}_{-581}$	71.2 $\pm$ 0.4 $^{+2.4}_{-3.6}$	24.5 $\pm$ 0.4 $^{+2.9}_{-2.0}$	4.3 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -1423	+1007 -0	+427 -0	+0.00 -1.07	+0.75 -0.00	+0.32 -0.00
LP5	+766 -0	+0 -547	+0 -210	+0.57 -0.00	+0.00 -0.41	+0.00 -0.16
15 - 20	84378 $\pm$ 554 $^{+3046}_{-4405}$	31870 $\pm$ 526 $^{+3533}_{-2484}$	4998 $\pm$ 168 $^{+873}_{-540}$	69.6 $\pm$ 0.5 $^{+2.5}_{-3.6}$	26.3 $\pm$ 0.4 $^{+2.9}_{-2.1}$	4.1 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -1353	+983 -0	+374 -0	+0.00 -1.12	+0.81 -0.00	+0.31 -0.00
LP5	+839 -0	+0 -670	+0 -159	+0.69 -0.00	+0.00 -0.55	+0.00 -0.13
20 - 30	132425 $\pm$ 660 $^{+4740}_{-6841}$	47361 $\pm$ 617 $^{+5600}_{-3943}$	6551 $\pm$ 193 $^{+1243}_{-772}$	71.1 $\pm$ 0.3 $^{+2.5}_{-3.7}$	25.4 $\pm$ 0.3 $^{+3.0}_{-2.1}$	3.5 $\pm$ 0.1 $^{+0.7}_{-0.4}$
LP2	+0 -2001	+1501 -0	+503 -0	+0.00 -1.08	+0.81 -0.00	+0.27 -0.00
LP5	+1240 -0	+0 -1029	+0 -195	+0.66 -0.00	+0.00 -0.55	+0.00 -0.10
30 - 40	90025 $\pm$ 532 $^{+3248}_{-4824}$	28102 $\pm$ 479 $^{+4150}_{-2764}$	3574 $\pm$ 149 $^{+655}_{-472}$	74.0 $\pm$ 0.4 $^{+2.7}_{-4.0}$	23.1 $\pm$ 0.4 $^{+3.4}_{-2.3}$	2.9 $\pm$ 0.1 $^{+0.5}_{-0.4}$
LP2	+0 -1510	+1313 -0	+178 -0	+0.00 -1.23	+1.08 -0.00	+0.15 -0.00
LP5	+772 -0	+0 -614	+0 -141	+0.62 -0.00	+0.00 -0.51	+0.00 -0.12
40 - 50	56974 $\pm$ 414 $^{+2066}_{-3116}$	16062 $\pm$ 362 $^{+2678}_{-1796}$	1558 $\pm$ 102 $^{+429}_{-266}$	76.4 $\pm$ 0.5 $^{+2.8}_{-4.2}$	21.5 $\pm$ 0.5 $^{+3.6}_{-2.4}$	2.1 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -976	+790 -0	+170 -0	+0.00 -1.29	+1.06 -0.00	+0.23 -0.00
LP5	+428 -0	+0 -364	+0 -62	+0.57 -0.00	+0.00 -0.49	+0.00 -0.08
50 - 60	32351 $\pm$ 314 $^{+1208}_{-1784}$	9218 $\pm$ 273 $^{+1523}_{-1046}$	725 $\pm$ 73 $^{+263}_{-158}$	76.5 $\pm$ 0.7 $^{+2.8}_{-4.2}$	21.8 $\pm$ 0.7 $^{+3.6}_{-2.5}$	1.7 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -524	+398 -0	+117 -0	+0.00 -1.22	+0.95 -0.00	+0.28 -0.00
LP5	+268 -0	+0 -216	+0 -45	+0.62 -0.00	+0.00 -0.51	+0.00 -0.11
60 - 70	17841 $\pm$ 232 $^{+671}_{-995}$	4989 $\pm$ 207 $^{+842}_{-587}$	442 $\pm$ 56 $^{+179}_{-85}$	76.7 $\pm$ 0.9 $^{+2.9}_{-4.3}$	21.4 $\pm$ 0.9 $^{+3.6}_{-2.5}$	1.9 $\pm$ 0.3 $^{+0.8}_{-0.4}$
LP2	+0 -267	+158 -0	+101 -0	+0.00 -1.12	+0.69 -0.00	+0.43 -0.00
LP5	+115 -0	+0 -89	+0 -27	+0.50 -0.00	+0.00 -0.38	+0.00 -0.12
70 - 100	16464 $\pm$ 232 $^{+659}_{-983}$	4642 $\pm$ 207 $^{+857}_{-576}$	478 $\pm$ 58 $^{+119}_{-84}$	76.3 $\pm$ 1.0 $^{+3.1}_{-4.5}$	21.5 $\pm$ 1.0 $^{+4.0}_{-2.7}$	2.2 $\pm$ 0.3 $^{+0.6}_{-0.4}$
LP2	+0 -328	+274 -0	+45 -0	+0.00 -1.49	+1.28 -0.00	+0.21 -0.00
LP5	+172 -0	+0 -140	+0 -31	+0.79 -0.00	+0.00 -0.65	+0.00 -0.14
100 - 13000	2192 $\pm$ 74 $^{+65}_{-106}$	461 $\pm$ 58 $^{+100}_{-59}$	35 $\pm$ 13 $^{+9}_{-9}$	81.6 $\pm$ 2.3 $^{+2.4}_{-3.9}$	17.1 $\pm$ 2.3 $^{+3.7}_{-2.2}$	1.3 $\pm$ 0.5 $^{+0.3}_{-0.3}$
LP2	+0 -37	+40 -0	+0 -3	+0.00 -1.38	+1.49 -0.00	+0.00 -0.10
LP5	+4 -0	+0 -2	+0 -4	+0.19 -0.00	+0.00 -0.05	+0.00 -0.14

Table B.14: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma}$ jet veto[60].

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma}$ jet veto [60]						
-100 - 0	163478 $\pm$ 617 $^{+5542}_{-8237}$	29996 $\pm$ 493 $^{+7343}_{-4958}$	2798 $\pm$ 135 $^{+926}_{-571}$	83.3 $\pm$ 0.3 $^{+2.8}_{-4.2}$	15.3 $\pm$ 0.3 $^{+3.7}_{-2.5}$	1.4 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -2227	+1910 -0	+367 -0	+0.00 -1.16	+0.97 -0.00	+0.19 -0.00
LP5	+935 -0	+0 -799	+0 -127	+0.47 -0.00	+0.00 -0.41	+0.00 -0.06
0 - 5	55464 $\pm$ 327 $^{+1320}_{-1990}$	8373 $\pm$ 229 $^{+1374}_{-892}$	1693 $\pm$ 81 $^{+392}_{-285}$	84.6 $\pm$ 0.4 $^{+1.8}_{-2.8}$	12.8 $\pm$ 0.4 $^{+2.1}_{-1.4}$	2.6 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -556	+398 -0	+130 -0	+0.00 -0.81	+0.61 -0.00	+0.20 -0.00
LP5	+186 -0	+0 -73	+0 -103	+0.27 -0.00	+0.00 -0.11	+0.00 -0.16
5 - 10	95805 $\pm$ 513 $^{+3184}_{-4711}$	24702 $\pm$ 466 $^{+3999}_{-2710}$	4330 $\pm$ 150 $^{+667}_{-423}$	76.7 $\pm$ 0.4 $^{+2.5}_{-3.7}$	19.8 $\pm$ 0.4 $^{+3.2}_{-2.2}$	3.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1450	+1191 -0	+278 -0	+0.00 -1.17	+0.95 -0.00	+0.22 -0.00
LP5	+757 -0	+0 -620	+0 -130	+0.60 -0.00	+0.00 -0.50	+0.00 -0.10
10 - 15	96287 $\pm$ 572 $^{+3317}_{-4874}$	33010 $\pm$ 535 $^{+3944}_{-2710}$	5767 $\pm$ 175 $^{+944}_{-591}$	71.3 $\pm$ 0.4 $^{+2.4}_{-3.6}$	24.4 $\pm$ 0.4 $^{+2.9}_{-2.0}$	4.3 $\pm$ 0.1 $^{+0.7}_{-0.4}$
LP2	+0 -1443	+1022 -0	+433 -0	+0.00 -1.07	+0.75 -0.00	+0.32 -0.00
LP5	+776 -0	+0 -552	+0 -213	+0.57 -0.00	+0.00 -0.41	+0.00 -0.16
15 - 20	86099 $\pm$ 558 $^{+3113}_{-4499}$	32487 $\pm$ 531 $^{+3612}_{-2542}$	5050 $\pm$ 169 $^{+886}_{-549}$	69.6 $\pm$ 0.5 $^{+2.5}_{-3.6}$	26.3 $\pm$ 0.4 $^{+2.9}_{-2.1}$	4.1 $\pm$ 0.2 $^{+0.7}_{-0.4}$
LP2	+0 -1385	+1015 -0	+374 -0	+0.00 -1.12	+0.82 -0.00	+0.30 -0.00
LP5	+864 -0	+0 -696	+0 -156	+0.69 -0.00	+0.00 -0.57	+0.00 -0.13
20 - 30	137319 $\pm$ 686 $^{+4950}_{-7083}$	48666 $\pm$ 637 $^{+5803}_{-4139}$	6777 $\pm$ 197 $^{+1285}_{-787}$	71.2 $\pm$ 0.3 $^{+2.6}_{-3.7}$	25.2 $\pm$ 0.3 $^{+3.0}_{-2.2}$	3.5 $\pm$ 0.1 $^{+0.7}_{-0.4}$
LP2	+0 -2045	+1531 -0	+517 -0	+0.00 -1.06	+0.79 -0.00	+0.27 -0.00
LP5	+1341 -0	+0 -1148	+0 -175	+0.69 -0.00	+0.00 -0.60	+0.00 -0.09
30 - 40	96612 $\pm$ 554 $^{+3468}_{-5189}$	29717 $\pm$ 500 $^{+4458}_{-2945}$	3787 $\pm$ 150 $^{+712}_{-516}$	74.3 $\pm$ 0.4 $^{+2.7}_{-4.0}$	22.8 $\pm$ 0.4 $^{+3.4}_{-2.3}$	2.9 $\pm$ 0.1 $^{+0.5}_{-0.4}$
LP2	+0 -1634	+1412 -0	+203 -0	+0.00 -1.25	+1.09 -0.00	+0.16 -0.00
LP5	+785 -0	+0 -604	+0 -165	+0.59 -0.00	+0.00 -0.47	+0.00 -0.13
40 - 50	66017 $\pm$ 438 $^{+2372}_{-3597}$	17512 $\pm$ 381 $^{+3124}_{-2067}$	1775 $\pm$ 108 $^{+462}_{-300}$	77.4 $\pm$ 0.5 $^{+2.8}_{-4.2}$	20.5 $\pm$ 0.5 $^{+3.7}_{-2.4}$	2.1 $\pm$ 0.1 $^{+0.5}_{-0.4}$
LP2	+0 -1120	+938 -0	+169 -0	+0.00 -1.30	+1.10 -0.00	+0.20 -0.00
LP5	+453 -0	+0 -370	+0 -78	+0.53 -0.00	+0.00 -0.43	+0.00 -0.09
50 - 60	41251 $\pm$ 347 $^{+1528}_{-2239}$	10822 $\pm$ 298 $^{+1944}_{-1339}$	908 $\pm$ 81 $^{+292}_{-184}$	77.9 $\pm$ 0.6 $^{+2.9}_{-4.2}$	20.4 $\pm$ 0.6 $^{+3.7}_{-2.5}$	1.7 $\pm$ 0.2 $^{+0.6}_{-0.3}$
LP2	+0 -630	+509 -0	+113 -0	+0.00 -1.18	+0.96 -0.00	+0.21 -0.00
LP5	+335 -0	+0 -284	+0 -44	+0.62 -0.00	+0.00 -0.54	+0.00 -0.08
60 - 70	24879 $\pm$ 266 $^{+918}_{-1387}$	6087 $\pm$ 229 $^{+1201}_{-813}$	579 $\pm$ 64 $^{+198}_{-108}$	78.9 $\pm$ 0.8 $^{+2.9}_{-4.4}$	19.3 $\pm$ 0.8 $^{+3.8}_{-2.6}$	1.8 $\pm$ 0.2 $^{+0.6}_{-0.3}$
LP2	+0 -401	+290 -0	+103 -0	+0.00 -1.25	+0.92 -0.00	+0.33 -0.00
LP5	+145 -0	+0 -109	+0 -36	+0.46 -0.00	+0.00 -0.35	+0.00 -0.12
70 - 80	13983 $\pm$ 204 $^{+539}_{-792}$	3506 $\pm$ 177 $^{+696}_{-481}$	350 $\pm$ 49 $^{+92}_{-58}$	78.4 $\pm$ 1.1 $^{+3.0}_{-4.4}$	19.7 $\pm$ 1.0 $^{+3.9}_{-2.7}$	2.0 $\pm$ 0.3 $^{+0.5}_{-0.3}$
LP2	+0 -243	+200 -0	+37 -0	+0.00 -1.33	+1.13 -0.00	+0.21 -0.00
LP5	+135 -0	+0 -120	+0 -15	+0.75 -0.00	+0.00 -0.67	+0.00 -0.08
80 - 100	11487 $\pm$ 174 $^{+439}_{-669}$	2828 $\pm$ 154 $^{+605}_{-394}$	251 $\pm$ 43 $^{+65}_{-46}$	78.9 $\pm$ 1.1 $^{+3.0}_{-4.6}$	19.4 $\pm$ 1.1 $^{+4.2}_{-2.7}$	1.7 $\pm$ 0.3 $^{+0.4}_{-0.3}$
LP2	+0 -232	+220 -0	+7 -0	+0.00 -1.57	+1.52 -0.00	+0.05 -0.00
LP5	+108 -0	+0 -103	+0 -8	+0.75 -0.00	+0.00 -0.70	+0.00 -0.05
100 - 13000	4119 $\pm$ 100 $^{+123}_{-191}$	839 $\pm$ 76 $^{+173}_{-111}$	43 $\pm$ 16 $^{+18}_{-14}$	82.4 $\pm$ 1.6 $^{+2.5}_{-3.8}$	16.8 $\pm$ 1.6 $^{+3.5}_{-2.2}$	0.9 $\pm$ 0.3 $^{+0.4}_{-0.3}$
LP2	+0 -62	+57 -0	+5 -0	+0.00 -1.25	+1.14 -0.00	+0.10 -0.00
LP5	+19 -0	+0 -15	+0 -6	+0.41 -0.00	+0.00 -0.30	+0.00 -0.11

Table B.15: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma j}$ and $p_T^{\gamma\gamma jj}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma j}$						
-100 - 0	489942 $\pm$ 1281 $^{+17348}_{-25388}$	159881 $\pm$ 1189 $^{+21128}_{-14526}$	24809 $\pm$ 372 $^{+4199}_{-2736}$	72.6 $\pm$ 0.2 $^{+2.6}_{-3.7}$	23.7 $\pm$ 0.2 $^{+3.1}_{-2.2}$	3.7 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -7755	+5970 -0	+1749 -0	+0.00 -1.15	+0.89 -0.00	+0.26 -0.00
LP5	+4405 -0	+0 -3424	+0 -930	+0.65 -0.00	+0.00 -0.51	+0.00 -0.14
0 - 30	188811 $\pm$ 656 $^{+6368}_{-9545}$	38872 $\pm$ 539 $^{+8416}_{-5620}$	3885 $\pm$ 156 $^{+1100}_{-701}$	81.5 $\pm$ 0.2 $^{+2.7}_{-4.1}$	16.8 $\pm$ 0.2 $^{+3.6}_{-2.4}$	1.7 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -2758	+2407 -0	+385 -0	+0.00 -1.20	+1.04 -0.00	+0.17 -0.00
LP5	+1141 -0	+0 -990	+0 -131	+0.49 -0.00	+0.00 -0.43	+0.00 -0.06
30 - 60	135869 $\pm$ 612 $^{+4733}_{-6990}$	32668 $\pm$ 534 $^{+6045}_{-4127}$	4413 $\pm$ 163 $^{+977}_{-602}$	78.6 $\pm$ 0.3 $^{+2.7}_{-4.0}$	18.9 $\pm$ 0.3 $^{+3.5}_{-2.4}$	2.6 $\pm$ 0.1 $^{+0.6}_{-0.3}$
LP2	+0 -1903	+1517 -0	+406 -0	+0.00 -1.11	+0.87 -0.00	+0.23 -0.00
LP5	+892 -0	+0 -729	+0 -159	+0.51 -0.00	+0.00 -0.42	+0.00 -0.09
60 - 120	62848 $\pm$ 408 $^{+2280}_{-3349}$	14086 $\pm$ 345 $^{+2926}_{-2023}$	1369 $\pm$ 98 $^{+454}_{-257}$	80.3 $\pm$ 0.5 $^{+2.9}_{-4.3}$	18.0 $\pm$ 0.5 $^{+3.7}_{-2.6}$	1.7 $\pm$ 0.1 $^{+0.6}_{-0.3}$
LP2	+0 -896	+716 -0	+201 -0	+0.00 -1.17	+0.91 -0.00	+0.26 -0.00
LP5	+442 -0	+0 -402	+0 -42	+0.57 -0.00	+0.00 -0.51	+0.00 -0.05
120 - 13000	17274 $\pm$ 191 $^{+604}_{-903}$	2313 $\pm$ 143 $^{+829}_{-556}$	168 $\pm$ 37 $^{+81}_{-49}$	87.4 $\pm$ 0.8 $^{+3.1}_{-4.6}$	11.7 $\pm$ 0.8 $^{+4.2}_{-2.8}$	0.9 $\pm$ 0.2 $^{+0.4}_{-0.2}$
LP2	+0 -228	+202 -0	+35 -0	+0.00 -1.19	+1.01 -0.00	+0.18 -0.00
LP5	+66 -0	+0 -54	+0 -13	+0.34 -0.00	+0.00 -0.27	+0.00 -0.07
$p_T^{\gamma\gamma jj}$ [GeV]						
-100 - 0	741485 $\pm$ 1529 $^{+26011}_{-38353}$	218249 $\pm$ 1393 $^{+32424}_{-22106}$	31913 $\pm$ 428 $^{+5968}_{-3815}$	74.8 $\pm$ 0.1 $^{+2.6}_{-3.9}$	22.0 $\pm$ 0.1 $^{+3.3}_{-2.2}$	3.2 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -11505	+9107 -0	+2480 -0	+0.00 -1.17	+0.92 -0.00	+0.25 -0.00
LP5	+6062 -0	+0 -4792	+0 -1203	+0.61 -0.00	+0.00 -0.48	+0.00 -0.12
0 - 30	67272 $\pm$ 391 $^{+2250}_{-3299}$	11626 $\pm$ 308 $^{+2929}_{-2025}$	1154 $\pm$ 85 $^{+389}_{-208}$	84.0 $\pm$ 0.4 $^{+2.8}_{-4.1}$	14.5 $\pm$ 0.4 $^{+3.7}_{-2.5}$	1.4 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -806	+644 -0	+185 -0	+0.00 -1.03	+0.80 -0.00	+0.23 -0.00
LP5	+367 -0	+0 -336	+0 -29	+0.46 -0.00	+0.00 -0.42	+0.00 -0.04
30 - 60	55884 $\pm$ 372 $^{+1886}_{-2845}$	11392 $\pm$ 305 $^{+2512}_{-1674}$	1120 $\pm$ 86 $^{+358}_{-447}$	81.7 $\pm$ 0.5 $^{+2.8}_{-4.2}$	16.7 $\pm$ 0.5 $^{+3.7}_{-2.4}$	1.6 $\pm$ 0.1 $^{+0.5}_{-0.7}$
LP2	+0 -710	+578 -0	+150 -0	+0.00 -1.06	+0.84 -0.00	+0.22 -0.00
LP5	+88 -0	+193 -0	+0 -282	+0.13 -0.00	+0.28 -0.00	+0.00 -0.41
60 - 120	25729 $\pm$ 259 $^{+911}_{-1352}$	5658 $\pm$ 218 $^{+1189}_{-804}$	573 $\pm$ 63 $^{+168}_{-110}$	80.5 $\pm$ 0.7 $^{+2.9}_{-4.2}$	17.7 $\pm$ 0.7 $^{+3.7}_{-2.5}$	1.8 $\pm$ 0.2 $^{+0.5}_{-0.3}$
LP2	+0 -348	+290 -0	+61 -0	+0.00 -1.10	+0.90 -0.00	+0.19 -0.00
LP5	+136 -0	+0 -108	+0 -30	+0.43 -0.00	+0.00 -0.34	+0.00 -0.09
120 - 13000	4745 $\pm$ 100 $^{+176}_{-274}$	666 $\pm$ 70 $^{+246}_{-161}$	63 $\pm$ 7 $^{+30}_{-16}$	86.7 $\pm$ 1.4 $^{+3.2}_{-5.0}$	12.2 $\pm$ 1.4 $^{+4.5}_{-2.9}$	1.2 $\pm$ 0.2 $^{+0.5}_{-0.3}$
LP2	+0 -81	+67 -0	+14 -0	+0.00 -1.48	+1.22 -0.00	+0.26 -0.00
LP5	+7 -0	+0 -5	+0 -2	+0.12 -0.00	+0.00 -0.09	+0.00 -0.04

Table B.16: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma 1}/m_{\gamma\gamma}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma 1}/m_{\gamma\gamma}$						
0.3 - 0.5	188228 $\pm$ 857 $^{+7069}_{-10482}$	68791 $\pm$ 862 $^{+8423}_{-5629}$	17021 $\pm$ 322 $^{+2008}_{-1432}$	68.7 $\pm$ 0.3 $^{+2.6}_{-3.8}$	25.1 $\pm$ 0.3 $^{+3.1}_{-2.1}$	6.2 $\pm$ 0.1 $^{+0.7}_{-0.5}$
LP2	+0 -3520	+2674 -0	+819 -0	+0.00 -1.28	+0.98 -0.00	+0.30 -0.00
LP5	+1927 -0	+0 -1296	+0 -594	+0.69 -0.00	+0.00 -0.48	+0.00 -0.22
0.5 - 0.5	153596 $\pm$ 663 $^{+5243}_{-7511}$	41755 $\pm$ 583 $^{+6356}_{-4520}$	6001 $\pm$ 177 $^{+1121}_{-681}$	76.3 $\pm$ 0.3 $^{+2.6}_{-3.7}$	20.7 $\pm$ 0.3 $^{+3.2}_{-2.2}$	3.0 $\pm$ 0.1 $^{+0.6}_{-0.3}$
LP2	+0 -2162	+1688 -0	+455 -0	+0.00 -1.07	+0.84 -0.00	+0.23 -0.00
LP5	+1406 -0	+0 -1241	+0 -144	+0.69 -0.00	+0.00 -0.62	+0.00 -0.07
0.5 - 0.6	192832 $\pm$ 718 $^{+6274}_{-9252}$	48444 $\pm$ 602 $^{+8035}_{-5440}$	5038 $\pm$ 166 $^{+1183}_{-796}$	78.3 $\pm$ 0.3 $^{+2.5}_{-3.7}$	19.7 $\pm$ 0.3 $^{+3.3}_{-2.2}$	2.0 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -2659	+2282 -0	+392 -0	+0.00 -1.08	+0.93 -0.00	+0.16 -0.00
LP5	+1348 -0	+0 -1123	+0 -209	+0.54 -0.00	+0.00 -0.46	+0.00 -0.09
0.6 - 0.6	113912 $\pm$ 573 $^{+3811}_{-5752}$	32978 $\pm$ 488 $^{+4923}_{-3275}$	2811 $\pm$ 131 $^{+821}_{-520}$	76.1 $\pm$ 0.3 $^{+2.5}_{-3.8}$	22.0 $\pm$ 0.3 $^{+3.3}_{-2.2}$	1.9 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1763	+1458 -0	+303 -0	+0.00 -1.18	+0.97 -0.00	+0.20 -0.00
LP5	+739 -0	+0 -608	+0 -112	+0.48 -0.00	+0.00 -0.41	+0.00 -0.08
0.6 - 0.7	73994 $\pm$ 435 $^{+2542}_{-3836}$	18710 $\pm$ 370 $^{+3375}_{-2225}$	1756 $\pm$ 106 $^{+469}_{-327}$	78.3 $\pm$ 0.4 $^{+2.7}_{-4.1}$	19.8 $\pm$ 0.4 $^{+3.6}_{-2.4}$	1.9 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1108	+960 -0	+164 -0	+0.00 -1.19	+1.01 -0.00	+0.17 -0.00
LP5	+407 -0	+0 -299	+0 -110	+0.43 -0.00	+0.00 -0.32	+0.00 -0.12
0.7 - 0.8	84834 $\pm$ 475 $^{+3052}_{-4601}$	19263 $\pm$ 392 $^{+4098}_{-2733}$	1449 $\pm$ 103 $^{+506}_{-315}$	80.4 $\pm$ 0.4 $^{+2.9}_{-4.4}$	18.3 $\pm$ 0.4 $^{+2.9}_{-2.6}$	1.4 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1346	+1172 -0	+182 -0	+0.00 -1.28	+1.11 -0.00	+0.17 -0.00
LP5	+520 -0	+0 -471	+0 -45	+0.49 -0.00	+0.00 -0.45	+0.00 -0.04
0.8 - 0.8	43199 $\pm$ 333 $^{+1621}_{-2384}$	8094 $\pm$ 274 $^{+2141}_{-1477}$	717 $\pm$ 74 $^{+284}_{-150}$	83.1 $\pm$ 0.6 $^{+3.1}_{-4.6}$	15.6 $\pm$ 0.5 $^{+4.1}_{-2.8}$	1.4 $\pm$ 0.2 $^{+0.5}_{-0.3}$
LP2	+0 -541	+397 -0	+149 -0	+0.00 -1.05	+0.76 -0.00	+0.29 -0.00
LP5	+198 -0	+0 -153	+0 -46	+0.38 -0.00	+0.00 -0.29	+0.00 -0.09
0.8 - 0.9	21818 $\pm$ 241 $^{+873}_{-1267}$	4355 $\pm$ 197 $^{+1157}_{-800}$	246 $\pm$ 48 $^{+110}_{-74}$	82.6 $\pm$ 0.8 $^{+3.3}_{-4.8}$	16.5 $\pm$ 0.8 $^{+4.4}_{-3.0}$	0.9 $\pm$ 0.2 $^{+0.4}_{-0.3}$
LP2	+0 -348	+322 -0	+28 -0	+0.00 -1.32	+1.22 -0.00	+0.11 -0.00
LP5	+201 -0	+0 -191	+0 -11	+0.76 -0.00	+0.00 -0.72	+0.00 -0.04
0.9 - 10.0	23440 $\pm$ 225 $^{+780}_{-1159}$	3851 $\pm$ 162 $^{+1082}_{-723}$	125 $\pm$ 32 $^{+89}_{-62}$	85.5 $\pm$ 0.6 $^{+2.8}_{-4.2}$	14.0 $\pm$ 0.6 $^{+3.9}_{-2.6}$	0.5 $\pm$ 0.1 $^{+0.3}_{-0.2}$
LP2	+0 -343	+345 -0	+6 -0	+0.00 -1.28	+1.25 -0.00	+0.02 -0.00
LP5	+166 -0	+0 -168	+6 -0	+0.59 -0.00	+0.00 -0.62	+0.02 -0.00

Table B.17: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma 2}/m_{\gamma\gamma}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma 2}/m_{\gamma\gamma}$						
0.2 - 0.3	313257 $\pm$ 1056 $^{+12315}_{-17979}$	110358 $\pm$ 1068 $^{+14698}_{-10206}$	21190 $\pm$ 362 $^{+3428}_{-2099}$	70.4 $\pm$ 0.2 $^{+2.8}_{-4.0}$	24.8 $\pm$ 0.2 $^{+3.3}_{-2.3}$	4.8 $\pm$ 0.1 $^{+0.8}_{-0.5}$
LP2	+0 -5541	+3977 -0	+1607 -0	+0.00 -1.25	+0.89 -0.00	+0.36 -0.00
LP5	+3221 -0	+0 -2447	+0 -745	+0.72 -0.00	+0.00 -0.55	+0.00 -0.17
0.3 - 0.4	203192 $\pm$ 758 $^{+6704}_{-10041}$	55645 $\pm$ 655 $^{+8597}_{-5760}$	7229 $\pm$ 195 $^{+1445}_{-920}$	76.4 $\pm$ 0.3 $^{+2.5}_{-3.8}$	20.9 $\pm$ 0.3 $^{+3.2}_{-2.2}$	2.7 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -3175	+2623 -0	+576 -0	+0.00 -1.20	+0.98 -0.00	+0.22 -0.00
LP5	+1519 -0	+0 -1245	+0 -258	+0.57 -0.00	+0.00 -0.47	+0.00 -0.10
0.4 - 0.5	199242 $\pm$ 693 $^{+6100}_{-9208}$	46823 $\pm$ 573 $^{+7983}_{-5308}$	4606 $\pm$ 152 $^{+1218}_{-764}$	79.5 $\pm$ 0.2 $^{+2.1}_{-3.7}$	18.7 $\pm$ 0.2 $^{+3.2}_{-2.1}$	1.8 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -2774	+2291 -0	+503 -0	+0.00 -1.11	+0.91 -0.00	+0.20 -0.00
LP5	+1122 -0	+0 -883	+0 -219	+0.44 -0.00	+0.00 -0.35	+0.00 -0.09
0.5 - 0.5	157775 $\pm$ 562 $^{+4443}_{-6714}$	25285 $\pm$ 405 $^{+6043}_{-3995}$	2211 $\pm$ 100 $^{+628}_{-394}$	85.2 $\pm$ 0.2 $^{+2.4}_{-3.6}$	13.6 $\pm$ 0.2 $^{+3.3}_{-2.2}$	1.2 $\pm$ 0.1 $^{+0.3}_{-0.2}$
LP2	+0 -1955	+1772 -0	+243 -0	+0.00 -1.08	+0.95 -0.00	+0.13 -0.00
LP5	+716 -0	+0 -647	+0 -91	+0.40 -0.00	+0.00 -0.35	+0.00 -0.05
0.5 - 0.6	16301 $\pm$ 174 $^{+426}_{-625}$	2196 $\pm$ 114 $^{+578}_{-392}$	100 $\pm$ 23 $^{+48}_{-33}$	87.7 $\pm$ 0.7 $^{+2.3}_{-3.4}$	11.8 $\pm$ 0.7 $^{+3.1}_{-2.1}$	0.5 $\pm$ 0.1 $^{+0.3}_{-0.2}$
LP2	+0 -145	+136 -0	+10 -0	+0.00 -0.78	+0.73 -0.00	+0.05 -0.00
LP5	+57 -0	+0 -49	+0 -5	+0.29 -0.00	+0.00 -0.27	+0.00 -0.03
0.6 - 0.7	6957 $\pm$ 108 $^{+172}_{-272}$	787 $\pm$ 62 $^{+254}_{-159}$	17 $\pm$ 4 $^{+19}_{-12}$	89.6 $\pm$ 0.9 $^{+2.2}_{-3.5}$	10.1 $\pm$ 0.9 $^{+3.3}_{-2.1}$	0.2 $\pm$ 0.1 $^{+0.2}_{-0.2}$
LP2	+0 -97	+90 -0	+6 -0	+0.00 -1.24	+1.17 -0.00	+0.07 -0.00
LP5	+31 -0	+0 -25	+0 -2	+0.35 -0.00	+0.00 -0.32	+0.00 -0.03
0.7 - 0.8	2011 $\pm$ 55 $^{+51}_{-58}$	202 $\pm$ 28 $^{+42}_{-52}$	3 $\pm$ 4 $^{+18}_{-10}$	90.8 $\pm$ 1.4 $^{+2.3}_{-2.6}$	9.1 $\pm$ 1.4 $^{+1.9}_{-2.3}$	0.1 $\pm$ 0.2 $^{+0.8}_{-0.5}$
LP2	+0 -13	+7 -0	+4 -0	+0.00 -0.50	+0.31 -0.00	+0.18 -0.00
LP5	+24 -0	+0 -30	+7 -0	+1.04 -0.00	+0.00 -1.37	+0.33 -0.00
0.8 - 0.8	842 $\pm$ 36 $^{+16}_{-31}$	73 $\pm$ 18 $^{+31}_{-16}$	4 $\pm$ 3 $^{+1}_{-2}$	91.6 $\pm$ 2.1 $^{+1.8}_{-3.4}$	8.0 $\pm$ 2.1 $^{+3.4}_{-1.8}$	0.5 $\pm$ 0.4 $^{+0.1}_{-0.2}$
LP2	+0 -15	+16 -0	+0 -1	+0.00 -1.60	+1.71 -0.00	+0.00 -0.11
LP5	+4 -0	+0 -3	+0 -1	+0.35 -0.00	+0.00 -0.29	+0.00 -0.06
0.8 - 10.0	765 $\pm$ 35 $^{+18}_{-26}$	106 $\pm$ 17 $^{+24}_{-17}$	0 $\pm$ 0 $^{+1}_{-1}$	87.8 $\pm$ 2.2 $^{+2.0}_{-2.9}$	12.1 $\pm$ 2.2 $^{+2.7}_{-1.9}$	0.0 $\pm$ 0.0 $^{+0.1}_{-0.1}$
LP2	+0 -9	+7 -0	+0 -0	+0.00 -0.83	+0.83 -0.00	+0.01 -0.00
LP5	+6 -0	+0 -5	+0 -0	+0.56 -0.00	+0.00 -0.56	+0.00 -0.01

Table B.18: Yield and purity outputs from the 2x2D Sideband Method for $|y_{\gamma\gamma}|$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$ y_{\gamma\gamma} $						
0.0 - 0.1	87470 $\pm$ 492 $^{+2867}_{-4227}$	24183 $\pm$ 416 $^{+3643}_{-2473}$	3219 $\pm$ 119 $^{+581}_{-371}$	76.1 $\pm$ 0.4 $^{+2.5}_{-3.7}$	21.1 $\pm$ 0.4 $^{+3.2}_{-2.2}$	2.8 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1363	+1143 -0	+241 -0	+0.00 -1.20	+0.99 -0.00	+0.21 -0.00
LP5	+755 -0	+0 -628	+0 -116	+0.65 -0.00	+0.00 -0.55	+0.00 -0.10
0.1 - 0.3	86308 $\pm$ 473 $^{+2815}_{-4137}$	23055 $\pm$ 402 $^{+3568}_{-2439}$	3245 $\pm$ 120 $^{+564}_{-353}$	76.6 $\pm$ 0.4 $^{+2.5}_{-3.7}$	20.5 $\pm$ 0.4 $^{+3.2}_{-2.2}$	2.9 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1332	+1095 -0	+246 -0	+0.00 -1.19	+0.97 -0.00	+0.22 -0.00
LP5	+754 -0	+0 -625	+0 -115	+0.66 -0.00	+0.00 -0.56	+0.00 -0.10
0.3 - 0.5	82854 $\pm$ 461 $^{+2736}_{-4048}$	21862 $\pm$ 388 $^{+3498}_{-2358}$	3023 $\pm$ 117 $^{+537}_{-352}$	76.9 $\pm$ 0.4 $^{+2.5}_{-3.7}$	20.3 $\pm$ 0.4 $^{+3.3}_{-2.2}$	2.8 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1331	+1119 -0	+219 -0	+0.00 -1.24	+1.04 -0.00	+0.20 -0.00
LP5	+729 -0	+0 -589	+0 -118	+0.66 -0.00	+0.00 -0.55	+0.00 -0.11
0.5 - 0.6	77179 $\pm$ 461 $^{+2560}_{-3757}$	20558 $\pm$ 393 $^{+3216}_{-2221}$	2695 $\pm$ 114 $^{+549}_{-314}$	76.8 $\pm$ 0.4 $^{+2.5}_{-3.7}$	20.5 $\pm$ 0.4 $^{+3.2}_{-2.2}$	2.7 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1152	+913 -0	+250 -0	+0.00 -1.16	+0.91 -0.00	+0.25 -0.00
LP5	+642 -0	+0 -545	+0 -72	+0.62 -0.00	+0.00 -0.55	+0.00 -0.07
0.6 - 0.8	73755 $\pm$ 461 $^{+2589}_{-3776}$	19877 $\pm$ 406 $^{+3219}_{-2268}$	2724 $\pm$ 122 $^{+572}_{-313}$	76.5 $\pm$ 0.4 $^{+2.7}_{-3.9}$	20.6 $\pm$ 0.4 $^{+3.3}_{-2.4}$	2.8 $\pm$ 0.1 $^{+0.6}_{-0.3}$
LP2	+0 -1142	+895 -0	+259 -0	+0.00 -1.20	+0.93 -0.00	+0.27 -0.00
LP5	+661 -0	+0 -618	+0 -29	+0.67 -0.00	+0.00 -0.64	+0.00 -0.03
0.8 - 0.9	71321 $\pm$ 467 $^{+2538}_{-3949}$	20178 $\pm$ 423 $^{+3376}_{-2175}$	2825 $\pm$ 132 $^{+562}_{-351}$	75.6 $\pm$ 0.5 $^{+2.7}_{-4.2}$	21.4 $\pm$ 0.5 $^{+3.6}_{-2.3}$	3.0 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -1409	+1200 -0	+210 -0	+0.00 -1.49	+1.27 -0.00	+0.22 -0.00
LP5	+561 -0	+0 -486	+0 -69	+0.59 -0.00	+0.00 -0.52	+0.00 -0.07
0.9 - 1.2	137920 $\pm$ 635 $^{+4848}_{-7471}$	39178 $\pm$ 587 $^{+6304}_{-4137}$	6112 $\pm$ 192 $^{+1164}_{-705}$	75.3 $\pm$ 0.3 $^{+2.6}_{-4.1}$	21.4 $\pm$ 0.3 $^{+3.4}_{-2.3}$	3.3 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -2455	+1958 -0	+493 -0	+0.00 -1.34	+1.07 -0.00	+0.27 -0.00
LP5	+900 -0	+0 -736	+0 -176	+0.50 -0.00	+0.00 -0.40	+0.00 -0.10
1.2 - 1.6	156933 $\pm$ 725 $^{+5719}_{-8644}$	44984 $\pm$ 692 $^{+7181}_{-4803}$	7641 $\pm$ 231 $^{+1554}_{-1025}$	74.9 $\pm$ 0.3 $^{+2.7}_{-4.1}$	21.5 $\pm$ 0.3 $^{+3.4}_{-2.3}$	3.6 $\pm$ 0.1 $^{+0.7}_{-0.5}$
LP2	+0 -2455	+1746 -0	+734 -0	+0.00 -1.18	+0.83 -0.00	+0.35 -0.00
LP5	+829 -0	+0 -410	+0 -437	+0.40 -0.00	+0.00 -0.19	+0.00 -0.21
1.6 - 2.0	89262 $\pm$ 572 $^{+3959}_{-5553}$	26915 $\pm$ 544 $^{+4659}_{-3340}$	2897 $\pm$ 178 $^{+952}_{-628}$	75.0 $\pm$ 0.5 $^{+3.3}_{-4.7}$	22.6 $\pm$ 0.5 $^{+3.9}_{-2.8}$	2.4 $\pm$ 0.2 $^{+0.8}_{-0.5}$
LP2	+0 -1170	+801 -0	+388 -0	+0.00 -0.99	+0.67 -0.00	+0.33 -0.00
LP5	+903 -0	+0 -687	+0 -214	+0.76 -0.00	+0.00 -0.58	+0.00 -0.18
2.0 - 2.5	29797 $\pm$ 304 $^{+1077}_{-1528}$	8671 $\pm$ 266 $^{+1306}_{-923}$	554 $\pm$ 67 $^{+215}_{-152}$	76.4 $\pm$ 0.7 $^{+2.8}_{-3.9}$	22.2 $\pm$ 0.7 $^{+3.4}_{-2.4}$	1.4 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -370	+309 -0	+52 -0	+0.00 -0.93	+0.80 -0.00	+0.13 -0.00
LP5	+255 -0	+0 -217	+0 -36	+0.65 -0.00	+0.00 -0.56	+0.00 -0.09

Table B.19: Yield and purity outputs from the 2x2D Sideband Method for VBF p_T^{j1} vs. $\Delta\phi(j, j)$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
VBF $p_T^{j1}[\text{GeV}](-3.15 < \Delta\phi(j, j) < 0)$						
30 - 120	3189 $\pm$ 99 $^{+108}_{-174}$	914 $\pm$ 90 $^{+153}_{-92}$	125 $\pm$ 28 $^{+24}_{-28}$	75.4 $\pm$ 2.2 $^{+2.6}_{-4.1}$	21.6 $\pm$ 2.2 $^{+3.6}_{-2.2}$	3.0 $\pm$ 0.7 $^{+0.6}_{-0.7}$
LP2	+0 -58	+54 -0	+4 -0	+0.00 -1.36	+1.27 -0.00	+0.09 -0.00
LP5	+0 -12	+28 -0	+0 -16	+0.00 -0.28	+0.67 -0.00	+0.00 -0.39
120 - 500	921 $\pm$ 43 $^{+31}_{-44}$	140 $\pm$ 29 $^{+41}_{-28}$	10 $\pm$ 3 $^{+3}_{-2}$	86.0 $\pm$ 2.9 $^{+2.9}_{-4.1}$	13.0 $\pm$ 2.9 $^{+3.8}_{-2.7}$	0.9 $\pm$ 0.3 $^{+0.3}_{-0.2}$
LP2	+0 -6	+6 -0	+0 -0	+0.00 -0.53	+0.57 -0.00	+0.00 -0.04
LP5	+0 -1	+1 -0	+0 -0	+0.00 -0.13	+0.13 -0.00	+0.00 -0.01
VBF $p_T^{j1}[\text{GeV}](0 < \Delta\phi(j, j) < 3.15)$						
30 - 120	3101 $\pm$ 98 $^{+114}_{-177}$	964 $\pm$ 90 $^{+151}_{-99}$	127 $\pm$ 29 $^{+28}_{-17}$	74.0 $\pm$ 2.3 $^{+2.7}_{-4.3}$	23.0 $\pm$ 2.2 $^{+3.6}_{-2.4}$	3.0 $\pm$ 0.8 $^{+0.7}_{-0.4}$
LP2	+0 -65	+58 -0	+10 -0	+0.00 -1.60	+1.36 -0.00	+0.24 -0.00
LP5	+28 -0	+0 -28	+0 -0	+0.67 -0.00	+0.00 -0.68	+0.00 -0.00
120 - 500	887 $\pm$ 42 $^{+32}_{-44}$	155 $\pm$ 29 $^{+41}_{-30}$	6 $\pm$ 2 $^{+3}_{-2}$	84.7 $\pm$ 2.9 $^{+3.0}_{-4.2}$	14.8 $\pm$ 2.9 $^{+3.9}_{-2.8}$	0.5 $\pm$ 0.2 $^{+0.3}_{-0.2}$
LP2	+0 -2	+2 -0	+1 -0	+0.00 -0.30	+0.16 -0.00	+0.14 -0.00
LP5	+5 -0	+0 -4	+0 -1	+0.48 -0.00	+0.00 -0.43	+0.00 -0.05
VBF $p_T^{j1}[\text{GeV}](\Delta\phi(j, j) < 1.04)$						
30 - 120	1564 $\pm$ 69 $^{+63}_{-92}$	514 $\pm$ 58 $^{+82}_{-55}$	59 $\pm$ 8 $^{+10}_{-8}$	73.2 $\pm$ 2.9 $^{+3.0}_{-4.3}$	24.1 $\pm$ 2.9 $^{+3.8}_{-2.6}$	2.7 $\pm$ 0.5 $^{+0.5}_{-0.4}$
LP2	+0 -25	+24 -0	+2 -0	+0.00 -1.23	+1.12 -0.00	+0.11 -0.00
LP5	+14 -0	+0 -12	+0 -3	+0.67 -0.00	+0.00 -0.53	+0.00 -0.14
120 - 500	213 $\pm$ 23 $^{+7}_{-12}$	50 $\pm$ 19 $^{+11}_{-6}$	4 $\pm$ 5 $^{+1}_{-1}$	79.9 $\pm$ 7.5 $^{+2.6}_{-4.5}$	18.8 $\pm$ 7.4 $^{+4.2}_{-2.3}$	1.3 $\pm$ 2.1 $^{+0.5}_{-0.5}$
LP2	+0 -5	+5 -0	+0 -1	+0.00 -1.72	+1.91 -0.00	+0.00 -0.20
LP5	+0 -1	+2 -0	+0 -1	+0.00 -0.44	+0.67 -0.00	+0.00 -0.23
VBF $p_T^{j1}[\text{GeV}](1.04 < \Delta\phi(j, j) < 2.08)$						
30 - 120	1896 $\pm$ 73 $^{+65}_{-113}$	616 $\pm$ 59 $^{+98}_{-57}$	52 $\pm$ 7 $^{+15}_{-8}$	73.9 $\pm$ 2.5 $^{+2.5}_{-4.4}$	24.0 $\pm$ 2.4 $^{+3.8}_{-2.2}$	2.0 $\pm$ 0.3 $^{+0.6}_{-0.3}$
LP2	+0 -47	+40 -0	+7 -0	+0.00 -1.81	+1.55 -0.00	+0.26 -0.00
LP5	+3 -0	+0 -3	+0 -1	+0.14 -0.00	+0.00 -0.12	+0.00 -0.02
120 - 500	385 $\pm$ 28 $^{+15}_{-20}$	78 $\pm$ 20 $^{+19}_{-14}$	2 $\pm$ 1 $^{+2}_{-1}$	82.7 $\pm$ 4.5 $^{+3.1}_{-4.4}$	16.8 $\pm$ 4.5 $^{+4.1}_{-2.9}$	0.4 $\pm$ 0.3 $^{+0.4}_{-0.2}$
LP2	+0 -3	+2 -0	+1 -0	+0.00 -0.66	+0.44 -0.00	+0.23 -0.00
LP5	+2 -0	+0 -2	+0 -0	+0.47 -0.00	+0.00 -0.44	+0.00 -0.03
VBF $p_T^{j1}[\text{GeV}](2.08 < \Delta\phi(j, j) < 3.15)$						
30 - 120	2841 $\pm$ 93 $^{+98}_{-156}$	730 $\pm$ 87 $^{+137}_{-84}$	150 $\pm$ 30 $^{+19}_{-15}$	76.4 $\pm$ 2.5 $^{+2.6}_{-4.2}$	19.6 $\pm$ 2.4 $^{+3.7}_{-2.3}$	4.0 $\pm$ 0.9 $^{+0.5}_{-0.4}$
LP2	+0 -52	+48 -0	+4 -0	+0.00 -1.40	+1.28 -0.00	+0.12 -0.00
LP5	+9 -0	+0 -2	+0 -6	+0.22 -0.00	+0.00 -0.07	+0.00 -0.15
120 - 500	1210 $\pm$ 48 $^{+41}_{-59}$	164 $\pm$ 32 $^{+55}_{-39}$	11 $\pm$ 3 $^{+3}_{-2}$	87.4 $\pm$ 2.5 $^{+3.0}_{-4.2}$	11.8 $\pm$ 2.5 $^{+4.0}_{-2.8}$	0.8 $\pm$ 0.2 $^{+0.2}_{-0.2}$
LP2	+0 -6	+5 -0	+0 -0	+0.00 -0.42	+0.38 -0.00	+0.03 -0.00
LP5	+3 -0	+0 -2	+0 -0	+0.16 -0.00	+0.00 -0.16	+0.00 -0.00

Table B.20: Yield and purity outputs from the 2x2D Sideband Method for $|y|_{\gamma\gamma}$ vs. $p_T^{\gamma\gamma}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$ y _{\gamma\gamma}(p_T^{\gamma\gamma} < 45[GeV])$						
0.0 - 0.5	203151 $\pm$ 761 $^{+6826}_{-9971}$	61027 $\pm$ 677 $^{+8428}_{-5786}$	9427 $\pm$ 202 $^{+1498}_{-976}$	74.2 $\pm$ 0.3 $^{+2.5}_{-3.6}$	22.3 $\pm$ 0.3 $^{+3.1}_{-2.1}$	3.4 $\pm$ 0.1 $^{+0.5}_{-0.4}$
LP2	+0 -3330	+2690 -0	+639 -0	+0.00 -1.22	+0.98 -0.00	+0.23 -0.00
LP5	+1998 -0	+0 -1613	+0 -345	+0.72 -0.00	+0.00 -0.59	+0.00 -0.13
0.5 - 1.0	171342 $\pm$ 732 $^{+6097}_{-9138}$	52372 $\pm$ 663 $^{+7676}_{-5187}$	8037 $\pm$ 216 $^{+1422}_{-860}$	73.9 $\pm$ 0.3 $^{+2.6}_{-3.9}$	22.6 $\pm$ 0.3 $^{+3.3}_{-2.2}$	3.5 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -3116	+2539 -0	+568 -0	+0.00 -1.34	+1.10 -0.00	+0.25 -0.00
LP5	+1602 -0	+0 -1395	+0 -159	+0.68 -0.00	+0.00 -0.61	+0.00 -0.07
1.0 - 1.5	157599 $\pm$ 705 $^{+5448}_{-8366}$	47513 $\pm$ 669 $^{+6977}_{-4560}$	8704 $\pm$ 226 $^{+1374}_{-951}$	73.7 $\pm$ 0.3 $^{+2.5}_{-3.9}$	22.2 $\pm$ 0.3 $^{+3.3}_{-2.1}$	4.1 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -2549	+1978 -0	+549 -0	+0.00 -1.18	+0.93 -0.00	+0.26 -0.00
LP5	+770 -0	+0 -428	+0 -363	+0.37 -0.00	+0.00 -0.20	+0.00 -0.17
1.5 - 2.5	104985 $\pm$ 635 $^{+4414}_{-6216}$	34749 $\pm$ 619 $^{+5106}_{-3649}$	3923 $\pm$ 196 $^{+1116}_{-757}$	73.1 $\pm$ 0.4 $^{+3.1}_{-4.3}$	24.2 $\pm$ 0.4 $^{+3.6}_{-2.5}$	2.7 $\pm$ 0.1 $^{+0.8}_{-0.5}$
LP2	+0 -1443	+1044 -0	+386 -0	+0.00 -1.00	+0.73 -0.00	+0.27 -0.00
LP5	+1060 -0	+0 -827	+0 -224	+0.73 -0.00	+0.00 -0.58	+0.00 -0.16
$ y _{\gamma\gamma}(45 < p_T^{\gamma\gamma} < 120[GeV])$						
0.0 - 0.5	71736 $\pm$ 403 $^{+2261}_{-3441}$	13813 $\pm$ 305 $^{+3120}_{-2045}$	1102 $\pm$ 75 $^{+312}_{-208}$	82.8 $\pm$ 0.4 $^{+2.6}_{-4.0}$	15.9 $\pm$ 0.4 $^{+3.6}_{-2.4}$	1.3 $\pm$ 0.1 $^{+0.4}_{-0.2}$
LP2	+0 -1060	+964 -0	+92 -0	+0.00 -1.22	+1.11 -0.00	+0.11 -0.00
LP5	+395 -0	+0 -349	+0 -39	+0.45 -0.00	+0.00 -0.40	+0.00 -0.04
0.5 - 1.0	63811 $\pm$ 402 $^{+2214}_{-3366}$	13664 $\pm$ 329 $^{+2970}_{-1980}$	1188 $\pm$ 89 $^{+392}_{-232}$	81.1 $\pm$ 0.4 $^{+2.8}_{-4.3}$	17.4 $\pm$ 0.4 $^{+3.8}_{-2.5}$	1.5 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1060	+895 -0	+156 -0	+0.00 -1.34	+1.14 -0.00	+0.20 -0.00
LP5	+424 -0	+0 -394	+0 -29	+0.54 -0.00	+0.00 -0.50	+0.00 -0.04
1.0 - 1.5	51083 $\pm$ 395 $^{+1959}_{-3114}$	12117 $\pm$ 362 $^{+2649}_{-1702}$	1543 $\pm$ 114 $^{+484}_{-300}$	78.9 $\pm$ 0.6 $^{+3.0}_{-4.8}$	18.7 $\pm$ 0.6 $^{+4.1}_{-2.6}$	2.4 $\pm$ 0.2 $^{+0.7}_{-0.5}$
LP2	+0 -1048	+792 -0	+246 -0	+0.00 -1.61	+1.23 -0.00	+0.38 -0.00
LP5	+208 -0	+0 -90	+0 -128	+0.33 -0.00	+0.00 -0.14	+0.00 -0.20
1.5 - 2.5	40925 $\pm$ 371 $^{+1825}_{-2516}$	10416 $\pm$ 346 $^{+2155}_{-1586}$	982 $\pm$ 104 $^{+444}_{-240}$	78.2 $\pm$ 0.7 $^{+3.5}_{-4.8}$	19.9 $\pm$ 0.7 $^{+4.1}_{-3.0}$	1.9 $\pm$ 0.2 $^{+0.8}_{-0.5}$
LP2	+0 -479	+250 -0	+234 -0	+0.00 -0.92	+0.48 -0.00	+0.45 -0.00
LP5	+444 -0	+0 -357	+0 -82	+0.84 -0.00	+0.00 -0.68	+0.00 -0.16
$ y _{\gamma\gamma}(120 < p_T^{\gamma\gamma} < 350[GeV])$						
0.0 - 0.5	8330 $\pm$ 117 $^{+198}_{-291}$	975 $\pm$ 66 $^{+275}_{-186}$	18 $\pm$ 10 $^{+18}_{-12}$	89.4 $\pm$ 0.8 $^{+2.1}_{-3.1}$	10.5 $\pm$ 0.8 $^{+2.9}_{-2.0}$	0.2 $\pm$ 0.1 $^{+0.2}_{-0.1}$
LP2	+0 -83	+82 -0	+2 -0	+0.00 -0.90	+0.88 -0.00	+0.02 -0.00
LP5	+44 -0	+0 -43	+3 -0	+0.43 -0.00	+0.00 -0.47	+0.03 -0.00
0.5 - 1.0	7540 $\pm$ 116 $^{+200}_{-321}$	942 $\pm$ 73 $^{+306}_{-185}$	40 $\pm$ 15 $^{+20}_{-15}$	88.5 $\pm$ 0.9 $^{+2.3}_{-3.8}$	11.1 $\pm$ 0.9 $^{+3.6}_{-2.2}$	0.5 $\pm$ 0.2 $^{+0.2}_{-0.2}$
LP2	+0 -118	+120 -0	+0 -3	+0.00 -1.37	+1.41 -0.00	+0.00 -0.03
LP5	+35 -0	+0 -31	+0 -0	+0.37 -0.00	+0.00 -0.37	+0.00 -0.00
1.0 - 1.5	6443 $\pm$ 114 $^{+206}_{-301}$	911 $\pm$ 81 $^{+291}_{-197}$	58 $\pm$ 19 $^{+24}_{-21}$	86.9 $\pm$ 1.2 $^{+2.8}_{-4.1}$	12.3 $\pm$ 1.1 $^{+3.9}_{-2.7}$	0.8 $\pm$ 0.3 $^{+0.3}_{-0.3}$
LP2	+0 -98	+109 -0	+0 -11	+0.00 -1.33	+1.47 -0.00	+0.00 -0.14
LP5	+58 -0	+0 -65	+6 -0	+0.79 -0.00	+0.00 -0.88	+0.09 -0.00
1.5 - 2.5	5398 $\pm$ 104 $^{+166}_{-252}$	864 $\pm$ 69 $^{+235}_{-154}$	31 $\pm$ 6 $^{+19}_{-14}$	85.8 $\pm$ 1.2 $^{+2.7}_{-4.0}$	13.7 $\pm$ 1.2 $^{+3.7}_{-2.4}$	0.5 $\pm$ 0.1 $^{+0.3}_{-0.2}$
LP2	+0 -80	+78 -0	+2 -0	+0.00 -1.28	+1.25 -0.00	+0.03 -0.00
LP5	+33 -0	+0 -33	+0 -2	+0.54 -0.00	+0.00 -0.52	+0.00 -0.02

Table B.21: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma}$ vs. $p_T^{\gamma j}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma}[\text{GeV}](p_T^{\gamma j} < 0)$						
0 - 350	895083 $\pm$ 1603 $^{+31293}_{-46143}$	247645 $\pm$ 1471 $^{+39260}_{-26831}$	34941 $\pm$ 446 $^{+7047}_{-4367}$	76.0 $\pm$ 0.1 $^{+2.6}_{-3.9}$	21.0 $\pm$ 0.1 $^{+3.3}_{-2.3}$	3.0 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -13497	+10623 -0	+3045 -0	+0.00 -1.16	+0.90 -0.00	+0.26 -0.00
LP5	+6958 -0	+0 -5571	+0 -1325	+0.59 -0.00	+0.00 -0.47	+0.00 -0.11
$p_T^{\gamma j}[\text{GeV}](0 < p_T^{\gamma\gamma} < 30)$						
0 - 100	176708 $\pm$ 646 $^{+6002}_{-9068}$	36815 $\pm$ 537 $^{+7981}_{-5286}$	3875 $\pm$ 160 $^{+1055}_{-672}$	81.3 $\pm$ 0.3 $^{+2.7}_{-4.2}$	16.9 $\pm$ 0.3 $^{+3.7}_{-2.4}$	1.8 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -2714	+2359 -0	+377 -0	+0.00 -1.26	+1.08 -0.00	+0.17 -0.00
LP5	+1066 -0	+0 -910	+0 -137	+0.48 -0.00	+0.00 -0.42	+0.00 -0.06
100 - 350	12274 $\pm$ 153 $^{+343}_{-485}$	1850 $\pm$ 97 $^{+451}_{-320}$	51 $\pm$ 7 $^{+34}_{-23}$	86.6 $\pm$ 0.7 $^{+2.4}_{-3.4}$	13.0 $\pm$ 0.7 $^{+3.2}_{-2.3}$	0.4 $\pm$ 0.1 $^{+0.2}_{-0.2}$
LP2	+0 -87	+75 -0	+9 -0	+0.00 -0.59	+0.53 -0.00	+0.06 -0.00
LP5	+62 -0	+0 -56	+0 -2	+0.41 -0.00	+0.00 -0.40	+0.00 -0.01
$p_T^{\gamma j}[\text{GeV}](30 < p_T^{\gamma\gamma} < 60)$						
0 - 45	66540 $\pm$ 449 $^{+2378}_{-3425}$	18471 $\pm$ 412 $^{+2885}_{-2038}$	3059 $\pm$ 133 $^{+553}_{-334}$	75.6 $\pm$ 0.5 $^{+2.7}_{-3.9}$	21.0 $\pm$ 0.5 $^{+3.3}_{-2.3}$	3.5 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -905	+677 -0	+228 -0	+0.00 -1.03	+0.77 -0.00	+0.26 -0.00
LP5	+552 -0	+0 -476	+0 -73	+0.62 -0.00	+0.00 -0.54	+0.00 -0.08
45 - 120	61455 $\pm$ 397 $^{+2126}_{-3226}$	12943 $\pm$ 331 $^{+2850}_{-1887}$	1339 $\pm$ 94 $^{+384}_{-250}$	81.1 $\pm$ 0.5 $^{+2.8}_{-4.3}$	17.1 $\pm$ 0.5 $^{+3.8}_{-2.5}$	1.8 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -926	+767 -0	+159 -0	+0.00 -1.22	+1.01 -0.00	+0.21 -0.00
LP5	+295 -0	+0 -212	+0 -83	+0.39 -0.00	+0.00 -0.28	+0.00 -0.11
120 - 350	7908 $\pm$ 122 $^{+219}_{-358}$	1127 $\pm$ 81 $^{+344}_{-201}$	52 $\pm$ 16 $^{+24}_{-19}$	87.0 $\pm$ 1.0 $^{+2.4}_{-3.9}$	12.4 $\pm$ 0.9 $^{+3.8}_{-2.2}$	0.6 $\pm$ 0.2 $^{+0.3}_{-0.2}$
LP2	+0 -144	+149 -0	+0 -6	+0.00 -1.58	+1.65 -0.00	+0.00 -0.07
LP5	+48 -0	+0 -42	+0 -1	+0.48 -0.00	+0.00 -0.47	+0.00 -0.02
$p_T^{\gamma j}[\text{GeV}](p_T^{\gamma\gamma} < 350)$						
0 - 80	50626 $\pm$ 378 $^{+1895}_{-2823}$	11938 $\pm$ 332 $^{+2438}_{-1659}$	1372 $\pm$ 100 $^{+404}_{-237}$	79.2 $\pm$ 0.6 $^{+3.0}_{-4.4}$	18.7 $\pm$ 0.5 $^{+3.8}_{-2.6}$	2.1 $\pm$ 0.2 $^{+0.6}_{-0.4}$
LP2	+0 -794	+609 -0	+184 -0	+0.00 -1.24	+0.95 -0.00	+0.29 -0.00
LP5	+343 -0	+0 -274	+0 -64	+0.53 -0.00	+0.00 -0.43	+0.00 -0.10
80 - 250	27537 $\pm$ 238 $^{+891}_{-1315}$	4069 $\pm$ 171 $^{+1211}_{-828}$	208 $\pm$ 39 $^{+114}_{-69}$	86.6 $\pm$ 0.6 $^{+2.8}_{-4.2}$	12.8 $\pm$ 0.6 $^{+3.8}_{-2.6}$	0.7 $\pm$ 0.1 $^{+0.4}_{-0.2}$
LP2	+0 -340	+316 -0	+41 -0	+0.00 -1.12	+0.99 -0.00	+0.13 -0.00
LP5	+152 -0	+0 -162	+4 -0	+0.49 -0.00	+0.00 -0.51	+0.01 -0.00
250 - 450	1221 $\pm$ 42 $^{+24}_{-44}$	122 $\pm$ 19 $^{+43}_{-22}$	3 $\pm$ 3 $^{+3}_{-2}$	90.7 $\pm$ 1.6 $^{+1.8}_{-3.3}$	9.1 $\pm$ 1.6 $^{+3.2}_{-1.6}$	0.3 $\pm$ 0.2 $^{+0.2}_{-0.2}$
LP2	+0 -23	+24 -0	+0 -1	+0.00 -1.68	+1.76 -0.00	+0.00 -0.08
LP5	+8 -0	+0 -8	+0 -0	+0.58 -0.00	+0.00 -0.56	+0.00 -0.02

Table B.22: Yield and purity outputs from the 2x2D Sideband Method for $\Delta p_T^{\gamma\gamma}$ vs. $\Sigma p_T^{\gamma\gamma}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$\Delta p_T^{\gamma\gamma} (0.6 < \Sigma p_T^{\gamma\gamma} < 0.8)$						
0.0 - 0.3	172457 $\pm$ 851 $^{+6776}_{-9899}$	70975 $\pm$ 888 $^{+7778}_{-5299}$	18237 $\pm$ 333 $^{+2091}_{-1460}$	65.9 $\pm$ 0.3 $^{+2.6}_{-3.8}$	27.1 $\pm$ 0.3 $^{+3.0}_{-2.0}$	7.0 $\pm$ 0.2 $^{+0.8}_{-0.6}$
LP2	+0 -3329	+2433 -0	+865 -0	+0.00 -1.26	+0.93 -0.00	+0.33 -0.00
LP5	+2000 -0	+0 -1371	+0 -589	+0.75 -0.00	+0.00 -0.53	+0.00 -0.23
$\Delta p_T^{\gamma\gamma} (0.8 < \Sigma p_T^{\gamma\gamma} < 1.1)$						
0.0 - 0.1	164337 $\pm$ 589 $^{+4779}_{-7163}$	27961 $\pm$ 448 $^{+6366}_{-4240}$	3259 $\pm$ 120 $^{+700}_{-450}$	84.0 $\pm$ 0.2 $^{+2.4}_{-3.6}$	14.3 $\pm$ 0.2 $^{+3.3}_{-2.2}$	1.7 $\pm$ 0.1 $^{+0.4}_{-0.2}$
LP2	+0 -2123	+1898 -0	+274 -0	+0.00 -1.11	+0.97 -0.00	+0.14 -0.00
LP5	+920 -0	+0 -811	+0 -129	+0.48 -0.00	+0.00 -0.41	+0.00 -0.07
0.1 - 0.1	118720 $\pm$ 549 $^{+3596}_{-5389}$	28248 $\pm$ 451 $^{+4659}_{-3110}$	3182 $\pm$ 124 $^{+712}_{-464}$	79.1 $\pm$ 0.3 $^{+2.4}_{-3.6}$	18.8 $\pm$ 0.3 $^{+3.1}_{-2.1}$	2.1 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1584	+1325 -0	+283 -0	+0.00 -1.07	+0.88 -0.00	+0.19 -0.00
LP5	+677 -0	+0 -535	+0 -145	+0.45 -0.00	+0.00 -0.36	+0.00 -0.10
0.1 - 0.2	156322 $\pm$ 657 $^{+5086}_{-7501}$	47325 $\pm$ 554 $^{+6344}_{-4358}$	4275 $\pm$ 154 $^{+1149}_{-706}$	75.2 $\pm$ 0.3 $^{+2.4}_{-3.6}$	22.8 $\pm$ 0.3 $^{+3.1}_{-2.1}$	2.1 $\pm$ 0.1 $^{+0.6}_{-0.3}$
LP2	+0 -2211	+1796 -0	+423 -0	+0.00 -1.07	+0.86 -0.00	+0.20 -0.00
LP5	+1144 -0	+0 -1023	+0 -93	+0.54 -0.00	+0.00 -0.49	+0.00 -0.05
0.2 - 0.8	191557 $\pm$ 761 $^{+7032}_{-10528}$	53758 $\pm$ 668 $^{+9154}_{-6117}$	5357 $\pm$ 189 $^{+1390}_{-912}$	76.4 $\pm$ 0.3 $^{+2.8}_{-4.2}$	21.4 $\pm$ 0.3 $^{+3.7}_{-2.4}$	2.1 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -3133	+2638 -0	+524 -0	+0.00 -1.26	+1.05 -0.00	+0.21 -0.00
LP5	+1386 -0	+0 -1114	+0 -264	+0.55 -0.00	+0.00 -0.45	+0.00 -0.11
$\Delta p_T^{\gamma\gamma} (1.1 < \Sigma p_T^{\gamma\gamma} < 4)$						
0.0 - 0.3	22067 $\pm$ 198 $^{+586}_{-902}$	2523 $\pm$ 124 $^{+846}_{-547}$	97 $\pm$ 24 $^{+58}_{-40}$	89.4 $\pm$ 0.5 $^{+2.4}_{-3.7}$	10.2 $\pm$ 0.5 $^{+3.4}_{-2.2}$	0.4 $\pm$ 0.1 $^{+0.2}_{-0.2}$
LP2	+0 -285	+271 -0	+14 -0	+0.00 -1.15	+1.10 -0.00	+0.06 -0.00
LP5	+95 -0	+0 -85	+0 -5	+0.36 -0.00	+0.00 -0.35	+0.00 -0.02
0.3 - 0.6	42740 $\pm$ 315 $^{+1492}_{-2168}$	7237 $\pm$ 242 $^{+1965}_{-1364}$	440 $\pm$ 58 $^{+225}_{-132}$	84.8 $\pm$ 0.5 $^{+3.0}_{-4.3}$	14.4 $\pm$ 0.5 $^{+3.9}_{-2.7}$	0.9 $\pm$ 0.1 $^{+0.4}_{-0.3}$
LP2	+0 -469	+374 -0	+104 -0	+0.00 -0.95	+0.74 -0.00	+0.21 -0.00
LP5	+218 -0	+0 -184	+0 -38	+0.44 -0.00	+0.00 -0.36	+0.00 -0.07
0.6 - 4.0	28920 $\pm$ 271 $^{+1112}_{-1651}$	5637 $\pm$ 214 $^{+1532}_{-1029}$	237 $\pm$ 47 $^{+134}_{-92}$	83.1 $\pm$ 0.7 $^{+3.2}_{-4.8}$	16.2 $\pm$ 0.6 $^{+4.4}_{-3.0}$	0.7 $\pm$ 0.1 $^{+0.4}_{-0.3}$
LP2	+0 -502	+500 -0	+20 -0	+0.00 -1.48	+1.43 -0.00	+0.06 -0.00
LP5	+252 -0	+0 -261	+9 -0	+0.72 -0.00	+0.00 -0.75	+0.03 -0.00

Table B.23: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma}$ vs. $\tau_{y,y,j}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma} [GeV] (\tau_{y,y,j} < 0)$						
0 - 350	895083 $\pm$ 1603 $^{+31293}_{-46143}$	247645 $\pm$ 1471 $^{+39260}_{-26831}$	34941 $\pm$ 446 $^{+7047}_{-4367}$	76.0 $\pm$ 0.1 $^{+2.6}_{-3.9}$	21.0 $\pm$ 0.1 $^{+3.3}_{-2.3}$	3.0 $\pm$ 0.0 $^{+0.6}_{-0.4}$
LP2	+0 -13497	+10623 -0	+3045 -0	+0.00 -1.16	+0.90 -0.00	+0.26 -0.00
LP5	+6958 -0	+0 -5571	+0 -1325	+0.59 -0.00	+0.00 -0.47	+0.00 -0.11
$p_T^{\gamma\gamma} [GeV] (0 < \tau_{y,y,j} < 15)$						
0 - 100	179334 $\pm$ 724 $^{+6275}_{-9389}$	47375 $\pm$ 645 $^{+8032}_{-5404}$	6437 $\pm$ 197 $^{+1345}_{-854}$	76.9 $\pm$ 0.3 $^{+2.7}_{-4.0}$	20.3 $\pm$ 0.3 $^{+3.4}_{-2.3}$	2.8 $\pm$ 0.1 $^{+0.6}_{-0.4}$
LP2	+0 -2764	+2254 -0	+504 -0	+0.00 -1.18	+0.97 -0.00	+0.22 -0.00
LP5	+1211 -0	+0 -1007	+0 -197	+0.52 -0.00	+0.00 -0.43	+0.00 -0.08
100 - 350	7231 $\pm$ 128 $^{+224}_{-318}$	1530 $\pm$ 99 $^{+280}_{-201}$	77 $\pm$ 23 $^{+41}_{-25}$	81.8 $\pm$ 1.2 $^{+2.5}_{-3.6}$	17.3 $\pm$ 1.2 $^{+3.2}_{-2.3}$	0.9 $\pm$ 0.3 $^{+0.5}_{-0.3}$
LP2	+0 -67	+57 -0	+15 -0	+0.00 -0.80	+0.63 -0.00	+0.17 -0.00
LP5	+44 -0	+0 -47	+2 -0	+0.52 -0.00	+0.00 -0.53	+0.02 -0.00
$p_T^{\gamma\gamma} [GeV] (15 < \tau_{y,y,j} < 25)$						
0 - 120	104026 $\pm$ 505 $^{+3631}_{-5397}$	20428 $\pm$ 415 $^{+4780}_{-3221}$	2069 $\pm$ 118 $^{+620}_{-403}$	82.2 $\pm$ 0.4 $^{+2.9}_{-4.3}$	16.1 $\pm$ 0.3 $^{+3.8}_{-2.5}$	1.6 $\pm$ 0.1 $^{+0.5}_{-0.3}$
LP2	+0 -1457	+1229 -0	+239 -0	+0.00 -1.16	+0.97 -0.00	+0.19 -0.00
LP5	+610 -0	+0 -480	+0 -119	+0.47 -0.00	+0.00 -0.38	+0.00 -0.09
120 - 350	4020 $\pm$ 87 $^{+111}_{-176}$	605 $\pm$ 54 $^{+165}_{-103}$	12 $\pm$ 3 $^{+12}_{-7}$	86.7 $\pm$ 1.3 $^{+2.4}_{-3.8}$	13.1 $\pm$ 1.2 $^{+3.6}_{-2.2}$	0.3 $\pm$ 0.1 $^{+0.3}_{-0.2}$
LP2	+0 -64	+61 -0	+5 -0	+0.00 -1.40	+1.30 -0.00	+0.10 -0.00
LP5	+22 -0	+0 -20	+0 -0	+0.44 -0.00	+0.00 -0.43	+0.00 -0.00
$p_T^{\gamma\gamma} [GeV] (25 < \tau_{y,y,j} < 40)$						
0 - 200	64091 $\pm$ 383 $^{+2243}_{-3357}$	10968 $\pm$ 303 $^{+3019}_{-2025}$	1001 $\pm$ 83 $^{+342}_{-211}$	84.3 $\pm$ 0.4 $^{+2.9}_{-4.4}$	14.4 $\pm$ 0.4 $^{+4.0}_{-2.7}$	1.3 $\pm$ 0.1 $^{+0.4}_{-0.3}$
LP2	+0 -997	+878 -0	+134 -0	+0.00 -1.33	+1.15 -0.00	+0.18 -0.00
LP5	+443 -0	+0 -397	+0 -44	+0.58 -0.00	+0.00 -0.52	+0.00 -0.06
200 - 350	605 $\pm$ 33 $^{+13}_{-18}$	103 $\pm$ 20 $^{+16}_{-12}$	1 $\pm$ 3 $^{+2}_{-1}$	85.4 $\pm$ 3.1 $^{+1.8}_{-2.5}$	14.5 $\pm$ 3.0 $^{+2.3}_{-1.7}$	0.1 $\pm$ 0.4 $^{+0.2}_{-0.2}$
LP2	+0 -6	+5 -0	+0 -0	+0.00 -0.69	+0.69 -0.00	+0.01 -0.00
LP5	+4 -0	+0 -4	+0 -0	+0.60 -0.00	+0.00 -0.56	+0.00 -0.03
$p_T^{\gamma\gamma} [GeV] (40 < \tau_{y,y,j} < 400)$						
0 - 250	44218 $\pm$ 303 $^{+1470}_{-2189}$	6417 $\pm$ 223 $^{+2009}_{-1355}$	408 $\pm$ 56 $^{+186}_{-119}$	86.6 $\pm$ 0.5 $^{+2.9}_{-4.3}$	12.6 $\pm$ 0.5 $^{+3.9}_{-2.7}$	0.8 $\pm$ 0.1 $^{+0.4}_{-0.2}$
LP2	+0 -561	+516 -0	+56 -0	+0.00 -1.12	+1.01 -0.00	+0.11 -0.00
LP5	+197 -0	+0 -206	+10 -0	+0.38 -0.00	+0.00 -0.40	+0.02 -0.00
250 - 650	1658 $\pm$ 49 $^{+30}_{-56}$	204 $\pm$ 22 $^{+51}_{-28}$	2 $\pm$ 1 $^{+3}_{-2}$	89.0 $\pm$ 1.4 $^{+1.6}_{-2.9}$	10.9 $\pm$ 1.4 $^{+2.7}_{-1.5}$	0.1 $\pm$ 0.1 $^{+0.2}_{-0.1}$
LP2	+0 -29	+26 -0	+0 -0	+0.00 -1.42	+1.40 -0.00	+0.02 -0.00
LP5	+11 -0	+0 -9	+0 -0	+0.48 -0.00	+0.00 -0.47	+0.00 -0.01

B.0.2 Diphoton + Heavy Flavor Outputs

Table B.24: Yield and purity outputs from the 2x2D Sideband Method for the inclusive template.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
Inclusive						
-0.5 - 24.5	$234859 \pm 704^{+1043}_{-3609}$	$34540 \pm 524^{+2950}_{-890}$	$2743 \pm 135^{+817}_{-150}$	$86.3 \pm 0.2^{+0.4}_{-1.4}$	$12.7 \pm 0.2^{+1.1}_{-0.3}$	$1.0 \pm 0.1^{+0.3}_{-0.1}$
LP2	$+0 -2552$	$+2090 -0$	$+578 -0$	$+0.00 -0.97$	$+0.76 -0.00$	$+0.21 -0.00$
LP5	$+737 -0$	$+0 -629$	$+0 -106$	$+0.27 -0.00$	$+0.00 -0.23$	$+0.00 -0.04$

Table B.25: Yield and purity outputs from the 2x2D Sideband Method for $N_{\text{jets}}^{\text{central}}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$N_{\text{jets}}^{\text{central}}$						
0 - 1	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$
LP2	$+0 -0$	$+0 -0$	$+0 -0$	$+0.00 -0.00$	$+0.00 -0.00$	$+0.00 -0.00$
LP5	$+0 -0$	$+0 -0$	$+0 -0$	$+0.00 -0.00$	$+0.00 -0.00$	$+0.00 -0.00$
1 - 2	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$
LP2	$+0 -0$	$+0 -0$	$+0 -0$	$+0.00 -0.00$	$+0.00 -0.00$	$+0.00 -0.00$
LP5	$+0 -0$	$+0 -0$	$+0 -0$	$+0.00 -0.00$	$+0.00 -0.00$	$+0.00 -0.00$
2 - 3	$156465 \pm 581^{+751}_{-2491}$	$23916 \pm 439^{+2036}_{-665}$	$1952 \pm 115^{+566}_{-78}$	$85.8 \pm 0.3^{+0.4}_{-1.4}$	$13.1 \pm 0.3^{+1.1}_{-0.4}$	$1.1 \pm 0.1^{+0.3}_{-0.0}$
LP2	$+0 -1761$	$+1440 -0$	$+400 -0$	$+0.00 -1.00$	$+0.78 -0.00$	$+0.22 -0.00$
LP5	$+531 -0$	$+0 -470$	$+0 -55$	$+0.29 -0.00$	$+0.00 -0.26$	$+0.00 -0.03$
3 - 4	$54309 \pm 333^{+216}_{-827}$	$7338 \pm 242^{+730}_{-162}$	$604 \pm 62^{+132}_{-55}$	$87.2 \pm 0.4^{+0.3}_{-1.4}$	$11.8 \pm 0.4^{+1.2}_{-0.3}$	$1.0 \pm 0.1^{+0.2}_{-0.1}$
LP2	$+0 -585$	$+516 -0$	$+93 -0$	$+0.00 -0.97$	$+0.82 -0.00$	$+0.15 -0.00$
LP5	$+153 -0$	$+0 -114$	$+0 -39$	$+0.25 -0.00$	$+0.00 -0.18$	$+0.00 -0.06$
4 - 5	$16843 \pm 183^{+112}_{-226}$	$2291 \pm 130^{+182}_{-105}$	$153 \pm 32^{+60}_{-11}$	$87.3 \pm 0.7^{+0.6}_{-1.2}$	$11.9 \pm 0.7^{+0.9}_{-0.5}$	$0.8 \pm 0.2^{+0.3}_{-0.1}$
LP2	$+0 -160$	$+129 -0$	$+42 -0$	$+0.00 -0.88$	$+0.66 -0.00$	$+0.22 -0.00$
LP5	$+79 -0$	$+0 -74$	$+0 -8$	$+0.42 -0.00$	$+0.00 -0.38$	$+0.00 -0.04$
5 - 10	$7204 \pm 117^{+0}_{-46}$	$1008 \pm 75^{+19}_{-0}$	$48 \pm 5^{+47}_{-2}$	$87.2 \pm 1.0^{+0.0}_{-0.6}$	$12.2 \pm 1.0^{+0.2}_{-0.0}$	$0.6 \pm 0.1^{+0.6}_{-0.0}$
LP2	$+0 -32$	$+0 -0$	$+33 -0$	$+0.00 -0.40$	$+0.00 -0.00$	$+0.40 -0.00$
LP5	$+0 -12$	$+14 -0$	$+0 -2$	$+0.00 -0.15$	$+0.17 -0.00$	$+0.00 -0.02$

Table B.26: Yield and purity outputs from the 2x2D Sideband Method for μ .

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
μ						
0 - 10	234859 $\pm$ 704 $^{+1043}_{-3609}$	34540 $\pm$ 524 $^{+2956}_{-890}$	2743 $\pm$ 135 $^{+817}_{-150}$	86.3 $\pm$ 0.2 $^{+0.4}_{-1.4}$	12.7 $\pm$ 0.2 $^{+1.1}_{-0.3}$	1.0 $\pm$ 0.1 $^{+0.3}_{-0.1}$
LP2	+0 -2552	+2090 -0	+578 -0	+0.00 -0.97	+0.76 -0.00	+0.21 -0.00
LP5	+737 -0	+0 -629	+0 -106	+0.27 -0.00	+0.00 -0.23	+0.00 -0.04
10 - 20	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
20 - 30	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
30 - 40	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
40 - 60	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
60 - 100	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00

Table B.27: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{j_1}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{j_1}$ [GeV]						
25 - 40	35688 $\pm$ 298 $^{+270}_{-523}$	7006 $\pm$ 245 $^{+328}_{-259}$	765 $\pm$ 71 $^{+209}_{-4}$	82.1 $\pm$ 0.6 $^{+0.6}_{-1.2}$	16.1 $\pm$ 0.6 $^{+0.7}_{-0.6}$	1.8 $\pm$ 0.2 $^{+0.5}_{-0.0}$
LP2	+0 -370	+232 -0	+147 -0	+0.00 -0.87	+0.53 -0.00	+0.34 -0.00
LP5	+191 -0	+0 -183	+0 -3	+0.43 -0.00	+0.00 -0.42	+0.00 -0.01
40 - 60	54771 $\pm$ 354 $^{+316}_{-964}$	9472 $\pm$ 278 $^{+746}_{-257}$	836 $\pm$ 75 $^{+227}_{-62}$	84.2 $\pm$ 0.5 $^{+0.5}_{-1.5}$	14.6 $\pm$ 0.4 $^{+1.1}_{-0.4}$	1.3 $\pm$ 0.1 $^{+0.3}_{-0.1}$
LP2	+0 -681	+527 -0	+160 -0	+0.00 -1.06	+0.81 -0.00	+0.25 -0.00
LP5	+224 -0	+0 -181	+0 -44	+0.35 -0.00	+0.00 -0.28	+0.00 -0.07
60 - 80	41721 $\pm$ 300 $^{+144}_{-726}$	6180 $\pm$ 228 $^{+609}_{-73}$	562 $\pm$ 61 $^{+126}_{-67}$	86.1 $\pm$ 0.5 $^{+0.3}_{-1.5}$	12.8 $\pm$ 0.5 $^{+1.3}_{-0.2}$	1.2 $\pm$ 0.1 $^{+0.3}_{-0.1}$
LP2	+0 -513	+430 -0	+89 -0	+0.00 -1.07	+0.89 -0.00	+0.18 -0.00
LP5	+102 -0	+0 -52	+0 -48	+0.21 -0.00	+0.00 -0.11	+0.00 -0.10
80 - 100	28585 $\pm$ 244 $^{+146}_{-476}$	4000 $\pm$ 179 $^{+407}_{-126}$	307 $\pm$ 46 $^{+79}_{-14}$	86.9 $\pm$ 0.6 $^{+0.4}_{-1.5}$	12.2 $\pm$ 0.6 $^{+1.2}_{-0.4}$	0.9 $\pm$ 0.1 $^{+0.2}_{-0.0}$
LP2	+0 -337	+288 -0	+56 -0	+0.00 -1.04	+0.87 -0.00	+0.17 -0.00
LP5	+103 -0	+0 -89	+0 -10	+0.30 -0.00	+0.00 -0.27	+0.00 -0.03
100 - 120	19986 $\pm$ 197 $^{+10}_{-234}$	2517 $\pm$ 137 $^{+172}_{-4}$	140 $\pm$ 32 $^{+73}_{-9}$	88.3 $\pm$ 0.7 $^{+0.1}_{-1.1}$	11.1 $\pm$ 0.6 $^{+0.8}_{-0.0}$	0.6 $\pm$ 0.1 $^{+0.3}_{-0.0}$
LP2	+0 -165	+122 -0	+51 -0	+0.00 -0.76	+0.53 -0.00	+0.23 -0.00
LP5	+7 -0	+0 -3	+0 -6	+0.04 -0.00	+0.00 -0.01	+0.00 -0.03
120 - 140	13849 $\pm$ 161 $^{+50}_{-260}$	1606 $\pm$ 109 $^{+256}_{-62}$	88 $\pm$ 25 $^{+14}_{-0}$	89.1 $\pm$ 0.8 $^{+0.3}_{-1.7}$	10.3 $\pm$ 0.7 $^{+1.6}_{-0.3}$	0.6 $\pm$ 0.2 $^{+0.1}_{-0.0}$
LP2	+0 -184	+181 -0	+9 -0	+0.00 -1.22	+1.16 -0.00	+0.06 -0.00
LP5	+35 -0	+0 -37	+4 -0	+0.22 -0.00	+0.00 -0.24	+0.02 -0.00
140 - 160	9809 $\pm$ 132 $^{+57}_{-120}$	1033 $\pm$ 81 $^{+109}_{-54}$	56 $\pm$ 6 $^{+13}_{-1}$	90.0 $\pm$ 0.8 $^{+0.5}_{-1.1}$	9.5 $\pm$ 0.8 $^{+1.0}_{-0.5}$	0.5 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -85	+77 -0	+9 -0	+0.00 -0.79	+0.70 -0.00	+0.09 -0.00
LP5	+40 -0	+0 -38	+0 -1	+0.36 -0.00	+0.00 -0.35	+0.00 -0.01
160 - 180	7110 $\pm$ 111 $^{+19}_{-89}$	660 $\pm$ 71 $^{+81}_{-24}$	37 $\pm$ 16 $^{+10}_{-0}$	91.1 $\pm$ 1.0 $^{+0.3}_{-1.2}$	8.5 $\pm$ 1.0 $^{+1.0}_{-0.3}$	0.5 $\pm$ 0.2 $^{+0.1}_{-0.0}$
LP2	+0 -63	+57 -0	+7 -0	+0.00 -0.83	+0.73 -0.00	+0.09 -0.00
LP5	+14 -0	+0 -17	+1 -0	+0.20 -0.00	+0.00 -0.21	+0.01 -0.00
180 - 200	5199 $\pm$ 95 $^{+27}_{-25}$	489 $\pm$ 60 $^{+18}_{-22}$	32 $\pm$ 14 $^{+12}_{-5}$	90.9 $\pm$ 1.1 $^{+0.5}_{-0.5}$	8.5 $\pm$ 1.1 $^{+0.3}_{-0.4}$	0.6 $\pm$ 0.2 $^{+0.2}_{-0.1}$
LP2	+0 -18	+13 -0	+9 -0	+0.00 -0.37	+0.21 -0.00	+0.15 -0.00
LP5	+19 -0	+0 -16	+0 -3	+0.33 -0.00	+0.00 -0.28	+0.00 -0.06
200 - 220	3993 $\pm$ 77 $^{+6}_{-66}$	310 $\pm$ 48 $^{+77}_{-14}$	32 $\pm$ 12 $^{+3}_{-15}$	92.1 $\pm$ 1.2 $^{+0.2}_{-1.4}$	7.2 $\pm$ 1.1 $^{+1.8}_{-0.3}$	0.7 $\pm$ 0.3 $^{+0.1}_{-0.3}$
LP2	+0 -46	+55 -0	+0 -10	+0.00 -1.02	+1.26 -0.00	+0.00 -0.24
LP5	+4 -0	+0 -10	+2 -0	+0.17 -0.00	+0.00 -0.22	+0.05 -0.00
220 - 240	2930 $\pm$ 68 $^{+11}_{-41}$	260 $\pm$ 38 $^{+45}_{-10}$	8 $\pm$ 2 $^{+2}_{-1}$	91.6 $\pm$ 1.3 $^{+0.3}_{-1.5}$	8.1 $\pm$ 1.3 $^{+1.4}_{-0.3}$	0.2 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -29	+32 -0	+1 -0	+0.00 -1.03	+0.99 -0.00	+0.04 -0.00
LP5	+8 -0	+0 -7	+0 -0	+0.24 -0.00	+0.00 -0.23	+0.00 -0.01
240 - 260	2167 $\pm$ 61 $^{+8}_{-33}$	212 $\pm$ 37 $^{+32}_{-9}$	7 $\pm$ 8 $^{+4}_{-0}$	90.8 $\pm$ 1.7 $^{+0.3}_{-1.5}$	8.9 $\pm$ 1.7 $^{+1.3}_{-0.4}$	0.3 $\pm$ 0.3 $^{+0.2}_{-0.0}$
LP2	+0 -24	+23 -0	+3 -0	+0.00 -1.06	+0.94 -0.00	+0.11 -0.00
LP5	+5 -0	+0 -7	+1 -0	+0.24 -0.00	+0.00 -0.27	+0.03 -0.00
260 - 280	1701 $\pm$ 54 $^{+11}_{-37}$	200 $\pm$ 31 $^{+38}_{-11}$	2 $\pm$ 1 $^{+2}_{-0}$	89.4 $\pm$ 1.8 $^{+0.6}_{-2.1}$	10.5 $\pm$ 1.8 $^{+2.0}_{-0.6}$	0.1 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -26	+27 -0	+1 -0	+0.00 -1.46	+1.40 -0.00	+0.07 -0.00
LP5	+8 -0	+0 -8	+0 -0	+0.41 -0.00	+0.00 -0.40	+0.00 -0.02
280 - 300	1341 $\pm$ 44 $^{+0}_{-16}$	78 $\pm$ 21 $^{+14}_{-0}$	2 $\pm$ 1 $^{+1}_{-1}$	94.3 $\pm$ 1.6 $^{+0.0}_{-1.1}$	5.5 $\pm$ 1.6 $^{+1.0}_{-0.0}$	0.2 $\pm$ 0.1 $^{+0.1}_{-0.1}$
LP2	+0 -11	+10 -0	+1 -0	+0.00 -0.76	+0.70 -0.00	+0.06 -0.00
LP5	+0 -0	+0 -0	+0 -1	+0.03 -0.00	+0.02 -0.00	+0.00 -0.05
300 - 13000	6056 $\pm$ 88 $^{+0}_{-46}$	420 $\pm$ 35 $^{+42}_{-0}$	6 $\pm$ 2 $^{+2}_{-0}$	93.4 $\pm$ 0.6 $^{+0.0}_{-0.7}$	6.5 $\pm$ 0.6 $^{+0.7}_{-0.0}$	0.1 $\pm$ 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -33	+30 -0	+1 -0	+0.00 -0.48	+0.46 -0.00	+0.02 -0.00
LP5	+0 -2	+3 -0	+0 -0	+0.00 -0.04	+0.04 -0.00	+0.00 -0.00

Table B.28: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{j_2}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{j_2}$ [GeV]						
25 - 40	121339 ± 526 $^{+644}_{-1876}$	20718 ± 412 $^{+1450}_{-540}$	1924 ± 113 $^{+490}_{-95}$	84.3 ± 0.3 $^{+0.4}_{-1.3}$	14.4 ± 0.3 $^{+1.0}_{-0.4}$	1.3 ± 0.1 $^{+0.3}_{-0.1}$
LP2	+0 -1326	+1025 -0	+347 -0	+0.00 -0.95	+0.71 -0.00	+0.24 -0.00
LP5	+455 -0	+0 -382	+0 -67	+0.31 -0.00	+0.00 -0.27	+0.00 -0.05
40 - 60	55007 ± 337 $^{+292}_{-985}$	7809 ± 245 $^{+863}_{-237}$	508 ± 61 $^{+147}_{-48}$	86.9 ± 0.4 $^{+0.5}_{-1.6}$	12.3 ± 0.4 $^{+1.4}_{-0.4}$	0.8 ± 0.1 $^{+0.2}_{-0.1}$
LP2	+0 -697	+610 -0	+104 -0	+0.00 -1.12	+0.96 -0.00	+0.16 -0.00
LP5	+207 -0	+0 -168	+0 -34	+0.32 -0.00	+0.00 -0.27	+0.00 -0.05
60 - 80	24667 ± 216 $^{+37}_{-394}$	2964 ± 154 $^{+304}_{-25}$	260 ± 39 $^{+109}_{-15}$	88.4 ± 0.6 $^{+0.1}_{-1.5}$	10.6 ± 0.6 $^{+1.1}_{-0.1}$	0.9 ± 0.1 $^{+0.4}_{-0.1}$
LP2	+0 -279	+215 -0	+77 -0	+0.00 -1.04	+0.76 -0.00	+0.28 -0.00
LP5	+26 -0	+0 -18	+0 -11	+0.10 -0.00	+0.00 -0.06	+0.00 -0.04
80 - 100	12258 ± 152 $^{+47}_{-116}$	1427 ± 103 $^{+100}_{-51}$	57 ± 24 $^{+30}_{-2}$	89.2 ± 0.8 $^{+0.4}_{-0.9}$	10.4 ± 0.8 $^{+0.7}_{-0.4}$	0.4 ± 0.2 $^{+0.2}_{-0.0}$
LP2	+0 -82	+70 -0	+21 -0	+0.00 -0.66	+0.50 -0.00	+0.16 -0.00
LP5	+33 -0	+0 -36	+0 -1	+0.27 -0.00	+0.00 -0.26	+0.00 -0.01
100 - 120	7065 ± 110 $^{+12}_{-75}$	626 ± 69 $^{+74}_{-24}$	30 ± 15 $^{+11}_{-0}$	91.5 ± 1.0 $^{+0.2}_{-1.0}$	8.1 ± 0.9 $^{+1.0}_{-0.3}$	0.4 ± 0.2 $^{+0.1}_{-0.0}$
LP2	+0 -53	+52 -0	+2 -0	+0.00 -0.70	+0.67 -0.00	+0.03 -0.00
LP5	+8 -0	+0 -17	+7 -0	+0.13 -0.00	+0.00 -0.22	+0.09 -0.00
120 - 140	4332 ± 86 $^{+24}_{-44}$	354 ± 52 $^{+48}_{-25}$	10 ± 10 $^{+2}_{-1}$	92.2 ± 1.2 $^{+0.6}_{-1.1}$	7.5 ± 1.2 $^{+1.0}_{-0.5}$	0.2 ± 0.2 $^{+0.0}_{-0.0}$
LP2	+0 -31	+34 -0	+1 -0	+0.00 -0.75	+0.72 -0.00	+0.02 -0.00
LP5	+17 -0	+0 -18	+0 -1	+0.40 -0.00	+0.00 -0.38	+0.00 -0.02
140 - 160	2806 ± 66 $^{+0}_{-68}$	195 ± 35 $^{+66}_{-0}$	8 ± 2 $^{+1}_{-0}$	93.3 ± 1.2 $^{+0.0}_{-2.2}$	6.5 ± 1.2 $^{+2.2}_{-0.0}$	0.3 ± 0.1 $^{+0.0}_{-0.0}$
LP2	+0 -48	+47 -0	+1 -0	+0.00 -1.58	+1.56 -0.00	+0.02 -0.00
LP5	+0 -1	+0 -0	+0 -0	+0.00 -0.00	+0.00 -0.00	+0.00 -0.00
160 - 180	1864 ± 53 $^{+8}_{-28}$	124 ± 28 $^{+25}_{-7}$	1 ± 1 $^{+0}_{-0}$	93.7 ± 1.5 $^{+0.4}_{-1.3}$	6.2 ± 1.5 $^{+1.3}_{-0.4}$	0.1 ± 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -20	+18 -0	+0 -0	+0.00 -0.93	+0.91 -0.00	+0.02 -0.00
LP5	+6 -0	+0 -5	+0 -0	+0.27 -0.00	+0.00 -0.26	+0.00 -0.00
180 - 200	1387 ± 44 $^{+0}_{-9}$	67 ± 20 $^{+10}_{-0}$	2 ± 1 $^{+0}_{-0}$	95.3 ± 1.5 $^{+0.0}_{-0.7}$	4.6 ± 1.5 $^{+0.7}_{-0.0}$	0.1 ± 0.1 $^{+0.0}_{-0.0}$
LP2	+0 -6	+6 -0	+0 -0	+0.00 -0.45	+0.44 -0.00	+0.01 -0.00
LP5	+0 -4	+4 -0	+0 -0	+0.00 -0.26	+0.26 -0.00	+0.00 -0.01
200 - 220	955 ± 38 $^{+8}_{-17}$	72 ± 20 $^{+17}_{-8}$	1 ± 1 $^{+0}_{-0}$	92.9 ± 2.1 $^{+0.8}_{-1.7}$	7.0 ± 2.1 $^{+1.7}_{-0.8}$	0.1 ± 0.1 $^{+0.0}_{-0.0}$
LP2	+0 -12	+12 -0	+0 -0	+0.00 -1.19	+1.17 -0.00	+0.02 -0.00
LP5	+6 -0	+0 -6	+0 -0	+0.57 -0.00	+0.00 -0.56	+0.00 -0.01
220 - 240	655 ± 27 $^{+0}_{-3}$	27 ± 7 $^{+6}_{-0}$	1 ± 0 $^{+0}_{-1}$	96.0 ± 1.2 $^{+0.0}_{-0.8}$	3.9 ± 1.2 $^{+0.9}_{-0.0}$	0.1 ± 0.1 $^{+0.0}_{-0.1}$
LP2	+0 -0	+4 -0	+0 -0	+0.00 -0.53	+0.52 -0.00	+0.01 -0.00
LP5	+0 -2	+3 -0	+0 -0	+0.00 -0.40	+0.46 -0.00	+0.00 -0.06
240 - 260	542 ± 29 $^{+1}_{-17}$	28 ± 17 $^{+17}_{-0}$	1 ± 4 $^{+0}_{-1}$	94.9 ± 3.2 $^{+0.2}_{-3.0}$	4.8 ± 3.1 $^{+3.0}_{-0.1}$	0.2 ± 0.7 $^{+0.0}_{-0.2}$
LP2	+0 -12	+12 -0	+0 -0	+0.00 -2.10	+2.15 -0.00	+0.00 -0.05
LP5	+1 -0	+0 -0	+0 -1	+0.16 -0.00	+0.00 -0.05	+0.00 -0.11
260 - 280	390 ± 21 $^{+0}_{-4}$	10 ± 6 $^{+3}_{-0}$	1 ± 2 $^{+1}_{-1}$	97.3 ± 1.7 $^{+0.0}_{-1.1}$	2.4 ± 1.6 $^{+0.9}_{-0.0}$	0.3 ± 0.5 $^{+0.3}_{-0.2}$
LP2	+0 -3	+2 -0	+1 -0	+0.00 -0.75	+0.51 -0.00	+0.24 -0.00
LP5	+0 -2	+2 -0	+0 -0	+0.00 -0.35	+0.46 -0.00	+0.00 -0.12
280 - 300	288 ± 20 $^{+1}_{-1}$	13 ± 9 $^{+1}_{-2}$	1 ± 1 $^{+0}_{-0}$	95.3 ± 3.2 $^{+0.7}_{-0.2}$	4.4 ± 3.1 $^{+0.6}_{-0.6}$	0.3 ± 0.5 $^{+0.0}_{-0.1}$
LP2	+1 -0	+0 -1	+0 -0	+0.48 -0.00	+0.00 -0.40	+0.00 -0.08
LP5	+0 -1	+1 -0	+0 -0	+0.00 -0.13	+0.17 -0.00	+0.00 -0.03
300 - 13000	1325 ± 40 $^{+0}_{-4}$	35 ± 12 $^{+6}_{-0}$	1 ± 0 $^{+1}_{-0}$	97.4 ± 0.9 $^{+0.0}_{-0.5}$	2.6 ± 0.9 $^{+0.5}_{-0.0}$	0.0 ± 0.0 $^{+0.1}_{-0.0}$
LP2	+0 -2	+4 -0	+1 -0	+0.00 -0.34	+0.31 -0.00	+0.04 -0.00
LP5	+0 -2	+2 -0	+0 -0	+0.00 -0.16	+0.12 -0.00	+0.03 -0.00

Table B.29: Yield and purity outputs from the 2x2D Sideband Method for m_{jj} . (Continued on next page.)

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
m_{jj} [GeV]						
0 - 20	$733 \pm 40^{+5}_{-16}$	$116 \pm 27^{+14}_{-1}$	$37 \pm 12^{+2}_{-3}$	$82.8 \pm 3.6^{+0.5}_{-1.8}$	$13.1 \pm 3.3^{+1.6}_{-0.1}$	$4.1 \pm 1.5^{+0.2}_{-0.4}$
LP2	$+0 - 12$	$+10 - 0$	$+1 - 0$	$+0.00 - 1.28$	$+1.13 - 0.00$	$+0.16 - 0.00$
LP5	$+4 - 0$	$+0 - 1$	$+0 - 2$	$+0.37 - 0.00$	$+0.00 - 0.09$	$+0.00 - 0.28$
20 - 40	$14195 \pm 180^{+57}_{-252}$	$2417 \pm 141^{+179}_{-39}$	$237 \pm 39^{+80}_{-18}$	$84.2 \pm 0.9^{+0.3}_{-1.5}$	$14.3 \pm 0.9^{+1.1}_{-0.2}$	$1.4 \pm 0.2^{+0.5}_{-0.1}$
LP2	$+0 - 178$	$+127 - 0$	$+57 - 0$	$+0.00 - 1.09$	$+0.75 - 0.00$	$+0.34 - 0.00$
LP5	$+40 - 0$	$+0 - 27$	$+0 - 13$	$+0.24 - 0.00$	$+0.00 - 0.16$	$+0.00 - 0.08$
40 - 60	$20277 \pm 214^{+132}_{-240}$	$3600 \pm 165^{+175}_{-126}$	$262 \pm 43^{+81}_{-5}$	$84.0 \pm 0.7^{+0.5}_{-1.0}$	$14.9 \pm 0.7^{+0.7}_{-0.5}$	$1.1 \pm 0.2^{+0.3}_{-0.0}$
LP2	$+0 - 170$	$+124 - 0$	$+57 - 0$	$+0.00 - 0.74$	$+0.50 - 0.00$	$+0.24 - 0.00$
LP5	$+94 - 0$	$+0 - 89$	$+0 - 4$	$+0.39 - 0.00$	$+0.00 - 0.37$	$+0.00 - 0.02$
60 - 80	$26853 \pm 249^{+154}_{-442}$	$4602 \pm 196^{+327}_{-117}$	$478 \pm 55^{+139}_{-34}$	$84.1 \pm 0.7^{+0.5}_{-1.4}$	$14.4 \pm 0.6^{+1.0}_{-0.4}$	$1.5 \pm 0.2^{+0.4}_{-0.1}$
LP2	$+0 - 313$	$+231 - 0$	$+98 - 0$	$+0.00 - 1.02$	$+0.72 - 0.00$	$+0.31 - 0.00$
LP5	$+109 - 0$	$+0 - 83$	$+0 - 24$	$+0.34 - 0.00$	$+0.00 - 0.26$	$+0.00 - 0.08$
80 - 100	$26177 \pm 243^{+167}_{-427}$	$4599 \pm 187^{+356}_{-171}$	$331 \pm 48^{+85}_{-0}$	$84.2 \pm 0.6^{+0.5}_{-0.6}$	$14.8 \pm 0.6^{+1.1}_{-0.6}$	$1.1 \pm 0.2^{+0.3}_{-0.0}$
LP2	$+0 - 302$	$+251 - 0$	$+60 - 0$	$+0.00 - 1.00$	$+0.80 - 0.00$	$+0.19 - 0.00$
LP5	$+118 - 0$	$+0 - 121$	$+5 - 0$	$+0.37 - 0.00$	$+0.00 - 0.39$	$+0.02 - 0.00$
100 - 120	$23139 \pm 223^{+93}_{-330}$	$3490 \pm 169^{+259}_{-100}$	$325 \pm 45^{+82}_{-0}$	$85.8 \pm 0.7^{+0.4}_{-1.3}$	$12.9 \pm 0.7^{+1.0}_{-0.4}$	$1.2 \pm 0.2^{+0.3}_{-0.0}$
LP2	$+0 - 233$	$+183 - 0$	$+58 - 0$	$+0.00 - 0.89$	$+0.67 - 0.00$	$+0.21 - 0.00$
LP5	$+66 - 0$	$+0 - 71$	$+2 - 0$	$+0.25 - 0.00$	$+0.00 - 0.26$	$+0.01 - 0.00$
120 - 140	$19714 \pm 205^{+109}_{-269}$	$2774 \pm 156^{+201}_{-91}$	$304 \pm 43^{+83}_{-17}$	$86.5 \pm 0.7^{+0.5}_{-1.2}$	$12.2 \pm 0.7^{+0.9}_{-0.4}$	$1.3 \pm 0.2^{+0.4}_{-0.1}$
LP2	$+0 - 190$	$+142 - 0$	$+59 - 0$	$+0.00 - 0.87$	$+0.62 - 0.00$	$+0.26 - 0.00$
LP5	$+77 - 0$	$+0 - 64$	$+0 - 12$	$+0.33 - 0.00$	$+0.00 - 0.28$	$+0.00 - 0.05$
140 - 160	$16158 \pm 184^{+73}_{-263}$	$2362 \pm 135^{+199}_{-60}$	$156 \pm 34^{+71}_{-15}$	$86.5 \pm 0.8^{+0.4}_{-1.4}$	$12.6 \pm 0.8^{+1.1}_{-0.3}$	$0.8 \pm 0.2^{+0.4}_{-0.1}$
LP2	$+0 - 186$	$+141 - 0$	$+50 - 0$	$+0.00 - 1.02$	$+0.75 - 0.00$	$+0.27 - 0.00$
LP5	$+52 - 0$	$+0 - 42$	$+0 - 10$	$+0.28 - 0.00$	$+0.00 - 0.23$	$+0.00 - 0.06$
160 - 180	$13010 \pm 167^{+48}_{-287}$	$1913 \pm 125^{+245}_{-28}$	$150 \pm 32^{+40}_{-14}$	$86.3 \pm 0.9^{+0.3}_{-1.9}$	$12.7 \pm 0.9^{+1.6}_{-0.2}$	$1.0 \pm 0.2^{+0.3}_{-0.1}$
LP2	$+0 - 203$	$+173 - 0$	$+28 - 0$	$+0.00 - 1.34$	$+1.15 - 0.00$	$+0.19 - 0.00$
LP5	$+34 - 0$	$+0 - 20$	$+0 - 10$	$+0.20 - 0.00$	$+0.00 - 0.13$	$+0.00 - 0.07$
180 - 200	$10571 \pm 147^{+31}_{-146}$	$1488 \pm 107^{+110}_{-13}$	$121 \pm 27^{+42}_{-18}$	$86.8 \pm 0.9^{+0.3}_{-1.2}$	$12.2 \pm 0.9^{+0.9}_{-0.1}$	$1.0 \pm 0.2^{+0.3}_{-0.1}$
LP2	$+0 - 103$	$+78 - 0$	$+30 - 0$	$+0.00 - 0.88$	$+0.63 - 0.00$	$+0.25 - 0.00$
LP5	$+22 - 0$	$+0 - 9$	$+0 - 13$	$+0.18 - 0.00$	$+0.00 - 0.08$	$+0.00 - 0.10$
200 - 220	$9088 \pm 134^{+43}_{-172}$	$1106 \pm 97^{+137}_{-39}$	$109 \pm 26^{+37}_{-6}$	$88.2 \pm 1.0^{+0.4}_{-1.7}$	$10.7 \pm 1.0^{+1.3}_{-0.4}$	$1.1 \pm 0.3^{+0.4}_{-0.1}$
LP2	$+0 - 122$	$+97 - 0$	$+26 - 0$	$+0.00 - 1.19$	$+0.94 - 0.00$	$+0.25 - 0.00$
LP5	$+31 - 0$	$+0 - 28$	$+0 - 4$	$+0.31 - 0.00$	$+0.00 - 0.27$	$+0.00 - 0.04$
220 - 240	$7634 \pm 122^{+24}_{-91}$	$900 \pm 87^{+84}_{-7}$	$76 \pm 22^{+14}_{-17}$	$88.7 \pm 1.1^{+0.3}_{-1.1}$	$10.5 \pm 1.1^{+1.0}_{-0.1}$	$0.9 \pm 0.3^{+0.2}_{-0.2}$
LP2	$+0 - 65$	$+59 - 0$	$+10 - 0$	$+0.00 - 0.80$	$+0.68 - 0.00$	$+0.11 - 0.00$
LP5	$+17 - 0$	$+0 - 5$	$+0 - 12$	$+0.19 - 0.00$	$+0.00 - 0.05$	$+0.00 - 0.14$
240 - 260	$6373 \pm 110^{+0}_{-101}$	$724 \pm 75^{+88}_{-0}$	$55 \pm 19^{+17}_{-5}$	$89.1 \pm 1.1^{+0.0}_{-1.5}$	$10.1 \pm 1.1^{+1.2}_{-0.0}$	$0.8 \pm 0.3^{+0.2}_{-0.1}$
LP2	$+0 - 71$	$+62 - 0$	$+12 - 0$	$+0.00 - 1.04$	$+0.87 - 0.00$	$+0.17 - 0.00$
LP5	$+0 - 1$	$+3 - 0$	$+0 - 3$	$+0.01 - 0.00$	$+0.04 - 0.00$	$+0.00 - 0.05$

Table B.30: Yield and purity outputs from the 2x2D Sideband Method for m_{jj} continued.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
m_{jj} [GeV]						
260 - 280	$5457 \pm 99^{+9}_{-83}$	$570 \pm 66^{+93}_{-3}$	$45 \pm 16^{+0}_{-7}$	$89.9 \pm 1.2^{+0.2}_{-1.4}$	$9.4 \pm 1.1^{+1.5}_{-0.1}$	$0.7 \pm 0.3^{+0.0}_{-0.1}$
LP2	+0 -58	+66 -0	+0 -4	+0.00 -1.02	+1.08 -0.00	+0.00 -0.06
LP5	+7 -0	+0 -2	+0 -4	+0.11 -0.00	+0.00 -0.04	+0.00 -0.07
280 - 300	$4450 \pm 91^{+6}_{-73}$	$544 \pm 58^{+70}_{-2}$	$26 \pm 4^{+8}_{-3}$	$88.7 \pm 1.2^{+0.1}_{-1.5}$	$10.8 \pm 1.2^{+1.4}_{-0.0}$	$0.5 \pm 0.1^{+0.2}_{-0.0}$
LP2	+0 -52	+49 -0	+5 -0	+0.00 -1.08	+0.98 -0.00	+0.11 -0.00
LP5	+4 -0	+0 -1	+0 -2	+0.07 -0.00	+0.00 -0.03	+0.00 -0.04
300 - 320	$3841 \pm 85^{+20}_{-91}$	$440 \pm 58^{+97}_{-13}$	$24 \pm 14^{+0}_{-7}$	$89.2 \pm 1.5^{+0.5}_{-2.2}$	$10.2 \pm 1.4^{+2.2}_{-0.3}$	$0.6 \pm 0.3^{+0.0}_{-0.2}$
LP2	+0 -64	+68 -0	+0 -2	+0.00 -1.53	+1.58 -0.00	+0.00 -0.05
LP5	+14 -0	+0 -10	+0 -5	+0.33 -0.00	+0.00 -0.22	+0.00 -0.11
320 - 340	$3274 \pm 78^{+13}_{-61}$	$338 \pm 53^{+67}_{-10}$	$29 \pm 13^{+0}_{-5}$	$89.9 \pm 1.6^{+0.3}_{-1.7}$	$9.3 \pm 1.5^{+1.8}_{-0.3}$	$0.8 \pm 0.4^{+0.0}_{-0.1}$
LP2	+0 -43	+47 -0	+0 -3	+0.00 -1.20	+1.29 -0.00	+0.00 -0.09
LP5	+9 -0	+0 -7	+0 -1	+0.23 -0.00	+0.00 -0.20	+0.00 -0.03
340 - 360	$2844 \pm 71^{+10}_{-20}$	$303 \pm 43^{+13}_{-10}$	$14 \pm 3^{+7}_{-1}$	$90.0 \pm 1.5^{+0.4}_{-0.6}$	$9.6 \pm 1.5^{+0.4}_{-0.3}$	$0.4 \pm 0.1^{+0.2}_{-0.0}$
LP2	+0 -14	+9 -0	+5 -0	+0.00 -0.45	+0.29 -0.00	+0.16 -0.00
LP5	+7 -0	+0 -7	+0 -1	+0.25 -0.00	+0.00 -0.23	+0.00 -0.02
360 - 380	$2379 \pm 64^{+10}_{-21}$	$243 \pm 39^{+11}_{-14}$	$14 \pm 3^{+15}_{-0}$	$90.3 \pm 1.6^{+0.4}_{-1.0}$	$9.2 \pm 1.6^{+0.4}_{-0.5}$	$0.5 \pm 0.1^{+0.6}_{-0.0}$
LP2	+0 -15	+8 -0	+11 -0	+0.00 -0.69	+0.28 -0.00	+0.40 -0.00
LP5	+7 -0	+0 -10	+2 -0	+0.29 -0.00	+0.00 -0.38	+0.09 -0.00
380 - 400	$1893 \pm 62^{+22}_{-33}$	$313 \pm 42^{+35}_{-23}$	$8 \pm 2^{+2}_{-0}$	$85.5 \pm 2.0^{+1.0}_{-1.7}$	$14.2 \pm 2.0^{+1.6}_{-1.0}$	$0.4 \pm 0.1^{+0.1}_{-0.0}$
LP2	+0 -23	+25 -0	+1 -0	+0.00 -1.17	+1.11 -0.00	+0.06 -0.00
LP5	+15 -0	+0 -16	+0 -0	+0.72 -0.00	+0.00 -0.72	+0.01 -0.00
420 - 440	$1618 \pm 51^{+0}_{-29}$	$92 \pm 30^{+27}_{-0}$	$11 \pm 7^{+4}_{-3}$	$94.0 \pm 1.9^{+0.0}_{-1.7}$	$5.3 \pm 1.8^{+1.5}_{-0.0}$	$0.7 \pm 0.5^{+0.2}_{-0.2}$
LP2	+0 -18	+15 -0	+3 -0	+0.00 -1.04	+0.89 -0.00	+0.15 -0.00
LP5	+0 -14	+15 -0	+0 -2	+0.00 -0.76	+0.89 -0.00	+0.00 -0.13
440 - 460	$1368 \pm 49^{+7}_{-29}$	$154 \pm 30^{+30}_{-7}$	$7 \pm 2^{+1}_{-0}$	$89.5 \pm 2.1^{+0.5}_{-2.0}$	$10.1 \pm 2.1^{+2.0}_{-0.5}$	$0.4 \pm 0.1^{+0.1}_{-0.0}$
LP2	+0 -21	+21 -0	+1 -0	+0.00 -1.43	+1.39 -0.00	+0.04 -0.00
LP5	+5 -0	+0 -5	+0 -0	+0.34 -0.00	+0.00 -0.32	+0.00 -0.02
460 - 480	$1149 \pm 47^{+4}_{-28}$	$169 \pm 30^{+29}_{-5}$	$6 \pm 2^{+0}_{-1}$	$86.8 \pm 2.5^{+0.4}_{-2.1}$	$12.7 \pm 2.4^{+2.2}_{-0.3}$	$0.5 \pm 0.2^{+0.0}_{-0.1}$
LP2	+0 -20	+20 -0	+0 -1	+0.00 -1.48	+1.53 -0.00	+0.00 -0.05
LP5	+3 -0	+0 -3	+0 -0	+0.25 -0.00	+0.00 -0.24	+0.00 -0.01
500 - 13000	$9918 \pm 126^{+23}_{-72}$	$803 \pm 68^{+72}_{-23}$	$29 \pm 4^{+9}_{-0}$	$92.3 \pm 0.7^{+0.2}_{-0.7}$	$7.5 \pm 0.7^{+0.7}_{-0.2}$	$0.3 \pm 0.0^{+0.1}_{-0.0}$
LP2	+0 -51	+51 -0	+6 -0	+0.00 -0.53	+0.47 -0.00	+0.06 -0.00
LP5	+16 -0	+0 -16	+0 -0	+0.15 -0.00	+0.00 -0.15	+0.00 -0.00

Table B.31: Yield and purity outputs from the 2x2D Sideband Method for $m_{\gamma\gamma jj}$.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$m_{\gamma\gamma jj}$ [GeV]						
0 - 50	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$
LP2	$+0 - 0$	$+0 - 0$	$+0 - 0$	$+0.00 - 0.00$	$+0.00 - 0.00$	$+0.00 - 0.00$
LP5	$+0 - 0$	$+0 - 0$	$+0 - 0$	$+0.00 - 0.00$	$+0.00 - 0.00$	$+0.00 - 0.00$
50 - 100	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$
LP2	$+0 - 0$	$+0 - 0$	$+0 - 0$	$+0.00 - 0.00$	$+0.00 - 0.00$	$+0.00 - 0.00$
LP5	$+0 - 0$	$+0 - 0$	$+0 - 0$	$+0.00 - 0.00$	$+0.00 - 0.00$	$+0.00 - 0.00$
100 - 150	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0 \pm 0^{+0}_{-0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$	$0.0 \pm 0.0^{+0.0}_{-0.0}$
LP2	$+0 - 0$	$+0 - 0$	$+0 - 0$	$+0.00 - 0.00$	$+0.00 - 0.00$	$+0.00 - 0.00$
LP5	$+0 - 0$	$+0 - 0$	$+0 - 0$	$+0.00 - 0.00$	$+0.00 - 0.00$	$+0.00 - 0.00$
150 - 200	$3843 \pm 114^{+46}_{-95}$	$1168 \pm 107^{+66}_{-22}$	$143 \pm 34^{+29}_{-24}$	$74.6 \pm 2.2^{+0.9}_{-1.8}$	$22.7 \pm 2.1^{+1.3}_{-0.4}$	$2.8 \pm 0.7^{+0.6}_{-0.5}$
LP2	$+0 - 67$	$+47 - 0$	$+21 - 0$	$+0.00 - 1.30$	$+0.91 - 0.00$	$+0.40 - 0.00$
LP5	$+32 - 0$	$+0 - 15$	$+0 - 17$	$+0.63 - 0.00$	$+0.00 - 0.30$	$+0.00 - 0.33$
200 - 250	$22601 \pm 246^{+228}_{-391}$	$5030 \pm 208^{+285}_{-247}$	$470 \pm 60^{+111}_{-0}$	$80.4 \pm 0.8^{+0.8}_{-1.4}$	$17.9 \pm 0.8^{+1.0}_{-0.9}$	$1.7 \pm 0.2^{+0.4}_{-0.0}$
LP2	$+0 - 276$	$+202 - 0$	$+78 - 0$	$+0.00 - 0.99$	$+0.72 - 0.00$	$+0.28 - 0.00$
LP5	$+161 - 0$	$+0 - 175$	$+18 - 0$	$+0.56 - 0.00$	$+0.00 - 0.62$	$+0.06 - 0.00$
250 - 300	$33405 \pm 285^{+229}_{-593}$	$5834 \pm 235^{+495}_{-186}$	$751 \pm 70^{+102}_{-36}$	$83.5 \pm 0.6^{+0.6}_{-1.5}$	$14.6 \pm 0.6^{+1.2}_{-0.5}$	$1.9 \pm 0.2^{+0.3}_{-0.1}$
LP2	$+0 - 419$	$+350 - 0$	$+72 - 0$	$+0.00 - 1.05$	$+0.87 - 0.00$	$+0.18 - 0.00$
LP5	$+162 - 0$	$+0 - 132$	$+0 - 26$	$+0.39 - 0.00$	$+0.00 - 0.33$	$+0.00 - 0.06$
300 - 350	$32750 \pm 271^{+95}_{-557}$	$5017 \pm 213^{+434}_{-59}$	$570 \pm 60^{+124}_{-40}$	$85.4 \pm 0.6^{+0.3}_{-1.5}$	$13.1 \pm 0.6^{+1.1}_{-0.2}$	$1.5 \pm 0.2^{+0.3}_{-0.1}$
LP2	$+0 - 394$	$+307 - 0$	$+88 - 0$	$+0.00 - 1.03$	$+0.80 - 0.00$	$+0.23 - 0.00$
LP5	$+67 - 0$	$+0 - 42$	$+0 - 28$	$+0.18 - 0.00$	$+0.00 - 0.11$	$+0.00 - 0.07$
350 - 400	$28808 \pm 242^{+128}_{-425}$	$3763 \pm 177^{+314}_{-124}$	$319 \pm 46^{+122}_{-7}$	$87.6 \pm 0.6^{+0.4}_{-1.3}$	$11.4 \pm 0.6^{+1.0}_{-0.4}$	$1.0 \pm 0.1^{+0.4}_{-0.0}$
LP2	$+0 - 300$	$+222 - 0$	$+86 - 0$	$+0.00 - 0.93$	$+0.67 - 0.00$	$+0.26 - 0.00$
LP5	$+91 - 0$	$+0 - 88$	$+0 - 5$	$+0.28 - 0.00$	$+0.00 - 0.27$	$+0.00 - 0.01$
400 - 450	$23078 \pm 216^{+14}_{-264}$	$3159 \pm 155^{+192}_{-0}$	$181 \pm 37^{+77}_{-24}$	$87.4 \pm 0.6^{+0.0}_{-1.0}$	$12.0 \pm 0.6^{+0.7}_{-0.0}$	$0.7 \pm 0.1^{+0.3}_{-0.1}$
LP2	$+0 - 187$	$+135 - 0$	$+54 - 0$	$+0.00 - 0.72$	$+0.51 - 0.00$	$+0.21 - 0.00$
LP5	$+10 - 0$	$+10 - 0$	$+0 - 17$	$+0.03 - 0.00$	$+0.04 - 0.00$	$+0.00 - 0.07$
450 - 500	$18534 \pm 192^{+87}_{-399}$	$2309 \pm 137^{+372}_{-84}$	$191 \pm 35^{+38}_{-1}$	$88.1 \pm 0.7^{+0.4}_{-1.9}$	$11.0 \pm 0.7^{+1.8}_{-0.4}$	$0.9 \pm 0.2^{+0.2}_{-0.0}$
LP2	$+0 - 282$	$+263 - 0$	$+27 - 0$	$+0.00 - 1.37$	$+1.25 - 0.00$	$+0.13 - 0.00$
LP5	$+62 - 0$	$+0 - 59$	$+0 - 0$	$+0.28 - 0.00$	$+0.00 - 0.28$	$+0.00 - 0.00$
500 - 550	$14418 \pm 167^{+69}_{-256}$	$1759 \pm 117^{+252}_{-44}$	$134 \pm 29^{+8}_{-22}$	$88.4 \pm 0.8^{+0.4}_{-1.6}$	$10.8 \pm 0.8^{+1.5}_{-0.3}$	$0.8 \pm 0.2^{+0.0}_{-0.1}$
LP2	$+0 - 181$	$+178 - 0$	$+5 - 0$	$+0.00 - 1.12$	$+1.09 - 0.00$	$+0.03 - 0.00$
LP5	$+49 - 0$	$+0 - 31$	$+0 - 16$	$+0.29 - 0.00$	$+0.00 - 0.19$	$+0.00 - 0.10$
550 - 600	$11412 \pm 142^{+49}_{-152}$	$1199 \pm 86^{+139}_{-41}$	$70 \pm 6^{+20}_{-9}$	$90.0 \pm 0.7^{+0.4}_{-1.2}$	$9.5 \pm 0.7^{+1.1}_{-0.3}$	$0.5 \pm 0.1^{+0.2}_{-0.1}$
LP2	$+0 - 107$	$+98 - 0$	$+14 - 0$	$+0.00 - 0.88$	$+0.77 - 0.00$	$+0.11 - 0.00$
LP5	$+35 - 0$	$+0 - 29$	$+0 - 6$	$+0.28 - 0.00$	$+0.00 - 0.23$	$+0.00 - 0.05$
600 - 650	$8640 \pm 124^{+42}_{-108}$	$1063 \pm 75^{+97}_{-36}$	$40 \pm 5^{+14}_{-3}$	$88.7 \pm 0.8^{+0.4}_{-1.1}$	$10.9 \pm 0.8^{+1.0}_{-0.4}$	$0.4 \pm 0.1^{+0.1}_{-0.0}$
LP2	$+0 - 77$	$+69 - 0$	$+10 - 0$	$+0.00 - 0.81$	$+0.70 - 0.00$	$+0.10 - 0.00$
LP5	$+29 - 0$	$+0 - 26$	$+0 - 2$	$+0.28 - 0.00$	$+0.00 - 0.27$	$+0.00 - 0.02$
650 - 700	$7018 \pm 110^{+9}_{-115}$	$807 \pm 65^{+95}_{-17}$	$23 \pm 3^{+26}_{-0}$	$89.4 \pm 0.9^{+0.2}_{-1.5}$	$10.3 \pm 0.9^{+1.2}_{-0.2}$	$0.3 \pm 0.0^{+0.3}_{-0.0}$
LP2	$+0 - 81$	$+67 - 0$	$+18 - 0$	$+0.00 - 1.08$	$+0.85 - 0.00$	$+0.23 - 0.00$
LP5	$+6 - 0$	$+0 - 12$	$+1 - 0$	$+0.13 - 0.00$	$+0.00 - 0.15$	$+0.02 - 0.00$
700 - 750	$5529 \pm 98^{+17}_{-112}$	$593 \pm 61^{+104}_{-15}$	$23 \pm 13^{+6}_{-0}$	$90.0 \pm 1.1^{+0.3}_{-1.8}$	$9.7 \pm 1.1^{+1.7}_{-0.2}$	$0.4 \pm 0.2^{+0.1}_{-0.0}$
LP2	$+0 - 80$	$+73 - 0$	$+5 - 0$	$+0.00 - 1.27$	$+1.19 - 0.00$	$+0.07 - 0.00$
LP5	$+12 - 0$	$+0 - 11$	$+0 - 0$	$+0.18 - 0.00$	$+0.00 - 0.18$	$+0.00 - 0.00$
750 - 800	$4600 \pm 86^{+29}_{-72}$	$427 \pm 47^{+73}_{-26}$	$11 \pm 2^{+3}_{-1}$	$91.3 \pm 1.0^{+0.5}_{-1.5}$	$8.5 \pm 1.0^{+1.4}_{-0.5}$	$0.2 \pm 0.0^{+0.1}_{-0.0}$
LP2	$+0 - 51$	$+52 - 0$	$+2 - 0$	$+0.00 - 1.06$	$+1.02 - 0.00$	$+0.04 - 0.00$
LP5	$+21 - 0$	$+0 - 18$	$+0 - 1$	$+0.37 - 0.00$	$+0.00 - 0.36$	$+0.00 - 0.01$
800 - 850	$3465 \pm 78^{+11}_{-95}$	$340 \pm 50^{+92}_{-7}$	$29 \pm 12^{+3}_{-4}$	$90.4 \pm 1.4^{+0.3}_{-2.5}$	$8.9 \pm 1.4^{+2.4}_{-0.2}$	$0.7 \pm 0.3^{+0.1}_{-0.1}$
LP2	$+0 - 67$	$+65 - 0$	$+2 - 0$	$+0.00 - 1.75$	$+1.69 - 0.00$	$+0.05 - 0.00$
LP5	$+8 - 0$	$+0 - 5$	$+0 - 3$	$+0.20 - 0.00$	$+0.00 - 0.13$	$+0.00 - 0.07$
850 - 900	$2791 \pm 69^{+6}_{-64}$	$327 \pm 43^{+66}_{-6}$	$13 \pm 9^{+0}_{-2}$	$89.1 \pm 1.5^{+0.2}_{-2.0}$	$10.5 \pm 1.5^{+2.1}_{-0.2}$	$0.4 \pm 0.3^{+0.0}_{-0.1}$
LP2	$+0 - 45$	$+47 - 0$	$+0 - 1$	$+0.00 - 1.45$	$+1.50 - 0.00$	$+0.00 - 0.05$
LP5	$+4 - 0$	$+0 - 4$	$+0 - 1$	$+0.15 - 0.00$	$+0.00 - 0.13$	$+0.00 - 0.02$
900 - 950	$2337 \pm 61^{+14}_{-0}$	$249 \pm 34^{+0}_{-15}$	$6 \pm 2^{+2}_{-0}$	$90.2 \pm 1.4^{+0.5}_{-0.0}$	$9.6 \pm 1.4^{+0.0}_{-0.6}$	$0.2 \pm 0.1^{+0.1}_{-0.0}$
LP2	$+10 - 0$	$+0 - 10$	$+1 - 0$	$+0.34 - 0.00$	$+0.00 - 0.39$	$+0.05 - 0.00$
LP5	$+3 - 0$	$+0 - 3$	$+0 - 0$	$+0.12 - 0.00$	$+0.00 - 0.12$	$+0.00 - 0.00$
950 - 1000	$1792 \pm 54^{+6}_{-25}$	$180 \pm 31^{+35}_{-2}$	$8 \pm 6^{+0}_{-7}$	$90.5 \pm 1.7^{+0.3}_{-1.4}$	$9.1 \pm 1.7^{+1.7}_{-0.1}$	$0.4 \pm 0.3^{+0.0}_{-0.3}$
LP2	$+0 - 18$	$+24 - 0$	$+0 - 4$	$+0.00 - 1.00$	$+1.23 - 0.00$	$+0.00 - 0.22$
LP5	$+4 - 0$	$+0 - 2$	$+0 - 2$	$+0.18 - 0.00$	$+0.00 - 0.09$	$+0.00 - 0.09$

Table B.32: Yield and purity outputs from the 2x2D Sideband Method for p_T^{jj} . (Continued on next page.)

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
p_T^{jj} [GeV]						
0 - 10	6809 $\pm$ 130 $^{+0}_{-45}$	1540 $\pm$ 112 $^{+0}_{-7}$	164 $\pm$ 32 $^{+53}_{-0}$	80.0 $\pm$ 1.4 $^{+0.0}_{-0.5}$	18.1 $\pm$ 1.4 $^{+0.0}_{-0.1}$	1.9 $\pm$ 0.4 $^{+0.6}_{-0.0}$
LP2	+0 -32	+0 -5	+37 -0	+0.00 -0.38	+0.00 -0.06	+0.44 -0.00
LP5	+0 -0	+0 -2	+2 -0	+0.00 -0.00	+0.00 -0.03	+0.03 -0.00
10 - 20	14420 $\pm$ 188 $^{+107}_{-224}$	2733 $\pm$ 154 $^{+147}_{-94}$	295 $\pm$ 44 $^{+69}_{-12}$	82.6 $\pm$ 0.9 $^{+0.6}_{-1.2}$	15.7 $\pm$ 0.9 $^{+0.8}_{-0.5}$	1.7 $\pm$ 0.3 $^{+0.4}_{-0.1}$
LP2	+0 -158	+104 -0	+49 -0	+0.00 -0.88	+0.60 -0.00	+0.28 -0.00
LP5	+75 -0	+0 -66	+0 -8	+0.43 -0.00	+0.00 -0.38	+0.00 -0.05
20 - 30	17344 $\pm$ 196 $^{+97}_{-309}$	2910 $\pm$ 151 $^{+235}_{-72}$	300 $\pm$ 43 $^{+71}_{-22}$	84.4 $\pm$ 0.8 $^{+0.5}_{-1.5}$	14.2 $\pm$ 0.8 $^{+1.1}_{-0.4}$	1.5 $\pm$ 0.2 $^{+0.3}_{-0.1}$
LP2	+0 -219	+166 -0	+50 -0	+0.00 -1.05	+0.81 -0.00	+0.25 -0.00
LP5	+69 -0	+0 -51	+0 -16	+0.32 -0.00	+0.00 -0.25	+0.00 -0.08
30 - 40	19245 $\pm$ 204 $^{+133}_{-441}$	2917 $\pm$ 155 $^{+119}_{-121}$	253 $\pm$ 41 $^{+22}_{-5}$	85.9 $\pm$ 0.7 $^{+0.6}_{-2.0}$	13.0 $\pm$ 0.7 $^{+1.9}_{-0.5}$	1.1 $\pm$ 0.2 $^{+0.1}_{-0.0}$
LP2	+0 -312	+296 -0	+15 -0	+0.00 -1.39	+1.32 -0.00	+0.07 -0.00
LP5	+94 -0	+0 -85	+0 -4	+0.40 -0.00	+0.00 -0.38	+0.00 -0.02
40 - 50	20864 $\pm$ 213 $^{+70}_{-285}$	3051 $\pm$ 164 $^{+187}_{-45}$	306 $\pm$ 45 $^{+98}_{-23}$	86.1 $\pm$ 0.7 $^{+0.3}_{-1.2}$	12.6 $\pm$ 0.7 $^{+0.8}_{-0.2}$	1.3 $\pm$ 0.2 $^{+0.4}_{-0.1}$
LP2	+0 -201	+132 -0	+69 -0	+0.00 -0.83	+0.55 -0.00	+0.29 -0.00
LP5	+50 -0	+0 -32	+0 -16	+0.20 -0.00	+0.00 -0.13	+0.00 -0.07
50 - 60	23336 $\pm$ 225 $^{+127}_{-403}$	3432 $\pm$ 173 $^{+320}_{-90}$	328 $\pm$ 47 $^{+83}_{-29}$	86.1 $\pm$ 0.7 $^{+0.4}_{-1.5}$	12.7 $\pm$ 0.7 $^{+1.2}_{-0.3}$	1.2 $\pm$ 0.2 $^{+0.3}_{-0.1}$
LP2	+0 -285	+226 -0	+59 -0	+0.00 -1.05	+0.84 -0.00	+0.22 -0.00
LP5	+90 -0	+0 -64	+0 -21	+0.31 -0.00	+0.00 -0.24	+0.00 -0.08
60 - 70	21548 $\pm$ 219 $^{+103}_{-356}$	3496 $\pm$ 169 $^{+300}_{-102}$	265 $\pm$ 44 $^{+64}_{-3}$	85.1 $\pm$ 0.7 $^{+0.4}_{-1.4}$	13.8 $\pm$ 0.7 $^{+1.2}_{-0.4}$	1.0 $\pm$ 0.2 $^{+0.3}_{-0.0}$
LP2	+0 -252	+212 -0	+45 -0	+0.00 -1.01	+0.83 -0.00	+0.18 -0.00
LP5	+72 -0	+0 -72	+0 -2	+0.29 -0.00	+0.00 -0.28	+0.00 -0.01
70 - 80	19106 $\pm$ 196 $^{+69}_{-294}$	2636 $\pm$ 149 $^{+215}_{-38}$	254 $\pm$ 41 $^{+82}_{-37}$	86.9 $\pm$ 0.7 $^{+0.3}_{-1.3}$	12.0 $\pm$ 0.7 $^{+1.0}_{-0.2}$	1.2 $\pm$ 0.2 $^{+0.4}_{-0.2}$
LP2	+0 -208	+152 -0	+58 -0	+0.00 -0.95	+0.69 -0.00	+0.26 -0.00
LP5	+49 -0	+0 -27	+0 -26	+0.24 -0.00	+0.00 -0.12	+0.00 -0.12
80 - 90	15969 $\pm$ 181 $^{+52}_{-304}$	2025 $\pm$ 134 $^{+278}_{-32}$	209 $\pm$ 37 $^{+38}_{-19}$	87.7 $\pm$ 0.8 $^{+0.3}_{-1.7}$	11.1 $\pm$ 0.8 $^{+1.5}_{-0.2}$	1.2 $\pm$ 0.2 $^{+0.2}_{-0.1}$
LP2	+0 -215	+197 -0	+27 -0	+0.00 -1.22	+1.07 -0.00	+0.15 -0.00
LP5	+37 -0	+0 -22	+0 -13	+0.20 -0.00	+0.00 -0.12	+0.00 -0.07
90 - 100	12689 $\pm$ 160 $^{+56}_{-276}$	1943 $\pm$ 107 $^{+257}_{-51}$	112 $\pm$ 9 $^{+23}_{-11}$	86.1 $\pm$ 0.8 $^{+0.4}_{-1.9}$	13.2 $\pm$ 0.8 $^{+1.7}_{-0.3}$	0.8 $\pm$ 0.1 $^{+0.2}_{-0.1}$
LP2	+0 -195	+181 -0	+16 -0	+0.00 -1.34	+1.23 -0.00	+0.11 -0.00
LP5	+40 -0	+0 -36	+0 -8	+0.29 -0.00	+0.00 -0.24	+0.00 -0.05
100 - 110	10725 $\pm$ 143 $^{+64}_{-219}$	1372 $\pm$ 92 $^{+203}_{-62}$	99 $\pm$ 8 $^{+17}_{-1}$	87.9 $\pm$ 0.8 $^{+0.5}_{-1.8}$	11.3 $\pm$ 0.8 $^{+1.7}_{-0.5}$	0.8 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -155	+143 -0	+12 -0	+0.00 -1.27	+1.18 -0.00	+0.10 -0.00
LP5	+45 -0	+0 -44	+0 -1	+0.36 -0.00	+0.00 -0.36	+0.00 -0.00
110 - 120	8667 $\pm$ 131 $^{+37}_{-69}$	1130 $\pm$ 94 $^{+39}_{-41}$	83 $\pm$ 24 $^{+38}_{-0}$	87.7 $\pm$ 1.0 $^{+0.4}_{-0.8}$	11.4 $\pm$ 1.0 $^{+0.4}_{-0.4}$	0.8 $\pm$ 0.3 $^{+0.4}_{-0.0}$
LP2	+0 -49	+27 -0	+27 -0	+0.00 -0.54	+0.27 -0.00	+0.27 -0.00
LP5	+26 -0	+0 -29	+2 -0	+0.27 -0.00	+0.00 -0.29	+0.02 -0.00
120 - 130	7050 $\pm$ 116 $^{+29}_{-98}$	856 $\pm$ 81 $^{+80}_{-36}$	58 $\pm$ 20 $^{+22}_{-0}$	88.5 $\pm$ 1.1 $^{+0.4}_{-1.3}$	10.7 $\pm$ 1.1 $^{+1.0}_{-0.4}$	0.7 $\pm$ 0.3 $^{+0.3}_{-0.0}$
LP2	+0 -69	+57 -0	+15 -0	+0.00 -0.89	+0.71 -0.00	+0.19 -0.00
LP5	+20 -0	+0 -25	+5 -0	+0.25 -0.00	+0.00 -0.32	+0.07 -0.00
130 - 140	5862 $\pm$ 105 $^{+58}_{-82}$	731 $\pm$ 70 $^{+75}_{-50}$	44 $\pm$ 14 $^{+10}_{-4}$	88.3 $\pm$ 1.1 $^{+0.8}_{-1.3}$	11.0 $\pm$ 1.1 $^{+1.1}_{-0.8}$	0.7 $\pm$ 0.2 $^{+0.2}_{-0.1}$
LP2	+0 -58	+53 -0	+7 -0	+0.00 -0.90	+0.79 -0.00	+0.11 -0.00
LP5	+41 -0	+0 -35	+0 -3	+0.58 -0.00	+0.00 -0.54	+0.00 -0.04
140 - 150	4542 $\pm$ 94 $^{+0}_{-50}$	577 $\pm$ 66 $^{+55}_{-0}$	53 $\pm$ 17 $^{+0}_{-4}$	87.8 $\pm$ 1.4 $^{+0.0}_{-1.0}$	11.2 $\pm$ 1.3 $^{+1.1}_{-0.0}$	1.0 $\pm$ 0.3 $^{+0.0}_{-0.1}$
LP2	+0 -35	+39 -0	+0 -2	+0.00 -0.71	+0.75 -0.00	+0.00 -0.04
LP5	+0 -1	+2 -0	+0 -2	+0.00 -0.01	+0.05 -0.00	+0.00 -0.04

Table B.33: Yield and purity outputs from the 2x2D Sideband Method for p_T^{jj} continued.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
p_T^{jj} [GeV]						
150 - 160	3953 $\pm$ 85 $^{+8}_{-9}$	449 $\pm$ 56 $^{+8}_{-8}$	27 $\pm$ 13 $^{+7}_{-0}$	89.3 $\pm$ 1.4 $^{+0.2}_{-0.3}$	10.1 $\pm$ 1.3 $^{+0.2}_{-0.2}$	0.6 $\pm$ 0.3 $^{+0.2}_{-0.0}$
LP2	+0 -6	+6 -0	+5 -0	+0.00 -0.24	+0.12 -0.00	+0.12 -0.00
LP5	+4 -0	+0 -5	+0 -0	+0.12 -0.00	+0.00 -0.12	+0.00 -0.00
160 - 170	3355 $\pm$ 75 $^{+11}_{-45}$	353 $\pm$ 44 $^{+43}_{-9}$	13 $\pm$ 3 $^{+3}_{-0}$	90.2 $\pm$ 1.3 $^{+0.3}_{-1.2}$	9.5 $\pm$ 1.3 $^{+1.2}_{-0.3}$	0.3 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -32	+31 -0	+2 -0	+0.00 -0.88	+0.82 -0.00	+0.06 -0.00
LP5	+8 -0	+0 -7	+0 -0	+0.18 -0.00	+0.00 -0.18	+0.00 -0.00
170 - 180	2791 $\pm$ 71 $^{+10}_{-3}$	306 $\pm$ 47 $^{+0}_{-9}$	16 $\pm$ 10 $^{+10}_{-3}$	89.6 $\pm$ 1.6 $^{+0.4}_{-0.1}$	9.8 $\pm$ 1.6 $^{+0.0}_{-0.3}$	0.5 $\pm$ 0.3 $^{+0.3}_{-0.1}$
LP2	+0 -2	+0 -4	+7 -0	+0.00 -0.09	+0.00 -0.13	+0.22 -0.00
LP5	+7 -0	+0 -6	+0 -2	+0.25 -0.00	+0.00 -0.19	+0.00 -0.06
180 - 190	2339 $\pm$ 64 $^{+11}_{-0}$	230 $\pm$ 42 $^{+0}_{-24}$	17 $\pm$ 10 $^{+16}_{-0}$	90.4 $\pm$ 1.7 $^{+0.4}_{-0.0}$	8.9 $\pm$ 1.7 $^{+0.0}_{-0.9}$	0.7 $\pm$ 0.4 $^{+0.6}_{-0.0}$
LP2	+6 -0	+0 -16	+11 -0	+0.19 -0.00	+0.00 -0.61	+0.43 -0.00
LP5	+7 -0	+0 -8	+2 -0	+0.23 -0.00	+0.00 -0.31	+0.08 -0.00
190 - 200	1929 $\pm$ 57 $^{+8}_{-5}$	222 $\pm$ 33 $^{+4}_{-10}$	5 $\pm$ 1 $^{+1}_{-0}$	89.5 $\pm$ 1.7 $^{+0.4}_{-0.3}$	10.3 $\pm$ 1.7 $^{+0.2}_{-0.4}$	0.2 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -3	+3 -0	+1 -0	+0.00 -0.19	+0.14 -0.00	+0.05 -0.00
LP5	+6 -0	+0 -7	+0 -0	+0.31 -0.00	+0.00 -0.31	+0.00 -0.00
210 - 220	1393 $\pm$ 49 $^{+1}_{-19}$	133 $\pm$ 31 $^{+18}_{-1}$	10 $\pm$ 7 $^{+3}_{-0}$	90.7 $\pm$ 2.1 $^{+0.1}_{-1.3}$	8.7 $\pm$ 2.1 $^{+1.1}_{-0.0}$	0.6 $\pm$ 0.5 $^{+0.2}_{-0.0}$
LP2	+0 -14	+13 -0	+2 -0	+0.00 -0.95	+0.81 -0.00	+0.14 -0.00
LP5	+1 -0	+0 -0	+0 -0	+0.04 -0.00	+0.00 -0.03	+0.00 -0.01
220 - 230	1134 $\pm$ 45 $^{+13}_{-53}$	165 $\pm$ 28 $^{+47}_{-13}$	1 $\pm$ 1 $^{+4}_{-0}$	87.2 $\pm$ 2.3 $^{+1.0}_{-3.9}$	12.7 $\pm$ 2.3 $^{+3.6}_{-1.0}$	0.1 $\pm$ 0.1 $^{+0.3}_{-0.0}$
LP2	+0 -37	+33 -0	+3 -0	+0.00 -2.76	+2.56 -0.00	+0.21 -0.00
LP5	+9 -0	+0 -9	+0 -0	+0.72 -0.00	+0.00 -0.71	+0.00 -0.01
230 - 240	1068 $\pm$ 41 $^{+0}_{-10}$	75 $\pm$ 25 $^{+11}_{-0}$	9 $\pm$ 6 $^{+5}_{-2}$	92.7 $\pm$ 2.3 $^{+0.0}_{-0.8}$	6.5 $\pm$ 2.2 $^{+1.0}_{-0.0}$	0.8 $\pm$ 0.6 $^{+0.5}_{-0.2}$
LP2	+0 -4	+0 -0	+4 -0	+0.00 -0.32	+0.00 -0.01	+0.33 -0.00
LP5	+0 -6	+8 -0	+0 -2	+0.00 -0.54	+0.68 -0.00	+0.00 -0.14
250 - 260	740 $\pm$ 33 $^{+2}_{-20}$	53 $\pm$ 18 $^{+24}_{-1}$	6 $\pm$ 4 $^{+0}_{-5}$	92.6 $\pm$ 2.5 $^{+0.3}_{-2.4}$	6.7 $\pm$ 2.4 $^{+3.0}_{-0.1}$	0.7 $\pm$ 0.6 $^{+0.0}_{-0.7}$
LP2	+0 -14	+17 -0	+0 -4	+0.00 -1.70	+2.16 -0.00	+0.00 -0.46
LP5	+2 -0	+0 -1	+0 -1	+0.19 -0.00	+0.00 -0.08	+0.00 -0.11
260 - 270	624 $\pm$ 32 $^{+1}_{-19}$	75 $\pm$ 18 $^{+18}_{-1}$	1 $\pm$ 0 $^{+0}_{-0}$	89.2 $\pm$ 2.8 $^{+0.2}_{-2.6}$	10.7 $\pm$ 2.8 $^{+2.6}_{-0.2}$	0.1 $\pm$ 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -14	+13 -0	+0 -0	+0.00 -1.84	+1.85 -0.00	+0.00 -0.01
LP5	+1 -0	+0 -1	+0 -0	+0.16 -0.00	+0.00 -0.14	+0.00 -0.01
270 - 280	562 $\pm$ 30 $^{+1}_{-1}$	70 $\pm$ 18 $^{+2}_{-1}$	3 $\pm$ 4 $^{+2}_{-1}$	88.6 $\pm$ 3.2 $^{+0.0}_{-0.2}$	11.0 $\pm$ 3.1 $^{+0.2}_{-0.2}$	0.4 $\pm$ 0.7 $^{+0.4}_{-0.2}$
LP2	+1 -0	+1 -0	+0 -1	+0.00 -0.06	+0.17 -0.00	+0.00 -0.11
LP5	+0 -1	+0 -1	+2 -0	+0.00 -0.14	+0.00 -0.11	+0.26 -0.00
280 - 290	489 $\pm$ 25 $^{+2}_{-2}$	45 $\pm$ 10 $^{+6}_{-0}$	2 $\pm$ 1 $^{+0}_{-1}$	91.2 $\pm$ 2.1 $^{+0.0}_{-1.1}$	8.3 $\pm$ 2.1 $^{+1.1}_{-0.0}$	0.5 $\pm$ 0.2 $^{+0.0}_{-0.1}$
LP2	+0 -1	+4 -0	+0 -0	+0.00 -0.78	+0.76 -0.00	+0.01 -0.00
LP5	+1 -0	+1 -0	+0 -0	+0.00 -0.11	+0.20 -0.00	+0.00 -0.08
290 - 300	433 $\pm$ 26 $^{+7}_{-0}$	35 $\pm$ 15 $^{+2}_{-8}$	2 $\pm$ 4 $^{+4}_{-1}$	92.1 $\pm$ 3.5 $^{+0.9}_{-0.2}$	7.5 $\pm$ 3.4 $^{+0.3}_{-1.7}$	0.5 $\pm$ 0.8 $^{+0.8}_{-0.1}$
LP2	+5 -0	+0 -6	+3 -0	+0.65 -0.00	+0.00 -1.22	+0.56 -0.00
LP5	+0 -0	+1 -0	+0 -0	+0.00 -0.14	+0.24 -0.00	+0.00 -0.10
300 - 13000	3481 $\pm$ 74 $^{+12}_{-34}$	465 $\pm$ 39 $^{+33}_{-11}$	5 $\pm$ 1 $^{+2}_{-1}$	88.1 $\pm$ 1.1 $^{+0.3}_{-0.9}$	11.8 $\pm$ 1.1 $^{+0.8}_{-0.3}$	0.1 $\pm$ 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -24	+23 -0	+1 -0	+0.00 -0.61	+0.59 -0.00	+0.03 -0.00
LP5	+9 -0	+0 -8	+0 -1	+0.21 -0.00	+0.00 -0.19	+0.00 -0.01

Table B.34: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma}$. (Continued on next page.)

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma}$ [GeV]						
0 - 10	$6135 \pm 120^{+52}_{-108}$	$1063 \pm 99^{+94}_{-58}$	$160 \pm 31^{+16}_{-0}$	$83.4 \pm 1.4^{+0.7}_{-1.5}$	$14.4 \pm 1.4^{+1.3}_{-0.8}$	$2.2 \pm 0.5^{+0.2}_{-0.0}$
LP2	+0 -76	+66 -0	+11 -0	+0.00 -1.04	+0.90 -0.00	+0.15 -0.00
LP5	+37 -0	+0 -41	+5 -0	+0.49 -0.00	+0.00 -0.56	+0.07 -0.00
10 - 20	$14080 \pm 193^{+127}_{-107}$	$2933 \pm 168^{+9}_{-92}$	$465 \pm 54^{+103}_{-34}$	$80.6 \pm 1.0^{+0.7}_{-0.6}$	$16.8 \pm 1.0^{+0.0}_{-0.5}$	$2.7 \pm 0.3^{+0.6}_{-0.2}$
LP2	+0 -76	+7 -0	+73 -0	+0.00 -0.45	+0.03 -0.00	+0.42 -0.00
LP5	+90 -0	+0 -65	+0 -24	+0.51 -0.00	+0.00 -0.37	+0.00 -0.14
20 - 30	$19153 \pm 219^{+194}_{-335}$	$3859 \pm 183^{+206}_{-199}$	$438 \pm 54^{+76}_{-0}$	$81.7 \pm 0.8^{+0.8}_{-1.4}$	$16.5 \pm 0.8^{+1.1}_{-0.8}$	$1.9 \pm 0.2^{+0.3}_{-0.0}$
LP2	+0 -237	+188 -0	+53 -0	+0.00 -1.02	+0.80 -0.00	+0.23 -0.00
LP5	+137 -0	+0 -141	+5 -0	+0.58 -0.00	+0.00 -0.60	+0.02 -0.00
30 - 40	$22005 \pm 227^{+86}_{-517}$	$3654 \pm 184^{+432}_{-54}$	$423 \pm 54^{+88}_{-28}$	$84.4 \pm 0.8^{+0.3}_{-2.0}$	$14.0 \pm 0.7^{+1.7}_{-0.2}$	$1.6 \pm 0.2^{+0.3}_{-0.1}$
LP2	+0 -366	+305 -0	+62 -0	+0.00 -1.41	+1.17 -0.00	+0.24 -0.00
LP5	+61 -0	+0 -38	+0 -19	+0.22 -0.00	+0.00 -0.15	+0.00 -0.07
40 - 50	$22782 \pm 226^{+112}_{-448}$	$3436 \pm 179^{+382}_{-90}$	$381 \pm 51^{+70}_{-22}$	$85.6 \pm 0.7^{+0.4}_{-1.7}$	$12.9 \pm 0.7^{+1.4}_{-0.3}$	$1.4 \pm 0.2^{+0.3}_{-0.1}$
LP2	+0 -316	+270 -0	+50 -0	+0.00 -1.20	+1.01 -0.00	+0.19 -0.00
LP5	+79 -0	+0 -64	+0 -16	+0.30 -0.00	+0.00 -0.24	+0.00 -0.06
50 - 60	$21710 \pm 220^{+101}_{-336}$	$3488 \pm 168^{+224}_{-91}$	$218 \pm 42^{+107}_{-10}$	$85.4 \pm 0.7^{+0.4}_{-1.3}$	$13.7 \pm 0.7^{+0.9}_{-0.4}$	$0.9 \pm 0.2^{+0.4}_{-0.0}$
LP2	+0 -238	+158 -0	+76 -0	+0.00 -0.92	+0.63 -0.00	+0.30 -0.00
LP5	+72 -0	+0 -64	+0 -7	+0.28 -0.00	+0.00 -0.25	+0.00 -0.03
60 - 70	$20412 \pm 212^{+64}_{-317}$	$3033 \pm 162^{+227}_{-35}$	$224 \pm 42^{+93}_{-26}$	$86.2 \pm 0.7^{+0.3}_{-1.3}$	$12.8 \pm 0.7^{+1.0}_{-0.2}$	$0.9 \pm 0.2^{+0.4}_{-0.1}$
LP2	+0 -224	+160 -0	+66 -0	+0.00 -0.95	+0.68 -0.00	+0.28 -0.00
LP5	+45 -0	+0 -25	+0 -19	+0.19 -0.00	+0.00 -0.11	+0.00 -0.08
70 - 80	$18257 \pm 195^{+60}_{-353}$	$2661 \pm 142^{+305}_{-53}$	$156 \pm 34^{+46}_{-5}$	$86.6 \pm 0.7^{+0.3}_{-1.7}$	$12.6 \pm 0.7^{+1.4}_{-0.3}$	$0.7 \pm 0.2^{+0.2}_{-0.0}$
LP2	+0 -250	+216 -0	+33 -0	+0.00 -1.18	+1.02 -0.00	+0.15 -0.00
LP5	+42 -0	+0 -37	+0 -3	+0.19 -0.00	+0.00 -0.18	+0.00 -0.02
80 - 90	$15647 \pm 181^{+47}_{-281}$	$2011 \pm 135^{+249}_{-10}$	$196 \pm 36^{+44}_{-37}$	$87.6 \pm 0.8^{+0.3}_{-1.6}$	$11.3 \pm 0.8^{+1.4}_{-0.1}$	$1.1 \pm 0.2^{+0.2}_{-0.2}$
LP2	+0 -198	+176 -0	+31 -0	+0.00 -1.15	+0.98 -0.00	+0.17 -0.00
LP5	+33 -0	+0 -7	+0 -26	+0.18 -0.00	+0.00 -0.04	+0.00 -0.15
90 - 100	$13043 \pm 158^{+36}_{-225}$	$1614 \pm 108^{+185}_{-38}$	$81 \pm 24^{+40}_{-0}$	$88.5 \pm 0.8^{+0.2}_{-1.5}$	$11.0 \pm 0.8^{+1.3}_{-0.3}$	$0.6 \pm 0.2^{+0.3}_{-0.0}$
LP2	+0 -159	+131 -0	+29 -0	+0.00 -1.08	+0.89 -0.00	+0.19 -0.00
LP5	+25 -0	+0 -27	+1 -0	+0.17 -0.00	+0.00 -0.18	+0.01 -0.00
100 - 110	$10647 \pm 143^{+30}_{-207}$	$1317 \pm 98^{+180}_{-23}$	$75 \pm 22^{+20}_{-8}$	$88.4 \pm 0.9^{+0.3}_{-1.7}$	$10.9 \pm 0.9^{+1.5}_{-0.2}$	$0.6 \pm 0.2^{+0.2}_{-0.1}$
LP2	+0 -146	+128 -0	+14 -0	+0.00 -1.18	+1.07 -0.00	+0.12 -0.00
LP5	+21 -0	+0 -16	+0 -5	+0.18 -0.00	+0.00 -0.14	+0.00 -0.05
110 - 120	$8884 \pm 122^{+56}_{-146}$	$891 \pm 70^{+129}_{-52}$	$37 \pm 5^{+13}_{-4}$	$90.5 \pm 0.8^{+0.6}_{-1.5}$	$9.1 \pm 0.8^{+1.3}_{-0.5}$	$0.4 \pm 0.1^{+0.1}_{-0.0}$
LP2	+0 -103	+91 -0	+9 -0	+0.00 -1.03	+0.93 -0.00	+0.09 -0.00
LP5	+40 -0	+0 -37	+0 -3	+0.40 -0.00	+0.00 -0.37	+0.00 -0.03
120 - 130	$7150 \pm 111^{+17}_{-103}$	$697 \pm 68^{+110}_{-13}$	$33 \pm 14^{+0}_{-13}$	$90.7 \pm 0.9^{+0.2}_{-1.2}$	$8.8 \pm 0.9^{+1.4}_{-0.2}$	$0.4 \pm 0.2^{+0.0}_{-0.2}$
LP2	+0 -73	+78 -0	+0 -9	+0.00 -0.88	+0.99 -0.00	+0.00 -0.11
LP5	+12 -0	+0 -9	+0 -4	+0.16 -0.00	+0.00 -0.11	+0.00 -0.05
130 - 140	$5900 \pm 99^{+34}_{-80}$	$593 \pm 56^{+78}_{-31}$	$15 \pm 3^{+3}_{-0}$	$90.7 \pm 0.9^{+0.5}_{-1.2}$	$9.1 \pm 0.9^{+1.2}_{-0.5}$	$0.2 \pm 0.0^{+0.0}_{-0.0}$
LP2	+0 -57	+55 -0	+2 -0	+0.00 -0.88	+0.85 -0.00	+0.03 -0.00
LP5	+24 -0	+0 -22	+1 -0	+0.33 -0.00	+0.00 -0.34	+0.01 -0.00

Table B.35: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma}$ continued.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma}$ [GeV]						
140 - 150	4775 $\pm$ 89 $^{+4}_{-11}$	457 $\pm$ 53 $^{+0}_{-2}$	16 $\pm$ 10 $^{+17}_{-2}$	91.0 $\pm$ 1.1 $^{+0.0}_{-0.3}$	8.7 $\pm$ 1.1 $^{+0.0}_{-0.1}$	0.3 $\pm$ 0.2 $^{+0.3}_{-0.0}$
LP2	+0 -7	+0 -2	+12 -0	+0.00 -0.20	+0.00 -0.04	+0.23 -0.00
LP5	+2 -0	+0 -0	+0 -1	+0.04 -0.00	+0.00 -0.01	+0.00 -0.03
150 - 160	4032 $\pm$ 79 $^{+6}_{-39}$	336 $\pm$ 42 $^{+39}_{-6}$	8 $\pm$ 2 $^{+1}_{-1}$	92.1 $\pm$ 1.0 $^{+0.2}_{-0.9}$	7.7 $\pm$ 1.0 $^{+0.9}_{-0.1}$	0.2 $\pm$ 0.1 $^{+0.0}_{-0.0}$
LP2	+0 -28	+27 -0	+1 -0	+0.00 -0.64	+0.62 -0.00	+0.02 -0.00
LP5	+4 -0	+0 -4	+0 -1	+0.11 -0.00	+0.00 -0.09	+0.00 -0.01
160 - 170	3150 $\pm$ 72 $^{+18}_{-47}$	299 $\pm$ 41 $^{+43}_{-20}$	7 $\pm$ 7 $^{+3}_{-4}$	91.1 $\pm$ 1.3 $^{+0.5}_{-1.1}$	8.7 $\pm$ 1.3 $^{+1.3}_{-0.6}$	0.2 $\pm$ 0.2 $^{+0.1}_{-0.1}$
LP2	+0 -33	+30 -0	+0 -3	+0.00 -0.81	+0.89 -0.00	+0.00 -0.08
LP5	+13 -0	+0 -14	+2 -0	+0.35 -0.00	+0.00 -0.41	+0.06 -0.00
170 - 180	2607 $\pm$ 64 $^{+2}_{-44}$	223 $\pm$ 36 $^{+38}_{-3}$	12 $\pm$ 7 $^{+6}_{-0}$	91.7 $\pm$ 1.4 $^{+0.1}_{-0.1}$	7.8 $\pm$ 1.3 $^{+1.3}_{-0.1}$	0.4 $\pm$ 0.3 $^{+0.2}_{-0.0}$
LP2	+0 -31	+27 -0	+4 -0	+0.00 -1.09	+0.94 -0.00	+0.15 -0.00
LP5	+1 -0	+0 -2	+1 -0	+0.04 -0.00	+0.00 -0.07	+0.03 -0.00
180 - 190	2186 $\pm$ 58 $^{+3}_{-68}$	162 $\pm$ 32 $^{+63}_{-0}$	9 $\pm$ 6 $^{+1}_{-2}$	92.7 $\pm$ 1.5 $^{+0.1}_{-2.7}$	6.9 $\pm$ 1.4 $^{+2.7}_{-0.0}$	0.4 $\pm$ 0.3 $^{+0.0}_{-0.1}$
LP2	+0 -48	+45 -0	+1 -0	+0.00 -1.94	+1.91 -0.00	+0.03 -0.00
LP5	+2 -0	+0 -0	+0 -2	+0.07 -0.00	+0.00 -0.00	+0.00 -0.07
190 - 200	1927 $\pm$ 53 $^{+5}_{-31}$	117 $\pm$ 26 $^{+33}_{-9}$	7 $\pm$ 5 $^{+2}_{-0}$	94.0 $\pm$ 1.4 $^{+0.3}_{-1.6}$	5.7 $\pm$ 1.3 $^{+1.6}_{-0.4}$	0.4 $\pm$ 0.3 $^{+0.1}_{-0.0}$
LP2	+0 -22	+23 -0	+0 -0	+0.00 -1.14	+1.14 -0.00	+0.01 -0.00
LP5	+4 -0	+0 -6	+2 -0	+0.23 -0.00	+0.00 -0.30	+0.07 -0.00
210 - 220	1357 $\pm$ 45 $^{+4}_{-55}$	100 $\pm$ 22 $^{+51}_{-5}$	3 $\pm$ 1 $^{+0}_{-0}$	93.0 $\pm$ 1.6 $^{+0.4}_{-3.5}$	6.8 $\pm$ 1.6 $^{+3.5}_{-0.4}$	0.2 $\pm$ 0.1 $^{+0.0}_{-0.0}$
LP2	+0 -39	+36 -0	+0 -0	+0.00 -2.51	+2.51 -0.00	+0.00 -0.00
LP5	+3 -0	+0 -4	+0 -0	+0.25 -0.00	+0.00 -0.25	+0.00 -0.00
220 - 230	1086 $\pm$ 40 $^{+9}_{-14}$	86 $\pm$ 21 $^{+7}_{-6}$	2 $\pm$ 3 $^{+4}_{-1}$	92.5 $\pm$ 1.9 $^{+0.6}_{-0.9}$	7.3 $\pm$ 1.9 $^{+0.6}_{-0.6}$	0.2 $\pm$ 0.3 $^{+0.3}_{-0.1}$
LP2	+0 -10	+5 -0	+3 -0	+0.00 -0.66	+0.43 -0.00	+0.22 -0.00
LP5	+6 -0	+0 -5	+0 -1	+0.44 -0.00	+0.00 -0.40	+0.00 -0.05
230 - 240	951 $\pm$ 38 $^{+1}_{-16}$	94 $\pm$ 18 $^{+16}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	91.0 $\pm$ 1.9 $^{+0.0}_{-1.6}$	9.0 $\pm$ 1.9 $^{+1.6}_{-0.0}$	0.0 $\pm$ 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -11	+12 -0	+0 -0	+0.00 -1.10	+1.10 -0.00	+0.00 -0.00
LP5	+1 -0	+0 -0	+0 -0	+0.01 -0.00	+0.00 -0.01	+0.00 -0.00
250 - 260	716 $\pm$ 30 $^{+0}_{-10}$	33 $\pm$ 12 $^{+7}_{-0}$	1 $\pm$ 1 $^{+1}_{-0}$	95.4 $\pm$ 1.7 $^{+0.0}_{-1.1}$	4.4 $\pm$ 1.7 $^{+0.9}_{-0.0}$	0.1 $\pm$ 0.1 $^{+0.2}_{-0.0}$
LP2	+0 -7	+5 -0	+1 -0	+0.00 -0.77	+0.64 -0.00	+0.13 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.01 -0.00	+0.01 -0.00	+0.00 -0.02
260 - 270	591 $\pm$ 27 $^{+7}_{-0}$	38 $\pm$ 11 $^{+0}_{-6}$	0 $\pm$ 1 $^{+1}_{-0}$	94.0 $\pm$ 1.8 $^{+0.9}_{-0.0}$	6.0 $\pm$ 1.8 $^{+0.0}_{-1.0}$	0.1 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+5 -0	+0 -4	+0 -0	+0.62 -0.00	+0.00 -0.69	+0.07 -0.00
LP5	+3 -0	+0 -2	+0 -0	+0.32 -0.00	+0.00 -0.34	+0.02 -0.00
270 - 280	480 $\pm$ 26 $^{+0}_{-25}$	49 $\pm$ 12 $^{+22}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	90.6 $\pm$ 2.6 $^{+0.0}_{-4.3}$	9.3 $\pm$ 2.6 $^{+4.2}_{-0.0}$	0.1 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -18	+16 -0	+0 -0	+0.00 -3.06	+3.00 -0.00	+0.06 -0.00
LP5	+0 -1	+2 -0	+0 -0	+0.00 -0.27	+0.29 -0.00	+0.00 -0.01
280 - 290	451 $\pm$ 25 $^{+0}_{-10}$	33 $\pm$ 11 $^{+10}_{-1}$	2 $\pm$ 2 $^{+0}_{-1}$	92.9 $\pm$ 2.5 $^{+0.0}_{-1.8}$	6.8 $\pm$ 2.4 $^{+2.1}_{-0.1}$	0.3 $\pm$ 0.3 $^{+0.1}_{-0.3}$
LP2	+0 -7	+7 -0	+0 -1	+0.00 -1.26	+1.46 -0.00	+0.00 -0.20
LP5	+0 -0	+0 -0	+0 -0	+0.03 -0.00	+0.00 -0.08	+0.05 -0.00
290 - 300	374 $\pm$ 22 $^{+3}_{-4}$	31 $\pm$ 9 $^{+4}_{-4}$	0 $\pm$ 0 $^{+1}_{-0}$	92.3 $\pm$ 2.5 $^{+0.9}_{-1.1}$	7.7 $\pm$ 2.5 $^{+0.9}_{-0.9}$	0.1 $\pm$ 0.0 $^{+0.1}_{-0.0}$
LP2	+0 -3	+3 -0	+0 -0	+0.00 -0.76	+0.67 -0.00	+0.09 -0.00
LP5	+2 -0	+0 -3	+0 -0	+0.63 -0.00	+0.00 -0.62	+0.00 -0.01
300 - 13000	2830 $\pm$ 63 $^{+0}_{-42}$	293 $\pm$ 26 $^{+33}_{-0}$	2 $\pm$ 3 $^{+2}_{-1}$	90.6 $\pm$ 1.0 $^{+0.0}_{-1.2}$	9.4 $\pm$ 1.0 $^{+1.1}_{-0.0}$	0.1 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -29	+23 -0	+2 -0	+0.00 -0.81	+0.76 -0.00	+0.05 -0.00
LP5	+0 -2	+2 -0	+0 -1	+0.00 -0.05	+0.07 -0.00	+0.00 -0.02

Table B.36: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma,jj}$. (Continued on next page.)

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma\gamma,jj}$ [GeV]						
0 - 10	20513 $\pm$ 198 $^{+103}_{-322}$	2243 $\pm$ 140 $^{+297}_{-92}$	248 $\pm$ 37 $^{+28}_{-9}$	89.2 $\pm$ 0.7 $^{+0.4}_{-1.4}$	9.7 $\pm$ 0.6 $^{+1.3}_{-0.4}$	1.1 $\pm$ 0.2 $^{+0.1}_{-0.0}$
LP2	+0 -228	+210 -0	+20 -0	+0.00 -1.00	+0.91 -0.00	+0.09 -0.00
LP5	+73 -0	+0 -65	+0 -6	+0.31 -0.00	+0.00 -0.28	+0.00 -0.03
10 - 20	42286 $\pm$ 295 $^{+195}_{-590}$	5752 $\pm$ 216 $^{+473}_{-169}$	456 $\pm$ 55 $^{+149}_{-18}$	87.2 $\pm$ 0.5 $^{+0.4}_{-1.3}$	11.9 $\pm$ 0.5 $^{+1.0}_{-0.4}$	0.9 $\pm$ 0.1 $^{+0.3}_{-0.0}$
LP2	+0 -417	+335 -0	+105 -0	+0.00 -0.90	+0.68 -0.00	+0.22 -0.00
LP5	+138 -0	+0 -120	+0 -13	+0.27 -0.00	+0.00 -0.25	+0.00 -0.03
20 - 30	41810 $\pm$ 300 $^{+114}_{-683}$	6464 $\pm$ 226 $^{+550}_{-79}$	540 $\pm$ 59 $^{+149}_{-33}$	85.7 $\pm$ 0.5 $^{+0.2}_{-1.4}$	13.2 $\pm$ 0.5 $^{+1.1}_{-0.2}$	1.1 $\pm$ 0.1 $^{+0.3}_{-0.1}$
LP2	+0 -483	+393 -0	+105 -0	+0.00 -1.02	+0.80 -0.00	+0.22 -0.00
LP5	+80 -0	+0 -56	+0 -23	+0.16 -0.00	+0.00 -0.12	+0.00 -0.05
30 - 40	34857 $\pm$ 273 $^{+60}_{-547}$	5362 $\pm$ 205 $^{+435}_{-36}$	446 $\pm$ 54 $^{+126}_{-23}$	85.7 $\pm$ 0.5 $^{+0.1}_{-1.4}$	13.2 $\pm$ 0.5 $^{+1.1}_{-0.1}$	1.1 $\pm$ 0.1 $^{+0.3}_{-0.1}$
LP2	+0 -387	+308 -0	+89 -0	+0.00 -0.97	+0.75 -0.00	+0.22 -0.00
LP5	+43 -0	+0 -25	+0 -16	+0.10 -0.00	+0.00 -0.06	+0.00 -0.04
40 - 50	26021 $\pm$ 238 $^{+206}_{-275}$	4108 $\pm$ 182 $^{+197}_{-182}$	378 $\pm$ 49 $^{+104}_{-13}$	85.3 $\pm$ 0.6 $^{+0.6}_{-1.0}$	13.5 $\pm$ 0.6 $^{+0.6}_{-0.6}$	1.2 $\pm$ 0.2 $^{+0.3}_{-0.0}$
LP2	+0 -194	+140 -0	+73 -0	+0.00 -0.69	+0.45 -0.00	+0.24 -0.00
LP5	+145 -0	+0 -129	+0 -9	+0.46 -0.00	+0.00 -0.42	+0.00 -0.03
50 - 60	18451 $\pm$ 196 $^{+129}_{-318}$	3129 $\pm$ 134 $^{+265}_{-115}$	199 $\pm$ 11 $^{+59}_{-17}$	84.7 $\pm$ 0.7 $^{+0.6}_{-1.5}$	14.4 $\pm$ 0.7 $^{+1.2}_{-0.5}$	0.9 $\pm$ 0.1 $^{+0.3}_{-0.1}$
LP2	+0 -225	+187 -0	+42 -0	+0.00 -1.05	+0.86 -0.00	+0.19 -0.00
LP5	+92 -0	+0 -81	+0 -12	+0.43 -0.00	+0.00 -0.37	+0.00 -0.06
60 - 70	12878 $\pm$ 169 $^{+75}_{-236}$	2212 $\pm$ 130 $^{+212}_{-71}$	153 $\pm$ 34 $^{+21}_{-7}$	84.5 $\pm$ 0.9 $^{+0.5}_{-1.5}$	14.5 $\pm$ 0.9 $^{+1.4}_{-0.5}$	1.0 $\pm$ 0.2 $^{+0.1}_{-0.0}$
LP2	+0 -167	+150 -0	+15 -0	+0.00 -1.08	+0.99 -0.00	+0.10 -0.00
LP5	+53 -0	+0 -50	+0 -5	+0.36 -0.00	+0.00 -0.33	+0.00 -0.03
70 - 80	9339 $\pm$ 141 $^{+51}_{-90}$	1417 $\pm$ 105 $^{+40}_{-45}$	118 $\pm$ 28 $^{+57}_{-8}$	85.9 $\pm$ 1.0 $^{+0.5}_{-0.9}$	13.0 $\pm$ 1.0 $^{+0.4}_{-0.4}$	1.1 $\pm$ 0.3 $^{+0.5}_{-0.1}$
LP2	+0 -64	+28 -0	+40 -0	+0.00 -0.63	+0.26 -0.00	+0.37 -0.00
LP5	+36 -0	+0 -32	+0 -6	+0.34 -0.00	+0.00 -0.29	+0.00 -0.05
80 - 90	6555 $\pm$ 119 $^{+33}_{-125}$	1060 $\pm$ 90 $^{+122}_{-17}$	80 $\pm$ 24 $^{+10}_{-17}$	85.2 $\pm$ 1.3 $^{+0.4}_{-1.7}$	13.8 $\pm$ 1.2 $^{+1.6}_{-0.2}$	1.0 $\pm$ 0.3 $^{+0.1}_{-0.2}$
LP2	+0 -89	+86 -0	+7 -0	+0.00 -1.20	+1.11 -0.00	+0.09 -0.00
LP5	+23 -0	+0 -12	+0 -12	+0.30 -0.00	+0.00 -0.15	+0.00 -0.15
90 - 100	4715 $\pm$ 98 $^{+25}_{-52}$	764 $\pm$ 66 $^{+41}_{-24}$	47 $\pm$ 5 $^{+14}_{-2}$	85.3 $\pm$ 1.3 $^{+0.5}_{-1.0}$	13.8 $\pm$ 1.3 $^{+0.7}_{-0.4}$	0.9 $\pm$ 0.1 $^{+0.3}_{-0.0}$
LP2	+0 -37	+29 -0	+10 -0	+0.00 -0.70	+0.52 -0.00	+0.18 -0.00
LP5	+18 -0	+0 -17	+0 -1	+0.33 -0.00	+0.00 -0.30	+0.00 -0.02
100 - 110	3576 $\pm$ 83 $^{+16}_{-62}$	497 $\pm$ 54 $^{+61}_{-10}$	32 $\pm$ 4 $^{+8}_{-6}$	87.1 $\pm$ 1.4 $^{+0.4}_{-1.6}$	12.1 $\pm$ 1.4 $^{+1.5}_{-0.2}$	0.8 $\pm$ 0.1 $^{+0.2}_{-0.1}$
LP2	+0 -44	+43 -0	+6 -0	+0.00 -1.16	+1.03 -0.00	+0.13 -0.00
LP5	+11 -0	+0 -7	+0 -4	+0.27 -0.00	+0.00 -0.17	+0.00 -0.10
110 - 120	2718 $\pm$ 72 $^{+8}_{-24}$	381 $\pm$ 47 $^{+25}_{-10}$	14 $\pm$ 3 $^{+1}_{-1}$	87.3 $\pm$ 1.6 $^{+0.3}_{-0.9}$	12.2 $\pm$ 1.6 $^{+0.8}_{-0.3}$	0.4 $\pm$ 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -17	+17 -0	+2 -0	+0.00 -0.63	+0.55 -0.00	+0.08 -0.00
LP5	+6 -0	+0 -7	+0 -0	+0.24 -0.00	+0.00 -0.23	+0.00 -0.01

Table B.37: Yield and purity outputs from the 2x2D Sideband Method for $p_T^{\gamma\gamma,jj}$ continued.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
$p_T^{\gamma,jj}$ [GeV]						
120 - 130	2121 ± 64 $^{+17}_{-50}$	277 ± 41 $^{+47}_{-18}$	11 ± 3 $^{+5}_{-0}$	88.0 ± 1.8 $^{+0.7}_{-2.1}$	11.5 ± 1.8 $^{+1.9}_{-0.7}$	0.5 ± 0.1 $^{+0.2}_{-0.0}$
LP2	+0 -35	+33 -0	+4 -0	+0.00 -1.51	+1.36 -0.00	+0.16 -0.00
LP5	+12 -0	+0 -13	+1 -0	+0.50 -0.00	+0.00 -0.52	+0.02 -0.00
130 - 140	1705 ± 56 $^{+9}_{-23}$	193 ± 35 $^{+23}_{-0}$	10 ± 2 $^{+4}_{-0}$	89.3 ± 1.9 $^{+0.0}_{-1.4}$	10.1 ± 1.9 $^{+1.2}_{-0.0}$	0.5 ± 0.1 $^{+0.2}_{-0.0}$
LP2	+0 -16	+16 -0	+3 -0	+0.00 -0.99	+0.84 -0.00	+0.15 -0.00
LP5	+0 -1	+0 -0	+0 -0	+0.00 -0.02	+0.02 -0.00	+0.00 -0.00
140 - 150	1248 ± 49 $^{+0}_{-22}$	165 ± 32 $^{+17}_{-0}$	10 ± 2 $^{+4}_{-1}$	87.7 ± 2.4 $^{+0.0}_{-1.5}$	11.6 ± 2.4 $^{+1.2}_{-0.0}$	0.7 ± 0.2 $^{+0.3}_{-0.1}$
LP2	+0 -15	+12 -0	+3 -0	+0.00 -1.05	+0.84 -0.00	+0.20 -0.00
LP5	+0 -2	+1 -0	+0 -1	+0.00 -0.06	+0.10 -0.00	+0.00 -0.05
150 - 160	1091 ± 37 $^{+7}_{-12}$	73 ± 15 $^{+5}_{-5}$	6 ± 6 $^{+9}_{-1}$	93.2 ± 1.5 $^{+0.5}_{-1.2}$	6.3 ± 1.4 $^{+0.4}_{-0.4}$	0.5 ± 0.5 $^{+0.8}_{-0.1}$
LP2	+0 -9	+3 -0	+6 -0	+0.00 -0.83	+0.28 -0.00	+0.55 -0.00
LP5	+5 -0	+0 -4	+0 -1	+0.38 -0.00	+0.00 -0.31	+0.00 -0.07
160 - 170	839 ± 35 $^{+0}_{-12}$	74 ± 16 $^{+13}_{-0}$	5 ± 2 $^{+2}_{-0}$	91.4 ± 1.9 $^{+0.0}_{-1.6}$	8.0 ± 1.9 $^{+1.4}_{-0.0}$	0.5 ± 0.2 $^{+0.2}_{-0.0}$
LP2	+0 -8	+9 -0	+1 -0	+0.00 -1.07	+0.93 -0.00	+0.14 -0.00
LP5	+0 -4	+4 -0	+0 -0	+0.00 -0.47	+0.47 -0.00	+0.00 -0.00
170 - 180	656 ± 34 $^{+1}_{-6}$	59 ± 23 $^{+1}_{-0}$	3 ± 5 $^{+4}_{-0}$	91.4 ± 3.4 $^{+0.1}_{-0.8}$	8.3 ± 3.3 $^{+0.2}_{-0.1}$	0.4 ± 0.8 $^{+0.6}_{-0.0}$
LP2	+0 -4	+1 -0	+3 -0	+0.00 -0.54	+0.12 -0.00	+0.42 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.05 -0.00	+0.00 -0.04	+0.00 -0.01
180 - 190	489 ± 31 $^{+3}_{-4}$	80 ± 21 $^{+3}_{-3}$	1 ± 0 $^{+2}_{-0}$	85.9 ± 3.9 $^{+0.5}_{-0.8}$	14.0 ± 3.9 $^{+0.5}_{-0.5}$	0.1 ± 0.1 $^{+0.4}_{-0.0}$
LP2	+0 -2	+2 -0	+1 -0	+0.00 -0.60	+0.34 -0.00	+0.26 -0.00
LP5	+2 -0	+0 -2	+0 -0	+0.37 -0.00	+0.00 -0.37	+0.00 -0.00
190 - 200	439 ± 26 $^{+8}_{-0}$	25 ± 13 $^{+0}_{-7}$	10 ± 5 $^{+1}_{-0}$	92.6 ± 3.2 $^{+1.3}_{-0.0}$	5.3 ± 3.0 $^{+0.0}_{-1.5}$	2.0 ± 1.2 $^{+0.2}_{-0.0}$
LP2	+5 -0	+0 -5	+1 -0	+0.94 -0.00	+0.00 -1.05	+0.11 -0.00
LP5	+2 -0	+0 -1	+0 -0	+0.24 -0.00	+0.00 -0.21	+0.00 -0.03
210 - 220	296 ± 19 $^{+3}_{-0}$	21 ± 6 $^{+0}_{-3}$	1 ± 1 $^{+3}_{-0}$	93.0 ± 2.3 $^{+0.7}_{-0.6}$	6.8 ± 2.3 $^{+0.0}_{-0.9}$	0.3 ± 0.3 $^{+0.8}_{-0.0}$
LP2	+0 -0	+0 -0	+2 -0	+0.00 -0.40	+0.00 -0.15	+0.55 -0.00
LP5	+2 -0	+0 -2	+1 -0	+0.47 -0.00	+0.00 -0.63	+0.17 -0.00
220 - 230	190 ± 20 $^{+0}_{-5}$	31 ± 14 $^{+5}_{-4}$	1 ± 2 $^{+6}_{-1}$	85.6 ± 6.9 $^{+0.0}_{-2.0}$	13.9 ± 6.8 $^{+2.1}_{-1.6}$	0.5 ± 0.9 $^{+2.5}_{-0.3}$
LP2	+0 -2	+0 -3	+4 -0	+0.00 -0.68	+0.00 -1.12	+1.80 -0.00
LP5	+0 -3	+3 -0	+0 -0	+0.00 -1.30	+1.49 -0.00	+0.00 -0.19
230 - 240	231 ± 15 $^{+0}_{-1}$	9 ± 1 $^{+0}_{-0}$	1 ± 1 $^{+0}_{-0}$	95.8 ± 0.8 $^{+0.0}_{-0.3}$	3.8 ± 0.6 $^{+0.2}_{-0.0}$	0.3 ± 0.3 $^{+0.2}_{-0.2}$
LP2	+0 -0	+0 -0	+0 -0	+0.00 -0.24	+0.09 -0.00	+0.14 -0.00
LP5	+0 -1	+0 -0	+0 -0	+0.01 -0.00	+0.12 -0.00	+0.00 -0.13
250 - 260	156 ± 13 $^{+3}_{-0}$	8 ± 4 $^{+0}_{-3}$	0 ± 1 $^{+2}_{-0}$	95.1 ± 2.8 $^{+1.8}_{-0.0}$	4.6 ± 2.8 $^{+0.0}_{-2.0}$	0.3 ± 0.4 $^{+1.2}_{-0.1}$
LP2	+2 -0	+0 -2	+0 -0	+1.22 -0.00	+0.00 -1.13	+0.00 -0.09
LP5	+2 -0	+0 -2	+1 -0	+0.35 -0.00	+0.00 -1.17	+0.82 -0.00
260 - 270	110 ± 11 $^{+6}_{-2}$	5 ± 1 $^{+0}_{-0}$	0 ± 0 $^{+0}_{-0}$	95.2 ± 1.0 $^{+0.2}_{-0.1}$	4.6 ± 1.0 $^{+0.1}_{-0.3}$	0.2 ± 0.1 $^{+0.1}_{-0.0}$
LP2	+5 -0	+0 -0	+0 -0	+0.16 -0.00	+0.00 -0.22	+0.06 -0.00
LP5	+0 -1	+0 -0	+0 -0	+0.00 -0.07	+0.08 -0.00	+0.00 -0.01
270 - 280	110 ± 10 $^{+2}_{-0}$	4 ± 1 $^{+0}_{-0}$	0 ± 0 $^{+0}_{-0}$	95.8 ± 1.1 $^{+0.1}_{-0.0}$	3.8 ± 0.9 $^{+0.1}_{-0.0}$	0.4 ± 0.5 $^{+0.0}_{-0.2}$
LP2	+1 -0	+0 -0	+0 -0	+0.05 -0.00	+0.07 -0.00	+0.00 -0.11
LP5	+1 -0	+0 -0	+0 -0	+0.00 -0.01	+0.05 -0.00	+0.00 -0.04
280 - 290	90 ± 10 $^{+0}_{-0}$	6 ± 3 $^{+1}_{-0}$	0 ± 0 $^{+0}_{-0}$	94.1 ± 3.8 $^{+0.3}_{-1.4}$	5.8 ± 3.8 $^{+1.3}_{-0.3}$	0.1 ± 0.0 $^{+0.0}_{-0.0}$
LP2	+0 -0	+1 -0	+0 -0	+0.00 -0.96	+0.92 -0.00	+0.03 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.19 -0.00	+0.00 -0.19	+0.00 -0.00
290 - 300	73 ± 9 $^{+5}_{-42}$	3 ± 1 $^{+46}_{-0}$	0 ± 0 $^{+1}_{-0}$	95.2 ± 1.3 $^{+0.0}_{-58.1}$	4.5 ± 1.3 $^{+58.2}_{-0.6}$	0.4 ± 0.3 $^{+0.7}_{-0.1}$
LP2	+0 -30	+33 -0	+0 -0	+0.00 -41.08	+41.17 -0.00	+0.00 -0.08
LP5	+3 -0	+0 -0	+0 -0	+0.00 -0.06	+0.00 -0.45	+0.50 -0.00
300 - 13000	554 ± 31 $^{+3}_{-7}$	55 ± 16 $^{+11}_{-3}$	2 ± 1 $^{+1}_{-0}$	90.7 ± 2.9 $^{+0.4}_{-1.8}$	9.0 ± 2.8 $^{+1.7}_{-0.5}$	0.3 ± 0.1 $^{+0.1}_{-0.0}$
LP2	+0 -5	+8 -0	+0 -0	+0.00 -1.26	+1.21 -0.00	+0.05 -0.00
LP5	+2 -0	+0 -2	+0 -0	+0.30 -0.00	+0.00 -0.35	+0.05 -0.00

Table B.38: Yield and purity outputs from the 2x2D Sideband Method for the expanded DL1 dijet template. (Continued on next page.)

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
(Leading DL1 bin) * 5 + subleading DL1 bin						
0.5 - 1.5	8423 $\pm$ 133 $^{+18}_{-132}$	1133 $\pm$ 99 $^{+96}_{-9}$	113 $\pm$ 27 $^{+43}_{-9}$	87.1 $\pm$ 1.1 $^{+0.2}_{-1.4}$	11.7 $\pm$ 1.1 $^{+1.0}_{-0.1}$	1.2 $\pm$ 0.3 $^{+0.4}_{-0.1}$
LP2	+0 -93	+68 -0	+30 -0	+0.00 -1.01	+0.70 -0.00	+0.31 -0.00
LP5	+13 -0	+0 -7	+0 -6	+0.13 -0.00	+0.00 -0.07	+0.00 -0.07
1.5 - 2.5	3563 $\pm$ 83 $^{+25}_{-40}$	377 $\pm$ 60 $^{+19}_{-26}$	47 $\pm$ 17 $^{+24}_{-0}$	89.4 $\pm$ 1.6 $^{+0.6}_{-1.1}$	9.5 $\pm$ 1.6 $^{+0.5}_{-0.6}$	1.2 $\pm$ 0.4 $^{+0.6}_{-0.0}$
LP2	+0 -29	+13 -0	+17 -0	+0.00 -0.75	+0.33 -0.00	+0.43 -0.00
LP5	+18 -0	+0 -18	+0 -0	+0.44 -0.00	+0.00 -0.45	+0.01 -0.00
2.5 - 3.5	2322 $\pm$ 69 $^{+5}_{-17}$	291 $\pm$ 51 $^{+11}_{-3}$	22 $\pm$ 13 $^{+6}_{-5}$	88.1 $\pm$ 2.1 $^{+0.3}_{-0.7}$	11.1 $\pm$ 2.0 $^{+0.4}_{-0.1}$	0.8 $\pm$ 0.5 $^{+0.2}_{-0.2}$
LP2	+0 -12	+8 -0	+4 -0	+0.00 -0.46	+0.30 -0.00	+0.16 -0.00
LP5	+3 -0	+0 -2	+0 -3	+0.19 -0.00	+0.00 -0.06	+0.00 -0.12
3.5 - 4.5	3464 $\pm$ 86 $^{+34}_{-53}$	496 $\pm$ 65 $^{+29}_{-34}$	38 $\pm$ 17 $^{+24}_{-0}$	86.6 $\pm$ 1.8 $^{+0.8}_{-1.3}$	12.4 $\pm$ 1.7 $^{+0.7}_{-0.8}$	1.0 $\pm$ 0.5 $^{+0.6}_{-0.0}$
LP2	+0 -37	+21 -0	+17 -0	+0.00 -0.94	+0.52 -0.00	+0.43 -0.00
LP5	+24 -0	+0 -24	+0 -0	+0.59 -0.00	+0.00 -0.60	+0.01 -0.00
4.5 - 5.5	8962 $\pm$ 131 $^{+41}_{-167}$	1026 $\pm$ 92 $^{+157}_{-42}$	71 $\pm$ 23 $^{+16}_{-0}$	89.1 $\pm$ 1.0 $^{+0.4}_{-1.7}$	10.2 $\pm$ 1.0 $^{+1.6}_{-0.4}$	0.7 $\pm$ 0.2 $^{+0.2}_{-0.0}$
LP2	+0 -118	+111 -0	+11 -0	+0.00 -1.21	+1.10 -0.00	+0.11 -0.00
LP5	+29 -0	+0 -30	+0 -0	+0.29 -0.00	+0.00 -0.29	+0.00 -0.00
5.5 - 6.5	471 $\pm$ 30 $^{+0}_{-12}$	59 $\pm$ 20 $^{+10}_{-0}$	3 $\pm$ 2 $^{+4}_{-0}$	88.4 $\pm$ 3.9 $^{+0.0}_{-2.2}$	11.1 $\pm$ 3.9 $^{+1.9}_{-0.0}$	0.5 $\pm$ 0.3 $^{+0.7}_{-0.1}$
LP2	+0 -8	+4 -0	+3 -0	+0.00 -1.29	+0.82 -0.00	+0.47 -0.00
LP5	+0 -6	+6 -0	+0 -0	+0.00 -1.13	+1.18 -0.00	+0.00 -0.04
6.5 - 7.5	270 $\pm$ 17 $^{+0}_{-7}$	8 $\pm$ 5 $^{+8}_{-0}$	1 $\pm$ 1 $^{+0}_{-0}$	96.9 $\pm$ 1.8 $^{+0.0}_{-2.8}$	2.8 $\pm$ 1.8 $^{+2.7}_{-0.0}$	0.3 $\pm$ 0.2 $^{+0.0}_{-0.0}$
LP2	+0 -4	+4 -0	+0 -0	+0.00 -1.29	+1.29 -0.00	+0.00 -0.01
LP5	+0 -4	+5 -0	+0 -0	+0.00 -1.72	+1.71 -0.00	+0.02 -0.00
7.5 - 8.5	159 $\pm$ 19 $^{+5}_{-3}$	23 $\pm$ 15 $^{+1}_{-4}$	2 $\pm$ 4 $^{+3}_{-1}$	86.1 $\pm$ 8.7 $^{+2.6}_{-1.7}$	12.6 $\pm$ 8.4 $^{+0.3}_{-2.2}$	1.3 $\pm$ 2.3 $^{+1.4}_{-0.3}$
LP2	+0 -2	+0 -0	+2 -0	+0.00 -1.23	+0.24 -0.00	+0.99 -0.00
LP5	+4 -0	+0 -3	+0 -0	+1.81 -0.00	+0.00 -1.58	+0.00 -0.23
8.5 - 9.5	238 $\pm$ 22 $^{+0}_{-2}$	34 $\pm$ 14 $^{+2}_{-0}$	0 $\pm$ 1 $^{+0}_{-0}$	87.4 $\pm$ 5.6 $^{+0.0}_{-0.8}$	12.5 $\pm$ 5.6 $^{+0.8}_{-0.0}$	0.2 $\pm$ 0.2 $^{+0.1}_{-0.1}$
LP2	+0 -1	+1 -0	+0 -0	+0.00 -0.42	+0.32 -0.00	+0.10 -0.00
LP5	+0 -1	+1 -0	+0 -0	+0.00 -0.46	+0.51 -0.00	+0.00 -0.05
9.5 - 10.5	3669 $\pm$ 84 $^{+33}_{-39}$	396 $\pm$ 60 $^{+33}_{-30}$	33 $\pm$ 15 $^{+8}_{-3}$	89.5 $\pm$ 1.6 $^{+0.8}_{-1.0}$	9.7 $\pm$ 1.5 $^{+0.8}_{-0.7}$	0.8 $\pm$ 0.4 $^{+0.2}_{-0.1}$
LP2	+0 -28	+23 -0	+6 -0	+0.00 -0.70	+0.56 -0.00	+0.14 -0.00
LP5	+23 -0	+0 -21	+0 -2	+0.56 -0.00	+0.00 -0.51	+0.00 -0.05
10.5 - 11.5	243 $\pm$ 20 $^{+0}_{-3}$	16 $\pm$ 11 $^{+2}_{-0}$	0 $\pm$ 1 $^{+2}_{-0}$	93.7 $\pm$ 4.6 $^{+0.0}_{-1.3}$	6.1 $\pm$ 4.6 $^{+0.7}_{-0.0}$	0.1 $\pm$ 0.4 $^{+0.6}_{-0.0}$
LP2	+0 -2	+1 -0	+1 -0	+0.00 -0.89	+0.47 -0.00	+0.42 -0.00
LP5	+0 -1	+0 -0	+0 -0	+0.00 -0.15	+0.17 -0.00	+0.00 -0.02
11.5 - 12.5	103 $\pm$ 15 $^{+0}_{-0}$	18 $\pm$ 11 $^{+1}_{-0}$	0 $\pm$ 0 $^{+0}_{-0}$	84.9 $\pm$ 9.4 $^{+0.0}_{-0.8}$	14.9 $\pm$ 9.4 $^{+0.7}_{-0.0}$	0.2 $\pm$ 0.3 $^{+0.2}_{-0.0}$
LP2	+0 -0	+1 -0	+0 -0	+0.00 -0.53	+0.39 -0.00	+0.14 -0.00
LP5	+0 -0	+1 -0	+0 -0	+0.00 -0.38	+0.39 -0.00	+0.00 -0.01
12.5 - 13.5	85 $\pm$ 13 $^{+2}_{-2}$	11 $\pm$ 11 $^{+2}_{-3}$	2 $\pm$ 4 $^{+1}_{-0}$	86.3 $\pm$ 11.9 $^{+1.8}_{-2.3}$	11.2 $\pm$ 11.4 $^{+2.4}_{-3.3}$	2.5 $\pm$ 4.0 $^{+1.4}_{-0.1}$
LP2	+2 -0	+0 -2	+1 -0	+1.30 -0.00	+0.00 -2.31	+1.00 -0.00
LP5	+0 -2	+2 -0	+0 -0	+0.00 -1.63	+1.73 -0.00	+0.00 -0.10
13.5 - 14.5	130 $\pm$ 13 $^{+3}_{-0}$	5 $\pm$ 1 $^{+12}_{-0}$	10 $\pm$ 4 $^{+1}_{-12}$	89.7 $\pm$ 3.5 $^{+0.3}_{-0.7}$	3.3 $\pm$ 0.8 $^{+0.1}_{-0.0}$	7.0 $\pm$ 3.2 $^{+0.5}_{-8.4}$
LP2	+0 -0	+0 -0	+1 -0	+0.00 -0.46	+0.11 -0.00	+0.35 -0.00
LP5	+2 -0	+8 -0	+0 -9	+0.21 -0.00	+5.75 -0.00	+0.00 -5.96

Table B.39: Yield and purity outputs from the 2x2D Sideband Method for the expanded DL1 dijet template continued.

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
(Leading DL1 bin) * 5 + subleading DL1 bin						
14.5 - 15.5	$2480 \pm 69^{+25}_{-58}$	$240 \pm 48^{+59}_{-24}$	$17 \pm 12^{+1}_{-0}$	$90.6 \pm 1.9^{+0.8}_{-2.2}$	$8.8 \pm 1.8^{+2.2}_{-0.9}$	$0.6 \pm 0.5^{+0.0}_{-0.0}$
LP2	+0 -41	+42 -0	+0 -0	+0.00 -1.53	+1.53 -0.00	+0.00 -0.00
LP5	+18 -0	+0 -17	+1 -0	+0.59 -0.00	+0.00 -0.62	+0.03 -0.00
15.5 - 16.5	$177 \pm 19^{+2}_{-2}$	$15 \pm 14^{+0}_{-3}$	$2 \pm 3^{+2}_{-0}$	$91.4 \pm 7.7^{+1.4}_{-0.5}$	$7.7 \pm 7.5^{+0.0}_{-1.6}$	$0.9 \pm 1.9^{+1.0}_{-0.0}$
LP2	+0 -1	+0 -1	+1 -0	+0.00 -0.35	+0.00 -0.37	+0.72 -0.00
LP5	+2 -0	+0 -2	+0 -0	+1.00 -0.00	+0.00 -1.07	+0.07 -0.00
16.5 - 17.5	$73 \pm 12^{+4}_{-0}$	$12 \pm 7^{+0}_{-5}$	$1 \pm 2^{+1}_{-0}$	$84.3 \pm 9.5^{+1.6}_{-0.0}$	$14.1 \pm 9.2^{+0.0}_{-5.6}$	$1.6 \pm 2.5^{+1.0}_{-0.1}$
LP2	+3 -0	+0 -3	+1 -0	+3.26 -0.00	+0.00 -3.93	+0.68 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.22 -0.00	+0.00 -0.13	+0.00 -0.09
17.5 - 18.5	$56 \pm 10^{+0}_{-1}$	$4 \pm 6^{+0}_{-0}$	$2 \pm 3^{+1}_{-0}$	$89.9 \pm 10.9^{+0.0}_{-1.5}$	$6.2 \pm 9.9^{+0.7}_{-0.8}$	$3.9 \pm 4.7^{+2.3}_{-0.5}$
LP2	+0 -1	+0 -0	+1 -0	+0.00 -1.05	+0.00 -0.56	+1.61 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.00 -0.14	+0.47 -0.00	+0.00 -0.33
18.5 - 19.5	$125 \pm 16^{+0}_{-3}$	$23 \pm 11^{+3}_{-0}$	$0 \pm 0^{+0}_{-0}$	$84.2 \pm 8.1^{+0.0}_{-2.0}$	$15.7 \pm 8.1^{+2.1}_{-0.0}$	$0.1 \pm 0.0^{+0.0}_{-0.1}$
LP2	+0 -2	+2 -0	+0 -0	+0.00 -1.28	+1.37 -0.00	+0.00 -0.10
LP5	+0 -1	+1 -0	+0 -0	+0.00 -0.79	+0.80 -0.00	+0.00 -0.00
19.5 - 20.5	$3654 \pm 92^{+29}_{-75}$	$603 \pm 72^{+54}_{-20}$	$58 \pm 20^{+22}_{-8}$	$84.7 \pm 1.8^{+0.7}_{-1.7}$	$14.0 \pm 1.7^{+1.2}_{-0.5}$	$1.3 \pm 0.5^{+0.5}_{-0.2}$
LP2	+0 -53	+38 -0	+15 -0	+0.00 -1.24	+0.88 -0.00	+0.35 -0.00
LP5	+20 -0	+0 -14	+0 -6	+0.47 -0.00	+0.00 -0.33	+0.00 -0.13
21.5 - 22.5	$144 \pm 13^{+0}_{-7}$	$22 \pm 5^{+3}_{-0}$	$0 \pm 0^{+4}_{-0}$	$86.4 \pm 3.5^{+0.0}_{-4.3}$	$13.3 \pm 3.4^{+1.9}_{-0.0}$	$0.3 \pm 0.2^{+2.4}_{-0.0}$
LP2	+0 -5	+2 -0	+3 -0	+0.00 -3.06	+1.34 -0.00	+1.72 -0.00
LP5	+0 -0	+0 -0	+0 -0	+0.00 -0.07	+0.09 -0.00	+0.00 -0.02
22.5 - 23.5	$150 \pm 21^{+5}_{-0}$	$22 \pm 21^{+1}_{-7}$	$9 \pm 8^{+2}_{-1}$	$83.0 \pm 12.4^{+2.6}_{-0.0}$	$12.1 \pm 11.8^{+0.8}_{-3.7}$	$4.9 \pm 5.1^{+1.2}_{-0.8}$
LP2	+3 -0	+0 -5	+1 -0	+1.82 -0.00	+0.00 -2.65	+0.82 -0.00
LP5	+0 -0	+1 -0	+0 -1	+0.00 -0.01	+0.57 -0.00	+0.00 -0.56
23.5 - 24.5	$589 \pm 37^{+0}_{-20}$	$100 \pm 30^{+25}_{-0}$	$5 \pm 8^{+0}_{-5}$	$84.9 \pm 4.6^{+0.0}_{-2.8}$	$14.4 \pm 4.5^{+3.6}_{-0.0}$	$0.7 \pm 1.2^{+0.0}_{-0.8}$
LP2	+0 -12	+16 -0	+0 -4	+0.00 -1.76	+2.29 -0.00	+0.00 -0.53
LP5	+0 -11	+11 -0	+0 -2	+0.00 -1.39	+1.62 -0.00	+0.00 -0.23

Table B.40: Yield and purity outputs from the 2x2D Sideband Method for η^{j1} .

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
η^{j1}						
-2.5 - -2.0	13585 $\pm$ 177 $^{+63}_{-118}$	2520 $\pm$ 138 $^{+74}_{-58}$	184 $\pm$ 35 $^{+56}_{-7}$	83.4 $\pm$ 0.9 $^{+0.4}_{-0.8}$	15.5 $\pm$ 0.9 $^{+0.4}_{-0.4}$	1.1 $\pm$ 0.2 $^{+0.3}_{-0.0}$
LP2	+0 -83	+52 -0	+40 -0	+0.00 -0.55	+0.31 -0.00	+0.24 -0.00
LP5	+45 -0	+0 -41	+0 -5	+0.28 -0.00	+0.00 -0.25	+0.00 -0.03
-2.0 - -1.5	18135 $\pm$ 201 $^{+116}_{-317}$	3076 $\pm$ 154 $^{+257}_{-119}$	255 $\pm$ 41 $^{+71}_{-0}$	84.5 $\pm$ 0.8 $^{+0.5}_{-1.5}$	14.3 $\pm$ 0.8 $^{+1.2}_{-0.6}$	1.2 $\pm$ 0.2 $^{+0.3}_{-0.0}$
LP2	+0 -224	+181 -0	+51 -0	+0.00 -1.07	+0.84 -0.00	+0.23 -0.00
LP5	+82 -0	+0 -84	+0 -0	+0.39 -0.00	+0.00 -0.39	+0.00 -0.00
-1.5 - -1.0	24950 $\pm$ 227 $^{+181}_{-448}$	3611 $\pm$ 166 $^{+385}_{-148}$	305 $\pm$ 43 $^{+84}_{-30}$	86.4 $\pm$ 0.6 $^{+0.6}_{-1.6}$	12.5 $\pm$ 0.6 $^{+1.3}_{-0.5}$	1.1 $\pm$ 0.2 $^{+0.3}_{-0.1}$
LP2	+0 -317	+273 -0	+60 -0	+0.00 -1.14	+0.94 -0.00	+0.21 -0.00
LP5	+128 -0	+0 -105	+0 -22	+0.44 -0.00	+0.00 -0.36	+0.00 -0.07
-1.0 - -0.5	28731 $\pm$ 243 $^{+88}_{-474}$	3897 $\pm$ 179 $^{+436}_{-50}$	342 $\pm$ 47 $^{+58}_{-36}$	87.1 $\pm$ 0.6 $^{+0.3}_{-1.5}$	11.8 $\pm$ 0.6 $^{+1.3}_{-0.2}$	1.0 $\pm$ 0.2 $^{+0.2}_{-0.1}$
LP2	+0 -335	+308 -0	+41 -0	+0.00 -1.05	+0.93 -0.00	+0.12 -0.00
LP5	+62 -0	+0 -36	+0 -25	+0.19 -0.00	+0.00 -0.11	+0.00 -0.08
-0.5 - 0.0	31871 $\pm$ 251 $^{+105}_{-490}$	4000 $\pm$ 179 $^{+445}_{-79}$	330 $\pm$ 46 $^{+71}_{-26}$	88.0 $\pm$ 0.5 $^{+0.3}_{-1.4}$	11.0 $\pm$ 0.5 $^{+1.2}_{-0.2}$	0.9 $\pm$ 0.1 $^{+0.2}_{-0.1}$
LP2	+0 -346	+315 -0	+50 -0	+0.00 -1.00	+0.86 -0.00	+0.14 -0.00
LP5	+75 -0	+0 -56	+0 -18	+0.21 -0.00	+0.00 -0.15	+0.00 -0.05
0.0 - 0.5	31300 $\pm$ 255 $^{+181}_{-541}$	4466 $\pm$ 187 $^{+449}_{-204}$	290 $\pm$ 46 $^{+112}_{-0}$	86.8 $\pm$ 0.6 $^{+0.5}_{-1.5}$	12.4 $\pm$ 0.5 $^{+1.2}_{-0.6}$	0.8 $\pm$ 0.1 $^{+0.3}_{-0.0}$
LP2	+0 -383	+317 -0	+78 -0	+0.00 -1.09	+0.88 -0.00	+0.22 -0.00
LP5	+128 -0	+0 -145	+17 -0	+0.35 -0.00	+0.00 -0.40	+0.05 -0.00
0.5 - 1.0	28706 $\pm$ 242 $^{+58}_{-411}$	3843 $\pm$ 176 $^{+344}_{-49}$	301 $\pm$ 45 $^{+82}_{-11}$	87.4 $\pm$ 0.6 $^{+0.2}_{-1.3}$	11.7 $\pm$ 0.6 $^{+1.0}_{-0.1}$	0.9 $\pm$ 0.1 $^{+0.2}_{-0.0}$
LP2	+0 -291	+243 -0	+58 -0	+0.00 -0.91	+0.74 -0.00	+0.18 -0.00
LP5	+41 -0	+0 -35	+0 -7	+0.13 -0.00	+0.00 -0.11	+0.00 -0.02
1.0 - 1.5	24900 $\pm$ 231 $^{+76}_{-388}$	3697 $\pm$ 174 $^{+288}_{-34}$	322 $\pm$ 46 $^{+111}_{-40}$	86.1 $\pm$ 0.6 $^{+0.3}_{-1.4}$	12.8 $\pm$ 0.6 $^{+1.0}_{-0.1}$	1.1 $\pm$ 0.2 $^{+0.4}_{-0.1}$
LP2	+0 -274	+204 -0	+78 -0	+0.00 -0.97	+0.70 -0.00	+0.27 -0.00
LP5	+54 -0	+0 -24	+0 -29	+0.18 -0.00	+0.00 -0.08	+0.00 -0.10
1.5 - 2.0	19040 $\pm$ 203 $^{+67}_{-253}$	2824 $\pm$ 154 $^{+172}_{-50}$	278 $\pm$ 42 $^{+105}_{-20}$	86.0 $\pm$ 0.7 $^{+0.3}_{-1.2}$	12.8 $\pm$ 0.7 $^{+0.8}_{-0.2}$	1.3 $\pm$ 0.2 $^{+0.5}_{-0.1}$
LP2	+0 -179	+121 -0	+75 -0	+0.00 -0.87	+0.54 -0.00	+0.34 -0.00
LP5	+47 -0	+0 -36	+0 -14	+0.22 -0.00	+0.00 -0.16	+0.00 -0.06
2.0 - 2.5	13614 $\pm$ 179 $^{+109}_{-211}$	2634 $\pm$ 141 $^{+192}_{-101}$	135 $\pm$ 37 $^{+23}_{-4}$	83.1 $\pm$ 0.9 $^{+0.6}_{-1.3}$	16.1 $\pm$ 0.9 $^{+1.2}_{-0.6}$	0.8 $\pm$ 0.2 $^{+0.1}_{-0.0}$
LP2	+0 -149	+136 -0	+16 -0	+0.00 -0.93	+0.83 -0.00	+0.10 -0.00
LP5	+77 -0	+0 -71	+0 -3	+0.45 -0.00	+0.00 -0.44	+0.00 -0.02

Table B.41: Yield and purity outputs from the 2x2D Sideband Method for η^{j2} .

	Yield $\pm$ stat. $\pm$ syst.			Fraction $\pm$ stat. $\pm$ syst. [%]		
	$\gamma\gamma$	γ -jet	jet-jet	$\gamma\gamma$	γ -jet	jet-jet
η^{j2}						
-2.5 - -2.0	17130 $\pm$ 194 $^{+93}_{-159}$	2759 $\pm$ 149 $^{+70}_{-69}$	243 $\pm$ 40 $^{+98}_{-20}$	85.1 $\pm$ 0.8 $^{+0.4}_{-0.8}$	13.7 $\pm$ 0.8 $^{+0.3}_{-0.3}$	1.2 $\pm$ 0.2 $^{+0.5}_{-0.1}$
LP2	+0 -113	+49 -0	+69 -0	+0.00 -0.58	+0.24 -0.00	+0.34 -0.00
LP5	+66 -0	+0 -49	+0 -14	+0.32 -0.00	+0.00 -0.25	+0.00 -0.07
-2.0 - -1.5	19422 $\pm$ 204 $^{+83}_{-346}$	2915 $\pm$ 155 $^{+268}_{-46}$	275 $\pm$ 42 $^{+95}_{-35}$	85.9 $\pm$ 0.7 $^{+0.4}_{-1.6}$	12.9 $\pm$ 0.7 $^{+1.2}_{-0.2}$	1.2 $\pm$ 0.2 $^{+0.4}_{-0.2}$
LP2	+0 -244	+189 -0	+67 -0	+0.00 -1.13	+0.83 -0.00	+0.30 -0.00
LP5	+58 -0	+0 -33	+0 -24	+0.25 -0.00	+0.00 -0.15	+0.00 -0.11
-1.5 - -1.0	24540 $\pm$ 229 $^{+131}_{-363}$	3672 $\pm$ 171 $^{+298}_{-131}$	310 $\pm$ 45 $^{+81}_{-0}$	86.0 $\pm$ 0.6 $^{+0.5}_{-1.3}$	12.9 $\pm$ 0.6 $^{+1.0}_{-0.5}$	1.1 $\pm$ 0.2 $^{+0.3}_{-0.0}$
LP2	+0 -257	+211 -0	+57 -0	+0.00 -0.93	+0.73 -0.00	+0.20 -0.00
LP5	+93 -0	+0 -93	+2 -0	+0.32 -0.00	+0.00 -0.33	+0.01 -0.00
-1.0 - -0.5	26515 $\pm$ 235 $^{+83}_{-408}$	3804 $\pm$ 173 $^{+312}_{-74}$	316 $\pm$ 45 $^{+123}_{-6}$	86.6 $\pm$ 0.6 $^{+9.3}_{-1.4}$	12.4 $\pm$ 0.6 $^{+1.0}_{-0.2}$	1.0 $\pm$ 0.2 $^{+0.4}_{-0.0}$
LP2	+0 -288	+221 -0	+87 -0	+0.00 -0.99	+0.71 -0.00	+0.28 -0.00
LP5	+59 -0	+0 -52	+0 -4	+0.18 -0.00	+0.00 -0.17	+0.00 -0.01
-0.5 - 0.0	29043 $\pm$ 244 $^{+121}_{-552}$	4107 $\pm$ 177 $^{+480}_{-110}$	278 $\pm$ 44 $^{+80}_{-15}$	86.9 $\pm$ 0.6 $^{+0.4}_{-1.7}$	12.3 $\pm$ 0.6 $^{+1.4}_{-0.3}$	0.8 $\pm$ 0.1 $^{+0.2}_{-0.0}$
LP2	+0 -390	+340 -0	+56 -0	+0.00 -1.18	+1.01 -0.00	+0.17 -0.00
LP5	+86 -0	+0 -78	+0 -10	+0.26 -0.00	+0.00 -0.23	+0.00 -0.03
0.0 - 0.5	28780 $\pm$ 243 $^{+129}_{-452}$	4031 $\pm$ 178 $^{+397}_{-113}$	334 $\pm$ 46 $^{+74}_{-14}$	86.8 $\pm$ 0.6 $^{+0.4}_{-1.4}$	12.2 $\pm$ 0.6 $^{+1.2}_{-0.3}$	1.0 $\pm$ 0.1 $^{+0.2}_{-0.0}$
LP2	+0 -320	+281 -0	+53 -0	+0.00 -1.00	+0.84 -0.00	+0.16 -0.00
LP5	+91 -0	+0 -80	+0 -10	+0.27 -0.00	+0.00 -0.24	+0.00 -0.03
0.5 - 1.0	26568 $\pm$ 234 $^{+127}_{-423}$	3758 $\pm$ 172 $^{+376}_{-112}$	292 $\pm$ 44 $^{+68}_{-19}$	86.8 $\pm$ 0.6 $^{+0.4}_{-1.4}$	12.3 $\pm$ 0.6 $^{+1.2}_{-0.4}$	1.0 $\pm$ 0.2 $^{+0.2}_{-0.1}$
LP2	+0 -299	+266 -0	+48 -0	+0.00 -1.02	+0.86 -0.00	+0.16 -0.00
LP5	+90 -0	+0 -79	+0 -14	+0.30 -0.00	+0.00 -0.26	+0.00 -0.04
1.0 - 1.5	25456 $\pm$ 231 $^{+135}_{-281}$	3685 $\pm$ 171 $^{+180}_{-137}$	307 $\pm$ 45 $^{+120}_{-0}$	86.4 $\pm$ 0.6 $^{+0.5}_{-1.0}$	12.5 $\pm$ 0.6 $^{+0.6}_{-0.5}$	1.0 $\pm$ 0.2 $^{+0.4}_{-0.0}$
LP2	+0 -199	+127 -0	+85 -0	+0.00 -0.71	+0.43 -0.00	+0.29 -0.00
LP5	+95 -0	+0 -97	+0 -0	+0.33 -0.00	+0.00 -0.33	+0.00 -0.00
1.5 - 2.0	19914 $\pm$ 208 $^{+29}_{-258}$	3166 $\pm$ 156 $^{+213}_{-7}$	187 $\pm$ 39 $^{+59}_{-25}$	85.6 $\pm$ 0.7 $^{+0.1}_{-1.2}$	13.6 $\pm$ 0.7 $^{+0.9}_{-0.0}$	0.8 $\pm$ 0.2 $^{+0.3}_{-0.1}$
LP2	+0 -182	+151 -0	+41 -0	+0.00 -0.82	+0.64 -0.00	+0.18 -0.00
LP5	+20 -0	+0 -5	+0 -18	+0.10 -0.00	+0.00 -0.02	+0.00 -0.08
2.0 - 2.5	17468 $\pm$ 194 $^{+113}_{-368}$	2663 $\pm$ 146 $^{+360}_{-87}$	201 $\pm$ 38 $^{+21}_{-22}$	85.9 $\pm$ 0.8 $^{+0.5}_{-1.9}$	13.1 $\pm$ 0.8 $^{+1.8}_{-0.4}$	1.0 $\pm$ 0.2 $^{+0.1}_{-0.1}$
LP2	+0 -260	+255 -0	+15 -0	+0.00 -1.32	+1.25 -0.00	+0.07 -0.00
LP5	+80 -0	+0 -61	+0 -16	+0.38 -0.00	+0.00 -0.30	+0.00 -0.08

APPENDIX C

STUDY OF B -TAGGING WITH THE DIPHOTON PRIMARY VERTEX

Additional studies were performed on the efficiency of the b -tagging algorithm. The original DL1 algorithm efficiency working points (60%, 70%, 77%, and 85%) were computed using the highest Σp_T as the default primary vertex (PV). The PV selection is very important in b -tagging as it defines the reference point from which the displacement of tracks and other vertices is computed. However, as unconverted photons do not leave tracks, a neural-network was developed to identify the PV in diphoton events. After selection of the PV, jets are recomputed with the updated information, including the b -tagging. The efficiency to select a diphoton vertex within 0.3 mm of the production vertex is shown in Figure C.1 compared to the amount of pileup per events and the number of vertices per event. In both distributions, the efficiency when using the neural-network chosen vertex is higher than when using the hardest vertex as measured in simulated Higgs boson events produced via gluon-gluon fusion.

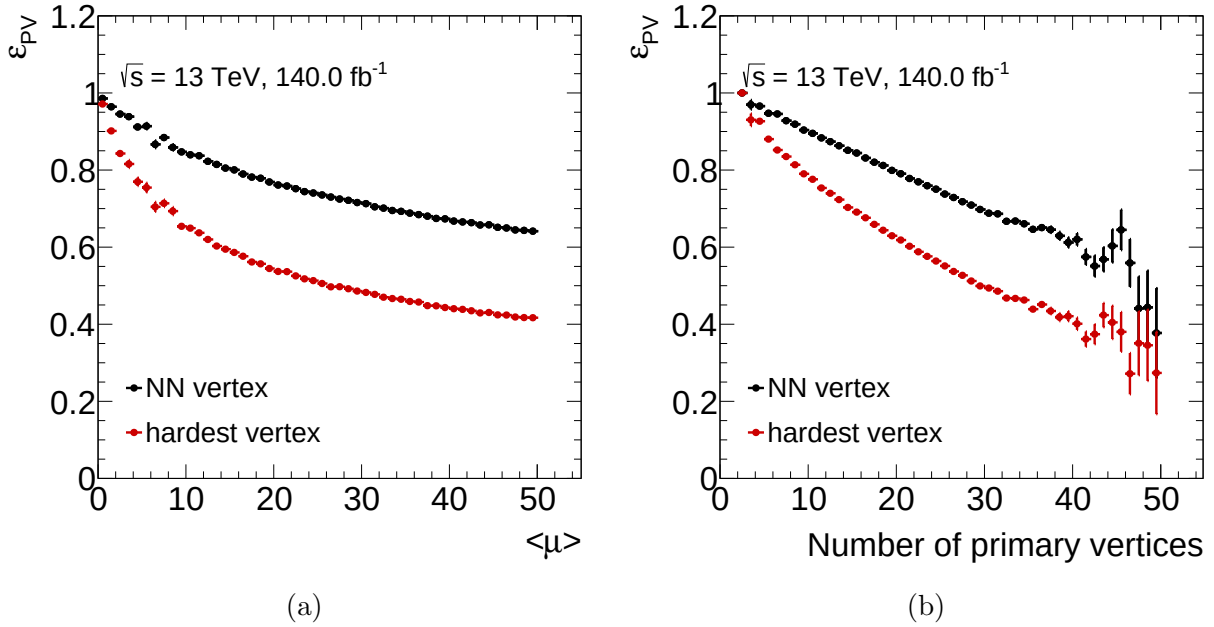


Figure C.1: Efficiencies for selecting the correct primary vertex in ggH simulation comparing the neural-network chosen PV vs. using the hardest vertex as a function of (a) the average number of interactions per bunch crossing (pileup) and (b) the number of potential primary vertices. [149]

Studies were conducted to confirm the efficiency of b -tagging with the new PV using the selections employed for the $H \rightarrow \gamma\gamma$ fiducial cross-section measurement and the diphoton + 1 HF jet measurement but with an additional requirement that there must be one truth b -jet in the event that is central and has $p_T > 25$ GeV. The results are reported separately in Chapter C.1 and C.2 for the Higgs cross-section and diphoton + HF, respectively. In both cases, the efficiency is calculated as the probability to tag a jet using the DL1 b -tagging algorithm that has a truth label indicating a b -hadron origin. Events are sorted into two categories based on the distance from the true PV. Events considered “good” have $|z_{\gamma\gamma} - z_{\text{true}}| \leq 0.1$ mm, indicating that chosen vertex is very close to the true PV, else events are considered “wrong” if $|z_{\gamma\gamma} - z_{\text{true}}| > 0.1$ mm.

C.1 $H \rightarrow \gamma\gamma$ Selections

In this the Higgs boson cross-section analysis, only the $t\bar{t}H$ -enhanced fiducial cross-section and the $N_{b\text{-jets}}$ differential cross-section use b -tagging and would be impacted by any additional uncertainties. The b -tagging efficiencies were studied using the DL1 tagger in ggH and $t\bar{t}H$ processes as well as a $HH \rightarrow \gamma\gamma b\bar{b}$ sample where the Higgs bosons were produced via ggF. For each sample, the fraction of events that had a correctly identified PV by the neural-network is shown in Table C.1.

Table C.1: Fraction of events with the correctly chosen PV in events with 1 truth b -jet in $H \rightarrow \gamma\gamma$ processes.

NN PV Category	% of ggH Events	% of $\gamma\gamma b\bar{b}$ Events	% of $t\bar{t}H$ Events
Good ($\Delta z \leq 0.1\text{mm}$)	86.0	97.3	96.5
Wrong ($\Delta z > 0.1\text{mm}$)	14.0	2.7	3.5

Only the 70% efficiency working point (WP) was analyzed as for this analysis as it was the targeted WP for the reconstructed jets to be considered b -jets. The efficiency to correctly tag a b -jet at the 70% WP for each process is shown in Figure C.2. The ggH process has the lowest b -tagging efficiency, however this isn't especially surprising given the difficulty to choose the correct PV shown above which is very important in b -tagging. This b -tagging efficiency as a function of $|\eta|$ is shown in Figures C.3 split by if the chosen PV is correct (good) or wrong. When the NN chooses correctly, the average b -tagging efficiency is at or above the 70% target WP though begins to dip slightly when reaching the limits of the inner detector acceptance of $|\eta| < 2.5$. When the NN does not choose the correct PV, the efficiency drops, most dramatically in $t\bar{t}H$ events, though as this only occurs in roughly 3% of events, it was deemed to be acceptable.

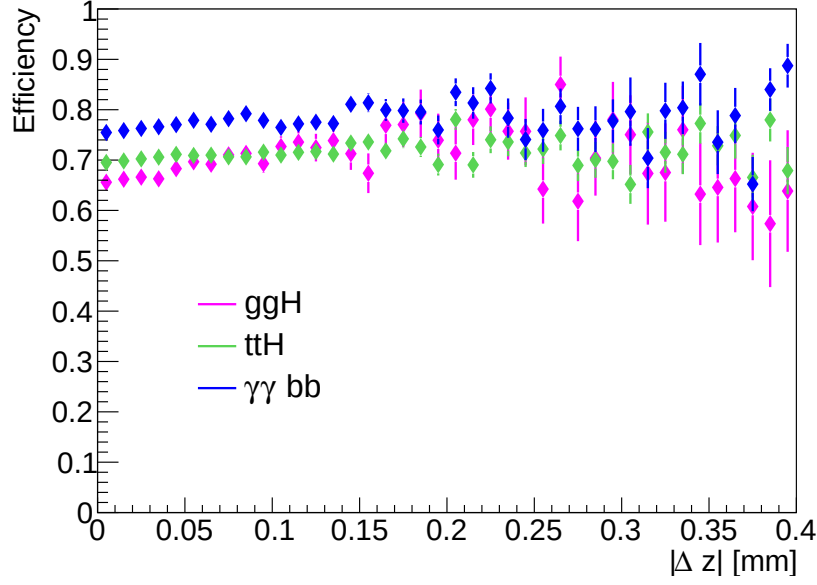


Figure C.2: Efficiencies for correctly tagging a b -jet at the 70% WP in ggH , ttH , and $\gamma\gamma bb$ simulated events as a function of ΔZ between the NN chosen PV and the true PV.

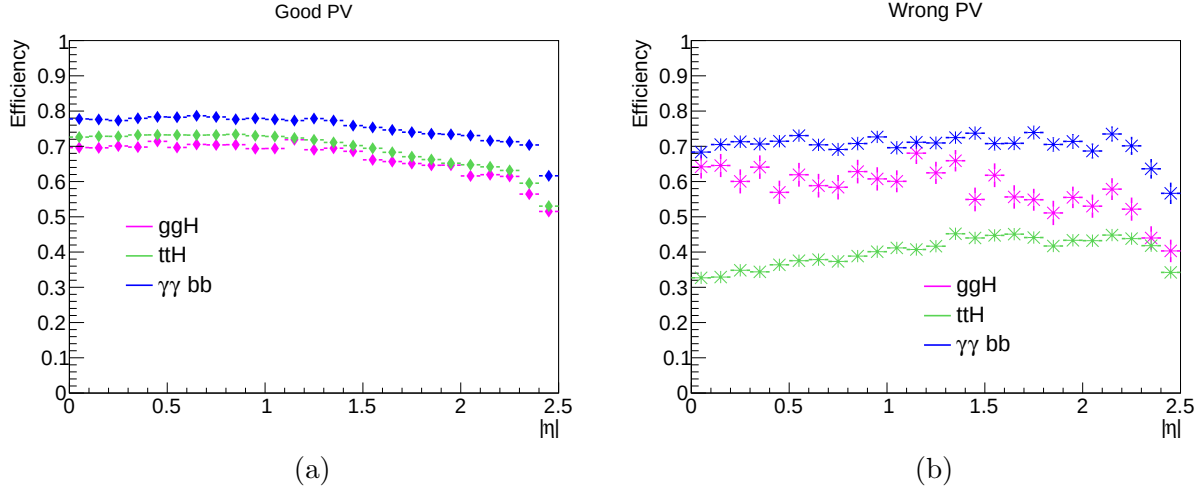


Figure C.3: Efficiencies for correctly tagging a b -jet at the 70% WP in ggH , ttH , and $\gamma\gamma bb$ simulated events as a function of $|\eta|$ (a) when the correct PV is identified and (b) when the chosen PV is wrong.

Checks were also done on c -jet and light-jet mistags. In this case, the b -tagging efficiency was checked on jets that were labeled as a truth c -jet else on all other jets (non- c and non- b)

categorized as light-jets. The efficiency values were all found to be extremely small and very statistically limited.

These combined studies show that the efficiencies are close enough to the target DL1 working points that no further uncertainties were needed due to the primary vertex choice.

C.2 Diphoton + HF Selections

The efficiencies were studied using the DL1 tagger in the diphoton + jets samples as well as a $t\bar{t}\gamma\gamma$ and $t\bar{t}\gamma$ processes. These studies were done for this analysis independently of the cross-section analysis as b -tagging plays a central role in the diphoton + HF analysis compared to the Higgs cross-section analysis. Only one b -tagged jet is required still with no additional requirement for a second central jet. The event selection follows that of the diphoton + 1 HF jet measurement. It was determined that in 77% of the $\gamma\gamma$ + jets events, the hardest vertex is the same as the neural-network chosen vertex. This is higher in the $t\bar{t}\gamma$ and $t\bar{t}\gamma\gamma$ processes, rising to 93% and 96% of events, respectively. The fraction of events with a correctly chosen vertex is also quite high in these types of events, as shown in Table C.2.

Table C.2: Fraction of events with the correctly chosen PV in events with 1 truth b -jet in diphoton + HF processes.

NN PV Category	% of $\gamma\gamma$ Events	% of $t\bar{t}\gamma$ Events	% of $t\bar{t}\gamma\gamma$ Events
Good ($\Delta z \leq 0.1\text{mm}$)	94.4	97.5	97.0
Wrong ($\Delta z > 0.1\text{mm}$)	5.6	2.5	3.0

The efficiency to correctly tag a b -jet at the inclusive 85% WP for each process is shown in Figure C.4. All processes have a very similar efficiency here compared to the distance from the true PV. Figures C.5 and C.6 show the efficiency to correctly identify a b -jet at each WP vs $|\eta|$ when the NN chosen PV is good and wrong, respectively. When the NN is correct, the

distribution is roughly flat, with a slight dip in efficiency towards the acceptance limits of the inner detector (more notably in the tighter WPs), though all three tested processes hit the targeted efficiency values in this case. When the NN chooses the wrong vertex, a drop in efficiency is seen more dramatically in the $t\bar{t}$ types of events, however as this is less than 3% of each of these processes events, no further studies were done. It was determined that no additional uncertainties were needed to account for the b -tagging when using the NN chosen PV.

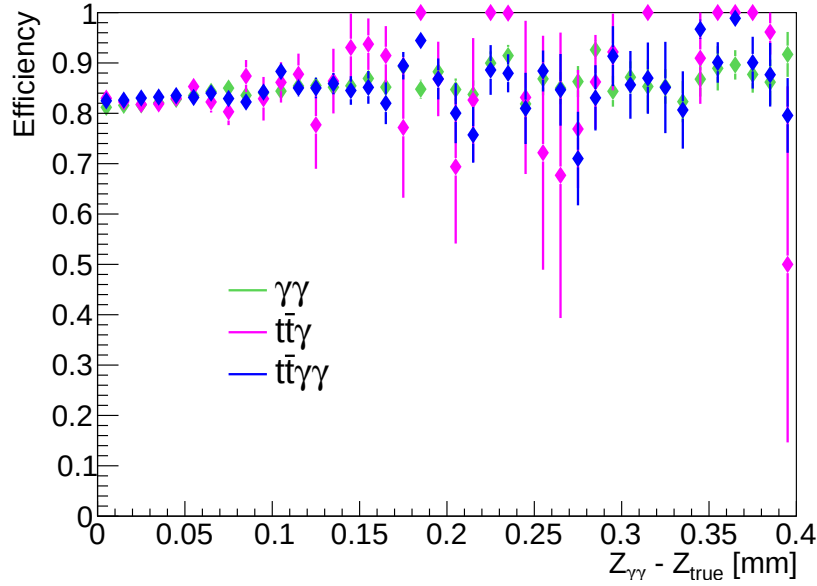
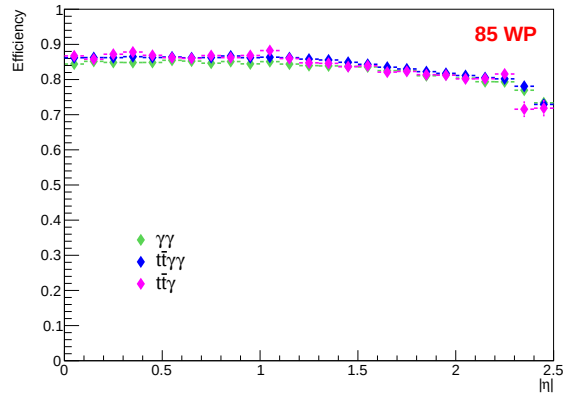
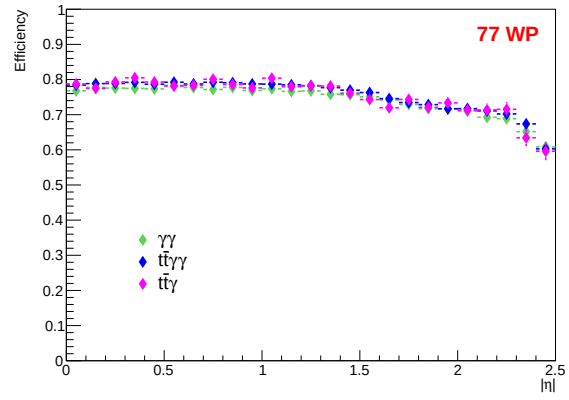


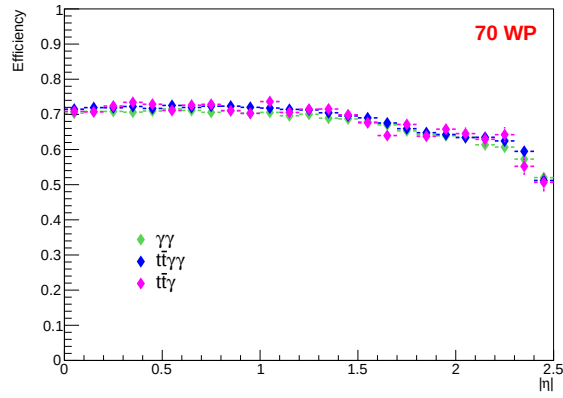
Figure C.4: Efficiencies for correctly tagging a b -jet at the inclusive 85% WP in $\gamma\gamma$, $t\bar{t}\gamma\gamma$ and $t\bar{t}\gamma$ simulated events as a function of ΔZ between the NN chosen PV and the true PV.



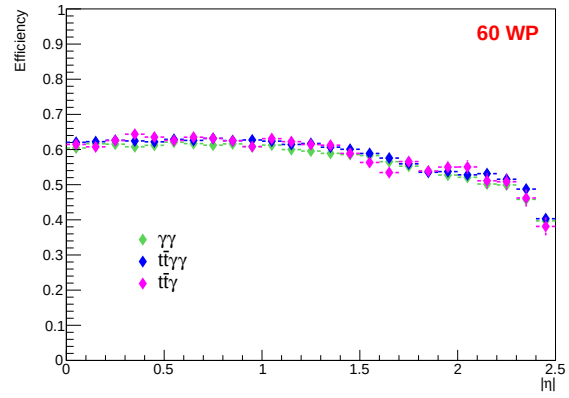
(a)



(b)

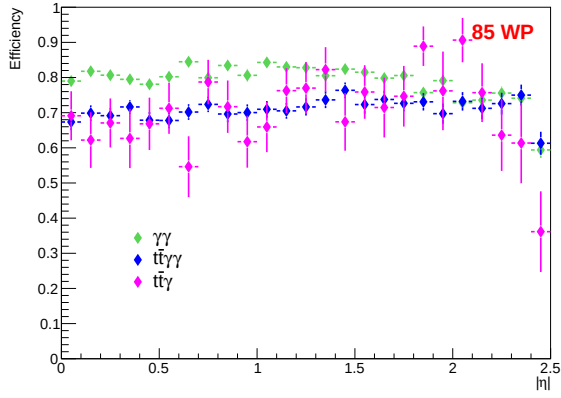


(c)

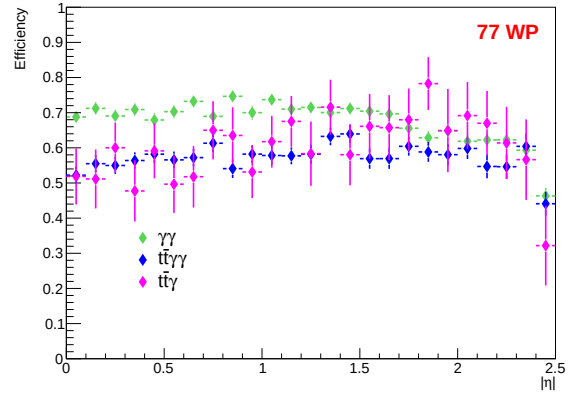


(d)

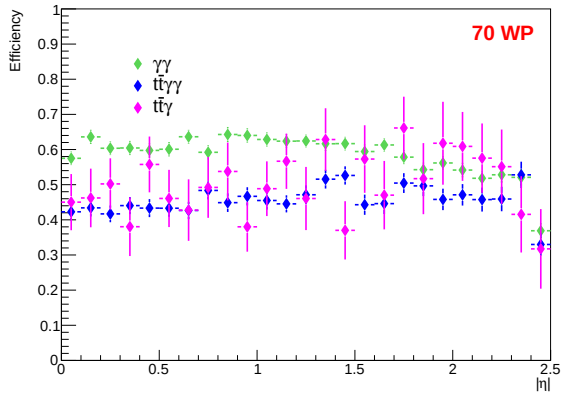
Figure C.5: Efficiencies for correctly tagging a b -jet at the (a) 85%, (b) 77%, (c) 70%, and (d) 60% WP in $\gamma\gamma$, $t\bar{t}\gamma\gamma$ and $t\bar{t}\gamma$ simulated events as a function of $|\eta|$ when the PV chosen by the NN is correct.



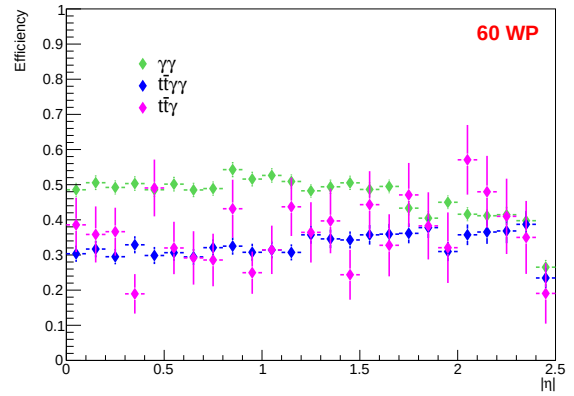
(a)



(b)



(c)



(d)

Figure C.6: Efficiencies for correctly tagging a b -jet at the (a) 85%, (b) 77%, (c) 70%, and (d) 60% WP in $\gamma\gamma$, $t\bar{t}\gamma\gamma$ and $t\bar{t}\gamma$ simulated events as a function of $|\eta|$ when the PV chosen by the NN is wrong.