

A search for low mass resonances decaying into two jets and
produced in association with a photon and development of
pattern recognition algorithms for identifying track candidates
in the ATLAS ITk detector

Dissertation

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Abstract

This thesis presents a search for new subatomic particles by looking for localized excesses in the dijet mass distribution of low-mass dijet events produced in association with a high transverse momentum initial state radiated photon. The search uses the full LHC Run 2 dataset (140 fb^{-1}) from Large Hadron Collider proton-proton collisions collected by the ATLAS experiment between 2015 and 2018 at a center-of-mass energy of 13 TeV. Two variants are presented: one which makes no jet flavor requirements and one which requires both jets originate from b-quarks. In the absence of a statistically significant excess in the dijet invariant mass spectrum in either channel, limits were set on the production cross-section for a benchmark Z' model and on generic beyond the Standard Model scenarios that produce Gaussian-shaped signals with a width of up to 15% of the resonance mass in the dijet invariant mass spectrum. The analysis improves the sensitivity to the coupling of the Z' to quarks by up to 50% compared to previously published results.

The future HL-LHC is expected to deliver an integrated luminosity of 3000 fb^{-1} during its operation, increasing the sensitivity to new physics that could elucidate the interaction between dark matter and matter or explain the underlying mechanism of electroweak symmetry breaking. The high instantaneous luminosity creates multiple proton-proton interactions per proton beam crossing that pose significant challenges for object and event reconstruction algorithms, particularly for tracking algorithms used in trigger selections. The online system known as the Event Filter implements a track reconstruction chain and reduces the data rate from 40 MHz to 10kHz. In this thesis, I present a new method for data preparation as part of track reconstruction and a novel application of pattern recognition on FPGAs used in the online trigger to efficiently identify track candidates within the future ATLAS Inner Tracker. This algorithm is found to significantly reduce the number of fake candidates found, making the process of track fitting less computationally intensive.

This is dedicated to my parents,
Lisa and Mark,
and my brothers,
Evan, Alex, Peter, and Jonathan

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Chapter 1: Our current understanding of the Standard Model

The Standard Model [47] is a quantum field theory that formulates the fundamental quantum fields that satisfy particular field equations and the particles that are perturbations of these fields. Section 1.1 introduces all the particles in the Standard Model. Section 1.2 goes through the symmetries in the Standard Model. Section 1.3 discusses some of the phenomenology of particle collisions and the observable quantities that physicists measure. Section 1.4 presents the current Standard Model measurements, while Section 1.5 highlights just a few limitations of the Standard Model. Unless indicated otherwise, bibliographic references for the Standard Model are in [48], [49], and [50].

1.1 Particles of the Standard Model

Figure 1.1 summarizes the fundamental particles of the SM and their properties. The mass, charge, and spin of each particle are provided in the table. The leftmost three columns contain fermions which have half-integer spin and obey Fermi-Dirac statistics. The rightmost two columns contain the bosons which have integer spin and obey Bose-Einstein statistics. Gauge bosons are spin-1 (vector) mediators, while the Higgs boson is a spin-0 (scalar) mediator.

There are three generations of fermions, each represented by a column. All of stable matter is composed of fermions in the first generation. Particles in the second and third generation can be thought of as heavier versions of the first generation fermions. Antiparticles are denoted by a bar over the symbol of their associated particle.

The two subcategories of fermions, quarks and leptons, are distinguished by their electrical and color charges. Quarks carry color charge and come in six flavors. The

Standard Model of Elementary Particles

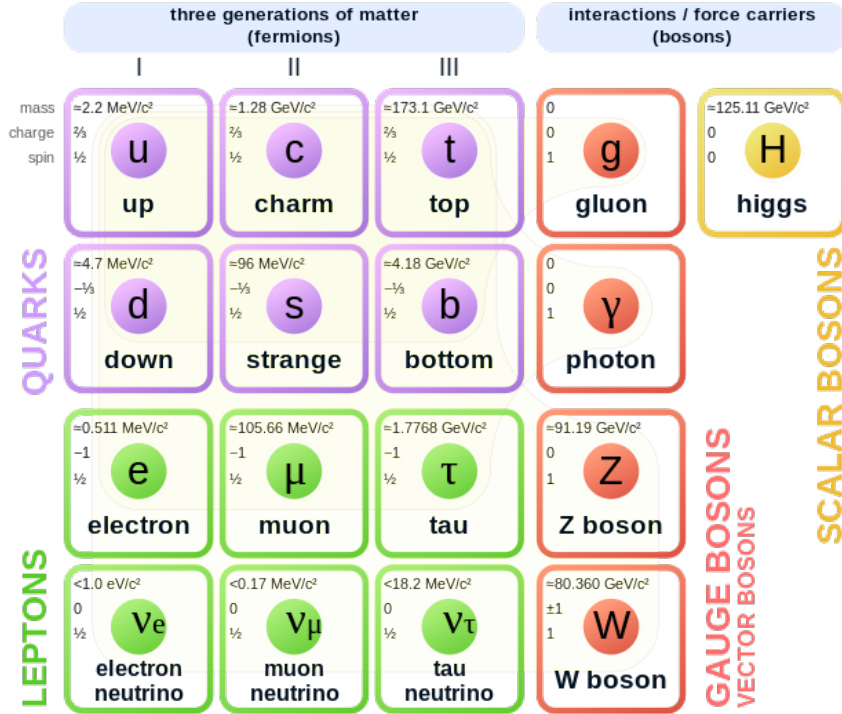


Figure 1.1: A diagram of the fundamental particles of the Standard Model. From [2].

up, charm, and top quarks are “up-like” and carry an electrical charge of $\frac{2}{3}|e|$, while the down, strange, and bottom quarks are “down-like” and carry an electrical charge of $-\frac{1}{3}|e|$. The color charge - which can take on values of red, green, or blue - indicates that quarks couple via the strong force. As a result of color confinement [51] [52] [53], quarks are only found in nature in color neutral bound states, known as hadrons. A meson is a hadron that consists of a quark with one color charge bound to a quark with the corresponding anti-color charge. A baryon is a hadron composed of three quarks or three anti-quarks.

Unlike quarks, leptons carry no color charge. The charged leptons consist of the electron, muon, and tau-lepton. They have an integer electrical charge of $-e$. They exist in the same generational structure that the fermions are organized into and interact both electromagnetically and weakly. Each lepton has a neutral counterpart, known as a neutrino. For the electron, muon, and tau-lepton, they are the electron

neutrino (ν_e), muon neutrino (ν_μ), and tau neutrino (ν_τ), respectively. Unlike the charged leptons, neutrinos only interact via the weak nuclear force.

The spin-1 gauge bosons, shown in the red column of Fig. 1.1, mediate forces by carrying four-momentum between interacting particles. The photon is the electrically neutral mediator of the electromagnetic force, coupling to all electrically charged particles. There are 8 gluons [54] that mediate strong interactions, coupling to color charge. The photon and gluons are massless whereas the mediators of the weak force, the $W^\pm$ and Z bosons, are massive and consequently interact at short ranges. Noticeably absent from the SM is a mediator of gravity, which is currently only explained by the theory of General Relativity [55]. The final fundamental particle in the SM theory is the massive spin-0 Higgs boson.

1.2 Symmetries in the Standard Model

The Lagrangian density, $\mathcal{L}$, for the Standard Model characterizes the dynamics of the fields representing each point-like particle in the Standard Model. The equations of motion for all particles are derived directly from this Lagrangian.

$$\mathcal{L} = \mathcal{L}(\psi(x), \partial_\mu \psi(x)) \tag{1.1}$$

This Lagrangian exhibits invariance for particular transformations that correspond to local and global symmetries which characterize the allowed interactions between particles. The three local symmetries, also known as gauge transformations, are associated with electromagnetism, strong interactions, and the weak force. Additionally, there exist a number of global symmetries that differ from the local symmetries in that the Lagrangian density is invariant under transformations that are identical for all points in spacetime. These transformations include temporal and spatial translations that give rise to the conservation of energy and linear momentum, and rotational transformations that correspond to the conservation of angular momentum.

The Dirac equation in Eq. 1.2 governs the dynamics of free fermions in quantum mechanics.

$$(i\gamma^\mu \partial_\mu - m)\psi = 0 \tag{1.2}$$

In this equation, $\psi = \psi(x)$ is a field spinor describing a fermion with mass m . γ^μ is one of four Dirac matrices. Of the four energy solutions to the Dirac equation, two are negative energy quantum states, indicating that the energy flux is in the opposite direction of the momentum vector of the particle. The interpretation of this is that for every particle, there is an anti-particle having the same mass and spin but opposite charge.

Quantum Electrodynamics

Quantum Electrodynamics (QED) is a U(1) gauge symmetry. By Noether's theorem, each continuous symmetry represents a quantity conserved in the system and for QED, this quantity is the electrical charge and it is conserved locally. The electrical charge, e , is defined in Eq. 1.3, where α_{QED} is the EM coupling constant. This constant is a fundamental parameter of the theory that determines the strength of electromagnetic interactions. Observables for any quantum field theory are typically expressed a function of the coupling strength associated with them.

$$e = \sqrt{4\pi\alpha_{QED}} \quad (1.3)$$

The QED Lagrangian is in Eq. 1.4. D_μ is the covariant derivative, defined in Eq. 1.5 and the electromagnetic field tensor, $F_{\mu\nu}$, is in Eq. 1.6.

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (1.4)$$

$$D_\mu = \partial_\mu + igA_\mu \quad (1.5)$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \quad (1.6)$$

As a consequence of the Lagrangian being invariant under the U(1) gauge transformation, there exists a spin-1 particle (gauge boson) that serves as the mediator of this interaction. The photon (γ) is a massless, electrically neutral force carrier of this field.

Quantum Chromodynamics

Quantum Chromodynamics (QCD) is the quantum field theory of strong interactions. It is a $SU(3)$ symmetry. $SU(3)$ is a subgroup of the $U(3)$ group, a group of all 3×3 unitary matrices. Color is the conserved quantity of this symmetry and it comes in three flavors: red, green, and blue. Quarks are massive spin- $\frac{1}{2}$ fermions that carry color charge and their color states are $SU(3)$ triplets. Quarks additionally carry electric charge (either $-\frac{1}{3}$ or $\frac{2}{3}$) and participate in weak interactions as a part of weak isospin doublets.

Gluons are the spin-1 gauge bosons for the strong interactions, carrying both color and anti-color charge. They are not charge-neutral force carriers. A quark (or anti-quark) emits a gluon that is absorbed by another quark (or anti-quark) and exchanges momentum and color between the quarks. There are 8 total gluons, corresponding to one of the 8 generators of the $SU(3)$ groups, known as Gell-Mann matrices.

The QCD Lagrangian in Eq. 1.7 is invariant under the gauge transformation of the $SU(3)$ symmetry group. In this expression, the sum indicates a sum over all quark flavors.

$$\mathcal{L}_{QCD} = \sum_q \bar{\psi}_q (i\gamma^\mu D_\mu - m_q) \psi_q - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} \quad (1.7)$$

The covariant derivative in this expression is defined in Eq. 1.8 to ensure invariance under the $SU(3)$ transformation.

$$D_\mu = \partial_\mu + ig_s \frac{\lambda^a}{2} G_\mu^a \quad (1.8)$$

λ^a are 8 independent Gell-Mann matrices that generate the group and g_s is coupling constant for the strong interaction and G_μ^a represents the 8 gluons that mediate the strong interaction. The strong interaction tensor in Eq. 1.7, $G_{\mu\nu}^a$, is defined in Eq. 1.9

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f^{abc} G_\mu^b G_\nu^c \quad (1.9)$$

The terms represented by f^{abc} are just the structure constants corresponding to each of the 8 Gell-Mann matrices, meaning that each Gell-Mann matrix (t) satisfies:

$$[t^a, t^b] = if^{abc}t^c \quad (1.10)$$

One consequence of the Lagrangian is that the gluon is self-interacting and has 3-point and 4-point interactions.

Quarks and gluons will act as free particles at high energies and over short distances. This is known as asymptotic freedom. At large distances, inter-quark coupling increases and quarks cannot be separated from hadrons. This is known as quark confinement.

Electroweak Interactions

Weak interactions are responsible for radioactive decays and participate in nuclear fission and nuclear fusion. The electroweak interaction unifies the electromagnetic and weak nuclear interactions. All fermions, including neutrinos, are subject to this force. The gauge symmetry group for this interaction is $SU(2) \times U(1)$. The Lagrangian associated with this symmetry group generates four fields: the W_μ^1 , W_μ^2 , W_μ^3 , and B_μ . Their associated conserved quantities are three weak isospins (I^1 , I^2 , I^3) and one hypercharge (Y), respectively. Linear combinations of these fields produce the fields for four gauge bosons: the photon, the two massive charged mediators of the weak force (the $W^\pm$ bosons), and the neutral mediator of the weak force (the Z boson).

The field of the photon (A_μ , in Eq. (1.11)), the fields of the two W bosons ($W_\mu^\pm$, in Eq. (1.12)), and the field of the Z boson (Z_μ , in Eq. (1.13)) are related to the four fields of the $SU(2) \times U(1)$ symmetry group by the weak mixing angle, θ_W , which is the angle at which the $SU(2)$ and $U(1)$ gauge fields mix.

$$A_\mu = W_\mu^3 \sin\theta_W + B_\mu \cos\theta_W \quad (1.11)$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \quad (1.12)$$

$$Z_\mu = W_\mu^3 \cos\theta_W - B_\mu \sin\theta_W \quad (1.13)$$

The conserved quantity of electric charge, Q , is related to the $SU(2) \times U(1)$ gauge symmetries by the third component of the weak isospin and the hypercharge.

$$Q = I^3 + \frac{1}{2}Y \quad (1.14)$$

Due to electrical charge conservation within QED and color charge conservation in QCD, the photon and gluons are all massless. The electroweak theory described so far predicts massless gauge bosons, however, experimental observations have shown that the $W^\pm$ and Z bosons have masses of $m_{W^\pm} = 80.377 \pm 0.012 \text{ GeV}/c^2$ and $m_Z = 91.187 \pm 0.0021 \text{ GeV}/c^2$, respectively [56].

Electroweak symmetry breaking and the Higgs Mechanism

A mechanism of electroweak symmetry breaking must be introduced and this is called the Brout-Englert-Higgs mechanism [57] [58] [59] [60]. Also referred to as just the Higgs mechanism, this phenomena explains how the gauge bosons acquire mass through interactions with a new field, the Higgs field, ϕ . This field is a complex scalar field that is invariant under the $SU(2) \times U(1)$ symmetry group.

$V(\phi)$ is a scalar potential that is introduced to the Lagrangian of the $SU(2) \times U(1)$ symmetry group.

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \quad (1.15)$$

The first term in the expression for $V(\phi)$ is a mass term and the second term describes the self-interaction of this new field. μ and λ are just scalar constraints. Figure 1.2 shows the shape of this potential. The minimum occurs at $|\phi|^2 = -\frac{\mu^2}{2\lambda}$. At the bottom of the potential, rotational $U(1)$ symmetry is spontaneously broken.

If $\mu^2 < 0$, the potential has non-zero minima. These degenerate minima are located at:

$$\phi = \pm \frac{\nu}{\sqrt{2}} \quad (1.16)$$

ν is also referred to as the vacuum expectation value of the field. Another way of expressing this is by saying that the Higgs field can be perturbed around the minimum value according to:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + h(x) \end{pmatrix} \quad (1.17)$$

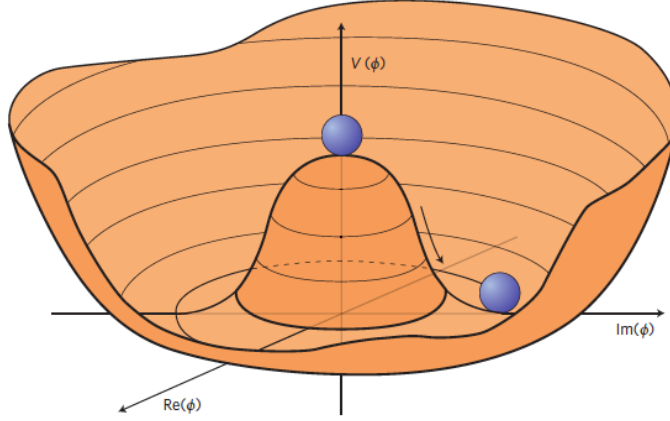


Figure 1.2: The shape of the Higgs potential for the case that $\mu^2 < 0$. From [3].

In this expression, $h(x)$ is defined as excitations of the field, corresponding to the physically observable Higgs boson. All of the minima are equivalent and connected by an $SU(2)$ transformation.

If $\mu^2 > 0$, there is one unique minimum of the Higgs potential and this corresponds to the vacuum state at $\psi = 0$. When the Higgs field is at an equilibrium, the field is ϕ_0 :

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix} \quad (1.18)$$

The mass of the weak gauge bosons are generated by three of the real scalar degrees of freedom. m_W is in Eq. 1.19 and m_Z is in Eq. 1.20, where g_W and g' are the $SU(2)$ gauge coupling and the $U(1)$ gauge coupling, respectively. v is the Higgs vacuum expectation value.

$$m_W = \frac{g_W v}{2} \quad (1.19)$$

$$m_Z = \frac{v}{2} \sqrt{g_W^2 + g'^2} \quad (1.20)$$

The masses of the W and Z bosons are related by the weak mixing angle in Eq. 1.21.

$$\cos\theta_W = \frac{m_W}{m_Z} \quad (1.21)$$

The fourth corresponds to the Higgs itself. This boson gives rise to the masses of fermions and heavy bosons in the Standard Model. The mass of the Higgs boson is:

$$m_H = \sqrt{2|\mu|^2} \quad (1.22)$$

The Higgs mechanism also provides mass to fermions. y_f is the Yukawa coupling of the Higgs to fermion f and is related to the fermion mass in Eq. 1.23.

$$y_f = \sqrt{2} \frac{m_f}{v} \quad (1.23)$$

The Cabbibo-Kobayashi-Maskawa (CKM) matrix transforms the mass eigenstates into the eigenstate basis for weak interactions [56]. This matrix accounts for transitions between different quark flavors using weak charged-current interactions.

1.3 Phenomenology of Particle Collisions

The LHC explores the structure of particle interactions and particle decays by accelerating and colliding protons in bunches. The energy of a proton beam is expressed as the total energy of the collision in a frame where the total momentum of the two colliding protons is zero. If the two beams have energies of E_1 and E_2 and it is assumed that they have a small or zero crossing angle, the center-of-mass energy is $E \approx 2\sqrt{E_1 E_2}$. In the case of the LHC, the proton beams are equal in energy, resulting in a center-of-mass energy that is twice the beam energy. The proton is not a fundamental particle and is composed of three valence quarks, uud , and what are known as sea quarks and gluons. Together, these constituents of the proton are referred to as partons.

Figure 1.3 is an artist's sketch of a simulated proton-proton collision [4]. The large green ellipses are the colliding protons and the three green arrows pointing to them represent the three valence quarks within them, uud . The blue spirals and lines coming from the green protons are too energetic to form bound states. Through radiation or gluon splitting, they produce initial state radiation in the form of quarks and gluons, represented by secondary lines and spirals, respectively. The process of radiation and gluon splitting is also referred to as parton shower generation. Two gluons

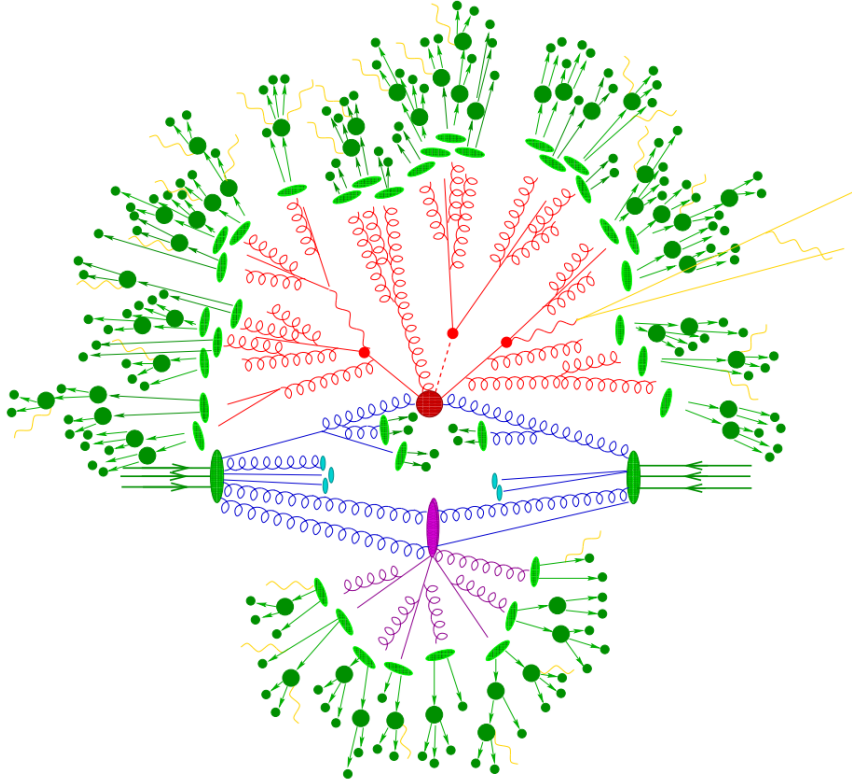


Figure 1.3: An artist's depiction of a hadron-hadron collision generated by a MC generator. From [4].

interact to create the hard scatter, represented by the solid red circle. The purple ellipse represents an additional interaction between the initial state radiated objects that are not a part of the hard scatter. This additional interaction is considered an underlying event. Colored particles present in the initial state radiate gluons that further split into quark/anti-quark pairs. The remaining gluons and quarks shown in blue are initial state radiation. The smaller red dots and red spiral emanating from the hard scatter are the final state products of the interaction and all other red products are final state radiation. Electrically charged particles are also capable of radiating photons that are represented by yellow lines, though this happens more infrequently than the generation of quark/anti-quark pairs. The photon radiation and hadronization are collectively referred to as “fragmentation” products of the interaction.

The two experimentally observable phenomena are the cross section of a given process and the decay rate of a particle.

Cross Sections

The cross section of an interaction is related to the quantum mechanical probability that an interaction will occur. It is expressed in the unit of barns ($1b = 10^{-28} \text{ m}^2$). Any observed deviations from the SM predicted value would indicate the presence of new physics.

The differential cross section of a $2 \rightarrow 2$ process is given in Eq. 1.24.

$$d\sigma = \frac{(2\pi)^4 |M|^2}{4\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}} \times d\Phi(p_1 + p_2; p_3, p_4) \quad (1.24)$$

p_i and m_i ($i = 1, 2$) are the four-momenta and masses of the initial state particles to the scattering process. The final state particles have four momenta p_i ($i = 3, 4$). M is the Lorentz invariant matrix element factors that are used to calculate the probability of different final states in a scattering event. $d\Phi$ is evaluated over all particles and describes all possible final states satisfying the kinematic constraints that momentum and energy be conserved and is evaluated over all particles. The production cross section of any given process is just the sum of the cross sections of all possible interactions that produce that process.

Decay Rates

The probability that a particle makes it to time t before decaying is given in Eq. 1.25, where τ is the mean proper lifetime of the particle and γ is the Lorentz factor.

$$P(t) = e^{-t/\gamma\tau} \quad (1.25)$$

Inversely proportional to the mean proper lifetime is the total width of the process, Γ , given in Eq. 1.26.

$$\Gamma = \frac{\hbar}{\tau} \propto \frac{1}{2M} \int |M^2| d\Phi_n(P; p_1, \dots, p_n) \quad (1.26)$$

Branching Ratio

A parent particle P can decay in multiple modes. The total width is the sum of the partial widths of those modes. A branching ratio is just the probability that particle P decays to a specific final state, X_i , and is defined in Eq. 1.27.

$$BR(P \rightarrow X_i) = \frac{\Gamma(P \rightarrow X_i)}{\Gamma_P} = \frac{\Gamma(P \rightarrow X_i)}{\sum_j \Gamma(P \rightarrow X_j)} \quad (1.27)$$

In this expression, $\Gamma(P \rightarrow X_i)$ is the partial decay width and Γ_P is the total width of the particle.

Proton-proton collisions

In proton-proton collisions, the interaction cross-section of the hard scatter, $d\sigma_{pp \rightarrow m}$, is the sum of the individual partonic cross-sections between all pair combinations of partons that initiate the hard scatter, $\frac{d\hat{\sigma}_{ij \rightarrow m}}{dx_i dx_j d\phi_m}$.

$$d\sigma_{pp \rightarrow m} = \sum_{i,j} \int_0^1 dx_i \int_0^1 dx_j \int d\phi_m f_{i/p_i}(x_i, \mu_F^2) f_{j/p_j}(x_j, \mu_F^2) \cdot \frac{d\hat{\sigma}_{ij \rightarrow m}}{dx_i dx_j d\phi_m} \quad (1.28)$$

An individual parton within the proton, parton i , carries a fraction of the proton's momentum, x_i . The parton density function $f_{i/p_i}(x_i, \mu_F^2)$ is a probability distribution for finding a parton carrying a fraction x_i of the proton's momentum within the proton. A result of QCD is that these parton density functions, or PDFs, run with energy and are therefore a function of the energy scale that the protons are probed at, μ_F , also known as the factorization scale. Below the factorization scale, UV divergences appear in the partonic cross sections and the PDFs must be measured experimentally at specific scales [61] [62].

1.4 State of the art measurements of the Standard Model

The discoveries of the W [63] and Z bosons [64], top quark [65], and Higgs boson [66] [67] having properties consistent with those predicted by the SM theory demonstrates the validity of the model.

Figure 1.4 summarizes the total production cross-sections of various SM processes, as measured by ATLAS. The different colors indicate the center-of-mass energy that

the measurements were performed at. The bands indicate the theoretical predictions, obtained at NLO or higher perturbative accuracy [5]. The right panel within the figure shows the ratios of the data and theory values of the production cross sections. The agreement shows the success of the SM in predicting the observed cross sections. The paper references corresponding to each measurement are listed on the far right of the figure.

A compelling piece of evidence for the internal consistency of the SM comes from comparing the simultaneous indirect determination of the top mass (m_t) and W boson mass (M_W). Inputting the measured mass of the Higgs into a fit of the electroweak sector overconstrains it and provides indirect measurements of M_W , m_t , and the effective weak mixing angle for charged and neutral leptons and light quarks at a precision better than that of the direct measurements [68]. Figure 1.5 shows a scan of the confidence level profile over the phase space defined by M_W and m_t . The most updated direct measurements are shown as the green contours, with the darker and lighter shades indicating the 1σ and 2σ error bands, respectively. The grey contours are the results of the electroweak fit when the Higgs mass is not provided as an input to the fit. The blue regions are obtained by performing this same fit including the measured Higgs mass in the fit. The uncertainties arise from the uncertainties on each of the fit input values. The agreement between the direct and indirect measurements demonstrates the self consistency of the SM.

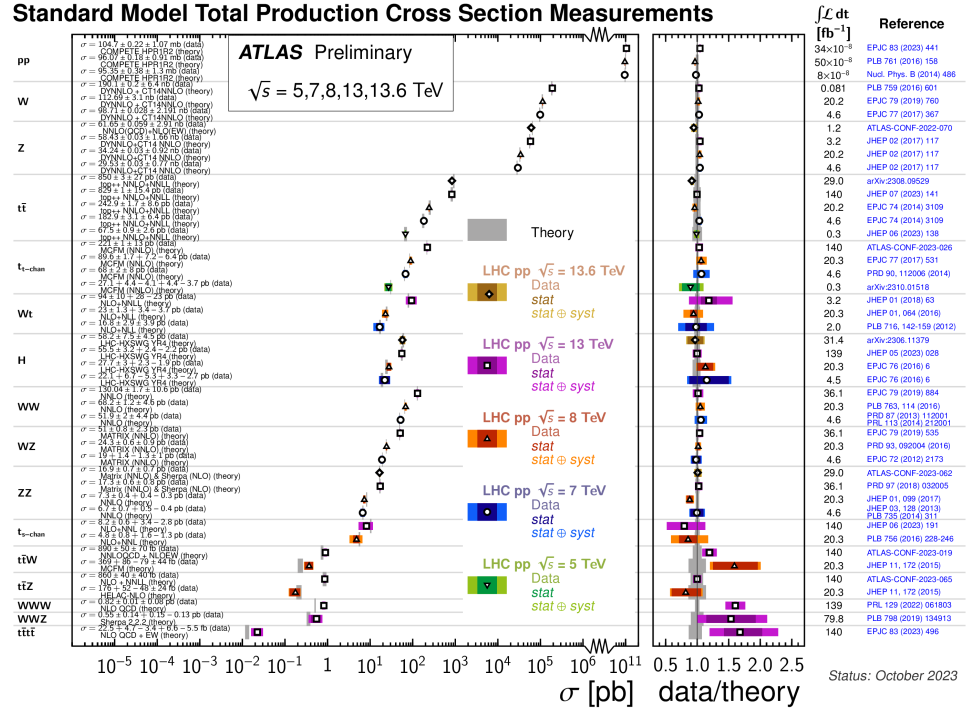


Figure 1.4: Standard Model total production cross-section measurements, corrected by branch fractions made By the ATLAS detector at various center-of-mass energies. From [5].

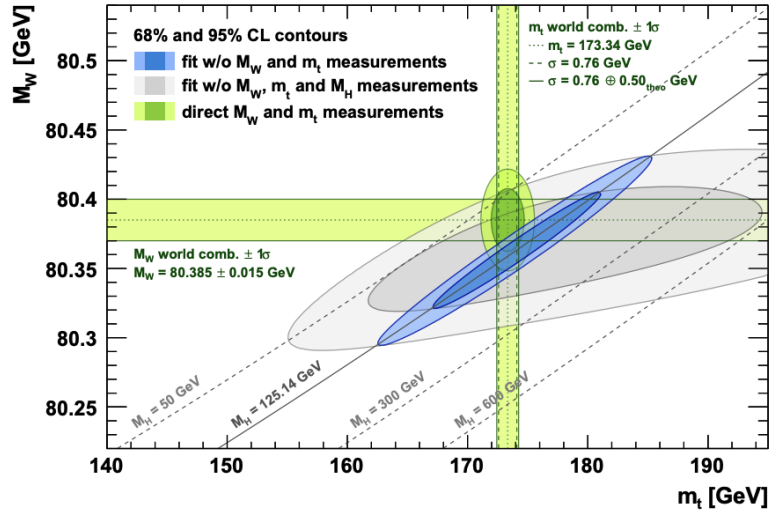


Figure 1.5: The contours show the 68% and 95% CL obtained from scans of M_W and m_t for the global electroweak fit including M_H (blue) and excluding M_H (grey). The direct measurements of M_W and m_t are shown in the vertical and horizontal green bands and ellipses. From [6].

1.5 Limitations of the Standard Model

A main goal of present day experimental particle physics experiments is to provide an explanation for the hierarchy problem [69], which cannot be accounted for by the Standard Model. The Standard Model corrects the Higgs mass with loops of other particles, the dominant one being the one-loop radiative correction to m_H from the top quark. These loops are represented in Feynman diagrams as virtual particles. The relevant scale, Λ , can be defined as where the momentum of these virtual particles is cut off.

The correction term Δm_h^2 is given in Eq. 1.29 and m_h^2 becomes Eq. 1.30.

$$\Delta m_h^2 = -\frac{\lambda_f^2}{16\pi^2}(2\Lambda^2 + \mathcal{O}(m_f^2 \ln(\frac{\Lambda}{m_f}))) \quad (1.29)$$

$$m_h^2 = m_{h,0}^2 + \Delta m_h^2 \quad (1.30)$$

The correction is proportional to Λ^2 . m_f is mass of that fermion and λ_f is the coupling parameter of the Higgs field to the the respective fermion field. At the Planck scale, equivalent to the energy of a Planck mass $\approx 10^{19}$ GeV, gravity becomes similar in magnitude to that of the three other fundamental forces. If the cutoff scale, Λ , is set to the Planck scale, m_h becomes very large. It would be “natural” then for the mass of the Higgs to be around 1 TeV. In 2012, ATLAS and CMS discovered a particle consistent with being a scalar boson predicted by the SM produced in the $ZZ^* \rightarrow 4l$ channel. This new boson, the Higgs boson, was found to have a mass of $m_H = 125$ GeV [70]. This discrepancy is known as the electroweak hierarchy problem or “fine-tuning” problem since m_H must be finely tuned to cancel out the large radiative corrections.

Our understanding of the SM is also limited by the observations that have been made so far. Between 2015 and 2018, the LHC collected data at $\sqrt{s} = 13$ TeV. ATLAS and CMS both observed couplings of the Higgs to vector bosons and third generation quarks, to tau-leptons [71] [72], to the top quark in $t\bar{t}H$ production [73] [74], and to the bottom quark in the $H \rightarrow b\bar{b}$ channel [75] [76]. As the first and second generation fermions have significantly lower masses than the third generation fermions, their Yukawa couplings are also lower and more data is needed to declare discovery of these processes [77] [78] [79]. Figure 1.6 summarizes all the couplings that have been measured by ATLAS.

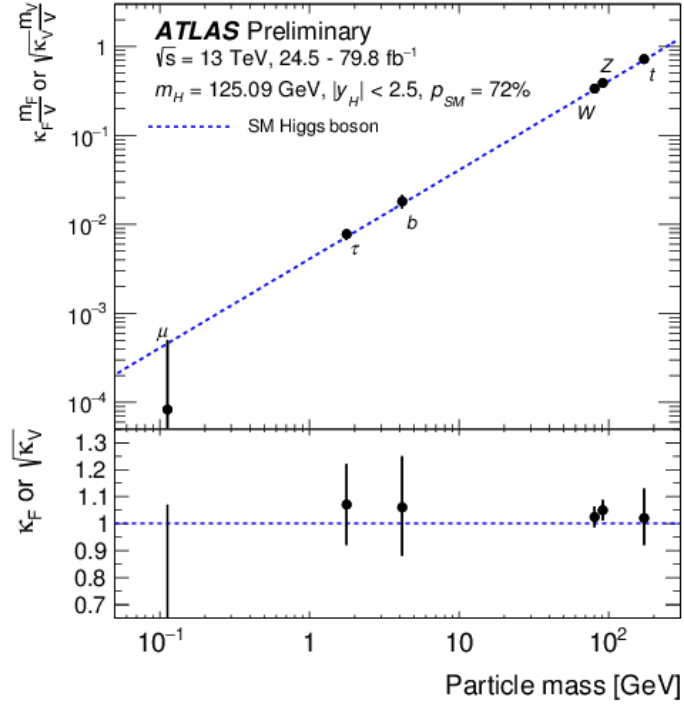


Figure 1.6: Measurements of the Higgs boson coupling strength to the top and bottom quarks, W and Z bosons, and muon and tau-lepton. The blue dotted line is the Standard Model prediction. From [7].

Chapter 2: The Mystery of Dark Matter

There exist many independent observations, across a wide range of astrophysical scales, of the gravitational effects of non-baryonic matter on the luminous matter in the universe. This non-baryonic matter is referred to as “Dark Matter” because it is not visible. Section 2.1 presents a collection of evidence of gravitating dark matter at various astrophysical scales. Section 2.2 introduces the theory of the thermal freeze-out mechanism, which has not been verified, but is the popular explanation for the observed relic density of dark matter in the universe today. Section 2.3 briefly presents the types of searches for dark matter that are being performed at telescopes, underground laboratories, and particle colliders.

2.1 Evidence for Dark Matter

One of the most frequently cited observations of the gravitational effects of dark matter are the observed systematic anomalies in the rotation curves of spiral galaxies. The appearance of spiral galaxies is typically characterized by a spherical bulge, where luminous stars are concentrated within a stellar disk of stars and an outer disk of atomic gas, predominantly neutral atomic hydrogen gas. General relativity predicts a rotation curve for these galaxies of the form shown by the white dashed line in Fig. 2.1.

Optical telescopes have been used to measure the Doppler shifts of the stars within the stellar disk as a function of their linear distance from the center of the galaxy, shown as the yellow data points in the galactic rotation curve in Fig. 2.1. Radio-telescopes have extended this curve by measuring the rotational velocity of the neutral hydrogen within the galaxy, shown as blue data points in Fig. 2.1. Instead of declining at the predicted rate of $v \propto r^{-\frac{1}{2}}$, the rotational velocity grows and eventually flattens out. Assuming the gravitational force law is correct, this implies that a large amount

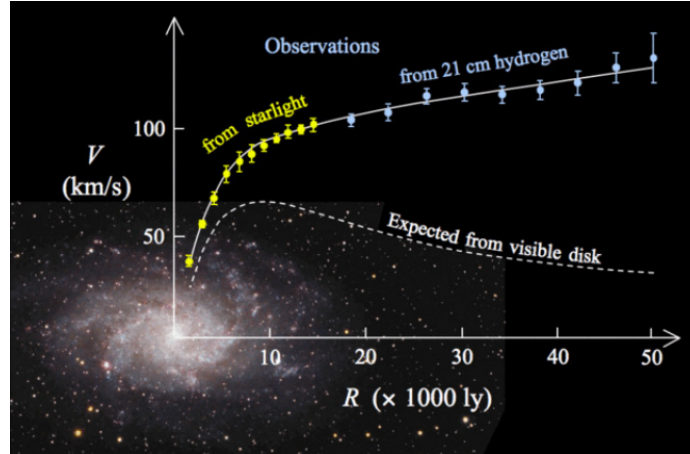


Figure 2.1: The galactic rotation curve of the spiral galaxy Messier 33 (M33). The gray dashed line is the predicted distribution from observations of visible matter. From [8].

of non-luminous matter exists to produce the necessary gravitational potential needed to maintain the observed rotational velocities at distances further away from the galactic center.

Another observation of the gravitational effects of dark matter comes from studying the strong gravitational lensing of dense objects like galaxy clusters. The light rays passing through these massive objects are deflected around the object, or lens, producing a distorted image of the light source. Fig 2.2 shows the galaxy cluster CL0024+17 as observed from an optical telescope. Comparing the distortions to the distribution of visible mass indicates there must be a significant amount of non-luminous matter present to produce the observed gravitational lensing. In Fig 2.2, a “blue map,” showing the ring-like structure of the cluster’s dark matter component is superimposed on an image of the cluster from the Hubble Telescope.

The presence of dark matter is also observed when studying the head-on collision of two galaxy clusters. A famous example is the Bullet Cluster. A majority of the baryonic mass in this clusters is contained within hot clouds of gas that can be observed by their x-ray emission. In Figure 2.3, the density of the baryonic matter is shown, with the green contours indicating the mass density determined from gravitational lensing. The x-ray image shows that the gas remains near the center of the collision. The contours of the gravitational map indicate that most of the mass



Figure 2.2: A composite image of the galaxy cluster ZwCL0024+1652, taken by the Hubble Space Telescope. From [9].

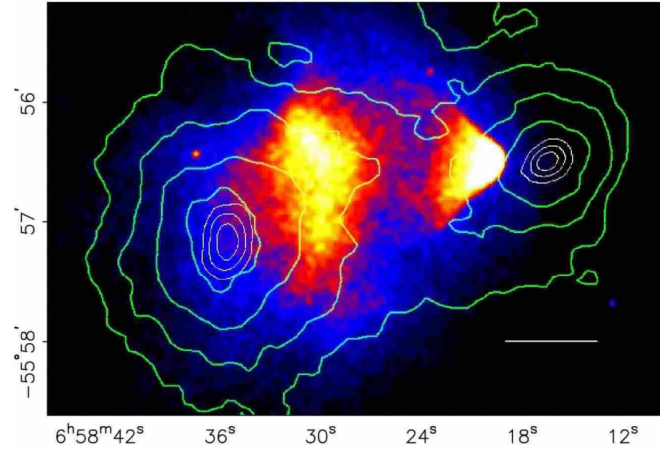


Figure 2.3: A Chandra x-ray image of the bullet cluster (color) overlaid with a weak gravitational mapping. From [10].

is located to the left and right of the gas. We can infer the presence of additional non-baryonic matter present that would be needed to cause this clear separation.

Studying the Cosmic Background Radiation (CMB) also provides support for the dark matter hypothesis. The Cosmic Microwave Background was discovered in 1965 [80][81] and is remnant radiation from the recombination era. It is an almost homogeneous and isotropic source of low energy photons, with energies on the eV level. Fluctuations of matter density during the decoupling and recombination epoch produced large structures we observe in the universe. These fluctuations are observed as anisotropies, small inhomogeneities in the distribution of the temperature of the universe that are on the order of hundreds of μK .

The Planck collaboration has measured the temperature of the universe, shown in Figure 2.4 [11]. The color scale indicates variations in temperature with respect to the average measured temperature of the universe. Observations of the CMB are consistent with emissions of a black-body at a temperature of 2.73K [82][81]. The observed anisotropies correspond to the existence of gravity wells in the early universe that gave rise to large structures. This requires the presence of a matter component that was decoupled from ordinary matter prior to the CMB era, this component being dark matter.

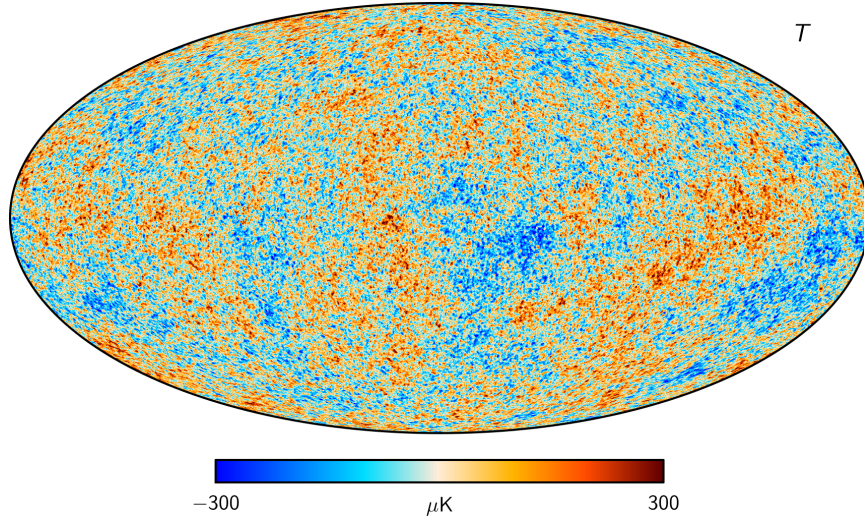


Figure 2.4: A full sky map of the CMB temperature anisotropies produced from data collected by the Planck satellite in 2018. From [11].

2.2 Thermal Freeze-out and the relic abundance

Thermal freeze-out [12] is a popular explanation for the observed thermal relic. When the universe was very young and hot, Standard Model particles and dark matter were in thermal equilibrium and the production and annihilation of dark matter particles balanced each other out.

The Boltzmann equation [83] describes the time evolution of the density of a stable and non-relativistic species of dark matter particles while the universe was expanding.

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2) \quad (2.1)$$

In this equation, n is the number density of the dark matter particles and n_{eq} is this density at equilibrium. H is the Hubble parameter [12] and represents the expansion rate of the universe. The term $\langle \sigma v \rangle$ is the thermal average of the annihilation cross-section of dark matter particles into Standard Model particles and the particle's velocity. After freeze-out, the dark matter yield is given as a function of the average energy density of the annihilating particles ($\langle E \rangle$):

$$\frac{d\rho_R}{dt} = -4H\rho_R + \langle \sigma v \rangle \langle E \rangle (n^2 - n_{eq}^2) \quad (2.2)$$

Figure 2.5 shows the time evolution of the dark matter abundance for different choices of the annihilation cross-section. In the early universe ($T \gg m$), production and annihilation rates exceeded the expansion rate. As a result, the particle number density (n) follows the expectation value at thermal equilibrium. When $T \leq m$, pair production of DM is suppressed and consequently, the annihilation rate is also reduced. Eventually, this process ends and the relic density is achieved.

The rate of DM-SM interactions, roughly less than the expansion rate of the universe ($\Lambda_{ann} \lesssim H \approx T_F^2/\bar{M}_P$, where T_F is the temperature at freeze-out, and $\bar{M}_P$ is the reduced Planck mass), lowered as the universe expanded until it could no longer maintain thermal equilibrium between dark matter and matter. This time is known as “freeze-out”. When the dark matter decoupled from Standard Model particles at freeze-out, the relic abundance became fixed to its observed present-day value.

A new model, the Λ CDM model [84][85], was developed and included a cosmological constant (Λ) as a central parameter. Simplifying the Einstein equations results in the Friedman equations [55], the first of which parameterizes the expansion rate of the universe in terms of the total energy density (Ω), which includes a component

dependent on Λ . The second Friedman equation describes how the energy density of the universe evolves over time. Within the Λ CDM model, the Friedman equations indicate that as the universe expanded, the large energy densities associated to matter and radiation decreased. At the beginning of the universe, the energy scale exceeded the Planck scale and gravitational effects consequently dominated. As the energy density was diluted when the universe expanded, the universe transitioned to the electroweak era, which ended at $T \sim 10^2$ GeV, when electroweak symmetry was broken. When the energies reached the QCD scale, quarks and gluons began to hadronize. Around an energy of one electron volt, photons decoupled from baryonic matter and this resulted in the low energy photons we observe as the CMB.

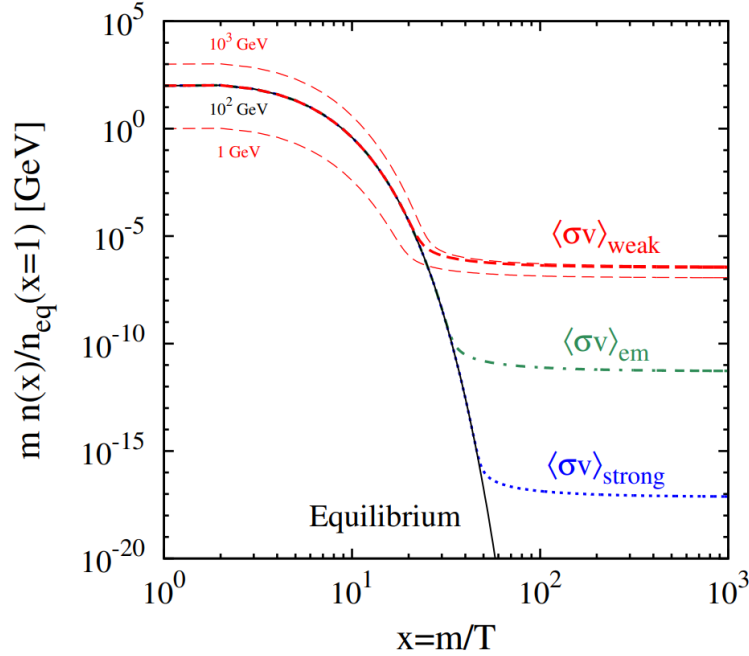


Figure 2.5: The time evolution of the WIMP abundance. $n(x)$ in the quantity plotted on the y-axis is the particle number density as a function of $x = m/T$, the ratio of the dark matter particle mass, m , and the initial density, T . This figure is taken from [12].

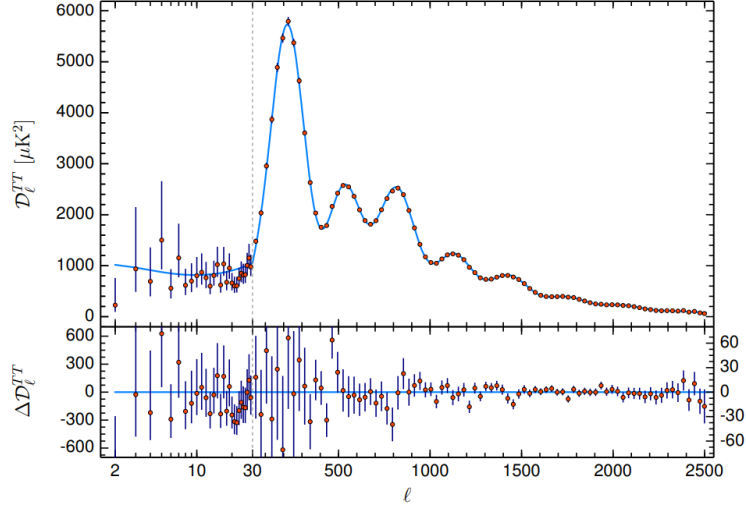


Figure 2.6: The angular power spectrum measured by Planck using the 2018 data. The blue curve is the best fit to the Planck data using the base Λ CDM model. The bottom panel shows residuals for the fit. From [13].

Figure 2.6 shows a power spectrum of the temperature anisotropies as a function of the angular scale of the sky. Using the Λ CDM model and the location and amplitudes of peaks in this spectrum, cosmological energy densities and the total matter composition of the universe can be obtained. The results indicate that only 30% of the total energy component of the universe is attributable to matter and of this 30%, roughly 85% is dark matter.

The current values of the critical density of baryonic matter, Ω_b , and non-baryonic dark matter, Ω_{DM} [13] are found to be

$$\Omega_b h^2 = 0.02226(23) \quad (2.3)$$

$$\Omega_{DM} = 0.1186(20) \quad (2.4)$$

In these expressions, $h = \frac{H_0}{100 kmMPcs}$ is the reduced Hubble constant. This is calculated from the Hubble constant today, H_0 .

2.3 Searches for Dark Matter

The observational evidence for dark matter that was previously discussed indicates that dark matter consists of electrically neutral particles that interact feebly with the Standard Model and itself. Observations of the CMB indicate that dark matter should be non-baryonic and has a certain cosmic density. Observations of the stellar motion of the Milky Way indicate its local density is $\sim 0.3 - 0.4 \text{ GeV}/\text{cm}^3$ and that its local velocity dispersion is $\sigma_v = 200 \text{ km s}^{-1}$, where the galactic rest frame is in the direction of the Cygnus constellation.

Up until the last decade, experiments focused on looking for Weakly Interacting Massive Particles. Cold dark matter ($v/c \lesssim 0.1$) would have to have a cross-section for interactions with SM around $\sigma_{SM-DM} \gtrsim 1 \text{ pb}$ to produce the observed relic abundance [86]. This cross-section is on the order of the typical cross-sections of weak interactions and this result is known as the “WIMP miracle.” Many candidates exist that are electrically neutral, interact weakly, are non-baryonic, and are non-relativistic. Some candidates, like the lightest neutralino from SUSY are part of complete theories, while many other candidates are predicted by models that do not contain UV completion. These more complete frameworks pose a difficult task for experimental results to resolve a large number of degeneracies as the only known property for dark matter is its relic abundance. Some examples of WIMP candidates are introduced below. Experimentally distinguishing between WIMP candidates will be difficult.

As WIMPs have been increasingly excluded, scientists have pursued other theoretically well motivated candidates, including particles of a “Hidden Sector” or wave-like particles.

2.3.1 Direct and indirect detection experiments for WIMPs

Dark matter could annihilate into gamma rays, charged leptons, anti-matter, and a variety of other final-states. Indirect detection experiments search for an excess of these annihilation products in the data. Since there are many possible final-states produced by mechanisms in the SM or beyond the SM, indirect detection searches have a relatively large uncertainty that is due to the modeling of the expected flux from background sources.

Particular models assume that when dark matter annihilates in Standard Model particles, a spectrum of gamma-rays is produced in the final state when the Standard Model particles produced by the dark matter annihilation interact with the interstellar medium. These interactions include inverse Compton scattering, bremsstrahlung radiation off galactic gas, natural pion decays originating from interactions of hadronic cosmic rays with interstellar gas, or synchrotron emission induced by propagation in magnetic fields [87]. A review of experiments looking for an excess of gamma rays at the galactic center are given in [88], [89], [90], and [91].

The principle behind the method of direct detection is to measure small energy deposits produced in the elastic scattering of dark matter particles off of some target nuclei [92]. If DM-SM interactions exist, this scattering occurs with a low probability and would produce a continuous energy spectrum. Various mechanisms are implemented to measure these energy deposits, but the experiments that employ them have the following requirements in common: very low energy thresholds, ability to identify distinctive signatures, ultra-low backgrounds, and the ability to discriminate signals from background [87]. Various reviews of the method of direct detection are in Refs. [93] [94] [95] [96]. These experiments probe masses of dark matter from the eV to TeV range.

The signature of dark matter particles scattering off target nuclei would appear as some excess of events above the background predictions consistent with an annual modulation of interactions rates [97][98], a directionality of a signal indicative of dark matter [99][100], or the Migdal effect [101][102][103]. Dark matter particles can interact with matter in a spin-independent or spin-dependent manner. The scattering could occur off nuclei, resulting in a nuclear recoil, or could occur off an electron, resulting in an electronic recoil. The nuclear and electronic recoils are measured as charge produced, light or heat signals, or some combination of charge production, light, and heat [104] [105]. Standard nuclear and electronic recoils constitute backgrounds for these experiments, but can be distinguished from a WIMP recoil because different quenching factors relate the recorded signal and measured recoil energy.

2.3.2 Searches for wave-like particles

Charge conjugation (C) and Parity reversal (P) in combination have been observed to be violated in weak decays [106] and this is thought to explain some of the differences in the interactions of particles and anti-particles. However, this alone

cannot resolve the matter-antimatter asymmetry [107] and gives rise to the question of why CP violation does not exist in strong interactions. A new global axial U(1) symmetry with an associated pseudo-scalar field present in all of space that couples to quarks and underwent spontaneous symmetry breaking in the early stages of the universe would resolve this. The boson produced by this broken symmetry is known as the “axion” [108][109][110][111].

The axion has recently garnered significant experimental interest as a leading candidate for dark matter as null results for axions of masses of a few hundred keV indicate axions would have to have small masses and interact feebly with matter [112]. Axions are considered “wave-like” because as light bosons, they do not obey the exclusion principle and can exhibit collective wavelike behavior [111]. These candidates would be slow-moving and satisfy the criteria that dark matter is cold.

An axion dark matter candidate would look like an additional electrical current or anomalous magnetic field [113], making emergence of photons out of a vacuum placed in a magnetic field a distinctive signature of its presence [114]. Axions cause the nuclear and electron spins to precess due to the invisible axion field that couples the spins to anomalous magnetization [115][116]. Experiments that look for axion and axion-like particles search for direct conversions and this requires strong magnetic fields given the weak interaction between axions and photons. The Axion Dark Matter eXperiment (ADMX) uses resonant cavities immersed in superconducting magnets to try to observe axions converting into microwave photons. Telescopes like the CERN Axion Search Telescope (CAST) search for axions produced when X-rays in the sun scatter off strong electric fields or are converted into photons in the magnetosphere of neutron stars. Laser beams have also been used with magnets to convert light to axions and vice versa.

The mass range of axions spans μeV to eV and while some constraints exist from astrophysical observations [117], the mass is not theoretically predictable and must be determined experimentally.

2.3.3 Accelerator-based searches

Dark matter can be produced at colliders. While a signature of dark matter cannot be directly observed by detectors, colliders can study the mediator of the interaction between the Standard Model and dark matter and these searches benefit from high center-of-mass energies and high statistics. High energy physicists use a variety of benchmark models to conduct their searches: dark sector models, simplified model of a spin-1 mediator, simplified Higgs portal model, SUSY scenarios, and long-lived particle signatures. Complete models, like SUSY, are theoretically robust and provide a number of final states to search for, but are difficult to compare across experiments. On the other hand, simplified models provide a tractable parameter space and make it easy to compare to results from direct and indirect detection experiments, though they can lead to oversimplifications in exclusions.

The next subsection covers MET and non-MET based searches, as they are complementary. SUSY searches are not covered here, but a very interesting and recent article can be found here [\[118\]](#).

MET and non-MET based searches

The observation of a signature from DM in a direct detection experiment would indicate there is an effective coupling between quarks and DM particles, mediated by a new force. If DM can couple to quarks, it can also be produced in proton-proton collisions at the LHC, as in the process depicted in Fig 2.7(a). This process would leave no visible signature in the detector because of dark matter’s extremely weak interactions with the SM particles that make up the detector. If the pair of DM particles recoiled off of highly energetic visible particles, the presence of the DM particles can be inferred by the presence of missing transverse momentum, the negative vector sum of all visible objects and soft energy deposits.

The event selection used in these analyses require a high momentum object (jet, photon, boson), denoted by “X,” radiated by the initial state quarks and gluons that recoil off large missing p_T . The event selection would contain a significant amount of missing transverse energy as well. Mono-X searches enhance the signal in their searches by requiring signal regions have high missing p_T and requiring the X object satisfy strict quality requirements. Reviews of mono-X searches and a summary of recent results of mono-X searches at ATLAS during Run 2 are provided in [\[119\]](#) and in [\[120\]](#), [\[121\]](#), [\[122\]](#), [\[123\]](#), [\[124\]](#), [\[125\]](#), [\[126\]](#), [\[127\]](#), and [\[128\]](#).

Instead of looking for DM particles, dijet searches target the interaction between SM and DM by looking for the mediators that, when produced, decay back to a pair of quarks, as in Fig. 2.7(b), producing a visible signature of two jets in the ATLAS detector. Dijet resonance searches for dark matter is the subject of Chapter 5

Leptons have no role at tree-level in the phenomenology of hadron collider or detector searches [129] [130], but have couplings at higher order. Some collider searches do look at models with non-zero couplings to leptons. A non-zero coupling of the mediator to leptons will not increase the width of the mediator appreciably, but new constraints are placed in the parameter space from measurements from Drell-Yan processes. If leptonic mediator couplings were considered in the theory, di-lepton resonance searches could provide constraints on those models. Those searches are not discussed here.

Limits from accelerator-based searches

I will present the results of mono-“X” and dijet searches together in the context of one another here. The model explored by the analysis in this thesis uses a leptophobic mediator to search for a dark matter mediator because hadron collider and direct detection searches primarily probe interactions between dark matter with quarks. Fig. 2.8 shows regions in the (mediator-mass, DM-mass) plane excluded at 95% CL by visible and invisible searches, for leptophobic axial-vector and vector mediators. The shaded regions show the union of the exclusion limits of individual analyses listed, including the mono-“X” and standard dijet searches. The dashed curves that are

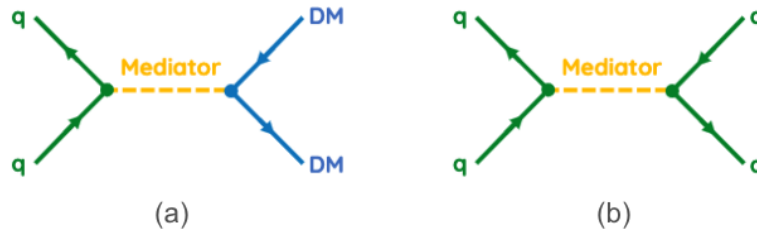
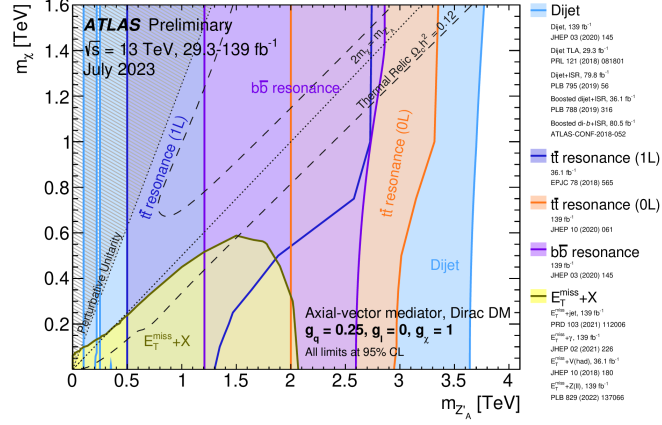


Figure 2.7: Feynman diagrams showing the production of a DM mediator and its decay to (a) a pair of dark matter particles ($qq \rightarrow \chi\chi$) and (b) a pair of quarks. From [14].

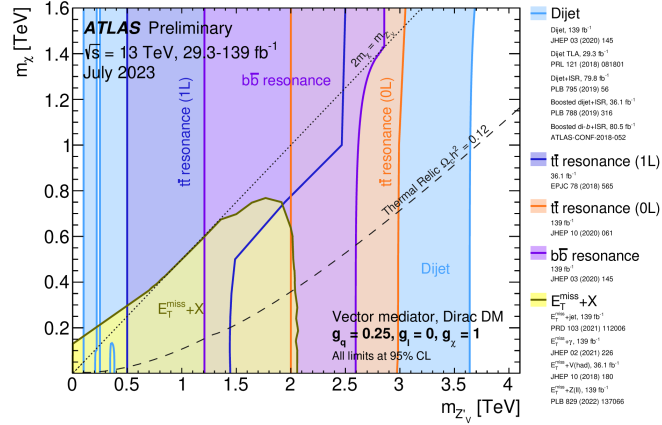
labelled the “thermal relic” indicate values of the DM mediator mass and coupling values that are consistent with the dark matter relic density of $\Omega_{h^2} = 0.12$, as computed by the MadDM package [131][132]. Between the dashed curves, annihilation processes cause the relic density to be below this value. The dotted line shows the kinematic threshold where the mediator decays on-shell into DM. The limits from the Trigger Level Analysis (TLA) analysis come from [36]. The high mass dijet analysis come from [133].

The yellow exclusion regions come from the mono-“X” analyses. We can see some regions at low mass that aren’t covered by the intersection of all the searches. This region below 1 TeV is of interest to this thesis and can be probed with the TLA and ISR techniques, discussed in Chapter 5.

Adding a leptonic coupling changes the exclusions in phase space considerably, shown in Fig 2.9, though di-lepton analyses exclude some of the phase space.

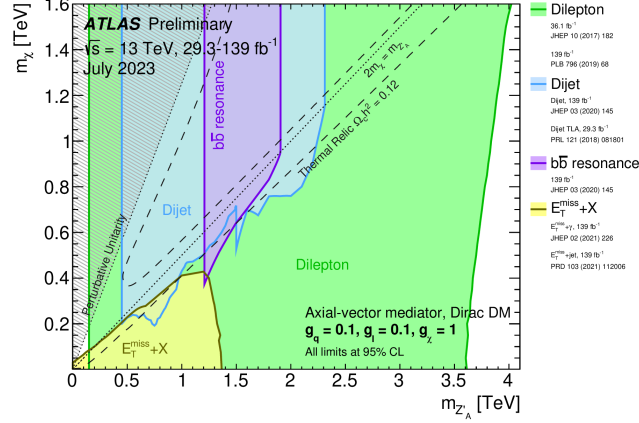


(a) Axial-vector mediator, Dirac DM. $g_q = 0.1$, $g_l = 0.0$, and $g_\chi = 1$

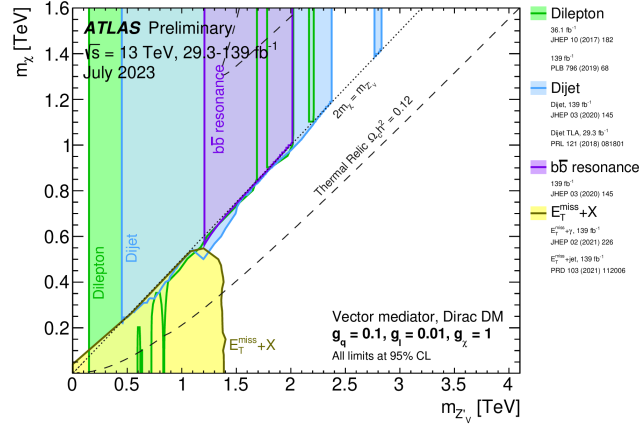


(b) Vector mediator, Dirac DM. $g_q = 0.1$, $g_l = 0.0$, and $g_\chi = 1$

Figure 2.8: Regions in the (mediator-mass, DM-mass) plane excluded at 95% CL by visible and invisible searches, for (a) a leptophobic axial-vector mediator and (b) a leptophobic vector mediator that are part of a simplified model. From [15].



(a) Axial-vector mediator, Dirac DM. $g_q = 0.1$, $g_l = 0.1$, and $g_{\chi} = 1$



(b) Vector mediator, Dirac DM. $g_q = 0.1$, $g_l = 0.01$, and $g_{\chi} = 1$

Figure 2.9: Regions in the (mediator-mass, DM-mass) plane excluded at 95% CL by visible and invisible searches, for (a) a leptophilic ($g_l = 0.1$) axial-vector mediator and (b) a leptophilic ($g_l = 0.01$) vector mediator that are part of a simplified model. From [15].

Chapter 3: Experimental Setup

This chapter presents the experimental setup used to perform the search for dijet resonances in association with an initial state radiated photon presented in Chapter 6. The Large Hadron Collider (LHC) produces proton-proton (pp) collisions that are measured by the ATLAS detector. Section 3.1 describes the LHC machine layout, acceleration principles, and performance. Section 3.2 and its subsections detail the subsystems of the ATLAS detector and how they measure physical phenomena.

3.1 The Large Hadron Collider

The LHC is the world's largest particle accelerator, operating at the CERN laboratory. It has a circumference of 27 km. The LHC complex uses a series of smaller accelerators in an acceleration chain to accelerate protons or heavy ions in two counter-rotating beams. These beams enter the LHC collider ring at peak energies and are collided at four interaction points where the ATLAS [134], CMS [135], LHCb [136], and ALICE [137] experiments are located. These detectors study the particles produced during pp or heavy ion collisions and their decay products.

3.1.1 Acceleration Chain

The acceleration chain is shown in Fig. 3.1. Protons are first obtained by using an electric field to strip the electron from a hydrogen atom. The protons are first accelerated in a linear accelerator, the LINAC2. Radio-frequency (RF) cavities are used to provide time-varying electric fields that accelerate the protons. When the protons are released from the LINAC2, they have been brought up to an energy of 50 MeV and proceed through three circular accelerator rings that increase in size. The circular accelerators also use RF cavities to accelerate the protons and strong dipole magnetic fields to guide the protons in circular rotating beams. After the

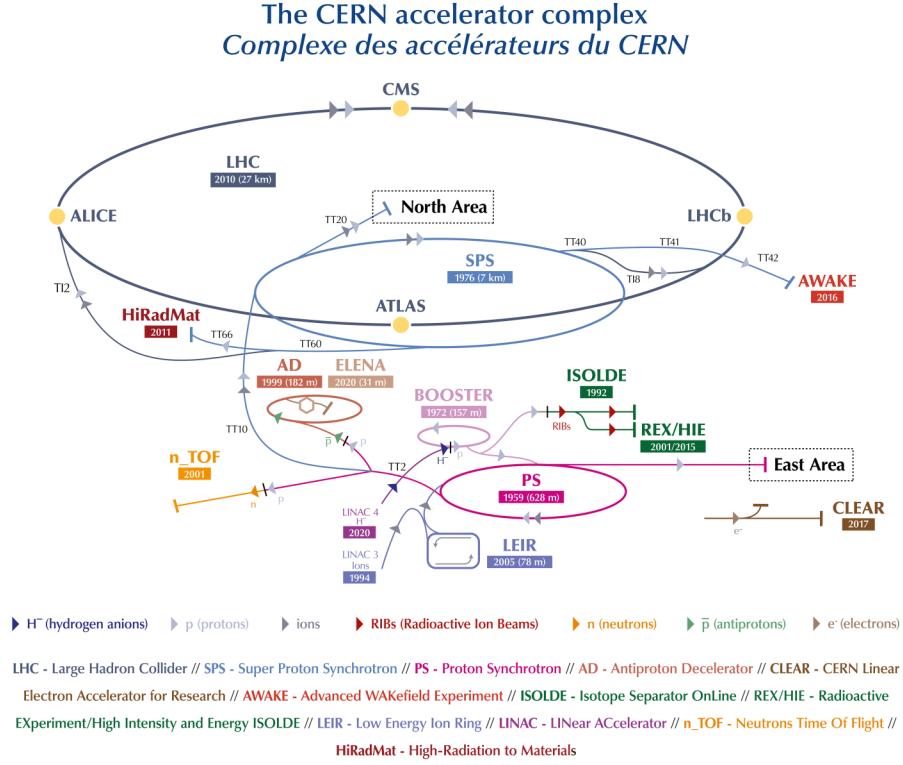


Figure 3.1: The CERN accelerator complex [16].

protons have made their way through the Proton Synchrotron Booster (BOOSTER), they have achieved energies of up to 1.4 GeV. They are then accelerated by the Proton Synchrotron (PS) up to energies of 25 GeV. These protons then enter the Super Proton Synchrotron where they attain energies of up to 450 GeV and are ready to be injected into the LHC rings in two separate vacuum pipes. Each pipe contains a beam circulating in opposite directions. When the beams are ready to be collided at the four interaction points where the four detectors are located, triplet magnets are used to squeeze the beams, reducing their width in the transverse plane prior to the actual collision.

3.1.2 Performance

The performance of a particle collider is evaluated by the energy available for collisions and the number of useful interactions it is able to produce [138]. These quantities are referred to as center-of-mass energy and luminosity, respectively. An additional parameter that affects the ability of the experiments to accurately reconstruct physics events of interest from the interactions provided by the LHC collider is the number of additional interactions per bunch crossing that occur with the hard-scatter. This quantity is known as pile-up.

Center-of-mass energy

The center-of-mass energy, denoted by the square root of the Mandelstam variable s ($\sqrt{s}$), is the total energy of a particle collision in the center-of-mass reference frame where the sum of the momentum of the two particles is zero. When it is said that the LHC is run at $\sqrt{s} = 13$ TeV, this means that 13 TeV is the maximum available energy for producing particles. The center-of-mass energy provided by an accelerator is determined by the size of that accelerator and the magnetic fields used to circulate the beam of charged particles.

Luminosity

The rate of pp collisions per second at LHC is given by Eq. 3.1 [138].

$$\frac{dN}{dt} = \mathcal{L}\sigma_{pp}^{total} \quad (3.1)$$

In this expression, σ_{pp}^{total} is the total pp interaction cross section, measured in barns ($1b = 10^{-28} \text{ m}^2$). $\mathcal{L}$ is the instantaneous luminosity delivered by the accelerator, measured in $\text{cm}^{-2}\text{s}^{-1}$. It is calculated from parameters of the collider in Eq. 3.2 [56].

$$\mathcal{L} = S \frac{k f N_1 N_2}{4\pi\sigma_x\sigma_y} \quad (3.2)$$

N_1 and N_2 are the intensity of the two bunches of protons, measured as the number of protons in each bunch. $k \cdot f$ is the interaction frequency given k bunches with revolution frequency of f . S is the luminosity reduction factor. Due to geometric effects and a non-zero bunch crossing angle, the bunch sizes vary in size in the transverse plane when they collide and a factor $S < 1$ is applied to account for

these effects. If $\hat{z}$ is the the beam-axis, $\sigma_{x,y}$ are the rms widths of the beam density distributions in the x and y directions, assuming a Gaussian beam shape. During Run 1, the maximum instantaneous luminosity delivered to the ATLAS detector was measured to be $\mathcal{L} = 0.8 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [139]. For Run 2, $\mathcal{L} = 2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [140].

The integrated luminosity, $\mathcal{L}_{int}$, is the amount of data collected during a time period, expressed as an inverse of a cross-section, quoted in inverse femto-barns (fb^{-1}). It is calculated using Eq. 3.3.

$$\mathcal{L}_{int} = \int \mathcal{L} dt \quad (3.3)$$

For a process with a particular cross section of σ , the number of events produced is given in Eq. 3.4.

$$N = \mathcal{L}_{int} \times \sigma \quad (3.4)$$

The instantaneous luminosity decreases over time as the LHC operates due to decaying beam intensity, emittance growth, and increased bunch length. Figure 3.2 shows measures of integrated luminosity for the Run 2 performance. Of the data that ATLAS recorded, 139 fb^{-1} of that is usable for physics analysis.

Pile-up

When bunches are collided, there is a hard-scatter and additional soft interactions that arise from additional pp interactions that occur during each collision. The average number of these collisions, μ , is related to the machine parameters by Eq. 3.5 [141].

$$\langle \mu \rangle = \frac{\mathcal{L}_{bunch} \times \sigma_{inel}}{N_{bunch} \times f_{LHC}} \quad (3.5)$$

$\mathcal{L}_{bunch}$ is the average luminosity over a large period of time, σ_{inel} is the total inelastic pp cross section, N_{bunch} is the number of bunches, and f_{LHC} is the revolution frequency. The luminosity-weighted distribution of $\langle \mu \rangle$ per bunch crossing for all pp collisions in Run 2 is shown in Figure 3.3.

“In-time pile-up” refers to the additional collisions that happen in the same bunch crossing as the hard scatter and is estimated by the number of primary vertices, N_{PV} , reconstructed in the event [142]. “Out-of-time pile-up” occurs when additional collisions in neighboring bunches contribute to an event. This happens because the time

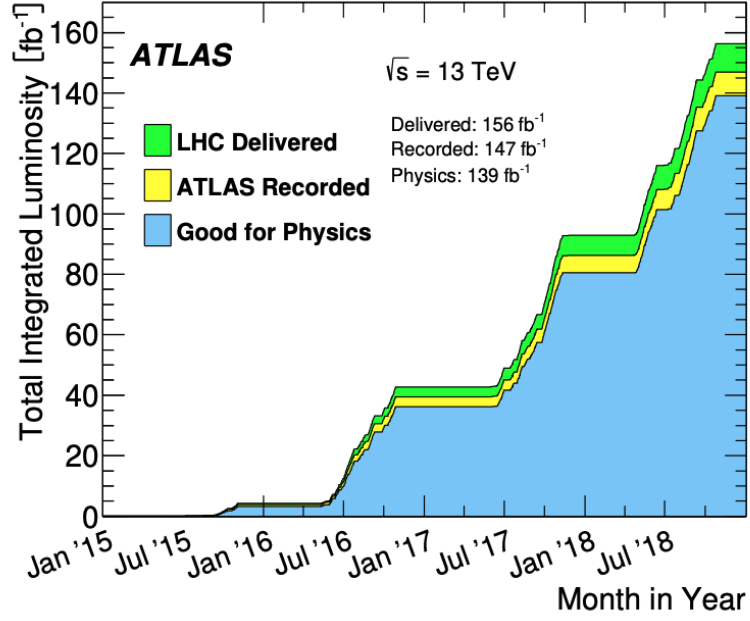


Figure 3.2: The total integrated luminosity delivered to (green) and recorded by (yellow) the ATLAS detector during the years 2015 through 2018 during stable beam pp collisions at $\sqrt{s} = 13 \text{ TeV}$. From [17].

it takes to read out the electric signals in the detector is greater than the timing space between bunches of 25 ns. The overall effect of pile-up is to degrade the reconstruction quality of the hard scatter during offline data analysis.

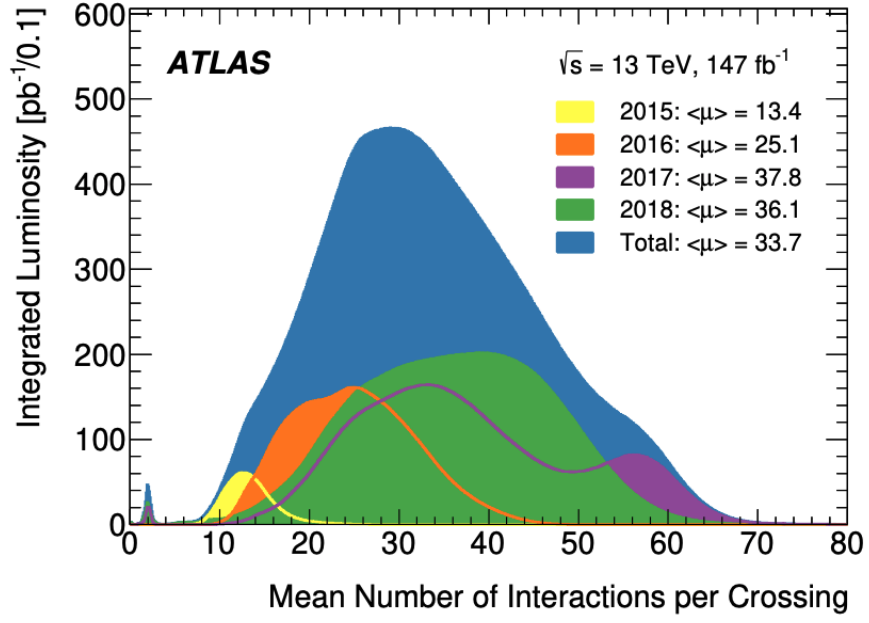


Figure 3.3: The luminosity-weighted distribution of the mean number of pp interactions per bunch crossing, $\langle \mu \rangle$, for all Run 2 data collected between 2015 and 2018 at $\sqrt{s} = 13$ TeV. The mean value of μ for each year is listed. From [17].

3.2 The ATLAS Detector

A Toroidal LHC Apparatus (ATLAS) is a general purpose detector designed to study pp collisions [134]. ATLAS is composed of an inner tracker, a calorimeter system, and a muon spectrometer arranged in the central barrel region and two identical end-caps in the forward region.

The Inner Detector is closest to the beamspot and reconstructs the trajectories of charged particles to measure their momentum with high efficiency and identify primary vertices. It covers pseudorapidities of $|\eta| < 2.5$ [143] and is contained within a superconducting solenoid with a 2T axial field. Surrounding the solenoid is the calorimeter system, segmented into towers and arranged in a projective geometry, each tower consisting of electromagnetic and hadronic components covering the barrel and end-cap regions up to $|\eta| < 4.9$. These calorimeters measure the energy of electromagnetic and hadronic showers produced by neutral and charged particles. The muon spectrometer is composed of precision measurement chambers with azimuthal symmetry that cover $|\eta| < 2.7$. They are held within three super-conducting toroids that allow for the measurement of muon momenta. Figure 3.4 shows the whole detector. The detector is cylindrically symmetric, hermetic, and has nearly full solid angle coverage around the interaction point.

3.2.1 Coordinate System

The ATLAS experiment utilizes a right-handed cylindrical coordinate system depicted in Figure 3.5. The directions of the incoming beams are along the longitudinal axis (z-axis) and the origin is defined as the interaction point along this axis. The x-y plane is defined as the transverse plane. The radial coordinate, r , is defined as the transverse distance to the beam axis. Using polar coordinates, the azimuthal angle, ϕ , is measured around the longitudinal axis and the polar angle, θ , measures the particle's direction from the $+\hat{z}$ direction.

The quarks and gluons from within the colliding protons contain a variable fraction of the proton's initial momentum. This means that the initial momentum of the colliding partons in the longitudinal direction is unknown. Conservation of momentum dictates that the net momentum of the partons in the transverse plane be close to zero. Any deviations from zero fall within the resolutions of the measurements of particles.

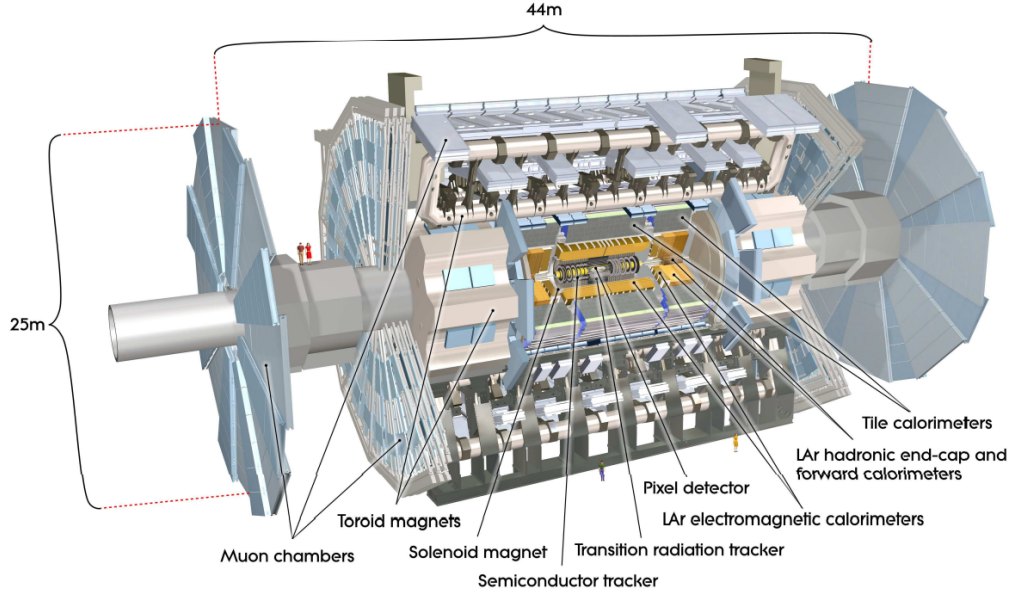


Figure 3.4: A schematic of the ATLAS detector with the various subsystems labeled. The whole apparatus is 44m in length and 22m in height.

The transverse momentum of any particle, p_T , is defined as the component of the momentum that is perpendicular to the beam axis.

Rapidity, y , is a relativistic measure of the longitudinal velocity of a particle. If E is the energy of a particle,

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right) \quad (3.6)$$

Rapidity differences are Lorentz invariant under boosts in the longitudinal direction. To indicate placement of sub-detectors within ATLAS and to describe the trajectories of charged particles, the quantity pseudorapidity (η) is commonly used.

$$\eta = -2 \ln \left[\tan \left(\frac{\theta}{2} \right) \right]. \quad (3.7)$$

Particles whose trajectories lie in the transverse plane have $\eta = 0$. An advantage of this formulation is that low polar angles can be expressed on an extended scale. In the limit of $\beta \rightarrow 1$, the pseudorapidity accurately estimates the rapidity.

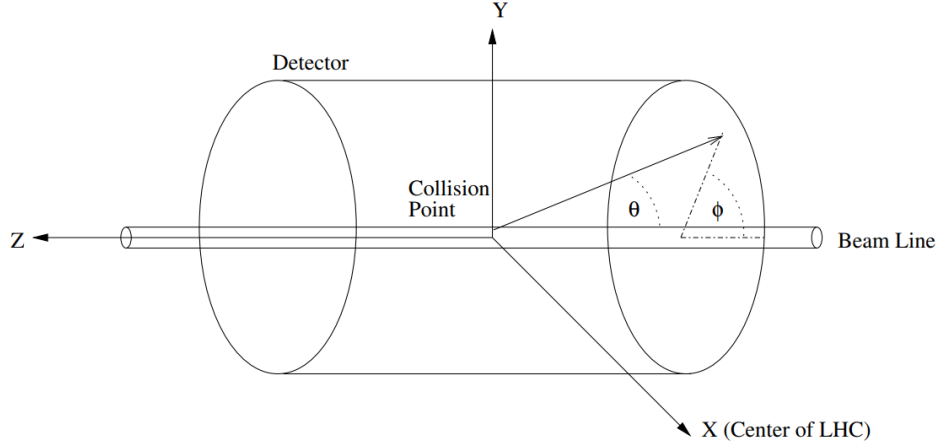


Figure 3.5: The right-handed cylindrical coordinate system used by the ATLAS detector. From [18].

3.2.2 Magnet System

The Lorentz force causes charged particles to follow a curved trajectory in a magnetic field. High magnetic fields are required to curve the particle's trajectory enough for a precise measurement of the momentum. The ATLAS magnet system contains a superconducting solenoid and three superconducting toroid magnets spanning an area of 11 m in radius and 26 m in length. Their layout is depicted in Fig. 3.6.

The central solenoid is located on the inside of the calorimeter system and encloses the Inner Detector. This field deflects charged particles along the ϕ -direction in the transverse plane. The solenoid magnet consists of an aluminum-stabilized ultra-thin superconductor which is indirectly cooled by a cryostat. Its dimensions are 5.8 m along z-axis and 2.5-2.6 m in diameter. By installing the solenoid between the inner wall and the Liquid Argon calorimeter surrounding the magnets, the total cryostat thickness is minimized.

A system of three large air-core toroid magnets surrounds the central solenoid and calorimeters in the ATLAS detector. A barrel toroid and two end-cap toroids deflect muons in the η -direction of the outer muon detector to produce a field between 0.5 T and 1T. This azimuthal magnetic field bends the trajectories of muons in the $r - z$ plane and allows for a precise momentum measurement. Since the central solenoid

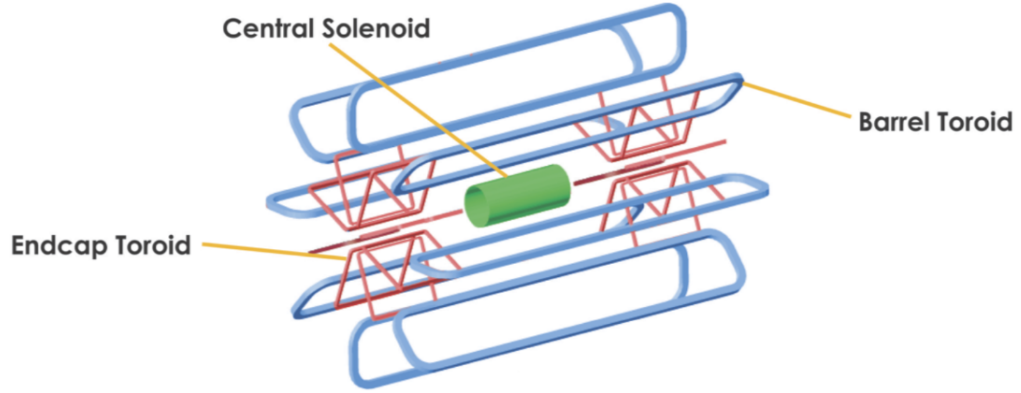


Figure 3.6: Arrangement of the central solenoid and toroid magnets that produce magnetic fields within the Inner Detector and Muon Spectrometer. From [19].

is sufficiently far from this system of toroid magnets, its field is not changed by the toroids' magnetic fields.

3.2.3 Inner Detector

The Inner Detector (ID) ([144] [145]) is the most central detector system in ATLAS, located nearest to the beam pipe. This region is characterized by a high track density. By reconstructing tracks from charged particles, the ID allows for the identification of primary and secondary vertices from the hard scatter in an event and the measurement of track momenta. This requires a fast and radiation tolerant detector made of lightweight material so that particles do not lose energy before reaching the calorimeter.

The Pixel Detector (PD), the SemiConductor Tracker (SCT), and the Transition Radiation Tracker (TRT) are the three subsystems that comprise the Inner Detector. These subsystems are arranged into a barrel and two identical end-caps within a cavity encompassed by the cryostat containing the Liquid Argon electromagnetic calorimeter [21]. Fig. 3.7 shows the position and arrangement of these three Inner Detector subsystems in the barrel region. The silicon-pixel layers, SCT layers, and transition-radiation tracker modules are shown. The red line depicts a charged track with $p_T = 10$ GeV and $\eta = 0.3$ traversing through the Inner Detector.

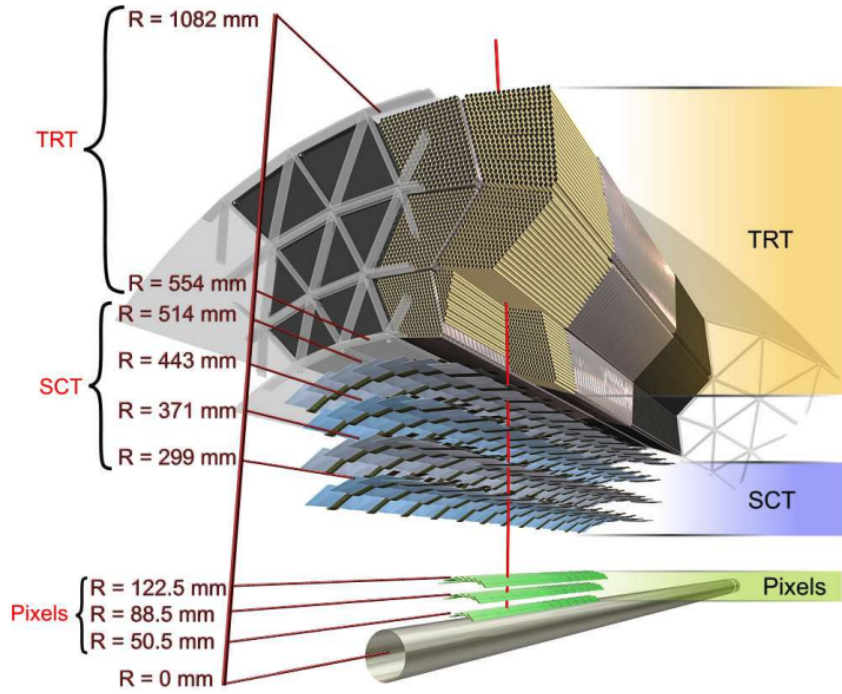


Figure 3.7: A cut-away view of the sensors in the barrel of the Inner Detector. From [20].

Figure 3.8 is a cutaway view of the Inner Detector systems in the barrel and end-caps. The red lines denote two charged particle tracks with $p_T = 10$ GeV and $|\eta| = 1.4$ and $|\eta| = 2.2$. The track with $|\eta| = 1.4$ traverses the three cylindrical silicon-pixel layers in the barrel, four of the nine SCT double-layer discs in the end-cap, and roughly 40 straw tubes in the TRT tracker wheels. The track with $|\eta| = 2.2$ traverses the first cylindrical silicon pixel layers, 2 end-cap pixel disks, and the last four disks of the end-cap SCT. It does not deposit any hits in the TRT which provides coverage up to $|\eta| = 2$.

The whole Inner Detector measures 6.2 m in length and 2.1 m in diameter. Together, the pixel and SCT detectors provide coverage of $|\eta| < 2.5$ in the radius between 30 mm and 1m, and the TRT covers the range of $|\eta| < 2.0$.

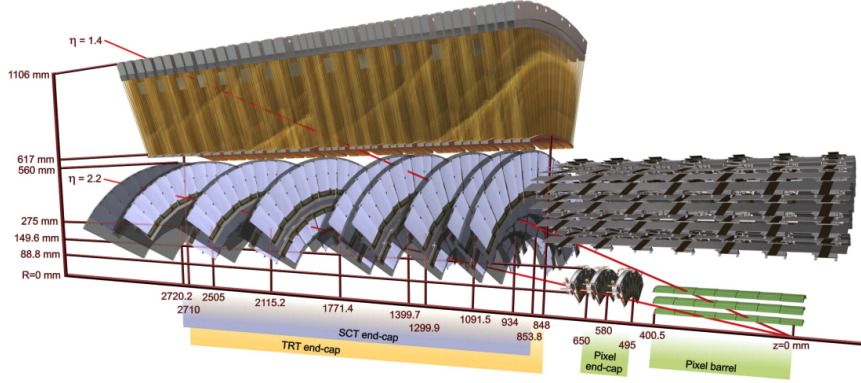


Figure 3.8: A cut-away view of the sensors in one of the end-caps of the Inner Detector. The pixel, SCT, and TRT end-cap subdetectors are labeled. From [20].

Silicon microstrip and semiconductor pixel detectors are used to achieve high granularity measurements and this allows for the measurement of impact parameters and reconstruction of particle trajectories with high position, angle, and momentum resolution. The transition radiation detectors provide additional track measurements and electron identification.

Pixel Detectors

The Pixel Detector [146] is closest to the beam pipe and is organized into three barrel layers and three end-cap layers with an additional layer of pixels, the Insertable B-Layer, which was installed during the LS1 of the LHC to compensate for the effects of radiation and improve the tracking performance. The barrel is arranged by placing four coaxial layers at increasing radial distances from the beam pipe. In the end-caps, the modules are arranged on discs along the longitudinal axis that are centered around the beam pipe. The end-cap discs are tilted to ensure that the full area is active. This design ensures that an individual track is measured at a minimum of four points within the full η range of the detector.

The pixels within each sensor module produce a two-dimensional hit position within the module and when combined with the surface constraint, the measurement can be made three-dimensional. The charge deposited by the traversing particles is typically shared among adjacent pixels and analysis of the relative pulse heights in

adjacent pixels allows for a precise position measurement which has a resolution of $10\mu\text{m} \times 115\mu\text{m}$, which is smaller than the pixel size.

The Insertable B-Layer was added during the first long shutdown of the LHC because the sensitivity of the pixels in the Pixel Detector degrade after prolonged exposure to radiation [147] [148]. It improves the precision robustness of individual track reconstruction and provides for precise flavor-tagging. The IBL is located at a radial distance of 3.3 cm from the beam pipe and has a resolution of about $8\mu\text{m} \times 40\mu\text{m}$.

The overall resolution of the Pixel Detector is measured using test beams and is found to be between $5\mu\text{m}$ and $12\mu\text{m}$ [148] [149].

SemiConductor Tracker (SCT)

The SCT detector is located further away from the interaction point, where the density of tracks is lower. For cost efficiency, silicon microstrip modules are used instead of pixel modules [150]. These strip modules are arranged in four concentric layers parallel to the z-axis in the barrel between $r = 30$ mm and $r = 51$ mm while they are radially oriented and arranged in 9 layer discs in each end-cap. Consequently, a track will measure 4 to 9 hits depending on which η and ϕ region the track originated from.

Each strip module contains two silicon sensor planes that are glued back-to-back to each other a distance of 1 mm apart. Since these sensors are strip detectors, a single sensor can constrain only one of the position coordinates. The barrel strip modules are rectangular in shape, while the end-cap modules are arranged in a trapezoidal shape. The strip detectors only provide position information of hits and not a measure of the charge deposition of the particle that traversed them. The resolution is $17\mu\text{m}$ in the $r - \phi$ coordinate and $580\mu\text{m}$ in the z-coordinate in the barrel and $580\mu\text{m}$ in the radial coordinate in the end-cap [151].

Transition Radiation Tracker (TRT)

The Transition Radiation Detector [152] [153] consists of 300,000 cylindrical drift tubes (straws) filled with a mixture of Xenon, CO_2 , and O_2 . These straws are placed in a matrix of polypropylene fibers that induce transition radiation. The purpose

of this outermost tracking detector is to continuously track the particles out to the calorimeter. In addition to providing hit position measurements, the TRT has radiation detectors and the number of hits above the energy-deposit threshold is related to the Lorentz boost of the particle. This can be used to determine the mass of particles of the same momentum since $\gamma = \frac{E}{m}$. Between 1 and 100 GeV, this technique is used to distinguish pions and electrons. The straw tubes are arranged in disks in the end-caps. The TRT provides coverage within $|\eta| < 1$ and has a spatial resolution of $\phi \approx 130\mu m$ in both the $r - \phi$ plane in the barrel and $z - \phi$ plane in the end-cap.

Performance of the Inner Detector

By combining measurements from all three detector subsystems, the ID can reconstruct tracks within $|\eta| < 2.5$ that have a $p_T > 0.4$ GeV with a designed momentum precision given in Eq. 3.8.

$$\frac{\sigma_{p_T}}{p_T} = 0.05\% \cdot p_T[GeV] \oplus 1\% \quad (3.8)$$

The first term is due to the intrinsic resolution of the detector while the constant term is due to multiple scattering in the material. By comparing hits and measured impact parameter resolutions in data and simulation, the performance of the Inner Detector is given in [154].

3.2.4 Calorimeter

Located outside the superconducting solenoid, the calorimeters interleave layers of materials that induce cascades of secondary particle showers with layers that measure the energy deposited by these showers. The technique of mixing multiple layers of active and passive material is known as sampling. The passive material usually consists of a dense material with a high atomic number that absorbs the initial particle and initiates showers. The active layers mainly consist of Liquid Argon (LAr) and measure the ionization and scintillation light produced by these showers [155]. Electronics are then used to read out these signals. The electromagnetic calorimeter absorbs photons and electrons, while the hadronic calorimeter absorbs hadrons. In addition to these two subsystems, a forward calorimeter is implemented within ATLAS to extend coverage to large pseudorapidities.

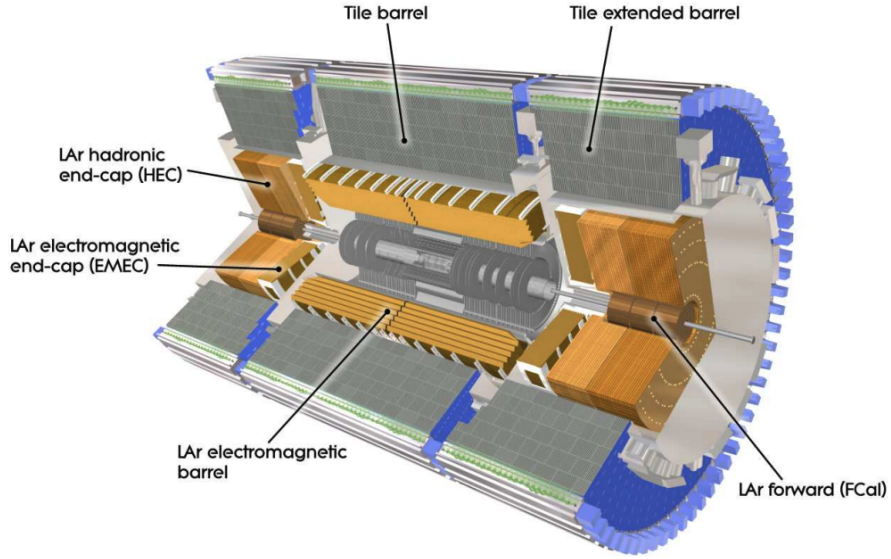


Figure 3.9: Cut-away view of the ATLAS calorimeter system, including electromagnetic and hadronic calorimeter detectors. From [20].

A diagram of the ATLAS calorimeter system from [20] is shown in Fig. 3.9. It is divided into the barrel, end-cap, and forward regions and provides hermetic coverage in ϕ and coverage within $|\eta| < 4.9$. The electromagnetic barrel is 6.4 m long and is located at radii between 1.4 and 2 m from the beam pipe, while the barrel region for the hadronic calorimeter is 5.8 m long and is located at radii between 2.3 m and 4.3 m from the beam pipe [155].

Measurements of the energies of neutral or charged particles produced in pp interactions that initiated these showers and any missing momentum in an event can be made by reconstructing the showers. The calorimeter is designed to fully contain the developing showers and maintain a lower probability that any particles other than muons will punch through the calorimeter and make it to the muon spectrometers. These requirements are met by carefully choosing materials with high radiation lengths for electromagnetic interactions and radiation interaction lengths for hadrons.

The Electromagnetic Calorimeter

The electromagnetic (EM) calorimeter [21] uses lead as its passive material and Liquid Argon (LAr) as its active material [155] to measure energy that is primarily deposited from electrons and photons. Jets also deposit some of their energy here.

The dominant process of energy loss for photons and electrons are bremsstrahlung, pair production, and ionization. Bremsstrahlung and pair production processes occur predominantly in the lead and have a cross section that is proportional to the atomic number of the material. This initiates the shower. Electrons produced in the shower then ionize the Argon and drift towards the anode to be read out. The barrel (providing coverage up to $|\eta| < 1.475$) and end-caps (covering $1.375 < |\eta| < 2.5$) are symmetric about the interaction point. The “crack” region between the coverage of the barrel and end-caps contains a large amount of inactive material and is typically vetoed in the reconstruction of electrons and photons.

Fig. 3.10 is a sketch showing the cell structure of the different sampling layers of the LAr calorimeter in the central region of the EM calorimeter. The three sampling layers shown have an accordion geometry and consist of two parallel lead planes with a Liquid Argon filled gap between them. This geometry is optimized for maintaining high sampling rates, low readout time, and having equal amounts of material to generate a shower in all ϕ

The Hadronic Calorimeter

The hadronic calorimeter is used to measure the energy of hadronic showers [156] and is made up of a tile calorimeter in the central region behind the electromagnetic calorimeter, a LAr hadronic end-cap calorimeter behind the end-caps in the electromagnetic calorimeter, and a LAr forward calorimeter. Copper and Tungsten are used as the passive material [156].

The tile calorimeter (TileCal) [157] covers the range of $|\eta| < 1.7$ in a central barrel structure and two extended end-caps and has an inner radius of 2.28 m and an outer radius of 4.25 m. A steel absorber is segmented into three radial layers of varying thickness and these layers are covered with scintillating plastic tiles that act as the active material. When a hadron interacts with the tiles, ultraviolet (UV) scintillation light is produced and two wavelength shifting optic fibers installed at the edges of each tile capture this light, which photomultipliers can efficiently measure and read out. In the end-cap calorimeter, covering $1.5 < |\eta| < 3.2$, the sampling is

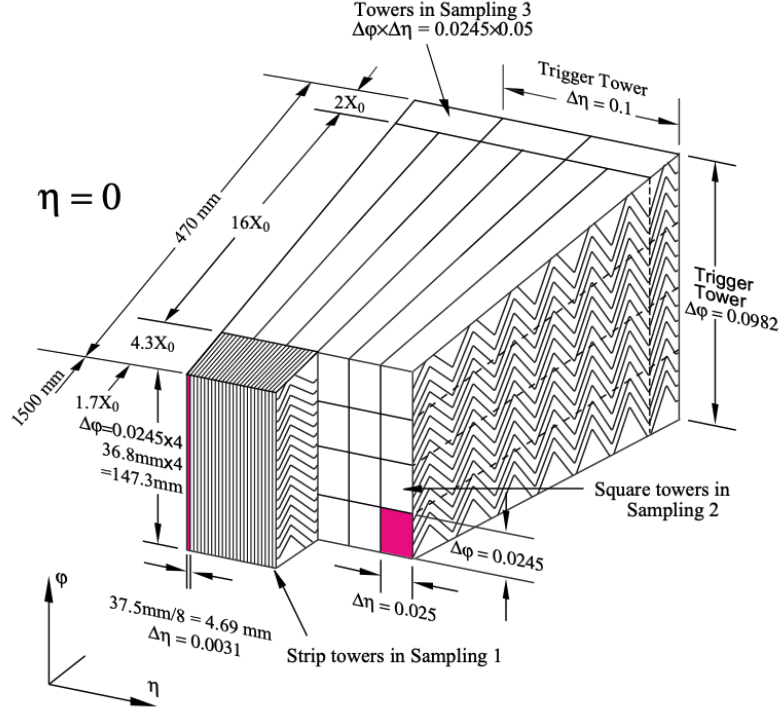


Figure 3.10: A slice of the ATLAS electromagnetic calorimeter. From [21].

instead obtained by alternating Copper plates and LAr in a planar geometry. The signal induced in the active material is read out in a capacitive way. The end-cap calorimeter is constructed as two independent wheels having different granularity.

The Forward Calorimeter

The forward calorimeter [158] [159] combines photon and electron absorption and hadronic absorption to more forward regions to extend coverage of the electromagnetic and hadronic calorimeters close to the beam pipe in the range of $3.1 < |\eta| < 4.9$. One electromagnetic calorimeter module and two hadronic calorimeter modules are used. LAr is the active material in both and Copper is used in the first module, while Tungsten is optimized for hadronic interactions in the latter two. Because most

collisions happen with low momentum transfer, this calorimeter is exposed to a high flux of particles and the granularity allows for precise measurements.

Energy Resolution of the ATLAS calorimeter system

By design, calorimeters are made of materials that respond in a manner proportional to the energy of a particle that passes through them. In contrast to detectors such as magnetic spectrometers, the precision of calorimetric measurement improves as the energy of the incident particle increases. The resolution of a calorimeter can be described by the functional form:

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a^2}{E} + b^2\right)} = \frac{a}{\sqrt{E}} \oplus b \quad (3.9)$$

The first term is stochastic, depending on the Poisson statistics of statistical fluctuations of EM and hadronic showers and sampling fluctuations. The constant term is related to instrumental effects like inefficiencies in signal collection, non-uniformity of the response of the detector, and noise from detector readout electronics. The energy resolutions of the electromagnetic, hadronic, and forward calorimeters are measured in test beams. The complexity of hadronic showers compared to electromagnetic ones results in poorer resolution. Hadronic calorimeters have been refined over the years to reduce the value of b .

The electromagnetic calorimeter has an energy resolution of [160]:

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E[\text{GeV}]}} \oplus 0.7\% \quad (3.10)$$

The hadronic tile calorimeter has an energy resolution of:

$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E[\text{GeV}]}} \oplus 3\% \quad (3.11)$$

The forward calorimeter has a combined energy resolution of:

$$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E[\text{GeV}]}} \oplus 10\% \quad (3.12)$$

3.2.5 Muon Spectrometer

Muons have a high mass and consequently emit less bremsstrahlung radiation than electrons, allowing them to penetrate through the electromagnetic calorimeter. Since muons do not interact strongly, they will not interact with material in the hadronic calorimeter. The muon spectrometer is located outside the calorimeter between radii of 5 m and 11m and integrates different detector technology to precisely track muons, allowing for determination of their momentum [161] [162].

The muon spectrometer consists of three layers in the barrel and three layers in the end-cap within a superconducting air-core toroid magnet, allowing for 3 measurements of the muon trajectory across the entire η range. The muon spectrometer allows for the measurement of the muon's momentum to a precision of 3% for low p_T muons and to 10% for high p_T muons.

The precision tracking chambers are the layers of detectors that cover the region $|\eta| < 2.7$. Monitored drift tubes are used in this entire region to provide spatial resolution of $35\mu\text{m}$ [163] [164]. In the high occupancy region between $2 < |\eta| < 2.7$, cathode strip chambers are used to provide a resolution of $60\mu\text{m}$ in the radial direction and 5 mm in the azimuthal direction [165]. The strip chambers are multi-wire proportional chambers in which the cathode is segmented. One cathode contains strips perpendicular to the wires, while the other has strips parallel to the wires, providing high-precision spatial measurements. The strip chambers have a high counting rate capability and a short electron drift time, resulting in high timing resolution.

Additionally, the muon spectrometer enables fast triggering on muons in the event using resistive plate chambers in the barrel up to $|\eta| = 1.05$ [166] and three to four layers of thin gap chambers in the end-cap between $1.05 < |\eta| < 2.4$ [167]. These systems provide additional three-dimensional measurements of the muon trajectory that complement measurements from the MDTs. By exploring the coincidence of hits in different layers, these systems serve as a hardware-based trigger for identifying muon trajectories.

The entire muon detector system is shown in Fig. 3.11.

3.2.6 Trigger Data Acquisition

The Trigger and Data Acquisition (TDAQ) system decides in real-time which data to record from a given collision using a two-level trigger system, playing a vital role in

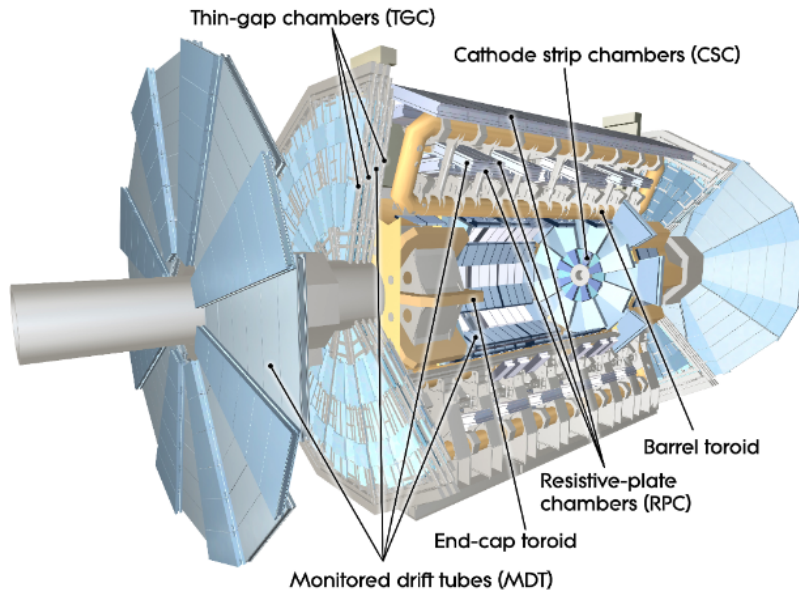


Figure 3.11: The layout of the ATLAS muon spectrometer. From [22].

defining the dataset used by a multitude of ATLAS physics analyses. The Level-1 (L1) Trigger and HLT Trigger are applied to reduce data from the initial bunch crossing rate of 40 MHz to a read-out rate of 100 kHz with a latency of 2.5 microseconds. As the instantaneous luminosity of the LHC and limitations in the detector readout, online processing farm, and offline storage change from year to year within a given run, the trigger system must be flexible so that it can maintain excellent performance.

Using custom electronics, the hardware-based L1 trigger takes reduced granularity data from the calorimeter and muon detectors and identifies physics objects to trigger on [168]. The Level-1 Muon Trigger (L1Muon) identifies tracks consistent with high- p_T muons originating from the interaction point. It does so using coincidence hits across multiple layers. The L1Calo trigger uses input signals from the electromagnetic and hadronic calorimeter to identify exclusive signatures from isolated high transverse-energy electrons, photons, muons, and tau leptons above a programmable threshold and measures global sums of missing and total transverse energy. The L1Calo trigger also identifies jet candidates. Results from the L1Muon and L1Calo are combined and processed by the Central Trigger processor in a trigger menu. Menu items may be pre-scaled to meet the allowable bandwidth rate.

The L1Topo trigger probes kinematic combinations and geometric requirements of trigger objects identified from the L1Calo and L1Muon triggers. This trigger also defines regions in η and ϕ where these objects were found and records the thresholds that they satisfied. Event-level quantities, multiplicity of objects above certain thresholds, and topological requirements help the L1Topo trigger to separate events from the predominant QCD jet production from potentially rare processes. When an event is accepted using the L1 trigger, front-end detector electronics read out event data from the detector subsystems. The data is then processed, formatted, buffered, and sent to a second-stage software-based trigger, called the High-Level Trigger (HLT).

The HLT is a software-based second stage of the trigger system. The HLT initially executes fast trigger algorithms on event-data fragments and makes a decision within a few hundred milliseconds whether or not to reject the event based on the features extracted by the algorithm [23]. After this early rejection stage, the HLT implements CPU-intensive algorithms that resemble the offline reconstruction and decides whether or not a specific trigger condition is satisfied based on the reconstructed features of the event. The HLT also makes a final decision whether or not to send the full event data to permanent storage.

The dataflow and readout between the components of the TDAQ system are shown diagrammatically in Fig. 3.12.

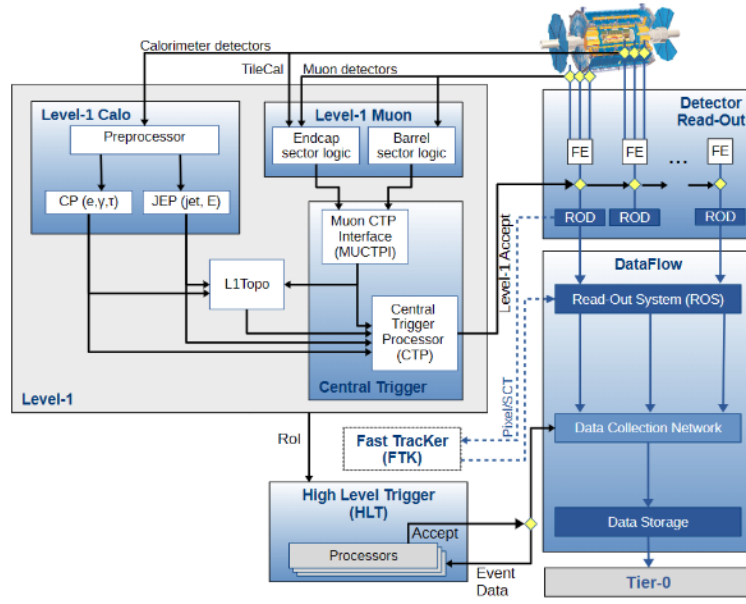


Figure 3.12: A schematic of the ATLAS TDAQ system used in Run 2 to process, select, and store events for offline analysis. [23].

Chapter 4: Offline Data Analysis

The initial step to any physics analysis is to define the topology being considered. Selecting events to analyze for a given analysis will require the presence or absence of physical particles like electrons, muons, tau leptons, and photons, or for jets and b-jets, which represent underlying physics processes involving quarks and gluons. These physics “objects” are reconstructed and measured from tracks, clusters, and vertices which are constructed using signals in the detector subsystems. Once these objects are reconstructed, they can be properly calibrated and used in physics analyses. Additionally, some particles including neutrinos will not interact with the detector and these invisible products create an imbalance of the measured momentum and energy within an event.

In this chapter, I am describing the reconstruction and performance of the final state physics objects and missing transverse energy. The analysis presented in the next chapter has a topology of an ISR photon and two jets, which are considered in one channel inclusively and are exclusively required to be b-tagged in a second channel. Photons and jets will be discussed at length after discussing the reconstruction level objects used to formulate them. The reconstruction of other objects is described in lesser detail.

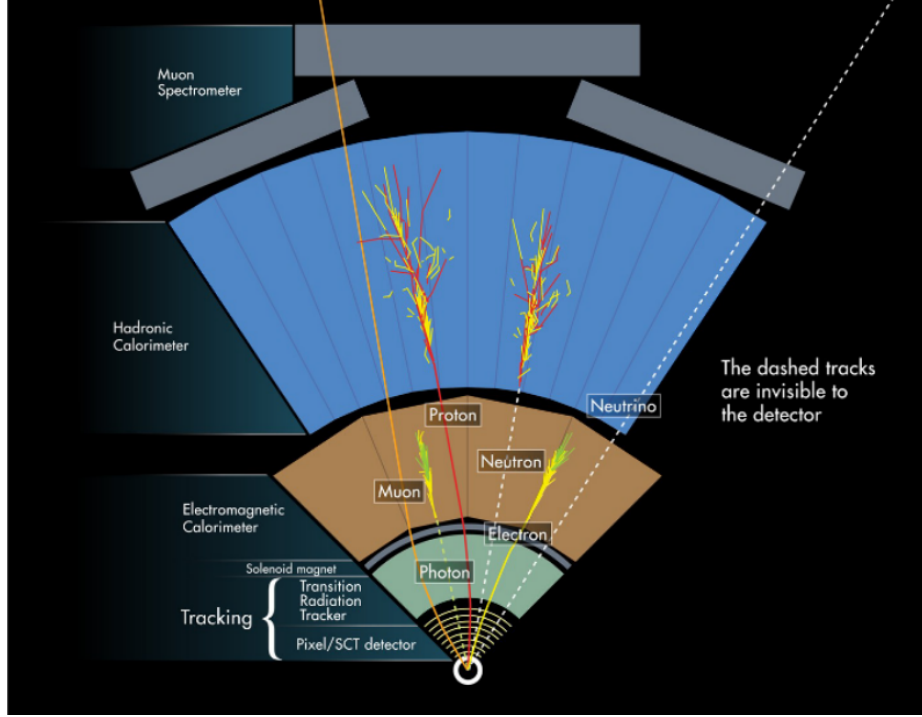


Figure 4.1: A visualization of various experimental signatures in the ATLAS detector. Signals measured in the detector are used to construct primary vertices, energy clusters, and tracks that are then used to assemble higher level objects like photons, electrons, muons, and jets. From [24].

4.1 Detector-Level Objects

Of the detector-level objects, tracks will be described in the most detail because track parameterization is discussed extensively in the tracking portions of this thesis.

Tracks

Charged particles produced from pp collisions will travel in circular or helical trajectories due to the solenoidal field within the tracking detector. Track reconstruction is the iterative process of identifying which hits are consistent with a single charged particle trajectory and measuring the properties of the particle that produced that trajectory [169]. A track is seeded by selecting triplets of neighboring pixel or strip hits in separate adjacent silicon layers. A search window is defined where a track

with that trajectory would produce additional hits in the detector and any additional hits found within this window are added to the seeds. Tracks are formed by taking the track seeds and adding those additional hits within the search window using a combinatorial Kalman filter [170][171][172]. The inside-out algorithm is first used to take hits in the silicon detector and form them into track segments that then get extrapolated into the TRT [173]. Any leftover hits from this first pass are used in an outside-in algorithm that takes standalone track segments in the outermost TRT detector and extrapolates them to the SCT and pixel detector. As additional hits are added to the fit while going from one layer to the next outermost layer, the track parameters are re-evaluated. If a layer contains multiple hits, multiple track candidates are defined and they proceed independently through the remaining track reconstruction steps.

The fit will produce an initial set of track parameters. Fig. 4.2 depicts the set of the five track parameters which are relevant to later portions of this thesis. The interaction point is along the beamline, which points in the $\hat{z}$ direction. Five quantities parameterize a charged particle track trajectory: the charge signed curvature ($\frac{q}{p_T}$), the polar angle of the track (θ), the azimuthal angle of the track in the transverse plane (ϕ_0), the longitudinal impact parameter (z_0), and the transverse impact parameter (d_0). The azimuthal angle ϕ_0 is measured in the transverse plane. The pseudorapidity $\eta = -\ln(\tan(\frac{\theta}{2}))$ is often used in physics analysis instead of the polar angle itself. The azimuthal angle ϕ_0 is measured with respect to the transverse plane, perpendicular to the beamline. The longitudinal impact parameter (z_0) is defined as the z position of the point of closest approach for the track of a charged particle produced in the collision. The transverse impact parameter (d_0) is the signed distance of the closest approach to the z -axis. This is the basis for 4-vector parameterization used in physics analysis. Since the material density is larger in the more forward regions, the uncertainty on track parameters increases at large $|\eta|$.

Primary Vertices

The primary vertex in a pp collision event is the location where the hard scatter occurs. Large pile-up contributes additional interaction vertices to an event and identifying the primary vertex allows for discrimination between activity in the event from the primary interaction and from pile-up. Primary vertex reconstruction is an iterative procedure that identifies vertices where at least two tracks originate close

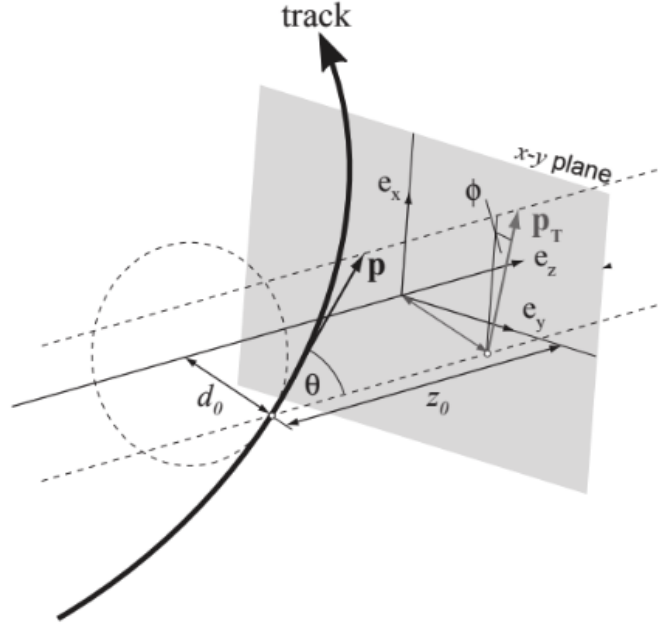


Figure 4.2: The perigee parameterization for tracks traversing through a cylindrical detector within a uniform solenoidal magnetic field.

to the beamline [174][175][176]. A vertex seed corresponding to the detector origin in x and y and to global maximum of z_0 distribution of the tracks in z_0 is defined using good quality tracks meeting the requirements in [177]). Any tracks that aren't compatible with this vertex are removed from consideration and considered in the construction of other vertices. A least squares based adaptive vertex fitter is used [178]. The procedure is iterated until no tracks are left in the event or no additional vertices are found. The primary vertex is the vertex for which the sum of the p_T^2 over all tracks is maximum.

Calorimeter Clusters

Two algorithms are used to cluster together adjacent calorimeter cells containing energy deposits [179]. The sliding-window algorithm [180] uses a fixed-size rectangular window and searches for the local maximum. The topological clustering algorithm [181] is used in the reconstruction of electrons, photons, and jets in ATLAS. This method has been used instead of the sliding-window since 2017 and implements a

variable-sized cluster. More specifics on the calorimeter clustering algorithm used to reconstruct electrons and photons is described in the next section.

4.2 Photons and electrons

Electrons can interact with the detector material as they traverse through the detector. Through bremsstrahlung interactions with the material, an electron can lose a significant amount of its energy that is converted into a radiated photon. The radiated photon can then convert into an electron-positron pair and these products can have their own bremsstrahlung interactions with the detector material. The photons, positrons, and electrons that are emitted in this process are emitted in a collimated way and are usually reconstructed as a part of the same electromagnetic cluster. The initial interaction of an electron from the hard scatter with the detector material can occur in the beam pipe, in the inner-detector, or downstream of the inner-detector in the electromagnetic calorimeter. If the conversion happens prior to the calorimeter, multiple tracks will be generated in the Inner Detector and can be matched to the primary electron in the process of electron reconstruction.

Photons that do not originate from hadron decays are considered prompt photons. Photons that convert to an electron-positron pair before reaching the electromagnetic calorimeter are converted photons and photons not associated with a conversion are unconverted photons.

Electron and Photon Reconstruction

Electrons and photons produce similar electromagnetic showers when they interact with the EM calorimeter, depositing a significant amount of their energy in a restricted number of neighboring calorimeter cells. Due to the similarities, electron and photon reconstruction occurs in parallel. Electron reconstruction is described in [182]. A detailed description of the reconstruction of unconverted and converted photons is in [25].

The EM calorimeter space defined in $\eta \times \phi$ is divided into a grid of 200×256 towers in units of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$, which is the granularity of the middle layer of the EM calorimeter. The energy in a tower is the sum of the first, second, and third calorimeter layers plus the energy deposited in the presampler. Initially, a sliding window algorithm [180] is used to search for electromagnetic cluster seeds with

total cluster transverse energy greater than 2.5 GeV. A clustering algorithm [183] is used to form clusters around the seeds and remove any duplicates. Then, tracks are loosely matched to seed clusters.

Photon reconstruction involves reconstructing both converted and unconverted photons. A two track conversion vertex is reconstructed from two tracks forming a vertex consistent with being from a massless particle. Single track vertices are formed from tracks without hits in the innermost sensitive layers. The tracks that are used to create conversion vertices must have a high probability to be electron tracks as determined by the TRT [184]. Any photon candidates not matched to a conversion vertex candidate or track candidate during electron reconstruction are considered unconverted photons. Clusters matched to conversion vertex candidates are converted photon candidates. If a converted photon candidate is also reconstructed as an electron, the electron track is evaluated against the properties of tracks originating from the conversion vertex candidate matched to the same cluster. Track hits, momentum, and E/p properties are used to recover unconverted photon candidates from reconstructed electron candidates.

The information from the calorimeter is used to measure the energy of the photon. A calibration procedure used in Run 1 [185] and adapted for Run 2 [186] is used to correct the photon energy to account for upstream energy loss and both lateral and longitudinal leakage. Additional simulation-based and data-driven corrections are determined separately for converted and unconverted photons. The photon E_T is found from the calibrated energy E of the photon and the η of the barycenter in the second layer of the EM calorimeter in Eq. 4.1.

$$E_T = \frac{E}{\cosh(\eta)} \quad (4.1)$$

The reconstruction of electrons relies on three characteristic features of an electron signature: a localized cluster of energy deposits within the EM calorimeter, charged-particle tracks reconstructed in the inner-detector, and close matching of tracks to the energy deposits in $\eta \times \phi$ space. An algorithm is used that takes into account the distance in both η and ϕ between extrapolated tracks and the cluster barycenters as measured in the second calorimeter layers, the number of hits in the silicon detectors, and the number of hits in the innermost silicon layer [187]. A cluster candidate that is associated to a track having at least four hits in the silicon layer that isn't associated with a photon conversion vertex is considered an electron.

Electron identification and isolation

A Likelihood-based identification is used to identify prompt electrons in the central region of the detector. The inputs are described in Table 1 of [187] and include measurements from the inner-detector, the calorimeter, and quantities combining information from both. Operating points are defined for fixed values of the Likelihood discriminant output to identify electrons as either VeryLoose, Loose, Medium, or Tight [187].

Isolation requirements help differentiate prompt electrons from electrons due to background processes like semi-leptonic decays of heavy quarks, hadrons misidentified as leptons, and photons converting into electron-positron pairs before reaching the electromagnetic calorimeter. Signatures from prompt electrons are characterized by little activity in the calorimeter and inner-detector in an area in $\Delta\eta \times \Delta\phi$ surrounding the electron candidate. Isolation variables are defined to quantify the amount of activity near the electron candidate by summing the transverse energy of the clusters in the calorimeter or p_T of the tracks within the Inner Detector that lie within a specific ΔR of the candidate.

More details on the identification and isolation of electrons can be found in [187].

Photon identification and isolation

Prompt photons are defined as photons that are directly from the hard scattering process. They are produced in SM processes like parton-parton scattering ($qg, q\bar{q} \rightarrow \gamma + X$, $gg, q\bar{q} \rightarrow \gamma\gamma$), QED radiation, Higgs boson decays ($H \rightarrow \gamma\gamma$). Prompt and non-prompt photons that convert to an electron-positron pair before reaching the EM calorimeter are referred to as converted photons and those that are not associated with a conversion are termed unconverted photons.

A large but reducible background for prompt photons comes from hadronic processes with high cross sections that produce jets and photons from hadronic decays of hadrons simply misidentified as photons. Jets from hadrons like π^0 deposit a large fraction of their energy in the EM calorimeter in a way that resembles that of a real prompt photon. Due to differences in the properties and shapes of associated electromagnetic showers for prompt photons and their background, these variables can be used to discriminate signal from background. The 9 discriminating variables are defined in the table in Fig. 4.3 and are based on the energy in the cells of the EM

calorimeter and the leakage in the hadronic calorimeter [25]. A schematic illustrating the definitions of the photon discriminating variables is shown in Fig. 4.4. In the schematic, E^{S_N} refers to the electromagnetic energy collected in the N-th longitudinal layer of the EM calorimeter. E_i refers to energy in the i-th cell. η_i is the pseudorapidity center of the cell.

Category	Description	Name	<i>loose</i>	<i>tight</i>
Acceptance	$ \eta < 2.37$, with $1.37 < \eta < 1.52$ excluded	–	✓	✓
Hadronic leakage	Ratio of E_T in the first sampling layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $ \eta < 0.8$ or $ \eta > 1.37$)	R_{had_1}	✓	✓
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \eta < 1.37$)	R_{had}	✓	✓
EM Middle layer	Ratio of $3 \times 7 \eta \times \phi$ to 7×7 cell energies	R_η	✓	✓
	Lateral width of the shower	w_{η_2}	✓	✓
	Ratio of $3 \times 3 \eta \times \phi$ to 3×7 cell energies	R_ϕ		✓
EM Strip layer	Shower width calculated from three strips around the strip with maximum energy deposit	w_{s3}		✓
	Total lateral shower width	$w_{s \text{ tot}}$		✓
	Energy outside the core of the three central strips but within seven strips divided by energy within the three central strips	F_{side}		✓
	Difference between the energy associated with the second maximum in the strip layer and the energy reconstructed in the strip with the minimum value found between the first and second maxima	ΔE		✓
	Ratio of the energy difference associated with the largest and second largest energy deposits to the sum of these energies	E_{ratio}		✓

Figure 4.3: A table of the discriminating variables used to identify a photon as loose or tight. From [25].

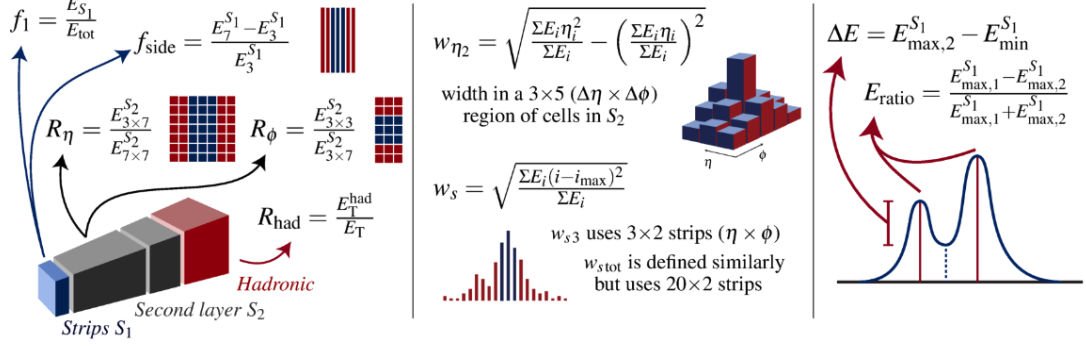


Figure 4.4: An illustration of the definitions of the photon discriminating variables. From [26].

A likelihood discriminant combines all these probabilities and three identification operating points are defined with increasingly stringent cuts on this discriminant, to match the desired efficiency of each point [25]. To correct for pile-up, the discriminant cut is designed to be linearly dependent on the number of vertices. The loose identification relies only on information from the HCAL and the middle layer of the ECAL. The tight identification places tighter cuts on these same variables in addition to variables describing the strip layer in the ECAL. The selections on these variables are optimized separately for converted and unconverted photons.

Hadrons that are reconstructed as photon deposit a large portion of their energy in the HCAL and produce a broader transverse energy deposit in the ECAL than signal photons. Consequently, signal photons are required to be isolated using cuts on the calorimetric and track isolation variables defined based on the transverse energy flow in a cone around the direction of the photon candidate [188]. One difference in definition of E_T^{iso} from the definition used for electron isolation, the energy deposited by the photon candidate that also contribute to the underlying event and pile-up are subtracted. For the track isolation of a photon candidate, the tracks considered must have a transverse momentum above 1 GeV and have a d_0 within 3 mm of the primary vertex, excluding any tracks associated to the photon conversion.

The specific isolation cuts are in Eqs. 4.2 and 4.3 [189].

$$E_T^{iso}|_{\Delta R < 0.4} < 0.022 \cdot E_T + 2.45 \text{ GeV} \quad (4.2)$$

$$p_T^{iso}|_{\Delta R < 0.2} < 0.05 \cdot E_T \quad (4.3)$$

4.3 Jets

Jets are produced in $2 \rightarrow 2$ scattering of partons inside colliding protons and from the hadronic decay of heavy particles like the top quark, the Higgs Boson, and potentially beyond the Standard Model particles. Jets can be reconstructed using topo-clusters [181] calibrated at the EM scale only, resulting in EMTopo jets [190], or topo-clusters and information about tracks in the Inner Detector, referred to as Particle Flow (PFlow) jets [191]. Jet reconstruction determines the jet's momentum and direction as well as the type of parton that created the jet. Jets can be reconstructed with different sizes as well. In the analysis described in this thesis, we use small-radius jets (small-R jets).

4.3.1 Jet reconstruction

The anti- k_t algorithm [27] is the standard jet reconstruction algorithm used within ATLAS. This algorithm is both infrared safe and collinear safe, meaning the algorithm produces results independent of the jet definition or the inclusion of soft radiation or adjustments from collinear splitting of the parton [190].

The anti- k_t algorithm combines topo-clusters into jets using their transverse momenta and separation. First, the distance between the highest p_T topo-cluster, known as the seed cluster and the closest cluster, $d_{i,j}$, is compared to a second distance, $d_{i,B}$, that measures the distance from the seed cluster to the beam axis in momentum space.

$$d_{ij} = \min\left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2}\right) \frac{\Delta R_{ij}^2}{R^2} \quad (4.4)$$

$$d_{iB} = \frac{1}{k_{ti}^2} \quad (4.5)$$

In this expression, $k_{t,i}$ and $k_{t,j}$ are the inverses of the transverse momenta associated with two clusters considered. $\Delta R_{i,j}^2$ is the angular separation between the two clusters and is found, where y_i is the rapidity and ϕ_i is the azimuthal angle of the

clusters. This expression can also be used to find the angular separation between any two physics objects i and j .

$$\Delta R_{i,j}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \quad (4.6)$$

In Eq. (4.6), R defines the maximum size of the jet and R is varied depending on the application of the jet object in an analysis. $R=0.4$ is the minimum distance between two jets used in any analysis and is used for jets initiated by quarks and gluons to define “small- R jets”. “Fat jets” are formed using $R = 1.0$ and this is useful for hadronic decays of massive particles like the W , Z , Higgs, or top quark.

In the anti- k_t algorithm, if $d_{i,j}$ is smaller than the distance $d_{i,B}$, a new cluster is formed by merging clusters i and j and this cluster is denoted as a seed cluster. The procedure is iterated with the seed cluster found and other clusters until $d_{i,j}$ is larger than $d_{i,B}$. When this happens, cluster i is called a jet and any associated clusters are removed from the collection.

Fig. 4.5 shows a simulation of jet reconstruction done in [27] using the anti- k_t algorithm applied to a HERWIG [192] generated parton-level event. The hard jets in the event are circular, while softer jets have an irregular shape.

Particle Flow Jets

The particle flow algorithm [191] is used in conjunction with the anti- k_t algorithm to improve the reconstruction and performance of the jets. Tracks are associated with jets, and energy contributions of charged hadrons associated with tracks are replaced by the p_T measured by the Inner Detector. This replacement only occurs for jets with $p_T < 100$ GeV, otherwise the particle flow algorithm produces the same reconstruction as the EMTopo jets. The subtraction happens by finding the expected energy deposited from the charged pions in the jet, which produced tracks in the Inner Detector. The expected energy is evaluated in MC simulations. An additional cell-based energy subtraction algorithm is applied to further remove any overlap between the momentum and energy measurements.

4.3.2 Jet Calibration

The process of calibration corrects the jet energy scale to match the scale of truth-jets. The jet energy scale of jets can be adjusted from the true value due to pile-up

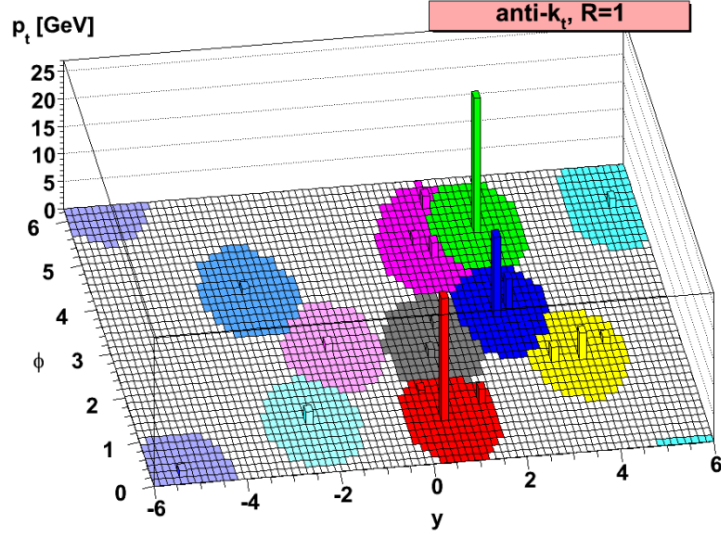


Figure 4.5: Results of the anti- k_t algorithm applied to a HERWIG generated parton-level event. Hard jets, like those colored in bright green, blue, and red, are circular in shape. Irregularly shaped energy deposits, like those in magenta, are from soft jets. From [27].

or detector effects including calorimeter non-compensation, differences between the electromagnetic and hadronic calorimeters, and leakage of the jet energy outside of the jet cone. Jet calibration proceeds in the same manner for EMTopo jets and PFlow jets. The procedure is depicted in Fig. 4.6. A detailed description can be found in [28].

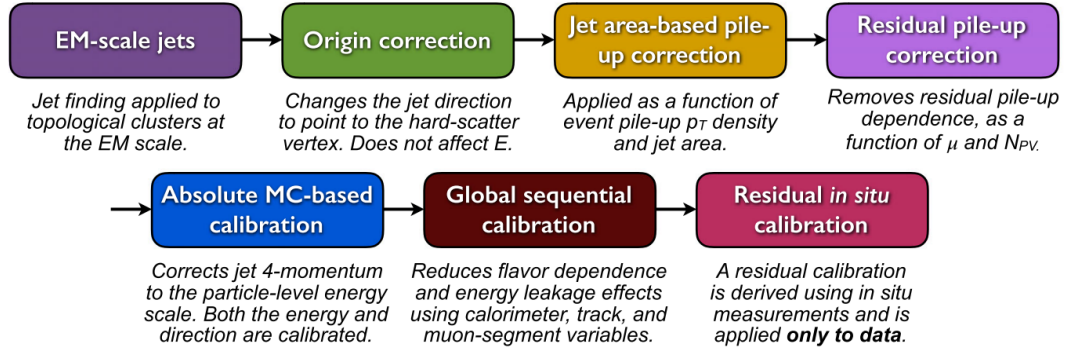


Figure 4.6: A flowchart of the calibration stages for EM-scale jets. From [28].

1. **Origin correction:** When the jet is first reconstructed using the anti- k_t algorithm, its jet axis is defined to point to the center of the detector. The origin correction [193] adjusts this direction so that the jet instead points back to the hard-scatter primary vertex in the event. Reconstructed jets are matched to truth jets using a requirement that they lie within $\Delta R = 0.3$ of one another.
2. **Pile-up corrections:** Additional energy deposits in the calorimeter from in-time and out-of-time pile-up increase the energy measured in the jet. A two-step procedure is implemented to remove these contributions [194]. The first correction subtracts energy from the jet p_T based on the average pile-up in the event. The second correction depends on the number of interactions per bunch crossing and the number of primary vertices in the event.
3. **Absolute JES calibration:** Simulated events are used to correct the reconstructed energy of the jet to the “particle-level” [28]. A correction factor of $\frac{E^{truth}}{E^{reco}}$ is applied as a function of E and η of the jet to the reconstructed jet energy, where the truth energy is determined from the truth matching that occurred previously.
4. **Eta-intercalibration:** This step is not shown as a separate box in the diagram but is included within the absolute MC-based calibration step. Jets in the central region are better measured compared to jets in the forward region. A correction is derived from the central jets ($|\eta| < 1.4$) and is applied to forward jets [195].

5. **Global Sequential Calibration (GSC):** The GSC [195][196] is depicted by the dark magenta box in the flow-diagram. This correction accounts for energy leakage in the calorimeter, which alters the jet response. Six observables are defined for each jet, relating to the shape and energy of the jet. A correction is derived for each observable that is a function of the jet p_T^{truth} and $|\eta|$. This step helps distinguish quark and gluon initiated jets.
6. **In-situ calibration:** The final step in this procedure corrects the jet energy scale to account for differences between the data and the simulation that arise from mismodeling of the hard-scatter, contributions from the underlying event, incorrect detector description within the simulation, or the jet formation process itself [195]. The p_T balance of reconstructed objects is calculated with respect to a well-calibrated object from a well measured process in data.

Jet Energy Scale and Jet Energy Resolution uncertainties

The calculation of the Jet Energy Scale takes into account many systematic uncertainties that arise from the statistics in the samples, mismodeling of pile-up or jet flavor composition in MC, and uncertainties related to the energy scales of other objects. By varying the parameters of the object selection and using other simulated samples, uncertainties are found for the JES calibration. There are 125 different nuisance parameters that describe all the systematic uncertainties on the JES. Fig 4.7 shows the total fractional JES uncertainty as a function of the (left) jet p_T and of the (right) jet η . The JES uncertainty is under 5% for all p_T shown. At lower p_T , the dominant contribution comes from pile-up and differing detector response between quark and gluon-initiated jets.

Fig. 4.8 a) shows the JER as a function of p_T of the jet. Fig. 4.8 b) shows the total systematic uncertainty on the JER. The JES uncertainties dominate the JER uncertainty at low p_T and high p_T . In between, non-closure dominates. The fluctuations in the jet production and the interaction of the jet with the detector are the dominant contributors to the JER uncertainty above 400 GeV.

Suppression of pile-up jets

Despite the initial pile-up corrections, local fluctuations in the presence of many overlapping low p_T QCD jets can result in the formation of spurious pile-up jets.

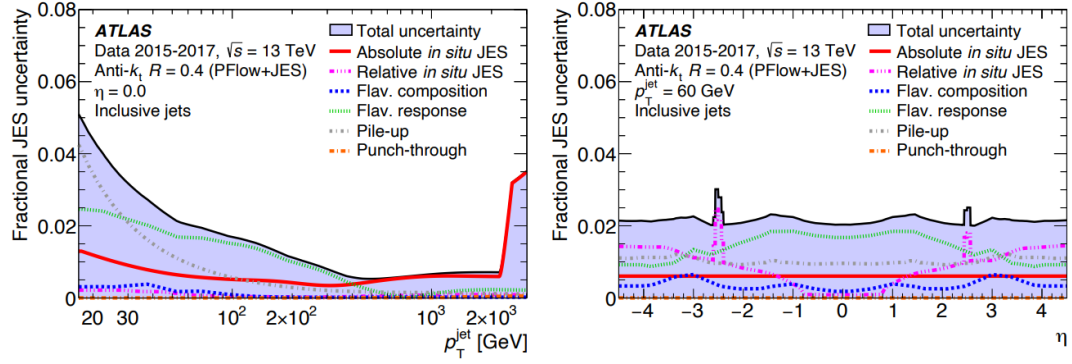


Figure 4.7: The combined uncertainty on the Jet Energy Scale of calibrated EM-scale jets. The left figure is as a function of jet p_T , evaluated at $\eta = 0$. The right figure is as a function of η at a $p_T = 80$ GeV. From [29].

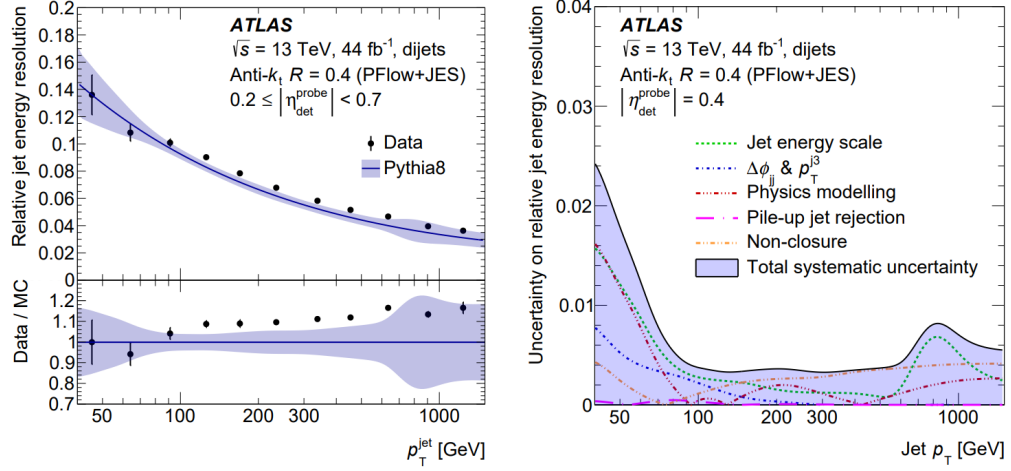


Figure 4.8: The average jet p_T response. From [29].

The Jet Vertex Tagger algorithm [197] takes information from tracks associated with reconstructed jets and constructs a 2D likelihood [198] to determine how likely it is that a jet is a pile-up jet. The Jet Vertex Fraction variable takes the ratio of the scalar sum of transverse momenta of tracks originating from the hard scatter and relates it to the sum over all interaction vertices reconstructed in the collision event.

This fraction is corrected to allow for stability as a function of the number of primary vertices. The result of the JVT algorithm is measured in Z+jets events and scale factors are derived to correct for any mismodeling in simulations. The efficiency for the JVT is nearly pile-up independent.

Calibration of particle-flow jets

Calibration of EMTopo and PFlow jets happens using the same steps. There are some differences. Instead of correcting pile-up using transverse energy density computed from the calorimeter inputs, the PFlow algorithm calculates corrections for charged and neutral particles differently [191]. Fig. 4.9 a) shows a comparison of the jet response. The response for the PFlow jets is closer to unity than the response for the EMTopo jets. The JES measurement also has smaller systematic uncertainties for PFlow jets at low and intermediate p_T . Fig. 4.9 shows the JER for EMTopo and PFlow jets. The JER of PFlow jets is improved at low p_T because of the incorporation of track information into the jet reconstruction. PFlow jets also have better angular resolution [191].

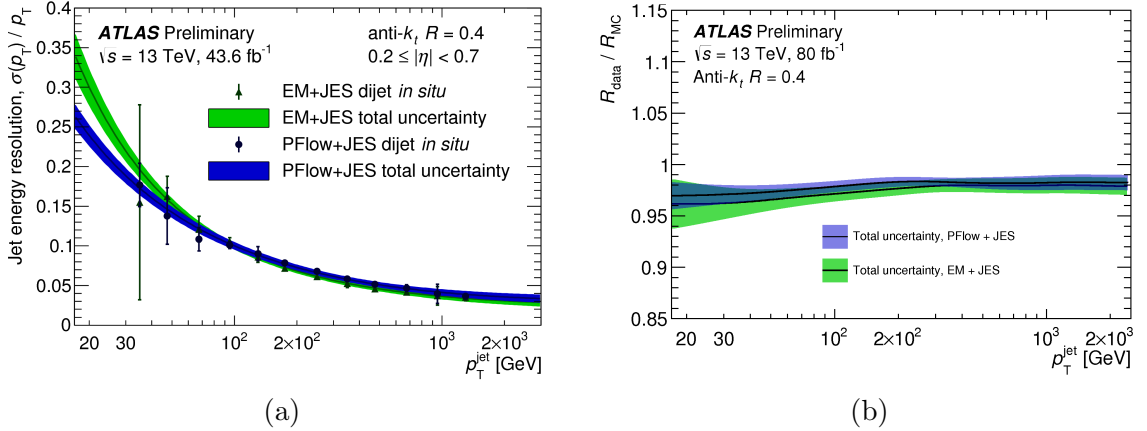


Figure 4.9: The average jet p_T response for the (left) JES [29], and (right) JER [30].

4.3.3 b-tagging of jets

The process that identifies jets initiating from a b-quark instead of a c-quark, light quarks and gluons [199], or hadronic tau-lepton is called b-tagging. When b-quarks hadronize to produce b-hadrons, the hadronization shower is a b-jet.

Tracks are matched to jets using an angular separation, $\Delta R(track, jet)$, between the tracks and jets. The cut on $\Delta R(track, jet)$ depends on the momentum. For higher momentum jets, the B-hadron is more boosted and its decay products will be collimated in the direction of the jet momentum, resulting in a tighter $\Delta R(track, jet)$ cut than for lower momentum jets [200]. If multiple jets match a track, the jet closest to the track is associated. The impact parameters are then calculated with respect to the jet axis. For the purpose of designing these taggers and studying their performance, jets are truth-labeled by matching them to a truth b-hadron, c-hadron, τ -lepton, or otherwise light-jets.

Low-level taggers

Low-level taggers produce inputs for higher level tagging-algorithms by using information about the tracks associated with jets in an event and the location of vertices. Four types of taggers are described.

- **Impact-parameter based algorithms (IP2D, IP3D):** The impact-parameter based algorithms [199] uses the impact parameters to distinguish tracks from b-hadrons from those originating from a primary vertex. Due to their long lifetime, b-hadrons are expected to have larger and positive signed impact parameters (d_0). A positive value of d_0 indicates that the point of closest approach of the track to the primary vertex is in front of the PV compared to the direction of the jet. A negative value of d_0 indicates it is behind the PV. The d_0 impact parameter significance is defined as $\frac{d_0}{\sigma_{d_0}}$ and the z_0 impact parameter significance is defined as $\frac{z_0}{\sigma_{z_0}}$. Two algorithms, IP2D [201] and IP3D [202] construct a ratio of the b-jet and light-jet probabilities for each track using the probability density functions of the impact parameter significances and combines them into a log-likelihood discriminant. The IP2D algorithm uses only the transverse impact parameter while the IP3D algorithm uses both.

- **Secondary vertex based algorithms:** The SV1 algorithm [203] reconstructs a single displaced vertex by taking a pair of tracks and utilizes a χ^2 fit to associate additional tracks to a secondary vertex. To be consistent with a b-hadron, the invariant mass of the system of tracks is required to be less than 6 GeV. The algorithm tries to reject tracks from decays of long-lived particles, photon conversion, or hadronic interactions within the detector material [204][205]. When the secondary vertex is identified, the algorithm outputs the mass of the secondary vertex, the significance of the decay length, the ratio of the energy associated with the secondary vertex to all tracks in the jet, and the number of tracks used to reconstruct the SV.
- **JetFitter:** The JetFitter algorithm [206][207] attempts to reconstruct the decay of a b-hadron into a c-hadron to light-hadrons and associated secondary and tertiary vertices. A modified Kalman filter is used to fit the secondary and tertiary vertices to a line and baked on the output, generating a set of variables that are used by higher-level algorithms.
- **RRNIP:** The RRNIP [208] is a recurrent neural network that takes the signed impact parameter of each track, the fraction of jet p_T carried by the track compared to the jet p_T , and the angular distance of the track to the jet axis as inputs and outputs probabilities that the jets are truth-labeled as b-jets, c-jets, light-jets, or tau-jets. These four probabilities are combined into a single score on the jet.

Higher-level flavor tagging

High-level flavor tagging algorithms use the outputs of the lower-level algorithms together to determine whether or not to tag a jet as a b-jet. In this thesis, the DL1r is chosen as the b-tagging algorithm to use.

- **DL1 and DL1r algorithms:** The DL1 tagger [199] is a deep neural network that takes inputs from all four low-level taggers and outputs probabilities that a jet is a b-jet, c-jet, or a light jet. A final DL1 discriminant, D_{DL1} , is defined as a function of each of these probabilities (p_b, p_c, p_{light}) and a c-jet fraction (f_c) determined from a background training sample in Eq. 4.7. The DL1r algorithm [209] is an extension of this algorithm, using the same inputs as the inputs to

the DL1 algorithm and additionally the jet RNNIP outputs to determine the jet probabilities used to construct the discriminant.

$$D_{DL1} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{light}}\right) \quad (4.7)$$

b-tagging calibration

The purpose of b-tagging calibration is to correct the simulation b-tagging efficiency to match b-tagging efficiency of the data. A scale factor (SF) is derived by comparing the efficiency of b-tagging on b-jet enriched data samples, ϵ_b^{data} , to the b-tagging efficiency within MC, ϵ_b^{MC} . The scale factor is defined in Eq. 4.8. The SFs are treated as independent among the different jets and get applied to the event weights in the physics analyses. The SFs are derived as a function of the p_T and η of the jet. If a jet is both labeled as a true b-jet and gets b-tagged, the b-tagging weight is the scale factor. If a jet is labeled as a true b-jet but does not get tagged, the b-tagging weight is expressed in Eq. 4.9

$$SF = \frac{\epsilon_b^{data}}{\epsilon_b^{MC}} \quad (4.8)$$

$$w_{jet} = \frac{1 - \epsilon_b^{data}(p_T)}{1 - \epsilon_b^{MC}(p_T)} = \frac{1 - SF(p_T)\epsilon_b^{MC}(p_T)}{1 - \epsilon_b^{MC}(p_T)} \quad (4.9)$$

4.4 Muons

As charged particles, muons will leave tracks in the Inner Detector, however because they are minimum ionizing, they only deposit a small fraction of their energy in the calorimeter. Muons don't interact with calorimeter in same way as electrons because they are much more massive. Muon reconstruction integrates measurements from the Inner Detector, calorimeter, and muon spectrometer and various algorithms are used depending on what information is available from these detector subsystems [167][163][166]. The muon is constructed from the fragments of each subsystem independently. Different combinations of information from these subsystems results in different definitions for muons.

Combined muons are the most commonly reconstructed type of muon. Tracks that were reconstructed independently in the Inner Detector and Muon Spectrometer are matched and a combined overall track fit is performed, starting from the MS and extrapolating inwards. The quality of the fit determines which tracks from the MS to match to tracks in the Inner Detector.

While combined muons have the highest purity, three other types of muons can be reconstructed. Segment-tagged muons are formed when a track is present in the Inner Detector and a matching segment in the MS is found, though no complete track was reconstructed in the MS. This type of muon typically has a low momentum or its trajectory ends outside the acceptance of the MS. The ID tracks are first matched to track segments in the first muon system layer. A stand-alone muon is produced when tracks identified in the MS with two or more hits are extrapolated to the beamline, taking into account the energy losses and multiple scattering in the calorimeter. This definition primarily applies to muons outside the detector's acceptance of $2.5 < |\eta| < 2.7$. Finally, calorimeter tagged muons are constructed when the MS information is missing. This occurs due to gaps in coverage or can happen in the central region of the detector, where the performance is degraded by higher material density. These muons combine the tracks constructed in the Inner Detector with energy deposits in the calorimeter.

Identification and isolation criteria are used to distinguish prompt photons from those produced by the decays of pions, kaons, or heavy flavor hadrons. Identification is based on the compatibility of the track momentum as measured in the ID and MS, a measure known as the q/p significance. Additionally, the reduced χ^2 of the combined fit to the tracks in the ID and MS are used to identify muons, particularly

because tracks from background muons produced in decays have a kink in them where the decay occurred. Track transverse momenta based isolation and calorimeter can be used to further distinguish prompt muons from background muons. The quality of the identification variables and the isolation criteria are used to construct working points that get increasingly more selective. The medium working point is the default point used, using combined muons in the central region of the detector and stand alone muons above $|\eta| = 2.5$.

4.5 Tau-leptons

Tau leptons are a third generation lepton and are the heaviest of the charged leptons, with a mass of 1.78 GeV [56]. The tau-lepton has a relatively short life-time before decaying within 5 mm of the beamline, in the LHC beampipe. It decays leptonically 35% of the time, producing two neutrinos and either an electron or a muon, or hadronically the remainder of the time. Reconstructing tau-leptons in an event require measuring their leptonic or hadronic decay products [210]. Distinguishing electrons or muons produced during tau-decays from prompt electrons or muons is difficult and so tau-lepton reconstruction instead focuses on the hadronic decay modes. The hadronic decay produces one pion in a one-prong structure roughly 75% of the time and produces three pions in a 3-pronged structure roughly 22% of the time. When the momentum of the τ -lepton is large compared to its mass, the product is a collimated jet. The hadronic decays are characterized by narrow jets ($\Delta R = 0.4$) in the calorimeter that are associated with tracks in the Inner Detector [211]. A boosted-decision-tree (BDT) is used to discriminate between the one and three pronged final states and the hadronic background [212] [213].

4.6 Missing Transverse Energy

Particles that do not interact with the strong or electromagnetic forces, including neutrinos and potential particles beyond the Standard Model, will not leave tracks in the Inner Detector or deposit significant amounts of energy in the calorimeters, making them undetectable and causing a momentum imbalance. This momentum imbalance is quantified as the negative vector sum of all fully reconstructed objects in the event.

$$\vec{p}_T^{miss} = -[\sum \vec{p}_T^{jet} + \sum \vec{p}_T^{electron} + \sum \vec{p}_T^{muon} + \sum \vec{p}_T^{photon} + \sum \vec{p}_T^{soft}] \quad (4.10)$$

The hard term consists of the first four sums in the expression for missing momentum and correspond to all physics objects passing the event selection. An ambiguity solving procedure is used to ensure no object contributes more than once in all four sums. The soft term quantifies all energy deposits or tracks associated with the primary vertex that aren't associated with the reconstructed jets, electrons, muons, and photons. This term is insensitive to pile-up because only tracks associated with the hard scatter are considered. Missing transverse energy (MET) [214][215] is defined as the magnitude of p_T^{miss} .

Chapter 5: Dijet resonance searches for Simplified Dark Matter Models

This chapter describes an experimental procedure of searching for dijet resonances at particle colliders and provides context and motivation for the analysis presented in this thesis. Section 5.1 is a benchmark model of a Z' mediator that is used as a benchmark by numerous dijet resonance searches, including the analysis presented in this thesis. Section 5.2 gives an overview of the analysis strategy used by traditional dijet analyses, presents the results from the most recent standard ATLAS dijet search for the Z' , and comments on the factors affecting the sensitivity of dijet searches at colliders. Sections 5.3 and 5.4 present two analysis strategies employed by ATLAS to overcome this limitation and probe even lower Z' masses. Section 5.5 gives the most up-to-date summary of the results of these various dijet searches and motivates performing a dijet search using an initial-state-radiated photon using the full Run 2 dataset collected by the ATLAS detector to probe lower unexplored values of the coupling between the Z' mediator and quarks.

5.1 Simplified Dark Matter Models

The Z' simplified model [31] extends the Standard Model with two new fields, dark matter and the mediator between dark matter and matter. The properties of these fields are specified by a minimum of four parameters: the mass of the dark matter particle (m_{DM}), the mass of the mediator (M_{Med}), the coupling of the quarks to the mediator (g_q), and the coupling of the mediator to dark matter (g_{DM}). These four parameters are sufficient to characterize the interaction of a variety of possible UV completions. More about this model is included in [216] [217] [218] [219] [220] [221] [222].

In this model, dark matter is assumed to be a Dirac fermion (χ). The quark-mediator coupling (g_q) is assumed to be equal for all quarks. The mediator is a

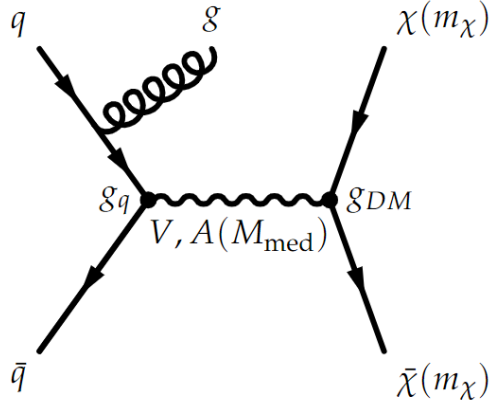


Figure 5.1: An example Feynman diagram of the pair production of Dark Matter particles in association with an initial state radiated gluon via a vector or axial-vector mediator. From Figure 2.1 of [31].

vector mediator (axial-vector or vector) that is exchanged via the s-channel, like in a representative process shown in Fig. 5.1, from the DM forum report [31]. In this diagram, the DM particles are pair produced in association with a parton from the initial state via a vector mediator with either vector or axial-vector couplings to quarks and dark matter. Discussions of this model in the context of collider and direct detection searches are discussed in [223] [224] [225] [226] [227] [228] [229] [230] [231] [232] [233] [234] [235] [236] [237] [238] [239] [240].

The phenomenology of vector and axial-vector mediators are similar for colliders but give rise to different behavior in direct detection experiments because in the non-relativistic limit, the vector interaction gives a spin-independent interaction that is enhanced by the presence of many nucleons, while the spin-dependent signal does not get enhanced. The following discussion will be about the axial-vector mediator only, as that mediator is the one being addressed by the search presented in this thesis.

The an axial-vector mediator that has no couplings to leptons has the following Lagrangian terms from Eq 2.2 of [31].

$$\mathcal{L}_{axial-vector} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi \quad (5.1)$$

The minimum widths of the Z' mediators are given in Eq 2.4 of [31].

$$\begin{aligned}\Gamma_{min}^{AV} &= \Gamma^{AV}(Z' \rightarrow \bar{\chi}\chi) + \Gamma^{AV}(Z' \rightarrow \bar{q}q) \\ &= \frac{g_\chi^2 M_{med}}{12\pi} \beta_{DM}^3 \theta(M_{med} - 2m_\chi) + \sum_q \frac{3g_q^2 M_{med}}{12\pi} \beta_q^3 \theta(M_{med} - 2m_q)\end{aligned}\quad (5.2)$$

The first term of Eq. 5.2 goes to zero when $M_{med} < 2m_\chi$. The second term is a sum over all quark flavors and the coupling constant is uniform for all decay channels. In this second term, the factor of β_q^3 that is multiplied by g_q^2 and the mediator mass (M_{med}) is the velocity of the quark in the mediator's rest frame. It comes from the phase space integrals that are written as part of the matrix elements to ensure energy conservation. The Lorentz boost from the rest frame of the fermion back to the rest frame of the Z' is defined as:

$$\beta_f = \sqrt{1 - \frac{4m_f^2}{M_{med}^2}} \quad (5.3)$$

Since the mass of all quarks is relatively small compared to the mediator mass, β_f is roughly the same for all quark types. The factor of three in the expression of the mediator width is just a color factor that is present for quark terms. The term $\theta(x)$ is the Heaviside step function that comes from the delta function in the matrix elements. It is important to note from Eq. 5.2, that all properties of the Z' are independent of the ISR jet in Fig. 5.1.

5.2 Traditional dijet searches

The traditional dijet search looks for narrow resonances in the observed dijet mass spectrum. While the natural width of the mediator is quite small, the resonance observed in data is wider due to the limitations of the experimental resolution of the detector. For these searches to be valid, the half-width of the resonance must be significantly smaller than the detector resolution. Most recent dijet searches at the LHC cannot probe below 1.5 TeV due to the current trigger thresholds.

Most searches confine the candidate jets to the central region of the detector. This is primarily because jets are best measured in the central region. This also ensures the trigger is efficient and reduces the QCD background. These searches also take

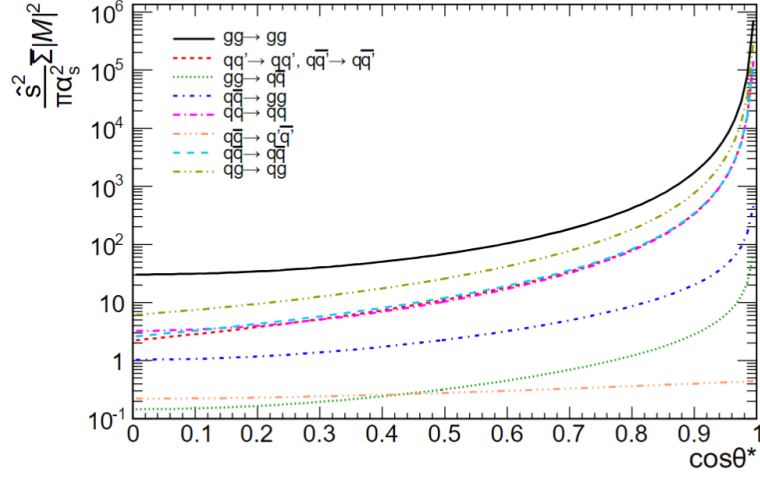


Figure 5.2: Leading order matrix elements for $2 \rightarrow 2$ parton scattering, as a function of $\cos(\theta^*)$. From [32].

advantage of the fact that QCD production of dijets in the mass range considered is primarily through Rutherford scattering in the t-channel that produce pairs of jets. Fig. 5.2 shows the leading order matrix elements for $2 \rightarrow 2$ massless parton scattering as a function of the cosine of the Collins-Soper angle ($\cos(\theta^*)$). A cut on $\cos(\theta^*)$ can be translated to a cut on the pseudorapidity, given that $\cos(\theta^*) = \tanh(\Delta\eta/2)$.

The rapidity difference between the two jets, y^* , defined in Eq. 5.4., can be used instead of $\cos(\theta^*)$ given the relationship in Eq. 5.5.

$$y^* = \frac{|y_1 - y_2|}{2} \quad (5.4)$$

$$e^{2|y^*|} \approx \frac{1 + \cos\theta^*}{1 - \cos\theta^*} \quad (5.5)$$

Resonances from heavy particles will be produced more isotropically in y^* , with the two jets having a lower $|y^*|$ than those produced by $2 \rightarrow 2$ parton scattering. By placing an optimized maximal cut on y^* , dijet searches can maximize their signal selection efficiency and signal significance.

The background is estimated using a fit to the data. The argument for this is two-fold. While MC can be used to accurately model the signal, it is unreliable for

the purpose of background estimation due to large theoretical uncertainties in QCD calculations that can result in significant discrepancies with the data that could mimic a resonant signal. $2 \rightarrow 2$ parton scattering produces a monotonically decreasing dijet invariant mass spectrum with high statistics and because the narrow width of signal resonance, the whole range can be considered a background dominated control region. The second reason is that many experimental uncertainties must be applied to the theoretical predictions if MC is to be used, including uncertainties on the jet energy scale and jet energy resolution, which are larger than the uncertainty from the data-driven fit. The principle of Occam’s razor can also be applied. If a background fit function alone satisfactorily describes the data and there is no significant evidence for a signal, the data is compatible with the background only hypothesis and the fit itself can be used for the background estimate. The fit applied to the data is validated using MC.

Dijet searches look for excesses in the dijet invariant mass spectrum that are consistent with coming from a new heavy mediator. ATLAS performed a dijet search using 139fb^{-1} of Run 2 data collected at $\sqrt{s} = 13$ TeV [33]. Fig. 5.3 shows the reconstructed dijet invariant mass distribution of the data in black points. The solid red line was the background prediction. The blue lines indicate the region with the most significant excess. The black and teal dashed lines depict benchmark signals added on top of the background fit. The fits are normalized to a cross section large enough to be distinguishable from the data. ATLAS uses the BumpHunter algorithm [241] to find the most discrepant upward fluctuation above the background prediction and quantify its global probability and significance. In Figure 5.3, this occurs between 4.3 to 4.6 TeV.

No significant excess was found in this traditional dijet search at ATLAS [242], so the data are used to place an experimental constraint on the number of signal events present and produce cross section limits on the dijet process. Theoretical cross sections can be calculated for specific models as a function of the mediator mass. When comparing the experimental upper limit on the cross section with the theoretical cross section, resonances masses for which the observed cross section is less than the theoretical cross section are excluded for that theoretical model. Cross section limits as a function of mediator mass can be translated into limits on the coupling of the Z' mediator to quarks as a function of the mediator mass (g_q), given

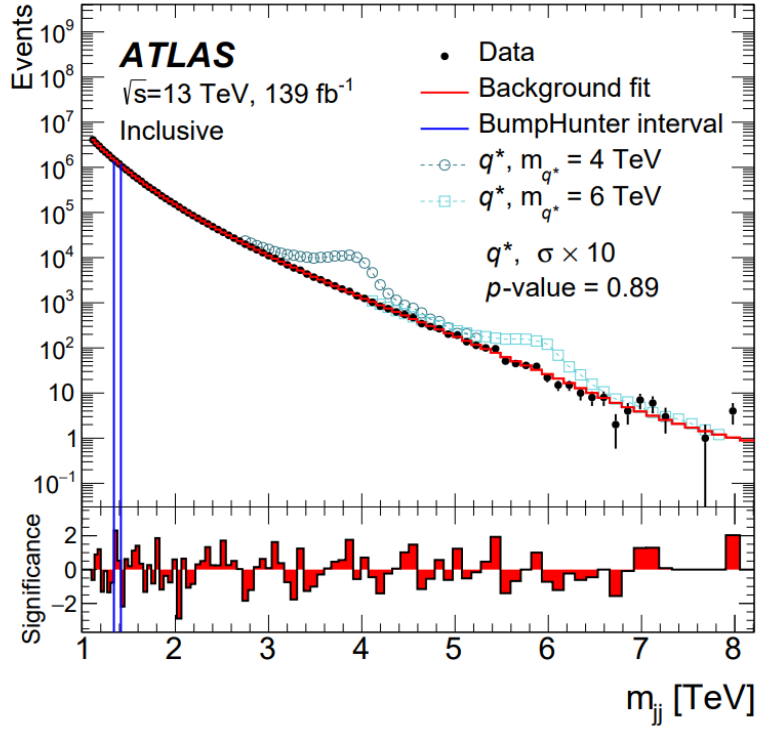


Figure 5.3: The black points show the dijet invariant mass of the data collected by the ATLAS dijet search performed using 139fb^{-1} of Run 2 data collected at $\sqrt{s} = 13$ TeV. From [33].

the expression for σ as a function of g_q^4 . This is a common way of expressing limits from dijet searches.

Dijet searches have been conducted at collider experiments prior to the LHC, at SPS and the Tevatron. The higher center-of-mass-energy of the LHC makes higher mediator masses accessible to the dijet searches. The increased luminosity allows ATLAS to record many more events and probe even lower values of the coupling of the DM mediator to quarks. However, the increased event rate overwhelms the triggers use to identify and store data of interest for analysis. At low p_T , the data-collection rates are much lower than the rate from multi-jet production [36] due to the limited bandwidth to record them. Below roughly 380 GeV, ATLAS records only a fraction of the events passing the trigger requirement. This is called pre-scaling of the triggers. This statistically limits ATLAS and CMS from searching for dijet

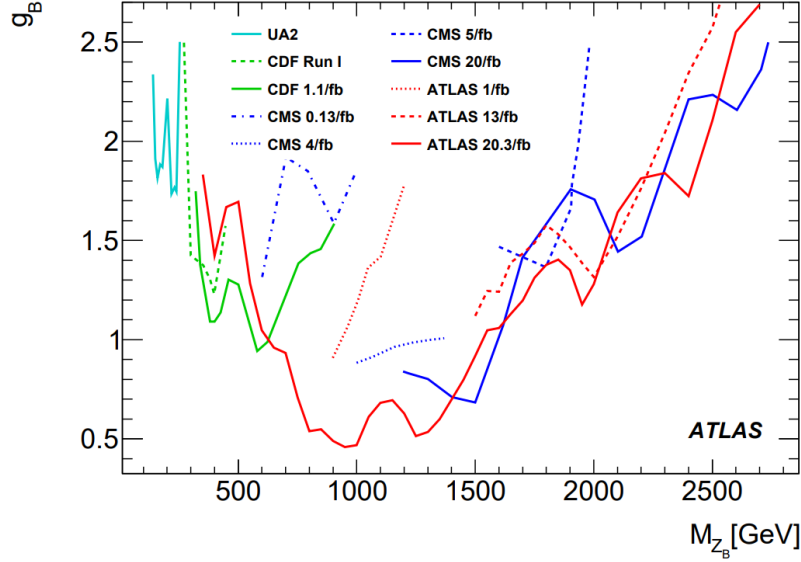


Figure 5.4: The observed 95% CL upper limits on the coupling of a leptophobic resonance as a function of mass by UA2, CDF, CMS, and ATLAS at the end of the LHC Run 1. The results come from [34] [35].

resonances at lower masses. As a result, traditional dijet searches at the LHC are less sensitive in the low mass region than the SPS and Tevatron. The impact of center-of-mass-energy, luminosity, and trigger thresholds on the sensitivity of traditional dijet searches is encapsulated in Fig. 5.4, taken from [243].

5.3 Trigger Level Analysis

The software-based High Level Trigger (HLT) processes events in ATLAS that were identified by the L1 hardware trigger and reconstructs and calibrates physics objects, including jets. Using these “trigger jets” and other reconstructed objects in the event, the HLT selects full events to record at a total rate of 1 kHz for offline reconstruction and analysis.

Instead of storing full events, the Trigger Level Analysis uses a dedicated “TLA data stream” to store the four-momentum of jets, calorimetry information about the structure of the jets, and identification variables for the jets in events with transverse momentum above a certain threshold. Measurements from individual calorimeter

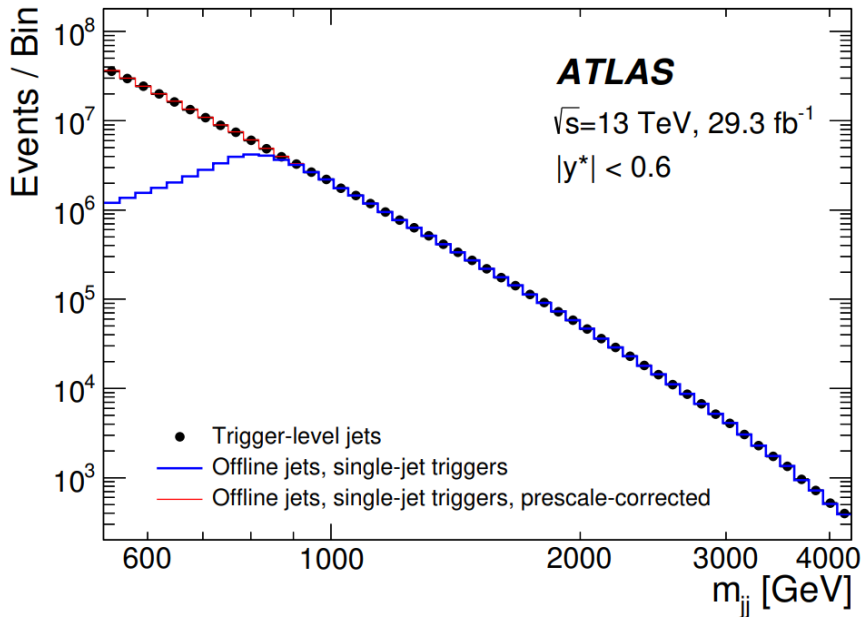


Figure 5.5: The black data is the dijet invariant mass distribution of events constructed from trigger level jets. From [36].

elements, tracking detectors, or muon detectors are not read out. Consequently, the size of these partial events is a small fraction of the size of a full event and the TLA does this using a small amount of the total trigger bandwidth.

Fig. 5.5 shows the success of the TLA at increasing event rates and reducing the threshold at which events can be collected without pre-scaling. The blue-line shows this distribution for events that are selected by only single-jet triggers and the red-line shows this distribution once the single-jet triggers are corrected with prescale factors.

The TLA technique has been implemented in a Run 2 analysis [36] and targeted low-mass dijet resonances in the range of 450 to 1800 GeV.

5.4 Dijet searches with Initial State Radiation

An alternate strategy to the TLA for probing lower resonance masses is to search for a light resonance that is boosted in the transverse direction by recoiling against a high p_T object, like a photon or jet [244] [245] [246]. Feynman diagrams of this

process are shown in Figure 5.6. The rate of emitting an ISR gluon is much higher than that of emitting an ISR photon.

The final states for these searches consist of two jets and a high p_T photon or jet. The analysis presented in this dissertation performs a search for a dijet resonance with an ISR photon using the full Run 2 dataset, but this analysis was part of a broader search that included ISR jet channels. The author also made numerous contributions to that search in [1], but they are not presented here. By selecting events with a high p_T photon, the signal acceptance drops, but the single-photon trigger used to select the events allows these searches to circumvent the single-jet trigger thresholds used by the traditional dijet search and access lower dijet masses. The first ISR photon search using partial Run 2 data at ATLAS [247] covered a mass range of 225 GeV to 1100 GeV, below the range accessible using the single-jet triggers or the trigger level jets.

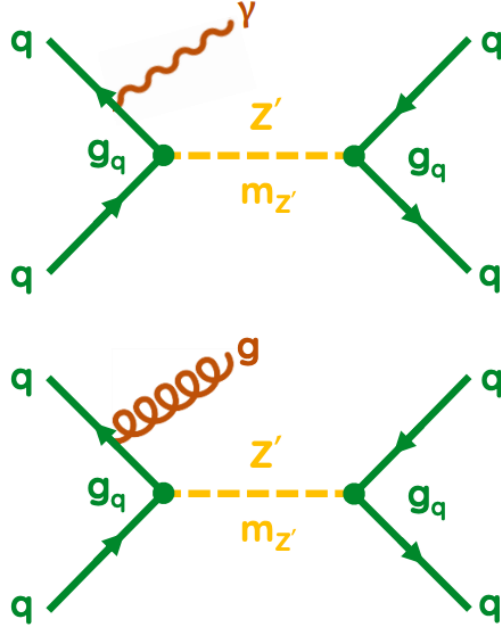


Figure 5.6: Feynman diagrams showing the production of a DM mediator and its decay to quarks in association with (top) a high p_T photon and (bottom) a high p_T gluon. From [14].

Dijet+ISR searches can be divided into two classes that utilize different search strategies. The separation of the two quark-jets is $\Delta R(q, q) \propto \frac{m_{Z'}}{p_T}$. A heavy Z' mediator that is not sufficiently boosted when recoiling off the high p_T ISR object will produce two distinct jets that are reconstructed separately using the standard jet cone size ($\Delta R = 0.4$). However, if the mass of the Z' mediator is below roughly 200 GeV, the jet products will be collimated and reconstructed as one large radius jet, depicted in Fig. 5.7. The jets are reconstructed separately using the standard jet cone size ($\Delta R = 0.4$). On the right, the mass of the Z' is now less than roughly 200 GeV. The Z' is boosted enough that the decay products are collimated and cannot be individually resolved. Instead, one large radius jet ($R = 1$) is constructed that contains the products of both quarks. Substructure within the large-R jet is used to distinguish it from large-R jets produced by backgrounds. The analysis presented in this thesis looks for resolved signatures.

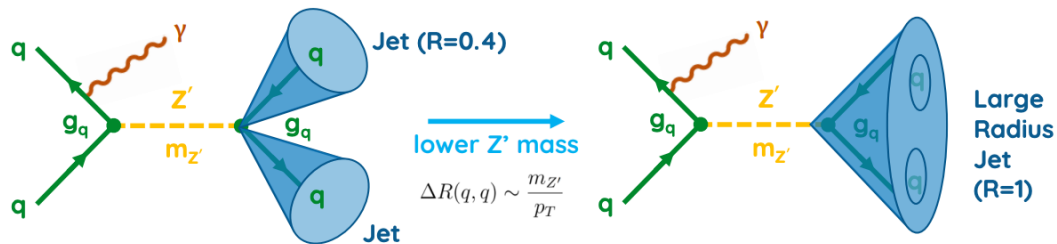


Figure 5.7: The left is a cartoon Feynman diagram of the dijet+ISR photon process, where the Z' is sufficiently heavy as to not acquire a large boost when recoiling off the high p_T ISR photon. On the right, the dijet system is sufficiently boosted that the two jets are collimated and reconstructed as one large-R jet. From [14].

5.5 Summary of results from dijet searches at ATLAS

A summary of the most updated ATLAS dijet search results prior to the writing of this thesis are shown in Figure 5.8. The information about each publication is listed in the right legend. The light-blue and orange colored curves show the results for two standard dijet searches looking for excesses in the dijet invariant mass spectra. The dark grey-blue colored curve is the result from the TLA search. The results of the

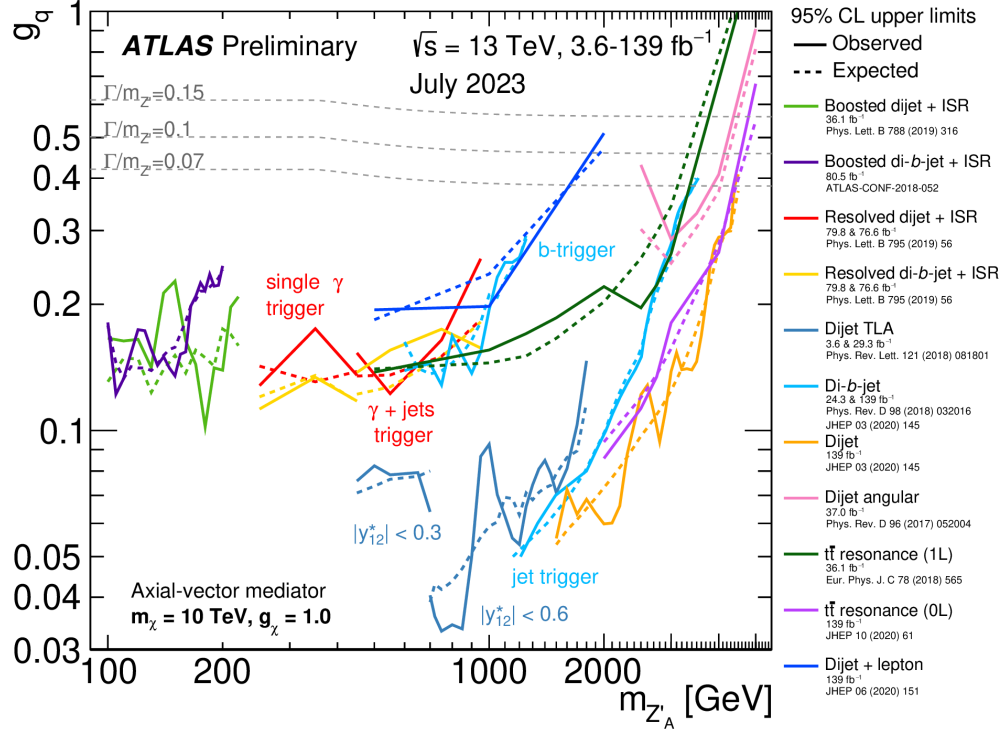


Figure 5.8: Observed limits are represented as solid lines while the expected limits are represented with dashed lines. From [37].

previous dijet+ISR analysis using partial Run 2 data are shown in red and yellow. Results are obtained in both an inclusive channel and a double b-tagged channel.

The lower-left-hand corner of the phase space in Fig. 5.8 shows an unexplored region of phase space, which includes the electroweak scale. Both the dijet+ISR photon and ISR jet analyses in [1] employ the full Run 2 dataset and this increase in the number of events analyzed allows the full Run 2 analysis to probe lower coupling values than the results from [247]. The ISR jet channel is entirely new compared to previously analyses. The full Run 2 dijet+ISR analyses are limited to searching above roughly 250 GeV and will be discussed in detail in Chp. 6.

Chapter 6: Search for low-mass resonances decaying into two jets and produced in association with a photon

6.1 Analysis Overview

This analysis uses data collected with the ATLAS detector between 2015 and 2018 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 140.0 fb^{-1} . This search targets the prompt production of a hadronically decaying two-prong resonance produced in association with an initial state radiated (ISR) photon, shown in the Feynman diagram in Figure 6.1. This is a resolved analysis because for the resonances we consider between the masses of 250 and 650 GeV, the Z' decay products are not collimated and can be reconstructed as two separate jets. This search is divided into two channels: an inclusive (γjj) channel and a b-tagged (γbb) channel. In some Beyond the Standard Model (BSM) physics, new particles are expected to preferentially decay to third-generation quarks. By requiring both jets from the resonance decay to be tagged as originating from a b-quark, the sensitivity to these models is increased.

We employ a traditional "bump-hunt" strategy, where we look for a presence of an excess of events in the distribution of the dijet invariant mass of the two jet candidates above the Standard Model prediction. The dominant sources of background are non-resonant QCD processes, including multi-jet and single-photon productions. These systems produce smoothly falling invariant mass distributions. To study the trigger used to select events for the analysis and for optimizing the event selection criteria, including a cut on the discriminant variable y^* to suppress the background, MC is used to simulate the SM background processes. A data-driven estimate of the background is used during the search phase because the experimental uncertainties to be applied to the background prediction are large. Additionally, the theoretical

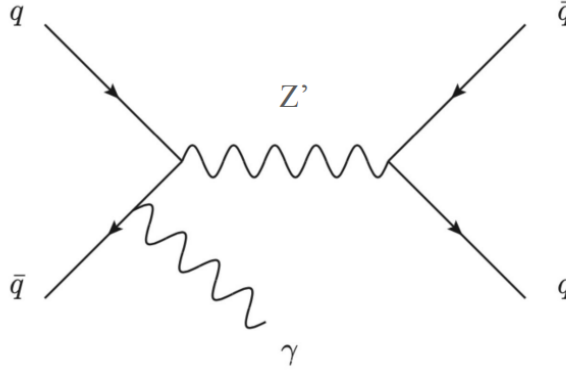


Figure 6.1: Feynman diagram for a generic new resonance produced in associations with a photon ISR object and decaying to 2 jets.

uncertainties associated with the QCD calculations exceed the statistical uncertainties for the signal process. Two types of models are used to generate signal samples used in the search phase. The first is generated using a model of a leptophobic axial-vector Z' mediator [31] produced at masses of $M_{Z'} = 250, 350, 450, 550$, and 650 GeV. Additional signal samples that are used in the limit setting phase are created by interpolating between these mass points. The second set of signals is generated assuming a process that produces a Gaussian signal distribution having a mean equal to the Z' mass and widths ranging from $5 - 15\%$ of that mass.

The contribution of background to the γjj process is estimated by fitting the data with a parametric fit function that was found to successfully describe the observed data in a variety of dijet resonance searches at ATLAS. This procedure is tested on MC and validated using spurious signal and signal injection tests. The statistics are low in the γbb channel and applying the same fit tests on the MC distribution will not ensure the procedure works in data. The y^* cut used in the event selection is inverted and applied to the inclusive spectra and then reweighted using the tagging efficiency of selected jets from the candidate resonances. This produces an estimated m_{jj} distribution with higher statistics and fewer statistical fluctuations. A data-driven estimate of this distribution is found using a fit that is validated on MC using the same spurious signal and signal injection tests.

The sources of uncertainty in the background and signal predictions are evaluated. Systematic uncertainties from object reconstruction are applied to the signals

generated using the Z' template. Additional systematic uncertainties on the luminosity and parton distribution functions used to generate the signal events are derived and applied. The background estimate is directly found from the data, so the only uncertainties come from the statistical uncertainty due to limited statistics in the fit, the choice of fit function, and the spurious signal uncertainty.

A likelihood function is constructed that combines the estimates for the background and signal, where the signal yields are controlled by a free multiplicative parameter. Systematic uncertainties are incorporated into the fits as nuisance parameters constrained by Gaussian penalty terms. The likelihood function is maximized to estimate the number of signal and background events in the observed data distribution. The BumpHunter algorithm looks for localized excesses within the m_{jj} distribution of the data compared to the background predictions and quantifies the statistical significance of the most discrepant regions, which may indicate the presence of resonant signals.

No statistically significant excess above the background prediction is observed and 95% confidence level upper limits are placed on the allowed cross-sections of particles as a function of their mass, using the signal templates and Gaussian templates. These limits are then expressed as a function of the coupling, g_q , and the mass of the Z' , $M_{Z'}$, or the mass of the Gaussian signal, M_G , taking into account the effects on the cross-section, acceptance, and efficiency.

6.2 Data and Simulated Samples

Datasets

The analysis presented in this thesis uses data collected with the ATLAS detector from pp collisions provided by the LHC between 2015 and 2018 at $\sqrt{s} = 13$ TeV. The dataset is taken from the GoodRunsList [248] and contains $140 \text{ fb}^{-1} \pm 0.83\%$ of data [249]. The uncertainty was obtained using measurements by the LUCID-2 detector [250] which measures the luminosity. The specific GoodRunsList files used are:

```
GoodRunsLists/data15_13TeV/20170619/data15_13TeV.periodAllYear_DetStatus-
v89-pro21-02_Unknown_PHYS_StandardGRL_All_Good_25ns.xml1213
```


GoodRunsLists/data16_13TeV/20180129/data16_13TeV.periodAllYear_DetStatus-
v89-pro21-01_DQDefects-00-02-04_PHYS_StandardGRL_All_Good_25ns.xml214

GoodRunsLists/data17_13TeV/20180619/data17_13TeV.periodAllYear_DetStatus-
v99-pro22-01_Unknown_PHYS_StandardGRL_All_Good_25ns_TriggerNo17e33prim.
xml215

GoodRunsLists/data18_13TeV/20190318/data18_13TeV.periodAllYear_DetStatus-
v102-pro22-04_Unknown_PHYS_StandardGRL_All_Good_25ns_TriggerNo17e33prim
.xml

Some of the events contained in the GRL data are flagged as containing errors from the liquid argon calorimeter, tile calorimeter, or semiconductor tracker and these events are rejected from consideration for the analysis. The data are collected using the HLT_g140_loose trigger. This is an unprescaled trigger and more on this trigger is detailed in Section 7.4.2.

Monte Carlo samples

The Monte Carlo method is described extensively in [251]. MC generators utilize the interaction Lagrangian, PDFs, and hadronization and factorization scales to find the matrix element and ultimately the hadronic cross-section of the hard scatter [252]. Perturbative QCD is initially used to model the parton shower. When the products within the shower reach an energy on the order of 1 GeV, the quarks and gluons will hadronize and produce bound states that are modeled instead by phenomenological QCD models. Modifications are made to account for soft QCD events.

There are a number of general-purpose Monte Carlo event generators that are used to simulate particle collisions at the ATLAS detector. These tools are used to predict scattering cross-sections, differential distributions, and event topologies using higher-order perturbative corrections from QCD, QED, and the electroweak sector. They can be used to both simulate Standard Model production processes and new physics signals.

The simulated Z' model and MC background predictions are propagated through and reconstructed using a full detector simulation using GEANT4 [253]. Pythia 8 with the A3 set of tune parameters [254] is used to superimpose minimum-bias interactions and NNPDF2.3 LO PDF [62] is used to determine the contributions from

pile-up. The distribution of the average number of pile-up interactions in simulation is reweighted to match that observed in the Run 2 data using the standard pile-up reweighting procedure developed for ATLAS [255]. Three Monte Carlo (MC) campaigns (mc16a, mc16d, and mc16e) were generated, each simulating the signal and background processes using different assumptions of the pile-up distributions. The mc16a samples are reweighted using the average μ distribution, while the mc16d and mc16e samples are reweighted with the actual μ distribution.

Background

Sherpa 2.2 [256] is used to simulate prompt single-photon production. The Comix [257] and OpenLoops [258] [259] [260] libraries are used to calculate NLO-accurate matrix elements for up to two partons and LO-accurate matrix elements for up to four partons. The default parton shower model [261] based on the Catani-Seymour dipole factorization and the cluster hadronization model [262] is used. The NNPDF 3.0 set [263] was used to evaluate systematic uncertainties.

A color-exact variant of the MC@NLO algorithm [264] was used to match the parton shower to the NLO matrix elements for a given jet multiplicity. The CKKW matching procedure [265] [266] was used to merge samples of different jet multiplicities into an inclusive sample, which was extended to NLO accuracy using the MEPS@NLO prescription [267]. The procedure in [268] was used to define a dynamic cut.

Factorization and renormalization scales must be introduced to address divergences when performing the QCD calculations for photon-plus-jets events. The renormalization and factorization scales for the photon-plus-jet core process are set to the transverse energy of the photon, E_T^γ . The strong coupling constant was set to $\alpha_S(M_{Z'}) = 0.118$. Lorentz and gauge invariance dictate that the zero-energy limit of Compton scatter, the Thomson limit, be applied for the QED coupling. When evaluating the matrix elements, the contributions from photons only considers central photons with a rapidity of $|\eta| < 2.7$. A smooth-cone isolation criterion [188] was used to isolate the photons, requiring $\delta_0 = 0.1$, $\epsilon_\gamma = 0.1$, and $n = 2$. QCD scale uncertainties were evaluated and incorporated using seven-point variations of the factorization and renormalization scales in the matrix elements [269]. To avoid using variations in opposite directions, the scales were varied independently by factors of 0.5 and 2.

The PDFs are determined from fits and these fits assume functional forms for which there are various correlated uncertainties. Experts do a component analysis to

figure out the 50 most important eigen-directions and make +1 and −1 variations for each of these 50 uncertainties, resulting in 100 PDF variations. 100 variation replicas, using ± 0.001 shifts in α_S , were used to evaluate PDF uncertainties for the nominal PDF set. Central values from the CT14_{NNLO} [270] and MMHT2014_{NNLO} [271] were used to cross-check the results from the NNDPF calculations.

The table below lists the samples used in the nominal MC-based estimation of the background for the γjj and γbb channels.

mc16_13TeV.364541.Sherpa_222_NNPDF30NNLO_SinglePhoton_pty_17_35.
deriv.DAOD_EXOT6.e6788_s3126*_p5522

mc16_13TeV.364542.Sherpa_222_NNPDF30NNLO_SinglePhoton_pty_35_70.
deriv.DAOD_EXOT6.e6788_s3126*_p5522

mc16_13TeV.364543.Sherpa_222_NNPDF30NNLO_SinglePhoton_pty_70_140.
deriv.DAOD_EXOT6.e5938_s3126*_p5522

mc16_13TeV.364544.Sherpa_222_NNPDF30NNLO_SinglePhoton_pty_140_280.
deriv.DAOD_EXOT6.e5938_s3126*_p5522

mc16_13TeV.364545.Sherpa_222_NNPDF30NNLO_SinglePhoton_pty_280_500.
deriv.DAOD_EXOT6.e5938_s3126*_p5522

mc16_13TeV.364546.Sherpa_222_NNPDF30NNLO_SinglePhoton_pty_500_1000.
deriv.DAOD_EXOT6.e5938_s3126*_p5522

mc16_13TeV.364547.Sherpa_222_NNPDF30NNLO_SinglePhoton_pty_1000_E\
_CMS.deriv.DAOD_EXOT6.e6068_s3126*_p5522

Signal

A simplified leptophobic Z' axial vector mediator signal is used to test the sensitivity of potential resonant signals in the search and limit-setting phases. The simplified model is described in [?] [272].

The Z' mediator arises from a simple extension of the Standard Model (SM) with an additional $U(1)$ gauge symmetry and a Dirac fermion DM particle. This particle only has charges under this new group. The Z' can mediate interactions between the SM and DM, assuming that some SM particles are also charged under this group. For a DM particle χ of mass m_χ and a spin-1 Z' mediator of mass $M_{Z'}$, the Lagrangian of this interaction is given in 5.1. This model is consistent with that recommended by the Dark Matter Forum [31].

The most relevant parameters of the model in this dijet search are the coupling to quarks, g_q and the Z' mass, $M_{Z'}$. The signals studied for this search have $g_l = 0$, $g_q = 0.1$, and $g_\chi = 1$. The mass of the dark matter candidate doesn't influence the width of the resonance in the search and the mediator cannot decay directly to DM, so m_χ is set to 1 TeV.

The Madgraph generator is used to generate the signal samples. NNPDF2.3 LO is used to generate the PDF [62] and Pythia 8 [254] is used to produce hadronic showers. The A14 tune is used [273]. Signal samples of at least 140k events per campaign (mc16a, mc16d, and mc16e) are generated for mediators with masses of $m_{Z'} = 250, 350, 450, 550$, and 650 GeV. A truth filter was applied on the photon p_T to enhance the statistics. The width of the mediator is calculated using the DarkMatterWidthCalculator [274], which implements Eq. 5.2. Table 6.1 shows the samples used for the Z' signal modeling for the γjj and γbb channels. The list of samples, their cross sections, and filter efficiencies are shown in Table 6.2.

The generated signal samples relevant to the analysis are at masses of $M_{Z'} = 250, 350, 450, 550$ and 650 GeV, however a real signal that occurs in between one of these masses could fail to be observed as an excess. To avoid generating additional samples while allowing for good model-dependent coverage in the limit-setting stage, a process of signal morphing was used to extrapolate the signal shapes and their associated systematics at intermediate masses. This was done using the RooMomentumMorph package [275].

mc16_13TeV.507483.MGPy8EG_S1_bba_Ph130_mRp25.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522
mc16_13TeV.507484.MGPy8EG_S1_bba_Ph130_mRp35.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522
mc16_13TeV.507487.MGPy8EG_S1_bba_Ph65_mRp45.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522
mc16_13TeV.507488.MGPy8EG_S1_bba_Ph65_mRp55.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522
mc16_13TeV.507489.MGPy8EG_S1_bba_Ph65_mRp65.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522
mc16_13TeV.507508.MGPy8EG_S1_qqa_Ph130_mRp25.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522
mc16_13TeV.507509.MGPy8EG_S1_qqa_Ph130_mRp35.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522
mc16_13TeV.507512.MGPy8EG_S1_qqa_Ph65_mRp45.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522
mc16_13TeV.507513.MGPy8EG_S1_qqa_Ph65_mRp55.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522
mc16_13TeV.507514.MGPy8EG_S1_qqa_Ph65_mRp65.gASp2.deriv.DAOD_EXOT6.e8352_s3126 × _p5522

Table 6.1: List of samples used for the Z' signal modeling, their cross sections, and filter efficiencies.

Channel	Z' mass	cross-section	Filter efficiency	Cross-section times filter eff.
$\gamma\gamma$	250 GeV	7.77 pb	0.12213	0.949
$\gamma\gamma$	350 GeV	3.35 pb	0.15751	0.528
$\gamma\gamma$	450 GeV	1.61 pb	0.18617	0.300
$\gamma\gamma$	550 GeV	0.870 pb	0.20866	0.182
$\gamma\gamma$	650 GeV	0.510 pb	0.22723	0.116
$\gamma\gamma$	750 GeV	0.317 pb	0.24299	0.0770
$\gamma\gamma$	850 GeV	0.206 pb	0.25698	0.0529
$\gamma\gamma$	950 GeV	0.139 pb	0.2686	0.0373
γbb	250 GeV	1.94 pb	0.12166	0.2360
γbb	350 GeV	0.839 pb	0.15554	0.1305
γbb	450 GeV	0.404 pb	0.1834	0.0741
γbb	550 GeV	0.217 pb	0.2049	0.0445
γbb	650 GeV	0.127 pb	0.22297	0.0283
γbb	750 GeV	0.0793 pb	0.23895	0.0189
γbb	850 GeV	0.0515 pb	0.25101	0.0129
γbb	950 GeV	0.0346 pb	0.26269	0.0091

Table 6.2: List of samples, their cross sections, and filter efficiencies.

6.3 Using kinematic quantities of the data as a precise check of the MC simulations

It is important to validate that the MC samples we are using to prepare our background fitting procedure and to measure our detector mass resolution describe the data well in both channels. One way to assess this is by comparing kinematic quantities in smaller unblinded datasets to those kinematic quantities in the MC campaigns over multiple years. The 2015 dataset has 3.0fb^{-1} of data and is compared to the mc16a MC campaign. The 2018 period L dataset has 3.2fb^{-1} of data and is compared to the mc16e MC campaign. Both unblinded datasets have representative pile-up distributions and differences between these two datasets could be due to changing pile-up conditions. pile-up reweighting is applied to both the MC and data. The MC samples are normalized to the luminosity of the datasets.

In the following figures, the ratio of kinematic distributions between the data and MC may not be exactly one because there is some uncertainty on the total cross-section. However, the shapes of kinematic distributions in data and MC must be continuous and proportional, to not introduce any features into the m_{jj} spectrum or generate behavior in the limits that are not representative of the data.

Figure 6.2 shows the comparison of p_T , η , and ϕ of the leading jet, subleading jet, and selected photon in the Data15 dataset to the mc16a campaign in the inclusive channel. Figure 6.3 shows the comparison of p_T , η , and ϕ of the leading jet, subleading jet, and selected photon in the Data15 dataset to the mc16a campaign in the 2 b-tagged channel. Figure 6.4 shows the comparison of p_T , η , and ϕ of the leading jet, subleading jet, and selected photon in the Data18L dataset to the MC16e campaign in the inclusive channel. Figure 6.5 shows the comparison of p_T , η , and ϕ of the leading jet, subleading jet, and selected photon in the Data18L dataset to the MC16e campaign in the γbb channel.

Some overall conclusions that can be drawn for all four comparisons are that there are no significant discrepancies between the data and MC distributions. No significant excesses are seen in the tails of each spectra and this indicates that the jet and photon cleaning requirements in Section 7.4.1 work properly. For the comparison between the Data15 dataset and the corresponding mc16a campaign, the most discrepant kinematic variable is the leading jet p_T below roughly 70 GeV. The leading jet p_T is also the most discrepant kinematic variable in the comparison between the Data 18L

dataset and the corresponding MC16e campaign. The ratio between the data and MC samples is smooth in the region and changes slowly. This ensures that this shape difference does not introduce a m_{jj} dependent feature into the final result.

In both years and for both channels, within the ratio panel of the comparison plot of the photon p_T , there appears a transition from a flat ratio below 280 GeV to a flat ratio that is 10% higher above 280 GeV. When the single-photon process was simulated, it was separated into different photon p_T bins and 280 GeV is a boundary between 2 adjacent slices. One explanation for this discrepancy is a statistical fluctuation due to low data in this region, however this behavior has been confirmed for samples generated with Sherpa 2.2.2 in other analyses and this is a more likely explanation given that this effect is seen in both the 2015 and 2018 comparisons. The photon momentum affects the momentum balance in the event and therefore the momentum of the jet, however, no discontinuity is seen in the leading and subleading jet p_T distributions, which are used in the event selection, unlike the photon momentum.

The requirement of there being two b-tagged jets in the b-tagged channel reduces the number of events compared to the inclusive channel, limiting the conclusions that can be drawn from these comparisons.

For these reasons, it can be concluded that the analysis of kinematics in both channels is sufficiently well understood in both the 2015 and 2018L datasets.

Data 2015: γjj channel

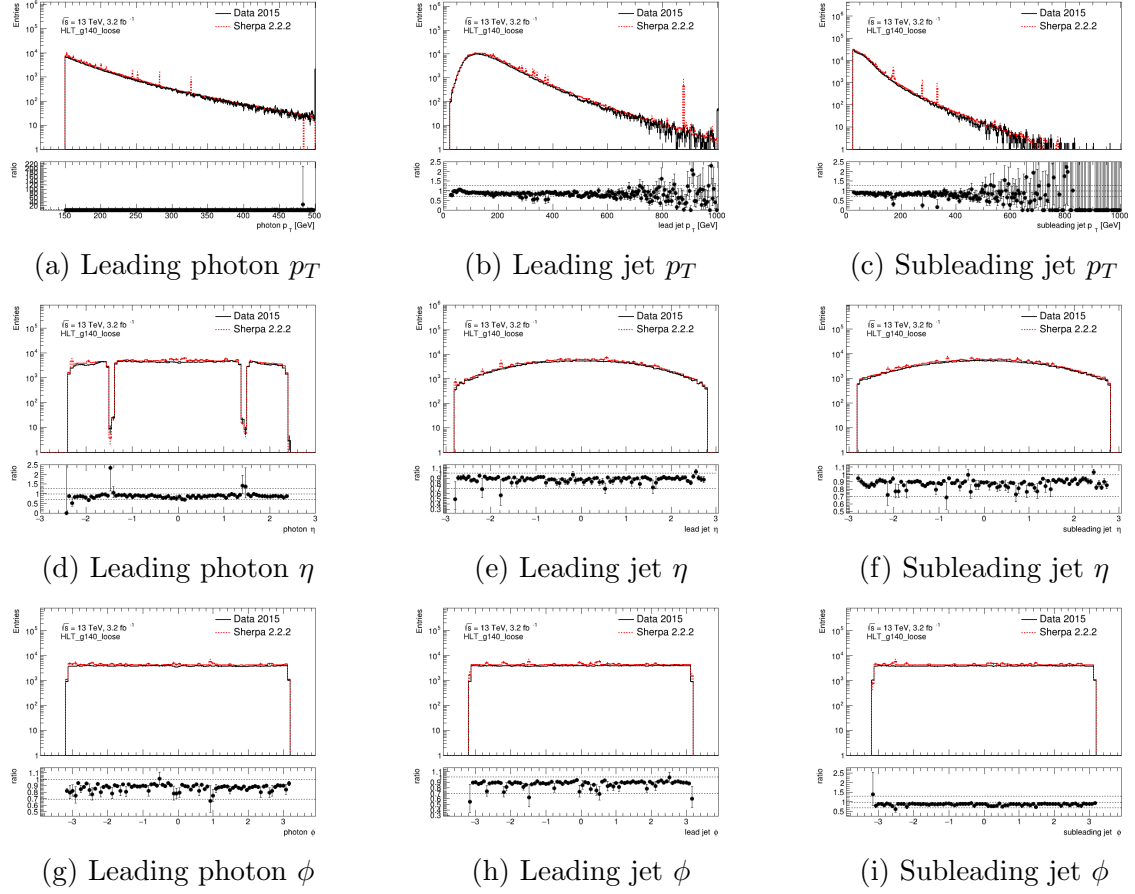


Figure 6.2: Data15 to mc16a comparisons of the p_T , η , and ϕ distributions of the selected photon, the leading jet, and the subleading jet, in the γjj channel. The MC is normalized to the observed luminosity.

Data 2015: γbb channel

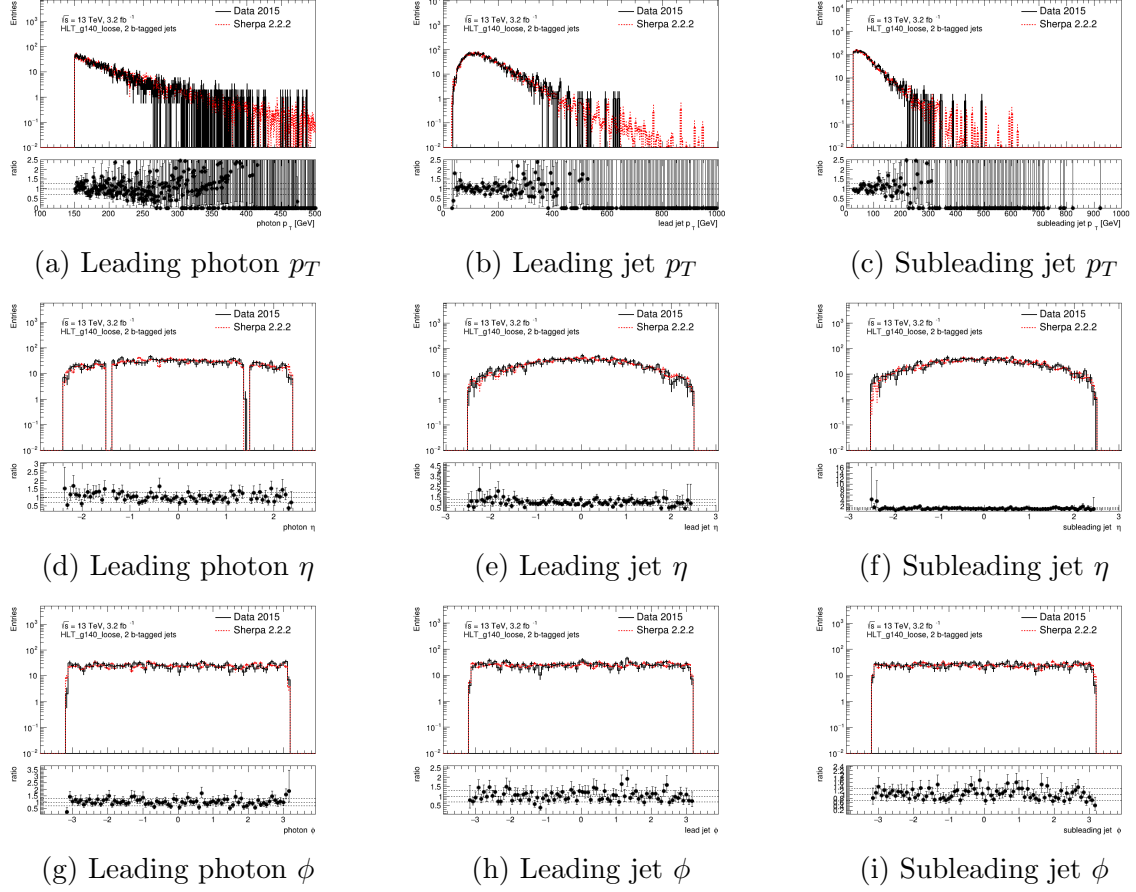


Figure 6.3: Data15 to mc16a comparisons of the p_T , η , and ϕ distributions of the selected photon, the leading jet, and the subleading jet, in the γbb channel. The MC is normalized to the observed luminosity.

Data 2018: γjj channel

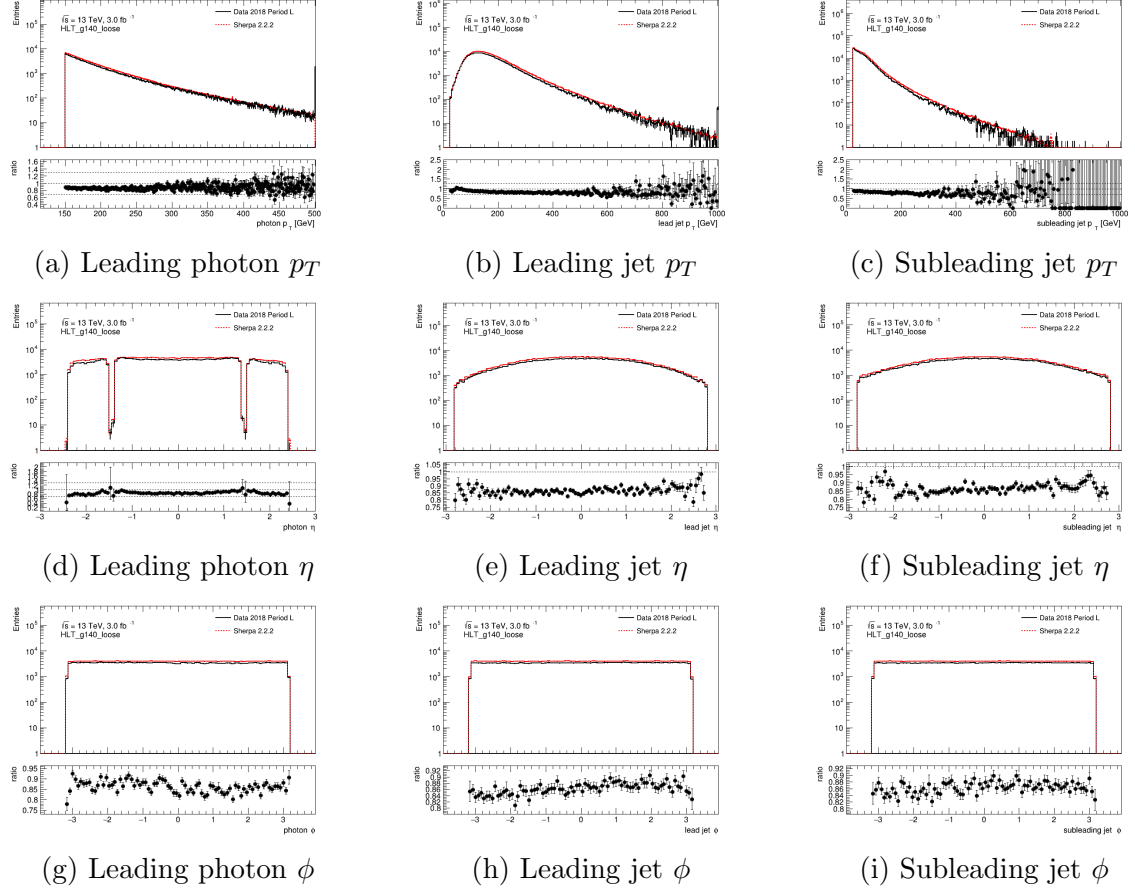


Figure 6.4: Data18 to mc16e comparisons of the p_T , η , and ϕ distributions of the selected photon, the leading jet, and the subleading jet, in the γjj channel. The MC is normalized to the observed luminosity.

Data 2018: γbb channel

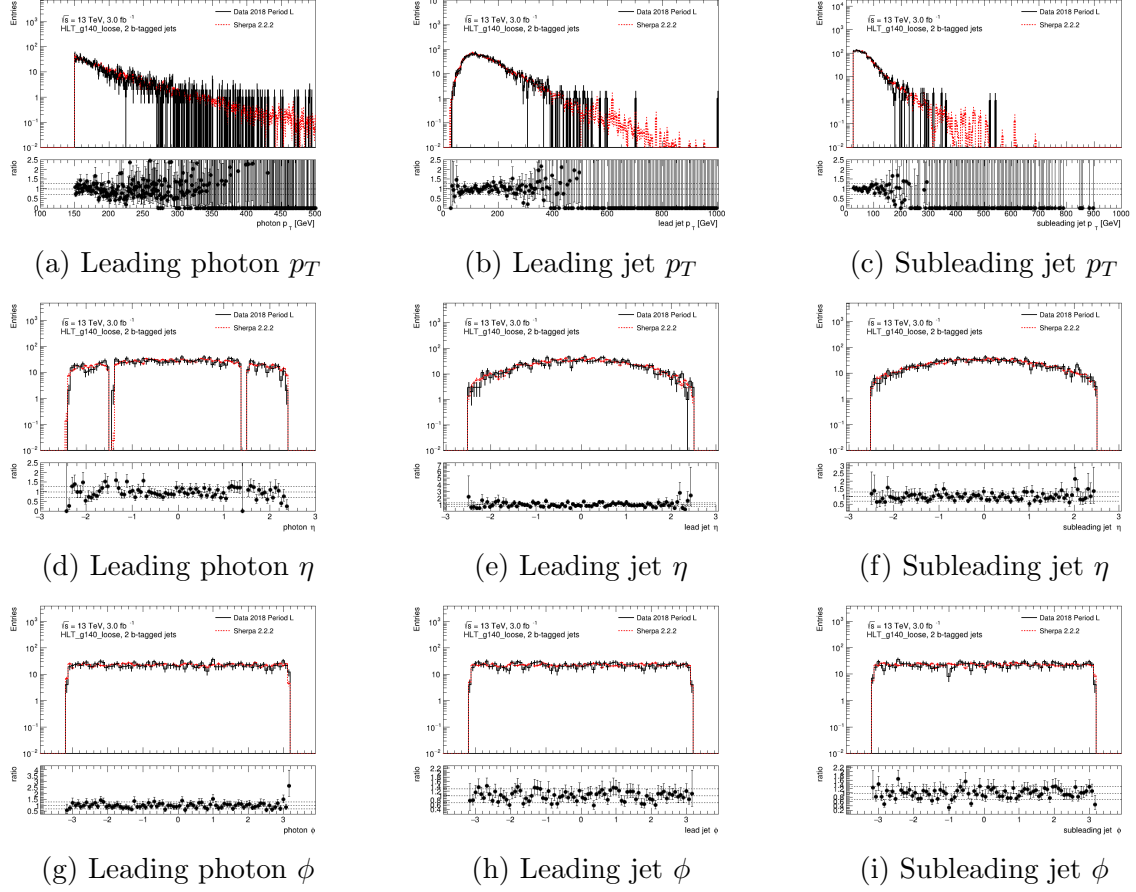


Figure 6.5: Data18 to mc16e comparisons of the p_T , η , and ϕ distributions of the selected photon, the leading jet, and the subleading jet, in the γbb channel. The MC is normalized to the observed luminosity.

6.4 Selection and Categorization

Object Definitions

The FastJet algorithm [276] uses the anti- k_T algorithm to reconstruct jets from particle-flow objects [191] within the event. The JetEtMissRecommendations [277] were used to select jets with a radius parameter of $\Delta R < 0.4$. The ATLAS particle-flow algorithm combines measurements from the inner detector and calorimeters to improve the jet energy resolution (JER), reduce sensitivity to pile-up effects, and improve jet reconstruction efficiency. The jet reconstruction is most enhanced for lower p_T jets. All jets selected for this analysis must have $p_T > 25$ GeV and be central, having $|\eta| < 2.5$. This threshold is chosen to be consistent with the JetEt-MissRecommendations [277] and removes pile-up jets. In situ corrections [195] and simulation-based corrections are used to calibrate the energy scale of the particle-flow jets. The jet uncertainties are calculated using the CategoryReduction_FullJER scheme. As recommended in the pileupJetRecommendations [278], jets with $p_T < 60$ GeV are tagged as being “tight” for their identification. This classification helps distinguish them from jets that are likely due to pile-up interactions in the event.

The DL1r algorithm is chosen to identify jets likely coming from b-hadrons produced from the hard scatter and the FlavourTaggingRecommendationsR21 [279]. A working point of 77% fixed efficiency is chosen to optimize the sensitivity of the analysis.

The photons reconstructed in each event are required to have $p_T > 25$ GeV. Only central photons with $|\eta| < 2.5$ are considered. Photons measured within the transition region of the calorimeter between the barrel and endcap regions ($1.37 < |\eta| < 1.52$) are excluded. Identification and isolation requirements are placed on photons to ensure their quality and suppress contamination from jets mistakenly identified as photons [189]. These misidentified photons are further excluded when the isolation requirements are imposed. The track-based isolation requirement is that the sum of the transverse momenta of all tracks within $\Delta R < 0.2$ of the photon direction, excluding tracks that have been associated with the reconstructed photon, must be less than 5% of the photon p_T . The energy-based isolation requirement is that the sum of the transverse momenta of all calorimeter energy deposits within $\Delta R < 0.4$ of the photon direction, excluding those associated with the reconstructed photon, is required to be less than $2.45 \text{ GeV} + 0.022 p_T^\gamma$. Only tracks originating from the primary

vertex are included in these sums. The calorimeter-based isolation also takes into account the underlying event by using the average energy density of the underlying event, determined from data [189].

The photon selected as the ISR photon within the analysis is chosen using the HLT_g140_loose trigger. The efficiency of this trigger is explored in the next subsection.

Events in data must be from a run included in the good runs list (GRL), listed in Section 7.2. Events in data must also pass the standard cleaning requirements: pass the liquid argon error veto, pass the tile error veto, pass the SCT corrupted event veto, and be “complete”. Finally, events in data must have 2 associated tracks with the highest Σp_T^2 vertex. Finally, the overlap removal algorithm [280] is used to ensure that the various physical objects are not double counted.

The requirements are summarized in Table 6.3.

Object	Requirements
trigger	HLT_g140_loose
jets	EMPflow, $p_T > 25$ GeV, $ \eta < 2.8$
photon	tight, $p_T > 25$ GeV, $ \eta < 2.5$
b-jets	2 leading p_T jets tagged with DL1r at 77% fixed eff. WP

Table 6.3: A table summarizing the object selection criteria for photons, jets, and b-tagged jets in events chosen for this analysis

Truth information about the objects simulated in events is used throughout this analysis for comparison to reconstructed objects. Muons and neutrinos are excluded within these truth events and particles are required to have a lifetime, τ , such that $c\tau > 10$ mm. “Truth jets” are reconstructed at the generator level within the simulations. They are subject to the same kinematic requirements as the reconstructed jets used in this analysis. This cut biases the event selection, so when measurements of the detector mass resolution are performed in Section 7.5, a higher cut of $p_T > 30$ GeV is placed on both the truth and reconstructed jets. This choice has no impact on the detector mass resolution.

Trigger Strategy

Events in simulation and data are selected for this analysis using the HLT_g140_loose trigger, an online cut-based selection suitable to the single photon in the final state of the γjj process. This trigger chain is seeded at L1 using the ROI of an isolated energy deposit in the electromagnetic calorimeter that contains transverse energy of at least $E_T > 22$ GeV. At the HLT stage, the ROI is examined for events containing at least one isolated photon with $E_T > 140$ GeV that passes the loose identification working point using a multivariate likelihood technique. The E_T requirement for this trigger is the lowest value for which all triggered events are recorded for offline analysis from 2015 through 2018. This triggering strategy is roughly the same as in a previous iteration of this analysis described in [247]. In the offline data analysis, a more precise estimate of this same quantity is found.

It is critical in any analysis to estimate the trigger efficiency, or the observed relative frequency that an event in a well-identified set of single photons passes the HLT_g140_loose trigger selection, as a function of the p_T of the photon in the event. The HLT_g60_loose trigger is used for pre-selection because it is fully efficient for isolated photons passing the tight identification and $p_T > 70$ GeV.

The efficiency of the HLT_g140_loose trigger was determined with respect to the offline reconstruction by a process of “bootstrapping”, which takes the bin-wise ratio of resonance candidate events reconstructed in the dataset passing the HLT_g140_loose and HLT_g60_loose triggers from events passing just the HLT_g60_loose trigger as a function of the transverse momentum of the leading isolated photon passing loose identification. These efficiency curves are also known as “turn-on curves.”

The trigger turn-on curve is fit with a modified error function in Equation 6.1. In this formula, p_0 is the maximum efficiency in the plateau region, p_1 is the p_T value for which the efficiency reaches half its maximum, and p_2 is the slope of the turn-on curve.

$$p_0 \cdot \left(1 + \operatorname{erf}\left(\frac{x - p_1}{\sqrt{2}p_2}\right)\right) \quad (6.1)$$

This is first done for all events passing the nominal criteria without any optimized cuts. The optimization of the cut on the discriminating variable y^* is discussed in the next section. The resulting efficiency curve is shown in Figure 6.6. Around a $p_T = 145$ GeV threshold, the trigger efficiency plateaus and stabilizes and the trigger is fully

efficient. This curve is representative of the other three years because the thresholds of the trigger did not change during this period and the trigger is relatively pile-up insensitive.

We wish to understand the trigger efficiency for events we look at in this analysis. After optimizing the y^* cut and requiring $m_{jj} > 169$ GeV, the turn-on curve was recalculated using the full analysis selection except for the cut on leading photon p_T . This is shown in Figure 6.7. This figure shows that placing a cut on the leading photon p_T of 150 GeV results in full efficiency and is appropriate for this analysis.

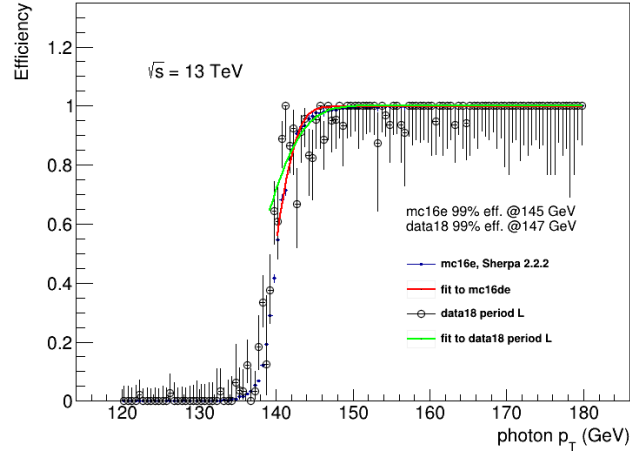


Figure 6.6: The efficiency of the HLT_g140_loose trigger as a function of the leading isolating photon passing tight identification for events passing all selection criteria excluding the optimized y^* cut. The efficiencies in the 2018 data Period L and mc16e are shown. Fits to both are shown in green and red.

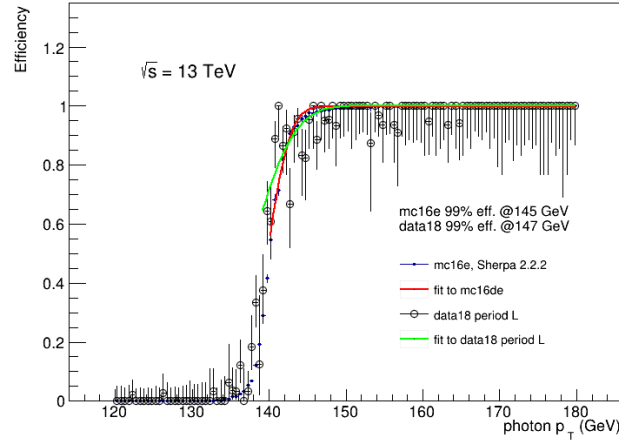


Figure 6.7: The efficiency of the HLT_g140_loose trigger as a function of the leading isolating photon passing tight identification for events passing all selection criteria including the optimized y^* cut. The efficiencies in the 2018 data Period L and mc16e are shown. Fits to both are shown in green and red.

Event Selection

Using an appropriate cut selection on discriminant variables, the background to the γjj process can be suppressed by a large factor while leaving the signal events relatively intact. This results in increased signal sensitivity (Eq. 6.2). For large statistics, this is approximated with $\frac{S}{\sqrt{B}}$.

$$Z = \sqrt{2(s+b)\log(1 + \frac{s}{b}) - s} \quad (6.2)$$

A study is performed to see how placing cuts on one or two discriminant variables increases the sensitivity. The invariant mass distributions for signal and background events were compared and used to calculate the signal sensitivity. Only rectangular cuts on potential discriminant variables are explored. The variables considered include the rapidity difference between the leading two jets (Eq. 6.3), p_T asymmetry (Eq. 6.4), and the angular separation (Eq. 6.5) between the leading jets in the dijet system and various combination pairs of the photon and the two leading jets. The boost of the dijet system and $\Delta\phi$ between the leading jets were also studied.

$$y_{i,j}^* = \frac{|y_i - y_j|}{2} \quad (6.3)$$

$$A_{i,j} = \frac{|p_{T,i}| - |p_{T,j}|}{|p_{T,i}| + |p_{T,j}|} \quad (6.4)$$

$$\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \quad (6.5)$$

This study was done for Z' signals with masses of 250, 350, 450, 550 and 650 GeV during the mc16a, mc16d, and mc16e campaigns. Each mass has a m_{jj} range of ± 50 GeV and this study identifies the ideal selection cut value for each discriminant variable for all Z' masses considered. The signal and background distributions in these variables are plotted in Figures 6.8 to 6.12. Eq. 6.2 is used to calculate the signal significance in each bin, where s and b represent the cumulative sums of the events in that bin and all preceding bins of the signal and background distributions.

Table 6.4 shows the maximum value of significance found for different cuts on individual discriminant variables normalized to a luminosity of 1 pb^{-1} in each mass range. In all mass ranges, the discrimination power is highest for y^* between the

leading and subleading jets. The signal is expected to be produced roughly isotropically, but multi-jet and single photon background production preferentially generate forward jets with large rapidity differences. Placing a maximum cut on y^* selects jets that are relatively central in their center of mass frame. A cut on a correlated variable ΔR yields slightly lower significance than y^* . It is also seen that combining information from the farthest jet and the photon may be powerful. Varying cuts on two discriminant variables was also explored as a way to increase the sensitivity. Figure 6.13 shows the 2D scan over both y^* and asymmetry. No added sensitivity is gained by using multiple variables instead of y^* .

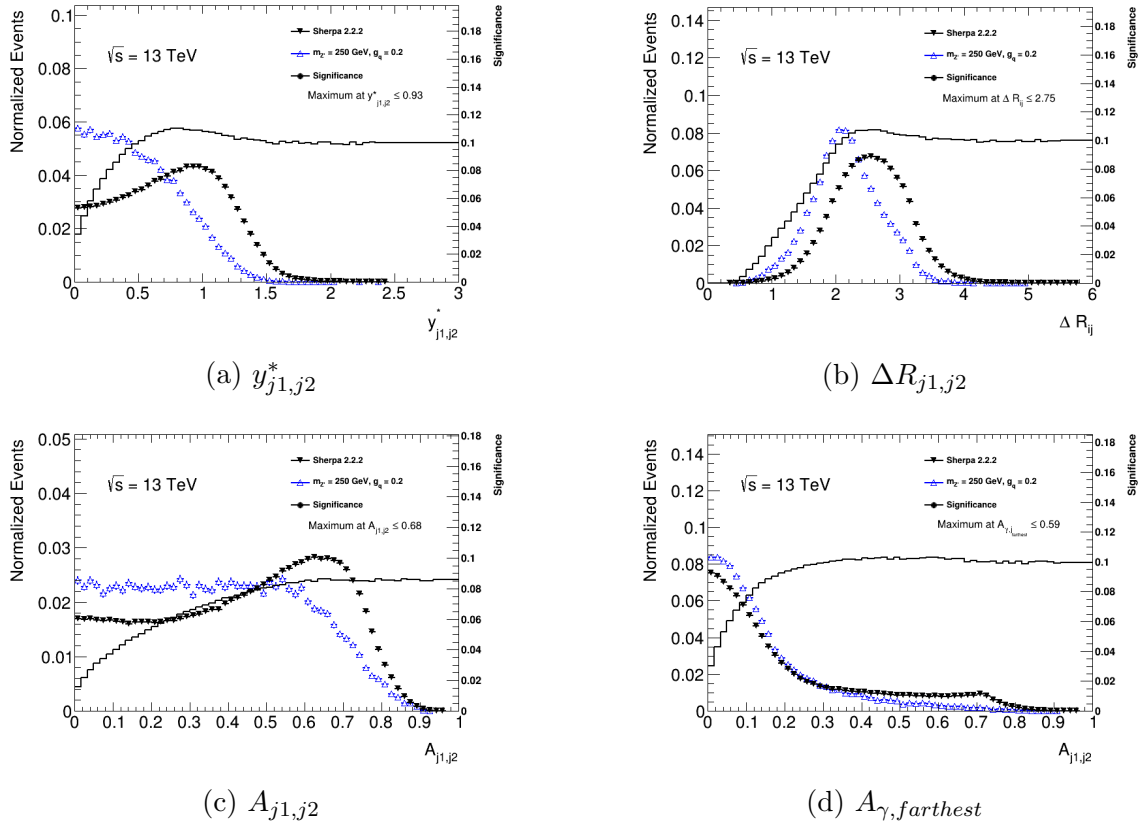
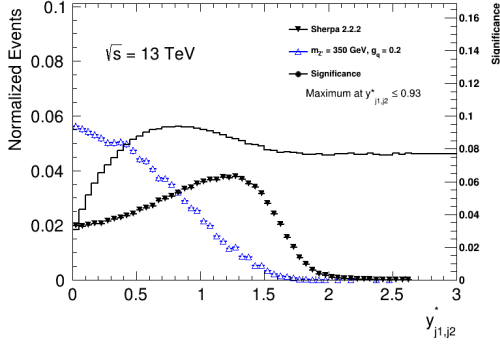
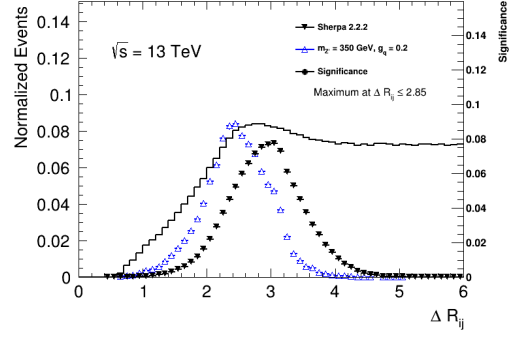


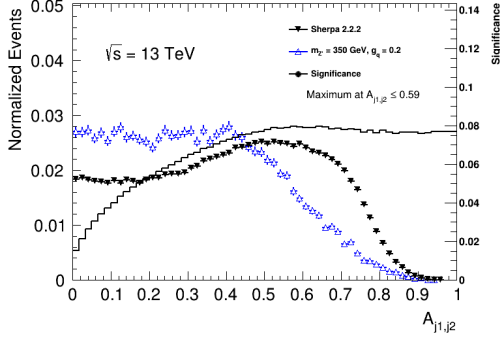
Figure 6.8: Signal (S) and background (B) distributions of four of the most discriminant variables, along with the signal significance distribution for the two leading jets in photon+jet events in the 200 GeV to 300 GeV mass range.



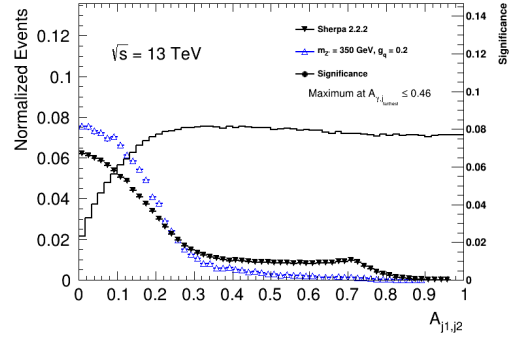
(a) $y_{j1,j2}^*$



(b) $\Delta R_{j1,j2}$

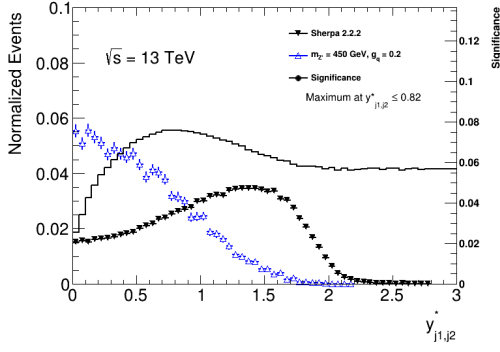


(c) $A_{j1,j2}$

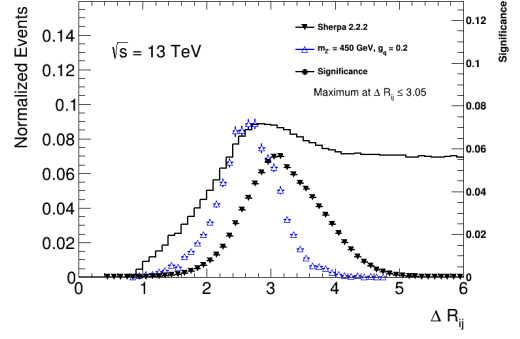


(d) $A_{\gamma,farthest}$

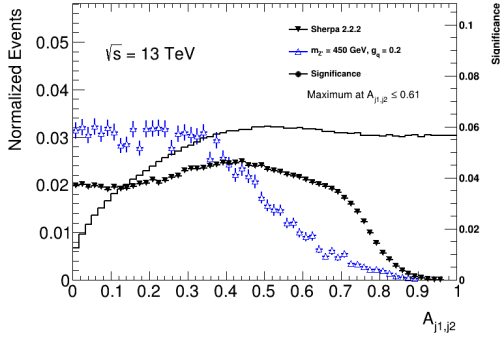
Figure 6.9: Signal (S) and background (B) distributions of four of the most discriminant variables, along with the signal significance distribution for the two leading jets in photon+jet events in the 300 GeV to 400 GeV mass range.



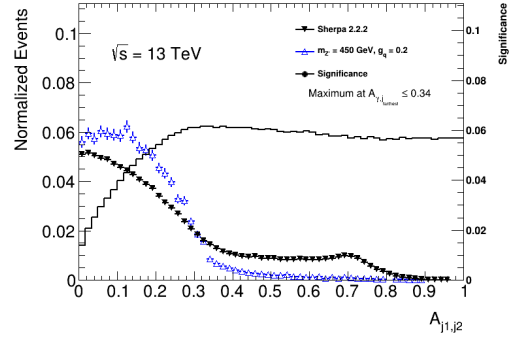
(a) $y_{j1,j2}^*$



(b) $\Delta R_{j1,j2}$

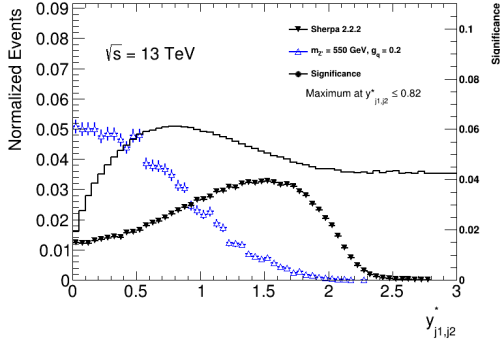


(c) $A_{j1,j2}$

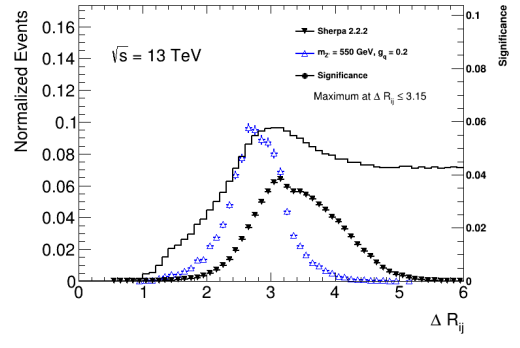


(d) $A_{\gamma,farthest}$

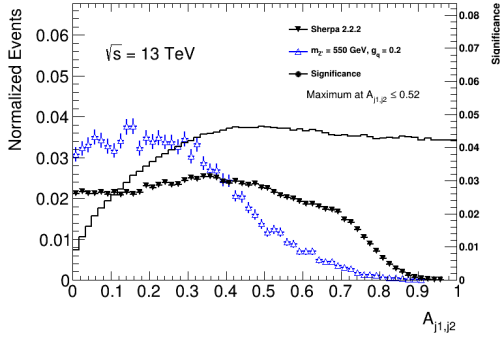
Figure 6.10: Signal (S) and background (B) distributions of four of the most discriminant variables, along with the signal significance distribution for the two leading jets in photon+jet events in the 400 GeV to 500 GeV mass range.



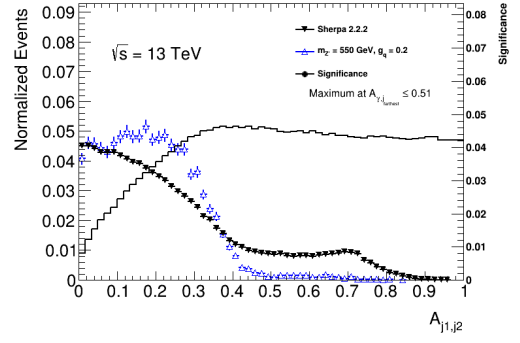
(a) $y_{j1,j2}^*$



(b) $\Delta R_{j1,j2}$

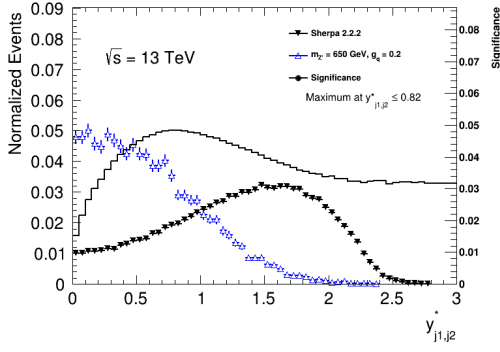


(c) $A_{j1,j2}$

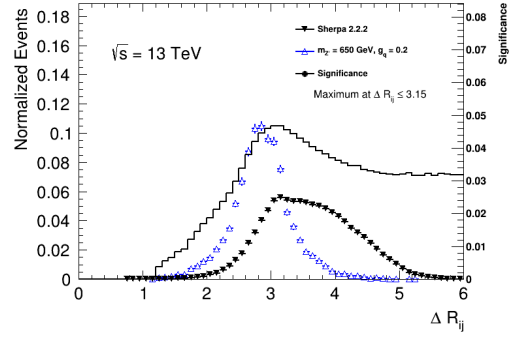


(d) $A_{\gamma,farthest}$

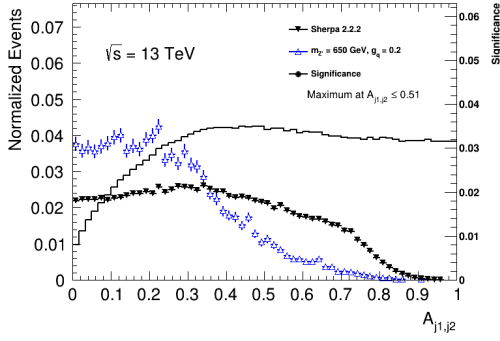
Figure 6.11: Signal (S) and background (B) distributions of four of the most discriminant variables, along with the signal significance distribution for the two leading jets in photon+jet events in the 500 GeV to 600 GeV mass range.



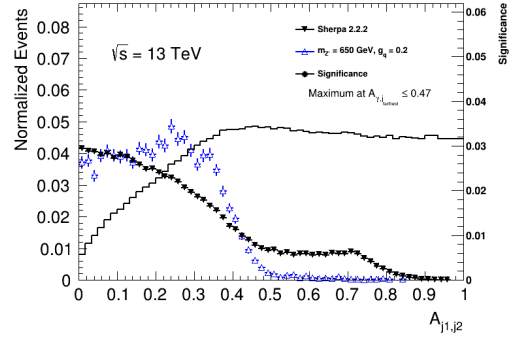
(a) $y_{j1,j2}^*$



(b) $\Delta R_{j1,j2}$

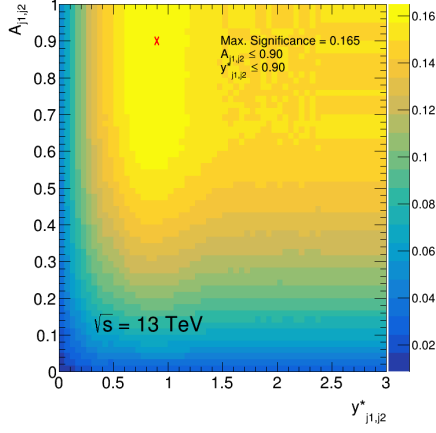


(c) $A_{j1,j2}$

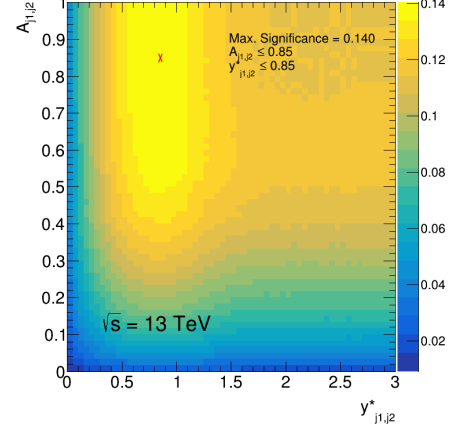


(d) $A_{\gamma,farthest}$

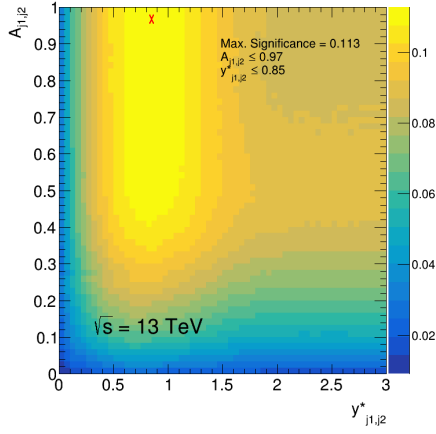
Figure 6.12: Signal (S) and background (B) distributions of four of the most discriminant variables, along with the signal significance distribution for the two leading jets in photon+jet events in the 600 GeV to 700 GeV mass range.



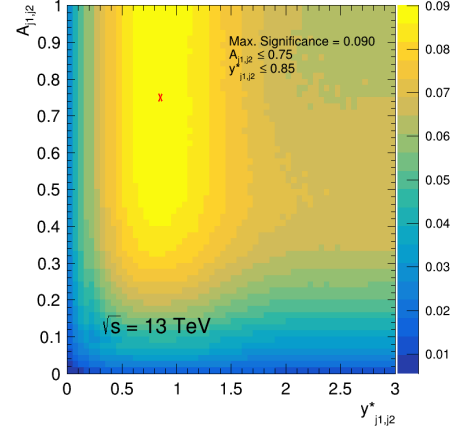
(a) $M_{Z'} = 250$ GeV



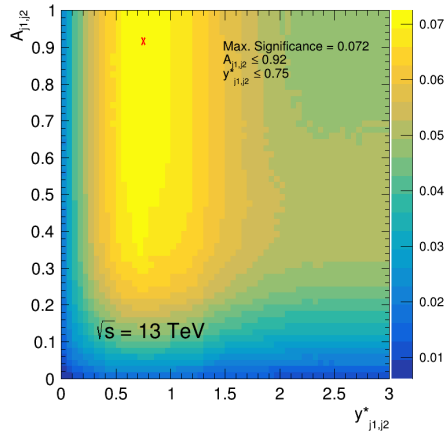
(b) $M_{Z'} = 350$ GeV



(c) $M_{Z'} = 450$ GeV



(d) $M_{Z'} = 550$ GeV



(e) $M_{Z'} = 650$ GeV

Figure 6.13: Two dimensional signal significance scan over the variables y^* and asymmetry at different mass points.

Mass Range [GeV]	y^* sig.	y^* cut	ΔR sig.	ΔR cut	A sig.	A cut
$200 \leq m_{jj} \leq 300$	0.164	≤ 0.925	0.161	≤ 2.75	0.155	≤ 0.73
$300 \leq m_{jj} \leq 400$	0.140	≤ 0.925	0.133	≤ 2.85	0.122	≤ 0.73
$400 \leq m_{jj} \leq 500$	0.114	≤ 0.825	0.107	≤ 3.05	0.092	≤ 0.95
$500 \leq m_{jj} \leq 600$	0.092	≤ 0.825	0.087	≤ 3.15	0.069	≤ 0.78
$600 \leq m_{jj} \leq 700$	0.073	≤ 0.825	0.07	≤ 3.15	0.052	≤ 0.48

Table 6.4: Maximum value of the significance for each mass range, for different choices of individual variables.

Mass range [GeV]	Maximum significance for $y^* \leq 0.825$
$200 \leq M_{jj} \leq 300$	0.163
$300 \leq M_{jj} \leq 400$	0.138
$400 \leq M_{jj} \leq 500$	0.112
$500 \leq M_{jj} \leq 600$	0.092
$600 \leq M_{jj} \leq 700$	0.073

Table 6.5: Maximum value of the significance for each range for $y_{j1,j2}^* \leq 0.825$ as used in the analysis.

The optimized cut value is determined using the mass range with the lowest significance. It is verified in Table 6.5 that this cut does not significantly reduce the significance value for other masses studied. The final event selection criteria, summarized in Table 6.6 implements a rectangular of $y^* \leq 0.825$.

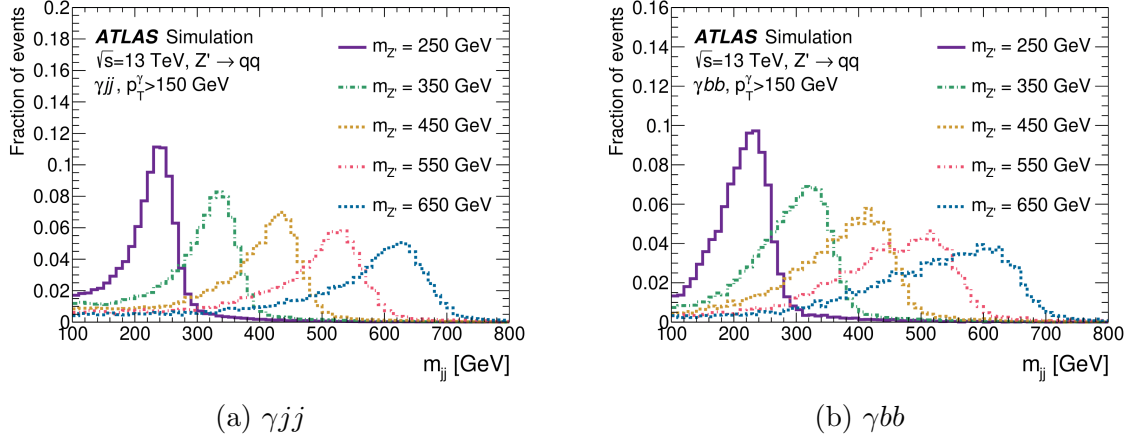


Figure 6.14: Invariant mass distribution for Z' signals after the event selection was applied for $M_{Z'} = 250, 350, 450, 550, 650$ GeV. From [1].

Cut	Single-photon trigger (HLT_g140_loose)
Number of jets	$n_{jet} \geq 2$
Number of photons	$n_{\gamma} \geq 1$
Lead γ p_T	$p_T^{\gamma} > 150$ GeV
Lead and sublead jet p_T	$p_T^j > 25$ GeV
Centrality	$ y_{12}^* < 0.825$
Invariant Mass	$m_{jj} > 169$ GeV

Table 6.6: A summary of the selection criteria used in the inclusive dijet+ISR photon analysis. An additional requirement that the two leading jets be b-tagged is placed for the γbb channel.

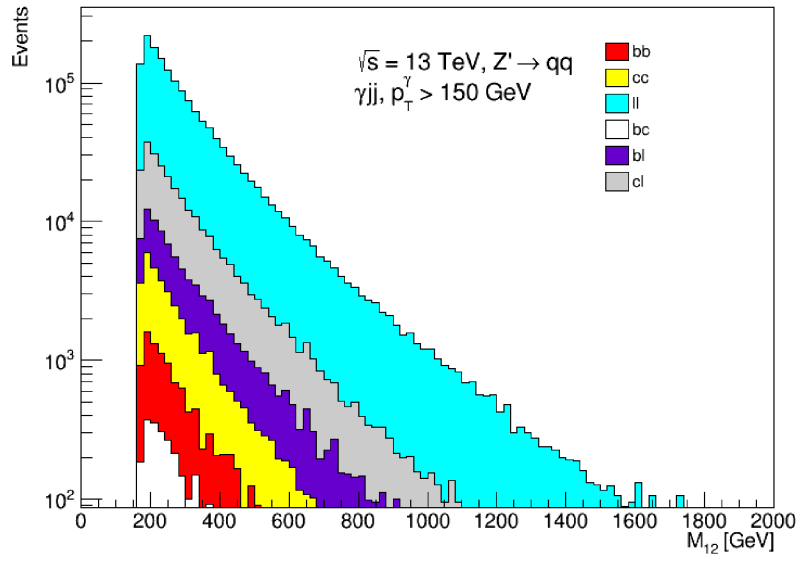
Fig. 6.14 shows the invariant mass distributions of the simulated Z' signals after selection criteria was applied.

Flavor Tagging Selection

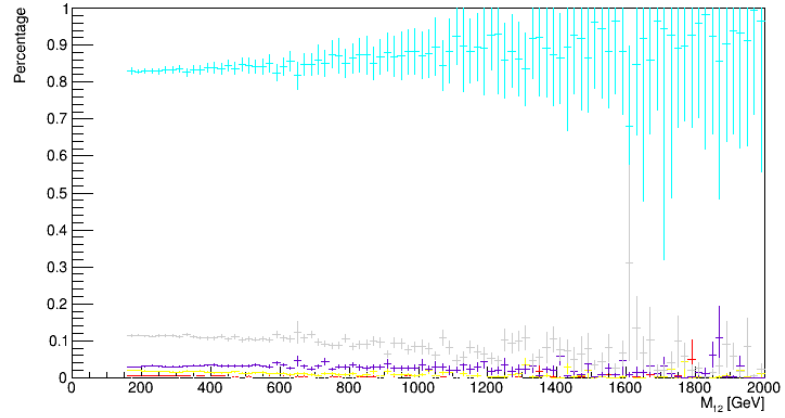
In addition to an inclusive search, a search is performed where the resonance is reconstructed from two b-tagged jets. In addition to the full analysis selection criteria used in the inclusive channel, the two jets forming the resonance are required to pass the tagging requirements. The DL1r tagger was used at a 77% efficiency fixed cut working point.

We study the impact of applying the b-tagging algorithm to the composition of the MC background m_{jj} spectrum. In Fig. 6.15a), the m_{jj} distribution for events passing the inclusive selection criteria is shown, broken down by flavor combinations to demonstrate how the composition of the two jets changes as a function of m_{jj} . In Fig. 6.15b) the relative contribution of each flavor pairing is plotted. In the inclusive channel, the dominant contribution comes from pairs of light jets and this proportion is stable for all masses. Figure 6.16a) shows the m_{jj} distribution for events passing the b-tagged selection criteria, broken down by flavor combinations. Fig. 6.16b) shows the relative contribution of each flavor pairing. At lower masses, there is a higher proportion of true di-b-jet events. At higher masses, the b-tagging performance degrades and mis-tagged light jets dominate the composition. No sharp features in the composition of the m_{jj} spectrum are found. If the m_{jj} distributions were to contain sharp variations, the background may not be accurately described

The benefit of using this tagger to select jets for the resonance is seen in Fig. 6.17. The sensitivity in this channel is increased compared to the inclusive channel. This thesis presents the results of this analysis in both the γjj and γbb channels because they offer different opportunities for reinterpretation. The tagging efficiencies of the signal are later utilized in the analysis interpretations.

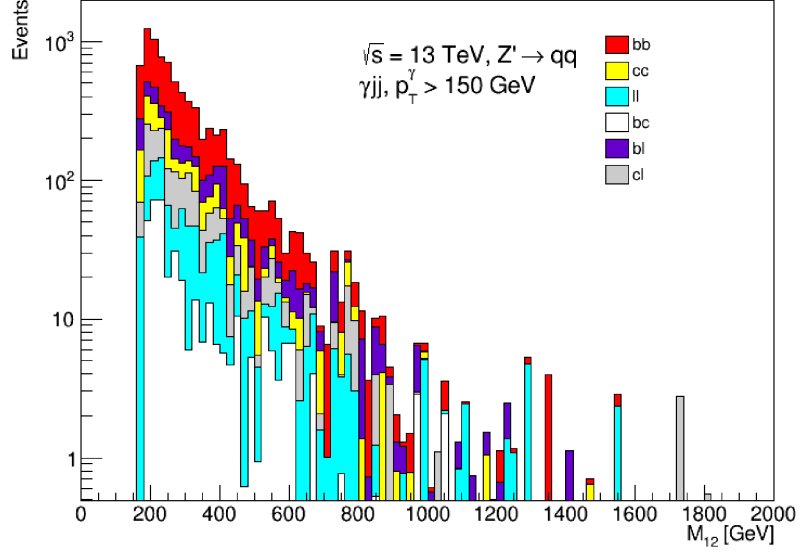


(a)

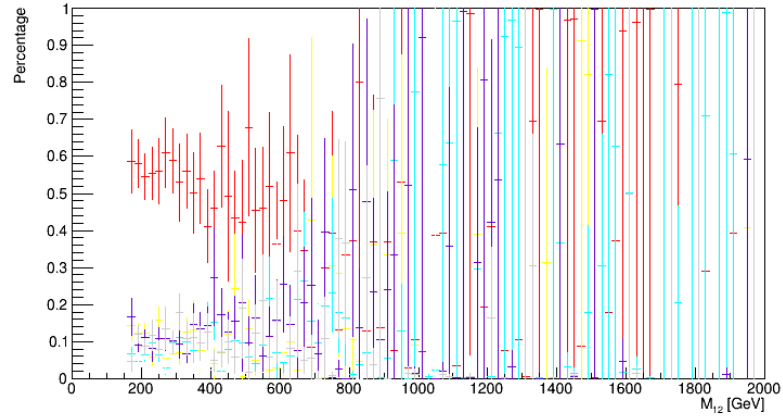


(b)

Figure 6.15: (a) The invariant mass distribution of the MC background without the double b-tagging requirement on jets. (b) The relative contribution of various combination pairs of jet types.



(a)



(b)

Figure 6.16: (a) The invariant mass distribution of the MC background with the double b-tagging requirement on jets. (b) The relative contribution of various combination pairs of jet types.

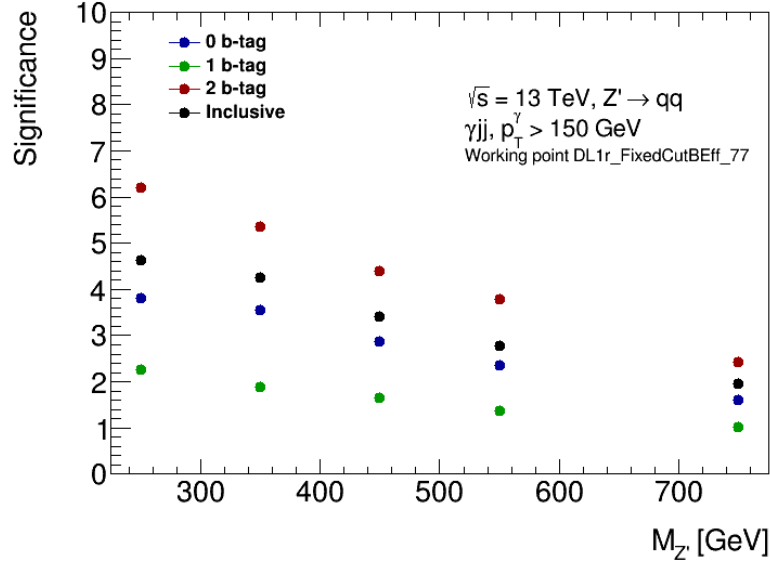


Figure 6.17: Signal significance versus mass in the inclusive, 0-tag, 1-tag, and 2-tag channels as well as a combination of the 0, 1, and 2-tag channels. The DL1r tagger is used at the 77% fixed efficiency working point.

6.5 A data driven estimate of the SM backgrounds

We utilize a data-driven estimate for the SM contribution. The dominant sources of background for the γjj process are backgrounds due to multi-jet events with a single photon. Next-to-leading order (NLO) calculations for strong interactions are possible in Monte Carlo event generators, however, the theoretical uncertainties associated with these calculations are larger than statistical uncertainties for the signal process. In our particular case of the dijet spectrum, the m_{jj} distribution predicted by QCD is a complicated non-analytic convolution of t-channel and s-channel processes. Additionally, with more final-state hadronic jets in an event, the accuracy of the NLO calculations degrades. Parton showering, hadronization, and underlying events have a smaller but non-negligible impact on the theoretical uncertainty. This is further complicated by the effects of detector response and kinematic selection. The primary reason for a data-driven estimate is that large uncertainties on the detector response, particularly the jet energy scale and jet energy resolution, would have to be

applied during the simulation and at TeV masses, this is the dominant experimental uncertainty.

The properties of theoretical models producing resonances in our m_{jj} range imply that while there may be a signal region where interesting events may be found, a majority of the m_{jj} fit range considered is a background-dominated control region. We use a parametric global fit to the m_{jj} spectrum using a smooth analytic functional form that ATLAS have previously found to provide satisfactory fits for dijet spectra predicted by leading and NLO QCD MC predictions and to data. These functional forms and the analyses they were used in is shown in Table 6.7. We consider the 4, 5, and 6-parameter fit functions and setup and validate our procedure in MC and in a small unblinded dataset.

The analysis strategy will create a nominal background estimate using whatever function performs the best in the real data. An uncertainty on the function selection will be defined using the second best of the three functions.

Functional Form	Experiment	Citation
$f(x) = p_1(1 - x)^{p_2}x^{p_3}$	ATLAS	Phys. Lett. B 754 (2016) 302,
$f(x) = p_1(1 - x)^{p_2}x^{p_3+p_4\ln x}$	ATLAS	Phys. Rev. D 91 (2015) 052007
$f(x) = p_1(1 - x)^{p_2}x^{p_3+p_4\ln x+p_5(\ln x)^2}$	ATLAS	Phys. Rev. D 91 (2015) 052007
$f(x) = p_1(1 - x)^{p_2}x^{p_3+p_4\ln x+p_5(\ln x)^2+p_6(\ln x)^3}$	ATLAS	

Table 6.7: Functional forms explored for fitting the QCD background, where $x \equiv m_{jj}/\sqrt{s}$. The paper where each function was first successfully applied to dijet and multi-jet resonance searches are listed as well.

Mass binning

The detector mass resolution must be measured to choose the appropriating m_{jj} binning scheme used in the limit setting stage of the analysis. The detector mass resolution is estimated using PYTHIA simulated background samples by fitting the width of a Gaussian fit to the core of the jet mass response divided by the fitted jet mass response, σ_R/R .

Cuts similar to the analysis cuts are applied to the simulated background samples at the truth level as to avoid biasing the distribution. The requirement that the leading and subleading jet $p_T > 25$ GeV is raised to $p_T > 30$ GeV because the samples did not contain any truth jets with p_T below 25 GeV and this results in biases in the m_{reco}/m_{truth} distributions used to evaluate the relative resolution in a given m_{truth} bin. The impact of this choice is minimal on the final binning and will enable a better estimation of the actual mass resolution at low dijet masses.

The jet mass resolution as a function of m_{jj} is determined by measuring the relative resolution at different bins in the m_{truth} distribution. Sturges' rule is used to determine the number of m_{truth} bins to use within the range of: 160 GeV to 1300 GeV. This range is then divided into bins containing an equal number of events. For all events in each bin, a histogram is constructed for m_{reco}/m_{truth} . Each histogram is fit with a Gaussian and the standard deviation of the Gaussian divided by its mean is the relative resolution in the m_{truth} bin. These fits are not shown here.

The relative energy resolution of a typical calorimeter is described by the form in Eq. 6.6.

$$\frac{\sigma_E}{E} \propto \alpha \frac{1}{E} + b \frac{1}{\sqrt{E}} + c. \quad (6.6)$$

The jet mass resolution curve is fit with this form, substituting m_{jj} for E . The curve and fit are shown in Fig. 6.18. The absolute resolution is interpolated from the fit function and is used to determine the bin centers and optimal bin widths, requiring the first bin to have a lower bound of $m_{jj} = 169$ GeV. The binning schemes for the γjj channel are shown in Table 6.8.

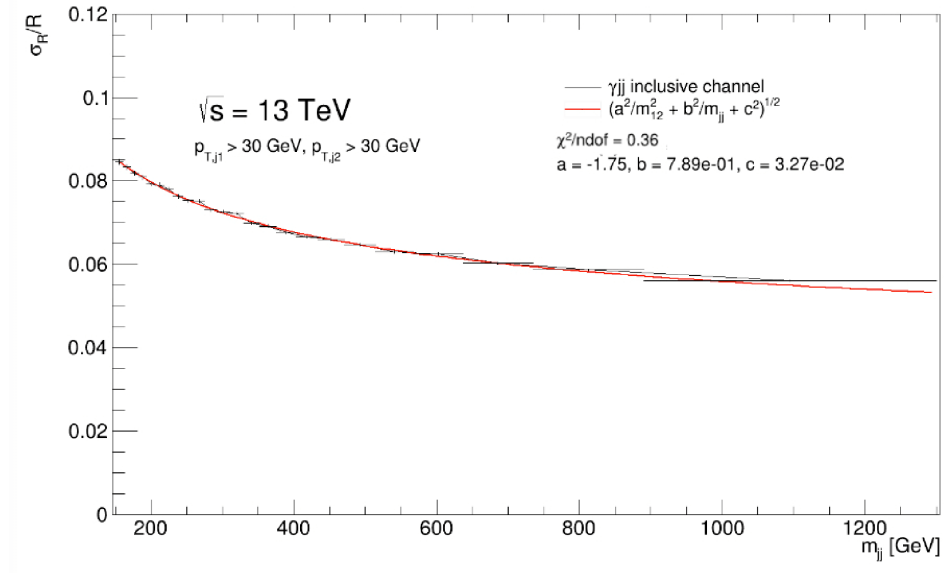


Figure 6.18: The jet mass resolution as a function of m_{jj} , for the inclusive channel.

169	196	212	229	246	265	285	306
328	351	376	402	429	458	488	519
553	587	624	662	703	745	789	835
884	934	987	1042	1100	1161	1124	1274

Table 6.8: List of bins for the γjj channel. The same binning scheme is applied to the γbb channel.

In the limit setting stage, this derived binning is applied, however, for the background fits and associated tests, bins of 1 GeV are used. For γbb channel, the statistical uncertainty on the fits is quite large and it is safe to apply the same resolution to this channel.

Fit setup and pseudodata generation

The functional fit that we choose for the data-driven estimate is studied in both MC and subsets of data to ensure convergence, robustness, and flexibility. In the inclusive channel, the statistical power of MC is roughly half of what it is expected to be in data. The quality of the fit is assessed using a reduced χ^2 metric and p-values greater than 0.1 are considered to indicate a good fit. Pseudodata distributions obtained from the global fit function to the background-only MC distribution are generated to perform tests on the stability and robustness of the fit procedure.

The fit itself is a 1 GeV-binned likelihood fit setup provided by the `FrequentistFramework` package [281], based on two packages available for ATLAS statistical analysis: `xmlAnaWsBuilder` [282] and `quickFit` [283]. The fit range is chosen based on the fit convergence and m_{jj} resolution. The total number of events in the m_{jj} spectra is parameterized in Eq. 6.7. The signal PDF function is taken from MC simulation for the Z' model-dependent case or as a Gaussian for the model-independent interpretations. The Gaussians are considered to have widths comparable to those from the expected MC signals as nuisance parameters. Systematic effects are applied to the signal. The background PDF function is chosen among typical functions used in dijet searches.

$$N_{total}(m_{jj}) = N_{sig}PDF_{sig}(m_{jj}, NP_{sig}) + N_{bkg}PDF_{bkg}(m_{jj}, NP_{bkg}) \quad (6.7)$$

Having success in fitting the MC background distributions does not guarantee the fitting procedure will work in data. Consequently, the background-only fits are also validated by fitting unblinded data from 2015 and 2018.

Assessing the performance of the fitting procedure

The residual of the fits to the m_{jj} as a function of resonance mass should contain no structure, including oscillatory behavior. This could be introduced if the analytic fit function used to describe the background isn't sufficient to describe the high statistics in the data.

The spurious signal and signal injection tests assess whether the fit function being explored correctly infers the number of signal events present in the m_{jj} distribution being fit. A spurious signal measures the bias in a fit by quantifying the difference

between the median fitted signal yield and the expected signal yield when fitting a template with a known signal yield using a smooth background model [284]. The spurious signal test is designed to test that a fit for signal plus background to a background-only distribution yields a measured number of signal events that are compatible with zero. The signal injection test investigates the potential bias in the background configuration by quantifying the median difference between the injected signal cross-section and fitted signal cross-section when fitting a background distribution that has an injected signal in it with a specific cross-section.

Spurious signal test: For this analysis, the simulated MC sample of the background is used to generate many unique pseudodata distributions that mimic the expected m_{jj} shape, within statistical variations. The pseudodata can be generated from a 6-parameter background-only fit to the MC by varying the expected data yield within its associated Poisson uncertainty. For each pseudodata distribution, a 5-parameter fit of the same configuration as the eventual functional form used to fit the data is performed, allowing for the presence of a Gaussian signal or a simulated Z' signal from MC. In the case of the Gaussian signal, no signal systematic nuisance parameters are considered while for the Z' signals, all NPs are free to float. The median of the distribution of the number of signal events found in a fit, S_{fit} , to each pseudodata distribution is found to be the spurious signal. The uncertainty on the number of signal events found in a fit, σ_{fit} , is taken as the RMS of that distribution and is determined as a function of $m_{Z'}$ [284]. At each mass point in both fits, $S_{spur} \leq 0.5 \cdot \sigma_{fit}$, and it is concluded that the fit is unbiased in the case of there being no signal in the distribution being fit.

Signal Injection Test: Pseudodata distributions are generated at each resonance mass point using a 6-parameter fit to the MC spectrum and a signal is injected with a cross-section ranging from 0 to 5σ where σ is defined as $S/\sqrt{(B)}$ within a 1σ window around the Z' mass. This procedure is done for Z' -like signals and Gaussian signals from MC of known widths. The 5-parameter fit is performed on the pseudo-experiments allowing for the presence of signal and background. The cross-section of the fit signal and its 68% CL standard deviations are obtained. The median difference between the injected signal cross-section and the fitted signal cross-section divided by the standard deviation of the fit is the bias of the fit. It is expressed in units of standard deviations.

Fit validation in the γjj channel using MC

The range for which the fit converges in the γjj channel is 250 to 875 GeV and this range is used to set limits in this channel.

The results of the spurious signal test for the background fits to the m_{jj} spectrum in the γjj channel are shown in Figures 6.19 for the Z' signals and Figure 6.20 for Gaussian signals. In each of the fits, the fit bias is less than half the uncertainty on the number of signal events determined from the fit ($S_{spur} \leq 0.5 \cdot \sigma_{fit}$). For every $M_{Z'}$, this condition is satisfied, indicating that the fit is unbiased in the case of an absence of signal in the distribution to be fit.

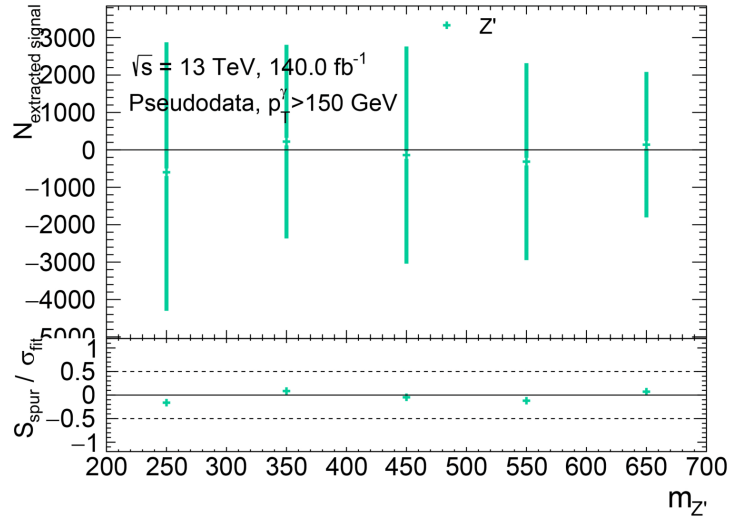


Figure 6.19: The spurious signal as a function of all tested $M_{Z'}$ in the γjj channel.

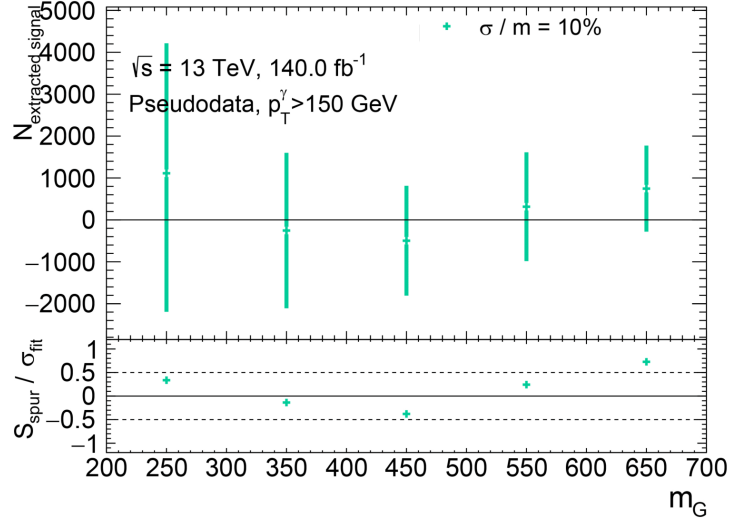


Figure 6.20: The spurious signal as a function of all tested M_G in the γjj channel. The Gaussian templates used have a width of 10%.

The results of the signal injection tests for the Z' signal in the γjj channel is in Figure 6.28. The mean bias is around or less than one-half a standard deviation for most resonance masses, widths, and signal strengths considered. The results of the signal injection tests for the Gaussian signals are in Figure 6.29. It is concluded that the fitting procedure is robust for the γjj channel.

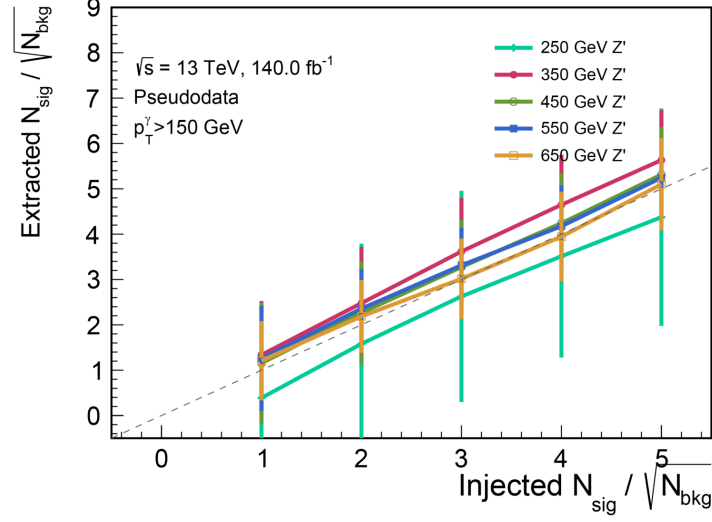


Figure 6.21: Average number of extracted signal significance as a function of the injected signal significance for the signal templates at all $M_{Z'}$ in the γjj channel.

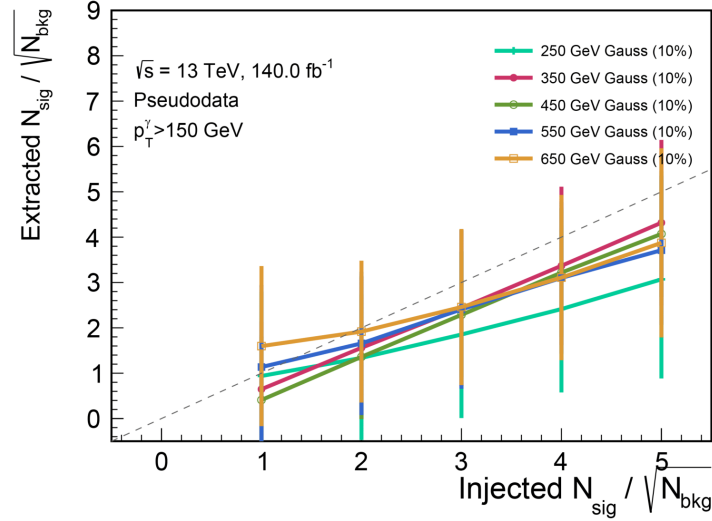


Figure 6.22: Average number of extracted signal significance as a function of the injected signal significance for the Gaussian signals at all M_G in the γjj channel. The Gaussian templates used have a width of 10%.

Fit validation in the γbb channel using MC

The multi-jet MC sample generated for the γbb process has limited statistics compared to the inclusive channel and much fewer compared to the Run 2 data. This makes the MC difficult to fit and yields large statistical uncertainties. The “ABCD method” implemented in [247] is an extrapolation technique that re-weights inclusive events using the tagging efficiencies of the two selected jets from two candidate control regions to determine the background of the γbb sample with smaller statistical uncertainties.

This technique requires separating all events in the inclusive spectra meeting the nominal selection criteria into 4 regions. There is one signal region (A) and 3 control regions (B, C, and D). Region A uses our selection criteria. A control region is ideally rich in events produced from background processes that we are trying to estimate with this method. Since the selection criteria require $|y^*| < 0.825$ and two b-tagged jets for the γbb channel, we can invert these requirements to create three background-rich regions. Regions B and D use an inverted y^* cut and therefore have no signal contamination. Region B is technically two regions.

To summarize, the four regions are:

- **Signal Region A:** Require both jets in the resonance be b-tagged and that $|y^*| < 0.825$.
- **Control Region B:**
 1. Only require that the leading jet be b-tagged and that $|y^*| > 0.825$
 2. Require both jets b-tagged and $|y^*| > 0.825$
- **Control Region C:** No b-tag requirement (inclusive) and $|y^*| < 0.825$
- **Control Region D:** No b-tag requirement (inclusive) and $|y^*| > 0.825$

Assuming no correlation between the two conditions being inverted (y^* and the b-tagging requirement), the number of events in each region (N_A, N_B, N_C, N_D), are related.

$$\frac{N_A}{N_C} = \frac{N_B}{N_D} \tag{6.8}$$

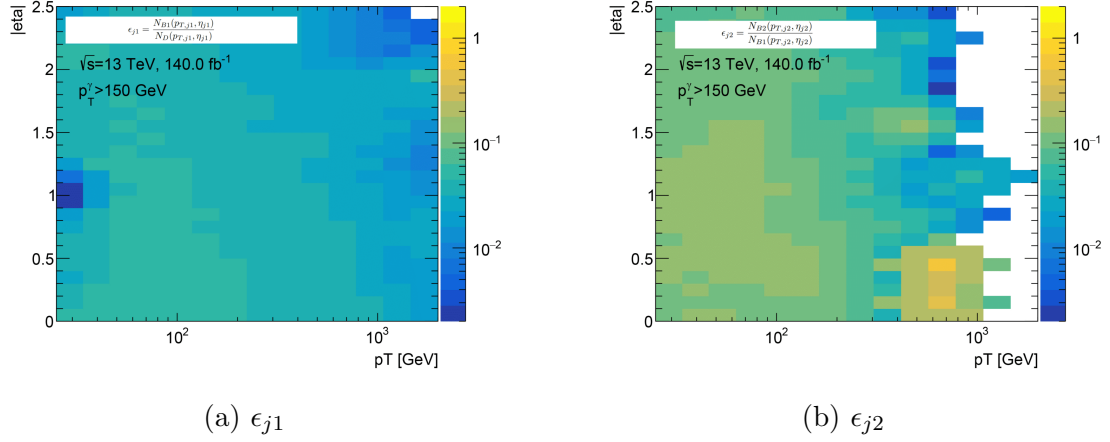


Figure 6.23: The (left) independent and (right) conditional efficiency factors used to estimate the γbb channel spectra.

The overall efficiency for tagging both jets as b-jets can be derived from Regions B and D. The b-tagging performance depends on both η and p_T of the jets involved. The efficiency of the leading jet to be tagged as a b-jet is found as a function of $p_{T,j1}$ and η_{j1} .

$$\epsilon_{j1} = \frac{N_{B1}(p_{T,j1}, \eta_{j1})}{N_D(p_{T,j1}, \eta_{j1})} \quad (6.9)$$

The conditional probability of tagging the subleading jet as a b-jet, given that the leading jet is also b-tagged, is found.

$$\epsilon_{j2} = \frac{N_{B2}(p_{T,j2}, \eta_{j2})}{N_{B1}(p_{T,j2}, \eta_{j2})} \quad (6.10)$$

The overall b-tagging efficiency is then given as ϵ_{tot} .

$$\epsilon_{tot} = \epsilon_{j1} \cdot \epsilon_{j2} \quad (6.11)$$

Figure 6.23 shows the independent and conditional efficiency factors used in the re-weighting of the m_{jj} distribution to estimate the γbb channel spectra.

Modifying Eq. 6.8 to account for both cases in B gives that the event yield in signal region A due to the background process can be predicted by measuring the event yields to the background in B, C, D.

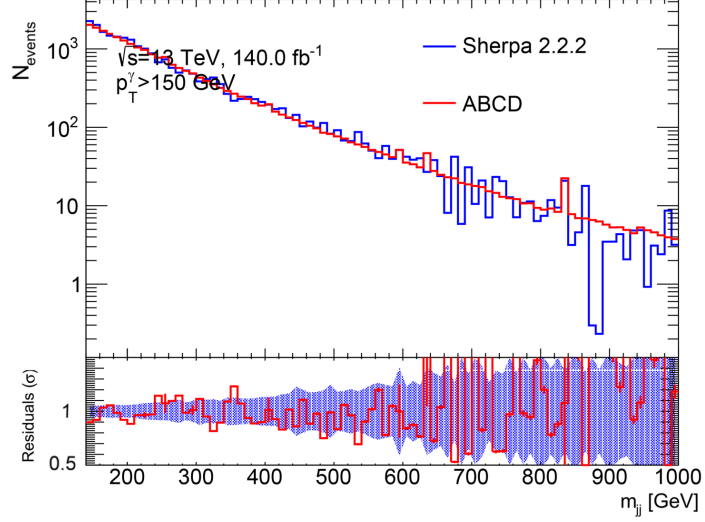


Figure 6.24: In blue is the m_{jj} distribution after applying the γbb selection criteria to the γbb MC sample. In red is the m_{jj} spectra found by re-weighting the γjj events and applying the γbb selection event selection criteria.

$$\frac{N_B}{N_D} = \frac{N_{B1}(p_{T,j1}, \eta_{j1}) \cdot N_{B2}(p_{T,j2}, \eta_{j2})}{N_D(p_{T,j1}, \eta_{j1}) \cdot N_{B1}(p_{T,j2}, \eta_{j2})} = \frac{N_A}{N_C} \quad (6.12)$$

N_A is evaluated for each m_{jj} bin in the final spectra and a distribution is constructed that has more statistics than the γbb sample with the applied selection.

Figure 6.24 shows that the ABCD reweighted m_{jj} spectrum is compatible with the one obtained by applying the event selection criteria to the γbb sample. The reweighted spectrum exhibits smaller statistical fluctuations.

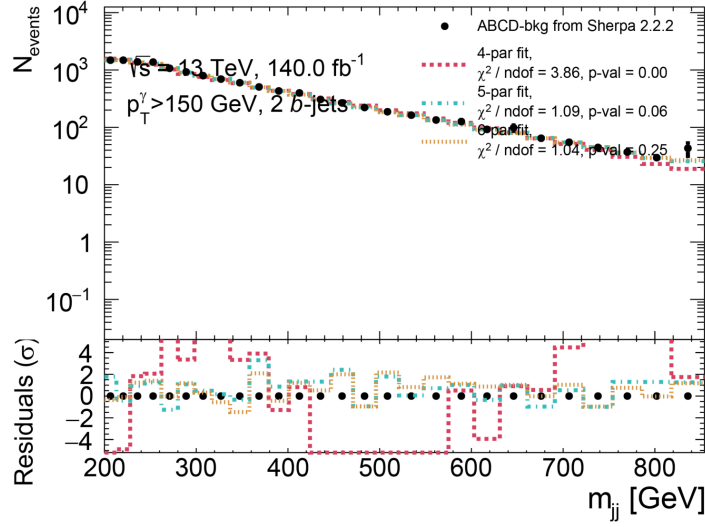


Figure 6.25: Parametric fit functions applied to the reweighted m_{jj} spectra. The 5- and 6-parameter fit functions describe the distribution well.

The same fit tests that were applied to the inclusive channel are applied to this MC-based m_{jj} spectrum. This spectrum is fitted with the 4-, 5-, and 6-parameter fit functions in Figure 6.25. The 5- and 6- parameter functions are adequate to describe the spectrum. The 6-parameter function is used to generate pseudodata distributions and the 5-parameter function is used to parameterize the background in the tests of fit stability. The range for which the fit converges is 200 to 854 GeV.

In Figures 6.26 and 6.27, the spurious signal tests for Z' templates and Gaussian signals are shown, respectively, for the γbb channel. Because the ABCD reweighted spectrum has smaller statistical fluctuations than the MC based ones, the spurious signal estimates are more accurate than if they were obtained from fitting the γbb sample directly. The spurious signal uncertainties are taken from this plot.

The signal extraction tests are shown in Figures 6.28 and 6.29 for the Z' templates and Gaussian signals, respectively. The fit procedure is robust in this channel.

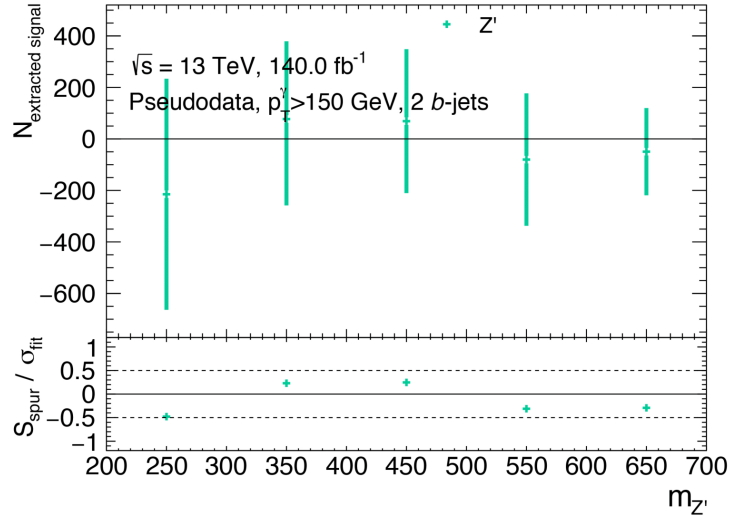


Figure 6.26: The spurious signal as a function of all test $M_{Z'}$ in the γbb channel.

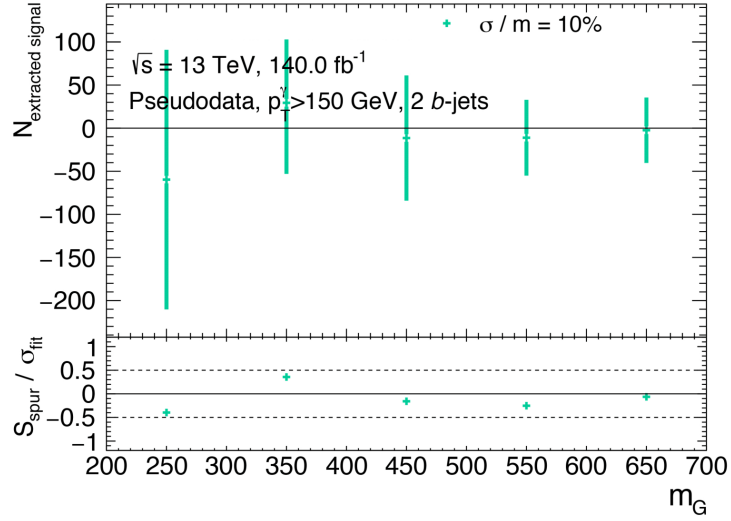


Figure 6.27: The spurious signal as a function of all tested m_G in the γbb channel. The Gaussian templates used have a width of 10%.

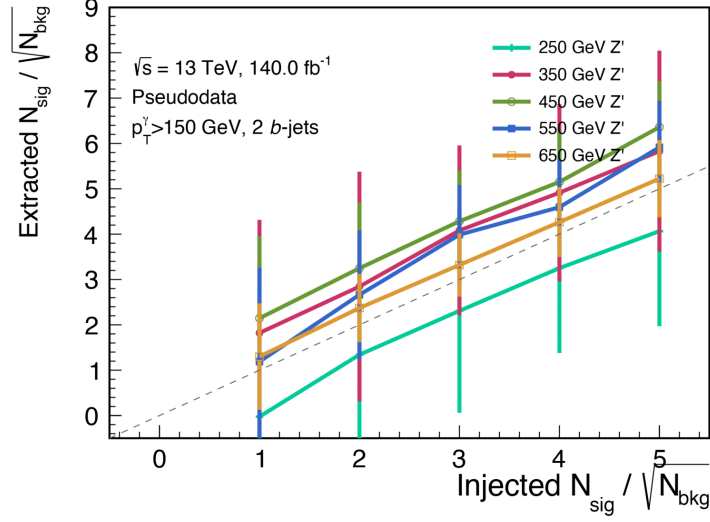


Figure 6.28: Average number of extracted signal significance as a function of the injected signal significance for the signal templates at all $M_{Z'}$.

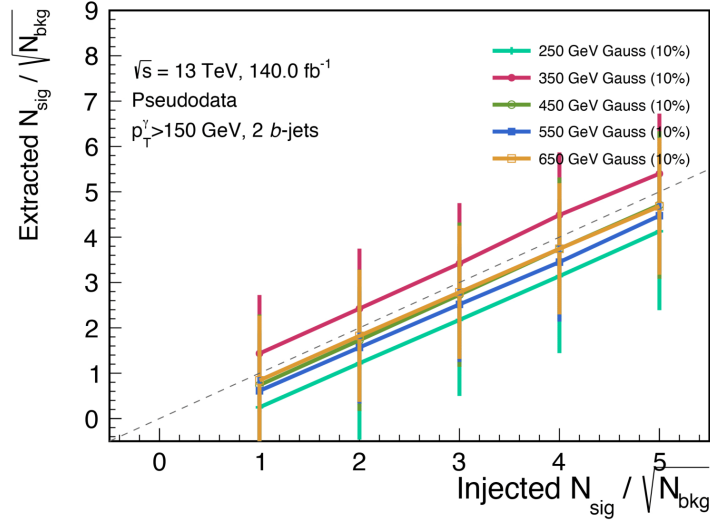


Figure 6.29: Average number of extracted signal significance as a function of the injected signal significance for the Gaussian signals having a width of 10%.

Fits to partial datasets

We tested our fitting strategy on small unblinded sets of the data because a successful fit to MC doesn't ensure that the fitting procedure will work in data. Fig 6.30 shows the results for the 5-parameter fit to the data15 dataset (3.2fb^{-1}) in both channels. Figure 6.31 shows the results for the 5-parameter fit to data18 period L dataset (3.0fb^{-1}) in both channels. The p-values of all fits in Fig 6.30 and and 6.31 indicate the fits are satisfactory at describing the data.

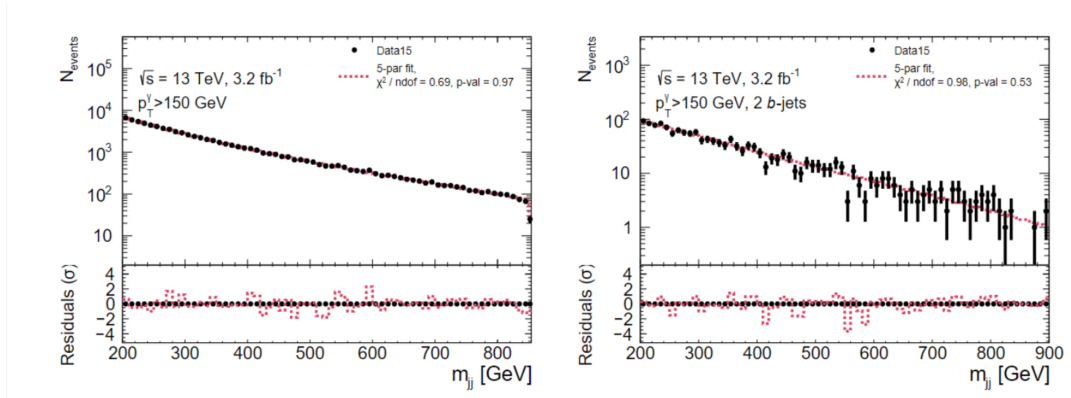


Figure 6.30: 5-parameter fit of the Data 15 dataset in the (left) γjj channel and (right) γbb channel.

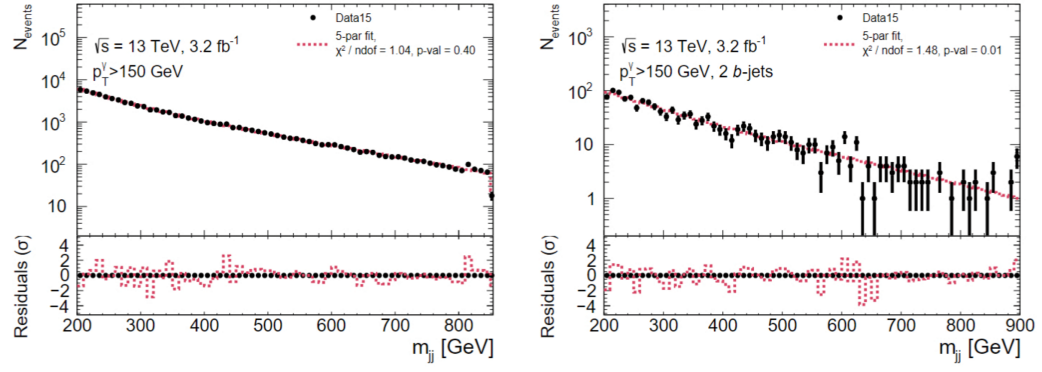


Figure 6.31: 5-parameter fit of the Data 18 period L dataset in the (left) γjj channel and (right) γbb channel.

6.6 Systematic Uncertainties

This section details the treatment of all uncertainties used in this analysis. Uncertainties from object reconstruction are applied to the MC signal samples. These include uncertainties on the Jet Energy Scale (JES), Jet Energy Resolution (JER), photon energy scale, photon energy resolution, photon identification, and b-tagging scale factors. Additional uncertainties on the signal estimate come from uncertainties on the luminosity and uncertainties on the PDFs used to simulate the signals. It is not necessary to apply these uncertainties to the background estimation because our estimation of the background comes from a fit to the data. Instead, only the statistical uncertainty and the uncertainty based on the estimation strategy are considered.

Background modeling Uncertainty

The systematic uncertainty to cover any potential modeling biases is constructed from the spurious signal uncertainty. We can define $S_{modeling}$ as the envelope of the spurious signal $|S_{spur}|$ as a function of m_{jj} . It is implemented in the fit as an additional signal contribution.

$$N_{signal}(m_{Z'}) = \sigma \times A \times BR \times L + S_{modeling}(m_{Z'})\Theta_{modeling} \quad (6.13)$$

In this expression, $N_{signal}(m_{Z'})$ is the number of extracted signal events at a given mass, $m_{Z'}$, σ is the signal cross-section, A is the acceptance, BR refers to the signal branching ratio, and L is the integrated luminosity. The modeling uncertainty is expressed as the nuisance parameter $\Theta_{modeling}$. Together with the statistical uncertainty, the spurious signal uncertainty is the leading source of uncertainty on the extracted number of signal events.

Jet Energy Scale

The consolidated recommendations for particle flow jets ($\Delta R = 0.4$) are used to apply uncertainties on the jet energy scale to the signal templates. The technique includes a series of in situ measurements and simulation-based techniques, thoroughly documented in [195]. They include all the category reduction nuisance parameters for small-radius jets. These uncertainties are accounted for in the model-dependent limit-setting procedure by using MC templates with $\pm 1\sigma$ variation in each parameter in the limit calculations. There are 125 uncertainty NPs on the JES.

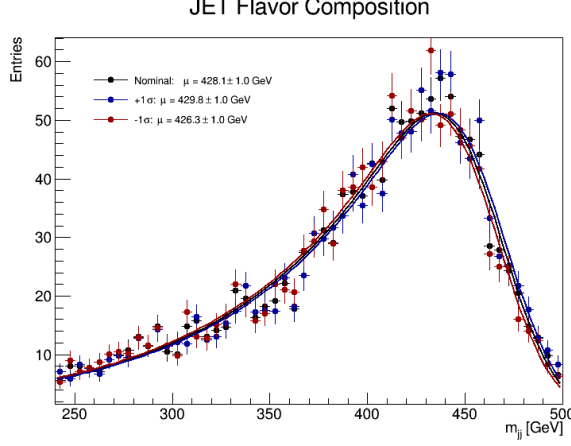


Figure 6.32: Fits to the nominal and $\pm 1\sigma$ variations for the JET Flavor Composition. The Z' point with a mass of $M_{Z'} = 450$ GeV is used as an illustrative example. The inclusive selection is used.

Fig 6.32 shows an example of the effect of the $\pm 1\sigma$ variations due to the flavor composition on the m_{jj} distribution of a signal template with $M_{Z'} = 450$ GeV. A Bukin fit [285] with a Gaussian core was performed and the resulting Gaussian fit parameters are printed on the plot, indicating that the effect of this uncertainty is to change the peak location, not the acceptance.

The effects of the JES uncertainties on Gaussian signals used for the model-independent limit setting are simulated by finding the shift caused by each uncertainty in the mean of the Gaussian core on the Z' template at that mass. Fits like those shown in Fig. 6.32 are performed on each signal template for each uncertainty component. At each Z' mass, the shifts in fitted mean caused by the $\pm 1\sigma$ variations independent nuisance parameters are added in quadrature. The results at masses $M_{Z'} = 250, 350, 450, 550$, and 650 GeV are shown in Fig. 6.33.

The most significant source of uncertainty on the JES originates from uncertainties on the flavor of the jet. Uncertainties on the JVT are also included, but are negligible since the uncertainties are applied only to the signal.

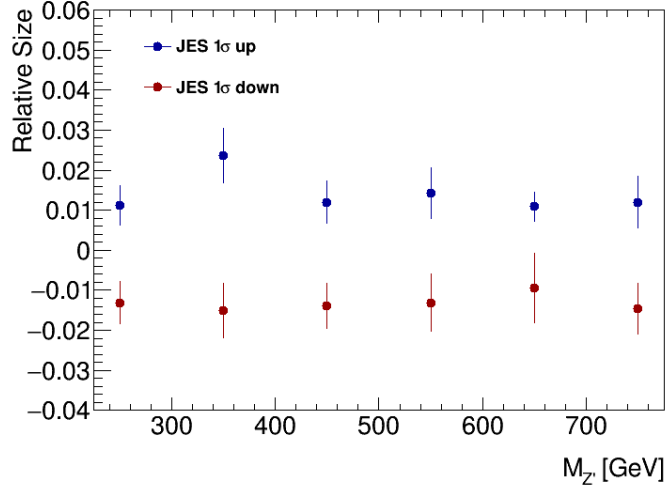


Figure 6.33: Combined impact of the $\pm 1\sigma$ variations of the JES uncertainties on the mean location of a Z' signal. The inclusive selection is used.

Jet Energy Resolution

The JetEtMissRecommendations [277] are followed to vary the signal templates by 1σ for each nuisance parameter associated with the JER measurement. Fig. 6.34 shows the impact of this variation for the largest JER nuisance parameter on the m_{jj} distribution. The effect is to widen the m_{jj} distribution for a signal sample of mass $M_{Z'} = 450$ GeV, indicating a poorer resolution when there is increased uncertainty. The statistical effects are substantial.

The procedure for evaluating the total uncertainty on the JER is taken from a previous iteration of the dijet+ISR photon analysis that used a partial Run 2 dataset and a similar analysis strategy [247].

We create the plot in Fig. 6.34 for all NPs related to JER and combine them by summing the width variations in quadrature at each Z' mass. The resulting plots have their binning increased to 100 GeV to reduce the statistical fluctuations. The weighted average effect of the total JER uncertainty of all $M_{Z'}$ samples is used to obtain Fig. 6.35. A linear fit is applied and a flat uncertainty of 2.5% is assigned for the JER in both channels.

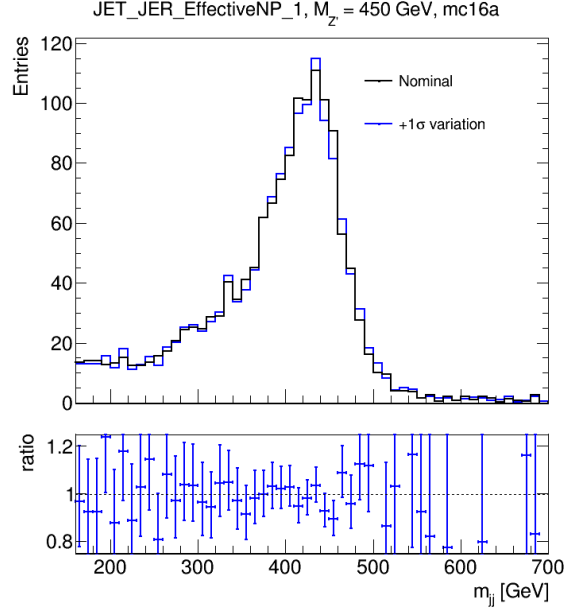


Figure 6.34: Impact of the JER variation on a representative signal sample with $M_{Z'} = 450$ GeV.

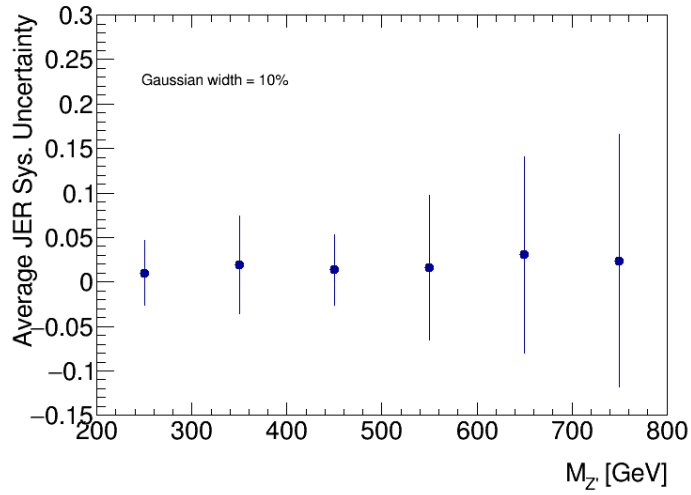


Figure 6.35: Impact of the JER variation on the bin-by-bin average of all signal samples in the inclusive channel. By rebinning to 100 GeV bins, statistical fluctuations are suppressed. The plot supports the use of a flat 2.5% uncertainty.

Photon Systematics

Certain requirements on photon identification and photon isolation are imposed when reconstructing and selecting photons to be used in this analysis. The procedures outlined in [286] are used to quantify the uncertainties on the photon energy scale, energy resolution, and identification scale factor that affect signal acceptance. The first two uncertainties vary the normalization by affecting which events pass the selection. The final parameter also varies the normalization of the signal templates, however it does so by affecting the MC weights of the events passing the selections. The observable in this analysis, m_{jj} , is calculated from the properties of the leading two jets in the events and contains no information about the photon. As a result, these photon uncertainties have no impact on the signal shape and only alter the signal normalization. The procedure described here for evaluating the systematic uncertainty associated with the variation of the selection efficiency is applied to other uncertainties that only affect the signal normalization.

A representative mass of $M_{Z'} = 450$ GeV is chosen to demonstrate the procedure. The top panel of Figure 6.36 shows the nominal dijet invariant mass distribution for the template with $M_{Z'} = 450$ GeV, rebinned into bins of 10 GeV. Drawn on the same canvas in blue and red are the dijet invariant distributions for the templates where the nuisance parameter corresponding to the photon energy scale is varied by $+1\sigma$ and -1σ respectively. The bottom panel shows the ratios of these two variations to the nominal distribution and the difference from unity represents the uncertainty on this nuisance parameter in each bin. The uncertainties have negligible impact on the signal shape or location. The variations affect the acceptance.

The systematic uncertainties in each bin of the m_{jj} distribution are constructed for the photon energy scale nuisance parameter (“EG_SCALE_ALL”), the photon energy resolution nuisance parameter (“EG_RESOLUTION_ALL”), and the photon ID factor (“EG_SCALE_AF2”) at all Z' masses considered in Figures 6.37, 6.38, and 6.39 respectively. A normalized nominal m_{jj} distribution is shown in grey. The variations in acceptance are plotted for the $+1$ and -1 σ variations in red and blue, respectively. The impact of the systematic uncertainty on the efficiency of the signal region is also listed on the plot. Labeled on each of these summary plots is a quantity Δ_{eff} , which gives the impact of the systematic uncertainty on the efficiency of the signal region definition.

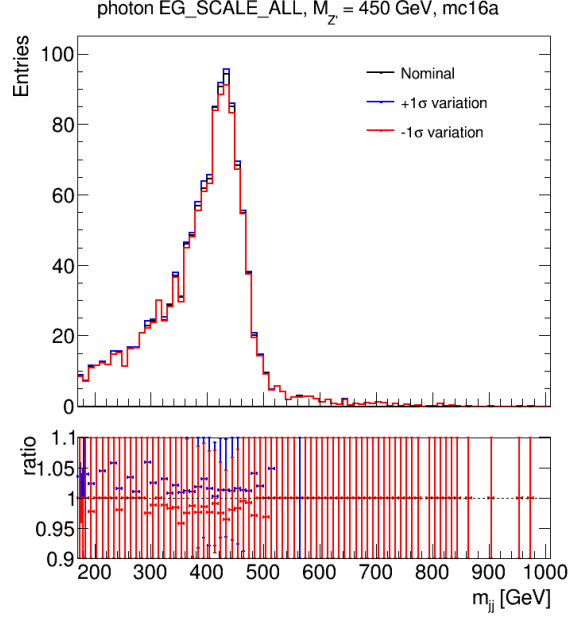
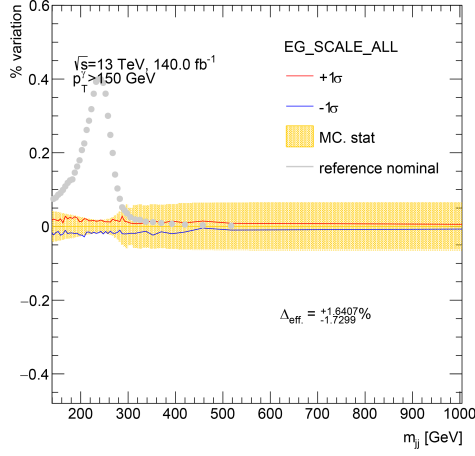
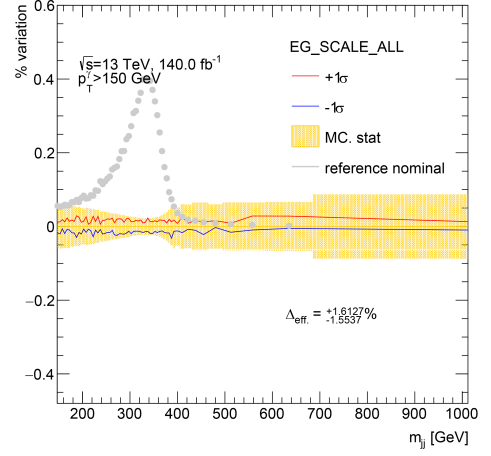


Figure 6.36: Impact on a representative Z' signal MC sample ($M_{Z'} = 450$ GeV) of $\pm 1\sigma$ variations in the photon energy scale. The sample has $g_q = 0.2$ and uses the single photon trigger with the inclusive selection criteria applied.

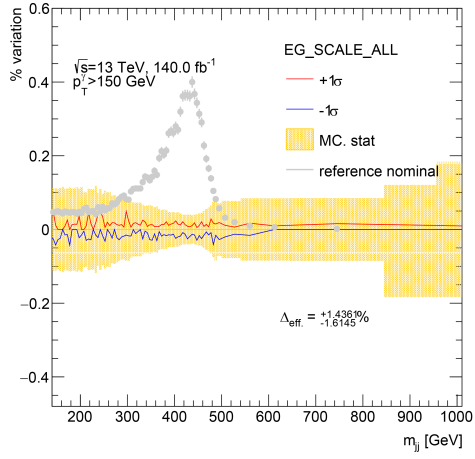
At each $M_{Z'}$ and within each m_{jj} bin, the uncertainties for the energy scale, energy resolution, and identification are summed in quadrature, removing statistical fluctuations. This is not shown here. This combined quantity is treated as one signal nuisance parameter that scales the number of events in the signal template. A fit is done to this resulting m_{jj} distribution and a flat value of 2.1% is chosen as the uncertainty for photon-related systematics.



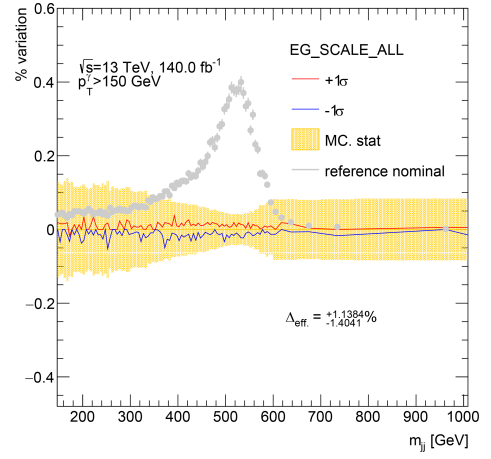
(a) $M_{Z'} = 250$ GeV



(b) $M_{Z'} = 350$ GeV

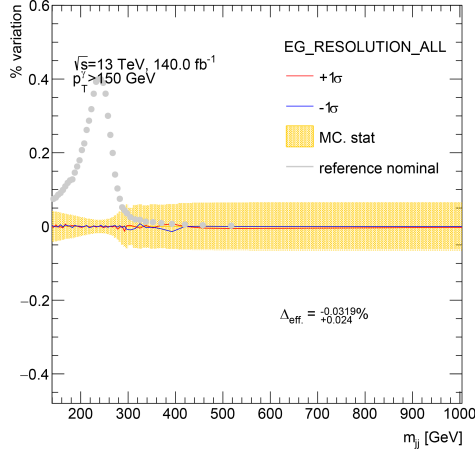


(c) $M_{Z'} = 450$ GeV

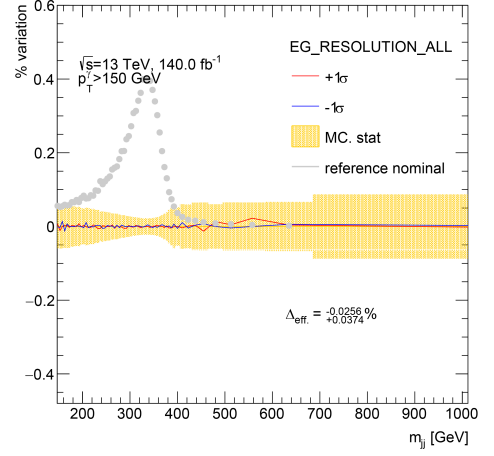


(d) $M_{Z'} = 550$ GeV

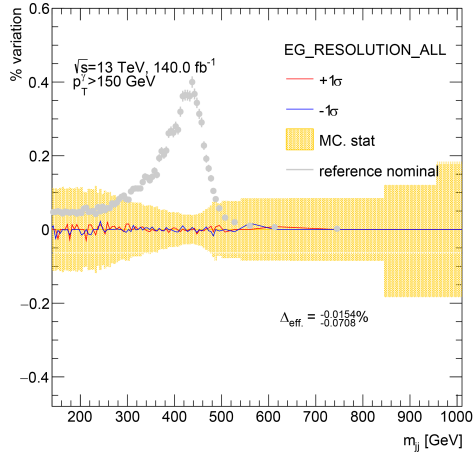
Figure 6.37: The impact of the photon energy scale on different $M_{Z'}$ signals.



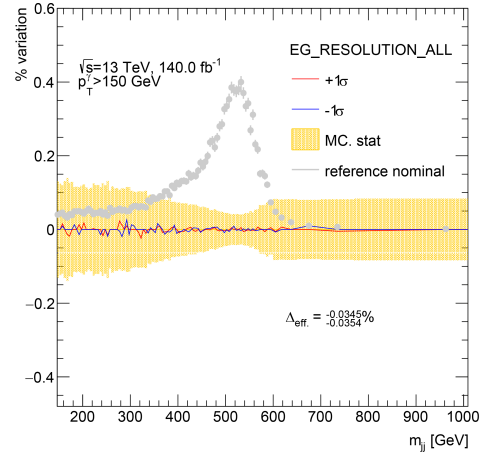
(a) $M_{Z'} = 250$ GeV



(b) $M_{Z'} = 350$ GeV

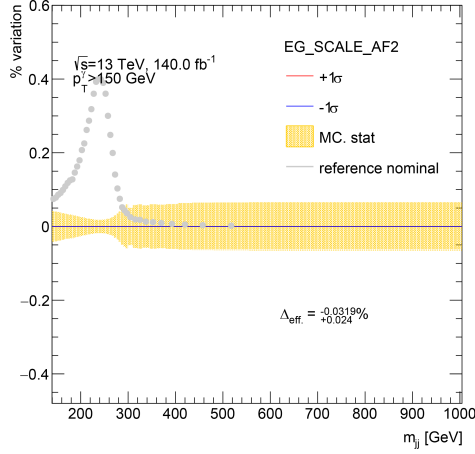


(c) $M_{Z'} = 450$ GeV

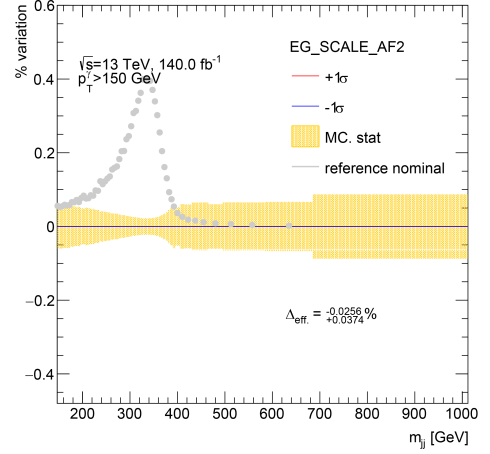


(d) $M_{Z'} = 550$ GeV

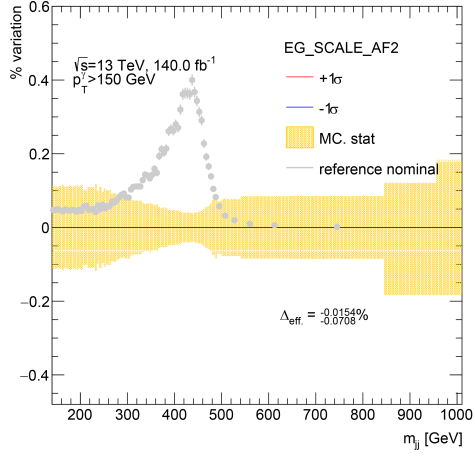
Figure 6.38: The impact of the photon energy resolution on different $M_{Z'}$ signals.



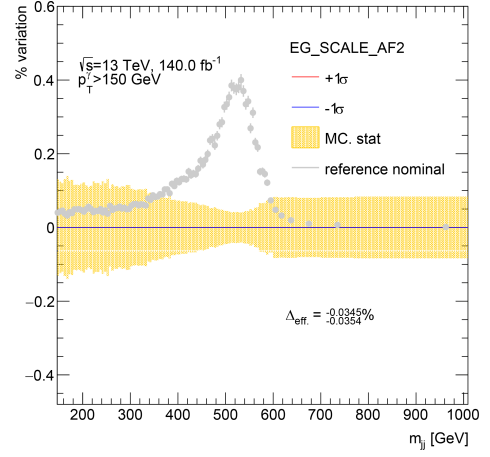
(a) $M_{Z'} = 250$ GeV



(b) $M_{Z'} = 350$ GeV



(c) $M_{Z'} = 450$ GeV



(d) $M_{Z'} = 550$ GeV

Figure 6.39: The impact of the photon energy scale factor on different $M_{Z'}$ signals.

Uncertainties on the b-tagging scale factors

In the 2 b-tagged channel, an additional source of uncertainty on the scale factors used to correct for differences between the b-tagging efficiency and mis-tag efficiencies in data and simulation must be evaluated. There are 20 scale factors provided by the flavor-tagging CP group that are varied by $\pm 1\sigma$ and applied to the signal templates. The uncertainties from these 20 parameters are simplified into one nuisance parameter

by summing their effects in quadrature. These parameters affect the normalization and so the procedure used to evaluate the photon-related systematics is used again.

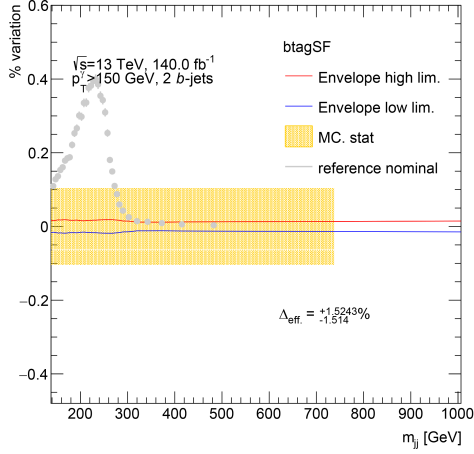
There is considerable dependence of the uncertainties for the individual scale factors on m_{jj} . When the 20 uncertainties are combined into one NP, the resulting distribution for each signal mass inherits the effects of the m_{jj} dependencies. Taking into account the relative weights of the different signal masses in each bin, the combined uncertainties from the 20 SFs at each signal mass are weighted to provide robustness against statistical fluctuations. The resulting distribution is in Fig. 6.40. The ratio of the m_{jj} distributions constructed with the $+1\sigma$ and -1σ variations on the combined nuisance parameter to the nominal distribution are shown in red and blue, respectively. The impact of the systematic uncertainty on the efficiency of the signal region is also listed on the plot. The uncertainty is not constant for all m_{jj} , but a conservative value of 2.2% is chosen to be applied to all samples.

Uncertainties on the luminosity

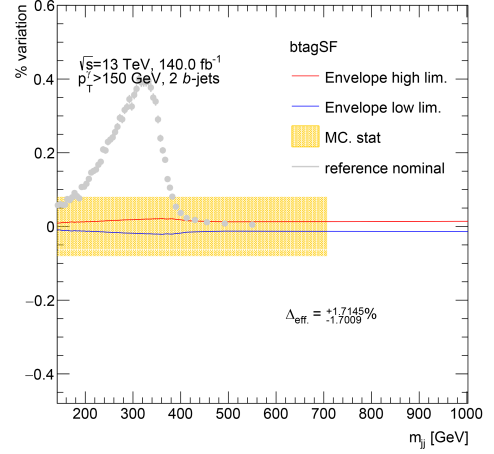
This analysis uses the full Run 2 dataset, spanning the years 2015 through 2018. The LUCID-2 detector is used to make measurements of the luminosity and define calibrations of the luminosity scale by measuring the x-y beam separation. From these measurements, made using the procedure detailed in [250] that was defined by the luminosity working group [249], a total of uncertainty on the integrated luminosity from the full Run 2 dataset is chosen to be $\pm 0.83\%$. This uncertainty is applied as a single nuisance parameter affecting the normalization of the signal sample.

Uncertainties associated with the PDF models

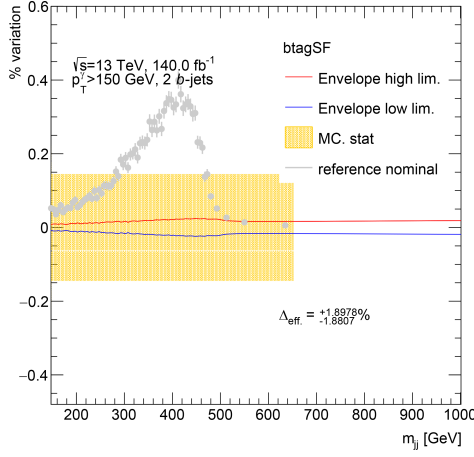
A number of PDFs can be utilized and the choice of which PDF is used and the uncertainties in that model affect the normalization of the signal. The NNPDF group that produced the specific PDF used in this analysis produced an ensemble of PDFs [263] and events for the analysis are generated and processed using these PDFs. We explore the variations for the NNPDF3.0nnlo models. 100 replicas with variations are generated and the LHAPDF tool is used to work on the combined uncertainties. According to the recommendations by the PMGJetAndPhoton group [287], variations including MMHT2014nnlo68c1, CT14nnlo, and two α_3 variations of NNPDF3.0nnlo are included.



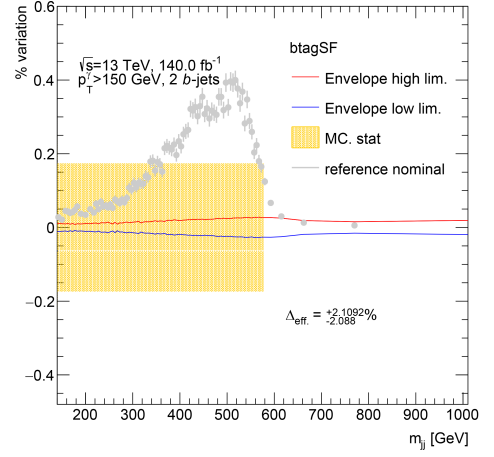
(a) $M_{Z'} = 250$ GeV



(b) $M_{Z'} = 350$ GeV



(c) $M_{Z'} = 450$ GeV



(d) $M_{Z'} = 550$ GeV

Figure 6.40: The combined impact of the 20 b-tagging scale factors on different $M_{Z'}$ signals. A normalized nominal m_{jj} distribution is shown in grey.

The 100 members of the NNPDF3.0nnlo ensemble are used to perform the analysis and the method described to evaluate the uncertainties on the nuisance parameters for photon-related uncertainties is used here to find the differences in acceptance. Plots are made to show the combined impact on the acceptance from the 100 PDF variations. The PMG [287] recommends that the standard deviation of all acceptance variations be used as the systematic uncertainty of a given signal sample mass. The

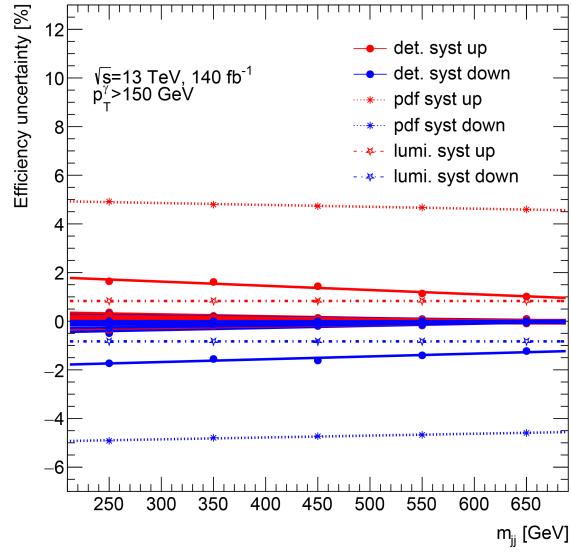
uncertainty as a function of $M_{Z'}$ is plotted in Figure 6.41, along with uncertainties from other sources. The PDF uncertainty, roughly 5%, is the dominant source of uncertainty on the signal.

Summary of systematic uncertainties on the signal

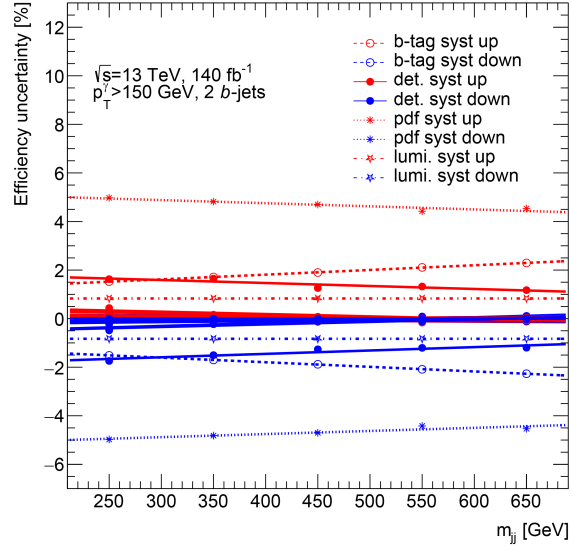
Table 6.9 summarizes the systematic uncertainties found in this section.

Uncertainty	γjj	γbb
JES (on peak location)	1.7%	1.7%
JER (on peak width)	2.5%	2.5%
Photon (on acceptance)	2.1%	2.1%
Luminosity (on acceptance)	0.83%	0.83%
b -tag (on acceptance)	-	2.2%
PDF (on acceptance)	5%	5%

Table 6.9: Summary of the systematic uncertainties on the signal. In parentheses is the impact of each effect on the main signal features.



(a)



(b)

Figure 6.41: Impact of the b-tagging, detector, PDF, and luminosity systematic uncertainties on the acceptance within the (a) γjj and (b) γbb channels.

6.7 Statistical Analysis

This section describes the statistical techniques used to obtain the results in this analysis. They were implemented using several software packages, including `FrequentistFramework` [281] and `quickFit` [283]. In this analysis, the observable quantity that we measure for the data is the invariant mass distribution, m_{jj} . This distribution is always binned and the number of counts within each m_{jj} bin are considered to be independent counting experiments.

Likelihood Function

The likelihood function is utilized to determine what the signal strength is, given the observed m_{jj} distribution. The likelihood function is constructed from Poissonian probability terms based on the expected and observed event yields in all bins.

$$L(\mu) = \prod_{j=1}^N \text{Pois}(n_j | \mu s_j + b_j) = \prod_{j=1}^N \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \quad (6.14)$$

In this expression, n_j is the number of measured data events in bin j , s_j and b_j are the number of expected signal and SM background events, and $\mu = \sigma_{obs}/\sigma_{theory}$, which is known as the signal strength. μ is the main parameter of interest in this analysis.

Various sources of systematic uncertainties affect the expected number of counts in each bin. The likelihood function is modified to incorporate systematic uncertainties in the form of nuisance parameters, denoted by $\vec{\theta} = \theta_1, \theta_2, \dots, \theta_m$, which can modify the expected signal and background yields. The quantities s_j and b_j now depend on the values of the components of θ . We are not actually interested in measuring the nuisance parameters themselves. They are included in the total likelihood function in the form of Gaussian penalty terms, having a mean value of zero and a variance of 1. The effects of the nuisance parameters were determined in section 7.6.

$$L(\mu, \vec{\theta}) = \prod_{j=1}^N \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \times \prod_{\theta \in \vec{\theta}} \frac{1}{\sqrt{2\pi}} e^{-\theta^2/2} \quad (6.15)$$

Parameter Estimation

The maximum likelihood method is used to determine the values of model parameters of interest along with their associated uncertainties. For a model parameter, θ , the maximum-likelihood estimate (MLE) of that parameter is referred to as $\hat{\theta}$. By finding the global maximum of the likelihood function, $L(\theta)$, the maximum-likelihood estimation of θ is produced. Often, the logarithm of the likelihood function, the log-likelihood, is used instead of the likelihood function and the minimum of the negative log-likelihood is found instead:

$$-\ln L(\theta, x) = -\sum_{i=1}^N \ln f(x_i; \theta) \quad (6.16)$$

By setting the partial derivative to zero, one can find the minima:

$$\frac{\partial \ln L(\theta; x)}{\partial \theta_j} = 0 \quad (6.17)$$

This is for $j = 1, 2, \dots m$. The estimated parameters, $\hat{\theta}$, end up being asymptotically normally distributed.

Hypothesis testing and the test statistic

In addition to finding the parameter value for a model given the data, it is useful to compare different hypotheses that are distinguished by their respective values for μ and sets of nuisance parameters. In this dissertation, the null hypothesis for hypothesis testing is H_0 and corresponds to $\mu = 0$, which is the SM prediction (no signal is present). An alternative hypothesis represented by some BSM prediction will be specified by a $\mu > 0$.

A test statistic is a lower dimensional summary of the data with discriminatory power to support or reject H_0 . One such statistic is the likelihood ratio. The Neyman-Pearson lemma [288] states that the likelihood ratio maximizes the statistical power to reject H_0 in favor of some alternative hypothesis, H_1 . This statistic lies in the range $[0, 1]$ and a quantity q is defined using the likelihood ratio as:

$$\lambda(\mu) = \frac{L(H_0, \mu)}{L(H_1, \mu)} = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})} \quad (6.18)$$

In this expression, $\hat{\theta}$ denotes the value of θ that maximizes the likelihood for the specific μ , also known as the conditional maximum likelihood. The denominator is the maximized likelihood function, also known as the unconditional likelihood function, where $\hat{\mu}$ and $\hat{\theta}$ are the values that maximize the likelihood overall. The distribution of the profile likelihood is broadened with the incorporation of nuisance parameters. Values of λ that are close to 1 reflect good agreement between the observed data and the hypothesis and data while values of λ that are closer to 0 reflect greater disagreement.

When the data sample is large, the likelihood distribution approaches a Gaussian distribution. In this limit, Wilk's theorem states that the quantity $2\ln\lambda(\theta)$ follows a chi-squared distribution with m degrees of freedom, where m corresponds to the number of parameters of the model [289].

A test statistic, q_μ , can be defined from the likelihood ratio. The factor of -2 is a choice of convention.

$$q_\mu = \begin{cases} -2\ln\lambda(\mu) & \text{if } \hat{\mu} \geq \mu \\ 0 & \text{if } \hat{\mu} < \mu \end{cases} \quad (6.19)$$

To test the null hypothesis that no signal is present, we evaluate the statistic with the value $\mu = 0$. For any chosen value of μ , a higher value of q_μ indicates increasing incompatibility between the data and μ . This test statistic is further discussed in [290].

A p-value helps quantify the compatibility of the observed data with this background-only hypothesis.

$$p_\mu = \int_{q_{\mu,obs}}^{\infty} f(q_\mu, \mu) dq_\mu \quad (6.20)$$

In this expression for p_μ , $q_{\mu,obs}$ is the value of the statistic q_μ observed from the data and $f(q_\mu, \mu)$ is the PDF of q_μ under the assumption of a signal strength μ . The interpretation of p_μ is the probability of finding data incompatible with $\mu = 0$. Background-only pseudo-experiments in the asymptotic approximation are used to define global significance values that correspond to the p-value.

It is common for p-values to be expressed as a significance, Z , defined from one-sided tail probabilities of a unit Gaussian distribution.

$$Z = \Phi^{-1}(1 - p) = \frac{1 - \text{erf}(Z/\sqrt{2})}{2} \quad (6.21)$$

where erf is the error function.

$$\text{erf}(z) = \frac{2}{\pi} \int_0^z e^{-t^2} dt \quad (6.22)$$

In addition to comparing a specific hypothesis H_1 with the null hypothesis (H_0), one could create a test statistic that gives power to reject H_0 without specific regard to the choice of H_1 . This is known as a discovery test statistic. It is one-sided and is defined for $\mu = 0$ as:

$$q_0 = \begin{cases} t_0 = -2\ln\lambda(0) & \text{if } \hat{\mu} \geq 0 \\ 0 & \text{if } \hat{\mu} < 0 \end{cases} \quad (6.23)$$

In summary, q_0 is used to reject the H_0 hypothesis that $\mu = 0$ from a positive signal hypothesis, which is specified only by the fact that $\mu \geq 0$. A p-value corresponding to this test statistic q_0 is defined as:

$$p_0 = \int_{q_{0,obs}}^{\infty} f(q_0|0) dq_0 \quad (6.24)$$

In this expression, $f(q_0|0)$ is the probability density function of q_0 under the $\mu = 0$ hypothesis.

BumpHunter method for identifying local excesses

The most direct evidence of resonant production of a new particle is a statistically significant local excess of the data above the data-driven background estimate. The BumpHunter [291] [241] [292] algorithm has been implemented in the search phase analyses for the CDF and ATLAS experiments and will be used in this analysis to identify resonances having a natural width that would appear as a Gaussian signal with a width equal to the detector mass resolution on top of the SM background. BumpHunter scans with a sliding window having a width equal to twice the typical detector resolution over the m_{jj} range and evaluates the statistical significance of these excesses, or “bumps,” in each window.

BumpHunter ultimately identifies the most significant localized excess for both the γjj and γbb channels. This algorithm is attractive for the analysis because it

makes no prior assumptions about the nature of new physics models and is global: the scan does not assume the location of the most discrepant excess and allows the excess to occur in consecutive dijet mass bins. A key limitation of the BumpHunter algorithm is that it is sensitive to local features in the m_{jj} spectrum that can arise if the data-driven background estimate doesn't describe the data satisfactorily. The last chapter detailed the procedures and results of validating the data-driven background estimate.

Statistical fluctuations in the number of background events measured could introduce an excess in the dijet mass spectrum for the background-only hypothesis. Consequently, it is required that the excess is highly unlikely to have occurred from these fluctuations to claim a discovery. We use a p-value to quantify the significance of any observed excess. The p-value is simply the probability under the background-only hypothesis of obtaining an excess which is at least as discrepant as the excess found in data. The BumpHunter algorithm defines a new test statistic to calculate the p-value of an excess in some set of consecutive bins in the m_{jj} distribution. We will assume that there is a greater number of data events in a window, d , than the number of events from the data-driven estimate of the background in that same window, b . The probability that an excess that is at least as discrepant would occur in the background-only hypothesis, H_0 , for this set of bins is calculated using Poisson statistics in Eq. 6.25.

$$P(d, b) = \sum_{n=d}^{\infty} \left(\frac{b^n e^{-b}}{n!} \right) \quad (6.25)$$

The BumpHunter test statistic, t , represents how discrepant an excess is. Larger values of t indicate greater differences between data and the background-only hypothesis. The BumpHunter algorithm calculates the value of t for all excesses found in all possible combinations of consecutive bins. For this analysis, the narrowest excess is at least two bins wide and the widest allowed excess can contain up to half the number of bins in the entire m_{jj} fit range. The excess with the largest BumpHunter test statistic has an observed t value of t_0 and is the most discrepant excess seen in the entire spectra.

$$t = -\ln(P(b, d)) \quad (6.26)$$

These excesses are calculated with respect to many pseudo-experiments drawn from the data-driven estimate of the background which are used to estimate the probability density function of t under the background-only hypothesis, $f_{P.E.}(t|H_{Bkg})$. The p-value of the most discrepant excess is data can be expressed as:

$$p = \int_{t_{obs}}^{\infty} f_{P.E.}(t|H_{Bkg}) \quad (6.27)$$

There exist many statistical “hypothesis tests” or “goodness of fit tests”, including Pearson’s χ^2 test and Kolmogorov-Smirnov test, to assess the probability that we mistakenly reject the null hypothesis when it is true. A p-value of α simply means there is some discovery algorithm that would have ruled out the null hypothesis with a type-1 error probability equal to α , where $\alpha \in [0, 1]$. It is not a statement about the null hypothesis itself: while we can claim the discovery of new phenomena by establishing that the number of data events is inconsistent with the null hypothesis, such hypothesis tests only establish inconsistency of the data with the background-only hypothesis and do not establish the consistency of the data with any alternative theory. The type 1 error is consequently in Eq. 6.28. Regardless of how the test statistic, t , is defined, the type-1 error probability of an algorithm that declares a discovery when $p \leq \alpha$ is just α .

$$P(\text{Type} - I) = P(p \leq \alpha|H_0) = P(P(t \geq t_0|H_0) \leq \alpha|H_0) = \alpha \quad (6.28)$$

Unlike the tests mentioned earlier, the BumpHunter algorithm accounts for a trials factor, also known as the “look elsewhere effect” [293]. [294]. When searching for resonances in consecutive bins of a dijet mass spectra, we must consider that there are many possible hypothesis tests one could consider simultaneously. The “look elsewhere effect” could also be described as a “look in different ways effect” [241]. A set of N statistically independent tests that are considered when evaluating the consistency of the data with the null hypothesis is said to have a trials factor of N . If all N hypothesis tests behave identically, the trials factor would be 1. In the case that the N hypothesis tests are partially independent, the trials factor is an effective trials factor with a value between 1 and N that depends on how each of the N hypothesis tests is correlated and on the threshold α being considered. A common misunderstanding of the trials factor is that it is related to how many bins there are in the data, given that each bin counts as a trial with its own chance of triggering a

discovery. BumpHunter defines a new hypothesis test that is sensitive to every feature that each of the N tests is sensitive to and by accounting for this trials factor in this way, the BumpHunter algorithm could be considered a hypothesis “hypertest.”

The BumpHunter statistic is a measure of the statistical significance of any localized excesses or deficits measured in the data m_{jj} distribution with respect to the background. For N predetermined hypothesis tests each with a p-value of p_i where $i \in [1, N]$, the BH test statistic is just the smallest p-value of all N hypothesis tests:

$$t = -\log(\min_i p_i) \quad (6.29)$$

The negative log function is used in the definition of t to ensure that t increases monotonically as $\min(p_i)$ decreases, staying consistent with the convention that t_0 should increase with increasing discrepancy.

The CLs method

We would like to use a statistical method to decide if the invariant mass distribution we observe in the data supports the hypothesis that there are both signal and background present. Typically, estimating the upper limit on the signal strength using the CL_{s+b} method would require that we compare the signal plus background hypothesis, H_{s+B} directly to the background-only hypothesis, H_b . A p-value, p_{s+b} , quantifies the probability of finding a test statistic q that is equally or less compatible with the H_{s+b} hypothesis with respect to the test statistic observed using the data, q_{obs} . The H_{s+b} hypothesis can be excluded at a confidence level of $1 - \alpha$ if it is found that $p_{s+b} \leq \alpha$ [295]. It would be ideal to draw an exact confidence interval for a signal hypothesis, but in the presence of background, only an approximation can be found. For instance, a signal hypothesis that has a probability close to α can be excluded even if the sensitivity to that signal model is very low. Physicists define another set of limits, known as CL_s limits [295], by dividing p_{s+b} by the power of the test, $1 - p_b$.

$$CL_s = \frac{p_{s+b}}{1 - p_b} \quad (6.30)$$

If the test statistics distributed under both the H_{s+b} and H_b hypotheses are nearly identical, $p_{s+b} \approx 1 - p_b$ and $CL_s \rightarrow 1$. It becomes more difficult to exclude the p_{s+b} hypothesis in this case. If they are well separated, the power of the test will be much greater than p_{s+b} and the exclusion based on CL_s will be approximately CL_{s+b} .

Caution must be taken when interpreting CL_s limits. The probability used to construct CL_s limits is not truly Frequentist. If the distributions for the signal plus background and background only hypothesis are well separated, the confidence intervals would suggest that CL_s makes a statement about the signal, just as CL_{s+b} conclusively makes a statement about the $s+b$ hypothesis. If there is a large contamination of background in the data, however, this would be an incorrect conclusion. It is convention to report the exclusion intervals in high energy physics experiments using the CL_s limits anyway in the cases where there is no significant evidence for a signal and the intervals will be approximately true. The value of μ for which $CL_s < \alpha = 0.05$ is considered the exclusion limit on μ that is set at 95% confidence level. The probability of observing a dataset with a μ that exceeds the limit is 5%. In the case that there is significant evidence for a signal being present, the Feldman Cousins method would be used to construct confidence intervals. Expected limits can be obtained by generating pseudodata from the background-only hypothesis.

This analysis uses the `FrequentistFramework` package [281] to implement the statistical procedures summarized here used to construct the 95% CLs limits.

6.8 Results

Background fits to data

The dijet mass distributions for the entire Run 2 dataset passing the selection criteria are shown in the black data points in Fig. 6.42. The bin size is set by the detector mass resolution. A 5-parameter global fit is performed on the data to estimate the background contribution. This function is evaluated at the center of each m_{jj} bin and is shown in the red histogram. The bottom panel of the plot shows the fit residuals, expressed as a number of significances (σ) the data fluctuates away from the background expectation.

The p-values of the fit indicate that the 5-parameter fit function provides a satisfactory description of the data in both channels. The fit range for the γjj channel extends from 200 to 875 GeV, while the fit range for the γbb channel extends from 200 to 854 GeV. These specific ranges were chosen because they are where the fitting strategy was satisfactory.

The BumpHunter algorithm is implemented for this analysis using the `PyBumpHunter` package [296]. An excess would indicate the possible presence of a resonant

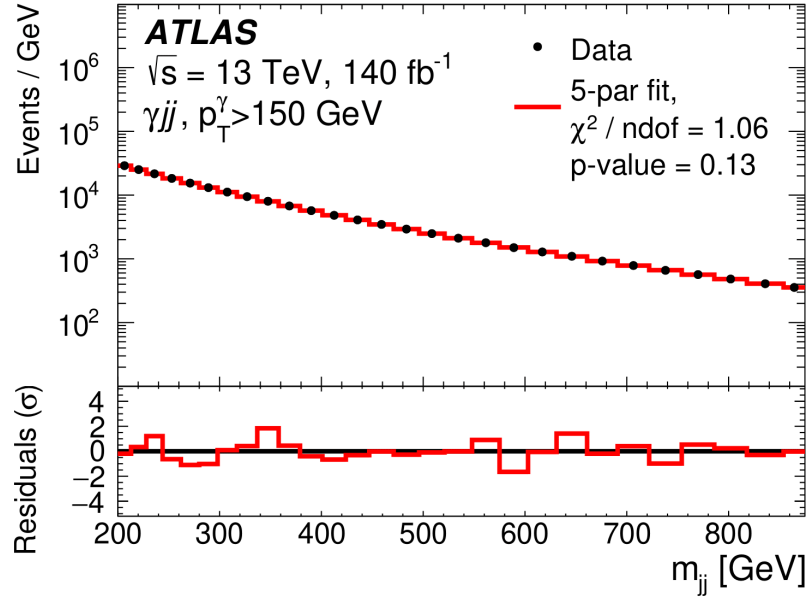
signal. The location of the maximum p-value for the m_{jj} distributions were found at 380 GeV and 348 GeV for the γjj and γbb channels, respectively. These excesses have local significances of 1.8σ and 1.9σ for the γjj and γbb channels respectively. The significances of the most, discrepant excesses are consistent with the presence of no resonant processes.

Limits

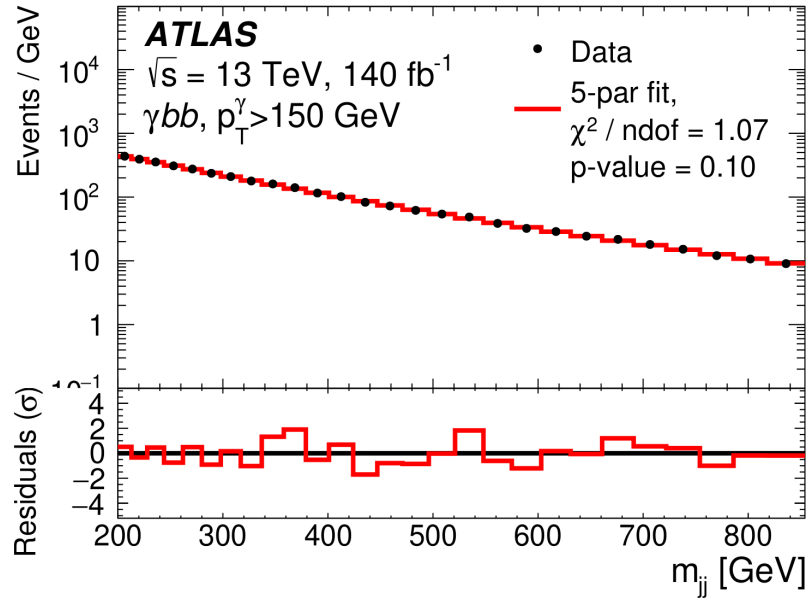
The background fits presented in the last section do not show a statistically significant excess that would indicate the presence of signal. Consequently, limits are set on the possible number of events from resonant new physics processes. The previous iterations of this analysis in Run 1 and Run 2 utilized a Bayesian method to set these limits, however, we choose a Frequentist approach to setting these limits because they don't depend on the signal priors. In Section 7.7, I presented the method used to calculate the expected and measured limits on the cross-section times acceptance times branching ratio. The limits were found using the `FrequentistFramework` package [281].

In the case of model-dependent limits on the Z' model, the MC samples are simulated at 250, 350, 450, 550, and 650 GeV and are weighted according to the proportion of luminosity collected during each year of data taking. We calculate the 95% CL limit on the cross-section times the acceptance for the number of signal events as a function of the mass of the mediator resonance, accounting for all uncertainties on the signal and background when calculating the results. The widths of these resonances are smaller than the 100 GeV window between each simulated mass point, so to create a more continuous limit curve vs m_{jj} , the `RooMomentMorph` package [275] is used to interpolate logarithmically between the limits at adjacent simulated mass points. We define the value of m_{jj} where the limit on $\sigma \times A \times BR$ from data is equal to the theoretical value as the exclusion limit on the mass of the Z' signal model.

In Figure 6.43, the observed and expected limits are labeled with markers and a dashed line, respectively. The 1σ and 2σ uncertainty ranges on the expected limits are shown in the dark and light bands. Most of the observed limits fall within 1σ of the expected limits and all values fall within 2σ of them. A signal from the simulated γjj process is excluded at 95% CL for measured effective cross-sections ($\sigma \times A \times BR$) above 0.1 in the inclusive channel. The limits are weaker in the γbb channel due to lower statistics.



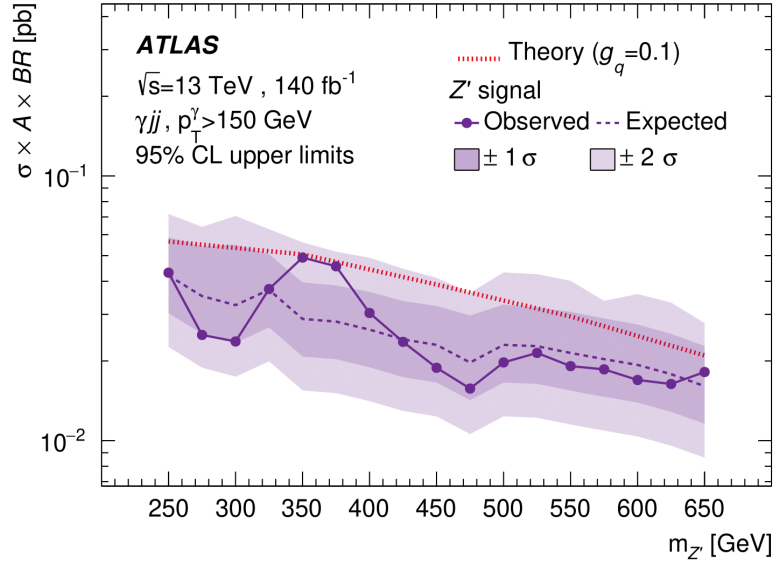
(a)



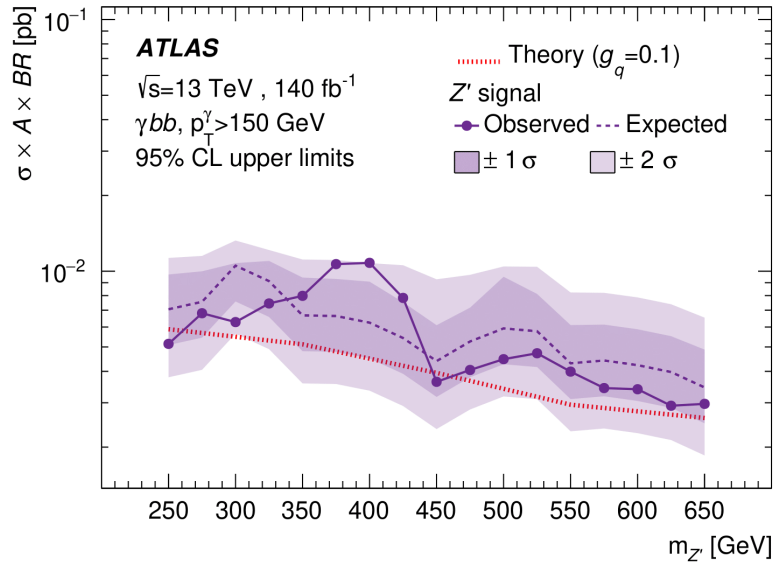
(b)

Figure 6.42: The background only-fits to the measured m_{jj} distributions evaluated at each data point are shown for the (a) γjj and (b) γbb channels. From [1].

Additionally, a set of model independent limits on $\sigma \times A \times \epsilon \times BR$ are calculated for a collection of hypothetical signal shapes assumed to be Gaussian distributed after application of the analysis selection and jet reconstruction efficiency in m_{jj} with resonance mass of m_G and having width σ_G instead of the signal MC samples. The standard deviations of the Gaussians correspond to dijet mass resolutions estimated from MC and range between 5% and 15%. These limits incorporate the same signal-related uncertainties that were utilized in the model-dependent limits, though the prescription for obtaining limits on the Jet Energy Scale is different for the model independent case.

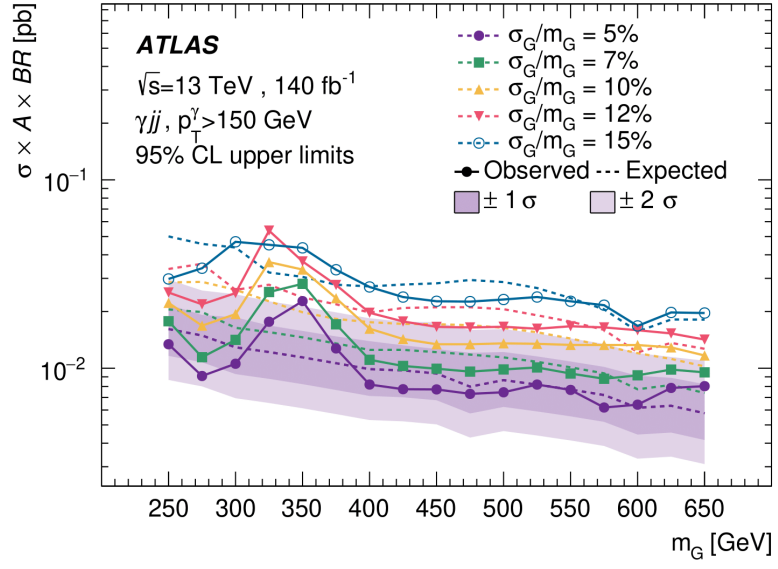


(a) γjj

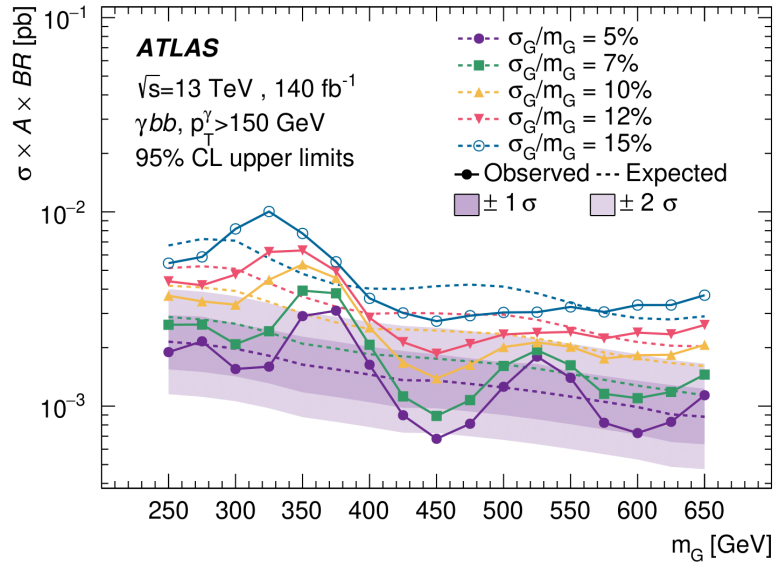


(b) γbb

Figure 6.43: Expected and observed limits on the cross-section times branching ratio times acceptance of Z' signal as a function of the signal mass in the (a) γjj and (b) γbb channels. From [1].



(a) γjj



(b) γbb

Figure 6.44: Expected and observed limits on the cross-section times branching ratio times acceptance of a generic Gaussian signal as a function of the signal mass in the (a) γjj and (b) γbb channels. From [1].

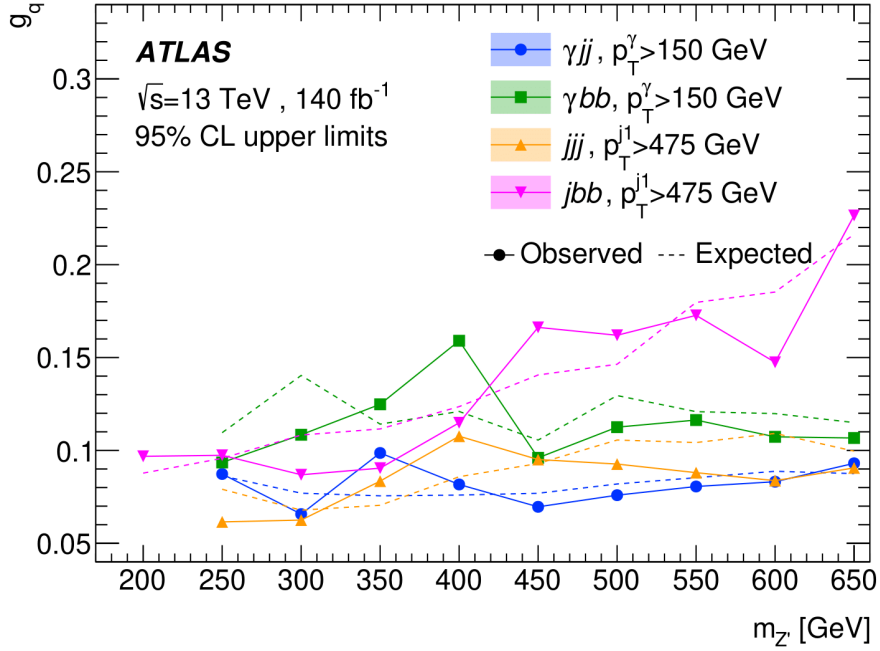


Figure 6.45: The expected and observed limits for signal templates as a function of coupling g_q and Z' mass for the γjj (blue) and γbb (green) channels. From [1].

Limits on effective cross-section are corrected by acceptance and efficiency effects, as well as the expected cross-section value, to obtain limits on the Z' to quark coupling, g_q . Fig. 6.45 shows the limits for the γjj and γbb channels in blue and green, respectively. The limits were found using a 5-parameter fit function. The expected and observed limits are indicated with a dashed line and solid markers, respectively. Values of the coupling higher than around 0.1 are excluded at 95% CL. These limits improve on the previously set limits by up to 50%.

Interpretations

Comparing the limits on the template model and Gaussian models, the limits on the Gaussian models are stronger than the ones obtained for the signal templates. When interpreting the Gaussian limits, if the new physics model being considered has approximate widths smaller than 5%, the resulting limits should be directly compared to results with a width equal to the experimental resolution. If the model has larger

widths after detector effects are taken into consideration, the limit used for comparison should be the limit of the Gaussian signal with the closest width.

Fig. 6.46 shows that the most stringent limits on the dijet plus an initial state radiated object are set in the trijet channel at lower Z' masses and by the γjj channel for higher Z' masses. The trijet analysis was not discussed in this thesis. The overall production cross-section for the Z' in the photon channel is smaller than the jet channel since the photon is radiated less often than the gluon. Additionally, the relative limits are affected by the acceptances in both channels. The p_T threshold on the leading jet used in the multi-object trigger in the trijet analysis is $p_T > 475$ GeV, while the threshold on the leading photon in the single-photon trigger is $p_T > 150$ GeV. In the photon ISR channels, the g' vs. $M_{Z'}$ limits are weaker in the γbb channel than in the inclusive channel due to lower statistics, however, the cross-section limits are stronger due to the factor of 5 included in the width term of the process in 5.2.

Fig. 6.46 summarizes the results of the analysis presented here and the results of the previous iteration of this analysis. Previous results of other dijet searches obtained by ATLAS are shown in grey. In most cases, the limits in the γjj and γbb channels are stronger than the previous result done with $79.8 fb^{-1}$ of Run 2 data using the same single photon trigger, by up to 50%. The analyses have some fundamental differences. This current analysis used the full Run 2 dataset with $140 fb^{-1}$ of data. While the analysis strategy is similar, limits for the analysis presented in this thesis utilized a Frequentist approach to calculate limits, unlike the Bayesian method used in the previous analysis. Additionally, the b-tagging algorithm used here was the DL1r algorithm instead of the DL1 algorithm that was used in the previous iteration of the analysis. For instances like the γbb limit at 400 GeV, the new limit is weaker than the previous result, but is well within the uncertainty of the previous result when the uncertainty bands are considered. The previous iteration of the analysis used a sliding window fit strategy to produce their data-driven estimate of the background. This method benefits the limits at higher mass signals and could result in lower expected coupling vs mediator mass limits.

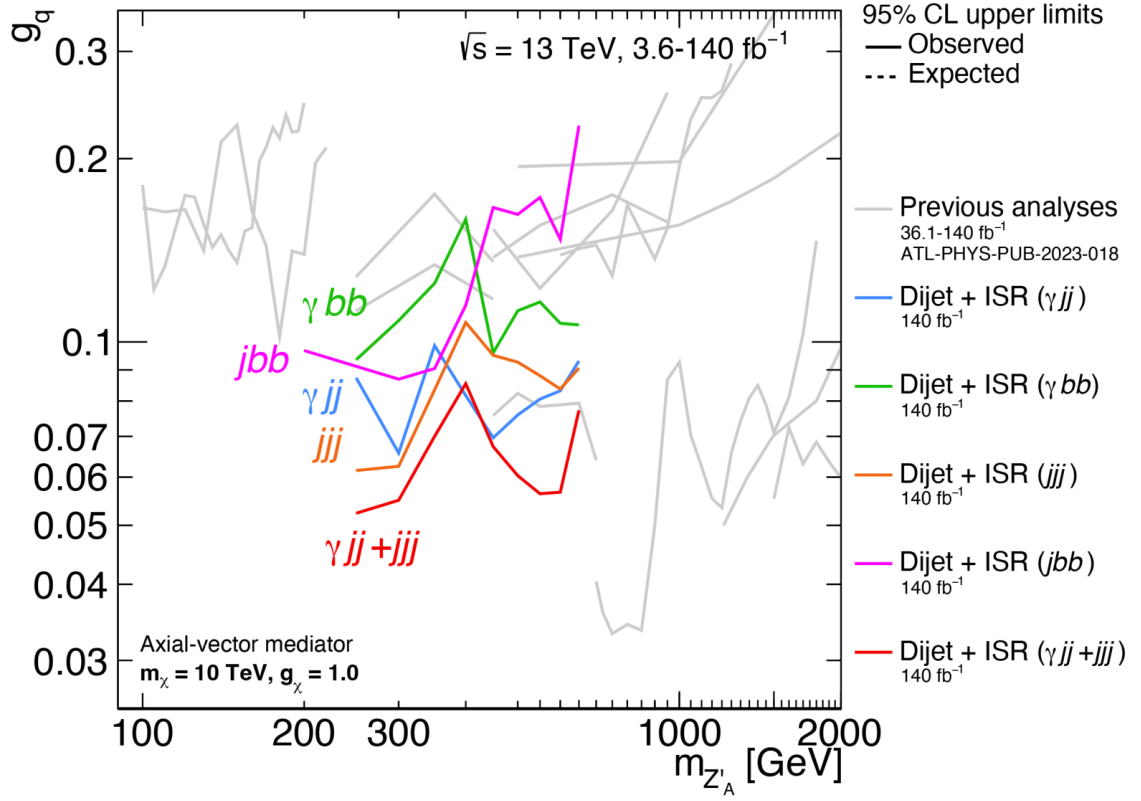


Figure 6.46: The observed limits on γjj (blue) and γbb (green) as a function of coupling g_q and the Z' mass.

Chapter 7: Online Track Reconstruction for the upgraded ATLAS detector at the HL-LHC

The major physics goals of the HL-LHC program include studying the mechanism of electroweak symmetry breaking through properties of the Higgs boson, searching for hints of new physics by studying rare SM processes, searching for new heavy states and LLPs, searching for new heavy mediators like the Z' , and making more precise measurements of the Standard Model [297].

To increase the sensitivity of the ATLAS experiment to new physics and to improve accuracy of the Standard Model measurements, the luminosity of the LHC will need to be increased beyond its designed value. The LHC will be upgraded to the High Luminosity LHC (HL-LHC) by installing stronger superconducting magnets, implementing new technology for beam collimation and superconducting cavities for beam rotation [298]. As a result, the HL-LHC will provide roughly 2500 fb^{-1} of luminosity during 10 years of operation. ATLAS is also undergoing a number of upgrades to the various detector subsystems. New muon chambers will be installed, improving the trigger efficiency, momentum resolution, and reducing the fake rate. A new all-silicon inner tracker (ITk) will be installed, with finer segmentation and less material than the Inner Detector. ATLAS will also install a new High Granularity Timing Detector (HGTD) to improve pile-up separation [299] in the forward regions of the detector.

Run 4 of the HL-LHC program is expected to start in 2027 with a maximum peak luminosity reaching $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. This will result in an average of 140 proton-proton interactions per bunch crossing [297]. Run 5 will start in 2025 and the instantaneous luminosity will reach an even higher value of $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, corresponding to 200 simultaneous pile-up interactions per bunch crossing. The trigger system will be overwhelmed with higher rates due to coincident track candidates generated from the multiple pp interactions that overlap with the hard scatter. The

L0 trigger output rate will be 1 MHz and doesn't include tracking of charged particles in the Inner Tracker to filter-out trivial collisions.

The Event Filter is the final element of the ATLAS trigger system. The Event Filter has access to the fully built raw event data and uses a farm of software processors to run offline algorithms on stored data and process and filter this data, reducing the event rate before writing the data to mass storage. These algorithms include reconstruction algorithms and physics based algorithms used to decide if events conform to the physics requirements. The Event Filter also implements data compression techniques to reduce the data-flow. The Event Filter is able to perform global monitoring, calibration, and perform alignment functions. It was decided to drop the low-latency L1 hardware track trigger in favor of an online-based tracking system that will reduce the rate from 40 MHz to 10 kHz. The Event Filter Tracking system consists of software-only, heterogeneous commodity servers and custom servers.

This chapter serves as a transition into the work in the rest of this thesis on contributions to the Event Filter Tracking project, used to reconstruct tracks online for the upgraded ATLAS detector used at the HL-LHC. Section 7.1 will introduce the new Inner Tracker detector. Section 7.2 will go into more detail about the Event Filter itself and the track reconstruction chain.

7.1 The Inner Tracker (ITk) Detector

The Inner Tracker (ITk) detector replaces the Inner Detector within ATLAS for the start of the HL-LHC. It is an all-silicon tracking detector that is divided into two subsystems: a pixel detector [300] and a strip detector [40].

P-n junctions are formed in strip and pixel sensors in a diode structure (add citation). An external reverse bias voltage is applied to create a depletion zone where the sensor is sensitive to charged particles. When a charged particle travels through the pixel or strip, it produces electron-hole pairs in the bulk. The electric field created by the reverse bias voltage separates electron-hole pairs before they recombine. Electrons (holes) drift through the bulk to positive (negative) voltage connections. The drift of charges correspond to a current pulse, measured by external electronics as a hit. This observed ionization is defined as a “hit” in the silicon sensor.

Fig. 7.1 [38] shows a schematic of one quarter of the ITk detector. The pixel detectors are shown in red. In the barrel region, the pixels are arranged in five flat barrel layers and vertical discs and in the end-cap region, the pixels are mounted on

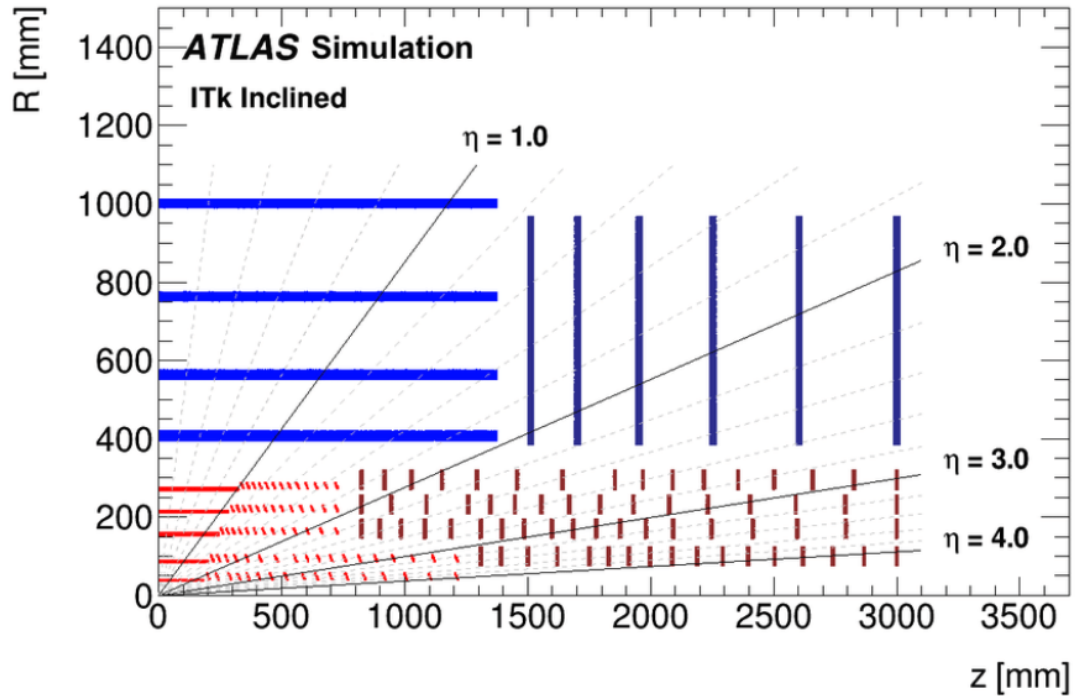


Figure 7.1: The ITk layout. Silicon pixel detector layers are in red and silicon strip detector layers are in blue. The darker red and blue detector elements indicate the detector layers are in the end-caps of the detector. From [38].

multiple inclined or vertical reign-shaped end-cap disks. The pixel detectors provide a coverage up to $|\eta| = 4.0$. The strip detector consists of four double-sided strip module layers in the barrel and six end-cap disks containing silicon modules. The strip detector provides coverage in a pseudorapidity up to $|\eta| \leq 2.7$.

The design was chosen to limit the distance between adjacent hits and optimize the number of hits used to reconstruct high purity tracks at any η . This allows for at least 9 hits in a track trajectory. It is a trade off between the accuracy of the track measurements and the amount of dead or inactive material.

7.2 Event Filter Tracking

The Event Filter system takes data from the Dataflow system and decides whether to accept or reject the event and select which reconstructed data should be stored.

The Event Filter tracking system integrates multiple types of computational units like multi-core CPUs, FPGAs, and GPUs and selects reconstruction data for online storage. It will be implemented as a multi-threaded asynchronous processing farm of commodity servers that reconstruct trajectories of charged particles using data from ITk using track reconstruction algorithms similar to those used offline and filter out bunch crossings to be stored on disk. The Event Filter tracking group is exploring a heterogeneous group of different technical solutions for track reconstruction, including CPU, FPGAs, and GPUs. FPGAs are one option for a computational accelerator that will be discussed in this thesis and are attractive because an FPGA-based heterogeneous commodity prototype costs less than the software-only equivalent [39]. Instead of building costly custom integrated circuits, Field Programmable Gate Arrays (FPGAs) use arrays of configurable logic blocks in a programmable logic chip with a programmable interconnect layer.

Figure 7.2 shows how the Event Filter is implemented in DAQ. The black dotted arrows show the Dataflow from the detector subsystems to the Level-0 trigger system at 40 MHz. The Level-0 trigger has 10 microseconds to identify physics objects and calculate event level physics quantities. The red dashed arrows show the resulting decision of the Level-0 trigger being transmitted to the various detectors. The black solid arrows show the resulting trigger data and detector data being transmitted through the Data Acquisition System at 1 MHz. The Event Filter farm then reduces the event rate to 10 kHz and transmits its accept/reject signal back to the dataflow in the blue dashed arrow. Selected data is written out to permanent storage.

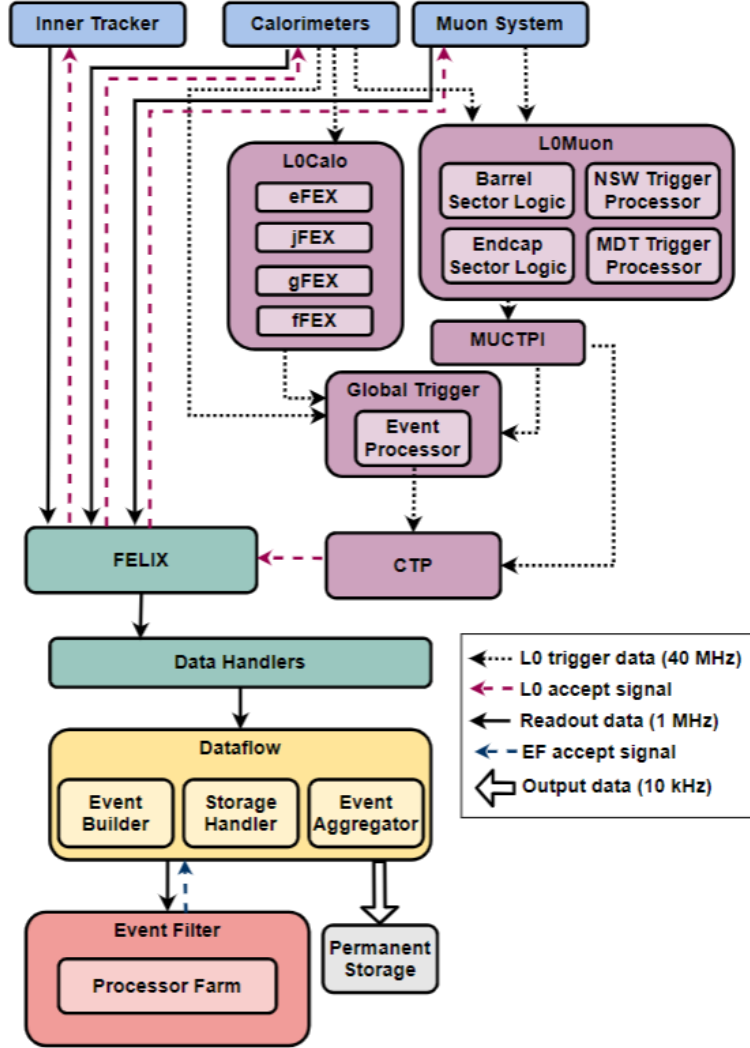


Figure 7.2: The TDAQ Phase-II architecture with the Event Filter shown in red. From [39].

7.2.1 Requirements for Event Filter Tracking

The Event Filter needs to be robust against pile-up so that the fake rate is low at high instantaneous luminosity. The tracking needs to reconstruct vertices and tracks to mitigate pile-up. The efficiency of Event Filter track finding should be close to that of the offline tracking algorithm. A detailed list of requirements can be found in [39].

7.2.2 Track Reconstruction Chain

The track reconstruction chain implemented within the Event Filter uses a series of stages that were developed in collaboration with the offline tracking group. All stages are executed on CPUs or using accelerator hardware like GPUs or FPGAs. The chain begins with the preparation of raw ITk data to be used by algorithms for track finding. After track reconstruction, track candidates are made available to the various trigger algorithms.

ITk Data Preparation

For an event containing $\mu = 200$ pile-up interactions, the ITk detector collects 1.6 MB (pixel detector) and 0.5 MB (strip detector) of raw data, read in as a data byte stream [39]. The data needs to be translated into hits. Groups of pixel or strip hits with a common edge or corner are clustered and are related to a charged particle going through the corresponding sensors. After that, a pairing and filtering algorithm can be applied to strip hits so space-points can be constructed from hits on opposite sides of a strip sensors, using information about the stereo angle between the strips on each side. The construction of space-points is the subject of the next chapter of this thesis, which presents a novel construction method and compares its performance to an existing space-point construction algorithm. This space-point may eventually be implemented in firmware.

Track Seeding and Pattern Recognition

This stage of the reconstruction chain identifies subsets of the hit clusters and/or space-points in the event that are consistent with being from a track. These collections of hit clusters and space-points are referred to as track candidates and will also be referred to in Chapter 9 of this thesis as roads. There are two approaches to this, where a track seed is formed from measurements in the outer or inner silicon sensors and then extrapolated to the remainder. The “inside-out” method takes advantage of the five-layer ITk pixel detector which covers a range of $|\eta| < 4$ and uses hits in these layers to find initial track seeds, later extending the seed with hits from the strip layers. The “outside-in” approach seeds the track with hits from 7 or 8 strip layers and the outermost pixel layer.

Several approaches to pattern recognition exist. Chapter 9 presents the Hough Transform as a method to perform outside-in based pattern recognition and discusses its implementation and optimization on firmware. As currently designed, the pattern recognition algorithm to be implemented on FPGAs uses a single stage Hough Transform that checks for the consistency of hits in the outer layers with coming from the same track by finding all possible track parameter values for $\frac{q}{p_T}$ and ϕ that would generate those hits and seeing if there is a common combination indicating those hits are consistent with coming from a single track trajectory. The relevance to this thesis is that we present a novel second stage Hough Transform filter that processes all hits from track candidates identified in the first stage and checks for their consistency given the possible η and z_0 track parameters tracks that produced them could have. The performance of this algorithm in both software and firmware is studied.

Machine Learning algorithms are also being studied for track reconstruction. They are ubiquitous and have been used widely to improve the ATLAS physics program and detector capabilities. Graphical Neural Networks (GNNs) [301] [302] can perform a geometric deep learning of hit cluster patterns, representing hits as graph nodes and relating them together in possible track segments using graph edges. These are being studied using FPGAs and GPUs as the accelerator choice.

Track extension, fitting and ambiguity resolution

A combinatorial Kalman filter is applied that extends the track candidates. Algorithms are applied to identify and remove duplicate tracks, reject fake tracks, and resolve tracks with shared clusters. A final fit is performed to determine the track parameters ($p_T, \phi_0, d_0, z_0,$ and η) with high precision.

Chapter 8: A Novel Method for Space-point Construction

Space-point construction is a step of the data preparation that combines information from hits on the inner and outer strips of a strip module using the stereo angle between them to create a three-dimensional measurement of a hit on the sensor. In the barrel, the sensors are each rotated by 26 mRad, resulting in a total stereo angle of 52 mRad between the strips. In the end-caps, the sensors are rotated to point slightly off center, with the inner and outer strips being rotated by a stereo angle of 40 mRad relative to one another. The stereo angle in the end-caps is constrained by the space available. Combining hits on opposite sides of the strip sensors not only provides three-dimensional information about the location of the track, it reduces the number of measurements to be handled in later stages of the track reconstruction chain.

Prior to these studies, space-points were implemented in a manner described in Section 8.2 and are referred to as “v2” space-points. Sasha Paramonov, a physicist at Argonne National Laboratory, and I wanted to see if we could improve the performance of space-points by exploiting additional information about the sensors and the track itself. A novel idea for constructing space-points was conceived by Sasha Paramonov. The method that we have developed at Ohio State and Argonne uses information about the geometry of the strip sensors themselves (including the stereo angle between the sides of the strip sensors), constraints on the beamspot location (z_0), and the requirement on the p_T of the reconstructed track to constrain the location of the space-point. These space-points are defined by coordinates r , ϕ , and z and we can construct “sizes” in $\phi - z$ or $r - \phi$ space. This method also allows us to place a weak constraint on $\gamma = \frac{Aq}{p_T}$ of the track.

Section 8.1 details the ITk silicon strip detector and strip sensor designs needed to make sense of the work presented here. Section 8.2 presents the original “v2” implementation of the space-points that will be used as a baseline for comparison with

our new space-point construction. Sections 8.3 and 8.4 are dedicated to space-point construction in the barrel and end-cap respectively using this new method developed at OSU and ANL, which we refer to as the “constraints method” throughout the resulting figures. The definitions, assumptions, and constraints used to derive the final space-point coordinates are summarized in Sections 8.3.1 for the barrel and 8.4.1 for the end-caps. The final expressions for the space-point quantities and their related quantities are detailed in Sections 8.3.2 and 8.4.2 for the barrel and end-caps, respectively. Sections 8.3.3 and 8.4.3 outline the parameters and configurations of the simulations used to test the space-point construction using the “v2” method and this “constraints” method. Hit clusters measured in the detector simulation are used to construct space-points in the barrel and end-caps and the performance is assessed as the residual difference between the calculated coordinates of the space-points and the expected location of the truth track. These performance measures are defined and evaluated in Section 8.3.4 and Section 8.4.4 for the barrel and end-cap space-points, respectively.

8.1 Design of the ITk strip detector

The design of the ITk strip detector is modular. The cylinders in the barrel and disks in the end-caps are composed of staves and petals, respectively. These structures are comprised of modules, the most basic unit of the strip detector. A silicon strip module consists of individual strip sensors, one or two flex hybrid circuit boards, and a power board [40]. The locations of these modules within the ITk detector are given by η and ϕ module IDs. The silicon sensors are chosen to be n^+ -in-p flat zone sensors to withstand the harsh radiation environment. A schematic of a stave in the barrel is in Fig. 8.1. The dimensions of the strip sensors are in Fig. 8.2.

In the end-caps, six different annular shapes are used to fit the sensors into the nearly trapezoidal shape of the petals that make up the disks. A depiction of the support structure of the disks and the petal design are shown in Fig. 8.3. Six disks are shown and it is shown how the petals are arranged in the disks (only 4 shown per disk). Petals are tiled with alternating petals on the inside and outside. The petals within the disks are all perpendicular to the beam axis. Within each petal, there are 6 rings, with the three outermost rings having two identical sensors and the three innermost rings having only one. The strips on the front side of a petal are rotated at a stereo angle of 40 mRad relative to those on the back side of that petal.

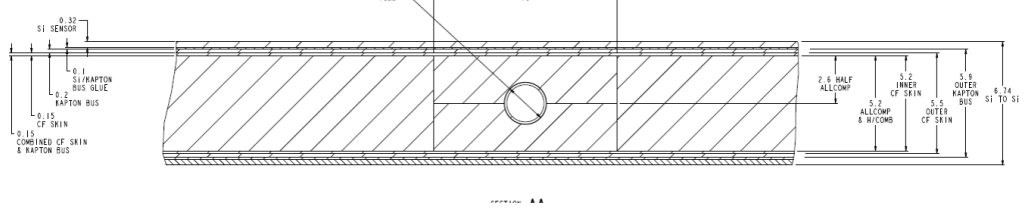


Figure 8.1: A schematic of a stave module in the barrel.

Layer	Radius [mm]	Channels in ϕ	Strip Pitch [μm]	Strip Length [mm]	Tilt Angle [$^\circ$]
0	405	28×1280	75.5	24.1	11.5
1	562	40×1280	75.5	24.1	11.0
2	762	56×1280	75.5	48.2	10.0
3	1000	72×1280	75.5	48.2	10.0

Figure 8.2: Dimensions of the strips in the barrel. From [40].

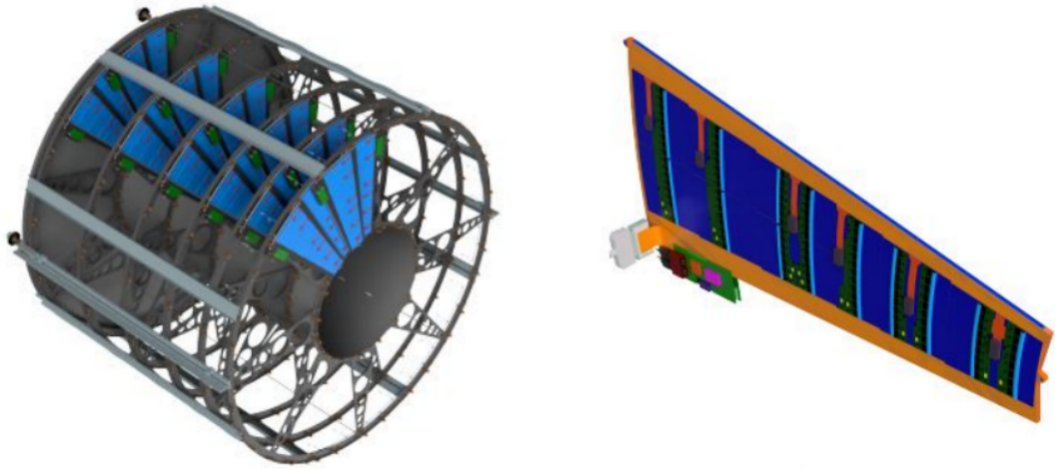


Figure 8.3: (Left) ITk strips in the end-cap support structure. (Right) The front side of a petal is shown, with 9 modules. From [41].

An image of a strip module within a petal is shown in Fig. 8.4 to demonstrate the arrangement of the silicon strips. Silicon sensors are contained on each side, rotated with a stereo angle of 20 mRad relative to their radial distance from the beampipe. As a consequence, they point slightly off center. The specific lengths are chosen based on the expected track density at different radii on the petal and are shown in the table in Fig. 8.5. The strip pitch of the sensors in the barrel is $75.5\ \mu\text{m}$ and varies from $70\mu\text{m}$ to $80\mu\text{m}$ in the end-caps [40].

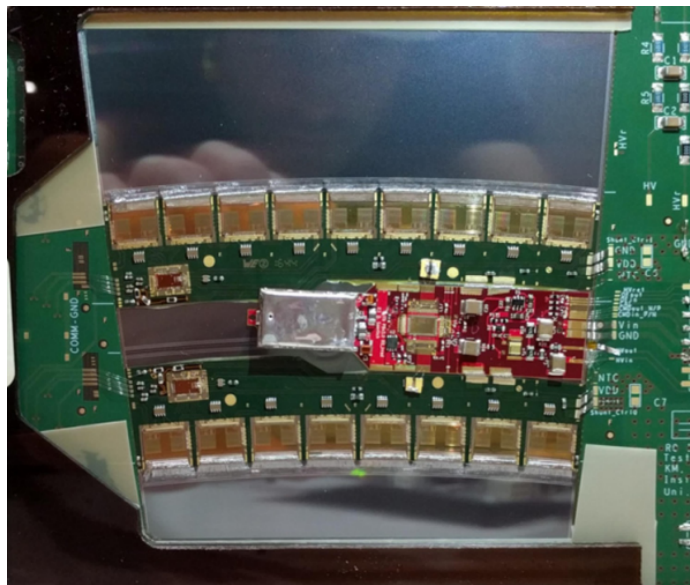


Figure 8.4: A picture of an ITk strip module in the end-caps. From [42].

Ring/Row	Inner Radius [mm]	Strip Length [mm]	Strip Pitch [μm]
Ring 0 Row 0	384.5	19	75.0
Ring 0 Row 1	403.5	24	79.2
Ring 0 Row 2	427.5	29	74.9
Ring 0 Row 3	456.4	32	80.2
Ring 1 Row 0	489.8	18.1	69.9
Ring 1 Row 1	507.9	27.1	72.9
Ring 1 Row 2	535	24.1	75.6
Ring 1 Row 3	559.1	15.1	78.6
Ring 2 Row 0	575.6	30.8	75.7
Ring 2 Row 1	606.4	30.8	79.8
Ring 3 Row 0	638.6	32.2	71.1
Ring 3 Row 1	670.8	26.2	74.3
Ring 3 Row 2	697.1	26.2	77.5
Ring 3 Row 3	723.3	32.2	80.7
Ring 4 Row 0	756.9	54.6	75.0
Ring 4 Row 1	811.5	54.6	80.3
Ring 5 Row 0	867.5	40.2	76.2
Ring 5 Row 1	907.6	60.2	80.5

Figure 8.5: Dimensions of strips in the end-caps. From [40].

8.2 Current implementation (“v2”)

The exact implementation of this reconstruction algorithm may have changed since these studies were performed, but the reconstruction that was used to assess “v2” space-points and compare them to these new space-points was taken from the `HTTSpacepointsTool_v2` class from the `TrigHTT` repository [303].

Before constructing space-points, hits within each layer are separated into those on the inner and outer sides of a given physical layer. This algorithm only considers pairs of hits on opposite sides of the same strip module or modules adjacent in η and ϕ for space-point construction in the barrel. The first step is to loop through all the “inner” hits. For each “inner” hit, the algorithm loops through all “outer” hits on strip modules within ± 1 η and ϕ modules.

A cut is placed, requiring the pair fall within a “phi-window” of each other. If the two hits are too far apart in the ϕ coordinate, they can’t have originated from the same prompt track with $p_T > 1$ GeV. The coordinates of each hit are assigned to the center of the strip sensor they occurred on. If the coordinates of the inner hit are $(r_{10}, \phi_{10}, z_{10})$ and the coordinates of the outer hit are $(r_{20}, \phi_{20}, z_{20})$, then the following condition in Eq. 8.1 is applied to see if the hits are consistent with being from the same track, where 0.008 is measured in mRad.

Phi-window condition:

$$|\phi_{10} - \phi_{20}| < 0.0008 \quad (8.1)$$

Initially, the coordinates of the space-point are assigned to be the center between the coordinates of each hit:

$$r_{sp} = \frac{r_{10} + r_{20}}{2} \quad (8.2)$$

$$\phi_{sp} = \frac{\phi_{10} + \phi_{20}}{2} \quad (8.3)$$

$$z_{sp} = \frac{z_{10} + z_{20}}{2} \quad (8.4)$$

Corrections need to be made to account for the stereo angle between the inner and outer strips. The physical distance in the ϕ direction between the two hits is defined in Eq. 8.5.

$$\Delta\phi_{local} = (\phi_{10} - \phi_{20}) \cdot r_{sp} \quad (8.5)$$

If the hit is in the barrel, the z coordinate is corrected to Eq. 8.6, where 26 mRad is the stereo angle that the strips on each side of the sensor were rotated by, resulting in a total stereo angle of 52 mRad between the two strips.

$$z_{sp} = \frac{z_{10} + z_{20}}{2} + \frac{\Delta\phi_{local}}{2 \cdot \tan(0.026)} \quad (8.6)$$

Similarly, corrections to the r coordinate can be made for space-points constructed from hits in the end-caps. The new expression for r_{sp} is in Eq. 8.7.

$$r_{sp} = \frac{r_{10} + r_{20}}{2} + \frac{\Delta\phi_{local}}{2 \cdot \tan(0.02)} \quad (8.7)$$

For hits on the same η module within the end-caps, if r_{sp} is outside the range of the edges of the module the hits were contained within, r_{sp} is assigned the location of the nearest edge. For hits on adjacent η modules, if r_{sp} is outside the range, r_{sp} is assigned the r of the edge plus an additional 3 mm, which is an approximation of the maximum possible distance between hits from the same track within a reasonable incline to the module.

8.3 Space-point construction in the barrel

We study space-point construction first in the barrel, due to the more uniform magnetic field. We expect the constraints method of constructing space-points to improve the resolution of z_{sp} for space-points in the barrel because the layout of the strip modules in the barrel allows us to precisely know the radii of each of the strips.

8.3.1 Definitions and Assumptions

1. The magnetic field within the solenoid is uniform and A is a constant.
2. A strip module in the barrel consists of two strip sensors, an inner strip sensor that will be denoted as Strip 1 and an outer strip that will be denoted as Strip 2. These strips are placed at a stereo angle of 52 mRad with respect to each other [40].
3. For the purposes of these calculations, only cases where Strips 1 and 2 lie on the same module in η and ϕ or adjacent modules in η or ϕ are considered.
4. The length of the strip in z is in the Table in Fig. 8.2. The definition of ϕ_{st} is in Eq. 8.8 and relies on the fact that the stereo angle is small. Definitions of Strip 1 and Strip 2 are in Eqs. 8.9 and 8.10 and also rely on the fact that the stereo angle is small. Simulation is used to verify the orientation of the strips (ie. sign of the slopes).

$$\phi_{st} = \frac{z_{st} \cdot (26 \text{ mRad})}{r_{sp}} \quad (8.8)$$

$$\phi_1 - \phi_{10} = -\frac{\phi_{st}}{z_{st}}(z_1 - z_{10}) \quad (8.9)$$

$$\phi_2 - \phi_{20} = \frac{\phi_{st}}{z_{st}}(z_2 - z_{20}) \quad (8.10)$$

5. Hit cluster 1 occurs on strip 1. The hit information read out from the detector corresponds to the center of strip 1 at a position with coordinates $(r, \phi, z) = (r_{10}, \phi_{10}, z_{10})$. The true location of the hit on Strip 1 is defined as (r_{10}, ϕ_1, z_1) . ϕ_1 and z_1 are unknown.
6. Hit cluster 2 occurs on strip 2. The hit information read out from the detector corresponds to the center of strip 2 at a position with coordinates $(r, \phi, z) = (r_{20}, \phi_{20}, z_{20})$. The true location of the hit on Strip 2 is defined as (r_{20}, ϕ_2, z_2) . ϕ_2 and z_2 are unknown.
7. Hits 1 and 2 must lie on their respective strips, meaning:

- $|z_1 - z_{10}| \leq \frac{z_{st}}{2}$
- $|\phi_1 - \phi_{10}| \leq \frac{\phi_{st}}{2}$
- $|z_2 - z_{20}| \leq \frac{z_{st}}{2}$
- $|\phi_2 - \phi_{20}| \leq \frac{\phi_{st}}{2}$

8. The positions of where the track traversed sensors 1 and 2 satisfy the first Hough Transform equation (derived in the appendix), where q , p_T , and ϕ_0 are the charge, transverse momentum, and the azimuthal angle of the track containing hits 1 and 2. The variables ϕ_{hit} and r_{hit} indicate positions of a hit along the particle trajectory.

$$\frac{Aq}{p_T} = \frac{\sin(\phi_{hit} - \phi_0)}{r_{hit}}$$

9. The positions of where the track traversed sensors 1 and 2 satisfy the second Hough Transform equation (derived in the appendix), where q , p_T , z_0 , and η are the charge, transverse momentum, longitudinal impact parameter, and

pseudorapidity of the track containing hits 1 and 2. The variables z_{hit} and r_{hit} indicate positions of a hit along the particle trajectory.

$$z_{hit} = z_0 + \frac{p_T}{Aq} \sin\left(\frac{Aq}{p_T} r_{hit}\right) \sinh(\eta)$$

10. The beamspot constraint is that $|z_0| \leq 150$ mm or $|z_0| \leq 200$ mm. For the purpose of these studies, we use $|z_0| \leq 150$ mm.

11. Only tracks with $|p_T| > 1$ GeV are considered.

8.3.2 Space-point Coordinates in the Barrel

The exact positions of the strips are known in r and so we choose r_{sp} as the middle between the two strips.

$$r_{sp} = \frac{r_{10} + r_{20}}{2}$$

Definition of $\gamma = \frac{Aq}{p_T}$

The first interval for γ is taken from the p_T constraint on the reconstructed track.

$$\gamma_{1,min} = -0.0003$$

$$\gamma_{1,max} = 0.0003$$

The next interval for γ comes from the first Hough Transform equation.

$$\gamma_{2,min} = \frac{\Delta\phi - \phi_{st}}{r_{20} - r_{10}}$$

$$\gamma_{2,max} = \frac{\Delta\phi + \phi_{st}}{r_{20} - r_{10}}$$

The following two intervals for γ are found using both Hough Transform equations and the constraint on the beamspot location that $|z_0| < 150$ mm.

$$\gamma_{3,min} = \left(\frac{\phi_{10}r_{20} + \phi_{20}r_{10}}{r_{20} - r_{10}} \right) \cdot \frac{1}{r_{20}} - \left(\phi_{20} + \frac{\phi_{st}}{2} \right) \cdot \frac{r_{10} + r_{20}}{r_{20} - r_{10}} \cdot \frac{1}{r_{20}} \\ + \frac{\phi_{st}}{z_{st}} \cdot \frac{(z_{10}r_{20} - z_{20}r_{10})}{r_{20} - r_{10}} \cdot \frac{1}{r_{20}} - 150 \cdot \frac{\phi_{st}}{z_{st}} \cdot \frac{1}{r_{20}}$$

$$\gamma_{3,max} = \left(\frac{\phi_{10}r_{20} + \phi_{20}r_{10}}{r_{20} - r_{10}} \right) \cdot \frac{1}{r_{20}} - \left(\phi_{20} - \frac{\phi_{st}}{2} \right) \cdot \frac{r_{10} + r_{20}}{r_{20} - r_{10}} \cdot \frac{1}{r_{20}} \\ + \frac{\phi_{st}}{z_{st}} \cdot \frac{(z_{10}r_{20} - z_{20}r_{10})}{r_{20} - r_{10}} \cdot \frac{1}{r_{20}} + 150 \cdot \frac{\phi_{st}}{z_{st}} \cdot \frac{1}{r_{20}}$$

$$\gamma_{4,min} = -\left(\frac{\phi_{10}r_{20} + \phi_{20}r_{10}}{r_{20} - r_{10}} \right) \cdot \frac{1}{r_{10}} + \left(\phi_{10} - \frac{\phi_{st}}{2} \right) \cdot \frac{r_{10} + r_{20}}{r_{20} - r_{10}} \cdot \frac{1}{r_{10}} \\ - \frac{\phi_{st}}{z_{st}} \cdot \frac{(z_{10}r_{20} - z_{20}r_{10})}{r_{20} - r_{10}} \cdot \frac{1}{r_{10}} - 150 \cdot \frac{\phi_{st}}{z_{st}} \cdot \frac{1}{r_{10}}$$

$$\gamma_{4,max} = -\left(\frac{\phi_{10}r_{20} + \phi_{20}r_{10}}{r_{20} - r_{10}} \right) \cdot \frac{1}{r_{10}} + \left(\phi_{10} + \frac{\phi_{st}}{2} \right) \cdot \frac{r_{10} + r_{20}}{r_{20} - r_{10}} \cdot \frac{1}{r_{10}} \\ - \frac{\phi_{st}}{z_{st}} \cdot \frac{(z_{10}r_{20} - z_{20}r_{10})}{r_{20} - r_{10}} \cdot \frac{1}{r_{10}} + 150 \cdot \frac{\phi_{st}}{z_{st}} \cdot \frac{1}{r_{10}}$$

The final interval for γ is taken as the intersection of the four intervals:

$$\gamma = [\gamma_{min}, \gamma_{max}] = \gamma_1 \cap \gamma_2 \cap \gamma_3 \cap \gamma_4 \quad (8.11)$$

The final value of γ assigned for the space-point is given as:

$$\gamma_{sp} = \frac{\gamma_{min} + \gamma_{max}}{2} \quad (8.12)$$

The “size” of the space-point in this coordinate is

$$\Delta\gamma_{sp} = \frac{\gamma_{max} - \gamma_{min}}{2} \quad (8.13)$$

Placing a weak constraint on γ_{sp}

The initial constraint considered for track reconstruction is that tracks have $p_T > 1$ GeV. Given the strength of the solenoidal field, this restricts $\gamma = \frac{Aq}{p_T}$ to $[-0.0003, 0.0003]$. By our definition, this interval has size $\Delta\gamma_{sp} = 0.0003$. To demonstrate that the interval for γ is being further constrained by implementing the Hough Transform equations and beamspot constraint in the space-point construction, Fig. 8.6 shows $\Delta\gamma_{sp}$ for all space-points constructed in the barrel, plotted separately for each layer. Looking at the γ_{min} and γ_{max} values themselves shows that there is a weak constraint placed on γ_{sp} that is finer than that from the requirement that $p_T > 1$ GeV.

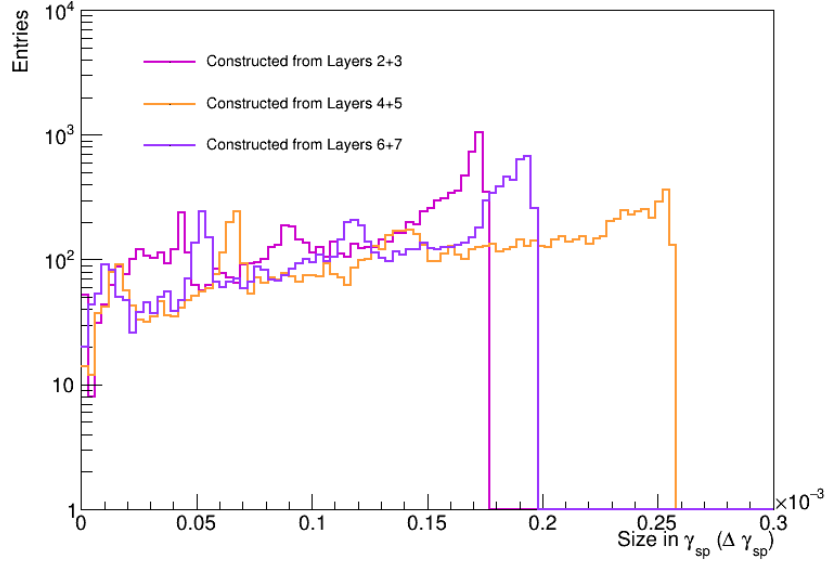


Figure 8.6: A distribution of the “size” of the possible values of γ that a track containing reconstructed space-point could have.

Definition of ϕ_{sp}

From the first Hough Transform equation and the constraint that the space-point not lie outside of the strip modules, no space-point can be constructed if:

$$|\Delta\phi| > \phi_{st} + 0.0003 \cdot (r_{20} - r_{10}) \quad (8.14)$$

If a space-point can be constructed, the geometric constraint that the actual hit location of the hit on each strip lie on that strip, one interval on ϕ_{sp} can be constructed and two cases exist.

If $\Delta\phi > 0.0003 \cdot (r_{20} - r_{10})$, then:

$$\phi_{1,min} = \frac{\phi_{10} + \phi_{20}}{2} - \frac{\Delta\phi}{2} + \frac{\phi_{st}}{2}$$

$$\phi_{1,max} = \frac{\phi_{10} + \phi_{20}}{2} + \frac{\Delta\phi}{2} + \frac{\phi_{st}}{2}$$

Otherwise:

$$\phi_{1,min} = \frac{\phi_{10} + \phi_{20}}{2} - \frac{\phi_{st}}{2}$$

$$\phi_{1,max} = \frac{\phi_{10} + \phi_{20}}{2} + \frac{\phi_{st}}{2}$$

By combining both Hough Transform equations and the constraint on the beamspot location, another interval for ϕ_{sp} can be constructed. Three constants C_1 , C_2 , and C_3 are introduced.

$$C_1 = -\frac{\phi_{st}}{z_{st}} \cdot \frac{r_{20} - r_{10}}{r_{20} + r_{10}}$$

$$C_2 = -\frac{1}{2} \cdot \frac{(r_{20} - r_{10})^2}{r_{20} + r_{10}}$$

$$C_3 = \frac{\phi_{st}}{z_{st}} \cdot \frac{-z_{20}r_{10} + z_{10}r_{20}}{r_{10} + r_{20}} + \frac{\phi_{10}r_{20} + \phi_{20}r_{10}}{r_{10} + r_{20}}$$

Now, the interval for ϕ_{sp} can be defined as a function of these constants and the minimum and maximum values of γ_{sp} found previously.

$$\phi_{2,max} = C_1 \cdot 150 + C_2 \cdot \gamma_{sp,min} + C_3$$

$$\phi_{2,min} = -C_1 \cdot 150 - C_2 \cdot \gamma_{sp,max} + C_3$$

The final interval for ϕ_{sp} is taken as the intersection of the four intervals:

$$\phi_{sp} = [\phi_{min}, \phi_{max}] = \phi_1 \cap \phi_2 \quad (8.15)$$

The final value of ϕ_{sp} assigned for the space-point is given as:

$$\phi_{sp} = \frac{\phi_{min} + \phi_{max}}{2} \quad (8.16)$$

The “size” of the space-point in this coordinate is

$$\Delta\phi_{sp} = \frac{\phi_{max} - \phi_{min}}{2} \quad (8.17)$$

Definition of z_{sp}

By combining both Hough Transform equations, the beamspot constraint, the requirement that the actual locations of hits 1 and 2 lie on their respective strips, and the geometric definitions of the strips, a piece-wise function with 7 intervals can be defined for z_{sp} .

Using the second HT equation, the beamspot constraint, and geometric definitions, no space-point can be constructed if:

$$|z_{20}r_{10} - z_{10}r_{20}| > z_{st} \cdot \frac{r_{20} + r_{10}}{2} + 150 \cdot (r_{20} - r_{10})$$

In the case that a space-point can be constructed, the second HT equation and constraint that both hits be located on their respective strips create several scenarios.

Let's say Condition A is that:

$$|z_{20}r_{10} - z_{10}r_{20}| \leq 150 \cdot (r_{20} - r_{10}) - z_{st} \cdot \frac{r_{20} - r_{10}}{2} \quad (8.18)$$

If Condition A is true, then:

$$z_{1,max} = \frac{z_{10} + z_{20} + z_{st}}{2}$$

and

$$z_{1,min} = \frac{z_{10} + z_{20} - z_{st}}{2}$$

If Condition A is not true, the definition of z_{sp} depends on whether or not another Condition B is satisfied.

Let's say Condition B is that:

$$|z_{20}r_{10} - z_{10}r_{20}| \leq \frac{z_{st} \cdot (r_{20} - r_{10})}{2} + 150 \cdot (r_{20} - r_{10}) \quad (8.19)$$

If Condition B is true, two subcases exist.

If Condition B is satisfied and $\frac{z_{20}}{r_{20}} > \frac{z_{10}}{r_{10}}$:

$$z_{1,max} = \frac{z_{10} + z_{20} + z_{st}}{2}$$

$$z_{1,min} = z_{20} \cdot \frac{r_{20} + r_{10}}{2r_{20}} - \frac{1}{2} \frac{z_{st} \cdot (r_{20} + r_{10})}{2r_{20}} - 150 \cdot \frac{(r_{20} - r_{10})}{2r_{20}} \quad (8.20)$$

If Condition B is satisfied and $\frac{z_{20}}{r_{20}} < \frac{z_{10}}{r_{10}}$:

$$z_{1,max} = z_{20} \cdot \frac{r_{20} + r_{10}}{2r_{20}} + \frac{1}{2} \frac{z_{st} \cdot (r_{20} + r_{10})}{2r_{20}} + 150 \cdot \frac{(r_{20} - r_{10})}{2r_{20}}$$

$$z_{1,min} = \frac{z_{10} + z_{20} - z_{st}}{2}$$

If Condition B is false and $\frac{z_{20}}{r_{20}} > \frac{z_{10}}{r_{10}}$:

$$z_{1,max} = z_{10} \cdot \frac{r_{20} + r_{10}}{2r_{10}} + \frac{1}{2} z_{st} \cdot \frac{r_{20} + r_{10}}{2r_{10}} + 150 \cdot \frac{r_{20} - r_{10}}{2r_{10}}$$

$$z_{1,min} = z_{20} \cdot \frac{r_{20} + r_{10}}{2r_{20}} - \frac{1}{2} z_{st} \cdot \frac{r_{20} + r_{10}}{2r_{20}} - 150 \cdot \frac{r_{20} - r_{10}}{2r_{20}}$$

If Condition B is false and $\frac{z_{20}}{r_{20}} < \frac{z_{10}}{r_{10}}$

$$z_{1,max} = z_{20} \cdot \frac{r_{20} + r_{10}}{2r_{20}} + \frac{1}{2} z_{st} \cdot \frac{r_{20} + r_{10}}{2r_{20}} + 150 \cdot \frac{r_{20} - r_{10}}{2r_{20}}$$

$$z_{1,min} = z_{10} \cdot \frac{r_{20} + r_{10}}{2r_{10}} - \frac{1}{2} z_{st} \cdot \frac{r_{20} + r_{10}}{2r_{10}} - 150 \cdot \frac{r_{20} - r_{10}}{2r_{10}}$$

A second interval for z_{sp} can be found using the first Hough Transform equation, the geometric definitions of the strips, and the value of interval for γ_{sp} that was found earlier.

$$z_{2,max} = \frac{1}{2}(z_{10} + z_{20}) = \frac{z_{st}}{\phi_{st}} \cdot (\phi_{10} - \phi_{20} - \gamma_{min} \cdot \frac{z_{st}}{\phi_{st}} \cdot (r_{20} - r_{10}))$$

$$z_{2,min} = \frac{1}{2}(z_{10} + z_{20}) = \frac{z_{st}}{\phi_{st}} \cdot (\phi_{10} - \phi_{20} - \gamma_{max} \cdot \frac{z_{st}}{\phi_{st}} \cdot (r_{20} - r_{10}))$$

The final interval for z_{sp} is taken as the intersection of the two intervals:

$$z_{sp} = [z_{min}, z_{max}] = z_1 \cap z_2 \quad (8.21)$$

The final value of z_{sp} assigned for the space-point is given as:

$$z_{sp} = \frac{z_{min} + z_{max}}{2} \quad (8.22)$$

The “size” of the space-point in this coordinate is

$$\Delta z_{sp} = \frac{z_{max} - z_{min}}{2} \quad (8.23)$$

8.3.3 Configuration for Simulation in the ITk Barrel

The parameters of the simulation in the barrel are:

- File with 10k simulated single muon events
- The simulation uses version 22-02-00 of the ITk layout geometry
- Eta region: $0.1 < \eta < 0.3$
- Phi region: $0.3 < \phi < 0.5$
- Space-points constructed in ITk strip layers 1, 2, and 3.

8.3.4 Performance Results for Space-points in the Barrel

Residuals are a way to quantify how close the constructed space-point coordinate is to where the track is expected to traverse the r_{sp} cylinders. For the barrel, they are defined in Eqs. 8.24 and 8.25.

$$\phi_{resid} = \phi_{sp} - \phi_{exp} \quad (8.24)$$

$$z_{resid} = z_{sp} - z_{exp} \quad (8.25)$$

The expected locations of the hit were calculated using the Hough Transform and the generated track parameters of the single muons, defining $r_{exp} = \frac{r_{10} + r_{20}}{2}$. The expression for ϕ_{exp} in Eq. 8.26 uses a correction to account for tracks having a non-negligible d_0 impact parameter. The expression for z_{exp} in Eq. 8.27 was found using the Hough Transform equations for the track, evaluated for r_{sp} .

$$\phi_{exp} = \phi_0 - a \sin\left(\frac{r_{exp}^2 + (R - d_0)^2 - R^2}{2 \cdot r_{exp} \cdot (R - d_0)}\right) \quad (8.26)$$

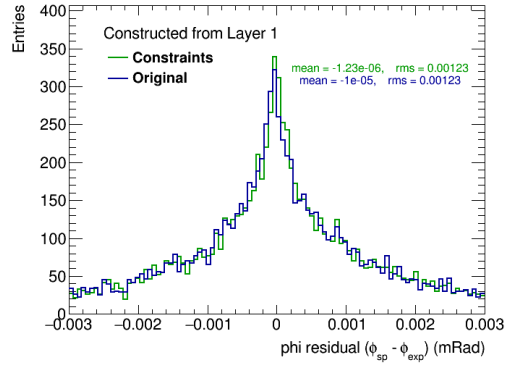
$$z_{exp} = z_0 + \frac{p_T}{Aq} a \sin\left(\frac{Aq}{p_T} r_{sp}\right) \sinh(\eta) \quad (8.27)$$

Residuals for ϕ_{sp}

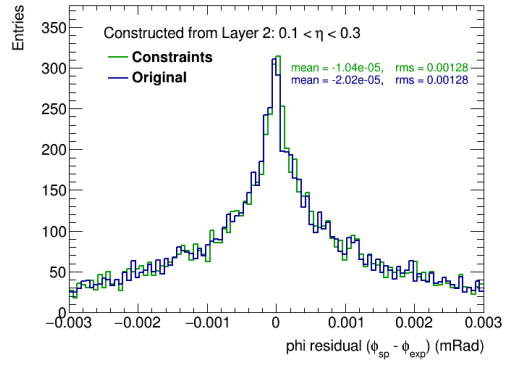
Fig. 8.7 shows the residuals between the calculated ϕ coordinate of the constructed space-point, ϕ_{sp} , and the expected ϕ_{exp} location of a truth track from a single muon evaluated at r_{sp} for space-points constructed in Layer 1, 2, and 3 in the barrel, respectively.

In all three plots, the RMS width of the residual distribution remained unchanged. We expected this to be the case because scattering limits the ability to improve the resolution in ϕ_{sp} .

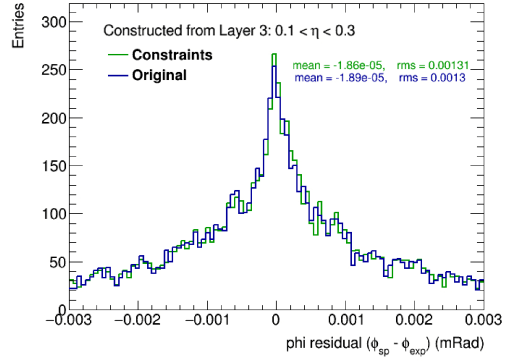
The negative mean of the residuals seen in all three plots could be due to a minimal impact of scattering. Another observation is that the residual distribution produced for these new space-points is centered closer to zero.



(a)



(b)



(c)

Figure 8.7: Comparison of ϕ_{sp} residuals found using both space-point construction methods to construct space-points in (a) Layer 1 of the barrel, (b) Layer 2 of the barrel, and (c) Layer 3 of the barrel.

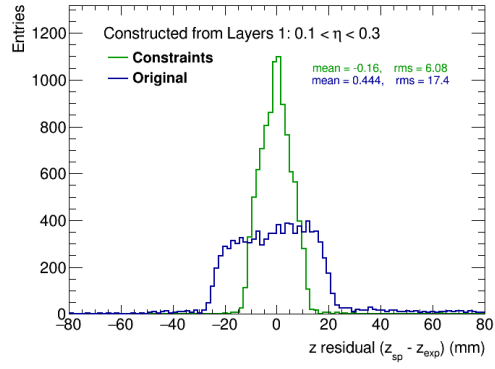
Residuals for z_{sp}

Fig. 8.8 shows the residuals between the calculated z coordinate of the constructed space-point, z_{sp} , and the expected z_{exp} location of a truth track from a single muon evaluated at r_{sp} for space-points constructed in Layers 1, 2, and 3.

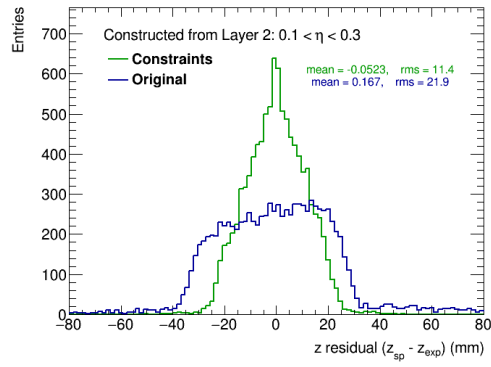
In Layer 1, which has 24.1 mm long strips, the residual distribution is much more peaked for space-points constructed using the constraints method. These space-points have a resolution, as measured by the RMS of the residual distribution, that is a factor of 2.86 times smaller than that of the space-points constructed with the original method.

For space-points constructed in ITk Strip Layers 2 and 3, respectively, which each have strip sensor lengths of 48.2 mm, the improvement in resolution, represented by the reduction of the RMS of the residual distribution, isn't as pronounced as in Layer 1, but it is significant nonetheless. In Layer 2, the RMS decreases by a factor of over 1.92. In Layer 3, the RMS decreases by a little over a factor of 2. The smaller improvement in performance of these new space-points at calculating the z_{sp} coordinate in these outer layers may be due to the larger effect of scattering at the farther radii these layers are located at.

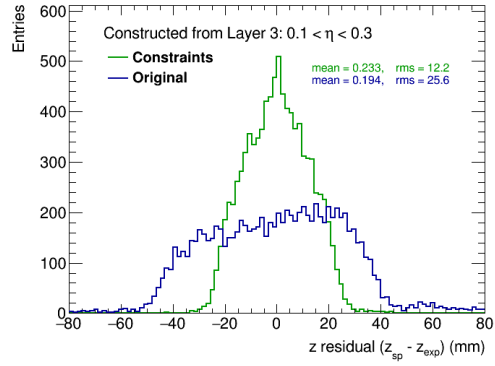
The improvement in residuals seen across all three layers is significant and studies should be done to assess the performance of these space-points in the track fitting stage. Improving the resolution of space-points can result in improved track parameter resolutions after track fitting.



(a)



(b)



(c)

Figure 8.8: Comparison of z_{sp} residuals found using both space-point construction methods to construct space-points in (a) Layer 1 of the barrel, (b) Layer 2 of the barrel, and (c) Layer 3 of the barrel.

“Size” of space-points in the z-coordinate: Δz_{sp}

Our method for finding space-point coordinates generates intervals of possible values for each coordinate, the center of which we defined as that coordinate and half the length of the interval we defined as the “size”. This quantity is useful in track fits.

Fig. 8.9 shows three two-dimensional histograms of the space-point size, Δz_{sp} , as a function of the z_{sp} residual for space-points constructed in each layer. Space-points with the smallest residuals were confined to the smallest intervals along the strip sensor. Two concentrated populations can be seen for space-points with small z_{sp} sizes and then z_{sp} whose location on the sensor was hardly constrained at all. There are some outliers, where space-points are constructed off the sensors. This is due to scattering.

Loss of Efficiency

There are small losses in efficiency when constructing space-points with the constraints method due to scattering within the support structure between the sensors. These losses and scattering get smaller for more energetic muons.

To demonstrate this, Fig. 9.13 plots the angular separation between hits used to construct space-points against the distance between the space-points. The distance between the two space-points is calculated in Eq. 8.28.

$$d_{12} = \sqrt{(\Delta\eta_{12})^2 + (\Delta\phi_{12})^2} \quad (8.28)$$

The plot was chosen to show angular separation as a function of distance between the two hits and not the radial distance between the hits because hits on adjacent modules will not be at a fixed distance from one another.

The two-dimensional histogram with the color z-scale shows this distribution for successfully constructed space-points. The red dots indicate 1.6% of the space-points found by the original “v2” method that failed to be constructed with the constraints method. We accept this inefficiency to improve rejection in the dense environment.

A couple observations can be made here. The shape of the curve in Fig. 8.10 roughly obeys the form $\Delta\phi \approx \arccos\left(\frac{6.5}{d_{12}}\right) - 0.0026$, where 26 mRad is the tilt of one sensor with respect to the axis between the two and 6.5 mm is roughly the stave thickness. The smearing in the horizontal direction reflects that as the momentum

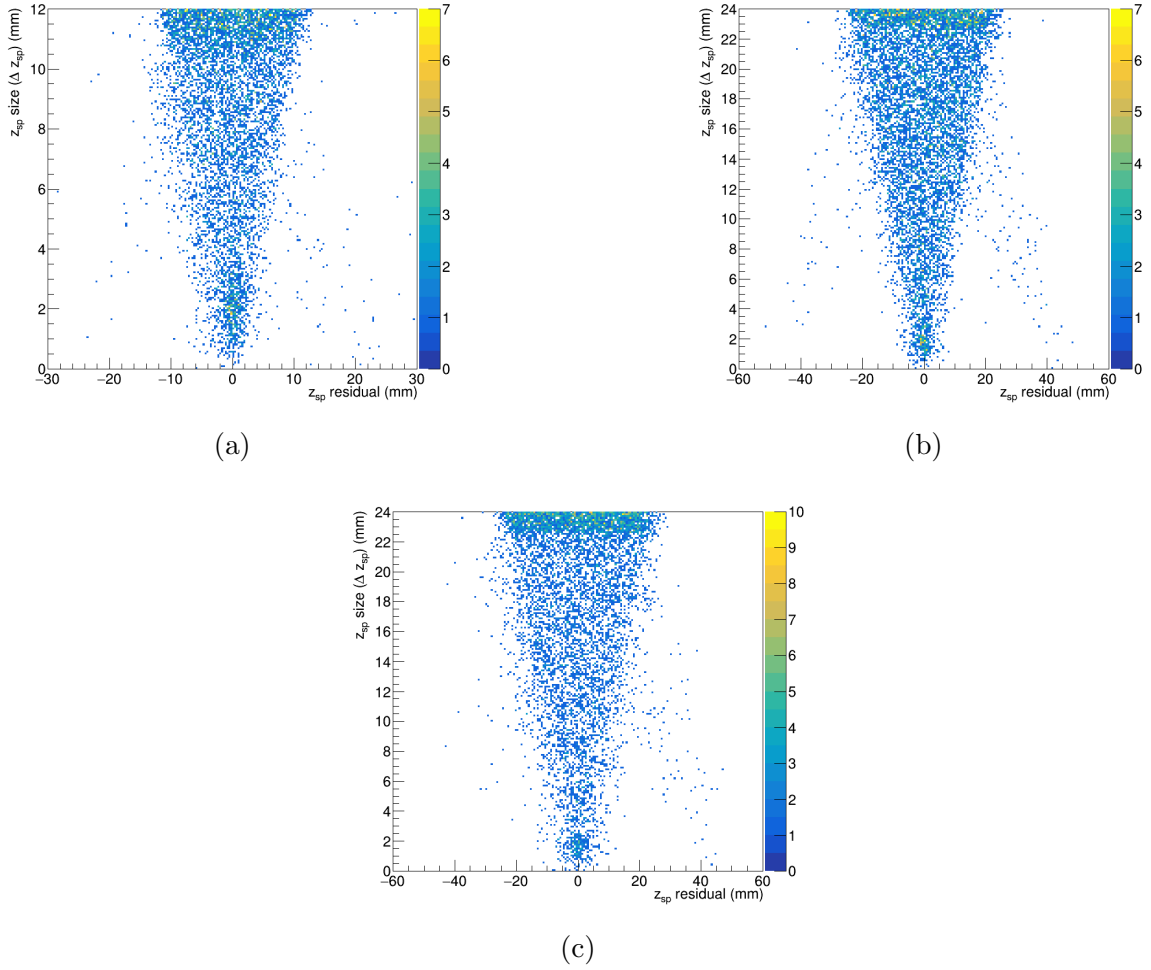


Figure 8.9: Two dimensional histograms comparing the size of the space-points in the z-coordinate, Δz_{sp} to the z_{sp} residual for space-points constructed in (a) Layer 1, (b) Layer 2, and (c) Layer 3.

of the particle increases, the distance between the hits increases. Most of the lost space-points, seen in red, are from soft tracks.

By printing the γ intervals calculated by this space-point construction method for pairs of hits that should have constructed space-points but didn't, it was because the calculated γ interval did not intersect the requirement that $\gamma \in [-0.0003, 0.0003]$ that a space-point was not constructed.

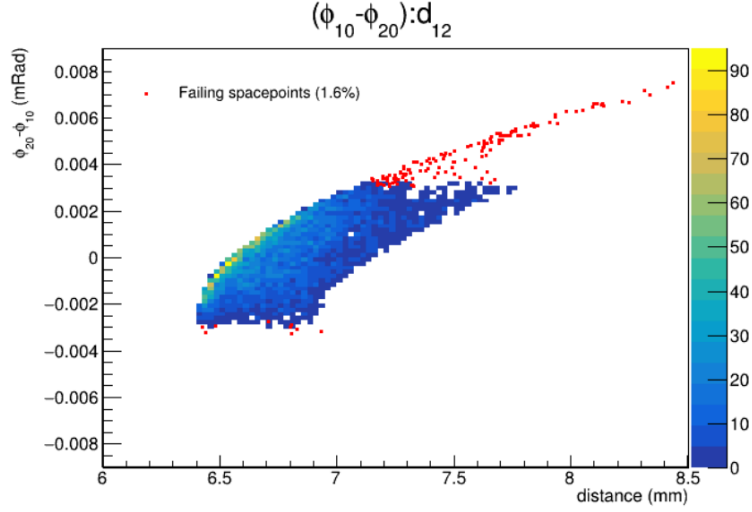


Figure 8.10: A two dimensional histogram of the angular distance and actual distance between hits considered for space-points construction.

8.4 Space-point Construction in the end-caps

Space-point construction using the constraints method proved successful at improving the resolution of z_{sp} in the barrel and for this reason, we similarly expect that the resolution of r_{sp} in the end-caps will be improved because the layout of the strip modules in the end-caps allows us to precisely know the z-locations of each strip.

8.4.1 Definitions and Assumptions

1. We ignore scattering and energy losses. We still assume that the magnetic field is uniform outside the barrel.
2. A strip module in the end-cap consists of two strips, an inner strip that will be denoted as Strip 1 and an outer strip that will be denoted as Strip 2. These strips are placed at a stereo angle of 40 with respect to each other.
3. Strip sensors 1 and 2 lie on opposite sides of the same module in η and ϕ .
4. Strips in the end-cap have a variable length, L_{st} , which depends on which ring and row within a petal they are located. These lengths are shown in the table

in Fig. 8.5. Defining the strip length in the r and ϕ coordinates in the end-cap is not as straightforward as it was to define z_{st} and ϕ_{st} in the barrel given the geometry of the sensors in the end-caps.

If we consider in an individual strip in a given ring and row, having length L_{st} , the strip is oriented at a tilt of 20 mRad from the radius of the origin in the transverse plane to the middle of that sensor. The law of cosines can be used to find the radius of the closest edge of the sensors and the farthest edge of the sensor. We can call these r_{min} and r_{max} and take r_{st} as half the difference between these two. ϕ_{strip} is found directly from the length of the strip and the radius of the center of the strip and the 20 mRad rotation between the strip and the radius to the center.

$$r_{sp,0} = \frac{r_{10} + r_{20}}{2}$$

$$r_{max} = \sqrt{r_{sp,0}^2 + \left(\frac{L_{st}}{2}\right)^2 + r_{sp,0} \cdot L_{st} \cdot \cos(0.02)}$$

$$r_{min} = \sqrt{r_{sp,0}^2 + \left(\frac{L_{st}}{2}\right)^2 - r_{sp,0} \cdot L_{st} \cdot \cos(0.02)}$$

Define r_{st} :

$$r_{st} = \frac{r_{max} - r_{min}}{2}$$

$$\phi_{st} = \frac{1}{2} \text{atan}\left(L_{st} \cdot \frac{0.02}{r_{sp,0}}\right)$$

5. Strip 1 and Strip 2 can be expressed as the equations of lines in the $r - \phi$ plane in Eqs. 8.29 and 8.30 and have half lengths in each dimension of r_{st} and ϕ_{st} ,

respectively. This is actually not true, as the equations should be of the form in Eq. 8.31, but we use this linear approximation instead.

$$r_1 - r_{10} = \frac{r_{st}}{\phi_{st}}(\phi_1 - \phi_{10}) \quad (8.29)$$

$$r_2 - r_{20} = -\frac{r_{st}}{\phi_{st}}(\phi_2 - \phi_{20}) \quad (8.30)$$

$$r = \frac{c}{a \cdot \cos(\phi) + b \cdot \sin(\phi)} \quad (8.31)$$

Explorations with the exact relationship between r and ϕ could be performed in future studies.

6. Hit 1 occurs on strip 1. The hit information read out from the detector corresponds to the center of strip 1 at a position with coordinates $(r, \phi, z) = (r_{10}, \phi_{10}, z_{10})$. The true location of the hit on Strip 1 is defined as (r_1, ϕ_1, z_{10}) . ϕ_1 and r_1 are unknown.
7. Hit 2 occurs on strip 2. The hit information read out from the detector corresponds to the center of strip 2 at a position with coordinates $(r, \phi, z) = (r_{20}, \phi_{20}, z_{20})$. The true location of the hit on Strip 2 is defined as (r_2, ϕ_2, z_{20}) . ϕ_2 and r_2 are unknown.
8. Hits 1 and 2 must lie on their respective strips, meaning:
 - $|r_1 - r_{10}| \leq r_{st}$
 - $|\phi_1 - \phi_{10}| \leq \phi_{st}$
 - $|r_2 - r_{20}| \leq r_{st}$
 - $|\phi_2 - \phi_{20}| \leq \phi_{st}$
9. The true positions of hits 1 and 2 satisfy the first Hough Transform equation, where q , p_T , and ϕ_0 are the charge, transverse momentum, and the azimuthal angle of the track containing hits 1 and 2. The variables ϕ_{hit} and r_{hit} indicate positions of a hit along the particle trajectory.

$$\frac{Aq}{p_T} = \frac{\sin(\phi_{hit} - \phi_0)}{r_{hit}}$$

10. The true positions of hits 1 and 2 satisfy the second Hough Transform equation, where q , p_T , z_0 , and η are the charge, transverse momentum, longitudinal impact parameter, and η of the track containing hits 1 and 2. The variables z_{hit} and r_{hit} indicate positions of a hit along the particle trajectory.

$$z_{hit} = z_0 + \frac{p_T}{Aq} a \sin\left(\frac{Aq}{p_T} r_{hit}\right) \sinh(\eta)$$

11. The beamspot of the track must be such that $|z_0| \leq 150$ mm.
12. Only tracks with $|p_T| > 1$ GeV are considered.

8.4.2 Space-point Coordinates in the end-caps

Definition of z_{sp}

The exact positions of the strips in the petals are known in z . fixed by the structure, and so we choose z_{sp} as the center between the two strips. The inner and outer sensors are always separated by a distance of about 12 mm.

$$z_{sp} = \frac{z_{10} + z_{20}}{2}$$

Definition of γ_{sp}

The first interval for γ_{sp} comes from the p_T requirements on the tracks:

$$\gamma_1 \in [-0.0003, 0.0003]$$

Four intervals for γ can be constructed by by applying the equations of both strips to both Hough Transform equations and implementing the constraint on the beamspot.

The ordering of the minimum and maximum of these intervals depends on if a certain condition is met. Let's call this condition C:

$$\frac{\phi_{st}}{r_{st}}(r_{10} + r_{20}) > \phi_{20} - \phi_{10}$$

If Condition C is met: (note the ordering of z_{10} and z_{20})

$$\gamma_{2,min} = -\frac{\phi_{st}}{r_{st}} \cdot \frac{(z_{10} + z_{20} - 300)}{z_{20} - z_{10}} +$$

$$\left[\left(\frac{\phi_{st}}{r_{st}} \right) (r_{10} + r_{20}) - (\phi_{20} - \phi_{10}) \right] \cdot \frac{z_{10} - 150}{(z_{20} - z_{10}) \cdot (r_{10} + r_{st})}$$

$$\gamma_{2,max} = -\frac{\phi_{st}}{r_{st}} \cdot \frac{(z_{10} + z_{20} - 300)}{z_{20} - z_{10}} +$$

$$\left[\left(\frac{\phi_{st}}{r_{st}} \right) (r_{10} + r_{20}) - (\phi_{20} - \phi_{10}) \right] \cdot \frac{z_{10} - 150}{(z_{20} - z_{10}) \cdot (r_{10} - r_{st})}$$

$$\gamma_{3,min} = -\frac{\phi_{st}}{r_{st}} \cdot \frac{(z_{10} + z_{20} - 300)}{z_{20} - z_{10}} +$$

$$\left[\left(\frac{\phi_{st}}{r_{st}} \right) \cdot (r_{10} + r_{20}) - (\phi_{20} - \phi_{10}) \right] \cdot \frac{z_{10} - 150}{(z_{20} - z_{10}) \cdot (r_{20} + r_{st})}$$

$$\gamma_{3,max} = -\frac{\phi_{st}}{r_{st}} \cdot \frac{(z_{10} + z_{20} - 300)}{z_{20} - z_{10}} +$$

$$\left[\left(\frac{\phi_{st}}{r_{st}} \right) \cdot (r_{10} + r_{20}) - (\phi_{20} - \phi_{10}) \right] \cdot \frac{z_{10} - 150}{(z_{20} - z_{10}) \cdot (r_{20} - r_{st})}$$

$$\gamma_{4,min} = -\frac{\phi_{st}}{r_{st}} \cdot \frac{(z_{10} + z_{20} + 300)}{z_{20} - z_{10}} +$$

$$\left[\left(\frac{\phi_{st}}{r_{st}} \right) (r_{10} + r_{20}) - (\phi_{20} - \phi_{10}) \right] \cdot \frac{z_{10} + 150}{(z_{20} - z_{10}) \cdot (r_{10} + r_{st})}$$

$$\begin{aligned}
\gamma_{4,max} &= -\frac{\phi_{st}}{r_{st}} \cdot \frac{(z_{10} + z_{20} + 300)}{z_{20} - z_{10}} + \\
& \left[\left(\frac{\phi_{st}}{r_{st}} \right) (r_{10} + r_{20}) (\phi_{20} - \phi_{10}) \right] \cdot \frac{z_{10} - 150}{(z_{20} - z_{10}) \cdot (r_{10} - r_{st})} \\
\gamma_{5,min} &= -\frac{\phi_{st}}{r_{st}} \cdot \frac{(z_{10} + z_{20} + 300)}{z_{20} - z_{10}} + \\
& \left[\left(\frac{\phi_{st}}{r_{st}} \right) \cdot (r_{10} + r_{20}) - (\phi_{20} - \phi_{10}) \right] \cdot \frac{z_{10} + 150}{(z_{20} - z_{10}) \cdot (r_{20} + r_{st})} \\
\gamma_{5,max} &= -\frac{\phi_{st}}{r_{st}} \cdot \frac{(z_{10} + z_{20} + 300)}{z_{20} - z_{10}} + \\
& \left[\left(\frac{\phi_{st}}{r_{st}} \right) \cdot (r_{10} + r_{20}) - (\phi_{20} - \phi_{10}) \right] \cdot \frac{z_{10} + 150}{(z_{20} - z_{10}) \cdot (r_{20} - r_{st})}
\end{aligned}$$

If Condition C is not satisfied, these expressions for γ_2 , γ_3 , γ_4 , and γ_5 are identical except that the minimum and maximum values are swapped.

The final interval for γ is taken as the intersection of the five intervals:

$$\gamma = [\gamma_{min}, \gamma_{max}] = \gamma_1 \cap \gamma_2 \cap \gamma_3 \cap \gamma_4 \cap \gamma_5 \quad (8.32)$$

The final value of γ assigned for the space-point is given as:

$$\gamma_{sp} = \frac{\gamma_{min} + \gamma_{max}}{2} \quad (8.33)$$

When the intervals themselves are printed, it is always true that if any weak constraint is placed on γ that is tighter than the nominal one, it is one-sided.

The “size” of the space-point in this coordinate is in Eq. 8.34 and the distribution for all space-points constructed from the simulation is shown in Fig. 8.11. The peak at $\Delta\gamma_{sp} = 0.0003$ indicates that for a little less than half the space-points, we were unable to constrain γ better than the nominal constraint. This is due to the small stereo angle between the sensors, which limits the momentum resolution.

$$\Delta\gamma_{sp} = \frac{\gamma_{max} - \gamma_{min}}{2} \quad (8.34)$$

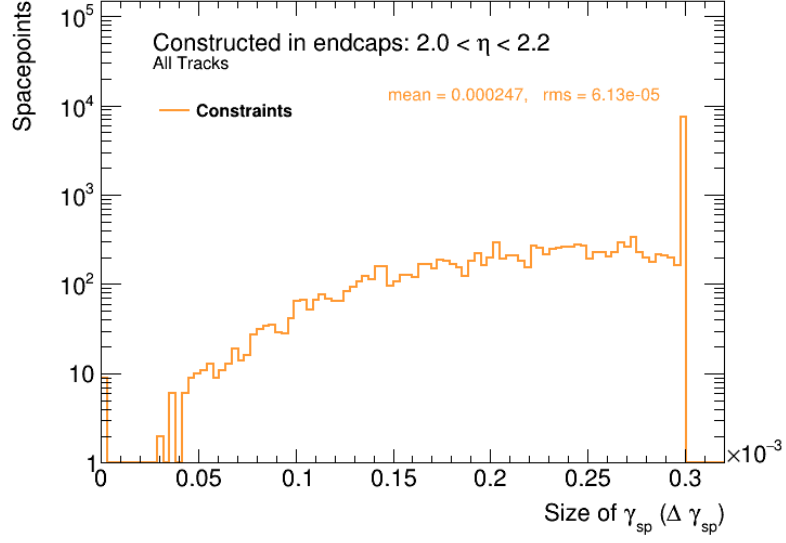


Figure 8.11: Distribution of the “size” of γ_{sp} , $\Delta\gamma_{sp}$.

Definition of r_{sp}

The interval r_1 is found by combining the second Hough Transform equation with the requirement that the hits be on the strips and given the specific geometry of the strips.

$$r_{1,max} = \frac{(r_{10} + r_{st}) \cdot (z_{10} + z_{20})}{2 \cdot (z_{20} + 150)} + 150 \cdot \frac{r_{10} + r_{st}}{z_{20} + 150}$$

$$r_{1,min} = \frac{(r_{10} - r_{st}) \cdot (z_{10} + z_{20})}{2 \cdot (z_{10} + 150)} + 150 \cdot \frac{r_{10} - r_{st}}{z_{10} + 150}$$

The remaining intervals are found by incorporating the first Hough Transform equation and uses the interval we previously found for γ_{sp} .

$$r_{2,max} = \frac{1}{2} \cdot (z_{10} + z_{20} - 300) \cdot \frac{[(\frac{\phi_{st}}{r_{st}})(r_{10} + r_{20}) - (\phi_{20} - \phi_{10})]}{(\frac{\phi_{st}}{r_{st}})(z_{10} + z_{20} - 300) + \gamma_{min} \cdot (z_{20} - z_{10})}$$

$$r_{2,max} = \frac{1}{2} \cdot (z_{10} + z_{20} - 300) \cdot \frac{[(\frac{\phi_{st}}{r_{st}})(r_{10} + r_{20}) - (\phi_{20} - \phi_{10})]}{(\frac{\phi_{st}}{r_{st}})(z_{10} + z_{20} - 300) + \gamma_{max} \cdot (z_{20} - z_{10})}$$

$$r_{3,max} = (z_{10} + z_{20} + 300) \cdot \frac{[(\frac{\phi_{st}}{r_{st}})(r_{10} + r_{20}) - (\phi_{20} - \phi_{10})]}{(\frac{\phi_{st}}{r_{st}})(z_{10} + z_{20} + 300) + \gamma_{min} \cdot (z_{20} - z_{10})}$$

$$r_{3,min} = (z_{10} + z_{20} + 300) \cdot \frac{[(\frac{\phi_{st}}{r_{st}})(r_{10} + r_{20}) - (\phi_{20} - \phi_{10})]}{(\frac{\phi_{st}}{r_{st}})(z_{10} + z_{20} + 300) + \gamma_{max} \cdot (z_{20} - z_{10})}$$

The final interval for r_{sp} is taken as the intersection of the three intervals:

$$r_{sp} = [r_{min}, r_{max}] = r_1 \cap r_2 \cap r_3 \quad (8.35)$$

The final value of r_{sp} assigned for the space-point is given as:

$$r_{sp} = \frac{r_{min} + r_{max}}{2} \quad (8.36)$$

The “size” of the space-point in this coordinate is

$$\Delta r_{sp} = \frac{r_{max} - r_{min}}{2} \quad (8.37)$$

Definition of ϕ_{sp}

The interval ϕ_1 comes directly from requiring the space-point be on the strips.

$$\phi_{1,min} = -\phi_{st} + \frac{\phi_{10} + \phi_{20}}{2}$$

$$\phi_{1,max} = \phi_{st} + \frac{\phi_{10} + \phi_{20}}{2}$$

The second interval, ϕ_2 , is an exact calculation of ϕ_{sp} given the interval for r_{sp} that was previously found.

$$\begin{aligned} \phi_{2,min} &= \frac{(\phi_{10} + \phi_{20})}{2} + \frac{1}{2} \frac{\phi_{st}}{r_{st}} \cdot (r_{10} - r_{20}) \\ &+ \frac{\phi_{st}}{r_{st}} \cdot (z_{20} - z_{10}) \cdot \frac{r_{sp,min}}{z_{10} + z_{20} + 300} \end{aligned}$$

$$\begin{aligned} \phi_{2,max} &= \frac{(\phi_{10} + \phi_{20})}{2} + \frac{1}{2} \frac{\phi_{st}}{r_{st}} \cdot (r_{10} - r_{20}) \\ &+ \frac{\phi_{st}}{r_{st}} \cdot (z_{20} - z_{10}) \cdot \frac{r_{sp,max}}{z_{10} + z_{20} - 300} \end{aligned}$$

8.4.3 Configuration for Simulation in the end-caps

The parameters of the simulation in the end-caps are:

- File with 10k simulated single muon events with no pile-up events
- The simulation uses version 22-02-00 of the ITk layout geometry
- Eta region: $2.0 < \eta < 2.2$
- Phi region: $0.3 < \phi < 0.5$

- Space-points constructed in end-cap discs 2, 3, 4, and 5 (given this range of η)

8.4.4 Performance Results for Space-points in the end-caps

Residual Definitions

The expected locations of the hit were calculated using the Hough Transform and the truth track parameters, defining $z_{sp} = \frac{z_{10} + z_{20}}{2}$. The expression for ϕ_{exp} uses a correction to account for tracks having a non-negligible transverse impact parameter d_0

$$\phi_{exp} = \phi_0 - a \sin\left(\frac{r_{exp}^2 + (R - d_0)^2 - R^2}{2 \cdot r_{exp} \cdot (R - d_0)}\right) \quad (8.38)$$

$$r_{exp} = \frac{p_T}{Aq} \sin\left(\frac{Aq}{p_T} \frac{z - z_0}{\sinh(\eta)}\right) \quad (8.39)$$

Since these space-points are constructed from different rings and rows within the petals that have different strip lengths, to make a universal comparison of the residuals, a fractional residual is defined where the residual in r or ϕ is normalized by the strip length in r or ϕ for the particular sensor.

The residuals for space-points constructed in the end-caps are defined in Eqs. 8.40 and 8.41.

$$\phi_{resid} = \phi_{sp} - \phi_{exp} \quad (8.40)$$

$$r_{resid} = r_{sp} - r_{exp} \quad (8.41)$$

Residuals for ϕ_{sp}

Fig. 8.12 shows the residual between the calculated ϕ coordinate of the constructed space-point, ϕ_{sp} , and the expected ϕ_{exp} location of a generated track from a single muon evaluated at z_{sp} for space-points constructed all end-cap disks within the region $2.0 < \eta < 2.2$ in the end-cap.

There is no improvement in the resolution of measuring the ϕ_{sp} coordinate by using either method due to scattering. Scattering limits any ability to improve the fractional ϕ_{sp} residual using this method.

It is important to notice that there is no loss of efficiency with the constraints space-point construction method in this region of the end-cap

Residuals for r_{sp}

Given the success of the constraints method at improving the resolution of the z space-point coordinate of space-points in the barrel, we would expect similar performance in the end-caps. The calculation of r_{sp} depends on the strip geometry but moreso on the constraint on gamma, which was shown to be much less useful than when it was found for the barrel. We hypothesize that the limiting factor for a stronger constraint on γ is the small stereo angle between the strips.

Fig. 8.13 a shows the fractional r_{sp} residual for all space-points reconstructed in the region $2.0 < \eta < 2.2$ for tracks with $p_T > 1GeV$. As a result, the fractional r_{sp} residual is only reduced by 12%. This indicates we will be significantly limited in our ability to resolve p_T of reconstructed tracks. The positive residual indicates that the field is getting weaker as we move further away from the barrel.

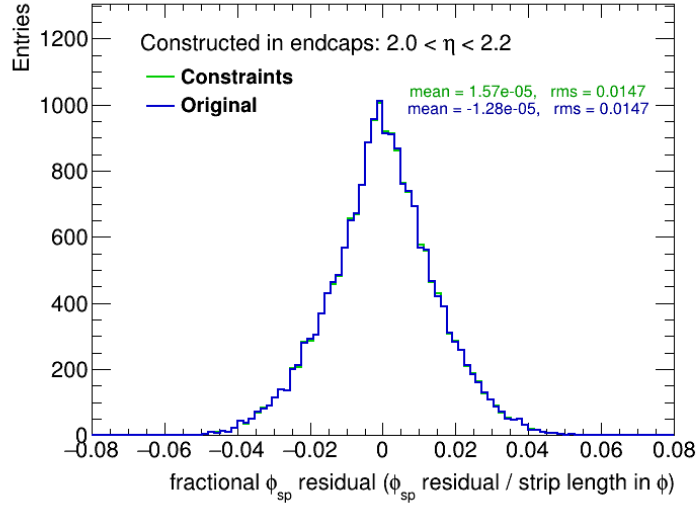


Figure 8.12: Comparison of ϕ_{sp} residuals found using both space-point construction methods to construct space-points in the region $2.0 < \eta < 2.2$ in the end-caps.

Fig. 8.14 shows this same distribution for tracks with $p_T > 10$ GeV. As expected, higher p_T tracks have better resolution, because lower p_T tracks experience more scattering.

Figure 8.15 shows a two dimensional histogram comparing the r_{sp} residual against the truth p_T of the track. Residuals are better for high p_T tracks and the sign of the curvature affects the sign of the residual. The curvature of the track affects in which direction the calculated value of r_{sp} is offset from the true value.

The non-uniformity of the B field in the end-caps

The layer discs in the end-caps are spaced at increasing z . Hits occurring in the region $2.0 < \eta < 2.2$ occur on Layer discs 2, 3, and 4. Figure 8.16 show the fractional r_{sp} residuals for constraints space-points constructed from tracks with $p_T < 5$ GeV, separated by layer discs they were constructed in. It can be seen that as the z location of the disc layer increases, the mean r_{sp} residual increases, providing a verification that the B field is decreasing with increasing z outside of the barrel ITk region.

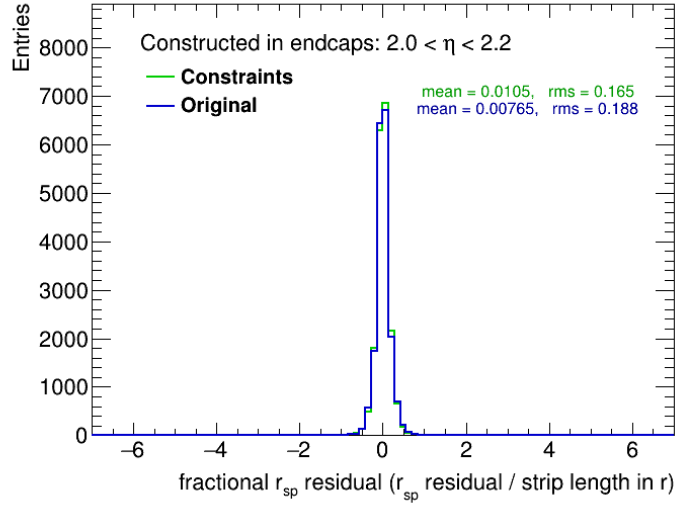


Figure 8.13: Fractional r_{sp} residuals for space-points reconstructed using the constraints method in the end-cap region between $2.0 < \eta < 2.2$ for tracks with $p_T > 1\text{GeV}$.

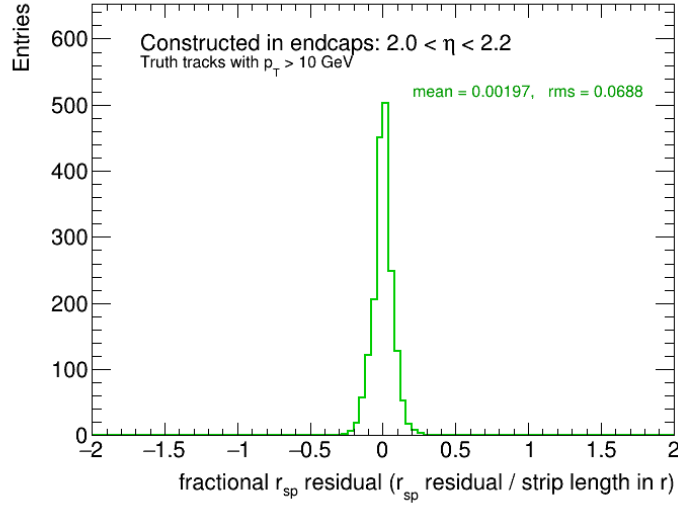


Figure 8.14: Fractional r_{sp} residuals for space-points reconstructed using the constraints method in the end-cap region between $2.0 < \eta < 2.2$ for high p_T tracks with $p_T > 10 \text{ GeV}$.

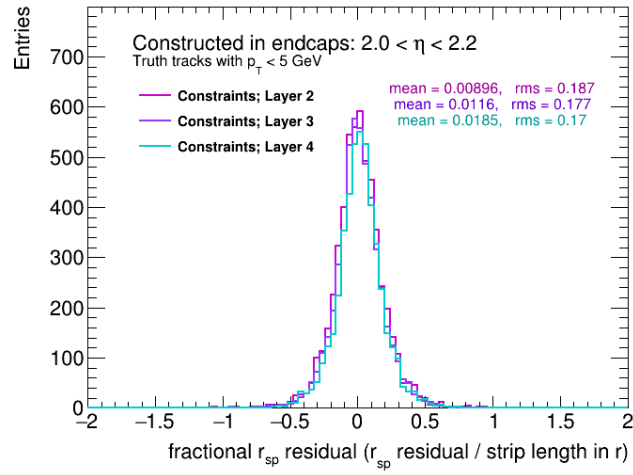


Figure 8.16: A comparison of the fractional r_{sp} residuals for space-points separated by different layer discs in the end-caps.

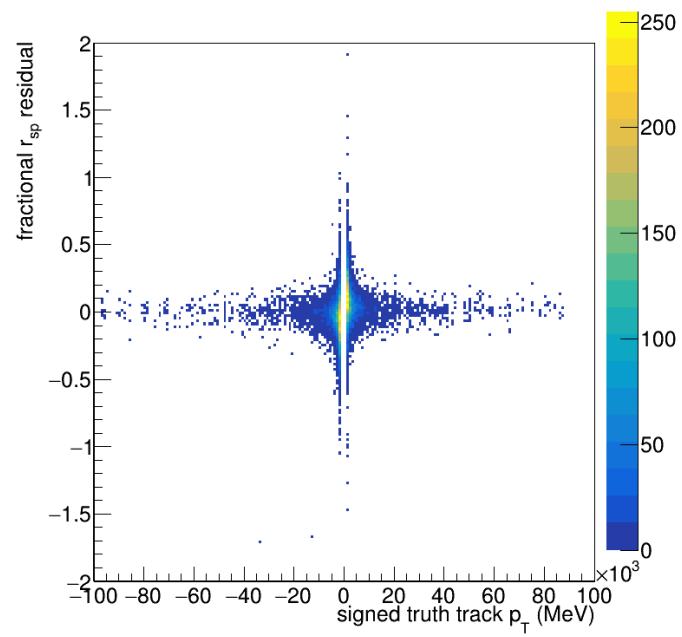


Figure 8.15: Two dimensional histogram of the fractional r_{sp} residual for space-points constructed in the end-cap as a function of the truth track p_T .

Chapter 9: A second-stage (η, z_0) Hough Transform filter for pattern recognition

Track reconstruction from hit clusters in the various detector layers is a combinatorial problem. For example, consider two charged particles travelling through a three layer detector in Figure 9.1. If each layer detects only one hit cluster from each particle, there are $2^3 = 8$ possible hit combinations, however, only two of these combinations are consistent with charged particle trajectories. This means that the number of possible hit combinations grows as a power law with the number of charged particles. Exploring all such combinations for the condition that $\mu = 200$ pp collisions is computationally intensive. Fig. 9.2 is an image of all tracks in the ITk detector that were produced when $\mu = 200$ pile-up collisions were simulated.

This chapter investigates using a two-stage Hough Transform algorithm to reduce the computational difficulty of identifying tracks. Software simulation is used to evaluate the performance of this algorithm. It is then implemented on an FPGA and the resource utilization is evaluated. Using FPGAs is highly advantageous because the pattern recognition algorithm can be simply implemented and parallelized. A Xilinx

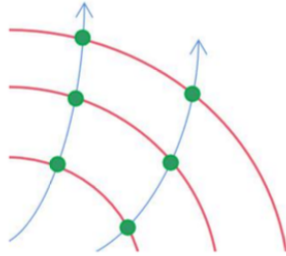


Figure 9.1: A depiction of two charged particle trajectories (blue) interacting with 3 layers of a detector (red) and depositing hits. From [43].

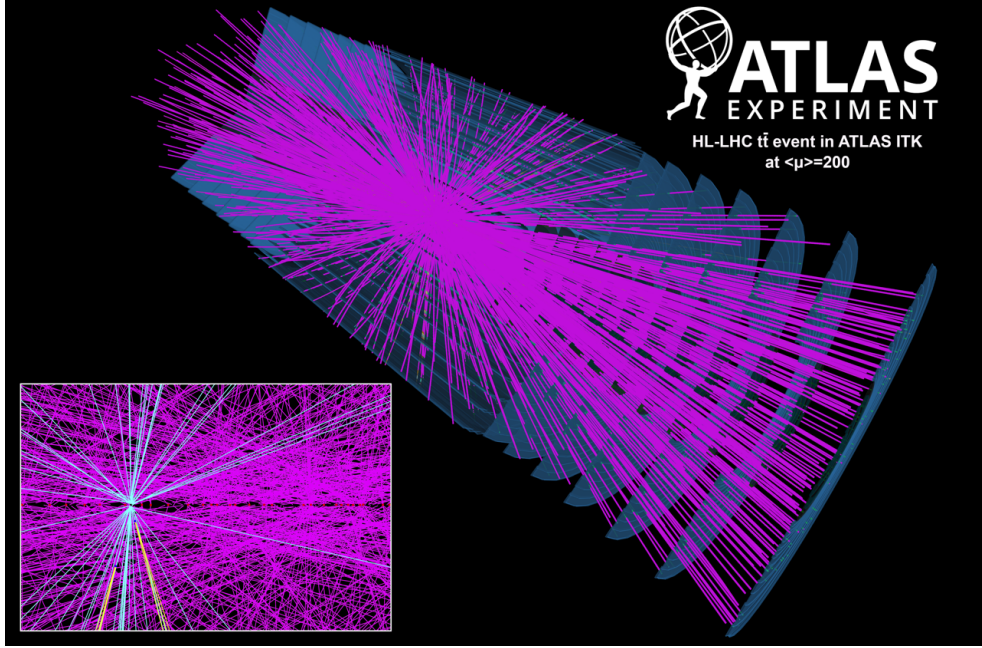


Figure 9.2: The baseline layout of the proposed ITk inner detector with the track trajectories from $\mu = 200$ simulated pile-up events. From [44].

Alveo U250 FPGA board is used for the prototype design. Additional algorithms are necessary in the final track reconstruction chain to calculate the track parameters and remove duplicate tracks. Those procedures are not discussed here.

9.1 The Hough Transform Equations

Within the ITk barrel region, the central solenoid provides a uniform axial 2T magnetic field along the beamline. A charged particle in a uniform solenoidal field will follow a trajectory described by the first Hough Transform equation (Eq. 9.1), derived in Appendix 1 assuming the absence of scattering and energy losses. This equation makes the assumption that $d_0 = 0$, but is considered a valid approximation for $|d_0| < 2$ mm.

$$\frac{Aq}{p_T} = \frac{\sin(\phi_0 - \phi)}{r} \quad (9.1)$$

In this equation, p_T is the charged particle's momentum (in $\text{kg}\cdot\text{m}/\text{s}$), q is the charge of the particle (in Coulombs), and $A = 3 \times 10^{-4} \text{GeV} \cdot \text{mm}^{-1} \cdot \text{C}^{-1}$ is a unity constant for a magnetic field with a strength of $B = 2 \text{ T}$. The momentum measurement of a charged particle track is degraded by at most roughly 10% in the high-rapidity region ($\eta > 1.6$). If the difference $\phi_0 - \phi$ is small, Eq. 9.1 is reduced to Eq. 9.2.

$$\frac{Aq}{p_T} = \frac{\phi_0 - \phi}{r} \quad (9.2)$$

The charged particle trajectory also obeys the second Hough Transform equation (Eq. 9.3), which makes no assumption about the value of d_0 .

$$z = z_0 + \frac{p_T}{Aq} \text{asin}\left(\frac{Aq}{p_T} r\right) \sinh(\eta) \quad (9.3)$$

By approximating $\text{asin}(x) \approx x$, Eq. 9.3 becomes Eq. 9.4.

$$z = z_0 + r \sinh(\eta) \quad (9.4)$$

An expression for ϕ is obtained when d_0 is not neglected (Eq. 9.5), where R is the radius of curvature of the track.

$$\phi = -\text{asin}\left(\frac{r^2 + (R - d_0)^2 - R^2}{2 \cdot r \cdot (R - d_0)}\right) + \phi_0 \quad (9.5)$$

9.2 The Hough Transform

The Hough Transform is a mathematical approach to minimization problems and to solving equations. It extracts features from images, making it a popular method for digital image processing and edge detection. It is employed by the Event Filter Tracking group as a pattern recognition tool to identify hits in the tracker that are consistent with being from the same charged particle trajectory.

The left figure of Fig. 9.3 shows the x-y coordinate space containing one quadrant of the transverse plane of a four-layer tracker with hit clusters along a signal track, shown as solid circles, and other hit clusters not associated with the track, depicted as crosses. ϕ_0 is the azimuthal angle of the track. Each cluster in the left figure corresponds to one line in the accumulator defined in a Hough Space parameterized by the track parameters $\frac{Aq}{p_T}$ and ϕ_0 . The line gives all possible values of $\frac{Aq}{p_T}$ and

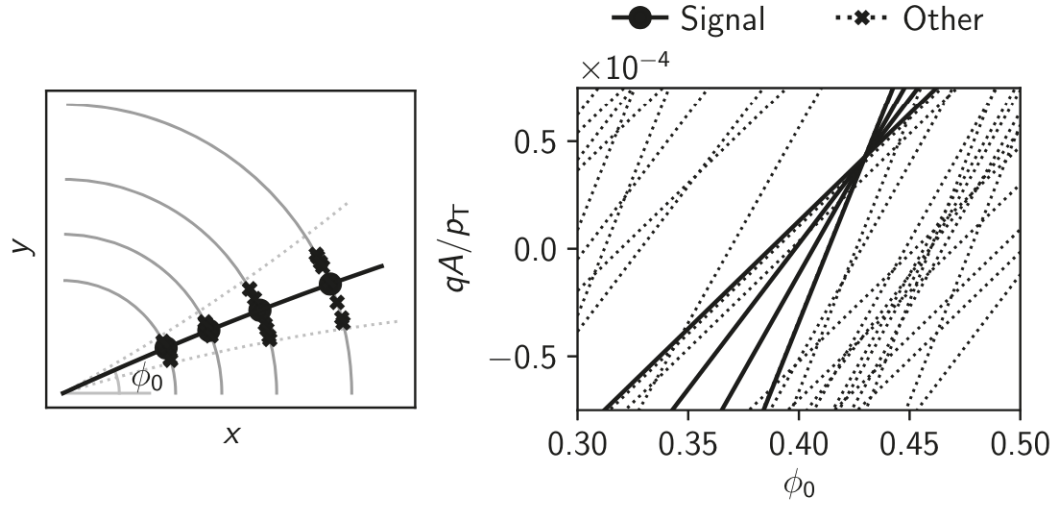


Figure 9.3: (Left) Four hit clusters along a track (solid dots) and un-associated hit clusters (crosses). (Right) The hits are transformed into lines in Hough Space defined by $\frac{Aq}{p_T}$ and ϕ_0 . From [45].

ϕ_0 that are compatible with track passing through the hit cluster. The solid lines in the accumulator corresponding to the hit clusters from the signal track intersect at one point in the accumulator and the intersection values of the track parameters here correspond to the track parameters that the signal track has. The process of transforming hit clusters in coordinate space into linear features in Hough space is known as the Hough Transform.

9.3 A first-stage $(q/p_T, \phi)$ Hough Transform for pattern recognition

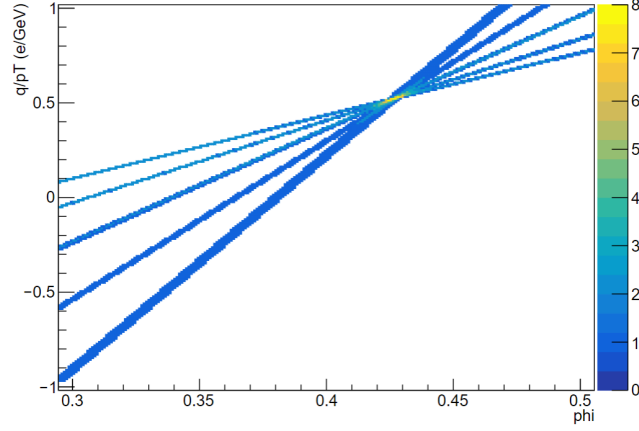
A two-dimensional Hough Transform in $(q/p_T, \phi)$ space is developed to identify and form groups of hit clusters from the outermost pixel layer and 7 of the strip layers that are consistent with a track candidate. Studies done since this project have included all 8 strip layers. This implementation is part of a larger “outside-in” tracking approach because it seeds the track fit with roads identified using hits that are primarily from the strip detectors. In the next stage, the track fit will

extrapolate to all pixel layers, including those hits into the fit. Using this first-stage Hough Transform wouldn't be appropriate if used in an "inside-out" approach that uses all of the pixel detectors because at the distances the pixel detectors are from the beampipe, the non-zero d_0 becomes relevant.

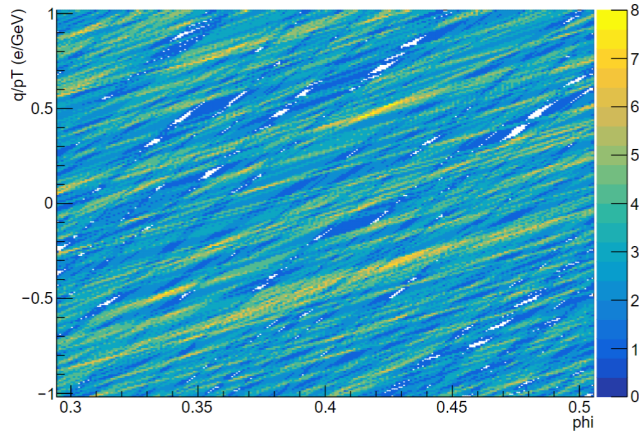
Each hit is deposited in the two-dimensional histogram called an accumulator according to the track parameters q/p_T and ϕ that are consistent with a charged particle trajectory containing that hit. One hit can contribute to multiple cells in the accumulator. All ITk hits from the 8 layers within a single event are deposited into the accumulator. A simulation is performed in a central region of the detector, within the barrel. 750,000 single muon events are simulated and propagated through the ITk detector. Our pattern recognition algorithm is applied to this simulated data to obtain measures of the performance of this algorithm.

Figure 9.4a) shows the accumulator generated for a simulation of a single muon with $q/p_T = 0.52$ and $\phi_0 = 0.43$. The number of bins on each axis can be varied. The color palette indicates how many hits are in each accumulator bin. We can distinctly see the hits forming lines in the $(q/p_T, \phi_0)$ space on the left. Accumulator bins with hits from at least 7 ITk layers are considered track candidates, called roads. In Figure 9.4 a), we can see that multiple accumulator bins satisfy this criteria, generating multiple possible roads for a muon.

Figure 9.4b) is the accumulator image for an event containing a single muon in the presence of a $t\bar{t}$ interaction and $\mu = 200$ pile-up collisions. This scenario is a more realistic approximation of what we will measure during the conditions of Run 4. Each layer contains a multitude of hits from the pile-up and $t\bar{t}$ interactions. This two-dimensional Hough Transform is vulnerable to identifying roads from the random overlay of hits from different particles in the same bin. Exploring all such combinations at later stages in the track reconstruction chain is computationally expensive and removing some of these erroneous track candidates is the main motivation for a second-stage (η, z_0) Hough Transform filter. For each road identified by the first-stage HT, the filter will deposit each hit one-by-one into an (η, z_0) accumulator. This way, we can evaluate if the set of hits that comprise a road are consistent with being from a single track in the (η, z_0) plane.



(a) A single muon without pile-up



(b) A single muon with $\mu = 200$ pile-up events

Figure 9.4: Hough Transform accumulator images in $(q/p_T, \phi)$ Hough space after application of the first-stage Hough Transform for hits from a single muon event with a truth track $q/p_T = 0.52$ and $\phi_0 = 0.43$ (a) without pile-up and (b) with pile-up. From [39].

9.4 A second-stage (η, z_0) Hough Transform for filtering roads

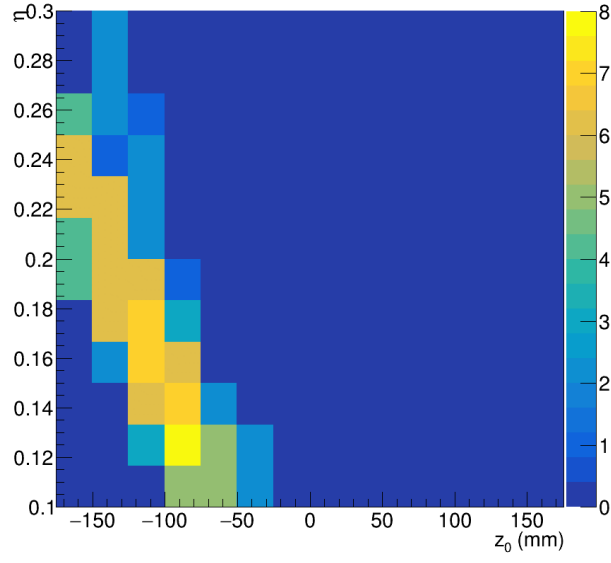
Dr. Sasha Paramonov, a physicist at Argonne National Laboratory, came up with the idea to use a subsequent “second-stage” Hough Transform in (η, z_0) coordinate space to remove some of the erroneous track candidates identified by the first-stage $(q/p_T, \phi)$ Hough Transform. This algorithm is a “filter” in the sense that it processes roads identified from the 1st Hough Transform and for each road, deposits all of the

hits into an (η, z_0) accumulator. The η and z_0 track parameters corresponding to the hits are calculated using the second Hough Transform equation given in Eq. 9.4.

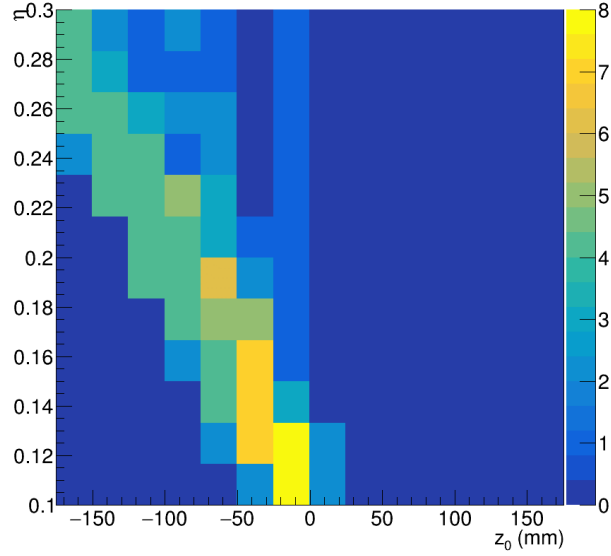
The accumulator is designed with $\eta \in [0.1, 0.3]$ because we test the performance of the Hough Transform initially on the region of the detector using a single muon sample with $\eta \in [0.1, 0.3]$ and $\phi \in [0.3, 0.5]$. The accumulator is designed with $z_0 \in [-175, 175]$ mm, driven by the requirement that $|z_0| < 150$ mm with 25 mm of padding added on each side. The number of bins in z_0 is 14 and this is driven by the size of the strip sensors (24.1 mm in layers 0 and 1 and 48.2 mm in layers 2 and 3). The number of bins in η is also 14 and this is based on the bin size in z divided by the radius of the detector. Increasing the number of bins would reduce the number of possible roads found and give a better estimate of the true values of the track parameters. We simulate this by adding our filter to the tracking algorithm [304].

Figure 9.5 shows two examples of second-stage (η, z_0) accumulator images produced for two different roads outputted by the $(q/p_T, \phi)$ Hough Transform, each from a separate muon. As indicated by the color palette, the initial roads do pass the filter, meaning the hits from those roads are compatible in (η, z_0) space with coming from the same track.

Figures 9.6 a), b), and c) show (η, z_0) accumulators for roads outputted by the first Hough Transform for events containing a single muon, a $t\bar{t}$ interaction, and $\mu = 200$ pile-up collisions. It is evident that there is a lot of diffuse activity in these events with multiple pp collisions because these combination of hits from the roads considered do not pass the (η, z_0) HT filter, indicating they likely do not correspond to a track candidate. Figure 9.6 d) shows an accumulator for a road found by the first-stage HT in an event of $\mu = 200$ pile-up events. The diffuse activity overlaps in such a way that there is an accumulator bin where at least seven hits are found, indicating the road passes the filter and will be considered by the next stage of the track reconstruction chain.



(a)



(b)

Figure 9.5: Hough Transform accumulator images in (η, z_0) Hough space after application of the second-stage filter to a single road from two separate single muon events containing no pile-up. Each road passes the filter.

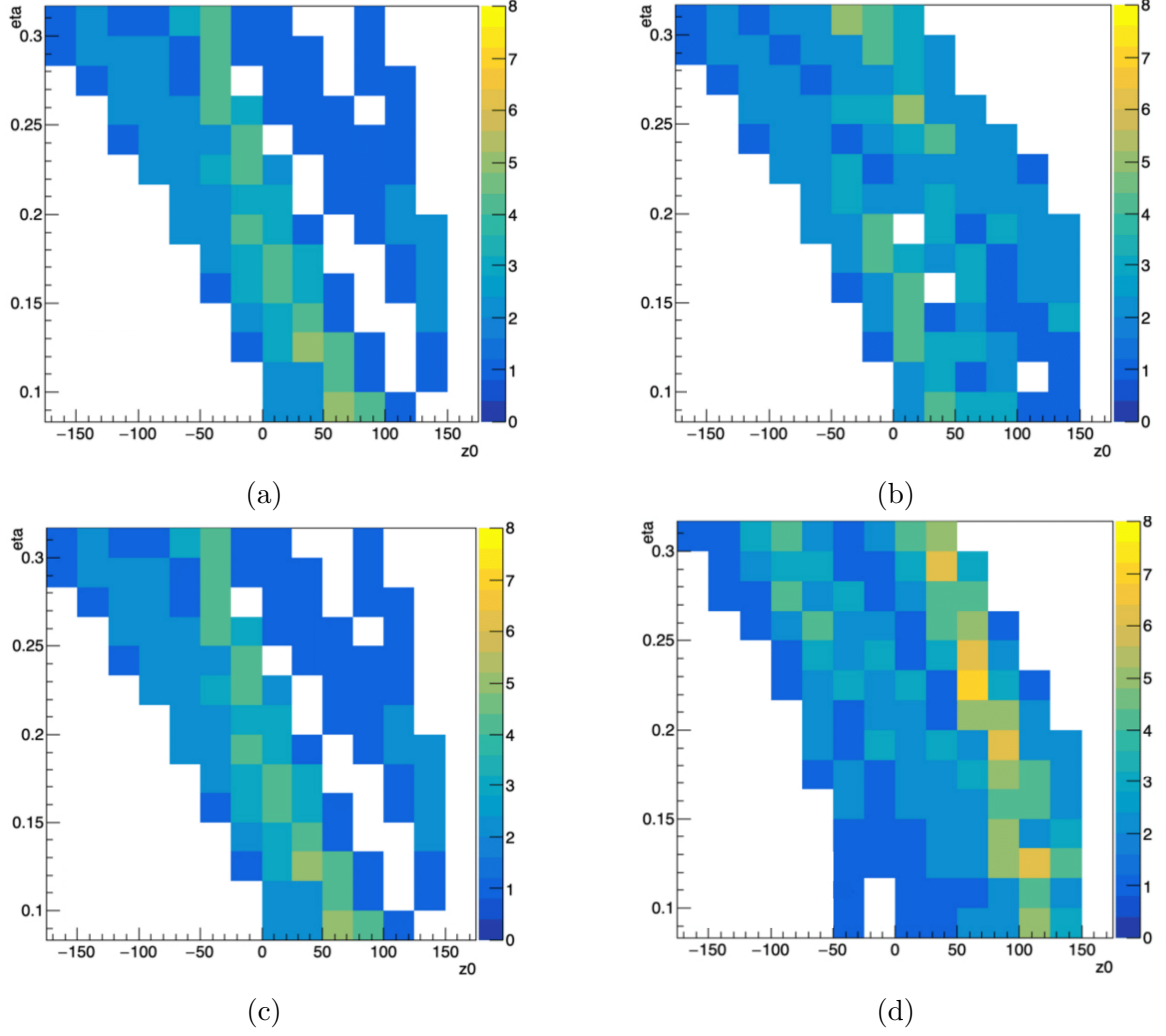


Figure 9.6: Hough Transform accumulator images in (η, z_0) Hough space after application of the second-stage filter to a single road from four separate events containing a single muon, a $t\bar{t}$ interaction, and $\mu = 200$ pile-up collisions. Roads processed in accumulators in (a), (b), and (c) pass the filter, while the road in (d) does not pass the required threshold and will no longer be considered a candidate to be processed by the next stage in the track reconstruction chain.

9.5 Performance of the (η, z_0) Hough Transform

Two performance measures are efficiency and rejection. The efficiency of the algorithm quantifies its ability to correctly identify roads in events that contain tracks

from charged particle originating from the hard scatter. If N_{total} is the number of single muon events simulated that meet the selection criteria and N_{pass} are the number of single muon events that find roads after the (η, z_0) filter is applied, the efficiency is given as:

$$\epsilon = \frac{N_{pass}}{N_{total}} \quad (9.6)$$

Rejection quantifies the ability of the algorithm to correctly determine that a collection of hits that are not actually from a real track trajectory but were identified as a road by the first Hough Transform are not consistent with being from the same track trajectory once being passed through the second-stage filter. It is critical for our pattern recognition algorithms implemented in EF Tracking to maintain efficiency nearly as good as the offline algorithms to be viable to be used in the trigger.

The performance is measured for single muons in this specific region because they leave the cleanest signature in the detector. After studying muons, we should explore the performance of the first and second-stage HT for electrons and pions. The efficiency of finding roads is expected to be slightly worse for electrons because they have more material interactions (bremsstrahlung) than muons. The performance of both Hough Transform algorithms is expected to be substantially worse for pions, which will be a dominant source of charged particle tracks from hadronizing particles. Pions have substantially more interactions with the detector material, losing more p_T . This means the Hough Transform equations will not accurately describe the trajectory of those particles through the detector.

9.5.1 Efficiency

The baseline efficiency of the 1st stage H.T. is found by evaluating how many of the total single muon events find at least one road. This can be extracted from a plot of the number of roads found per event. Figure 9.7 shows a histogram of the road multiplicity per event for 750,000 events processed with the first-stage HT (in red) and after the 2nd stage HT (blue). The histograms show 658,961 entries, which is fewer than the 750,000 events processed because some events fail to satisfy the event selection applied at the beginning of the track reconstruction chain.

The first bin in this figure indicates the number of events for which no road was found by the first-stage (red) and after the second-stage (blue). Entries in the bin

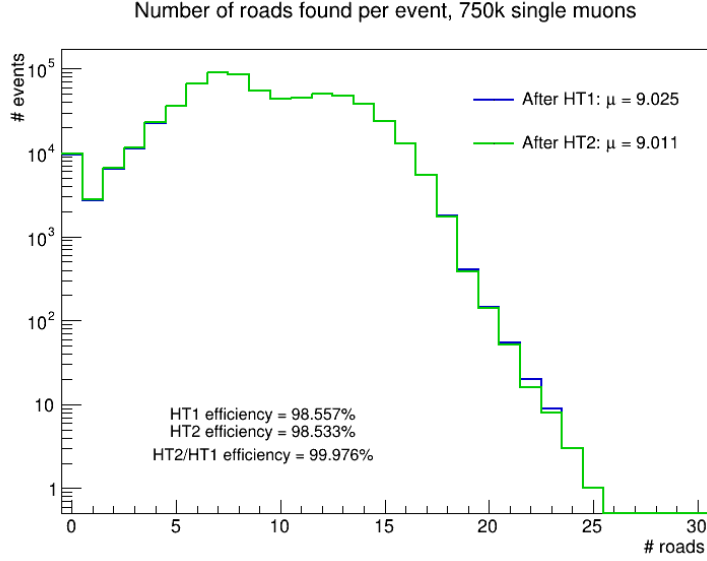


Figure 9.7: The number of roads found per event after the first (blue) and second (green) stage Hough Transforms in a sample of 750,000 single muon events without pile-up. Within the $(q/p_T, \phi_0)$.

corresponding to zero roads found are interpreted as lost efficiency. Similar to the $(q/p_T, \phi)$ Hough Transform, adjacent bins in the (η, z_0) accumulator can contain the same hits and pass the threshold, resulting in events having multiple roads. This is not ideal as it means the track fitting stage will have to evaluate all those combinations.

At least one road was found in 98.557% of events passing the initial selection criteria. Consequently there is a 1.443% loss of efficiency. 98.533% of events are found to have roads after applying the second-stage (η, z_0) HT filter to events containing roads found by the first HT. This efficiency loss is negligible.

Efficiency can also be studied as a function of all five track parameters. Looking at these plots is more informative because we may identify specific hypotheses as to the causes for the loss of efficiency. Figure 9.8 shows the efficiency as a function of truth track p_T for all single muons. The sample of events was generated with a uniform distribution in curvature, resulting in larger error bars on the efficiency measurements for higher p_T muons. Figure 9.8a shows this distribution for a p_T range of 1 GeV to 10 GeV, rebinned into 1 GeV bins.

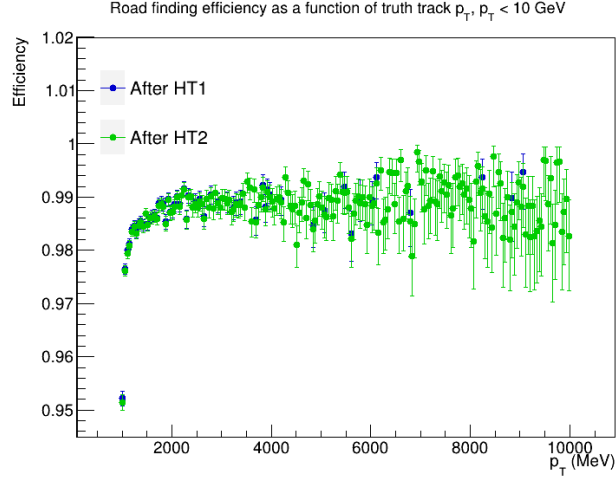
Starting from the right with the highest p_T muons, as we look at events with decreasing values of muon p_T , we see the efficiency remains flat, up until very low p_T . The minimum cut on track p_T is 1 GeV. These tracks have a high curvature and lose a higher fraction of their momentum when they interact with the tracking detector elements. This makes identifying track candidates more difficult and results in lower efficiency.

Figure 9.9 shows the road finding efficiency as a function of a) track d_0 , b) track ϕ_0 , c) track η , and d) track z_0 . The efficiency as a function of d_0 is roughly symmetric about $d_0 = 0$ and peaks there, where tracks have zero transverse displacement. The first HT equation used in this road finding process was derived assuming $d_0 = 0$, which is not true for all muons, and is certainly not true for objects like b-jets, taus, and other objects with displaced vertices that are present in real collision data. It is indeed seen that the road finding efficiency decreases with increasing d_0 . In the plot of efficiency as a function of ϕ_0 , the uniformly sized errors correspond to the fact that the distribution of the track ϕ_0 in simulation was uniform between $\phi_0 \in [0.3, 0.5]$. Only at the very edges do we see efficiency loss. This is considered an “edge effect” and is expected. The plot of efficiency as a function of η contains a significant global trend where as η increases, the road finding efficiency increases, though it does not do so monotonically. A similar observation is made for the efficiency as a function of z_0 .

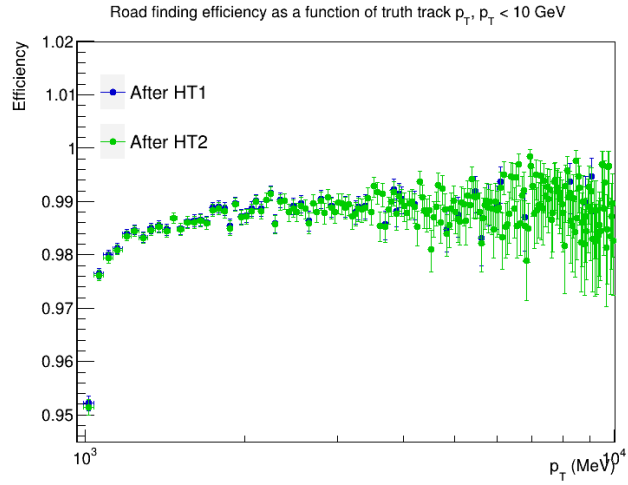
To try and better understand efficiency loss with respect to η and z_0 and see if there are any correlations in the behavior, a two dimensional efficiency plot is made in Fig. 9.10. If N_i is the total number of events with truth track η and ϕ that fall in bin i and $N_{roads,i}$ is the number of events in bin i that contain roads, the efficiency evaluated in the i – th bin in the η/z_0 accumulator is calculated as:

$$\epsilon_i = \frac{N_{roads,i}}{N_i} \quad (9.7)$$

The diffuse distribution of efficiency loss in Fig. 9.10 is likely a loss of low p_T tracks, but there exist clear linear features in this plot due to an unidentified cause. Linear features are observed and given the range of η considered here, linear features would also be observed in a plot of z_0 vs. $\sinh(\eta)$. By eye, there appear linear features with at least 4 different negative slopes. Linear features with the same slope are separated by about 100mm in z_0 .



(a)



(b)

Figure 9.8: Comparison of road find efficiency as a function of truth track p_T for both stages of the Hough Transform (a) for $1 < p_T < 50$ GeV and (b) for $1 < p_T < 10$.

Inefficiencies are characterized by events containing no roads, despite coming from the truth track of a single muon, so Fig. 9.11 shows the (η, z_0) accumulators for (a) all events that don't contain roads found by the 1st HT, (b) only events with $p_T \leq 2$ GeV that don't contain roads found by the 1st HT, and (c) only events with $p_T > 2$ GeV that don't contain roads found by the 1st HT. The features are sharper at higher p_T , but exist at low p_T as well. In the low p_T plot, there exists a lot of diffuse activity

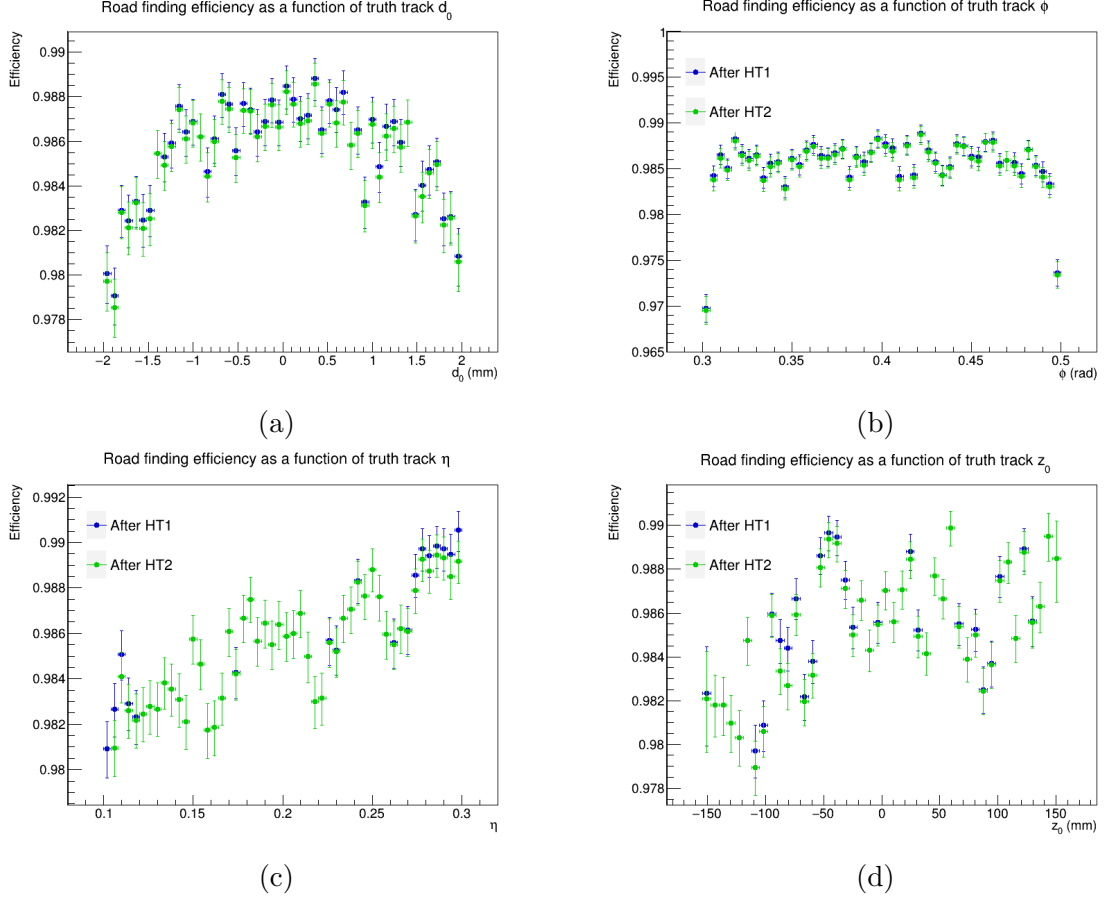


Figure 9.9: Comparison of road find efficiency as a function of truth track (a) d_0 , (b) ϕ , (c) η , and (d) z_0 for both stages of the Hough Transform

that may just represent lost efficiency that was expected for low p_T tracks. Eq. 9.4 states that z_0 has a roughly linear dependence on η , with a negative slope equal to the radius along the track trajectory. The 4 different slopes in Fig. 9.9d could be determined from linear fits and may correspond to the radii of each of the 4 strip layers. The author suggests whatever effect causes these inefficiencies could be due to the geometry of the ITk detector. It is present at all p_T and is another significant contribution to efficiency loss in addition to the loss of tracks at low p_T .

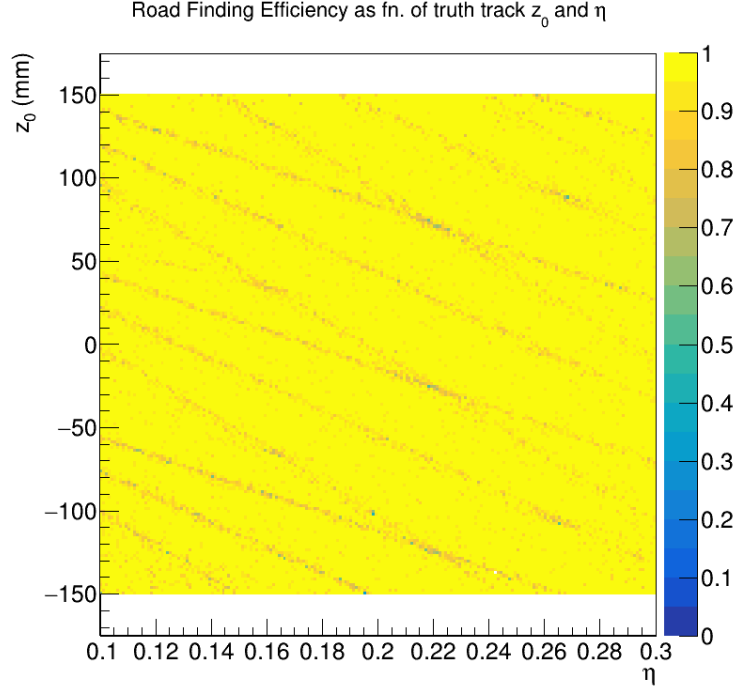


Figure 9.10: Road finding efficiency of the first-stage $(q/p_T, \phi)$ Hough Transform as a function of η and z_0 . The color scale indicates the efficiency for events having truth track η and z_0 within a particular bin.

9.5.2 Rejection

The presence of overlapping collisions (pile-up) drastically increases the number of erroneous roads found from the $(q/p_T, \phi_0)$ HT algorithm. The effect of reducing the number of these roads by applying the $(q/p_T, \phi)$ HT or (η, z_0) HT filter is quantified by the rejection. It is ideal to have a high rejection without compromising efficiency.

Figure 9.12 shows a distribution of the number of roads found per event for a sample of events with a single muon and $\mu = 200$ pile-up collisions. The red histogram is the number of roads found after application of the first HT only. The blue histogram shows the number of roads found for these same events after the second-stage HT filter is applied. 8752 of the 10,000 events pass the initial event selection criteria. The mean number of roads found by the 1st stage Hough Transform is 357.9. After application of the 2nd stage filter, this number is reduced to roughly 50. This is a

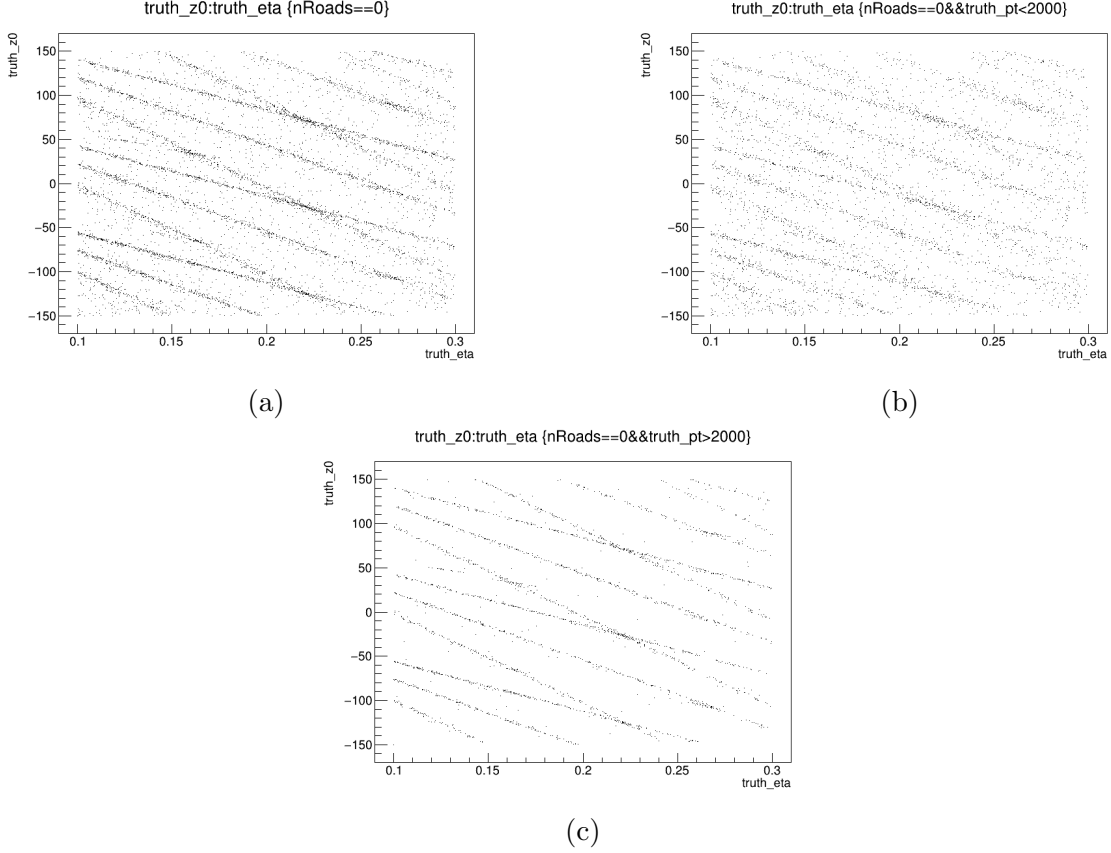


Figure 9.11: The truth track z_0 and η for single muon events for which the $(q/p_T, \phi)$ Hough Transform did not find any roads for (a) all events, (b) events with a truth track $p_T < 2$ GeV, and (c) events with a truth track $p_T > 2$ GeV.

factor of 7 decrease in the number of roads found. This factor depends on the number of bins used in the (η, z_0) accumulator. We used a 14×14 sized accumulator, driven by the size of the strip sensors in z and the radii of the detector layers.

A true measure of rejection would be calculated as:

$$R = \frac{\langle N_{roads/ev, HT_2} \rangle - N_{truth, HT_2} \cdot \langle N_{roads/truth, HT_2} \rangle}{\langle N_{roads/ev, HT_1} \rangle - N_{truth, HT_1} \cdot \langle N_{roads/truth, HT_1} \rangle} \quad (9.8)$$

In this expression, $N_{roads/ev, HT_i}$ ($i = 1, 2$) is the average number of roads found per event in the single muon plus $t\bar{t}$ plus $\mu = 200$ pileup sample. N_{truth, HT_i} is the number of truth tracks in those events for which at least one road was found. Since the samples studied here don't keep track of the truth tracks corresponding the pile-up interactions

which require larger data storage than is feasible, we can only approximate a lower bound on the rejection. Future studies can be performed with pile-up truth tracks to reject fake tracks.

The fake rate can be further explored by looking at additional information available to us in our simulations. Both the samples containing single muons only and single muons plus $\mu = 200$ pile-up contain a single track associated to the single muon, called a “matched truth track” in the simulation. One could plot the overall road multiplicity found per each matched truth track. Figure 9.13a) shows this number for samples with $\mu = 0$ after the 1st and 2nd stage HT. Duplicates aren’t removed by the algorithm, which is again why there are events for which more than one road was found. Figure 9.13b) shows the number of roads matched to the muon in a sample containing an additional $\mu = 200$ pile-up interactions before and after the second-stage filter, in red and blue, respectively.

Tables 9.1 and 9.2 summarize the resulting number of roads per matched truth track for each sample after each stage. The number of bins in z_0 and η is both 14. Some of the roads identified still contain pile-up hits before and after the filter, so an exact measure of rejection can’t be obtained.

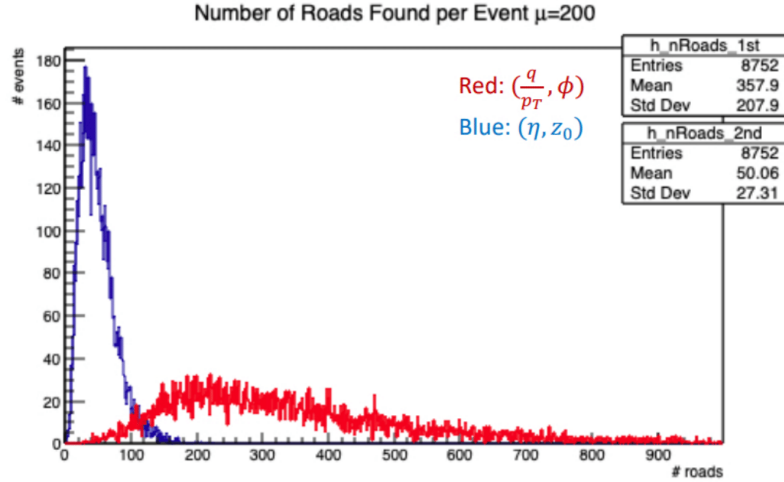
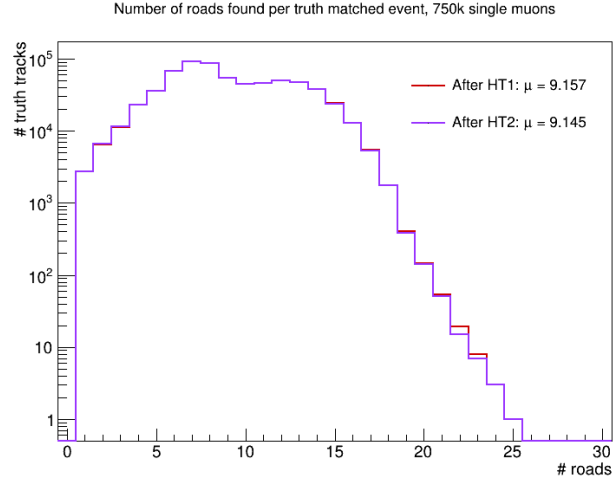
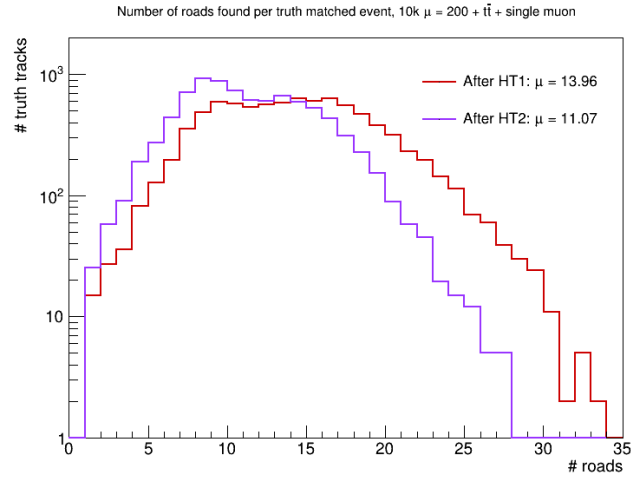


Figure 9.12: The number of roads found per event after the first (red) and second (blue) stage Hough Transforms in a sample of 10,000 single muon + $t\bar{t}$ + $\mu = 200$ pile-up events.



(a)



(b)

Figure 9.13: Number of roads found per truth matched event for a sample of 750,000 (a) single muon events and (b) single muon events with a $t\bar{t}$ interaction and $\mu = 200$ pile-up interactions.

$\mu = 0$	Mean # roads per matched truth track
After HT1:	9.157
After HT2:	9.145

Table 9.1: Number of roads per matched truth track in the pile-up sample after the first-stage HT

$\mu = 200$	Mean # roads per matched truth track
After HT1:	13.96
After HT2:	11.07

Table 9.2: Number of roads per matched truth track in the pile-up sample after the second-stage HT filter

If $N_{match,\mu=X}$ is the average number of roads matched to truth tracks in an event with $\mu = X$ pile-up events and $N_{roads,\mu=X}$ is the average number of roads found per event with $\mu = X$ pile-up events, the factor by which the number of extra matched roads to the muons is reduced is:

$$R_{approx} = \frac{N_{roads,\mu=200} - N_{match,\mu=200}}{N_{roads,\mu=0} - N_{match,\mu=0}} = \frac{13.96 - 9.156}{11.07 - 9.151} \approx 2.5 \quad (9.9)$$

If we could estimate the number of roads from pile-up, we could arrive at a more realistic estimation of the rejection. Fig. 9.14, taken from Ref [46], shows the primary-charged-particle multiplicities as a function of η . The black dots are the data and the colored curves are predictions from different MC models of charged-particle distributions. The bottom panel shows the ratio of simulation to data. This figure needs to be interpreted with caution in the context of our analysis because it is valid for tracks with $p_T > 500$ MeV, unlike the 1 GeV threshold we consider for track reconstruction here.

For the pseudorapidity range we consider in our analysis of the performance of the first and second-stage HT, the number of tracks is roughly $N_{track} \approx 20$ per event. It would be nice to know the multiplicity as a function of p_T , but if we guess that N_{track} with $p_T > 500$ MeV is approximately 2 per event above the 1 GeV threshold, a new rejection estimate is calculated as:

$$R_{approx} \approx \frac{357.9 - 3 \cdot 13.98}{50.05 - 3 \cdot 11.07} \geq 18 \quad (9.10)$$

The number three used to evaluate the numerator and denominator comes from the two tracks from pile-up plus the one track from the single muon.

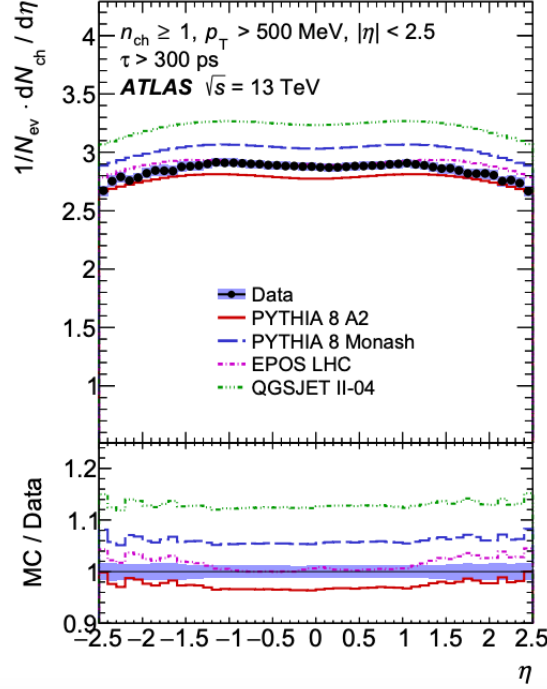


Figure 9.14: The primary-charged-particle multiplicities as a function of pseudorapidity, η . From [46].

9.6 An implementation of the (η, z_0) Hough Transform on FPGAs

A Xilinx Alveo U250 board is used to prototype the firmware for both Hough Transforms. The first-stage firmware was developed by Tong Xu [43], an engineer at Argonne National Laboratory, and I wrote the firmware for the second-stage. The Alveo 250 board was used to evaluate the system size and resource utilization. The firmware for the first-stage $(q/p_T, \phi_0)$ Hough Transform is implemented as a pipeline and a summary of pipeline is as follows: the ITk hit data, in the form of pixel and strip clusters, stubs, or space-points are loaded into an accumulator, an array of memories that each store a group of ID numbers for the hits and a number of hit clusters or space-points. Each hit is processed once. The hits are read layer by layer in the detector, sequentially processed as slices. These slices are produced by a slicing engine firmware. Once all hit data is read into the accumulator, accumulator bins

containing at least 7 hits from 7 different slices are read out as track candidates, known as roads. Figure 9.15 shows the firmware block diagram. The same block diagram is utilized for each HT stage.

In Fig. 9.15, an $N \times M$ accumulator is constructed. Every cell in the accumulator corresponds to a portion of phase-space in (η, z_0) coordinates and has a memory address. For the 1st HT, the N rows correspond to different q/p_T values a track could have given the different possible $\phi \in [0, 2\pi]$ values contained in each of the M columns. The number of rows and columns can be configured and simulation is used to determine the appropriate dimensions of the accumulator.

The light blue arrows represent two ITk clusters or space-points being input to the Hough Transform pattern recognition block. This is done once per clock cycle. The information for each cluster contains the module IDs of the detector elements hit, the local coordinates of the hit within the strip or pixel, and a bitmask identifying which layer of the detector the hit occurred in. A local to global converter block is used to convert the local coordinates of the hit on a silicon detector element into global coordinates in the radius and phi coordinates. This author did not design the firmware for the local to global coordinate conversion block during the course of the development of the second-stage Hough Transform firmware. The local coordinate and module ID of the clusters of hits processed by this block are stored in random access memory using BRAMs. This step is represented by the “Cluster Storage” block in the block diagram. The BRAMs used for the cluster storage are multiplexed so that cluster information can be read out separately later, when necessary. The cluster IDs are 10 bits each, while the module ID and local coordinates are stored using at least 32 bits. An address, referred to as a “cluster ID”, is stored for each cluster.

Write enable signals are calculated for hits that are loaded separately into the “write enable” block using the Hough Transform. Each row is read in separately. The accumulator uses DSPs to implement the approximate HT equations in Eqs. 9.11 and 9.12, calculated using the global hit coordinates. The Hough Transform calculation is performed for each row separately using multiplexers to determine which pairs of q/p_T and ϕ are consistent with the hit and consequently which bins to fill in the 2D accumulator.

$$\frac{Aq}{p_T} = \frac{\phi_0 - \phi_{hit}}{r_{hit}} \quad (9.11)$$

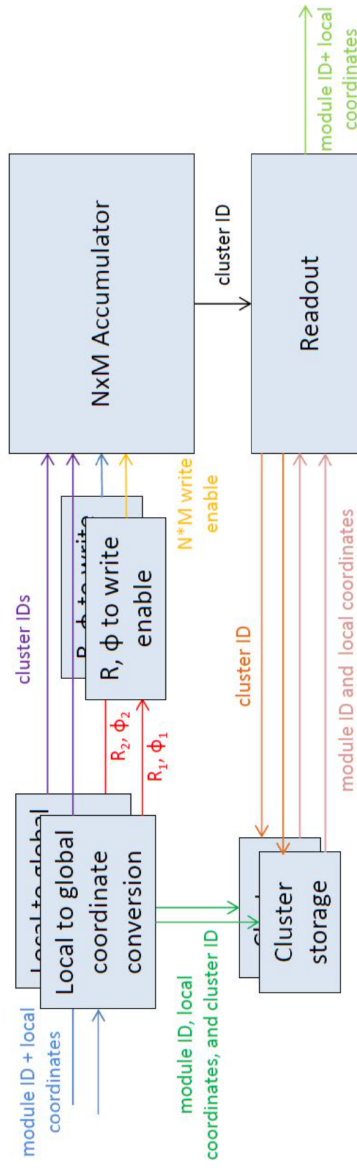


Figure 9.15: The pattern recognition firmware block diagram that is implemented for both stages of the Hough Transform

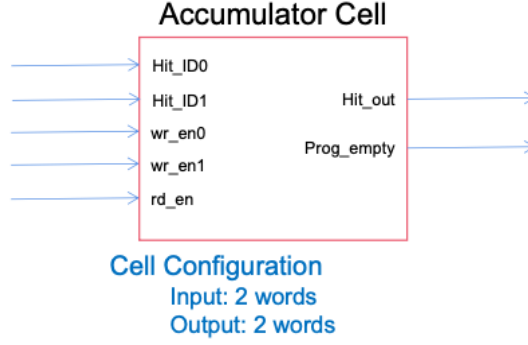


Figure 9.16: A schematic of an accumulator cell in the HT firmware. From [43].

$$z_0 = z_{hit} - r_{hit} \cdot \sinh(\eta) \quad (9.12)$$

An accumulator cell in firmware is depicted in Fig. 9.16 and Fig. 9.17 is a cartoon of how the accumulator for the 1st HT is filled using calculated quantities produced by the write-enable block. Two words containing the memory addresses for the cluster IDs and two write enable signals are read in per clock cycle. For the $(q/p_T, \phi)$ HT accumulator, each bin uses 11 LUT to control the layer mask registers. The accumulator cell only stores the cluster information if the write enable signal corresponding to the hit is ‘1’.

After all hits are loaded into the accumulator, accumulator cells with at least 7 hits are read out by the “readout block” to be further processed. Each column is read out simultaneously and roads are stored in BRAM based FIFOs. The cells are the memory addresses that are read out and then used to retrieve the module IDs and coordinates that were stored in memory. After the whole slice is read in, the dead time before the next slice is read into the accumulator is 8 clock cycles.

LUT:	0.14% of U250 FPGA
FF:	0.04% of U250 FPGA
DSP:	13 DSPs

Table 9.3: Resource utilization of the second-stage Hough Transform.

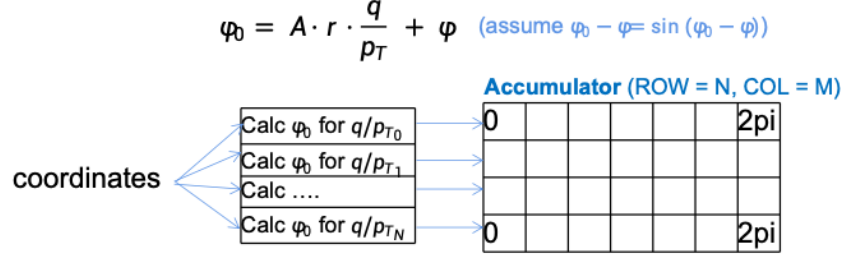


Figure 9.17: Diagram of first HT calculation performed in the accumulator [43].

For both Hough Transforms, the majority of the LUTs and FFs are used by the accumulators. The post utilization resources for both the second-stage Hough Transform are in Table 9.3.

The (η, z_0) Hough Transform firmware filters track candidates identified by the $(q/p_T, \phi_0)$ Hough Transform firmware. The rows of the (η, z_0) accumulator correspond to different z_0 values while the columns correspond to possible η values. While the $(q/p_T, \phi_0)$ accumulator stores hit cluster ROIs, the number of hits per layer, and the number of hits, the (η, z_0) accumulator stores just the number of hits per layer. There is no need to read the hits back. We check if there is a cell with enough hits.

9.7 Discussion

The studies performed here are not complete. The performance of this second-stage filter was evaluated using single muons since is a best-case scenario. More studies need to be done to evaluate the performance of the filter in identifying roads in events with electrons and pions. Pions constitute a majority of the charged particles that

ATLAS measures from pp collisions. The studies in this chapter are also limited to the barrel only.

The algorithm as presented here could be improved. Since Layer 0 considered in this pattern recognition stage is from the pixel layer 0, which is considerably smaller in length than the 25 mm long strip layers, and we applied an accumulator the same size for all layers, the rejection could be improved if the number of bins is higher or if the z resolution is smaller.

The (η, z_0) Hough Transform was implemented as a second-stage filter in these studies. The approach to pattern recognition described here was an “outside-in” approach to tracking. However, one could imagine performing an “inside-out” tracking algorithm, using pixel hits, which is advantageous because low p_T tracks are more likely to contain pixel hits than both pixel and strip hits, the latter of which are needed for the “outside-in” approach. Such an approach could not rely on a $(q/p_T, \phi)$ Hough Transform as the first-stage to identify roads because the pixels are much closer to the beampipe and consequently, the non-zero value of d_0 is not negligible in evaluating the first Hough Transform equation. In this case, the second-stage Hough Transform could be used as it is valid regardless of the track d_0 . An accumulator for the pixel layers would have a much finer resolution in z_0 than the strip layers studied here. If or when strip hits are used, the space-point construction method developed in the previous chapter could be used to combine hits on opposite sides of the strip layers, producing four measurements with much finer precision that could then be used in a more finely binned (η, z_0) accumulator. A second-stage filter based on the $(q/p_T, \phi)$ Hough Transform could then be explored.

Appendix A: Derivation of Hough Transform Equations

I've included these derivations in an appendix because I found it useful to see them myself when working on the Hough Transform and spacepoint construction projects. While the first hough transform equation was already widely used, I had to derive the second for myself and went through the exercise of deriving the first anyway. Both hough transform equations assume that the transverse impact parameter, $d_0 = 0$, which is sufficient for applications to particles whose primary vertices are within 2 mm of the beampipe, but is not sufficient to describe tracks with displaced vertices.

Section A.1 derives the first Hough Transform equation. Section A.2 derives the second Hough Transform equation.

A.1 Derivation of the First Hough Transform Equation

I chose to do this in Cartesian coordinates.

Take a magnetic vector potential defined as $\vec{A} = (\frac{A_0 y}{q}, -\frac{A_0 x}{2}, 0)$.

This means the magnetic field is given as:

$$\vec{B} = \vec{\nabla} \times \vec{A} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ \frac{A_0 y}{2} & -\frac{A_0 x}{2} & 0 \end{vmatrix} = (0, 0, -A_0)$$

The Lagrangian is given by:

$$\mathcal{L} = \frac{1}{2}mv^2 + q\vec{v} \cdot \vec{A} \tag{A.1}$$

For our charged particle in a uniform solenoidal field, this is:

$$\mathcal{L} = \frac{1}{2}m(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) + \frac{A_0}{2}q(y\dot{x} - x\dot{y}) \quad (\text{A.2})$$

Lagrange's equations result in a system of differential equations:

$$\ddot{x} = -\alpha\dot{y} \quad (\text{A.3})$$

$$\ddot{y} = \alpha\dot{x} \quad (\text{A.4})$$

where $\alpha = \frac{2A_0q}{m}$. It is important to note that $\phi = \frac{\alpha t}{2} + \phi_0$.

The solutions for $x(t)$ and $y(t)$ are in Eqs. A.5 and A.6, where c_1 , c_2 , c_3 , and c_4 are constants to be solved for using initial conditions.

$$x(t) = \frac{c_2}{\alpha}\sin(\alpha t) + \frac{c_4}{\alpha}(\cos(\alpha t) - 1) + c_1 \quad (\text{A.5})$$

$$y(t) = \frac{c_4}{\alpha}\sin(\alpha t) - \frac{c_2}{\alpha}(\cos(\alpha t) - 1) + c_3 \quad (\text{A.6})$$

The initial conditions that $x(0) = y(0) = 0$ indicate that $c_1 = c_3 = 0$.

We can take the derivatives of Eqs. A.5 and A.6 to get Eqs. A.7 and A.8.

$$\dot{x}(t) = c_2\cos(\alpha t) - c_4\sin(\alpha t) \quad (\text{A.7})$$

$$\dot{y}(t) = c_4\cos(\alpha t) + c_2\sin(\alpha t) \quad (\text{A.8})$$

From geometry, the polar angle is:

$$\tan(\phi) = \frac{y}{x} = \frac{c_4\sin(\alpha t) - c_2(\cos(\alpha t) - 1)}{c_2\sin(\alpha t) + c_4(\cos(\alpha t) - 1)} \quad (\text{A.9})$$

It can easily be seen that the p_T of the particle in the magnetic field is related to the constants in the expressions for $x(t)$ and $y(t)$:

$$\left(\frac{p_T}{m}\right)^2 = \dot{x}^2 + \dot{y}^2 = c_2^2 + c_4^2 \quad (\text{A.10})$$

To manipulate Eq. A.9 a bit, we define a new variable $\beta = \frac{\alpha t}{2}$. Trigonometric identities give us that $\sin(\alpha t) = 2\sin(\beta)\cos(\beta)$ and $\cos(\alpha t) = \cos^2(\beta) - \sin^2(\beta)$. This reduces Eq. A.9 to Eq. A.11.

$$\tan(\phi) = \frac{c_4 \cos(\beta) + c_2 \sin(\beta)}{c_2 \cos(\beta) - c_4 \sin(\beta)} \quad (\text{A.11})$$

When $t = 0$, $\beta = 0$. This means that $\tan(\phi_0) = \frac{c_4}{c_2}$ and $c_4 = c_2 \tan(\phi_0)$.

c_2 and c_4 can be expressed as functions of p_T , m , and ϕ_0 of the particle in Eqs. A.12 and A.13.

$$c_2 = \left(\frac{p_T}{m}\right) \frac{1}{\sqrt{1 + \tan^2(\phi_0)}} \quad (\text{A.12})$$

$$c_4 = \left(\frac{p_T}{m}\right) \frac{\tan(\phi_0)}{\sqrt{1 + \tan^2(\phi_0)}} \quad (\text{A.13})$$

Substituting in A.12 and A.13 into A.5 and A.6 and solving for the radius of the particle gives:

$$r^2 = x(t)^2 + y(t)^2 = \left(\frac{2}{\alpha} \frac{p_T}{m} \sin(\beta)\right)^2 \quad (\text{A.14})$$

Since $\beta = \phi - \phi_0$ and $\alpha = \frac{2A_0 q}{m}$, the resulting expression for r^2 is:

$$r^2 = \frac{p_T^2}{A_0^2 q^2} \sin^2(\phi - \phi_0) \quad (\text{A.15})$$

This gives us the first hough transform equation:

$$\frac{Aq}{p_T} = \frac{\sin(\phi - \phi_0)}{r} \quad (\text{A.16})$$

A.2 Derivation of the Second Hough Transform Equation

The angle θ was discussed in the perigee parameterization of tracks earlier in this thesis. It is defined in relation to the components of the track momentum such that:

$$\tan(\theta) = \frac{p_T}{p_z} \quad (\text{A.17})$$

Rearranging this gives:

$$p_T = p_z \tan(\theta) \quad (\text{A.18})$$

With the definition that $\theta = 2\arctan(e^{-\eta})$, Eq. A.18 can be rewritten as:

$$p_z = p_T \sinh(\eta) \quad (\text{A.19})$$

A particle travelling through a solenoidal field whose magnetic field points in the $\hat{z}$ direction will move with a constant velocity, $\dot{z}$. It can be written that:

$$z = z_0 + \dot{z}t = z_0 + \frac{p_z}{m}t \quad (\text{A.20})$$

This can be further re-written as:

$$z = z_0 + \frac{p_T}{m} \sinh(\eta)t \quad (\text{A.21})$$

Remembering that $\phi = \frac{A_0 q t}{m} + \phi_0$, the expression for z becomes:

$$z = z_0 + \frac{p_T}{A_0 q} (\phi - \phi_0) \sinh(\eta) \quad (\text{A.22})$$

By applying the first Hough Transform equation to substitute for the $(\phi - \phi_0)$ term, we arrive at the final expression for the second Hough Transform equation:

$$z = z_0 + \frac{p_T}{A_0 q} \sin^{-1}\left(\frac{Aq}{p_T}r\right) \sinh(\eta) \quad (\text{A.23})$$

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