

A search for leptoquarks decaying to muons and bottom quarks in proton-proton collisions
at $\sqrt{s} = 13$ TeV with the full Run II data recorded by CMS

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Abstract of Dissertation

Many of the proposed extensions to the Standard Model of particle physics posit the existence of a new massive boson called a leptoquark that would couple directly to a quark and a lepton. Compelling evidence for new physics in flavor anomalies and the muon magnetic anomaly could indicate the involvement of these leptoquarks. High-energy proton-proton collisions at the Large Hadron Collider (LHC) are capable of producing leptoquark pairs—primarily through gluon-gluon fusion—providing LHC experiments like the Compact Muon Solenoid (CMS) collaboration with the perfect opportunity to look for these exotic particles. Presented in this thesis is a search for pair-produced scalar leptoquarks decaying to muons and bottom quarks, using 138 fb^{-1} of data collected by the CMS detector during the 2016–2018 proton-proton running of the LHC at a center-of-mass energy of 13 TeV. The final state event signature considered contains two high-transverse-momentum muons and two jets, one of which is tagged as originating from a bottom quark. This analysis is the first search for leptoquarks decaying to muons with the full LHC Run II dataset recorded by the CMS detector, as well as the first search by the CMS collaboration for leptoquarks in the $\mu\mu bj$ channel. Boosted decision trees were trained on the kinematics of the muons and jets in signal and background simulated data to select signal-like events for analysis. Observed and expected asymptotic upper limits were obtained at 95 % confidence level on the product of the signal production cross section and decay branching fraction into charged leptons as a function of the leptoquark mass. Comparison of these observed and expected limits with the theoretical cross sections establishes exclusion limits on leptoquark masses below 1803 GeV and 1796 GeV, respectively. The results of this study mark the strongest limits to date on leptoquarks decaying to muons and bottom quarks.

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Chapter 1

Introduction

The ultimate aim of particle physics is to build a complete theoretical model consistent with all observed natural phenomena at the smallest size-scales. Experiments over the past century have revealed that matter is composite in nature, formed from irreducible constituents called elementary particles. Particles are also responsible for three of the four fundamental forces in the universe. The mathematical framework used to describe the catalog of observed particles was developed is called the Standard Model (SM) of particle physics. The SM has been hugely succesful in describing the properties and behavior of elementary particles, and has predicted new particles that were subsequently discovered. The massive particles composing matter—called fermions—include six leptons (the electrically charged electron, muon, and tau, and their neutral counterparts, neutrinos) and six quarks (up, down, charm, strange, top, and bottom), both of which are grouped into three “families” or “generations.” The force carrying particles are the gauge bosons: a massless photon responsible for electromagnetism (or light), the charged W and neutral Z bosons responsible for the weak nuclear force (causing neutron decay), and eight massless gluons responsible for the strong nuclear force (this binds quarks together to form hadrons, e.g., protons and neutrons, and similarly binds protons and neutrons together inside atomic nuclei). The remaining particle in the SM is the Higgs boson, which through a phenomena called the Higgs mechanism is responsible for providing masses to all the SM particles.

Most elementary particles at rest are not stable; heavier particles rapidly decay into lighter particles like electrons found in atomic orbitals, up or down quarks that form stable nuclei, or the photons we observe as light or radiation. To study the more massive, unstable elementary particles rarely found in nature, particle physicists produce them by generating

a sufficient quantity of energy. High Energy Physics (HEP) experiments accomplish this feat by accelerating particles—either along a ring or a linear tunnel—until they are brought into contact in spectacular head-on collisions. In rare instances, a heavy particle is created from the energy of the collision before decaying back into lighter constituents. Extremely sensitive detectors surrounding the collision points record the particles that emerge from the collisions. By studying the species of particles that emerge from each collision and their kinematics, the properties of the original heavy particle can be deduced.

Many particle accelerators have been built that vary in the particles they collide and the center-of-mass collision energies they can generate. The current highest energy collisions belong to the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland. The LHC is a 27 km ring that delivers nearly a billion proton-proton collisions per second to a number of experiments along its circumference, reaching collision energies of 13 TeV. The CMS experiment is one of two general purpose detectors at the LHC that has successfully tested a wide range of SM phenomena with astonishing precision; most notably, it codiscovered the Higgs boson with the ATLAS experiment in 2012.

Although the SM has continued to hold up against the most stringent experimental tests, the theory still suffers from a number of shortcomings, such as: the remarkable symmetry between the lepton and quark generations lacks any explanation; the electromagnetic and weak forces unite at high energy scales into a single electroweak force (verified at the LHC), but the strong force remains separate at all energy scales; and the measured hierarchy of the electroweak force and gravity—spanning 24 orders of magnitude—requires excessive fine-tuning to model. Supersymmetry (SUSY), Grand Unified Theories (GUTs), composite models with lepton and quark substructure, and Technicolor schemes are several extensions to the SM put forward to explain some of these limitations. Predicted in these theories are new heavy bosons that would couple to both a lepton and quark. Such leptoquarks (an obvious portmanteau) are color-triplet spin 0 or spin 1 bosons, carrying both baryon and lepton quantum numbers, as well as fractional electric charge. The values of these parameters

classify each leptoquark model, while other parameters including the mass M_{LQ} , coupling strength at a leptoquark-lepton-quark vertex λ_{LQ} , and decay branching fraction into charged leptons β are model independent. Leptoquarks remain excellent candidates to test theories of new physics, as they could be readily produced in hadron colliders.

Searches by the CDF and D0 collaborations at Fermilab’s Tevatron collider in the 1990s and 2000s looked for pair-produced leptoquarks constrained to decays into quarks and leptons of the same generation. Proton-antiproton collision energies at the Tevatron reaching 1.96 TeV allowed the experiments to place lower bounds on the masses of first-, second-, and third-generation scalar leptoquarks, assuming decays into two charged leptons or one charged lepton and one neutrino.

Overlapping with this time period, the H1 and ZEUS collaborations at the DESY HERA collider searched for both single- and pair-produced leptoquarks in 300 GeV electron-proton collisions. These searches similarly looked for leptoquarks by fermion generation, but also included searches that allowed mixing of quark-lepton generations. In 1997, the H1 and ZEUS collaborations reported a data excess corresponding to a first-generation leptoquark with a mass of roughly 200 GeV, known as the HERA anomaly. However, this conclusion was ultimately ruled out with the accumulation of more data.

With data collected during Run I of the LHC, the CMS and ATLAS collaborations brought the hunt for leptoquarks into a new energy regime with 7 and 8 TeV proton-proton collisions. The wide-ranging scope of both collaborations’ leptoquark search programs led to numerous publications placing exclusion limits on single- and pair-production leptoquarks in a host of search channels. Run II of the LHC increased collision energies to 13 TeV, opening up sensitivity to higher kinematic regimes. In October 2022, the ATLAS experiment published results in a single paper covering searches for pair-produced scalar and vector leptoquarks decaying into third generation quarks (t and b) and first or second generation leptons (e, μ , and ν). The extensive analysis placed lower bounds on leptoquark masses in eight final state channels. The most rigorous experimental limits to date on scalar lep-

toquarks decaying into muons have been set by the CMS collaboration. Using 35.9 fb^{-1} of data recorded by the CMS detector in 2016, leptoquarks in the $\mu\mu jj$ channel with masses below 1530 GeV were excluded with a 95 % CL.

Interest in leptoquarks has grown in recent years with a rise in experimental hints of new physics. Flavor anomalies observed by the LHCb collaboration in the rare decays of B mesons (quark-antiquark bound-states containing a bottom quark or antiquark) could arise from leptoquarks with couplings to cross-generational fermions, like a muon and bottom quark. The Muon $g - 2$ collaboration has reported precise measurements of the muon magnetic anomaly in tension with the SM expectation, and these could also point to second-generation leptoquarks (i.e., coupling to muons) by considering their contribution to the quantum corrections of the anomaly. Both experiments strongly motivate searches for leptoquarks decaying to bottom quarks (seen in a detector as “jets” of particles) and muons.

The following thesis details a novel search for pair-produced scalar leptoquarks decaying to a pair of muons and two jets, with at least one jet identified as originating from a bottom quark. Proton-proton collision data at 13 TeV collected with the CMS detector in 2016, 2017, and 2018 are used, corresponding to an integrated luminosity of 138 fb^{-1} . Leptoquark searches requiring two muons are promising as they leave a clean signature in the detector. While past leptoquark searches by the CMS collaboration have confined couplings to leptons and quarks of the same generation, the inclusion of a b-tag requirement in association with muons targets leptoquark models that allow intergenerational mixing, motivated by the flavor anomalies. This represents the first analysis of CMS data targeting leptoquarks decaying to muons and b quarks, and the first leptoquark search with a muon in the final state to make use of the entire Run II dataset recorded by the CMS detector. Thirty mass hypotheses will be tested from 300 to 4000 GeV , guided by limits from previous searches. The analysis will place expected and observed upper limits on leptoquark pair-production cross sections for each mass hypothesis, and by comparing results to the theoretical cross sections, these limits can be translated into an experimental lower bound on the leptoquark mass.

Following the introduction, Chapter 2 offers a primer the SM of particle physics: specifically, it explains how elementary particles interact via fundamental forces and how spontaneous breaking of symmetry in the equations governing their kinematics provides them with the masses we observe. The chapter then concludes with a description of leptoquark models and the experimental motivation for this thesis. Chapter 3 covers the design of the LHC and an overview of each CMS subdetector. Chapter 4 recounts the program of upgrades to the CMS muon detectors that stretched from 2018 to 2022, a program I personally participated in. Chapter 5 elaborates on the performance of the CMS muon detectors, which includes data processing, reconstruction of muon objects from detector information, and the alignment and calibration of the CMS muon detectors. Activity I performed during my Ph.D. studies related to the calibration of the CMS muon system concludes the detector-focused chapters. Chapter 6 contains the analysis I carried out with CMS collision data in search of leptoquarks, including: the recorded and simulated datasets analyzed, the event selection, the data-to-simulation corrections, the estimation of SM background processes, the machine learning techniques used to separate signal-like events from background-like events, the sources of systematic uncertainty accounted for, and the results of the search. Closing remarks summarizing the results of the leptoquark search and exploring possible future studies are provided in Chapter 7, the conclusion.

Chapter 2

Theoretical background

2.1 The Standard Model

The prevailing description of nature at the fundamental level is a relativistic quantum field theory called the Standard Model (SM). Developed in the latter half of the 20th century, the SM has seen extraordinary success in its predictive power and is widely considered the most rigorously tested physical theory. The characteristics of the SM proceed from symmetries embedded in the Lagrangian of the theory. At the heart of the SM are the local gauge transformations associated with the gauge group product:

$$\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{W} \times \mathrm{U}(1)_\mathrm{Y}, \tag{2.1}$$

where the subscript on each gauge group identifies an associated conserved quantity: color charge C, weak isospin W, and weak hypercharge Y (all detailed in Section 2.1.2), which generate three of the four fundamental forces of nature (electromagnetic, weak, and strong; gravity is absent in the SM). Adding a collection of 17 quantized fields (by one way of counting) that respect this symmetry completes the SM. Experiments have revealed that the constituent building blocks of the universe are point-like particles, understood in the SM as excitations in the quantum fields, with each observed “matter” particle corresponding to an excitation in one of 12 fields, listed in detail in Section 2.1.1. Interactions among particles by the three fundamental forces are understood as the exchange of “virtual” particles, excitations in one of four fields, reviewed in Section 2.1.2. The remaining field corresponds to the Higgs particle and is responsible for the masses of the other particles, explained in Section 2.1.2.4.

2.1.1 Elementary particles

Localized excitations, or quanta, of the quantum fields in the SM are called elementary particles. Particles are observed either directly or indirectly through experiment and carry intrinsic properties that distinguish them from one another, such as electric charge, mass, and quantum numbers like spin. Every particle has a corresponding antiparticle, which, roughly speaking, is identical to the particle save for its carrying some opposite quantum numbers, e.g., electric charge for charged particles. All SM particles (and antiparticles) can be classified as either fermions or bosons, depending on their spin quantum number, detailed below in Sections 2.1.1.1 and 2.1.1.2. Provided in Fig. 2.1 is a diagram of all the particles in the SM, practically organized, and includes a number of important properties for each; this diagram may be used as a map of the theory described in the following Sections.

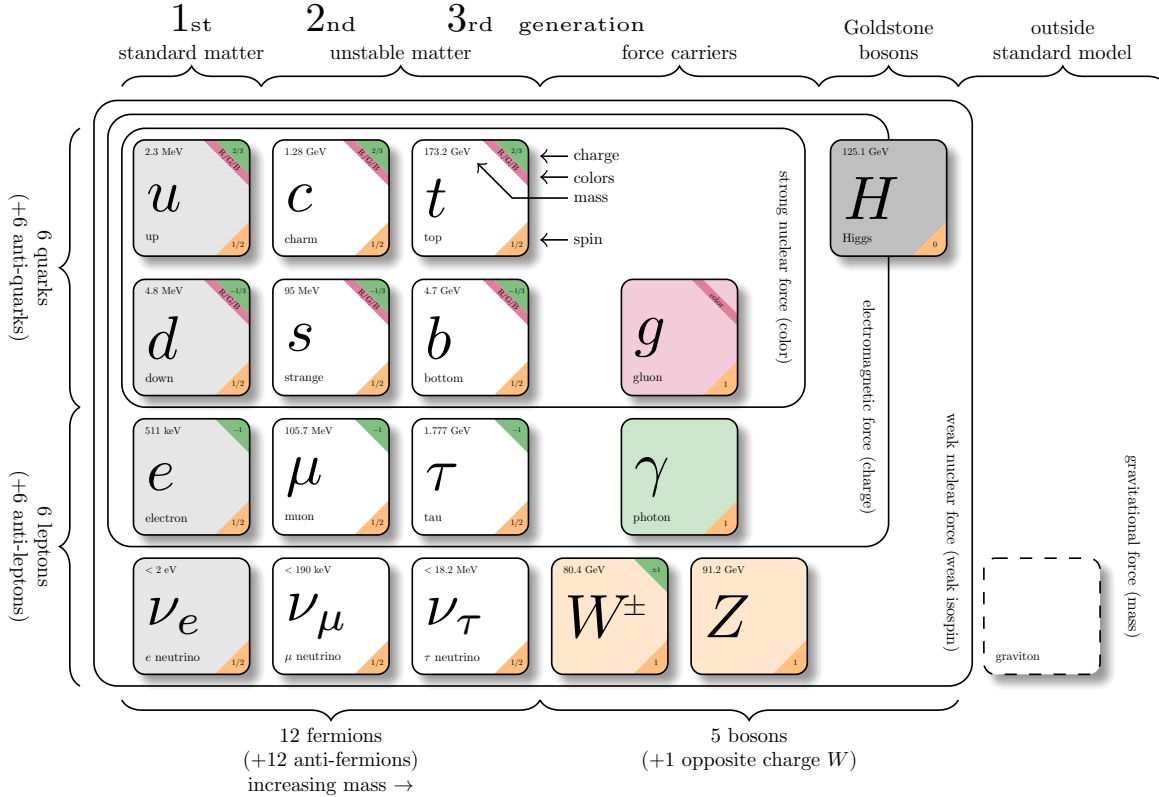


Figure 2.1: Every elementary particle in the SM

2.1.1.1 Fermions

Particles with half-integer spin quantum numbers obey Fermi-Dirac spin-statistics, which prevents any two identical particles from occupying the same state in a system at thermodynamic equilibrium, leading to the famous Pauli exclusion principle. Particles following a Fermi-Dirac distribution are given the eponymous name fermions, and while they are a general classification of any particle with half-integer spin, within the SM, fermions refer to a specific set of massive, interacting, “matter” particles that are subdivided into two key types: leptons and quarks.

Leptons ℓ are spin 1/2 fermions that can be electrically charged or neutral and interact via the weak nuclear force; they do not interact via the strong nuclear force (see Sections 2.1.2.2 and 2.1.2.3). There are six types, or flavors, of leptons: the electron e^- , muon μ^- , tau τ^- , electron neutrino ν_e , muon neutrino ν_μ , and tau neutrino ν_τ . These can be grouped into three generations: electronic, muonic, and tauonic, each with an electrically charged lepton and an electrically neutral lepton, dubbed a neutrino. Each lepton carries a lepton family quantum number L_e , L_μ , or L_τ , equal to 1 (−1 for antileptons), that is approximately conserved (neutrino oscillations violate this). What is always conserved in interactions is lepton number $L = n_\ell - n_{\bar{\ell}}$, where n_ℓ and $n_{\bar{\ell}}$ are the number of leptons and antileptons at the start or end of an SM process.

An important characteristic of both fermions and bosons is their helicity, being the sign of the projection of a particle’s spin onto its momentum: “right-handed” if the spin and momentum vectors align (1), “left-handed” if the vectors are opposed (−1), denoted with an R or L subscript, respectively. In the limit where the particle is massless, helicity is essentially chirality, an intrinsic property of a particle that determines the representation it transforms under (for this reason we refer to left-handed and right-handed particles as

chiral). Each generation of left-handed leptons form a weak isospin doublet with $T = 1/2$:

$$\begin{pmatrix} \nu_{eL} \\ e_L^- \end{pmatrix}, \quad \begin{pmatrix} \nu_{\mu L} \\ \mu_L^- \end{pmatrix}, \quad \begin{pmatrix} \nu_{\tau L} \\ \tau_L^- \end{pmatrix}, \quad (2.2)$$

while the right-handed leptons form singlets: e_R^- , μ_R^- , and τ_R^- with $T = 0$. Note that there are no right-handed neutrinos in the SM, and that only left-handed leptons participate in charged weak interactions. For antileptons, the inverse is true: there are only right-handed antineutrinos and only right-handed charged antileptons participate in weak interactions.

Leptons are initially massless in the SM. Charged leptons acquire mass via the Higgs mechanism, while neutrinos remain massless. No neutrino mass has ever been measured (although upper bounds have been placed); however, observations of neutrino flavor oscillations confirm that neutrinos do indeed have very small masses, contrary to the SM. Table 2.1 lists for each lepton the flavor, spin, lepton family number, electric charge Q , weak isospin T_3 , weak hypercharge Y_W , and observed mass (or upper bound on the mass for the neutrinos). There is a corresponding antiparticle for each lepton, where the charges are sign-flipped but retain the same mass.

Table 2.1: Quantum numbers and masses of the SM leptons. This table only lists the properties of left-handed leptons, with right-handed antileptons forming a similar table with the charges sign-flipped.

Flavor	Spin	L_e	L_μ	L_τ	Q	T_3	Y_W	Obs. mass [MeV]
e	1/2	1	0	0	-1	-1/2	1	0.511
μ	1/2	0	1	0	-1	-1/2	1	105.7
τ	1/2	0	0	1	-1	-1/2	1	1.777×10^3
ν_e	1/2	1	0	0	0	1/2	-1	$< 2.2 \times 10^{-6}$
ν_μ	1/2	0	1	0	0	1/2	-1	< 0.17
ν_τ	1/2	0	0	1	0	1/2	-1	< 15.5

Quarks q are chiral spin $1/2$ fermions that carry fractional electric charge (in multiples of $1/3$), weak isospin and weak hypercharge, and—unique among the SM fermions—interact with the strong force. Analogous to lepton number, quarks carry a baryon quantum number B of $1/3$. Baryon number is strictly conserved in the SM, and—for any interaction—is defined as $3B = n_q - n_{\bar{q}}$, where n_q and $n_{\bar{q}}$ are the number of quarks and antiquarks at the start or end of a process. Remarkably, quarks—identical to leptons—come in six flavors that can likewise be grouped into three generations (this unexplained parallel partly motivates the search for new physics in this thesis). The quark flavors are: up u and down d (first-generation), charm c and strange s (second-generation), and top t and bottom b (third-generation). Also, similar to leptons, quarks acquire mass via the Higgs mechanism. Table 2.2 lists the quantum numbers and masses of each flavor of quark.

Table 2.2: Quantum numbers of quarks. Color charges are not considered. This table only lists the properties of quarks, with antiquarks forming a similar table with the charges sign-flipped.

Flavor	Spin	B	Q	T_3	Y_W	Obs. Mass [MeV]
up	$1/2$	$1/3$	$2/3$	$-1/2$	$1/3$	2.3
down	$1/2$	$1/3$	$-1/3$	$-1/2$	$1/3$	4.8
charm	$1/2$	$1/3$	$2/3$	$-1/2$	$1/3$	1.274×10^3
strange	$1/2$	$1/3$	$-1/3$	$1/2$	$1/3$	9.5×10^1
top	$1/2$	$1/3$	$2/3$	$1/2$	$1/3$	$1.732 \cdot 10 \times 10^5$
bottom	$1/2$	$1/3$	$-1/3$	$1/2$	$1/3$	4.180×10^3

Each flavor of quark transforms as a color triplet under $SU(3)_C$, meaning it has a red, blue, or green color charge (antired, antiblue, or antigreen for antiquarks). As a quark absorbs or emits a gluon (carrying a color-anticolor charge), its color charge will change correspondingly. Quarks combine via the strong interaction to form color-neutral hadrons that are either a quark-antiquark pair called a meson (e.g., a pion) or a combination of three

quarks called a baryon (e.g., the proton and the neutron). Color confinement restricts quarks inside of hadrons, and in the instance of a free quark (or gluon), QCD matter will spontaneously be pulled from the vacuum to neutralize the bare color charge, a process known as hadronization. Hard proton-proton collisions as seen in the LHC will often emit quarks, which must undergo hadronization repeatedly until all color fragments are neutralized, generating a slew of mesons and baryons all traveling within a tight cone with the momentum of the original quark. These cones of hadrons, colloquially called jets, are ubiquitous in collider experiments and are essential ingredients in many physics analyses.

2.1.1.2 Bosons

The spin statistics of particles with integer-valued spin quantum numbers follow a Bose-Einstein distribution, which allows an arbitrary number of identical particles to occupy quantum states and maintain thermal equilibrium (as opposed to Fermi-Dirac statistics). Particles with this behavior are naturally called bosons. After the SM fermions, a collection of four SM bosons constitute the remainder of all observed fundamental particles. SM bosons can be massive or massless and are responsible for mediating the interactions between all particles. As the local gauge transformations of the SM are responsible for the fundamental interactions, the associated bosons are often called gauge bosons. In the SM there are three types of vector (spin 1) gauge bosons: the photon, the weak bosons, and the gluons; and one scalar (spin 0) boson: the Higgs boson.

The photon γ is a massless spin 1 gauge boson that mediates the electromagnetic force, meaning it couples to any fermion with an electric charge (all but neutrinos). Photons themselves are uncharged, so they do not self-interact. The weak gauge bosons are also spin 1 and mediate the weak force. There are three kinds of weak gauge bosons: two charged, W^+ and W^- , and one neutral, Z^0 . They are all massive, acquiring their masses via the Higgs mechanism as explained in Section 2.1.2.4. There are eight Gluons g , massless spin 1 gauge bosons that mediate the strong force between particles with color charge, i.e., quarks. Gluons

carry color charge and thus self-interact, leading to color confinement. The Higgs boson H^0 is a massive, scalar boson that results from the addition of the Higgs field to the SM Lagrangian. It is both electrically and color neutral. The Higgs is theorized to self-interact and in 2012 was the last SM particle to be discovered.

2.1.2 Fundamental interactions

2.1.2.1 The electromagnetic interaction

The Electromagnetic (EM) interaction is described in the SM by an Abelian gauge theory called Quantum Electrodynamics (QED) with the gauge group $U(1)$. The $U(1)$ symmetry allows a gauge transformation of the EM vector field A^μ to be made:

$$A^\mu \rightarrow A'^\mu = A^\mu + \partial^\mu \chi \quad (2.3)$$

with no change to the free-field lagrangian. Allowing the EM field to couple to (interact with) electrically charged Dirac fermions ψ , while imposing invariance on the whole QED lagrangian (free field + interacting terms), requires a simultaneous (and local) phase transformation of ψ :

$$\psi \rightarrow \psi' = e^{-ie\chi(x)}\psi \quad (2.4)$$

with the factor e on the phase being the experimentally measured charge of the electron (related to the coupling strength of A^μ to ψ). These gauge transformations forbid any mass and self-interacting terms of A^μ from appearing in the QED lagrangian, and restrict the quanta of A^μ to vector bosons. Photons are consistent with the constraints of the $U(1)$ symmetry of QED (being massless spin 1 bosons that do not self-interact) and were confirmation that QED was an accurate description of the EM force. As with the other two forces in the SM, we say that the photon “mediates” EM interactions between particles charged under QED, as the photon’s coupling to electrically charged particles is responsible

for the forces between them. For example, the Feynman diagram in Fig. 2.2 shows the electromagnetic repulsion of two electrons propagating through space-time by the exchange of a virtual photon, the mediator of the EM force.

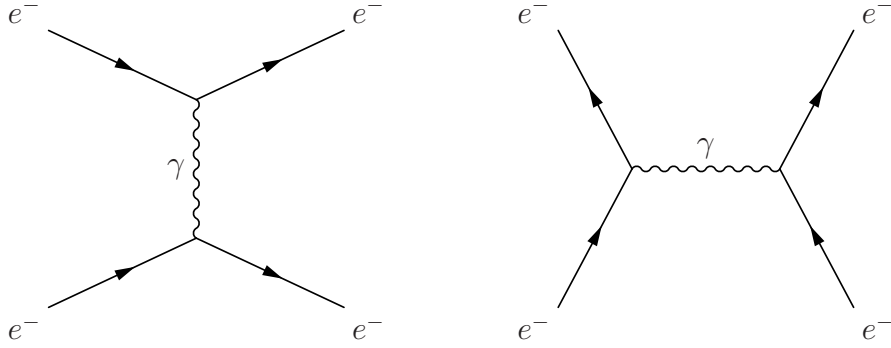


Figure 2.2: Left: A tree-level Feynman diagram in the t-channel showing two electrons interacting (repelling) via the exchange of a virtual photon. Right: Rotating the t-channel diagram 90 degrees gives the s-channel diagram, showing the annihilation of an electron-antielectron pair into a virtual photon, which propagates before decaying again into an electron-antielectron pair. Both phenomena are described with QED.

At very high energies (such as shortly after the big bang) the EM interaction is understood to be unified with the weak interaction, collectively called the electroweak force, that is only broken into separate forces at a temperature of approximately 10^{15} K (explained in more detail in Section 2.1.2.2).

2.1.2.2 The weak interaction

Weak interactions are best described in a unified framework with electromagnetism called Electroweak Theory (EWT). The gauge fields of EWT are the weak isospin triplet W_μ^i ($i = 1, 2, 3$) and the weak hypercharge field B_μ which are symmetric under the gauge group $SU(2) \times U(1)_Y$. (The Y subscript of $U(1)_Y$ distinguishes this symmetry from the $U(1)_{EM}$ symmetry of QED.) These four fields correspond to the unphysical gauge bosons of EWT: the W_1 , W_2 , W_3 , and B bosons, all of which are massless.

Spontaneous symmetry breaking of EWT results in the manifestation of the physical bosons of the weak and electromagnetic interactions. Electric charge Q is the unique linear combination of weak isospin T and weak hypercharge Y_W :

$$Q = T_3 + \frac{1}{2}Y_W \quad (2.5)$$

The neutral weak boson Z^0 and the photon γ are a linear combination of the W_3 and B bosons:

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix} \quad (2.6)$$

where the parameter θ_W is the weak mixing angle. The W_1 and W_2 bosons likewise combine to form the charged weak bosons $W^\pm$ according to the complex linear combination:

$$\begin{pmatrix} W^+ \\ W^- \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -i \\ 1 & i \end{pmatrix} \begin{pmatrix} W_1 \\ W_2 \end{pmatrix}. \quad (2.7)$$

The weak bosons acquire mass from the Higgs field, while the photon remains massless.

2.1.2.3 The strong interaction

The strong force emerges from the $SU(3)_C$ gauge group of the SM which is described by the non-abelian gauge theory called Quantum Chromodynamics (QCD). The $SU(3)_C$ symmetry of QCD generates eight massless vector (spin 1) gauge bosons called gluons, the carriers of the strong force, that exclusively interact with particles carrying “color” charge: either red, blue, green, antired, antiblue, or antigreen. Of the fermions, only quarks carry color charge and interact with gluons. As gluons themselves carry a color and anticolor charge, they self-couple and may interact at four- and three-point vertices. This self-interaction among the force-carrying gluons prevents any energy fall-off between two color-charged quarks as the distance between them increases. At a certain distance of separation, the binding energy

becomes so large that it is energetically favorable to produce two new quarks from the vacuum to bind to the original, separated quarks, and form two color-neutral hadrons rather than two “free” or color-bare quarks. This phenomenon is called confinement, and is responsible for the hadronization of free quarks into jets, and why it is impossible to observe a free quark; quarks will always be observed in bound states as hadrons (see Section 2.1.1.1). The beta function of QCD, which charts how the strong coupling constant α varies with energy scale (or inversely, interaction distance) is given by:

$$\beta_1(\alpha) = \frac{\alpha_s^2}{\pi} \left(-\frac{11N}{6} + \frac{n_f}{6} \right) \quad (2.8)$$

with $N = 3$ for the SU(3) gauge of QCD, and n_f the number of quark-like fermions. As long as $n_f < 16$, which experiment has so far confirmed (only six known quarks in the SM have been observed), the beta function is negative and is asymptotically free, i.e., the coupling strength of QCD decreases with the energy scale of the interaction. Asymptotic freedom allows for the binding of protons together with neutrons within the close-proximity of an atomic nucleus, on the order of 1-3 fm, and likewise the binding of quarks within protons and neutrons (and other hadrons), on the order of < 0.8 fm.

2.1.2.4 The Higgs field

The Higgs field ϕ is a complex scalar field with a potential $V(\phi)$ of the form:

$$V(\phi) = -\frac{1}{2}\mu^2|\phi|^2 + \frac{1}{4}\lambda|\phi|^4, \quad (2.9)$$

where λ and μ are parameters (ultimately related to the Higgs self-coupling and Higgs mass). The potential has the famous “mexican hat” shape, symmetric about rotations in ϕ , with a non-zero minimum expectation value $\langle\phi\rangle \neq 0$, as seen in the graph in Fig. 2.3. Initially, the Higgs potential exists in the unstable state where $\langle\phi\rangle = 0$, preserving the ϕ symmetry. A fluctuation in the Higgs field will minimize the potential as ϕ acquires some non-zero vacuum

expectation value (VEV) $\langle 0|\phi|0\rangle = v$, and in doing so breaks the rotational symmetry of ϕ ; this is called spontaneous symmetry breaking. It is convenient to now parameterize ϕ in terms of two real scalar fields h and χ and expand about v , like:

$$\phi = \frac{1}{\sqrt{2}}(v + h)e^{i\chi/v}, \quad (2.10)$$

and after substituting the fields back into the lagrangian, we emerge with a massive physical higgs boson h and a massless “Goldstone” boson χ .

In EWT, the spontaneous symmetry breaking of the Higgs field is embedded in the $SU(2)_W \times U(1)_Y$ local gauge symmetry, where the Higgs field is now a weak isospin doublet. In a similar way to the above example, the electroweak symmetry is broken, and we are left with a massive Higgs field, and four massless Goldstone bosons. Through choosing a gauge, the Goldstone bosons are “eaten” and we are left with the physical gauge bosons of EWT: a massless photon and three massive weak gauge bosons.

The SM fermions couple to the Higgs field with so-called Yukawa couplings, like $\bar{\ell}_L \phi e_R$, $\bar{q}_L \phi d_R$, and $\bar{q}_L \tilde{\phi} u_R$ which form weak isospin singlets. After spontaneous symmetry breaking of the Higgs field, the fermions acquire masses in a similar way to the gauge bosons, while the absence of any right-handed neutrinos in the SM prevents them from coupling to the Higgs field and leaves them massless.

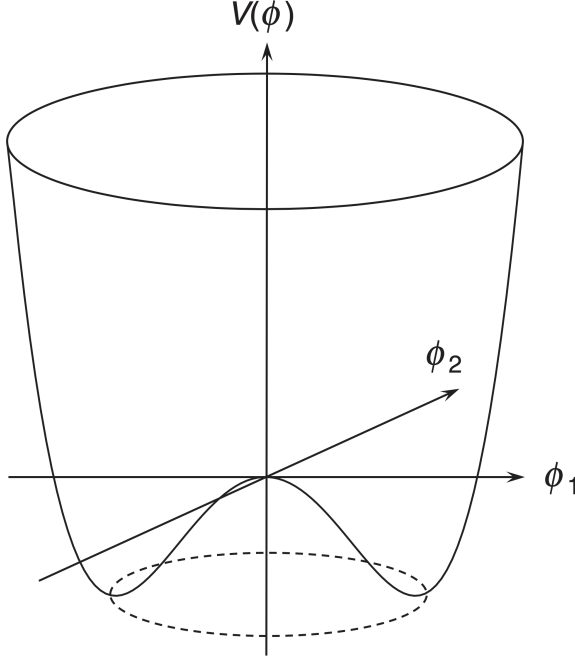


Figure 2.3: A graph of the Higgs potential $V(\phi)$ as a function of the complex scalar Higgs field ϕ with real and imaginary components ϕ_1 and ϕ_2 .

2.2 Leptoquarks

Many observed phenomena are conspicuously absent in the SM, confirming that while self-consistent, the SM is ultimately an incomplete theory. The gravitational force; the matter composition of the universe (including dark matter and dark energy); the matter-antimatter asymmetry in the universe; and massive, oscillating neutrinos, to name a few, all lack any prediction in the SM. Attempts to model these phenomena within the paradigm of QFT and merge them with the SM are often called extensions to the SM or beyond the SM theories. Many extensions to the SM, including Grand Unification [1][2], Technicolor schemes [3][4][5], composite models, and Supersymmetry [6] can—in certain models—predict the existence of a new heavy boson that would simultaneously carry a non-zero baryon number B and lepton number L , generically called a leptoquark (symbolically, LQ). Such a boson would mediate quark-lepton transitions and answer many of the questions left in the SM, such as

the remarkable symmetry of the quark and lepton generations.

2.2.1 Models

Leptoquarks can be scalar (spin 0) or vector (spin 1) bosons, are color-triplets under $SU(3)_C$, carry fractional electric charge and weak isospin. Listed in Table 2.3 are the possible quantum numbers a leptoquark may take assuming dimensionless couplings to SM fermions and invariance under the gauge group of the SM. The first two columns list the spin and fermion quantum numbers, followed by the QCD and weak isospin representations, the weak hypercharge, and the allowed couplings to chiral SM fermions (color indices, flavor indices, and charge conjugates have been suppressed). As the right-most column of Table 2.3 shows, leptoquarks may couple to only right-chiral fermions or left-chiral fermions, called chiral leptoquarks, or one left-chiral and one right-chiral fermion, called non-chiral leptoquarks. The allowed lepton and quark generations have historically been constrained to the same generation, motivated by experimental limits placed on rare processes like proton decay, and FCNCs [7]. However, as detailed in Section 2.2.2, allowing intergenerational mixing can provide an explanation for phenomena like the flavor anomalies and muon magnetic moment anomaly.

For a given leptoquark model there are also a set of free parameters, which include the mass M_{LQ} the Yukawa coupling at the leptoquark-quark-lepton vertex λ , and the decay branching fraction into a charged lepton β (with $\beta - 1$ the branching fraction into a neutrino). Specific to vector leptoquark models are two additional parameters λ_G and κ_G that correspond to the couplings of leptoquarks to SM gauge bosons at the gLQ and ggLQ vertices. The LHC is capable of both single- and pair-production of leptoquarks through large QCD cross sections, as shown in Figs. 2.4 and 2.5.

Table 2.3: List of quantum numbers and allowed couplings to quarks/leptons for different leptoquark models.

Spin	$3B + L$	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	Allowed coupling
0	-2	$\bar{3}$	1	1/3	$\bar{q}_L^c \ell_L$ or $\bar{u}_R^c e_R$
0	-2	$\bar{3}$	1	4/3	$\bar{d}_R^c e_R$
0	-2	$\bar{3}$	3	1/3	$\bar{q}_L^c \ell_L$
1	-2	$\bar{3}$	2	5/6	$\bar{q}_L^c \gamma^\mu e_R$ or $\bar{d}_R^c \gamma^\mu \ell_L$
1	-2	$\bar{3}$	2	-1/6	$\bar{u}_R^c \gamma^\mu \ell_L$
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$
0	0	3	2	1/6	$\bar{d}_R \ell_L$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$

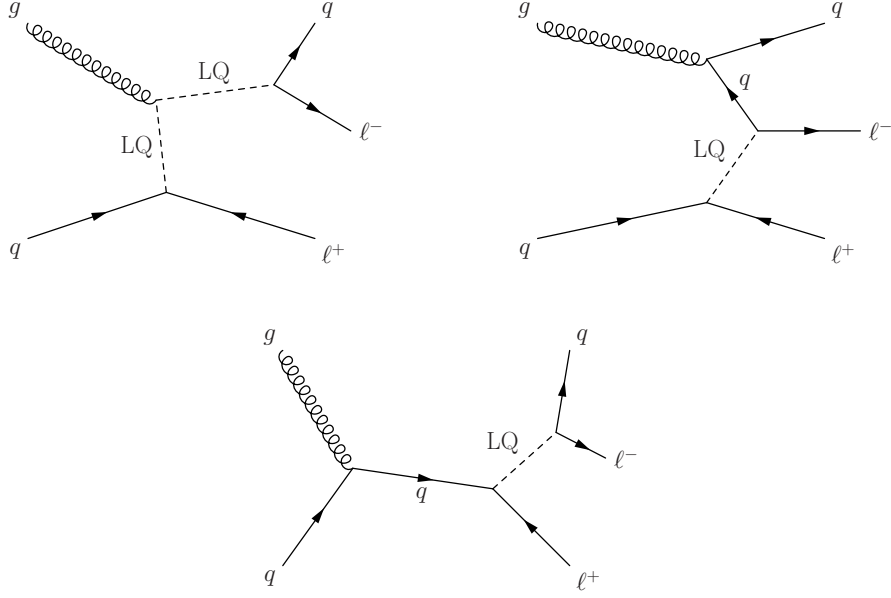


Figure 2.4: Production mechanisms of single leptoquarks at the LHC. Clockwise from top left: a t-channel processes that results in a resonant $q\ell$ pair and a non-resonant ℓ , a t-channel processes resulting in a non-resonant $\ell\ell q$ final state, and an t-channel process resulting in a resonant $q\ell$ pair and a non-resonant ℓ .

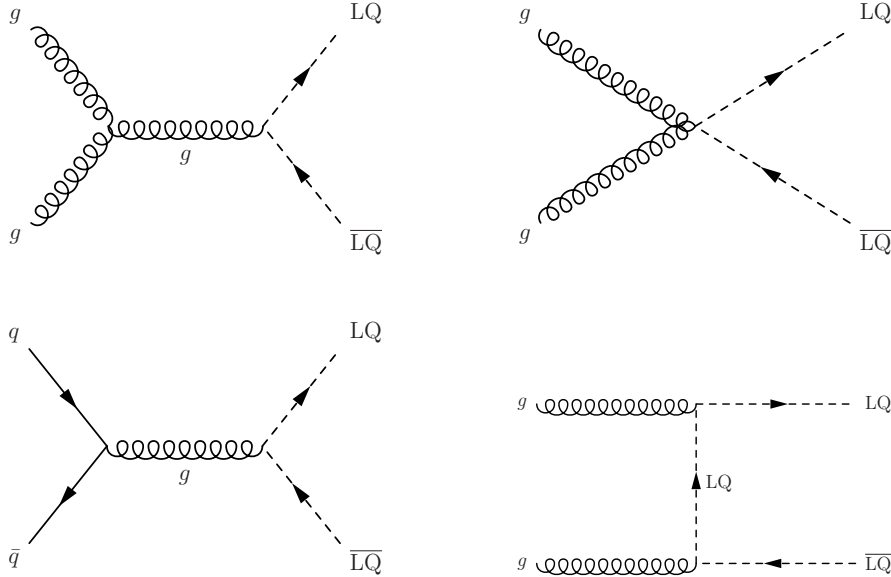


Figure 2.5: Production mechanisms of $LQ\bar{LQ}$ pairs at the LHC. Clockwise from top-left: s-channel gluon-gluon fusion, gluon-gluon four-point interaction, t-channel gluon-gluon interaction via leptoquark exchange, and s-channel quark-antiquark annihilation.

2.2.2 Experimental motivation

The SM assumes that the weak gauge bosons couple to each lepton flavor identically (or close to it), a phenomenon called lepton flavor universality. Tests of lepton flavor universality can be performed by studying flavor-changing neutral current (FCNC) transitions, such as when a bottom quark transforms into strange quark in the decay: $B \rightarrow K \ell^+ \ell^-$. As FCNC are suppressed at tree-level in the SM, occuring only via higher order electroweak processes (as shown in the left-hand diagram of Fig. 2.6), these decays are a powerful probe into new physics. Measurements by the LHCb, BaBar, and Belle collaborations of observables such as R_K , R_{K^*} , R_D , and R_{D^*} —the decay branching fractions of B mesons into an electron-positron pair over a muon-antimuon pair—hint at a possible violation of lepton flavor universality. Combining the flavor anomalies from each collaboration in R_{K^*} (Fig. 2.7, left) yields tension between experiment and the SM at 2 standard deviations [8], and for R_K (Fig. 2.7, right) up to 3.1 standard deviations [9]. Leptoquarks coupling to muons and bottom quarks are prime candidates to explain these flavor anomalies at tree-level, as shown in the right-hand diagram of Fig. 2.6.

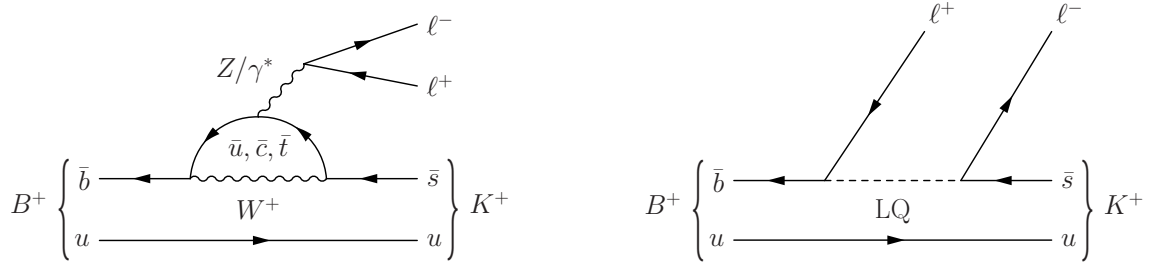


Figure 2.6: The decay of a charged B meson into a charged kaon and a pair of opposite-sign charged leptons. Left: An example of a loop diagram FCNC process in the SM that is strongly suppressed. Right: A tree-level FCNC solution with a leptoquark mediating the transition.

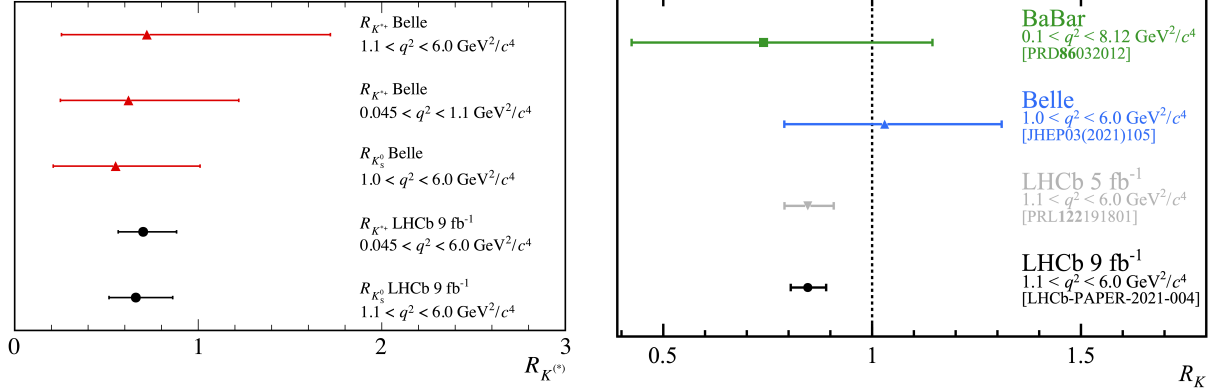


Figure 2.7: Left: A comparison of R_{K^*} measurements by the Belle and LHCb collaborations for several bands of the dilepton invariant mass squared q^2 . Right: A comparison of R_K measurements (combining $B^+ \rightarrow K^+ \ell^+ \ell^-$ and $B^0 \rightarrow K^0 \ell^+ \ell^-$ decays) by the BaBar, Belle, and LHCb collaborations for several bands of the dilepton invariant mass squared q^2 .

Another notable inconsistency between the SM prediction and experiment in which leptoquarks may play a role is the anomalous muon magnetic dipole moment. The magnetic moment of the muon is defined as:

$$\vec{\mu} = g_\mu \left(\frac{q}{2m_\mu} \right) \vec{s} \quad (2.11)$$

where the factor g_μ as predicted by the Dirac equation is equal to 2. Considering a number of EM, EW, and QCD radiative corrections (a few example diagrams are shown in Fig. 2.8, left), the SM value of g_μ is predicted with high precision to deviate from 2, encapsulated in the muon magnetic anomaly $a_\mu = (g_\mu - 2)/2$. Recent calculations set the SM theoretical value $a_\mu(\text{SM}) = 116\,591\,810(43) \times 10^{-11}$, a precision of 0.37 parts-per-million (ppm) [10]. Measurements of a_μ by the Muon $g - 2$ experiment at Brookhaven National Laboratory (BNL) and Fermilab National Accelerator Laboratory (FNAL) found a combined experimental average of $a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11}$, with an astonishing precision of 0.34 ppm [11], as shown in Fig. 2.9. The difference between the theoretical prediction and the experimental average has a significance of 4.2 standard deviations. Introducing leptoquarks that couple to muons could explain the deviation from the SM, as seen in the diagram in

Fig. 2.10.

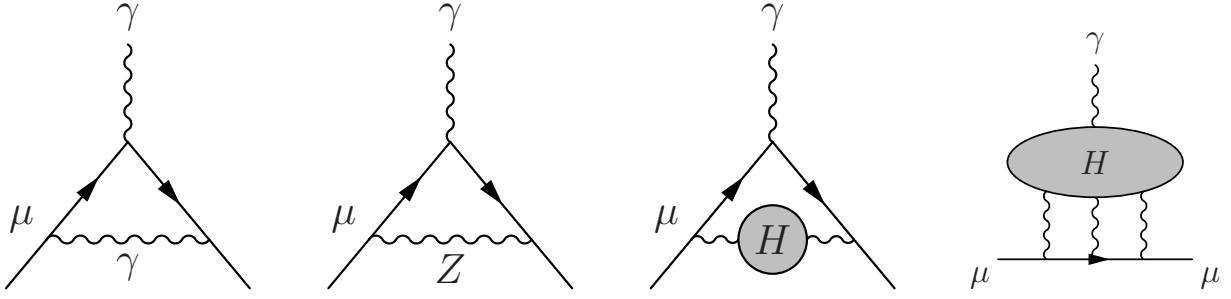


Figure 2.8: The Feynman diagrams of SM contributions to the muon anomaly. From left to right: the first-order QED and weak processes, leading-order hadronic vacuum polarization, and hadronic light-by-light contributions.

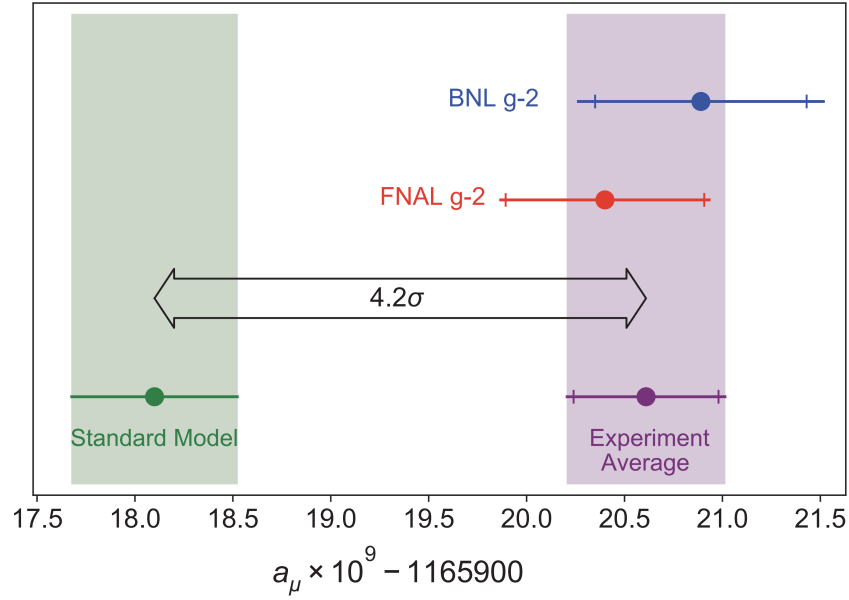


Figure 2.9: A comparison of a_μ measured by BNL, FNAL, and the combined average beside the SM prediction.

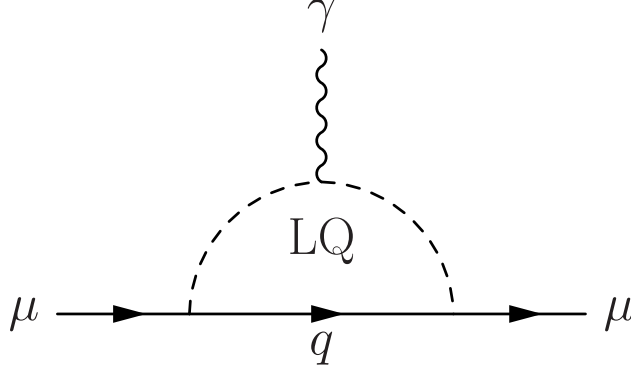


Figure 2.10: A Feynman diagram of a leptoquark solution to the magnetic anomaly a_μ .

2.2.3 This search

The leptoquark search detailed in Chapter 6 considers only pair-produced scalar leptoquarks that couple to a bottom quark and muon, but is otherwise model independent. These search parameters constrain λ_G and κ_G to zero, β to unity, and keeps the search insensitive to λ , leaving M_{LQ} the only search variable. Previous limits on leptoquark masses [12] motivate a mass scan of 30 points ranging from 300 GeV to 4000 GeV. This search is the first leptoquark search with muons in the final state to analyze the entire LHC Run II dataset collected by CMS and the first ever search for the process $LQ\overline{LQ} \rightarrow \mu^- \mu^+ b\overline{b}$ by CMS.

Chapter 3

Experimental Setup: The LHC and the CMS Detector

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [13] is a dual-ring high-energy particle accelerator and collider located at CERN, the European Laboratory for Particle Physics, in Geneva, Switzerland. Built in the tunnel of the dismantled LEP collider 50 m below the Swiss-French border (see Fig. 3.1), the LHC spans 27 km in circumference and currently holds the world record for the highest-energy particle collisions, having reached center-of-mass energies of 13 TeV during Run 2. Four independent detectors located at points along the circumference of the LHC record the collisions: Compact Muon Solenoid (CMS), A Toroidal LHC Apparatus (ATLAS), Large Hadron Collider beauty (LHCb), and A Lead Ion Collider Experiment (ALICE).



Figure 3.1: Left: A tracing of the LHC tunnel over the Swiss-French border near Geneva. Right: A section of the LHC beam pipe in the underground LHC tunnel.

Within the LHC, two beams of protons or heavy ions are accelerated in opposite direc-

tions, captured and stored by 400 MHz radiofrequency (RF) cavities located at 16 points along the LHC ring that longitudinally sort the beams into 2808 bunches of 1.15×10^{11} protons or Pb ions, with each bunch spaced 25 ns apart. The beams at the LHC are steered along each ring by 1232 8.3 T superconducting dipole magnets, while 392 superconducting quadrupole magnets focus the beams into a narrow transverse cross section of 3.8 μm . The beams cross at four insertion points along the LHC, where the proton-proton or lead ion collisions occur and are recorded by each of the four LHC experiments.

The LHC was designed to operate in several sequential phases. Phase-1 saw first collisions at $\sqrt{s} = 7 \text{ TeV}$ in 2010, followed by $\sqrt{s} = 8 \text{ TeV}$ collisions in 2012, and $\sqrt{s} = 13 \text{ TeV}$ in 2015. Phase-2 of the LHC will increase the instantaneous luminosity by a factor of ten, dubbed the High-Luminosity LHC (HL-LHC) era, slated to begin operation in 2027. Upgrades to the LHC and detectors are performed during long shutdown (LS) periods that separate data-taking runs.

The physics goals of the LHC could be broadly summerized with the following: to observe the last undiscovered particle in the SM, the Higgs boson; to search for evidence of beyond the SM physics; and to perform precision measurements of existing SM phenomena. On July 4th, 2012 it was announced that the ATLAS and CMS collaborations had independently observed the Higgs boson, which remains the hallmark achievement at the LHC.

3.2 The CMS detector

To meet the wide-ranging goals expected by the LHC physics program, the CMS detector [14] was installed at insertion point 5 (P5) along the LHC ring, and records the proton-proton collisions delivered by the LHC. The distinguishing feature of the CMS detector is a powerful superconducting solenoid magnet. Hermetic in coverage and cylindrical in geometry, the CMS detector is divided into three subsystems: the inner tracker, the hadronic and electromagnetic calorimeters, and the muon system. A two-level trigger system is responsible

for rejecting uninteresting physics events to reduce the storage size of the collision data. A diagram of the CMS detector is shown in Fig. 3.2.

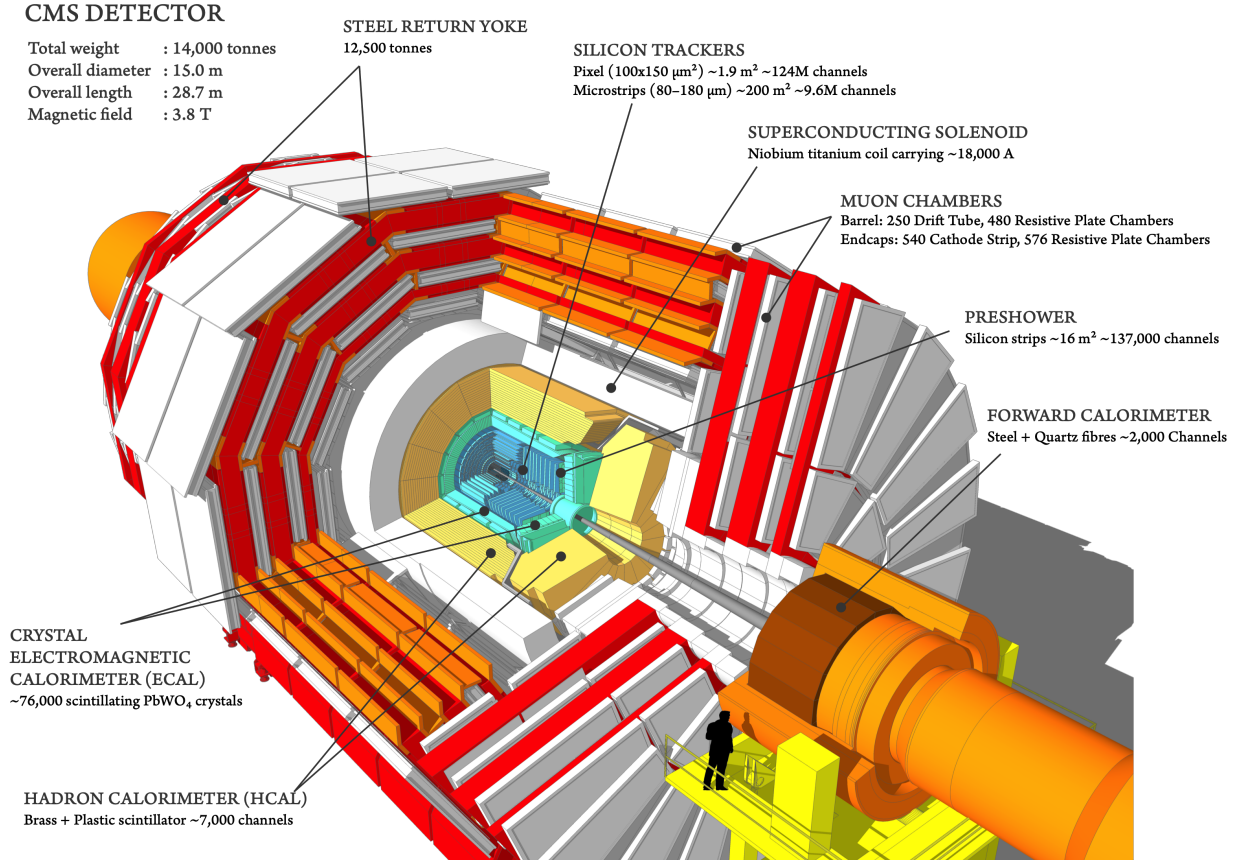


Figure 3.2: A cutaway diagram of the CMS detector

Data-taking periods at LHC experiments are grouped into runs each lasting several years, separated by long shutdowns (LS) where important upgrades to the detectors are made. Run 1 saw the CMS detector begin data-taking in 2010 with the recording of collisions at $\sqrt{s} = 7 \text{ TeV}$, followed by $\sqrt{s} = 8 \text{ TeV}$ collisions in 2012, at which point the CMS and ATLAS collaborations famously co-discovered the Higgs boson. Following the success of Run 1, the LHC ramped down for two years of upgrades in what would be the first long shutdown (LS1). In 2015, CMS started recording $\sqrt{s} = 13 \text{ TeV}$ collisions for Run 2 of data-taking which lasted until 2018. Following Run 2, more upgrades to the detector were made, and in 2022 CMS launched Run 3 of data-taking at $\sqrt{s} = 13.6 \text{ TeV}$, which remains ongoing.

3.2.1 Tracker

The inner-most detector, closest to the beam pipe, is the CMS tracker system, which uses two technologies: silicon pixels and silicon microstrips (photos of each shown in Fig. 3.3). The purpose of the CMS tracking system is to reconstruct the trajectories of electromagnetically charged physics objects close to the interaction point and measure the positions of the primary vertex (PV) of collisions and secondary vertexes of displaced decays (e.g., B hadrons). Owing to its proximity to the primary-interaction point, the CMS tracker is subject to the highest dosage radiation of all the subsystems.

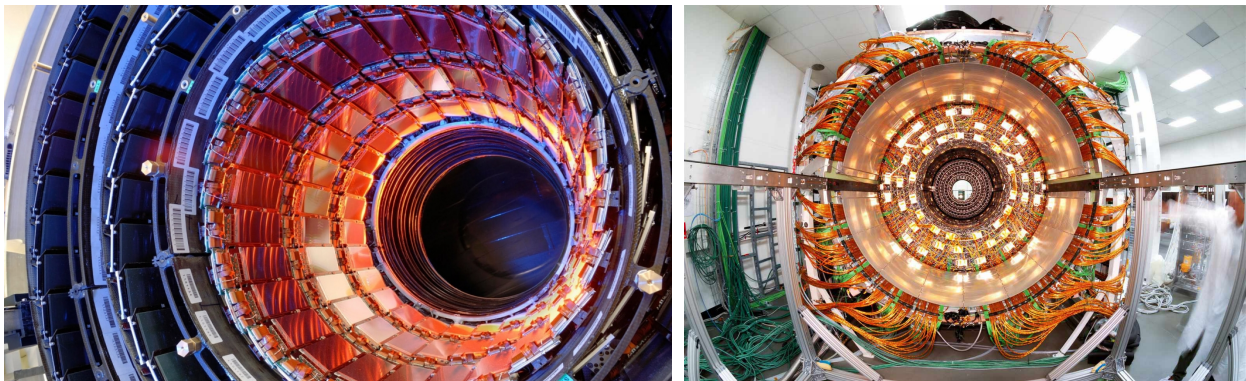


Figure 3.3: Photographs of the silicon strip detectors (left) and the pixel detectors (right) in the tracker barrel prior to installation.

3.2.1.1 Pixel tracker

The silicon pixel detector, upgraded to the Phase-1 pixel detector [15] during the 2016-2017 year-end technical stop of Run 2 to cope with higher integrated luminosities, provides a four-hit coverage in the pseudorapidity range $|\eta| < 2.5$. This is accomplished through silicon sensor modules, where each module is a 160×416 pixel sensor connected to 16 readout chips. The modules are arranged in two configurations: four concentric barrel pixel detectors (BPIX) with 1,184 modules, and three endcap disk pixel detectors in the forward regions (FPIX) with 672 modules, for a total of 1856 silicon sensor modules and 124 million readout channels. A schematic of the upgraded Phase-1 pixel detector is provided in Fig. 3.4 showing

the pseudorapidity coverage.

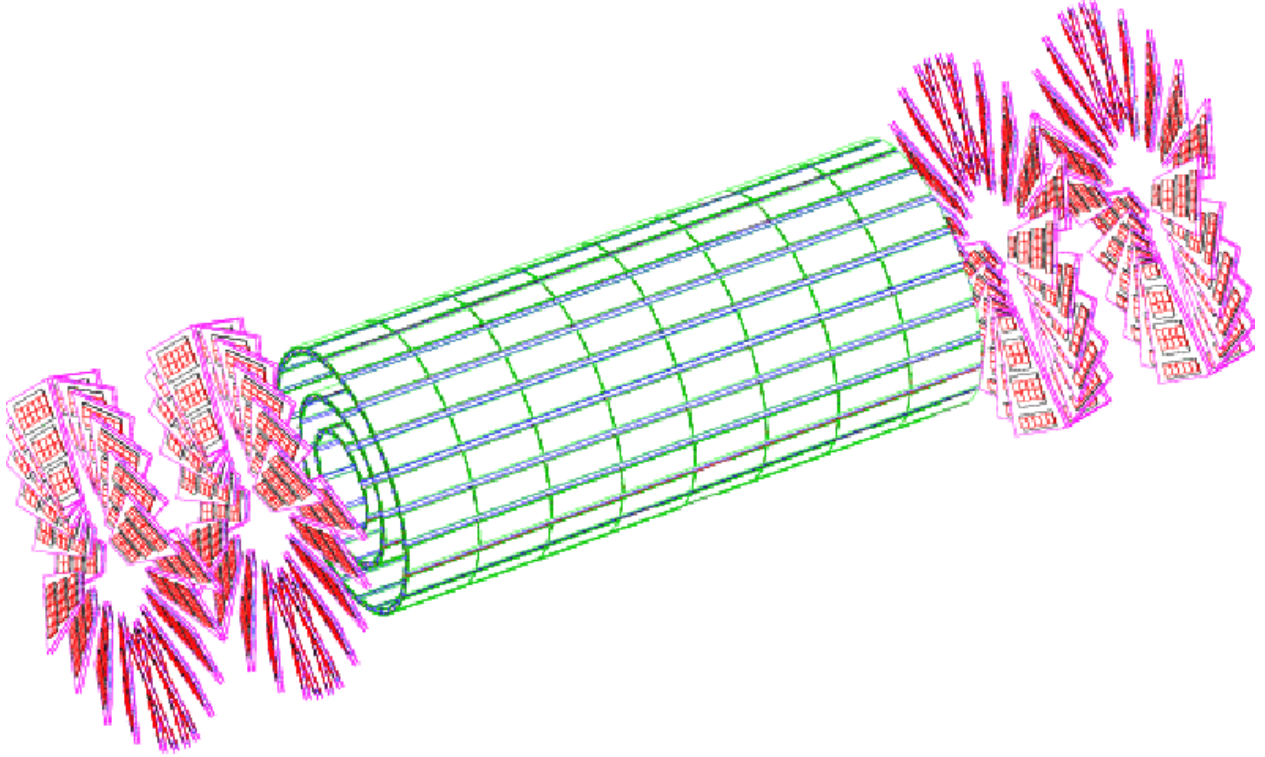


Figure 3.4: A diagram of the Phase-1 pixel detector with the BPIX drawn in green and the FPIX drawn in magenta.

3.2.1.2 Strip tracker

Surrounding the pixel detector is the silicon strip tracker [16] which serves the same function as the pixel tracker and covers hits in the same pseudorapidity $|\eta| < 2.5$ range. The silicon strip detector is also built with a modular structure, with 15,148 tracker modules each housing one or two silicon sensors totaling 24,244 strip sensors. The silicon strip tracker is divided into four sections: inner barrel (TIB), outer barrel (TOB), inner disks (TID), and outer endcaps (TEC). The TIB and TOB consist of four and six concentric shells respectively, while the TID consists of three disks in each of the forward regions, divided into three concentric rings, and the TEC consists of nine disks with four to seven concentric rings, also in the forward regions. A schematic of the silicon strip detector is provided in Fig. 3.5

showing the pseudorapidity coverage.

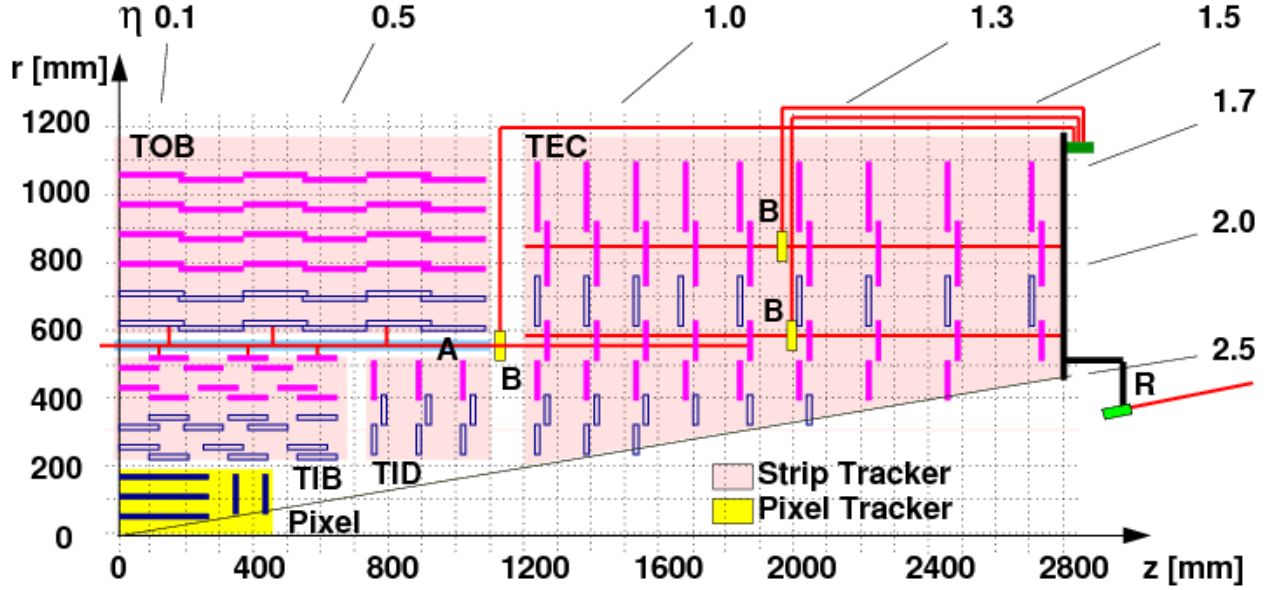


Figure 3.5: A schematic cutaway showing one quadrant of the strip and pixel trackers.

3.2.2 Calorimeters

To measure the energy deposits of electromagnetic particles (e.g., electrons, photons) and hadrons (e.g., neutrons, mesons, jets), CMS relies on two calorimeters: the electromagnetic calorimeter and the hadronic calorimeter, both surrounding the CMS tracker and inside the solenoid magnet.

3.2.2.1 The Electromagnetic Calorimeter

Immediately surrounding the CMS tracker is the CMS Electromagnetic Calorimeter (ECAL) [17], which allows CMS to measure the energy deposits left by electrons and photons: highly-favored decay modes of the Higgs boson and critical in its discovery. To optimize performance, the ECAL was designed with the following performance goals: excellent energy and spacial resolution, hermeticity and high-granularity, fast particle identification and fast energy and isolation measurements at trigger-level, a wide energy range (5 GeV to 5 TeV), and high radiation tolerance. Energy showers from electrons and photons are measured by an

array of lead tungstate (PbWO_4) scintillating crystals (Fig. 3.6, left). The ECAL is fully hermetic, composed of a barrel (EB) with a pseudorapidity coverage of $|\eta| < 1.48$ and two endcaps (EE) that extend the range to $|\eta| < 3.0$, (Cutaways of the EE and EB are shown on the right of Fig. 3.6). Within the EB, crystals are grouped into 36 supermodules each containing 1700 crystals, and in each EE crystals are grouped into two dees with 3662 crystals in each, for a total of 75848 crystals in the ECAL. Crystals are oriented in a projective geometry, with an approximately 3° tilt to avoid aligning crystal gaps with radial particle trajectories. Lining the inner faces of the EE dees in the range $1.65 < |\eta| < 2.6$ are preshower detectors (ES) made from lead absorbers and silicon strip sensors. A diagram of the ECAL showing the supermodule placement and pseudorapidity coverage is provided on the right of Fig. 3.7.

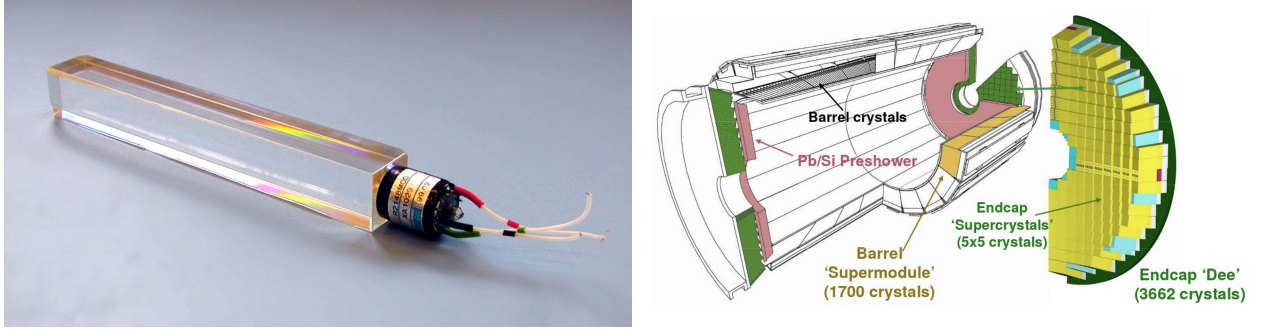


Figure 3.6: Left: A photograph of an ECAL crystal. Right: A cutaway showing the orientation of the ECAL supermodules in the barrel and endcap.

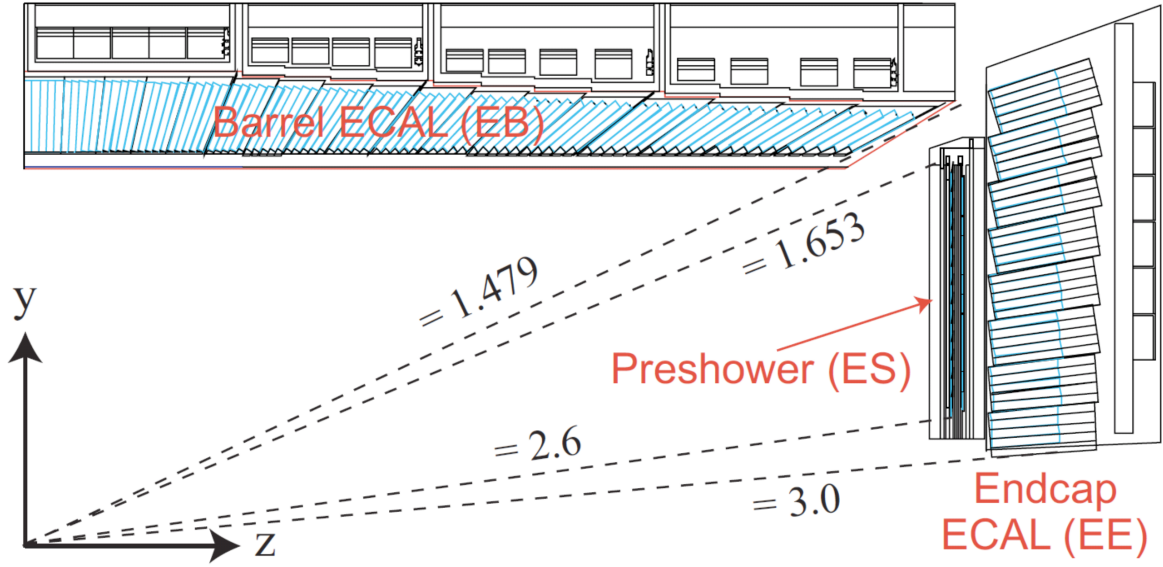


Figure 3.7: A schematic cutaway showing one quadrant of the ECAL.

3.2.2.2 The Hadron Calorimeter

The CMS Hadron Calorimeter (HCAL) [18] measures quark, gluon, and neutral particle energy and direction by observing jet energy and missing transverse energy. Within the solenoid magnet, the HCAL is separated into a barrel (HB) and two endcaps (HE), forming the “central” HCAL, with a combined pseudorapidity coverage of $|\eta| < 3.0$. An additional two detectors are located outside the solenoid magnet: an array of scintillators that catch the tails of hadronic showers and aid in muon identification called the HCAL Outer calorimeter (HO); and the forward calorimeter (HF), located 6 m down the beamline from the “central” HCAL (one at each end) and covering the pseudorapidity range $3.0 < |\eta| < 5.0$, required for accurate missing transverse energy measurements (a diagram showing the arrangement and pseudorapidity coverage of the HCAL and HF is shown in Fig. 3.9). The HB is divided into two half-barrels, each housing 18 wedges (20° in ϕ) of brass alloy absorber plates with a wavelength shifting fiber (WSF) readout. Both the HEs and HFs are composed of quartz fibers embedded in a copper absorber matrix. Optical signals are transmitted to hybrid

photo diodes (HPD) in the HB and HE, and by photomultiplier tubes (PMT) in the HFs. A photograph of the HB during installation is shown in Fig. 3.8.

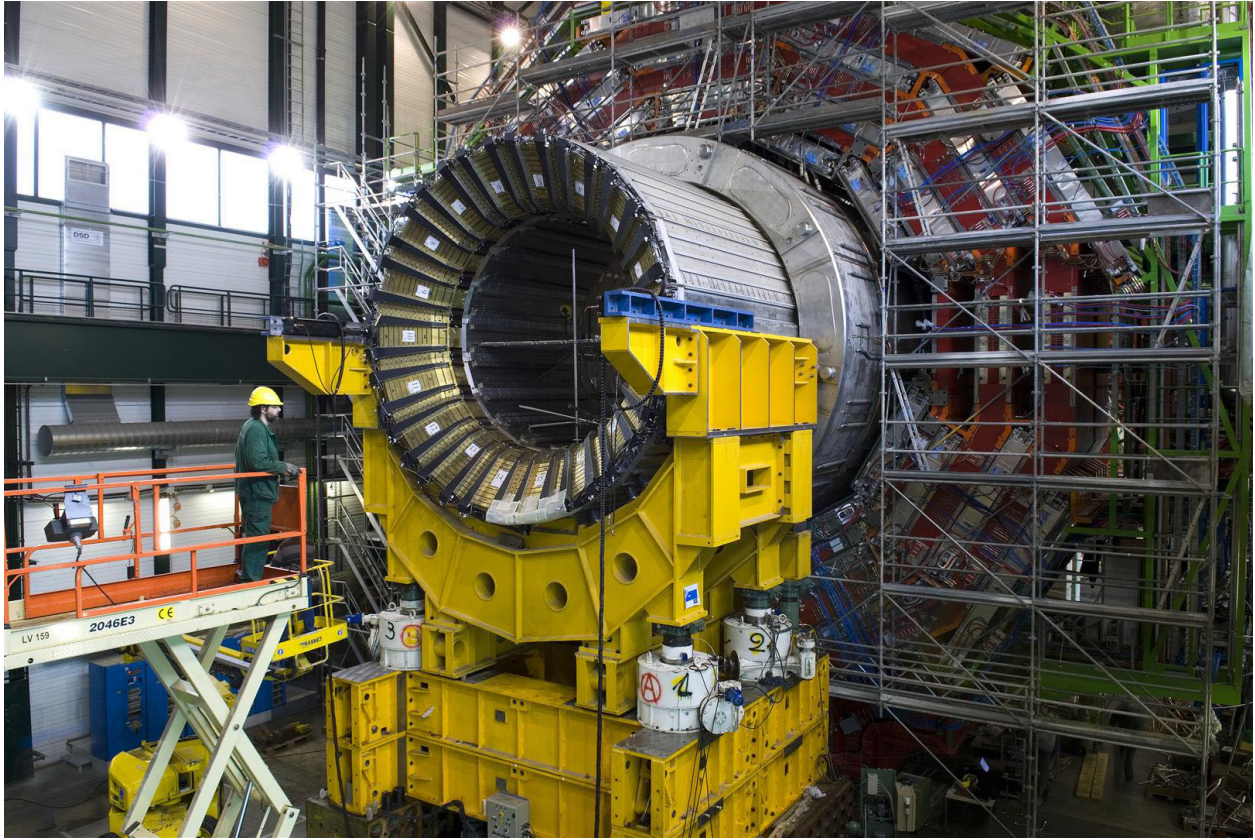


Figure 3.8: A photograph showing the HCAL barrel during installation.

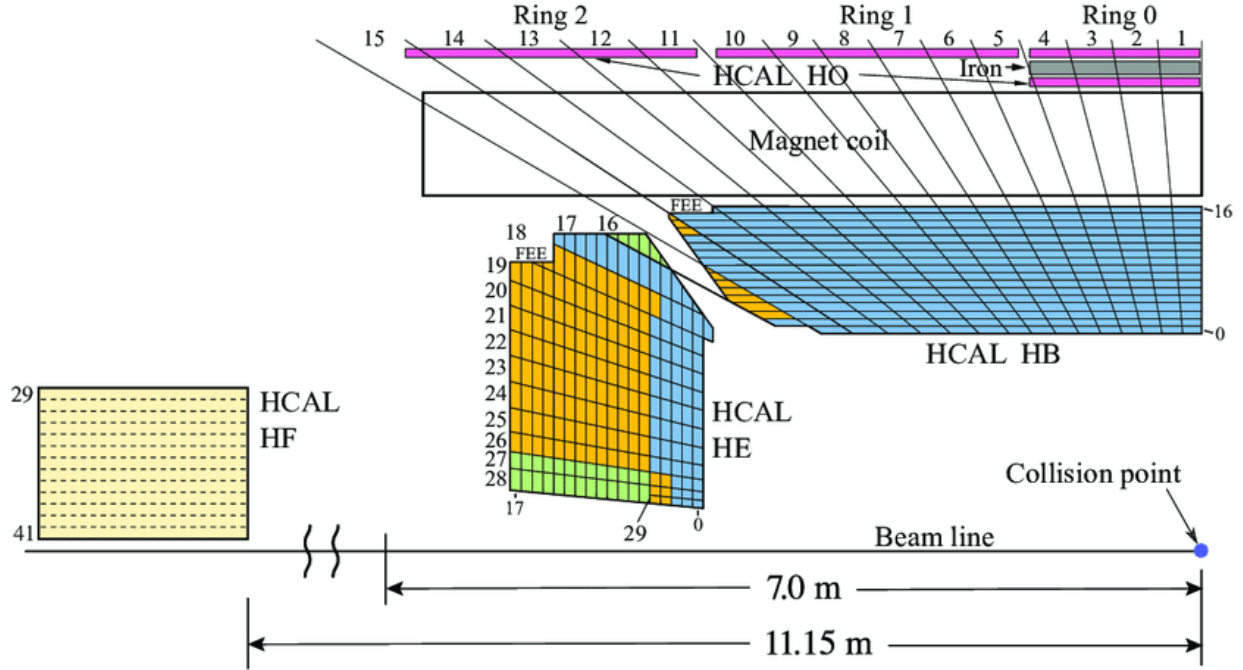


Figure 3.9: A schematic cutaway showing one quadrant of the HCAL.

3.2.3 Solenoid magnet

Enclosing the CMS tracker and calorimeters is a 3.8 T superconducting solenoid magnet—the most powerful in the world. The cylindrical structure of the solenoid measures 6 m in internal diameter and 12.5 m long, seen in the photograph in Fig. 3.10. The high magnetic field inside the solenoid is necessary to induce sufficient bending of charged particle trajectories in the transverse plane so precise p_T measurements can be made by the tracker. Outside the solenoid is a ferromagnetic return yoke made of construction steel, divided into five wheels in the barrel region labeled YBw and three disks in each (positive and negative) endcap labeled $YE\pm n$. The return yoke induces a strong magnetic field within the muon system (mounted to the return yoke) that improves the p_T measurements of muons. The direction of the bending of particles inside the tracker and muon systems is also used to identify the charge sign. The solenoid magnet also serves as a support structure for the 10 000 ton steel return yoke.

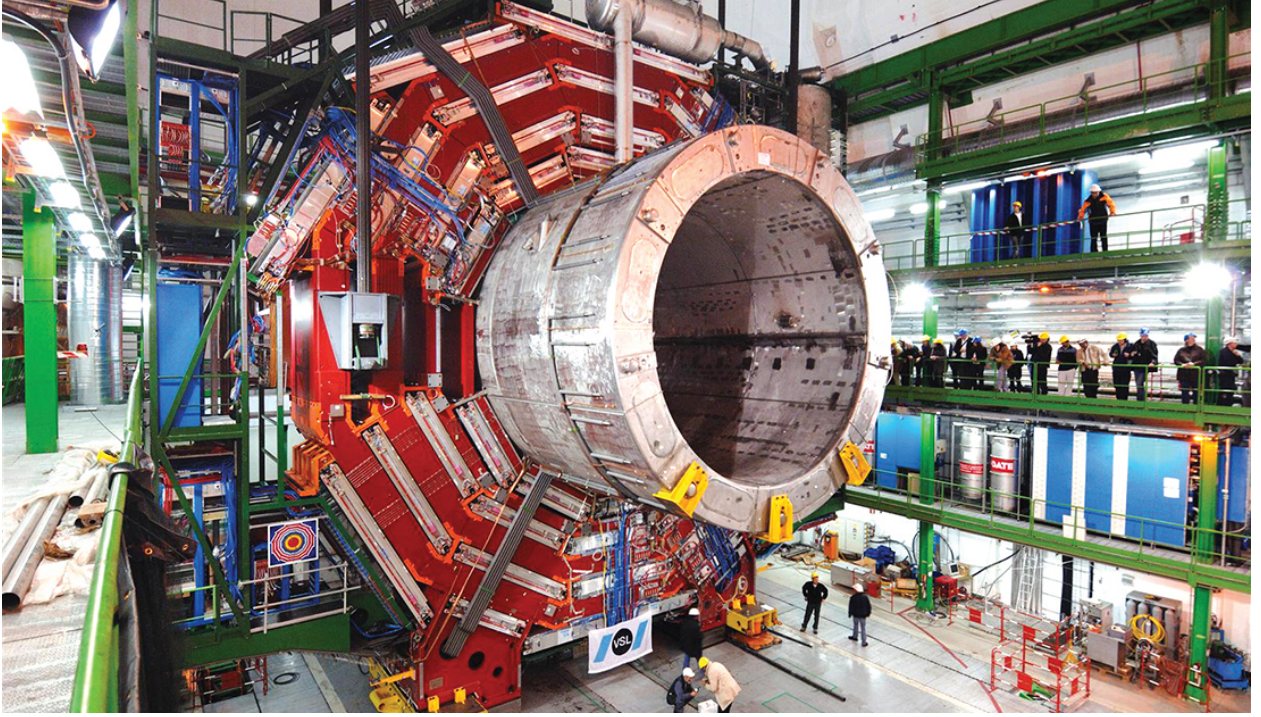


Figure 3.10: The solenoid magnet of CMS together with a wheel of the steel return yoke.

3.2.4 Muon system

The muon system [19] is responsible for recording the momenta of muons in the outer-most layer of CMS. As muons provide a clean signature in many physics analyses, obtaining high-resolution measurements of muon momenta is critical. It comprises four separate technologies that provide redundancy in both the barrel and endcap regions. The subsystems are the Drift Tubes (DTs) in the barrel, the Cathode Strip Chambers (CSCs) in the endcap regions, the Resistive Plate Chambers (RPCs) in both the barrel and endcaps, and as of Run 3, the Gas Electron Multipliers (GEMs) located in the outer-most layer of the endcaps. Each subsystem uses a different technology and records muon hits separately, with reconstruction combining the information from all the subsystems. The muon barrel (MB) system is divided into four concentric shells, or stations, in each of the five wheels of the CMS barrel, labeled from inner-most to outer-most (along the r -coordinate): MB1, MB2, MB3, and MB4. Similarly, the muon endcap (ME) system is arranged into four disks in both the plus and minus endcaps,

also called stations, labeled from inner-most to outer-most (along the z -coordinate): $ME\pm 1$, $ME\pm 2$, $ME\pm 3$, and $ME\pm 4$ ($\pm$ of course identifies the plus or minus endcap). Figure 3.11 shows a diagram including each subsystem and the pseudorapidity coverage of the muon system.

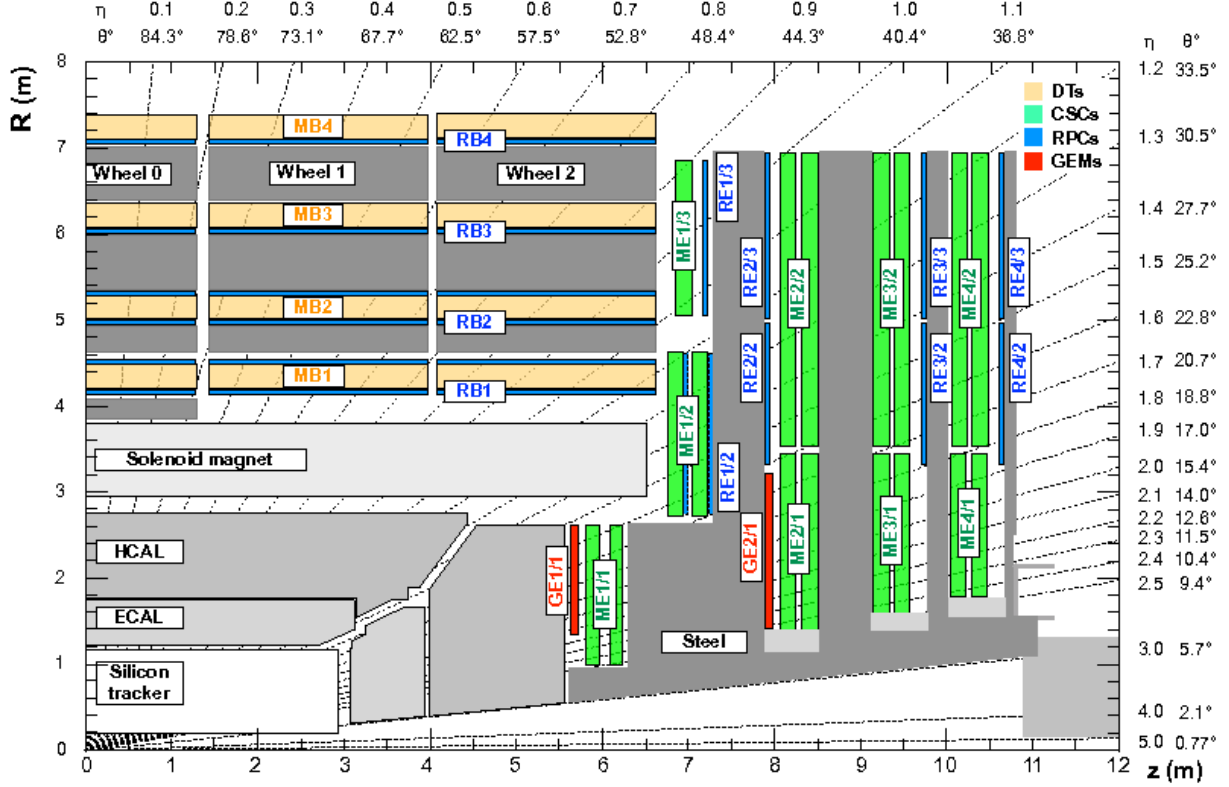


Figure 3.11: A cutaway schematic of one quadrant of the muon system. Included are the CSCs, DT chambers, RPCs, and GEM detectors.

3.2.4.1 Cathode Strip Chambers

Providing coverage in the plus and minus MEs within $0.9 < |\eta| < 2.4$ are the Cathode Strip Chambers (CSCs), which occupy the four ME stations along with RPCs. CSCs are labeled by ME station $\pm n$, then by ring m , like “ $ME\pm n/m$.” In $ME\pm 2$ to $ME\pm 4$, each station consists of two concentric rings of CSCs, while $ME\pm 1$ supports three rings of chambers (see Fig. 3.12). All rings contain 36 chambers, except for the inner-most rings of stations 2-4 ($ME\pm 2/1$, $ME\pm 3/1$, and $ME\pm 4/1$) which hold only 18 chambers, for a total of 540 CSCs.

Within each ring, CSCs are azimuthally overlapping with no gaps, offering full ϕ coverage. Each chamber is constructed from seven layers of polycarbonate honeycomb panels, with a gas mixture of 50% Ar, 40% CO₂, and 10% CF₄ filling the six gaps between the panels. Embedded in a thin FR4 (fire-resistant fiberglass epoxy) surface on each panel are radially-extended cathode strips. Within each gap are azimuthally-running anode wires supplied with 2.9–3.5 kV of voltage. Muons passing through a chamber will locally ionize the gas in each gap, while the high voltage will induce a charge avalanche that drifts toward the cathode strips and an image charge will drift toward the anode wires (see Fig. 3.13). Each chamber provides a spatial resolution of 50 to 140 μm (depending on the chamber) and a timing resolution of 3 ns.

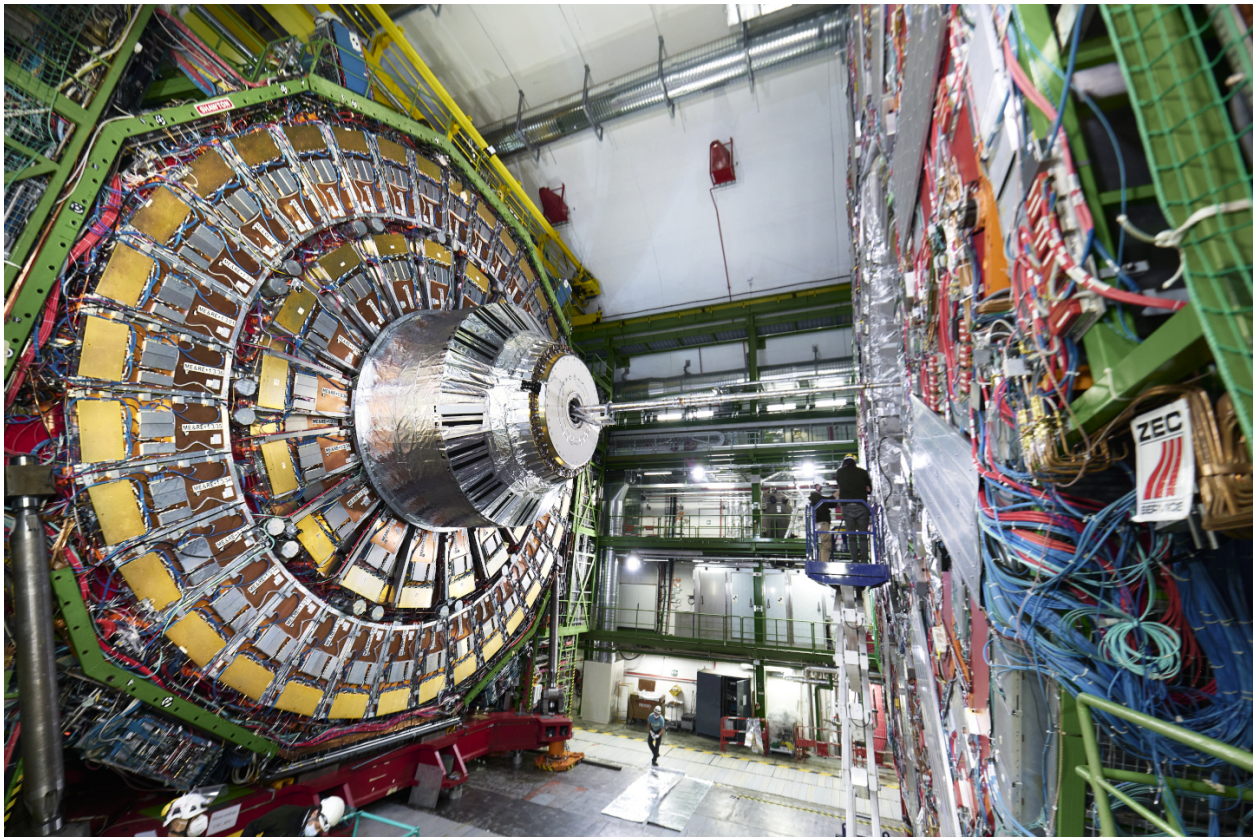


Figure 3.12: A photograph of CSCs mounted to the first endcap station.

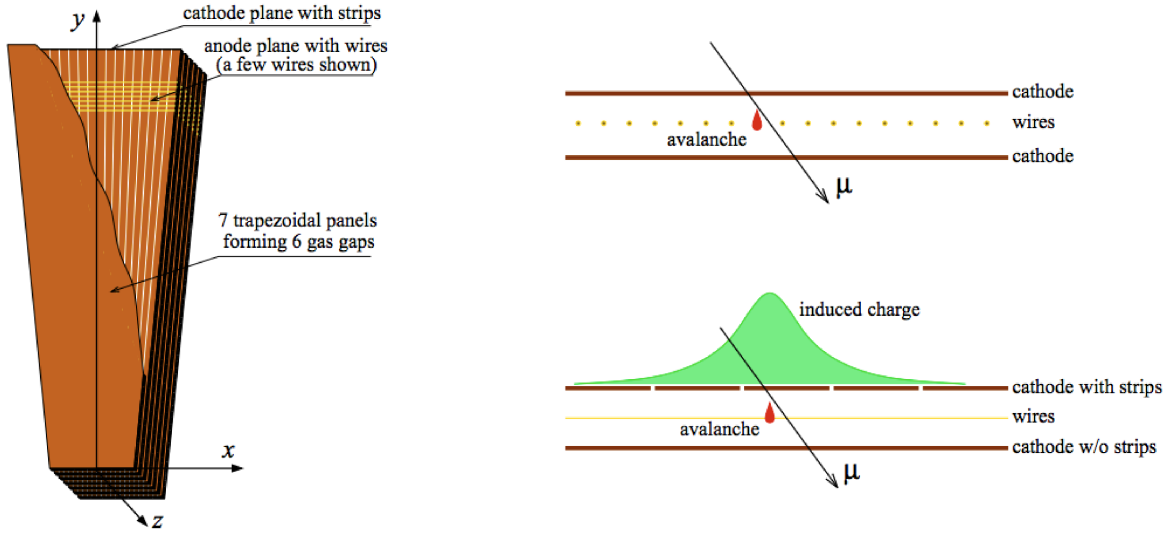


Figure 3.13: Left: A schematic of a CSC. Right: A muon passing through a CSC will induce a charge avalanche.

3.2.4.2 Drift Tubes

Located in the MB are 250 Drift Tube (DT) chambers, layered between RPCs, and arranged to provide coverage within $|\eta| < 1.2$ overlapping with the CSC coverage in the muon endcaps (see Fig. 3.14). DT chambers are labeled by MB station n , then by wheel w , like “MB $n \pm w$.” A single DT consists of a long aluminum drift cell filled with a gas mixture of 85 % Ar and 15 % CO₂ and a central anode wire strung length-wise inside the cell held at 3600 V. Electrode strips held at 1800 V and cathode strips held at -1200 V line the walls of each cell and help shape the electric field inside (see the diagram in Fig. 3.15). In MB1-MB3, the DT chambers are grouped into three collections of four consecutive, staggered layers of drift tubes called Super Layers (SLs), while in MB4 there are only two SLs per chamber. The inner-most and outer-most SL in a DT chamber measure r - ϕ coordinates in the bending plane, while the middle SL measures along the z -coordinate. Between the outer-most and middle SL is a honeycomb layer that produces a 28 cm separation of measurements in the bending plane, which aid in determining muon track bending. In MB4, DT chambers consist only of the two SLs measuring the r - ϕ -coordinate, with no honeycomb spacer or z -coordinate SL. The

spatial resolution per cell is at least $250\text{ }\mu\text{m}$, corresponding to a roughly $100\text{ }\mu\text{m}$ resolution per chamber, while the time resolution per DT chamber is 2 ns .

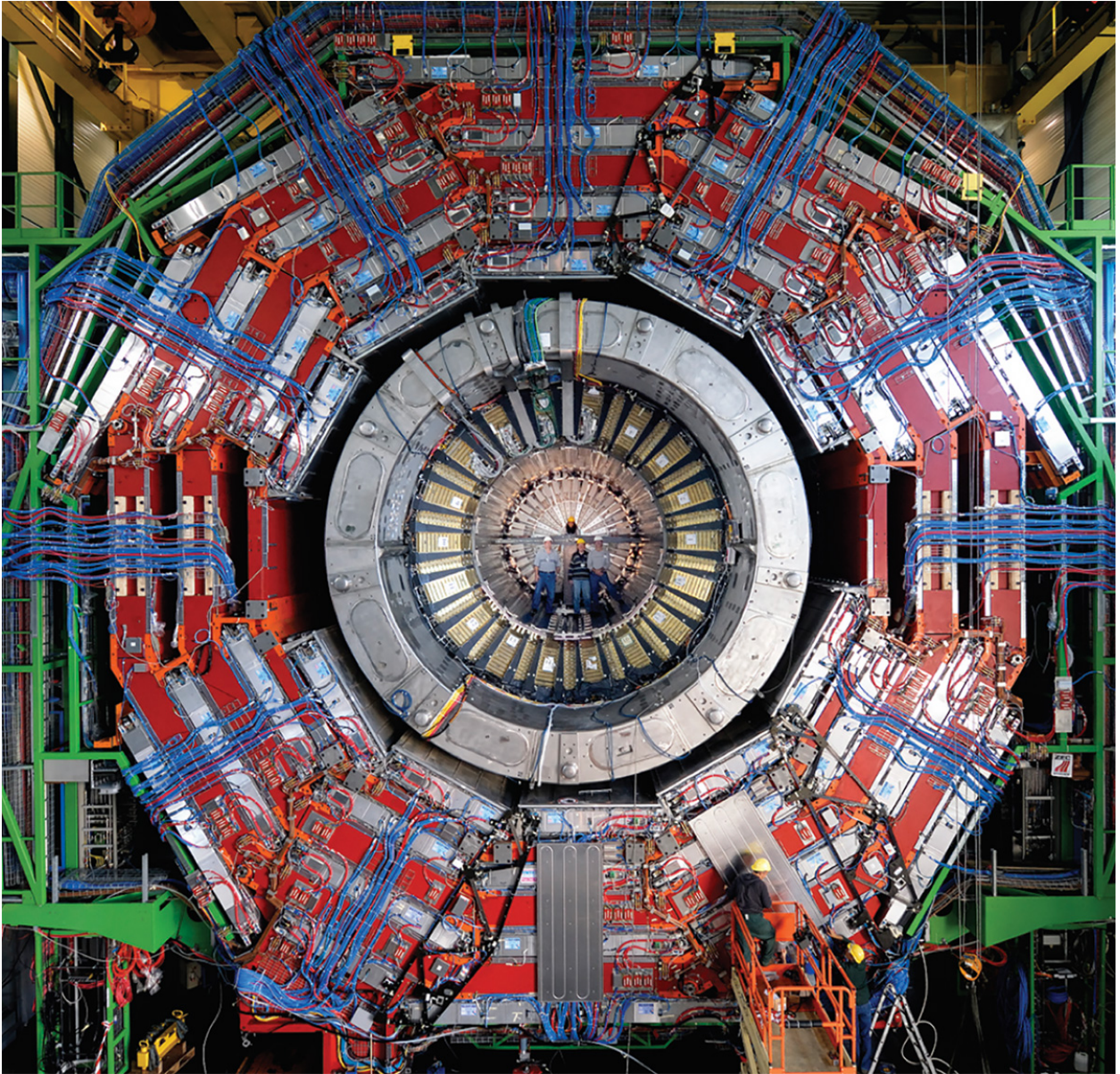


Figure 3.14: A photograph of DT chambers (silver boxes) installed in the return yoke (red structure) of a wheel in the muon barrel.

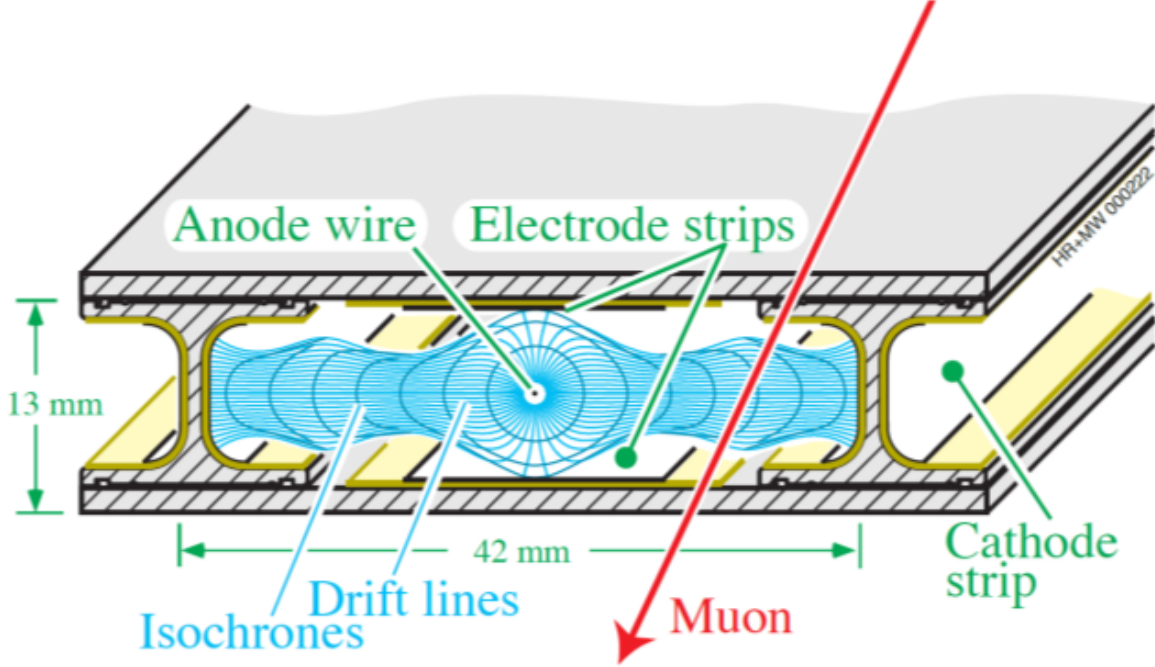


Figure 3.15: A diagram of a single DT chamber.

3.2.4.3 Resistive Plate Chambers

Complementing the DT chambers and CSCs are the Resistive Plate Chambers (RPCs) located in both the MB and ME (shown in Fig. 3.17). RPCs have two naming conventions, depending on the region of the detector they occupy: in the barrel, “ $RB_{n\pm w}$,” and in the endcaps, “ $RE_{\pm n/m}$,” where $(\pm)n$ denotes the MB or ME $\pm$ station (1-4), $\pm w$ the MB wheel (1-5), and m the ME ring (1, 2, or 3 in $RB_{\pm 1}$; 1 or 2 in all other stations). Pseudorapidity coverage by the RPCs overlaps with the other muon subsystems at $0.0 < |\eta| < 1.9$. In stations RB1 and RB2, two RPCs sandwich each DT chamber, while in RB3 and RB4, anywhere from one to four RPCs (depending on the station and sector) are layered on the inside of a single DT chamber. This leads to 480 total RPCs in the barrel. In the endcaps, RPCs are mounted to the opposite side of a yoke disk as the CSCs, forming alternating layers of CSCs and RPCs, and totalling 576 RPCs in the endcaps. Each RPC is a 2 mm double-gap chamber, using Bakelite (a high pressure laminate) electrodes, operated in avalanche mode (see the diagram in Fig. 3.16). Electrode strips are longitudinally-running and segmented

into two or three parts, depending on the station/sector. A RPC detector is optimized to record accurate timing and fast triggering, as well as identification the associated bunch crossing for a given muon track. Compared to the DTs and CSCs, RPCs have a coarse-grain spatial resolution of only 0.8 to 1.3 cm, but provide excellent timing resolution at 1.5 ns.

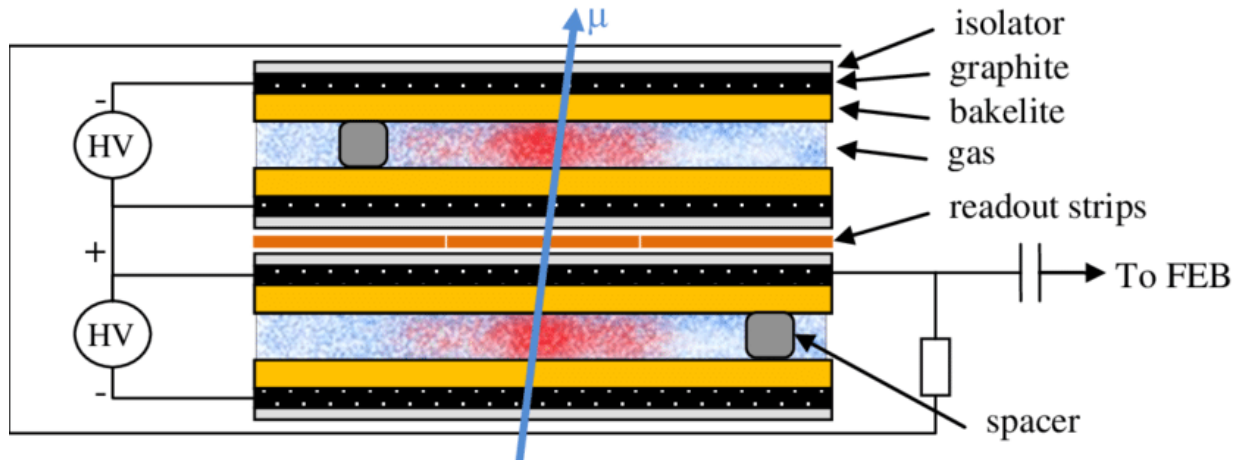


Figure 3.16: A diagram of an RPC.

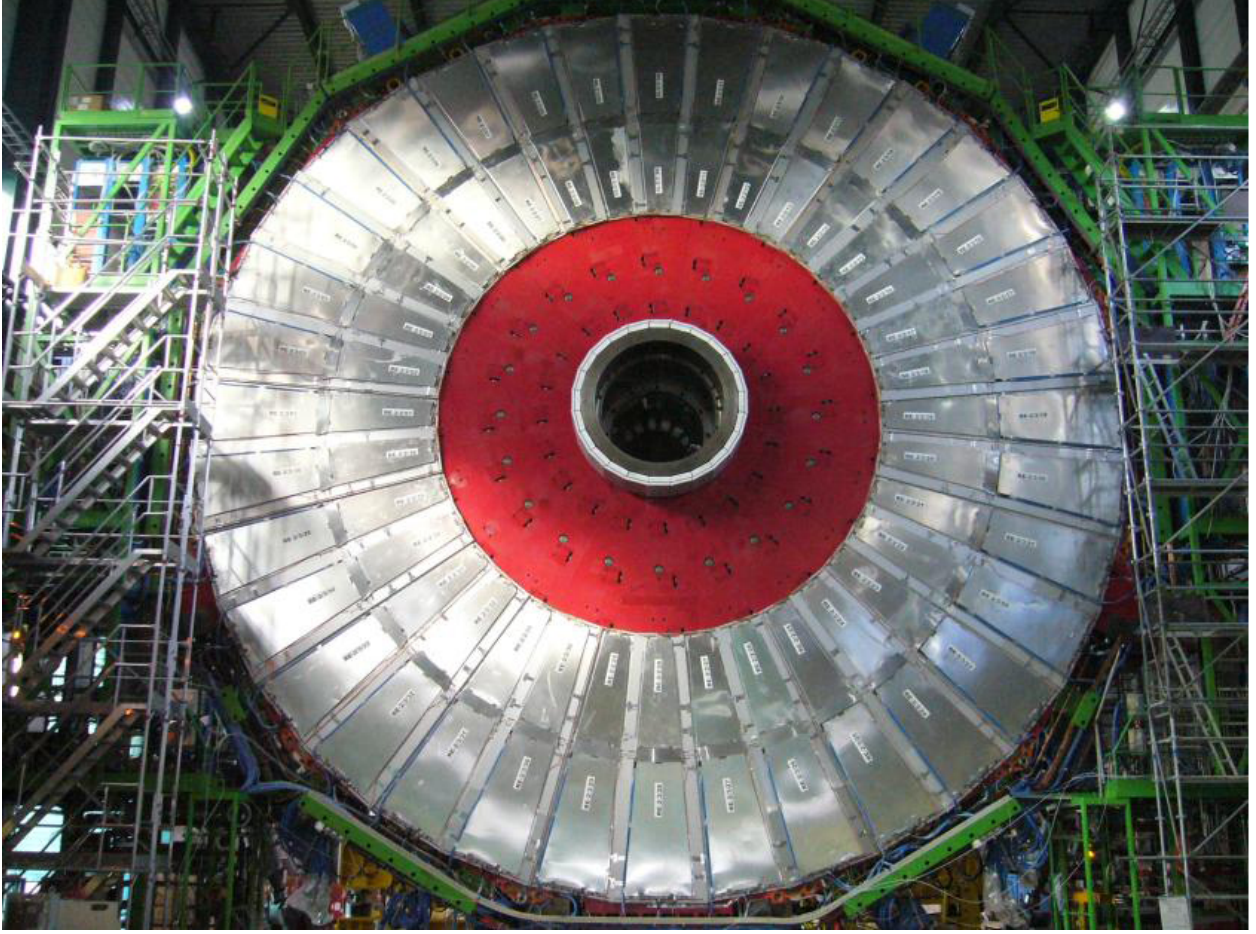


Figure 3.17: A photograph of RPCs mounted to the second endcap station.

3.2.4.4 Gas Electron Multipliers

Following Run 2, a staged installation of Gas Electron Multipliers (GEMs) [20] began as part of the Phase 2 upgrades to the muon system. Located in the very forward regions of each ME and complementing the CSCs, the GEMs cover the pseudorapidity range of $1.5 < |\eta| < 2.8$ and are labeled $GE\pm 1/1$ (installed during LS2), $GE\pm 2/1$ (installation slated for year-end technical stops in Run 3), and $ME\pm 0$ (installation slated for LS3). Each GEM detector consists of a triple-layer of copper-cladded polyimide foil into which are etched $70\text{ }\mu\text{m}$ holes spaced $70\text{ }\mu\text{m}$ apart, in a hexagonal geometry, as can be seen in the diagrams in Figs. 3.18 and 3.19 (left). A 70 % Ar and 30 % CO_2 gas mixture fills mm-sized gaps between the foil layers and a voltage is applied in steps ranging from -3200 V to ground (see Fig. 3.19, right).

The foil layers are sandwiched between a drift PCB and a readout PCB with 3072 radial strips. A total of 144 GEM chambers were installed during LS2 occupying the GE $\pm$ 1/1 station/ring, with the remaining chambers, ME $\pm$ 0 and GE $\pm$ 2/1 to be installed in LS3.

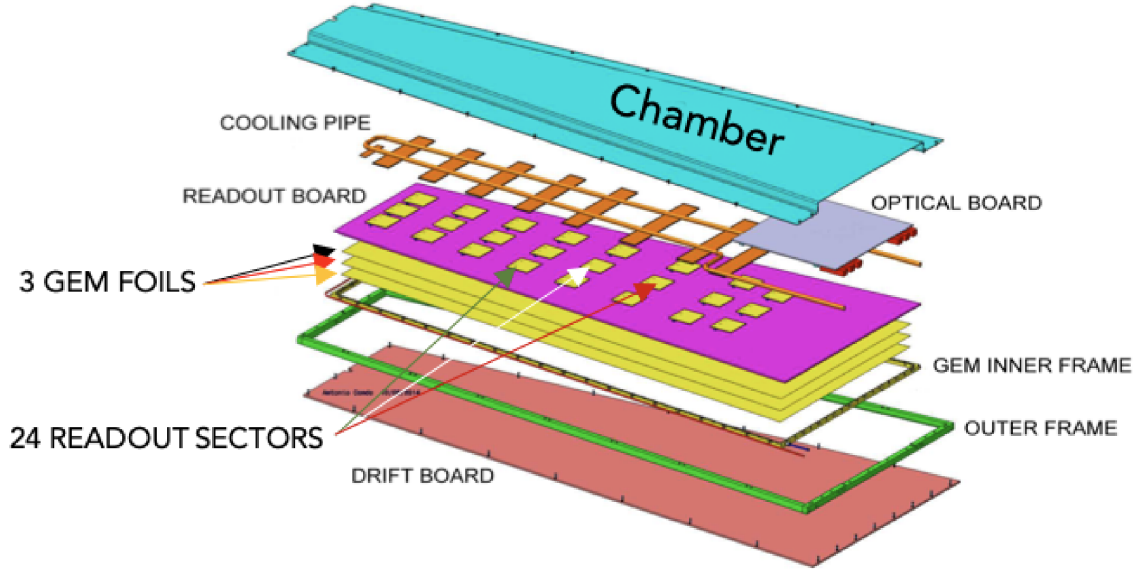


Figure 3.18: An exploded view of a GEM chamber.

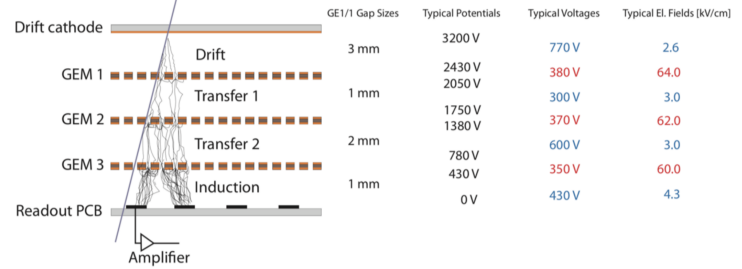
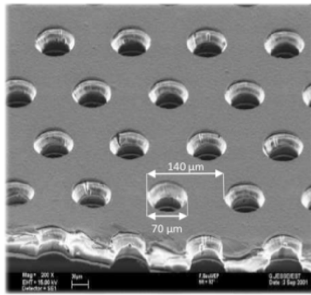


Figure 3.19: Left: a photograph of the micron-scale holes in the GEM foil. Right: The typical voltages in each layer of a GEM chamber.

3.2.5 Trigger system

At the LHC's design luminosity, bunch crossings occur every 25 ns. Most of these collisions result in low-energy multi-jet events with little potential for new physics searches. More rare

are interesting physics events with smaller cross-sections (e.g., single- and pair-production of heavy bosons, top-antitop creation, digamma events, etc.), however, offline storage capacity limits the fraction of these events that can be kept. This requires CMS to include a fast trigger system [21] to identify events of potential interest with clean, high-quality particle signatures. The CMS trigger system is two-tiered: a low-level trigger built from custom-designed electronics and a high-level trigger that runs reconstruction and selection algorithms on commercial PCs.

3.2.5.1 Level one trigger

The CMS Level-1 (L1) trigger makes the initial event selection to reduce the 40 MHz collision rate. Both the muon system and the calorimeters separately generate packets of coarse-grain spatial and kinematic information of particle-candidates called trigger primitives (TPs). The L1 muon trigger is segmented into three regional track finders: the barrel muon track finder (BMTF), the overlap muon track finder (OMTF), and the endcap muon track finder (EMTF). Each muon subdetector (CSCs, DTs, and RPCs) passes hit information in the form of TPs carrying position, direction, and timing information to the regional track finders. The track finders then separately reconstruct muon tracks and send that information to the Global Muon Trigger (GMT) which eliminates any redundant tracks based off p_T and quality. The L1 calorimeter trigger combines TPs carrying energy information from the ECAL, HCAL, and HF. In the EB, a five-by-five array of ECAL crystals are combined into a trigger tower (TT), whose transverse energy sum forms a single TP (similarly in the EE, where TTs may have 5-25 crystals). Trigger Concentrator Cards (TCCs) collect TPs from the ECAL and HCAL and form electron, photon, jet, and hadronically-decaying tau candidates before they are combined in the Global Calorimeter Trigger (GCT). Reconstructed L1 trigger objects form the GMT and GCT are merged in the Global Trigger (GT), where they are compared to a “menu” of up to 128 algorithms (referred to as “seeds”). If an event satisfies the criteria of at least one seed, an L1 accept (L1A) is sent upstream to the subdetectors. Upon receipt

of an L1A, TPs and all detector information from the data acquisition (DAQ) system—stored in the buffers of onboard electronics—are sent downstream to be processed by the high-level trigger. The latency of the L1 trigger is fixed at approximately $4\text{ }\mu\text{s}$, a requirement set by the collision rate and the buffer sizes of the different subsystems, and sustains an output rate of 100 kHz . A flow chart of the L1 trigger system is shown in Fig. 3.20.

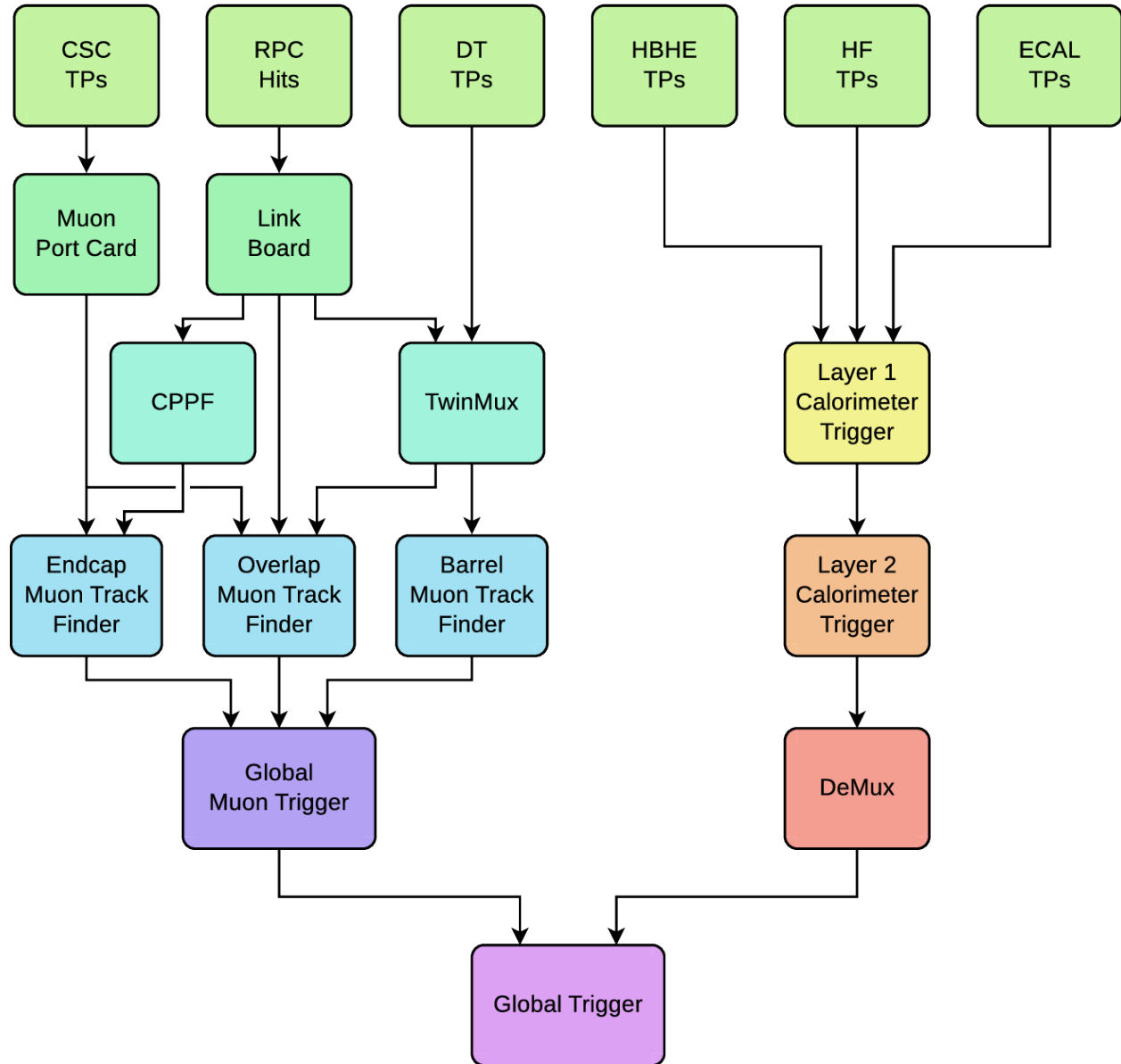


Figure 3.20: A flow chart of the CMS L1 trigger system.

3.2.5.2 High-level trigger

To further reduce the L1A output rate, the high-level trigger (HLT) makes a final selection of events with a 1 kHz readout rate, acceptable for offline reconstruction and permanent storage. Implemented in software running on a farm of commercial computers, the HLT takes an L1A seed and performs a streamlined reconstruction with a similar efficiency to that used in offline processing. The HLT then filters events in roughly two stages: first, using only muon system and calorimeter information, and second, using full tracks. Events selected by the HLT algorithms are sent to permanent storage. A photograph of a GPU used to process the HLT algorithms is shown in Fig. 3.21.



Figure 3.21: A GPU used to process the HLT algorithms.

Chapter 4

Phase-2 upgrades

4.1 High-Luminosity LHC

Since its commissioning in 2010, the LHC has provided experiments like CMS the opportunity to test the SM with astonishing precision. Using data collected in Runs 1 and 2, the LHC experiments have had a prolific 13 years of scientific study, boasting a combined total of roughly 3000 publications in refereed journals, with CMS contributing over 1000 physics papers to that total. Even still, theories of physics beyond the SM remain undiscovered at the LHC, with questions of Supersymmetry, Dark Matter, Grand Unification left on the table. To heighten the sensitivity of new physics searches and expand the scope of the LHC physics program, a significant upgrade to the collider is planned that will increase the integrated luminosity by a factor of ten beyond the original design. The High-Luminosity LHC (HL-LHC) is slated to begin proton-proton collisions in 2029 with the start of Run 4, kicking off Phase-2 of data-taking. Infrastructure work for the HL-LHC concluded during LS2, making way for construction of the machine in LS3 including upgrades to the quadrupole magnets, cryogenics, and collimators. In addition to increased luminosity, the HL-LHC will boost the proton-proton collision energies to 14 TeV.

Over the next two decades, the HL-LHC is expected to deliver an integrated luminosity of 3000 fb^{-1} , overshadowing the projected 350 fb^{-1} for Phase-1. To accumulate this much data, the collision rate inside CMS will have to be much higher than in Phase-1, which will necessarily present challenges to each subsystem. Inside CMS, the number of overlapping secondary collisions coinciding with the primary interaction, called Pile-Up (PU), averaged about 30 interactions per bunch crossing in Run 2. Specialized algorithms, such as Pile-Up

Per Particle Identification (PUPPI), are used to mitigate the effects of PU. At the HL-LHC, PU within CMS may reach up to 200 interactions per bunch crossing. To reject the abundance of unwanted particles recorded in these high-PU events will require the development of more sophisticated filtering techniques and higher granularity detectors. An event display showcasing the sheer volume of particle tracks within CMS of a high-PU event can be found in Fig. 4.1.

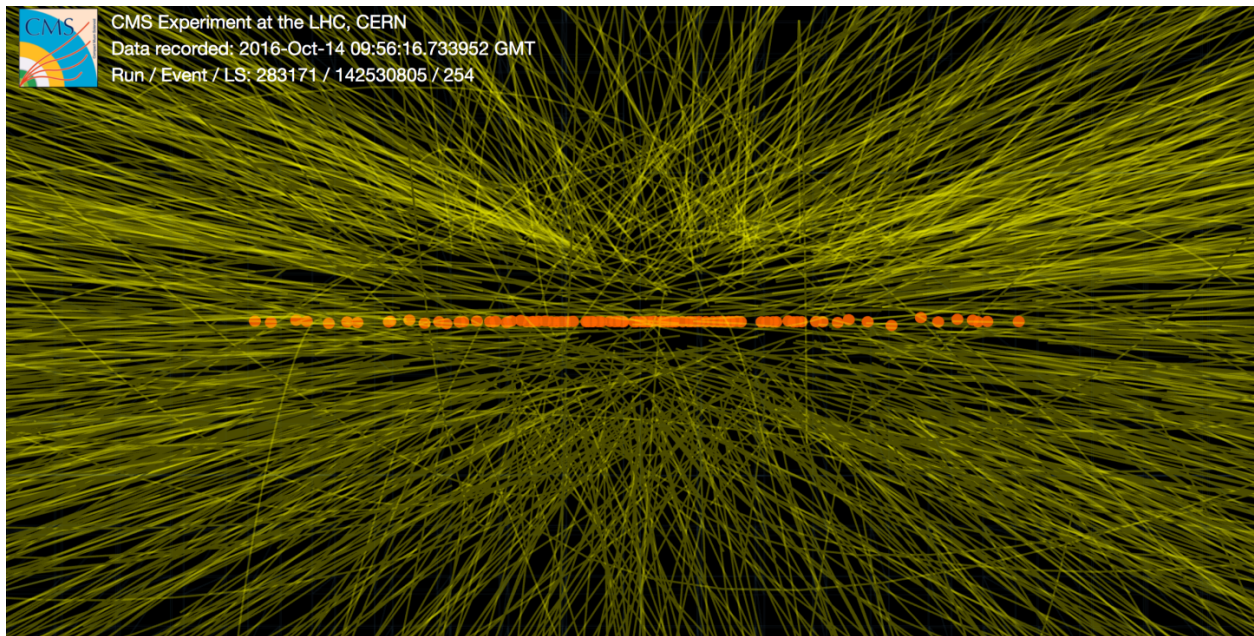


Figure 4.1: An event display of a 130 PU event recorded by CMS.

The environment inside the detector throughout Phase-2 will place additional performance demands on CMS. The increase in particle flux will rapidly age current detector components, especially close to the beam pipe. Improved radiation hardness, especially of front-end detector electronics, will be required to withstand the harsh conditions. Furthermore, limited data readout bandwidth coupled with the current L1 trigger rate and latency will prove insufficient to handle the expected occupancies in Phase-2, resulting in unacceptable data loss. To cope with the challenges presented in Phase-2 of running, while profiting from the increase in luminosity, an extensive program of upgrades to the CMS subsystems was prepared and will be fully integrated prior to the first HL-LHC collisions in Run 4.

4.2 CSC electronics

4.2.1 Phase-1 electronics

CSC trigger and DAQ channels rely on a sequence of on- and off-chamber electronics for reading, storing, processing, and transmitting the analog signals from the strips and wires. Before explaining the Phase-2 upgrades to the CSCs, a more detailed description of the electronics prior to the upgrades—both on- and off-chamber—is necessary.

Cathode strip signals are read by five Cathode Front-End Boards (CFEBs) mounted to each CSC (see Fig. 4.2). A number of custom Application Specific Integrated Circuits (ASICs) fused to each CFEB are responsible for shaping, amplifying, and storing cathode strip signals and identifying hits: Buckeye ASICs amplify and shape the signals from each cathode strip before sending signals down trigger and DAQ streams; Comparator ASICs rapidly identify hits with half-strip resolution and send these downstream to an off-chamber Trigger Motherboard (TMB); and Switched Capacitor Arrays (SCAs) store strip charges in analog form of up to six events while waiting for an L1A from the TMB. Upon receipt of an L1A the SCAs will send precision data to be digitized by Analog-to-Digital Converters (ADCs) before both data and trigger information is forwarded to an off-chamber DAQ Motherboard (DMB). Anode wire signals—“ganged” into groups of 10-15 wires—are amplified by 42 on-chamber Anode Front-End Boards (AFEBs) and sent to an Anode Local Charged Track (ALCT) board, also on-chamber. A mezzanine on the ALCT baseboard identifies patterns among the anode hits in the six wire layers (a minimum of four layers is consistent with a muon). The two patterns with the most layer hits are sent off-chamber for processing by the TMB. A Low-Voltage Distribution Board (LVDB) on each chamber supplies power to all the electronics.

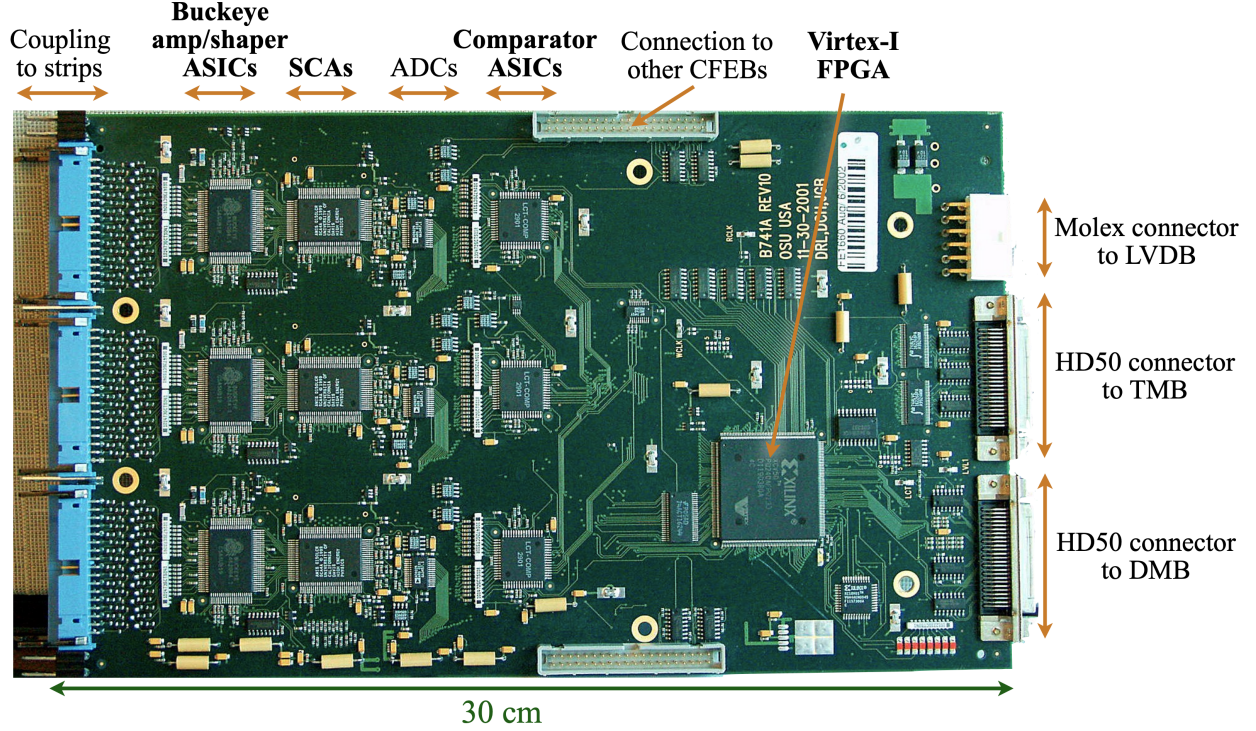


Figure 4.2: One of five CFEBs used to read cathode strip signals on a CSC.

The TMB reads the trigger primitives generated from the on-chamber electronics—Cathode Local Charged Tracks (CLCTs) from the CFEB Comparators and ALCTs from the ALCT board—and from these constructs 2D Local Charged Tracks (LCTs), requiring four layer hits, which are sent to the EMTF. The DMB builds data packets with cathode strip data from the CFEBs, Anode wire data from the ALCT (through the TMB), and trigger data from the TMB. CSC data packets from 15 DMBs corresponding to chambers in a different 20 degree sector in each station (to balance the readout load) are read by Detector Dependent Units (DDUs) with 1.6 Gb/s links, unpacked in real-time, then merged and sent to CMS DAQ. DMBs are also responsible for controlling on-chamber voltages via the LVMB and controls the CFEBs. Photographs of a TMB and DMB are shown in Fig. 4.3.

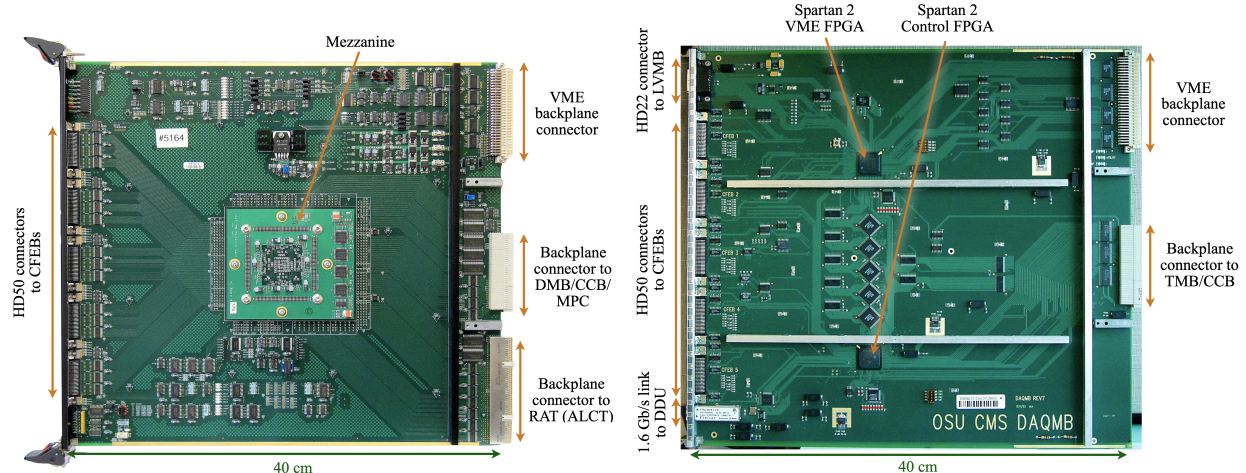


Figure 4.3: Left: A TMB for reading CSC trigger primitives and processing L1As. Right: A DMB for reading and transmitting precision data packets from CSCs.

TMBs and DMBs are housed in “peripheral” VME crates, each supporting nine CSCs, secured to the edges of each ME disk (six peripheral crates per station). Each peripheral crate also houses the following: a Muon Port Card (MPC) that collects the LCTs from each of the nine TMBs in the crate and sends them to the muon track finder system; A Clock and Control Board (CCB) acting as an interface between the CSCs and the Trigger, Timing and Control (TTC) system of CMS, synchronizing the crate operations; and a VME Crate Controller (VCC) that distributes the VME commands received from the control room to the other boards in the peripheral crate.

4.2.2 Phase-2 electronics

Cathode strips on each ME1/1 chamber are divided into two groups: the “inner” ME1/1a covering $2.0 < |\eta| < 2.4$ and ME1/1b covering $1.5 < |\eta| < 2.0$. Prior to LS2, the 48 cathode strips in ME1/1a were ganged into 16 groups of three (e.g., 1, 17, and 33 in channel 1). Issues observed during Run I with muon triggering in the triply-ganged ME1/1a strips required unganging of these strips. To accommodate the now threefold increase in channels after the unganging from 16 to 48 strip channels, two additional CFEs were needed. At the same time, to better cope with an increased trigger rate, ME1/1 chamber electronics

underwent a number of upgrades. The five CFEBs were replaced by seven Digital CFEBs (DCFEBs) to read cathode strip signals. DCFEBs (shown in Fig. 4.4) continuously digitize strip signals with flash ADCs and store digitized signals in the deep buffers of a Virtex-6 Field Programmable Gate Array (FPGA). Trigger and data readout bandwidth on DCFEBs were upgraded to 3.2 Gb/s Finisar optical links. To receive the optical links from the DCFEBs, the off-chamber TMB/DMB were correspondingly upgraded to an OTMB/ODMB (see Figs. 4.5 and 4.6) with powerful Virtex-6 FPGAs and 1.6 Gb/s output links. The LVDB was upgraded to an LVDB7 and the ALCT mezzanine was upgraded with a Spartan-6 FPGA (ALCT-S6, also ALCT-LX150) capable of improved algorithms for pattern finding. The CFEBs formerly on the ME1/1 chambers were adopted to construct the 72 ME4/2 chambers, which prior to LS1 had not been built due to a lack of funding.

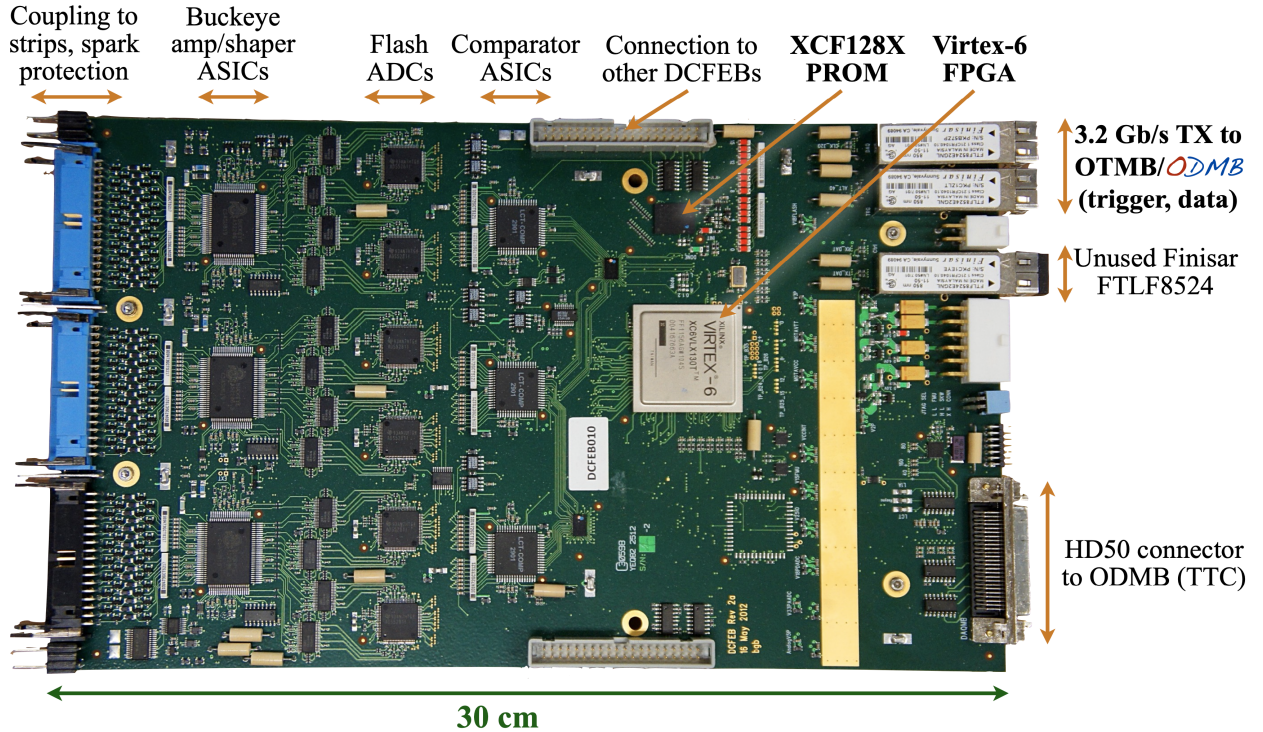


Figure 4.4: DCFEBs used to upgrade the ME1/1 chambers in LS1 and ME234/1 chambers in LS2.

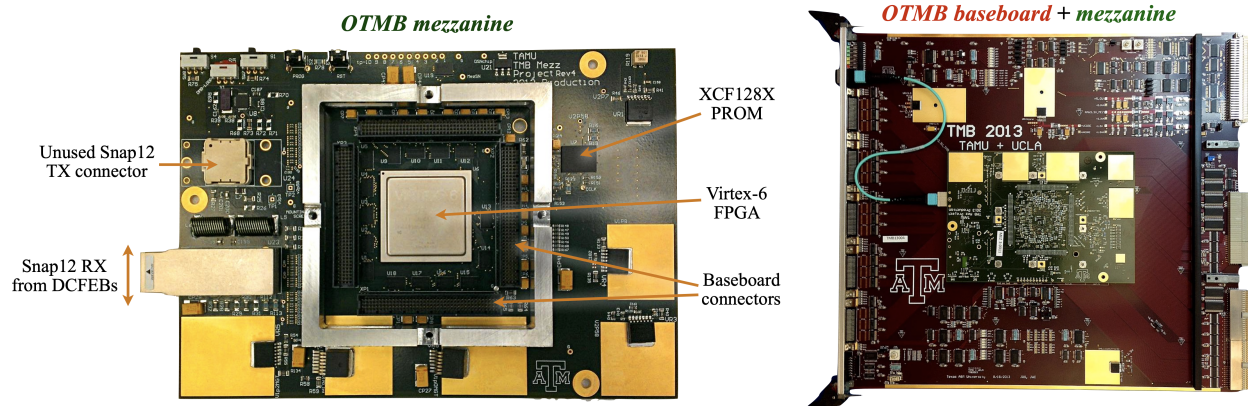


Figure 4.5: Left: an OTMB mezzanine. Right: an OTMB baseboard. The OTMBs replaced the TMBs for ME1/1 chambers in LS1.

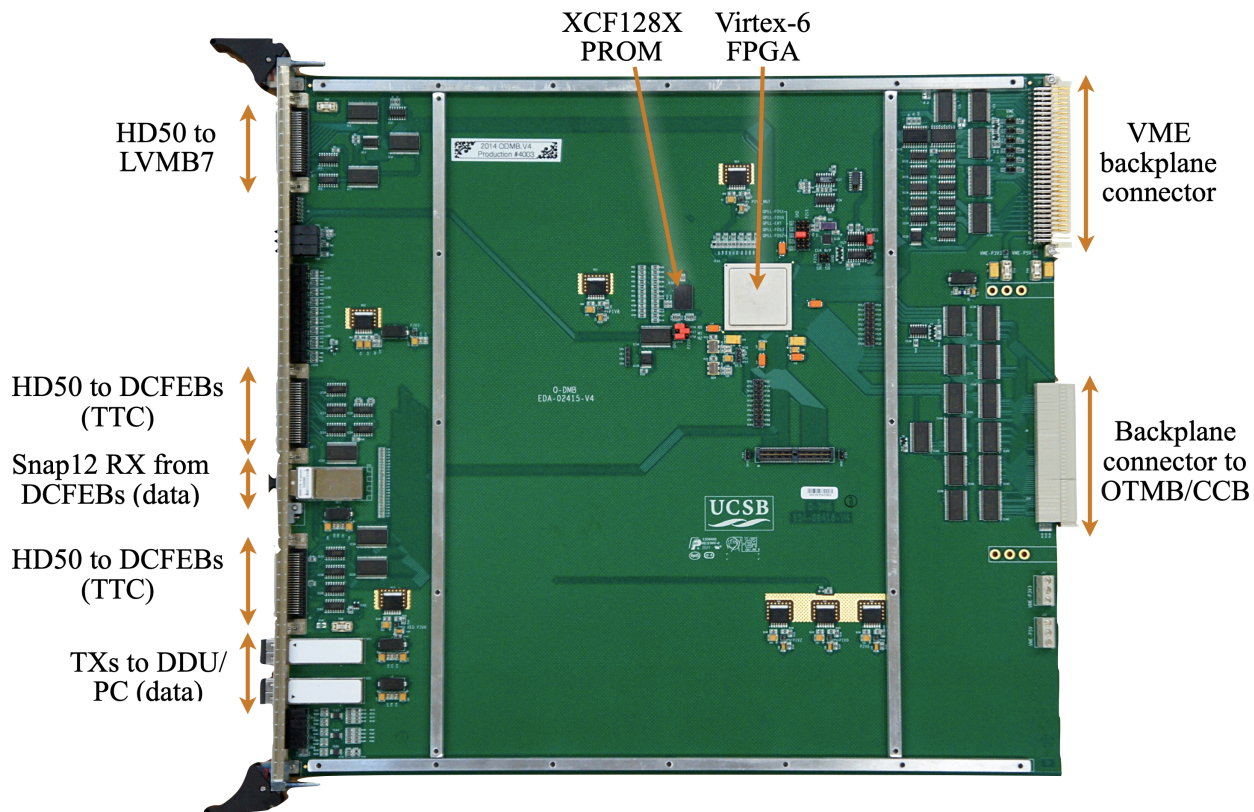


Figure 4.6: An ODMB used to upgrade the DMBs for ME1/1 chambers in LS1

Radiation tests of CSC modules simulating a decade of HL-LHC data taking revealed that chambers are exceptionally robust, demonstrating adequate performance consistent with Phase-1. Even still, the higher radiation doses anticipated during Phase-2 are expected to

cause certain electronic readout components on CSCs at high pseudorapidities to die. Along with mitigating radiation failure, higher PU scenarios will require a faster L1 trigger rate of 750 Hz and latency of 12.5 μ s; without remedy, the analog readout of CFEBs on the inner CSC rings would lead to catastrophic event losses, as demonstrated in Fig. 4.7. To avoid these hazards during Phase-2, CSCs in the inner rings were refurbished with upgrades to their front-end electronics, installed during LS2, with minor upgrades to off-chamber electronics following in LS3. ME1/1 DCFEBs were replaced by more radiation-hard xDCFEBs with improved VTTx/VTRx optical receivers in place of the Finisars (see Fig. 4.8). Both the new xDCFEBs and ALCT-LX100s (installed during LS1) provide PROM-less solutions for ME1/1 chambers that mitigate any failures from radiation damage. As for ME234/1 chambers, their ALCTs were upgraded to ALCT-LX150Ts (a picture of the mezzanine is in Fig. 4.9) and their CFEBs were replaced with the disused DCFEBs from the ME1/1 chambers. The Finisar optical transceivers on the DCFEBs were replaced with VTTx links on the ME234/1 chambers to supply sufficient trigger and data readout speeds (3.2 Gb/s). To receive the now optical trigger links from ME234/1 DCFEBs, TMBs were upgraded to OTMBv2s.

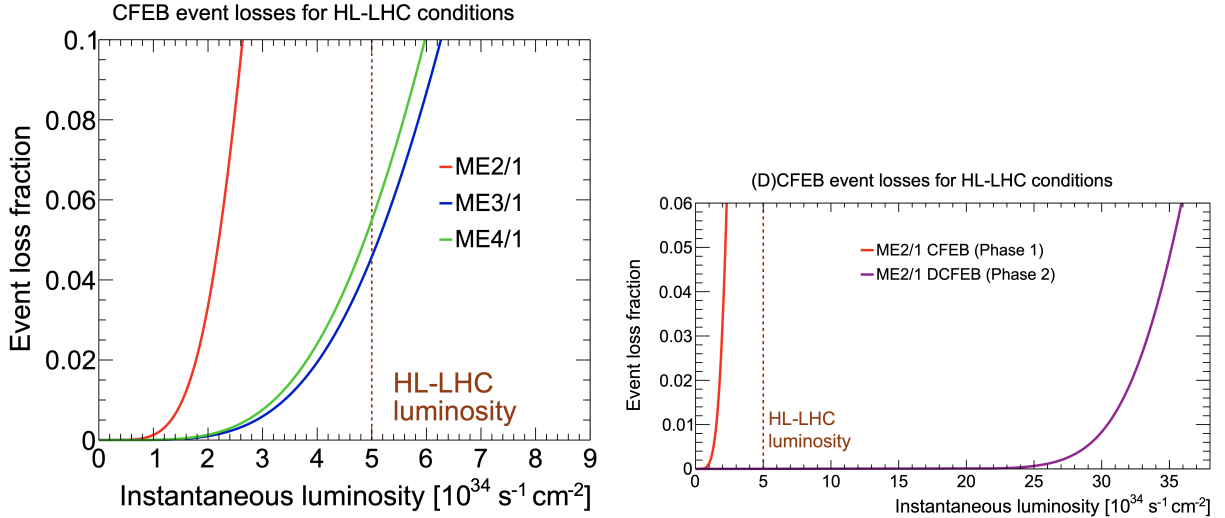


Figure 4.7: Left: CFEB event loss fractions as a function of instantaneous luminosity on ME2/1, ME3/1, and ME4/1 chambers. Right: CFEB and DCFEB event loss fractions as a function of instantaneous luminosity on ME2/1 chambers. The plots demonstrate the need to replace the CFEBs with DCFEBs on ME234/1 chambers to avoid unacceptable data loss under HL-LHC conditions.

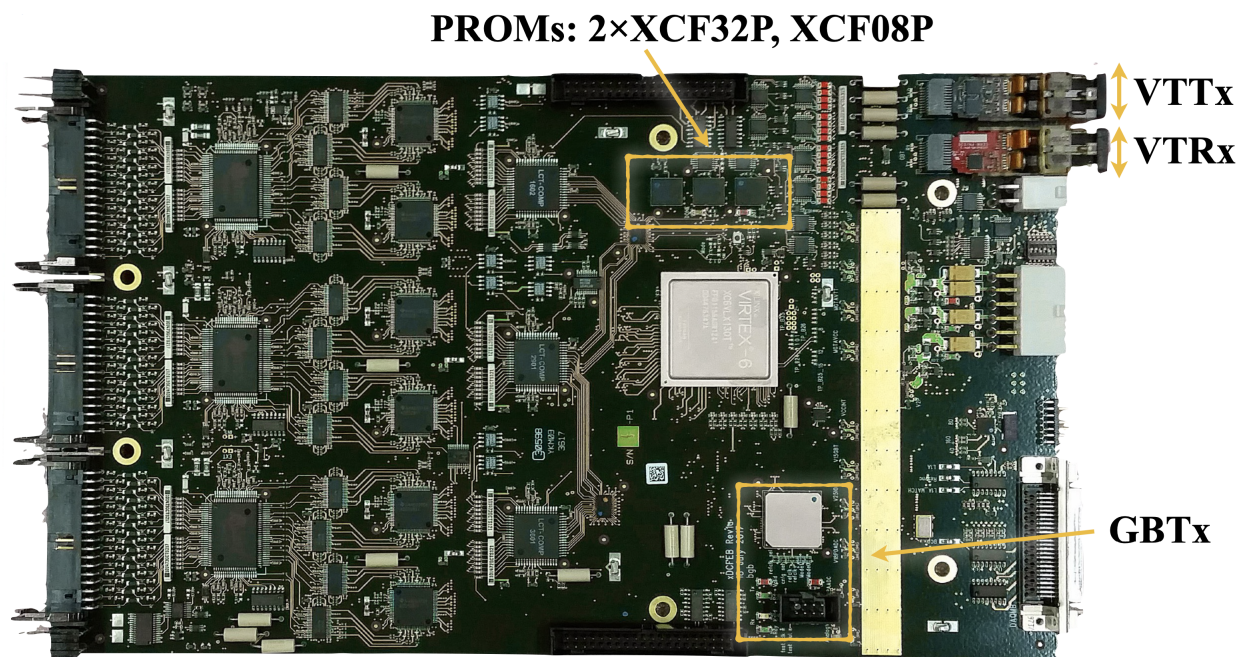


Figure 4.8: One of seven xDCFEBs that replaced the seven DCFEBs on ME1/1 chambers in LS2.

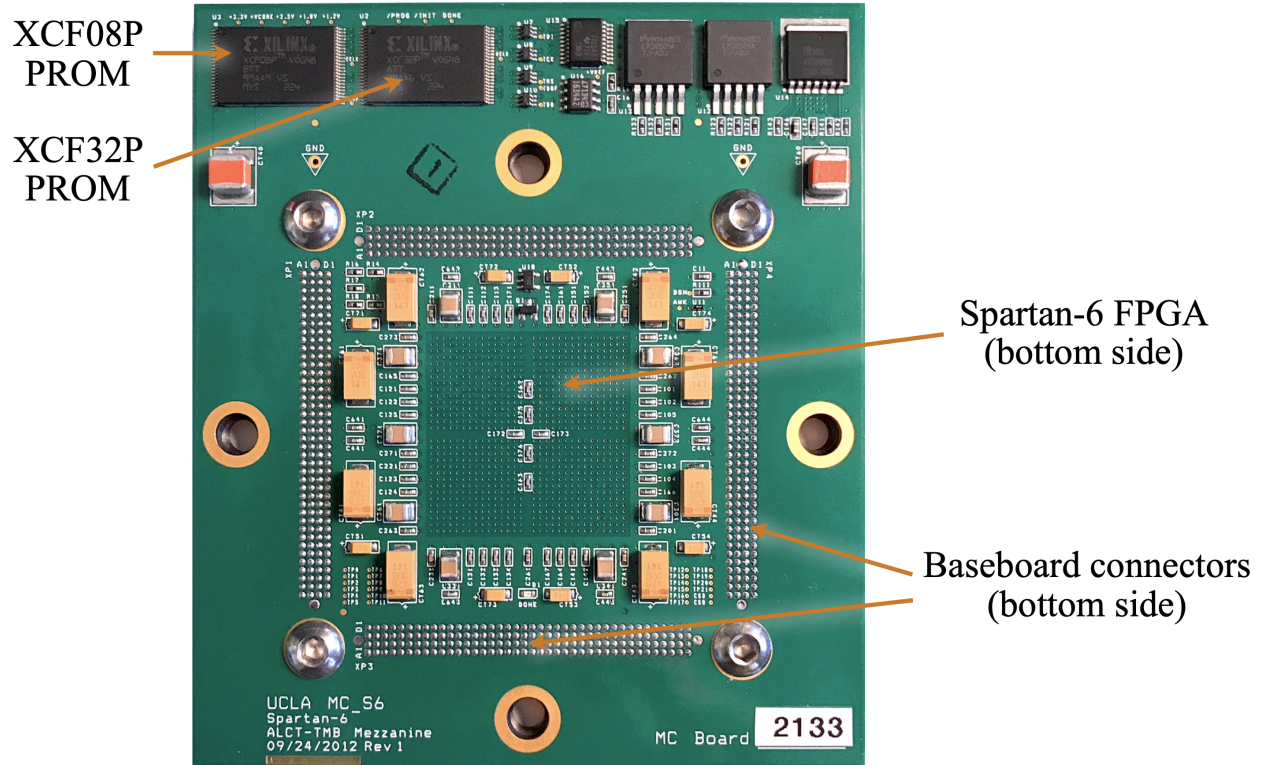


Figure 4.9: The ALCT-LX150 mezzanine that replaced the old ALCT mezzanines on ME1/1 chambers in LS2.

A final set of Phase-2 upgrades will be implemented in LS3 only to off-chamber electronics. The ODMBs and DMBs of ME1/1 and ME234/1 chambers, respectively, will be replaced with ODMB7s and ODMB5s, critically increasing the output bandwidth from 1.6 Gb/s to 10 Gb/s. The ODMB5s will also provide optical links to the DCFEBs, replacing the legacy copper DAQ channels still in use on ME234/1 chambers throughout Run 3. An upgrade to the backend system to handle the output DAQ rates of the ODMB7 and ODMB5, featuring new FED boards for all MEx/1 chambers, will also be installed during LS3. A schematic of ME1/1 and ME234/1 CSC electronics prior to and following the Phase 2 upgrades is shown in Fig. 4.10.

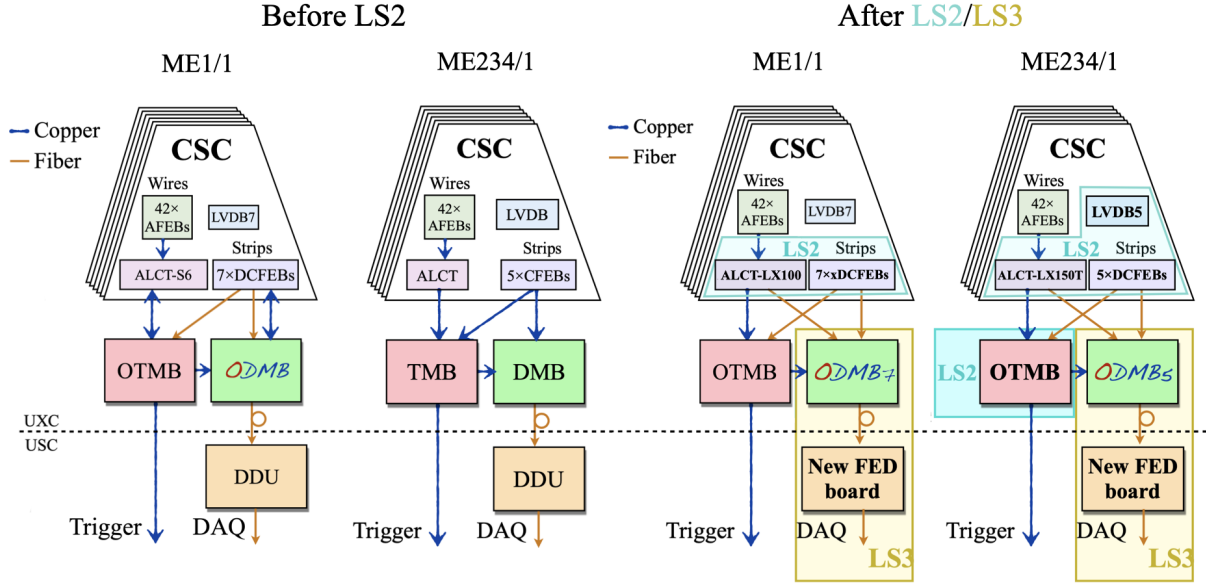


Figure 4.10: Left: Diagrams showing CSC electronics prior to LS2 on ME1/1 (far-left) and ME234/1 (second-from-left) chambers. Right: Diagrams showing CSC electronics after LS3 on ME1/1 (second-from-right) and ME234/1 (far-right) chambers. Upgrades installed during LS2 are highlighted in blue, while upgrades planned for LS3 are highlighted in gold.

4.3 CSC activity during LS2

Phase-2 upgrades of CMS subsystems including the replacement of the tracker, barrel ECAL and DT front-end electronics, and forward calorimeters, will be given priority during LS3. These projects require prolonged access to the CMS inner barrel and YE1 disks, so throughout LS3, CMS will remain in a configuration with both endcaps open away from the barrel. This will prevent access to the YE2 and YE3 disks on which CSCs in stations 1, 2, and 3 are mounted. Therefore, Phase-2 upgrades of the CSCs requiring the removal of chambers in those stations was scheduled for LS2, when the YE disks could be spaced apart. Upgrades of on-chamber CSC electronics would be given preference during LS2, while replacement of boards off-chamber in the peripheral crates will wait to be upgraded until LS3. Other upgrades during LS2 included Phase-1 upgrades to the HCAL and the installation of new

Phase-2 GEM detectors. The full schedule of LS2 activity for CSCs upgrades followed a highly-optimized timetable of parallel chamber extraction, refurbishment, testing, installation, and commissioning of all 180 MEx/1 chambers, to be completed in just 60 weeks. The timetable was divided into four staggered workstreams based on chamber type: 1. ME+1/1, 2. ME+234/1, 3. ME-1/1, and 4. ME-234/1. Excellent progress at approximately two chambers per day was sustained throughout 2019 with workstreams 1-3, however, the outbreak of the Covid-19 pandemic presented significant setbacks to workflow and manpower, causing delays toward the end of LS2. In response, the CSC team made every effort to finish the upgrades as quickly and safely as possible, and despite a two-and-a-half month shift and a two month extension of the 4th work stream, by 2021 all CSC upgrade activity had successfully concluded in time for Run 3 preparations.

4.3.1 Chamber extraction

One at a time, chambers were disconnected from water, gas, and cabling before they were detached from the endcap yokes. Once dismounted, CSCs were brought to the surface with an overhead crane. Inside the surface building SX5 is a CSC facility where refurbishment and testing sites are located. Extracted chambers were placed horizontally on rolling tables for in situ refurbishment and transport to each testing site within the CSC facility, while a backlog of chambers awaiting refurbishment or installation were kept vertically on storage cradles. Extraction began with the ME1/1 chambers so their DCFEBs could be harvested for the ME234/1 chambers, but parallel testing sites allowed both types to undergo refurbishment and testing simultaneously. A photograph of the CSC facility in SX5 is shown in Fig. 4.11.



Figure 4.11: An aerial view of the CSC facility in SX5 used for the Phase-2 refurbishment and testing of CSC modules during LS1 and LS2.

4.3.2 DCFEB temperature study

The on-chamber electronics boards mounted to the face of each CSC generate a significant amount of heat while operating, a load of roughly 70 W per chamber, and need a cooling system to prevent overheating. Beneath the (D)CFEBs, ALCTs, LVDB(5)s, and AFEBS, are copper plates, with a continuous 1/4" copper tube brazed to each plate. Thermal pads are layered on each electronics component (ASICs, FPGAs, etc.) to provide good thermal contact with the copper plates, efficiently carrying heat away from the electronics. A photograph of a cooling cover and thermal pad strips for a DCFEB is shown in Fig. 4.12. A pressurized water system flows through each chamber's copper loop and cools the plates.

The supply and return ends of each chamber's copper pipe are connected via flexible hosing to neighboring CSCs forming three-chamber circuits, which are then connected to a larger cooling manifold secured to each YE disk, allowing water to flow through all the CSCs. Input water temperature is approximately 18-20 °C and is optimized to limit the temperature rise per connection to 2 °C.

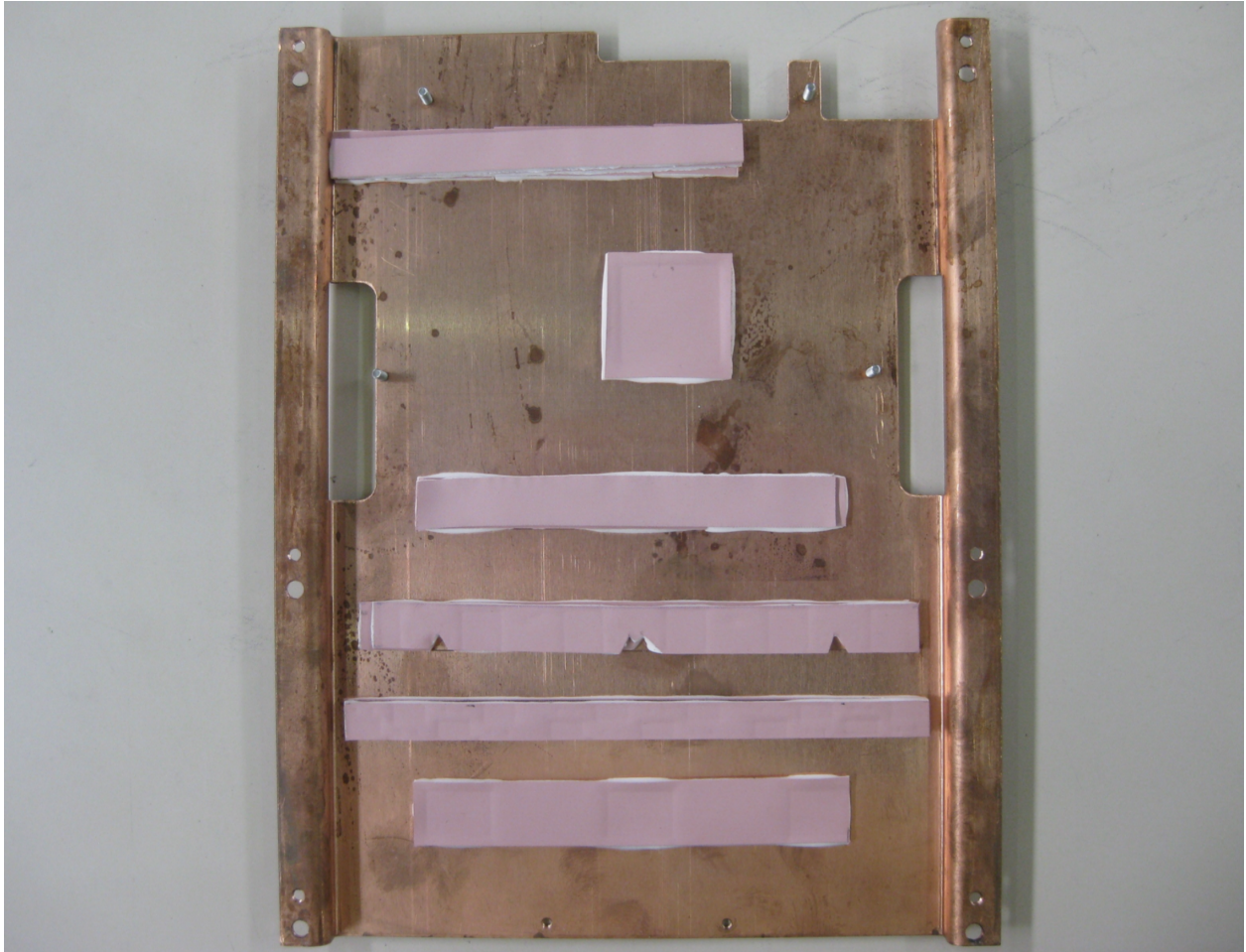


Figure 4.12

To validate that the cooling system on ME234/1 chambers is sufficient to cool the DCFEBs that will replace the CFEBS, the efficiency of the thermal-pad-to-cooling-plate configuration was studied. An ME3/1 chamber refurbished with DCFEBs was connected to cooling and LV power using one of the FAST sites in the CSC lab at SX5 (see Sec. 4.3.5). With the power supply on and the DCFEBs left idle, the temperature of each DCFEBs'

FPGA (using a built-in thermometer) was collected via a web-based monitor (the so-called “yellow page”) on a minute-by-minute basis in half-hour sessions. The cooling efficiency of several configurations were studied by varying the thermal pad thickness, DCFEB location on-chamber, and type of copper cooling cover.

It was observed that that FPGAs exhibit a large temperature variation, roughly a 10°C range between DCFEBs. By swapping the location of two of the five DCFEBs on the chamber, which are arranged side-by-side, it was established that the temperature variations were an artifact of each DCFEB and that the cooling system provides a homogenous temperature map accross the DCFEBs, shown in Figs. 4.13-4.14. The rise in temperature of FPGA 466 in the right-hand plot of Fig. 4.13 was due to poor thermal contact with the cooling cover. DCFEBs (and CFEBs) are not actually mounted to the cooling baseplate, rather, they are secured to copper cooling covers, offset with 5.0 mm stand-offs, and the cover is screwed to the baseplate. It is the cover that the FPGAs (and most other electronics) are in thermal contact with, while strips of thermal padding between the cover and the baseplate carry heat from the cover to the cooling system. By removing the threading in the holes of the cover it can be screwed down closer to the baseplate, providing better thermal contact, and reducing the overall temperature of the FPGAs (see Fig. 4.14). A later study revealed that 1.5 mm-thick thermal pads provided better thermal contact over 1.0 mm-thick thermal pads.

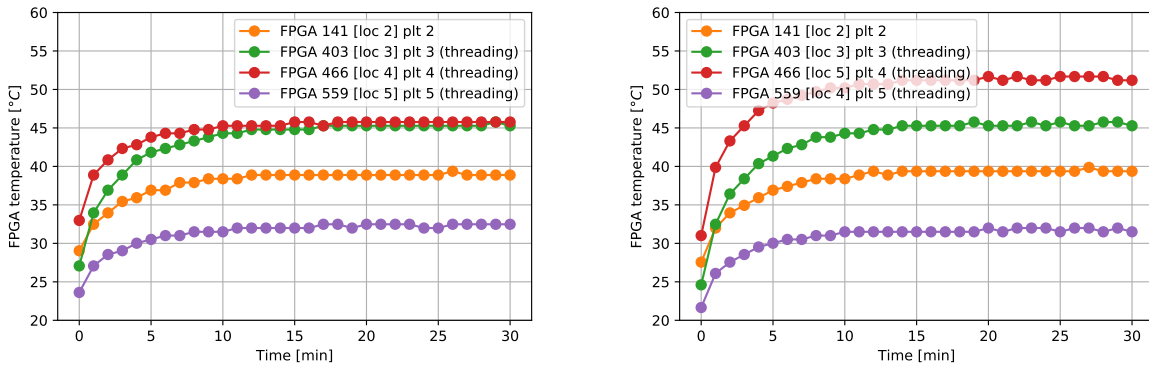


Figure 4.13: FPGA temperature sampled every minute of five idle DCFEBs on an ME3/1 CSC. The location on-chamber of DCFEBs 466 and 559 have been swapped between the two plots. The cooling plates on DCFEBs 403, 466, and 559 have threading.

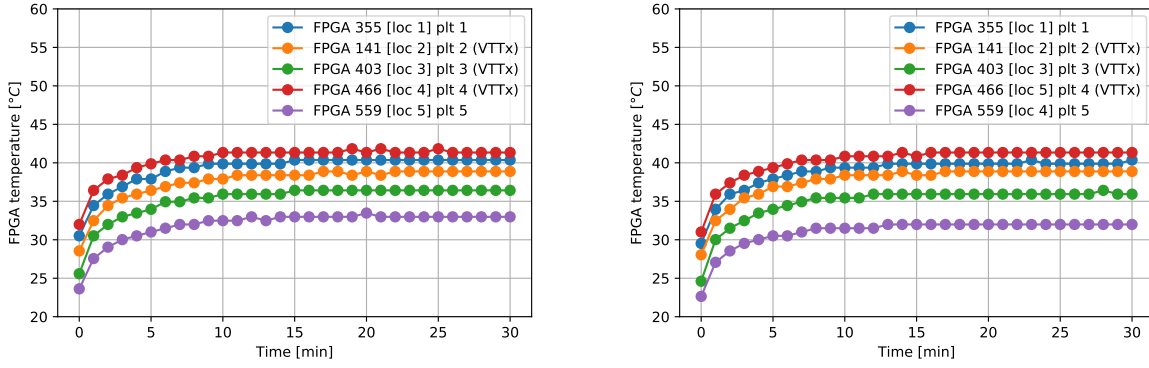


Figure 4.14: FPGA temperature sampled every minute of five idle DCFEBs on an ME3/1 CSC. The location on-chamber of DCFEBs 466 and 559 have been swapped between the two plots. The cooling plates on all DCFEBs have no threading.

4.3.3 ME1/1 refurbishment

Refurbishment of each chamber was performed by a dedicated team: roughly 20 CSC group members comprised of post-docs, graduate students, and some undergraduate students, all of whom received training in the assembly and disassembly for both ME1/1 and ME234/1 chambers, as the construction and placement of the on-chamber electronics are somewhat different between the two chamber types. Chambers were refurbished at the CSC lab in SX5, following a detailed checklist. The refurbishment procedure of the ME1/1 chambers during LS2 was modeled after the ME1/1 upgrade program from LS1. A rough outline of the steps required to upgrade each electronic component is:

- LVDB7:

1. LVDB7 cover is removed and inspected for any damage
2. LVDB7 cover is reattached (no LVDB upgrades on ME1/1)

- xDCFEBs:

1. DCFEB covers are removed, and strip cables, LV cables, and patch cables (connecting CFEs together) are all disconnected

2. Starting from the top of the chamber, and working down, all seven DCFEBs are unscrewed, removed, serialized and dated, and taken to temporary storage following radiation-safe guidelines
 3. Clean xDCFEBs covers with ethanol, cut and place thermal pads onto covers
 4. New xDCFEBs are installed, screwed down, and reconnected to strip, LV, and patch cables
 5. DCFEB covers are reattached
- ALCT-LX100:
 1. ALCT-S6 cover is removed and all cables disconnected
 2. ALCT-S6 mezzanine is removed
 3. Thermal block with thermal pad placed on baseboard
 4. New ALCT-LX100 inserted gently to connector and secured

4.3.4 ME234/1 refurbishment

As each ME1/1 chamber was refurbished, the DCFEBs harvested from that chamber were taken off-site to have their VTTx adapter boards installed. After the DCFEBs returned to the CSC lab in SX5, refurbishment of the ME234/1 chambers was carried out by the refurbishment team in situ, following a checklist similar to that used for ME1/1 chambers. The procedure is as follows:

- LVDB5:
 1. LVDB cover, LVMB mezzanine, and thermal pads are removed
 2. LVDB baseboard is unscrewed and barcodes are applied to LVDB baseboard and LVMB mezzanine
 3. New thermal padding is cut and applied to LVDB5 baseboard

4. New LVDB5 baseboard is installed and screwed down
 5. LVMB mezzanine is installed
- DCFEBs:
 1. CFEB cover and individual cooling plates are removed, and strip cables, LV cables, and patch cables (connecting CFEBs together) are all disconnected
 2. All five CFEBs are unscrewed, removed, serialized and dated, and taken to storage following radiation-safe guidelines
 3. DCFEBs harvested from ME1/1 chambers are installed, screwed down, and re-connected to strip, LV, and patch cables
 4. DCFEB cooling plates and covers are reattached
 - ALCT-LX150T:
 1. ALCT mezzanine is removed
 2. Thermal block with thermal pad placed on baseboard
 3. New ALCT-LX150T inserted gently to connector and secured
 - Optical fibers:
 1. LC connectors on the optical fiber fan-out are connected to each DCFEB and ALCT, while the MTP connector is secured to the side of the chamber (more info on the optical fibers in Sec. 4.4)

4.3.5 Chamber testing

Once a CSC has been refurbished but prior to reinstallation, it undergoes a series of tests designed to load firmware, validate the performance of the newly installed electronics, and identify any mistakes made during refurbishment. Chamber testing prior to reinstallation is

a three-stage process: initial testing at the Final Assembly and System Testing (FAST) site, long-term testing at the Long-Term Testing (LTT) site, and final testing again at the FAST site. Both FAST and LTT sites are located inside the CSC lab at SX5 and consist of parallel testing stands (FAST 1 and FAST 2; LTT 1, LTT 2, and a third ME1/1-dedicated LTT stand) that allow 2-3 chambers to efficiently undergo testing simultaneously. A photograph of the author inspecting a CSC at the FAST testing sites in SX5 is shown in Fig. 4.15.



Figure 4.15: FAST test stands at the CSC facility in SX5. An ME1/1 chamber undergoing testing is connected to one FAST site (left-hand-side of photo), while the author inspects an ME2/1 chamber connected to the other FAST site (middle of photo).

The FAST sites are equipped to supply each CSC with high and low voltage, gas, cooling, and trigger and data links to a dedicated peripheral crate. After connecting the chamber to power, high voltage supply, trigger/DAQ readout cables to OTMB and ODMB, and both

gas and water supplies, the (x)DCFEB and ALCT mezzanine firmware is uploaded and the trigger timing is synchronized. Next, a comprehensive assessment of the health of a CSC's on-chamber electronics is conducted with a suite of tests called the System Test of Endcap Peripheral crates and chamber electronics (STEP) . The STEP tests follow the sequence:

- AFEB threshold and analog noise
- AFEB connectivity and crosstalk
- AFEB counting noise
- ALCT-AFEB time delay
- CFEB pedestals
- CFEB connectivity
- CFEB pulse shape and crosstalk
- CFEB gain
- Comparator thresholds and analog noise
- Comparator logic
- ALCT trigger
- High-statistics cosmics

Typically, all the FAST testing, including the STEP tests, takes about six hours to perform for two chambers in parallel. However, when problems with the electronics are revealed, it can take up to a day of debugging until the chamber again passes all testing at the FAST site. Common issues revealed from FAST tests include connection issues (usually fixed with reseating cables), problematic electronic boards (requires examination, repair, or

replacement by experts), and chamber problems like shorted strips, broke, wires, etc., which are noted but left alone.

After finishing the STEP tests, chambers are brought to the neighboring LTT sites for 48-hour monitoring. The LTT stands supply the chambers with low voltage, gas, and cooling—no high voltage is needed. Voltage, current, and temperature stability are all monitored for a minimum of 48 hours, finishing with the low voltage portion of the STEP tests. Finally, two hours of post-LTT tests back at the FAST sites reveal if there are any gas leaks.

4.3.6 Chamber installation and commissioning

Immediately following refurbishment and testing, each CSC was lowered back down into the experimental cavern (UXC) to be reinstalled on CMS. Chambers are reinstalled onto the YE disks in nearly the same way they are extracted, however, prior to connecting gas, water, and HV—with only LV to power the electronics—the chambers undergo initial testing of connectivity and mapping. Next, the on-board clocks of the electronics for each CSC must be configured with respect to each other to account for differences in location and cable length. After reconnecting all services, the chambers are commissioned by recording cosmic rays. Following successful commissioning, the upgraded CSCs are integrated with the rest of CMS and the global DAQ system, where the chambers can participate in global data taking. Hit occupancy and timing plots allow the overall functioning of the CSCs to be monitored.

4.4 Optical fibers

The Phase-2 transition of ME234/1 chambers from CFEBs to DCFEBs with optical links, and from DMBs to ODMBs for the corresponding chambers, requires replacing the copper connections with optical fibers for fast trigger and data readout. Throughout LS2, the muon endcaps were opened to access to the CSCs so the ME234/1 chambers could be extracted, refurbished with DCFEBs above ground, brought back down into the experimental cavern,

and reinstalled. In LS3 however, access to the CSCs will not be possible as other subsystems will have priority access to complete Phase-2 upgrades to their detectors. However, access to the peripheral crates is possible during LS3 and that is when the ODMBs will be installed. However, this constraint meant that the optical fibers had to be installed in LS2, despite not seeing use until LHC Run 4 after the ODMBs are in place.

Each ME234/1 chamber has five DCFEBs, each with an optical trigger and data readout, and an ALCT with data readout. In Phase-2, these readouts will be mapped to an OTMB and ODMB, with housed in a peripheral crate with OTMBs and ODMBs for three nearby chambers. ME234/1 chambers are connected to a peripheral crate with a single Sylex 48-fiber bundle trunk per peripheral crate. The chamber side of each trunk splits into four 12-fiber bundles (labeled 1-4) with MTP connections that map to eight 5- or 7- fiber bundles (labeled A-H), also with MTP connections. Specifications and for the trunk from Sylex are provided in Fig. 4.16, along with a table of the channel mapping. Three of the chamber-side fiber bundles are connected to a chamber, while the fourth fiber bundle is kept as a spare. Each fiber bundle is connected to the five DCFEBs of a CSC via a 12-fiber optical “fanout,” with an MTP connection to the fiber bundle and LC connections to the DCFEBs. Channel mapping is as follows: one fiber for the trigger VTTx connection and the DAQ VTRx connection on each of the five DCFEBs (2×5), and two fibers for the ALCT with a trigger VTTx connection, totalling twelve channels. Figure 4.17 shows a cartoon of how the 12-fiber fanout and 48-fiber bundle trunk will connect from chamber to peripheral crate.

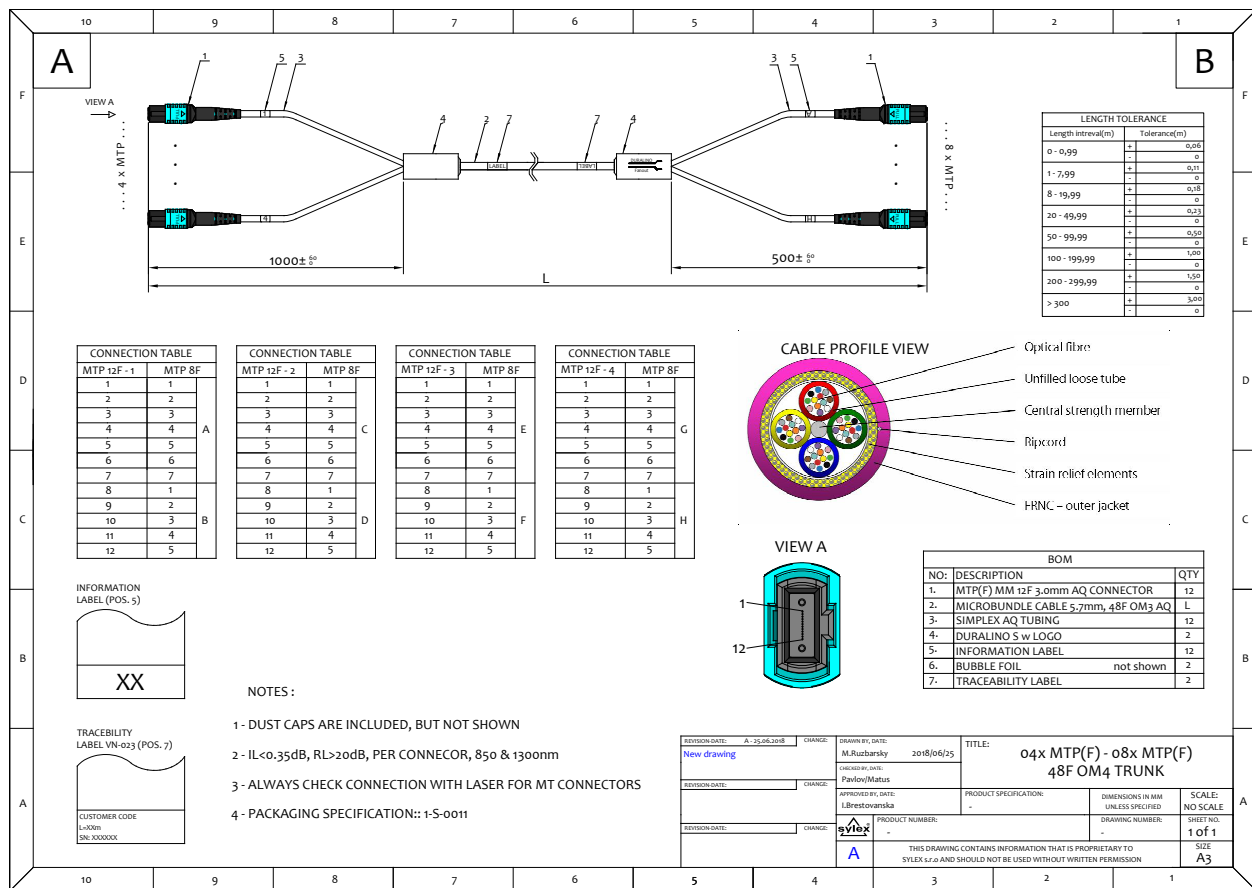


Figure 4.16: A technical diagram and manufacturer's specifications for a 48-fiber bundle trunk.

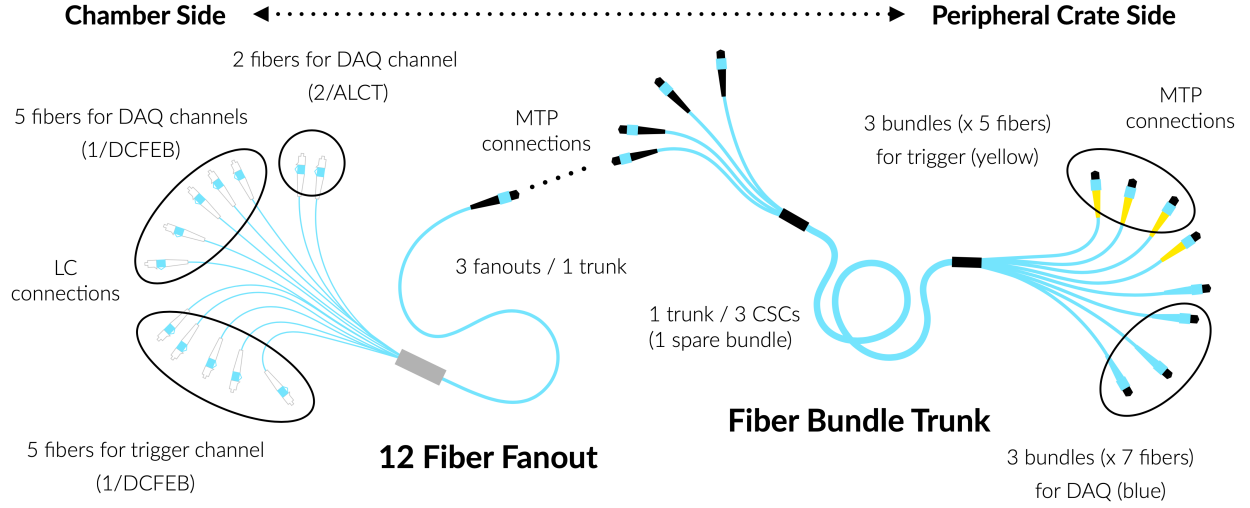


Figure 4.17: A cartoon diagram depicting the fanout-to-trunk setup for three CSCs, from chamber to peripheral crate.

Functionality and mapping of the 48-fiber bundle trunks were tested in building 904 at the CERN Preveessin site. The testing setup consisted of an ME1/1 chamber, who's DCFEB acted as a constant light source. The LC ends of a 12-fiber fanout were connected to the DCFEB and the MTP end was connected to fiber bundles 1-4. The other end of the trunk, bundles A-H, were also connected to the MTP end of a second fiber fanout, and the LC connectors of those were connected to an attenuation meter. By observing light in all 48 fibers channel, one by one, the mapping of each fiber on the four-bundle-split to the eight-bundle-split of the trunk was validated. Optical attenuation measurements were consistent accross channels and within the manufacturer's specifications, shown in Fig.. At the CSC facility in SX5, mapping and attenuation of ten 12-fiber fanouts were studied, using a setup similar to the one used in bulding 904, the difference being the 48 fiber bundle trunk was replaced with a single 12-fiber bundle trunk with just one MTP connection on each end. A photograph of the SX5 setup is provided in Fig. 4.18. Optical attenuation measurements made for each of the ten 12-fiber fanouts can be found in Fig. 4.19.

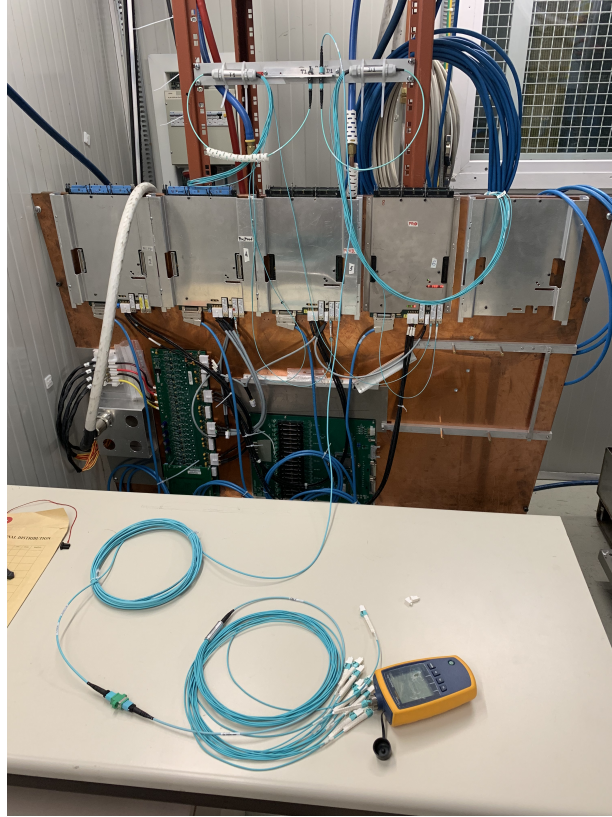


Figure 4.18: The 12-fiber fanout testing setup at the CSC facility in SX5. The LC-ends of a fanout were connected to the Finnesar links on right-most DCFEB (obscured by a cooling cover). On the table in the foreground is one of the 12-fiber fanouts being tested, connected to the the 12-fiber trunk and the optical attenuation meter.

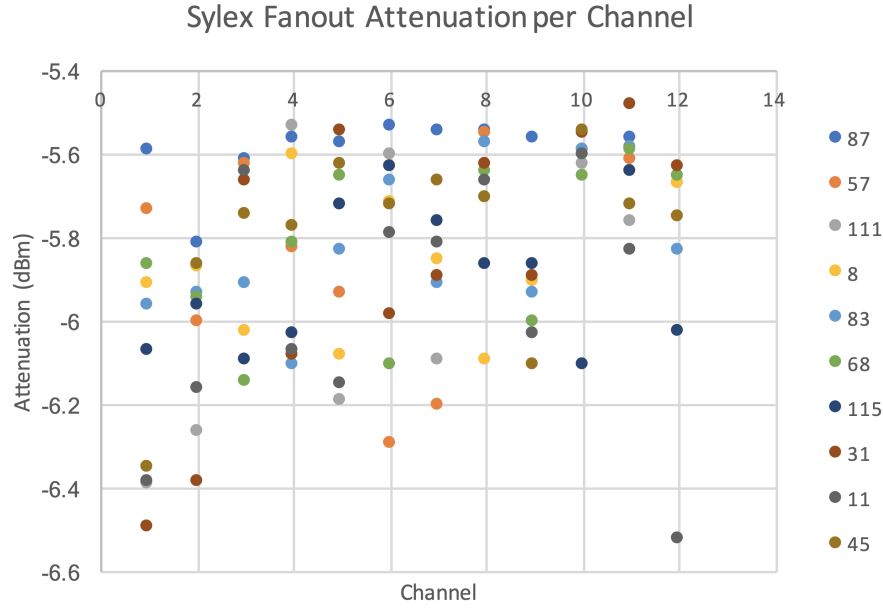


Figure 4.19: Optical attenuation in each channel of ten 12-fiber fanouts. Each color corresponds to a different fanout.

Routing of the thirty-six 48-fiber bundle trunks was performed during LS2 when access to CSC stations 1, 2, and 3 was possible. As the orientation of chambers in stations alternate in each endcap, two routing configurations were used, shown in Fig. 4.20. Fiber bundle trunks were secured to the sides of ME234/2 chambers with sticky pads and cable ties (the procedure is demonstrated in the two photographs of Fig. 4.21), while the MTP ends on the rack-side of the trunk were bound together and wrapped in a plastic bag. During LS3, the fiber bundles will be connected to each chamber and to the OTMB and ODMB in the peripheral racks. Prior to routing, labels were applied to all the trunks: two on the middle trunk near the two splits, and one near the MTP connector on each bundle. Chamber-side bundles were labeled with either the chamber (e.g., “ME-1/1/1”) or “SPARE,” while crate-side bundles were labeled with the rack/crate/slot numbers, chamber, and either TRG or DAQ, depending on if the bundle was for trigger or data channels. The middle of the trunks were labeled with the chamber range/TRG+DAQ/rack/crate and a barcode.

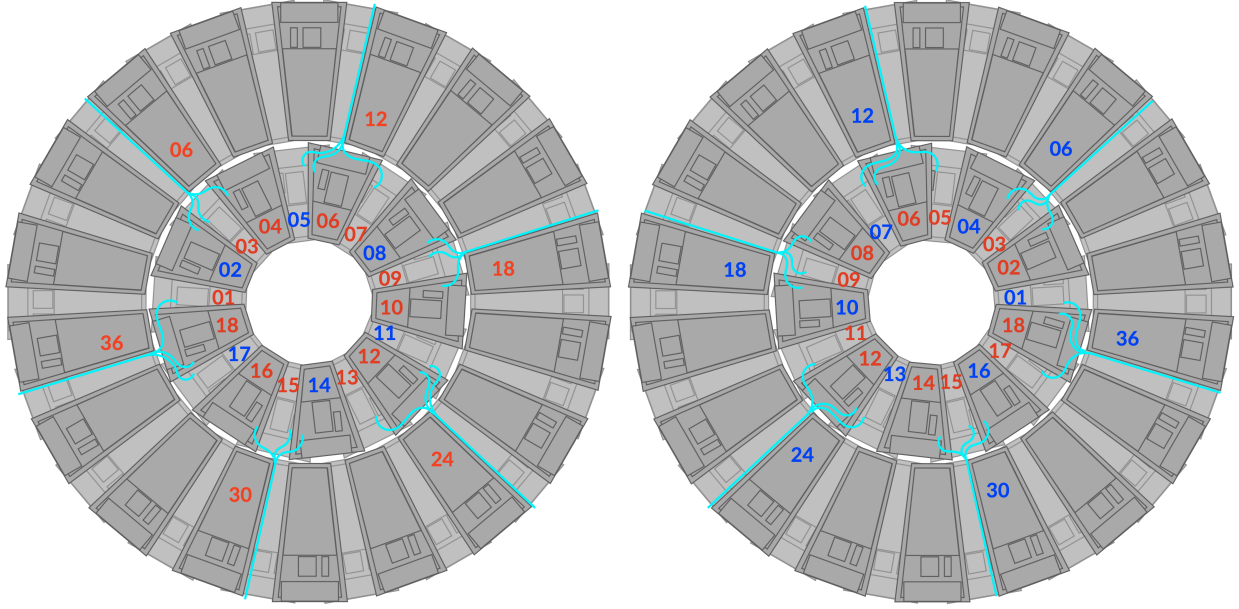


Figure 4.20: A schematic of the 48-fiber bundle trunk routing configurations on different endcap disks. Left: Fiber routing for clockwise-oriented stations, ME+2, ME-3, and ME-4. Right: Fiber routing for counter-clockwise-oriented stations, ME-2, ME+3, and ME+4. Chambers where the fiber bundle/trunk is connected/secured to the HV side are labeled in red, while chambers where the fiber bundle/trunk is connected/secured to the non-HV side are labeled in blue.

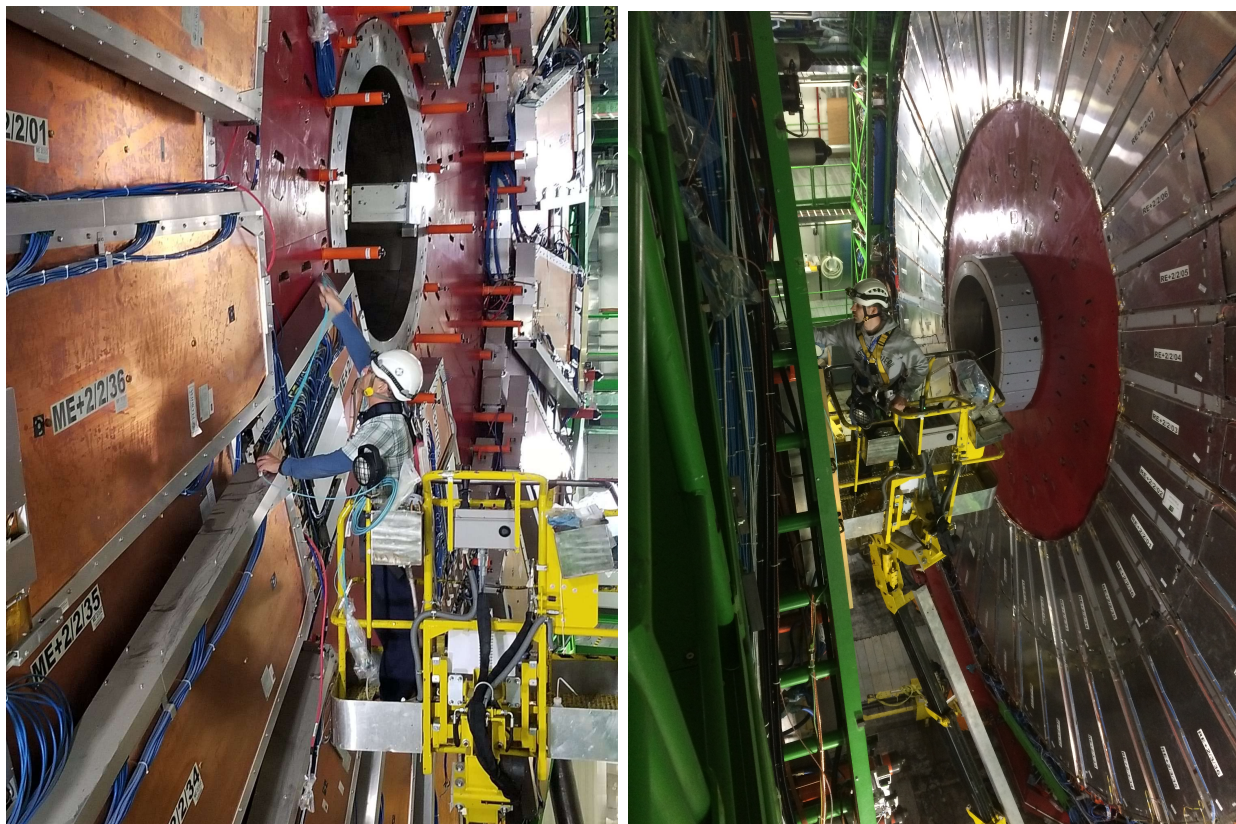


Figure 4.21: Routing of the 48-fiber bundle trunks on the ME+2 disk by Misha Ignatenko (left) and the author (right).

Chapter 5

Detector Performance

5.1 CMS physics performance and datasets

5.1.1 Data formats and quality monitoring

The CMS experiment stores recorded and simulated collision data in several file formats with differing size, compression, structure, etc., categorized into tiers. As data undergo successive processing, they are refined from detector-level hits all the way to high-level physics objects, with each stage being supported by a different data tier. The lowest-level data format is DAQ-RAW, which comes directly from the front-end electronics with an L1A. These DAQ-RAW files feed the online HLT algorithms, and after online formatting, events are stored in the RAW data tier. RAW files contain detector data, L1 trigger result, HLT trigger bits, and a few high-level quantities needed for HLT decisions, and range in size from 0.70-0.75 MB per event. Simulated events generated with Monte Carlo (MC) are stored as GEN files. Particle interactions with detector components are realized as energy depositions, also called sim hits, stored as SIM data. The detector response to sim hits are stored in the DIGI format at 1.5 MB per event. DIGI files are effectively the same format as RAW data from the detector. Event reconstruction at Tier-0 of RAW and DIGI data builds complex physics objects like tracks, vertices, jets, etc. and reconstructed hits and clusters, and stores the output in the RECO format. Events in RECO contain more sophisticated data than in RAW, resulting in a substantially larger event size of 1.3-1.4 MB per event. Physics analyses during Run I relied on centrally-stored datasets in a special format called Analysis Object Data (AOD). AOD files are much smaller than RECO, making them easier to store and faster to process, by compressing each event down to a mere 0.05 MB. From these AOD datasets, analyses

could generate their own ntuples with analysis-specific data according to their needs. During Run II, more size-efficient versions of AOD were released, called Mini-AOD and Nano-AOD, which are both on the order of 1 KB per event.

CMS Data Quality Monitoring (DQM) is divided into two streams: online DQM, where any problems during CMS detector operation are identified, and offline DQM combined with Data Certification (DC), for establishing if data are suitable for physics analysis. DQM is performed by experts within each subsystem, while the DQM-DC subgroup of Physics Performance and Datasets organizes the centralization of the monitoring modules in CMSSW, operates the live monitoring applications and visualization tool (DQM GUI), organizes the DQM shifts of each subsystem, coordinates the experts to certify data, and publishes the list of good data for physics analysis.

5.1.2 Alignment, Calibration, and Database

Physics Performance and Datasets (PPD) is a CMS-wide coordination area responsible for the centralized software, called CMSSW, used to process all data originating from CMS. CMSSW is the full collection of software modules used in processing CMS data. Development of CMSSW code by the different detector subsystems, coordination areas, and physics groups, gets included in scheduled production and pre-production releases, with approval going through the PPD group using pre-production physics validation samples. The mandate of the PPD group is to develop the necessary code and validate the physics performance of data processed with CMSSW in event generation, physics and detector simulation, reconstruction, detector alignment and calibration, data quality monitoring, analysis and statistical tools, and trigger validation. The management and execution of each task within PPD is performed by a dedicated subgroup. Inside PPD, the Alignment, Calibration, and Database (AlCaDB) group oversee the storage, application, and monitoring of conditions data supplied by the CMS subsystems for the alignment and calibration of the detector. The AlCaDB group comprises a core team of experts, plus at least one contact from each Detector Performance

Group, Physics Object Group, and the Trigger Studies Group. Contacts act as representatives of their respective DPG/POG/TSG, communicating news, activity, and requests from the AlCaDB core team, and are responsible for subsystem/physics/trigger-dependant activity within AlCaDB.

5.1.2.1 Detector alignment and calibration

Inevitable misalignment of the CMS detector caused by by tolerances, static fields (magnetic, gravitational), and temperature fluctuations, presents an incredible challenge for offline reconstruction. In particular, the fine-grain resolution of the tracking technologies—pixel, strip, and muon—requires precision alignment of the many independent sensors to fully exploit. To accurately model the true detector geometry in reconstruction, a set of alignment corrections to the ideal geometry must be measured by each subsystem. The tools used to extract the alignment corrections vary accross the subsytems, from purpose-built optical sensors to data-derived studies.

The signals read out by the electronics of each CMS subsystem require some degree of calibration to accurately interpret. A set of parameters for the signals in each channel, like gain, pedestal, arrival time, etc., are extracted by controlled measurements. These calibration constants are used in reconstruction to normalize signals in real data-taking or model real signals in simulation, although the exact applications vary significantly for each subdetector.

5.1.2.2 Conditions data

Conditions data is a CMS Collaboration term that encompasses all detector-related information not contained in RAW data required by the online (HLT) and Offline processing streams that might be time-, run-, or event-dependent, or cannot be easily hard-coded. For example, the HLT runs on a self-contained binary executable, meaning any dynamic information required by the HLT algorithms must be accessed through an external source. In Offline

processing, it is simply more convenient to retrieve certain parameters that may frequently change rather than hard-coding them in software. Simulated data likewise use conditions data, where modeling the detector-response should reflect the real state of the CMS detector during a given data-taking period. Examples of conditions data are calibration constants, alignment corrections, dead channels, cable mapping, geometry, etc., although the exact conditions are highly detector-specific. All conditions data are uploaded on an as-needed basis to a central SQLite database where they can be read out

A collection of conditions data is uploaded and stored in the conditions database as a Payload (identified with a hash), along with a collection of metadata. Each Payload represents a set of conditions data covering a specific time period of data-taking, specified by a metadata parameter called the Interval Of Validity (IOV). An IOV is the run number from which the conditions data are valid; a range of time defined by a lower bound and extending to infinity. Payloads are accessed in every physics data processing workflow through a Record, representing each “type” of conditions data, that imports the database content. Another metadata parameter is a label called a Tag that identifies a set of Payload and IOV together. The insertion time defines the time of each Payload’s creation in the database. The last piece of metadata is a Global Tag (GT): a label identifying the set of Tags associated to each Record used in a given workflow. For every CMSSW release, different production workflows are configured to retrieve conditions data under a specific GTs that address different data processing, e.g., HLT, data reconstruction, MC GEN-SIM, MC DIGI-RECO, etc. For this reason GTs, as well as Tags, are always associated with specific data reconstruction scenarios: Online (Express, Prompt, and HLT), Offline, and MC. A GT is always prepared by the AlCaDB experts, while contacts are responsible for either approving existing Tags currently in a GT or uploading new Tags.

5.2 Muon reconstruction

Local muon reconstruction begins in the endcaps with information from the multi-layered CSCs (DTs provide position information in the barrel region). Charged particles passing through a CSC are registered when they initiate a charge shower in a gas layer that collects on the cathode strips (and a corresponding image charge collects on the anode wires). Strip and wire signals are sampled by the SCAs on the front-end electronics and digitized into strip and wire digis. Typically, the charge deposition of a single muon is distributed onto three to five contiguous strips. These strips get clustered and fit with a “Gatti” function to obtain the centroid and width of the charge distribution, providing a position measurement and uncertainty in the bending coordinate ϕ , or local x . Anode wires provide a radial measurement, or local y , read out in groups of 5-16 wires with resolution $w/\sqrt{12}$ for a wire group width w (around 0.5 cm). A traversing muon will typically only register on one to two wire groups in a given layer. Two-dimensional spacial points called reconstructed hits or “rechits” are built in software from strip and wire digis that correspond to a time coincidence of overlapping strip clusters and hit wire groups (or pairs of groups). Local non-orthogonal x and y coordinates are converted to the three-dimensional orthogonal global coordinates x , y , z , where z is the global z position of a CSC. Three-dimensional per-chamber track segments are constructed by identifying the straightest pattern of rechits in the six layers of a CSC. The algorithm first connects a straight line to a rechit in the first and last layers, and additional rechits in the intermediate layers are successively added to the fit according to χ^2 compatibility. Each segment is allowed to use only one rechit per layer and is required to use a minimum of three rechits. Rechit sharing among segments is forbidden. CSCs and DTs build rechits and segments individually. Stand-alone muon reconstruction combines information only from the muon detectors, with CSCs, DTs, and RPCs all participating. The state vectors of local track segments from the CSCs and DTs are used to progressively build muon trajectories, moving from the inner-most chambers to the outer-most, with a

Kalman filter technique. Hits reconstructed by the RPCs are likewise included in the filter. The resulting muon track is extrapolated to the nominal IP. Global muon reconstruction extends the stand-alone muon tracks to include silicon tracker hits.

5.3 CSC conditions data

5.3.1 Alignment

Sources of misalignment within the muon spectrometer include: chamber construction tolerances, e.g., wire-positioning; detector assembly, opening, and closing tolerances, and static deformations in the YE disks from magnetic field distortions can all result in individual chamber displacement of up to several cm from their nominal positions; and dynamic sub-millimeter misalignment from temperature fluctuations during operation. To capitalize on the 100 μm -level rehit resolution in the muon system, knowledge of each sensor and module position must be acquired to an even greater precision. The Muon Alignment (MA) system continuously monitors the detector geometry with LEDs and laser beams, along with distance and angle measuring devices. All 250 DTs are continuously monitored, while only 12 select CSCs are monitored in each ME station are directly monitored.

5.3.2 Electronics calibration

CSC front-end electronics require calibration to homogenize the signals in each cathode channel for HLT and offline reconstruction. Periodic tests are performed by the CSC Operations Group to configure parameters for each electronics module and extract the data needed to calibrate, usually at the start of LHC runs or after major changes to the CSCs have been made. Each CFEB on a CSC reads 96 cathode strip channels distributed across six 16-channel amplifier-shaper ASIC chips. The shaper-amplifiers are sampled every 50 ns and voltages are stored by the same number of 16-channel SCAs while waiting for an L1A

(latency of 120 bunch crossings). The amplifier-shaper chips come equipped with internal capacitors for generating test pulses. Calibration runs inject these test pulses into all cathode channels, and by measuring the corresponding output, the constants needed to calibrate each channel can be extracted, specifically:

- Strip channel electronic gains
- Strip pedestals
- Strip channel noise
- Strip-to-strip crosstalk

Calibrating these parameters can improve the accuracy of hit positions in recorded data reconstruction and allow for more truthful modeling of the CSCs in simulation.

5.3.2.1 Gains

Electronic gain in each strip channel is measured by incrementing the test pulse amplitude and sampling the output. During reconstruction of muon hit positions, the raw pulse heights in each channel are normalized to the average pulse-height gain accross all channels in all CSCs.

5.3.2.2 Pedestals

Pedestal values for each strip are gathered by sampling the amplifier output at 20 MHz without any input signal and measuring the charge in each SCA bin, referred to as “static” pedestals. Static pedestals are used in simulation to supply a baseline for simulated signals. High-rates during normal operation can result in a baseline shift. To account for this, reconstruction instead uses “dynamic” pedestals, where the average charge on each strip of only the first two SCA time bins—prior to the signal arrival—are taken as the pedestal values.

5.3.2.3 Noise matrix

As the pedestal noise (RMS) is correlated accross SCA time bins, it can be described for each strip by the covariance between the charge in each SCA time bin, forming a symmetric “noise matrix.” Each element of the noise matrix is defined as

$$C_{ij} = \langle Q_i \cdot Q_j \rangle - \langle Q_i \rangle \cdot \langle Q_j \rangle, \quad (5.1)$$

where Q_i is the charge in SCA time bin i , and the average is taken over many calibration runs.

5.3.2.4 Crosstalk

Undesirable signal transfer called crosstalk can occur between neighboring strips in a CSC through inductive coupling. To measure the effect, an approximate delta-function pulse is fired into each amplifier channel. The induced charge on an adjacent strip normalized to the charge deposited on a strip are measured in each SCA time bin. This charge ratio is then convoluted with the expected ion drift time and electron arrival time distributions to model the amplifier response to a pulse shape typically seen during CSC operation (instead of a delta-function pulse). The crosstalk fraction for each channel, per SCA time bin, is defined as the ratio of the left or right neighboring strips divided by the sum of all three adjacent strips. Crosstalk fractions ordinarily range from 5 % to 10 %. As the crosstalk fraction is linear in time (within 160 ns of the charge peak), it can be encoded for each channel into just four constants: the slope and intercept of a straight line representing the crosstalk coupling to the left and right neighbors of a strip as a function of SCA time bin. For every strip and SCA time bin, these conditions are stored as a 3×3 matrix whose elements transform the measured charges on a strip and its two neighbors to the input charge on the strip. The matrices are used in simulated data to model crosstalk, while the inverse matrices can be applied in recorded data to remove the effect of crosstalk.

5.3.3 Offline timing corrections

In addition to supplying the muon system with precise muon track positions and directions, the CSCs assist the RPCs in determining the arrival time of muons in the endcaps. As mentioned in Sec. 5.3.2, the CFEB amplifier channels are only sampled every 50 ns, where the first two of the eight SCA time bins are used to measure the dynamic pedestal. To obtain a precise measurement of the arrival time of a signal peak, the signal shape is compared to the known analytical form of the pulse shaped by the CFEB amplifier-shaper ASICs. The resulting rehit time resolution in each CSC is measured to be 5 ns. The average cathode rehit times in each chamber are shifted to zero using “heuristic” corrections that are data-derived using muons from collisions. Anode clocks are more coarse-grain than the cathode timing, defined by identifying the closest cathode time bin with a 12.5 ns resolution, modulo a roughly 205 ns offset. Cathode hit times and anode hit times are combined to arrive at CSC segment times. A Gaussian fit to the segment time distribution in each chamber provides a segment timing resolution of roughly 3 ns.

5.3.4 Dead channels and chambers

During operation, it is possible for CSC strip and wire channels to die, and in more extreme cases, entire chambers. These can sometimes be recovered, but often the chamber is inaccessible, preventing any hands-on intervention to revive it. Dead chambers are identified when CSC data quality monitoring does not see rechits in the chamber. A catalogue of dead channels and chambers for a given period of running are classified as CSC conditions data. While not needed for processing real data, these conditions data are important to accurately model the state of the real CSCs in simulation. In practice, the CSC group only used a list of “bad” chambers, represented in simulation by not generating rechits in the channels of those chambers.

5.3.5 Mapping, geometry, and gas gain

Other CSC conditions data are stored in the conditions database but are never updated. Electronics cable mapping (for crates, chambers, and DDUs) are used in real data as hardware labels to geometric values. CSC strip and wire geometry information is used in simulation for digitization and in real data during local reconstruction. Chamber parameters traditionally associated with strip and wire geometry are likewise used in simulation and real data. Precise corrections to the system gas gain were derived in a detailed analysis during Run I.

5.4 CSC detector performance activity

The following is an account of activity I performed in my roles as CSC DPG contact to the AlCaDB group and as a member of the CSC Validation team during my Ph.D. studies from late 2018 to the present. For conditions-related work, this covers the studies and validation performed on new calibration constants and timing corrections, updates to bad chambers conditions, and any new payloads uploaded to the conditions database. A description of CSC Validation, a function of the CSC DPG, is also provided along with a brief account of software development required during the same time period.

5.4.1 Contact to AlCaDB

Immediately following the conclusion of LHC Run II, CSC operations performed several calibration runs (325875, 325656, and 325875). The “new” calibration constants were extracted from run 325875 with `CMSSW_10_2_11`. These were compared to “old” constants already in the conditions database under the Express tags: `CSCDBPedestals_express`, `CSCDBGains_express`, `CSCDBNoiseMatrix_express`, and `CSCDBCrosstalk_v2_express`, each with an IOV of run 266576. Figures x-x show the relative differences in each cathode channel between the new

constants and the old. Validation of the new conditions data on reconstruction is necessary to determine if the conditions are fit to upload. Using RAW SingleMuon data from Run 2018D, events were reconstructed using the old and new conditions data separately. Validation plots showing the rehit-to-segment residuals in layer 3 of the CSCs ring ME1/1 are shown in Figs. 5.1. These studies were presented to the CSC experts (including the CSC DPG) in the CSC weekly meeting on April 17, 2019. The conclusion was drawn that the constants were stable and did not need replacing in the conditions database.

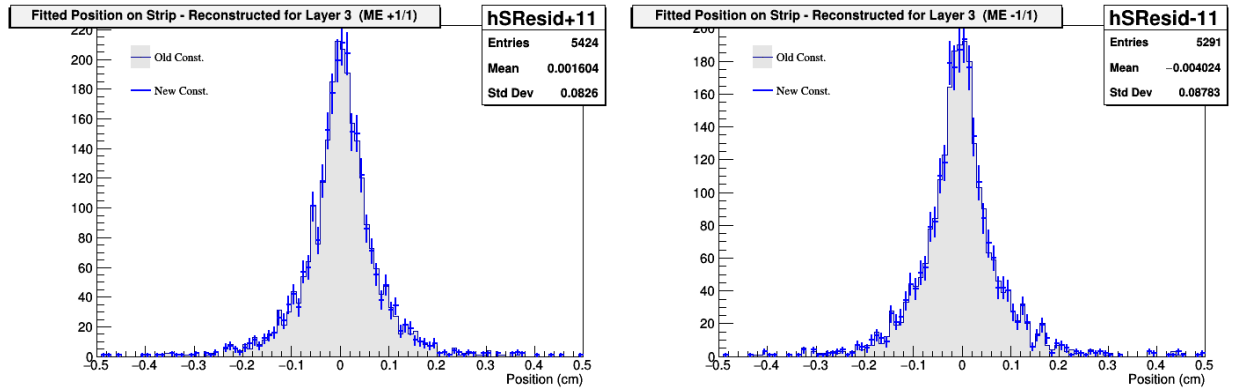


Figure 5.1: Rehit-to-segment residuals in layer 3 of ME1/1 chambers in RAW SingleMuon 2018D data using newly-derived calibration constants in Run 2. Left: Chambers in the positive muon endcap. Right: Chambers in the negative muon endcap.

With the LHC shutdown and chambers extracted for LS2, no updates to the conditions data were necessary. However, a campaign by AlCaDB to test run-dependant conditions resulting from needs by other CMS detectors required attention from the CSC DPG contact. Mock conditions were prepared to mimic a dead chamber. This was uploaded to the conditions database for AlCaDB to test the new run-dependant workflow.

It is important to make sure CSC conditions data in the conditions database reflect the state of the detector, especially before starting a new data-taking period, a MC or ReReco campaign, or when significant changes to the CSCs are made. The replacement of cathode front-end electronics on all CSCs in Ring 1 during LS2 meant new calibrations and timing corrections had to be studied. In fall of 2022, shortly after the LHC resumed collisions at

13 TeV for Run 3, CSC Operations performed a number of calibration runs. New calibration constants were extracted from these runs with `CMSSW_12_0_4` and were compared to old constants currently in the conditions database under the HLT tags: `CSCDBPedestals_hlt`, `CSCDBGains_hlt`, `CSCDBNoiseMatrix_hlt`, and `CSCDBCrosstalk_v2_hlt`, each with an IOV of run 266566. The relative differences between the new constants and the old in each cathode channel were found to vary only slightly, mostly in the channels of chambers refurbished in LS2. The new constants were validated using Run 357735 from the RAW Muon 2022D-v1 dataset. Old calibrations for used in processing the data for validation were under the GT 124X_dataRun3_v9, and the Offline tags `CSCDBPedestals_v2_offline`, `CSCDBGains_v2_offline`, `CSCDBNoiseMatrix_v2_offline`, and `CSCDBCrosstalk_v2_offline`, each with an IOV of 232000. The validation was performed using `CMSSW_12_4_6`. Figure 5.2 show validation plots comparing the effect on the rechit-to-segment residuals when using the old and new calibrations constants in layer 3 of ME+3/1 chambers. Initially, poor position resolution in the ME1/1A chambers (ME1/1 strips were ganged into groups “A” and “B” for Run 1, but were unganged during Run 2) was observed in data reconstructed with the new constants. However, after replacing all the new calibrations constants in these channels with old constants, and reperforming the validation, the poor resolution persisted, shown in Fig. 5.3 Good hit resolution seen in CSC DQM with the old constants confirms that the poor resolution in validation is not a result of the conditions data used in reconstruction, but some issue with the validation code. Work identifying and resolving the issue is underway.

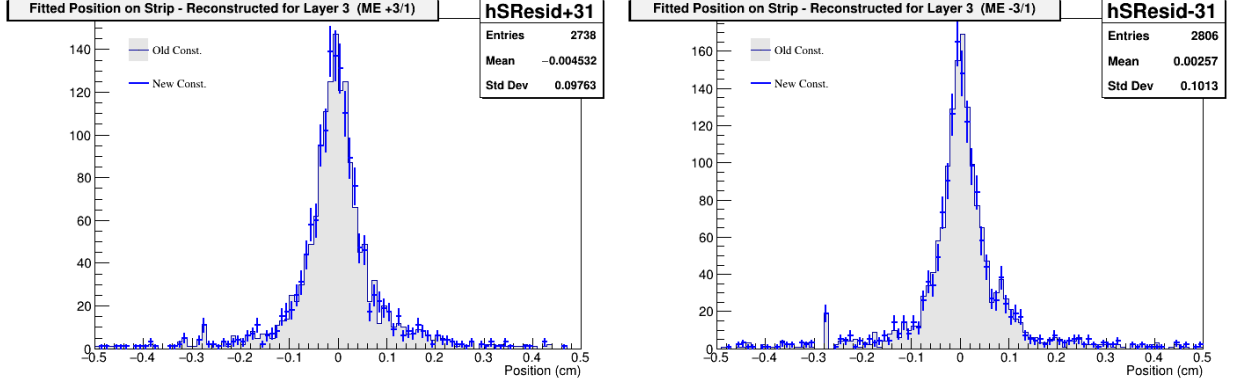


Figure 5.2: Rechit-to-segment residuals in layer 3 of ME3/1 chambers in Run 357735 of the RAW Muon 2022D-v1 dataset using newly-derived calibration constants in Run 3. Left: Chambers in the positive muon endcap. Right: Chambers in the negative muon endcap.

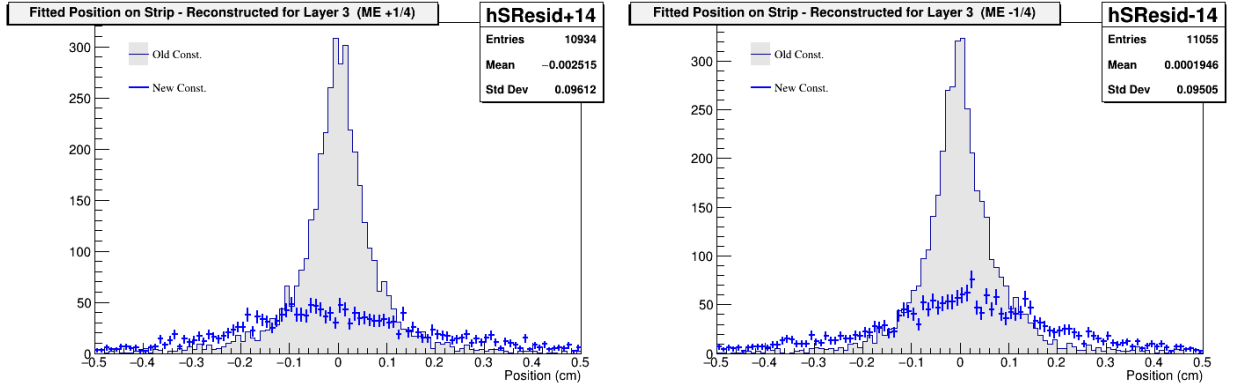


Figure 5.3: Rechit-to-segment residuals in layer 3 of ME1/1A (labeled ME $\pm$ 1/4) chambers in Run 357735 of the RAW Muon 2022D-v1 dataset using old calibration constants extracted in Run 2. Left: Chambers in the positive muon endcap. Right: Chambers in the negative muon endcap.

Split-peaks were observed in ME234/1 (chambers refurbished in LS2) cathode rechit and segment times with early Run 3 data, when reconstructed with the timing corrections derived in Run 2, as shown for ME+2/1 CSCs in Fig. 5.4. New timing constants were derived with Run 357900 in the Muon 2022D dataset. The constants were checked and found not to vary in 2022. The constants were validated with the same run in the RAW Muon dataset from 2022D. Use of the new timing constants in Run 3 data greatly improved the cathode rechit

and segment times, as shown in Fig. 5.4. The new constants were uploaded to the conditions database, first for the Offline stream, ahead of the ReReco campaign of 2022A-E data:

- GT: 124X_dataRun3
- Record: CSCChamberTimeCorrections
- Tag: CSCChamberTimeCorrections_v3_offline
- IOV: 347750
- Insertion time: 10/10/2022

Following a Fast-Track validation by the AlCaDB group of the Express/Prompt/HLT tags with a RAW Muon 2022E-v1 dataset (Run 359699) the constants were uploaded for real data taking:

- GT: 124X_dataRun3_[Prompt/Express/HLT]
- Record: CSCChamberTimeCorrections
- Tag: CSCChamberTimeCorrections_hlt
- IOV: 361040
- Insertion time: 24/10/2022

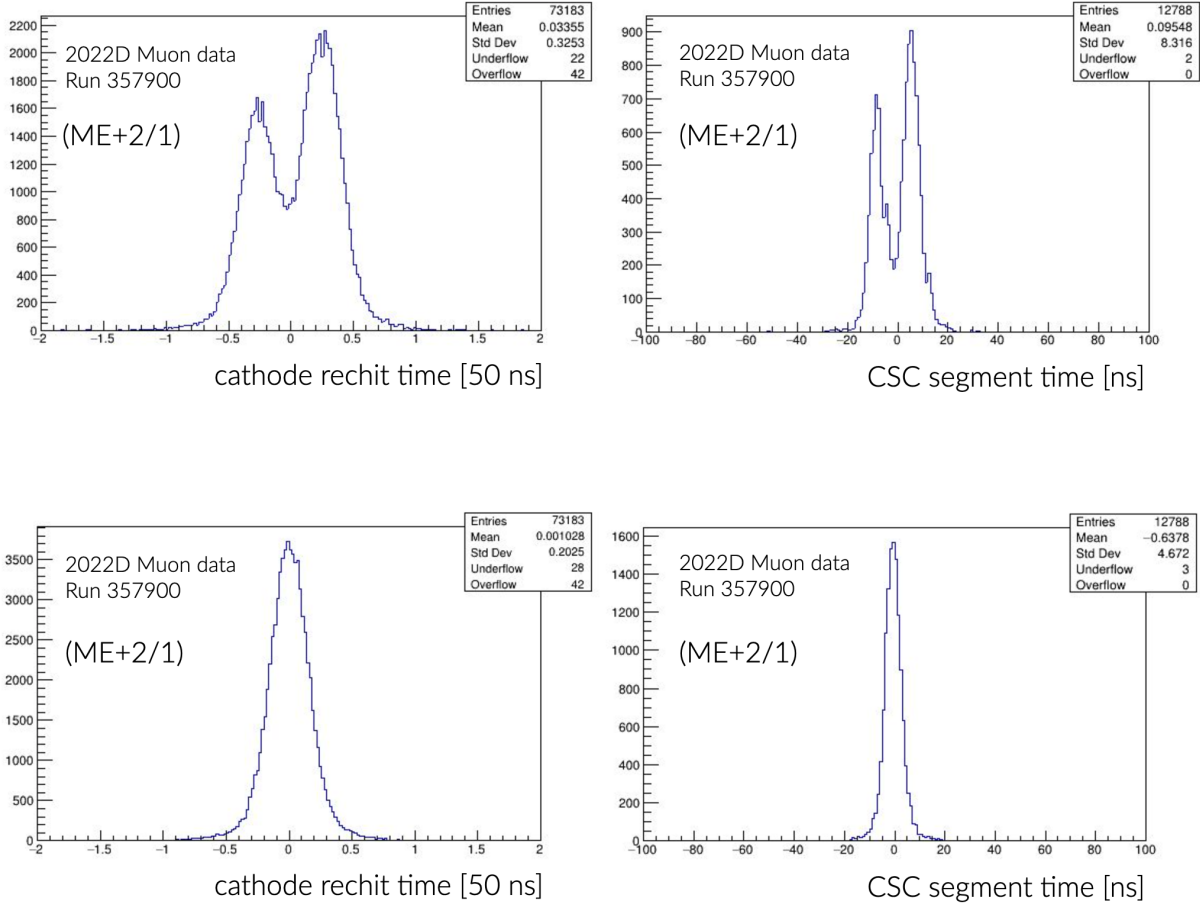


Figure 5.4: Top-left: Cathode rechit times using Run 2 timing corrections. Top-right: CSC segment times using Run 2 corrections. Bottom-left: Cathode rechit times using Run 3 timing corrections. Bottom-right: CSC segment time using Run 3 timing corrections. All times are for ME+2/1 chambers in RAW Muon data from Run 2022D. Left: Chambers in the positive muon endcap. Right: Chambers in the negative muon endcap.

AlCaDB workshops are held annually. These workshops are designed to allow each sub-system to share the current status and plans for their conditions and alignment. It also serves as an opportunity for AlCaDB to review news, upcoming campaigns, and host tutorials for common tools. The CSC DPG contact to AlCaDB always prepares an oral presentation outlining what conditions data are used by CSCs, the current status of conditions data in offline, HLT/Express/Prompt, and MC streams, and any plans to update the conditions data.

5.4.2 CSC Validation

During normal CSC operation, it is important to verify the status of detector-components. An automated procedure called CSC Validation generates simple plots (similar to CSC DQM plots) and posts them to the CSC Validation website to be monitored. A software package called auto-validation submits lxplus batch jobs via a cron daemon that run the CSC Validation code producing the validation plots. Data consumed are usually RAW Muon files from Express and PromptReco runs. The auto-validation software is mostly self-contained; human intervention is rarely needed. Even so, a support team within the CSC DPG is tasked with the maintenance and development of CSC Validation. A familiarity with the workflow by the CSC Validation team ensures the success of occasional special tasks or deployment of new features, in cases when external modules depreciate or centralized services like lxplus batch get phased out.

The HTCondor software suite offers users on CERN lxplus machines access to a High-Throughput Computing (HTC) environment. This allows the shared computing resources in CERN's machine network to be used fairly and efficiently for all users. When a user submits jobs to HTCondor on lxplus, the jobs are placed in a queue. Parameters such as number of CPUs requested, expected job duration, quantity of jobs, share of resources allotted to different experiments, and a user's priority score, impact queue placement. Once at the front of the queue, a job is sent to an available worker node on the distributed computing service to be run. If a machine crashes or is otherwise unavailable, HTCondor will automatically restart the job on a free machine. This is essential when running thousands of jobs with on numerous datasets. When a job finishes running, the output and any errors are returned to the user. During the author's tenure on the CSC Validation team, he migrated the auto-validation code from submitting jobs via lxplus batch to submitting jobs via HTCondor.

Chapter 6

Search for pair-produced leptoquarks decaying to bottom quarks and muons

6.1 Samples

6.1.1 Data samples

This search analyzes the 2016, 2017, and 2018 Run II datasets of proton-proton collisions recorded by CMS at $\sqrt{s} = 13$ TeV. Reconstruction of RAW data is performed with CMSSW_10_2_22. Luminosity sections with known detector issues are excluded from analysis for quality assurance; only centrally approved run ranges are selected according to the so-called Golden JSON files in Table 6.1.

Table 6.1: Golden JSON files containing approved CMS run ranges in each year of Run II data-taking.

Year	Golden JSON
2016	Cert_271036-284044_13TeV_ReReco_07Aug2017_Collisions16_JSON.txt
2017	Cert_294927-306462_13TeV_EOY2017ReReco_Collisions17_JSON.txt
2018	Cert_314472-325175_13TeV_17SeptEarlyReReco2018ABC_PromptEraD_Collisions18_JSON.txt

The datasets and respective integrated luminosities (after applying the Golden JSON) are listed in Tables 6.2–6.4. Events are further selected using the single muon trigger requirements for high- p_T muons, listed in Table 6.5. These triggers select events containing at least one muon in an event passing a p_T threshold of 50 or 100 GeV (if “50” or “100”

is in the trigger name) as measured by the muon system or the inner tracker (if “Mu” or “TkMu” is in the trigger name). The momentum thresholds of these triggers are higher than most analyses, as the TeV-scale leptoquark masses considered in this search push the event kinematics into a high-momentum regime.

Table 6.2: 2016 recorded datasets and corresponding luminosities used in this analysis.

Dataset	Run Range
SingleMuon/Run2016B-02Apr2020_ver2-v2	273150–275376
SingleMuon/Run2016C-02Apr2020-v1	275656–276283
SingleMuon/Run2016D-02Apr2020-v1	276315–276811
SingleMuon/Run2016E-02Apr2020-v1	276831–277420
SingleMuon/Run2016F-02Apr2020-v1	277932–278808
SingleMuon/Run2016G-02Apr2020-v1	278820–280385
SingleMuon/Run2016H-02Apr2020-v1	281613–284044
Total (Certified) [with brilcalc]	$\mathcal{L} = 36.3 \text{ fb}^{-1}$

Table 6.3: 2017 recorded datasets and corresponding luminosities used in this analysis.

Dataset	Run Range
SingleMuon/Run2017B-02Apr2020-v1	297047–299329
SingleMuon/Run2017C-02Apr2020-v1	299368–302029
SingleMuon/Run2017D-02Apr2020-v1	302031–302663
SingleMuon/Run2017E-02Apr2020-v1	303824–304797
SingleMuon/Run2017F-02Apr2020-v1	305040–306462
Total (Certified) [with brilcalc]	$\mathcal{L} = 41.5 \text{ fb}^{-1}$

Table 6.4: 2018 recorded datasets and corresponding luminosities used in this analysis.

Dataset	Run Range
SingleMuon/Run2018A-02Apr2020-v1	316219–316380
SingleMuon/Run2018B-02Apr2020-v1	317080–319310
SingleMuon/Run2018C-02Apr2020-v1	319941–319909
SingleMuon/Run2018D-02Apr2020-v1	321067–321051
Total (Certified) [with brilcalc]	$\mathcal{L} = 59.8 \text{ fb}^{-1}$

Table 6.5: Single muon trigger requirements by year.

Year	High-Level Trigger Path
2016	HLT_Mu50 HLT_TkMu50
2017	HLT_Mu50 HLT_OldMu100 HLT_TkMu100
2018	HLT_Mu50 HLT_OldMu100 HLT_TkMu100

6.1.2 Simulated signal samples

Leptoquark signal Monte Carlo (MC) samples are generated at leptoquark mass points ranging from 300 to 3000 GeV at intervals of 100 GeV, plus a 3500 GeV and 4000 GeV mass point. Cross sections and hard scattering are computed with MADGRAPH5_aMC@NLO and event generation uses the leading order (LO) PYTHIA generator [22, 23] (version 8.1). The parton distribution function (PDF) set used to generate leptoquark signal samples is NNPDF31 at LO. The tunes used for signal MC production vary by year, with 2016 using tune CUETP8M1, and both 2017 and 2018 using tune CP2. Additionally for 2016 signal MC, the PDFs are reweighted to NNPDF30 NLO, for consistency with the other background MC

samples of the same year. Monte Carlo digitization and reconstruction is performed using CMSSW_10_2_22 and the simulation of the CMS detector is based on GEANT4 [24].

The $LQ\bar{L}\bar{Q} \rightarrow b\bar{b}\mu^-\mu^+$ samples considered are provided in Tables 6.6–6.8 along with the datasets, the NLO cross sections at 13 TeV, and the total number of generated events. Each leptoquark signal sample is normalized in each year of data-taking to the expected number of signal events, equivalent to the product of the signal cross section listed in Tables 6.6–6.8 and the integrated luminosity, for a given year. Table 6.9 provides the NLO cross section used in generating each $LQ\bar{L}\bar{Q} \rightarrow b\bar{b}\mu^-\mu^+$ sample at 13 TeV, as well as uncertainties on the NLO cross sections introduced by statistical uncertainty, factorization/renormalization scale uncertainty, and PDF uncertainty.

Table 6.6: The 2016 NanoAOD v7 dataset, cross section, and number of events for each leptoquark signal sample used in the analysis.

Process	Dataset	Cross Section (pb)	Events
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-300_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	8.402	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-400_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	1.813	49800
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-500_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.5010	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-600_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.1706	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-700_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.06449	48400
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-800_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.02680	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-900_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.01190	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1000_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.005515	44600
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1100_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.002696	47732
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1200_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.001346	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1300_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0006991	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1400_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0003675	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1500_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0001964	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1600_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0001065	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1700_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.00005903	48800
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1800_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.00003288	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1900_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.00001828	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2000_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.00001042	47600
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2100_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.000005865	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2200_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.000003286	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2300_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.000001861	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2400_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.000001060	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2500_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0000006150	48600
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2600_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0000003470	49400
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2700_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0000001990	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2800_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0000001122	48400
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2900_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.00000006403	50000
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-3000_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.00000003698	48200
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-3500_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.000000002565	31600
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-4000_pair_TuneCUETP8M1_13TeV-madgraph-pythia8	0.0000000002426	47984

Table 6.7: The 2017 NanoAOD v7 dataset, cross section, and number of events for each leptoquark signal sample used in the analysis.

Process	Dataset	Cross Section (pb)	Events
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-300_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	8.402	49948
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-400_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	1.813	49939
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-500_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.5010	49130
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-600_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.1706	49926
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-700_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.06449	49921
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-800_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.02680	49916
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-900_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.01190	49911
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1000_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.005515	49908
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1100_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.002696	49309
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1200_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.001346	49904
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1300_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0006991	49902
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1400_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0003675	49895
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1500_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0001964	49892
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1600_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0001065	49888
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1700_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00005903	49890
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1800_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00003288	49884
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1900_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00001828	49884
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2000_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00001042	49879
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2100_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000005865	49875
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2200_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000003286	49875
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2300_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000001861	49873
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2400_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000001060	49875
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2500_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000006150	49872
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2600_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000003470	49864
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2700_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000001990	49867
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2800_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000001122	49862
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2900_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00000006403	49862
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-3000_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00000003698	47869
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-3500_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000000002565	49855
$LQ\overline{LQ} \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-4000_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000000002426	49856

Table 6.8: The 2018 NanoAOD v7 dataset, cross section, and number of events for each leptoquark signal sample used in the analysis.

Process	Dataset	Cross Section (pb)	Events
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-300_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	8.402	49949
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-400_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	1.813	49941
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-500_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.5010	49931
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-600_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.1706	49924
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-700_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.06449	49919
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-800_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.02680	49916
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-900_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.01190	49912
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1000_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.005515	49912
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1100_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.002696	49900
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1200_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.001346	49902
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1300_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0006991	49898
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1400_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0003675	49896
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1500_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0001964	49891
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1600_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0001065	49892
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1700_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00005903	49887
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1800_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00003288	49887
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-1900_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00001828	49879
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2000_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00001042	49884
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2100_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000005865	49876
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2200_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000003286	49876
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2300_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000001861	49877
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2400_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000001060	49873
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2500_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000006150	49874
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2600_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000003470	49868
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2700_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000001990	49862
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2800_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000001122	49868
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-2900_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00000006403	49866
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-3000_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.00000003698	49862
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-3500_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.000000002565	49852
$LQ\overline{L}Q \rightarrow b\overline{b}\mu^-\mu^+$	LQToBMu_M-4000_pair_TuneCP2_PSweights_13TeV-madgraph-pythia8	0.0000000002426	49859

Table 6.9: The leptoquark mass hypotheses used in the analysis, the corresponding NLO cross sections at 13 TeV, percent variations on statistical uncertainty, PDF uncertainty, and systematic uncertainty with the renormalisation/factorisation scale varied between half and twice the leptoquark mass.

M_{LQ} [GeV]	$\sigma(\text{NLO})$ [pb]	$\delta(\text{stat})$ [%]	$\delta(\text{scale up})$ [%]	$\delta(\text{scale down})$ [%]	$\delta(\text{PDF up/down})$ [%]
300	8.402	5.7×10^{-2}	12.2	12.7	3.4
400	1.813	1.3×10^{-2}	11.6	12.7	4.1
500	5.010×10^{-1}	2.9×10^{-3}	11.2	12.7	4.8
600	1.706×10^{-1}	9.8×10^{-4}	11.7	13.1	5.5
700	6.449×10^{-2}	3.7×10^{-4}	11.7	13.3	6.2
800	2.680×10^{-2}	1.5×10^{-4}	11.6	13.4	6.8
900	1.190×10^{-2}	6.7×10^{-5}	11.2	13.3	7.5
1000	5.515×10^{-3}	2.9×10^{-5}	11.4	13.5	8.3
1100	2.696×10^{-3}	1.7×10^{-5}	11.6	13.7	9.1
1200	1.346×10^{-3}	7.0×10^{-6}	11.9	13.9	9.9
1300	6.991×10^{-4}	3.7×10^{-6}	12.0	14.1	10.8
1400	3.675×10^{-4}	2.0×10^{-6}	12.4	14.4	11.8
1500	1.964×10^{-4}	1.0×10^{-6}	12.6	14.5	12.7
1600	1.065×10^{-4}	5.5×10^{-7}	12.5	14.6	13.8
1700	5.903×10^{-5}	3.1×10^{-7}	13.3	15.1	15.1
1800	3.288×10^{-5}	1.9×10^{-7}	13.5	15.2	16.4
1900	1.828×10^{-5}	9.5×10^{-8}	13.5	15.3	17.7
2000	1.042×10^{-5}	6.4×10^{-8}	14.3	15.8	19.4
2100	5.865×10^{-6}	3.9×10^{-8}	14.5	15.9	21.0
2200	3.286×10^{-6}	1.7×10^{-8}	14.5	16.0	23.1
2300	1.861×10^{-6}	1.0×10^{-8}	14.8	16.2	25.6
2400	1.060×10^{-6}	6.0×10^{-9}	15.0	16.3	28.7
2500	6.150×10^{-7}	3.8×10^{-9}	16.0	16.8	32.5
2600	3.470×10^{-7}	2.0×10^{-9}	15.6	16.7	37.3
2700	1.990×10^{-7}	1.2×10^{-9}	15.9	16.8	44.6
2800	1.122×10^{-7}	6.5×10^{-10}	15.9	16.8	54.9
2900	6.403×10^{-8}	3.7×10^{-10}	16.0	16.8	66.4
3000	3.698×10^{-8}	2.4×10^{-10}	16.2	16.8	83.3
3500	2.565×10^{-9}	1.7×10^{-11}	14.4	15.5	312.8
4000	2.426×10^{-10}	1.2×10^{-12}	13.4	14.8	3092.0

6.1.3 Simulated background samples

Several SM processes are considered in this analysis as backgrounds. MC samples are used to estimate or cross-check the contribution from most of these processes:

- $Z/\gamma^* + \text{jets}$ events and $W + \text{jets}$ events generated with MADGRAPH5_aMC@NLO [25, 26] in bins of boson p_T ;
- $t\bar{t} + \text{jets}$ events, generated with POWHEG [27], inclusive for 2016 and decay binned for 2017 and 2018;
- single top events, with t-channel and $t W$ events generated with PYTHIA and POWHEG, and s-channel generated with MADGRAPH5_aMC@NLO;
- VV events, where each V is either a W or Z boson, generated at NLO with MADGRAPH5_aMC@NLO;
- $t\bar{t}V$ events, where V is either a W or Z boson generated at NLO with MADGRAPH5_aMC@NLO, or a Higgs boson generated at LO with PYTHIA and POWHEG.

As with the signal samples, all of the background samples are reconstructed using CMSSW_10_2_22 and simulate the detector response with GEANT4 [24]. The SM background processes, datasets, and NLO cross sections at 13 TeV are listed for each year in Tables 6.10-6.12. Note that each cross section listed in Tables 6.10-6.12 is the production cross section for inclusive decays and the product of the production cross section and decay branching fraction for samples with specific decay channels. Each SM background sample is normalized in each year of data-taking to the expected number of events, equivalent to the product of the cross section listed in Tables 6.10-6.12 and the integrated luminosity, for a given year. For completeness, a LO mass-binned $Z/\gamma^* + \text{jets}$ sample covering the range $10 < M_Z < 50 \text{ GeV}$ was considered on top of the p_T -binned samples and ultimately deemed irrelevant; no events from the mass-binned sample passed preselection.

Table 6.10: The 2016 NanoAOD v7 dataset, cross-section, and number of events for each background sample used in the analysis.

Process	DataSet	Cross Section (pb)
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Zpt-0To50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	5352.57924
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-50To100_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	363.81428
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-100To250_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	84.014804
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-250To400_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	3.22826
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-400To650_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	0.436041
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-650ToInf_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	0.040981
$t\bar{t}$	TT_TuneCUETP8M2T4_13TeV-powheg-pythia8	831.76
$tb \rightarrow b\bar{b}\ell\nu$	ST_s-channel_4f_leptonDecays_13TeV-amcatnlo-pythia8_TuneCUETP8M1	3.38
$tq \rightarrow bq\ell^+\nu$	ST_t-channel_top_5f_leptDecays_TuneCUETP8M1_13TeV-powhegV2-pythia8	136.02
$\bar{t}q \rightarrow \bar{b}q\ell^-\bar{\nu}$	ST_t-channel_antitop_5f_leptDecays_TuneCUETP8M1_13TeV-powhegV2-pythia8	80.95
tW^-	ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.85
$\bar{t}W^+$	ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1	35.85
$W \rightarrow \ell\nu$	WJetsToLNu_Wpt-0To50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	57297.3926
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-50To100_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	3298.3733
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-100To250_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	689.7496
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-250To400_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	24.5069
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-400To600_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	3.110131
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-600ToInf_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	0.468318
$WW \rightarrow \ell\nu qq$	WWTo1L1Nu2Q_13TeV_amcatnloFXFX_madspin_pythia8	49.997
$WW \rightarrow qq qq$	WWTo4Q_4f_13TeV_amcatnloFXFX_madspin_pythia8	51.723
$WW \rightarrow \ell\nu\nu$	WWTo2L2Nu_13TeV-powheg	12.178
$WZ \rightarrow \ell\nu qq$	WZTo1L1Nu2Q_13TeV_amcatnloFXFX_madspin_pythia8	10.71
$WZ \rightarrow \ell\nu\nu$	WZTo1L3Nu_13TeV_amcatnloFXFX_madspin_pythia8	3.033
$WZ \rightarrow \ell\ell qq$	WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8	5.595
$WZ \rightarrow \ell\ell\nu$	WZTo3LNU_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	4.42965
$WZ \rightarrow \nu\nu qq$	WZTo2Q2Nu_13TeV_amcatnloFXFX_madspin_pythia8	6.324
$ZZ \rightarrow \ell\ell\ell\ell$	ZZTo4L_13TeV-amcatnloFXFX-pythia8	1.212
$ZZ \rightarrow \nu\nu qq$	ZZTo2Q2Nu_13TeV_amcatnloFXFX_madspin_pythia8	4.04
$ZZ \rightarrow qq qq$	ZZTo4Q_13TeV_amcatnloFXFX_madspin_pythia8	6.896587
$ZZ \rightarrow \ell\ell qq$	ZZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8	3.22
$VV \rightarrow \ell\ell\nu$	VVTo2L2Nu_13TeV_amcatnloFXFX_madspin_pythia8	11.95
$t\bar{t}H \rightarrow b\bar{b}$	ttHTobb_M125_TuneCP5_13TeV-powheg-pythia8	0.291
$t\bar{t}H \rightarrow \text{non-}b\bar{b}$	ttHTNonbb_M125_TuneCP5_13TeV-powheg-pythia8	0.213
$t\bar{t}W \rightarrow \ell\nu$	TTWJetsToLNu_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	0.179
$t\bar{t}W \rightarrow qq$	TTWJetsToQQ_TuneCUETP8M1_13TeV-amcatnloFXFX-madspin-pythia8	0.371
$t\bar{t}Z \rightarrow \ell\ell\nu$	TTZToLLNuNu_M-10_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.26
$t\bar{t}Z \rightarrow qq$	TTZToQQ_TuneCUETP8M1_13TeV-amcatnlo-pythia8	0.60

Table 6.11: The 2017 NanoAOD v7 dataset, cross-section, and number of events for each background sample used in the analysis.

Process	DataSet	Cross Section (pb)
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Zpt-0To50_TuneCP5_13TeV-amcatnloFXFX-pythia8	5352.57924
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-50To100_TuneCP5_13TeV-amcatnloFXFX-pythia8	363.81428
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-100To250_TuneCP5_13TeV-amcatnloFXFX-pythia8	84.014804
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-250To400_TuneCP5_13TeV-amcatnloFXFX-pythia8	3.22826
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-400To650_TuneCP5_13TeV-amcatnloFXFX-pythia8	0.436041
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-650ToInf_TuneCP5_13TeV-amcatnloFXFX-pythia8	0.040981
$t\bar{t} \rightarrow b\bar{b}qqqq$	TTToHadronic_TuneCP5_PSweights_13TeV-powheg-pythia8	377.96
$t\bar{t} \rightarrow b\bar{b}qq\ell\nu$	TTToSemiLeptonic_TuneCP5_PSweights_13TeV-powheg-pythia8	365.34
$t\bar{t} \rightarrow b\bar{b}b\ell^-\ell^+\bar{\nu}\nu$	TTTo2L2Nu_TuneCP5_PSweights_13TeV-powheg-pythia8	87.31
$tb \rightarrow b\bar{b}qq$	ST_s-channel_4f_hadronicDecays_TuneCP5_13TeV-amcatnlo-pythia8	10.32
$tb \rightarrow b\bar{b}\ell\nu$	ST_s-channel_4f_leptonDecays_TuneCP5_PSweights_13TeV-amcatnlo-pythia8	-
tq	ST_t-channel_top_5f_TuneCP5_13TeV-powheg-pythia8	136.02
$\bar{t}q$	ST_t-channel_antitop_5f_TuneCP5_PSweights_13TeV-powheg-pythia8	80.95
tW^-	ST_tW_top_5f_inclusiveDecays_TuneCP5_PSweights_13TeV-powheg-pythia8	35.85
$\bar{t}W^+$	ST_tW_antitop_5f_inclusiveDecays_TuneCP5_PSweights_13TeV-powheg-pythia8	35.85
$W \rightarrow \ell\nu$	WJetsToLNu_Wpt-0To50_TuneCP5_13TeV-amcatnloFXFX-pythia8	57297.39264
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-50To100_TuneCP5_13TeV-amcatnloFXFX-pythia8	3298.3733
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-100To250_TuneCP5_13TeV-amcatnloFXFX-pythia8	689.7496
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-250To400_TuneCP5_13TeV-amcatnloFXFX-pythia8	24.5069
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-400To600_TuneCP5_13TeV-amcatnloFXFX-pythia8	3.110131
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-600ToInf_TuneCP5_13TeV-amcatnloFXFX-pythia8	0.468318
$WW \rightarrow \ell\nu qq$	WWTo1L1Nu2Q_13TeV_amcatnloFXFX_madspin-pythia8	49.997
$WW \rightarrow qq qq$	WWTo4Q_NNPDF31_TuneCP5_PSweights_13TeV-powheg-pythia8	51.723
$WW \rightarrow \ell\ell\nu\nu$	WWTo2L2Nu_NNPDF31_TuneCP5_PSweights_13TeV-powheg-pythia8	12.178
$WZ \rightarrow \ell\nu qq$	WZTo1L1Nu2Q_13TeV_amcatnloFXFX_madspin-pythia8	10.71
$WZ \rightarrow \ell\nu\nu\nu$	WZTo1L3Nu_13TeV_amcatnloFXFX_madspin-pythia8_v2	3.033
$WZ \rightarrow \ell\ell qq$	WZTo2L2Q_13TeV_amcatnloFXFX_madspin-pythia8	5.595
$WZ \rightarrow \ell\ell\ell\nu$	WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8	4.42965
$WZ \rightarrow \nu\nu qq$	WZTo2Q2Nu_13TeV_amcatnloFXFX_madspin-pythia8	6.324
$ZZ \rightarrow \ell\ell\ell\ell$	ZZTo4L_TuneCP5_13TeV-amcatnloFXFX-pythia8	1.212
$ZZ \rightarrow \nu\nu qq$	ZZTo2Q2Nu_TuneCP5_13TeV_amcatnloFXFX_madspin-pythia8	4.04
$ZZ \rightarrow \ell\ell qq$	ZZTo2L2Q_13TeV_amcatnloFXFX_madspin-pythia8	3.22
$VV \rightarrow \ell\ell\nu\nu$	VVTo2L2Nu_13TeV_amcatnloFXFX_madspin-pythia8	11.95
$t\bar{t}H \rightarrow b\bar{b}$	ttHTobb_M125_TuneCP5_13TeV-powheg-pythia8	0.291
$t\bar{t}H \rightarrow \text{non-}b\bar{b}$	ttHToNonbb_M125_TuneCP5_13TeV-powheg-pythia8	0.213
$t\bar{t}W \rightarrow \ell\nu$	TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8	0.179
$t\bar{t}W \rightarrow qq$	TTWJetsToQQ_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8	0.371
$t\bar{t}Z \rightarrow \ell\ell\nu\nu$	TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8	0.26
$t\bar{t}Z \rightarrow qq$	TTZToQQ_TuneCP5_13TeV-amcatnlo-pythia8	0.60

Table 6.12: The 2018 NanoAOD v7 dataset, cross-section, and number of events for each background sample used in the analysis.

Process	DataSet	Cross Section (pb)
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Zpt-0To50_TuneCP5_13TeV-amcatnloFXFX-pythia8	5352.57924
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-50To100_TuneCP5_13TeV-amcatnloFXFX-pythia8	363.81428
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-100To250_TuneCP5_13TeV-amcatnloFXFX-pythia8	84.014804
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-250To400_TuneCP5_13TeV-amcatnloFXFX-pythia8	3.22826
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-400To650_TuneCP5_13TeV-amcatnloFXFX-pythia8	0.436041
$Z/\gamma^* \rightarrow \ell^- \ell^+$	DYJetsToLL_Pt-650ToInf_TuneCP5_13TeV-amcatnloFXFX-pythia8	0.040981
$t\bar{t} \rightarrow b\bar{b}qqqq$	TTToHadronic_TuneCP5_13TeV-powheg-pythia8	377.96
$t\bar{t} \rightarrow b\bar{b}qq\ell\nu$	TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8	365.34
$t\bar{t} \rightarrow b\bar{b}b\ell^- \ell^+ \bar{\nu}$	TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8	87.31
$tb \rightarrow b\bar{b}qq$	ST_s-channel_4f_hadronicDecays_TuneCP5_13TeV-madgraph-pythia8	10.32
$tb \rightarrow b\bar{b}\ell\nu$	ST_s-channel_4f_leptonDecays_TuneCP5_13TeV-amcatnlo-pythia8	-
$t\bar{b} \rightarrow b\bar{b}\ell^- \bar{\nu}$	ST_s-channel_top_leptonDecays_13TeV_PSweights_powheg-pythia	-
$\bar{t}b \rightarrow b\bar{b}\ell^+ \nu$	ST_s-channel_antitop_leptonDecays_13TeV_PSweights_powheg-pythia	-
tq	ST_t-channel_top_4f_TuneCP5_13TeV-powheg-pythia8	136.02
$\bar{t}q$	ST_t-channel_antitop_4f_TuneCP5_13TeV-powheg-pythia8	80.95
tW^-	ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	35.85
$\bar{t}W^+$	ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8	35.85
$W \rightarrow \ell\nu$	WJetsToLNu_Wpt-0To50_TuneCP5_13TeV-amcatnloFXFX-pythia8	57297.39264
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-50To100_TuneCP5_13TeV-amcatnloFXFX-pythia8	3298.3733
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-100To250_TuneCP5_13TeV-amcatnloFXFX-pythia8	689.7496
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-250To400_TuneCP5_13TeV-amcatnloFXFX-pythia8	24.5069
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-400To600_TuneCP5_13TeV-amcatnloFXFX-pythia8	3.110131
$W \rightarrow \ell\nu$	WJetsToLNu_Pt-600ToInf_TuneCP5_13TeV-amcatnloFXFX-pythia8	0.468318
$WW \rightarrow \ell\nu qq$	WWTo1L1Nu2Q_13TeV_amcatnloFXFX_madspin-pythia8	49.997
$WW \rightarrow qq qq$	WWTo4Q_NNPFD31_TuneCP5_PSweights_13TeV-powheg-pythia8	51.723
$WW \rightarrow \ell\ell\nu\nu$	WWTo2L2Nu_NNPFD31_TuneCP5_PSweights_13TeV-powheg-pythia8	12.178
$WZ \rightarrow \ell\nu qq$	WZTo1L1Nu2Q_13TeV_amcatnloFXFX_madspin-pythia8	10.71
$WZ \rightarrow \ell\nu\nu\nu$	WZTo1L3Nu_13TeV_amcatnloFXFX_madspin-pythia8_v2	3.033
$WZ \rightarrow \ell\ell qq$	WZTo2L2Q_13TeV_amcatnloFXFX_madspin-pythia8	5.595
$WZ \rightarrow \ell\ell\ell\nu$	WZTo3LNU_TuneCP5_13TeV-amcatnloFXFX-pythia8	4.42965
$WZ \rightarrow \nu\nu qq$	WZTo2Q2Nu_13TeV_amcatnloFXFX_madspin-pythia8	6.324
$ZZ \rightarrow \ell\ell\ell\ell$	ZZTo4L_TuneCP5_13TeV-amcatnloFXFX-pythia8	1.212
$ZZ \rightarrow \nu\nu qq$	ZZTo2Q2Nu_TuneCP5_13TeV_amcatnloFXFX_madspin-pythia8	4.04
$ZZ \rightarrow \ell\ell qq$	ZZTo2L2Q_13TeV_amcatnloFXFX_madspin-pythia8	3.22
$VV \rightarrow \ell\ell\nu\nu$	VVTo2L2Nu_13TeV_amcatnloFXFX_madspin-pythia8	11.95
$t\bar{t}H \rightarrow b\bar{b}$	ttHTobb_M125_TuneCP5_13TeV-powheg-pythia8	0.291
$t\bar{t}H \rightarrow \text{non-}b\bar{b}$	ttHTNonbb_M125_TuneCP5_13TeV-powheg-pythia8	0.213
$t\bar{t}W \rightarrow \ell\nu$	TTWJetsToLNu_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8	0.179
$t\bar{t}W \rightarrow qq$	TTWJetsToQQ_TuneCP5_13TeV-amcatnloFXFX-madspin-pythia8	0.371
$t\bar{t}Z \rightarrow \ell\ell\nu\nu$	TTZToLLNuNu_M-10_TuneCP5_13TeV-amcatnlo-pythia8	0.26
$t\bar{t}Z \rightarrow qq$	TTZToQQ_TuneCP5_13TeV-amcatnlo-pythia8	0.60

6.2 Event selection

6.2.1 Muon reconstruction and identification

Muon momentum assignment is performed by the TuneP algorithm: select the best fit among all refits of hits in the tracker and muon system. This analysis requires muon candidates to pass high- p_T identification (ID) criteria. High- p_T ID muons must be reconstructed as global muons; the global-muon track fit must include one or more muon chamber hits; muon segments must be found in two or more chambers; the relative error of muon p_T on the best track must be less than 30 %; the impact parameter with respect to the primary vertex of tracker tracks must be less than 2 mm in the transverse plane; the impact parameter with respect to the primary vertex of tracker tracks must be less than 5 mm in the longitudinal direction; there must be at least one pixel hit; and there must be greater than five tracker layers with hits. These criteria ensure good momentum measurement resolution and suppress hadronic punch-through, cosmic ray muons, and muons from meson decays in flight.

Reconstructed muons must also have loose tracker-based relative isolation; $\sum p_T(\text{tracker tracks from PV})/p_T(\mu) < 0.1$ within a cone surrounding the muon track of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$.

6.2.2 Jet reconstruction and identification

Jets are taken from the AK4CHS collection. AK4CHS jet constituents are reconstructed following the particle-flow (PF) prescription [28], which combines tracks and clusters from the entire CMS detector to identify final-state particles. After subtracting charged hadrons from pile-up, the PF candidates are clustered with the anti- k_T algorithm using a distance parameter of $R = 0.4$. Jets must also satisfy tight jet ID requirements [29]. The tight jet ID criteria consists of jet η -dependent cuts on the fraction and total count of various jet constituents. The exact requirements are listed for each year in Tables 6.13, 6.14, and 6.15.

Table 6.13: The tight ID requirements for AK4CHS jets in 2016 data and MC.

Requirement	$ \eta \leq 2.4$	$2.4 < \eta \leq 2.7$	$2.7 < \eta \leq 3.0$	$3.0 < \eta $
Neutral Hadron Fraction	< 0.90	< 0.90	< 0.98	–
Neutral EM Fraction	< 0.90	< 0.90	> 0.01	< 0.90
Number of Constituents	> 1	> 1	–	–
Charged Hadron Fraction	> 0	–	–	–
Charged Multiplicity	> 0	–	–	–
Charged EM Fraction	< 0.99	–	–	–
Number of Neutral Particles	–	–	> 2	> 10

Table 6.14: The tight ID requirements for AK4CHS jets in 2017 data and MC.

Requirement	$ \eta \leq 2.4$	$2.4 < \eta \leq 2.7$	$2.7 < \eta \leq 3.0$	$3.0 < \eta $
Neutral Hadron Fraction	< 0.90	< 0.90	–	> 0.02
Neutral EM Fraction	< 0.90	< 0.90	> 0.02 and < 0.99	< 0.90
Number of Constituents	> 1	> 1	–	–
Charged Hadron Fraction	> 0	–	–	–
Charged Multiplicity	> 0	–	–	–
Charged EM Fraction	–	–	–	–
Number of Neutral Particles	–	–	> 2	> 10

Table 6.15: The tight ID requirements for AK4CHS jets in 2018 data and MC.

Requirement	$ \eta \leq 2.6$	$2.6 < \eta \leq 2.7$	$2.7 < \eta \leq 3.0$	$3.0 < \eta \leq 5.0$
Neutral Hadron Fraction	< 0.90	< 0.90	–	> 0.02
Neutral EM Fraction	< 0.90	< 0.99	> 0.02 and < 0.99	< 0.9
Number of Constituents	> 1	–	–	–
Charged Hadron Fraction	> 0	–	–	–
Charged Multiplicity	> 0	> 0	–	–
Charged EM Fraction	–	–	–	–
Number of Neutral Particles	–	–	> 2	> 10

6.2.3 MET Reconstruction

Missing momentum in the transverse plane $\vec{p}_T^{\text{miss}}$ is reconstructed from the negative vector sum over all PF candidate momenta projected onto the plane orthogonal to the beam axis (i.e., the x-y plane). The magnitude of $\vec{p}_T^{\text{miss}}$ defines the missing transverse energy (MET) quantity E_T^{miss} . Differences between PF and TuneP momenta assigned to muons are propagated to the MET calculation to maintain consistency with muons in this analysis. While large MET measurements are intended to detect invisible particles like neutrinos or exotic particles like Dark Matter, the majority of large MET in the detector stems from undesired sources such as cosmic rays, detector noise, and beam-halo particles that can result in “fake” or “anomalous” MET. As recommended by the Jet/MET (JME) POG, a collection of filters stored in NanoAOD are applied to suppress anomalous MET, listed here along with a brief discription of each filter:

- goodVertices – Selects events with only good quality vertexes.
- GoodVertexCount ≥ 1 – Ensures at least one good quality vertex per event.

- **HBHENoiseFilter** – Reduce the fixed rate of sporadic anomalous signal spikes in the HB and HE with dedicated algorithms to build noise cluster candidates using pulse shapes, geometric patterns, and channel multiplicities.
- **HBHENoiseIsoFilter** – Similar filter to **HBHENoiseFilter** while additionally considering neighboring activity in ECAL, HCAL, and the tracker.
- **eeBadScFilter** – Topological filter to remove EB crystal spikes with the “Swiss-cross” method; suppress anomalous energy sharing of high energy signal with neighboring crystals.
- **EcalDeadCellTriggerPrimitiveFilter** – Varies the ECAL trigger primitive momentum thresholds to filter out oversaturated channels.
- **globalSuperTightHalo2016Filter** – Remove beam halo effects by building halo cluster candidates (using halo deposit shape) in each calorimeter, then check if it can be matched to a CSC flat segment and has a pattern characteristic of interacting halo muons (out of time hits, long eta size in barrel, etc.).
- **BadPFMuonFilter** – Reject cosmic ray muons if a muon passes the PF muon quality cuts but is still too low quality and has large p_T .

6.2.4 Preselection

Leptoquark decay products are selected as the two muons and two jets with the highest p_T (labeled in descending p_T : muon 1 (μ_1) and muon 2 (μ_2); jet 1 (j_1) and jet 2 (j_2)) satisfying the aforementioned object selection. These four objects are used to construct all kinematic and angular quantities used for analysis.

To reduce SM background, a set of cuts are applied that remove unwanted events in kinematic regions outside of the signal thresholds. The working points are loose enough to keep events necessary in extracting background normalization scale factors and in performing

validation of background MC against data, before final selection cuts reduce background statistics further. These preselection cuts are applied to all data and MC events in the analysis prior to final selection. The preselection requirements are: each muon must have $p_T > 53 \text{ GeV}$ and $|\eta| < 2.4$ while each jet must have $p_T > 50 \text{ GeV}$ and $|\eta| < 2.4$; the dimuon invariant mass $M_{\mu\mu}$ must be at least 50 GeV ; the scalar sum of the p_T of each muon and jet ($S_T = p_T(\mu_1) + p_T(\mu_2) + p_T(j_1) + p_T(j_2)$) must be at least 300 GeV ; the spatial separation ΔR of the two muons must be greater than 0.3 ; last, an event veto on events with three or more leptons with $p_T > 20 \text{ GeV}$.

6.2.5 b-Jet tagging

To target leptoquark decays in the $\mu\mu bj$ channel, we identify jets originating from bottom quarks using the DeepJet discriminator [30]. DeepJet is a multiclass jet-flavor-tagging algorithm that uses deep learning and exploits low-level features from a high number of jet constituents. A total of 650 input variables are used to train the DeepJet algorithm, broken into four categories:

- Global variables: including jet kinematics, the number of tracks in a jet, the number of secondary vertices in a jet, and the number of reconstructed primary vertices in an event
- Charged PF candidate features: 16 features including track kinematics, track fit quality, displacement, and displacement uncertainty with respect to the PV, considering the 25 leading-displacement-significance candidates.
- Neutral PF candidate features: similar information to charged PF candidates.
- Secondary vertex information: 12 variables, such as flight distance significance, of up to four secondary vertices.

Performance-wise, it far exceeds the b-jet identification efficiency of the CMS b-tagger DeepCSV at every misidentification benchmark, with as much as a 20 % increase in efficiency

at a 0.1 % misidentification rate (for jets with $p_T > 90$ GeV), making DeepJet a suitable choice of b-jet discriminator for this analysis. The DeepJet discriminator is available in NanoAOD v7.

The B Tag & Vertexing (BTV) POG recommends the use of loose, medium, or tight working points to identify b-jets, defined as b-jet misidentification rates of 10 %, 1 %, and 0.1 %, respectively [31]. This analysis uses the medium working point and corresponds to a 75 % b-jet identification efficiency. The cut values on the DeepJet b tag discriminator corresponding to the medium working point in years 2016, 2017, and 2018 are, respectively: 0.3093, 0.3033, and 0.2770, available on the Twiki pages in Refs. [32][33][34]. We require at least one b-jet in every event, where b-jet candidates are the two leading jets defined in Section 6.2.4.

6.3 Corrections

6.3.1 Muon momentum scale

Muon Momentum Scale (MES) bias introduced by detector misalignment, magnetic field uncertainties, reconstruction bias, etc., is calibrated in both data and MC for muons with p_T below 200 GeV using the Rochester method [35]. Corrective factors are Q -, η -, and ϕ -dependent and are accessible through the RoccoR package [36]. The Rochester method measures bias in $Z \rightarrow \mu\mu$ events using the inner tracker of CMS, and so does not scale to high- p_T muons ($p_T > 200$ GeV) where momentum measurements rely more heavily on the muon subsystem. As a result, muons above the $p_T = 200$ GeV threshold are left uncalibrated, however, a systematic uncertainty is assigned to these muons using the Generalized Endpoint (GE) method outlined on the Twiki pages in Refs. [37, 38, 39]. A detailed study describing the estimation of this uncertainty can be found in Appendix

6.3.2 Muon momentum resolution

Muon momenta are corrected in MC to better match the estimated resolution in data by applying a p - and η -dependent gaussian smearing. The Rochester method for correcting MES described in Section 6.3.1 also correct for Muon Momentum Resolution (MER). As this analysis uses high- p_T muons, an additional resolution correction is required. The extra smearing is defined as the relative difference in resolution between data and MC measured on the Z mass: $\sigma_{\text{extra}} = \sqrt{\sigma_{\text{data}}^2 - \sigma_{\text{MC}}^2}$. To apply the resolution corrections, muon momenta in MC are reassigned as follows:

$$p \rightarrow p(1 + \text{Gauss}(0, \gamma\sigma(p, \eta))), \quad (6.1)$$

where $\text{Gauss}(\alpha, \beta)$ is a number drawn randomly from a Gaussian distribution (where α is the mean and β is the standard deviation), γ is a smearing factor, with $\gamma = 0.57$ corresponding to a $\sigma_{\text{extra}} = 15\%$ smearing, and $\sigma(p, \eta)$ is a momentum resolution parametrization defined on the Twiki pages in Refs. [37][38][39]. Muons in 2017 and 2018 MC see good resolution agreement with data within $|\eta| < 1.2$, so resolution smearing is only applied to muons outside $|\eta| > 1.2$. For muons in 2016 MC, good resolution agreement with data is observed for all $|\eta|$, so no resolution smearing is applied.

6.3.3 Muon ID and isolation efficiency

Muon ID and isolation efficiencies are corrected as recommended by the Muon POG. Efficiencies are extracted with the data-driven Tag & Probe method performed on single muon data and Drell-Yan events. Oppositely charged muon pairs are selected with an invariant mass greater than 120 GeV as tag-probe pairs (this selection specifically targets high- p_T muons). Tag-probe pairs must also satisfy the kinematic requirements listed in Section 6.2.4 in addition to isolation requirements. Tags have a tight selection: they are reconstructed as global and tracker muons, matched to objects firing the trigger paths in Table 6.5, and

satisfy the high- p_T ID selection. Probes require a looser selection: they are reconstructed as global muons. Efficiency ϵ is defined as the number of probes that pass the desired criteria (e.g., high- p_T ID, loose tracker-based relative isolation) divided by the total number of probes (when determining isolation efficiency, probes must additionally pass the high- p_T ID selection). Corrections are p_T - and η -dependent scale factors defined by the ratio $\epsilon_{\text{data}}/\epsilon_{\text{MC}}$ and are applied as event weights. Scale factors are measured separately for each year and are binned in p_T at 20, 25, 30, 40, 50, 60, 120 GeV (muons outside of the 20–120 GeV range are adopted into the lowest or highest bin) and binned in η at < 0.2 , 0.2, 0.3, 0.5, 0.8, 1.2, 1.4, 1.5, 1.6, 1.7, 2.0, 2.1, 2.2, 2.3, 2.4.

ID and isolation efficiency scale factors for high- p_T muons are measured by the Muon POG [40][41]. The values are provided in JSON files (along with each scale factor’s statistical and systematic uncertainty) available on the Twiki pages in Refs. [37][38][39]. Per-muon ID or isolation efficiency scale factors $\text{SF}_{\mu_1}^{\text{ID}}$ and $\text{SF}_{\mu_2}^{\text{ID}}$, or $\text{SF}_{\mu_1}^{\text{ISO}}$ and $\text{SF}_{\mu_2}^{\text{ISO}}$ are converted to a per-event scale factor $\text{SF}_{\text{event}}^{\text{ID}}$ or $\text{SF}_{\text{event}}^{\text{ISO}}$, respectively, by the following formula:

$$\text{SF}_{\text{event}}^{\text{ID, ISO}} = \text{SF}_{\mu_1}^{\text{ID, ISO}} \text{SF}_{\mu_2}^{\text{ID, ISO}}. \quad (6.2)$$

6.3.4 Muon reconstruction efficiency

Following the Muon POG recommendation for analyses with high- p_T muons, corrections to muon reconstruction efficiency are applied. Efficiencies are extracted using the Tag & Probe method described above, however, the selection criteria for tags and probes slightly differ from the ID and isolation requirements. Notably, probes are tracker muons, while passing probes must be reconstructed as global muons. The reconstruction corrections are p - and η -dependent scale factors applied as event weights. Scale factors are measured separately for each year and are binned in p_T at 50, 100, 150, 200, 300, 400, 600, 1500, and 3500 GeV (muons outside of the 50–3500 GeV range are adopted into the lowest or highest bin) and divided by $|\eta|$ above and below 1.6.

Reconstruction efficiency scale factors for high- p_T muons are measured by the Muon POG [40][41]. The values are provided in a table (along with each scale factor’s statistical and systematic uncertainty) on the TWiki pages in Refs. [37][38][39]. Per-muon HLT efficiency scale factors $SF_{\mu_1}^{\text{RECO}}$ and $SF_{\mu_2}^{\text{RECO}}$ are converted to a per-event scale factor $SF_{\text{event}}^{\text{RECO}}$ by the following formula:

$$SF_{\text{event}}^{\text{RECO}} = SF_{\mu_1}^{\text{RECO}} SF_{\mu_2}^{\text{RECO}}. \quad (6.3)$$

6.3.5 Trigger efficiency

The Muon POG recommends corrections to trigger efficiencies. Efficiencies are measured using Tag & Probe and compared to independently obtained efficiencies using orthogonal datasets. The latter method measures the efficiency of HLT in the primary MET datasets and in boosted $W + \text{jets}$ MC (for 2016) or mass-binned $W^* \rightarrow \mu\nu$ MC (for 2017 and 2018). For η -dependent scale factors, MC are reweighted to match the muon p_T distributions in the MET datasets. The central values for scale factors are taken from the Tag & Probe method, while the uncertainties are estimated from the relative difference with the MET method. For the Tag & Probe measurements, tags and probes follow the same criteria as when measuring ID efficiency, with the additional requirement that probes satisfy the high- p_T ID selection. Passing probes must be matched to objects fired by the HLT paths listed in Table 6.5. Scale factors are measured separately for each year and are binned in p_T at 52, 55, 60, 120, 200, 300, 500, and > 500 GeV and binned in η at < 0.9 , 0.9, 1.2, 2.1, and 2.4.

HLT efficiency scale factors for high- p_T muons are measured by the Muon POG [40][41]. The values are provided in a table (along with each scale factor’s statistical and systematic uncertainty) on the TWiki pages in Refs. [37][38][39]. Per-muon HLT efficiency scale factors $SF_{\mu_1}^{\text{HLT}}$ and $SF_{\mu_2}^{\text{HLT}}$ are converted to a per-event scale factor $SF_{\text{event}}^{\text{HLT}}$ by the following formula:

$$SF_{\text{event}}^{\text{HLT}} = 1 - \left(1 - SF_{\mu_1}^{\text{HLT}}\right) \left(1 - SF_{\mu_2}^{\text{HLT}}\right) \quad (6.4)$$

6.3.6 Jet corrections

Jet energy corrections (JEC) are applied to all jets to translate the jet energy scale (JES) measured in the detector to the energy scale of true particles. L1 pile-up corrections and L2L3 MC-truth corrections are applied to both MC and data, while data additionally has L2L3 Residual corrections applied [42]. JECs are measured by the JME POG [43] and applied to jets in NanoAOD post-processing.

Measurements show that jet energy resolution (JER) is poorer in data than in MC. To better approximate the observed resolution, energy-corrected jet four-momenta are smeared in MC according to the so-called “hybrid” method: if a truth-level jet is matched to the reconstructed jet being smeared, a scaling technique is applied, otherwise, stochastic smearing is used. As with JECs, JER smearing parameters are measured by the JME POG [44] and the corrections are stored in NanoAOD.

Tables 6.16 and 6.17 list the JEC and JER versions applied to data and MC, respectively, for each year along with the corresponding Global Tag used to process the NanoAODv7 samples.

Table 6.16: Recommended JEC versions applied to jets in data by year. The NanoAODv7 Global Tag used in processing data samples is also provided.

Year	Global Tag (NanoAODv7)	JEC Version
2016B	102X_dataRun2_v14	Summer16.07Aug2017BCD_V11_DATA
2016C	102X_dataRun2_v14	Summer16.07Aug2017BCD_V11_DATA
2016D	102X_dataRun2_v14	Summer16.07Aug2017BCD_V11_DATA
2016E	102X_dataRun2_v14	Summer16.07Aug2017EF_V11_DATA
2016F	102X_dataRun2_v14	Summer16.07Aug2017EF_V11_DATA
2016G	102X_dataRun2_v14	Summer16.07Aug2017GH_V11_DATA
2016H	102X_dataRun2_v14	Summer16.07Aug2017GH_V11_DATA
2017B	102X_dataRun2_v14	Fall17_17Nov2017B_V32_DATA
2017C	102X_dataRun2_v14	Fall17_17Nov2017C_V32_DATA
2017D	102X_dataRun2_v14	Fall17_17Nov2017DE_V32_DATA
2017E	102X_dataRun2_v14	Fall17_17Nov2017DE_V32_DATA
2017F	102X_dataRun2_v14	Fall17_17Nov2017F_V32_DATA
2018A	102X_dataRun2_v14	Autumn18_RunA_V19_DATA
2018B	102X_dataRun2_v14	Autumn18_RunB_V19_DATA
2018C	102X_dataRun2_v14	Autumn18_RunC_V19_DATA
2018D	102X_dataRun2_Prompt_v16	Autumn18_RunD_V19_DATA

Table 6.17: Recommended JEC and JER versions applied to jets in MC by year. The NanoAODv7 Global Tag used in processing simulated samples is also provided.

Year	Global Tag (NanoAODv7)	JEC Version	JER Version
2016	102X_mcRun2_asymptotic_v8	Summer16_07Aug2017_V11_MC	Summer16_25nsV1_MC
2017	102X_mc2017_realistic_v8	Fall17_17Nov2017_V32_MC	Fall17_V3_MC
2018	102X_upgrade2018_realistic_v21	Autumn18_V19_MC	Autumn18_V7b_MC

6.3.7 MET corrections

Following the recommendations of the JME POG, Type-1 corrections are applied to MET, which propagate the JECs listed in Tables 6.16 and 6.17 to MET. JER smearing is propagated to MET in MC only. Type-1 corrections replace the vector p_T sum of particles which can be clustered by the vector p_T sum of JES- or JER-corrected jets and propagate the changes to MET.

6.3.8 b-Jet identification

b-Jet identification and non-b-jet misidentification efficiencies can differ between data and MC. To account for these differences, corrections need to be applied to each event in simulation. Per-jet scale factors that are flavor-, p_T -, and η -dependent are measured by the BTV POG. Several recommendations for combining these per-jet scale factors into a per-event weight w exist and are described by the BTV POG on the Twiki page in Ref. [45]. As this analysis only considers b-tagging on the two leading jets, a method that does not demand measuring the b-jet identification efficiencies in MC can be used. The prescription is as follows: for an event with n b-jets, given the requirement that there is at least one b-jet in the event, the event weight is

$$w(\geq 1|n) = 1 - w(0|n), \quad (6.5)$$

where $w(0|n)$ is the weight for events with n b-jets, given the requirement that there are at least zero b-jets in the event, defined as

$$w(0|n) = \prod_{i=1}^n (1 - \text{SF}_i). \quad (6.6)$$

where i indexes the b-jets in the event and SF_i is the scale factor for b-jet i . The BTV POG recommended scale factors used in this analysis are listed in Table 6.18 and are available on the Twiki pages in Refs. [32][33][34]. The scale factors are added to MC samples in NanoAOD post-processing.

Table 6.18: Recommended b-jet identification efficiency scale factors used in this analysis listed by year. The observed data reprocessing and MC campaigns used in extracting each scale factor set are also provided.

Year	Data Reprocessing	MC Campaign	b-Jet Tag Scale Factors
2016	17Jul2018 ReReco [B-F]	RunIISummer16	DeepJet_2016LegacySF_V1.csv
2017	31Mar2018 ReReco [B-F]	RunIIFall17	DeepFlavour_94XSF_V3_B_F.csv
2018	17Sep2018 ReReco/PromptReco [A-C/D]	RunIIAutumn18	DeepJet_102XSF_V1.csv

6.3.9 HEM 15/16 failure

Power loss in mid-2018 saw HCAL lose the function of two wedges, HEM 15 and 16, which remained dead for the duration of the year. Data have been studied to identify any effect from the HEM 15/16 failure, detailed in Appendix D, and no significant impact has been observed. No corrections related to the HEM 15/16 failure are applied.

6.3.10 Top p_T reweighting

Events in $t\bar{t}$ simulation are NNLO-reweighted to correct for known mismodeling of top p_T distributions [46]. Corrections follow the recommendation of the Top POG. SFs are extracted from a fit to the ratio of the NNLO theoretical cross-section to fully inclusive MC event yields as a function of generator-level top or antitop p_T [47]. The functional form of the fit is the exponential:

$$\text{SF}(p_T) = \exp \left(a_1 + a_2 p_T + a_3 p_T^2 + \frac{a_4}{p_T + a_5} \right), \quad (6.7)$$

where p_T is the generator-level top or antitop p_T , and a_i are fit parameters, listed in Table 6.19. The SFs for top and antitop p_T are combined into an overall event weight w :

$$w = \sqrt{\text{SF}(p_{T, \text{top}}) \text{SF}(p_{T, \text{antitop}})}, \quad (6.8)$$

and applied to $t\bar{t}$ events in 2016, 2017, and 2018 MC. As 2016 MC use the CUET tune, an additional weight is required, applied only to $t\bar{t}$ events in 2016 MC on top of the aforementioned reweighting. The additional weight follows the same definition in eq. 6.8, but the SFs are extracted from a different fit, of the form:

$$\text{SF}(p_T) = \exp (b_1 + b_2 \tanh (b_3 + b_4 p_T)), \quad (6.9)$$

where p_T is again the generator-level top or antitop p_T and b_i are fit parameters, listed in Table 6.19.

6.4 Background estimation

At preselection, the expected SM processes in the $\mu\mu b j$ channel that are considered are $Z/\gamma^* + \text{jets}$, $t\bar{t}$, diboson, $t\bar{t}V$, single top, and $W + \text{jets}$. The most dominant processes,

Table 6.19: Fit parameters used in Top p_T reweighting SFs.

Parameter	Value
a_1	$-2.022\,74 \times 10^{-1}$
a_2	$1.097\,34 \times 10^{-4}$
a_3	$-1.300\,88 \times 10^{-7}$
a_4	$5.834\,94 \times 10^1$
a_5	$1.962\,52 \times 10^2$
b_1	1.045 54
b_2	$5.190\,12 \times 10^{-2}$
b_3	-1.729 27
b_4	$2.571\,13 \times 10^{-3}$

$Z/\gamma^* + \text{jets}$, $t\bar{t}$, diboson, and $t\bar{t}V$ are estimated with MC simulation and renormalized to data using high-purity control regions (CR). The remaining background processes—single top and $W + \text{jets}$ —are taken directly from MC simulation.

6.4.1 Estimation of $Z/\gamma^* + \text{jets}$, $t\bar{t}$, diboson, and $t\bar{t}V$ backgrounds

The $Z/\gamma^* + \text{jets}$, $t\bar{t}$, diboson, and $t\bar{t}V$ processes are modeled via the same approach: MC simulation is used to first estimate the background shape, then the background is normalized to data at preselection with scale factors extracted inside a high sample purity CR. The CR used for $Z/\gamma^* + \text{jets}$ normalization is the Z-enriched mass window $80 < M_{\mu\mu} < 100$ GeV (the Z mass-pole), referred to as region A. The $Z/\gamma^* + \text{jets}$ normalization scale factors are also parameterized in bins of jet multiplicity. For normalizing $t\bar{t}$, a CR orthogonal to region A is used: the $t\bar{t}$ -enriched mass window $100 < M_{\mu\mu} < 100$ GeV (the top quark kinematic turn-on), referred to as region B. Diboson and $t\bar{t}V$ backgrounds are normalized simultaneously in the same CR within the mass window $80 < M_{\mu\mu} < 100$ GeV, referred to as region C. While regions A and C share a mass window, region C also inverts the veto on a third lepton into a requirement that there are at least three leptons and is thus orthogonal to both regions A and B, and to retain sufficient statistics the b-jet tag requirement is dropped. The sample

purity of the orthogonal regions A, B, and C were verified, being either Z-, $t\bar{t}$ -, or VV- and $t\bar{t}V$ -enriched in the respective CRs. The normalization scale factors R_Z , $R_{t\bar{t}}$, and $R_{VV/t\bar{t}V}$ are defined by:

$$R_Z = \frac{N_{\text{Data}}^A - R_{t\bar{t}} N_{t\bar{t}}^A - N_{VV}^A - N_{t\bar{t}V}^A - N_O^A}{N_Z^A}, \quad (6.10)$$

$$R_{t\bar{t}} = \frac{N_{\text{Data}}^B - R_Z N_Z^B - N_{VV}^B - N_{t\bar{t}V}^B - N_O^B}{N_{t\bar{t}}^B}, \quad (6.11)$$

and

$$R_{VV/t\bar{t}V} = \frac{N_{\text{Data}}^C - R_Z N_Z^C - R_{t\bar{t}} N_{t\bar{t}}^C - N_O^C}{N_{VV}^C + N_{t\bar{t}V}^C}, \quad (6.12)$$

where N_{Data} is the number of data events, N_X is the number of X-process SM background events, and N_O is the number of events produced by “other” SM processes (i.e., single top and W+jets), while the superscripts A, B, and C respectively denote the Z, $t\bar{t}$, and VV/ $t\bar{t}V$ CRs from which these event counts are extracted. Due to the codependency of R_Z , $R_{t\bar{t}}$, and $R_{VV/t\bar{t}V}$, their values are initialized to unity, and the normalization factors are iteratively computed until the factors are stable. There is a strong dependence of the normalization scale factor in the $Z/\gamma^* + \text{jets}$ background on the number of reconstructed jets, as seen in Fig. 6.1, so a jet-multiplicity-binned $Z/\gamma^* + \text{jets}$ is used. The $t\bar{t}$ background shows no such dependence. The scale factors and their uncertainties are listed for each year in Tables 6.20-6.22.

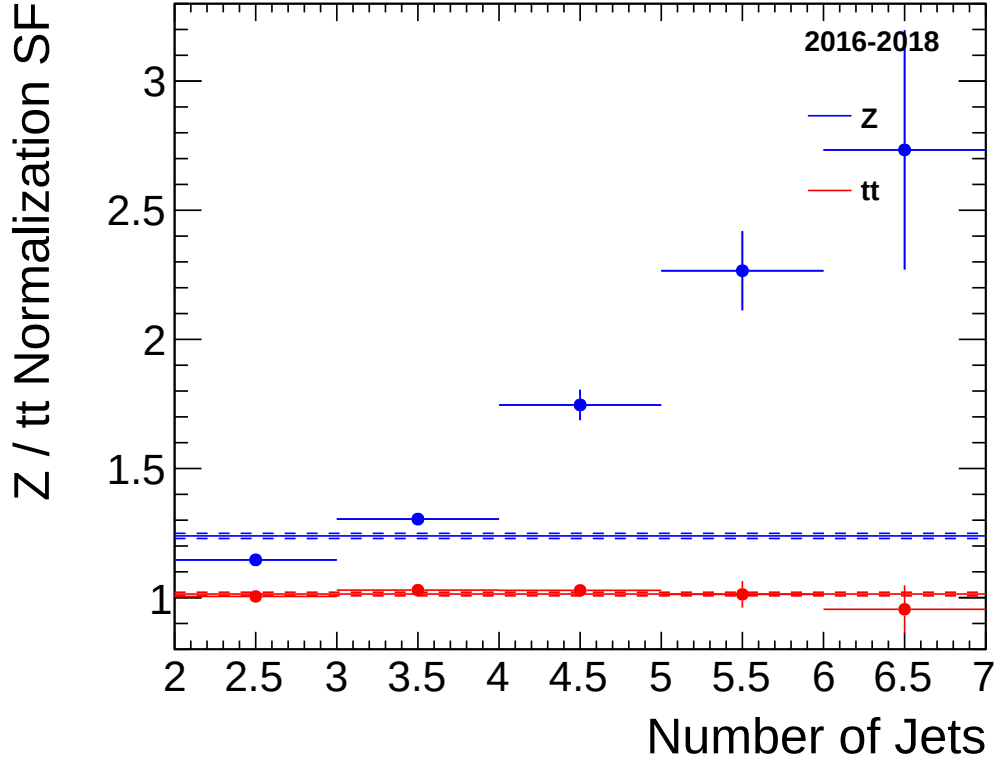


Figure 6.1: $Z/\gamma^* + \text{jets}$ (blue) and $t\bar{t}$ (red) normalization scale factors, in the full combined 2016-2018 dataset, binned in number of reconstructed jets. The horizontal dashed lines represent the inclusive scale factors.

Table 6.20: $Z/\gamma^* + \text{jets}$ normalization scale factors by year.

Year	Control Region A [GeV]	Z Purity	R_Z	Jet Count
2016	$80 < M_{\mu\mu} < 100$	89 %	1.03 ± 0.02 (stat)	2
2016	$80 < M_{\mu\mu} < 100$	89 %	0.95 ± 0.03 (stat)	3
2016	$80 < M_{\mu\mu} < 100$	89 %	1.15 ± 0.08 (stat)	4
2016	$80 < M_{\mu\mu} < 100$	89 %	1.47 ± 0.16 (stat)	≥ 5
2017	$80 < M_{\mu\mu} < 100$	89 %	1.24 ± 0.02 (stat)	2
2017	$80 < M_{\mu\mu} < 100$	89 %	1.50 ± 0.04 (stat)	3
2017	$80 < M_{\mu\mu} < 100$	89 %	2.05 ± 0.13 (stat)	4
2017	$80 < M_{\mu\mu} < 100$	89 %	2.82 ± 0.35 (stat)	≥ 5
2018	$80 < M_{\mu\mu} < 100$	88 %	1.16 ± 0.02 (stat)	2
2018	$80 < M_{\mu\mu} < 100$	88 %	1.44 ± 0.04 (stat)	3
2018	$80 < M_{\mu\mu} < 100$	88 %	2.02 ± 0.11 (stat)	4
2018	$80 < M_{\mu\mu} < 100$	88 %	2.80 ± 0.34 (stat)	≥ 5

Table 6.21: $t\bar{t}$ normalization scale factors by year.

Year	Control Region B [GeV]	$t\bar{t}$ Purity	$R_{t\bar{t}}$
2016	$100 < M_{\mu\mu} < 250$	87 %	0.99 ± 0.01 (stat)
2017	$100 < M_{\mu\mu} < 250$	89 %	1.09 ± 0.01 (stat)
2018	$100 < M_{\mu\mu} < 250$	88 %	0.98 ± 0.01 (stat)

Table 6.22: VV and $t\bar{t}V$ normalization scale factors by year.

Year	Control Region C [GeV]	Lepton Count	b-Jet Count	VV + $t\bar{t}V$ Purity	$R_{VV/t\bar{t}V}$
2016	$80 < M_{\mu\mu} < 100$	≥ 3	≥ 0	80 %	1.1 ± 0.1 (stat)
2017	$80 < M_{\mu\mu} < 100$	≥ 3	≥ 0	80 %	1.2 ± 0.1 (stat)
2018	$80 < M_{\mu\mu} < 100$	≥ 3	≥ 0	80 %	1.4 ± 0.1 (stat)

Studies on the stability of the background normalization scale factors can be found in Appendix B.

Observed and expected $M_{\mu\mu}$ distributions at preselection are shown in Figs. 6.2 and 6.3 that are zoomed into the respective CRs. Two representative signal MC samples are shown as well, with the normalization described in Section 6.1.2.

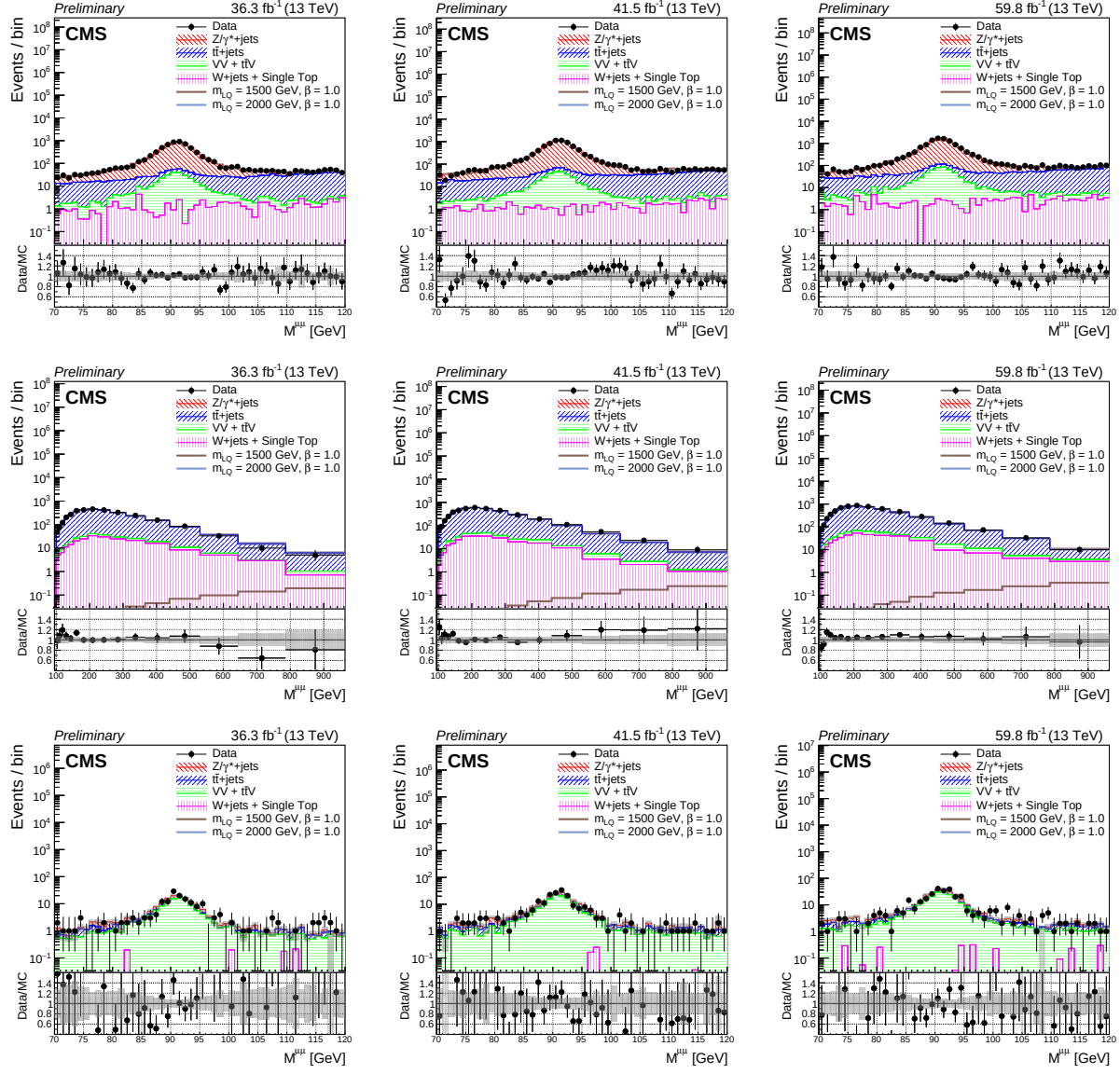


Figure 6.2: A comparison between observed data and SM expectation in $M_{\mu\mu}$ distributions zoomed into the $Z/\gamma^* + \text{jets}$ (top), $t\bar{t}$ (middle), and $VV/t\bar{t}V$ (bottom) CRs at preselection level. Left to right: 2016, 2017, 2018 data. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

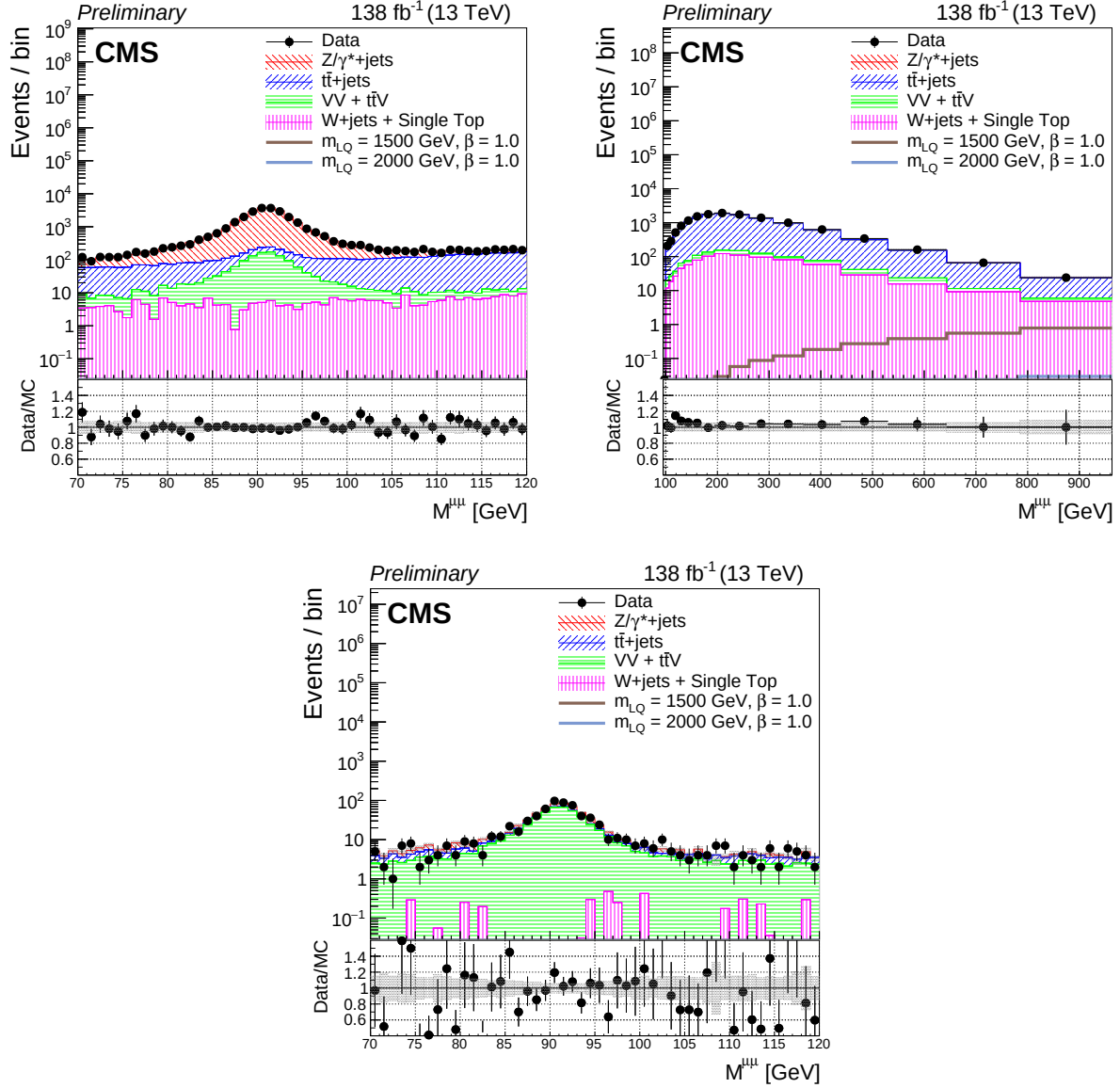


Figure 6.3: A comparison between observed data and SM expectation in $M_{\mu\mu}$ distributions zoomed into the $Z/\gamma^* + \text{jets}$ (top-left), $t\bar{t}$ (top-right), and $VV/t\bar{t}V$ (bottom) CRs at preselection level with the combination of 2016, 2017, and 2018 data. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

6.4.2 Data comparison

Agreement between observed data and SM expectation is found in each year of data-taking, illustrated with the kinematic distributions shown at preselection in Figures 6.4–6.9. The

combination of data from all three years is provided in Figures 6.10–6.15. In all preselection plots, $Z/\gamma^* + \text{jets}$ and $t\bar{t}$ MC are normalized to data as explained in Section 6.4.1, while the other background MC samples are normalized to the expected number of events (Section 6.1.3). Two representative signal MC samples are shown as well ($M_{LQ} = 1500$ and 2000 GeV), each normalized to the expected number of events (Section 6.1.2). All events must satisfy the b-jet tag requirement from Section 6.2.5, and signal and background events have been corrected according to Section 6.3. The kinematic distributions plotted, most of which are inputs to the final selection, include the momenta and spatial separation of final state objects, invariant masses, MET, object multiplicities, and DeepJet b tag scores. Additionally, we define a few variables that are either arcane or unique to this analysis. The kinematic S_T is the scalar sum of the p_T of the four final state objects:

$$S_T = p_T(\mu_1) + p_T(\mu_2) + p_T(j_1) + p_T(j_2). \quad (6.13)$$

The leptoquark candidates, identified as muon-jet invariant masses $M_{\mu j_1}$ and $M_{\mu j_2}$, are defined as the muon-jet pairings that minimize the absolute difference between the two masses, with $M_{\mu j_1}$ being the larger mass:

$$\min(|M_{\mu j_1} - M_{\mu j_2}|), M_{\mu j_1} > M_{\mu j_2} \quad (6.14)$$

The kinematics we have defined— S_T , $M_{\mu j_1}$ and $M_{\mu j_2}$ —are particularly strong signal/background discriminators, making them indispensable variables to the final selection, as explained in Section 6.5.

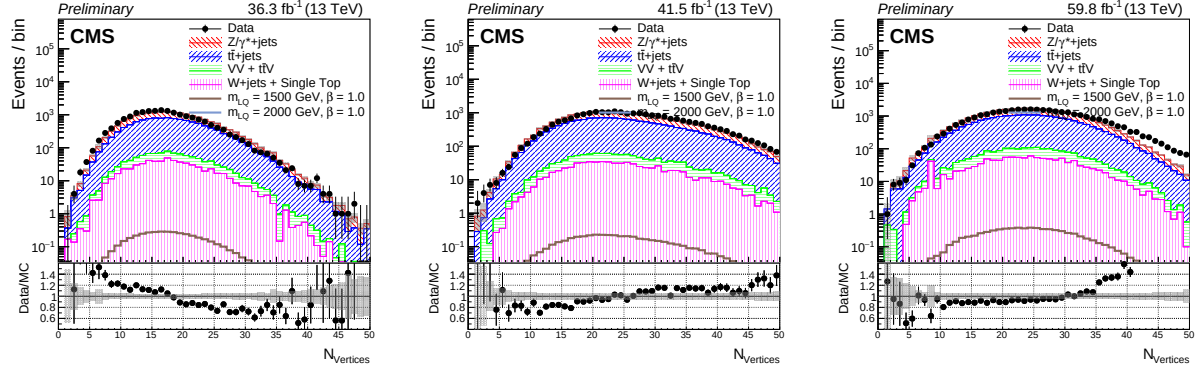


Figure 6.4: A comparison of the number of reconstructed vertices at preselection level in 2016 (left), 2017 (middle) and 2018 (right) data. Error bars shown represent statistical uncertainties, and systematic uncertainties are shown by gray hashing.

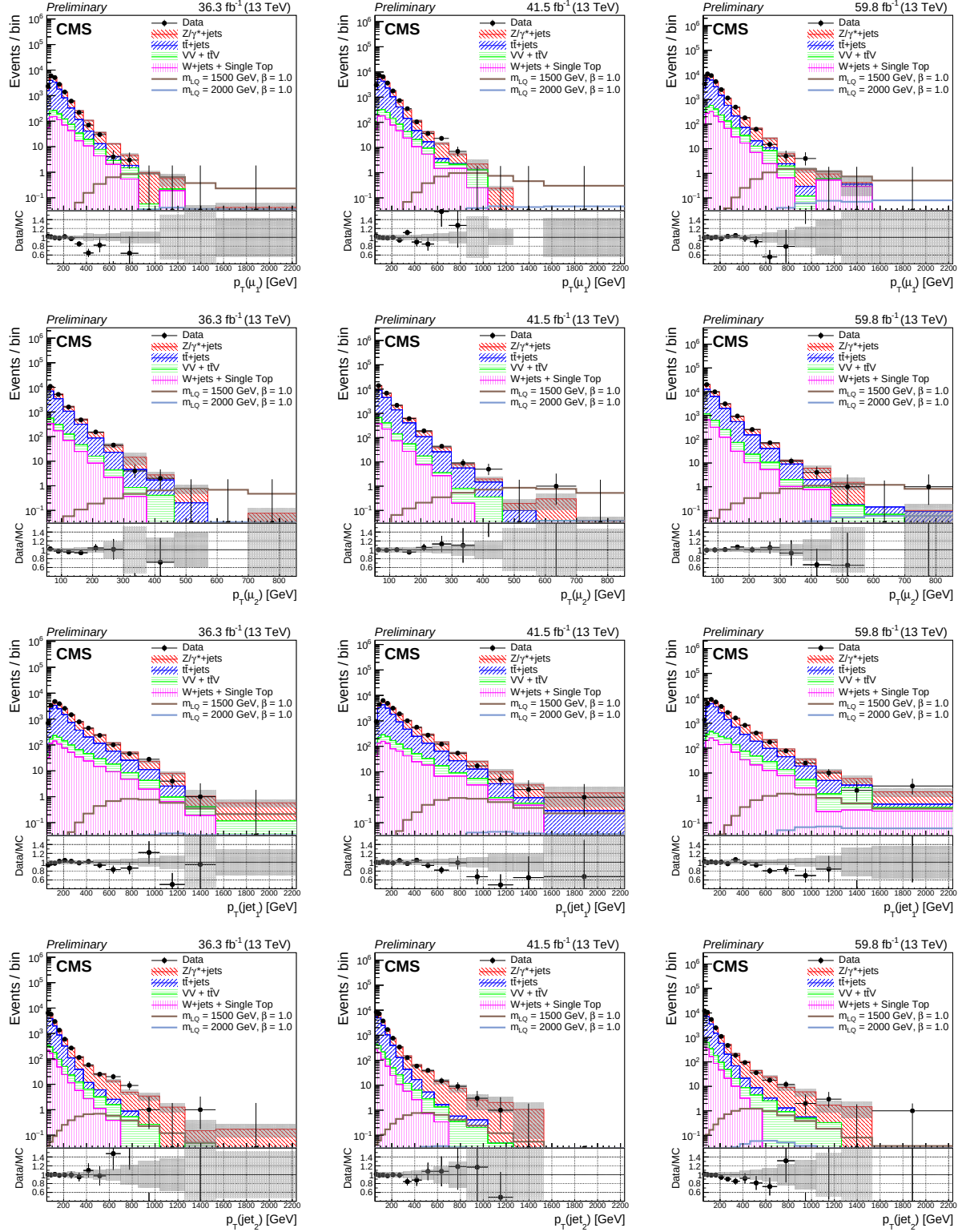


Figure 6.5: A comparison between distributions of observed data and SM expectation at preselection level. Left to right: 2016, 2017, 2018 data. Top to bottom: muon 1 p_T , muon 2 p_T , jet 1 p_T , and jet 2 p_T . Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

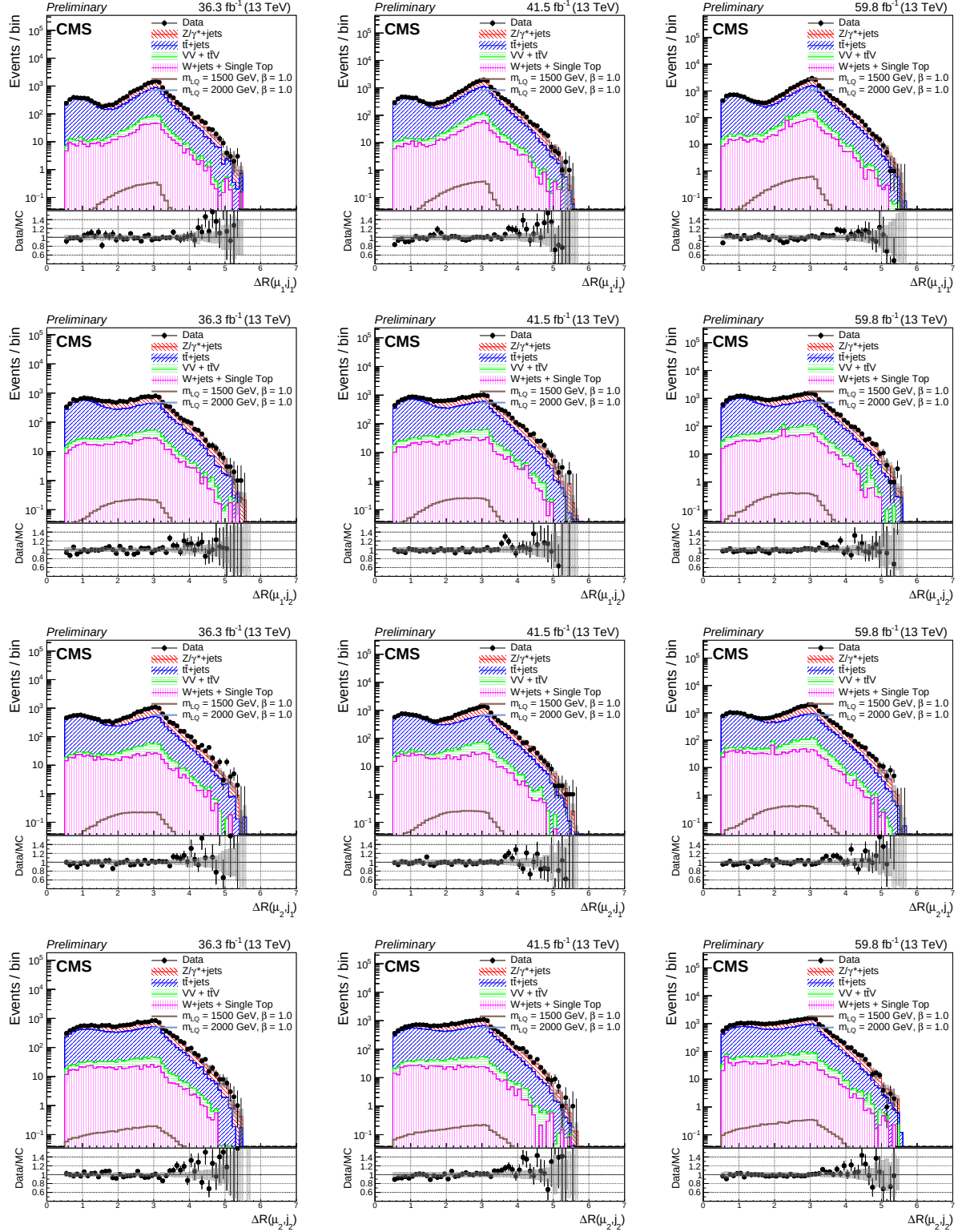


Figure 6.6: A comparison between distributions of observed data and SM expectation at preselection level. Left to right: 2016, 2017, 2018 data. Top to bottom: ΔR between muon 1 and jet 1, ΔR between muon 1 and jet 2, ΔR between muon 2 and jet 1, and ΔR between muon 2 and jet 2. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

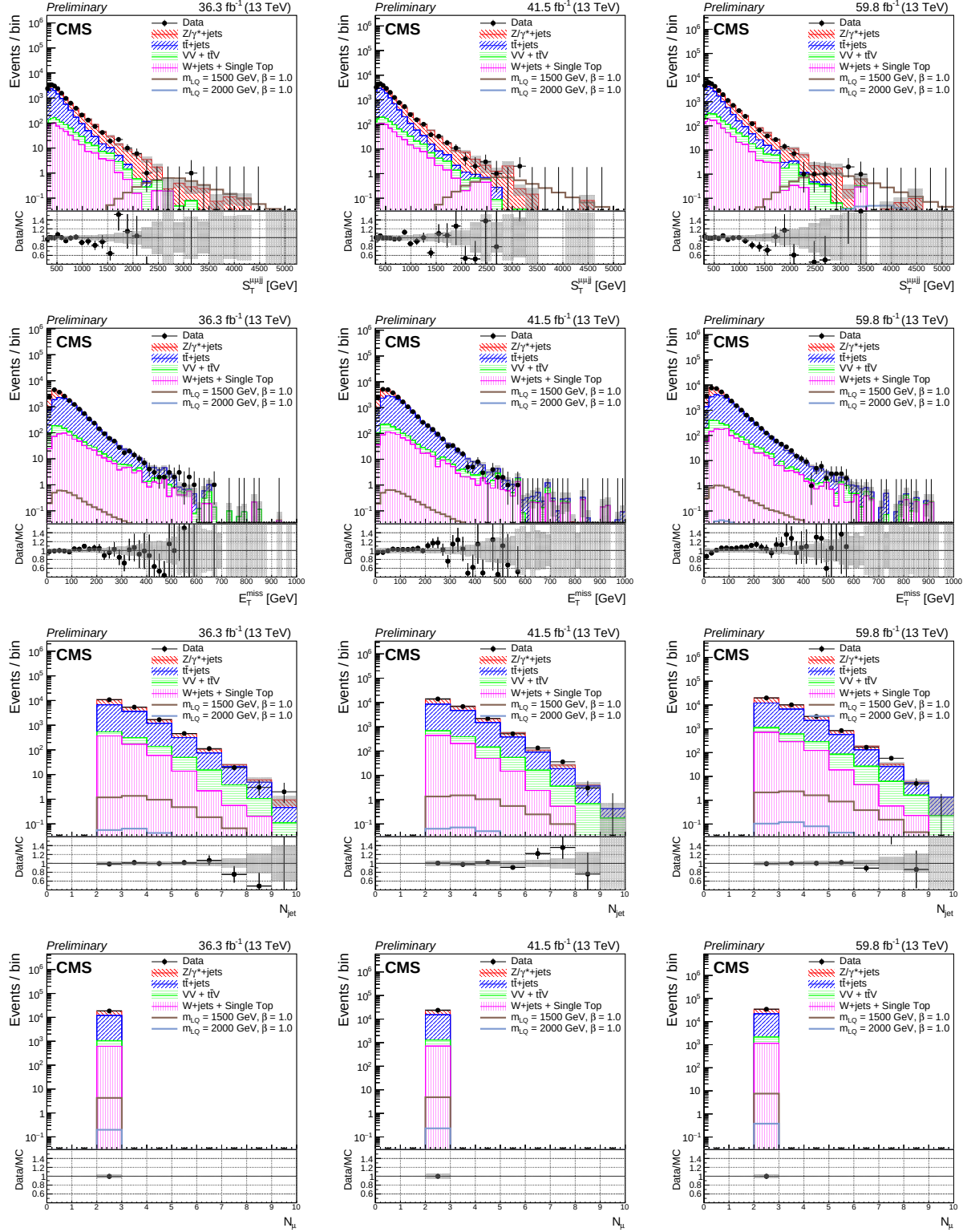


Figure 6.7: A comparison between distributions of observed data and SM expectation at preselection level. Left to right: 2016, 2017, 2018 data. Top to bottom: S_T^{miss} , p_T^{miss} , jet multiplicity, and muon multiplicity. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

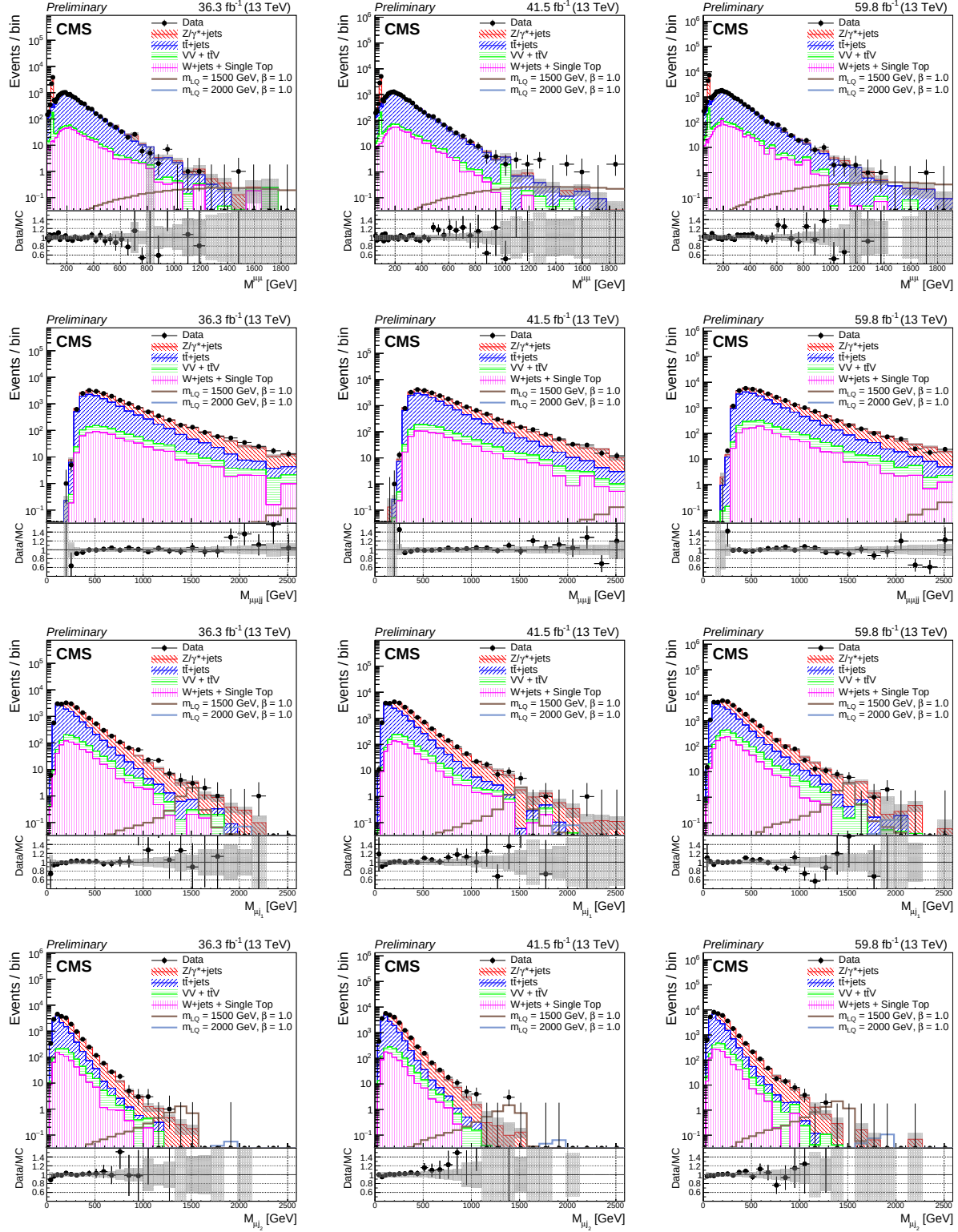


Figure 6.8: A comparison between distributions of observed data and SM expectation at preselection level. Left to right: 2016, 2017, 2018 data. Top to bottom: $M_{\mu\mu}$, $M_{\mu\mu jj}$, $M_{\mu j_1}$, and $M_{\mu j_2}$. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

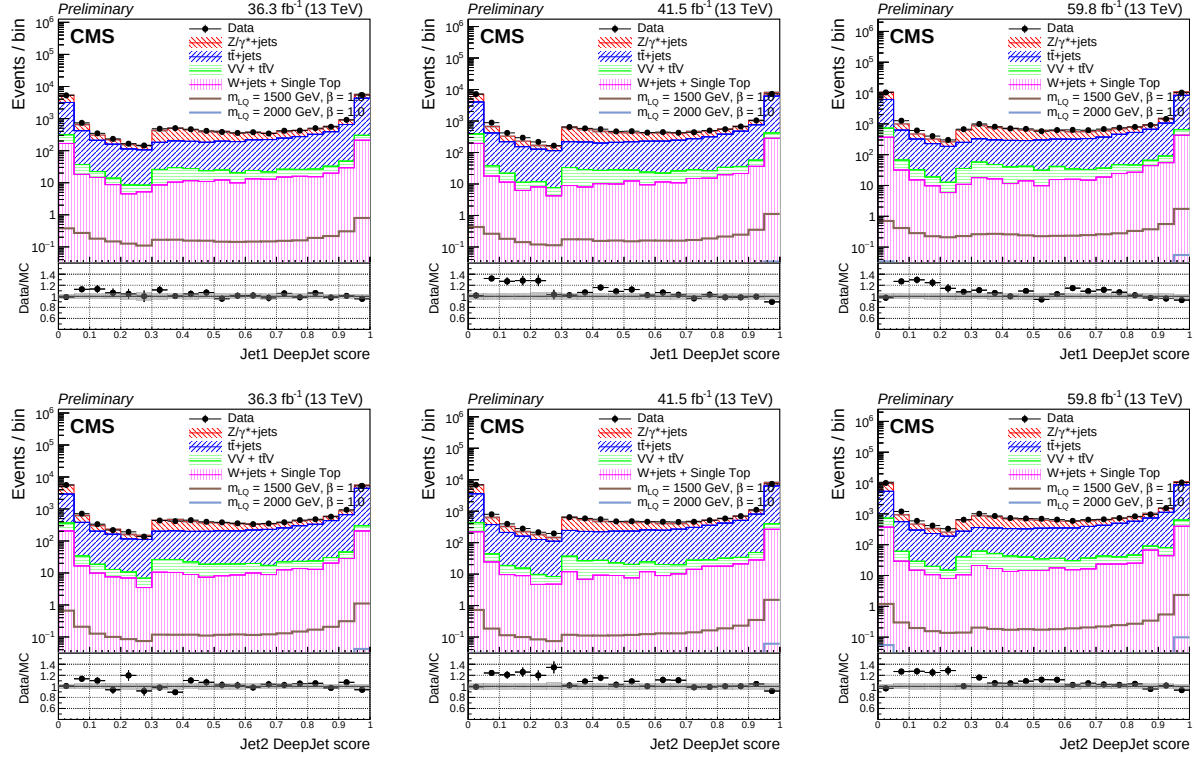


Figure 6.9: A comparison between distributions of observed data and SM expectation at preselection level. Left to right: 2016, 2017, 2018 data. Top to bottom: DeepJet b tag score of jet 1 and DeepJet b tag score of jet 2. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

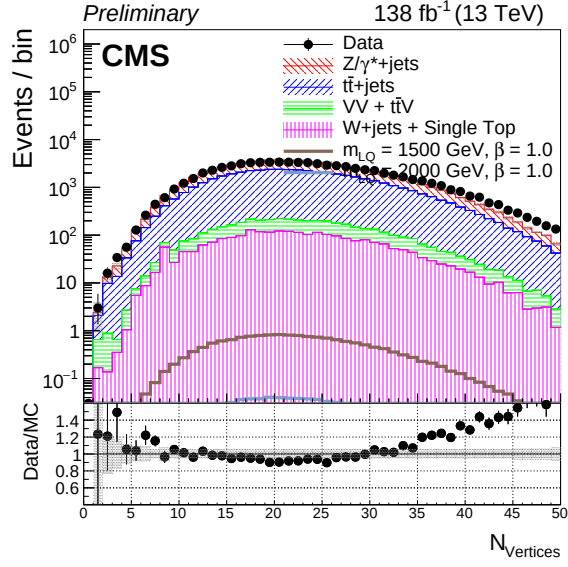


Figure 6.10: A comparison of the number of reconstructed vertices at preselection level in the combination of 2016, 2017, and 2018 data. Error bars shown represent statistical uncertainties, and systematic uncertainties are shown by gray hashing.

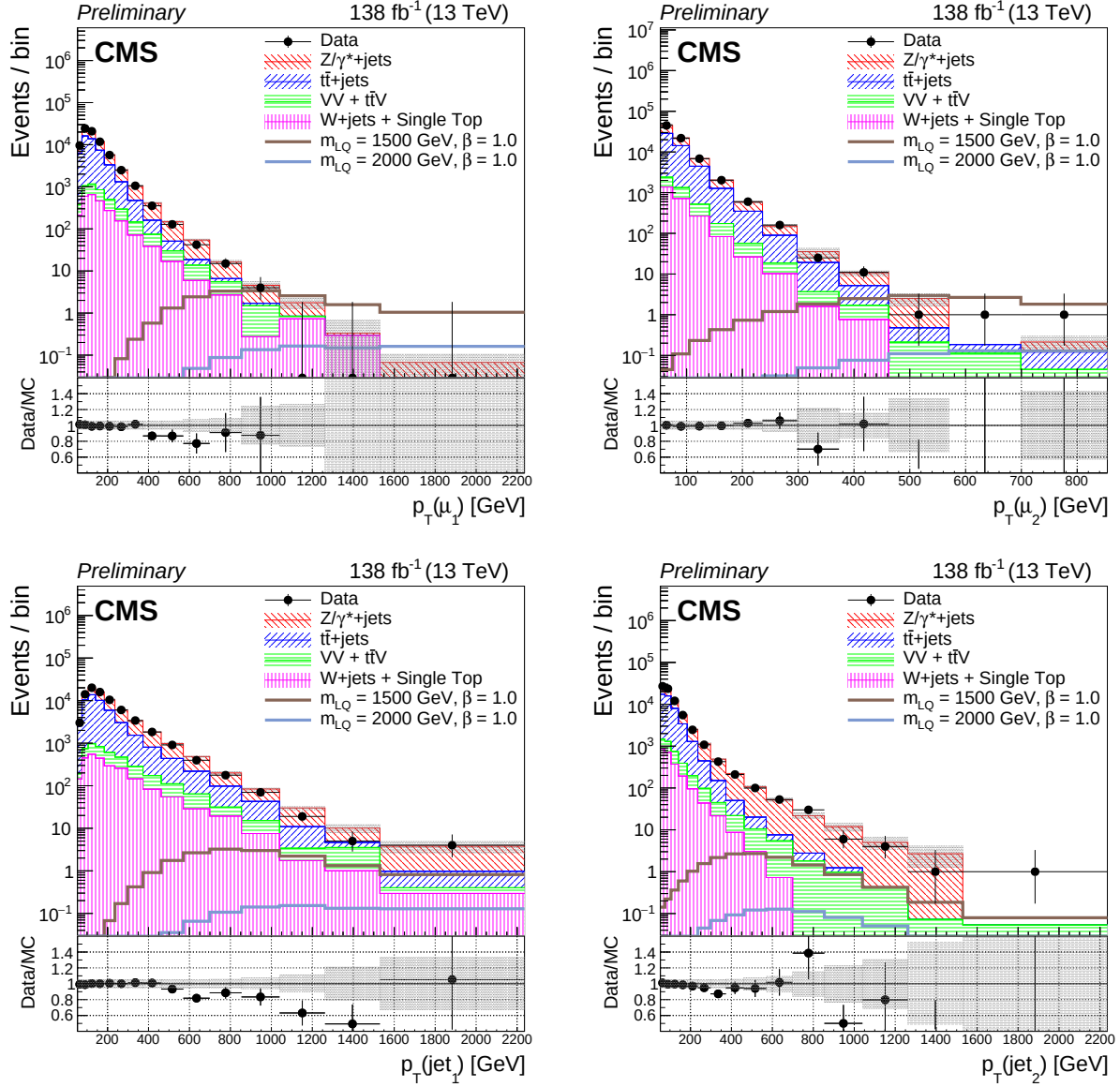


Figure 6.11: A comparison between distributions of observed data and SM expectation at preselection level in the combination of 2016, 2017, and 2018 data. Left to right, top to bottom: muon 1 p_T , muon 2 p_T , jet 1 p_T , and jet 2 p_T . Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

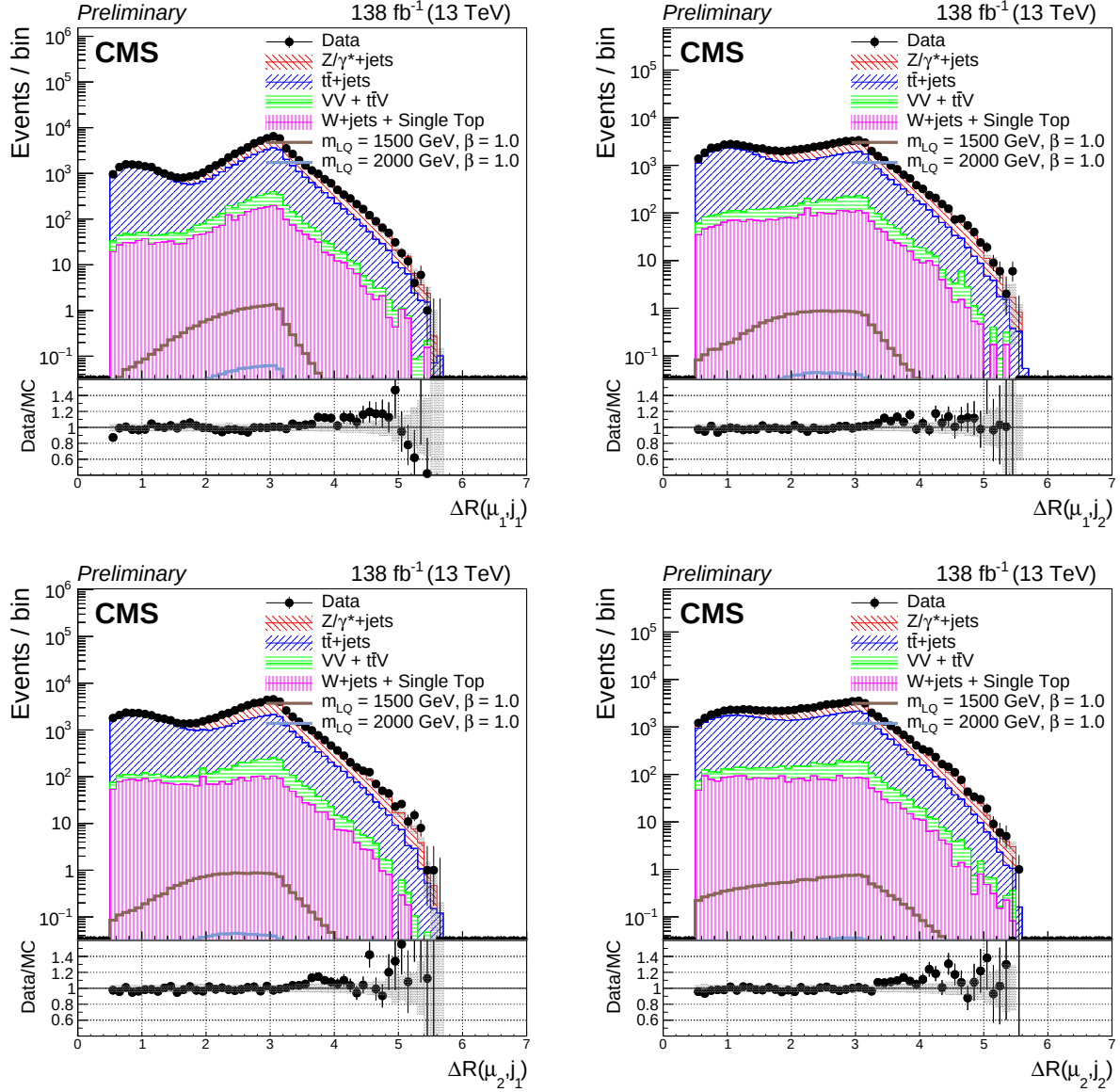


Figure 6.12: A comparison between distributions of observed data and SM expectation at preselection level in the combination of 2016, 2017, and 2018 data. Left to right, top to bottom: ΔR between muon 1 and jet 1, ΔR between muon 1 and jet 2, ΔR between muon 2 and jet 1, and ΔR between muon 2 and jet 2. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

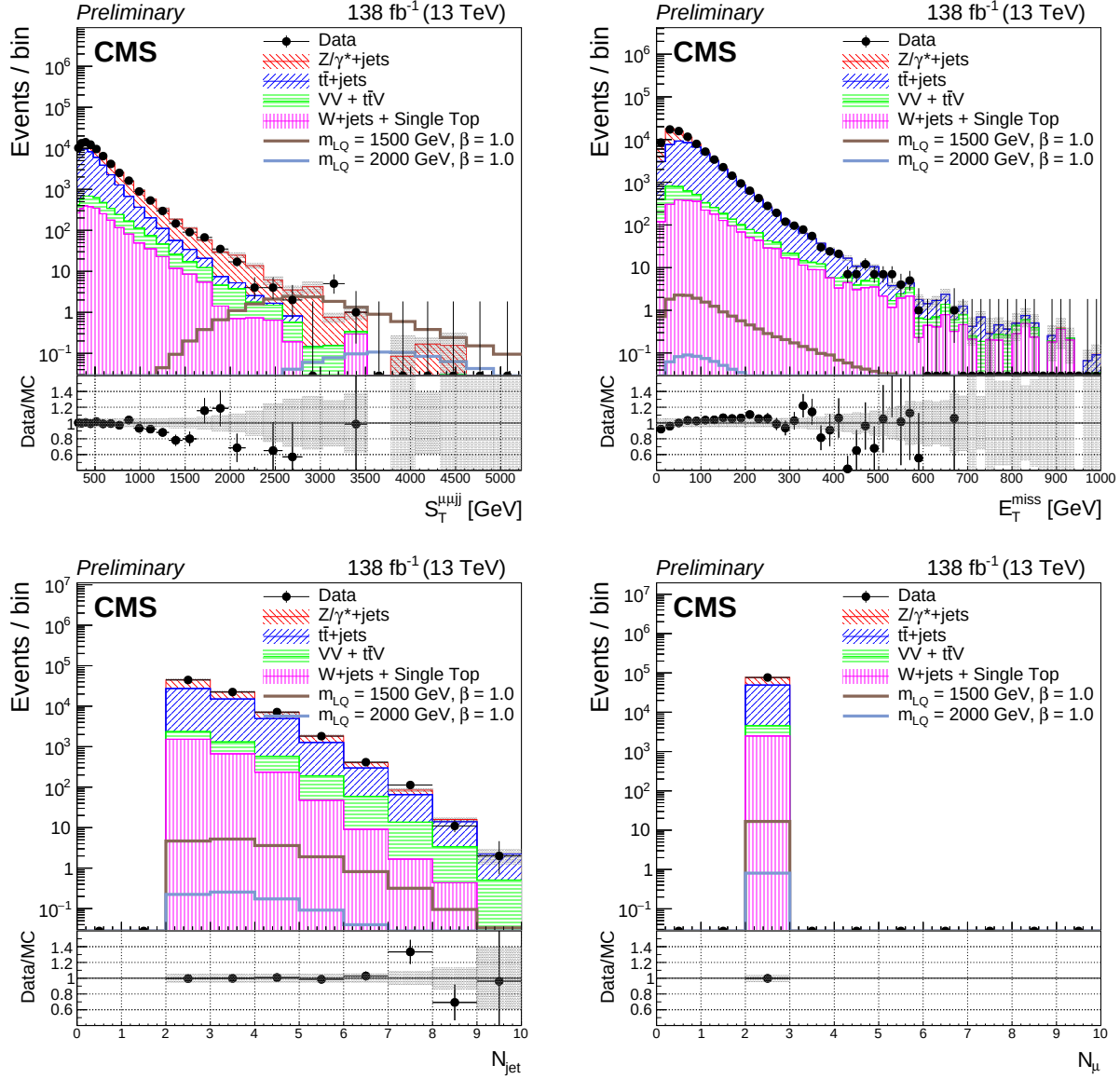


Figure 6.13: A comparison between distributions of observed data and SM expectation at preselection level in the combination of 2016, 2017, and 2018 data. Left to right, top to bottom: S_T , p_T^{miss} , jet multiplicity, and muon multiplicity. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

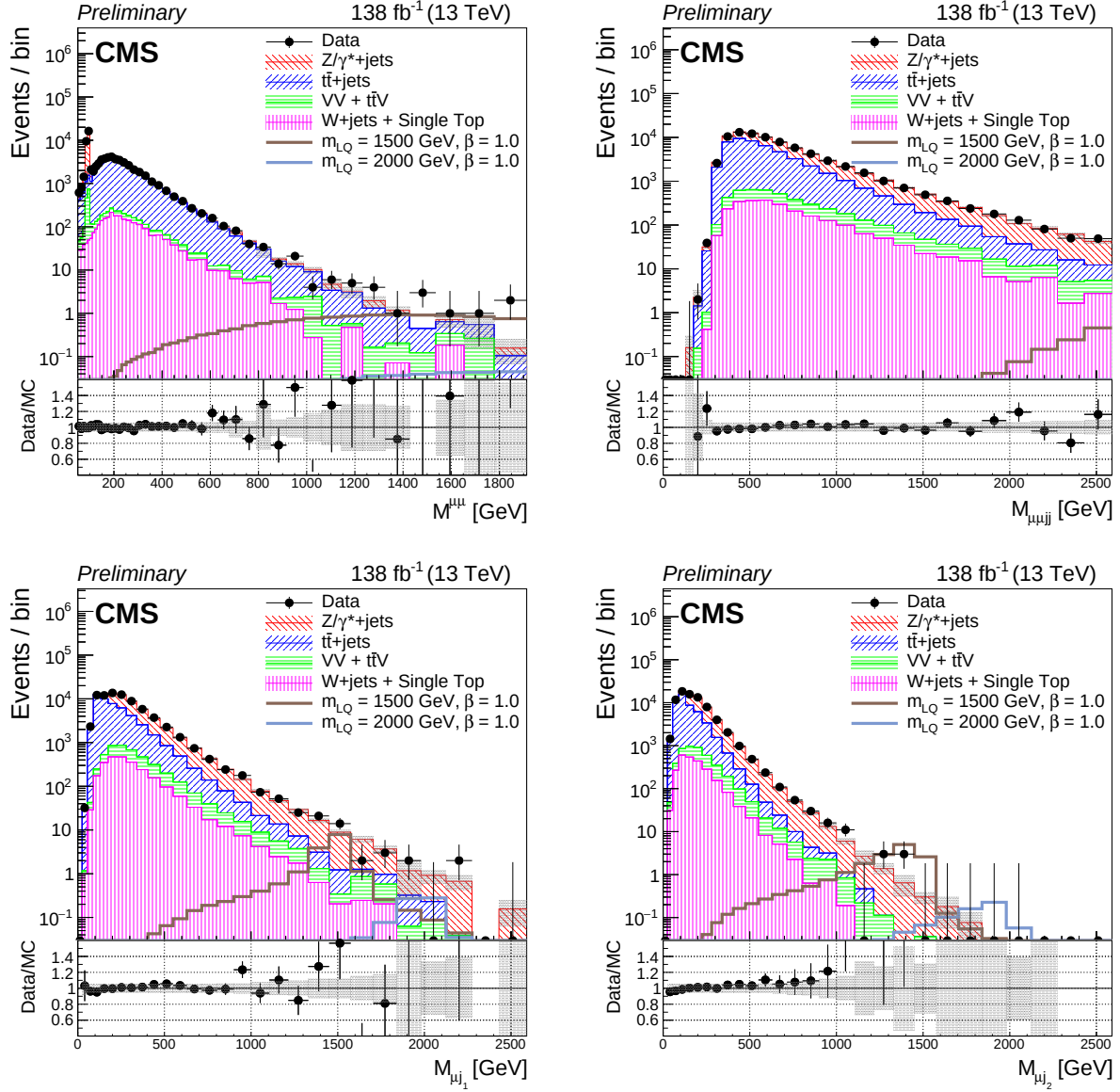


Figure 6.14: A comparison between distributions of observed data and SM expectation at preselection level in the combination of 2016, 2017, and 2018 data. Left to right, top to bottom: $M_{\mu\mu}$, $M_{\mu\mu jj}$, $M_{\mu j_1}$, and $M_{\mu j_2}$. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

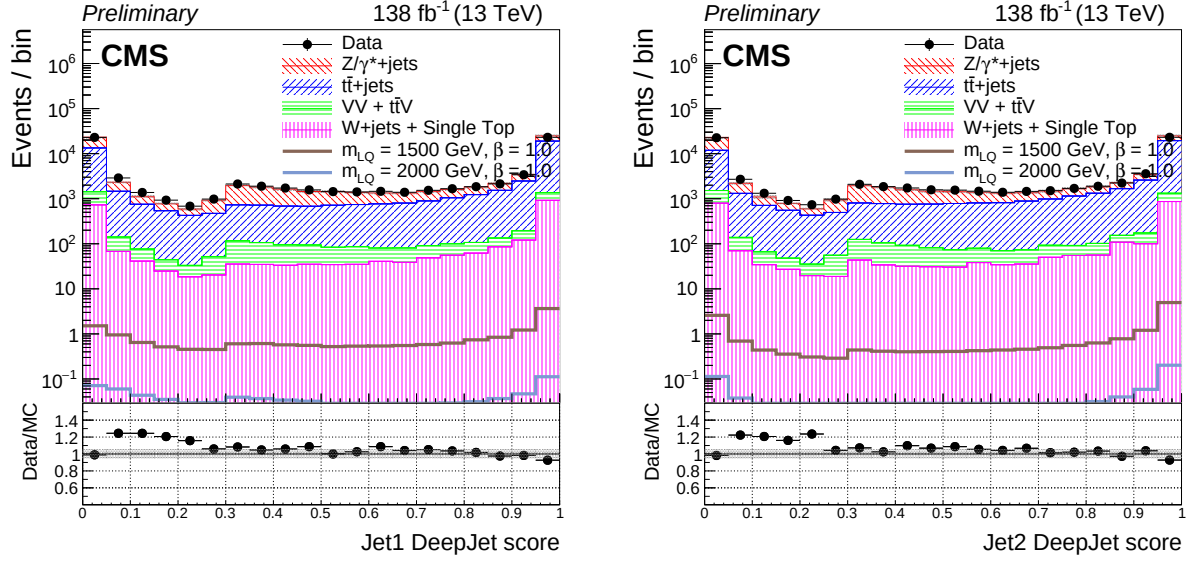


Figure 6.15: A comparison between distributions of observed data and SM expectation at preselection level in the combination of 2016, 2017, and 2018 data. Left to Right: DeepJet b tag score of jet 1 and DeepJet b tag score of jet 2. Error bars on observed data points represent statistical uncertainties, and systematic uncertainties on SM expectation are shown by gray hashing.

6.5 Final selection

After preselection, a final selection is required to optimize signal-to-background efficiency. A boosted decision tree (BDT) is trained and tested on signal and background MC, with one BDT per signal hypothesis, and a final cut is applied to each BDT discriminator.

Training samples are constructed by randomly selecting events from the combined 2016, 2017, and 2018 MC datasets detailed in Section 6.1. The same background normalization scale factors, data and MC corrections, b-jet requirement, and preselection described in Sections 6.2 and 6.3 are applied to the corresponding year's MC. Additional cuts of $M_{\mu\mu} > 250 \text{ GeV}$ and $M_{\mu\mu jj} > M_{LQ}$ are applied, to reduce training bias in background-enriched and low-signal regions. After training, a separate sample is constructed from the same MC and in the same way, and tested on each BDT to verify there is no overfitting (there is no overlap in training and testing events). A set of 11 kinematic variables—identified for their strong

signal-to-background separation power—are used as input variables to the BDTs:

- Invariant masses: $M_{\mu\mu}$, $M_{\mu\mu jj}$, $M_{\mu j_1}$, $M_{\mu j_2}$
- Final state object momenta: $p_T(\mu_1)$, $p_T(\mu_2)$, $p_T(j_1)$, $p_T(j_2)$
- Combined momenta: S_T , E_T^{miss}
- Spatial separation between the combined (vectorially-summed) momenta of the dimuon pair and the leading- p_T jet: $\Delta R(\mu_1 + \mu_2, j_1)$

Further details, including a number of studies, can be found in Appendix C.

To extract the highest possible signal, a cut on the BDT response is optimized using the Punzi significance [48] as a figure of merit, defined here:

$$\frac{\epsilon(t)}{a/2 + \sqrt{B(t)}} \quad (6.15)$$

where $\epsilon(t)$ is the signal efficiency for a cut t , a is the chosen sigma significance ($a = 5$ in this analysis), and $B(t)$ is the number of background events after applying a cut t .

A comparison between observed and expected data at preselection in the BDT score at every leptoquark mass point is shown in Figures 6.16–6.18. Final selection cuts are optimized and applied to the BDT score for each leptoquark mass, while the same cut value is used accross all years. A cut log is listed in Table 6.27. To ensure all events at final selection are contained within the signal region (SR) and do not overlap with events in the background normalization CRs (where the SR and CRs are defined in Table 6.23), an additional cut of $M_{\mu\mu} > 250 \text{ GeV}$ is applied. Additionally, the same M_{LQ} -dependent cut used in the BDT training is applied at final selection: $M_{\mu\mu jj} > M_{\text{LQ}}$. Efficiency in signal and background from applying each final selection cut is shown in Fig. 6.19 for all three years of data-taking. Efficiency here is defined as the number of events passing the final selection (optimized BDT score, $M_{\mu\mu} > 250 \text{ GeV}$, and $M_{\mu\mu jj} > M_{\text{LQ}}$ cuts) divided by the number of events present at preselection (in both the numerator and denominator, the b-jet

tag requirement, normalization scale factors, and MC corrections are applied). Event yields at final selection are provided for each year of data taking in Tables 6.24–6.26. W+Jets has been omitted from the tables as no events pass the final selection—it is kept in the analysis for the background normalization estimation, BDT training, systematic uncertainty estimation, etc. Figures 6.20–6.30 show the BDT input variables at final selection in 2016, 2017, and 2018 signal and background simulation for several representative leptoquark mass points. Plots showing the Punzi significance as a function of the BDT score, for each BDT, are shown in Figs. 6.31–6.32.

Table 6.23: The $Z/\gamma^* + \text{jets}$ (A), $t\bar{t}$ (B), and $VV + t\bar{t}V$ (C) background normalization CR, and SR definitions.

Region	Mass window [GeV]	Additional selection
Control A	$80 < M_{\mu\mu} < 100$	$N_{\text{jets}} = 2, N_{\text{jets}} = 3, N_{\text{jets}} = 4, \text{ or } N_{\text{jets}} \geq 5$
Control B	$100 < M_{\mu\mu} < 250$	-
Control C	$80 < M_{\mu\mu} < 100$	$N_{\text{leptons}} \geq 3, N_{\text{b-jets}} \geq 0$
Signal	$250 < M_{\mu\mu}$	-

Table 6.24: Event yields in 2016 data at the final selection level. Uncertainties are statistical unless otherwise indicated.

M_{LQ}	Signal	$Z/\gamma^* + \text{jets}$	$t\bar{t}$	$t\bar{t}V$	VV	Single Top	All BG (stat + syst)	Data
300	18810 ± 240	0.686 ± 0.089	0.13 ± 0.13	0.0423 ± 0.0061	0.242 ± 0.059	0.0 ± 0.0	$1.1 \pm 0.16 \pm 0.11$	0
400	5501 ± 59	0.79 ± 0.11	$0.0^{+0.13}_{-0.0}$	0.012 ± 0.003	$0.0^{+0.014}_{-0.0}$	0.378 ± 0.267	$1.18^{+0.32}_{-0.29} \pm 0.13$	0
500	3405 ± 24	0.719 ± 0.078	0.586 ± 0.338	0.025 ± 0.005	0.0537 ± 0.019	0.407 ± 0.288	$1.79 \pm 0.45 \pm 0.12$	2
600	1379.9 ± 8.9	0.218 ± 0.031	$0.0^{+0.13}_{-0.0}$	0.018 ± 0.005	0.0462 ± 0.0207	0.0 ± 0.0	$0.282^{+0.131}_{-0.037} \pm 0.037$	0
700	706.9 ± 4.0	0.283 ± 0.035	$0.0^{+0.13}_{-0.0}$	0.021 ± 0.004	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.304^{+0.132}_{-0.035} \pm 0.053$	0
800	333.1 ± 1.7	$0.0^{+0.011}_{-0.0}$	$0.0^{+0.13}_{-0.0}$	0.0057 ± 0.0015	0.0063 ± 0.0032	0.0 ± 0.0	$0.012^{+0.127}_{-0.003} \pm 0.001$	0
900	165.48 ± 0.81	0.103 ± 0.013	$0.0^{+0.13}_{-0.0}$	0.011 ± 0.004	0.065 ± 0.026	0.0 ± 0.0	$0.179^{+0.129}_{-0.03} \pm 0.018$	0
1000	83.44 ± 0.46	0.15 ± 0.018	$0.0^{+0.13}_{-0.0}$	0.01 ± 0.004	0.058 ± 0.026	0.0 ± 0.0	$0.219^{+0.13}_{-0.032} \pm 0.024$	1
1100	45.57 ± 0.2	0.4 ± 0.047	$0.0^{+0.13}_{-0.0}$	0.0181 ± 0.0064	0.0415 ± 0.0207	0.0 ± 0.0	$0.46^{+0.136}_{-0.052} \pm 0.086$	1
1200	21.345 ± 0.098	0.086 ± 0.016	$0.0^{+0.13}_{-0.0}$	0.0053 ± 0.0027	$0.0^{+0.014}_{-0.0}$	0.19 ± 0.19	$0.282^{+0.229}_{-0.191} \pm 0.03$	1
1300	11.244 ± 0.051	0.0466 ± 0.0113	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0478^{+0.1274}_{-0.0113} \pm 0.0078$	0
1400	7.011 ± 0.029	0.186 ± 0.028	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.19 ± 0.19	$0.376^{+0.23}_{-0.192} \pm 0.042$	0
1500	3.384 ± 0.015	0.0221 ± 0.0052	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	0.013 ± 0.013	0.0 ± 0.0	$0.037^{+0.127}_{-0.014} \pm 0.005$	0
1600	1.9368 ± 0.0081	0.174 ± 0.038	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.174^{+0.132}_{-0.038} \pm 0.032$	0
1700	1.0235 ± 0.0052	0.0306 ± 0.0092	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0306^{+0.1272}_{-0.0092} \pm 0.0058$	0
1800	0.56 ± 0.0	0.0 ± 0.0	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
1900	0.33 ± 0.0	0.088 ± 0.018	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.088^{+0.128}_{-0.018} \pm 0.02$	0
2000	0.185 ± 0.001	0.062 ± 0.019	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	0.013 ± 0.013	0.0 ± 0.0	$0.075^{+0.128}_{-0.024} \pm 0.017$	0
2100	0.102 ± 0.0	0.072 ± 0.02	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.072^{+0.128}_{-0.02} \pm 0.027$	0
2200	0.053 ± 0.0	0.0291 ± 0.0168	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0291^{+0.128}_{-0.0168} \pm 0.0084$	0
2300	0.03 ± 0.0	0.038 ± 0.016	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.038^{+0.128}_{-0.016} \pm 0.012$	0
2400	0.017 ± 0.0	0.0149 ± 0.0056	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0149^{+0.127}_{-0.0056} \pm 0.0061$	0
2500	0.0099 ± 0.0	0.0 ± 0.0	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
2600	0.0055 ± 0.0	0.0 ± 0.0	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
2700	0.0 ± 0.0	0.036 ± 0.016	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.036^{+0.128}_{-0.016} \pm 0.018$	0
2800	0.0 ± 0.0	$0.0^{+0.011}_{-0.0}$	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
2900	0.0 ± 0.0	$0.0^{+0.011}_{-0.0}$	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
3000	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
3500	0.0 ± 0.0	0.028 ± 0.016	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.028^{+0.128}_{-0.016} \pm 0.034$	0
4000	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.13}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.014}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.13}_{-0.0} \pm 0.0$	0

Table 6.25: Event yields in 2017 data at the final selection level. Uncertainties are statistical unless otherwise indicated.

M_{LQ}	Signal	$Z/\gamma^* + \text{jets}$	$t\bar{t}$	$t\bar{t}V$	VV	Single Top	All BG (stat + syst)	Data
300	20990 ± 260	1.45 ± 0.2	0.59 ± 0.17	0.026 ± 0.005	0.0 ± 0.0	0.241 ± 0.17	$2.31 \pm 0.31 \pm 0.23$	5
400	5952 ± 64	0.0491 ± 0.0091	0.093 ± 0.066	0.0351 ± 0.0083	0.014 ± 0.005	$0.0^{+0.12}_{-0.0}$	$0.191^{+0.138}_{-0.067} \pm 0.01$	0
500	3834 ± 27	1.59 ± 0.19	0.258 ± 0.097	0.0481 ± 0.0093	0.097 ± 0.028	0.384 ± 0.271	$2.38 \pm 0.35 \pm 0.26$	2
600	1547 ± 10	0.516 ± 0.077	0.068 ± 0.048	0.012 ± 0.003	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.597^{+0.151}_{-0.091} \pm 0.085$	1
700	792.8 ± 4.4	0.558 ± 0.055	0.055 ± 0.055	0.0 ± 0.0	0.0263 ± 0.0118	0.0 ± 0.0	$0.644 \pm 0.078 \pm 0.089$	0
800	376.3 ± 1.9	0.322 ± 0.031	0.056 ± 0.056	0.0426 ± 0.0093	0.065 ± 0.029	$0.0^{+0.12}_{-0.0}$	$0.486^{+0.14}_{-0.071} \pm 0.061$	1
900	186.01 ± 0.91	$0.0^{+0.027}_{-0.0}$	$0.0^{+0.049}_{-0.0}$	0.012 ± 0.004	0.0357 ± 0.0206	$0.0^{+0.12}_{-0.0}$	$0.0477^{+0.1345}_{-0.021} \pm 0.0094$	0
1000	94.65 ± 0.44	0.178 ± 0.018	$0.0^{+0.049}_{-0.0}$	0.0063 ± 0.0024	0.0357 ± 0.0206	$0.0^{+0.12}_{-0.0}$	$0.22^{+0.133}_{-0.027} \pm 0.031$	1
1100	51.05 ± 0.23	0.155 ± 0.016	$0.0^{+0.049}_{-0.0}$	0.014 ± 0.005	0.021 ± 0.012	$0.0^{+0.12}_{-0.0}$	$0.19^{+0.132}_{-0.02} \pm 0.027$	0
1200	24.26 ± 0.15	$0.0^{+0.027}_{-0.0}$	$0.0^{+0.049}_{-0.0}$	0.011 ± 0.005	0.067 ± 0.047	$0.0^{+0.12}_{-0.0}$	$0.077^{+0.141}_{-0.047} \pm 0.014$	0
1300	12.752 ± 0.08	$0.0^{+0.027}_{-0.0}$	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0258 ± 0.0258	$0.0^{+0.12}_{-0.0}$	$0.0285^{+0.1353}_{-0.0258} \pm 0.0059$	1
1400	7.961 ± 0.032	0.0709 ± 0.0082	$0.0^{+0.049}_{-0.0}$	0.01 ± 0.004	0.153 ± 0.088	$0.0^{+0.12}_{-0.0}$	$0.234^{+0.157}_{-0.089} \pm 0.035$	1
1500	3.851 ± 0.016	0.062 ± 0.01	$0.0^{+0.049}_{-0.0}$	0.0104 ± 0.0052	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.073^{+0.13}_{-0.012} \pm 0.014$	0
1600	2.2027 ± 0.0091	0.0234 ± 0.0043	$0.0^{+0.049}_{-0.0}$	0.0068 ± 0.0039	0.0259 ± 0.0183	$0.0^{+0.12}_{-0.0}$	$0.056^{+0.1314}_{-0.0192} \pm 0.0097$	1
1700	1.16 ± 0.0	0.0248 ± 0.005	$0.0^{+0.049}_{-0.0}$	0.0068 ± 0.0039	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0316^{+0.1301}_{-0.0063} \pm 0.0064$	0
1800	0.64 ± 0.0	0.0332 ± 0.0076	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0367^{+0.1302}_{-0.008} \pm 0.0093$	0
1900	0.39 ± 0.0	0.0202 ± 0.0032	$0.0^{+0.049}_{-0.0}$	0.0104 ± 0.0052	0.0259 ± 0.0183	$0.0^{+0.12}_{-0.0}$	$0.0565^{+0.1314}_{-0.0193} \pm 0.0087$	0
2000	0.22 ± 0.0	0.0371 ± 0.0069	$0.0^{+0.049}_{-0.0}$	0.0104 ± 0.0052	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0477^{+0.1302}_{-0.0086} \pm 0.0135$	0
2100	0.12 ± 0.0	0.0 ± 0.0	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0078^{+0.13}_{-0.0024} \pm 0.0017$	1
2200	0.063 ± 0.0	$0.0^{+0.027}_{-0.0}$	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
2300	0.036 ± 0.0	0.0 ± 0.0	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.007^{+0.13}_{-0.0034} \pm 0.0022$	0
2400	0.021 ± 0.0	0.014 ± 0.0038	$0.0^{+0.049}_{-0.0}$	0.0071 ± 0.0041	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0212^{+0.1301}_{-0.0056} \pm 0.0089$	0
2500	0.012 ± 0.0	0.0178 ± 0.004	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0178^{+0.13}_{-0.004} \pm 0.0077$	1
2600	0.0066 ± 0.0	$0.0^{+0.027}_{-0.0}$	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
2700	0.0 ± 0.0	0.0067 ± 0.0019	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0067^{+0.13}_{-0.0019} \pm 0.0037$	0
2800	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0^{+0.13}_{-0.0} \pm 0.0$	1
2900	0.0 ± 0.0	0.006 ± 0.0019	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.006^{+0.13}_{-0.0019} \pm 0.0033$	1
3000	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
3500	0.0 ± 0.0	$0.0^{+0.027}_{-0.0}$	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0^{+0.13}_{-0.0} \pm 0.0$	0
4000	0.0 ± 0.0	$0.0^{+0.027}_{-0.0}$	$0.0^{+0.049}_{-0.0}$	0.0 ± 0.0	0.0 ± 0.0	$0.0^{+0.12}_{-0.0}$	$0.0^{+0.13}_{-0.0} \pm 0.0$	1

Table 6.26: Event yields in 2018 data at the final selection level. Uncertainties are statistical unless otherwise indicated.

M_{LQ}	Signal	$Z/\gamma^* + \text{jets}$	$t\bar{t}$	$t\bar{t}V$	VV	Single Top	All BG (stat + syst)	Data
300	32440 ± 560	1.5 ± 0.23	0.928 ± 0.28	0.11 ± 0.016	0.393 ± 0.088	0.464 ± 0.328	$3.4 \pm 0.5 \pm 0.25$	0
400	8860 ± 140	0.0 ± 0.0	0.1387 ± 0.0801	0.0215 ± 0.0051	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.163^{+0.2462}_{-0.0802} \pm 0.006$	1
500	5692 ± 57	$0.0^{+0.037}_{-0.0}$	0.276 ± 0.123	0.108 ± 0.017	0.099 ± 0.025	0.334 ± 0.334	$0.818^{+0.359}_{-0.357} \pm 0.037$	2
600	2288 ± 21	$0.0^{+0.037}_{-0.0}$	0.211 ± 0.1218	0.0662 ± 0.0121	0.083 ± 0.028	$0.0^{+0.23}_{-0.0}$	$0.36^{+0.266}_{-0.126} \pm 0.016$	3
700	1169.6 ± 9.2	0.302 ± 0.038	0.22 ± 0.127	0.017 ± 0.004	0.0134 ± 0.006	$0.0^{+0.23}_{-0.0}$	$0.553^{+0.267}_{-0.133} \pm 0.046$	1
800	568.8 ± 4.1	0.127 ± 0.016	0.22 ± 0.127	0.0 ± 0.0	0.085 ± 0.028	$0.0^{+0.23}_{-0.0}$	$0.432^{+0.266}_{-0.131} \pm 0.027$	0
900	282.1 ± 1.9	0.338 ± 0.041	$0.0^{+0.084}_{-0.0}$	0.026 ± 0.0072	0.0435 ± 0.0177	$0.0^{+0.23}_{-0.0}$	$0.407^{+0.251}_{-0.045} \pm 0.057$	0
1000	143.72 ± 0.94	$0.0^{+0.037}_{-0.0}$	0.0687 ± 0.0687	0.007 ± 0.0019	0.0056 ± 0.0056	$0.0^{+0.23}_{-0.0}$	$0.0813^{+0.2447}_{-0.069} \pm 0.0074$	0
1100	78.21 ± 0.49	0.175 ± 0.023	0.0759 ± 0.0759	0.0217 ± 0.006	0.0627 ± 0.0362	$0.0^{+0.23}_{-0.0}$	$0.335^{+0.248}_{-0.087} \pm 0.032$	0
1200	37.27 ± 0.24	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0147 ± 0.0073	0.0056 ± 0.0056	$0.0^{+0.23}_{-0.0}$	$0.0203^{+0.2496}_{-0.0092} \pm 0.0021$	0
1300	19.64 ± 0.12	0.0285 ± 0.0064	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.0285^{+0.2476}_{-0.0064} \pm 0.0054$	0
1400	12.419 ± 0.071	0.176 ± 0.026	$0.0^{+0.084}_{-0.0}$	0.0213 ± 0.0081	0.025 ± 0.025	$0.0^{+0.23}_{-0.0}$	$0.223^{+0.25}_{-0.037} \pm 0.033$	0
1500	6.054 ± 0.036	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	0.018 ± 0.018	$0.0^{+0.23}_{-0.0}$	$0.02^{+0.25}_{-0.018} \pm 0.003$	0
1600	3.486 ± 0.02	0.0 ± 0.0	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.0^{+0.25}_{-0.0} \pm 0.0$	0
1700	1.878 ± 0.011	0.0374 ± 0.0132	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.0374^{+0.2479}_{-0.0132} \pm 0.0087$	0
1800	1.0336 ± 0.0061	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.0^{+0.25}_{-0.0} \pm 0.0$	0
1900	0.63 ± 0.0	$0.0^{+0.037}_{-0.0}$	0.105 ± 0.105	0.015 ± 0.011	0.018 ± 0.018	$0.0^{+0.23}_{-0.0}$	$0.138^{+0.258}_{-0.107} \pm 0.028$	0
2000	0.35 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.0^{+0.25}_{-0.0} \pm 0.0$	0
2100	0.2 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.0^{+0.25}_{-0.0} \pm 0.0$	0
2200	0.105 ± 0.001	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	0.0178 ± 0.0178	$0.0^{+0.23}_{-0.0}$	$0.0178^{+0.2501}_{-0.0178} \pm 0.0058$	0
2300	0.06 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.0^{+0.25}_{-0.0} \pm 0.0$	0
2400	0.035 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	0.018 ± 0.018	$0.0^{+0.23}_{-0.0}$	$0.018^{+0.25}_{-0.018} \pm 0.011$	0
2500	0.02 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.0^{+0.25}_{-0.0} \pm 0.0$	0
2600	0.011 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	0.0178 ± 0.0178	$0.0^{+0.23}_{-0.0}$	$0.0178^{+0.2501}_{-0.0178} \pm 0.0083$	0
2700	0.0064 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	0.024 ± 0.017	$0.0^{+0.23}_{-0.0}$	$0.024^{+0.25}_{-0.017} \pm 0.024$	0
2800	0.0 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	0.0063 ± 0.0063	$0.0^{+0.23}_{-0.0}$	$0.0063^{+0.2496}_{-0.0063} \pm 0.0031$	0
2900	0.0 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	0.0178 ± 0.0178	$0.0^{+0.23}_{-0.0}$	$0.0178^{+0.2501}_{-0.0178} \pm 0.009$	0
3000	0.0 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	$0.0^{+0.02}_{-0.0}$	$0.0^{+0.23}_{-0.0}$	$0.0^{+0.25}_{-0.0} \pm 0.0$	0
3500	0.0 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	0.0063 ± 0.0063	$0.0^{+0.23}_{-0.0}$	$0.0063^{+0.2496}_{-0.0063} \pm 0.0074$	0
4000	0.0 ± 0.0	$0.0^{+0.037}_{-0.0}$	$0.0^{+0.084}_{-0.0}$	0.0 ± 0.0	0.0063 ± 0.0063	$0.0^{+0.23}_{-0.0}$	$0.0063^{+0.2496}_{-0.0063} \pm 0.0169$	0

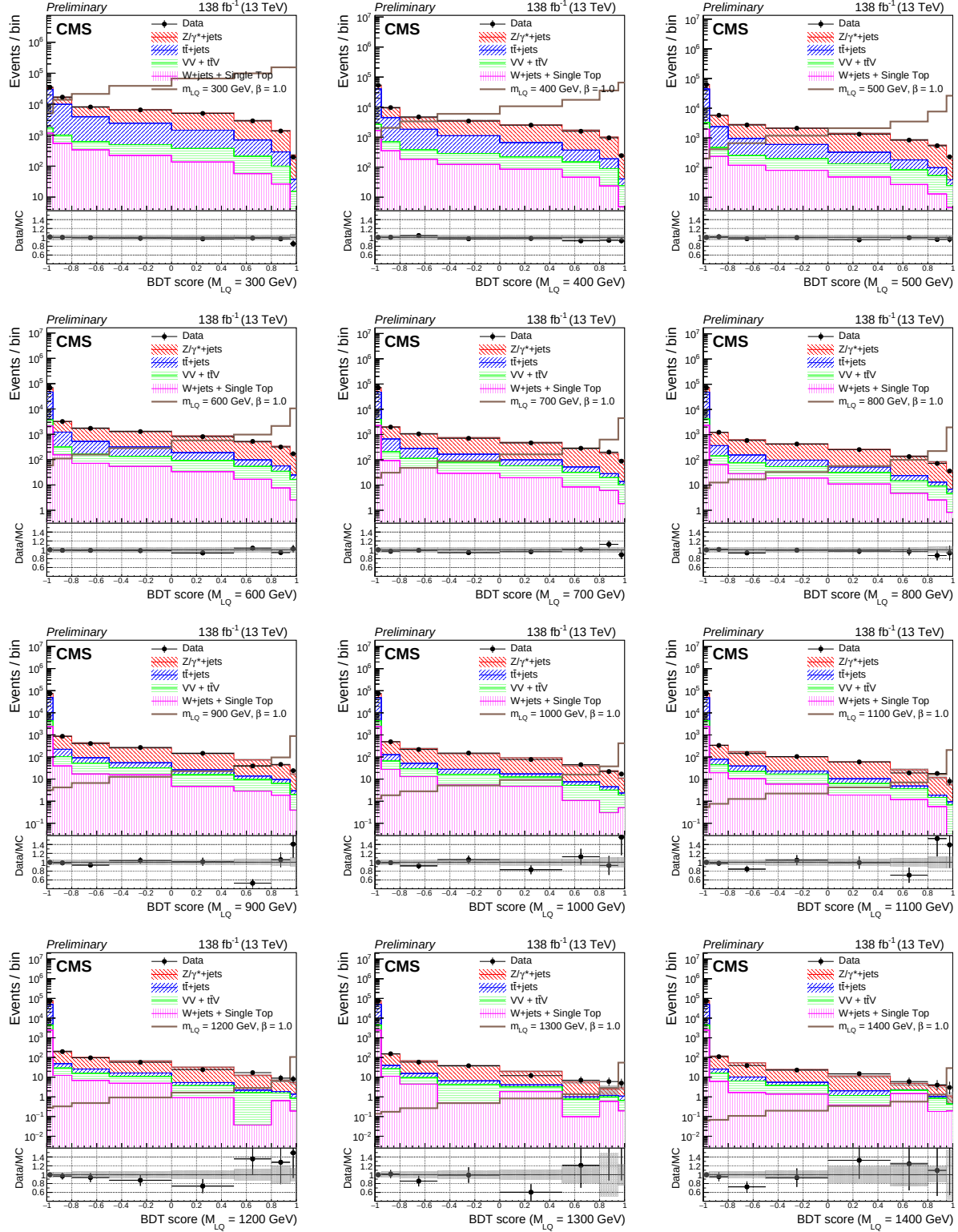


Figure 6.16: A comparison between observed and expected events in BDT responses at preselection level with the combination of 2016, 2017, and 2018 data. The leptoquark mass of the signal in each plot corresponds to the leptoquark mass used in the BDT training. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

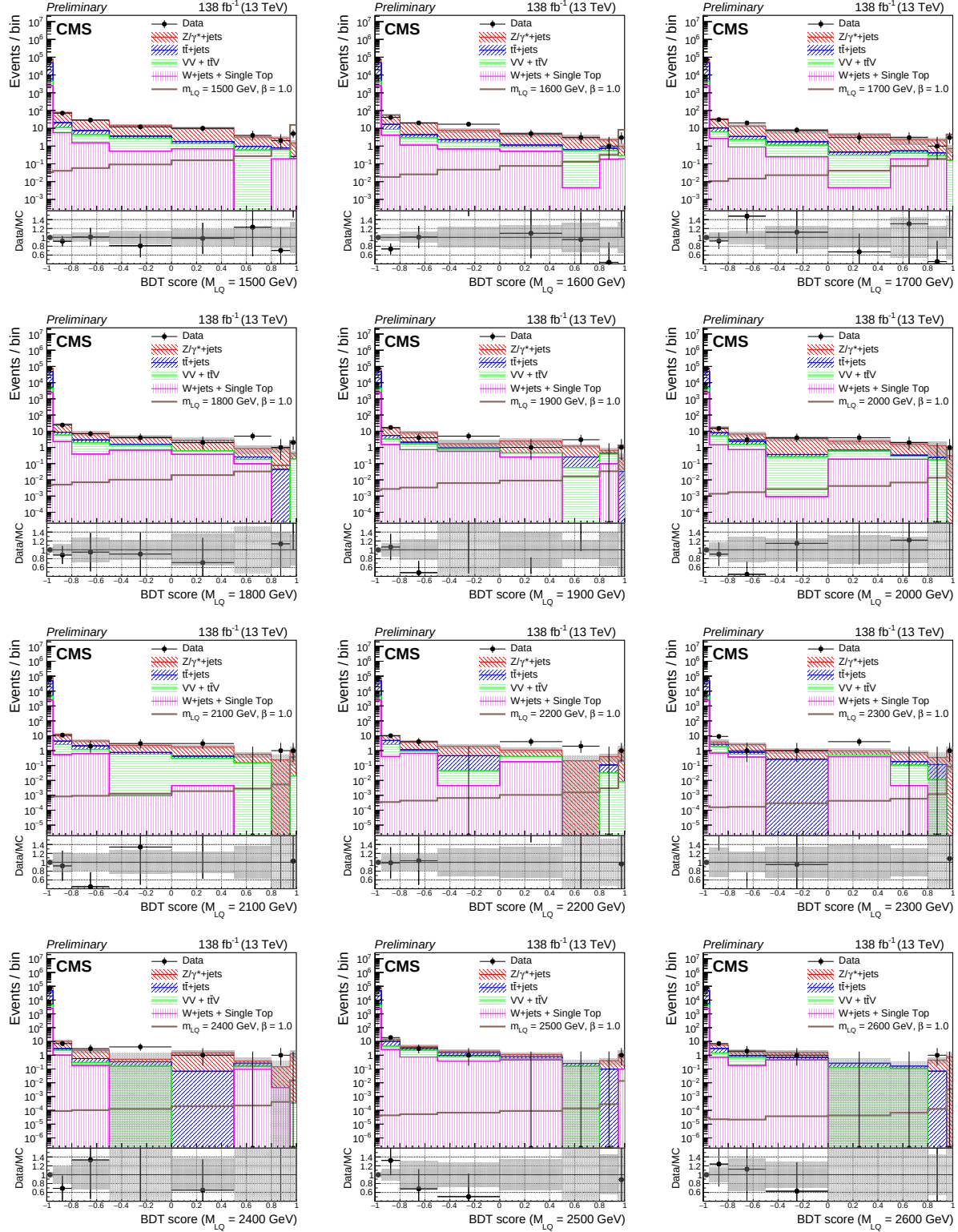


Figure 6.17: A comparison between observed and expected events of BDT responses at preselection level in the combination of 2016, 2017, and 2018 data. The leptoquark mass of the signal in each plot corresponds to the leptoquark mass used in the BDT training. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

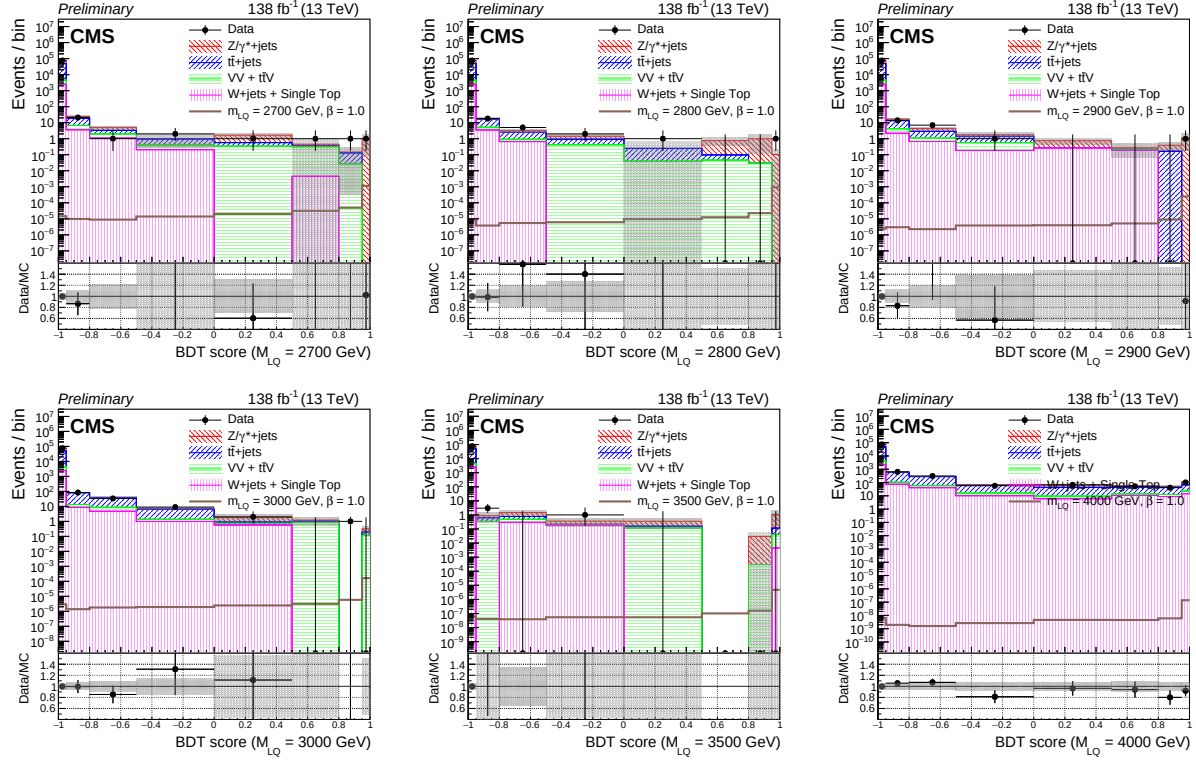


Figure 6.18: A comparison between observed and expected events of BDT responses at preselection level in the combination of 2016, 2017, and 2018 data. The leptotoquark mass of the signal in each plot corresponds to the leptotoquark mass used in the BDT training. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

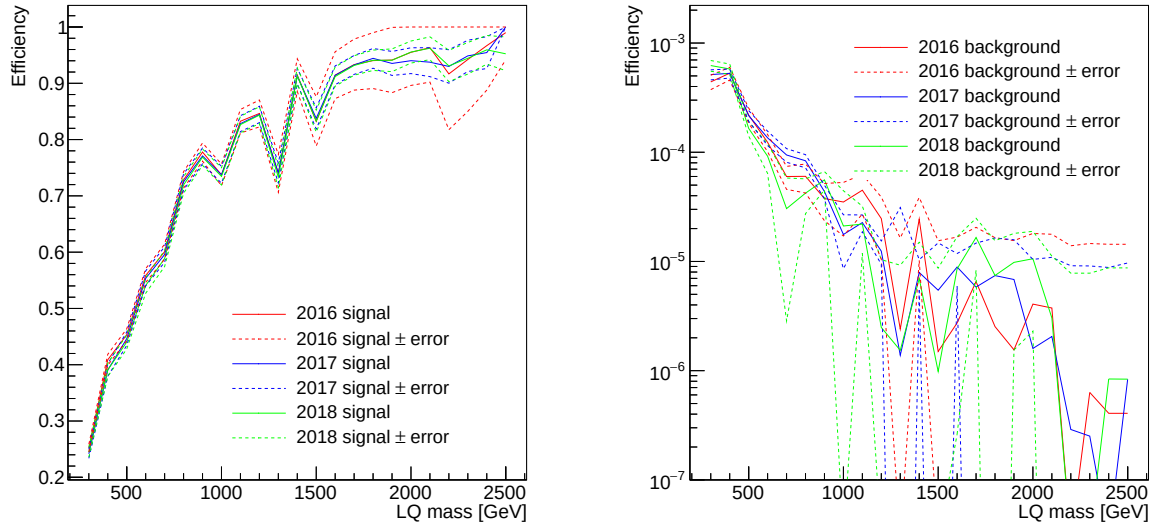


Figure 6.19: The signal (left) and background (right) efficiencies in 2016, 2017, and 2018 MC after applying each final selection cut as a function of leptoquark mass. Dashed lines are error bands that combine systematic and statistical uncertainties.

Table 6.27: Final selection cuts are defined for each leptoquark mass point consisting of the optimized cut on the BDT discriminant, a flat cut on $M_{\mu\mu}$, and a LQ-mass-dependent cut $M_{\mu\mu jj}$.

Leptoquark mass [GeV]	Final selection cuts		
	BDT score	$M_{\mu\mu jj}$ [GeV]	$M_{\mu\mu}$ [GeV]
300	0.978	300	250
400	0.99	400	250
500	0.99	500	250
600	0.994	600	250
700	0.994	700	250
800	0.994	800	250
900	0.993	900	250
1000	0.993	1000	250
1100	0.989	1100	250
1200	0.996	1200	250
1300	0.996	1300	250
1400	0.978	1400	250
1500	0.993	1500	250
1600	0.987	1600	250
1700	0.991	1700	250
1800	0.995	1800	250
1900	0.964	1900	250
2000	0.987	2000	250
2100	0.992	2100	250
2200	0.998	2200	250
2300	0.998	2300	250
2400	0.998	2400	250
2500	0.969	2500	250
2600	0.949	2600	250
2700	0.977	2700	250
2800	0.982	2800	250
2900	0.996	2900	250
3000	0.998	3000	250
3500	0.989	3500	250
4000	0.999	4000	250

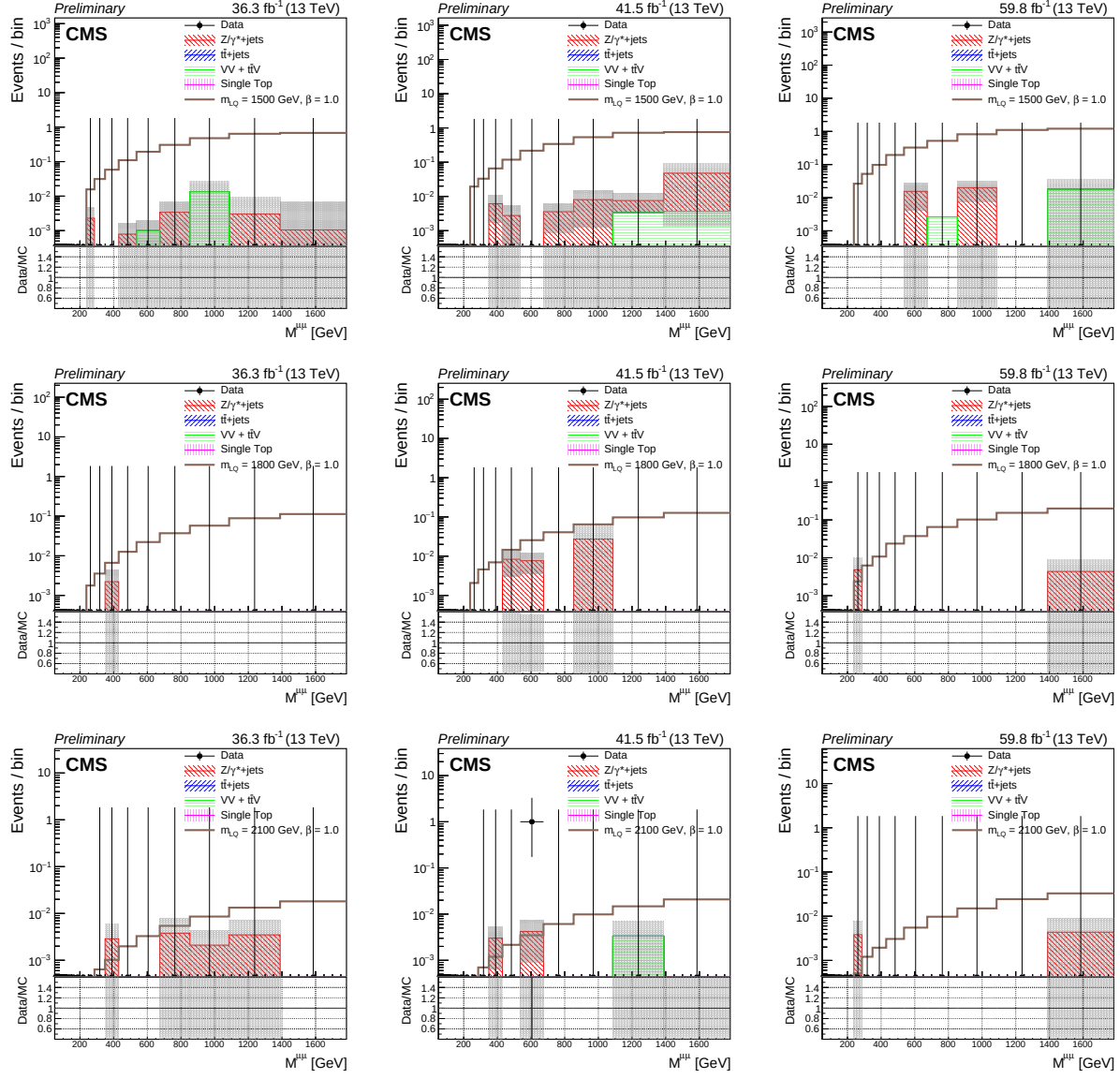


Figure 6.20: BDT input variable $M_{\mu\mu}$ at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptokquark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

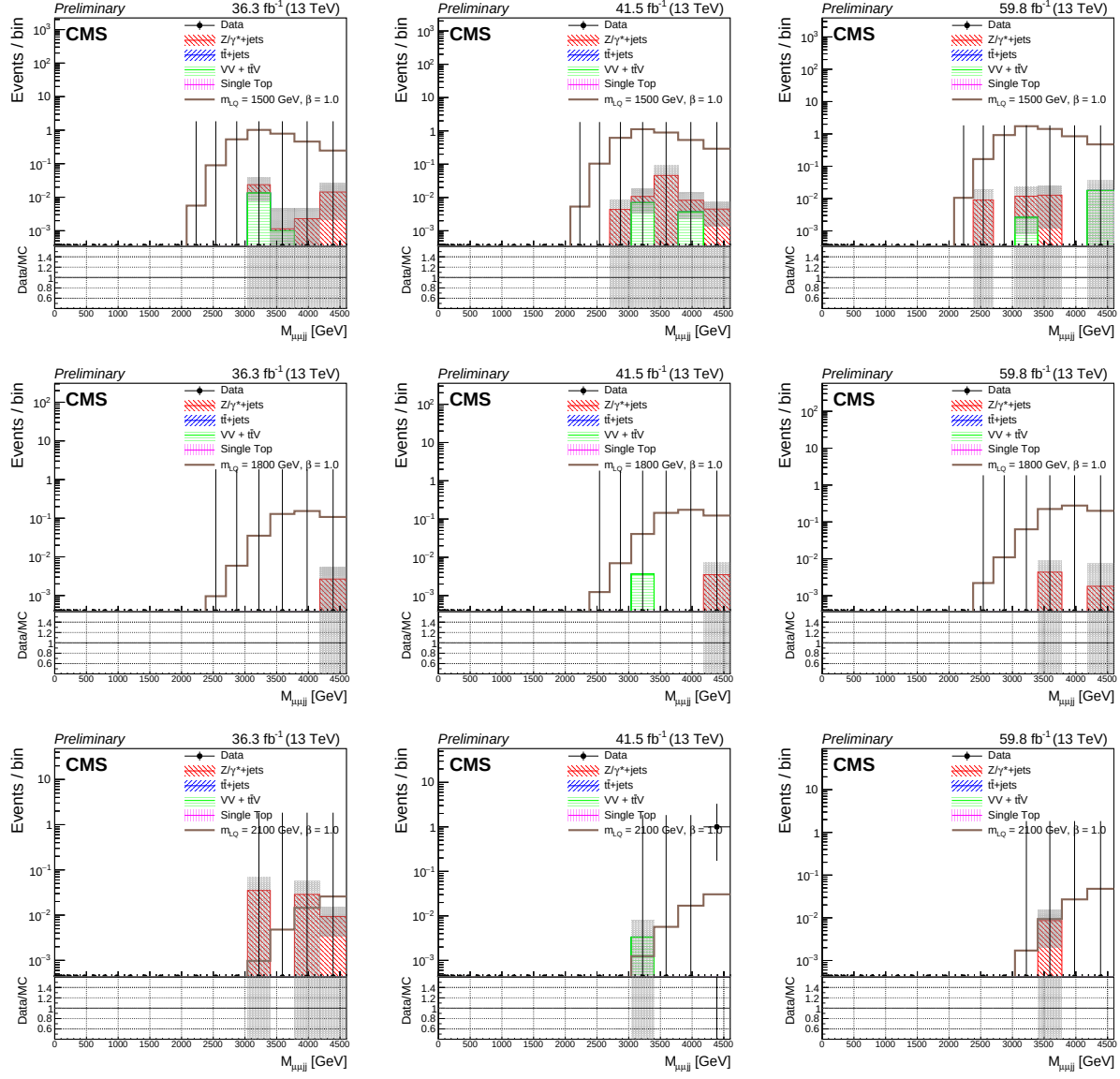


Figure 6.21: BDT input variable $M_{\mu\mu jj}$ at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptiquark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

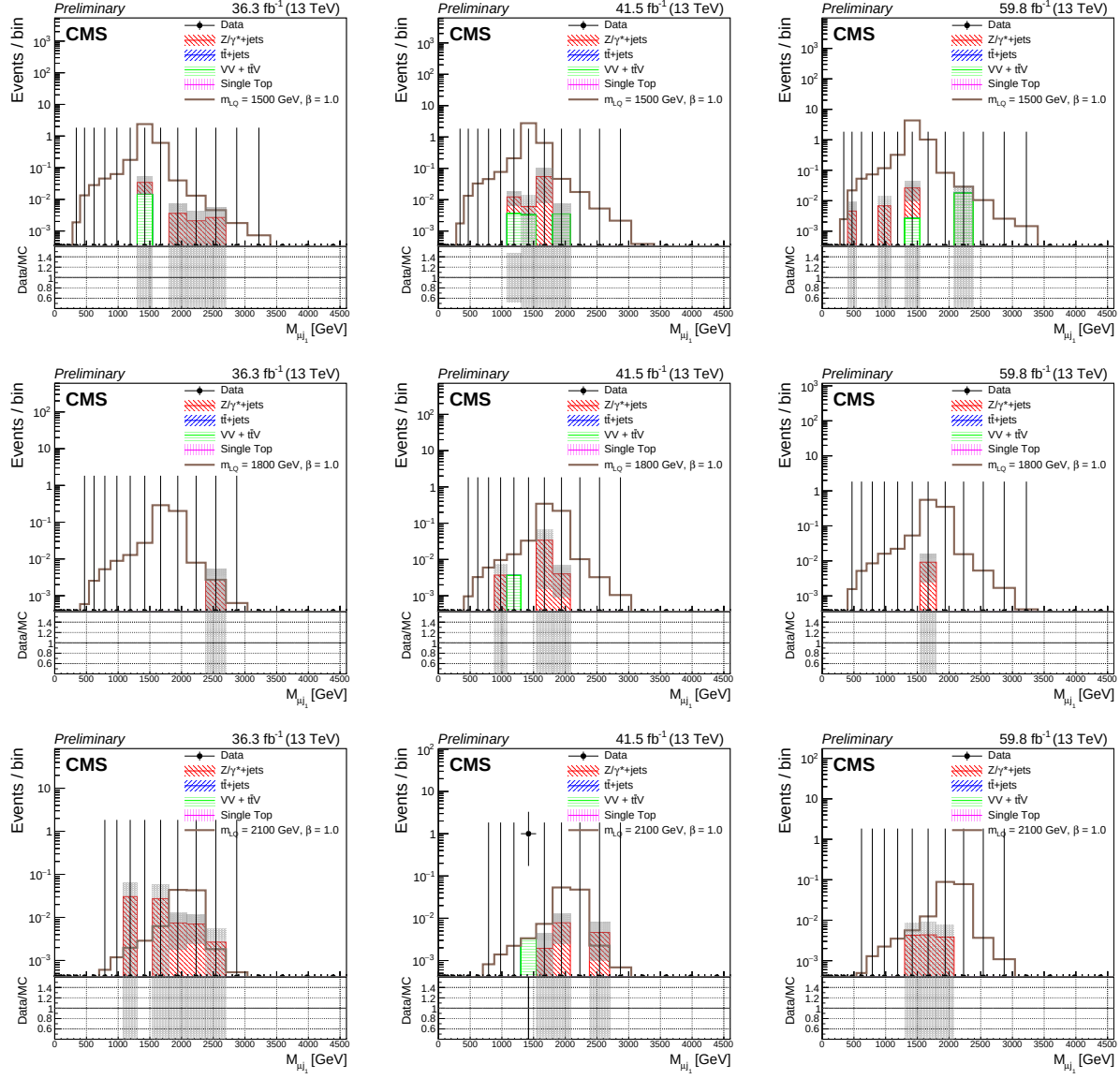


Figure 6.22: BDT input variable $M_{\mu j_1}$ at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptoquark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

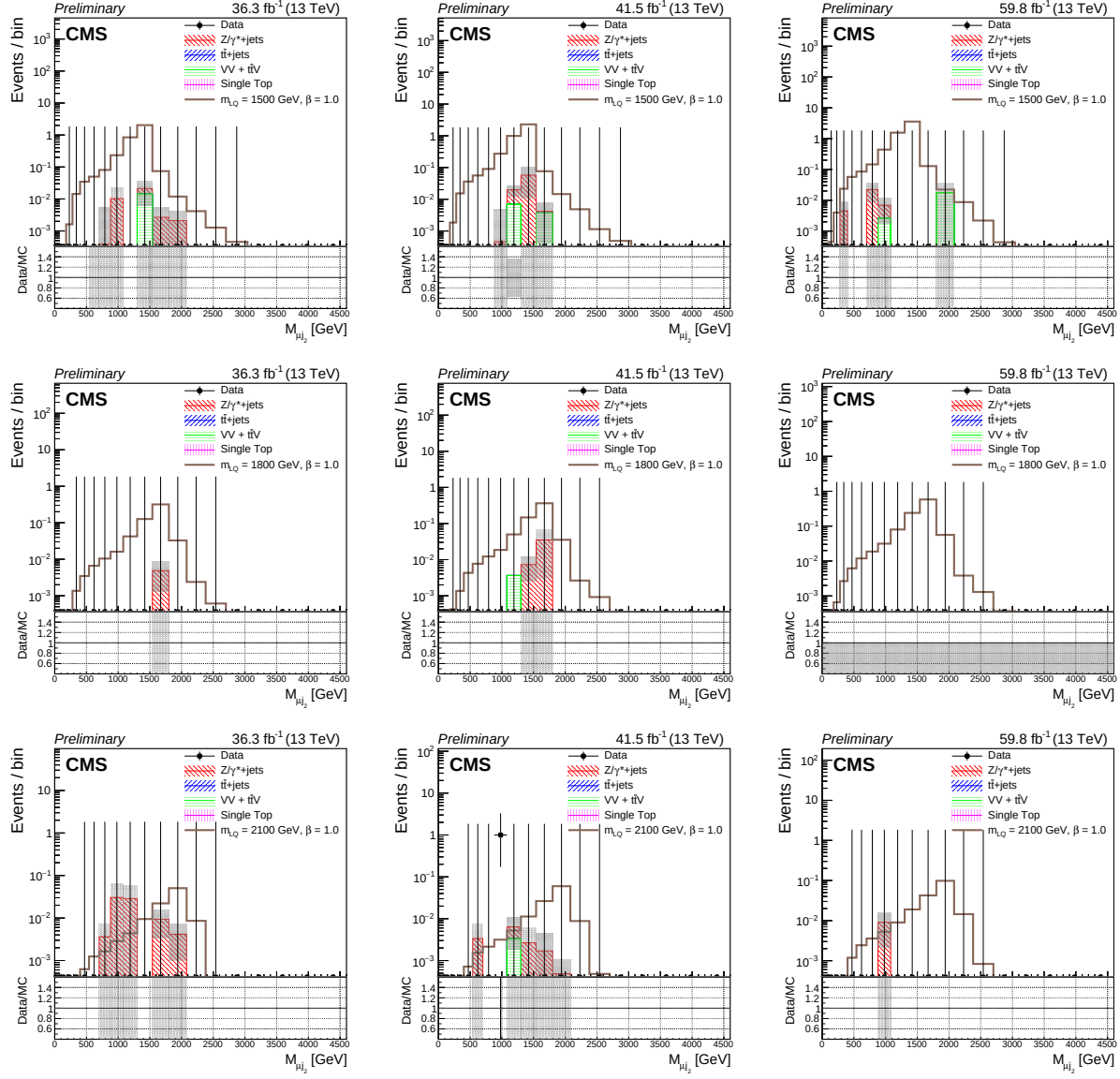


Figure 6.23: BDT input variable $M_{\mu j_2}$ at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptoquark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

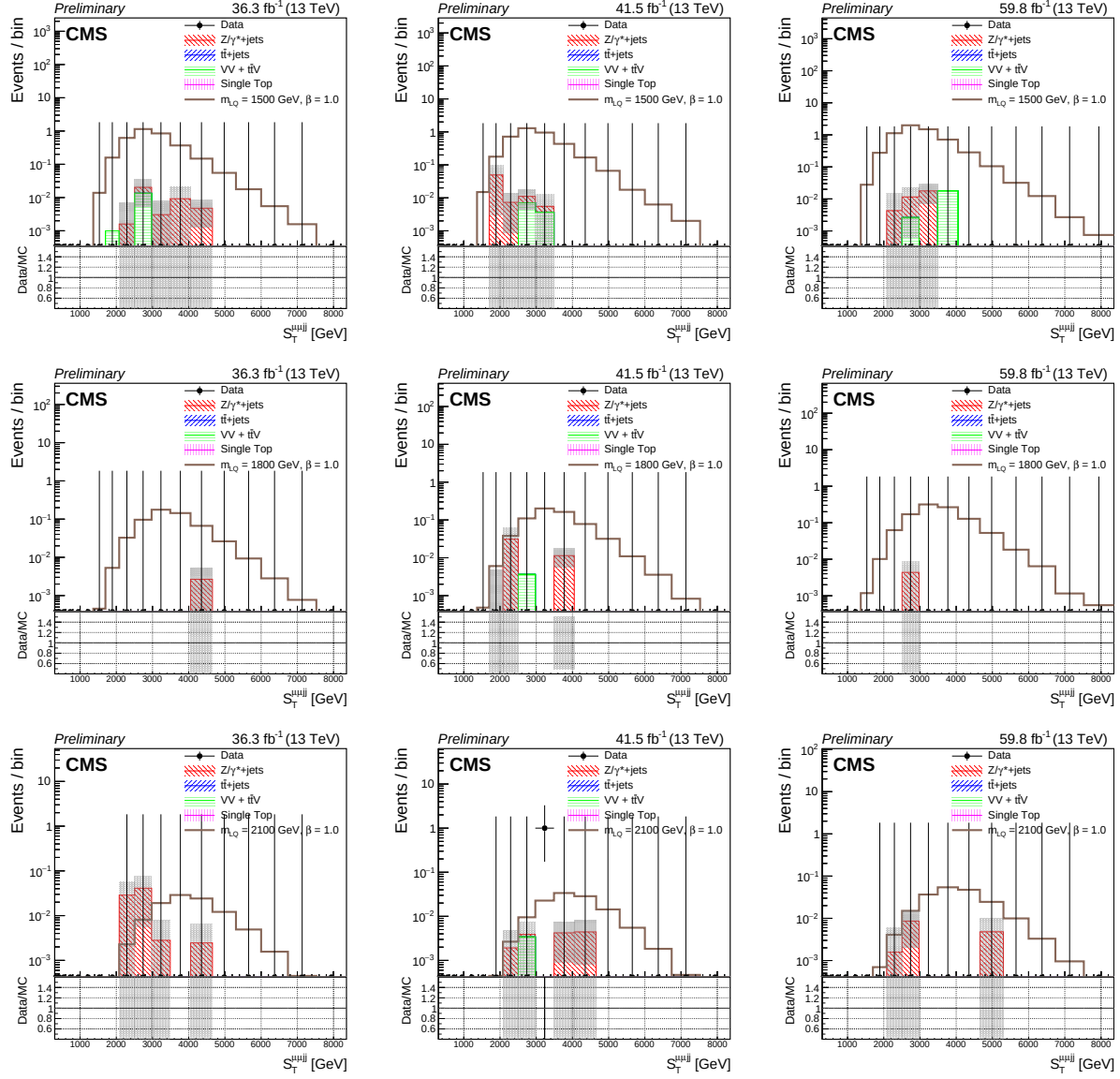


Figure 6.24: BDT input variable S_T at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptokuark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

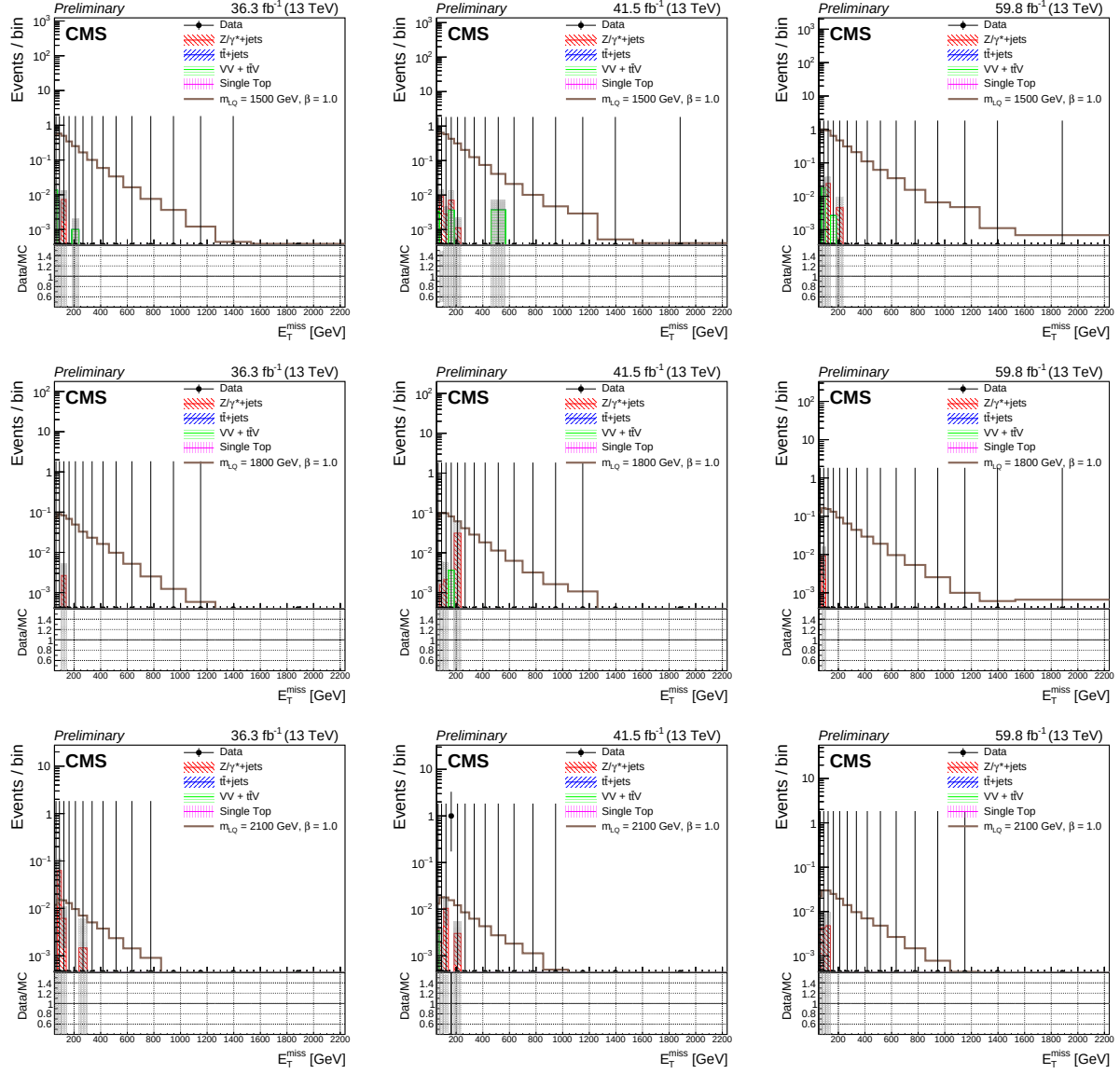


Figure 6.25: BDT input variable p_T^{miss} at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptokuark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

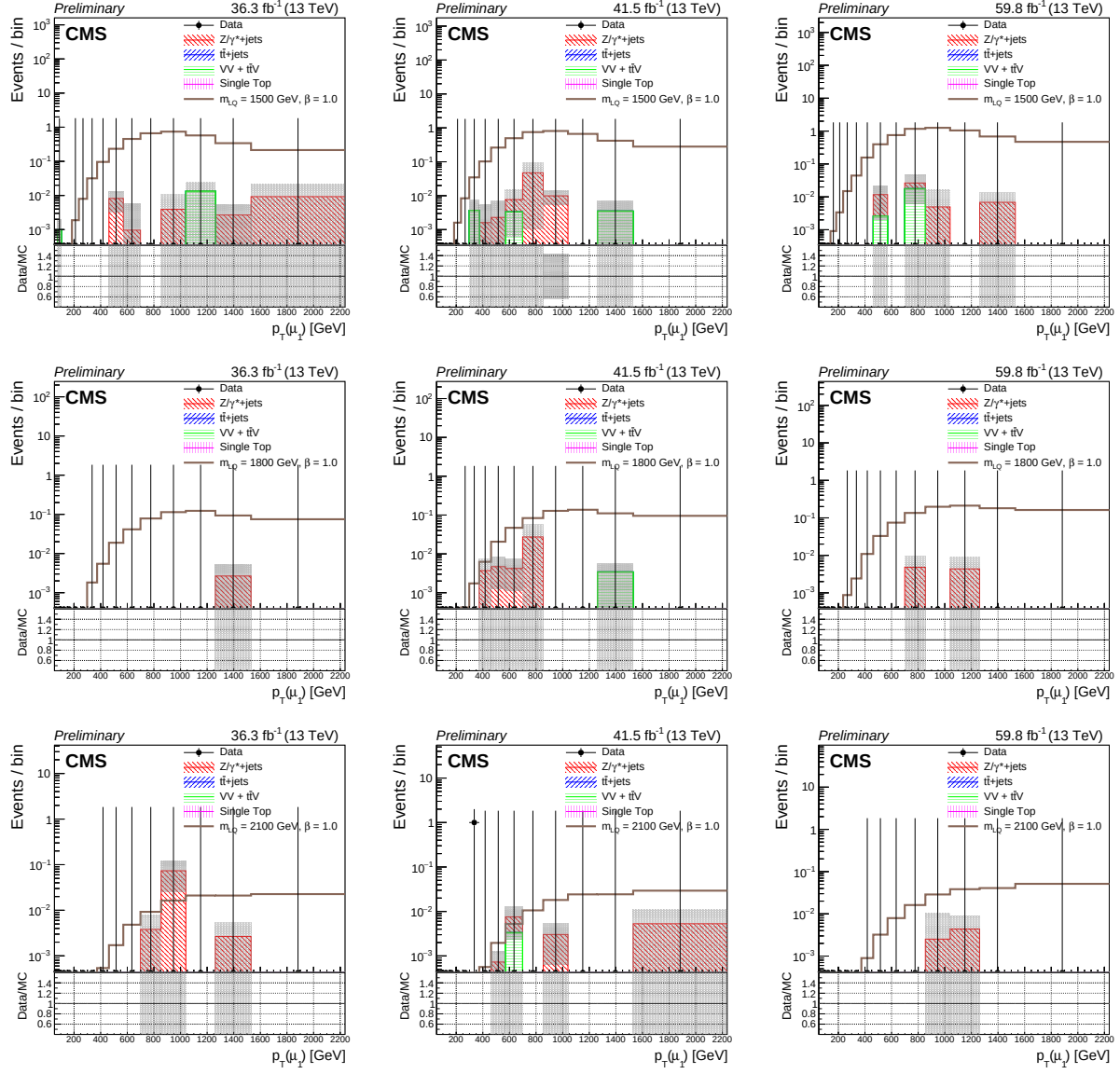


Figure 6.26: BDT input variable $p_T(\mu_1)$ at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptoquark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

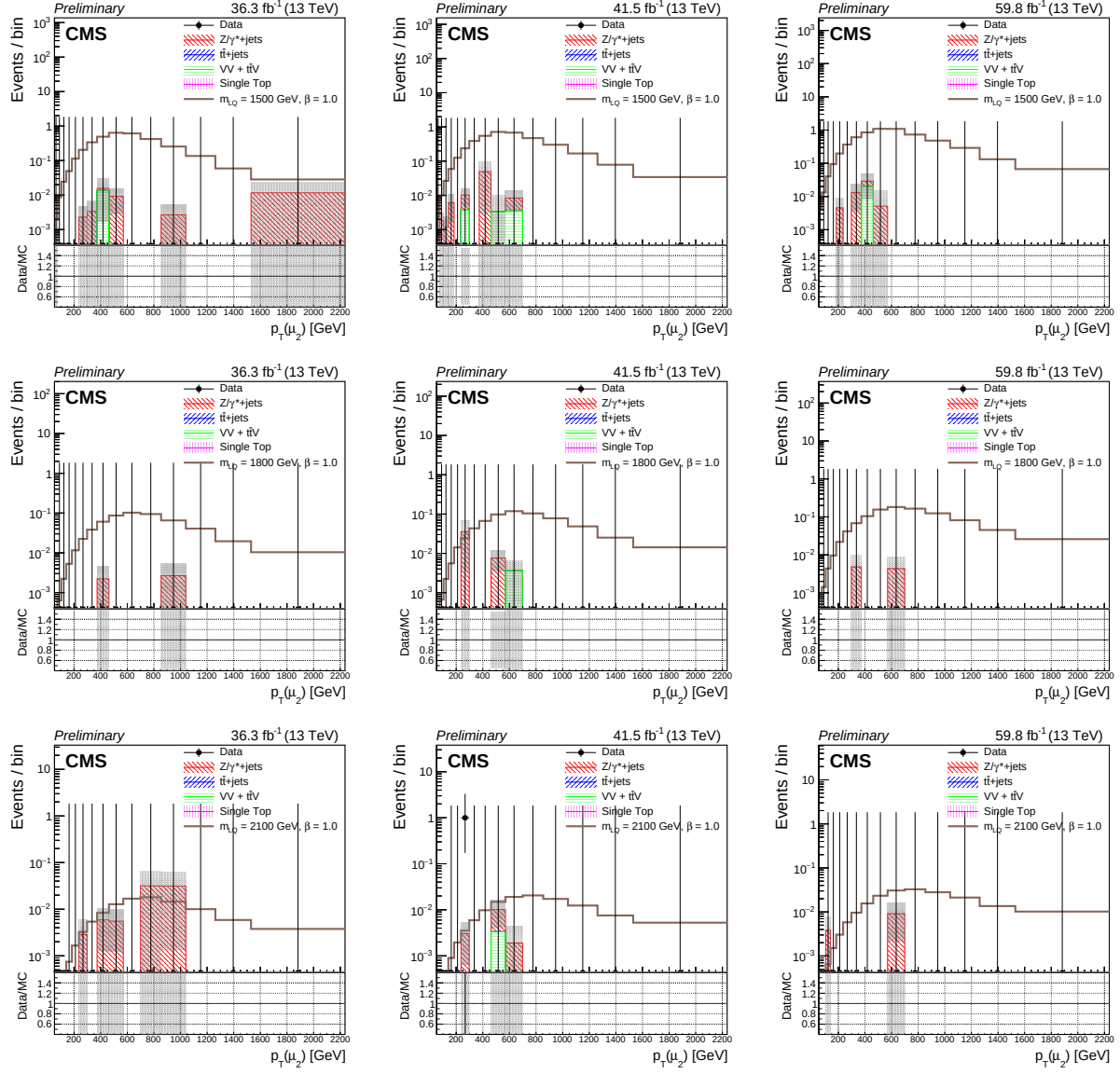


Figure 6.27: BDT input variable $p_T(\mu_2)$ at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptoquark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

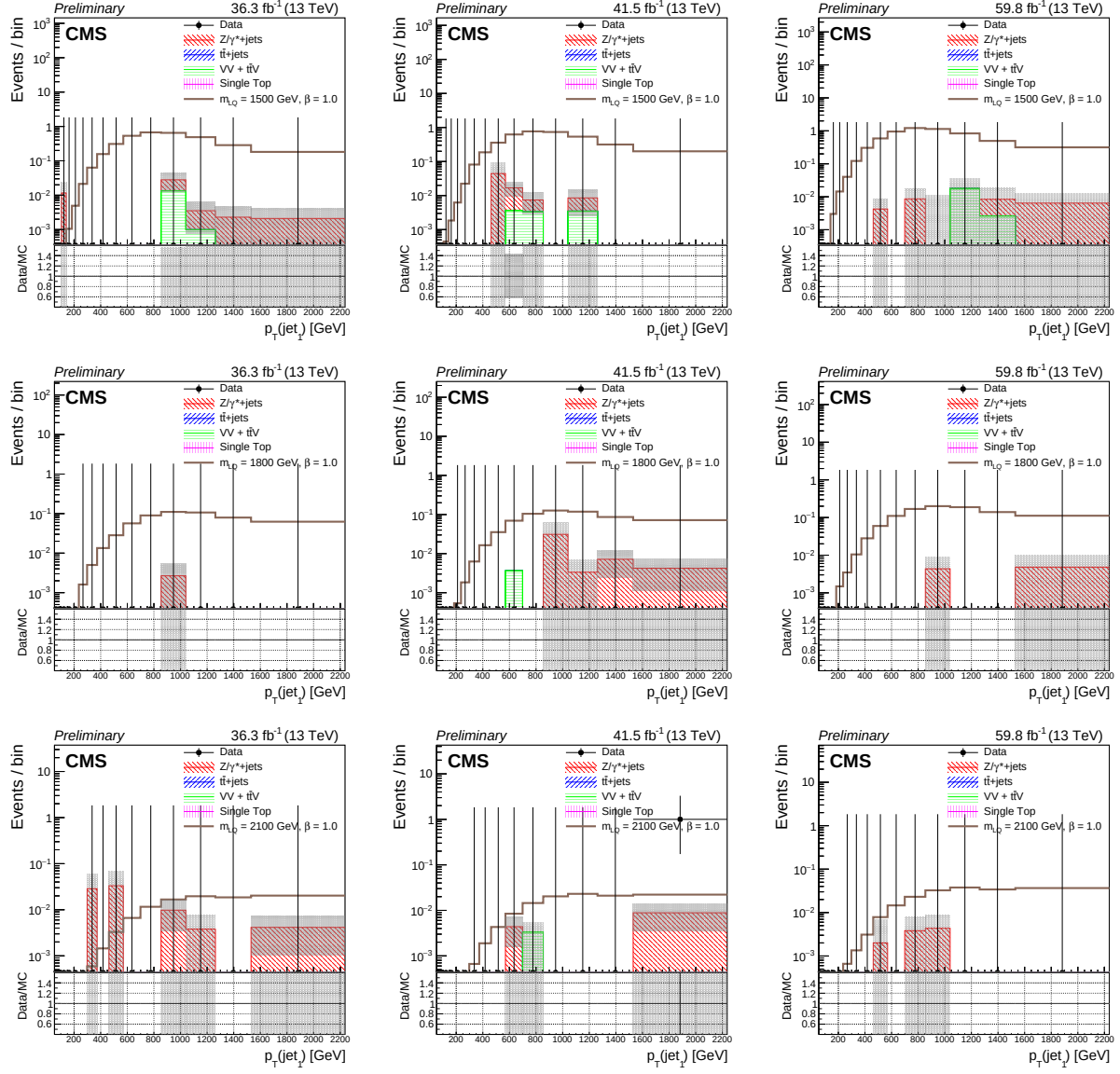


Figure 6.28: BDT input variable $p_T(\text{jet}_1)$ at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptoquark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

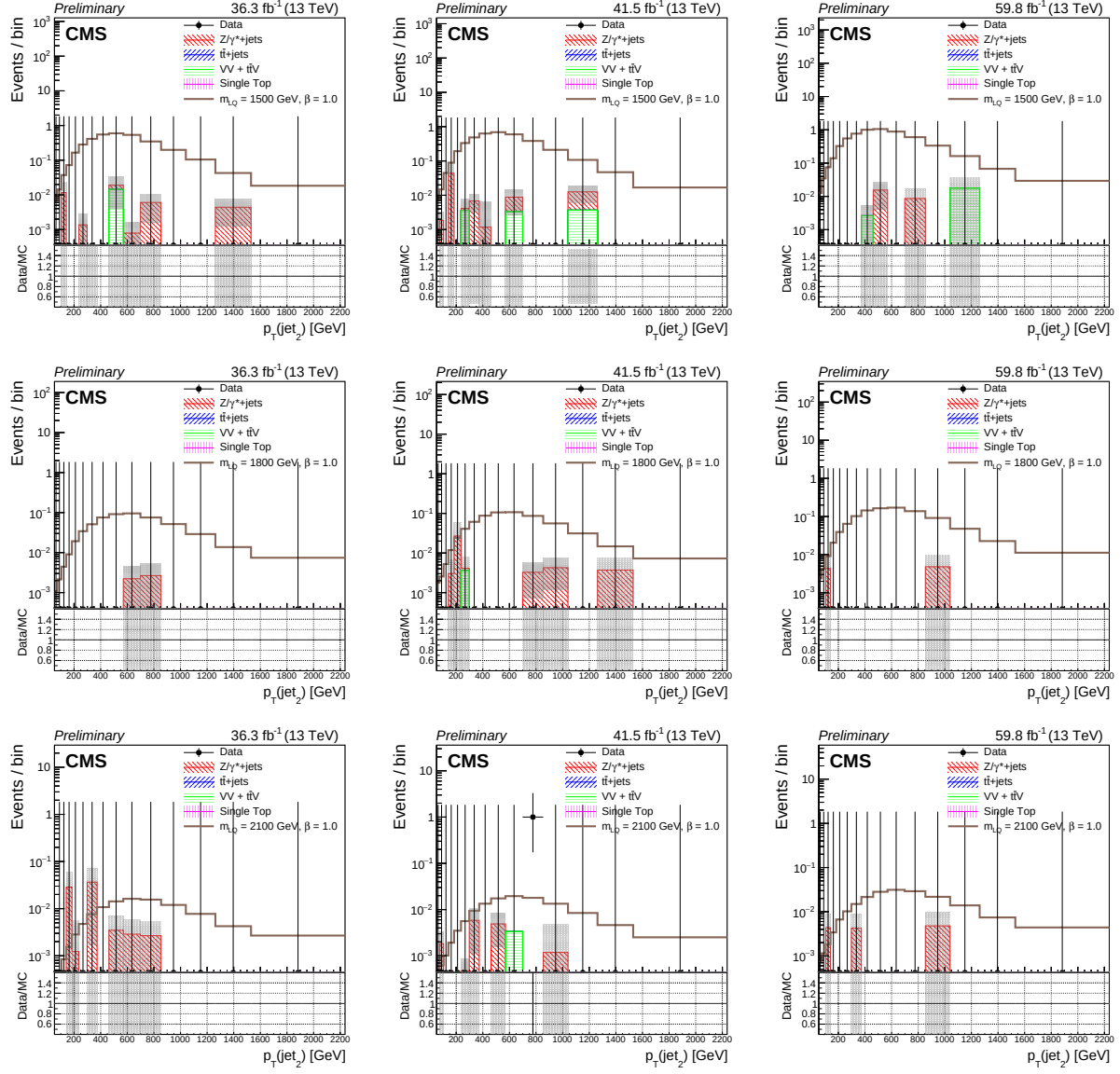


Figure 6.29: BDT input variable $p_T(\text{jet}_2)$ at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptoquark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

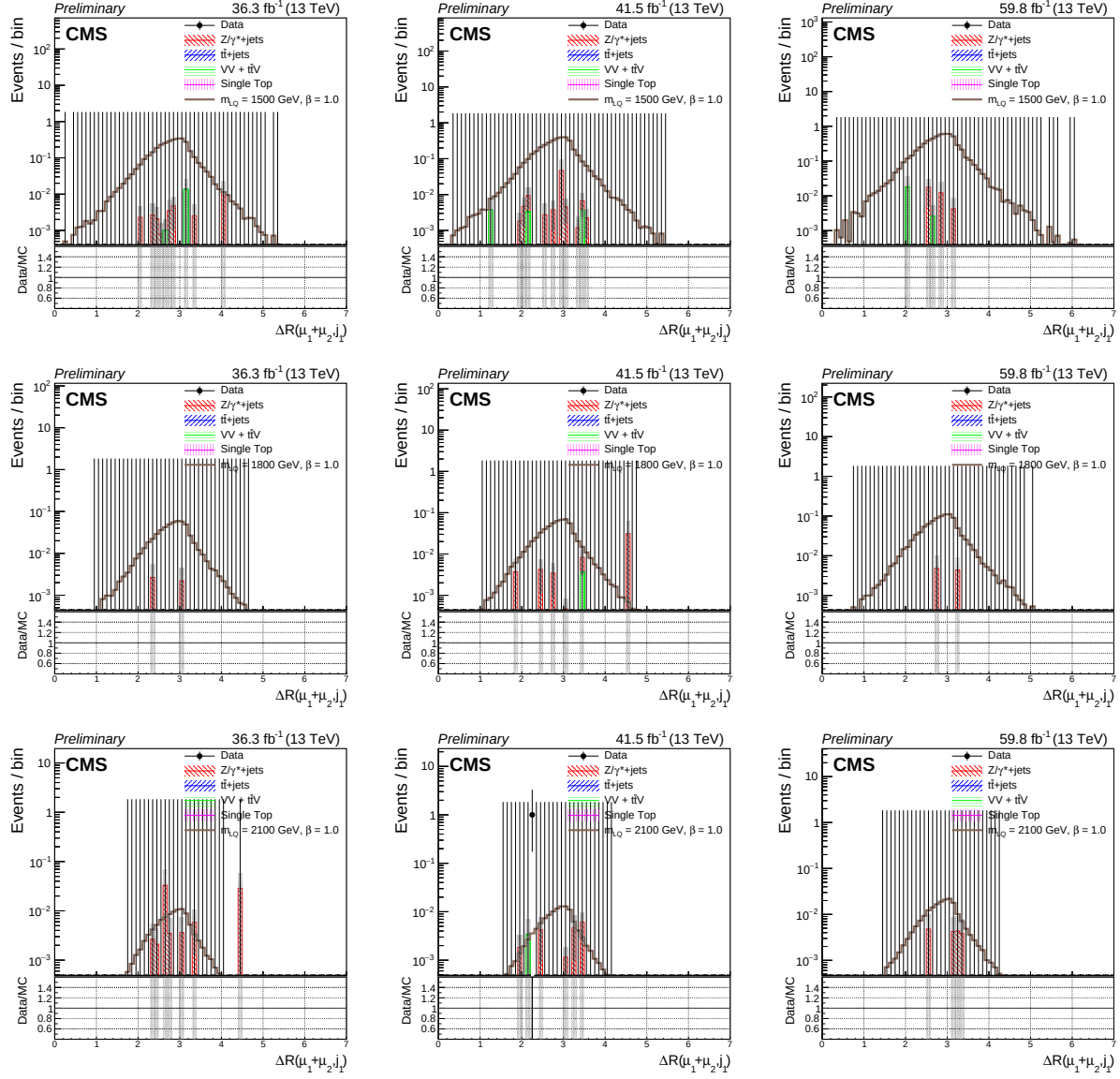


Figure 6.30: BDT input variable $\Delta R(M_{\mu\mu}, j_1)$ at final selection in 2016 (left), 2017 (middle), and 2018 (right) simulation. Final selection cuts correspond to 1500 GeV (top), 1800 GeV (middle), and 2100 GeV (bottom) leptoquark signal samples. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

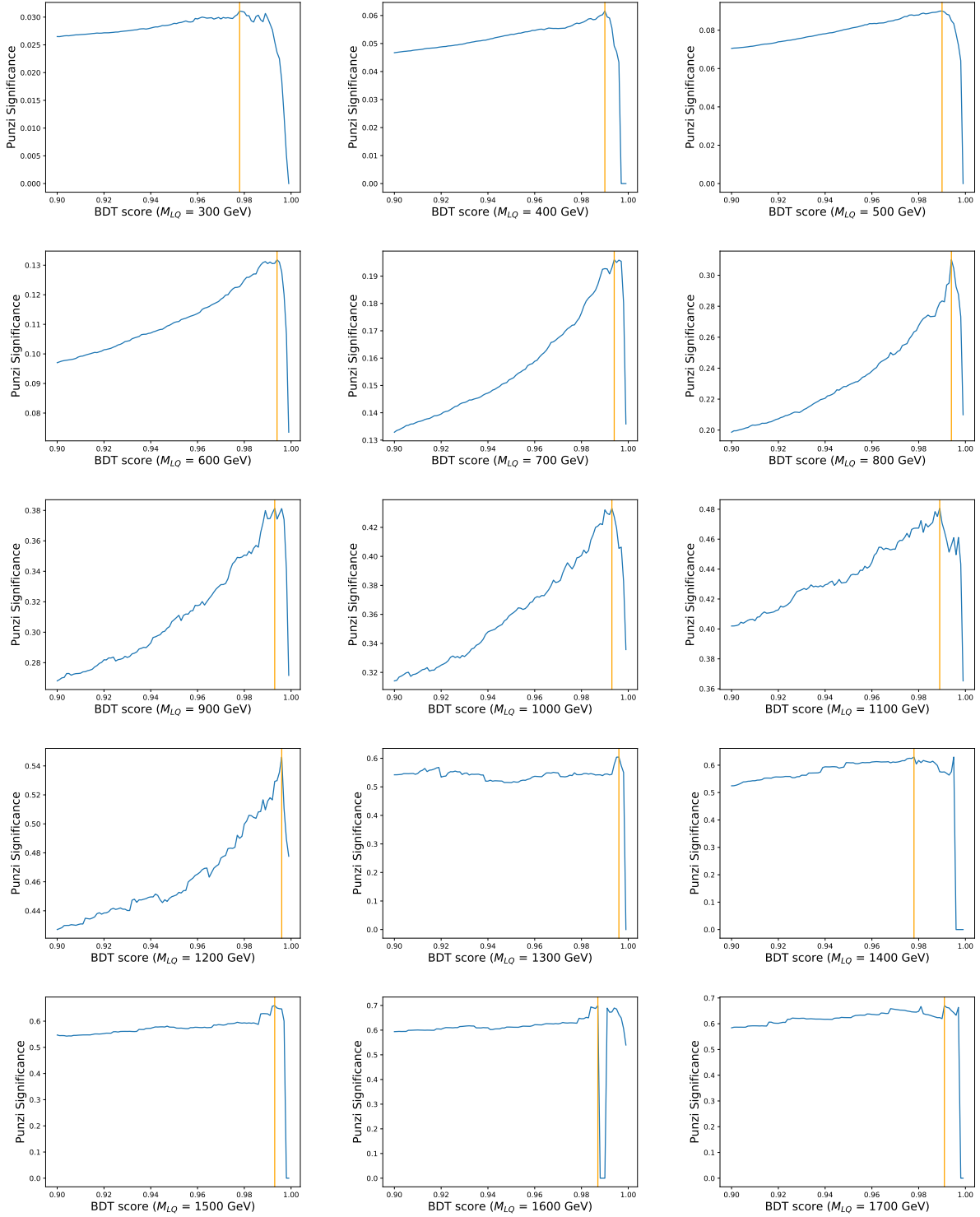


Figure 6.31: The Punzi significance as a function of the BDT score (blue) corresponding to BDT trainings on 300 to 1700 GeV leptquark signal samples. The optimized cut on the BDT score is marked with a vertical line (orange).

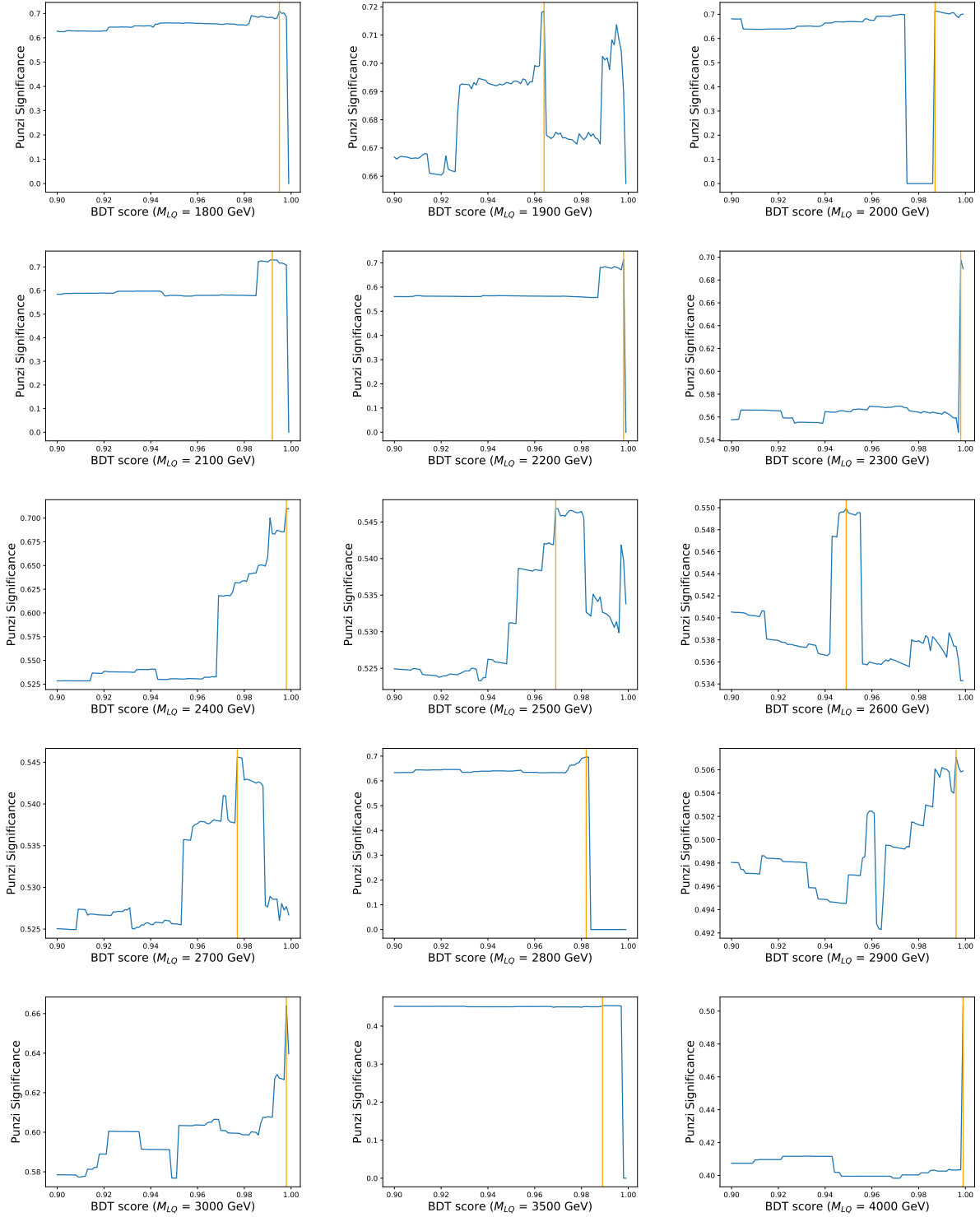


Figure 6.32: The Punzi significance as a function of the BDT score (blue) for corresponding to BDT trainings on 1800 to 4000 GeV leptquark signal samples. The optimized cut on the BDT score is marked with a vertical line (orange).

6.6 Systematic uncertainties

Sources of systematic uncertainty are bulleted, below, with a detailed description for how each systematic is estimated.

- **Jet Energy Scale and Resolution** - Uncertainties on JES and JER are estimated by shifting the corrections up and down by one standard deviation, provided by the JME POG, and taking the difference in shape between the shifted and nominal distributions as the systematic uncertainty.
- **Muon Momentum Scale** - Uncertainty on MES calibration with the Rochester method originates from several sources. Statistical uncertainty is estimated with the standard deviation of 100 pre-generated statistical replicas, provided in the RoccoR package [36]. Other uncertainty sources associated with corrections to the reference model MC used to derive the Rochester corrections (“Zpt,” “Ewk,” “deltaM,” and “Ewk2”) are available as sets of variations in the RoccoR package. Each uncertainty is estimated by taking the difference between the varied and central muon p_T . The quadrature sum of all the uncertainties (including statistical) is taken as the total. To propagate this uncertainty to final results, the analysis is repeated with muon p_T (below 200 GeV) shifted up and down by the total uncertainty, and the difference between the shifted and nominal distributions is taken as the systematic uncertainty on MES from Rochester corrections.

For high- p_T muons, the GE method is used to estimate uncertainty on MES bias. A detailed study of the estimation and assignment is provided in Appendix A.

- **Muon Momentum Resolution** - Uncertainty on MER from Rochester corrections is factored into the MES uncertainty (detailed above). For the additional resolution smearing, an uncertainty of 10 % on MER is obtained by varying the binning and fit window when measuring the resolution in MC and data at the Z mass. To propagate

this resolution uncertainty to final results, a muon p - and η -dependent smearing is applied in the same manner as the MER corrections detailed in Section 6.2. Muon momenta are corrected like $p \rightarrow p(1 + \text{Gauss}(0, \sigma(p, \eta)0.46))$, where the 0.46 factor corresponds to a 10% shift uncertainty, and $\sigma(p, \eta)$ is the same momentum resolution parametrization as in Section 6.2. The analysis is then repeated with the shifted momenta, and the difference between the shifted and nominal distributions is taken as the systematic uncertainty on MER.

- **Muon Reconstruction, Identification, Isolation, and Trigger Efficiency** - Uncertainty on muon efficiency is estimated by shifting the muon efficiency scale factors up and down by their uncertainties, provided by the Muon POG, and taking the difference between the shifted and nominal distributions as the systematic uncertainty.
- **B-Jet Identification Efficiency** - Uncertainty on the b-jet identification efficiency is estimated by shifting the efficiency scale factors up and down by their uncertainty, provided the BTV POG, and taking the difference in shape between the shifted and nominal distributions as the systematic uncertainty.
- **Prefire Weighting** - Uncertainty on the L1 prefire weighting in 2016 and 2017 is estimated by shifting the weights up and down by their uncertainty and taking the difference between the shifted and nominal distributions as the systematic uncertainty.
- **Top p_T Reweighting** - Uncertainty on the top p_T NNLO-reweighting is estimated by shifting the top p_T weight down to 1 and up the square of the nominal top p_T event weight, and taking the difference between the shifted and nominal distributions as the systematic uncertainty.
- **Background Normalization** - Uncertainties in the $Z/\gamma^* + \text{jets}$, $t\bar{t}$, and diboson MC normalization factors are obtained by varying results up and down by the statistical uncertainties of the scale factors.

- Background Shape** - Uncertainties in $Z/\gamma^* + \text{jets}$, $t\bar{t}$, and diboson shape are determined by varying the factorization and renormalization scale in simulation by half and twice their nominal values, which are embedded in the MC samples as weights (in total, there are eight renormalization and factorization scale variation weights, respectively: 0.5 and 0.5, 0.5 and 1.0, 0.5 and 2.0, 1.0 and 0.5, 1.0 and 2.0, 2.0 and 0.5, 2.0 and 1.0, 2.0 and 2.0). The $Z/\gamma^* + \text{jets}$, $t\bar{t}$, and diboson background normalization SFs are recomputed at preselection, within the CRs defined in Section 6.4.1, with the scale-varied weights applied. At final selection for each leptoquark mass, event yields using the scale-varied weights (and corresponding scale-varied normalization SFs) are compared to the event yields of the central samples in the analysis by taking the percent difference. The greatest percent difference is selected as the total shape uncertainty.
- Luminosity** - There are year-to-year uncorrelated, fully-correlated, and partially-correlated sources of uncertainty on the determination of the integrated luminosities [49][50][51] of pp collisions at $\sqrt{s} = 13 \text{ TeV}$ in 2016, 2017, and 2018 datasets. Uncorrelated uncertainties are 1.0 %, 2.0 %, and 1.5 % in 2016, 2017, and 2018, respectively. Fully-correlated uncertainties are 0.6 %, 0.9 %, and 2.0 % in 2016, 2017, and 2018, respectively. Partially-correlated uncertainties are only correlated between 2017 and 2018, and are 0.6 % and 0.2 % in 2017 and 2018, respectively.
- Pile Up** - Uncertainty on the total inelastic proton-proton cross section of $69\,200 \mu\text{b}$ used to model pileup is 4.6 % [52].

Figure 6.33 shows the total systematic uncertainty on signal and background MC for each year as a function of leptoquark signal mass. Table 6.28 lists the range of each systematic uncertainty on signal and background in each year, while Tables 6.29–6.58 show the contributions to the total uncertainty from each source of systematic in each year, for a given leptoquark mass.

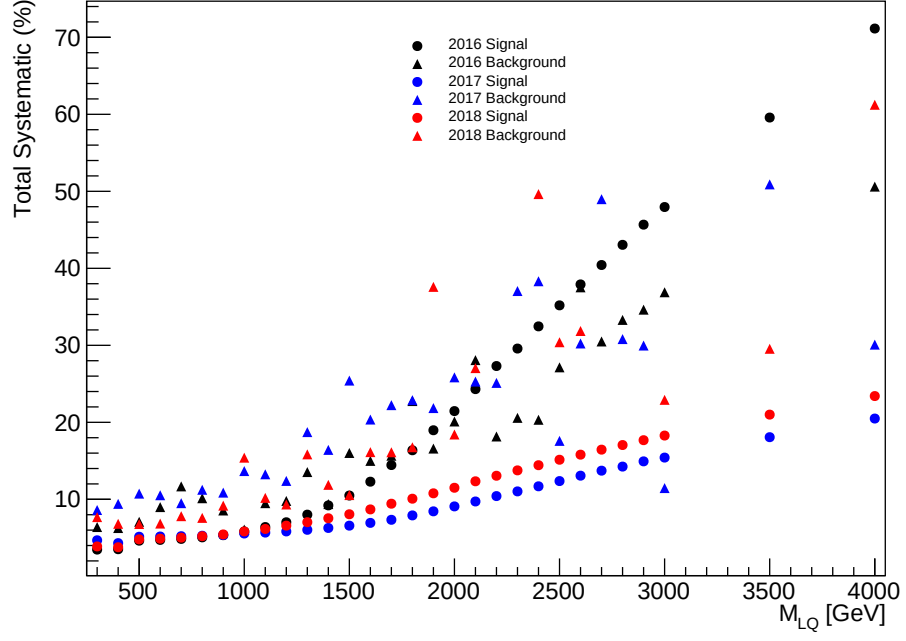


Figure 6.33: The total systematic uncertainty at each signal mass point in signal and background MC for 2016, 2017, and 2018.

Table 6.28: Range of systematic uncertainties on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018.

Systematic	2016 (min-max)		2017 (min-max)		2018 (min-max)	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
b-jet tagging efficiency	0.96–7.4	0.3–22.79	1.92–6.68	0.39–6.97	0.9–14.97	0.37–15.31
Jet energy resolution	0.0–0.14	0.25–9.39	0.0–0.21	0.31–13.2	0.0–0.17	0.17–20.66
Jet energy scale	0.02–0.74	0.58–10.79	0.01–0.64	0.56–16.08	0.02–1.24	0.7–51.76
Luminosity	1.17–1.17	0.14–0.44	2.27–2.27	0.27–0.91	2.51–2.51	0.33–0.65
Muon energy resolution	0.0–0.05	0.08–7.64	0.0–0.03	0.09–12.62	0.0–0.06	0.15–31.86
Muon energy scale	0.81–242.68	0.81–242.68	2.85–242.4	2.85–242.4	0.76–245.47	0.76–245.47
Muon identification	1.57–1.64	0.07–0.55	0.67–0.74	0.11–0.38	0.47–0.52	0.07–0.16
Muon isolation	0.31–0.31	0.03–0.18	0.23–0.24	0.03–0.15	0.16–0.17	0.05–0.08
Muon reconstruction	0.55–70.62	0.16–33.9	0.38–18.78	0.1–3.08	0.31–17.37	0.08–2.03
Muon trigger	0.05–0.78	0.02–0.52	0.05–0.91	0.02–0.83	0.02–0.3	0.03–0.08
PDF	8.28–100.0	2.25–9.78	7.78–100.0	2.71–12.67	9.72–100.0	2.83–13.78
Pileup	0.01–0.18	0.35–15.97	0.06–0.39	0.13–8.42	0.03–0.34	0.13–8.46
Prefire reweighting	0.59–0.83	0.19–3.76	0.56–0.84	0.15–2.39	–	–
Top p_T reweighting	0.0–0.0	0.14–1.7	0.0–0.0	0.26–2.48	0.0–0.0	0.68–2.87
TT normalization	–	0.07–1.31	–	0.28–1.06	–	0.23–0.92
TT shape	–	0.0–12.03	–	1.73–15.59	–	1.64–17.9
VV normalization	–	0.1–5.66	–	0.19–2.34	–	0.21–1.66
VV shape	–	0.04–6.06	–	0.02–5.99	–	0.09–2.98
Z normalization	–	0.55–15.37	–	0.31–11.31	–	0.33–10.16
Z shape	–	0.2–18.37	–	0.2–4.55	–	0.21–9.26

Table 6.29: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 300$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	0.96	0.3	1.92	0.42	0.9	0.38
GE	0.02	0.01	0.02	0.01	0.02	0.02
JER	0.1	0.3	0.12	0.57	0.16	0.44
JES	0.74	0.74	0.64	0.93	1.24	1.19
LUMI16Uncorr	1.0	0.11	–	–	–	–
LUMI1718	–	–	0.6	0.07	0.2	0.05
LUMI17Uncorr	–	–	2.0	0.24	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.21
LUMICorr	0.6	0.08	0.9	0.1	2.0	0.25
MER	0.03	0.08	0.02	0.09	0.06	0.27
MES	0.45	0.81	2.41	2.85	0.66	0.76
MUONHLT	0.05	0.02	0.05	0.02	0.02	0.03
MUONID	1.57	0.12	0.74	0.13	0.47	0.07
MUONISO	0.31	0.03	0.24	0.03	0.17	0.05
MUONRECO	0.55	0.16	0.38	0.1	0.31	0.08
PDF	8.28	2.25	7.78	2.71	9.72	2.83
PREFIRE	0.73	0.19	0.69	0.15	–	–
PU	0.02	0.35	0.12	0.15	0.05	0.13
SHAPETT	–	1.58	–	1.73	–	1.66
SHAPEVV	–	0.04	–	0.02	–	0.09
SHAPEZ	–	0.25	–	0.2	–	0.22
TOPPT	–	1.38	–	1.76	–	1.7
TTNORM	–	1.31	–	1.06	–	0.92
VVNORM	–	0.2	–	0.2	–	0.21
ZNORM	–	0.55	–	0.31	–	0.33
Total	8.66	3.63	8.77	4.94	10.19	4.15

Table 6.30: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 400$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	1.05	0.3	2.04	0.42	1.04	0.38
GE	0.02	0.01	0.02	0.01	0.02	0.02
JER	0.14	0.25	0.21	0.54	0.17	0.44
JES	0.4	0.66	0.45	0.94	0.62	1.23
LUMI16Uncorr	1.0	0.11	–	–	–	–
LUMI1718	–	–	0.6	0.07	0.2	0.05
LUMI17Uncorr	–	–	2.0	0.24	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.21
LUMICorr	0.6	0.08	0.9	0.1	2.0	0.26
MER	0.03	0.09	0.02	0.1	0.04	0.27
MES	0.25	0.8	1.27	2.89	0.36	0.78
MUONHLT	0.07	0.02	0.07	0.02	0.03	0.03
MUONID	1.58	0.12	0.72	0.13	0.48	0.07
MUONISO	0.31	0.03	0.24	0.03	0.17	0.05
MUONRECO	0.69	0.16	0.47	0.1	0.37	0.08
PDF	8.28	2.26	7.78	2.72	9.72	2.84
PREFIRE	0.79	0.2	0.75	0.15	–	–
PU	0.04	0.36	0.1	0.15	0.08	0.13
SHAPETT	–	1.58	–	1.73	–	1.67
SHAPEVV	–	0.04	–	0.02	–	0.09
SHAPEZ	–	0.24	–	0.2	–	0.22
TOPPT	–	1.38	–	1.77	–	1.71
TTNORM	–	1.31	–	1.06	–	0.92
VVNORM	–	0.2	–	0.2	–	0.21
ZNORM	–	0.55	–	0.31	–	0.33
Total	8.66	3.62	8.55	4.97	10.14	4.18

Table 6.31: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 500$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	1.2	0.31	2.15	0.39	1.28	0.37
GE	0.04	0.03	0.04	0.02	0.04	0.04
JER	0.06	0.27	0.13	0.38	0.06	0.35
JES	0.23	0.71	0.26	0.73	0.31	1.04
LUMI16Uncorr	1.0	0.11	–	–	–	–
LUMI1718	–	–	0.6	0.07	0.2	0.05
LUMI17Uncorr	–	–	2.0	0.24	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.22
LUMICorr	0.6	0.08	0.9	0.1	2.0	0.26
MER	0.02	0.17	0.02	0.17	0.05	0.19
MES	0.14	0.83	0.73	3.02	0.18	0.81
MUONHLT	0.1	0.02	0.1	0.02	0.04	0.03
MUONID	1.59	0.12	0.72	0.13	0.48	0.07
MUONISO	0.31	0.03	0.24	0.03	0.16	0.05
MUONRECO	0.89	0.17	0.58	0.11	0.45	0.09
PDF	8.28	2.34	7.87	2.94	9.72	3.07
PREFIRE	0.8	0.24	0.79	0.19	–	–
PU	0.1	0.4	0.06	0.13	0.11	0.17
SHAPETT	–	1.6	–	1.8	–	1.72
SHAPEVV	–	0.04	–	0.02	–	0.09
SHAPEZ	–	0.2	–	0.22	–	0.23
TOPPT	–	1.47	–	1.91	–	1.84
TTNORM	–	1.3	–	1.05	–	0.91
VVNORM	–	0.21	–	0.21	–	0.22
ZNORM	–	0.56	–	0.34	–	0.37
Total	8.69	3.74	8.6	5.19	10.15	4.36

Table 6.32: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 600$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	1.35	0.3	2.25	0.44	1.57	0.37
GE	0.04	0.06	0.04	0.05	0.04	0.07
JER	0.03	0.47	0.07	0.4	0.06	0.17
JES	0.14	0.68	0.16	0.67	0.25	0.83
LUMI16Uncorr	1.0	0.12	–	–	–	–
LUMI1718	–	–	0.6	0.08	0.2	0.05
LUMI17Uncorr	–	–	2.0	0.26	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.23
LUMICorr	0.6	0.08	0.9	0.11	2.0	0.28
MER	0.01	0.11	0.02	0.25	0.02	0.15
MES	0.09	0.95	0.43	3.09	0.12	0.72
MUONHLT	0.14	0.02	0.13	0.02	0.06	0.03
MUONID	1.59	0.13	0.71	0.12	0.49	0.08
MUONISO	0.31	0.03	0.24	0.04	0.16	0.05
MUONRECO	1.15	0.2	0.69	0.13	0.55	0.1
PDF	8.28	2.53	7.87	3.42	9.72	3.57
PREFIRE	0.83	0.33	0.8	0.29	–	–
PU	0.18	0.53	0.16	0.18	0.08	0.26
SHAPETT	–	2.57	–	1.81	–	1.64
SHAPEVV	–	0.04	–	0.04	–	0.1
SHAPEZ	–	0.35	–	0.32	–	0.21
TOPPT	–	1.57	–	2.09	–	2.01
TTNORM	–	1.27	–	1.03	–	0.89
VVNORM	–	0.24	–	0.24	–	0.24
ZNORM	–	0.68	–	0.41	–	0.45
Total	8.74	4.46	8.61	5.6	10.19	4.71

Table 6.33: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 700$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	1.53	0.49	2.34	0.66	1.91	0.51
GE	0.05	0.08	0.05	0.07	0.05	0.09
JER	0.01	0.51	0.05	0.31	0.03	0.28
JES	0.1	0.58	0.12	0.56	0.17	0.7
LUMI16Uncorr	1.0	0.13	–	–	–	–
LUMI1718	–	–	0.6	0.08	0.2	0.05
LUMI17Uncorr	–	–	2.0	0.28	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.24
LUMICorr	0.6	0.09	0.9	0.12	2.0	0.3
MER	0.05	0.24	0.01	0.22	0.01	0.19
MES	0.06	1.27	0.27	3.01	0.07	0.73
MUONHLT	0.19	0.02	0.18	0.02	0.08	0.03
MUONID	1.59	0.15	0.7	0.12	0.49	0.09
MUONISO	0.31	0.04	0.24	0.04	0.16	0.05
MUONRECO	1.44	0.24	0.81	0.15	0.66	0.12
PDF	8.28	2.83	7.87	4.11	9.72	4.2
PREFIRE	0.82	0.46	0.81	0.42	–	–
PU	0.02	0.58	0.14	0.2	0.06	0.19
SHAPETT	–	3.55	–	1.93	–	1.84
SHAPEVV	–	0.05	–	0.04	–	0.12
SHAPEZ	–	0.43	–	0.32	–	0.27
TOPPT	–	1.64	–	2.22	–	2.14
TTNORM	–	1.25	–	1.01	–	0.87
VVNORM	–	0.29	–	0.27	–	0.29
ZNORM	–	0.72	–	0.51	–	0.54
Total	8.81	5.37	8.64	6.11	10.26	5.33

Table 6.34: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 800$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	1.69	0.62	2.42	0.92	2.31	0.74
GE	0.07	0.16	0.07	0.15	0.07	0.17
JER	0.01	1.57	0.05	0.46	0.01	0.26
JES	0.06	0.74	0.09	0.85	0.13	0.78
LUMI16Uncorr	1.0	0.15	–	–	–	–
LUMI1718	–	–	0.6	0.09	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.3	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.26
LUMICorr	0.6	0.1	0.9	0.13	2.0	0.32
MER	0.0	0.27	0.02	0.55	0.02	0.4
MES	0.04	0.75	0.16	3.03	0.06	0.8
MUONHLT	0.24	0.03	0.22	0.02	0.1	0.03
MUONID	1.6	0.17	0.7	0.11	0.5	0.1
MUONISO	0.31	0.04	0.24	0.05	0.16	0.06
MUONRECO	1.86	0.29	0.94	0.18	0.81	0.14
PDF	8.28	3.17	7.87	4.75	10.59	4.82
PREFIRE	0.83	0.63	0.83	0.56	–	–
PU	0.11	0.52	0.14	0.35	0.04	0.31
SHAPETT	–	4.59	–	3.27	–	3.16
SHAPEVV	–	0.04	–	0.04	–	0.19
SHAPEZ	–	0.39	–	0.37	–	0.31
TOPPT	–	1.64	–	2.3	–	2.19
TTNORM	–	1.21	–	0.98	–	0.84
VVNORM	–	0.32	–	0.31	–	0.36
ZNORM	–	0.76	–	0.65	–	0.64
Total	8.93	6.4	8.67	7.21	11.17	6.46

Table 6.35: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 900$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	1.86	0.78	2.53	1.19	2.73	0.99
GE	0.12	0.18	0.12	0.16	0.12	0.18
JER	0.01	0.54	0.02	0.72	0.06	0.78
JES	0.07	0.77	0.09	0.89	0.12	1.32
LUMI16Uncorr	1.0	0.16	–	–	–	–
LUMI1718	–	–	0.6	0.1	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.33	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.27
LUMICorr	0.6	0.11	0.9	0.14	2.0	0.34
MER	0.01	0.34	0.01	0.36	0.02	0.66
MES	0.02	0.8	0.11	3.27	0.02	1.1
MUONHLT	0.29	0.03	0.27	0.03	0.12	0.03
MUONID	1.6	0.2	0.69	0.11	0.5	0.11
MUONISO	0.31	0.05	0.23	0.05	0.16	0.06
MUONRECO	2.4	0.34	1.12	0.21	1.0	0.16
PDF	8.28	3.57	7.87	5.44	11.96	5.4
PREFIRE	0.8	0.79	0.84	0.71	–	–
PU	0.06	0.5	0.16	0.43	0.04	0.3
SHAPETT	–	5.77	–	4.99	–	4.6
SHAPEVV	–	0.05	–	0.06	–	0.21
SHAPEZ	–	0.33	–	0.25	–	0.42
TOPPT	–	1.65	–	2.34	–	2.2
TTNORM	–	1.19	–	0.95	–	0.82
VVNORM	–	0.37	–	0.36	–	0.41
ZNORM	–	0.72	–	0.74	–	0.82
Total	9.09	7.37	8.73	8.72	12.57	7.89

Table 6.36: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1000$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	2.07	1.0	2.63	1.49	3.2	1.26
GE	0.23	0.28	0.23	0.26	0.23	0.28
JER	0.01	0.44	0.02	0.58	0.01	1.39
JES	0.06	1.13	0.06	0.92	0.11	1.81
LUMI16Uncorr	1.0	0.18	–	–	–	–
LUMI1718	–	–	0.6	0.11	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.36	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.28
LUMICorr	0.6	0.12	0.9	0.16	2.0	0.35
MER	0.02	0.5	0.0	0.23	0.02	0.46
MES	0.01	1.18	0.08	3.61	0.05	1.04
MUONHLT	0.33	0.03	0.33	0.03	0.14	0.03
MUONID	1.61	0.23	0.69	0.12	0.5	0.11
MUONISO	0.31	0.06	0.23	0.06	0.16	0.06
MUONRECO	3.01	0.39	1.35	0.25	1.23	0.19
PDF	9.43	3.95	9.26	6.13	13.41	6.03
PREFIRE	0.82	0.94	0.82	0.83	–	–
PU	0.09	0.8	0.22	0.5	0.03	0.34
SHAPETT	–	6.87	–	6.35	–	6.38
SHAPEVV	–	0.09	–	0.08	–	0.26
SHAPEZ	–	0.41	–	0.33	–	0.39
TOPPT	–	1.62	–	2.35	–	2.25
TTNORM	–	1.15	–	0.91	–	0.79
VVNORM	–	0.43	–	0.42	–	0.43
ZNORM	–	0.82	–	0.85	–	1.03
Total	10.35	8.59	10.05	10.15	14.08	9.63

Table 6.37: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1100$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	2.28	1.37	2.76	1.77	3.63	1.58
GE	0.28	0.46	0.28	0.44	0.28	0.46
JER	0.01	0.82	0.01	0.9	0.02	0.63
JES	0.05	1.66	0.05	0.93	0.11	1.88
LUMI16Uncorr	1.0	0.2	–	–	–	–
LUMI1718	–	–	0.6	0.12	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.38	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.28
LUMICorr	0.6	0.13	0.9	0.17	2.0	0.35
MER	0.04	0.97	0.0	0.41	0.01	0.54
MES	0.01	1.4	0.04	3.29	0.02	1.21
MUONHLT	0.39	0.04	0.38	0.04	0.16	0.04
MUONID	1.61	0.27	0.69	0.15	0.5	0.11
MUONISO	0.31	0.07	0.23	0.06	0.16	0.06
MUONRECO	3.9	0.46	1.58	0.28	1.54	0.21
PDF	9.51	4.44	10.06	6.72	15.17	6.59
PREFIRE	0.79	1.13	0.81	0.95	–	–
PU	0.06	1.17	0.14	0.71	0.12	0.37
SHAPETT	–	8.15	–	7.58	–	7.46
SHAPEVV	–	0.15	–	0.11	–	0.28
SHAPEZ	–	0.8	–	0.46	–	0.53
TOPPT	–	1.62	–	2.37	–	2.27
TTNORM	–	1.13	–	0.88	–	0.77
VVNORM	–	0.49	–	0.51	–	0.47
ZNORM	–	0.62	–	1.02	–	1.32
Total	10.76	10.14	10.86	11.32	15.89	10.77

Table 6.38: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1200$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	2.49	1.56	2.87	2.03	4.19	1.8
GE	0.41	0.61	0.41	0.59	0.41	0.61
JER	0.0	1.7	0.01	1.27	0.0	0.73
JES	0.05	2.86	0.06	1.97	0.08	2.06
LUMI16Uncorr	1.0	0.21	–	–	–	–
LUMI1718	–	–	0.6	0.13	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.42	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.3
LUMICorr	0.6	0.14	0.9	0.19	2.0	0.37
MER	0.01	0.76	0.01	0.86	0.01	0.94
MES	0.01	1.11	0.04	3.3	0.01	1.09
MUONHLT	0.42	0.04	0.43	0.04	0.18	0.04
MUONID	1.61	0.28	0.69	0.18	0.5	0.12
MUONISO	0.31	0.07	0.23	0.07	0.16	0.07
MUONRECO	4.75	0.54	1.86	0.32	1.84	0.24
PDF	10.19	4.77	10.06	7.32	17.69	7.14
PREFIRE	0.78	1.19	0.81	1.05	–	–
PU	0.08	1.11	0.23	1.04	0.24	0.69
SHAPETT	–	9.2	–	8.76	–	8.48
SHAPEVV	–	0.17	–	0.17	–	0.23
SHAPEZ	–	0.61	–	0.63	–	0.54
TOPPT	–	1.57	–	2.37	–	2.27
TTNORM	–	1.05	–	0.84	–	0.75
VVNORM	–	0.54	–	0.62	–	0.43
ZNORM	–	1.28	–	1.07	–	1.49
Total	11.73	11.49	10.94	12.76	18.46	11.94

Table 6.39: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1300$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	2.72	1.88	3.05	2.44	4.71	2.12
GE	0.53	0.77	0.53	0.75	0.53	0.77
JER	0.0	0.63	0.02	2.3	0.01	0.9
JES	0.04	2.23	0.05	3.16	0.07	2.25
LUMI16Uncorr	1.0	0.22	–	–	–	–
LUMI1718	–	–	0.6	0.13	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.45	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.31
LUMICorr	0.6	0.14	0.9	0.2	2.0	0.39
MER	0.01	0.7	0.03	0.79	0.02	1.5
MES	0.01	1.28	0.04	3.93	0.02	2.76
MUONHLT	0.47	0.04	0.47	0.05	0.19	0.04
MUONID	1.62	0.27	0.69	0.21	0.5	0.11
MUONISO	0.31	0.07	0.23	0.08	0.16	0.07
MUONRECO	6.02	0.63	2.2	0.36	2.23	0.26
PDF	13.61	5.01	10.06	7.84	21.05	7.73
PREFIRE	0.77	1.26	0.8	1.22	–	–
PU	0.14	1.72	0.18	1.28	0.12	0.67
SHAPETT	–	9.69	–	9.43	–	9.65
SHAPEVV	–	0.17	–	0.25	–	0.21
SHAPEZ	–	0.74	–	0.98	–	0.75
TOPPT	–	1.56	–	2.35	–	2.36
TTNORM	–	1.02	–	0.81	–	0.74
VVNORM	–	0.57	–	0.77	–	0.43
ZNORM	–	1.46	–	1.09	–	1.48
Total	15.3	11.93	11.06	14.17	21.84	13.55

Table 6.40: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1400$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	2.94	2.25	3.2	2.61	5.27	2.59
GE	0.69	1.26	0.69	1.25	0.69	1.26
JER	0.01	1.48	0.01	1.29	0.01	1.16
JES	0.04	2.57	0.03	1.49	0.06	2.62
LUMI16Uncorr	1.0	0.24	–	–	–	–
LUMI1718	–	–	0.6	0.14	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.48	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.32
LUMICorr	0.6	0.15	0.9	0.22	2.0	0.4
MER	0.0	1.14	0.01	0.93	0.01	1.3
MES	0.0	1.18	0.01	3.15	0.01	1.79
MUONHLT	0.5	0.05	0.52	0.06	0.21	0.04
MUONID	1.62	0.32	0.68	0.23	0.51	0.11
MUONISO	0.31	0.08	0.23	0.08	0.16	0.07
MUONRECO	7.46	0.73	2.63	0.41	2.63	0.3
PDF	15.84	5.55	16.42	8.47	25.09	8.33
PREFIRE	0.75	1.41	0.8	1.34	–	–
PU	0.04	2.05	0.18	1.3	0.11	1.08
SHAPETT	–	9.4	–	9.6	–	10.44
SHAPEVV	–	0.21	–	0.35	–	0.22
SHAPEZ	–	0.89	–	1.1	–	0.9
TOPPT	–	1.53	–	2.33	–	2.36
TTNORM	–	0.94	–	0.76	–	0.7
VVNORM	–	0.61	–	0.8	–	0.46
ZNORM	–	1.83	–	1.42	–	1.82
Total	17.9	12.33	17.14	14.18	25.91	14.55

Table 6.41: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1500$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	3.17	2.44	3.36	2.89	5.72	2.75
GE	0.87	1.65	0.87	1.63	0.87	1.64
JER	0.01	2.07	0.01	1.54	0.02	1.65
JES	0.04	3.41	0.03	2.17	0.05	3.43
LUMI16Uncorr	1.0	0.26	–	–	–	–
LUMI1718	–	–	0.6	0.15	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.51	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.33
LUMICorr	0.6	0.16	0.9	0.23	2.0	0.41
MER	0.0	1.81	0.0	1.15	0.01	1.01
MES	0.0	1.31	0.02	3.3	0.0	2.42
MUONHLT	0.53	0.05	0.55	0.07	0.22	0.04
MUONID	1.62	0.34	0.68	0.25	0.51	0.11
MUONISO	0.31	0.09	0.23	0.09	0.16	0.07
MUONRECO	8.92	0.83	3.11	0.46	3.16	0.31
PDF	17.74	5.81	20.19	8.88	29.32	9.02
PREFIRE	0.74	1.48	0.81	1.51	–	–
PU	0.14	2.26	0.17	1.7	0.12	0.53
SHAPETT	–	10.96	–	9.89	–	11.89
SHAPEVV	–	0.17	–	0.45	–	0.26
SHAPEZ	–	1.05	–	0.84	–	0.9
TOPPT	–	1.51	–	2.22	–	2.39
TTNORM	–	0.91	–	0.72	–	0.7
VVNORM	–	0.58	–	0.95	–	0.49
ZNORM	–	2.02	–	1.51	–	1.81
Total	20.25	14.15	20.88	14.91	30.16	16.3

Table 6.42: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1600$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	3.41	2.77	3.54	3.18	6.3	2.94
GE	1.02	2.88	1.02	2.86	1.02	2.87
JER	0.02	1.69	0.01	3.48	0.0	1.95
JES	0.04	1.27	0.04	4.75	0.06	2.99
LUMI16Uncorr	1.0	0.26	–	–	–	–
LUMI1718	–	–	0.6	0.16	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.53	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.34
LUMICorr	0.6	0.17	0.9	0.24	2.0	0.42
MER	0.0	1.2	0.0	2.23	0.01	2.21
MES	0.0	0.99	0.01	6.04	0.01	2.16
MUONHLT	0.56	0.06	0.58	0.08	0.23	0.04
MUONID	1.62	0.35	0.68	0.25	0.51	0.12
MUONISO	0.31	0.09	0.23	0.1	0.16	0.07
MUONRECO	10.9	0.95	3.65	0.52	3.68	0.32
PDF	22.37	6.34	25.03	9.49	35.0	10.07
PREFIRE	0.71	1.36	0.76	1.49	–	–
PU	0.1	2.42	0.19	1.44	0.09	1.5
SHAPETT	–	12.03	–	10.11	–	12.51
SHAPEVV	–	0.17	–	0.54	–	0.31
SHAPEZ	–	1.17	–	1.01	–	0.95
TOPPT	–	1.47	–	2.19	–	2.56
TTNORM	–	0.89	–	0.68	–	0.7
VVNORM	–	0.51	–	1.08	–	0.54
ZNORM	–	2.16	–	1.71	–	1.42
Total	25.24	15.03	25.69	17.39	35.86	17.61

Table 6.43: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1700$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	3.66	3.1	3.7	3.2	6.92	3.68
GE	1.14	2.95	1.14	2.93	1.14	2.95
JER	0.01	1.51	0.0	3.62	0.02	1.52
JES	0.03	1.13	0.02	3.72	0.08	4.64
LUMI16Uncorr	1.0	0.29	–	–	–	–
LUMI1718	–	–	0.6	0.16	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.54	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.34
LUMICorr	0.6	0.18	0.9	0.25	2.0	0.42
MER	0.02	1.48	0.01	2.11	0.0	2.09
MES	0.0	0.9	0.01	4.4	0.01	3.0
MUONHLT	0.59	0.06	0.61	0.09	0.24	0.05
MUONID	1.62	0.4	0.68	0.21	0.51	0.13
MUONISO	0.31	0.1	0.23	0.09	0.16	0.07
MUONRECO	13.23	1.17	4.24	0.38	4.33	0.34
PDF	24.66	6.51	28.57	9.95	41.74	10.35
PREFIRE	0.7	1.19	0.76	1.54	–	–
PU	0.02	2.45	0.15	2.61	0.19	2.14
SHAPETT	–	11.31	–	10.35	–	13.01
SHAPEVV	–	0.25	–	0.25	–	0.74
SHAPEZ	–	1.42	–	1.28	–	1.06
TOPPT	–	1.39	–	2.19	–	2.52
TTNORM	–	0.81	–	0.66	–	0.68
VVNORM	–	0.6	–	0.91	–	0.77
ZNORM	–	2.54	–	2.15	–	1.36
Total	28.33	14.69	29.26	17.26	42.62	18.76

Table 6.44: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1800$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	3.89	3.19	3.89	3.3	7.38	4.17
GE	1.29	7.46	1.29	7.42	1.29	7.46
JER	0.01	2.67	0.01	3.86	0.01	3.11
JES	0.03	4.93	0.03	4.29	0.08	5.91
LUMI16Uncorr	1.0	0.3	–	–	–	–
LUMI1718	–	–	0.6	0.17	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.57	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.32
LUMICorr	0.6	0.19	0.9	0.26	2.0	0.4
MER	0.0	2.55	0.01	2.54	0.0	3.04
MES	0.0	1.04	0.0	8.69	0.0	2.7
MUONHLT	0.6	0.07	0.65	0.1	0.25	0.05
MUONID	1.63	0.4	0.68	0.25	0.51	0.13
MUONISO	0.31	0.11	0.23	0.1	0.16	0.07
MUONRECO	15.24	1.41	5.0	0.42	4.97	0.37
PDF	33.73	6.81	35.85	10.64	48.16	10.33
PREFIRE	0.69	1.24	0.76	1.57	–	–
PU	0.11	2.78	0.17	1.62	0.16	1.6
SHAPETT	–	9.91	–	10.16	–	12.65
SHAPEVV	–	0.27	–	0.66	–	0.92
SHAPEZ	–	1.47	–	1.75	–	1.43
TOPPT	–	1.32	–	2.17	–	2.5
TTNORM	–	0.76	–	0.62	–	0.66
VVNORM	–	0.62	–	1.02	–	0.87
ZNORM	–	2.84	–	2.3	–	1.72
Total	37.31	16.55	36.52	20.45	49.06	20.43

Table 6.45: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 1900$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	4.13	3.51	4.05	3.46	7.83	4.28
GE	1.38	10.97	1.38	10.93	1.38	10.97
JER	0.01	1.38	0.0	3.76	0.01	3.49
JES	0.03	5.25	0.03	2.52	0.03	8.26
LUMI16Uncorr	1.0	0.33	–	–	–	–
LUMI1718	–	–	0.6	0.15	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.49	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.34
LUMICorr	0.6	0.2	0.9	0.23	2.0	0.42
MER	0.0	3.59	0.03	1.62	0.02	3.81
MES	0.0	0.68	0.01	4.91	0.02	2.72
MUONHLT	0.62	0.08	0.67	0.12	0.26	0.06
MUONID	1.63	0.44	0.68	0.22	0.51	0.14
MUONISO	0.31	0.12	0.23	0.09	0.16	0.08
MUONRECO	17.95	1.67	5.69	0.44	5.71	0.41
PDF	39.05	6.84	42.13	10.51	55.45	10.56
PREFIRE	0.68	1.12	0.74	1.57	–	–
PU	0.05	3.28	0.24	1.33	0.15	1.37
SHAPETT	–	10.7	–	10.85	–	13.1
SHAPEVV	–	0.31	–	0.83	–	0.73
SHAPEZ	–	1.81	–	2.15	–	1.65
TOPPT	–	1.2	–	2.23	–	2.67
TTNORM	–	0.69	–	0.62	–	0.66
VVNORM	–	0.62	–	1.17	–	0.85
ZNORM	–	3.21	–	2.8	–	1.55
Total	43.26	19.18	42.81	20.77	56.37	23.25

Table 6.46: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2000$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	4.37	3.48	4.22	3.66	8.31	5.32
GE	1.47	14.6	1.47	14.55	1.47	14.6
JER	0.01	2.42	0.0	4.9	0.03	4.12
JES	0.03	2.74	0.02	2.86	0.06	6.84
LUMI16Uncorr	1.0	0.32	–	–	–	–
LUMI1718	–	–	0.6	0.15	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.52	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.36
LUMICorr	0.6	0.2	0.9	0.24	2.0	0.44
MER	0.01	2.39	0.0	1.58	0.0	2.07
MES	0.0	0.55	0.02	7.66	0.01	2.69
MUONHLT	0.64	0.09	0.69	0.13	0.26	0.06
MUONID	1.63	0.46	0.68	0.28	0.51	0.15
MUONISO	0.31	0.12	0.23	0.1	0.16	0.08
MUONRECO	20.52	1.96	6.5	0.49	6.4	0.42
PDF	47.41	7.06	49.23	10.67	63.75	11.46
PREFIRE	0.66	1.03	0.72	1.64	–	–
PU	0.1	4.4	0.19	1.16	0.17	1.72
SHAPETT	–	9.68	–	11.03	–	12.37
SHAPEVV	–	0.49	–	0.98	–	1.22
SHAPEZ	–	2.16	–	2.73	–	1.31
TOPPT	–	1.3	–	2.13	–	2.69
TTNORM	–	0.65	–	0.57	–	0.62
VVNORM	–	0.72	–	1.24	–	0.97
ZNORM	–	3.61	–	3.26	–	1.88
Total	51.91	20.82	49.93	24.17	64.68	24.9

Table 6.47: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2100$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	4.54	3.6	4.39	3.88	8.8	5.74
GE	1.5	16.64	1.5	16.59	1.5	16.64
JER	0.0	3.59	0.01	11.68	0.0	6.54
JES	0.03	10.79	0.03	10.27	0.04	12.04
LUMI16Uncorr	1.0	0.37	–	–	–	–
LUMI1718	–	–	0.6	0.17	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.57	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.38
LUMICorr	0.6	0.23	0.9	0.26	2.0	0.47
MER	0.0	7.64	0.01	12.62	0.0	4.46
MES	0.0	1.59	0.01	13.65	0.0	4.26
MUONHLT	0.64	0.1	0.7	0.13	0.27	0.07
MUONID	1.63	0.55	0.67	0.31	0.52	0.16
MUONISO	0.31	0.14	0.23	0.11	0.16	0.08
MUONRECO	23.44	2.24	7.27	0.52	7.24	0.47
PDF	53.81	7.63	56.8	11.07	77.67	11.36
PREFIRE	0.65	0.98	0.69	1.8	–	–
PU	0.08	5.41	0.24	1.65	0.12	2.72
SHAPETT	–	10.09	–	10.07	–	12.99
SHAPEVV	–	0.49	–	1.12	–	1.97
SHAPEZ	–	1.76	–	2.64	–	1.41
TOPPT	–	1.27	–	1.83	–	2.66
TTNORM	–	0.59	–	0.49	–	0.62
VVNORM	–	0.72	–	1.26	–	1.17
ZNORM	–	3.42	–	3.93	–	1.25
Total	58.93	26.33	57.51	33.72	78.56	29.29

Table 6.48: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2200$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	4.79	4.09	4.57	3.86	9.28	6.4
GE	1.59	20.33	1.59	20.27	1.59	20.33
JER	0.0	0.79	0.01	8.34	0.01	7.25
JES	0.03	3.83	0.04	6.57	0.06	6.71
LUMI16Uncorr	1.0	0.28	–	–	–	–
LUMI1718	–	–	0.6	0.18	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.61	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.4
LUMICorr	0.6	0.17	0.9	0.28	2.0	0.51
MER	0.0	0.21	0.0	4.85	0.01	4.29
MES	0.0	0.51	0.01	9.83	0.01	7.45
MUONHLT	0.67	0.11	0.72	0.16	0.27	0.06
MUONID	1.63	0.42	0.68	0.23	0.52	0.15
MUONISO	0.31	0.11	0.23	0.1	0.16	0.08
MUONRECO	26.51	2.73	8.09	0.61	7.87	0.62
PDF	62.91	6.13	63.7	11.34	87.35	11.85
PREFIRE	0.63	1.17	0.69	1.84	–	–
PU	0.01	6.54	0.25	3.45	0.25	1.43
SHAPETT	–	11.2	–	11.2	–	13.98
SHAPEVV	–	0.7	–	0.38	–	0.82
SHAPEZ	–	1.71	–	2.14	–	2.05
TOPPT	–	1.59	–	2.11	–	2.87
TTNORM	–	0.69	–	0.54	–	0.62
VVNORM	–	0.88	–	0.78	–	0.77
ZNORM	–	4.01	–	3.25	–	1.41
Total	68.49	26.15	64.45	30.81	88.25	31.31

Table 6.49: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2300$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	4.98	4.14	4.69	4.0	9.69	6.82
GE	1.69	22.06	1.69	22.01	1.69	22.07
JER	0.01	0.57	0.03	11.76	0.01	7.78
JES	0.03	3.2	0.04	6.58	0.05	11.65
LUMI16Uncorr	1.0	0.25	–	–	–	–
LUMI1718	–	–	0.6	0.18	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.62	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.35
LUMICorr	0.6	0.16	0.9	0.28	2.0	0.43
MER	0.0	6.79	0.01	2.52	0.02	4.18
MES	0.0	0.64	0.01	13.28	0.01	4.27
MUONHLT	0.67	0.1	0.74	0.18	0.28	0.05
MUONID	1.63	0.38	0.67	0.25	0.52	0.15
MUONISO	0.31	0.1	0.23	0.11	0.16	0.07
MUONRECO	28.81	3.16	8.8	0.65	8.56	0.69
PDF	67.83	5.81	49.7	11.67	94.71	12.06
PREFIRE	0.63	1.24	0.66	1.63	–	–
PU	0.13	7.76	0.17	3.84	0.13	2.46
SHAPETT	–	11.58	–	12.3	–	13.2
SHAPEVV	–	0.76	–	0.58	–	0.86
SHAPEZ	–	2.07	–	1.95	–	2.44
TOPPT	–	1.7	–	2.18	–	2.87
TTNORM	–	0.73	–	0.52	–	0.56
VVNORM	–	0.96	–	0.92	–	0.86
ZNORM	–	4.03	–	3.28	–	2.74
Total	73.92	28.74	50.78	34.52	95.64	33.4

Table 6.50: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2400$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	5.15	4.04	4.84	4.48	10.06	7.95
GE	1.88	33.96	1.88	33.9	1.88	33.97
JER	0.0	7.24	0.01	8.83	0.02	4.64
JES	0.03	3.61	0.03	4.74	0.04	10.65
LUMI16Uncorr	1.0	0.29	–	–	–	–
LUMI1718	–	–	0.6	0.2	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.65	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.35
LUMICorr	0.6	0.19	0.9	0.3	2.0	0.43
MER	0.0	1.0	0.0	3.02	0.0	1.86
MES	0.0	0.56	0.0	16.75	0.01	6.21
MUONHLT	0.69	0.11	0.75	0.2	0.28	0.06
MUONID	1.64	0.49	0.67	0.29	0.52	0.15
MUONISO	0.31	0.12	0.23	0.12	0.16	0.08
MUONRECO	31.73	3.75	9.53	0.71	9.2	0.7
PDF	74.65	6.49	78.7	12.14	100.0	12.53
PREFIRE	0.61	1.18	0.66	1.61	–	–
PU	0.08	8.31	0.2	1.64	0.23	3.86
SHAPETT	–	8.08	–	12.76	–	11.46
SHAPEVV	–	0.57	–	0.48	–	1.64
SHAPEZ	–	1.93	–	2.91	–	2.7
TOPPT	–	1.61	–	2.11	–	2.44
TTNORM	–	0.67	–	0.5	–	0.51
VVNORM	–	0.6	–	1.0	–	1.18
ZNORM	–	4.34	–	3.02	–	2.91
Total	81.33	38.14	79.49	43.58	100.98	41.52

Table 6.51: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2500$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	5.34	4.61	4.97	4.48	10.47	7.71
GE	2.11	36.53	2.11	36.47	2.11	36.55
JER	0.01	2.52	0.01	11.04	0.01	4.57
JES	0.02	5.41	0.02	10.4	0.03	8.61
LUMI16Uncorr	1.0	0.22	–	–	–	–
LUMI1718	–	–	0.6	0.24	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.79	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.26
LUMICorr	0.6	0.15	0.9	0.37	2.0	0.32
MER	0.01	1.1	0.0	1.64	0.01	6.02
MES	0.0	0.62	0.0	9.21	0.01	4.51
MUONHLT	0.69	0.13	0.76	0.22	0.29	0.07
MUONID	1.64	0.33	0.67	0.37	0.52	0.12
MUONISO	0.31	0.1	0.23	0.14	0.16	0.07
MUONRECO	34.47	4.41	10.29	0.71	9.87	0.52
PDF	81.78	6.91	85.7	12.67	100.0	12.27
PREFIRE	0.61	1.24	0.64	1.92	–	–
PU	0.05	11.22	0.22	2.1	0.21	3.71
SHAPETT	–	7.37	–	11.4	–	13.4
SHAPEVV	–	0.68	–	0.42	–	1.98
SHAPEZ	–	3.92	–	1.96	–	3.11
TOPPT	–	1.66	–	1.97	–	2.53
TTNORM	–	0.68	–	0.46	–	0.52
VVNORM	–	0.67	–	1.03	–	1.35
ZNORM	–	5.23	–	2.28	–	3.36
Total	88.96	41.1	86.52	44.52	101.09	43.87

Table 6.52: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2600$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	5.43	5.42	5.1	4.89	10.83	8.28
GE	2.39	36.58	2.39	36.5	2.39	36.6
JER	0.0	3.38	0.02	13.04	0.01	5.59
JES	0.02	4.44	0.04	3.5	0.06	8.3
LUMI16Uncorr	1.0	0.23	–	–	–	–
LUMI1718	–	–	0.6	0.24	0.2	0.05
LUMI17Uncorr	–	–	2.0	0.8	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.17
LUMICorr	0.6	0.17	0.9	0.37	2.0	0.19
MER	0.01	7.38	0.0	3.27	0.0	7.29
MES	0.0	3.5	0.01	12.25	0.01	4.39
MUONHLT	0.7	0.18	0.78	0.26	0.29	0.08
MUONID	1.64	0.35	0.67	0.38	0.52	0.1
MUONISO	0.31	0.1	0.23	0.15	0.16	0.07
MUONRECO	37.24	6.66	11.06	0.8	10.48	0.58
PDF	88.43	7.28	92.8	12.65	100.0	11.9
PREFIRE	0.6	1.67	0.62	1.75	–	–
PU	0.04	12.52	0.33	2.99	0.25	5.76
SHAPETT	–	9.93	–	11.6	–	14.34
SHAPEVV	–	1.12	–	0.83	–	2.98
SHAPEZ	–	3.45	–	2.91	–	3.41
TOPPT	–	1.38	–	1.96	–	2.4
TTNORM	–	0.59	–	0.44	–	0.54
VVNORM	–	0.89	–	1.26	–	1.66
ZNORM	–	6.12	–	2.31	–	3.28
Total	96.16	43.3	93.66	45.03	101.19	44.74

Table 6.53: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2700$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	5.64	5.35	5.25	5.13	11.14	7.95
GE	2.66	39.28	2.66	39.2	2.66	39.3
JER	0.01	9.39	0.02	6.17	0.02	14.55
JES	0.02	10.18	0.03	5.24	0.05	14.06
LUMI16Uncorr	1.0	0.23	–	–	–	–
LUMI1718	–	–	0.6	0.21	0.2	0.05
LUMI17Uncorr	–	–	2.0	0.69	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.21
LUMICorr	0.6	0.16	0.9	0.32	2.0	0.23
MER	0.0	0.13	0.01	5.64	0.01	12.29
MES	0.01	4.0	0.01	6.7	0.0	8.37
MUONHLT	0.71	0.18	0.78	0.27	0.29	0.08
MUONID	1.64	0.29	0.67	0.33	0.52	0.14
MUONISO	0.31	0.11	0.23	0.14	0.16	0.07
MUONRECO	39.77	7.17	11.77	0.9	11.14	0.63
PDF	93.78	6.67	71.6	12.15	100.0	12.16
PREFIRE	0.59	1.68	0.6	2.18	–	–
PU	0.01	11.89	0.23	5.55	0.34	8.46
SHAPETT	–	7.97	–	14.13	–	17.9
SHAPEVV	–	1.37	–	0.61	–	0.93
SHAPEZ	–	4.38	–	2.54	–	3.68
TOPPT	–	1.23	–	2.3	–	2.72
TTNORM	–	0.53	–	0.46	–	0.58
VVNORM	–	1.17	–	1.28	–	1.22
ZNORM	–	6.47	–	2.74	–	2.91
Total	102.08	46.36	72.85	45.95	101.3	53.02

Table 6.54: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2800$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	5.83	5.03	5.38	4.73	11.39	9.71
GE	3.05	39.89	3.05	39.79	3.05	39.9
JER	0.0	2.18	0.02	4.74	0.01	20.66
JES	0.02	4.21	0.03	3.12	0.05	21.25
LUMI16Uncorr	1.0	0.21	–	–	–	–
LUMI1718	–	–	0.6	0.19	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.63	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.23
LUMICorr	0.6	0.14	0.9	0.3	2.0	0.28
MER	0.0	1.73	0.0	0.85	0.0	3.14
MES	0.0	0.62	0.01	11.99	0.01	22.12
MUONHLT	0.71	0.25	0.79	0.26	0.29	0.06
MUONID	1.64	0.19	0.67	0.3	0.52	0.11
MUONISO	0.31	0.13	0.23	0.13	0.16	0.06
MUONRECO	42.4	11.09	12.32	1.09	11.78	0.73
PDF	99.26	6.11	100.0	11.83	100.0	12.72
PREFIRE	0.59	2.26	0.61	2.08	–	–
PU	0.02	15.39	0.27	5.53	0.2	5.88
SHAPETT	–	6.22	–	13.77	–	15.02
SHAPEVV	–	2.38	–	0.68	–	0.44
SHAPEZ	–	6.55	–	1.72	–	4.84
TOPPT	–	0.69	–	2.22	–	2.34
TTNORM	–	0.26	–	0.46	–	0.48
VVNORM	–	1.83	–	1.25	–	0.93
ZNORM	–	9.11	–	3.3	–	5.69
Total	108.16	47.11	100.98	46.58	101.41	59.57

Table 6.55: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 2900$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	5.93	5.25	5.46	5.16	11.72	9.46
GE	3.36	44.48	3.36	44.37	3.36	44.49
JER	0.01	0.71	0.01	4.28	0.01	3.66
JES	0.03	1.72	0.02	6.61	0.03	3.59
LUMI16Uncorr	1.0	0.22	–	–	–	–
LUMI1718	–	–	0.6	0.17	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.55	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.24
LUMICorr	0.6	0.14	0.9	0.26	2.0	0.29
MER	0.01	1.5	0.01	2.52	0.0	1.24
MES	0.0	0.6	0.01	5.5	0.0	2.84
MUONHLT	0.73	0.26	0.81	0.29	0.29	0.05
MUONID	1.64	0.21	0.67	0.28	0.52	0.12
MUONISO	0.31	0.13	0.23	0.13	0.16	0.06
MUONRECO	45.06	12.27	13.06	1.14	12.37	0.74
PDF	100.0	6.56	100.0	11.41	100.0	12.74
PREFIRE	0.59	2.5	0.6	2.3	–	–
PU	0.03	15.31	0.33	5.6	0.16	5.59
SHAPETT	–	6.85	–	13.06	–	15.21
SHAPEVV	–	2.68	–	0.78	–	0.32
SHAPEZ	–	5.85	–	2.69	–	4.92
TOPPT	–	0.75	–	2.22	–	2.25
TTNORM	–	0.29	–	0.45	–	0.47
VVNORM	–	2.14	–	1.47	–	0.88
ZNORM	–	8.2	–	3.86	–	5.78
Total	109.92	51.06	101.09	49.63	101.53	50.93

Table 6.56: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 3000$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	6.13	5.93	5.6	4.93	12.19	10.03
GE	3.79	45.84	3.79	45.75	3.79	45.87
JER	0.0	4.57	0.01	13.2	0.01	2.31
JES	0.02	4.03	0.01	11.85	0.02	2.63
LUMI16Uncorr	1.0	0.13	–	–	–	–
LUMI1718	–	–	0.6	0.2	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.65	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.25
LUMICorr	0.6	0.09	0.9	0.3	2.0	0.31
MER	0.01	2.53	0.0	7.54	0.0	2.51
MES	0.0	0.67	0.02	9.85	0.01	3.84
MUONHLT	0.72	0.39	0.82	0.27	0.29	0.06
MUONID	1.64	0.07	0.67	0.27	0.52	0.12
MUONISO	0.31	0.13	0.23	0.13	0.16	0.06
MUONRECO	47.35	16.1	13.56	1.16	12.78	0.74
PDF	100.0	6.64	100.0	11.88	100.0	12.83
PREFIRE	0.6	3.76	0.57	2.04	–	–
PU	0.05	15.97	0.39	5.57	0.23	5.79
SHAPETT	–	0.05	–	12.47	–	15.11
SHAPEVV	–	3.99	–	2.45	–	0.33
SHAPEZ	–	9.92	–	2.17	–	5.93
TOPPT	–	0.16	–	2.21	–	2.22
TTNORM	–	0.07	–	0.44	–	0.42
VVNORM	–	2.76	–	1.1	–	0.94
ZNORM	–	10.94	–	3.52	–	6.31
Total	110.9	54.72	101.18	54.31	101.65	52.4

Table 6.57: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 3500$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	6.78	13.26	6.15	6.97	13.66	13.95
GE	4.2	114.25	4.2	113.88	4.2	114.16
JER	0.01	5.12	0.02	6.75	0.01	0.8
JES	0.03	3.01	0.02	16.08	0.04	1.87
LUMI16Uncorr	1.0	0.18	–	–	–	–
LUMI1718	–	–	0.6	0.04	0.2	0.07
LUMI17Uncorr	–	–	2.0	0.13	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.14
LUMICorr	0.6	0.09	0.9	0.08	2.0	0.16
MER	0.0	1.33	0.0	7.13	0.02	0.98
MES	0.0	0.66	0.01	6.19	0.01	2.1
MUONHLT	0.75	0.52	0.86	0.36	0.3	0.07
MUONID	1.64	0.33	0.67	0.14	0.52	0.09
MUONISO	0.31	0.11	0.23	0.09	0.16	0.07
MUONRECO	59.03	11.43	16.32	1.64	15.24	0.49
PDF	100.0	6.94	100.0	9.74	100.0	13.28
PREFIRE	0.6	0.51	0.56	2.39	–	–
PU	0.04	8.7	0.31	8.02	0.23	8.0
SHAPETT	–	0.01	–	15.59	–	9.25
SHAPEVV	–	6.06	–	5.99	–	0.8
SHAPEZ	–	6.83	–	2.27	–	9.26
TOPPT	–	0.2	–	2.48	–	0.94
TTNORM	–	0.16	–	0.55	–	0.25
VVNORM	–	5.66	–	2.34	–	1.1
ZNORM	–	7.56	–	4.99	–	9.77
Total	116.42	117.02	101.63	117.89	102.19	117.25

Table 6.58: Systematic uncertainties and their effects on signal (Sig.) and background (Bkg.) in 2016, 2017, and 2018 for $M_{LQ} = 4000$ GeV final selection. All uncertainties are symmetric.

Systematic	2016		2017		2018	
	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)	Sig. (%)	Bkg. (%)
BTAG	7.4	22.79	6.68	6.06	14.97	15.31
GE	4.7	242.68	4.7	242.39	4.7	242.74
JER	0.02	0.42	0.0	1.72	0.02	19.55
JES	0.05	4.22	0.01	4.08	0.04	51.76
LUMI16Uncorr	1.0	0.1	–	–	–	–
LUMI1718	–	–	0.6	0.04	0.2	0.06
LUMI17Uncorr	–	–	2.0	0.15	–	–
LUMI18Uncorr	–	–	–	–	1.5	0.12
LUMICorr	0.6	0.12	0.9	0.09	2.0	0.14
MER	0.01	2.73	0.01	3.59	0.0	31.86
MES	0.0	0.77	0.0	2.06	0.01	36.54
MUONHLT	0.78	0.39	0.91	0.83	0.29	0.07
MUONID	1.64	0.13	0.67	0.32	0.52	0.14
MUONISO	0.31	0.18	0.23	0.13	0.16	0.06
MUONRECO	70.62	33.9	18.78	3.08	17.37	2.03
PDF	100.0	9.78	100.0	8.98	100.0	13.78
PREFIRE	0.61	0.94	0.57	1.59	–	–
PU	0.09	5.48	0.29	8.42	0.24	6.32
SHAPETT	–	0.0	–	8.46	–	8.68
SHAPEVV	–	0.05	–	0.04	–	1.6
SHAPEZ	–	18.37	–	4.55	–	7.01
TOPPT	–	0.14	–	0.26	–	0.68
TTNORM	–	0.07	–	0.28	–	0.23
VVNORM	–	0.1	–	0.19	–	0.66
ZNORM	–	15.37	–	11.31	–	10.16
Total	122.76	247.57	102.11	243.33	102.74	255.02

6.7 Results

A cut and count analysis is performed using the asymptotic CL_s modified frequentist approach to place upper limits on the signal hypotheses [53, 54]. Systematic uncertainties are integrated over with a log-normal probability function, while statistical uncertainties are modeled by Γ distributions whose widths are taken to be the number of simulated events in MC samples.

Figure 6.34 shows the asymptotic upper limits on the product of the leptoquark pair-production cross section and branching fraction into two charged leptons $\sigma(\text{pp} \rightarrow \text{LQ}\overline{\text{LQ}}) \times \beta^2$ as a function of leptoquark mass in 2016, 2017, and 2018 datasets, together with the NLO prediction of scalar leptoquark pair production cross sections. The theoretical cross section curves are represented for the renormalization and factorization scale μ , varied by up by $2M_{\text{LQ}}$ and down by $M_{\text{LQ}}/2$. PDF uncertainties are accounted for in the theory cross sections.

Asymptotic upper limits on the combination of 2016, 2017, and 2018 datasets, shown in Figure 6.35 with the theory prediction, exclude leptoquark masses below 1803 GeV. This is an improvement of 273 GeV over the previous results with 2016 data [55].

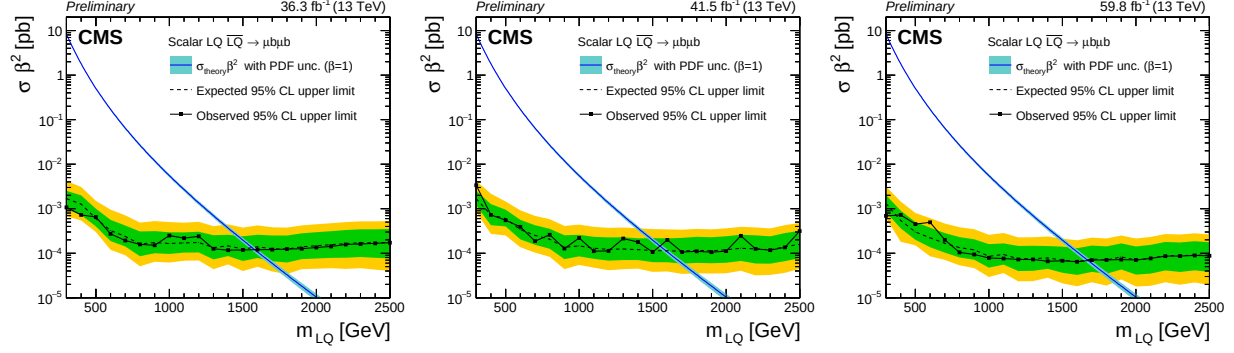


Figure 6.34: The asymptotic upper limits at 95% CL on the leptoquark pair production cross section times squared branching fraction as a function of leptoquark mass obtained with the $\mu\mu b\bar{b}$ analysis with 2016 (left), 2017 (middle), and 2018 (right) datasets. The expected limits and uncertainty bands represent the median expected limits and the 68% and 95% confidence intervals. The σ_{theory} curves and their bands represent, respectively, the theoretical scalar leptoquark pair production cross section and the uncertainties due to the choice of PDF and renormalization/factorization scales.

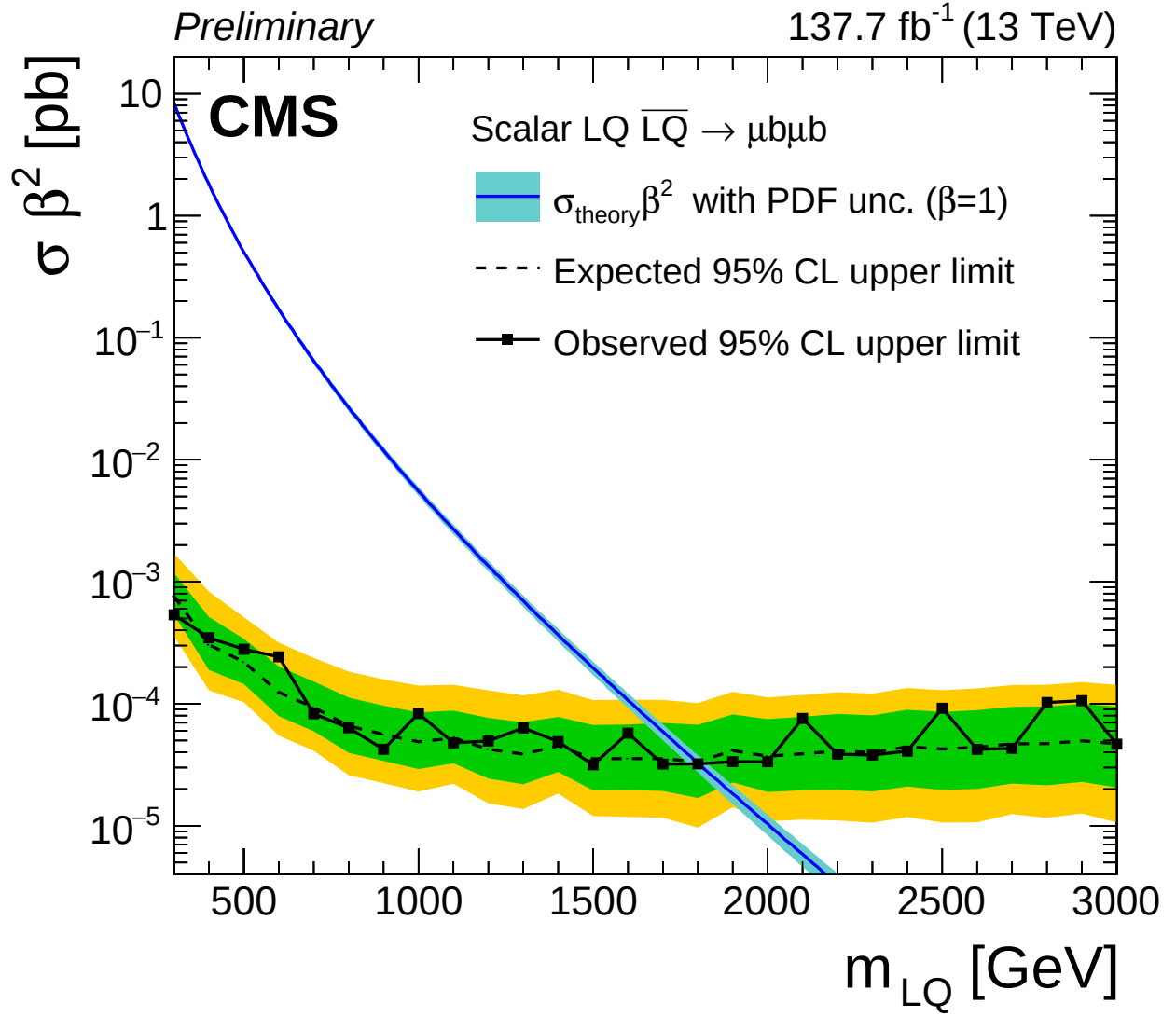


Figure 6.35: The asymptotic upper limits at 95% CL on $\sigma \times \beta^2$ as a function of leptoquark mass obtained with the $\mu\mu b j$ analysis. The expected limits and uncertainty bands represent the median expected limits and the 68 % and 95 % confidence intervals. The σ_{theory} curves and their bands represent, respectively, the theoretical scalar leptoquark pair production cross section and the uncertainties due to the choice of PDF and renormalization/factorization scales.

Chapter 7

Conclusion

The first search with CMS data for pair-produced scalar leptoquarks decaying to two muons and two jets, where at least one jet is tagged as originating from a bottom quark, has been presented. The search is also the first to consider second-generation leptoquarks to make use of the full LHC Run II proton-proton collision data set at $\sqrt{s} = 13$ TeV recorded by the CMS collaboration in 2016, 2017, and 2018, corresponding to an integrated luminosity of 138 fb^{-1} . Signal-like events have been separated from SM-background-like events using a boosted decision tree trained on simulated data at each leptoquark mass hypothesis. Observed upper limits have been placed at 95% CL on the product of the leptoquark pair-production cross section and decay branching fraction into two charged leptons $\sigma(\text{pp} \rightarrow \text{LQ}\overline{\text{LQ}}) \times \beta^2$ for $\beta = 1$. The upper limits were set as a function of the leptoquark mass M_{LQ} , and by comparing these limits to the theoretical leptoquark cross section σ_{theory} a lower bound on the leptoquark mass was placed that excludes $M_{\text{LQ}} < 1803 \text{ GeV}$. This is a 273 GeV improvement over the previous limits placed by CMS (with 2016 data only and without the use of b tagging) [55]. These results represent the most stringent limits to date.

Beyond setting limits on leptoquarks, these results are well-suited for interpretation in the context of R-parity violating (RPV) SUSY models. Prompt decays of pair-produced top squarks $\tilde{t}$ (supersymmetric quarks) are kinematically similar to the leptoquark-pair signature in this search. This feature can be leveraged to extrapolate the limits placed on leptoquarks in the prompt kinematic range, corresponding to a lifetime $c\tau = 0 \text{ cm}$, to the displaced decays of long-lived top squarks. This reinterpretation of leptoquark limits is easily performed with the existing analysis framework and would complement the sensitivity of dedicated searches for long-lived particles. Past leptoquark searches at CMS have set a precedent for this

reinterpretation. The second-generation leptoquark search analyzing the 2016 CMS dataset in the $\mu\mu jj$ channel placed expected and observed limits at 95 % CL on the displaced RPV SUSY top squark pair-production cross section. The exclusion limits were set as a function of both the top squark mass $M_{\tilde{t}}$ and lifetime $c\tau$ and translated to lower bounds on the coupling strength λ'_{233} of the RPV term in the SUSY Lagrangian. Excluded couplings corresponded to $\lambda'_{233} \cos \theta < 9.3 \times 10^{-8}$, 3.2×10^{-8} , and 1.8×10^{-8} , where $\cos \theta$ represents the left- and right-handed eigenstate mixing angle of the top squarks.

Future second-generation leptoquark searches using the full Run II dataset recorded by CMS could place upper limits on other leptoquark models by looking at different final state event signatures. In the leptoquark pair-production mode, allowing $\beta = 0.5$ would open up searches to the $\mu\nu jj$ channel. Past leptoquark searches at CMS have typically studied both $\beta = 1.0$ and 0.5 models in parallel with a 2D scan of both final state event signatures (with current limits on leptoquarks in the $\mu\nu jj$ channel excluding masses below 1285 GeV). Including a b-tag requirement on at least one of the jets in the $\mu\nu jj$ channel would target leptoquark models mixing second- and third-generations and would be the first of its kind by the CMS collaboration.

Leptoquark searches in single-production channels would also be advantageous as they are sensitive to the Yukawa coupling strength at a leptoquark-lepton-quark vertex λ_{LQ} . The dominant decay mode for singly-produced leptoquarks at the LHC is a resonant s-channel process with a $\ell\bar{\ell}j$ final state event signature. A search of this kind would be able to exclude second-generation leptoquark parameter space that has not yet been explored by CMS in Run II data. The most recent limits placed with single-production come from a paper released by CMS using 19.6 fb^{-1} of proton-proton collision data at $\sqrt{s} = 8 \text{ TeV}$. The search placed limits at 95 % CL on single production of first- and second-generation leptoquarks—assuming λ_{LQ} and β are 1.0—and excluded masses below 1730 GeV and 530 GeV, respectively. A new search for second-generation leptoquarks in 13 TeV collisions with the full Run II dataset would extend the sensitivity of past single leptoquark searches to a higher mass region.

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APPENDIX A

GE estimation of MES uncertainty

As this analysis selects only high- p_T -ID muons, a significant fraction of muons are in a momentum space where reconstruction relies less on the inner tracker and more on the muon system. While tracker-derived Rochester corrections adequately scale lower muon momenta, these corrections—and corresponding uncertainty estimates—do not cover muons at high p_T . To overcome this limitation and estimate a MES uncertainty at muon p_T beyond the 200 GeV threshold of the Rochester scale corrections, we use the Generalized Endpoint (GE) method to estimate an uncertainty of scale bias for muons with $p_T > 200$ GeV. This partitioning of the MES uncertainty estimation follows the recommendations set by the Muon POG for high- p_T ID muons provided on the Twiki pages in Refs. [37, 39]. The GE method uses statistical replicas of scale bias maps binned in ϕ and η , where each element of a copy $\kappa_{b,\text{copy}}$ is drawn from a gaussian distribution whose mean is the measured bias κ_b and standard deviation is the measurement uncertainty σ . For each copy, muon p_T is translated by:

$$\frac{q}{p_T} \rightarrow \frac{q}{p_T} + \kappa_{b,\text{copy}}, \quad (\text{A.1})$$

giving:

$$p_T \rightarrow \frac{p_T}{1 + qp_T\kappa_{b,\text{copy}}}, \quad (\text{A.2})$$

where q is the electric charge of the muon. The momentum translations are propagated to final results (defined below) for each copy and averaged, and the uncertainty estimated from the relative difference in events between nominal and average distributions (for the contribution from data-normalized $Z/\gamma^* + \text{jets}$ and $t\bar{t}$ backgrounds we use the relative difference in efficiency rather than the relative difference in the number of events). Premade

copies of scale biases and momentum translations are available through the GEScaleSyst package on GitLab [56]. Figure A.1 shows the nominal muon p_T compared to the corresponding statistical replicas and averaged distributions in background MC at preselection, while Figs. A.2 and A.3 show the nominal BDT scores of select masses compared to the corresponding statistical replicas and averaged distributions in signal MC at preselection.

The selection criteria used to estimate the GE scale uncertainty was studied at five working points, corresponding to different cuts on the BDT scores. Along with preselection, $M_{\mu\mu} > 250 \text{ GeV}$ and $M_{\mu\mu jj} > M_{LQ}$ requirements were additionally applied to data at all working points. Each working point was defined by the following cut:

- Enhanced: BDT score ≥ 0.0
- Loose: BDT score > 0.1
- Medium: BDT score > 0.5
- Tight: BDT score > 0.9
- Optimized: BDT score $>$ optimized cut (see: Table 6.27)

The uncertainty estimated with the GE method at each working point and leptoquark mass point in background and signal MC are listed in Tables A.1 and A.2, respectively. This analysis uses the enhanced working point to estimate the GE scale uncertainty, as it is loose enough (with no cut on the BDT score) to retain sufficient statistics, while the cut on $M_{\mu\mu jj} > M_{LQ}$ ensures events are characterized by the same kinematics as the signal region.

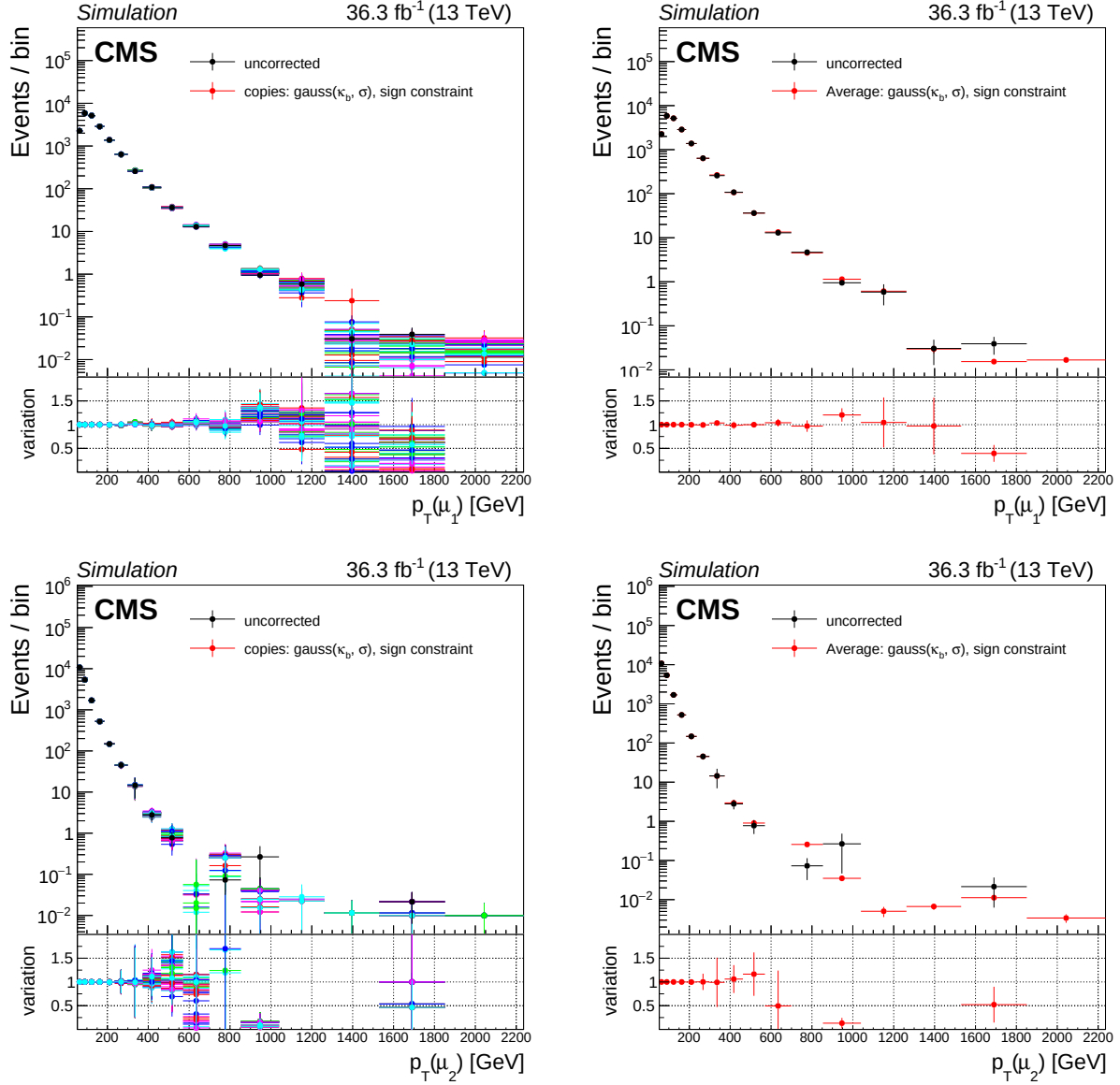


Figure A.1: Left: A comparison between the nominal and statistical replicas of muon 1 p_T (top) and muon 2 p_T (bottom). Right: A comparison between the nominal and average over the statistical replicas of muon 1 p_T (top) and muon 2 p_T (bottom). Distributions show 2016 background MC at preselection.

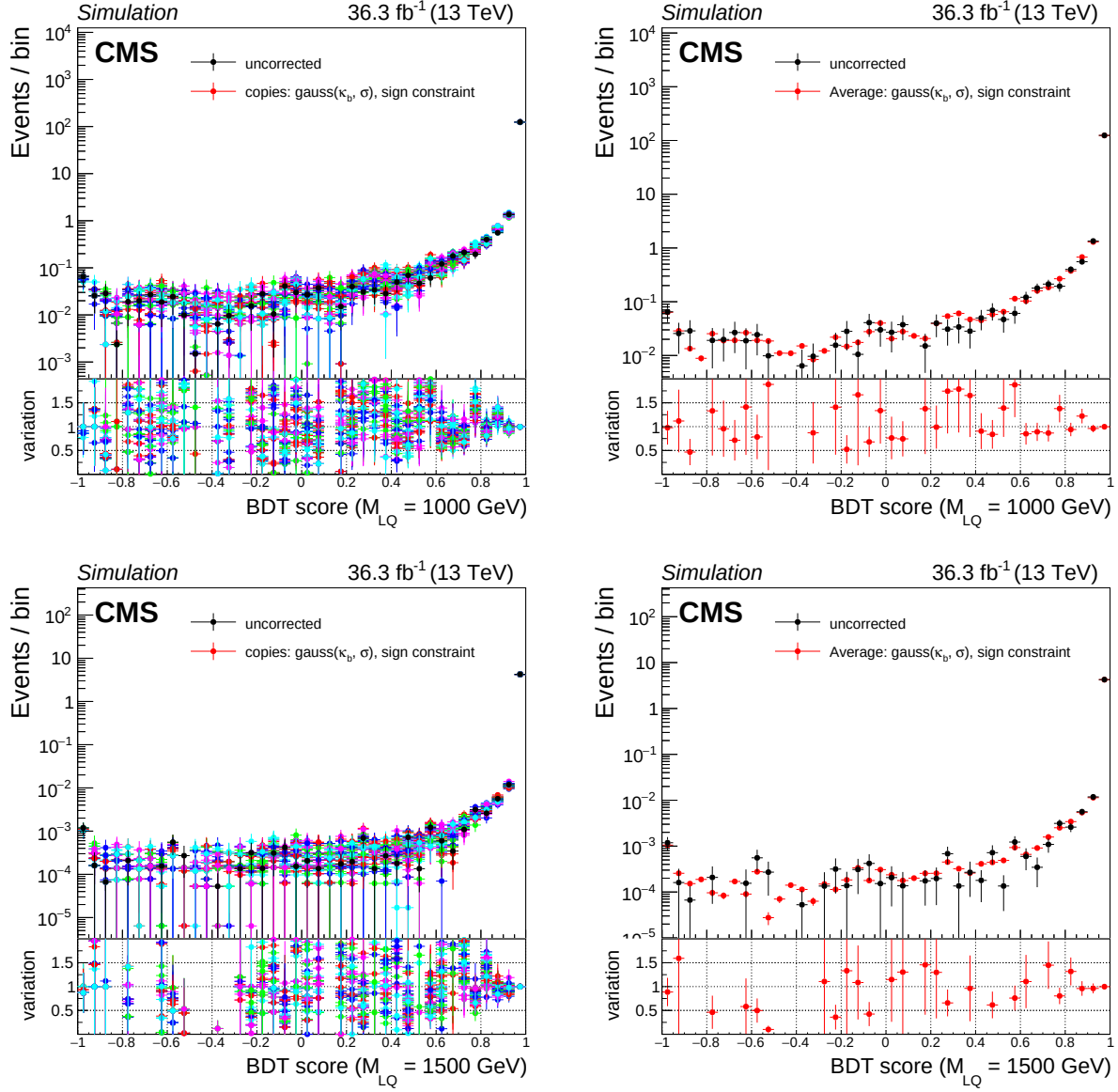


Figure A.2: Left: A comparison between the nominal and statistical replicas of 1000 GeV (top) and 1500 GeV (bottom) BDT scores. Right: A comparison between the nominal and average over the statistical replicas of 1000 GeV (top) and 1500 GeV (bottom) BDT scores. Distributions show 2016 signal MC at preselection.

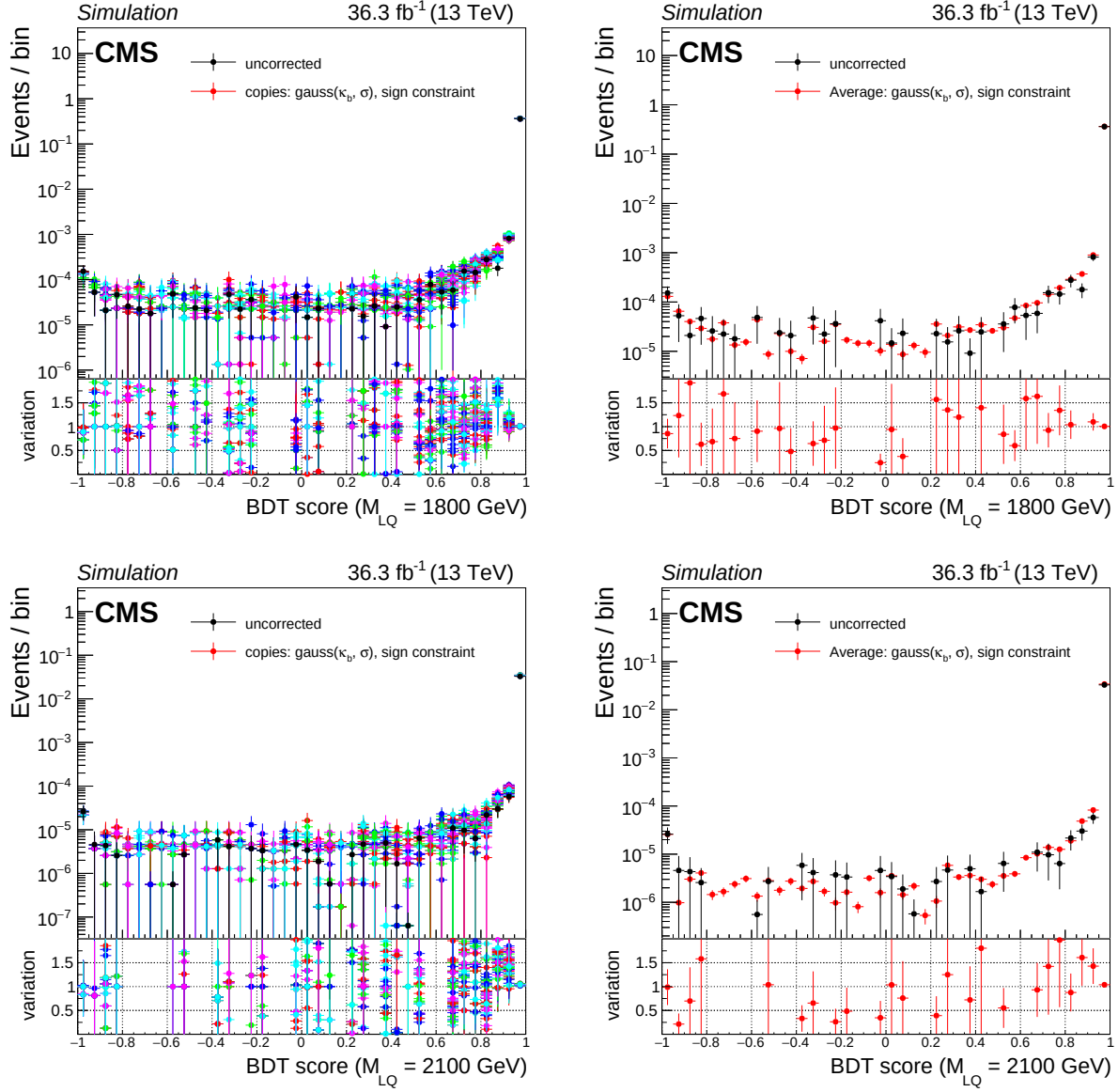


Figure A.3: Left: A comparison between the nominal and statistical replicas of 1800 GeV (top) and 2100 GeV (bottom) BDT scores. Right: A comparison between the nominal and average over the statistical replicas of 1800 GeV (top) and 2100 GeV (bottom) BDT scores. Distributions show 2016 signal MC at preselection.

Table A.1: Muon scale systematic uncertainties estimated with the Generalized Endpoint method and their effect on background in 2016, scanned over several selection working points. All uncertainties are symmetric.

LQ Mass [GeV]	Systematic error [%]				
	enhanced	loose	medium	tight	optimized
300	0.0	0.44	6.16	6.08	1.77
400	0.0	0.61	1.24	2.68	2.99
500	0.02	1.92	2.77	2.19	4.24
600	0.03	5.49	2.53	2.56	11.18
700	0.02	3.05	8.59	7.18	21.97
800	0.08	4.18	3.35	2.91	6.05
900	0.01	2.06	6.1	7.05	12.01
1000	0.1	5.38	3.35	22.39	13.35
1100	0.18	7.54	4.01	13.23	15.09
1200	0.15	6.12	5.79	24.85	29.74
1300	0.16	12.1	22.48	9.13	48.59
1400	0.49	29.06	30.76	12.21	14.11
1500	0.38	12.35	10.7	32.77	22.61
1600	1.22	21.9	31.33	45.47	7.02
1700	0.07	25.01	30.2	112.19	63.08
1800	4.38	16.45	20.2	22.11	22.35
1900	3.27	36.36	12.44	17.36	25.52
2100	1.78	86.8	239.12	293.8	321.2
2200	3.16	31.46	4.65	12.36	249.65
2300	1.44	97.77	112.71	234.21	588.68
2400	9.75	606.19	548.16	202.56	192.41
2500	1.92	106.58	106.67	40.07	259.96
2600	0.03	7.01	7.01	7.01	7.01
2700	1.98	105.55	261.41	177.83	177.83
2800	0.43	68.36	38.91	26.41	12.74
2900	3.28	626.01	487.37	54.57	140.7
3000	0.95	92.55	52.33	197.05	197.05
3500	46.79	206.29	213.06	195.41	212.36
4000	60.05	5.16	33.58	135.41	112.51

Table A.2: Muon scale systematic uncertainties estimated with the Generalized Endpoint method and their effect on signal in 2016, scanned over several selection working points. All uncertainties are ymmetric.

LQ Mass [GeV]	Systematic error [%]				
	enhanced	loose	medium	tight	optimized
300	0.02	0.1	0.09	0.33	0.65
400	0.0	0.0	0.02	0.26	0.28
500	0.02	0.04	0.03	0.13	0.48
600	0.0	0.03	0.04	0.08	0.2
700	0.01	0.02	0.04	0.09	0.39
800	0.02	0.04	0.06	0.03	0.16
900	0.05	0.08	0.08	0.1	0.11
1000	0.11	0.12	0.18	0.33	0.51
1100	0.05	0.06	0.08	0.08	0.14
1200	0.13	0.14	0.15	0.16	0.2
1300	0.12	0.12	0.14	0.13	0.18
1400	0.16	0.16	0.17	0.21	0.21
1500	0.18	0.18	0.18	0.21	0.21
1600	0.15	0.16	0.15	0.18	0.18
1700	0.11	0.12	0.1	0.14	0.14
1800	0.15	0.14	0.14	0.18	0.18
1900	0.09	0.1	0.1	0.11	0.11
2100	0.03	0.03	0.02	0.0	0.0
2200	0.09	0.09	0.09	0.08	0.06
2300	0.1	0.1	0.11	0.09	0.11
2400	0.18	0.18	0.19	0.18	0.18
2500	0.23	0.24	0.24	0.24	0.22
2600	0.27	0.28	0.28	0.28	0.28
2700	0.27	0.27	0.27	0.25	0.25
2800	0.38	0.38	0.37	0.37	0.35
2900	0.3	0.32	0.32	0.31	0.28
3000	0.41	0.41	0.42	0.41	0.41
3500	0.4	0.4	0.4	0.39	0.4
4000	0.48	0.48	0.48	0.47	0.47

APPENDIX B

Background normalization scale factors

To determine if systematic uncertainties need to be accounted for in the $Z/\gamma^* + \text{jets}$ and $t\bar{t}$ normalization scale factors listed in Section 6.4.1, each scale factor is studied, binned in S_T , $p_T(\mu_1)$, and $p_T(\text{jet}_1)$. The study was repeated for each year of data-taking, as shown in Figs. B.1–B.3.

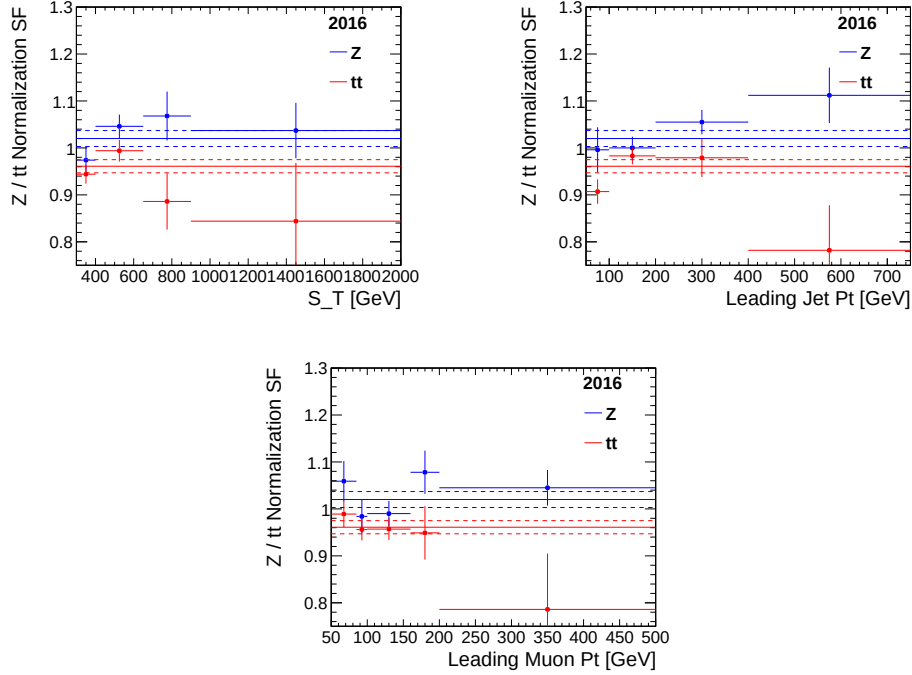


Figure B.1: $Z/\gamma^* + \text{jets}$ (red) and $t\bar{t}$ (blue) normalization scale factors and their statistical uncertainties in bins of S_T (left), $p_T(\mu_1)$ (center), and $p_T(\text{jet}_1)$ (right) in the 2016 data-taking period. The inclusive scale factors are represented by a solid horizontal line, while statistical uncertainties on the inclusive scale factors are represented by dashed lines.

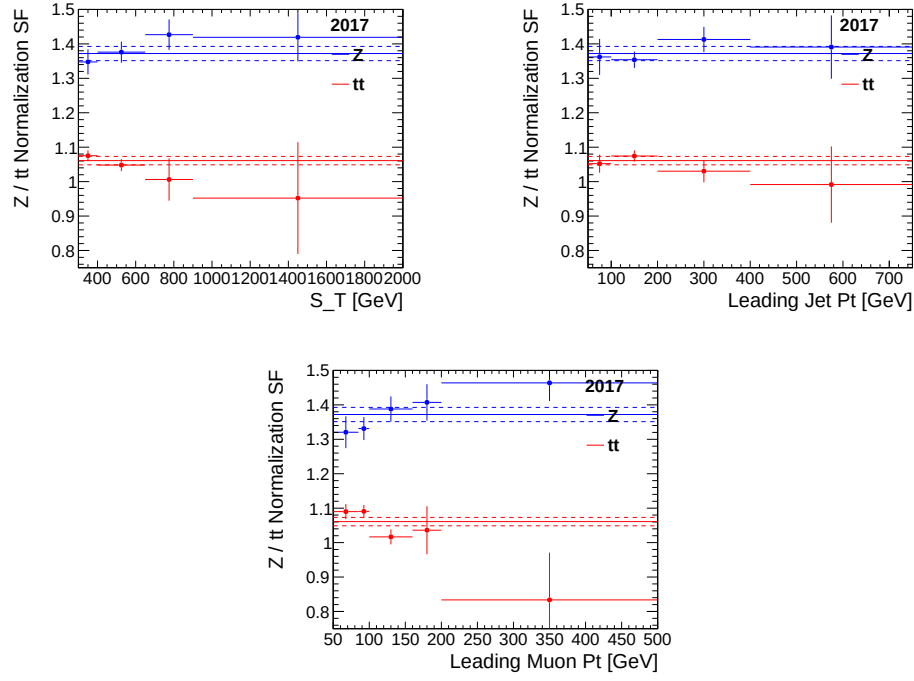


Figure B.2: $Z/\gamma^* + \text{jets}$ (red) and $t\bar{t}$ (blue) normalization scale factors and their statistical uncertainties in bins of S_T (left), $p_T(\mu_1)$ (center), and $p_T(\text{jet}_1)$ (right) in the 2017 data-taking period. The inclusive scale factors are represented by a solid horizontal line, while statistical uncertainties on the inclusive scale factors are represented by dashed lines.

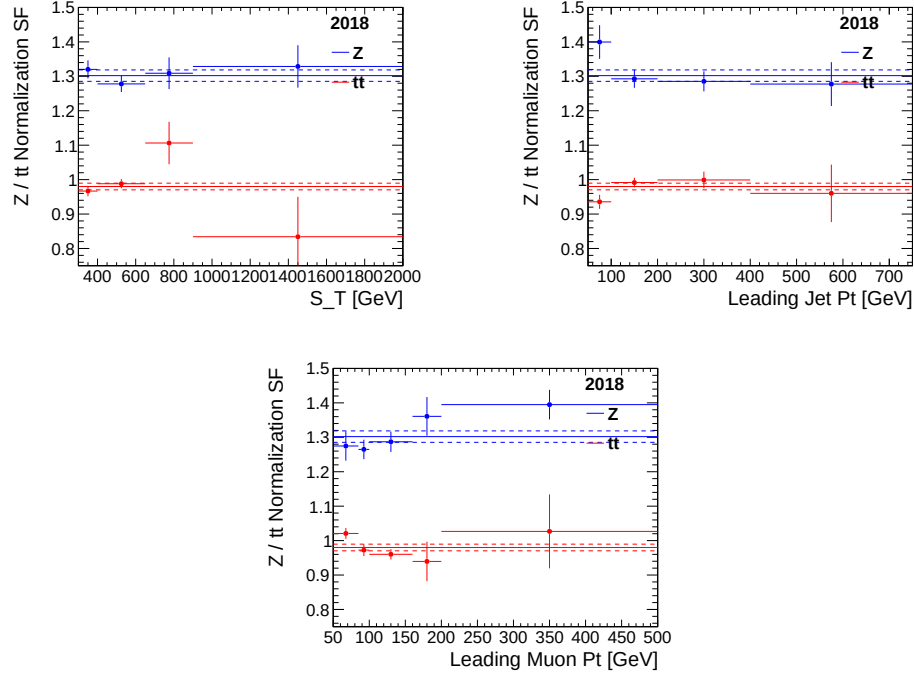


Figure B.3: $Z/\gamma^* + \text{jets}$ (red) and $t\bar{t}$ (blue) normalization scale factors and their statistical uncertainties in bins of S_T (left), $p_T(\mu_1)$ (center), and $p_T(\text{jet}_1)$ (right) in the 2018 data-taking period. The inclusive scale factors are represented by a solid horizontal line, while statistical uncertainties on the inclusive scale factors are represented by dashed lines.

Also studied was the stability of the normalization scale factors with and without topPt reweighting. Shown in Figs. B.4–B.6 are the comparisons without (left) and with (right) topPt reweighting. We in general see a better stability of the normalization scale factors after applying the topPt reweighting.

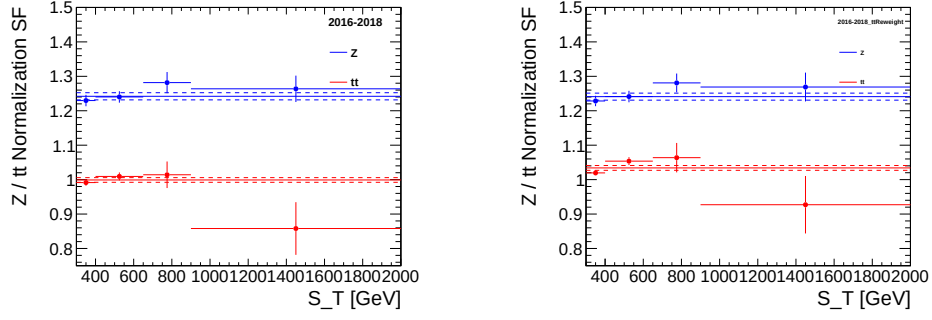


Figure B.4: $Z/\gamma^* + \text{jets}$ (red) and $t\bar{t}$ (blue) normalization scale factors and their statistical uncertainties in bins of S_T without (left) and with (right) topPt reweighting in the 2016-2018 data-taking period. The inclusive scale factors are represented by a solid horizontal line, while statistical uncertainties on the inclusive scale factors are represented by dashed lines.

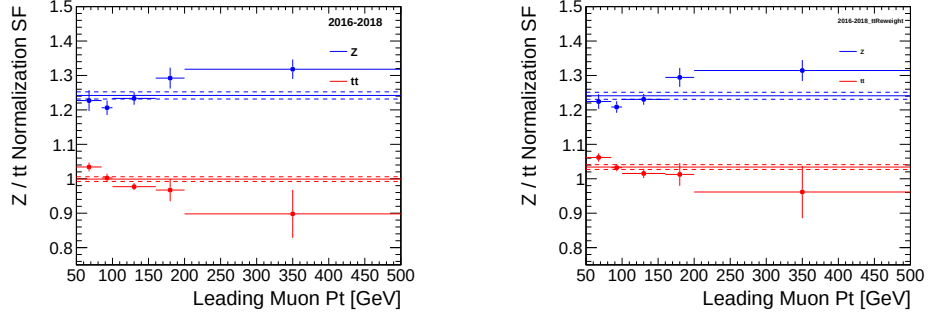


Figure B.5: $Z/\gamma^* + \text{jets}$ (red) and $t\bar{t}$ (blue) normalization scale factors and their statistical uncertainties in bins of $p_T(\mu_1)$ without (left) and with (right) topPt reweighting in the 2016-2018 data-taking period. The inclusive scale factors are represented by a solid horizontal line, while statistical uncertainties on the inclusive scale factors are represented by dashed lines.

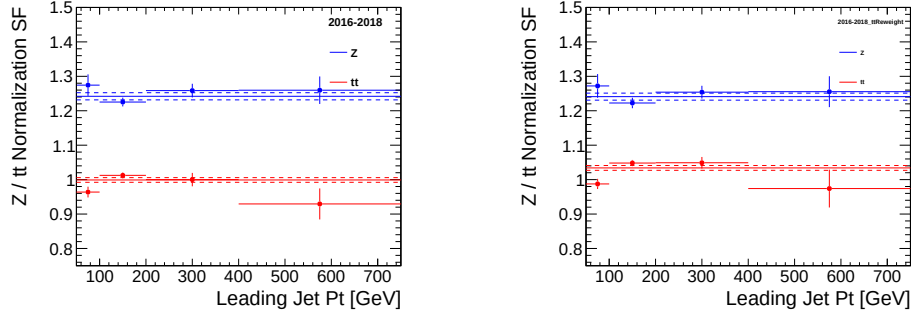


Figure B.6: $Z/\gamma^* + \text{jets}$ (red) and $t\bar{t}$ (blue) normalization scale factors and their statistical uncertainties in bins of $p_T(\text{jet}_1)$ without (left) and with (right) topPt reweighting in the 2016-2018 data-taking period. The inclusive scale factors are represented by a solid horizontal line, while statistical uncertainties on the inclusive scale factors are represented by dashed lines.

To ensure that systematic uncertainties originating from single top, $W + \text{Jets}$, $t\bar{t}V$, and diboson MC do not translate to the $Z + \text{Jets}$ and $t\bar{t}$ normalization scale factors, the “other” background simulations were varied $\pm 20\%$. Even with these variations, the background normalization scale factors agree within their errors. Table B.1 lists the background scale factors given each variation of the “other” backgrounds.

Table B.1: Background normalization scale factors for each variation in “other” backgrounds.

R_Z			$R_{t\bar{t}}$		
variation	scale factor	error (stat)	variation	scale factor	error (stat)
Nominal	1.017	0.017	Nominal	1.003	0.014
Other + 10 %	1.012	0.017	Other + 10 %	1.002	0.014
Other − 10 %	1.022	0.017	Other − 10 %	1.004	0.014
Other + 20 %	1.006	0.017	Other + 20 %	1.001	0.014
Other − 20 %	1.027	0.017	Other − 20 %	1.005	0.014

APPENDIX C

BDT performance

C.1 Training and testing

BDT training and testing is executed with the Toolkit for Multivariate Data Analysis (TMVA), a customizable machine learning environment available in ROOT [57]. Boosting is performed with the Gradient Boost algorithm, selected for its stability over other boosting methods (e.g., Adaptive Boost).

A BDT was trained for each leptoquark mass point using the combined 2016, 2017, and 2018 background and signal MC datasets described in Section 6.4. Samples have the same preselection, b-jet requirement, data and MC corrections, and background normalization scale factors applied as listed in Sections 6.2.4, 6.3, and 6.4.1. Two additional cuts are applied prior to training: one cut at $M_{\mu\mu} > 250 \text{ GeV}$ to exclude events in the background normalization control regions and a signal-dependent cut at $M_{\mu\mu jj} > M_{\text{LQ}}$, i.e., half of the $\text{LQ}\overline{\text{LQ}}$ resonance mass, to remove events far below the signal region. This additional selection ensures the training data are not dominated by background events that could result in bias. Complementary training and testing datasets are created by randomly selecting events from MC in a way that forbids any overlap. Events selected for training are reweighted such that the effective number of events in both signal and background classes are equal. Events with negative weights are ignored in training, as negative weights are not handled well in TMVA (specifically when using Gradient Boost).

A collection of 11 kinematic variables were selected as inputs to the BDT training for their ability to discriminate between signal and background:

- Invariant masses: $M_{\mu\mu}$, $M_{\mu\mu jj}$, $M_{\mu j_1}$, $M_{\mu j_2}$

- Particle momenta: $p_T(\mu_1), p_T(\mu_2), p_T(j_1), p_T(j_2)$
- Combined momenta: S_T, E_T^{miss}
- Spatial separation between the dimuon pair and the leading- p_T jet: $\Delta R(\mu_1 + \mu_2, j_1)$

Figures C.1–C.6 show the distribution of each variable in background and signal events. Linear correlations (Figs. C.7–C.12) between variables were studied alongside variable rankings to avoid including highly-correlated but low-ranking variables, which introduces information redundancy. A common risk when using Gradient Boost is overtraining, where the BDT is optimized to bias in the training samples, degrading its performance. To check for overtraining, the BDT response was compared between training and testing data using the Kolmogorov-Smirnov test; no overfitting was observed. Optimal performance of each BDT was verified by checking the area under the Receiver Operating Characteristic (ROC) curve, which plots background rejection vs. signal efficiency, shown in Figs. C.15–C.16. Figures C.13–C.14 show the BDT response in training and testing data and the corresponding ROC curves.

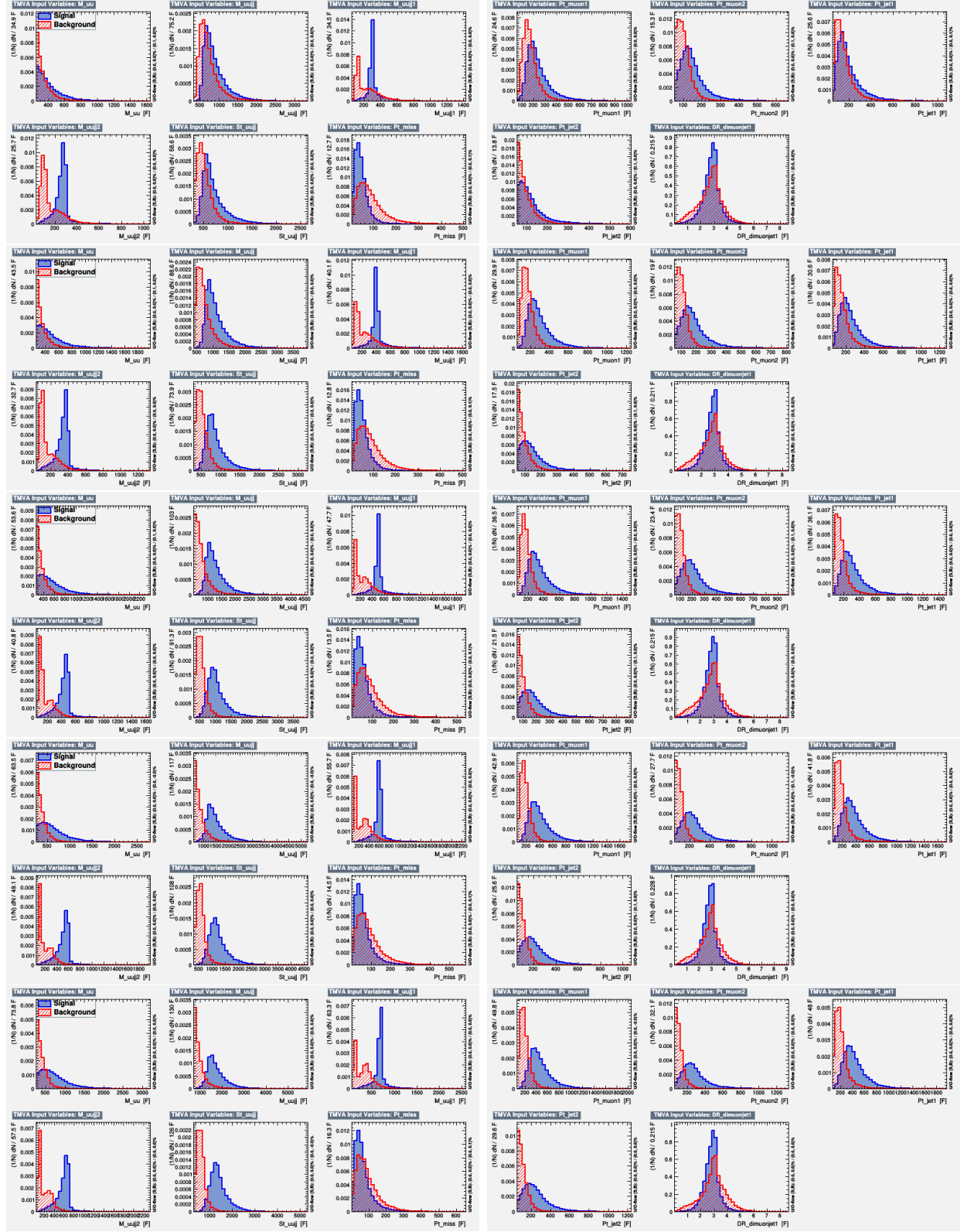


Figure C.1: A comparison between background and signal events in the BDT input variables corresponding to BDT trainings on 300 to 700 GeV leptoquark signal samples. Signal events are solid blue while background events are hashed red.

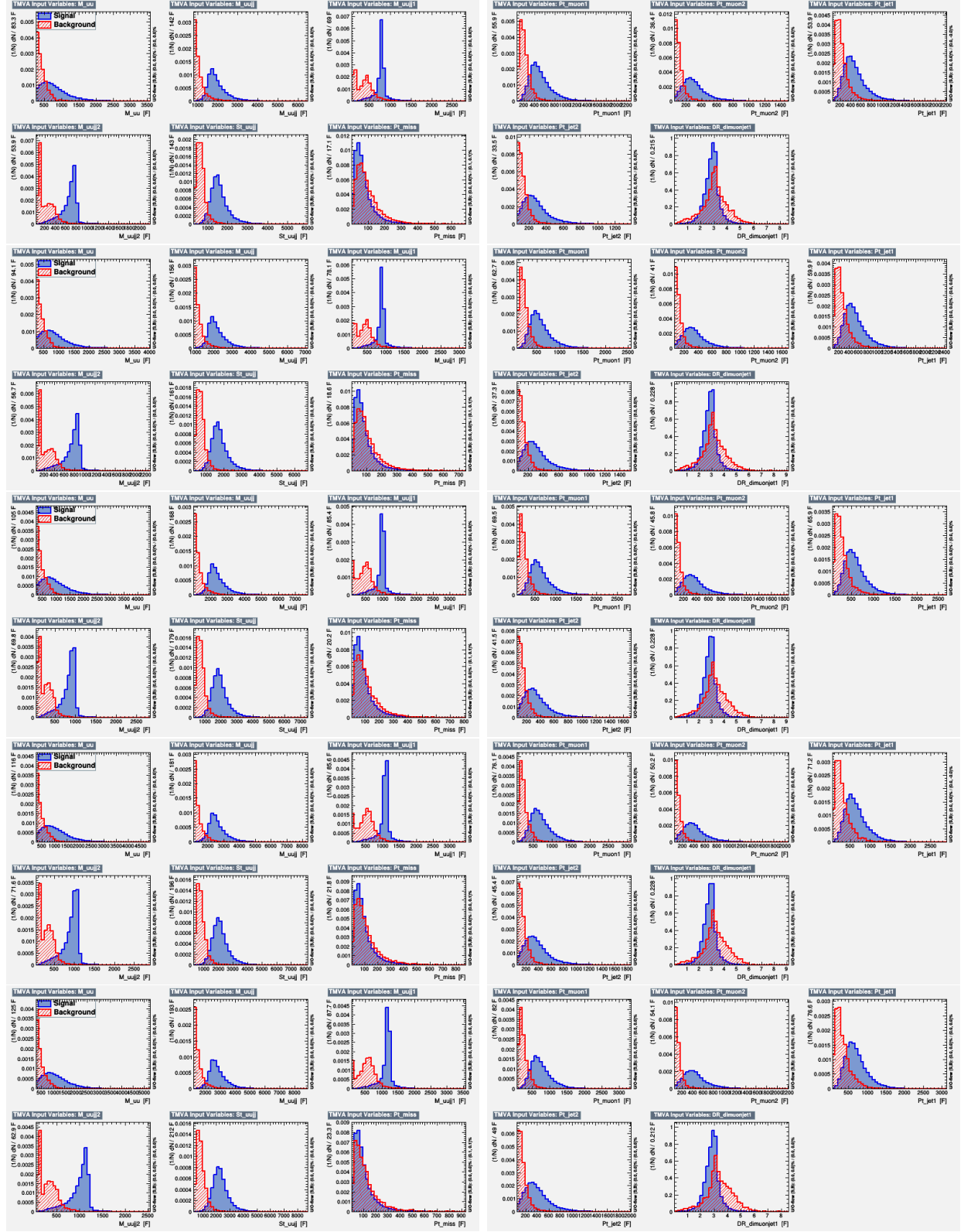


Figure C.2: A comparison between background and signal events in the BDT input variables corresponding to BDT trainings on 800 to 1200 GeV leptoquark signal samples. Signal events are solid blue while background events are hashed red.

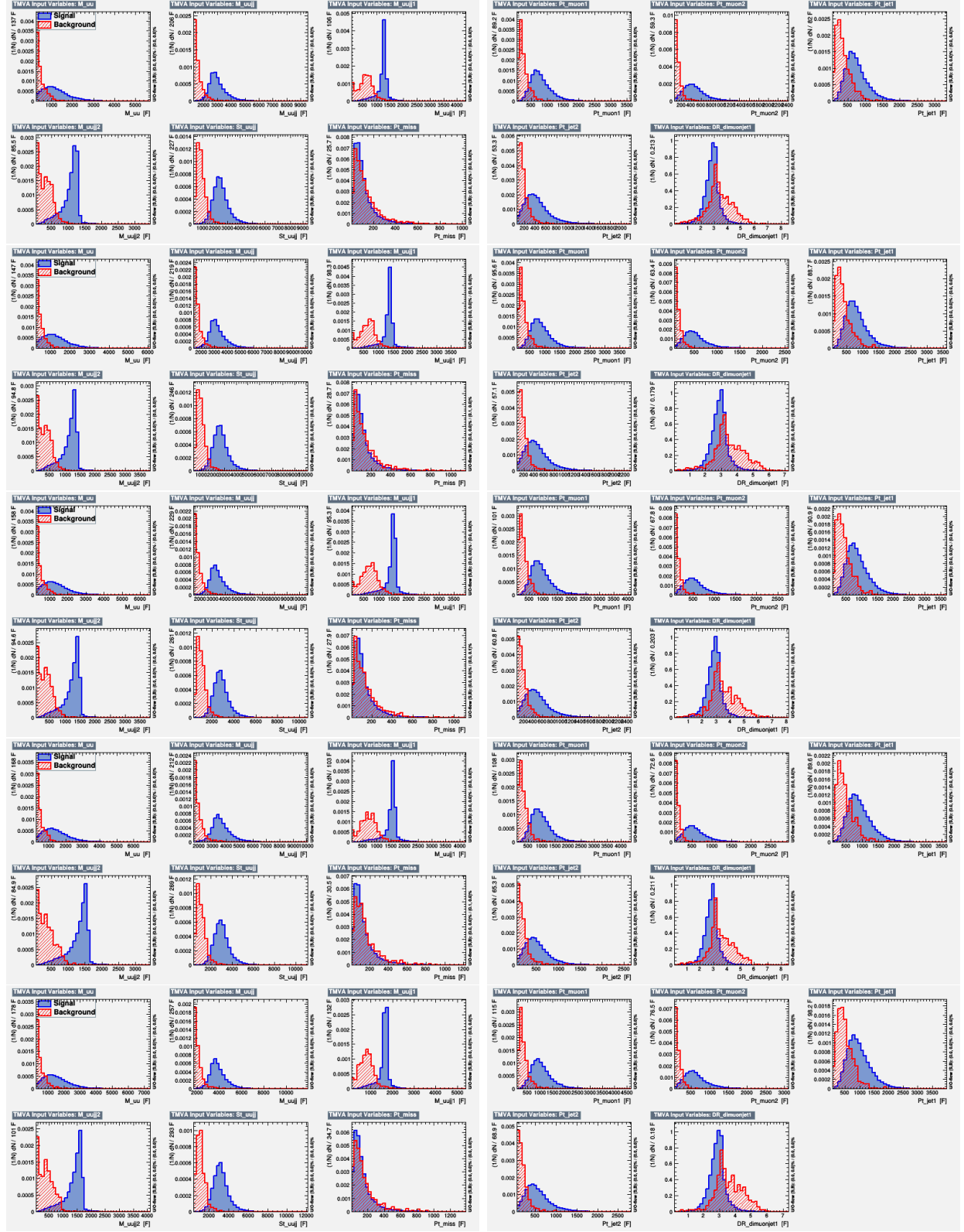


Figure C.3: A comparison between background and signal events in the BDT input variables corresponding to BDT trainings on 1300 to 1700 GeV leptoquark signal samples. Signal events are solid blue while background events are hashed red.

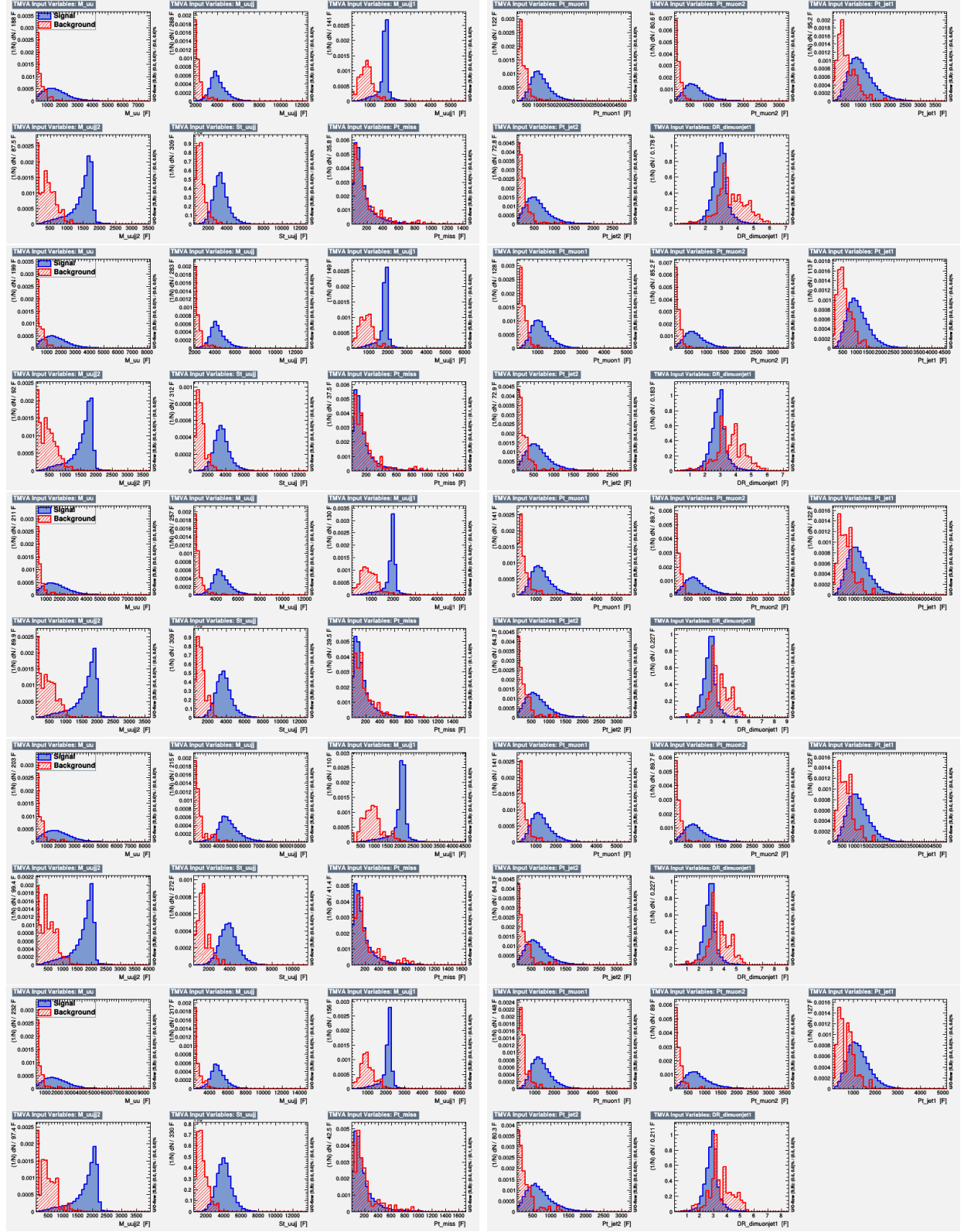


Figure C.4: A comparison between background and events in the BDT input variables corresponding to BDT trainings on 1800 to 2200 GeV leptoquark signal samples. Signal events are solid blue while background events are hashed red.

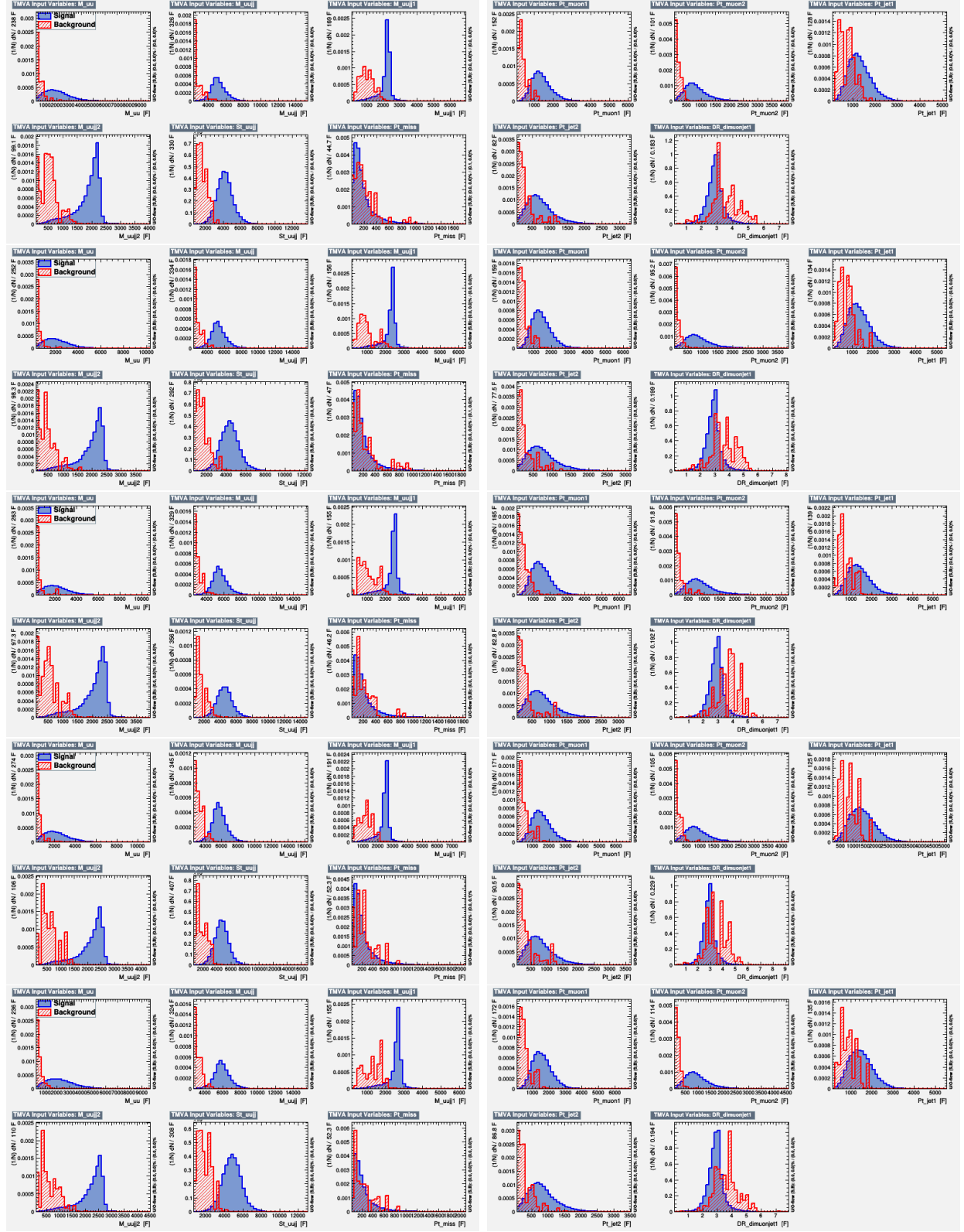


Figure C.5: A comparison between background and signal events in the BDT input variables corresponding to BDT trainings on 2300 to 2700 GeV leptoquark signal samples. Signal events are solid blue while background events are hashed red.

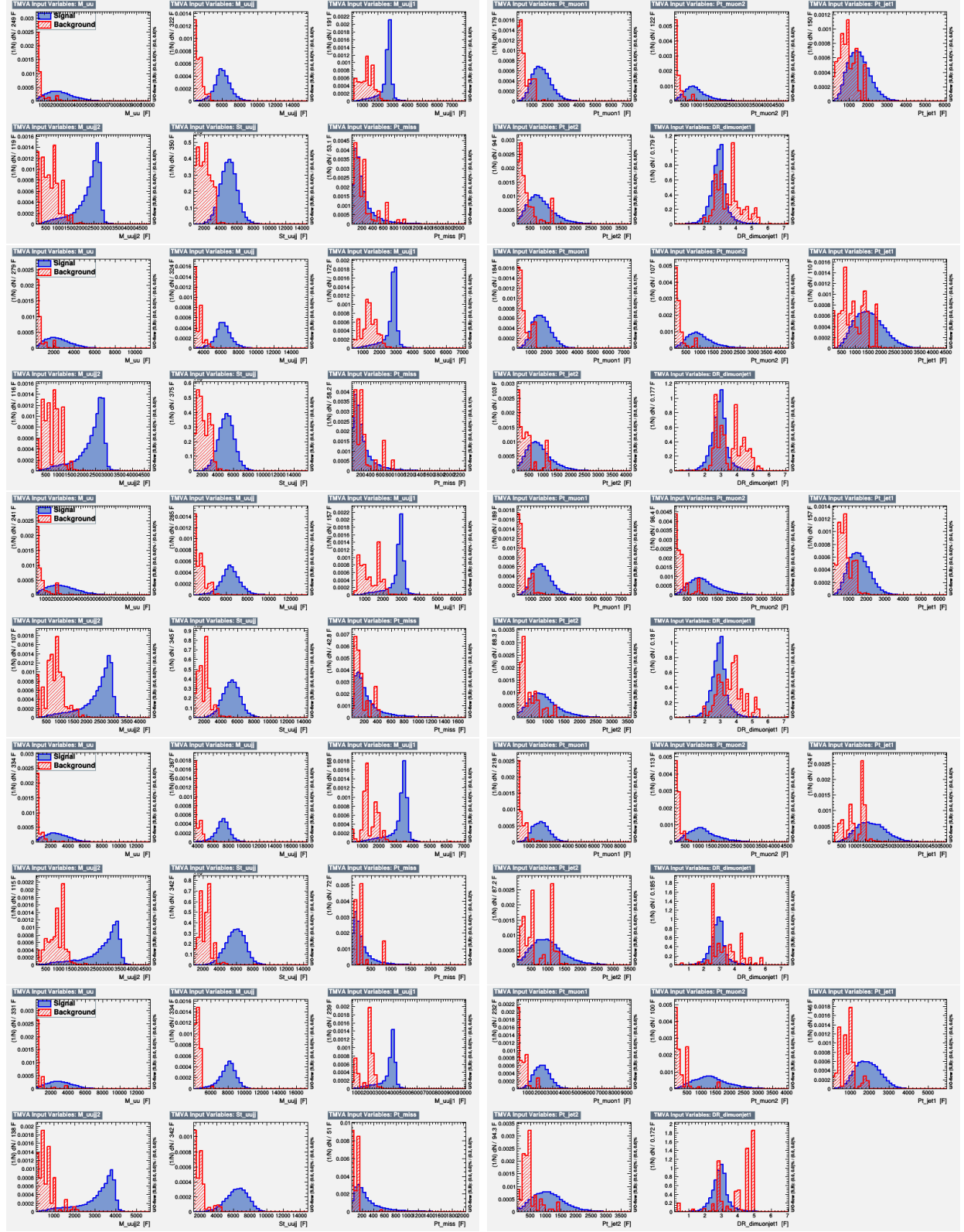


Figure C.6: A comparison between background and signal events in the BDT input variables corresponding to BDT trainings on 2800 to 4000 GeV leptoquark signal samples. Signal events are solid blue while background events are hashed red.

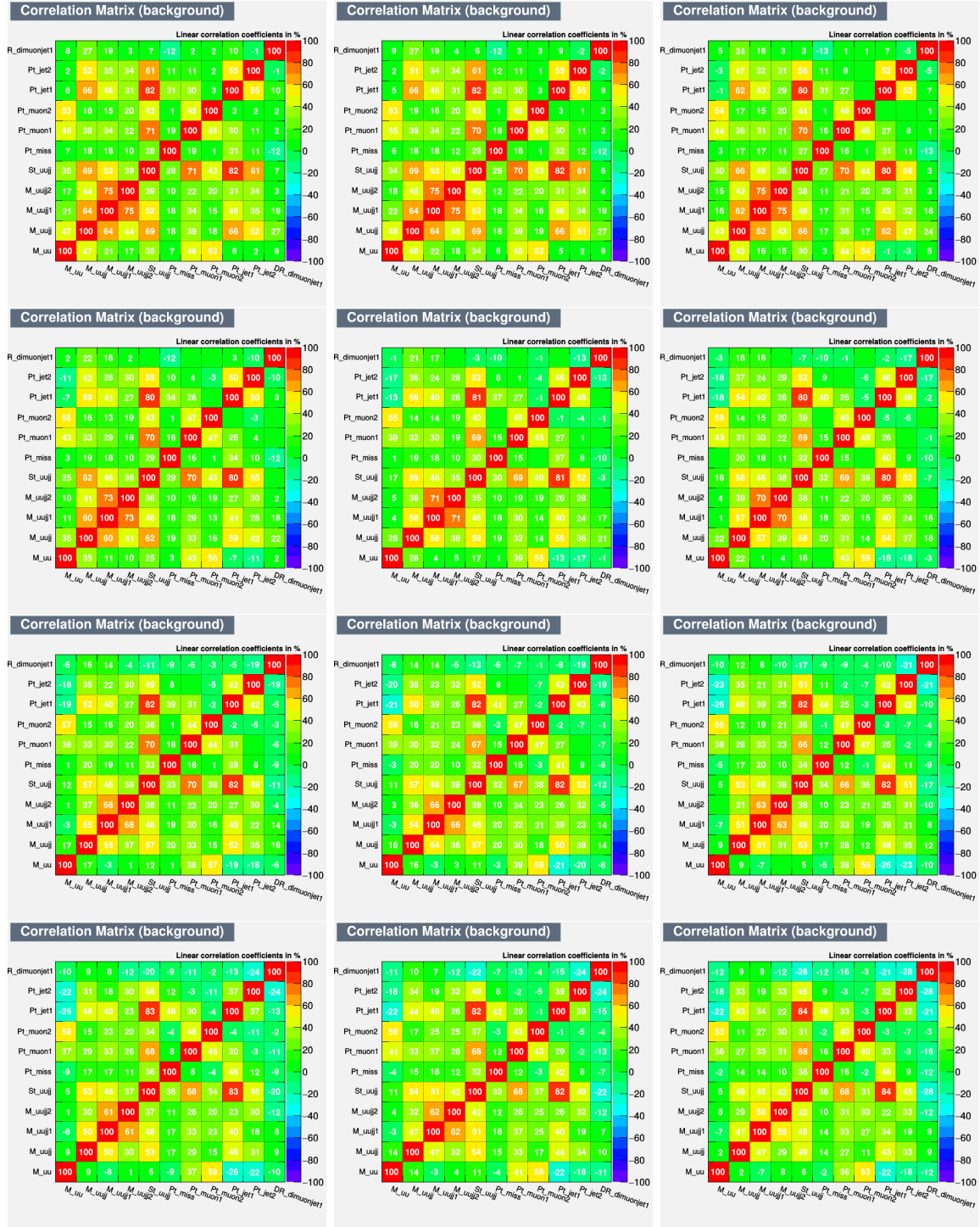


Figure C.7: The linear correlation matrices of BDT input variables in background events corresponding to BDT trainings on 300 to 1400 GeV leptoquark signal samples.

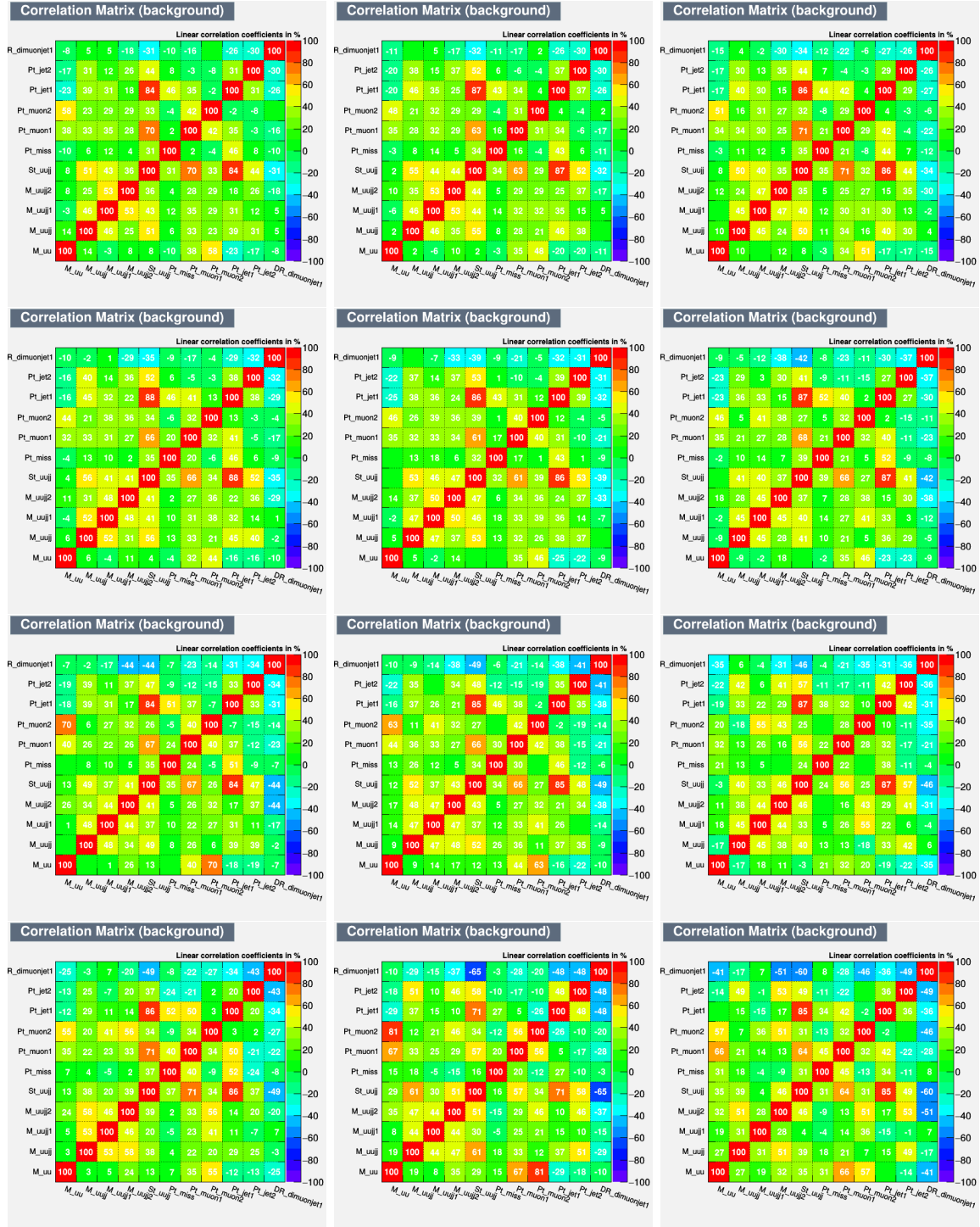


Figure C.8: The linear correlation matrices of BDT input variables in background events corresponding to BDT trainings on 1500 to 2600 GeV leptoquark signal samples.

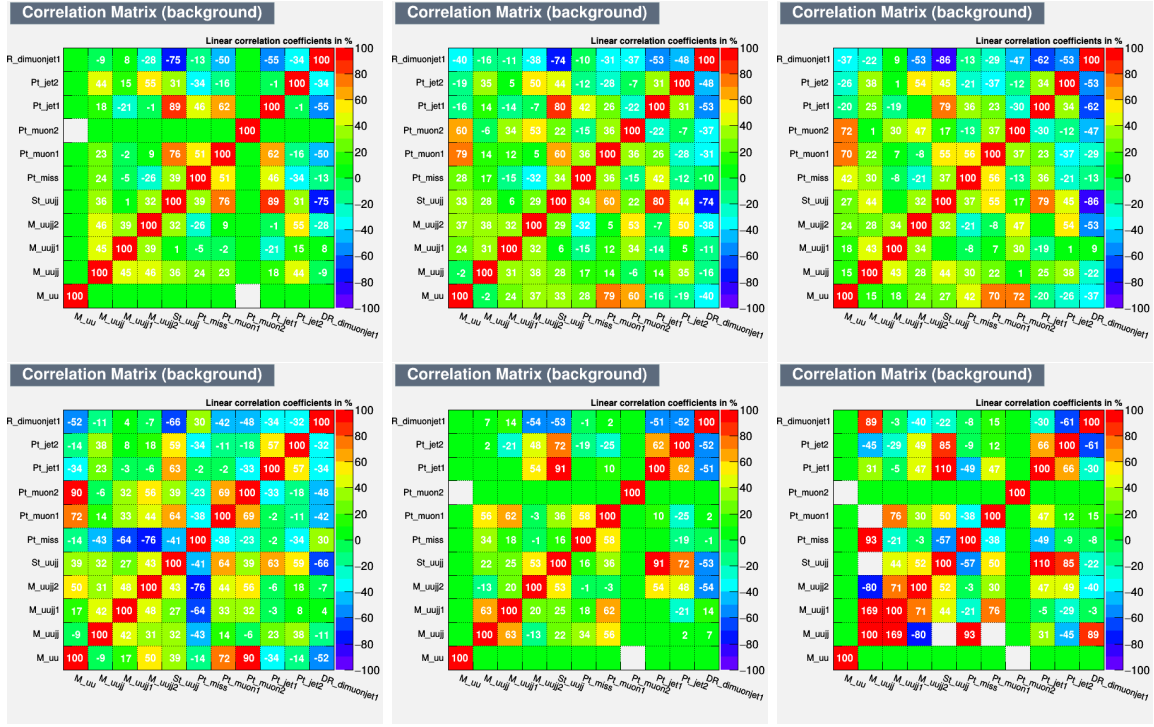


Figure C.9: The linear correlation matrices of BDT input variables in background events corresponding to BDT trainings on 2700 to 4000 GeV leptoquark signal samples.

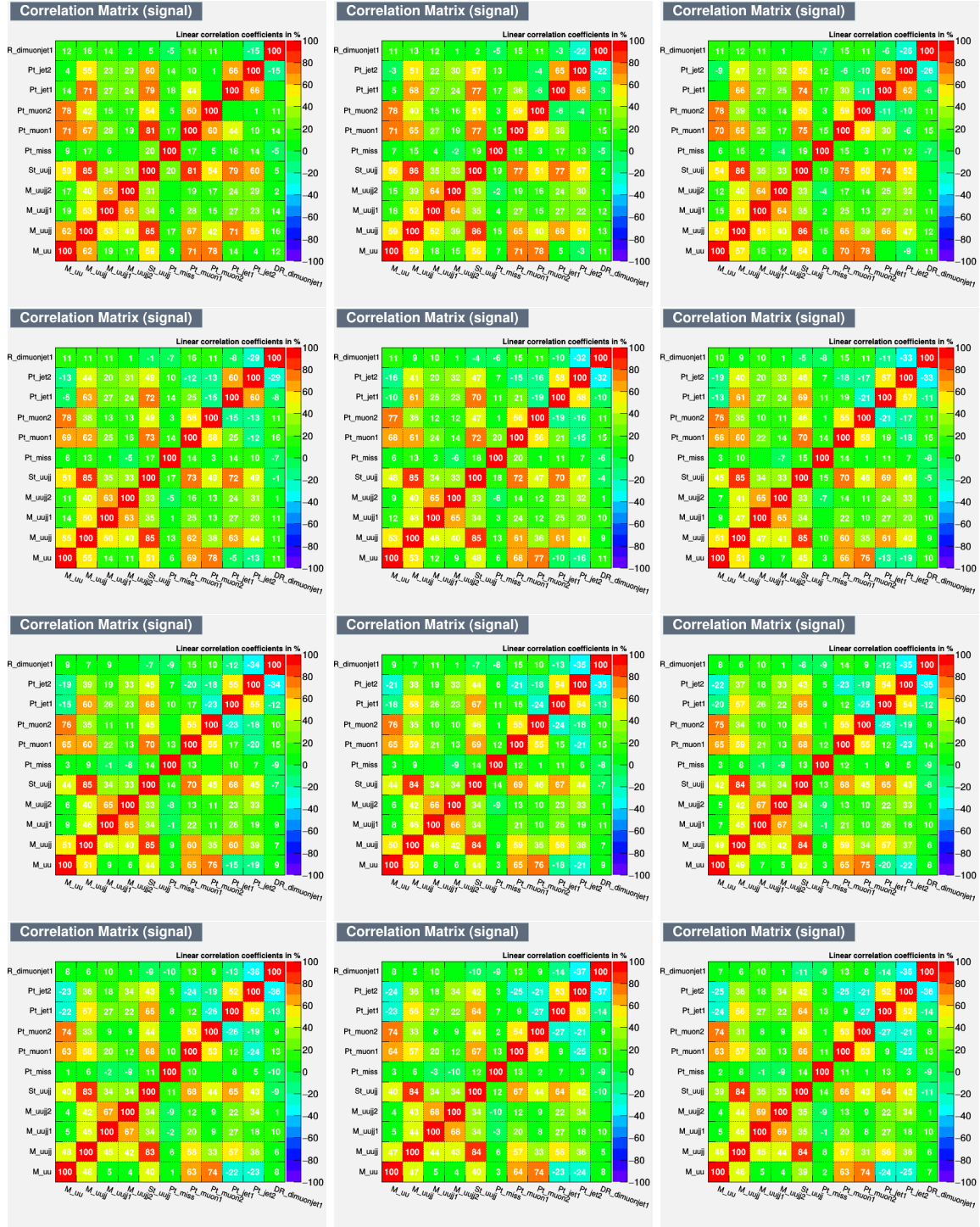
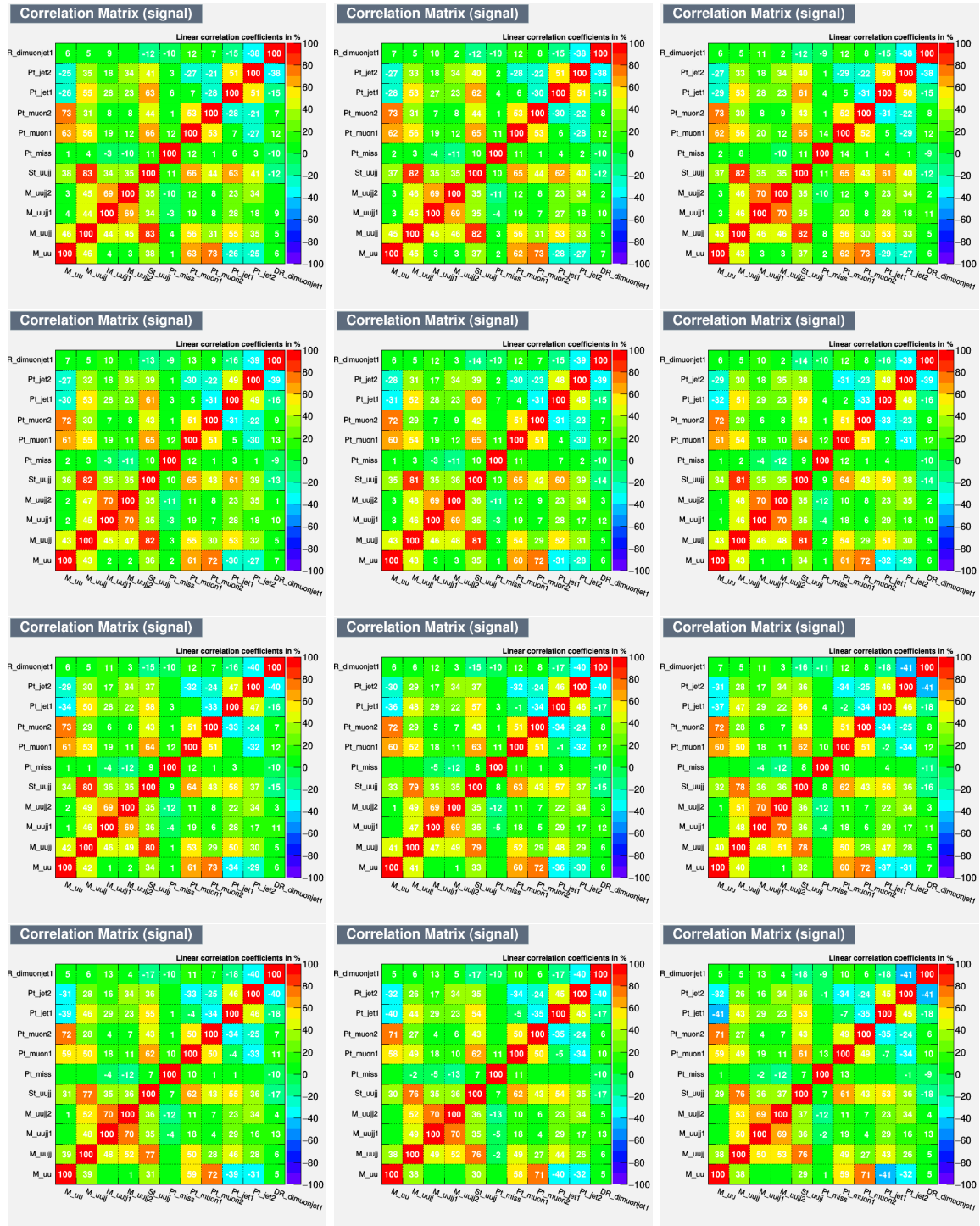


Figure C.10: The linear correlation matrices of BDT input variables in signal events corresponding to BDT trainings on 300 to 1400 GeV leptoquark signal samples.



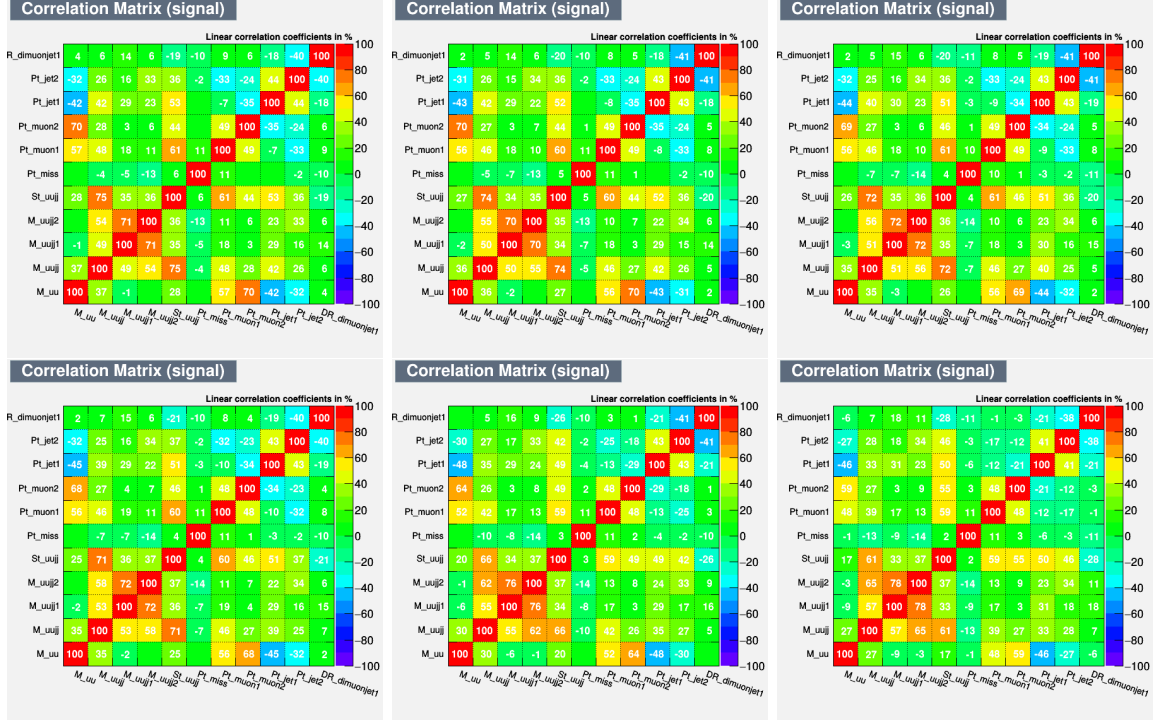


Figure C.12: The linear correlation matrices of BDT input variables in signal events corresponding to BDT trainings on 2700 to 4000 GeV leptoquark signal samples.

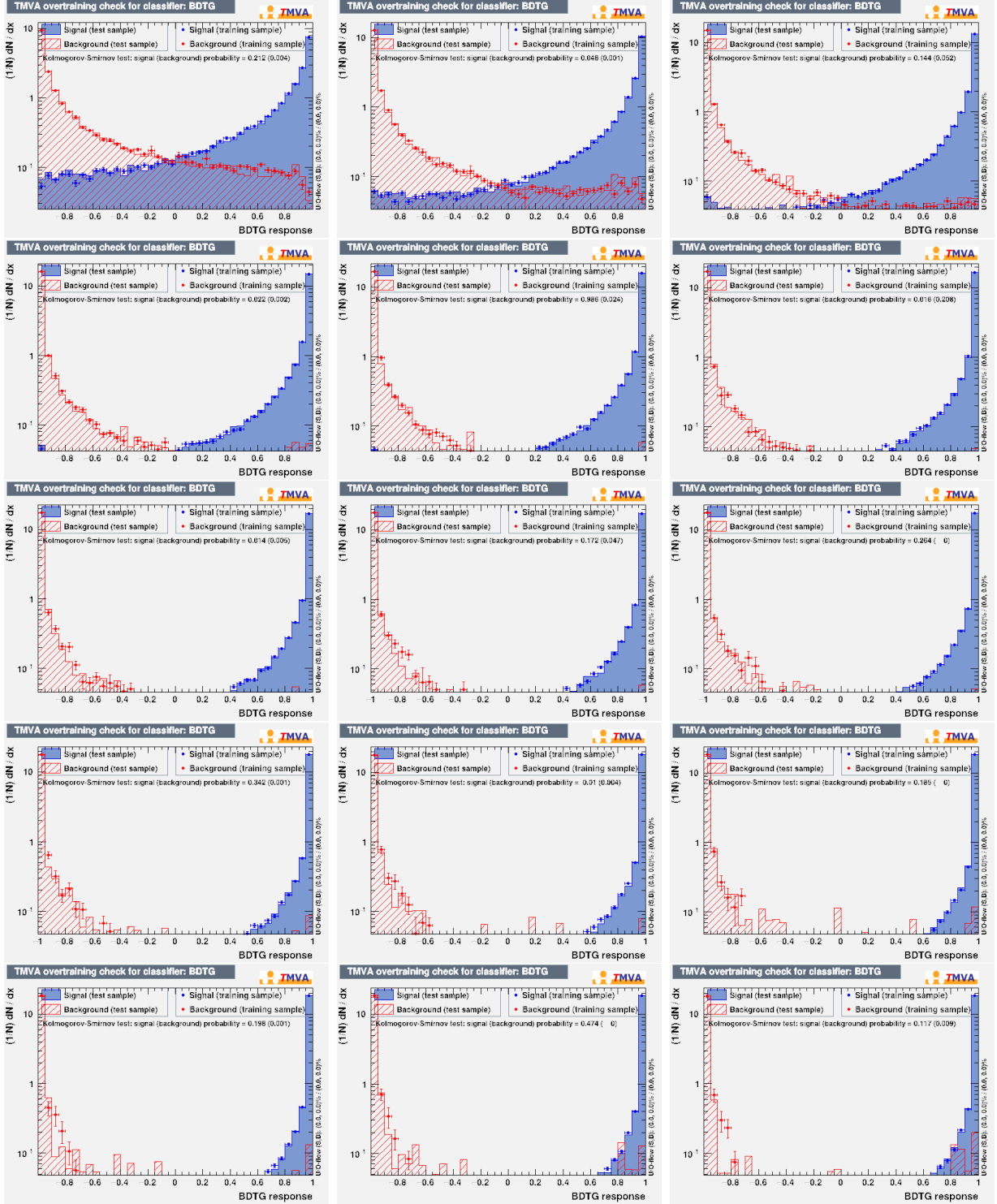


Figure C.13: The BDT responses in training and testing samples corresponding to BDT trainings on 300 to 1700 GeV leptoquark signal samples. In training, signal events are blue markers while background events are red markers (vertical bars are statistical uncertainties); in testing, signal events are the solid blue histogram while background events are the hashed red histogram.

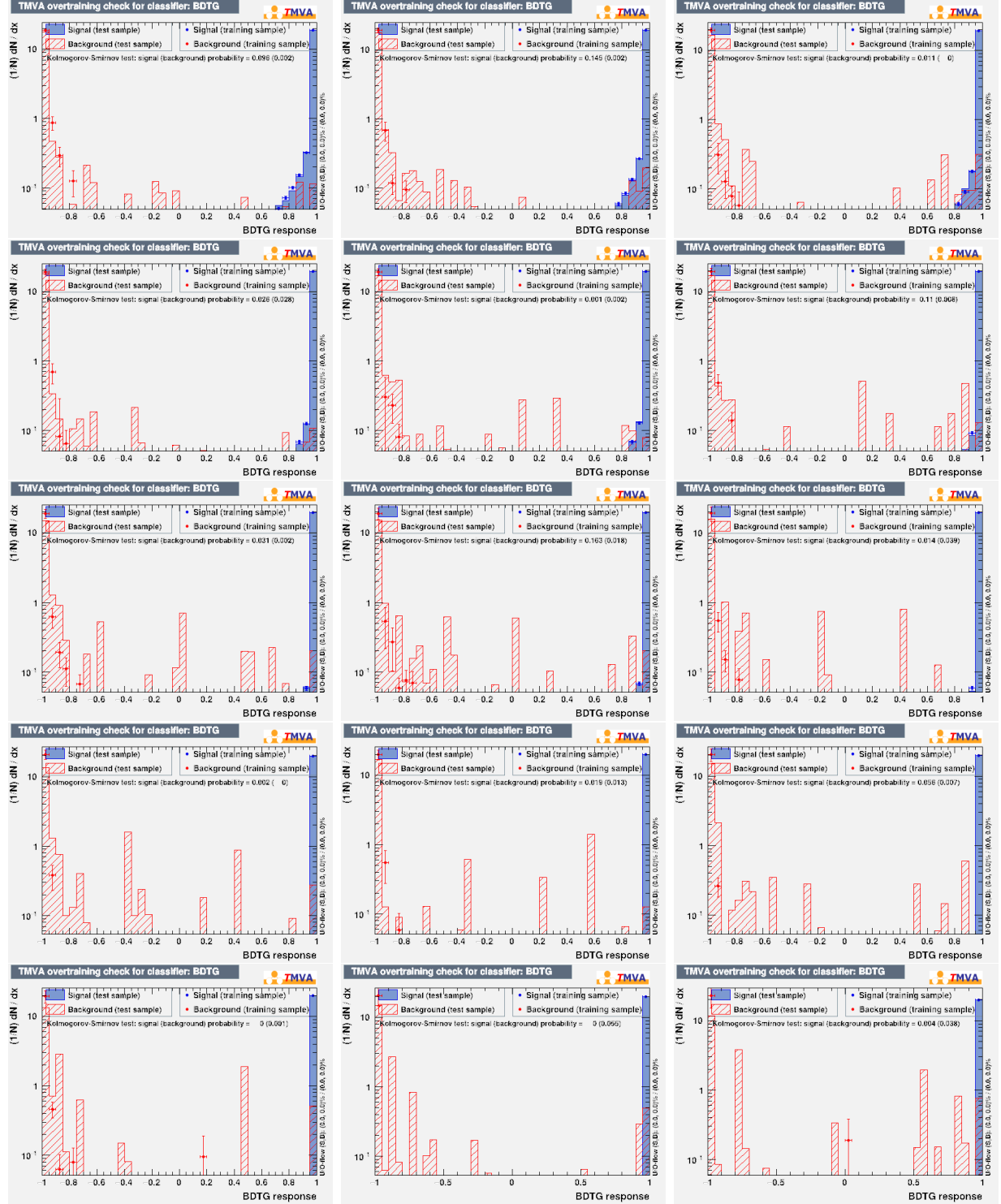


Figure C.14: The BDT responses in training and testing samples corresponding to BDT trainings on 1800 to 4000 GeV leptoquark signal samples. In training, signal events are blue markers while background events are red markers (vertical bars are statistical uncertainties); in testing, signal events are the solid blue histogram while background events are the hashed red histogram.

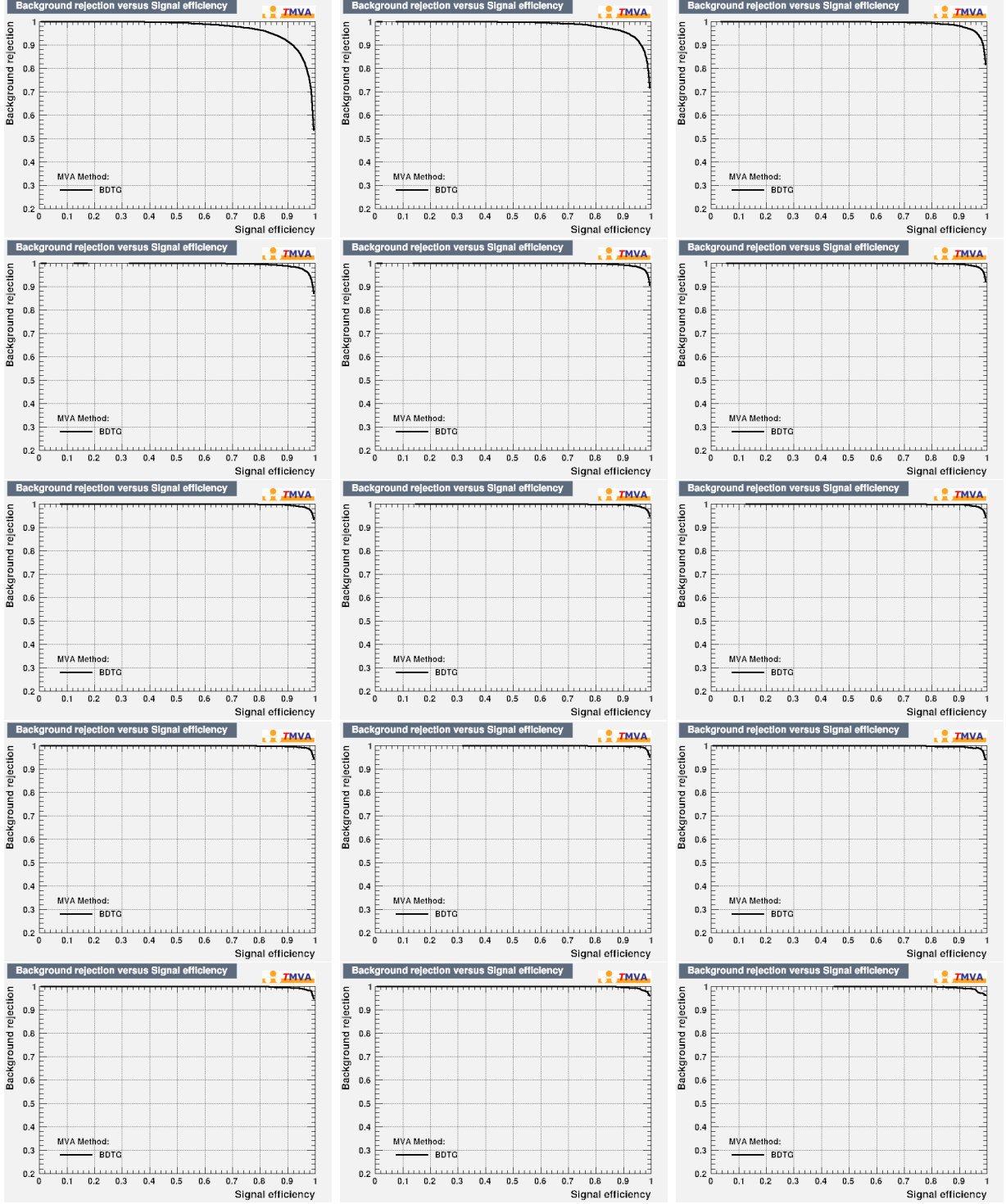


Figure C.15: The ROC curves corresponding to BDT trainings on 300 to 1700 GeV lepto-quark signal samples.

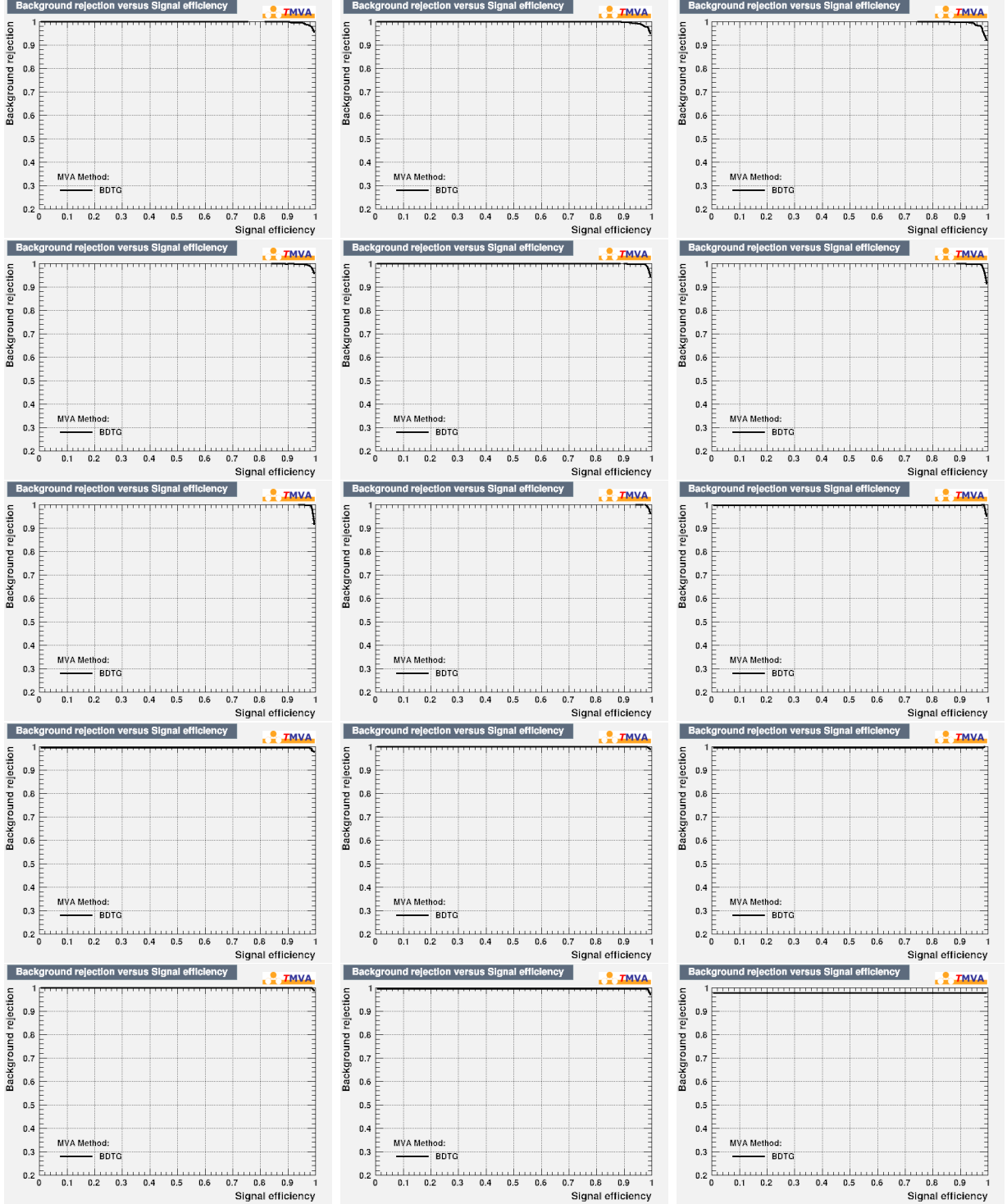


Figure C.16: The ROC curves corresponding to BDT trainings on 1800 to 4000 GeV lepto-quark signal samples.

C.2 Validation

To validate the stability of the BDTs, the impact on final results when varying the BDT training was studied for each leptoquark mass hypothesis. This study was performed with 2016, 2017, and 2018 simulation. The BDTs used are from an early training performed on just 2016 simulation, with only preselection, b-jet tag requirements, MC corrections, and background normalization applied. Additionally, the DeepJet scores of the two leading jets were included as input variables to the trainings (these were dropped for the final analysis). For each leptoquark mass hypothesis, a cut on the score of the BDT trained with the neighboring leptoquark mass point (up or down) was applied. BDT score thresholds are taken from Table 6.27 (where M_{LQ} would represent leptoquark mass point in the BDT training). Asymptotic expected upper limits at 95 % CL were set for each leptoquark mass hypothesis using the varied BDTs. Figure C.17 shows the asymptotic expected upper limit on $\sigma(pp \rightarrow LQ\bar{L}\bar{Q})$ as a function of the leptoquark mass hypothesis using the “up” and “down” varied BDTs. In the case where the BDT was trained at a leptoquark mass point below the leptoquark mass hypothesis, the lower bound placed on the leptoquark mass varied by year relative to the nominal bound. When the BDT was trained at a leptoquark mass point above the leptoquark mass hypothesis, the expected lower bound placed on the leptoquark mass was noticeably lower, compared to the nominal bound. Table C.1 lists the expected lower bounds on the leptoquark mass derived from this study for each year of data-taking. To observe BDT stability, the ratio of the expected limits (where the numerator is the “up” or “down” varied expected limit and the denominator is the nominal expected limit) is shown for 2016, 2017, and 2018 in Figure C.18.

Table C.1: Expected lower bounds on the leptoquark mass placed using a BDT trained with a leptoquark mass point equal to, varied down from, and varied up from the leptoquark mass hypothesis in 2016, 2017, and 2018 simulation. In parentheses are the percent differences of the varied lower bounds from the nominal lower bound.

Year	Expected asymptotic limit (relative difference)		
	Nominal [GeV]	Varied down [GeV] (%)	Varied up [GeV] (%)
2016	1591.2	1591.5 (0.02)	1572.9 (1.2)
2017	1597.3	1572.1 (1.6)	1578.7 (1.2)
2018	1641.6	1661.8 (1.2)	1620.2 (1.3)

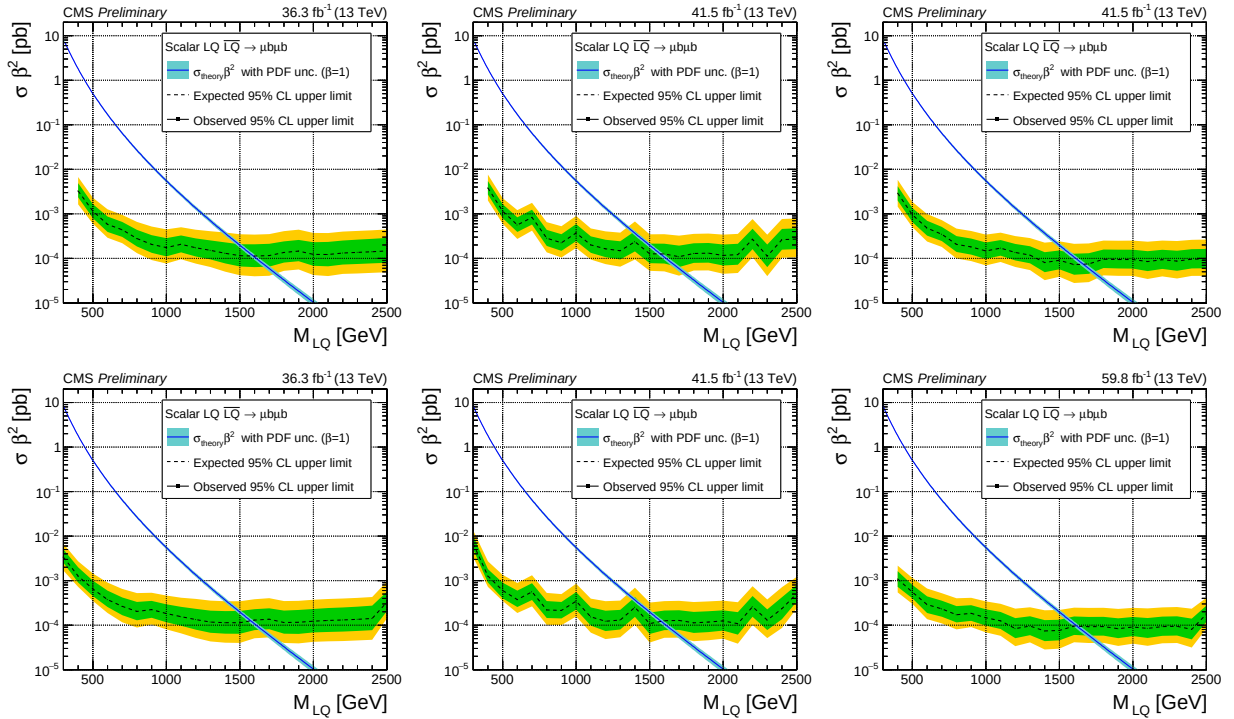


Figure C.17: The asymptotic expected upper limits at 95 % CL placed on $\sigma \times \beta^2$ at each leptoquark mass hypothesis M_{LQ} . Limits set with a BDT trained on one mass point above (top) and one mass point below (bottom) the leptoquark mass hypothesis in 2016 (left), 2017 (middle), and 2018 (right) simulation.

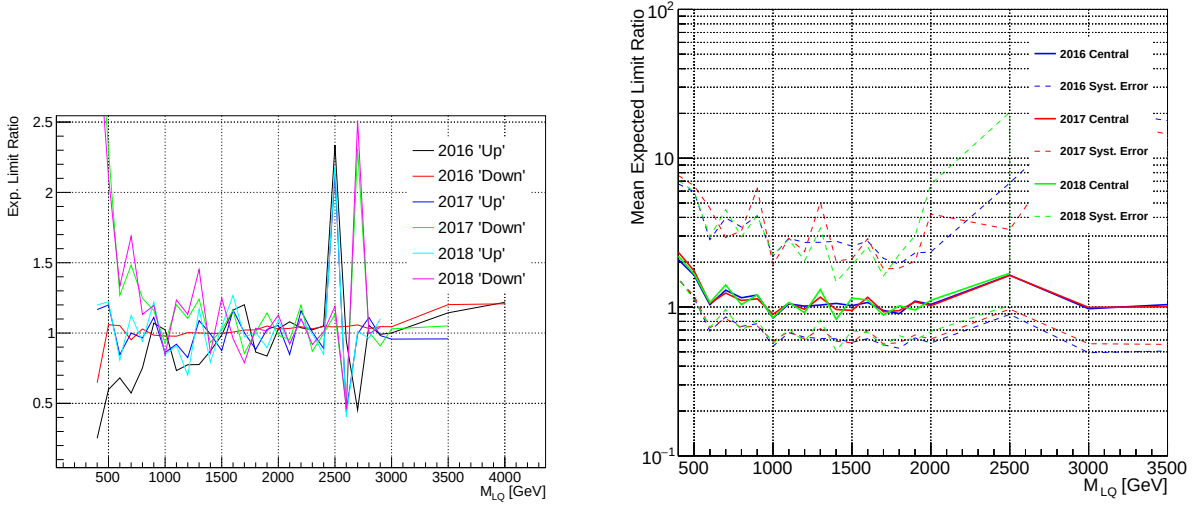


Figure C.18: (Left) The ratios of the asymptotic expected upper limits placed on $\sigma \times \beta^2$ at each leptoquark mass hypothesis, where the numerator is the limit using the “up” or “down” varied BDT training mass point and the denominator is the limit using the nominal BDT training mass point (the same mass as the leptoquark mass hypothesis). (Right) The average of the ratios over the two variations (solid lines) with uncertainty bands (dashed lines) corresponding to ± 1 standard deviations.

C.3 Input variable rankings

TMVA provides for each BDT a ranking of the input variables by their importance to the training. Importance here can be understood as a measure of the variable’s discrimination power, so higher ranking variables contribute more to the separation of signal and background. Several precise definitions of importance are provided in Ref. [57]. We use the BDT-specific ranking, which defines the importance of a variable (ranging from 0 to 1), as the frequency it is used to split decision tree nodes, weighted by the separation gain squared and the number of events in the node. The ranking and importance of all 11 input variables in each BDT are provided in Tables C.2–C.31.

Table C.2: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 300 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.316e-01
2.	$M_{\mu j_1}$	1.175e-01
3.	$p_T(\mu_2)$	1.078e-01
4.	$M_{\mu\mu}$	9.792e-02
5.	$\Delta R(\mu_1 + \mu_2, j_1)$	9.611e-02
6.	$M_{\mu\mu jj}$	8.920e-02
7.	E_T^{miss}	8.023e-02
8.	$p_T(\mu_1)$	7.219e-02
9.	$p_T(j_1)$	7.099e-02
10.	$p_T(j_2)$	6.964e-02
11.	S_T	6.688e-02

Table C.3: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 400 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.339e-01
2.	$M_{\mu j_1}$	1.312e-01
3.	$\Delta R(\mu_1 + \mu_2, j_1)$	1.049e-01
4.	$M_{\mu \mu jj}$	8.754e-02
5.	$p_{\text{T}}(\mu_2)$	8.529e-02
6.	$E_{\text{T}}^{\text{miss}}$	8.105e-02
7.	S_{T}	8.096e-02
8.	$p_{\text{T}}(j_1)$	8.011e-02
9.	$p_{\text{T}}(j_2)$	7.305e-02
10.	$M_{\mu \mu}$	7.226e-02
11.	$p_{\text{T}}(\mu_1)$	6.969e-02

Table C.4: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 500 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.260e-01
2.	$M_{\mu j_1}$	1.260e-01
3.	S_T	9.914e-02
4.	$\Delta R(\mu_1 + \mu_2, j_1)$	9.020e-02
5.	$p_T(\mu_2)$	8.933e-02
6.	$p_T(j_1)$	8.659e-02
7.	$M_{\mu\mu jj}$	8.243e-02
8.	$p_T(j_2)$	7.572e-02
9.	$p_T(\mu_1)$	7.554e-02
10.	E_T^{miss}	7.515e-02
11.	$M_{\mu\mu}$	7.386e-02

Table C.5: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 600 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.336e-01
2.	$M_{\mu j_1}$	1.230e-01
3.	S_T	1.132e-01
4.	$M_{\mu\mu jj}$	8.680e-02
5.	$p_T(\mu_2)$	8.241e-02
6.	$p_T(j_1)$	8.165e-02
7.	$p_T(\mu_1)$	8.148e-02
8.	E_T^{miss}	7.777e-02
9.	$\Delta R(\mu_1 + \mu_2, j_1)$	7.666e-02
10.	$M_{\mu\mu}$	7.424e-02
11.	$p_T(j_2)$	6.916e-02

Table C.6: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 700 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_1}$	1.330e-01
2.	$M_{\mu j_2}$	1.254e-01
3.	S_T	1.213e-01
4.	$M_{\mu\mu jj}$	9.052e-02
5.	$p_T(j_1)$	8.495e-02
6.	$p_T(\mu_2)$	7.970e-02
7.	$p_T(j_2)$	7.909e-02
8.	$p_T(\mu_1)$	7.734e-02
9.	E_T^{miss}	7.557e-02
10.	$\Delta R(\mu_1 + \mu_2, j_1)$	6.755e-02
11.	$M_{\mu\mu}$	6.561e-02

Table C.7: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 800 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_1}$	1.261e-01
2.	$M_{\mu j_2}$	1.244e-01
3.	S_T	1.201e-01
4.	E_T^{miss}	9.470e-02
5.	$M_{\mu\mu jj}$	8.987e-02
6.	$p_T(\mu_1)$	8.710e-02
7.	$p_T(\mu_2)$	8.143e-02
8.	$p_T(j_1)$	7.737e-02
9.	$p_T(j_2)$	7.279e-02
10.	$M_{\mu\mu}$	6.371e-02
11.	$\Delta R(\mu_1 + \mu_2, j_1)$	6.240e-02

Table C.8: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 900 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	S_T	1.390e-01
2.	$M_{\mu j_1}$	1.197e-01
3.	$M_{\mu j_2}$	1.178e-01
4.	$M_{\mu \mu jj}$	9.077e-02
5.	E_T^{miss}	8.502e-02
6.	$p_T(\mu_2)$	8.346e-02
7.	$p_T(\mu_1)$	7.988e-02
8.	$p_T(j_2)$	7.885e-02
9.	$p_T(j_1)$	7.117e-02
10.	$\Delta R(\mu_1 + \mu_2, j_1)$	6.851e-02
11.	$M_{\mu\mu}$	6.585e-02

Table C.9: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 1000 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	S_T	1.532e-01
2.	$M_{\mu j_2}$	1.275e-01
3.	$M_{\mu j_1}$	1.053e-01
4.	$M_{\mu\mu jj}$	9.230e-02
5.	$p_T(\mu_2)$	8.575e-02
6.	$p_T(\mu_1)$	8.449e-02
7.	$p_T(j_1)$	7.982e-02
8.	$p_T(j_2)$	7.372e-02
9.	E_T^{miss}	7.007e-02
10.	$M_{\mu\mu}$	6.714e-02
11.	$\Delta R(\mu_1 + \mu_2, j_1)$	6.071e-02

Table C.10: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 1100 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.276e-01
2.	S_T	1.229e-01
3.	E_T^{miss}	1.127e-01
4.	$M_{\mu j_1}$	1.016e-01
5.	$M_{\mu \mu jj}$	1.000e-01
6.	$p_T(\mu_1)$	8.213e-02
7.	$p_T(\mu_2)$	7.891e-02
8.	$p_T(j_1)$	7.566e-02
9.	$p_T(j_2)$	7.151e-02
10.	$\Delta R(\mu_1 + \mu_2, j_1)$	6.404e-02
11.	$M_{\mu\mu}$	6.297e-02

Table C.11: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 1200 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.494e-01
2.	S_{T}	1.323e-01
3.	$M_{\mu j_1}$	1.096e-01
4.	$M_{\mu\mu jj}$	9.828e-02
5.	$p_{\text{T}}(\mu_1)$	8.315e-02
6.	$p_{\text{T}}(\mu_2)$	8.204e-02
7.	$E_{\text{T}}^{\text{miss}}$	7.737e-02
8.	$p_{\text{T}}(j_2)$	7.249e-02
9.	$p_{\text{T}}(j_1)$	6.929e-02
10.	$M_{\mu\mu}$	6.444e-02
11.	$\Delta R(\mu_1 + \mu_2, j_1)$	6.156e-02

Table C.12: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 1300 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.492e-01
2.	S_{T}	1.296e-01
3.	$M_{\mu j_1}$	1.174e-01
4.	$M_{\mu\mu jj}$	1.057e-01
5.	$p_{\text{T}}(j_2)$	8.238e-02
6.	$p_{\text{T}}(\mu_1)$	8.118e-02
7.	$p_{\text{T}}(\mu_2)$	8.056e-02
8.	$p_{\text{T}}(j_1)$	6.887e-02
9.	$M_{\mu\mu}$	6.694e-02
10.	$E_{\text{T}}^{\text{miss}}$	6.032e-02
11.	$\Delta R(\mu_1 + \mu_2, j_1)$	5.788e-02

Table C.13: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 1400 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.537e-01
2.	$M_{\mu j_1}$	1.209e-01
3.	S_{T}	1.019e-01
4.	$M_{\mu \mu jj}$	1.007e-01
5.	$p_{\text{T}}(\mu_2)$	8.807e-02
6.	$p_{\text{T}}(j_2)$	8.733e-02
7.	$p_{\text{T}}(\mu_1)$	7.619e-02
8.	$p_{\text{T}}(j_1)$	7.316e-02
9.	$M_{\mu \mu}$	7.111e-02
10.	$\Delta R(\mu_1 + \mu_2, j_1)$	7.100e-02
11.	$E_{\text{T}}^{\text{miss}}$	5.591e-02

Table C.14: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 1500 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.400e-01
2.	S_{T}	1.150e-01
3.	$M_{\mu j_1}$	1.147e-01
4.	$M_{\mu \mu jj}$	9.521e-02
5.	$M_{\mu \mu}$	8.781e-02
6.	$p_{\text{T}}(j_2)$	8.158e-02
7.	$p_{\text{T}}(\mu_2)$	8.020e-02
8.	$p_{\text{T}}(\mu_1)$	7.542e-02
9.	$E_{\text{T}}^{\text{miss}}$	7.245e-02
10.	$p_{\text{T}}(j_1)$	6.946e-02
11.	$\Delta R(\mu_1 + \mu_2, j_1)$	6.821e-02

Table C.15: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 1600 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.338e-01
2.	S_{T}	1.227e-01
3.	$p_{\text{T}}(j_2)$	1.111e-01
4.	$M_{\mu\mu jj}$	1.002e-01
5.	$M_{\mu j_1}$	9.860e-02
6.	$p_{\text{T}}(\mu_2)$	8.682e-02
7.	$p_{\text{T}}(\mu_1)$	8.278e-02
8.	$M_{\mu\mu}$	7.693e-02
9.	$p_{\text{T}}(j_1)$	7.581e-02
10.	$\Delta R(\mu_1 + \mu_2, j_1)$	6.950e-02
11.	$E_{\text{T}}^{\text{miss}}$	4.178e-02

Table C.16: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 1700 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.328e-01
2.	S_{T}	1.300e-01
3.	$M_{\mu j_1}$	9.870e-02
4.	$M_{\mu \mu jj}$	9.638e-02
5.	$p_{\text{T}}(\mu_2)$	9.447e-02
6.	$M_{\mu \mu}$	9.214e-02
7.	$p_{\text{T}}(j_2)$	8.244e-02
8.	$p_{\text{T}}(\mu_1)$	7.774e-02
9.	$p_{\text{T}}(j_1)$	7.601e-02
10.	$\Delta R(\mu_1 + \mu_2, j_1)$	7.192e-02
11.	$E_{\text{T}}^{\text{miss}}$	4.745e-02

Table C.17: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 1800 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.471e-01
2.	S_{T}	1.389e-01
3.	$M_{\mu j_1}$	9.756e-02
4.	$M_{\mu\mu jj}$	9.420e-02
5.	$p_{\text{T}}(j_2)$	8.762e-02
6.	$p_{\text{T}}(\mu_2)$	8.128e-02
7.	$p_{\text{T}}(\mu_1)$	7.982e-02
8.	$\Delta R(\mu_1 + \mu_2, j_1)$	7.767e-02
9.	$p_{\text{T}}(j_1)$	7.610e-02
10.	$M_{\mu\mu}$	7.398e-02
11.	$E_{\text{T}}^{\text{miss}}$	4.582e-02

Table C.18: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 1900 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.472e-01
2.	S_{T}	1.046e-01
3.	$M_{\mu j_1}$	1.040e-01
4.	$M_{\mu \mu jj}$	1.039e-01
5.	$p_{\text{T}}(j_2)$	9.580e-02
6.	$\Delta R(\mu_1 + \mu_2, j_1)$	8.885e-02
7.	$p_{\text{T}}(\mu_2)$	8.688e-02
8.	$M_{\mu \mu}$	8.062e-02
9.	$p_{\text{T}}(j_1)$	7.420e-02
10.	$p_{\text{T}}(\mu_1)$	6.843e-02
11.	$E_{\text{T}}^{\text{miss}}$	4.545e-02

Table C.19: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 2000 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.528e-01
2.	$M_{\mu \mu jj}$	1.229e-01
3.	$M_{\mu j_1}$	1.052e-01
4.	S_T	9.633e-02
5.	$p_T(\mu_2)$	8.396e-02
6.	$M_{\mu\mu}$	8.386e-02
7.	$p_T(\mu_1)$	8.246e-02
8.	$p_T(j_2)$	7.480e-02
9.	$p_T(j_1)$	7.391e-02
10.	$\Delta R(\mu_1 + \mu_2, j_1)$	6.636e-02
11.	E_T^{miss}	5.742e-02

Table C.20: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 2100 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.394e-01
2.	$M_{\mu \mu jj}$	1.102e-01
3.	$M_{\mu j_1}$	1.079e-01
4.	S_{T}	9.849e-02
5.	$p_{\text{T}}(j_2)$	9.170e-02
6.	$p_{\text{T}}(\mu_2)$	9.073e-02
7.	$M_{\mu\mu}$	8.948e-02
8.	$\Delta R(\mu_1 + \mu_2, j_1)$	8.067e-02
9.	$p_{\text{T}}(\mu_1)$	7.590e-02
10.	$p_{\text{T}}(j_1)$	6.403e-02
11.	$E_{\text{T}}^{\text{miss}}$	5.145e-02

Table C.21: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 2200 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.464e-01
2.	$M_{\mu j_1}$	1.039e-01
3.	$M_{\mu \mu jj}$	1.017e-01
4.	S_{T}	9.975e-02
5.	$p_{\text{T}}(j_2)$	9.502e-02
6.	$M_{\mu \mu}$	8.895e-02
7.	$p_{\text{T}}(\mu_2)$	8.560e-02
8.	$p_{\text{T}}(j_1)$	7.941e-02
9.	$p_{\text{T}}(\mu_1)$	7.663e-02
10.	$\Delta R(\mu_1 + \mu_2, j_1)$	7.222e-02
11.	$E_{\text{T}}^{\text{miss}}$	5.051e-02

Table C.22: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 2300$ GeV signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.442e-01
2.	$M_{\mu\mu}$	1.015e-01
3.	$M_{\mu\mu jj}$	9.754e-02
4.	$p_T(j_2)$	9.717e-02
5.	$M_{\mu j_1}$	9.690e-02
6.	S_T	9.601e-02
7.	$p_T(\mu_2)$	9.404e-02
8.	$\Delta R(\mu_1 + \mu_2, j_1)$	8.741e-02
9.	$p_T(j_1)$	7.687e-02
10.	$p_T(\mu_1)$	6.720e-02
11.	E_T^{miss}	4.117e-02

Table C.23: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 2400 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.569e-01
2.	$M_{\mu j_1}$	1.209e-01
3.	$M_{\mu \mu jj}$	9.799e-02
4.	S_{T}	9.690e-02
5.	$M_{\mu \mu}$	9.151e-02
6.	$p_{\text{T}}(j_2)$	8.474e-02
7.	$p_{\text{T}}(\mu_2)$	8.233e-02
8.	$\Delta R(\mu_1 + \mu_2, j_1)$	8.222e-02
9.	$p_{\text{T}}(j_1)$	7.917e-02
10.	$p_{\text{T}}(\mu_1)$	6.313e-02
11.	$E_{\text{T}}^{\text{miss}}$	4.423e-02

Table C.24: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 2500 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.627e-01
2.	$M_{\mu \mu jj}$	1.043e-01
3.	$\Delta R(\mu_1 + \mu_2, j_1)$	1.041e-01
4.	$p_{\text{T}}(j_2)$	9.902e-02
5.	$M_{\mu j_1}$	9.823e-02
6.	$M_{\mu \mu}$	8.638e-02
7.	S_{T}	7.879e-02
8.	$p_{\text{T}}(\mu_2)$	7.725e-02
9.	$p_{\text{T}}(j_1)$	7.217e-02
10.	$p_{\text{T}}(\mu_1)$	6.300e-02
11.	$E_{\text{T}}^{\text{miss}}$	5.399e-02

Table C.25: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 2600 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.926e-01
2.	$M_{\mu j_1}$	1.097e-01
3.	$M_{\mu \mu jj}$	9.522e-02
4.	$p_{\text{T}}(j_2)$	8.970e-02
5.	$M_{\mu \mu}$	8.736e-02
6.	$p_{\text{T}}(j_1)$	8.684e-02
7.	$p_{\text{T}}(\mu_2)$	8.097e-02
8.	$\Delta R(\mu_1 + \mu_2, j_1)$	7.451e-02
9.	S_{T}	6.873e-02
10.	$p_{\text{T}}(\mu_1)$	6.480e-02
11.	$E_{\text{T}}^{\text{miss}}$	4.967e-02

Table C.26: A ranking of input variables by their importance in training a BDT with a $M_{\text{LQ}} = 2700 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.424e-01
2.	$M_{\mu \mu jj}$	1.136e-01
3.	S_{T}	1.061e-01
4.	$M_{\mu j_1}$	9.354e-02
5.	$M_{\mu \mu}$	9.253e-02
6.	$p_{\text{T}}(\mu_2)$	8.819e-02
7.	$\Delta R(\mu_1 + \mu_2, j_1)$	8.380e-02
8.	$p_{\text{T}}(j_1)$	8.160e-02
9.	$p_{\text{T}}(j_2)$	8.136e-02
10.	$p_{\text{T}}(\mu_1)$	6.445e-02
11.	$E_{\text{T}}^{\text{miss}}$	5.248e-02

Table C.27: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 2800 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$\Delta R(\mu_1 + \mu_2, j_1)$	2.236e-01
2.	$M_{\mu j_2}$	1.185e-01
3.	$M_{\mu \mu jj}$	1.028e-01
4.	$p_T(j_2)$	8.594e-02
5.	$M_{\mu j_1}$	7.977e-02
6.	S_T	7.824e-02
7.	$M_{\mu\mu}$	7.467e-02
8.	$p_T(j_1)$	7.253e-02
9.	$p_T(\mu_2)$	6.619e-02
10.	$p_T(\mu_1)$	5.698e-02
11.	E_T^{miss}	4.072e-02

Table C.28: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 2900$ GeV signal sample.

Rank	Variable	Importance
1.	$M_{\mu j_2}$	1.365e-01
2.	$\Delta R(\mu_1 + \mu_2, j_1)$	1.311e-01
3.	$M_{\mu \mu jj}$	1.073e-01
4.	$p_T(j_2)$	9.744e-02
5.	$M_{\mu j_1}$	9.404e-02
6.	$p_T(j_1)$	8.725e-02
7.	S_T	7.712e-02
8.	$M_{\mu\mu}$	7.657e-02
9.	$p_T(\mu_2)$	6.621e-02
10.	$p_T(\mu_1)$	6.421e-02
11.	E_T^{miss}	6.217e-02

Table C.29: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 3000$ GeV signal sample.

Rank	Variable	Importance
1.	$\Delta R(\mu_1 + \mu_2, j_1)$	2.242e-01
2.	$M_{\mu j_2}$	1.426e-01
3.	$M_{\mu j_1}$	1.026e-01
4.	$M_{\mu \mu jj}$	8.558e-02
5.	$p_T(j_2)$	7.792e-02
6.	S_T	7.135e-02
7.	$M_{\mu \mu}$	7.114e-02
8.	$p_T(\mu_2)$	6.500e-02
9.	$p_T(j_1)$	6.176e-02
10.	$p_T(\mu_1)$	5.723e-02
11.	E_T^{miss}	4.056e-02

Table C.30: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 3500$ GeV signal sample.

Rank	Variable	Importance
1.	$\Delta R(\mu_1 + \mu_2, j_1)$	1.510e-01
2.	$p_T(j_2)$	1.254e-01
3.	$M_{\mu j_2}$	1.211e-01
4.	$M_{\mu j_1}$	9.907e-02
5.	$M_{\mu \mu jj}$	9.332e-02
6.	$p_T(j_1)$	9.089e-02
7.	S_T	8.178e-02
8.	$p_T(\mu_1)$	6.857e-02
9.	$p_T(\mu_2)$	6.209e-02
10.	$M_{\mu\mu}$	5.962e-02
11.	E_T^{miss}	4.722e-02

Table C.31: A ranking of input variables by their importance in training a BDT with a $M_{LQ} = 4000 \text{ GeV}$ signal sample.

Rank	Variable	Importance
1.	$M_{\mu\mu}$	-nan
2.	$M_{\mu\mu jj}$	-nan
3.	$M_{\mu j_1}$	-nan
4.	$M_{\mu j_2}$	-nan
5.	S_T	-nan
6.	E_T^{miss}	-nan
7.	$p_T(\mu_1)$	-nan
8.	$p_T(\mu_2)$	-nan
9.	$p_T(j_1)$	-nan
10.	$p_T(j_2)$	-nan
11.	$\Delta R(\mu_1 + \mu_2, j_1)$	-nan

C.4 Discriminators

Figures C.19–C.28 show a comparison between observed and simulated data in the BDT scores trained at each leptoquark mass point. Plots shown are at preselection level (defined in Section 6.2.4), and signal and background MC have the normalizations and corrections listed in Sections 6.4.1 and 6.3. The leptoquark mass of signal MC in each distribution corresponds to the leptoquark mass point used to train the BDT.

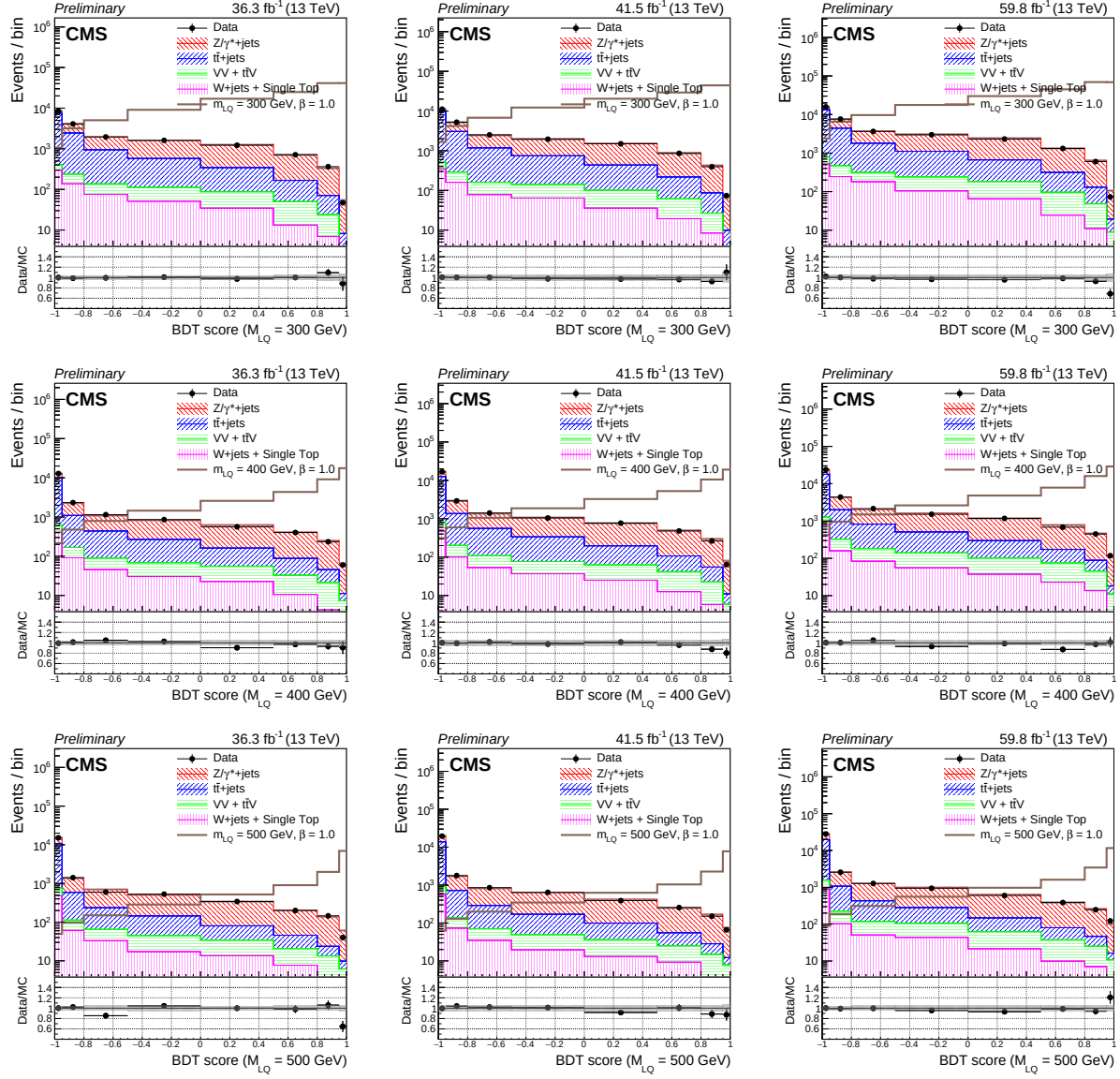


Figure C.19: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

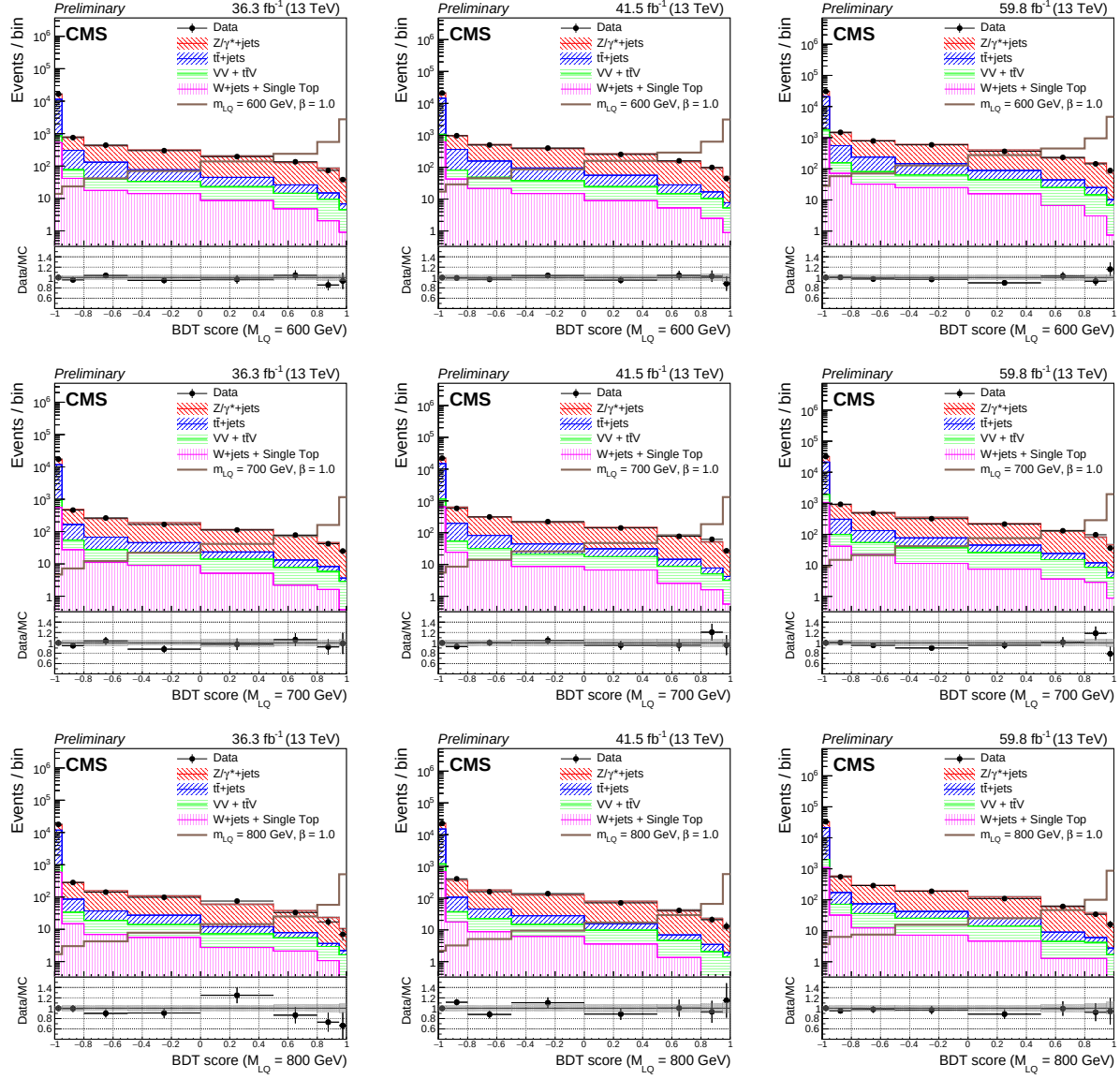


Figure C.20: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

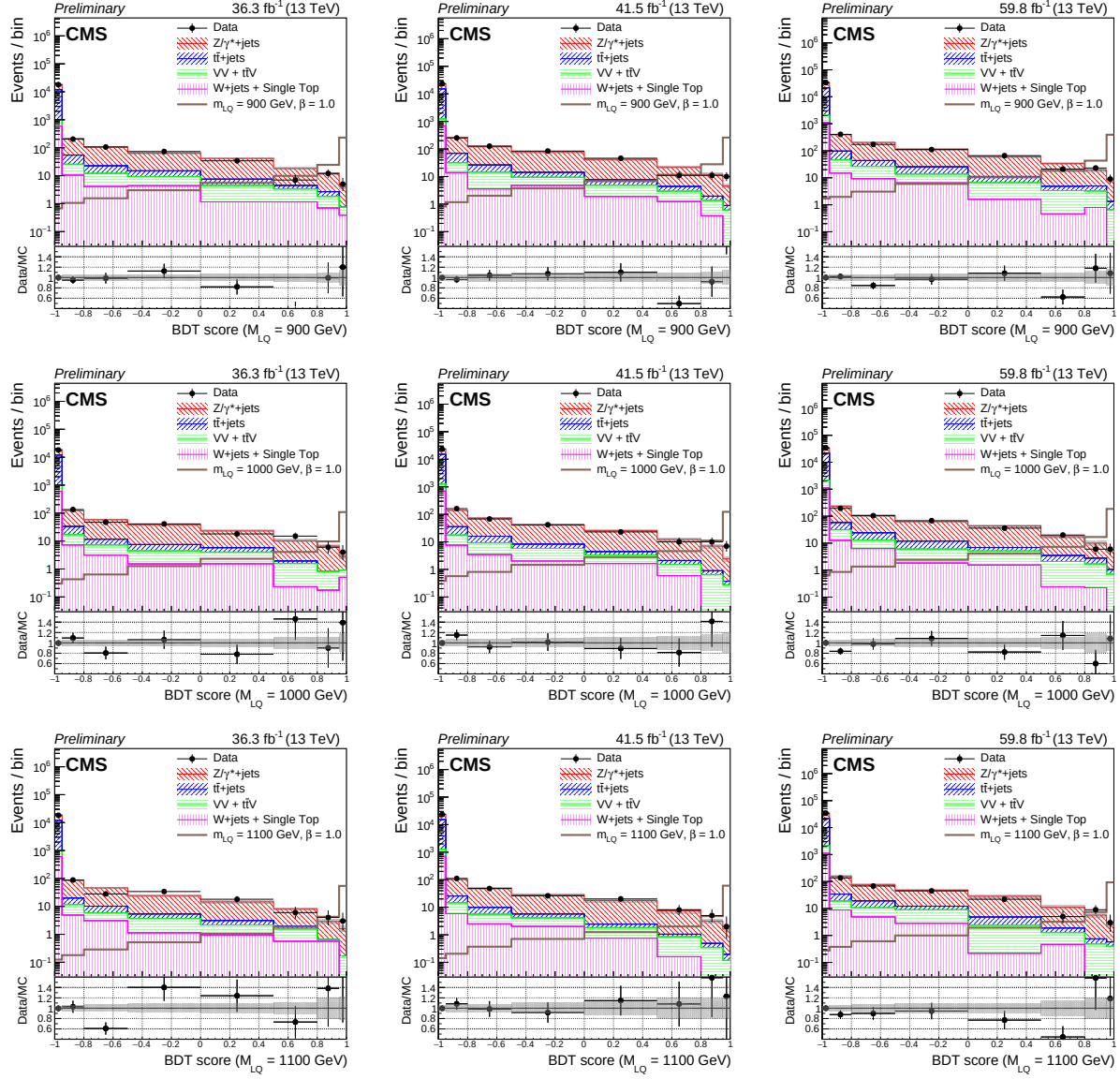


Figure C.21: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

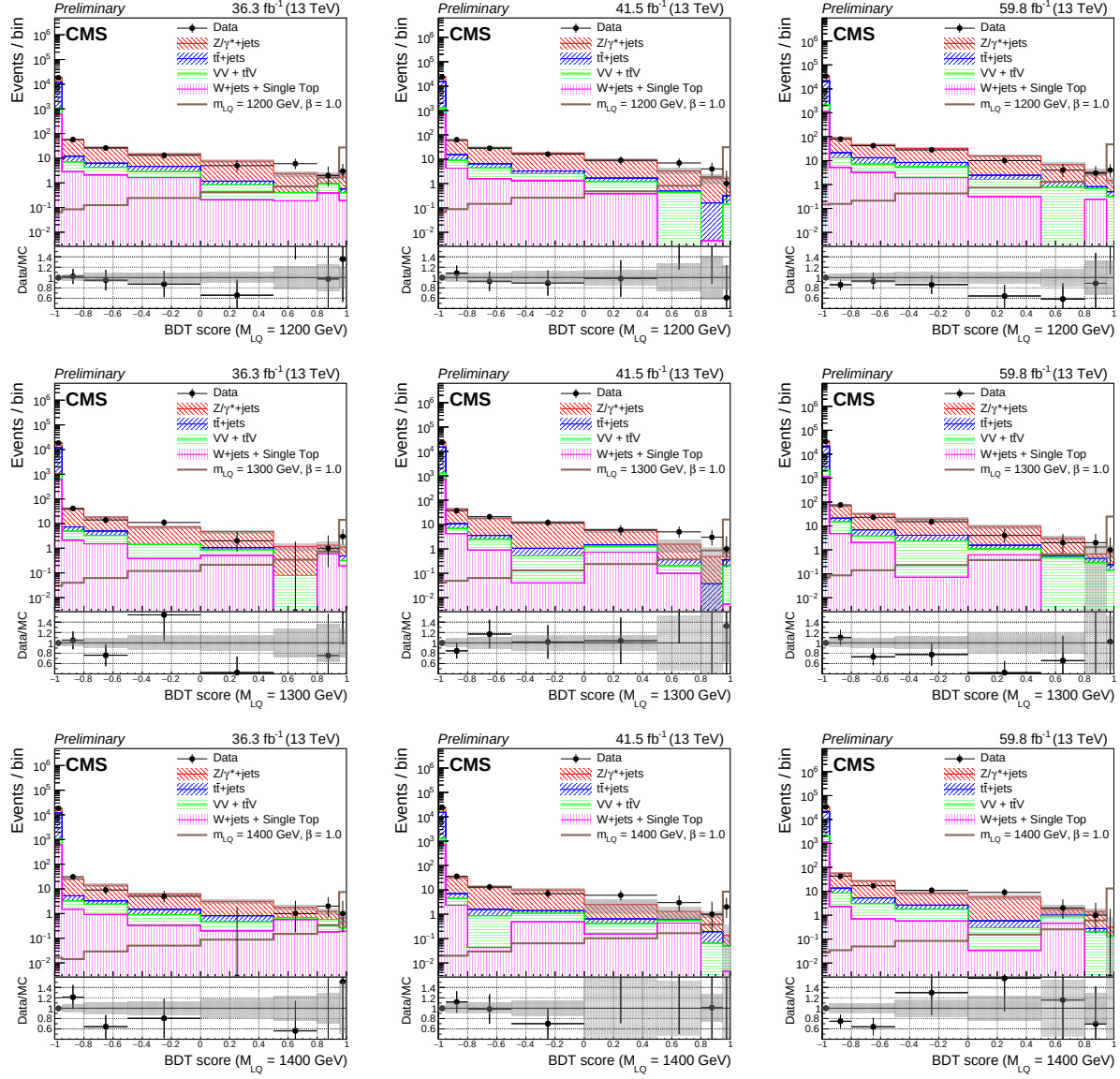


Figure C.22: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

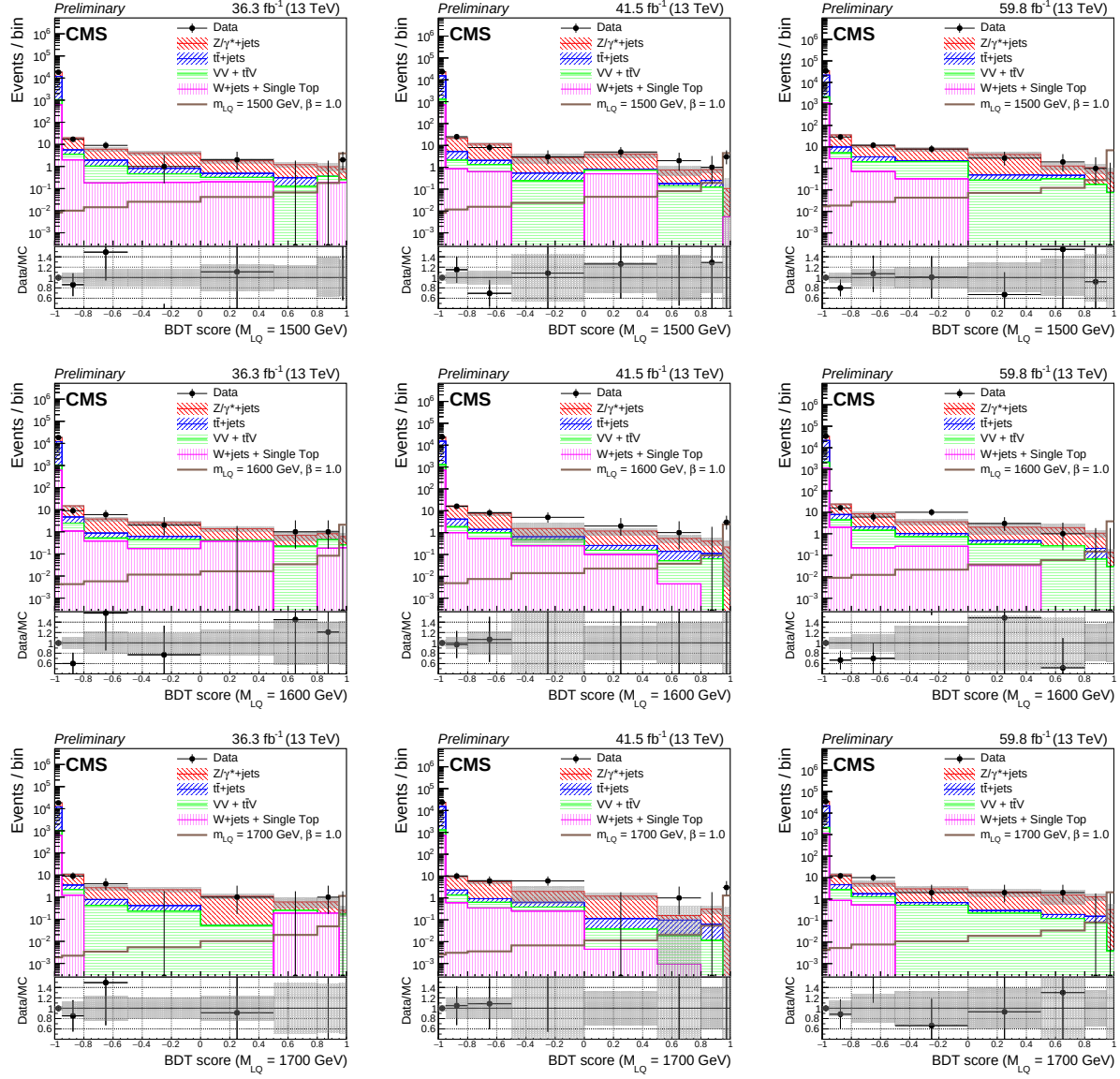


Figure C.23: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

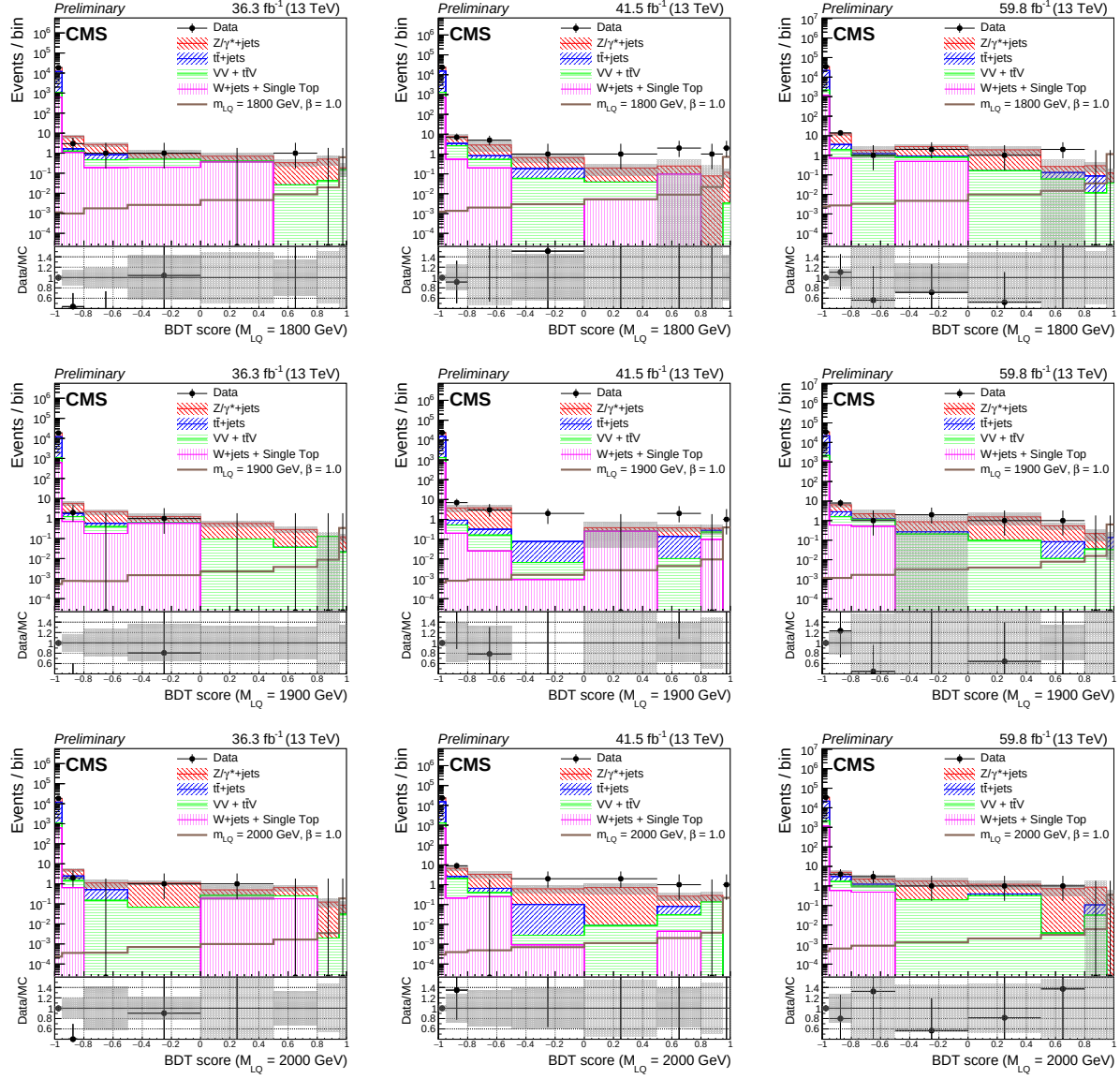


Figure C.24: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

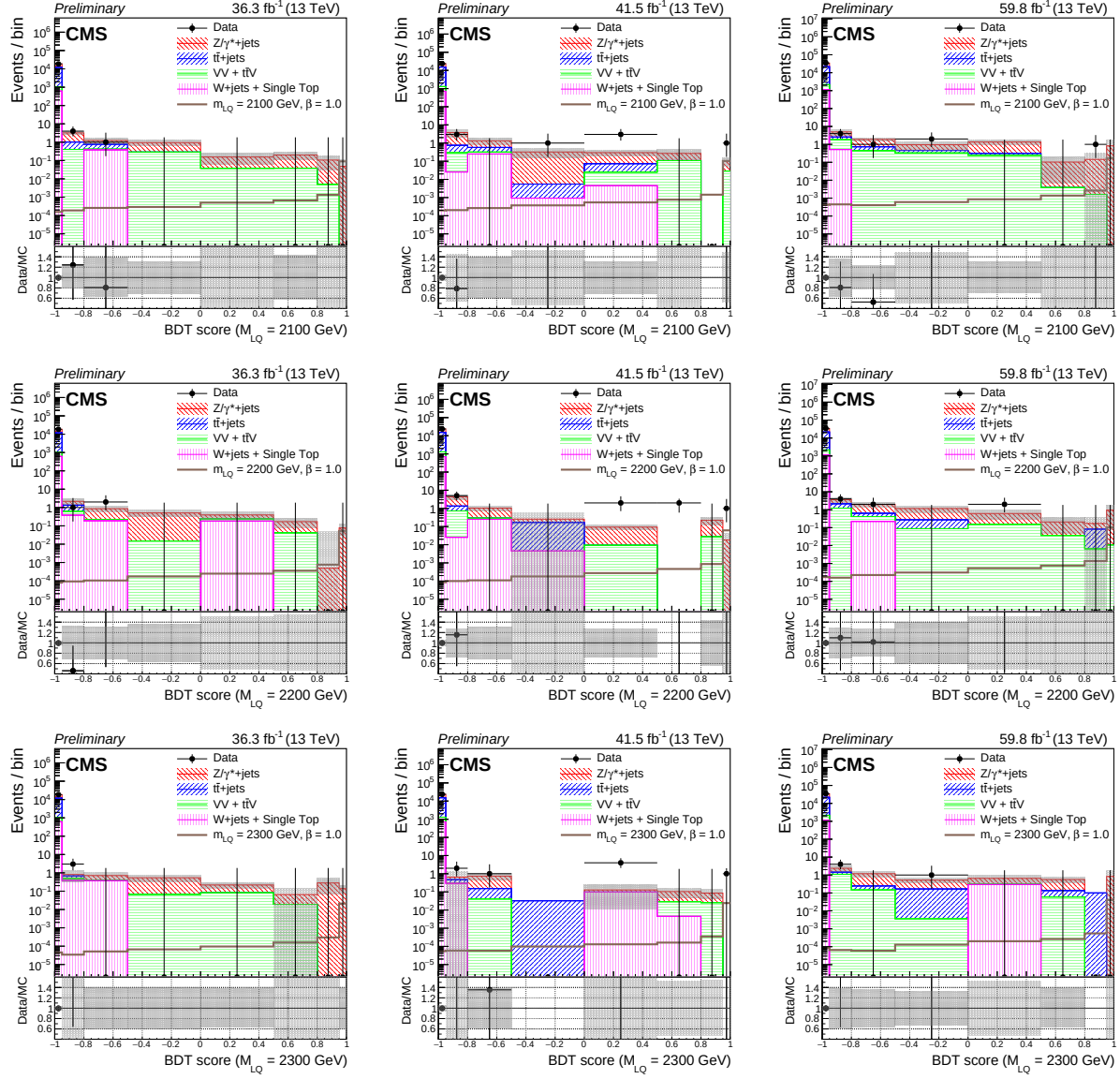


Figure C.25: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

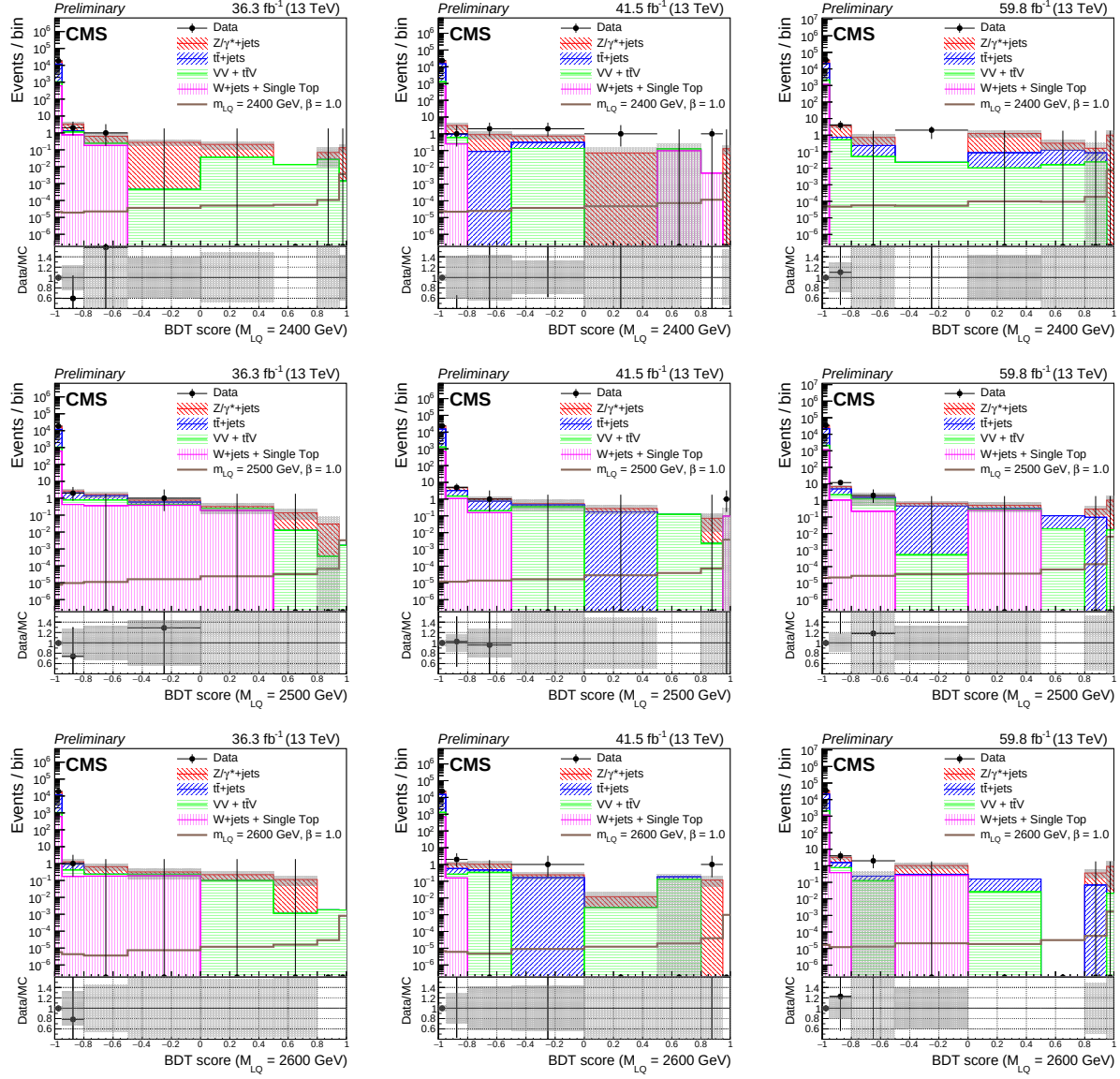


Figure C.26: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

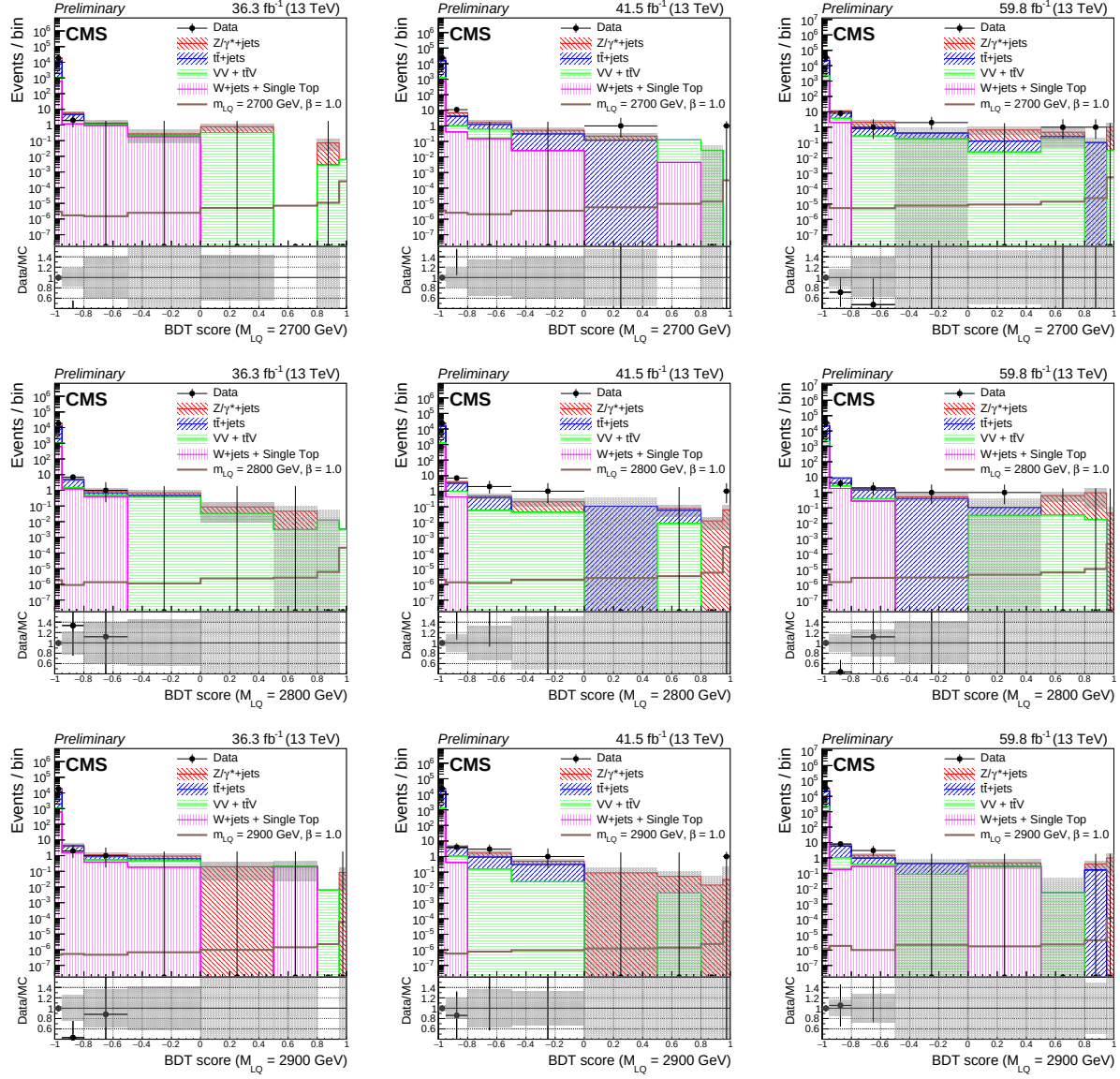


Figure C.27: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

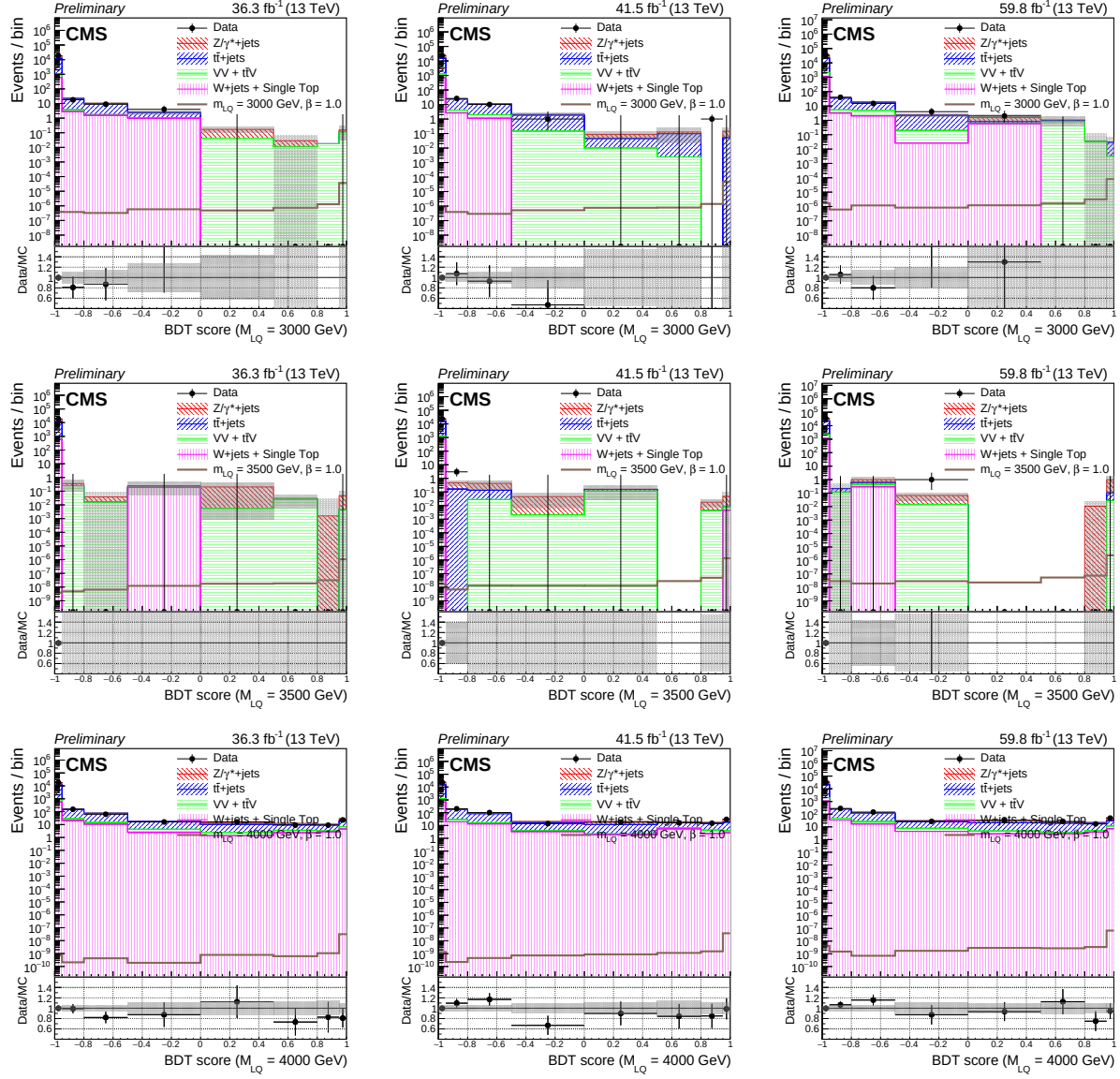


Figure C.28: A comparison between observed and simulated data in the BDT response at preselection level with 2016 (left), 2017 (middle), and 2018 (right) data. Error bars represent statistical uncertainties, while the shaded area represents systematic uncertainties.

APPENDIX D

HEM 15/16 failure study

On June 30th, 2018, a false fire alarm at Point 5 on the LHC triggered temporary power disruptions to CMS, resulting in two dead HCAL wedges in the minus endcap for the duration of 2018. The failed wedges, HEM 15 and 16, occupy a 40° region in the detector, specifically $-3.0 < \eta < -1.3$ and $-1.57 < \phi < -0.87$. The affected runs begin with run 319077 until the end of 2018. A study is performed to ensure the HEM 15/16 failure does not impact any kinematic distributions used in this analysis. 2018 data are divided into two periods: A and B, corresponding to all runs before run 319077 and all runs after and including run 319077, respectively. After preselection is applied, kinematic distributions for each data period are normalized to unity so a shape comparison can be performed. No significant difference in shape is observed in any distributions in periods A and B.

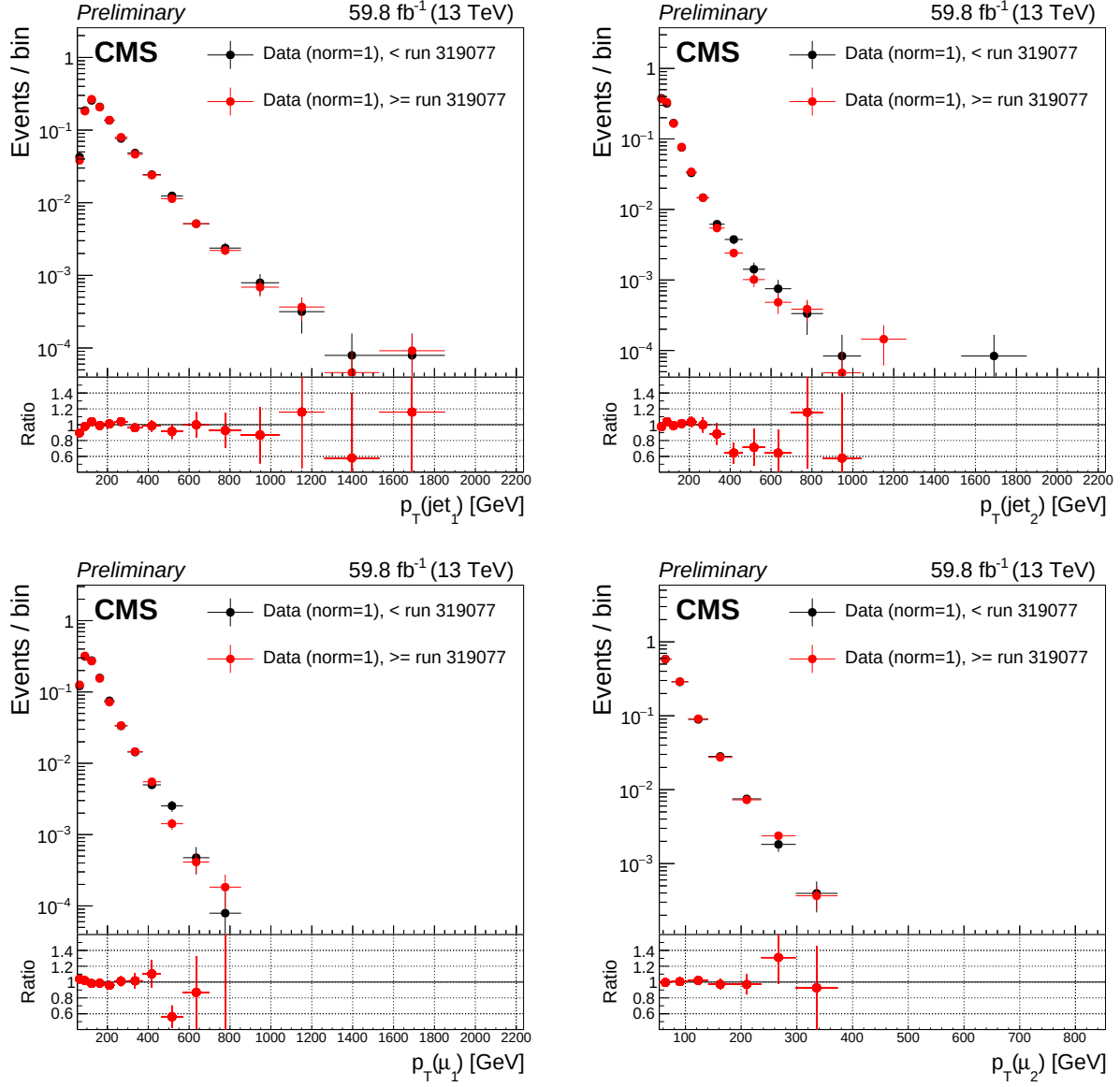


Figure D.1: A shape comparison of 2018 data in periods A (black) and B (red). Data in each period have been normalized to unity and have preselection applied. The ratio $\text{Data}^B / \text{Data}^A$ is shown in the subplot. Vertical error bars represent the statistical uncertainty in each bin.

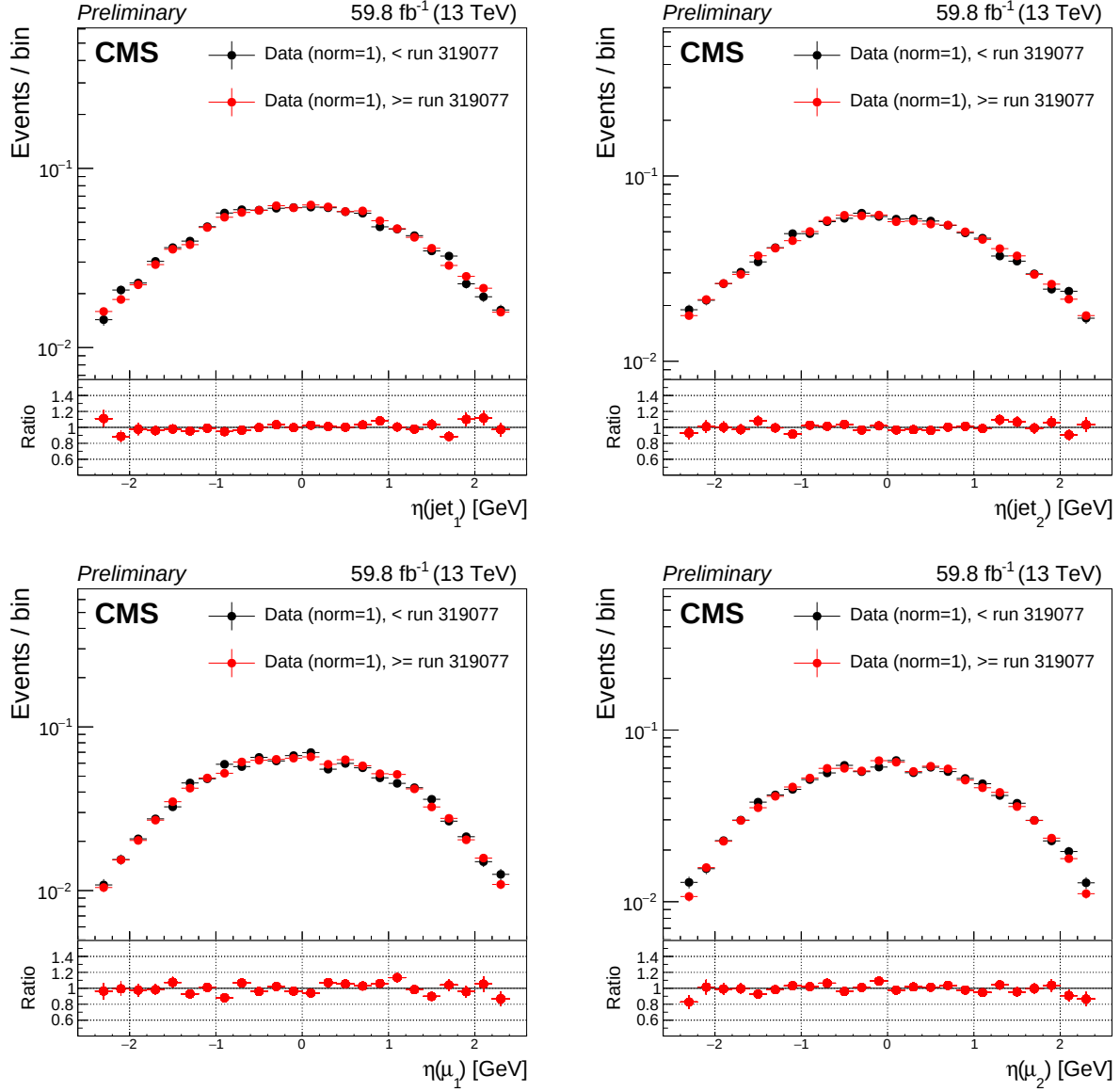


Figure D.2: A shape comparison of 2018 data in periods A (black) and B (red). Data in each period have been normalized to unity and have preselection applied. The ratio $\text{Data}^{\text{B}} / \text{Data}^{\text{A}}$ is shown in the subplot. Vertical error bars represent the statistical uncertainty in each bin.

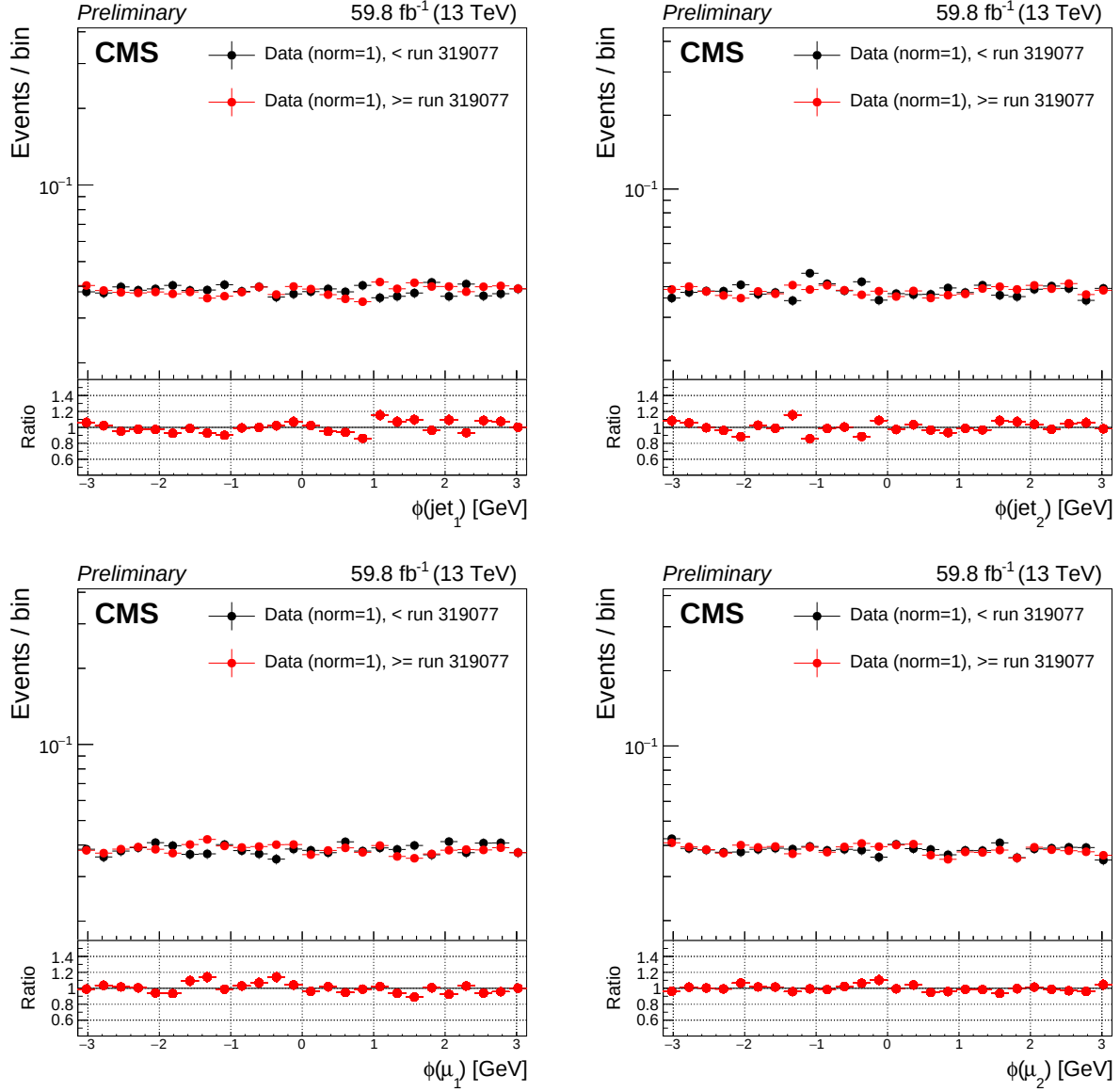


Figure D.3: A shape comparison of 2018 data in periods A (black) and B (red). Data in each period have been normalized to unity and have preselection applied. The ratio $\text{Data}^{\text{B}}/\text{Data}^{\text{A}}$ is shown in the subplot. Vertical error bars represent the statistical uncertainty in each bin.

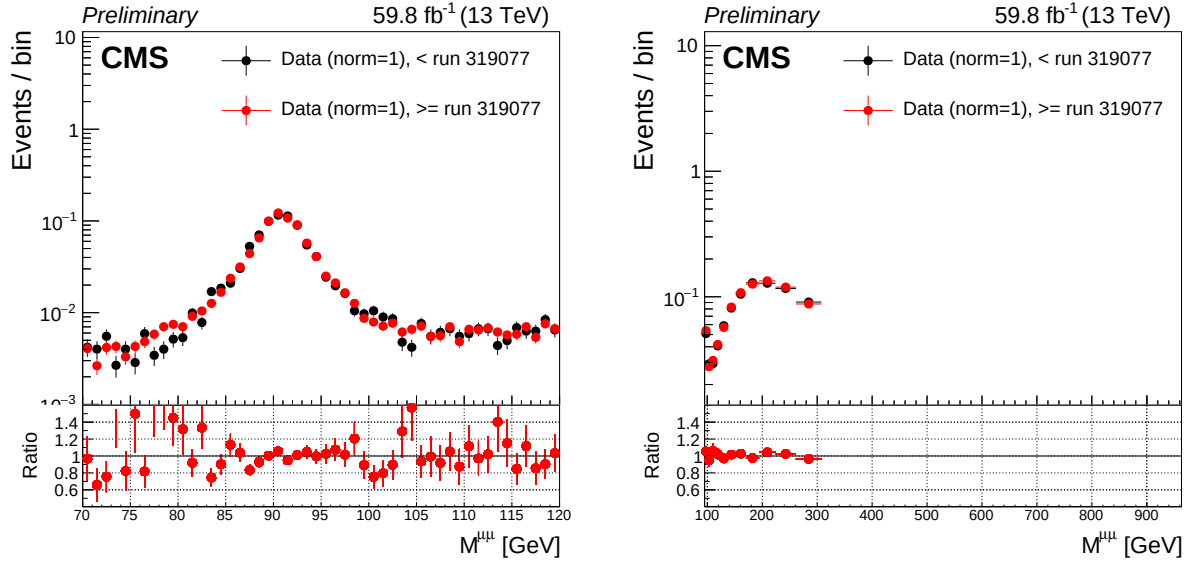


Figure D.4: A shape comparison of 2018 data in periods A (black) and B (red). Data in each period have been normalized to unity and have preselection applied. The ratio $\text{Data}^B / \text{Data}^A$ is shown in the subplot. Vertical error bars represent the statistical uncertainty in each bin.

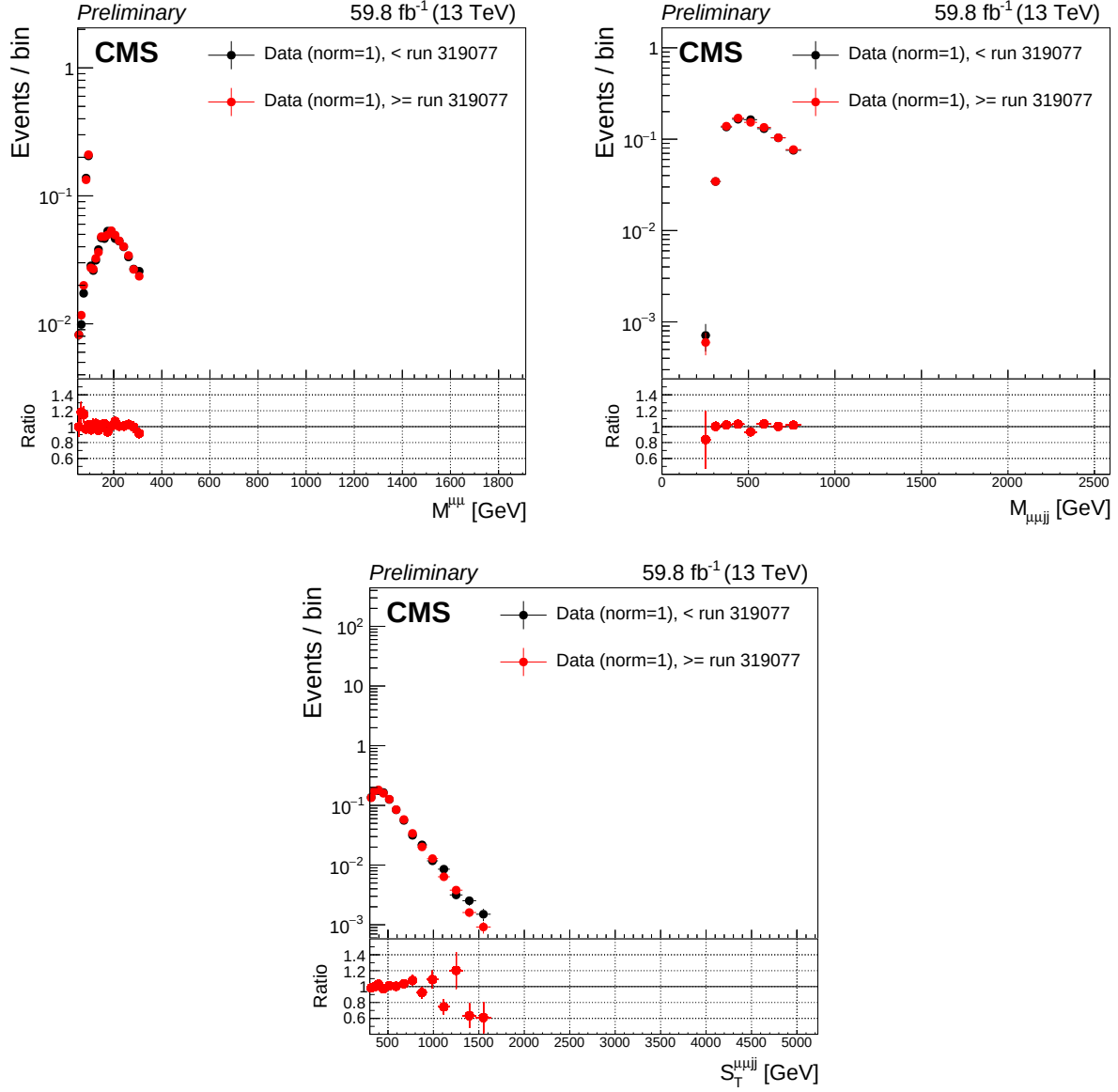


Figure D.5: A shape comparison of 2018 data in periods A (black) and B (red). Data in each period have been normalized to unity and have preselection applied. The ratio $\text{Data}^B/\text{Data}^A$ is shown in the subplot. Vertical error bars represent the statistical uncertainty in each bin.

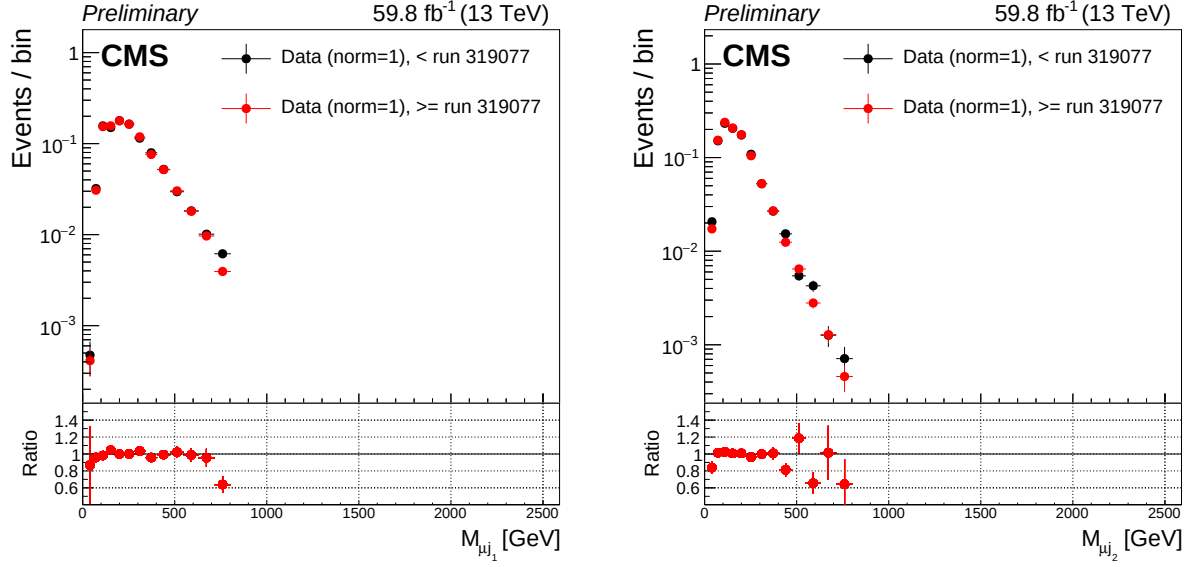


Figure D.6: A shape comparison of 2018 data in periods A (black) and B (red). Data in each period have been normalized to unity and have preselection applied. The ratio Data^B/Data^A is shown in the subplot. Vertical error bars represent the statistical uncertainty in each bin.

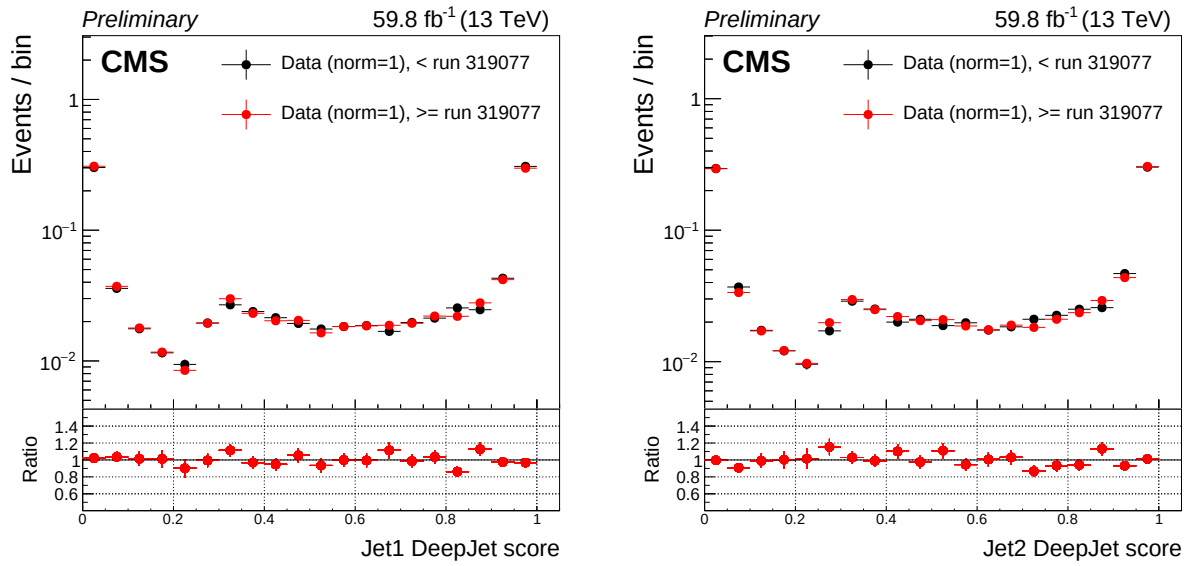


Figure D.7: A shape comparison of 2018 data in periods A (black) and B (red). Data in each period have been normalized to unity and have preselection applied. The ratio Data^B/Data^A is shown in the subplot. Vertical error bars represent the statistical uncertainty in each bin.

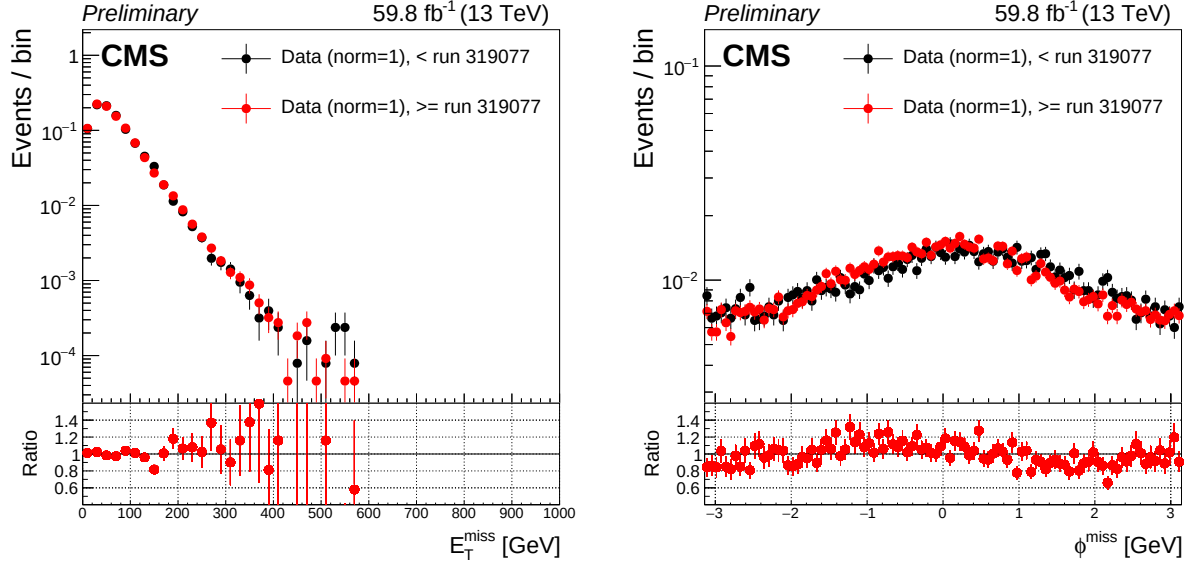


Figure D.8: A shape comparison of 2018 data in periods A (black) and B (red). Data in each period have been normalized to unity and have preselection applied. The ratio Data^B/Data^A is shown in the subplot. Vertical error bars represent the statistical uncertainty in each bin.

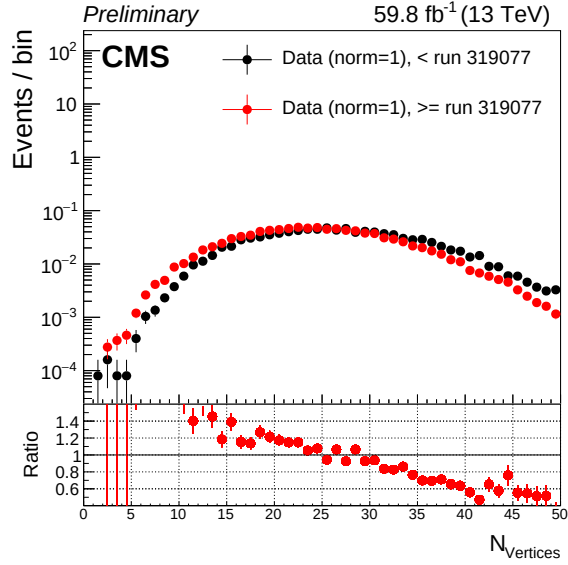


Figure D.9: A shape comparison of 2018 data in periods A (black) and B (red). Data in each period have been normalized to unity and have preselection applied. The ratio Data^B/Data^A is shown in the subplot. Vertical error bars represent the statistical uncertainty in each bin.

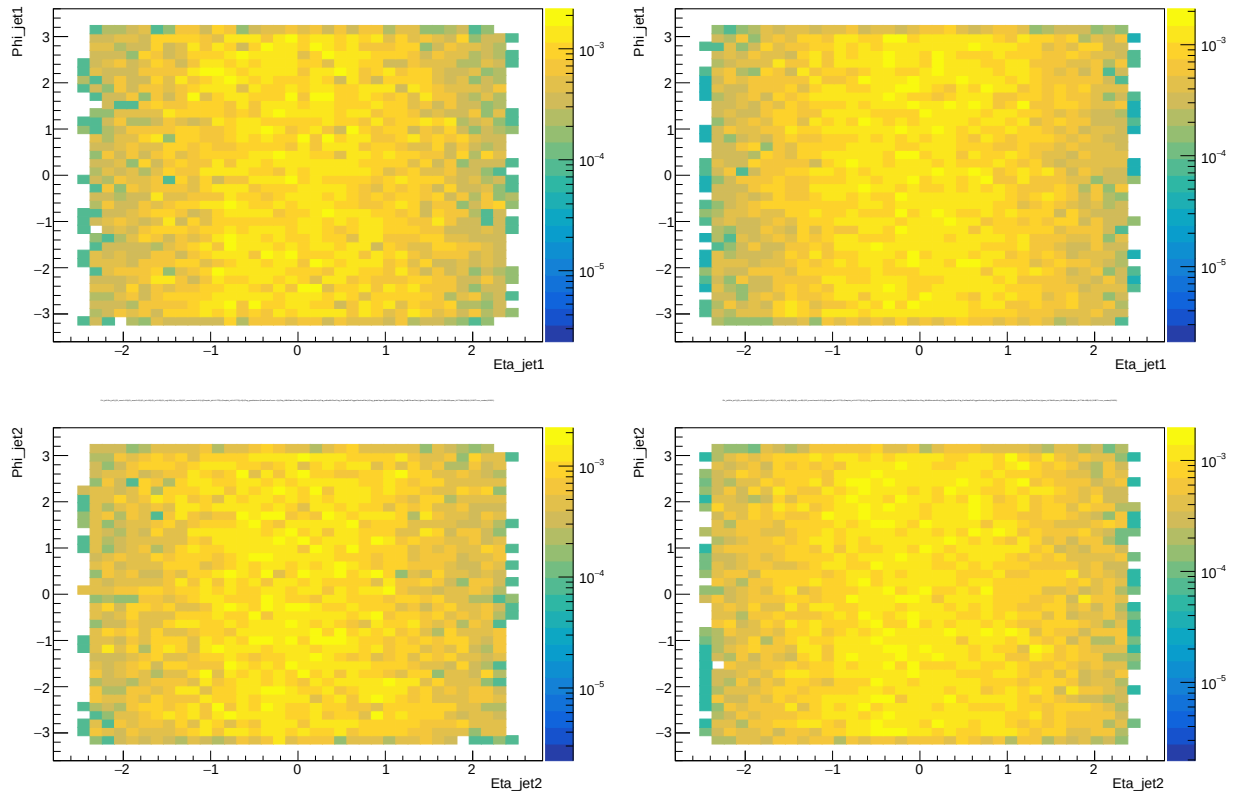


Figure D.10: A comparison of 2018 data in periods A (left) and B (right) shown in jet occupancy. Data in each period have been normalized to unity and have preselection applied.

APPENDIX E

Simulated LQ samples

The $M_{\mu\mu jj}$ distributions of simulated leptoquark samples in each year of data-taking are shown in Figs. E.1 and E.2. Samples are the same MC samples used in the rest of the analysis, described in Section 6.1.2. Each sample has the preselection, MC corrections, and b tag requirements applied, and is normalized to the product of the signal cross section and integrated luminosity in each data-taking year.

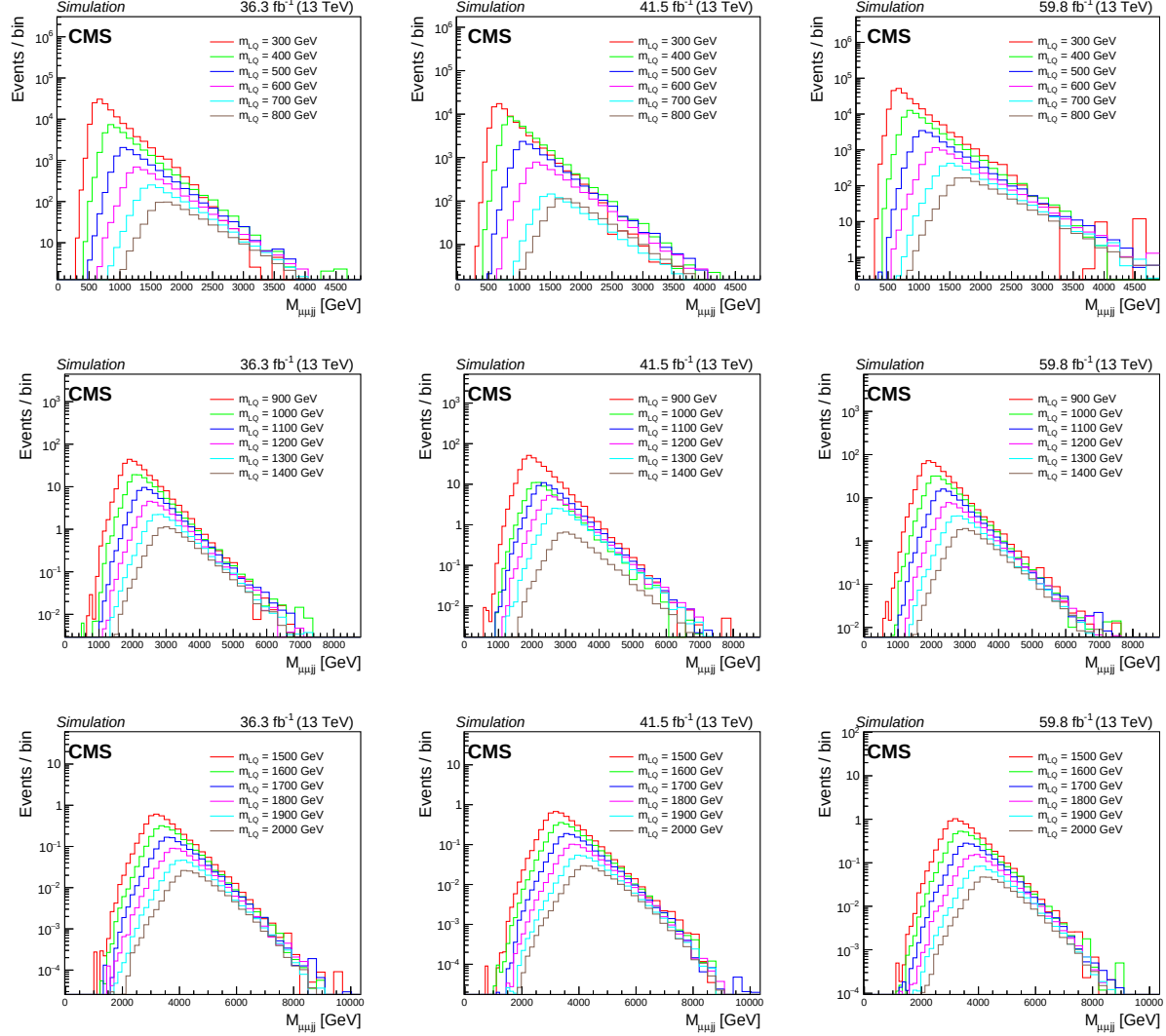


Figure E.1: The preselection-level $M_{\mu\mu jj}$ distributions of simulated leptoquark pair samples for the data-taking periods 2016 (left), 2017 (middle), and 2018 (right). For clarity, each plot overlays the distributions corresponding to a set of six leptoquark masses: 300 to 800 GeV (top), 900 to 1400 GeV (middle), and 1500 to 2000 GeV (bottom).

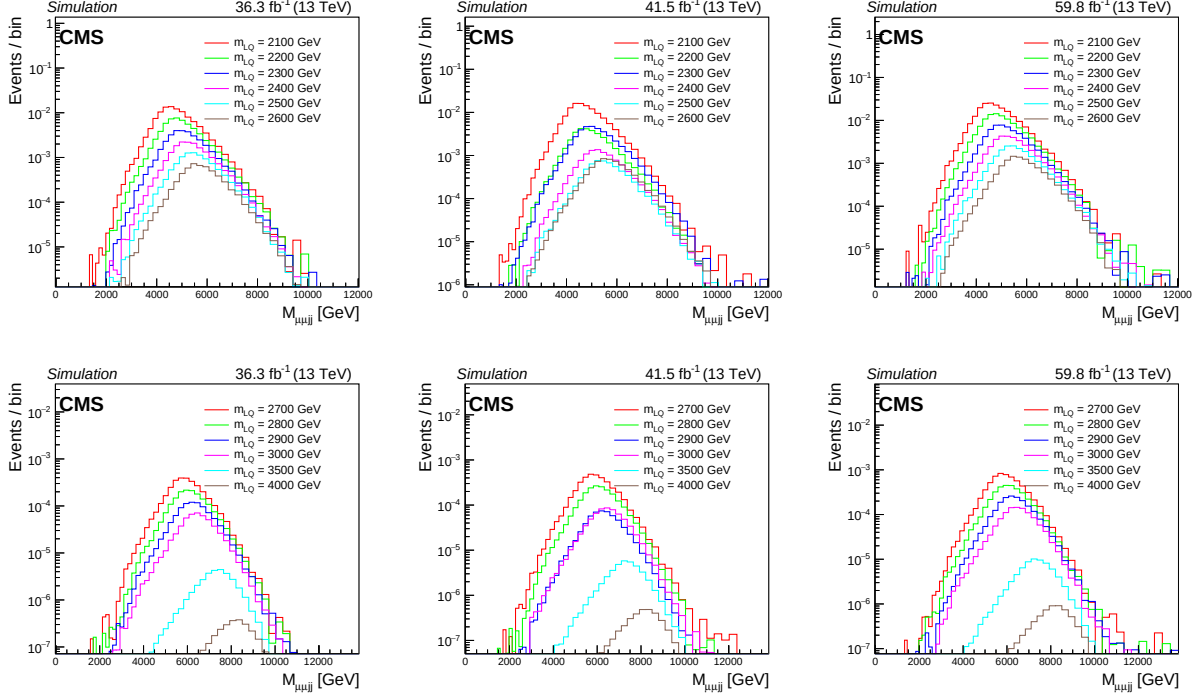


Figure E.2: The preselection-level $M_{\mu\mu jj}$ distributions of simulated leptoquark pair samples for the data-taking periods 2016 (left), 2017 (middle), and 2018 (right). For clarity, each plot overlays the distributions corresponding to a set of six leptoquark masses: 2100 to 2600 GeV (top) and 2700 to 4000 GeV (bottom).

APPENDIX F

3D optimization

To further motivate a BDT-based analysis, an alternative final selection derived from a 3-D optimization (similar to that used in Ref. [55]) was studied. MC samples correspond to those listed in Section 6.1 but are stored in the NanoAOD v6 format. The preselection, MC corrections, background normalization, and b-jet tag requirements described in Sections 6.2–6.4 were applied.

To separate signal from background, a 3-D scan of thresholds over the kinematic variables S_T , $M_{\mu\mu}$, and $M_{\mu j_2}$ was performed on 2016 simulation, while maximizing the Punzi significance for each leptoquark mass hypothesis. Any volatility or plateaus in the optimized thresholds introduced by sparse background MC statistics were smoothed out by fitting a quadratic to the points. To constrain the fit to a monotonically increasing function, a cutoff to the thresholds was applied approximately where they no longer increased, and a re-fit of the points below the cutoff was performed. For leptoquark hypotheses with masses above the cutoff, the thresholds were kept constant. Figure F.1 shows the optimized thresholds and the quadratic fits before and after the cutoff was applied. The final set of cuts on each variable were extracted from the fit at each leptoquark hypothesis mass, as shown in Fig. F.2.

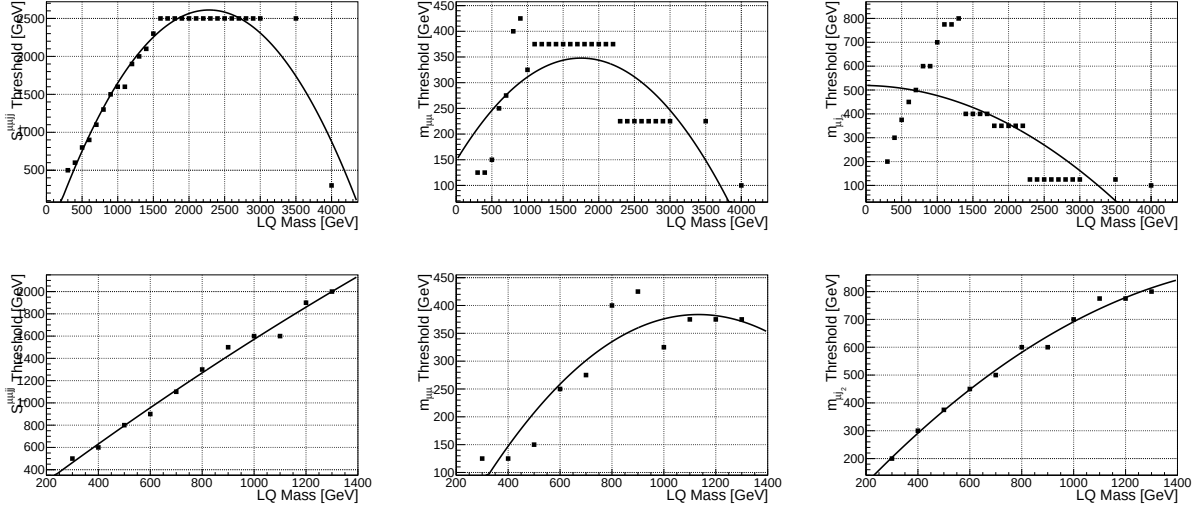


Figure F.1: Top: The optimized thresholds on the variables S_T (left), $M_{\mu\mu}$ (middle), and $M_{\mu j_2}$ (right), shown with a quadratic fit of all points. Bottom: The optimized thresholds on the variables S_T (left), $M_{\mu\mu}$ (middle), and $M_{\mu j_2}$ (right), up to the cutoff, shown with a quadratic fit of points below the cutoff.

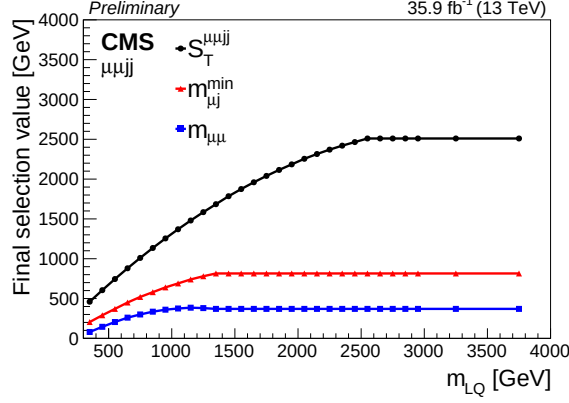


Figure F.2: The final selection values used in the 3-D optimization study with the variables $M_{\mu\mu}$, S_T , and $M_{\mu j_2}$ as functions of leptoquark mass hypothesis.

The same final selection was used to separate signal from background in all three data-taking years. Expected asymptotic limits at 95%CL were placed on the product of the signal production cross-section and branching fraction for the 2016, 2017, and 2018 data-taking years, and for the combined Run 2 dataset, shown in Figs. F.3 and F.4. As systematic uncertainties had not been finalized at the time this study was performed, only statistical

uncertainties are included. The expected upper limits place a lower bound on the leptoquark mass of 1650 GeV. Comparing this result with the combined expected lower bound of 1721.2 GeV from the main analysis demonstrates a notable improvement in the use of BDT discriminators over a 3-D optimization.

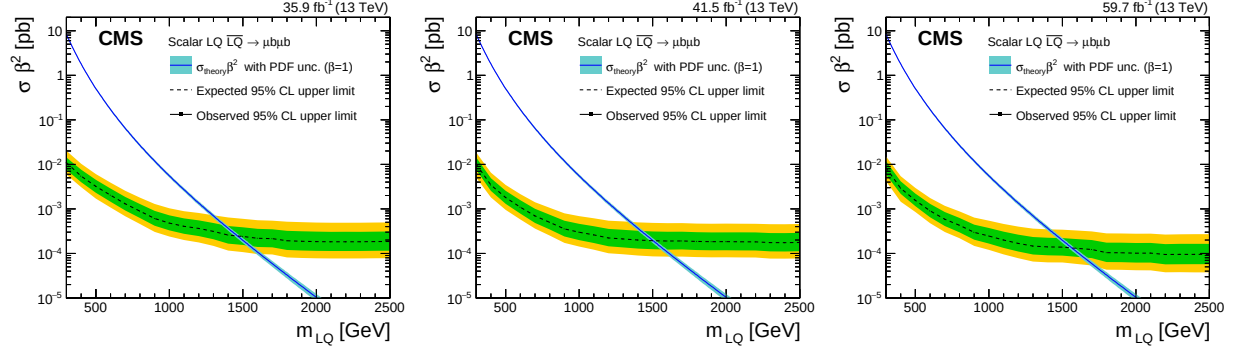


Figure F.3: The expected asymptotic upper limits at 95 % CL on the leptoquark pair production cross section times squared branching fraction as a function of leptoquark mass obtained from the 3-D optimization study with 2016 (left), 2017 (middle), and 2018 (right) datasets. The expected limits and uncertainty bands represent the median expected limits and the 68 % and 95 % confidence intervals. The σ_{theory} curves and their bands represent, respectively, the theoretical scalar leptoquark pair production cross section and the uncertainties due to the choice of PDF and renormalization/factorization scales.

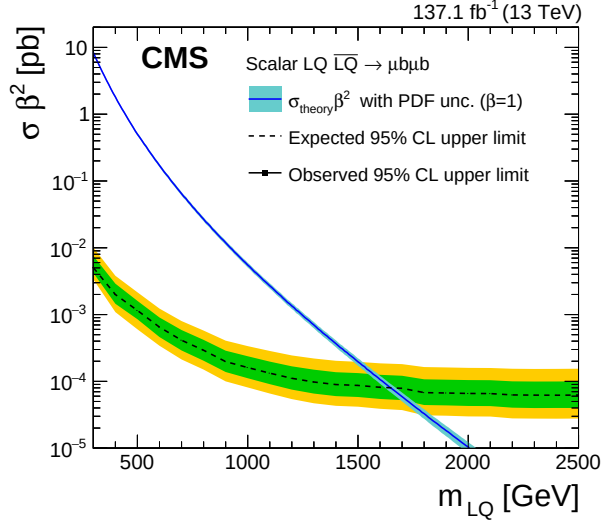


Figure F.4: The expected asymptotic upper limits at 95 % CL on the leptoquark pair production cross section times squared branching fraction as a function of leptoquark mass obtained from the 3-D optimization study with the combined Run 2 datasets. The expected limits and uncertainty bands represent the median expected limits and the 68 % and 95 % confidence intervals. The σ_{theory} curves and their bands represent, respectively, the theoretical scalar leptoquark pair production cross section and the uncertainties due to the choice of PDF and renormalization/factorization scales.