

¹ SEARCH FOR EXOTIC HIGGS DECAYS TO LIGHT
² NEUTRAL SCALARS IN FINAL STATES WITH
³ BOTTOM QUARKS AND TAU LEPTONS

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Abstract

Open questions in particle physics may be addressed by the existence of an extended Higgs sector beyond the Standard Model Higgs boson with mass 125 GeV, which was discovered in 2012 at the Large Hadron Collider (LHC) by the CMS and ATLAS experiments. Many properties of a potential extended Higgs sector remain unconstrained by current measurements, making direct searches of exotic Higgs decays a powerful probe of new physics. The decay of the 125 GeV Higgs boson into two light neutral scalar particles ($h \rightarrow aa$) is allowed in extensions of the Standard Model, such as Two Higgs Doublet Models extended with a scalar singlet (2HDM+S). We present a search at CMS for exotic decays of the 125 GeV Higgs boson to two light neutral scalars, which decay to two bottom quarks and two tau leptons ($h \rightarrow aa \rightarrow bb\tau\tau$). This analysis is combined with a different search where the light scalars decay to two bottom quarks and two muons. The results from the $bb\tau\tau$ analysis and the combined analyses are interpreted in 2HDM+S scenarios. In a different extension of the Standard Model, the Two Real Singlet Model (TRSM), the 125 GeV Higgs boson can decay to two light scalars with unequal mass ($h \rightarrow a_1a_2$). This decay has not been searched for to date at CMS. We present ongoing work on a search for $h \rightarrow a_1a_2$, where the a_2 decays into two a_1 , resulting in four bottom quarks and two tau leptons in the final state, in the $\mu\tau_h$ channel of the $\tau\tau$ decay. Such searches for rare processes will directly benefit from the increased datasets that will be generated by the High-Luminosity LHC (HL-LHC), which is scheduled to increase the LHC's number of simultaneous proton-proton collisions by a factor of five to seven. To contribute to the performance of the CMS Level-1 Trigger in selecting collisions with interesting physics, this thesis presents an upgraded algorithm for reconstructing electrons and photons in the barrel calorimeter, which will use information with higher spatial granularity to distinguish genuine electrons and photons from background.

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⁴²¹ Chapter 1

⁴²² Introduction

⁴²³ The Standard Model is the current prevailing theoretical framework that encompasses
⁴²⁴ all known elementary particles to date and describes their interactions, yet falls short
⁴²⁵ of describing open problems in physics. Here, we describe the history of the Standard
⁴²⁶ Model and its particle content (Section 1.1), and provide a mathematical motivation of
⁴²⁷ the SM as a gauge theory (Section 1.2). We introduce the Higgs mechanism (Section
⁴²⁸ 1.3), and outline two groups of theoretical extensions to the Standard Model that
⁴²⁹ feature extended Higgs sectors (Sections 1.4 and 1.5).

⁴³⁰ 1.1 History of the Standard Model

⁴³¹ The building blocks of our modern-day understanding of particle physics were estab-
⁴³² lished over the course of many decades by experimental discoveries and theoretical
⁴³³ advances, culminating in the development of a theoretical framework known as the
⁴³⁴ Standard Model (SM). In the 1880s, the electron was the first subatomic particle to
⁴³⁵ be identified, through measurements of particles produced by ionizing gas. By the
⁴³⁶ 1930s, atoms were known to consist mostly of empty space, with protons and neutrons
⁴³⁷ concentrated at the center and orbited by electrons. Spurred by advances in parti-
⁴³⁸ cle accelerator technology, the experimental discoveries of the positron, the muon,

and the pion, painted an increasingly complicated picture of particle physics that could not be described solely with atomic physics [1]. Quantum field theory (QFT) began to be developed in the early 20th century as an extension of the conceptual framework of quantum mechanics to electromagnetic fields [2]. In 1927, Dirac coined the name quantum electrodynamics (QED), which was the first part of QFT that was developed. QED quantized the electromagnetic field and supplied a relativistic theory of the electron, and could be applied to concrete physical processes such as the scattering of high-frequency photons by free electrons (Compton scattering), and the production of electron-positron pairs by photons [2]. In the 1940s the QED-only picture was challenged by the realization that the four-fermion theory of weak interactions had infinities at higher orders of perturbation theory which could not be removed via the technique of renormalization [3], i.e. shifting divergences into parts of the theory that do not influence empirical measurements [2].

In the 1950s and 1960s, QFT was extended to describe not only the electromagnetic force, but also the strong and weak force, with the final picture forming the Standard Model. This took place in the development and maturation of three principles: the quark model, the idea of gauge (or local) symmetry, and spontaneously broken symmetry [3]. In the fully fledged QFT, Lagrangians had to be formed that contained new classes of quantum fields, or particles [2].

The particle content of the Standard Model is summarized in Fig. 1.1. Particles are grouped into fermions, which comprise all known matter, and bosons, which mediate the interactions between particles. Fermions consist of quarks and leptons, and are grouped into three generations. For example, the electron belongs to the first generation of leptons. The second and third generation counterparts of the electron are the muon and the tau lepton, and are over 200 and 30,000 times heavier than the electron respectively. The quarks are also organized into three generations (top and bottom quarks, charm and strange quarks, and up and down quarks), and

466 carry fractional electric charge. Bosons are force carriers; the interaction of fermions
 467 with bosons corresponds to fundamental forces. The Standard Model describes the
 468 electromagnetic force, the strong nuclear force, and the weak nuclear force. Through
 469 the strong force, quarks can form composite particles known as hadrons. Familiar
 470 examples of hadrons are the protons and neutrons in the nucleus of an atom.

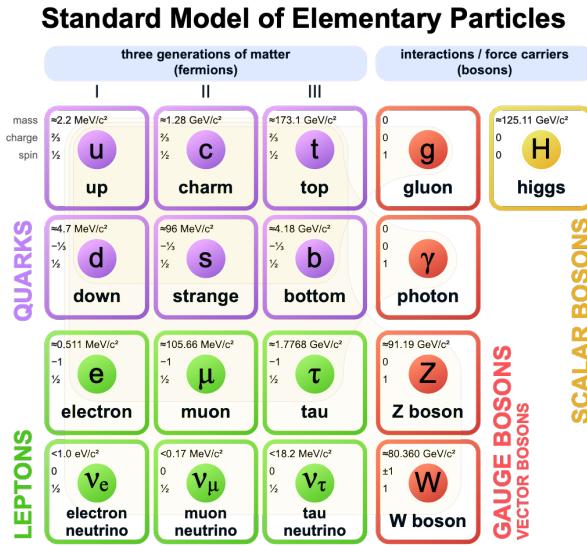


Figure 1.1: Table of Standard Model particles showing the grouping of the fermions into three generations of matter and the bosons, responsible for carrying the three fundamental forces in the Standard Model. The masses, charges, and spins of the particles are shown. The antimatter counterparts of the fermions are not shown. The possible interactions between the fermions and gauge bosons are highlighted.

471 1.2 The Standard Model as a gauge theory

472 In this section we lay the theoretical foundations of the Standard Model as a gauge
 473 theory, starting from the principle of gauge invariance (gauge symmetry), with local
 474 gauge symmetries giving rise to interactions between particles.

475 Gauge theories of elementary particle interactions originate from a freedom of
 476 choice in the mathematical description of particle fields which has no effect on the
 477 particles' physical states [4]. The existence and form of the particles' interactions,

478 can be deduced from the existence of physically indeterminate, gaugable quantities.

479 An example of this gauge invariance is classical physics is the electromagnetic
480 interaction, where the fundamental field is the four-vector potential A^μ [4]. The
481 physical electromagnetic fields and Maxwell's equations arise from the elements of
482 the tensor $F_{\mu\nu}(x) = \partial_\mu A_\nu(x) - \partial_\nu A_\mu(x)$. Any two choices of A^μ that are related by a
483 transformation of the form

$$A_\mu \rightarrow A_\mu + \partial_\mu \alpha \quad (1.1)$$

484 for any real, differentiable function $\alpha(x)$, describe the same physical configuration,
485 and has no effect on Maxwell's equations. This "redundancy" in the choice of gauge
486 in Eqn. 1.1 is called a gauge symmetry.

487 One important consequence of gauge symmetry comes from the application of
488 Noether's theorem, which states that for every global transformation under which the
489 Lagrangian density is invariant, there exists a conserved quantity. If $\mathcal{L}(\Psi(x), \partial_\mu \Psi(x))$
490 is invariant under the transformation of the wave function $\Psi(x) \rightarrow \Psi'(x)$, where
491 $\Psi'(x) = \Psi(x) + \delta\Psi(x)$, then there exists a conserved current

$$\partial_\mu \left(\frac{\partial \mathcal{L}(x)}{\partial (\partial_\mu \Psi(x))} \delta\Psi(x) \right) = 0 \quad (1.2)$$

492 In classical mechanics, the conservation of linear momentum, angular momentum,
493 and energy follows from translational invariance, rotational variance, and invariance
494 under translations in time [4]. Likewise, charge conservation can be shown to arise
495 from the invariance of the Dirac Lagrangian density $\mathcal{L}_{\text{Dirac}} = \bar{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi$ under the
496 particle wavefunction's phase transformation, $\Psi'(x) = \exp(i\epsilon\chi)\Psi(x)$. Thus Noether's
497 theorem establishes a correspondence between a gauge symmetry and a conserved
498 internal property (e.g. charge or momentum).

499 Interactions between particles arise if we modify the wave function with a phase

500 transformation $\Psi'(x) = \exp(ie\chi)\Psi(x)$, and allow the phase χ to be a function of
 501 spacetime [4]. A wave function of the form

$$\Psi'(x) = \exp(ie\chi(x))\Psi(x) \quad (1.3)$$

502 can be verified to *not* be a solution to the Dirac equation for free particles: $(i\gamma^\mu\partial_\mu -$
 503 $m)\Psi(x) = 0$. This necessitates a modified Dirac equation, where the derivative takes
 504 into account that the vector field $V(x)$ needs to be compared at two displaced space-
 505 time points in a curvilinear coordinate system:

$$\mathcal{D}_\mu \equiv \lim_{\Delta x^\mu \rightarrow 0} \frac{V_{||}(x + \Delta x) - V(x)}{\Delta x^\mu} \quad (1.4)$$

506 We define a covariant derivative,

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

507 where $A_\mu(x)$ is a 4-vector potential. Thus the modified Dirac equation reads:

$$(i\gamma^\mu\mathcal{D}_\mu - m)\Psi(x) = 0 \quad (1.6)$$

508 The simultaneous gauge transformation $A'_\mu(x) = A_\mu(x) - \partial_\mu\chi(x)$ and wavefunction
 509 transformation $\Psi'(x) = \exp(ie\chi(x))\Psi(x)$ leaves the covariant-derivative form of the
 510 Dirac equation (Eqn 1.1) invariant.

511 The generalization of this result is as follows: if a theory is invariant for unitary
 512 transformations U of the particle states according to

$$\Psi' = U\Psi \quad (1.7)$$

513 One must define a derivative of the form

$$D^\mu = \partial^\mu + igB^\mu \quad (1.8)$$

514 to keep the theory invariant under Eqn. 1.7. The four-potential B^μ represents the
515 interacting four-potential which must be added to keep the theory invariant.

516 In the case of the Standard Model, the theory is built around the gauge trans-
517 formations $G = SU(3) \times SU(2) \times U(1)$. $SU(3)$ is associated to the strong force
518 (subscripted C); $SU(2)$ is associated to the weak force (subscripted L); and $U(1)$ is
519 hypercharge (subscripted Y). The gauge-covariant derivative is

$$\mathcal{D}_\mu = \partial_\mu - ig'B_\mu \frac{Y}{2} - igW_\mu^\alpha \frac{\tau_a}{2} - ig_s G_\mu^k \frac{\lambda_k}{2} \quad (1.9)$$

520 • In the $U(1)_Y$ term, B_μ is the weak hypercharge field.

521 • In the $SU(2)_L$ term, $W_\mu(x) = (W_\mu^1(x), W_\mu^2(x), W_\mu^3(x))$ are a triplet of four-
522 potentials. $\tau/2$ are the Pauli matrices, generators of the $SU(2)$ transformation.

523 • In the $SU(3)_C$ term, the gluon (color) field is G_μ . λ_k are the Gell-Man matrices,
524 generators of the $SU(3)$ transformation.

525 The invariance of the Standard Model under $SU(3)_C \times SU(2)_L \times U(1)_Y$ requires
526 massless fermions and massless force carriers.

527 1.3 The Higgs mechanism

528 To introduce mass into the theory, i.e. to change the propagation of the gauge par-
529 ticles and all the fermions, the physical vacuum cannot have all the symmetries of
530 the Standard Model Lagrangian [4]. The symmetries of the physical vacuum must
531 be spontaneously broken, without affecting gauge invariance in the Lagrangian. The

532 Higgs mechanism proposes the existence of a scalar field, or fields, with nonzero vac-
 533 um expectation values, which reduce the gauge symmetries of the physical vacuum
 534 from $SU(3)_C \times SU(2)_L \times U(1)_Y$ down to $SU(3)_C \times U(1)_{EM}$.

535 The Higgs field interacts with the gauge bosons and fermions throughout space,
 536 impeding their free propagation. The resulting broken symmetry correctly predicts
 537 the mass ratio of the neutral (Z) and charged (W) massive electroweak bosons, and
 538 predicts that at least one physical degree of freedom in the Higgs field is a particle
 539 degree of freedom, called the Higgs boson. The location of the minimum of the Higgs
 540 potential can be constrained from previously measured Standard Model parameters,
 541 but the shape of the mass distribution of the Higgs boson must be experimentally
 542 measured.

543 The minimal choice of Higgs field comes from the breaking of $SU(2)_L \times U(1)_Y$
 544 down to $U(1)_{EM}$. The smallest $SU(2)$ multiplet is the doublet. The existence of three
 545 massive electroweak bosons leads the Higgs sector to have at least three degrees of
 546 freedom. The minimal single-doublet complex scalar Higgs field is

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+(x) + i\phi_2^+(x) \\ \phi_1^0(x) + i\phi_2^0(x) \end{pmatrix} \quad (1.10)$$

547 where ϕ_1^+ , ϕ_2^+ , ϕ_1^0 , and ϕ_2^0 are real (four degrees of freedom). By convention, the
 548 nonzero vacuum expectation value is assigned to ϕ_1^0 .

549 The minimal self-interacting Higgs potential that is invariant under $SU(2)_L \times$
 550 $U(1)_Y$ is given by

$$V(\Phi^\dagger \Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2, \quad \mu^2 > 0, \lambda > 0 \quad (1.11)$$

551 where λ is the coupling strength of the four-point Higgs interaction. The potential

552 energy is minimized at

$$\Phi_{\min} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \text{ where } v = \sqrt{\mu^2/\lambda} \quad (1.12)$$

553 Choosing a fixed orientation of $\langle \Phi \rangle$ out of a continuous set of possible ground states
 554 spontaneously breaks the symmetry of the physical vacuum, as illustrated in Fig 1.2.

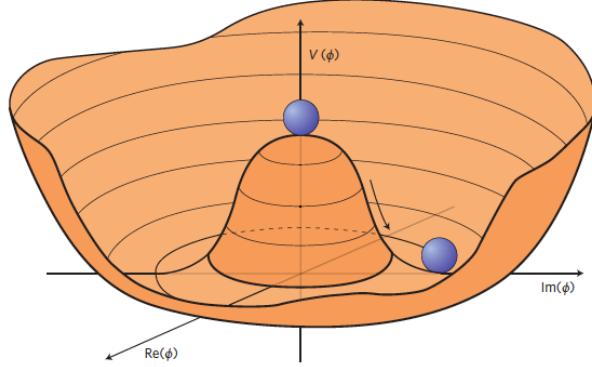


Figure 1.2: An illustration of the Higgs potential [5]. Choosing any of the points at the bottom of the potential breaks spontaneously the rotational $U(1)$ symmetry.

555 The excitations of the Higgs field with respect to the minimum Φ_{\min} are parame-
 556 terized by

$$\Phi(x) = \exp(i\xi(x) \cdot \tau) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \quad (1.13)$$

557 Three degrees of freedom are coupled directly to the electroweak gauge bosons; this
 558 is often referred to as the gauge bosons “eating” the Goldstone bosons to form the
 559 longitudinal polarizations of the massive spin-1 boson states. The $H(x)$ excitation is
 560 in the radial direction and corresponds to the free particle state of the Higgs boson.

561 1.4 Two-Higgs Doublet Models

562 One of the simplest possible extensions to the Standard Model is adding a doublet
 563 to the minimal Higgs sector of the Standard Model, which is a $SU(2)_L$ doublet H

564 with hypercharge $Y = +\frac{1}{2}$, denoted here as $H \sim 2_{+1/2}$. These extensions are found
 565 in several theories such as supersymmetry. A general 2HDM can be extended with a
 566 light scalar (2HDM+S) to obtain a rich set of exotic Higgs decays [6].

The charges of the Higgs fields are chosen to be $H_1 \sim 2_{-1/2}$ and $H_2 \sim 2_{+1/2}$, which
 acquire vacuum expectation values $v_{1,2}$ which are assumed to be real and aligned [6].
 Expanding about the minima yields two complex and four real degrees of freedom:

$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 + H_{1,R}^0 + iH_{1,I}^0 \\ H_{1,R}^- + iH_{1,I}^- \end{pmatrix} \quad (1.14)$$

$$H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} H_{2,R}^+ + iH_{2,I}^+ \\ v_2 + H_{2,R}^0 + iH_{2,I}^0 \end{pmatrix} \quad (1.15)$$

567 The charged scalar and pseudoscalar mass matrices are diagonalized by a rotation
 568 angle β , defined as $\tan \beta = v_2/v_1$. One charged (complex) field and one neutral
 569 pseudoscalar combination of $H_{1,2,I}^0$ are eaten by the SM gauge bosons after electroweak
 570 symmetry breaking [6]. The other complex field yields two charged mass eigenstates
 571 H^\pm , which are assumed to be heavy. The remaining three degrees of freedom yield
 572 one neutral pseudoscalar mass eigenstate

$$A = H_{1,I}^0 \sin \beta - H_{2,I}^0 \cos \beta \quad (1.16)$$

573 and two neutral scalar mass eigenstates (where $-\pi/2 \leq \alpha \leq \pi/2$)

$$\begin{pmatrix} h \\ H^0 \end{pmatrix} = \begin{pmatrix} -\sin \alpha & \cos \alpha \\ \cos \alpha & \sin \alpha \end{pmatrix} \begin{pmatrix} H_{1,R}^0 \\ H_{2,R}^0 \end{pmatrix} \quad (1.17)$$

574 We assume that the 2HDM is near or in the decoupling limit: $\alpha \rightarrow \pi/2 - \beta$, where the
 575 lightest state in the 2HDM is h , which we identify as the 125 GeV Higgs particle [6].
 576 In this limit, the fermion couplings of h become identical to the Standard Model

577 Higgs, while the gauge boson couplings are very close to Standard Model-like for
578 $\tan \beta \gtrsim 5$. All of the properties of h can be determined by just two parameters: $\tan \beta$
579 and α , and the fermion couplings to the two Higgs doublets.

580 2HDM can be extended by a scalar singlet (2HDM+S) [6]:

$$S = \frac{1}{\sqrt{2}}(S_R + iS_I) \quad (1.18)$$

581 If this singlet only couples to the Higgs doublets $H_{1,2}$ and has no direct Yukawa
582 couplings, all of its couplings to SM fermions result from mixing with $H_{1,2}$. Under
583 these simple assumptions, exotic Higgs decays $h \rightarrow ss \rightarrow X\bar{X}Y\bar{Y}$ or $h \rightarrow aa \rightarrow$
584 $X\bar{X}Y\bar{Y}$, and $h \rightarrow aZ \rightarrow X\bar{X}Y\bar{Y}$ are permitted, where $s(a)$ is a (pseudo)scalar mass
585 eigenstate mostly composed of $S_R(S_I)$, and X, Y are Standard Model fermions or
586 gauge bosons. There are two pseudoscalars in the 2HDM+S, and the mostly singlet-
587 like pseudoscalar can be chosen to be the one lighter than the SM-like Higgs. For
588 $m_a < m_h - m_Z \sim 35$ GeV, the exotic Higgs decay $h \rightarrow Za$ is possible, and for
589 $m_a < m_h/2 \approx 63$ GeV, the exotic Higgs decay $h \rightarrow aa$ is possible.

590 In 2HDM, and by extension 2HDM+S, there are four types of fermion couplings
591 commonly discussed in the literature that forbid flavor-changing neutral currents at
592 tree level [6]. These are referred to as Type I (all fermions couple to H_2), Type II
593 (MSSM-like, d_R and e_R couple to H_1 , u_R to H_2), Type III (lepton-specific, leptons
594 and quarks couple to H_1 and H_2 respectively) and Type IV (flipped, with u_R , e_R
595 coupling to H_2 and d_R to H_1). The exact branching ratios of the pseudoscalars to
596 Standard Model particles vary depending on the 2HDM+S model and the value of
597 $\tan \beta$ (e.g. Fig. 1.3).

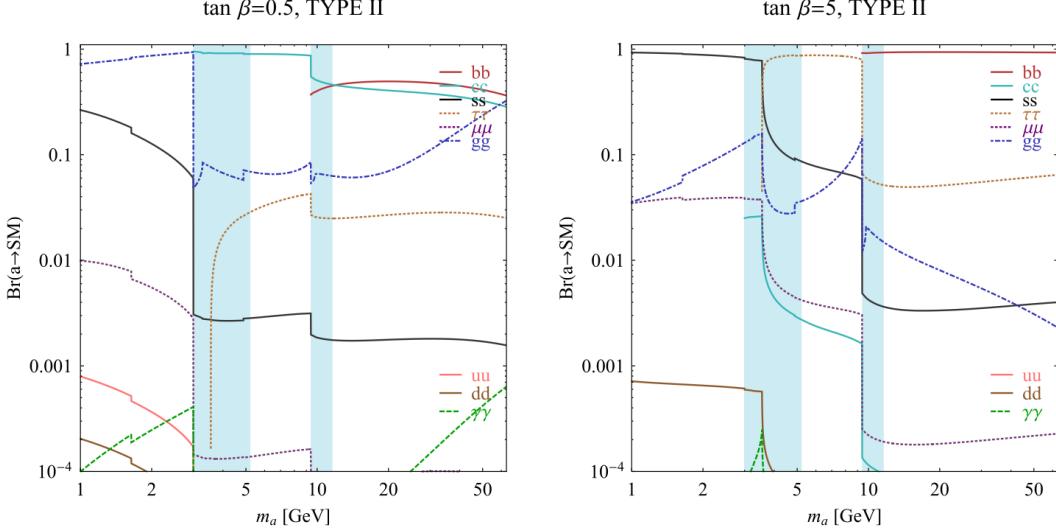


FIG. 7 (color online). Branching ratios of a singletlike pseudoscalar in the 2HDM + S for type-II Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.

Figure 1.3: Branching ratios of a singlet-like pseudoscalar in Type II 2HDM+S for $\tan\beta = 0.5$ (left) and $\tan\beta = 5$ (right) from [6], showing the dependence of the branching ratios on $\tan\beta$, as well as the prominence of the branching ratios to bb and $\tau\tau$, the channels searched for in the analysis presented here.

1.5 Two Real Singlet Model

The two real singlet model (TRSM) adds two real singlet degrees of freedom to the Standard Model. These are written as two real singlet fields S and X . Depending on the vacuum expectation values acquired by the scalars, different phases of the model can be realized [7]. To reduce the number of free parameters, two discrete \mathbb{Z}_2 symmetries are introduced. The fields are decomposed as

$$\Phi = \begin{pmatrix} 0 \\ \frac{\phi_h + v}{\sqrt{2}} \end{pmatrix}, S = \frac{\phi_S + v_S}{\sqrt{2}}, X = \frac{\phi_X + v_X}{\sqrt{2}} \quad (1.19)$$

To achieve electroweak-breaking symmetry, $v = v_{SM} \sim 246$ GeV is necessary. If the vacuum expectation values $v_S, v_X \neq 0$ the \mathbb{Z}_2 are spontaneously broken, and the fields $\phi_{h,S,X}$ mix into three physical scalar states. This is called the broken phase and leads to the most interesting collider phenomenology.

608 The mass eigenstates $h_{1,2,3}$ are related to the fields $\phi_{h,S,X}$ through a 3×3 orthogonal
609 mixing matrix denoted R . The mass eigenstates are assumed to be ordered $M_1 \leq$
610 $M_2 \leq M_3$. R is parameterized by the three mixing angles θ_{hS} , θ_{hX} , θ_{SX} . The nine
611 parameters of the scalar potential can be expressed in terms of the three physical
612 Higgs masses, the three mixing angles, and the three vacuum expectation values.

613 After fixing one of the Higgs masses to the mass of the observed Higgs boson, and
614 fixing the Higgs doublet vacuum expectation value to its Standard Model value, there
615 are seven remaining free parameters of the TRSM [7].

616 In one benchmark scenario of TRSM [7], the heaviest scalar state h_3 is identified
617 with the 125 GeV Higgs, h_{125} , and it can decay asymmetrically $h_{125} \rightarrow h_1 h_2$, which
618 we also denote $h \rightarrow a_1 a_2$ to highlight the similarity with the symmetric decay $h \rightarrow aa$
619 typically interpreted in 2HDM+S as discussed. The parameter values in TRSM are
620 chosen such that the coupling of h_3 to Standard Model particles are nearly identical
621 to the Standard Model predictions.

622 In benchmark scenario 1 (benchmark plane 1, or BP1) (Fig. 1.4) [7], the maximal
623 branching ratios for $h_3 \rightarrow h_1 h_2$ reach up to 7 – 8% which translates into a signal
624 rate of around 3 pb. These maximal branching ratios are reached in the intermediate
625 mass state for h_2 , $M_2 \sim 60 – 80$ GeV. For $M_2 < 40$ GeV, although phase space opens
626 up significantly for light decay products, the branching ratio becomes smaller.

627 If the decay channel $h_2 \rightarrow h_1 h_1$ is kinematically open (i.e. $M_2 > 2M_1$), it is the
628 dominant decay mode leading to a significant rate for the $h_1 h_1 h_1$ final state, in a
629 “cascade” decay. In BP1, $BR(h_2 \rightarrow h_1 h_1) \simeq 100\%$ above the red line in Fig. 1.4. If,
630 in addition, $M_1 \gtrsim 10$ GeV, the h_1 decays dominantly to $b\bar{b}$ leading to a sizable rate
631 for the $b\bar{b}b\bar{b}b\bar{b}$ final state as shown in Fig. 1.4 (*bottom right*).

632 If the $h_2 \rightarrow h_1 h_1$ decay is kinematically closed (i.e. $M_2 < 2M_1$), both scalars decay
633 directly to Standard Model particles, with branching ratios identical to a Standard
634 Model-like Higgs boson, i.e. with the $b\bar{b}b\bar{b}$ final state dominating, as shown in Fig. 1.4

₆₃₅ (*bottom left*), while at smaller masses, combinations with τ leptons and eventually
₆₃₆ final states with charm quarks and muons become relevant [7].

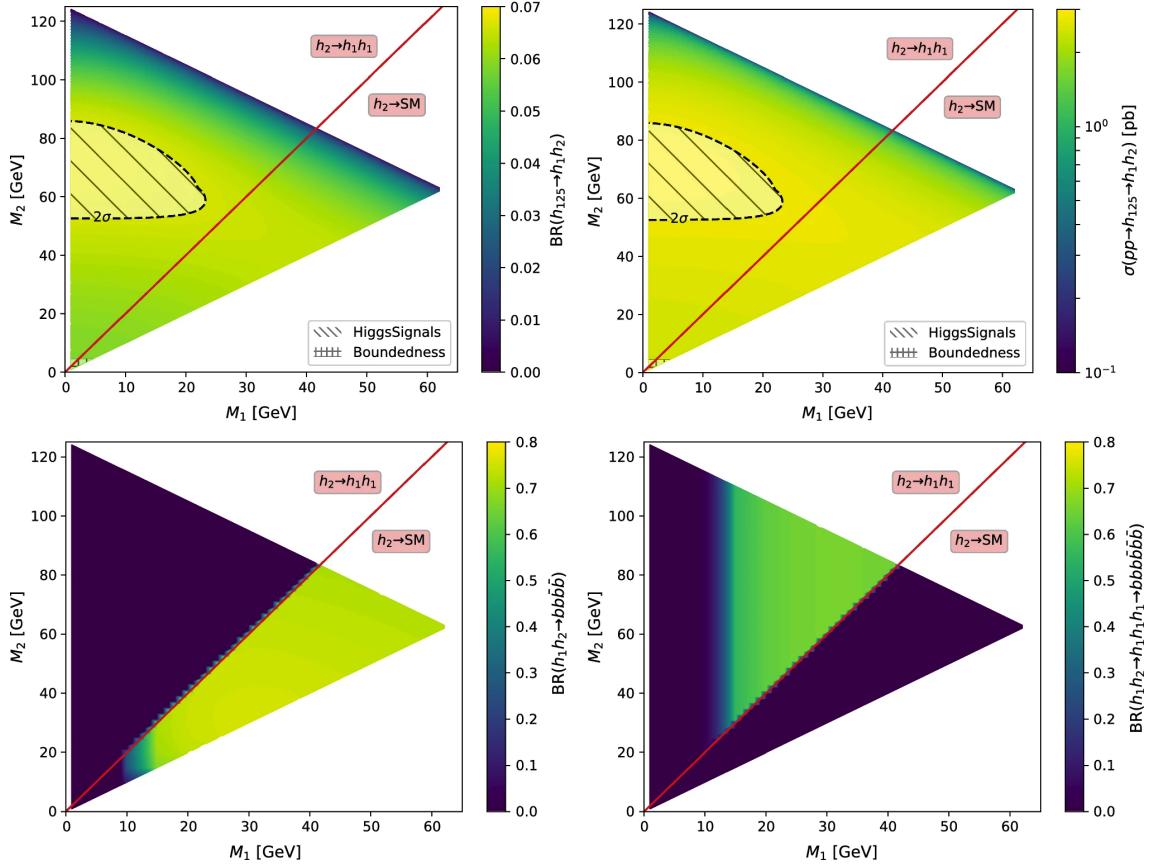


Figure 1.4: Benchmark plane BP1 for benchmark scenario 1 from [7], for the decay signature $h_{125} \rightarrow h_1 h_2$ with $h_{125} \equiv h_3$, defined in the (M_1, M_2) plane. The color code shows $\text{BR}(h_3 \rightarrow h_1 h_2)$ (*top left*) and the 13 TeV LHC signal rate for $pp \rightarrow h_3 \rightarrow h_1 h_2$ (*top right*). The red line separates the region $M_2 > 2M_1$, where $\text{BR}(h_2 \rightarrow h_1 h_1) \sim 100\%$, from the region $M_2 < 2M_1$, where $\text{BR}(h_2 \rightarrow F_{SM}) \sim 100\%$. The *bottom left* and *right* show the branching ratio of the $h_1 h_2$ into (respectively) $b\bar{b}b\bar{b}$, and through a $h_2 \rightarrow h_1 h_1$ cascade to $b\bar{b}b\bar{b}b\bar{b}$. The hatched region indicates where the decay rate slightly exceeds the 2σ upper limit inferred from the LHC Higgs rate measurements, though the region depends on the parameter choices and experimental searches should cover the whole mass range.

637 **Chapter 2**

638 **The Large Hadron Collider and the**
639 **CMS Experiment**

640 This chapter introduces the key aspects of the CERN Large Hadron Collider (LHC)
641 and the Compact Muon Solenoid (CMS) experiment where the work for this thesis was
642 conducted. Section 2.1 describes the history of accelerator developments at CERN
643 that led to the construction of the LHC, the current LHC configuration, and the
644 largest experiments located at the LHC. The concepts of beam luminosity and pile-
645 up, which are critical for understanding and measuring high-energy particle collisions,
646 are described in Section 2.2 and discussed in the context of the High-Luminosity
647 LHC (HL-LHC) upgrade in Section 2.3. Lastly, Section 2.4 describes the design
648 and function of CMS and its subdetectors, and terminates in a description of data
649 processing at CMS, beginning from online event filtering in the Level-1 Trigger, to
650 processing in the High-Level Trigger, to offline particle reconstruction, and finally
651 long-term storage and processing of measured events.

652 2.1 The Large Hadron Collider

653 CERN, the European Organization for Nuclear Research, is an international organiza-
654 tion based in Meyrin, Switzerland which operates the world's largest particle physics
655 laboratory, and is the site of the Large Hadron Collider (LHC) [8]. The very first
656 accelerator built at CERN was the 600 MeV Synchrocyclotron (SC), which initially
657 provided beams for CERN's first experiments. The newer and more powerful Proton
658 Synchrotron (PS), which could accelerate particles to an energy of 28 GeV, began op-
659 erations in 1959 and is still in use today. The first hadron collider at CERN was the
660 Intersecting Storage Rings (ISR), which consisted of two interlaced rings each with a
661 diameter of 200. The ISR collided protons at a center-of-mass energy of 62 GeV and
662 began measuring collisions in 1971. In 1968 CERN began to accelerate heavy ions
663 in the Super Proton Synchrotron (SPS), which is 7 kilometers in circumference and
664 was the first of CERN's giant underground rings to be built. The SPS became the
665 forefront of CERN's particle physics program in 1976, and in 1981 was converted into
666 a proton-antiproton collider. The final and largest underground ring constructed at
667 CERN was the Large Electron-Positron (LEP) collider, which was commissioned in
668 July 1989 and hosted 5176 magnets and 128 accelerating cavities located around a
669 27-kilometer circumference. Over 11 years of research, four detectors, ALEPH, DEL-
670 PHI, L3, and OPAL measured the collisions, with collision energies reaching up to
671 209 GeV in the year 2000. In November 2000, LEP was closed down to make way for
672 the construction of the LHC in the same tunnel.

673 In its current configuration, the LHC accelerator complex at CERN is a suc-
674 cession of machines that accelerate particles in stages until they reach their final energy
675 of 6.5 TeV per beam [9] [10]. In Linear accelerator 4 (Linac4), negative hydrogen
676 ions (hydrogen atoms with an additional electron) are accelerated to 160 MeV, and
677 stripped of their two electrons, leaving only protons, before entering the Proton Syn-
678 chrotron Booster (PSB). These protons are accelerated to 2 GeV, then to 26 GeV in

679 the Proton Synchrotron (PS), and 450 GeV in the Super Proton Synchrotron (SPS).
680 The protons are transferred to the two beam pipes of the Large Hadron Collider
681 (LHC). The LHC is a 27-kilometer ring of superconducting magnets, inside which
682 one beam circulates clockwise and the other counterclockwise. Each LHC ring takes
683 4 minutes and 20 seconds to fill, and it takes about 20 minutes for the protons to
684 reach their maximum energy. During normal operating conditions, beams circulate
685 for many hours inside the LHC ring.

686 The beams of particles in the LHC are made to collide at a center-of-mass energy
687 of up to 14 TeV, at four positions at particle detector experiments located around
688 the ring: ATLAS, CMS, ALICE, and LHCb. An aerial view of the four major
689 experiments' locations is shown in Fig. 2.1 [11]. ATLAS and CMS are the two
690 general-purpose detectors with broad physics programmes spanning Standard Model
691 measurements and searches for signatures of new physics [12] [13]. The two experi-
692 ments use different technical solutions and different magnet system designs. ALICE
693 is a general-purpose detector dedicated to measuring LHC heavy-ion collisions, and
694 is designed to address the physics of strongly interacting matter, and the properties
695 of quark-gluon plasma [14]. The LHCb experiment specializes in investigating CP vi-
696 olation through measuring the differences in matter and antimatter, by using a series
697 of subdetectors to detect mainly forward particles close to the beam direction [15].

698 2.2 Luminosity and pile-up

699 In order to search for rare processes, such as those resulting from a Higgs, W, or Z
700 boson, a large number of parton interactions per second are required at the LHC.
701 The number of events generated per second by the LHC collisions is given by

$$N_{event} = \mathcal{L} \cdot \sigma_{event} \quad (2.1)$$

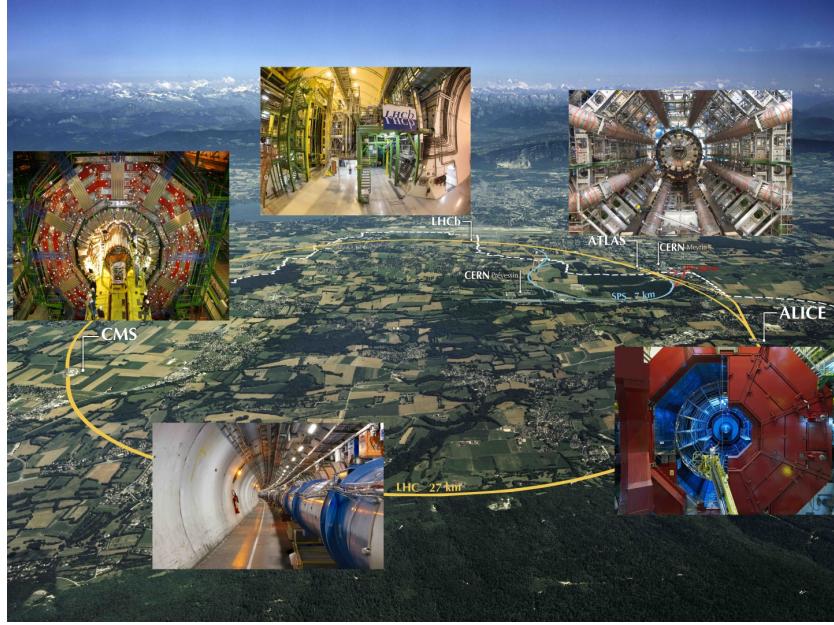


Figure 2.1: Aerial view of the Large Hadron Collider (LHC) spanning the border of France and Switzerland, and the four major experiments located around the ring: CMS (Compact Muon Solenoid), LHCb (LHC beauty), ATLAS (A Toroidal LHC Apparatus), and ALICE (A Large Ion Collider Experiment) [11].

where σ_{event} is the cross-section for the event under study, and \mathcal{L} the instantaneous luminosity. The instantaneous luminosity is measured in units of $\text{cm}^{-2} \text{ s}^{-1}$, and depends only on the beam parameters, and can be written for a Gaussian beam distribution as:

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (2.2)$$

where the parameters are as defined, along with some example typical nominal values in Phase-1 of the LHC [16] [17]:

- N_b is the number of particles per bunch ($N_b \approx 1.15 \times 10^{11}$ protons per bunch)
- n_b is the number of bunches per beam (maximum 2808),
- f_{rev} is the revolution frequency ($\approx 11 \text{ kHz}$),
- γ_r is the relativistic gamma factor,

- 712 • ϵ_n is the normalized transverse beam emittance (area in a transverse plane
 713 occupied by the beam particles),
 714 • β^* is the beta function at the collision point ($\beta^* = 0.55$ m),
 715 • and F is the geometric luminosity reduction factor due to the crossing angle at
 716 the interaction points ($F \approx 0.84$ for Phase-1. Note that complete overlap would
 717 give $F = 1$).

718 Peak luminosity at interaction points 1 and 5 reach values of $\sim 1.0 \times 10^{34}$ cm $^{-2}$ s $^{-1}$,
 719 with peak luminosity per bunch crossing reaching $\sim 3.56 \times 10^{34}$ cm $^{-2}$ s $^{-1}$.

720 Per Eqn. 2.1, the integrated luminosity over time is proportional to the number
 721 of events produced, and the size of LHC datasets is commonly presented in terms of
 722 integrated luminosity. Collider operation aims to optimize the integrated luminosity.
 723 Thus the exploration of rare events in the LHC collisions requires both high beam
 724 energies and high beam intensities.

725 The interaction vertex corresponding to the hard scattering of the protons is called
 726 the primary interaction vertex, or primary vertex (PV). The LHC's nominal beam
 727 luminosities are sufficiently large for multiple proton-proton collisions to occur in the
 728 same time window of 25 nanoseconds in which proton bunches collide [18]. To measure
 729 a proton-proton collision, the primary vertices must be separated from overlapping
 730 collisions, called “pile-up” collisions.

731 The pile-up is defined as the average number of pp collisions per bunch crossing,
 732 and can be estimated from the inelastic pp cross section of $\sigma_{\text{inel}} = 68.6$ millibarns at
 733 a center-of-mass energy of $\sqrt{s} = 13$ TeV [19]:

$$\text{Pile-up} = \frac{\mathcal{L} \times \sigma_{\text{inel}}}{n_b \cdot f} \sim 22 \quad (2.3)$$

734 A distribution of pile-up in the data-taking years 2016-2018 is shown in Fig. 2.2.

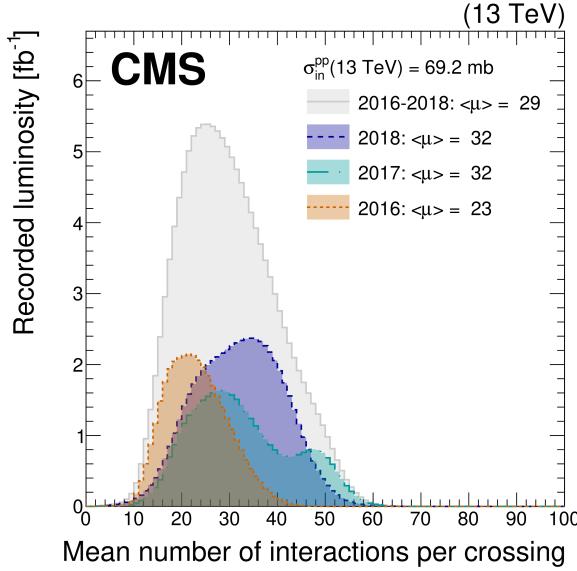


Figure 2.2: Distribution of the mean number of inelastic collisions per bunch crossing (pile-up) in data [18], for proton-proton collisions in 2016 (*dotted orange*), 2017 (*dotted light blue*), 2018 (*dotted dark blue*), and integrated over 2016-2018 (*solid grey*). A cross-section of inelastic proton-proton collisions of 69.2 mbarns is assumed. In the running conditions of the High-Luminosity LHC, pile-up will reach unprecedented levels of up to 200 per bunch crossing [20].

These multiple collisions will lead to higher occupancies in the detector, and particles originating from the pile-up interactions can be confused with those originating from the primary vertex. Thus, higher luminosities create more intense pile-up conditions, posing a greater challenge to detector performance and particle reconstruction and identification.

2.3 The High-Luminosity LHC

The High-Luminosity LHC (HL-LHC) is a major upgrade of the LHC scheduled to take place in the late 2020s, that will increase the instantaneous luminosity by a factor of five beyond the original design value, and the integrated luminosity by a factor of ten [20]. This will be accomplished through accelerator technological advances: for instance, reduction of the interaction point β^* from 0.55 m down to 0.15

746 m by installation of new final-focusing magnets, and improvements in the geometric
747 luminosity loss factor $F \approx 1$ through the installation of crab cavities that optimize
748 the orientation of colliding bunches. A further discussion of the HL-LHC upgrades
749 for the CMS detector follows in Chapter 3.

750 2.4 The CMS detector

751 We give a brief overview of the Compact Muon Solenoid (CMS) experiment here
752 and discuss each of the subdetectors in more detail in the following sections. The
753 CMS experiment was conceived to study proton-proton and lead-lead collisions at
754 a center-of-mass energy of 14 TeV (5.5 TeV nucleon-nucleon) and at luminosities up
755 to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ($10^{27} \text{ cm}^{-2} \text{ s}^{-1}$) [21] [22]. Starting from the beam interaction region
756 at the center of the CMS detector, particles first pass through a silicon pixel and
757 strip tracker, in which charged-particle trajectories (tracks) and origins (vertices)
758 are reconstructed from signals (hits) in the sensitive layers. The tracker, electro-
759 magnetic calorimeter (ECAL), and hadronic calorimeter (HCAL) are immersed in a
760 high-magnetic-field superconducting solenoid that bends the trajectories of charged
761 particles. After passing through the tracker, electrons and photons are then absorbed
762 in the electromagnetic calorimeter (ECAL) comprised of lead-tungstate scintillating-
763 crystals. The corresponding electromagnetic showers are detected as clusters of energy
764 recording in neighboring cells, from which the direction and energy of the particles can
765 be determined. Charged and neutral hadrons may initiate a hadronic shower in the
766 ECAL as well, which is then fully absorbed in the hadron calorimeter (HCAL). The
767 resulting clusters are used to estimate their direction and energies. Muons and neu-
768 trinos pass through the calorimeters with little to no interactions. Neutrinos escaped
769 undetected; muons produce hits in additional gas-ionization chamber muon detectors
770 housed in the iron yoke of the flux-return. A sketch of example particle interactions

in a transverse slice of the CMS detector is shown in Fig. 2.3. The collision data is recorded with the use of the Level-1 (L1) trigger (discussed in greater detail in 2.5.5), the High-Level Trigger (HLT), and data acquisition systems ensuring high efficiency in selecting physics events of interest.

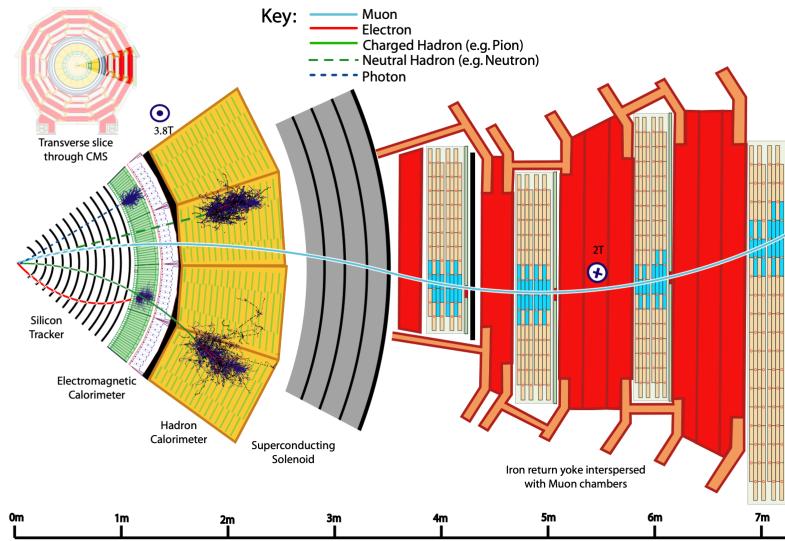


Figure 2.3: Sketch of particle trajectories of muons, electrons, charged and neutral hadrons, and photons in a transverse cross-section of the CMS detector [22].

CMS uses a right-handed coordinate system [21]. The origin is centered at the nominal collision point inside the experiment. The x axis points towards the center of the LHC, and the y axis points vertically upwards. The z axis points along the beam direction. The azimuthal angle, ϕ , is measured from the x axis in the x - y plane, and the radial coordinate in this plane is denoted by r . The polar angle, θ , is measured from the z axis. The pseudorapidity, η , is defined as $\eta = -\ln \tan(\theta/2)$. The momentum and energy transverse to the beam direction, denoted by p_T and E_T respectively, are computed from the x and y components. The momentum imbalance in the transverse plane is called the missing transverse momentum, and its magnitude is denoted by E_T^{miss} .

785 2.5 Sub-detectors of CMS and data processing

786 This section details the sub-detectors of CMS that operate to identify and precisely
787 measure muons, electrons, photons, and jets over a large energy range. The sections
788 are ordered starting from the innermost sub-detectors closest to the beam interaction
789 area: the tracker, the electromagnetic and hadronic calorimeters, and the muon de-
790 tectors. The two-stage trigger system is described, starting with the firmware-based
791 Level-1 Trigger and followed by the High-Level Trigger. Lastly, particle reconstruction
792 and data storage and computational infrastructure are discussed.

793 2.5.1 Inner tracking system

794 The CMS Tracker performs robust tracking and detailed vertex reconstruction in the
795 4 T magnetic field of the superconducting solenoidal magnet. The primary sensors
796 used in the tracker are p^+ on n -bulk devices, which allow high voltage operation and
797 are radiation-resistant [23] [24]. The active envelope of the CMS Tracker extends to a
798 radius of 115 cm, over a length of approximately 270 cm on each side of the interaction
799 point [23]. Charged particles in the region $|\eta| \lesssim 1.6$ benefit from the full momentum
800 measurement precision. In this region, a charged particle with p_T of 1000 GeV has a
801 sagitta of $\sim 195 \mu\text{m}$. The Tracker acceptance extends further to $|\eta| = 2.5$, with a
802 reduced radius of approximately 50 cm.

803 The high magnetic field of CMS causes low p_T charged particles to travel in helical
804 trajectories with small radii. The majority of events contain particles with a steeply
805 falling p_T spectrum, resulting in a track density which rapidly decreases at higher
806 radii.

807 A schematic view of the current Phase-1 CMS tracker [25], including the pixel
808 detector, is shown in Fig. 2.4. The Phase-1 pixel detector consists of three barrel
809 layers (BPIX) at radii of 4.4 cm, 7.3 cm, and 10.2 cm, and two forward/backward disks

810 (FPIX) at longitudinal positions of ± 34.5 cm and ± 46.5 cm, and extending in radius
 811 from about 6 cm to 15 cm. These pixelated detectors produce 3D measurements along
 812 the paths of charged particles with single hit resolutions between 10-20 μm .

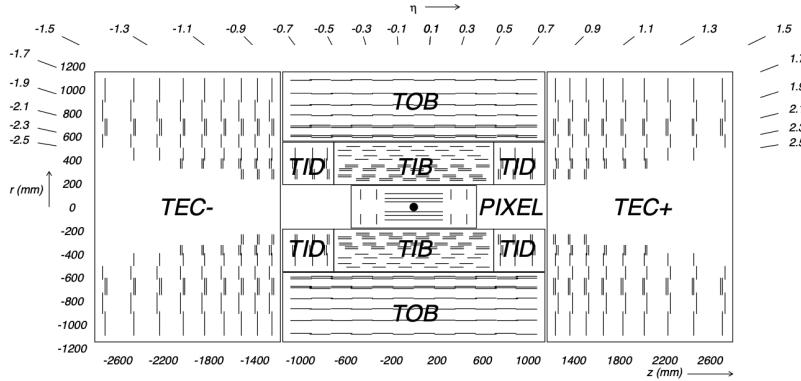


Figure 2.4: Cross section of the current Phase-1 CMS tracker [25]. Each line represents a detector module. Double lines indicate back-to-back modules which deliver two-dimensional (stereo) hits in the strip tracker.

813 After the pixel and on their way out of the tracker, particles pass through the
 814 silicon strip tracker which reaches out to a radius of 130 cm (Fig. 2.4). The sensor el-
 815 ements in the strip tracker are single-sided p -on- n type silicon micro-strip sensors [21].
 816 The silicon strip detector consists of four inner barrel (TIB) layers assembled in shells,
 817 with two inner endcaps (TID), each composed of three small discs. The outer barrel
 818 (TOB) consists of six concentric layers. Two endcaps (TEC) close off the tracker on
 819 either end.

820 2.5.2 ECAL

821 The electromagnetic calorimeter (ECAL) of CMS measures electromagnetic energy
 822 deposits with high granularity. One of the driving criteria in the design was the capa-
 823 bility of detecting the Standard Model Higgs boson decay to two photons (in fact, the
 824 channel in which the 125 GeV Higgs boson was discovered at CMS). ECAL is a her-
 825 metic homogeneous calorimeter comprised of 61,200 lead tungstate (PbWO_4) crystals

826 mounted in the central barrel, with 7,324 crystals in each of the two endcaps [21]. A
827 preshower detector is located in front of the endcap crystals. Avalanche photodiodes
828 (APDs) are used as photodetectors in the barrel and vacuum phototriodes (VPTs) in
829 the endcaps.

830 The design of the ECAL is driven by the behaviour of high-energy electrons, which
831 predominantly lose energy in matter via bremsstrahlung, and high-energy photons
832 by e^+e^- pair production. The characteristic amount of matter traversed for these
833 interactions is the radiation length X^0 , usually measured in units of $\text{g} \cdot \text{cm}^{-2}$. The
834 radiation length is also the mean distance over which a high-energy electron loses all
835 but $1/e$ of its energy via bremsstrahlung [26]. Thus high granularity in η and ϕ , and
836 the length of the ECAL crystals, is designed to capture the shower of e/γ produced
837 by electrons and photons.

838 The barrel part of the ECAL (EB) covers the pseudorapidity range $|\eta| < 1.479$ [21].
839 The barrel granularity is 360-fold in ϕ and (2×85) -fold in η . The crystal cross-section
840 corresponds to approximately 0.0174×0.0174 in $\eta - \phi$ or $22 \times 22 \text{ mm}^2$ at the front
841 face of the crystal, and $26 \times 26 \text{ mm}^2$ at the rear face. The crystal length is 230 mm,
842 corresponding to $25.8 X_0$.

843 The ECAL read-out acquires the signals of the photodetectors [21]. At each bunch
844 crossing, digital sums representing the energy deposit in a trigger tower, comprising
845 5×5 crystals in $\eta \times \phi$, are generated and sent to the Level-1 trigger system (detailed
846 in Section 2.5.5).

847 **2.5.3 HCAL**

848 The hadronic calorimeter (HCAL) of CMS measures hadronic energy, which is key to
849 characterizing the presence of apparent missing transverse energy which could arise
850 from hadron jets and neutrinos or exotic particles [21]. A schematic of the components
851 of HCAL are shown in Fig. 2.5. The HCAL barrel (HB) and endcaps (HE) are located

outside of the tracker and the ECAL, spanning a radius of 1.77 m (outer extent of
 ECAL) up to 2.95 m (inner extent of the magnet coil). An outer hadron calorimeter
 (HO) is placed outside the solenoid to complement the barrel calorimeter. Beyond
 $|\eta| = 3$, the forward hadron calorimeter (HF) at 11.2 m from the interaction point
 extend the pseudorapidity coverage to $|\eta| = 5.2$.

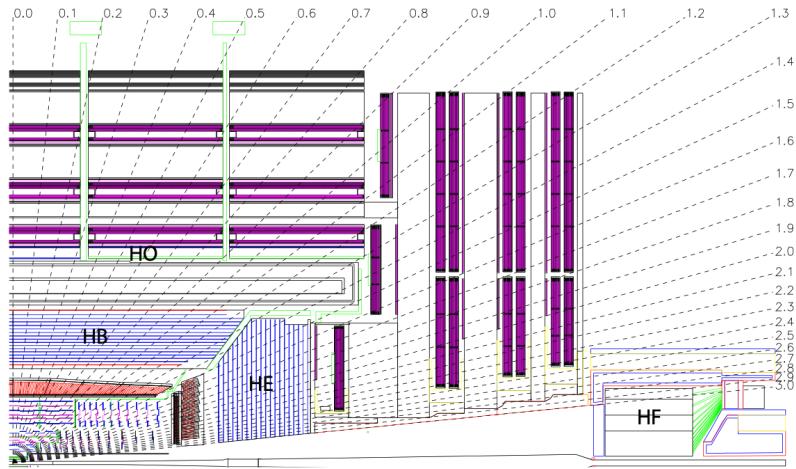


Figure 2.5: Longitudinal view of the CMS detector showing the hadron calorimeter barrel (HB), endcap (HE), outer (HO), and forward (HF) calorimeters from [21].

The HB is a sampling calorimeter covering the pseudorapidity range $|\eta| < 1.3$ [21]. It consists of 36 identical azimuthal wedges which form two half-barrels (HB+ and HB-), with a segmentation of $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$. The HE covers pseudorapidity $1.3 < |\eta| < 3$. The HB and endcap HE calorimeters are sampling calorimeters which use brass as the absorber and plastic scintillator as the active material. Light from the plastic scintillator is wavelength-shifted and captured in optic fibers which are read out by front-end electronics [27].

The HF is a Cherenkov calorimeter based on a steel absorber and quartz fibers which run longitudinally through the absorber and collect Cherenkov light, primarily from the electromagnetic component of showers developed in the calorimeter [27]. Photomultiplier tubes are used to collect light from the quartz fibers. The HF is designed to survive in the harsh radiation conditions and high particle flux of the for-

ward region. On average, 760 GeV per proton-proton interaction is deposited into the two forward calorimeters, compared to only 100 GeV for the rest of the detector [21]. Furthermore, this energy has a pronounced maximum at the highest rapidities.

2.5.4 Muon detectors

The CMS muon system is designed to have the capability of reconstructing the momentum and charge of muons over the kinematic range of the LHC, since muons are a powerful handle on signatures of interesting processes over the high background rate of the LHC [21]. For instance, the decay of the Standard Model Higgs boson into ZZ , which in turn decay to 4 leptons, can be reconstructed with high 4-particle mass resolution if all the leptons are muons, since muons are less affected than electrons by radiative losses in the tracker material.

The muon system consists of a cylindrical barrel section and two planar endcap regions [21]. The barrel muon detector consists of drift tube (DT) chambers covering the pseudorapidity region $|\eta| < 1.2$ (Fig. 2.6). The DTs can be used as tracking detectors due to the barrel region’s characteristic low neutron-induced backgrounds, low muon rate, and relatively uniform 4T magnetic field contained in the steel yoke.

In the two endcap regions, the muon rates and background levels are high and the magnetic field is large and non-uniform [21]. Here, the muon system uses cathode strip chambers (CSCs) to identify muons between $0.9 < |\eta| < 2.4$. The cathode strips of each chamber run radially outwards and provide a precision measurement in the $r - \phi$ bending plane. The anode wires run approximately perpendicular to the strips and are read out in order to measure η and the beam-crossing time of a muon.

In addition to the DT and CSC, a dedicated trigger system consisting of resistive plate chambers (RPCs) in the barrel and endcap regions provide a fast, independent, and highly-segmented trigger with a sharp p_T threshold over a large portion of the pseudorapidity range ($|\eta| < 1.6$) of the muon system [21]. RPCs have good time

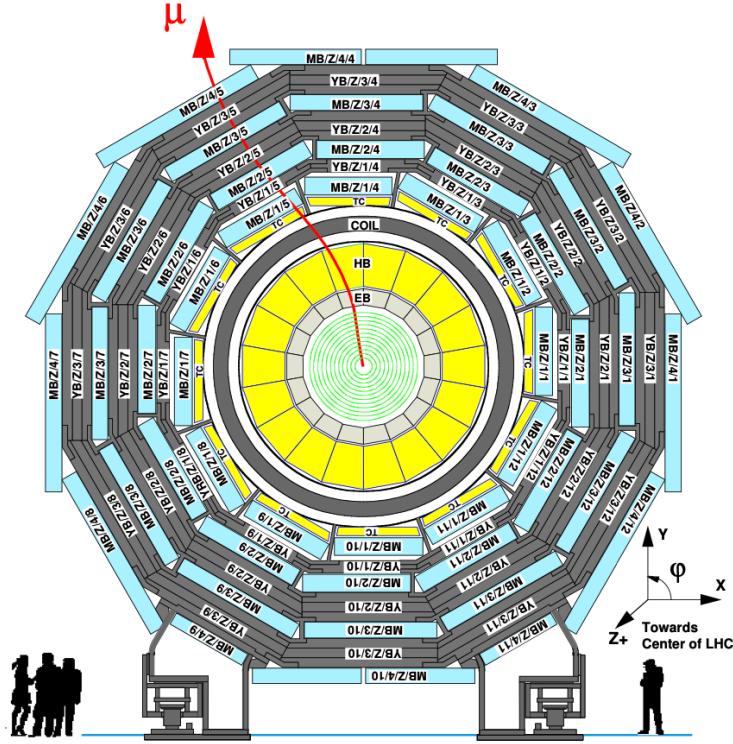


Figure 2.6: Layout of the CMS barrel muon drift tube (DT) chambers in one of the five wheels from [21]. The DTs are organized in 12 sectors of the yoke barrel (YB). In each of the 12 sectors of the yoke, there are 4 muon chambers per wheel (MB1, MB2, MB3, and MB4).

resolution but coarser position resolution compared to the DTs or CSCs. The RPCs also play a role in resolving ambiguities in reconstructing tracks from multiple hits in a chamber.

2.5.5 The Level-1 Trigger

The design performance of the LHC corresponds to an instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with a 25 ns bunch crossing rate, giving an average pile-up (number of simultaneous events) of 25 per bunch crossing [28]. However, during Run 2, in 2017 and 2018 the LHC was able to surpass this goal with a mean number of 32 interactions per bunch crossing, and reaching over 50 interactions in short periods (Fig.

904 2.2). The large number of events from inelastic collisions (minimum bias events) per
 905 bunch crossing, combined with the small cross-sections of possible physics discovery
 906 signatures, necessitates a sophisticated event selection system for filtering this large
 907 event rate, as it is impossible to save all events. This data filtering system is imple-
 908 mented by CMS in two stages. The first stage is the Level-1 (L1) Trigger, which is
 909 deployed in custom electronic hardware systems and is responsible for reducing the
 910 event rate to around 100 kHz. The second stage is the High-Level Trigger (HLT)
 911 which is described in Section 2.5.6. This section describes the Phase-1 configuration
 912 of the Level-1 Trigger.

913 The L1 Trigger data flow of Phase-1 is shown in Fig. 2.7 [28], with organization
 914 into the L1 calorimeter trigger, the L1 muon trigger, and the L1 Global Trigger (GT).

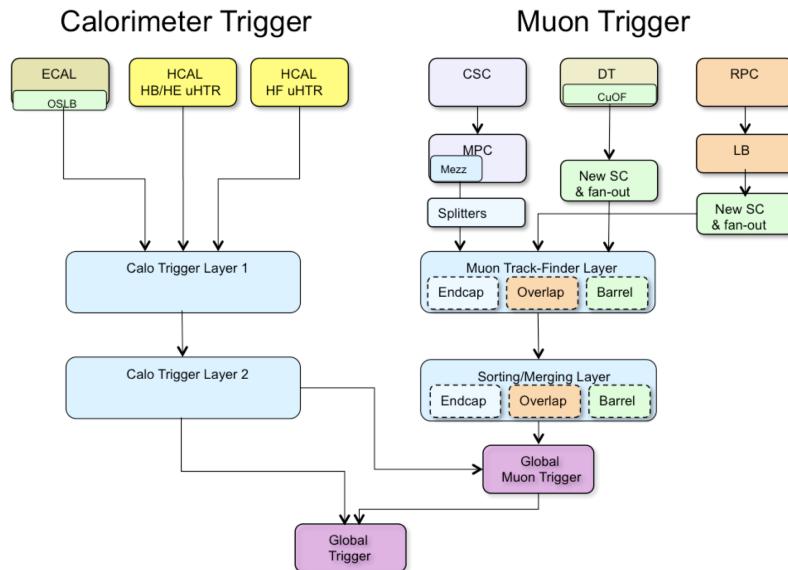


Figure 2.7: Dataflow for the Phase-1 Level-1 Trigger [28], which is implemented in custom hardware and is responsible for reducing the event rate from the LHC bunch crossing frequency of 400 MHz (bunch crossings every 25 ns) to a maximum rate of 100 kHz. In Phase-1, the Level-1 Trigger has access to information from the calorimeter and muon detectors.

915 The L1 calorimeter trigger begins with trigger tower energy sums formed by the
 916 ECAL, HCAL, and HF Trigger Primitive Generator (TPG) circuits from the indi-

917 individual calorimeter cell energies. In the original configuration, the ECAL energies
918 were accompanied by a bit indicating the transverse extent of the electromagnetic
919 energy deposits, and the HCAL energies were accompanied by a bit indicating the
920 presence of minimum ionizing energy [29]. During Long Shutdowns 1 and 2 (LS1
921 and LS2), HF was upgraded to provide finer granularity information to the trigger,
922 and the HCAL barrel and endcap front-end electronics were upgraded to provide
923 high-precision timing information and depth segmentation information.

924 In the original design of the L1 calorimeter trigger, the trigger primitives are pro-
925 cessed by the Regional Calorimeter Trigger (RCT, upgraded to Calo Layer 1 after
926 LS2) which finds isolated and non-isolated electron/photon candidates [28]. At this
927 stage, electrons/photons candidates are treated together since they cannot be defini-
928 tively distinguished at this stage due to lack of tracking information in the L1 trigger.
929 The Global Calorimeter Trigger (GCT, upgraded to Calo Layer 2 after LS2) sorts
930 further the candidate electrons/photons, finds jets (classified as central, forward, and
931 tau) using the E_T sums and performs calibration of the clustered jet energies, and
932 calculates global quantities such as missing E_T . It sends the top four candidates of
933 each type to the Global Trigger [28].

934 During LS2 and before Run-2, the legacy calorimeter trigger was upgraded to be
935 more flexible, maintainable, and performant [30] [31] [32]. These upgrades included
936 the replacement of legacy VME-based electronics with the MicroTCA (μ TCA) mod-
937 ern telecommunication standard, and system-wide usage of the latest generation of
938 FPGAs, Xilinx Virtex 7. Parallel copper links were replaced in almost all cases with
939 serial optical links, allowing link speeds to increase from 1 Gb/s to 10 Gb/s [30]. A
940 schematic of the current calorimeter trigger is shown in Fig. 2.8. The calorimeter
941 Layer-1 is implemented in 18 Calorimeter Trigger Processor (CTP7) boards, with
942 each card spanning 4 out of 72 towers in ϕ and all of η . Tower-level operations are
943 performed in Layer-1, such as the sum of ECAL and HCAL energies, energy cali-

bration, and the computation of the ratio of HCAL to ECAL energies. The Layer-1 cards each transmit 48 output links at 10 Gb/s to the nine Layer-2 Master Processor cards (MP7) cards, which host calorimeter algorithms that find particle candidates and compute global energy sums. Each MP7 takes 72 input links and has access to the whole event at trigger tower granularity, such that the algorithms are fully pipelined and start processing as soon as the minimum amount of data is received. The trigger candidates are sent to a demultiplexer (demux) board, also a MP7, which formats the data for the upgraded Global Trigger, also called the microGT (μ GT).

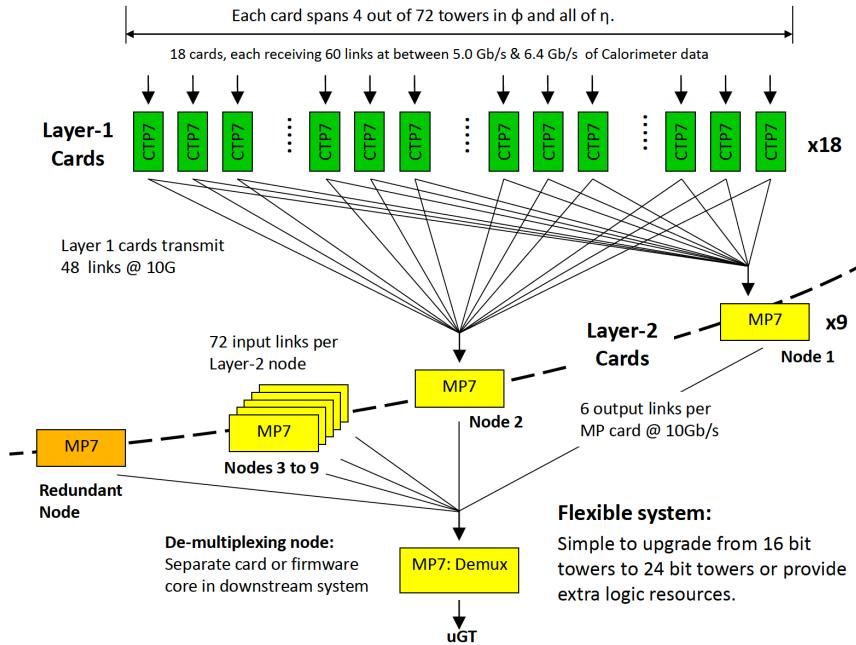


Figure 2.8: Schematic of the calorimeter trigger after Long Shutdown 2 [30]. The Layer-1 calorimeter trigger is implemented in CTP7 cards, which send time-multiplexed outputs to the Layer-2 MP7 cards. The Layer-2 cards handle the data in a round-robin style and the outputs are de-multiplexed, producing one output data stream to the Global Trigger.

Each of the L1 muon triggers has its own trigger logic [29]. The RPC strips are connected to a Pattern Comparator Trigger (PACT), which forms trigger segments that are used to build tracks and calculate p_T . The RPC logic also provides some hit data to the CSC trigger system to resolve ambiguities caused by two muons in

956 the same CSC. The CSCs form local charged tracks (LCTs) from the cathode strips,
957 which are combined with the anode wire information. LCTs are combined into full
958 muon tracks and assigned p_T values.

959 The Global Muon Trigger (GMT) sorts the RPC, DT, and CSC muon tracks,
960 converts these tracks to the same η , ϕ , and p_T scale, and validates the muon sign [29].
961 It improves the trigger efficiency by merging muon candidates that were detected
962 in two complementary sub-systems (i.e. DT+RPC, or CSC+RPC). The GMT also
963 contains logic to correlate the found muon tracks with an $\eta-\phi$ grid of quiet calorimeter
964 towers to determine if the muons are isolated, as well as logic to remove duplicate
965 candidates originating in the overlap regions from both DT and CSC systems. The
966 final collection of muons are sorted based on their initial quality, correlation, and p_T ,
967 and the top four muons are sent to the Global Trigger [29].

968 The Global Trigger (GT) receives information from the GCT and GMT, and
969 makes the Level-1 Accept (L1A) decision to either discard or accept the bunch cross-
970 ing [29]. This is accomplished by sorting ranked trigger objects that are accompanied
971 by positional information in η and ϕ , permitting the trigger to applying criteria with
972 thresholds that can vary based on the location of the trigger objects, and/or to re-
973 quire trigger objects to be close to or opposite from each other. The GT L1A decision
974 arrives at the detector front end with a $3.8\ \mu\text{s}$ latency after the interaction at a rate
975 which is required to be less than 100 kHz, and triggers a full readout of the detector
976 for further processing.

977 **2.5.6 The High-Level Trigger**

978 The HLT is implemented in software running on a large computer farm of fast com-
979 mercial processors [33] [34]. The algorithms in HLT have access to full data from
980 all CMS sub-detectors, including the tracker, with full granularity and resolution.
981 The HLT reconstruction software is similar to what is used offline for full CMS data

analysis. As a result, the HLT can calculate quantities with a resolution comparable to the final detector resolution, compared to the L1 Trigger. The HLT performs more computationally-intensive algorithms, such as combining tau-jet candidates in the calorimeter with high- p_T stubs in the tracker, to form a hadronic tau trigger. The maximum HLT input rate from the L1 Trigger is 100 kHz, and the HLT output rate is approximately 100 Hz.

The HLT contains trigger paths, each corresponding to a dedicated trigger [35]. A path consists of several steps implemented as software modules. Each HLT trigger path must be seeded by one or more L1 trigger bits: the first module always looks for a L1 seed, consisting of L1 bit(s) and L1 object(s). Each module performs a well-defined task such as unpacking (raw to digitized quantities), reconstruction of physics objects (electrons, muons, jet, missing transverse energy, etc.), making intermediate decisions that trigger more detailed reconstruction modules, and calculating the final decision for the trigger path. If an intermediate filter decision is negative, the rest of the path is not executed, and the trigger rejects the event.

2.5.7 Particle reconstruction

To build a description of the physics objects present in the particle collision, the basic elements from the detector layers (tracks and clusters of energy) are correlated to identify each particle in the final state. Measurements from different sub-detectors are combined to reconstruct the particle properties. This approach is called particle-flow (PF) reconstruction [22]. Key to the success of the PF reconstruction is the fine spatial granularity of the detector layers. Coarse-grained detectors can cause the signals from different particles to merge, especially within jets. However, if the subdetectors are sufficiently segmented to separate individual particles, it becomes possible to produce a global event description that identifies all physics objects with high efficiencies and resolution.

2.5.8 Data storage and computational infrastructure

The LHC generates over 15 petabytes (15 million gigabytes) of data every year, necessitating a flexible computing system that can be accessed by researchers working at the four main LHC experiments: ALICE, ATLAS, CMS, and LHCb. The Worldwide LHC Computing Grid (WLCG) [36] is a global collaboration of computer centers that links thousands of computers and storage systems in over 170 centers across 41 countries. These centers are arranged in “tiers”, and provide near real-time access to users processing, analyzing, and storing LHC data. One of the final stages of data analysis at LHC experiments is large-scale data processing taking place over distributing computing, for instance, with the use of Condor [37], a distributed, scalable, flexible batch processing system which accepts a computing job, allocates a resource to it, executes it, and returns the result back to a user transparently.

1020 **Chapter 3**

1021 **The Phase-2 Upgrade of CMS**

1022 This chapter gives an overview of the High-Luminosity LHC upgrade of the LHC in
1023 Section 3.1, and the upgrades for the Phase-2 CMS Level-1 (L1) Trigger in Section
1024 3.2. One of the major upgrades is the new availability of calorimeter crystal-level
1025 information to the L1 calorimeter trigger, compared to the current trigger which only
1026 has access to tower-level information (a tower being 5 by 5 in crystals). To capitalize
1027 on the increased spatial granularity of this information, an upgraded algorithm is
1028 presented which reconstructs and identifies electron and photon candidates in the the
1029 Layer-1 Calorimeter Trigger. A description of the algorithm and a validation of its
1030 performance in Phase-2 conditions is given in Section 3.3.

1031 **3.1 The High-Luminosity LHC**

1032 In order to sustain and extend the LHC’s physics discovery program and maintain
1033 operability for a decade or more, the LHC is undergoing a major upgrade to the High-
1034 Luminosity LHC (HL-LHC). In its final configuration, the HL-LHC will deliver a peak
1035 luminosity of $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, potentially leading to total integrated luminosity
1036 of 4000 fb^{-1} after ten years of operations, scheduled to begin in 2027 [38]. This
1037 integrated luminosity is about ten times the predicted luminosity reach of the LHC

1038 in its initial configuration. To enable the CMS experiment to continue operations and
1039 data-taking and to maximize the discovery potential of the unprecedented amount
1040 of data, the CMS detector is undergoing Phase-2 upgrades in order to perform high-
1041 precision measurements and searches for physics beyond the Standard Model in the
1042 intense running conditions of the HL-LHC.

1043 3.2 The Phase-2 Level-1 Trigger

1044 To achieve the goals of the HL-LHC program and to ensure the collection of information-
1045 rich datasets in the HL-LHC, the Phase-2 upgrade of the CMS Level-1 Trigger [38]
1046 must be upgraded in conjunction with the CMS sub-detectors and their readouts, to
1047 maintain physics selectivity. The HL-LHC will produce an intense hadronic environ-
1048 ment corresponding to 200 simultaneous collisions per beam crossing, necessitating
1049 comprehensive upgrades of the trigger system outlined below.

1050 In order to cope with the increased pile-up and high occupancies of the HL-LHC,
1051 the latency of the L1 trigger system (time available to produce a L1 Accept signal) will
1052 be increased significantly from $3.8 \mu\text{s}$ to $12.5 \mu\text{s}$, with an increased maximum output
1053 bandwidth of 750 kHz [38]. With the increased latency, in addition to information
1054 from calorimeters and muon detectors (as in the Phase-1 system), information from
1055 the new tracker and high-granularity endcap calorimeter can also be included at L1
1056 for the first time. This is illustrated in the functional diagram of the architecture of
1057 the Phase-2 trigger system in Fig. 3.1.

1058 The key feature of the Phase-2 L1 Trigger is the introduction of a correlator layer,
1059 where algorithms produce higher-level trigger objects by combining information from
1060 sub-detectors, with a selectivity approaching that of offline reconstruction in the
1061 HLT [38]. Four independent data processing paths (grouped together in Fig. 3.1) are
1062 implemented: tracking, calorimetry, muon systems, and particle-flow techniques:

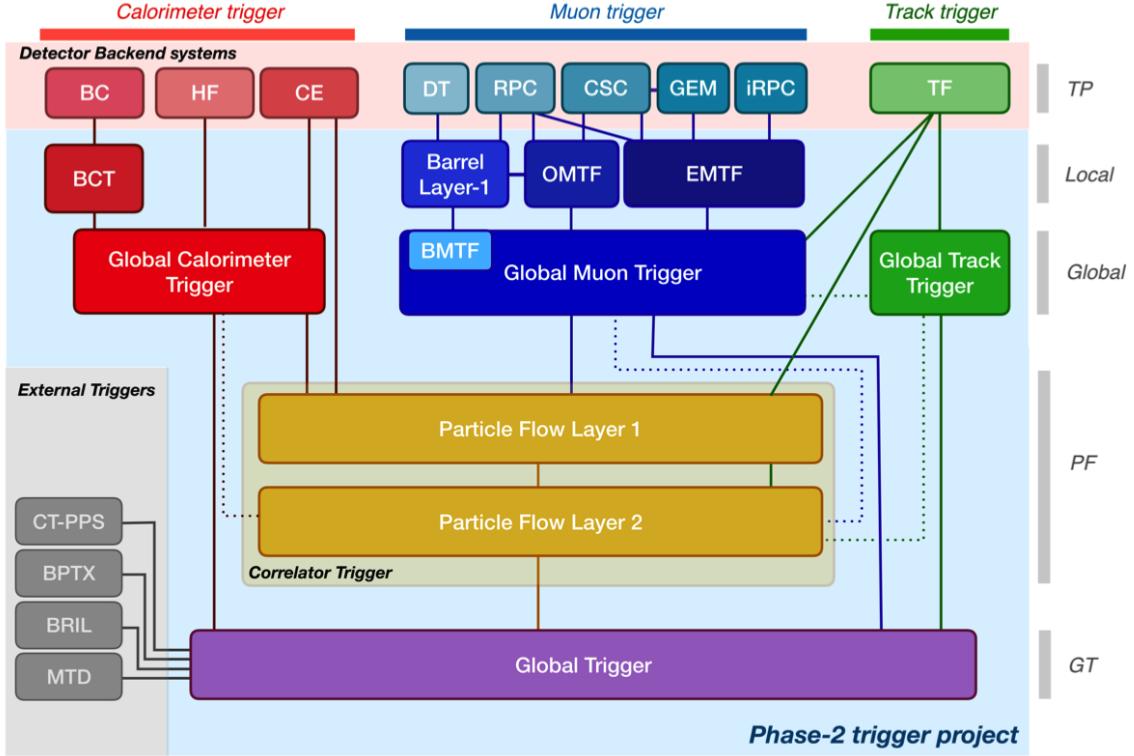


Figure 3.1: Functional diagram of the CMS L1 Phase-2 upgraded trigger design [38], showing the four trigger paths: calorimeter, muon, track, and Particle Flow. For the first time, tracking information will be available as early as the L1 Trigger.

- **Calorimeter Trigger path:** (red, Fig. 3.1) A barrel calorimeter trigger (BCT) and the HGCAL backend are used to process crystal-level information from the calorimeters to produce high-resolution clusters and identification variables used for later processing. Outputs from the BCT, HGCAL, and the HF are sent to a global calorimeter trigger (GCT), where calorimeter-only objects such as e/γ candidates, hadronically decaying tau lepton candidates, jets, and energy sums are built.
- **Track Trigger path:** (green, Fig. 3.1) Tracks from the Outer Tracker are reconstructed in the track finder (TF) processors as part of the detector backend. A global track trigger (GTT) will reconstruct the primary vertices of the event, along with tracker-only based objects, such as jets and missing transverse momentum.

- **Muon Trigger path:** (*blue*, Fig. 3.1) Trigger primitives are processed by muon track finder algorithms, again separated into the barrel (barrel muon track finder, BMTF), overlap (overlap muon track finder, OMTF), and endcap (endcap muon track finder, EMTF). Standalone muons and stubs containing information such as position, bend angle, and timing, as well as L1 tracks, are sent to the global muon trigger (GMT).
- **Particle-Flow Trigger path:** (*yellow*, Fig. 3.1) The correlator trigger (CT) aims to approach the performance of offline Particle Flow, and is implemented in two layers. “Layer-1” produces the particle-flow candidates from matching calorimeter clusters and tracks. “Layer 2” builds and sorts final trigger objects and applies additional identification and isolation criteria.

The outputs from the above trigger paths are combined in the Global Trigger (GT) (*purple*, Fig. 3.1), which calculates the final trigger decision (Level-1 Accept), transmitting it to the Trigger Control and Distribution System (TCDS), which distributes it to the detector backend systems, initiating the readout to the DAQ. The GT also provides the interface to external triggers (*grey*, Fig. 3.1), such as triggers for the precision proton spectrometer (PPS), beam position and timing monitors (BPTX), and luminosity and beam monitoring (BRIL) detectors [38]. The design of the Phase-2 Level-1 Trigger allows for future inclusion of triggering information, for instance information about minimum ionizing particles (MIPs) from the MIP Timing Detector (MTD) [39].

3.3 Standalone barrel calorimeter electron/photon reconstruction

The reconstruction and identification of electrons and photons (e/γ) begin with the trigger primitives of the barrel ECAL and HCAL detectors and endcap HGCAL calorimeters, covering the pseudorapidity region $|\eta| < 3$. The barrel and endcap regions of the detector are intrinsically different enough to warrant different approaches to e/γ reconstruction. This work presents a firmware-based emulator for the standalone e/γ reconstruction in the barrel calorimeter (Fig. 3.2). “Standalone” refers to the fact that the tracker information is not used in this particular reconstruction chain. This firmware-based emulator is based on the parallelized, computational logic that will be deployed in the firmware of the Phase-2 Level-1 trigger. The emulator uses fixed-precision integers to represent all values, such as in the computation of cluster energies, and closely mimics the firmware logic which uses arrays and performs computations in flattened loops. It represents an improved, more realistic understanding of the trigger, compared to the previous emulator which used idealized logic such as vector operations, and floats to represent all values [38].

3.3.1 Electron/photon standalone barrel procedure

In Phase-2, the upgrade of both on-detector and off-detector electronics of the barrel calorimeters’ trigger primitive generator (TPG) will enable the streaming of single crystal data from the on-detector to the backend electronics. Currently in Phase-1, the ECAL and HCAL TPGs is restricted to providing lower-granularity information of trigger tower sums of 5×5 crystals to the Level-1 Trigger [38]. A schematic of the geometry of the ECAL barrel in the Phase-2 Regional Calorimeter Trigger (RCT) is shown in Fig. 3.3. The barrel is spanned by 36 RCT cards, each spanning 17×4 towers in $\eta \times \phi$. Each RCT card is subdivided into five “regions” as shown in Fig.

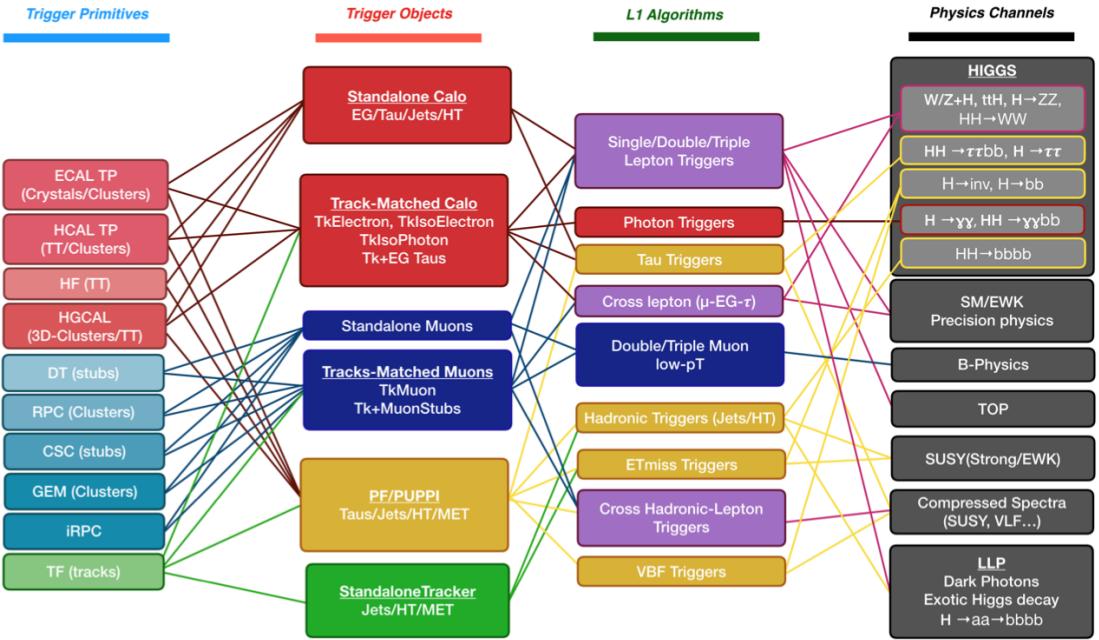


Figure 3.2: Summary of the links between the trigger primitives (*first column*), the trigger objects (*second column*), the Level-1 algorithms used in the menu (*3rd column*), and the physics channels (*4th column*), from [38], where a full description of the Phase-2 L1 algorithms can be found. This work focuses on developments for the Standalone Calorimeter electron and photon ("EG") reconstruction algorithm.

1121 3.4. After initial clustering and processing, the outputs of the RCT card are sent to
 1122 the Global Calorimeter (GCT) trigger, which is processed in three cards as shown in
 1123 Fig. 3.5. The reconstruction algorithm is detailed below.

1124 The standalone barrel algorithm for reconstructing and identifying electrons and
 1125 photons in the Phase-2 Level-1 Trigger takes as input the digitized response of each
 1126 crystal of the barrel ECAL, with a granularity 0.0175×0.0175 in $\eta \times \phi$, which is 25
 1127 times higher than the input to the Phase-1 trigger, which consisted of trigger towers
 1128 with a granularity of 0.0875×0.0875 . In HCAL the tower size of 0.0875×0.0875
 1129 is unchanged. The trigger algorithm is designed to closely reproduce the algorithm
 1130 used in the offline reconstruction, with limitations and simplifications due to trigger
 1131 latency.

1132 In the RCT, an initial requirement of $p_T > 0.5$ GeV is imposed on the input

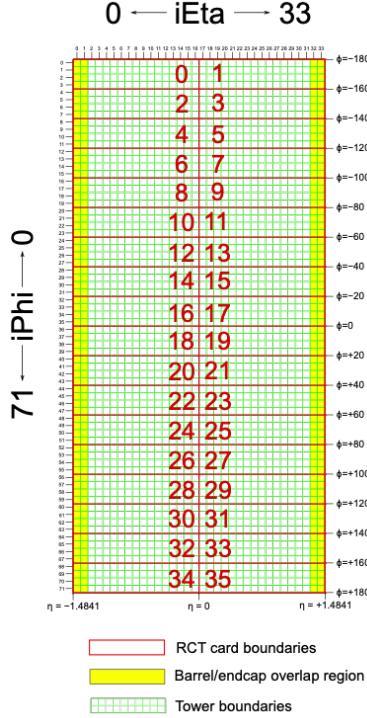


Figure 3.3: Schematic of the geometry of the Phase-2 ECAL barrel in the Regional Calorimeter Trigger (RCT), showing the division of the barrel region into 36 Regional Calorimeter Trigger (RCT) cards (*red*). Each card spans 17×4 towers in $\eta \times \phi$ (*green*), and each tower is 5×5 in single crystals in $\eta \times \phi$. Towers in the overlap region (*shaded yellow*) are read out to both the barrel and endcap.

trigger primitives (i.e. energies from the ECAL crystals and HCAL towers) to reject contribution from pile-up. In one of the regions inside a RCT card (Fig. 3.4), the crystal containing the highest energy deposit is identified as the seed crystal, as shown in Fig. 3.6. The energy in the crystals in a window of size 3×5 in $\eta \times \phi$ around the seed cluster is added into a cluster. The energy is considered “clustered”. The process is repeated with the remaining “unclustered” energy, until up to four clusters are produced in the region.

To improve e/γ identification and to reduce background contributions, identification and reconstruction algorithms are implemented at this stage:

- Shower shape: The energy deposit sums around the seed crystal is computed in windows of size 2×5 and 5×5 (Fig. 3.6, *dashed lines*), with true e/γ clusters

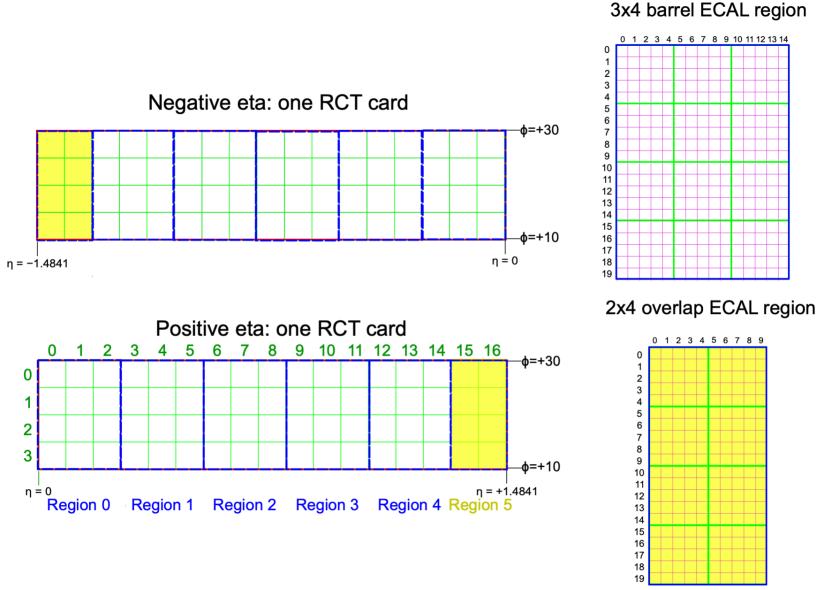


Figure 3.4: Schematic of two example RCT cards in the negative eta (*top left*) and positive eta (*bottom left*) regions of the ECAL barrel. Each RCT card is divided into six regions: five regions are of size 3×4 towers in $\eta \times \phi$ (*top right*), and a sixth smaller overlap region of size 2×4 towers (*bottom right*). Each tower is 5×5 ($\eta \times \phi$) in crystals.

1144 tending to produce showers that deposit most of their energy in a 2×5 region.

- 1145 • Bremsstrahlung recovery: e/γ tend to spread in the ϕ direction due to charged
 1146 particles being bent by the magnetic field of the CMS solenoid. If sufficient
 1147 energy comparable to the core 3×5 cluster is found in the adjacent 3×5
 1148 windows (Fig. 3.6, *shaded yellow*), the energy is added to the core cluster and
 1149 no longer considered unclustered energy.

1150 After parallel processing in the regions, the clusters in a RCT card are stitched
 1151 together if they are located directly along the borders of a region (Fig. 3.3). The
 1152 remaining unclustered ECAL energy is summed into ECAL towers.

1153 From each RCT card, the twelve highest-energy clusters, as well as any remaining
 1154 unclustered energy, are sent to the GCT. Since each GCT card has information from
 1155 sixteen RCT cards (Fig. 3.5), final stitching across the boundaries of the RCT cards
 1156 is performed. One more identification algorithm is performed at this stage:

GCT/“Layer 2”

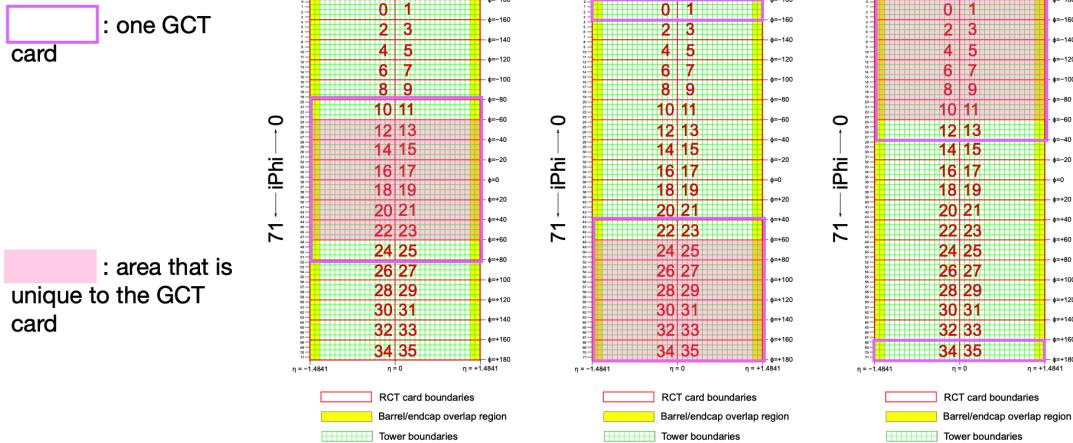


Figure 3.5: Schematic of the Phase-2 ECAL barrel in the Global Calorimeter Trigger (GCT), which will process the outputs of the Regional Calorimeter Trigger (RCT) in three GCT cards (*purple borders*). Each card in the GCT processes the equivalent of sixteen RCT cards, with the center twelve RCT cards being unique to that GCT card (*shaded pink*), and the remaining four RCT cards overlapping with one other GCT card.

- Isolation: One handle to reject backgrounds from e.g. pile-up, comes from the tendency for background to be spread more uniformly across a large area in the detector, whereas genuine e/γ are expected to produce showers concentrated in the 3×5 crystal window. The energy sum in a large window of 7×7 in towers is computed and used to reject background.

Flags that provide discrimination power between genuine e/γ and background, are computed using the relative isolation and shower shape quantities. The standalone working point (WP) is defined as the logical OR of the relative isolation and shower shape flags.

The information of the clusters in the event, including their energies, crystal-level position, the relative isolation flag, the shower shape flag, the standalone WP, and the ratio of the HCAL over ECAL energies, are sent in 64 bits to the Correlator Trigger and the Global Trigger. The towers in the event are computed as the sum of all unclustered energy in the ECAL with the corresponding HCAL energy at each

3x4 barrel ECAL region

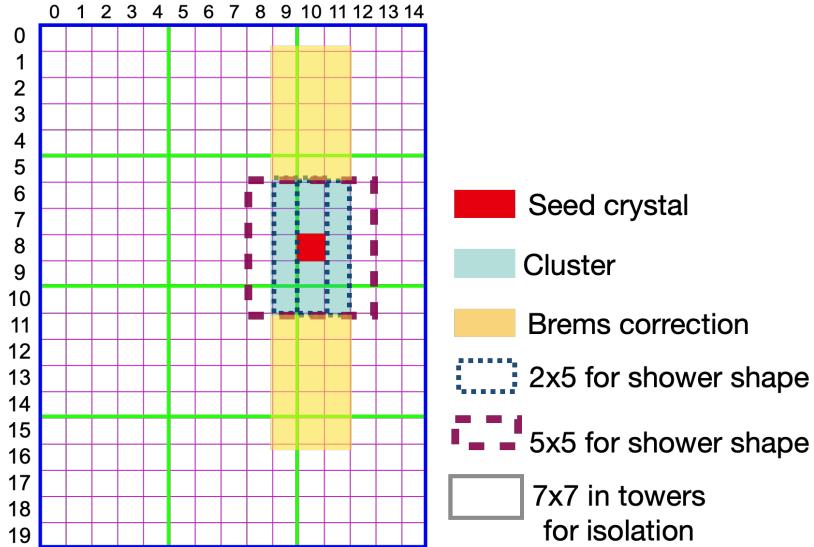


Figure 3.6: Illustration of an example electron/photon (e/γ) cluster in the Phase-2 Level-1 Trigger standalone barrel e/γ reconstruction, in a region of 15×20 crystals (3×4 towers) in $\eta \times \phi$. Each small pink square is one crystal, the highest-granularity ECAL trigger primitives available to the L1 Trigger in Phase-2. The core cluster consists of the energy sum in a 3×5 window of crystals (*shaded light blue*), centered around the seed crystal (*red*). The presence of energy lost to bremsstrahlung radiation is checked in the adjacent 3×5 windows in the ϕ direction (*shaded light yellow*). The ratio of the total energies in windows of size 2×5 and 5×5 in crystals (*dashed dark blue and dark red*) around the seed crystal, is computed and compared to the core cluster energy to obtain shower shape flags. Lastly, the isolation, defined as the sum of the energy in a large window of size 7×7 in towers (not shown in figure) is computed, and compared to the core cluster energy to obtain isolation flags.

¹¹⁷¹ tower location, and their energies are sent to the Correlator Trigger.

¹¹⁷² 3.3.2 Electron/photon standalone barrel results

¹¹⁷³ The performance of the current emulator of the standalone barrel e/γ algorithm in
¹¹⁷⁴ Phase-2 conditions is quantified in efficiencies and rates. Efficiency is the fraction of
¹¹⁷⁵ true electrons that the algorithm can reconstruct and identify, and is evaluated in
¹¹⁷⁶ a Monte Carlo simulated sample containing electrons with transverse momentum p_T
¹¹⁷⁷ ranging from 1 to 100 GeV. The efficiencies of the current and previous emulators as

1178 a function of the electron generator-level p_T are shown in Fig. 3.7.

1179 The rates are the event rates that this reconstruction and identification algorithm
1180 would obtain if it were deployed in a trigger, assuming that proton-proton collisions
1181 are occurring at the 40 MHz event rate of the HL-LHC. The rate is reported as a
1182 function of the minimum energy threshold required by the trigger, and is estimated
1183 using a simulated sample of minimum bias events, i.e. generic proton-proton colli-
1184 sions without any specific physics selections. The rates for the current and previous
1185 emulator are shown in Fig. 3.8.

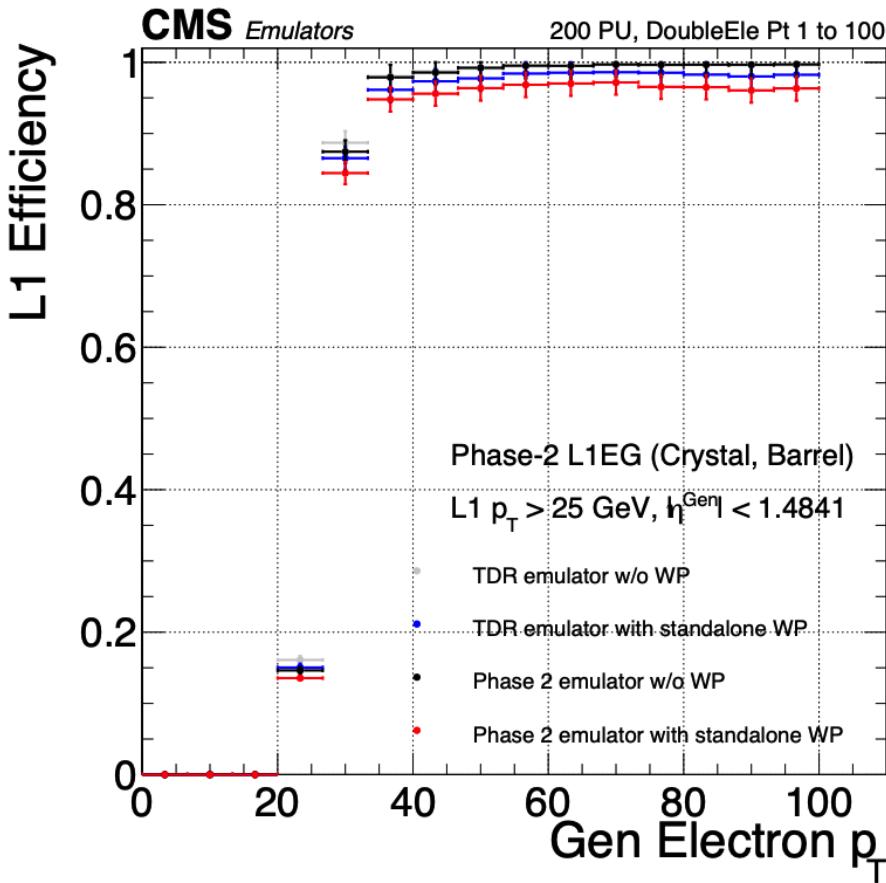


Figure 3.7: Efficiencies of the current and previous emulators of the standalone barrel e/γ algorithm for the Phase-2 Level-1 Trigger, evaluated in a simulated sample containing electrons, as a function of the electron's generator-level transverse momentum p_T . The standalone working point (WP) is defined as the logical OR of the isolation flag and shower shape flag. The efficiencies with and without requiring the standalone WP, are shown for the current emulator (labeled “Phase 2”, *black, red*) and the previous emulator (labeled “TDR”, *dark blue, grey*).

1186 The current emulator is incorporated into the full Phase-2 L1 menu, allowing an
1187 estimate of the rates produced by the standalone e/γ barrel trigger path and all
1188 other algorithms in the L1 Trigger. All rates are estimated with the assumption of
1189 an average pile-up of 200 and event rate of 40 MHz. The standalone working point
1190 single e/γ path with requirements on the e/γ candidate to have $|\eta| < 2.4$, offline p_T
1191 to be greater than 51 GeV, and online p_T to be greater than 41 GeV, is projected to
1192 have a rate of around 23 kHz. The standalone working point double e/γ path with
1193 requirements on the two e/γ candidates to have $|\eta| < 2.4$, offline p_T greater than 37
1194 and 24 GeV, and online p_T greater than 29 and 18 GeV, is projected to give a rate of
1195 around 6 kHz. For both paths, the objects efficiency plateau is 99%.

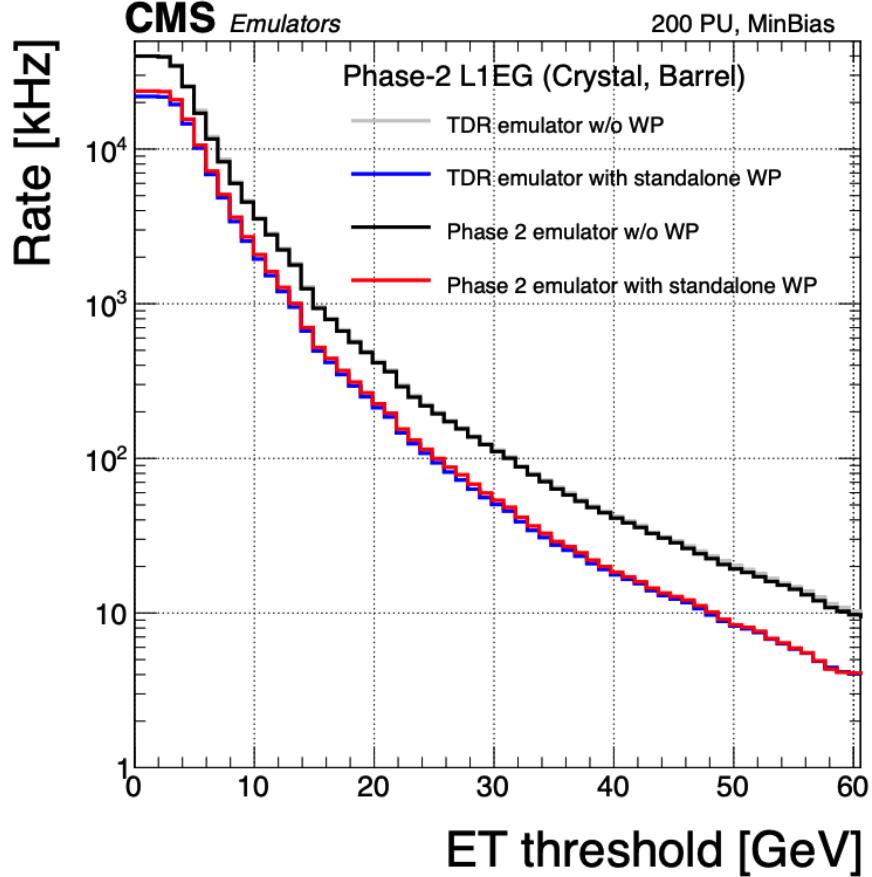


Figure 3.8: Rates in kHz of the current Phase-2 and previous (“TDR”) emulators of the standalone barrel e/γ algorithm for the Phase-2 Level-1 Trigger, evaluated on a minimum bias (MinBias) sample with 200 pile-up (PU), measured as a function of the minimum energy (E_T) required of the reconstructed e/γ object in each event. The standalone working point (standalone WP) is defined to be the logical OR of the isolation flag and the shower shape flag. The rates with and without requiring the standalone WP, are shown for the current emulator (labeled “Phase 2”, *black, red*) and the previous emulator (labeled “TDR”, *dark blue, grey*).

1196 **Chapter 4**

1197 **Datasets and Monte Carlo samples**

1198 The search for the exotic decay of the 125 GeV Higgs boson to two light neutral scalars
1199 decaying to a pair of bottom quarks and a pair of tau leptons ($h \rightarrow aa \rightarrow bb\tau\tau$) is
1200 based on proton-proton collision data at a center-of-mass energy 13 TeV collected
1201 in Run-2 of data-taking, spanning the data-taking years 2016, 2017, and 2018. The
1202 datasets used and the triggers used to collect the data are described in Section 4.1.
1203 Section 4.2 describes the Monte Carlo simulated samples that are used to model the
1204 $h \rightarrow aa \rightarrow bb\tau\tau$ signal and background Standard Model processes. Lastly, in order
1205 to obtain a better description of Standard Model backgrounds that contain two tau
1206 leptons, a data-Monte Carlo hybrid technique is used to generate embedded samples
1207 which model processes with genuine $\tau\tau$ in the final state, as detailed in Section 4.3.
1208 All samples are listed in Appendix A.

1209 **4.1 Datasets used**

1210 The $h \rightarrow aa \rightarrow bb\tau\tau$ analysis [40] is based on proton-proton collision data at a center-
1211 of-mass energy of 13 TeV collected in full Run-2 (2016-18) with the CMS detector.
1212 The data analyzed corresponds to a total integrated luminosity of 138 fb^{-1} (36.33 fb^{-1}
1213 for 2016, 41.53 fb^{-1} for 2017, and 59.74 fb^{-1} for 2018) [41] [42] [43]. The cumulative

1214 delivered and recorded luminosity versus time for 2015-2018 is shown in Fig. 4.1.

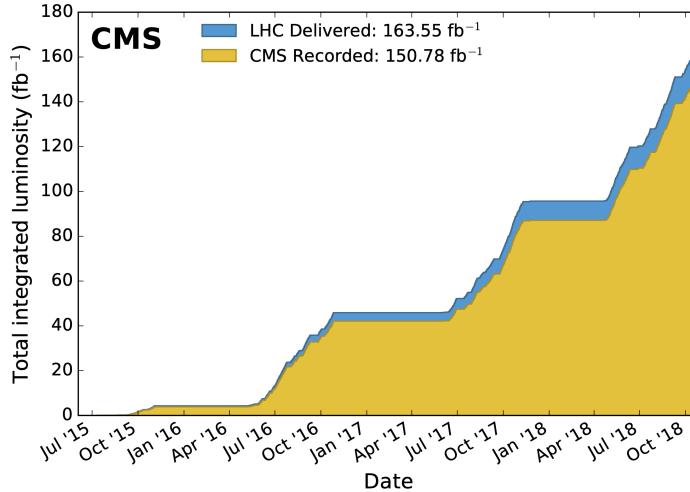


Figure 4.1: Cumulative delivered and recorded luminosity versus time for 2015-2018 at CMS, in proton-proton collision data only, at nominal center-of-mass energy [44].

1215 Data collected with the single muon trigger is used for the $\mu\tau_h$ channel. For the
1216 $e\tau_h$ channel, data collected with the single electron trigger is used; and for the $e\mu$
1217 channel, data collected with the electron + muon trigger is used. A more in-depth
1218 discussion of the triggers used follows in a later section. The datasets are listed in
1219 Appendix A in Tables A.1, A.2, and A.3.

1220 4.2 Monte Carlo samples

1221 Modeling and computing observables originating from arbitrary physics processes at
1222 the tree level and at next-to-leading order (NLO) is performed by Monte Carlo (MC)
1223 event generators, such as Powheg and MadGraph5_amCNLO [45] [46]. The informa-
1224 tion generated, e.g. the computation of the differential cross sections and kinematics
1225 of the final state particles, is saved in a compressed file and used to generate MC sam-
1226 ples that are used in physics analyses. The samples are digitized using GEANT4 [47],
1227 a platform used at the LHC and other facilities to comprehensively simulate the

1228 passage of particles through matter. The digitized samples are passed through the
1229 same detector reconstruction as real data events collected in the detector. The MC
1230 background samples used in this analysis for 2016-2018 are listed in Appendix A in
1231 Tables A.7, A.8, and A.9.

1232 The samples for modeling the signal ($h \rightarrow aa \rightarrow 2b2\tau$ and $h \rightarrow a_1a_2$) in the
1233 2HDM+S and TRSM are generated at tree-level, for a range of masses of the light
1234 neutral scalar a . For $h \rightarrow aa$, the mass hypotheses for the a range from $m_a =$
1235 (12 GeV, 62.5 GeV). For $h \rightarrow a_1a_2$, the mass hypotheses for the two light scalars span
1236 combinations of m_{a1} , m_{a2} ranging from (12 GeV, 62.5 GeV) for the two scalars. The
1237 MC signal samples used in this analysis for 2016-2018 are listed in Appendix A in
1238 Tables A.10, A.11 and A.12.

1239 4.3 Embedded samples

1240 An important background for Higgs boson studies and searches for additional Higgs
1241 bosons is the decay of Z bosons into pairs of τ leptons ($Z \rightarrow \tau\tau$). An embedded tech-
1242 nique was developed in the context of Standard Model Higgs to $\tau\tau$ measurements, to
1243 model $Z \rightarrow \tau\tau$ decays, and was expanded to also model all Standard Model processes
1244 that contain $\tau\tau$ [48]. The embedded technique has since been used successfully at
1245 CMS for the Standard Model $H \rightarrow \tau\tau$ measurement, as well as searches for minimal
1246 supersymmetric extensions to the Standard Model (MSSM) [49] [50].

1247 The advantage of the embedded technique is that aspects of the event that are
1248 difficult to model and describe are directly taken from data, resulting in a better
1249 data description than can be achieved with only the $Z \rightarrow \tau\tau$ simulation [48]. The
1250 simulation must be tuned extensively to accurately model aspects of the data, such
1251 as time-dependent pile-up profiles, the production of additional jets, e.g. in multijet
1252 and vector boson fusion topologies, the number of reconstructed primary interaction

1253 vertices, and the missing transverse momentum p_T^{miss} . Since all events with genuine
 1254 $\tau\tau$ are estimated with samples made with the embedded technique (referred to as
 1255 embedded samples from here on), events in Monte Carlo simulation with genuine $\tau\tau$
 1256 are not used, in order to avoid double-counting.

1257 Fig. 4.2 shows a schematic of how embedded samples are produced. Data events
 1258 containing $Z \rightarrow \mu\mu$ decays are selected. In these events, all energy deposits of the
 1259 recorded muons are removed, and are replaced with simulated tau leptons with the
 1260 same kinematic properties as the removed muons. This results in a hybrid data format
 1261 containing information from both observed and simulated events, as illustrated in Fig.
 1262 4.2 [48]. The embedded samples used for the years 2016-2018 are listed in Appendix
 1263 A in Tables A.4, A.5, and A.6.

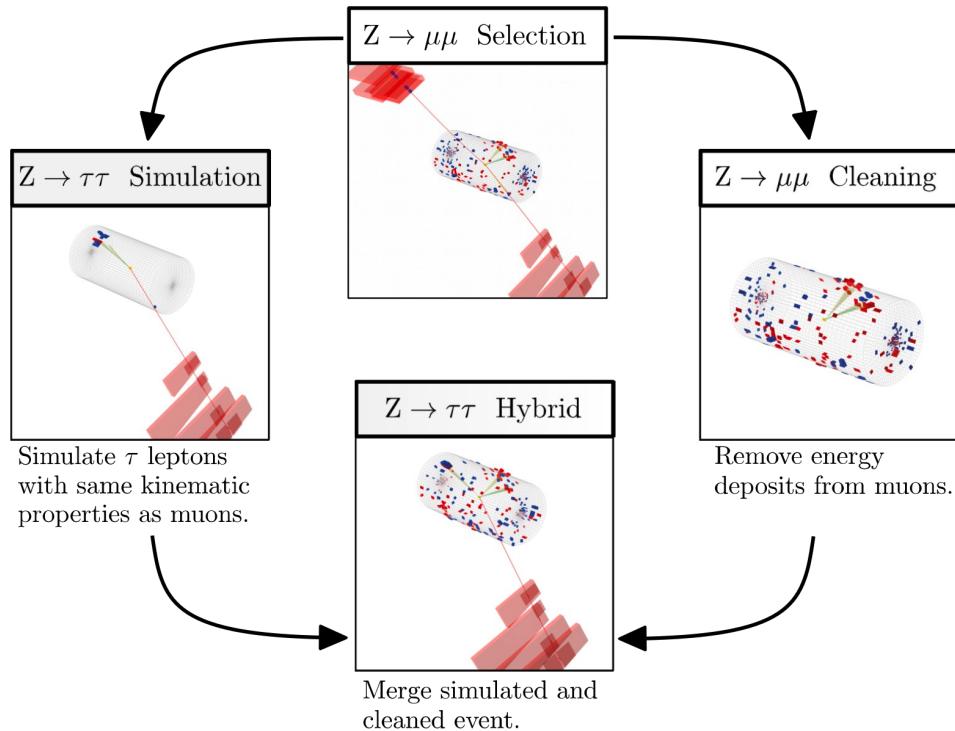


Figure 4.2: Schematic view of the four main steps of the embedding technique for τ leptons, as described in Section 4.3 [48]. A $Z \rightarrow \mu\mu$ event is selected in data ($Z \rightarrow \mu\mu$ selection), all of the energy deposits associated with the muons are removed ($Z \rightarrow \mu\mu$ cleaning), and two τ leptons and their decays are simulated in an empty detector ($Z \rightarrow \tau\tau$ simulation). Lastly, all energy deposits of the simulated τ decays are combined with the data event ($Z \rightarrow \tau\tau$ hybrid).

1264 In the selection step of the embedded technique, events are selected with at least
 1265 one of a set of $\mu\mu$ trigger paths, which require $p_T > 17(8)$ GeV for the leading
 1266 (sub-leading) muons, and a minimum requirement between 3.8 and 8.0 GeV on the
 1267 invariant di-muon mass $m_{\mu\mu}$ [48]. The offline reconstructed muons must match the
 1268 objects at trigger level and also have offline $p_T > 17(8)$ GeV. They must have $|\eta| < 2.4$
 1269 and be located at a distance $|d_z| < 0.2$ cm to the primary vertex along the beam
 1270 axis. To form a Z boson candidate, each muon is required to originate from a global
 1271 muon track. The muon pairs must have opposite charges with an invariant mass of
 1272 $m_{\mu\mu} > 20$ GeV. If more than two di-muon pairs are found, the pair with the invariant
 1273 mass closest to the Z boson mass (91.19 GeV) is chosen.

1274 This selection is designed to be tight enough to ensure a high purity of genuine
 1275 $\mu\mu$ events, and also loose enough to minimize biases of the embedded event samples.
 1276 Isolation requirements are avoided, since they would introduce a bias towards less
 1277 hadronic activity in the vicinities of the embedded leptons that will appear more
 1278 isolated than expected in data. The selection results in an expected mixture of events
 1279 summarized in Table 4.1 from [48]. $Z \rightarrow \mu\mu$ is the dominant process modeled by the
 1280 embedded technique, with $t\bar{t}$, QCD, and diboson and single top processes becoming
 1281 more significant when considering events with b-tag jets.

Process	Fraction (%)		
	Inclusive	$m_{\mu\mu} > 70$ GeV	$N(\text{b-tag jets}) > 0$
$Z \rightarrow \mu\mu$	97.36	99.11	69.25
QCD	0.84	0.10	2.08
$t\bar{t}$	0.78	0.55	25.61
$Z \rightarrow \tau\tau$	0.71	0.05	0.57
Diboson, single t	0.17	0.17	2.35
W+jets	0.08	0.02	0.14

Table 4.1: Expected event composition after selecting two muons in the embedded technique [48], before additional cuts (i.e. inclusive, *column 2*), and after adding a requirement on the di-muon mass $m_{\mu\mu} > 70$ GeV (*column 3*), or a requirement on the number of b-tag jets in the event (*column 4*).

₁₂₈₂ **Chapter 5**

₁₂₈₃ **Object reconstruction and
1284 corrections applied**

₁₂₈₅ In the data processing workflow, data events and simulated events are analyzed to
₁₂₈₆ reconstruct physics objects of interest, and algorithms for distinguishing genuine par-
₁₂₈₇ ticle candidates from background, are employed. Section 5.1 describes the physical
₁₂₈₈ properties of the most important objects in the $h \rightarrow aa \rightarrow bb\tau\tau$ analysis: taus,
₁₂₈₉ muons, electrons, jets, and jets originating from b-quarks (b-flavor jets), as well as
₁₂₉₀ their reconstruction and identification in CMS. In this analysis, the full energy and
₁₂₉₁ momentum of the two tau leptons ($m_{\tau\tau}$) is estimated from the measured (i.e. visible)
₁₂₉₂ components of the tau leptons using the SVFit/FastMTT algorithm, which is de-
₁₂₉₃ scribed in Section 5.2. Corrections are applied to the simulated samples at the object
₁₂₉₄ level and the event level to account for known discrepancies between simulations and
₁₂₉₅ the data that the simulations are intended to model. These corrections are listed and
₁₂₉₆ detailed in Section 5.3.

₁₂₉₇ **5.1 Object reconstruction**

₁₂₉₈ **5.1.1 Taus**

₁₂₉₉ The tau (τ) is the heaviest known lepton. With a rest mass of 1776.86 MeV, it can
₁₃₀₀ decay to not only electrons and muons, but also hadrons. In two thirds of the cases, τ
₁₃₀₁ leptons decay hadronically, typically into one or three charged mesons (predominantly
₁₃₀₂ π^+ , π^-), often accompanied by neutral pions (that decay $\pi^0 \rightarrow \gamma\gamma$), and a ν_τ . These
₁₃₀₃ hadronic decays are denoted τ_h . In the remainder of the decays, the tau decays to
₁₃₀₄ the lighter leptons (electron or muon), termed leptonic decays. The mean lifetime of
₁₃₀₅ the τ is $\tau = 290 \times 10^{-15}$ seconds, corresponding to $c\tau = 87.03 \mu\text{m}$, which is short
₁₃₀₆ enough that taus decay in the CMS detector before reaching the detector elements,
₁₃₀₇ but also long enough that some decay length variables can help with hadronic tau
₁₃₀₈ identification. The tau's largest decay branching ratios (proportional to probability
₁₃₀₉ of decay) are listed below [26]:

- ₁₃₁₀ • 17.8% decay to $e^-\bar{\nu}_e\nu_\tau$
- ₁₃₁₁ • 17.4% decay to $\mu^-\bar{\nu}_\mu\nu_\tau$
- ₁₃₁₂ • 25.5% decay to $\pi^-\pi^0\nu_\tau$ (ρ^- resonance at 770 MeV)
- ₁₃₁₃ • 10.8% decay to $\pi^-\nu_\tau$
- ₁₃₁₄ • 9.3% decay to $\pi^-\pi^0\pi^0\nu_\tau$ (a_1^- resonance at 1200 MeV)
- ₁₃₁₅ • 9.0% decay to $\pi^-\pi^-\pi^+\nu_\tau$ (a_1^- resonance at 1200 MeV)

₁₃₁₆ In all cases, at least one neutrino is produced. The neutrinos escape undetected
₁₃₁₇ from the CMS detector, resulting in missing transverse energy. Charged hadrons leave
₁₃₁₈ tracks in the tracking detector before being absorbed in the hadronic calorimeter; in
₁₃₁₉ CMS tau reconstruction terminology, they are often called “prongs”, i.e. the dominant

1320 τ_h decay modes are termed “1 prong” (π^\pm), “1 prong + π^0 (s)”, and “3-prong”. Neutral
1321 pions decay to two photons which lose their energy in the electromagnetic calorimeter.
1322 Taus that decay to electrons and muons, are typically triggered on and reconstructed
1323 as electrons and muons respectively.

1324 **Hadron plus strips (HPS) reconstruction of τ_h**

1325 At CMS, hadronically decaying tau leptons are reconstructed with the hadron plus
1326 strips (HPS) algorithm [51] [52]. The HPS algorithm capitalizes on photon conversions
1327 in the CMS tracker material, which originate from the neutral pion (π^0) decaying
1328 to two photons. The bending of electron/positron tracks due to the CMS solenoid
1329 magnetic field leads to a spread of the neutral pions’ calorimeter signatures in the ϕ
1330 direction. This motivates the reconstruction of photons in “strips”: objects that are
1331 built out of PF photons and electrons. The strip reconstruction starts with centering
1332 a strip on the most energetic electromagnetic particle in a PF jet. Among other
1333 electromagnetic particles located in a window of size $\Delta\eta = 0.05$ and $\Delta\phi = 0.20$
1334 around the strip center, the most energetic one is associated with the strip and its
1335 momentum is added to the strip momentum. This is repeated iteratively until no
1336 further particles can be associated. Lastly, strips satisfying a requirement of $p_T^{\text{strip}} > 1$
1337 GeV are combined with charged hadrons to reconstruct individual τ_h decay modes,
1338 where h stands for both π and K :

- 1339 • *Single hadron:* $h^- \nu_\tau$ and $h^- \pi^0 \nu_\tau$ decay modes, in which the neutral pions have
1340 too little energy to be reconstructed as strips.
- 1341 • *One hadron + one strip:* $h^- \pi^0 \nu_\tau$ decay modes, where the photons from the π^0
1342 decay are close together in the calorimeter.
- 1343 • *One hadron + two strips:* $h^- \pi^0 \nu_\tau$ decay modes, where the photons from the π^0
1344 decay are well separated.

- 1345 • *Three hadrons:* $h^-h^+h^-\nu_\tau$ decay modes. The three charged hadrons are re-
1346 quired to originate from the same secondary vertex.

1347 The $h^-\pi^0\pi^0\nu_\tau$ and $h^-h^+h^-\pi^0\nu_\tau$ decay modes do not have their own treatment are
1348 reconstructed with the above topologies.

1349 In the HPS algorithm, the direction of the reconstructed tau momentum \vec{p}^{τ_h}
1350 is required to fall within a distance of $\Delta R = 0.1$ from the original PF jet. All
1351 charged hadrons and strips are required to be contained within a cone of size $\Delta R =$
1352 $(2.8 \text{ GeV})/p_T^{\tau_h}$, from the τ_h as reconstructed by the HPS.

1353 All charged hadrons are assumed to be pions, and they are required to be consis-
1354 tent with the masses of the intermediate meson resonances (if applicable), with the
1355 following allowed windows for candidates: 50-200 MeV for π^0 , 0.3-1.3 GeV for ρ , and
1356 0.8-1.5 GeV for a_1 . If the τ_h decay is compatible with more than one hypothesis, the
1357 one giving the highest $p_T^{\tau_h}$ is chosen. Lastly, an isolation requirement is applied: aside
1358 from the τ_h decay products, no charged hadrons or photons can be present within
1359 an isolation cone of size $\Delta R = 0.5$ around the direction of the τ_h . The outputs of
1360 the HPS algorithm are the reconstructed decay mode and the visible four-momentum
1361 (i.e. the four-momenta of all decay products excluding the neutrinos).

1362 **DeepTau for identifying τ_h**

1363 The identification of τ_h candidates in CMS has historically been divided into separate
1364 discriminators against jets, electrons, and muons. Discriminators versus jets and
1365 electrons use information from derived quantities, such as the p_T sum of particles
1366 near the τ_h axis. Building on the previous multivariate analysis (MVA) classifier [53]
1367 based on a boosted decision tree (BDT), DeepTau is a more recent classifier based on a
1368 deep neural network (DNN) that simultaneously discriminates against jets, electrons,
1369 and muons. The DNN uses a combination of high-level inputs, similar to previous
1370 algorithms, and also uses convolutional layers in η - ϕ space to process information

1371 from all reconstructed particles near the τ_h axis. Convolutional layers are based on
1372 the principle that an image can be processed independently of its position.

1373 The final DeepTau discriminators against jets, muons, and electrons are given by

$$D_\alpha(y) = \frac{y_\tau}{y_\tau + y_\alpha} \quad (5.1)$$

1374 where y_τ (y_α) are estimates of the probabilities for the τ_h candidate to come from
1375 a genuine τ_h (jet, μ , e). Working points for each discriminator with different τ_h
1376 identification efficiencies are defined for D_e , D_μ , and D_{jet} , for usage in physics analyses
1377 and derivation of data-to-simulation corrections [54].

1378 5.1.2 Muons

1379 Muons are the next lightest lepton after taus, with a mass of 105.66 MeV and a
1380 mean lifetime of $\tau = 2.20 \times 10^{-6}$ seconds, or $c\tau = 658.64$ m. At CMS, muons are
1381 identified with requirements on the quality of the track reconstruction and on the
1382 number of measurements in the tracker and the muon systems [55]. In the standard
1383 CMS reconstruction, tracks are first reconstructed independently in the inner tracker
1384 (tracker track) and in the muon system (standalone-muon track). Next, these tracks
1385 are processed in two different methods.

1386 The first is Global Muon reconstruction (outside-in) [55], which fits combined hits
1387 from the tracker track and standalone-muon track, using the Kalman-filter technique.
1388 At large transverse momenta, $p_T \gtrsim 200$ GeV, the global-muon fit can improve the
1389 momentum resolution compared to the tracker-only fit.

1390 The second is Tracker Muon reconstruction (inside-out) [55], which starts with
1391 tracker tracks with $p_T > 0.5$ GeV and total momentum $p_T > 2.5$ GeV. These tracks
1392 are extrapolated outwards to the muon system and matched to detector segments
1393 there, taking into account the magnetic field, expected energy losses, and multiple

1394 Coulomb scattering in the detector material. Tracker Muon reconstruction is more
 1395 efficient than the Global Muon reconstruction at low momenta, $p \lesssim 5$ GeV, because
 1396 it only requires a single muon segment in the muon system, whereas Global Muon
 1397 reconstruction typically requires segments in at least two muon stations.

1398 To further suppress fake muons from decay in flight, isolation cuts are used. A
 1399 relative isolation variable is defined to quantify the energy flow of particles near the
 1400 muon trajectory. A relative isolation is defined similarly for muons and electrons:

$$I^\ell \equiv \frac{\sum_{\text{charged}} p_T + \max\left(0, \sum_{\text{neutral}} p_T - \frac{1}{2} \sum_{\text{charged, PU}} p_T\right)}{p_T^\ell} \quad (5.2)$$

1401 where $\sum_{\text{charged}} p_T$ is the scalar sum of the p_T of the charged particles originating from
 1402 the primary vertex and located in a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4(0.3)$
 1403 centered on the direction of the muon (electron). The sum $\sum_{\text{neutral}} p_T$ is the equivalent
 1404 for neutral particles. The sum $\sum_{\text{charged, PU}} p_T$ is the scalar sum of the p_T of the
 1405 charged hadrons in the cone originating from pile-up vertices. The factor 1/2 comes
 1406 from simulation estimations, which find that the ratio of neutral to charged hadron
 1407 production in the hadronization process of inelastic pp collisions is 1/2. Thus the
 1408 subtracted term is intended to subtract contribution from pile-up, from the neutral
 1409 particle contribution to the isolation sum. Finally, this is divided by the lepton
 1410 transverse momentum, p_T^ℓ .

1411 5.1.3 Electrons

1412 Electrons are the lightest lepton with a mass of 0.511 MeV. At CMS, electrons are
 1413 reconstructed by associating a track reconstructed in the silicon tracking detector
 1414 with a cluster of energy in the ECAL. Performance is maximized via a combination
 1415 of a stand-alone approach and the complementary global particle-flow approach [56].

1416 In the stand-alone approach, the electron energy, which is typically spread over

several crystals of the ECAL, is clustered with the “hybrid” algorithm in the barrel and the “multi- 5×5 ” in the endcaps [56]. The hybrid algorithm collects energy in a small window in η and an extended window in ϕ . It identifies a seed crystal, and adds arrays of 5×1 crystals in $\eta \times \phi$ in a range of $N = 17$ crystals in both directions of ϕ , if their energies exceed a minimum threshold, thus forming a supercluster (SC). In the endcap, crystals are not arranged in an $\eta \times \phi$ geometry; instead clusters are build around seed crystals in clusters of 5×5 crystals that can partly overlap. Nearby clusters are grouped into a supercluster, and energy is recovered from associated deposits in the preshower.

In the PF reconstruction [56], PF clusters are reconstructed by aggregating around a seed all contiguous crystals with energies two standard deviations above the electronic noise observed at the beginning of a data-taking run. The energy of a given crystal can be shared among two or more clusters.

The electron track reconstruction is performed in two ways [56]: the ECAL-based seeding, which begins with the SC energy and positioning, and the tracker-based seeding (part of the PF reconstruction algorithm), which uses tracks reconstructed from the general algorithm for charged particles, extrapolated towards the ECAL and matched to an SC. Kalman filter (KF) tracks with a small number of hits or that are not well-fitted, are re-fitted with a dedicated Gaussian sum Filter (GSF).

A global identification variable [56] is defined using a multivariate analysis (MVA) technique that combines information on track observables (kinematics, quality of the KF track and GSF track), the electron PF cluster observables (shape and pattern), and the association between the two (geometric and kinematic observables). For electrons seeded only through the tracker-based approach, a weak selection is applied on this MVA variable. For electrons seeded through both approaches, a logical OR is taken.

Electron isolation, i.e. the presence of energy deposits near the electron trajectory,

1444 is a separate key handle in rejecting significant background. Compared to isolated
1445 electrons, electrons from misidentified jets or genuine electrons within a jet resulting
1446 from semileptonic decays of b or c quarks tend to have significant energy deposits
1447 near the primary trajectory [56]. Offline analyses benefit from the PF technique
1448 for defining isolation, which sums the PF candidates reconstructed located within a
1449 specified isolation cone around the electron candidate, as in Eqn. 5.2.

1450 5.1.4 Jets

1451 The vast majority of processes of interest at the LHC contains quarks or gluons in
1452 the final state, but these particles cannot be observed directly. In a process called
1453 hadronization, they fragment into spatially-grouped collections of particles called jets,
1454 which can be detected in the tracking and calorimeter systems. Hadronization and
1455 the subsequent decays of unstable hadrons can produce hundreds of nearby particles
1456 in the CMS detector. Jets are reconstructed by the PF algorithm (PF jets), or from
1457 the sum of the ECAL and HCAL energies deposited in the calorimeter towers (Calo
1458 jets). In PF jets, typically used in offline analyses, jets are built using the anti- k_T
1459 (AK) clustering algorithm [57]. The anti- k_T algorithm iterates over particle pairs and
1460 finds the two that are closest in a distance measure d , and determines whether to
1461 combine them:

$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{\Delta_{ij}^2}{R^2}, \text{ combine when } d_{ij} < p_{T,i}^{-2}; \text{ stop when } d_{ij} > p_{T,i}^{-2} \quad (5.3)$$

1462 where $\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$ and $p_{T,i}$, η_i , ϕ_i are the transverse momentum, rapid-
1463 ity, and azimuthal angle of particle i . The power -2 means that higher-momentum
1464 particles are clustered first, leading to jets that tend to be centered on the hardest
1465 (highest p_T) particle.

1466 There are several methods to remove contributions of pile-up collisions from jet

1467 clustering [58]:

- 1468 • Charged hadron subtraction (CHS), which removes all charged hadron candidates associated with a track that is not associated with the primary vertex.
- 1470 • PileUp Per Particle Identification (PUPPI), which weighs input particles based
1471 on their likelihood of arising from pile-up. QCD particles tend to have a collinear
1472 structure, compared to soft diffuse radiation coming from pile-up. The local
1473 shape for charged pile-up, used as a proxy for all pile-up particles, is used on an
1474 event-by-event basis to calculate a weight for each particle. PUPPI is deployed
1475 in Run-2 and is more performant than CHS in high pile-up scenarios.

1476 **5.1.5 B-flavored jets**

1477 Jets that arise from bottom-quark hadronization (b-flavor jets) have overwhelming
1478 background from processes involving jets from gluons (g) and light-flavor quarks (u, d,
1479 s), and from c-quark fragmentation. The ability to identify b-flavor jets, or b-tagging,
1480 exploits the b hadrons' relatively large masses, long lifetimes, and daughter particles
1481 with hard momentum spectra [57].

1482 The impact parameter (IP) of a track is the 3-dimensional distance between the
1483 track and the primary vertex (PV) at the point of closest approach. The IP is positive
1484 if the track originates from the decay of particles travelling along the jet axis. The
1485 resolution of the IP depends on the p_T and η of the track, motivating the use of the
1486 impact parameter significance S_{IP} (ratio of the IP to its estimated uncertainty) as an
1487 observable [57].

1488 Because of the large but finite lifetimes of the b hadrons, b hadrons tend to
1489 travel a short distance before decaying at a secondary vertex (SV), which can be
1490 measured and reconstructed separately from the primary vertex due to the excellent
1491 position resolution of the pixel detector [57]. Previous b-tagging algorithms (e.g.

1492 CSV, cMVAv2, and DeepCSV) have capitalized on variables such as the presence of
1493 a SV, the flight distance and direction (computed from the vector between the PV
1494 and the SV), and kinematics of the system of associated secondary tracks (e.g. track
1495 multiplicity, mass, and energy).

1496 The DeepJet (formerly known as DeepFlavour) algorithm [59] is a deep-neural-
1497 network multi-classification algorithm, which uses 16 properties of up to 25 charged
1498 and 6 properties of 25 neutral particle-flow jet constituents, as well as 17 properties
1499 from up to 4 secondary vertices associate with the jet. Compared to the previous clas-
1500 sifying algorithm DeepCSV, DeepJet has been demonstrated to have higher efficiency
1501 with lower misidentification probability in Phase-1 data [60].

1502 5.2 Reconstruction of the di-tau mass

1503 The final signal extraction is done to the total di-tau ($\tau\tau$) mass, which is estimated
1504 from the visible $\tau\tau$ mass using the FastMTT algorithm [61]. FastMTT is based on the
1505 SVFit algorithm, originally developed for the Standard Model $H \rightarrow \tau\tau$ analysis [62].
1506 Both the SVFit algorithms, and the FastMTT algorithm, are described below, to give
1507 a complete picture of how the algorithms attempt to reconstruct the true invariant
1508 mass of a Higgs or Z boson decay.

1509 To specify a hadronic τ decay, six parameters are needed [62]: the polar and
1510 azimuthal angles of the visible decay product system in the τ rest frame, the three
1511 boost parameters from the τ rest frame to the laboratory frame, and the invariant
1512 mass m_{vis} of the visible decay products. For a leptonic τ decay, two neutrinos are
1513 produced, and a seventh parameter, the invariant mass of the two-neutrino system, is
1514 necessary. The unknown parameters are constrained by four observables that are the
1515 components of the four-momentum of the system formed by the visible decay products
1516 of the τ lepton, measured in the laboratory frame. The remaining unconstrained

1517 parameters for hadronic and leptonic τ decays are thus:

- 1518 • The fraction of the τ energy in the laboratory frame carried by the visible decay
1519 products,
- 1520 • ϕ , the azimuthal angle of the τ direction in the laboratory frame,
- 1521 • $m_{\nu\nu}$, the invariant mass of the two-neutrino system in leptonic τ decays (for
1522 hadronic τ decays, $m_{\nu\nu}$ is set to 0).

1523 E_x^{miss} and E_y^{miss} , the x and y components of the missing transverse energy E_T^{miss}
1524 provide two further constraints.

1525 5.2.1 Original SVFit ‘‘standalone’’: maximum likelihood

1526 In one of the original versions of SVFit, called ‘‘standalone’’ SVFit [62], a maximum
1527 likelihood fit method is used to reconstruct the mass $m_{\tau\tau}$ by combining the measured
1528 observables E_x^{miss} and E_y^{miss} with a likelihood model that includes terms for the τ
1529 decay kinematics and the E_T^{miss} resolution [62]. The likelihood function $f(\vec{z}, \vec{y}, \vec{a}_1 \vec{a}_2)$
1530 of the parameters $\vec{z} = (E_x^{\text{miss}}, E_y^{\text{miss}})$ in an event is constructed, where the remaining
1531 parameters are the kinematics of the two τ decays, denoted $\vec{a}_1 = (x_1, \phi_1, m_{\nu\nu,1})$ and
1532 $\vec{a}_2 = (x_2, \phi_2, m_{\nu\nu,2})$, and the four-momenta of the visible decay products with the
1533 measured values $\vec{y} = (p_1^{\text{vis}}, p_2^{\text{vis}})$.

1534 The likelihood f is the product of three likelihood functions. The first two likelihood
1535 functions model the decay parameters \vec{a}_1 and \vec{a}_2 of the two τ leptons. For leptonic
1536 decays, the likelihood function is modeled using matrix elements for τ decays,
1537 and integrated over the allowed phase space $0 \leq x \leq 1$ and $0 \leq m_{\nu\nu} \leq m_\tau \sqrt{1-x}$. For
1538 hadronic τ decays, a model based on the two-body phase space is used and integrated
1539 over $m_{\text{vis}}^2/m_{\tau\tau}^2 \leq x \leq 1$. The third likelihood function quantifies the compatibility of
1540 a τ decay hypothesis with the reconstructed \vec{E}_T^{miss} in an event, assuming the neutrinos
1541 are the only source of missing transverse energy. The expected \vec{E}_T^{miss} resolution

1542 is represented by a covariant matrix, estimated on an event-by-event basis using a
1543 significance algorithm [63].

1544 5.2.2 “Classic SVFit” with matrix element

1545 Classic SVFit is an improved algorithm of the original “standalone” SVFit using the
1546 formalism of the matrix element (ME) method [61]. In the ME method, an estimate
1547 for the unknown model parameter Θ (here, the mass $m_{\tau\tau}$) is obtained by maximizing
1548 the probability density \mathcal{P} . The key ingredients of the probability density are the
1549 squared modulus of the matrix element $|\mathcal{M}(\mathbf{p}, \Theta)|^2$ and the transfer function $W(\mathbf{y}|\mathbf{p})$
1550 (probability density to observe the measured observables \mathbf{y} given the phase space
1551 point \mathbf{p}). The best estimate $m_{\tau\tau}$ is obtained by computing the probability density \mathcal{P}
1552 for a range of mass hypotheses and finding the value of $m_{\tau\tau}$ that maximizes \mathcal{P} .

1553 Distributions illustrating the performance of the classic matrix element SVFit
1554 algorithm are shown in Fig. 5.1 from [61], showing the di-tau mass after and before
1555 application of SVFit to recover energy lost to neutrinos. The SVFit algorithm is
1556 found to improve the sensitivity of the Standard Model $H \rightarrow \tau\tau$ analysis performed
1557 by CMS by about 30%, compared to performing the same analysis using only the
1558 visible mass m_{vis} .

1559 5.2.3 FastMTT: optimized SVFit

1560 FastMTT [64] is a further simplification to the matrix element method of Classic
1561 SVFit which has comparable performance but is about 100 times faster. FastMTT
1562 drops the matrix element component of the computation without significant impact
1563 on the final mass resolution, and simplifies the computation of the transfer functions.
1564 The opening angle of the τ decay products with respect to the initial τ momenta ap-
1565 proaches 0 for τ with high $\gamma = E_\tau/m_\tau$, with typical τ decays from the Z boson decays
1566 already satisfying this condition. In this collinear approximation, the dimensionality

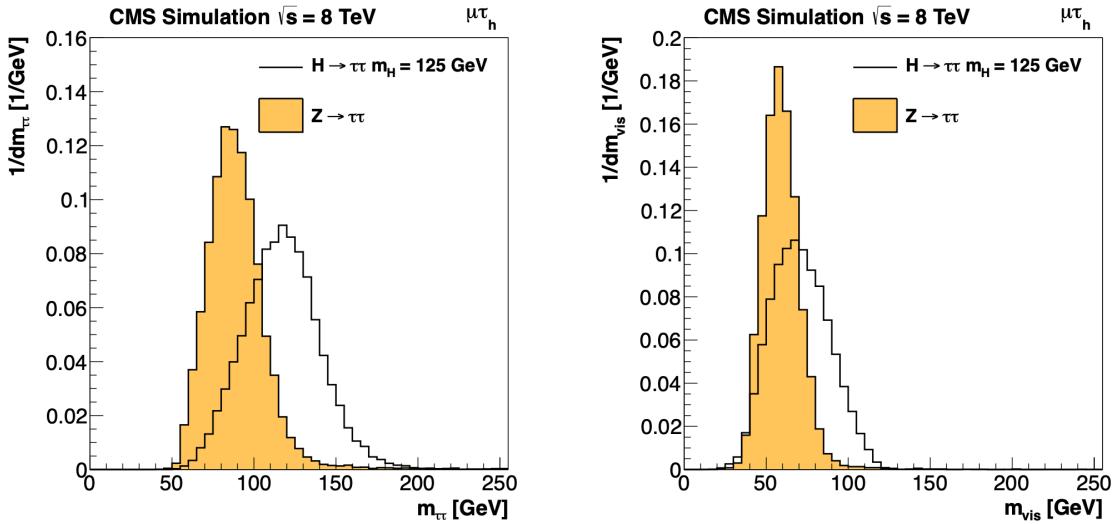


Figure 5.1: Distributions from [61], of $m_{\tau\tau}$ after reconstruction with the original SVFit algorithm (*left*), and before SVFit with only the visible tau decay products (*right*), for $H \rightarrow \tau\tau$ signal events of mass $m_H = 125$ GeV (*black line*) and the $Z/\gamma^* \rightarrow \tau\tau$ background (*orange, solid*), in the decay channel $\tau\tau \rightarrow \mu\tau_h$.

1567 of the transfer function can be reduced in the computation of FastMTT, while still
1568 yielding similar results to Classic SVFit [64].

1569 5.3 Corrections applied to simulation

1570 Corrections are applied to simulated samples to account for known effects in the event
1571 modeling and reconstruction and data-taking, and are intended to bring simulations
1572 in closer agreement with data. Corrections fall into two broad categories: *energy*
1573 *scale corrections* applied to physics objects, and *event-level corrections*. Energy scale
1574 corrections are multiplicative factors applied to the energy and transverse momentum
1575 p_T of simulated objects (e.g. leptons or jets), and bring the average reconstructed
1576 energies of simulated particles into better agreement with those of objects recon-
1577 structed from data. Event-level corrections are applied as a per-event multiplicative
1578 weight, and account for effects such as differences in object identification efficiencies
1579 and trigger efficiencies between data and simulated samples, mis-modeling in simu-

1580 lations of the underlying physics process, or changing detector operating conditions
 1581 during data-taking. Event-level corrections change the shapes of the distributions of
 1582 all the physical observables.

1583 Uncertainties in scale factors and corrections are also sources of systematic errors
 1584 in the analysis, detailed in Chapter 8. Systematic uncertainties in the tau, muon, and
 1585 electron energy scales can shift the p_T of the leptons up or down, which can change
 1586 whether events pass or fail the offline p_T thresholds for the trigger paths described in
 1587 the previous section, i.e. change the number of events in the signal region.

1588 **5.3.1 Tau energy scale**

1589 An energy scale is applied to the transverse momentum p_T and mass of the hadronic
 1590 tau τ_h in the $\mu\tau_h$ and $e\tau_h$ channels, to correct for a deviation of the average recon-
 1591 structed τ_h energy from the generator-level energy of the visible τ_h decay products.
 1592 These correction factors are derived centrally [53], by fitting to events in $e\tau_h$ and $\mu\tau_h$
 1593 final states in Z/γ^* events separately for the h^\pm , $h^\pm\pi^0$, and $h^\pm h^\mp h^\pm$ decays. The
 1594 values used are shown in Table 5.1.

1595 When applying the energy scale to the τ_h , the 4-momentum of the missing trans-
 1596 verse energy (MET) is adjusted such that the total 4-momenta of the τ_h and the MET
 1597 remains unchanged [65].

Tau energy scale factor				
Decay mode	2018	2017	2016 pre-VFP	2016 post-VFP
0	0.991 ± 0.008	0.986 ± 0.009	0.987 ± 0.01	0.993 ± 0.009
1	1.004 ± 0.006	0.999 ± 0.006	0.998 ± 0.006	0.991 ± 0.007
10	0.998 ± 0.007	0.999 ± 0.007	0.984 ± 0.008	1.001 ± 0.007
11	1.004 ± 0.009	0.996 ± 0.01	0.999 ± 0.011	0.997 ± 0.016

Table 5.1: Energy scales applied to genuine hadronic tau decays τ_h by data-taking year/era and decay mode, along with systematic errors.

1598 **5.3.2 Muon energy scale**

1599 An energy scale is applied to the p_T and mass of genuine muons from τ decays in the
1600 $e\mu$ and $\mu\tau_h$ channels [66]. The applied values are the same for MC and embedded
1601 samples and are shown in Table 5.2. Following the SM $H \rightarrow \tau\tau$ analysis, Rochester
1602 corrections are not applied, and instead prescriptions from [67] are followed.

Muon energy scale factor	
Eta range	Value for all years
$ \eta \in [0.0, 1.2)$	1.0 ± 0.004
$ \eta \in [1.2, 2.1)$	1.0 ± 0.009
$ \eta \in [2.1, 2.4)$	1.0 ± 0.027

Table 5.2: Energy scales and systematic errors applied to genuine muons. The values are the same for MC and embedded for all years [68] [67].

1603 **5.3.3 Electron energy scale**

1604 Corrections to the electron energy scale are applied to genuine e from τ decays, and
1605 are binned in two dimensions by electron p_T and η for barrel vs. endcap [69]. The
1606 scale factors are binned in p_T and η for MC samples: e.g. values for 2018 are shown
1607 in Fig. 5.2 from [70]. For embedded samples the electron energy scale is taken as
1608 only binned in η (Table 5.3).

Electron energy scale factor for embedded samples			
Eta range	2018	2017	2016
$ \eta \in [0.0, 1.479)$	0.973 ± 0.005	0.986 ± 0.009	0.9976 ± 0.0050
$ \eta \in [1.479, 2.4)$	0.980 ± 0.0125	0.887 ± 0.0125	0.993 ± 0.0125

Table 5.3: Energy scales and systematic errors applied to electrons in embedded samples, binned in the electron η , by data-taking year [71] [72] [73].

1609 **5.3.4 τ_h identification efficiency**

1610 The τ_h identification efficiency can differ in data and MC [65]. Recommended correc-
1611 tions are provided by the Tau POG, and we use the medium DeepTau vs. jet working

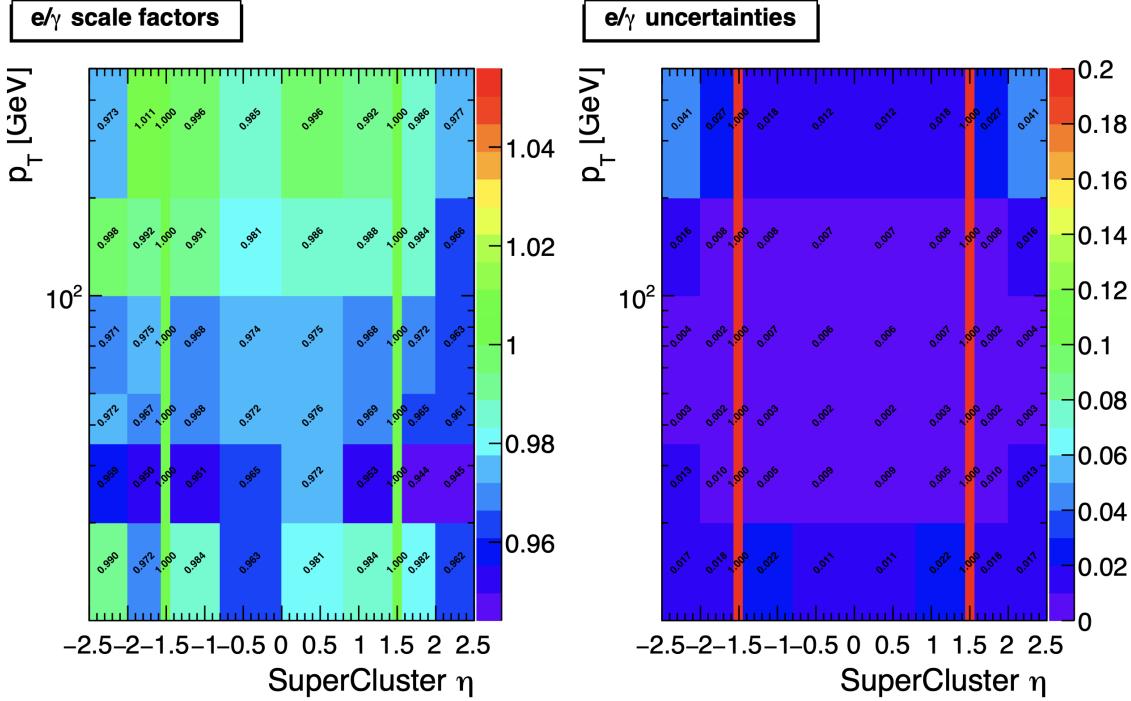


Figure 5.2: Electron/photon energy scale factors (*left*) and corresponding uncertainties (*right*) binned in the electron η and p_T , for the data-taking year 2018 [70].

point values. The identification efficiency is measured in $Z \rightarrow \tau\tau$ events in the $\mu\tau_h$ final state, and is binned in p_T due to clear p_T dependence of the DeepTau ID.

Tau ID efficiency for DeepTau Medium vs. jet WP in 2018						
p_T (GeV)	< 20	(20, 25]	(25, 30]	(30, 35]	(35, 40]	(40, 500]
Central value	0	0.945	0.946	0.916	0.921	1.005
Up value	0	1.001	0.981	0.946	0.950	1.035
Down value	0	0.888	0.981	0.883	0.893	0.953

Table 5.4: Tau ID efficiency for the DeepTau vs. jet medium working point, with central, up, and down values for 2018, binned in the tau p_T [65].

5.3.5 Trigger efficiencies definition

Scale factors are applied to correct for differences in trigger efficiencies between MC and embedded vs. data, with values taken from tools provided by the Standard Model $H \rightarrow \tau\tau$ working group which uses the same trigger paths [68]. In the following

1618 sections we review relevant trigger efficiencies in data, which form the basis of the
1619 trigger efficiency corrections applied to MC and embedded.

1620 **5.3.6 Tau trigger efficiencies**

1621 The efficiencies in data of the single- τ_h leg in $\mu\tau_h$, $e\tau_h$, and di- τ_h triggers is computed
1622 centrally per using a Tag and Probe (TnP) method [74] which is outlined here. In
1623 this method, $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$ are selected in data and a Drell-Yan simulated sample
1624 ($Z \rightarrow \ell\ell, \ell = e, \mu, \tau_h$) with high purity. Cuts are applied to reject events not in this
1625 final state, e.g. suppressing $Z \rightarrow \mu\mu$ by vetoing events with a single loose ID muon.
1626 An isolated muon candidate (the tag) with online $p_T > 27$ GeV and $|\eta| < 2.1$ is
1627 identified and matched to an offline μ . An offline τ_h candidate (the probe) is selected,
1628 which is separated from the tag μ , and has $p_T > 20$ GeV and $|\eta| < 2.1$. The probe
1629 τ_h must pass anti-muon and anti-electron discriminators to avoid fakes from muons
1630 and electrons, and must pass the medium MVA tau isolation to suppress fakes from
1631 QCD jets. The trigger efficiency in the TnP method is calculated as

$$\text{Efficiency} = \frac{\text{Number of events passing the TnP selection with fires the HLT path}}{\text{Number of events passing the TnP selection}} \quad (5.4)$$

1632 The efficiencies for the hadronic tau legs in the relevant channels of this analyses
1633 ($\mu\tau_h$ and $e\tau_h$) as a function of the offline tau p_T and η , are shown for data taken in
1634 2016, 2017, and 2018 in Figures 5.3a and 5.3b [74] [75]. In both figures, the different
1635 HLT thresholds and differences in the L1 seed result in higher efficiencies in 2016 and
1636 differences in shapes of the 2016 efficiencies compared to 2017 and 2018. The low
1637 pile-up in 2016 also leads to higher efficiencies in that year.

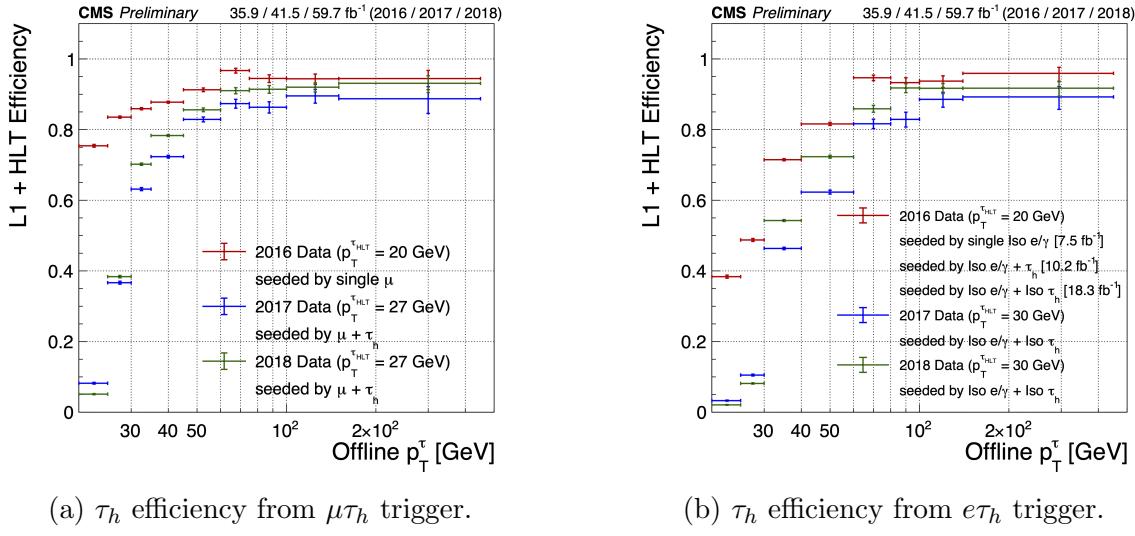
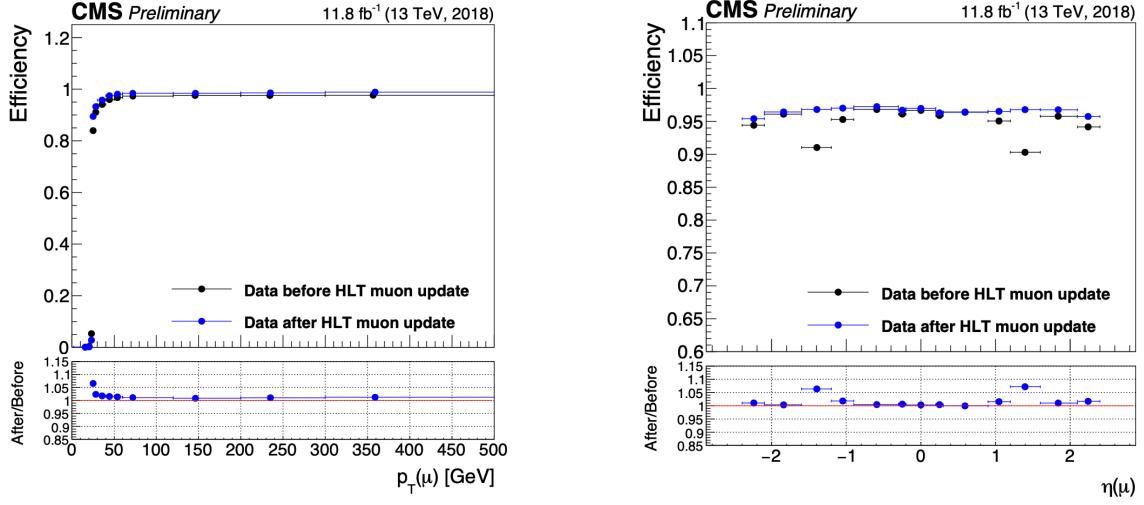


Figure 5.3: Hadronic tau leg efficiency of the cross-triggers for $\mu\tau_h$ (*left*) and $e\tau_h$ (*right*) triggers as a function of offline tau p_T for the years 2016 (red), 2017 (blue) and 2018 (green), from [75]. HLT p_T thresholds and L1 seeds are indicated in the legends.

1638 5.3.7 Single muon trigger efficiencies

1639 The efficiencies for the single isolated muon trigger with $p_T > 24$ GeV used in this
 1640 analysis, is shown for the data-taking year 2018 in Fig. 5.4a as a function of the muon
 1641 p_T and as a function of the muon $|\eta|$ in Fig. 5.4b from [76]. The data is split with
 1642 respect to a HLT muon reconstruction update that was deployed on 15/05/2018. A
 1643 small asymmetry in efficiencies between negative and positive η in Fig. 5.4b is due to
 1644 disabled muon chambers (CSCs). The efficiencies shown are estimated using a Tag
 1645 and Probe method using $Z \rightarrow \mu\mu$ events, with the tag being an offline muon with
 1646 $p_T > 29$ GeV and $|\eta| < 2.4$ passing a tight ID criteria, and the probe is an online (L1)
 1647 trigger object with $\Delta R < 0.3$ and passing tight ID and Particle Flow based isolation
 1648 requirements with $p_T > 26$ GeV.



(a) Muon efficiency vs p_T for SingleMuon.

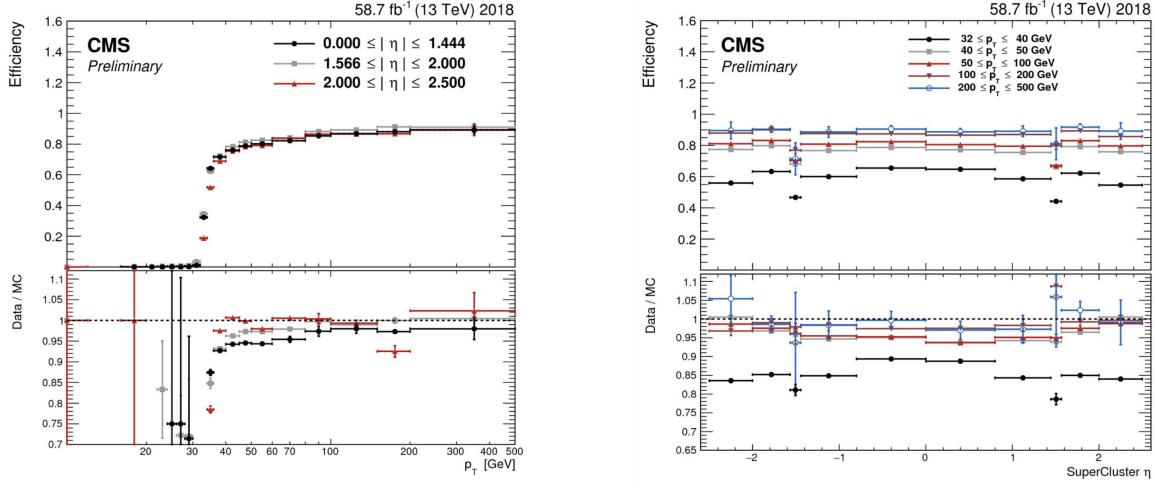
(b) Muon efficiency vs $|\eta|$ for SingleMuon.

Figure 5.4: Trigger efficiencies in data (*top panels*) and ratio of efficiencies after/before a HLT muon reconstruction update (*bottom panels*) for the muon in the isolated single muon trigger with threshold $p_T > 24$ GeV in the data-taking year 2018, as functions of the muon p_T (*left*) and muon $|\eta|$ (*right*). Only statistical errors are shown [76].

1649 5.3.8 Single electron trigger efficiencies

1650 The efficiencies in data, and the ratio between data and MC, of the single electron
 1651 HLT trigger with p_T threshold 32 GeV used in this analysis are shown for 2018,
 1652 as a function of the electron p_T in Fig. 5.5a and of the electron $|\eta|$ in Fig. 5.5b,
 1653 from [77]. In the Tag and Probe method used for the 2018 dataset, the tag is an
 1654 offline reconstructed electron with $|\eta| \leq 2.1$ and not in the barrel and endcap overlap
 1655 region, with $p_T > 35$ GeV with tight isolation and shower shape requirements, firing
 1656 the tag trigger. The probe is an offline reconstructed electron with $|\eta| \leq 2.5$ with
 1657 $E_T^{\text{ECAL}} > 5$ GeV with no extra identification criteria [77].

1658 The disagreement between data and MC, particularly at low transverse momentum,
 1659 is in part due to detector effects that are difficult to simulate, such as crys-
 1660 tal transparency losses in the ECAL and the evolution of dead regions in the pixel
 1661 tracker [77].



(a) Electron efficiency vs p_T for single electron.

(b) Electron efficiency vs $|\eta|$ for single electron.

Figure 5.5: Trigger efficiencies in data, and the data/MC ratio for the electron in the single electron trigger with threshold $p_T > 32$ GeV in the data-taking year 2018, as functions of the electron p_T (*left*) and electron $|\eta|$ (*right*) [77]. In the plot vs. p_T , the region $1.442 \leq |\eta| \leq 1.566$ is not included as it corresponds to the transition between barrel and endcap parts of the ECAL.

1662 5.3.9 $e\mu$ cross-trigger efficiencies

1663 The efficiencies of the electron and muons for the cross-trigger with leading muon
 1664 used in the $e\mu$ channel are shown for data in 2016, 2017, and 2018 in Figures 5.6a and
 1665 5.6b [78]. These efficiencies were measured centrally using a Tag and Probe in events
 1666 with Z to dileptons with the same flavor and opposite charge, where the tags are an
 1667 isolated muon or electron, and the probe (offline) candidate is required to satisfy the
 1668 same lepton selection as that of the tag candidate, be matched within $\Delta R < 0.1$ with
 1669 a corresponding online trigger object, and also to pass the cross-trigger. The trigger
 1670 efficiency is then:

$$\text{Efficiency} = \frac{\text{Events passing lepton pair selections and probe passing trigger}}{\text{Events passing lepton pair selections}} \quad (5.5)$$

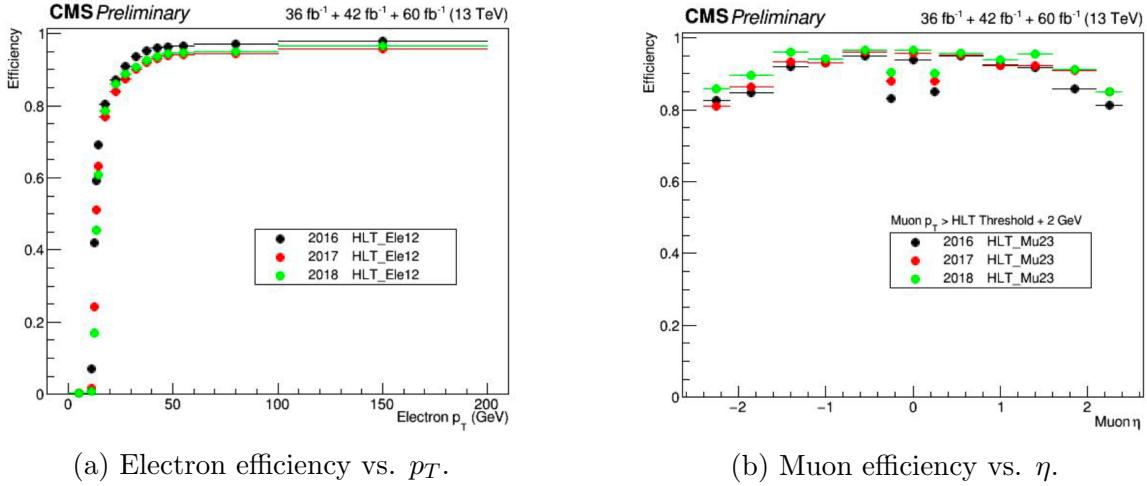


Figure 5.6: Efficiencies of the electron leg vs. p_T (*left*) and the muon leg vs. η (*right*), for the HLT path with online thresholds of 12 GeV for the electron and 23 GeV for the muon, for the data-taking years 2016 (*black*), 2017 (*red*), and 2018 (*green*) [78].

1671 5.3.10 Electrons and muons faking τ_h : energy scales

1672 Energy scales for electrons misidentified as hadronic tau decays (e faking τ_h) are
 1673 provided by the Tau POG, and were measured in the $e\tau_h$ channel with the visible
 1674 invariant mass of the electron and hadronic tau system [68]. This energy scale is
 1675 applied for τ_h with $p_T > 20$ GeV regardless of which DeepTau vs. electron working
 1676 point was used. Values for 2018 are shown in Table 5.5.

Electrons faking τ_h energy scale factor in 2018	
Reconstructed decay mode of the fake τ_h	Central value and (up, down) shifts
0	1.01362 (+0.00474, -0.00904)
1	1.01945 (+0.01598, -0.01226)
10	0.96903 (+0.0125, -0.03404)
11	0.985 (+0.04309, -0.05499)

Table 5.5: Energy scales and up/down systematic uncertainties applied to electrons misidentified as hadronic taus for 2018, binned in decay mode of the fake τ_h [68].

1677 No nominal energy scale is applied for muons mis-reconstructed as τ_h , and the
 1678 uncertainty is treated as $\pm 1\%$ and uncorrelated in the reconstructed decay mode [68].

1679 **5.3.11 Electrons and muons faking τ_h : misidentification effi-**
 1680 **ciencies**

1681 Corrections on identification efficiencies are applied to genuine electrons and muons
 1682 misidentified as τ to account for differences in data and MC.

1683 The specific values depend on the vs. electron and vs. muon discriminator working
 1684 points used. For misidentified $\mu \rightarrow \tau_h$, the scale factors are split into different $|\eta|$
 1685 regions, determined by the CMS muon and tracker detector geometries, as shown in
 1686 Table 5.6 for 2018 [65].

Tau ID efficiency for DeepTau vs. muon WPs in 2018		
$ \eta $	Tight working point	VLoose working point
(0.0, 0.2)	0.767 ± 0.127	0.954 ± 0.069
(0.2, 0.6)	1.255 ± 0.258	1.009 ± 0.098
(0.6, 1.0)	0.902 ± 0.203	1.029 ± 0.075
(1.0, 1.45)	0.833 ± 0.415	0.928 ± 0.145
(1.45, 2.0)	4.436 ± 0.814	5.000 ± 0.377
(2.0, 2.53)	1.000 ± 0.000	1.000 ± 0.000

Table 5.6: Tau mis-identification efficiency for the DeepTau Tight and Very Loose (VLoose) working points vs. muons in 2018, binned in the muon $|\eta|$ [65].

1687 For misidentified $e \rightarrow \tau_h$, the scale factors are split into barrel and endcap regions,
 1688 dictated by the ECAL detector geometry, as shown in Table 5.7 for 2018.

Tau ID efficiency for DeepTau vs. electron WPs in 2018		
$ \eta $	Tight working point	VLoose working point
(0.0, 0.73)	1.47 ± 0.27	0.95 ± 0.07
(0.73, 1.509)	1.509 ± 0.0	1.00 ± 0.0
(1.509, 1.929)	1.929 ± 0.2	0.86 ± 0.1
(1.929, 2.683)	2.683 ± 0.9	2.68 ± 0.0

Table 5.7: Tau mis-identification efficiency for the DeepTau Tight and Very Loose (VLoose) working points vs. electrons in 2018, binned in the electron $|\eta|$ [65].

1689 5.3.12 Electron ID and tracking efficiency

1690 Scale factors are applied to MC to correct for differences between MC and data in
 1691 the performance of electron identification (ID) and tracking.

1692 Electron and photon identification, as discussed earlier, use variables with good
 1693 signal vs. background discrimination power such as lateral shower shape and ratio
 1694 of energy deposited in the HCAL to energy deposited in the ECAL at the position
 1695 of the electron. The cut-based electron identification efficiencies in data and ratio of
 1696 efficiencies in data to MC are shown in Fig. 5.7a for the multivariate analysis (MVA)
 1697 identification working point.

1698 The tracking efficiencies in data and the data/MC ratio are shown in Fig. 5.7b
 1699 for the Gaussian-sum filter (GSF) tracking [79].

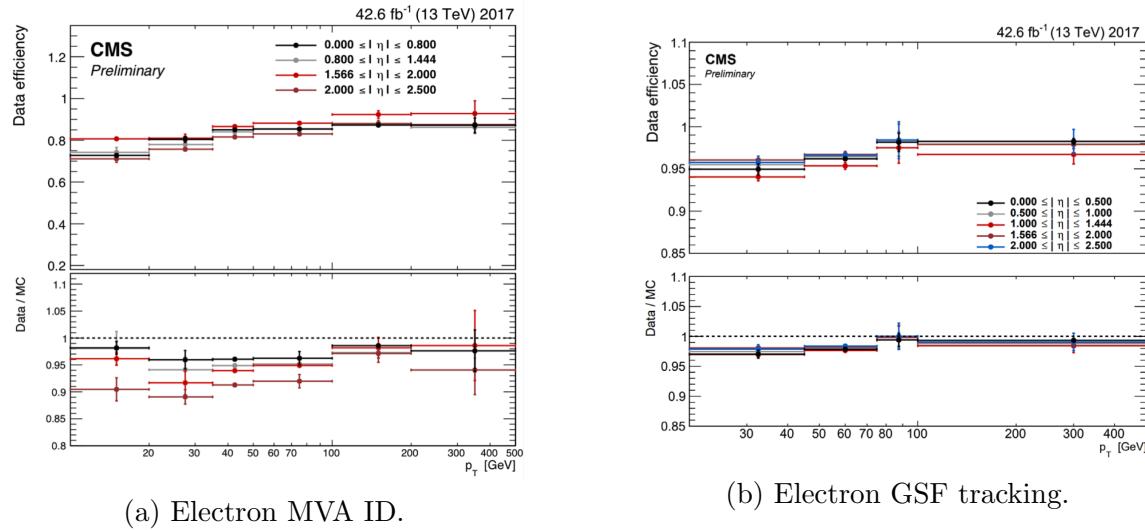


Figure 5.7: Efficiencies in data (*top panels*) and the ratio of efficiencies in data/MC (*bottom panels*), for the electron multivariate analysis (MVA) identification (*left*) and for the Gaussian-sum filter (GSF) tracking (*right*) [79]. Error bars represent statistical and systematic uncertainties.

1700 5.3.13 Muon ID, isolation, and tracking efficiencies

1701 Scale factors are applied to MC to correct for differences between MC and data in
 1702 the performance of muon identification, isolation, and tracking, as detailed below.

1703 The efficiencies for muon identification measured in 2015 data and MC simulation
 1704 are shown in Figures 5.8a and 5.8b for the loose ID and tight ID respectively [80]. The
 1705 loose ID is chosen such that efficiency exceeds 99% over the full η range, and the data
 1706 and simulation agree to within 1%. The tight ID is chosen such that efficiency varies
 1707 between 95% and 99% as a function of η , and the data and simulation agree to within
 1708 1-3%. The muon identification working point used in this analysis is the medium ID,
 1709 which has an efficiency of 98% for all η and an agreement within 1-2% [80].

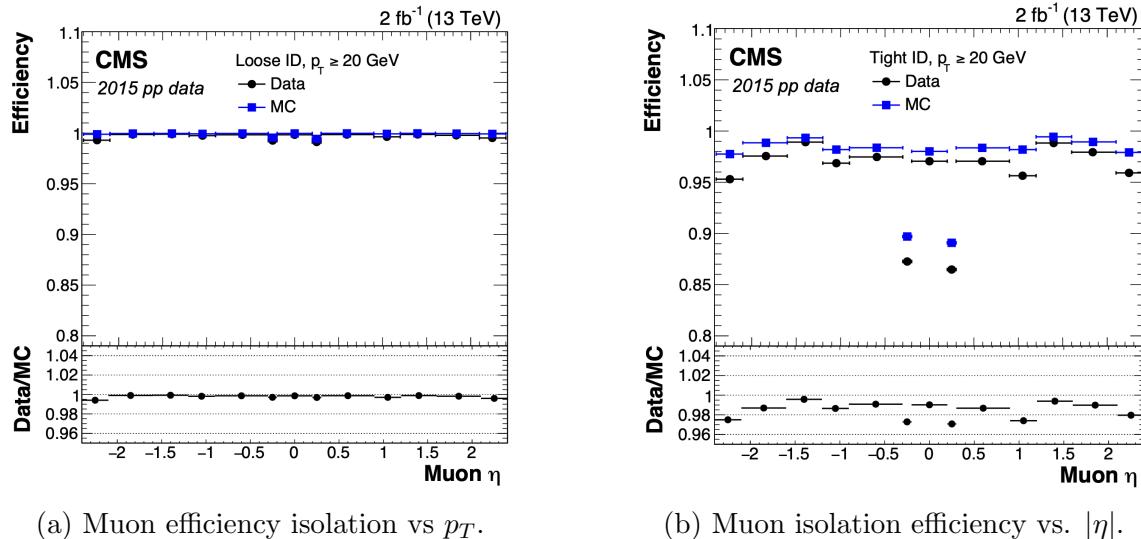
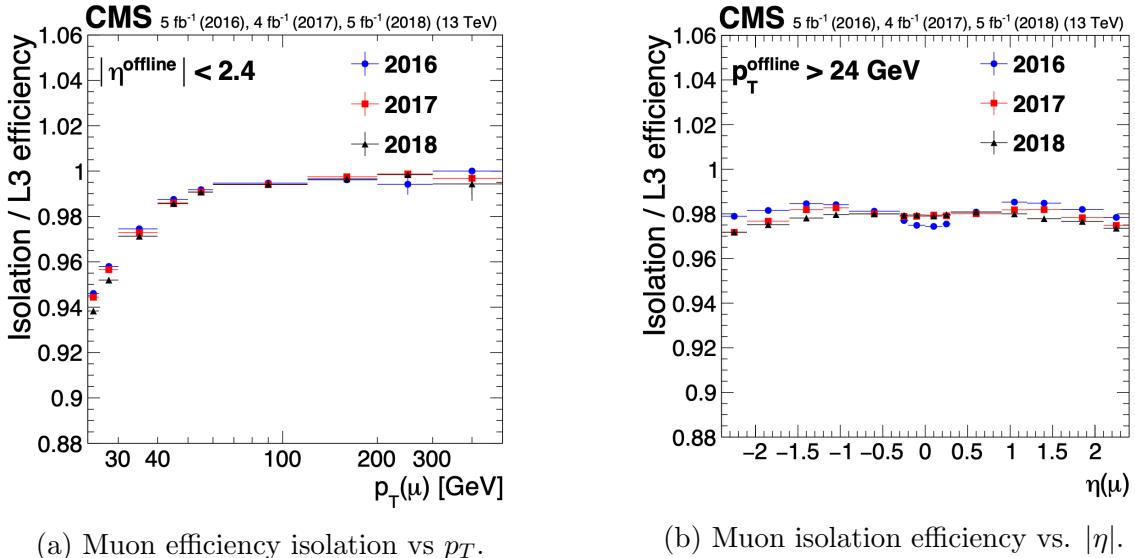


Figure 5.8: Muon identification efficiencies in 2015 data and MC as a function of the muon p_T for the loose ID (*left*) and tight ID (*right*) working points [80].

1710 The efficiencies in data for the muon isolation, as measured in Level-3 muons
 1711 (muons in one of the final stages of reconstruction in the HLT), as a function of the
 1712 muon p_T and $|\eta|$ are shown in Figures 5.9a and 5.9b [80]. The HLT muon reconstruc-
 1713 tion consists of two steps: Level-2 (L2), where the muon is reconstructed in the muon
 1714 subdetectors only, and Level-3 (L3) which is a global fit of tracker and muon hits (i.e.
 1715 the global muon reconstruction as described in Section 5.1.2) [81].

1716 The muon tracking efficiencies as a function of $|\eta|$ for standalone muons (i.e. tracks
 1717 from only the muon system, i.e. DT, CSC, and RPC, as discussed in Section 5.1.2),
 1718 is shown for data and simulated Drell-Yan samples in Fig. 5.10 [82].



(a) Muon efficiency isolation vs p_T .

(b) Muon isolation efficiency vs. $|\eta|$.

Figure 5.9: Muon isolation efficiencies in Run-2 data with respect to Level-3 muons (one of the final stages of HLT muon reconstruction) as a function of the muon p_T (*left*) and $|\eta|$ (*right*) [80].

1719 5.3.14 Recoil corrections

1720 In proton-proton collisions, W and Z bosons are predominantly produced through
1721 quark-antiquark annihilation. Higher-order processes can induce radiated quarks or
1722 gluons that recoil against the boson, imparting a non-zero transverse momentum to
1723 the boson [83]. Recoil corrections accounting for this effect are applied to samples
1724 with W+jets, Z+jets, and Higgs bosons [68]. The corrections are performed on the
1725 vectorial difference between the measured missing transverse momentum and the total
1726 transverse momentum of neutrinos originating from the decay of the W, Z, or Higgs
1727 boson. This vector is projected onto the axes parallel and orthogonal to the boson
1728 p_T . This vector, and the resulting correction to use, is measured in $Z \rightarrow \mu\mu$ events,
1729 since these events have leptonic recoil that do not contain neutrinos, allowing the
1730 4-vector of the Z boson to be measured precisely. The corrections are binned in
1731 generator-level p_T of the parent boson and also the number of jets in the event.

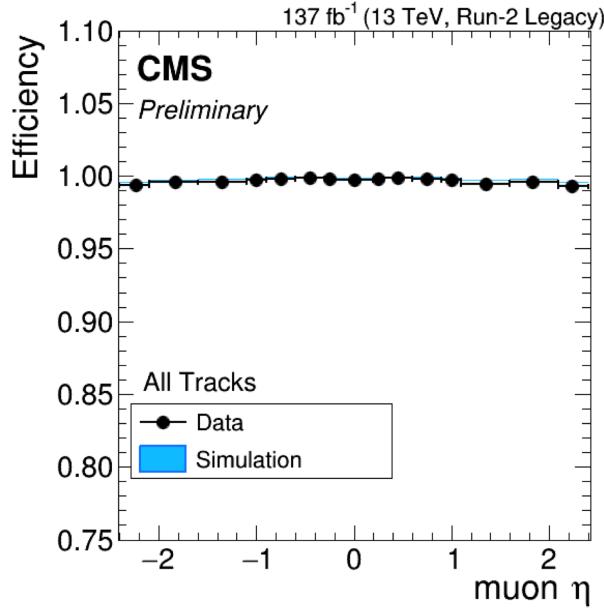


Figure 5.10: Muon tracking efficiencies as a function of $|\eta|$ for standalone muons in Run-2 data (*black*) and Drell-Yan MC simulation (*blue*) [82]. All Tracks refers to tracks which exploit the presence of muon candidates in the muon system to seed the track reconstruction in the inner tracker, in contrast to tracks that use tracker-only hits for seeding. Uncertainties shown are statistical.

5.3.15 Drell-Yan corrections

The Z boson transverse momentum distribution disagrees between leading-order (LO) simulations and data in a $Z \rightarrow \mu\mu$ control region with at least one b-tag jet [84]. Per-event weights derived by the 2016 data-only version of this analysis [84] are applied to $Z \rightarrow \tau\tau/\ell\ell$ events, as a function of the generator-level Z boson p_T to provide better matching of MC to data.

5.3.16 Pile-up reweighting

Reweighting is performed to rescale MC events to account for differences between MC and data, in the distribution of the pile-up (number of additional proton-proton interactions per bunch crossing). A tool for calculating the pile-up reweighting for the MC samples used is provided centrally by the Luminosity POG [85].

₁₇₄₃ **5.3.17 Pre-firing corrections**

₁₇₄₄ In 2016 and 2017 data-taking, a gradual timing shift of ECAL was not properly
₁₇₄₅ propagated to L1 trigger primitives (TPs), resulting in a large fraction of high η
₁₇₄₆ TPs being incorrectly associated with the previous bunch crossing. L1 trigger rules
₁₇₄₇ prevent two consecutive bunch crossings from firing, causing events to be rejected if
₁₇₄₈ significant ECAL energy was deposited in $2.0 < |\eta| < 3.0$. To account for this issue,
₁₇₄₉ MC simulations for 2016 and 2017 are corrected using an event-dependent weight.
₁₇₅₀ Embedded samples are not corrected [50].

₁₇₅₁ **5.3.18 Top p_T spectrum reweighing**

₁₇₅₂ In Run-1 and Run-2 it was observed that the p_T spectra of top quarks in $t\bar{t}$ data
₁₇₅₃ was significantly softer than those predicted by MC simulations [86]. Possible sources
₁₇₅₄ of this discrepancy are higher order QCD and/or electroweak corrections, and non-
₁₇₅₅ resonant production of $t\bar{t}$ -like final states. To account for this, corrections derived
₁₇₅₆ from Run-2 data by the Top Physics Analysis Group (PAG) are applied to the p_T
₁₇₅₇ of the top and anti-top quarks in MC simulations, computed as a function of their
₁₇₅₈ generator-level p_T [86].

₁₇₅₉ **5.3.19 B-tagging efficiency**

₁₇₆₀ In order to predict correct b-tagging discriminant distributions and event yields in
₁₇₆₁ data, the weight of selected MC events is reweighed according to recommendations by
₁₇₆₂ the BTV POG [87]. The reweighing depends on the jet p_T , η , and the b-tagging dis-
₁₇₆₃ criminant. In this method, there is no migration of events from one b-tag multiplicity
₁₇₆₄ bin to another.

1765 5.3.20 Jet energy resolution and jet energy smearing

1766 Calibration of jet energies, i.e. ensuring that the energy and momentum of the recon-
1767 structed jet matches that of the quark/gluon-initiated jet, is a challenging task due
1768 to time-dependent changes in the detector response and calibration and high pile-
1769 up [88] [89]. Jet calibration is done via jet energy corrections (JECs) applied to the
1770 p_T of jets in MC samples, accounting successively for the effects of pile-up, uniformity
1771 of the detector response, and residual data-simulation jet energy scale differences [90].
1772 Typical jet energy resolutions reported at $\sqrt{s} = 8$ TeV in the central rapidities are
1773 15-20% at 30 GeV and about 10% at 100 GeV [88]. Jet energy corrections are also
1774 propagated to the missing transverse energy.

1775 Measurements show that the jet energy resolution (JER) in data is worse than
1776 in simulation, and so the jets in MC need to be smeared to describe the data. JER
1777 corrections are applied after JEC on MC simulations, and adjust the width of the p_T
1778 distribution based on pile-up, jet size, and jet flavor [91]. Tools for applying JEC and
1779 JER are provided centrally by the JER Corrections group.

1780 **Chapter 6**

1781 **Event selection**

1782 This chapter describes how events in data and simulated samples are selected in the
1783 search for $h \rightarrow aa \rightarrow bb\tau\tau$. The event selection is motivated by optimization checks
1784 aimed at maximizing the final expected limit, and is also based on recommendations
1785 from CMS Physics Objects Groups. As described in the previous chapter, the tau
1786 lepton can decay to electrons (e), muons (μ), or hadronic states (τ_h). As a result,
1787 several different final states of the $\tau\tau$ system are possible, and are here referred to
1788 as “channels” since they are mutually exclusive. The three $\tau\tau$ final states studied in
1789 this analysis are muon and hadronic tau ($\mu\tau_h$), electron and hadronic tau ($e\tau_h$), and
1790 electron and muon ($e\mu$). The procedure for dividing events into these three channels
1791 begins with checking the High-Level Trigger paths passed by the events as detailed
1792 in Section 6.1. Events are further accepted or rejected based on criteria applied to
1793 the leptons in the event. These event selections are described for the $\mu\tau_h$ channel in
1794 Section 6.2, the $e\tau_h$ channel in Section 6.3, and the $e\mu$ channel in Section 6.4.

1795 **6.1 General procedure for all channels**

1796 For the search for $h \rightarrow aa \rightarrow bb\tau\tau$, three final states of the $\tau\tau$ system are considered:
1797 $\mu\tau_h$, $e\tau_h$, and $e\mu$. The $\tau_h\tau_h$ final state is not considered because signal events in the

1798 $\tau_h\tau_h$ channel would typically produce hadronic taus with momenta below data-taking
1799 trigger thresholds. In all three final states, events are required to have at least one
1800 b-tag jet passing the medium working point of the DeepFlavour tagger, with $p_T > 20$
1801 GeV, and $|\eta| < 2.4$. A second b-tag jet is not required because such a requirement
1802 would reduce signal acceptance by 80% compared to only requiring one b-tag jet.

1803 Events in MC samples are sorted into one of the three $\tau\tau$ channels if they pass the
1804 following trigger requirements and requirements on the offline reconstructed objects
1805 in the event, first checking the HLT paths for the $\mu\tau_h$ channel, then $e\tau_h$, and finally $e\mu$.
1806 The two leading leptons (e.g. muon and hadronic tau for the $\mu\tau_h$ channel) that were
1807 determined to have originated from the $\tau\tau$ decay, are called the $\tau\tau$ “legs”. For events
1808 in data and embedded samples, the HLT paths requirements for the corresponding
1809 channel are checked.

1810 After sorting events by HLT paths and identifying the leading tau legs in the offline
1811 reconstructed objects, the p_T of the offline objects is checked against the online trigger
1812 thresholds. Trigger matching is also performed, which checks the correspondence
1813 between each offline reconstructed object used in the analysis (e.g. a muon), and a
1814 trigger object in the HLT (e.g. a HLT muon). An offline object is considered to be
1815 matched, if it corresponds to a trigger object of the same object type, with $\Delta R < 0.5$.
1816 This matched trigger object is also required to pass the filter(s) of the HLT trigger.
1817 The trigger thresholds used for the $bb\mu\mu$ final state and the $bb\tau\tau$ final state (the focus
1818 of this work) are summarized in Tables 6.1.

1819 After checking the HLT paths and trigger objects in each channel, events are
1820 subject to further selection to ensure that they contain leptons and b-tag jet(s) of in-
1821 terest. These requirements are summarized in Table 6.2, and detailed in the following
1822 sections.

Year	Single/dilepton trigger p_T	$bb\mu\mu$	$bb\tau\tau$					
			$e\mu$		$e\tau_h$		$\mu\tau_h$	
		μ	e	μ	e	τ_h	μ	τ_h
2016	Single lepton	24	–	–	25	–	22	–
	p_T -leading lepton	17	23	23	–	–	–	20
	p_T -subleading lepton	8	12	8	–	–	19	–
2017	Single lepton	24	–	–	27, 32	–	24, 27	–
	p_T -leading lepton	17	23	23	–	30	–	27
	p_T -subleading lepton	8	12	8	24	–	20	–
2018	Single lepton	24	–	–	32, 35	–	24, 27	–
	p_T -leading lepton	17	23	23	–	30	–	27
	p_T subleading lepton	8	12	8	24	–	20	–

Table 6.1: Trigger thresholds used for the leptons in the $bb\mu\mu$ analysis and the $bb\tau\tau$ analysis (the focus of this work). The thresholds for the three $bb\tau\tau$ channels ($e\mu$, $e\tau_h$, and $\mu\tau_h$) are listed separately, with some channels and years taking the logical OR of two triggers with different thresholds.

6.2 Event selection in the $\mu\tau_h$ channel

In all three years, a single muon trigger is used if the muon has sufficiently high p_T , otherwise a dilepton $\mu\tau_h$ cross-trigger is used (Tables 6.3, 6.4, and 6.5). For data taken in 2017-2018 (2016), the logical OR of the single muon triggers with online p_T thresholds 24 and 27 (23) GeV is used, with the corresponding offline muon required to have with p_T 1 GeV above the online threshold. For data taken in 2017-2018 (2016), a dilepton $\mu + \tau_h$ cross-trigger with p_T thresholds of 20 (19) and 27 (20) GeV for the muon and tau respectively, is used. The τ_h is required to have $|\eta| < 2.3$ if the single trigger is fired, $|\eta| < 2.1$.

The muon and τ_h are required to have opposite charge and be separated by $\Delta R > 0.4$. The muon is required to have $|\eta| < 2.4$, and the τ_h is required to have $|\eta| < 2.3$ unless a cross-trigger is required, in which case we require $|\eta| < 2.1$ as discussed above.

The muon is required to pass the medium identification (ID) working point [92], which is defined by the Muon POG as a loose muon (i.e. a Particle Flow muon that is either a global or a tracker muon - see Section 5.1.2) with additional requirements

All years (2016, 2017, 2018) and eras				
Kinematic variable	$bb\mu\mu$		$bb\tau\tau$	
	μ	$e\mu$	$e\tau_h$	$\mu\tau_h$
ΔR between leptons	>0.4	>0.3	>0.4	>0.4
$ \eta $ of electron	-	<2.4	<2.1	-
$ \eta $ of muon	<2.4	<2.4	-	<2.1
$ \eta $ of hadronic tau	-	-	<2.3/< 2.1	<2.3/< 2.1
Relative isolation of electron	-	<0.10	-	<0.15
Relative isolation of muon	<0.25	<0.15	-	<0.15
Leading b-tag jet p_T	>15 GeV		>20 GeV	
Leading b-tag jet $ \eta $	<2.4		<2.4	
Leading b-tag jet WP	Tight		Medium	
Sub-leading b-tag jet p_T	>15 GeV		-	
Sub-leading b-tag jet $ \eta $	<2.4		-	
Sub-leading b-tag jet WP	Loose		-	
ΔR between jet(s) and leptons	>0.4		>0.5	

Table 6.2: Summary of requirements applied to the leptons in the $bb\mu\mu$ analysis and the $bb\tau\tau$ analysis (the focus of this work). $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is a measure of spatial separation. Relative isolation is defined in Eqn. 5.2 and Section 5.1.2. The b-tag jets are required to pass the listed DeepFlavour working points (WP), which are described in Section 5.1.5. In the $bb\tau\tau$ analysis, the required $|\eta|$ of the hadronic taus are listed for the single and cross triggers respectively. The $bb\mu\mu$ analysis requires two b-tag jets in all events, while the $bb\tau\tau$ analysis only requires one.

1839 on track quality and muon quality. This identification criteria is designed to be
1840 highly efficiently for prompt muons and for muons from heavy quark decays. In
1841 addition to the ID, for prompt muons it is recommended to apply cuts on the impact
1842 parameter [92]: we apply $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$. A cut is applied on the
1843 muon relative isolation (defined in Section 5.1.2), to be less than 0.15 in a cone size of
1844 $\Delta R = 0.4$, which corresponds to the Tight Particle Flow isolation requirement [92].

1845 The τ_h is required to pass a cut on its impact parameter of $|\Delta(z)| < 0.2$. The τ_h
1846 is also required to pass the VLoose (Very Loose) DeepTau working point vs. elec-
1847 tron, the Tight DeepTau working point vs. muons, and the VVVLoose and Medium
1848 DeepTau working point vs. jets. Events with taus reconstructed in two of the decay
1849 modes (labeled 5 and 6) are rejected, since these decay modes are meant to recover
1850 3-prong taus, but are only recommended for use in analyses where the benefits in final
1851 significance outweigh the resulting increase in background [65]. Decays reconstructed
1852 with 2 prongs are not considered as they are only recommended for taus with a very
1853 high transverse momentum, where the prongs may overlap.

1854 For the estimation of the background from jets faking τ_h , which is described in Sec-
1855 tion 7.7, anti-isolated events are selected, by requiring events to pass all the selections
1856 described above, except failing the Medium DeepTau working point vs. jets.

1857 6.3 Event selection in the $e\tau_h$ channel

1858 The HLT trigger paths for the $e\tau_h$ channel are summarized in Tables 6.3, 6.4, and
1859 6.5. Similarly to the $\mu\tau_h$ channel, a single electron trigger is used if the electron has
1860 sufficiently high p_T in 2018 and 2017. For data taken in 2018 (2017), the OR of the
1861 single electron triggers with online p_T thresholds at 32 and 35 (27 and 32) GeV are
1862 used, with the corresponding offline electrons required to have p_T greater than 33
1863 (28) GeV. A $e + \tau_h$ cross-trigger is used for electrons with lower offline p_T between

1864 25 and 33 GeV (25 and 28 GeV). For the 2016 dataset, there is no cross trigger but
1865 only a single electron trigger with online p_T threshold at 25 GeV, which is used if the
1866 offline electron has p_T greater than 26 GeV.

1867 The electron and τ_h are required to have opposite charge and be separated by
1868 $\Delta R > 0.4$. The electron is required to be within $|\eta| < 2.3$ when no cross trigger is
1869 used, and $|\eta| < 2.1$ when the cross trigger is fired. The τ_h is required to have $|\eta| < 2.3$
1870 if no cross trigger is fired, and have $|\eta| < 2.1$ if the cross trigger is fired.

1871 The electron is required to have a relative isolation (same definition as in Section
1872 5.1.2) of less than 0.1 in a cone size of $\Delta R = 0.3$, which is the standard recommended
1873 cone size giving minimal pile-up dependence and reduced probability of other objects
1874 overlapping with the cone. The isolation quantity used includes an “effective area”
1875 (EA) correction to remove the effect of pile-up in the barrel and endcap parts of the
1876 detector [93]. The electron is also required to pass cuts on its impact parameter of
1877 $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$. It is also required to pass the non-isolated MVA
1878 working point corresponding to 90% efficiency. The electron’s number of missing hits,
1879 which are gaps in its trajectory through the inner tracker [93], must be less than or
1880 equal to 1. The electron must pass a conversion veto, which rejects electrons coming
1881 from photon conversions in the tracker, which should instead be reconstructed as part
1882 of the photon [93].

1883 The impact parameter cut for the τ_h is $|\Delta(z)| < 0.2$. In contrast to the $\mu\tau_h$ event
1884 selection, the vs. electron and vs. muon DeepTau working points are flipped, to
1885 reject muons faking the τ_h leg. The τ_h is required to pass the Tight DeepTau working
1886 point vs. electrons, the VLoose DeepTau working point vs. muons, and the Medium
1887 DeepTau working point vs. jets.

1888 As in the $\mu\tau_h$ channel, for the estimation of the background from jets faking τ_h ,
1889 which is described in Section 7.7, anti-isolated events are selected by requiring events
1890 to pass all the selections described above, except failing the Medium DeepTau working

1891 point vs. jets.

1892 6.4 Event selection in the $e\mu$ channel

1893 The HLT trigger paths for the $e\mu$ channel are summarized in Tables 6.3, 6.4, and
1894 6.5. Events are selected with the logical OR of two $e + \mu$ cross triggers, where either
1895 the electron or muon can have larger p_T : (1) leading electron, where the electron has
1896 online $p_T > 23$ GeV and muon has online $p_T > 8$ GeV, or (2) leading muon, where
1897 electron has online $p_T > 12$ GeV and muon has online $p_T > 23$ GeV.

1898 The leading and sub-leading leptons are required to have an offline p_T greater
1899 than 1 GeV above the online threshold (i.e. $p_T > 24$ GeV). If the sub-leading lepton
1900 is the electron, the offline p_T threshold is 1 GeV above the online threshold ($p_T > 13$
1901 GeV), but if it is a muon, the offline p_T threshold is required to be at least 5 GeV
1902 greater than the online threshold (i.e. $p_T > 13$ GeV). This is because of poor data
1903 and simulation agreement for low- p_T muons with p_T between 9 GeV and 13 GeV, and
1904 the higher probability of mis-identifying jets as muons at lower p_T . With no effect on
1905 the expected limits, the offline p_T threshold for muons is raised to 13 GeV instead of
1906 9 GeV, even though it may lead to loss in signal acceptance. Both the electron and
1907 muon are required to have $|\eta| < 2.4$.

1908 The electron and muon are required to have opposite charge and be separated
1909 by $\Delta R > 0.3$ (note the decreased separation requirement compared to the other
1910 two channels). The electron is required to pass the non-isolated MVA identification
1911 working point corresponding to 90% efficiency, and to have a relative isolation less
1912 than 0.1 for a cone size of $\Delta R = 0.3$ with the EA pile-up subtraction correction.
1913 The electron must have one or fewer missing hits and pass the conversion veto (both
1914 described previously in Section 6.3).

1915 The muon is required to pass the medium identification working point (described

1916 earlier in 6.2), and to have a relative isolation less than 0.15 for a cone size of $\Delta R =$
1917 0.4. The muon impact parameter is required to have $|\Delta(z)| > 0.2$ and $|\Delta(xy)| < 0.045$.

1918 For the QCD multijet background estimation described in Section 7.8, the same-
1919 sign region is selected by requiring all the above selections, except the legs are required
1920 to have the same electric charge rather than opposite.

2016 $\mu\tau_h$ trigger paths	
Notes	HLT Path
	HLT_IsoMu22_v
	HLT_IsoMu22_eta2p1_v
	HLT_IsoTkMu22_v
	HLT_IsoTkMu22_eta2p1_v
	HLT_IsoMu19_eta2p1_LooseIsoPFTau20_v
	HLT_IsoMu19_eta2p1_LooseIsoPFTau20_SingleL1_v
2016 $e\tau_h$ trigger paths	
Notes	HLT Path
	HLT_Ele25_eta2p1_WPTight_Gsf_v
2016 $e\mu$ trigger paths	
Notes	HLT Path
runs B-F and MC	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v
runs B-F and MC	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v
runs G-H	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v
runs G-H	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v

Table 6.3: High-Level Trigger (HLT) paths used to select data and simulation events in 2016 for the three $\tau\tau$ channels.

1921 6.5 Extra lepton vetoes in all channels

1922 Events containing a third lepton (electron or muon) that is neither of the leading $\tau\tau$
1923 legs are rejected, and events with di-muons and di-electrons are vetoed, with criteria
1924 taken from the Standard Model $H \rightarrow \tau\tau$ working group [68]. These vetoes on extra
1925 leptons also ensure orthogonality of events to analyses such as the $bb\mu\mu$ final state,
1926 whose results are combined with this $bb\tau\tau$ final state as described in Section 10.2.

1927 The event is vetoed if a third electron is found with the following properties:
1928 $p_T > 10$ GeV, $|\eta| < 2.5$, impact parameter $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$, passing

2017 $\mu\tau_h$ trigger paths	
Notes	HLT Path
	HLT_IsoMu24_v
	HLT_IsoMu27_v
	HLT_IsoMu20_eta2p1_LooseChargedIso_PFTau27_eta2p1_CrossL1_v
2017 $e\tau_h$ trigger paths	
Notes	HLT Path
	HLT_Ele32_WPTight_Gsf_v
	HLT_Ele35_WPTight_Gsf_v
	HLT_Ele24_eta2p1_WPTight_Gsf_Loose_ChargedIsoPFTau30_eta2p1_CrossL1_v
2017 $e\mu$ trigger paths	
Notes	HLT Path
	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v
	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v

Table 6.4: High-Level Trigger (HLT) paths used to select data and simulation events in 2017 for the three $\tau\tau$ channels.

1929 non-isolation MVA identification with 90% efficiency, conversion veto, ≤ 1 missing
 1930 hits, and relative isolation < 0.3 with cone size $\Delta R = 0.3$. The event is also vetoed if
 1931 a third muon is found with the following properties: $p_T > 10$ GeV, $|\eta| < 2.4$, impact
 1932 parameter $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$, medium ID, and isolation < 0.3 with
 1933 cone size $\Delta R = 0.4$.
 1934 A di-muon veto is applied, which rejects events containing a pair of muons with
 1935 opposite charge and separation of $\Delta R > 0.15$, that both pass the following selections:
 1936 $p_T > 15$ GeV, $|\eta| < 2.4$, flag for global muons, flag for tracker muon, flag for Particle
 1937 Flow muon, $|\Delta(z)| < 0.2$, $|\Delta(xy)| < 0.045$, and isolation < 0.3 with cone size $\Delta R =$
 1938 0.4. A similar di-electron veto is applied to reject events containing a pair of electrons
 1939 with opposite charge and separation of $\Delta R > 0.15$, that both pass the following
 1940 selections: $p_T > 15$ GeV, $|\eta| < 2.5$, a dedicated electron ID (cut-based) for vetoing
 1941 third leptons, $|\Delta(z)| < 0.2$, $|\Delta(xy)| < 0.045$, with pile-up corrected relative isolation
 1942 < 0.3 with cone size $\Delta R = 0.3$.

2018 $\mu\tau_h$ trigger paths	
Notes	HLT Path
	HLT_IsoMu24_v
	HLT_IsoMu27_v
only data run < 317509	HLT_IsoMu20_eta2p1_ (contd.)
	LooseChargedIsoPFTauHPS27_eta2p1_CrossL1_v
MC and data run \geq 317509	HLT_IsoMu20_eta2p1_ (contd.)
	LooseChargedIsoPFTauHPS27_eta2p1_TightID_CrossL1_v
2018 $e\tau_h$ trigger paths	
Notes	HLT Path
	HLT_Ele32_WPTight_Gsf_v
	HLT_Ele35_WPTight_Gsf_v
only data run < 317509	HLT_Ele24_eta2p1_WPTight_Gsf_ (contd.)
	LooseChargedIsoPFTauHPS30_eta2p1_CrossL1_v
MC and data run \geq 317509	HLT_Ele24_eta2p1_WPTight_Gsf_ (contd.)
	LooseChargedIsoPFTauHPS30_eta2p1_TightID_CrossL1_v
2018 $e\mu$ trigger paths	
Notes	HLT Path
	HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v
	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v

Table 6.5: High-Level Trigger (HLT) paths used to select data and simulation events in 2018 for the three $\tau\tau$ channels. In 2018 a HLT trigger path using the hadron plus strips (HPS) tau reconstruction algorithm became available.

¹⁹⁴³ Chapter 7

¹⁹⁴⁴ Background estimation

¹⁹⁴⁵ This section describes methods used to estimate backgrounds from Standard Model
¹⁹⁴⁶ processes in the search for $h \rightarrow aa \rightarrow bb\tau\tau$. The background contributions directly
¹⁹⁴⁷ taken from MC are described in Sections 7.1 to 7.6. Section 7.7 describes the data-
¹⁹⁴⁸ driven method for estimating backgrounds from jets faking hadronic tau decays (jet
¹⁹⁴⁹ $\rightarrow \tau_h$), which is used in the $\mu\tau_h$ and $e\tau_h$ channels. Section 7.8 describes the data-driven
¹⁹⁵⁰ method for estimating background from quantum chromodynamic (QCD) processes
¹⁹⁵¹ in the $e\mu$ channel.

¹⁹⁵² 7.1 Z+jets

¹⁹⁵³ A major source of background for $\tau\tau$ analyses is the Drell-Yan (DY) process (Z+jets).
¹⁹⁵⁴ The Z boson decays to $\tau\tau/\mu\mu/ee$ with equal probability of 3.4% each, with the domi-
¹⁹⁵⁵ nant decay modes being to hadrons (around 70%) and neutrinos (invisible) (20%) [26].
¹⁹⁵⁶ The Drell-Yan contribution with genuine taus, $Z \rightarrow \tau\tau$, is estimated using embed-
¹⁹⁵⁷ ded samples, described in Section 4.3. To avoid double-counting between embedded
¹⁹⁵⁸ and MC samples, in all MC samples, events with legs that originated from genuine τ
¹⁹⁵⁹ are discarded.

¹⁹⁶⁰ The other decays of the Z, $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$, are estimated from MC simulation,

1961 and are hereafter referred to as simply the Drell-Yan background. These MC samples
1962 are generated to leading order (LO) with different numbers of jets (jet multiplicity) in
1963 the matrix element: Z+1 jet, Z+2jets, Z+3 jets, Z+4 jets, and inclusive Z+jets. The
1964 cross-sections of the samples with ≥ 1 jets are normalized to next-to-NLO (NNLO)
1965 in QCD. For the inclusive Drell-Yan sample, two samples are used with different
1966 thresholds for the di-lepton invariant mass ($m_{\ell\ell}$) at the generator level: one with
1967 $m_{\ell\ell} > 50$ GeV and the other with $10 < m_{\ell\ell} < 50$.

1968 7.2 W+jets

1969 The dominant W boson decay modes are to hadrons (67.4%), $e + \nu_e$ (10.7%), $\mu + \nu_\mu$
1970 (10.6%), and $\tau + \nu_\tau$ (11.4%) [26]. The W+jets background is estimated from MC
1971 simulation. Similarly to the Z+jets, the W+jets samples are generated with different
1972 jet multiplicities in the matrix element. LO samples are used for greater statistics
1973 and are normalized to NNLO cross sections.

1974 7.3 $t\bar{t}$ + jets

1975 In hadron collisions, top quarks are produced singly with the weak interaction, or in
1976 pairs via the strong interaction, with interference between these leading-order pro-
1977 cesses possible in higher orders of the perturbation theory. The top quark is the
1978 heaviest fermion in the Standard Model and has a short lifetime ($\sim 10^{-25}$ s), decay-
1979 ing without hadronization into a bottom quark and a W boson [26], with the decay
1980 modes of the W boson as listed in the previous section. With two top quarks, the
1981 final states of the two resulting W bosons can be described as fully leptonic, semilep-
1982 tonic, and fully hadronic. These three final states are modeled separately with MC
1983 simulation in 2018 and 2017, while for 2016 the sample used is inclusive.

7.4 Single top

There are three main production modes of the single top in pp collisions [94]: the exchange of a virtual W boson (t channel), the production and decay of a virtual W boson (s channel), and the associated production of a top quark and W boson (tW , or W-associated) channel. As the s channel process is rare and only 3% of the total production, the dominant production mode of the t -channel and the tW production are considered and modeled with MC.

7.5 Diboson

In pp collisions, the production of dibosons (pairs of electroweak gauge bosons, i.e. WW, WZ, and ZZ) is dominated by quark-antiquark annihilation, with a small contribution from gluon-gluon interaction [95]. MC is used to model the pair production and decays of VV to $2\ell 2\nu$, WZ to $2q 2\ell$ and $3\ell\nu$, and ZZ to 4ℓ and $2q 2\ell$ (q being quarks and ℓ being leptons).

7.6 Standard Model Higgs

MC is used to simulate backgrounds from major production modes of the Standard Model 125 GeV Higgs boson: gluon-gluon fusion (ggH), vector boson fusion (VBF), associated production with a W or Z (WH, ZH), and associated production with a top pair (ttH) (see Fig. 7.1 for leading-order diagrams). For these production modes, samples with the Higgs decaying to $\tau\tau$ or to WW are used. Samples made with higher-order diagrams for WH and ZH that include the production of a jet, with the Higgs decaying to WW, are also used.

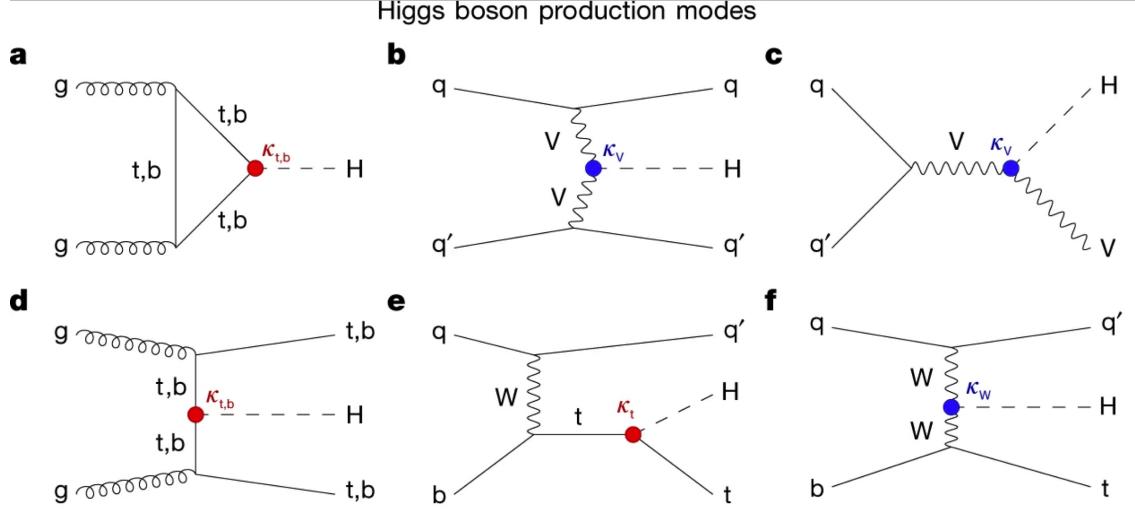


Figure 7.1: Leading-order Feynman diagrams of Higgs production from [96], in ggH (a) and vector boson fusion (VBF; b), associated production with a W or Z (V) boson (VH; c), associated production with a top or bottom quark pair (ttH or bbH); d, and associated production with a single top quark (tH; e, f).

2005 7.7 Jet faking τ_h

2006 Events with a jet mis-reconstructed as the hadronic tau leg τ_h are a major source of
 2007 background in the $\mu\tau_h$ and $e\tau_h$ channels. The main processes contributing to jet $\rightarrow \tau_h$
 2008 events are QCD multijet, W+jets, and $t\bar{t}$ production. These events are estimated
 2009 using a data-driven method adapted from past analyses [50] [84]. This background
 2010 includes contributions from W+jets, QCD multijets, and $t\bar{t}$ +jets. To estimate this
 2011 background, a sideband region is constructed, where events are required to pass all
 2012 baseline $\mu\tau_h/e\tau_h$ selection criteria, but fail the τ_h isolation criteria. The events in
 2013 this sideband region is reweighed with a factor $f/(1 - f)$, where f is the probability
 2014 for a jet to be misidentified as a τ_h . The jet $\rightarrow \tau_h$ background is the anti-isolated,
 2015 reweighed MC and embedded events subtracted from the anti-isolated, reweighted
 2016 data events.

2017 The fake factor is measured in $Z \rightarrow \mu\mu + \text{jets}$ events in data in the $\mu\mu\tau_h$ final
 2018 state, as any reconstructed τ_h in these events must originate from a jet. The two
 2019 muons are required to be isolated (< 0.15), have opposite electric charge, and have

2020 an invariant mass between 76 and 106 GeV (close to the Z mass). These events are
2021 selected with a double muon trigger, with the leading muon having offline $p_T > 20$
2022 GeV and the subleading muon $p_T > 10$ GeV. Simulated diboson (ZZ and WZ) events
2023 are subtracted to avoid contamination from events with real τ_h . The denominator of
2024 the fake rate corresponds to fake taus passing the VVVLoose working point of the
2025 discriminator vs. jets, while the numerator corresponds to those passing the Medium
2026 working point, i.e. $f = N_{\text{jet passing tight}} / N_{\text{jet passing loose}}$.

2027 f is measured as a function of the τ_h transverse momentum and is 8% - 10% in
2028 each of the data-taking years. f is derived separately for the $\mu\tau_h$ and $e\tau_h$ channels
2029 because the channels use different anti-lepton identification working points.

2030 7.8 QCD multijet background

2031 In the $e\mu$ channel, events with jets faking electrons or muons originating from QCD
2032 multijet, is estimated from data events with the same baseline selection as in the
2033 signal region, except with same-signed (SS) charged $e + \mu$, ensuring orthogonality
2034 with the signal region which requires opposite-sign (OS) $e\mu$ pairs. All same-sign MC
2035 events (both events with real and fake $e + \mu$) are subtracted from same-sign data
2036 events to remove contamination from other backgrounds. i.e. $\text{QCD}_{\text{SS}} = \text{Data}_{\text{SS}} -$
2037 MC_{SS} .

2038 Three scale factors are applied to the QCD_{SS} events to compute the QCD multijet
2039 background [84] [40]:

- 2040 • *OS-to-SS scale factor*: This scales the SS QCD to the OS region, and is mea-
2041 sured from an orthogonal region with an isolated electron and an anti-isolated
2042 muon. Only the muon is chosen to be anti-isolated because this scale factor was
2043 observed to depend more strongly on electron isolation than that of the muon.
2044 This scale factor is treated as a function of the ΔR separation of the trajectories

2045 of the electron and muon, and is measured separately for events with 0 jets, 1,
2046 jet, and greater than 1 jet.

- 2047 • *2D closure correction for the lepton p_T :* This factor accounts for subleading
2048 dependencies of the first scale factor on the p_T of the two leptons. A 2D weight
2049 is derived in a similar fashion, as a ratio of QCD_{OS} events to QCD_{SS} events,
2050 but parameterized by both electron and muon p_T , where the SS events have the
2051 previous scale factor applied.
- 2052 • *Isolation correction for the muon:* The third and final factor is an isolation
2053 correction, which is a bias correction to account for the fact that the fake
2054 factor was determined for less-isolated muons. This factor is obtained as the
2055 ratio of the OS-to-SS scale factors measured in two other control regions: (1)
2056 events where the electron is anti-isolated ($0.15 < \text{iso} < 0.5$) and the muon is
2057 isolated, and (2) events where both leptons are anti-isolated.

2058

Chapter 8

2059

Systematic uncertainties

2060 Uncertainties in the measurement of a physical observable can be statistical or sys-
2061 tematic in nature. Statistical uncertainties originate from limitations on the number
2062 of events and experiments that can be performed. Systematic uncertainties arise
2063 from the dependence of the physical observable on quantities whose exact values are
2064 unknown and which can only be modeled imperfectly.

2065 The handling of systematic uncertainties is separated into normalization uncer-
2066 tainties (those that affect the total yield of a variables' distribution) and shape un-
2067 certainties (those that shift the distribution of events). Normalization uncertainties
2068 are expressed as multiplicative factors, while shape uncertainties are represented as
2069 up and down shifts of a variable's distribution.

2070 Up/down shifts of shape uncertainties can change the number of background
2071 events in a distribution. For instance, hadronic taus receive corrections from the
2072 nominal tau energy scale, with the nominal, up, and down energy scales provided
2073 centrally by CMS. For the $\mu\tau_h$ channel, an event could have a τ_h with p_T just below
2074 the offline threshold of 20 GeV (for instance, 19.5 GeV), so in the nominal distribution
2075 of $m_{\tau\tau}$ (or any other variable for this channel), the event is excluded. However, when
2076 we build our distributions with the tau energy scale “up” shift, the energy of this τ_h

2077 may be scaled up to, say, 20.5 GeV, and now the event passes the offline p_T threshold
2078 for the single muon trigger, leading to the event’s inclusion in the distributions made
2079 with the tau energy scale “up” shift.

2080 In evaluating the up and down shifts of a specific source of uncertainty, all other
2081 corrections and scale factors are held at their nominal values, and the full chain of
2082 object and event selection and event categorization is performed to obtain the observ-
2083 able distributions. Any “downstream” variables that depend on the shifted variable,
2084 e.g. the invariant di-tau mass $m_{\tau\tau}$, must be computed for the nominal case, and then
2085 re-computed separately for each up and down shift of the tau legs’ energy scale. The
2086 objective of this process is to quantify the effect of a single source of uncertainty on
2087 the resulting observable distributions. Each scale factor and correction described in
2088 Section 5.3 has an associated uncertainty. The binning of the uncertainties follows
2089 that of the nominal scale factor value.

2090 Sections 8.1 to 8.5 describe uncertainties associated with physics objects, and
2091 Sections 8.6 and 8.7 describe uncertainties associated with sample-level effects. The
2092 pulls and impacts for the top sixty most important systematics are shown in Section
2093 8.8.

2094 8.1 Uncertainties in the lepton energy scales

2095 The uncertainties in the tau energy scales [65] are binned by the tau decay mode and
2096 are taken as shape uncertainties treated as uncorrelated across the tau decay modes
2097 and years. Same as with the application of the nominal scale factor, when applying
2098 the up or down shifts, the missing transverse energy (p_T^{miss}) of the event is adjusted
2099 so that the 4-vector sum of the tau p_T^{miss} is unchanged.

2100 The uncertainties in the muon energy scale [66] are 0.4% for $|\eta| < 1.2$, 0.9% for
2101 $1.2 < |\eta| < 2.1$, and 2.7% for $2.1 < |\eta| < 2.4$, and are treated as shape uncertainties,

2102 fully uncorrelated between embedded and MC samples.

2103 The uncertainties in the electron energy scale [69] in MC are binned in the electron
2104 $|\eta|$ and p_T , and are shown in Fig. 5.2. The uncertainties range from 0.5% to 2.2% in
2105 the barrel, and 0.3% to 4.1% in the endcap, across the p_T range. The uncertainties
2106 for the embedded sample are binned only in $|\eta|$ and are on the order of 0.5% and
2107 1.25% for the barrel and endcap [73].

2108 There are also uncertainties in the energy scales for electrons and muons misiden-
2109 tified as τ_h . The uncertainty for muons misidentified as τ_h is 1% [65]. For electrons
2110 misidentified as τ_h , the uncertainty is binned in barrel/endcap η and by 1-prong and
2111 1-prong + π_0 decays. The probability for e/μ faking a 3-prong decay mode is much
2112 lower.

2113 8.2 Uncertainties from other lepton corrections

2114 Uncertainties associated with the τ_h identification efficiencies are treated as shapes,
2115 uncorrelated across the seven p_T bins and years. The shape uncertainties in the em-
2116 bedded samples are taken as 50% correlated with those of the MC samples. The
2117 uncertainties on electron and muon identification efficiencies are taken as normaliza-
2118 tion uncertainties of 2% each, with a 50% correlation between embedded and MC
2119 samples.

2120 In the $e\tau_h$ channel, there is an additional uncertainty for the vs. jet discrimination
2121 efficiency [65], because the analysis uses a looser anti-lepton working point (VLoose
2122 WP) than the working points used in the measurement of the efficiency (namely,
2123 VLoose WP vs e, and Tight WP vs mu). For nominal $\tau_h p_T < 100$ GeV, an additional
2124 uncertainty of 3% (5%) is used in MC (embedded), and for high p_T an uncertainty of
2125 15% is used for both.

2126 The uncertainties in trigger efficiencies are taken as shapes [65]. In the $e\tau_h$ and $\mu\tau_h$

2127 channels, there are uncertainties for the single and cross lepton triggers, and in the
2128 $e\mu$ channel there is one uncertainty each for the two $e + \mu$ triggers, and one combined
2129 uncertainty since their trigger phase spaces are not mutually exclusive.

2130 8.3 Uncertainties from jet energy scale and reso- 2131 lution

2132 The jet energy scale uncertainties are taken as shape uncertainties: there are eleven
2133 in total, with seven correlated across years (labeled “Year” below) and the remainder
2134 uncorrelated across years. They affect the b-tag jet p_T and mass, and hence the
2135 missing transverse energy p_T^{miss} . The shifts are propagated through the b-tagging
2136 scale factor calculation and b-tag jet counting.

2137 The uncertainties in the jet energy correction and resolution [88] [97] are as follows:

- 2138 • *Absolute, AbsoluteYear*: flat absolute scale uncertainties.
- 2139 • *BBEC1, BBEC1Year*: for sub-detector regions, with barrel “BB” in $|\eta| < 1.3$
2140 and endcap region 1 “EC1”: $1.3 < |\eta| < 2.5$.
- 2141 • *EC2, EC2 year*: for sub-detector regions, with endcap region 2 “EC2” in $2.5 <$
2142 $|\eta| < 3.0$.
- 2143 • *HF, HF year*: for sub-detector regions, with hadron forward “HF” in $|\eta| > 3$.
- 2144 • *FlavorQCD*: for uncertainty in jet flavor (uds/c/b-quark and gluon) estimates
2145 based on comparing Pythia and Herwig (different MC generator) predictions.
- 2146 • *RelativeBal*: account for difference between log-linear fits of the two methods
2147 used to study the jet energy response: MPF (missing transverse momentum
2148 projection fraction) and p_T balance.

- 2149 • *RelativeSample*: account for η -dependent uncertainty due to a difference be-
2150 tween relative residuals, observed with dijet and Z+jets in Run D of 2018 data.
- 2151 • *JetResolution*: uncertainty in the jet energy resolution.

2152 8.4 Uncertainties from b-tagging scale factors

2153 The b-tagging scale factor has its own set of associated uncertainties (not to be
2154 confused with shifts in the b-tagging scale factor due to the propagation of the jet
2155 energy scale uncertainties described in the previous section 8.3). They are:

- 2156 • *hf*: contamination from heavy flavor (b+c) jets in the light flavor region.
- 2157 • *hfstats1, hfstats2*: linear and quadratic statistical fluctuations from b-flavor jets.
- 2158 • *lf*: contamination from light flavor (udsg+c jets) in the heavy flavor region.
- 2159 • *lfstats1, lfstats2*: linear and quadratic statistical fluctuations from udsg jets.
- 2160 • *cferr, cferr2*: uncertainty for charm jets.

2161 The variations for “lf, hf, hfstats1/2, lfstats1/2” are applied to both b and udsg jets.
2162 For c-flavor jets, only “cferr1/2” is applied.

2163 8.5 Uncertainties from MET

2164 Samples where recoil corrections were applied (Z+jets, W+jets, and Standard Model
2165 Higgs, as described in Section 5.3) have uncertainties from the response and resolution
2166 of the hadronic recoil against the leptonic system. These are each binned in jet
2167 multiplicity.

2168 8.6 Uncertainties associated with samples used

2169 Normalization uncertainties related to the samples used are:

2170 • *Cross-section uncertainties*: $\sigma(t\bar{t})$: 4.2%, $\sigma(\text{diboson})$: 5%, $\sigma(\text{single top})$: 5%,
2171 $\sigma(\text{ggH})$: 3.2%, $\sigma(\text{qqH})$: 2.1%, $\sigma(\text{WH})$: 1.9%, $\sigma(\text{ZH})$: 1.3%, $\sigma(\text{ttH})$: 3.6%

2172 • *Uncertainties in QCD renormalization scale*: QCD scale(qqH): +0.43%-0.33%,
2173 QCD scale(WH): +0.5%-0.7%, QCD scale(ttH): +5.8%-9.2%

2174 • *Branching ratio uncertainties*: $\text{BR}(\text{H} \rightarrow \tau\tau)$: 1.8%, and $\text{BR}(\text{H} \rightarrow \text{WW})$: 1.5%.

2175 • *Normalization uncertainties*: 2% for Drell-Yan, 4\$ for embedded, 20% pre-fit
2176 for the QCD multijet background in the $e\mu$ channel, 20% pre-fit for the jet
2177 faking background.

2178 The $t\bar{t}$ process has additional acceptance uncertainties from QCD scale variation
2179 and parton shower uncertainties [98]. Parton shower uncertainties originate from
2180 the modeling of perturbative and non-perturbative QCD effects handled in parton
2181 shower MC generators. The scale variations are determined from the envelope of the
2182 6 provided shapes due to variations in the factorization scale, renormalization scale,
2183 and their combined variation [98].

2184 The uncertainty in the Z p_T reweighting in Drell-Yan samples is taken as a shape
2185 uncertainty and the up and down values are 0.9 and 1.1 times the nominal reweighting.
2186 This 10% uncertainty is sufficient to cover uncertainties in the weights derived from
2187 the discrepancies between LO simulations and data in the di-muon mass in $Z \rightarrow \mu\mu$
2188 events.

2189 The weight applied to anti-isolated events in the $\mu\tau_h$ and $e\tau_h$ channels to estimate
2190 the background from jets faking τ_h , has shape uncertainties covering uncertainties in
2191 the derivation of the weight. There are six shape uncertainties corresponding to the
2192 binning of the fake rate in the τ_h transverse momentum. For the weight applied to

2193 scale up anti-isolated events in cross-trigger regions, 20% of the nominal weight is
2194 taken as a shape uncertainty.

2195 8.7 Other uncertainties

2196 A 3.6% yield uncertainty in the signal is used to cover uncertainties in the parton
2197 distribution functions (PDFs), knowledge of the α_s (fine structure constant), and
2198 QCD scale. The size of these uncertainties was estimated by a different analysis
2199 searching for two light scalars decaying to four muons, which compared the PDFs
2200 from different model libraries using recommendations from the PDF4LHC Working
2201 Group [99] [100].

2202 Uncertainties in the luminosity measurements can originate from uncertainties
2203 in the luminosity calibration in the van de Meer scan procedure and from detector
2204 operations [43]. Some effects are fully uncorrelated (e.g. if the systematic error is
2205 limited by the statistical uncertainty in the calibration scans taken independently in
2206 each year), and some are correlated, for example in the 2017 and 2018 measurements
2207 which used a method with the same systematic bias. The luminosity normalization
2208 uncertainties are applied all MC samples, divided into those uncorrelated across years
2209 (0.26% for 2016, 0.60% for 2017, and 0.65% for 2018), one correlated between 2017
2210 and 2018 (0.27%), and one correlated between all three years (1.30%) [41] [42] [43] [85].

2211 8.8 Pulls and impacts

2212 The top impacts and pulls computed for the combination of all channels and years is
2213 shown in Fig. 8.1. The top impacts are related to uncertainty in the signal sample and
2214 cross-section of the $t\bar{t}$ cross-section, and also the yields of the jet faking τ_h background,
2215 which is a major background in all channels and expected to be constrained due to
2216 the yield uncertainty which is taken to be 20% pre-fit.

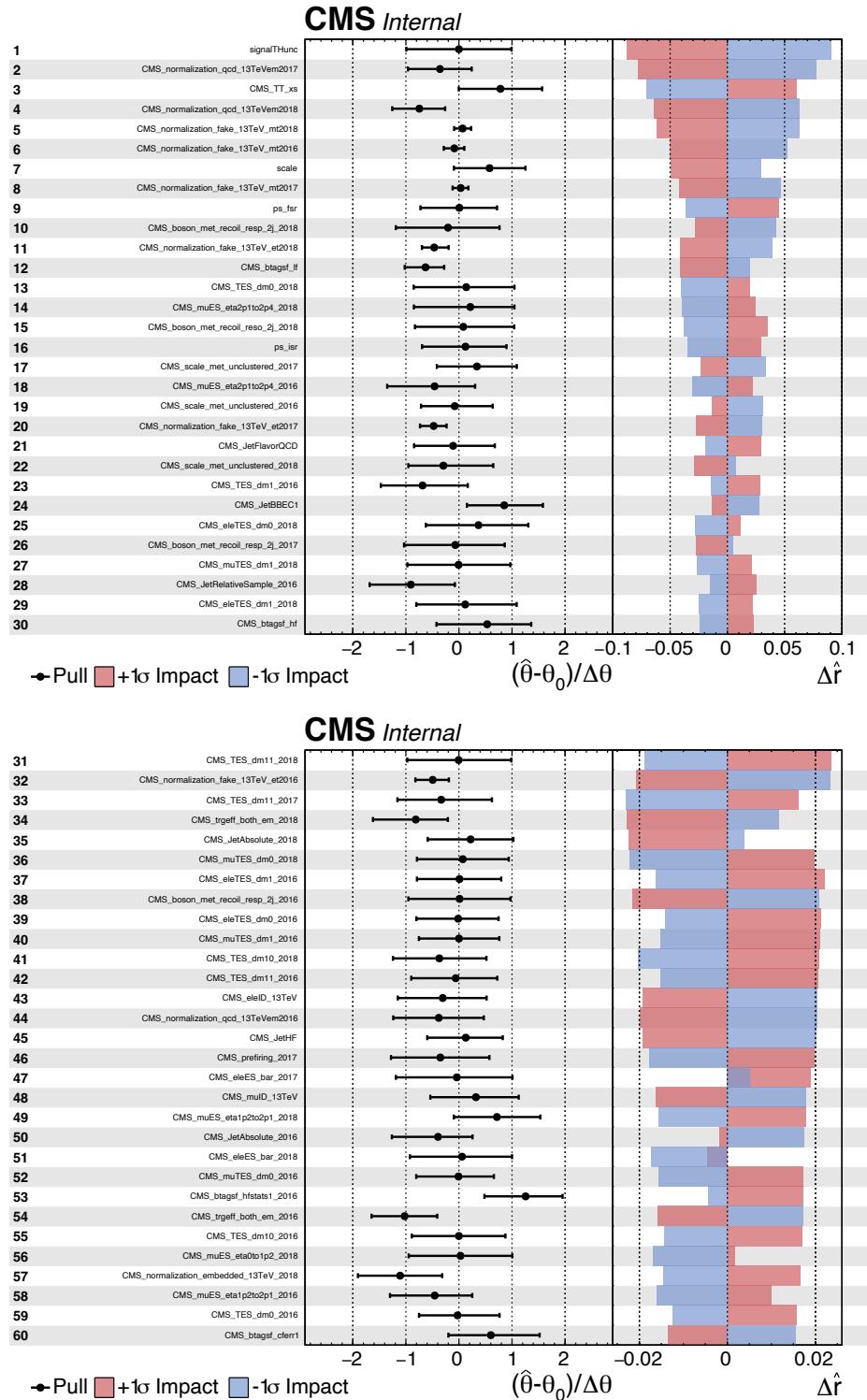


Figure 8.1: Top sixty pulls and impacts for the combination of all channels and years [101].

2217 **Chapter 9**

2218 **Event categorization and signal
extraction**
2219

2220 Measured events are divided into categories, based on cuts on values of observables
2221 in the event, or some derived quantity based on the observables in the event. The
2222 objective of event categorization is to divide events into signal regions, where the
2223 signal is enhanced and the background is suppressed, and control regions, which are
2224 signal-poor and used to check that the background estimation methods employed in
2225 the analysis in fact accurately models the data. In this analysis, events in each di-tau
2226 channel ($\mu\tau_h$, $e\tau_h$, and $e\mu$) are selected to contain one or more b-tag jets reconstructed
2227 in the event as described in Section 9.1. Events are further divided into signal and
2228 control regions using a deep learning-based approach described in Section 9.2. The
2229 signal is extracted from the di-tau mass distribution in the signal region using the
2230 statistical procedure described in Section 9.3.

2231 **9.1 B-tag jet multiplicity**

2232 Compared to the previous CMS $h \rightarrow aa \rightarrow bb\tau\tau$ analysis which used 2016 data corre-
2233 sponding to an integrated luminosity of 35.9 fb^{-1} [84], this analysis is performed on

the full Run-2 dataset corresponding to an integrated luminosity of 138 fb^{-1} . The increased statistics enables the separation of events into events with exactly 1 b-tag jet and events with greater than 1 b-tag jet, which was not possible in the previous analysis. Further event categorization is performed with deep neural networks (DNNs) described below. The DNNs are used only for separating events into signal and control regions in the 1 b-tag and 2 b-tag jets scenarios, and the final results are extracted from the di-tau mass.

9.2 DNN-based event categorization

Neural networks for event categorization are trained for each of the $\mu\tau_h$, $e\tau_h$, and $e\mu$ channels, for 1 and 2 b-tag jets, giving $3 \times 2 = 6$ networks in total for each year. In the training, the signal is taken to be all of the possible pseudoscalar mass m_a hypotheses added together. The backgrounds for each DNN are taken to be a representative combination of the three major backgrounds: $Z \rightarrow \tau\tau$, $t\bar{t}+\text{jets}$, and jet faking τ_h backgrounds. The proportions of each background for each channel and b-tag jet multiplicity are taken from the yields in the $m_{\tau\tau}$ distribution. For instance, in the $\mu\tau_h$ 1 b-tag jet category, the composition of the background for training is 17.4% from $Z \rightarrow \tau\tau$, 42.4% from $t\bar{t}+\text{jets}$, and 40.2% jet faking τ_h .

The input variables capture the key differences between the signal and the background:

- Transverse momentum p_T of the electron and muon in the $e\tau_h$ and $\mu\tau_h$ channels, where the signal tends to have a softer p_T spectrum (lower energy) than the background.
- p_T of the b-tag jet(s). The signal sample b-tag jet(s) tend to have softer p_T .
- Invariant masses of the various objects ($\tau\tau$ legs and the b-tag jet(s)), which tend to be smaller for the signal samples.

- 2259 • The angular separation ΔR between pairs of the objects, where signal samples
 2260 peak at smaller ΔR values.
- 2261 • The transverse mass between the missing transverse energy p_T^{miss} and each of
 2262 the four objects [84], defined as

$$m_T(\ell, p_T^{\text{miss}}) \equiv \sqrt{2p_T^\ell \cdot p_T^{\text{miss}}[1 - \cos(\Delta\phi)]} \quad (9.1)$$

2263 where p_T^ℓ is the transverse momentum of the object ℓ , and $\Delta\phi$ is the difference
 2264 in azimuthal angle between the object and the p_T^{miss} . Events from $t\bar{t}$ +jets and
 2265 jets faking τ_h backgrounds have larger p_T^{miss} resulting in larger transverse mass
 2266 values compared to the signal, which tends to have smaller p_T^{miss} that is also
 2267 more aligned with the lepton legs.

- 2268 • The variable D_ζ [84], defined as

$$D_\zeta \equiv p_\zeta - 0.85p_\zeta^{\text{vis}} \quad (9.2)$$

2269 where the ζ axis is the bisector of the transverse directions of the visible τ decay
 2270 products. p_ζ is the component of the p_T^{miss} along the ζ axis, and p_ζ^{vis} is the sum
 2271 of the components of the lepton p_T along the same axis. This variable captures
 2272 the fact that in signal the p_T^{miss} is small and approximately aligned with the $\tau\tau$.
 2273 In contrast, the $Z \rightarrow \tau\tau$ background tends towards large D_ζ values because the
 2274 p_T^{miss} is collinear to the $\tau\tau$, and the $t\bar{t}$ +jets events tend to have small D_ζ due to
 2275 a large p_T^{miss} not aligned with the $\tau\tau$.

- 2276 • For events with 2 b-tag jets, one additional variable is defined to capture the
 2277 difference in the invariant mass of the bb and the $\tau\tau$:

$$\Delta m_{a_1} \equiv (m_{bb} - m_{\tau\tau})/m_{\tau\tau} \quad (9.3)$$

2278 This variable peaks at zero for the $h \rightarrow aa \rightarrow 2b2\tau$ signal.

2279 The DNN model consists of an input layer, two fully-connected hidden layers,
2280 and one output layer, which has only one output for this binary classification of
2281 signal versus background. Two hidden layers were used, as one hidden layer led
2282 to undertraining, and three hidden layers led to overtraining. One dropout layer
2283 was inserted after each of the two hidden layers, which set zero weights at nodes
2284 chosen at a random rate (the dropout rate) during training to reduce overfitting. The
2285 output node uses a sigmoid activation function to produce a probability-like output
2286 $0 < y < 1$, where background samples were assigned a score of 0 and signal samples
2287 were assigned a score of 1. The training datasets were shuffled and divided into
2288 training, validation, and test sets, with an equal number of signal and background
2289 events in each set. Models were trained on the training set, and the performance on
2290 the training set was compared to the performance on the validation set in order to
2291 guide the tuning of hyperparameters in the DNN models (e.g. the number of nodes
2292 in the hidden layers and the dropout rate). The test set was used only to perform an
2293 unbiased evaluation of the final training.

2294 Events in the data, Monte Carlo, and embedded samples are evaluated with the six
2295 trained DNNs and assigned a raw score between 0 and 1 (background-like and signal-
2296 like respectively). In order to flatten the distribution of the score and define score
2297 thresholds for categorizing events, the raw output scores are transformed with the
2298 function $\tilde{p}(n) = \text{arctanh}(p \times \tanh(n))/n$ where n is a positive integer. The thresholds
2299 of the DNN score used for signal/control region definition are determined using scans
2300 that optimize the signal sensitivity and are shown in Tables 9.1 and 9.2.

	1bNN $\tilde{p}(n = 1.5)$			
	SR1	SR2	SR3	CR
$\mu\tau_h$ 2018	> 0.98	$\in [0.95, 0.98]$	$\in [0.90, 0.95]$	< 0.90
$\mu\tau_h$ 2017	> 0.97	$\in [0.94, 0.97]$	$\in [0.90, 0.94]$	< 0.90
$\mu\tau_h$ 2016	> 0.97	$\in [0.94, 0.97]$	$\in [0.89, 0.94]$	< 0.89
	1bNN $\tilde{p}(n = 1.5)$			
	SR1	SR2	SR3	CR
$e\tau_h$ 2018	> 0.97	$\in [0.945, 0.97]$	$\in [0.90, 0.945]$	< 0.90
$e\tau_h$ 2017	> 0.985	$\in [0.965, 0.985]$	$\in [0.93, 0.965]$	< 0.93
$e\tau_h$ 2016	> 0.985	$\in [0.965, 0.985]$	$\in [0.93, 0.965]$	< 0.93
	1bNN $\tilde{p}(n = 2.5)$			
	SR1	SR2	SR3	CR
$e\mu$ 2018	> 0.99	$\in [0.95, 0.99]$	$\in [0.85, 0.95]$	< 0.85
$e\mu$ 2017	> 0.985	$\in [0.95, 0.985]$	$\in [0.85, 0.95]$	< 0.85
$e\mu$ 2016	> 0.99	$\in [0.95, 0.99]$	$\in [0.85, 0.95]$	< 0.85

Table 9.1: Event categorization based on DNN scores for events with exactly 1 b-tag jet (1bNN), for the three $\tau\tau$ channels and three eras.

	2bNN $\tilde{p}(n = 1.5)$		
	SR1	SR2	CR
$\mu\tau_h$ 2018	> 0.99	$\in [0.96, 0.99]$	< 0.96
$\mu\tau_h$ 2017	> 0.98	$\in [0.94, 0.98]$	< 0.94
$\mu\tau_h$ 2016	> 0.97	$\in [0.93, 0.97]$	< 0.93
	2bNN $\tilde{p}(n = 1.5)$		
	SR1	SR2	CR
$e\tau_h$ 2018	> 0.96	NA	< 0.96
$e\tau_h$ 2017	> 0.985	NA	< 0.985
$e\tau_h$ 2016	> 0.96	NA	< 0.96
	2bNN $\tilde{p}(n = 2.5)$		
	SR1	SR2	CR
$e\mu$ 2018	> 0.98	$\in [0.94, 0.98]$	< 0.94
$e\mu$ 2017	> 0.97	$\in [0.93, 0.97]$	< 0.93
$e\mu$ 2016	> 0.98	$\in [0.94, 0.98]$	< 0.94

Table 9.2: Event categorization based on DNN scores for events with 2 b-tag jets (2bNN), for the three $\tau\tau$ channels and three eras.

2301 9.3 Methodology for signal extraction

2302 After events are divided into categories, the data is compared to the expected back-
2303 grounds in the signal region categories. Here, we describe the fundamental concepts
2304 behind hypothesis testing in high-energy physics, as well as how exclusion limits
2305 can be set on parameters whose true values we cannot measure, culminating in the
2306 modified frequentist method CL_S which is used to perform signal extraction in this
2307 analysis.

2308 9.3.1 Model building and parameter estimation

In the frequentist interpretation of probability, an experiment measuring an observable can be repeated, resulting in different values of the observable, e.g. the invariant mass of a candidate Higgs boson in a search for the Higgs [102]. The ensemble of values of the observable x gives rise to the probability density function (PDF) $f(x)$, which has the important property that it is normalized to unity:

$$\int f(x) dx = 1 .$$

A parametric family of PDFs

$$f(x|\alpha) ,$$

2309 read “ f of x given α ”, is referred to as a probability model or model. The parameters α
2310 typically represent parameters of the theory or an unknown property of the detector’s
2311 response. The parameters are not frequentist in nature, unlike x . Out of all the
2312 parameters, typically only a few are of interest, and are called the parameters of
2313 interest (POI), labeled μ here. The remaining are referred to as nuisance parameters
2314 (NP) [102] and are labeled $\boldsymbol{\theta}$.

2315 $f(x)$ is the probability density for the observable in one event and we wish to

2316 describe the probability density for a dataset with many events, $\mathcal{D} = \{x_1, \dots, x_n\}$,
 2317 called the total probability model \mathbf{f} . For instance, if we also have a prediction for
 2318 the total number of events expected, called ν , we also account for the overall Poisson
 2319 probability for observing n events given ν expected:

$$\mathbf{f}(\mathcal{D}|\nu, \alpha) = \text{Poisson}(n|\nu) \prod_{e=1}^n f(x_e|\alpha) \quad (9.4)$$

The likelihood function $L(\alpha)$ is numerically equivalent to $f(x|\alpha)$ for fixed x , or
 $\mathbf{f}(\mathcal{D}|\alpha)$ with \mathcal{D} fixed [102]. The likelihood function is not a probability density for α
 and is not normalized to unity:

$$\int L(\alpha) d(\alpha) \neq 1.$$

2320 i.e. the likelihood function is the value of f as a function of α given a fixed value of
 2321 x .

2322 To estimate the parameter α we use an estimator, which is a function of the
 2323 data. Take for example the measurement of data distributed according to a Gaussian
 2324 probability density $f(x|\mu, \sigma) = \text{Gauss}(x|\mu, \sigma)$. One possible estimator of the mean μ ,
 2325 is the mean of the measured data points $\bar{x} = \sum_{i=1}^n x_i/n$ [102].

2326 A commonly used estimator in physics is the maximum likelihood estimator
 2327 (MLE), defined as the value $\hat{\alpha}$ which maximizes the likelihood function $L(\alpha)$. This
 2328 value, labeled $\hat{\alpha}$, also maximizes $\ln L(\alpha)$ and minimizes $-\ln L(\alpha)$. By convention the
 2329 $-\ln L(\alpha)$ is minimized, in a process called “fitting”, and the maximum likelihood
 2330 estimate is called the “best fit value”.

2331 **9.3.2 Hypothesis testing**

2332 In this section we next introduce concepts related to hypothesis testing such as the
 2333 test statistic constructed from the ratio of likelihood functions.

2334 The objective of a likelihood analysis is to distinguish different models repre-
2335 senting the various hypotheses, and determine the one that best explains the ex-
2336 perimental outcome. In a search for new physics, a signal is additive on top of the
2337 background. The background-only hypothesis is the null hypothesis, and the signal-
2338 plus-background hypothesis is the alternative.

2339 As a simple example, take the p -value test, for an experiment where we count
2340 events in the signal region, n_{SR} , and expect ν_B background events and ν_S events from
2341 the signal [102]. Then

- 2342 1. The null hypothesis (H_0), i.e. the background-only hypothesis in this experi-
2343 ment, with the probability modeled by $\text{Poisson}(n_{SR}|\nu_B)$.
- 2344 2. The alternate hypothesis (H_1), i.e. signal-plus-background hypothesis, with the
2345 probability modeled by $\text{Poisson}(n_{SR}|(\nu_B + \nu_S))$.

2346 The compatibility of the observed data ν_{SR}^0 and the null hypothesis, is quantified as
2347 the probability that the background-only hypothesis would produce at least as many
2348 events as was observed. This probability is the p -value:

$$p = \sum_{n=n_{SR}^0}^{\infty} \text{Poisson}(n|\nu_B). \quad (9.5)$$

2349 If the p -value is very small, we might reject the null hypothesis. The p -value is not the
2350 probability of the null hypothesis given the data; rather, it expresses the probability
2351 that data with a certain property was obtained, assuming the null hypothesis [102].

2352 The p -value is an example of a test statistic T , which maps the data to a single
2353 real number. The Neyman-Pearson lemma states that out of the infinite possibilities
2354 of choices of test statistic, the uniformly most powerful test statistic is the likelihood
2355 ratio T_{NP} [102]:

$$T_{NP}(\mathcal{D}) = \frac{L(\mathcal{D}|H_1)}{L(\mathcal{D}|H_0)} \quad (9.6)$$

To reiterate, the test statistic T is a real-valued function of the data, implying that a particular probability model $\mathbf{f}(\mathcal{D}|\boldsymbol{\alpha})$ implies a distribution of the test statistic, $f(T|\boldsymbol{\alpha})$, which depends on the value of $\boldsymbol{\alpha}$. With this distribution in hand, the p -value can be evaluated in the following equivalent formulations:

$$p(\boldsymbol{\alpha}) = \int_{T_0}^{\infty} f(T|\boldsymbol{\alpha}) dT \quad (9.7)$$

$$= \int \mathbf{f}(\mathcal{D}|\boldsymbol{\alpha}) \theta(T(\mathcal{D}) - T_0) d\mathcal{D} \quad (9.8)$$

$$= P(T \geq T_0|\boldsymbol{\alpha}) \quad (9.9)$$

where T_0 is the value of T based on the observed data, and $\theta()$ is the Heaviside function. The size of the test is conventionally chosen to be 10%, 5%, or 1%. As the p -value depends on $\boldsymbol{\alpha}$ (both the POI and NP), the null hypothesis should not be rejected if the p -value is larger than the size of the test for any value of the nuisance parameters.

9.3.3 Confidence intervals

In an example of the measurement of the Standard Model Higgs boson, $\boldsymbol{\alpha}_{\text{POI}} = (\sigma/\sigma_{SM}, M_H)$, with σ/σ_{SM} is the ratio of the production cross-section for Higgs with respect to its value in the SM, and M_H is the unknown mass of the Higgs, values of these parameters outside specific bounds are said to be “excluded at the 95% confidence level”. These allowed regions are called confidence levels or confidence regions, and the parameter values outside of them are considered excluded [102]. A 95% confidence interval does not mean that there is a 95% chance that the true value of the parameter is inside the interval. Rather, a 95% confidence interval covers the

2370 true value 95% of the time (even though we do not know the true value).

2371 To construct a confidence interval for a parameter α , the Neyman Construction
2372 is used to invert a series of hypothesis tests; i.e. for each possible value of α , the null
2373 hypothesis is treated as α , and we perform a hypothesis test based on a test statistic.
2374 To construct a 95% confidence interval, we construct a series of hypothesis tests with
2375 size of 5%. The confidence interval $I(\mathcal{D})$ is constructed by taking the set of parameter
2376 values α where the null hypothesis is accepted:

$$I(\mathcal{D}) = \{\alpha | P(T(\mathcal{D}) > k_\alpha | \alpha) < \alpha\}, \quad (9.10)$$

2377 where $T(\mathcal{D})$ is the test statistic, and the last α (not bolded) and the subscript k_α
2378 refer to the size of the test. A schematic of the Neyman construction is shown in Fig.
2379 9.1. In a more generalized case, the x -axis is the test statistic T .

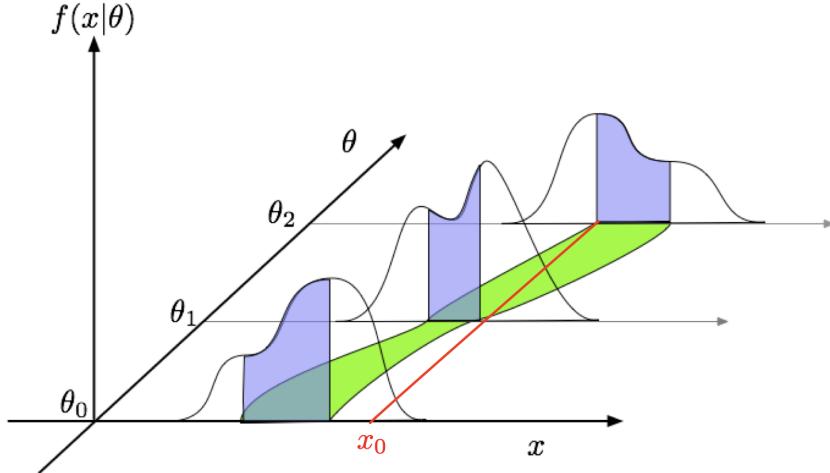


Figure 9.1: Schematic of the Neyman construction for confidence intervals [102]. For each value of θ , we find a region in x where $\int f(x|\theta)dx$ satisfies the size of the test (blue). These regions form a confidence belt (green). The intersection of the observation x_0 (red) with the confidence belt defines the confidence interval $[\theta_1, \theta_2]$ [102].

2380 **9.3.4 Profile likelihood ratio**

2381 In this section we describe a frequentist statistical procedure based on the profile
 2382 likelihood ratio test statistic, which is implemented using asymptotic distributions.

2383 With a multi-parameter likelihood function $L(\boldsymbol{\alpha})$, the maximum likelihood of
 2384 one specific parameter α_p with other parameters $\boldsymbol{\alpha}_o$ fixed, is called the conditional
 2385 maximum likelihood estimate and is denoted $\hat{\alpha}_p(\boldsymbol{\alpha}_0)$. The process of choosing specific
 2386 values of the nuisance parameters for a given value of μ , $\mathcal{D}_{\text{simulated}}$, and value of global
 2387 observables \mathcal{G} is called profiling. From the full list of parameters $\boldsymbol{\alpha}$, we denote the
 2388 parameter of interest μ , and the nuisance parameters $\boldsymbol{\theta}$.

2389 We construct the profile likelihood ratio,

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}}(\mu))}{L(\mu, \hat{\boldsymbol{\theta}})} \quad (9.11)$$

2390 which depends explicitly on the parameter of interest μ , implicitly on the data \mathcal{D}_{sim}
 2391 and global observables \mathcal{G} , and is independent of the nuisance parameters $\boldsymbol{\theta}$, which
 2392 have been eliminated in profiling [102].

2393 The main conceptual reason for constructing the test statistic from the profile
 2394 likelihood ratio is that asymptotically (i.e. for measurements with many events) the
 2395 distribution of the profile likelihood ratio $\lambda(\mu = \mu_{\text{true}})$ is independent of the values of
 2396 the nuisance parameters [102].

2397 The following p -value is used to quantify the consistency with the hypothesis of a
 2398 signal strength of μ :

$$p_\mu = \int_{\tilde{q}_{\mu, \text{obs}}}^{\infty} f(\tilde{q}_\mu | \mu, \hat{\boldsymbol{\theta}}(\mu, \text{obs})) d\tilde{q}_\mu \quad (9.12)$$

2399 **9.3.5 Modified frequentist method: CL_S**

2400 In the modified frequentist method called CL_S , to test a hypothesis with signal, we
2401 define p'_μ as a ratio of p -values [102]:

$$p'_\mu = \frac{p_\mu}{1 - p_b} \quad (9.13)$$

2402 where p_b is the p -value derived under the background-only hypothesis:

$$p_b = 1 - p_0 \equiv 1 - \int_{\tilde{q}_{\mu,\text{obs}}}^{\infty} f(\tilde{q}_\mu | 0, \hat{\theta}(\mu = 0, \text{obs})) d\tilde{q}_\mu. \quad (9.14)$$

2403 The CL_S upper limit on μ , denoted μ_{up} , is obtained by solving for $p'_{\mu_{up}} = 5\%$.
2404 If testing the compatibility of the data with the background-only hypothesis, we
2405 consider the p_b value defined above and conventionally convert it into the quantile
2406 or “sigma” of a unit Gaussian. z standard deviations (e.g. $z = 5$ in “ 5σ ”) means
2407 that the probability of falling above these standard deviations, equals p_b (e.g. 3σ
2408 corresponds to $p_b = 2.7 \times 10^{-3}$ or 95.43%, and 5σ corresponds to $p_b = 5.7 \times 10^{-7}$ or
2409 99.999943%).

2410 **Chapter 10**

2411 **Results**

2412 In this chapter, Section 10.1 presents the results from the $h \rightarrow aa \rightarrow bb\tau\tau$ analysis
2413 performed on 137 fb^{-1} of data from the full CMS Run-2 dataset in the years 2016 to
2414 2018, with interpretations provided for different 2HDM+S scenarios. This analysis
2415 was combined with a different search in the $h \rightarrow aa \rightarrow bb\mu\mu$ final state, which was
2416 also performed on the full Run-2 dataset. The combination procedure and results
2417 from the combined analyses ($h \rightarrow aa \rightarrow bb\ell\ell$, with $\ell = \mu, \tau$) are detailed in 10.2.
2418 The combined analysis places some of the most stringent limits to date at CMS for
2419 2HDM+S scenarios in the light scalar mass range $m_a = 12 \text{ GeV}$ to 60 GeV .

2420 **10.1 Results from $bb\tau\tau$**

2421 In each of the three $\tau\tau$ channels studied ($\mu\tau_h$, $e\tau_h$, and $e\mu$), events are divided based
2422 on whether they contain exactly 1 or 2 b-tag jets, and further divided into signal
2423 and control regions (SRs and CRs) using the DNN categorization score as described
2424 in Section 9.2. The control regions demonstrate good agreement between observed
2425 events in data, and the sum of the contributions from expected backgrounds that
2426 are modeled in simulated and embedded samples. The signal regions are defined to
2427 be sensitive to the $h \rightarrow aa \rightarrow bb\tau\tau$ signal. The postfit final observed and expected

2428 distributions of the di-tau invariant mass $m_{\tau\tau}$ reconstructed with SVFit (described
2429 in Section 5.2) are shown in Fig. 10.1 for the $\mu\tau_h$ channel, Fig. 10.2 for the $e\tau_h$
2430 channel, and Fig. 10.3 for the $e\mu$ channel. In all figures, the hypothesized yield for
2431 the $h \rightarrow aa \rightarrow bb\tau\tau$ signal is shown for the pseudoscalar mass $m_a = 35$ GeV and
2432 assuming a branching fraction $B(H \rightarrow aa \rightarrow bb\tau\tau) = 10\%$.

2433 The 95% CL expected and observed exclusion limits on the signal strength of the
2434 branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau)$ as a function of the pseudoscalar mass m_a
2435 ranging from 12 GeV to 60 GeV, are shown for the three $\tau\tau$ channels and all three
2436 channels combined in Fig. 10.4. The limits are shown as percentages and normalized
2437 to the production cross-section of the Standard Model Higgs boson. No excess of
2438 events above the Standard Model expectations is observed. In the limits for the three
2439 $\tau\tau$ channels combined, expected (observed) limits range from 1.4 to 5.6% (1.7 to
2440 7.6%) for pseudoscalar masses between 12 and 60 GeV.

2441 The $e\mu$ channel is the only channel that has signal sensitivity to the $m_a = 12$
2442 GeV pseudoscalar mass hypothesis, because the minimum required spatial separation
2443 $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ between the two τ legs is smaller than the other two channels
2444 ($\Delta R < 0.3$ for $e\mu$, compared to $\Delta R < 0.4$ for the other two channels). This decreased
2445 ΔR requirement results in better signal acceptance for low mass signals for the $e\mu$
2446 channel. The $\mu\tau_h$ and $e\tau_h$ channels are most sensitive to the intermediate mass points
2447 studied, since the analysis targets a resolved signature: at low mass points, the tau
2448 legs are boosted, and at high mass points, the $m_{\tau\tau}$ distributions in signal have larger
2449 overlap with background distributions. In the combination of the three $\tau\tau$ channels,
2450 the limit for $m_a = 12$ GeV comes only from the $e\mu$ channel, and the best sensitivity
2451 is attained at intermediate mass points around $m_a = 20$ GeV to 45 GeV.

2452 To set limits on the branching fraction of the 125 GeV Higgs to the two pseu-
2453 doscalars, $B(h \rightarrow aa)$, we interpret the results in four types of 2HDM+S, which were
2454 introduced in Section 1.4. In 2HDM+S, the theorized branching fraction of the pseu-

2455 doscalars depends on the 2HDM+S model type, the pseudoscalar mass m_a , and the
2456 ratio of the two Higgs doublets' vacuum expectation values $\tan \beta$. In Type I models,
2457 the branching fraction is independent of $\tan \beta$, while in Types II, III, and IV, it is
2458 a function of m_a and $\tan \beta$. Limits for the $bb\tau\tau$ final state as a function of m_a for
2459 2HDM+S Type I (valid for all $\tan \beta$ values), Type II with $\tan \beta = 2.0$, Type III with
2460 $\tan \beta = 2.0$, and Type IV with $\tan \beta = 0.6$ are overlaid and shown in Fig. 10.5a.

2461 10.2 Combination with $bb\mu\mu$ final state

2462 Results from this analysis for the $h \rightarrow aa \rightarrow bb\tau\tau$ final state are combined with the
2463 analysis for the $h \rightarrow aa \rightarrow bb\mu\mu$ final state [103]. While the predicted branching ratio
2464 for $aa \rightarrow bb\mu\mu$ is comparatively small, the $bb\mu\mu$ final state has competitive results
2465 due to the excellent di-muon resolution measured by CMS. The $bb\mu\mu$ analysis uses
2466 an unbinned fit to the data using the di-muon mass $m_{\mu\mu}$ distribution. Details can be
2467 found in [103].

2468 Combining the results is possible since the $bb\tau\tau$ analysis explicitly rejects events
2469 with extra leptons, so there is no overlap between the events studied in the $bb\tau\tau$
2470 analysis and the $bb\mu\mu$ analysis. In the statistical combination, several systematic
2471 uncertainties are treated as correlated: the integrated luminosity normalization, the
2472 b-tagging scale factor, the scale factors related to muon reconstruction, identifica-
2473 tion, and trigger efficiencies, the inefficiency in the ECAL trigger readout, and the
2474 theoretical uncertainties related to signal modeling.

2475 Since the results in both final states are statistically limited, the combination ben-
2476 efits from the additional data. For $m_a = 35$ GeV, all systematic uncertainties amount
2477 to around 6% of the total uncertainty, with the dominant systematic uncertainties
2478 coming from jet energy systematics in the $bb\mu\mu$ final state, theoretical uncertainties
2479 in the signal, and uncertainties in the QCD multijet backgrounds in the $e\mu$ channel

2480 of the $bb\tau\tau$ final state.

2481 The mass distributions of the di-muon and di-tau objects ($m_{\mu\mu}$ and $m_{\tau\tau}$) are
2482 compared to the data in a combined maximum likelihood fit to derive upper limits
2483 on $B(h \rightarrow aa)$. The observed limits at 95% CL on $B(h \rightarrow aa)$ for different 2HDM+S
2484 scenarios, are shown for the search for $h \rightarrow aa \rightarrow bb\mu\mu$ in Fig. 10.5b, and the
2485 combined analyses $h \rightarrow aa \rightarrow bb\ell\ell$ in Fig. 10.6.

2486 Exclusion limits in a two-dimensional plane as a function of $\tan\beta$ and m_a are
2487 set for 2HDM+S Types II, III, and IV in Fig. 10.7. The most stringent constraints
2488 are observed for 2HDM+S type III because of large branching fractions predicted in
2489 theory, with predicted branching fractions between 0.47 and 0.42 for $\tan\beta = 2.0$ and
2490 values of m_a between 15 and 60 GeV, compared to the observed 95% CL upper limits
2491 which are between 0.08 and 0.03. For 2HDM+S type IV, the predicted branching
2492 fractions from theory are between 0.26 and 0.20 for $\tan\beta = 0.6$ for values of m_a
2493 between 15 and 60 GeV, and the 95% CL observed upper limits are between 0.12 and
2494 0.05.

2495 The combined results from $h \rightarrow aa \rightarrow bb\ell\ell$ are compared with CMS results in
2496 other final states as a function of the pseudoscalar mass m_a : for 2HDM+S type I in
2497 Fig. 10.8, type II with $\tan\beta = 2.0$ in Fig. 10.9, and type III with $\tan\beta = 2.0$ in Fig.
2498 10.10. In other scenarios, e.g. type III with $\tan\beta = 5.0$, more stringent limits are set
2499 by analyses in other final states, $\mu\mu\tau\tau$ in this case. Other summary plots for other
2500 model types and $\tan\beta$ values can be found at [104].

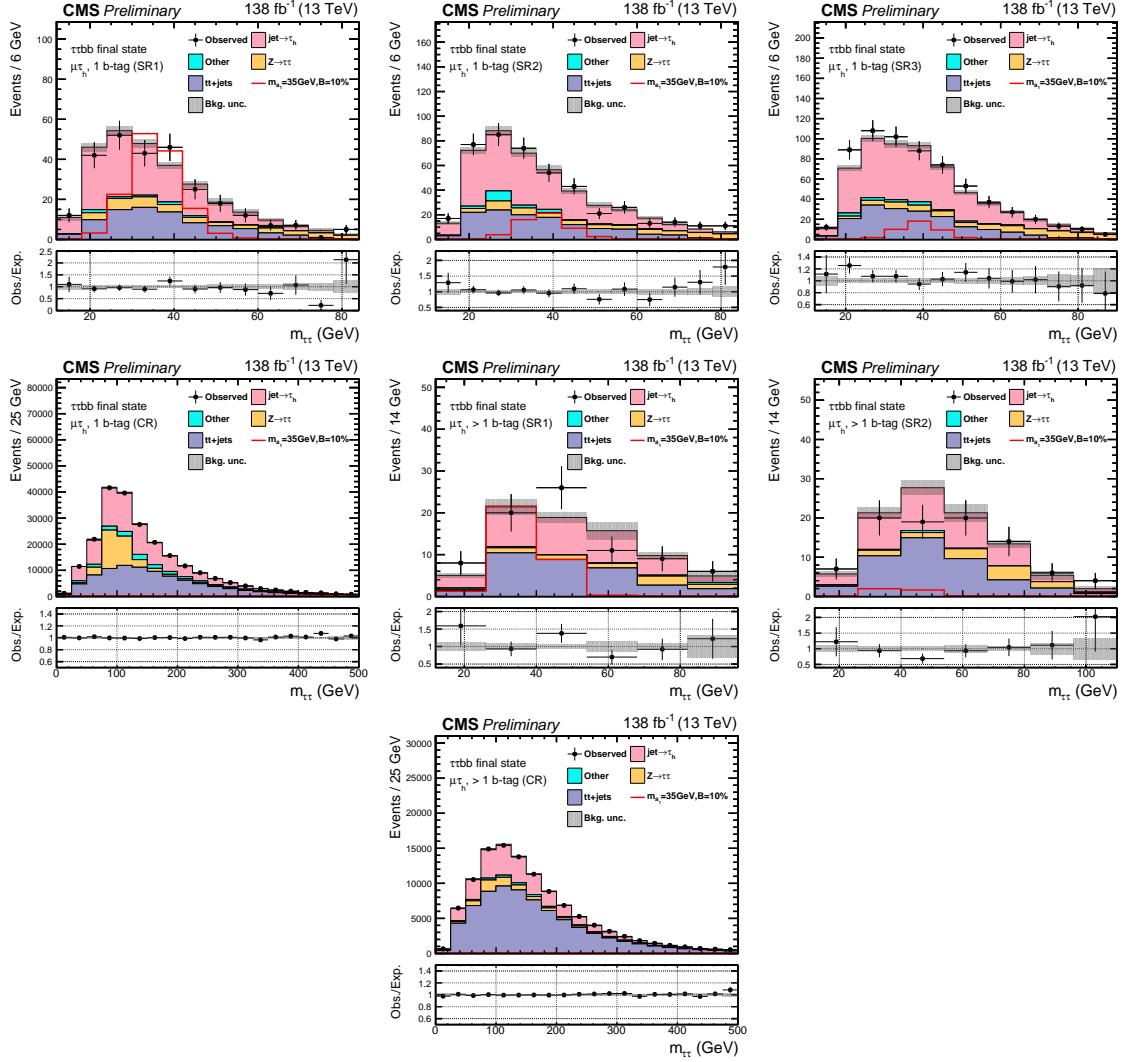


Figure 10.1: Postfit final $m_{\tau\tau}$ observed and expected distributions, and the observed/expected ratios, in the $\mu\tau_h$ channel [101]. Events are divided into the 1 b-tag jet signal regions (SR1, SR2, SR3) (*top row*), 1 b-tag jet control region (*middle row*), 2 b-tag jet signal regions (SR1, SR2) (*middle row*), and lastly the 2 b-tag jet control region (CR) (*bottom*). Statistical and systematic sources of uncertainties in the expected events are added in quadrature and labeled “Bkg. unc” (*shaded gray*). The dominant backgrounds in all categories are jets faking the τ_h leg (*pink*), $Z \rightarrow \tau\tau$ (*orange*), and $t\bar{t}+j$ ets (*purple*). For illustrative purposes, the beyond-Standard Model signal yield from $h \rightarrow aabb\tau\tau$ is shown for the pseudoscalar mass hypothesis $m_a = 35$ GeV, assuming a branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau) = 10\%$ (*red line*).

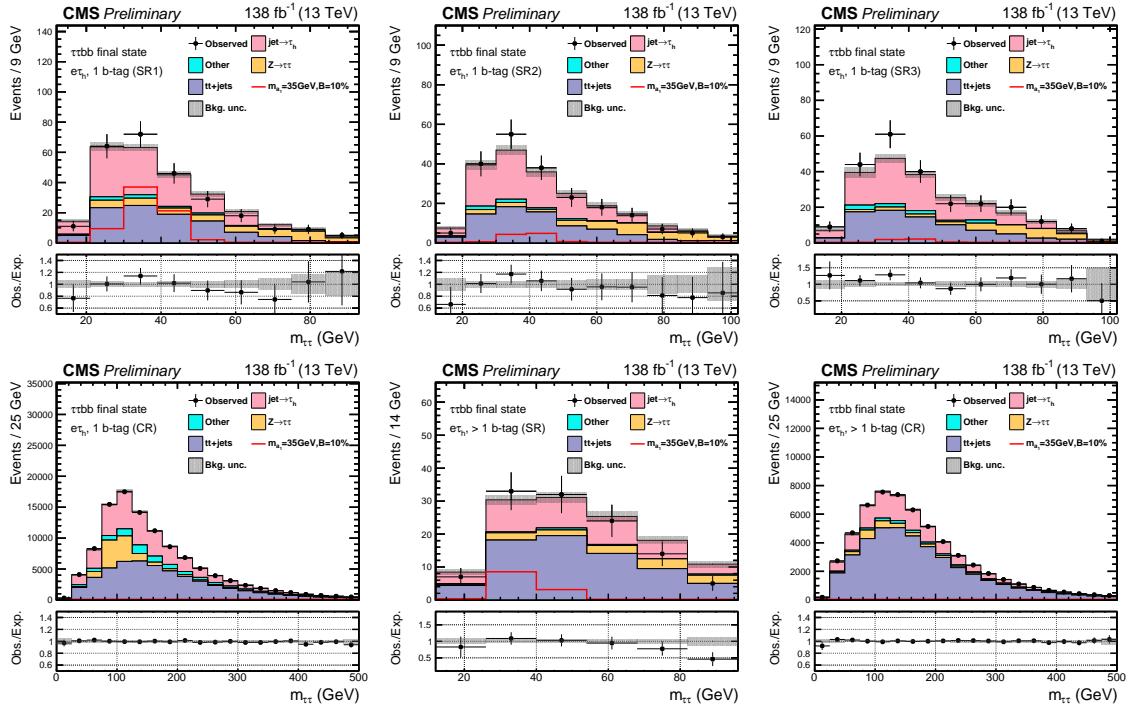


Figure 10.2: Postfit final observed and expected $m_{\tau\tau}$ distributions, and the observed/expected ratios, in the $e\tau_h$ channel [101]. Events are divided into the 1 b-tag jet signal regions (SR1, SR2, SR3) (*top row*), the 1 b-tag jet control region (CR) (*bottom row*), and 2 b-tag jet signal region (SR) and control region (CR) (*bottom row*). Statistical and systematic sources of uncertainties in the expected events are added in quadrature and labeled “Bkg. unc” (*shaded gray*). In this channel, the dominant backgrounds are jets faking the τ_h leg (*pink*), $Z \rightarrow \tau\tau$ (*orange*), and $t\bar{t}+{\rm jets}$ (*purple*). For illustrative purposes, the beyond-Standard Model signal yield from $h \rightarrow aabb\tau\tau$ is shown for the pseudoscalar mass hypothesis $m_a = 35$ GeV, assuming a branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau) = 10\%$ (*red line*).

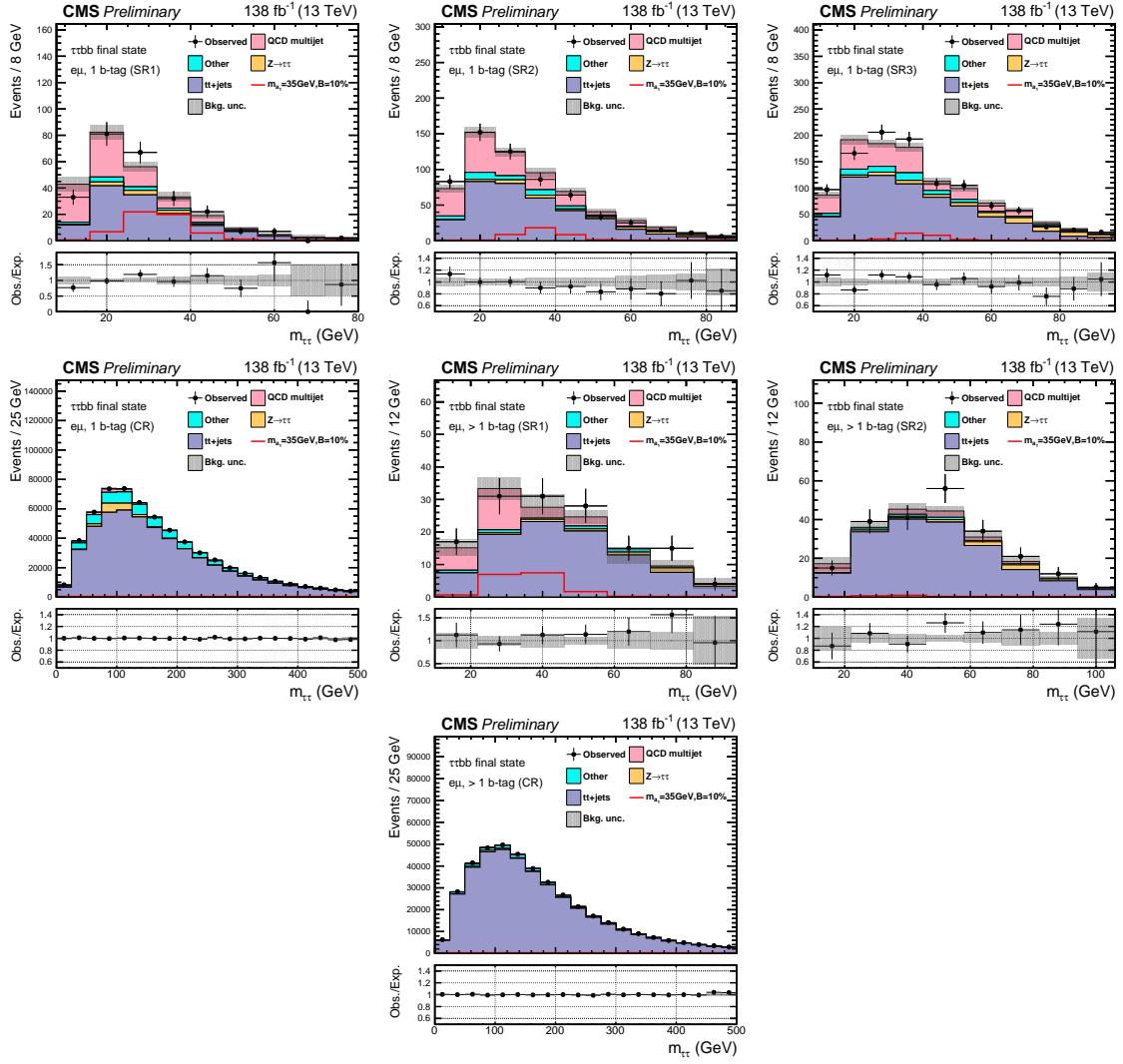


Figure 10.3: Postfit final observed and expected $m_{\tau\tau}$ distributions, and the observed/expected ratios, in the $e\mu$ channel [101]. Events are divided into the 1 b-tag jet signal regions (SR1, SR2, and SR3) (*top row*), 1 b-tag jet control region (CR) (*middle row*), 2 b-tag jet signal regions (SR1 and SR2) (*middle row*), and 2 b-tag jet control region (CR) (*bottom row*). Statistical and systematic sources of uncertainties in the expected events are added in quadrature and labeled “Bkg. unc” (*shaded gray*). The $t\bar{t}+j$ process (*purple*) is a major background, and in the signal regions the QCD multijet (*pink*) is also a major background. For illustrative purposes, the pseudoscalar mass hypothesis $m_a = 35$ GeV, assuming a branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau) = 10\%$ (*red line*).

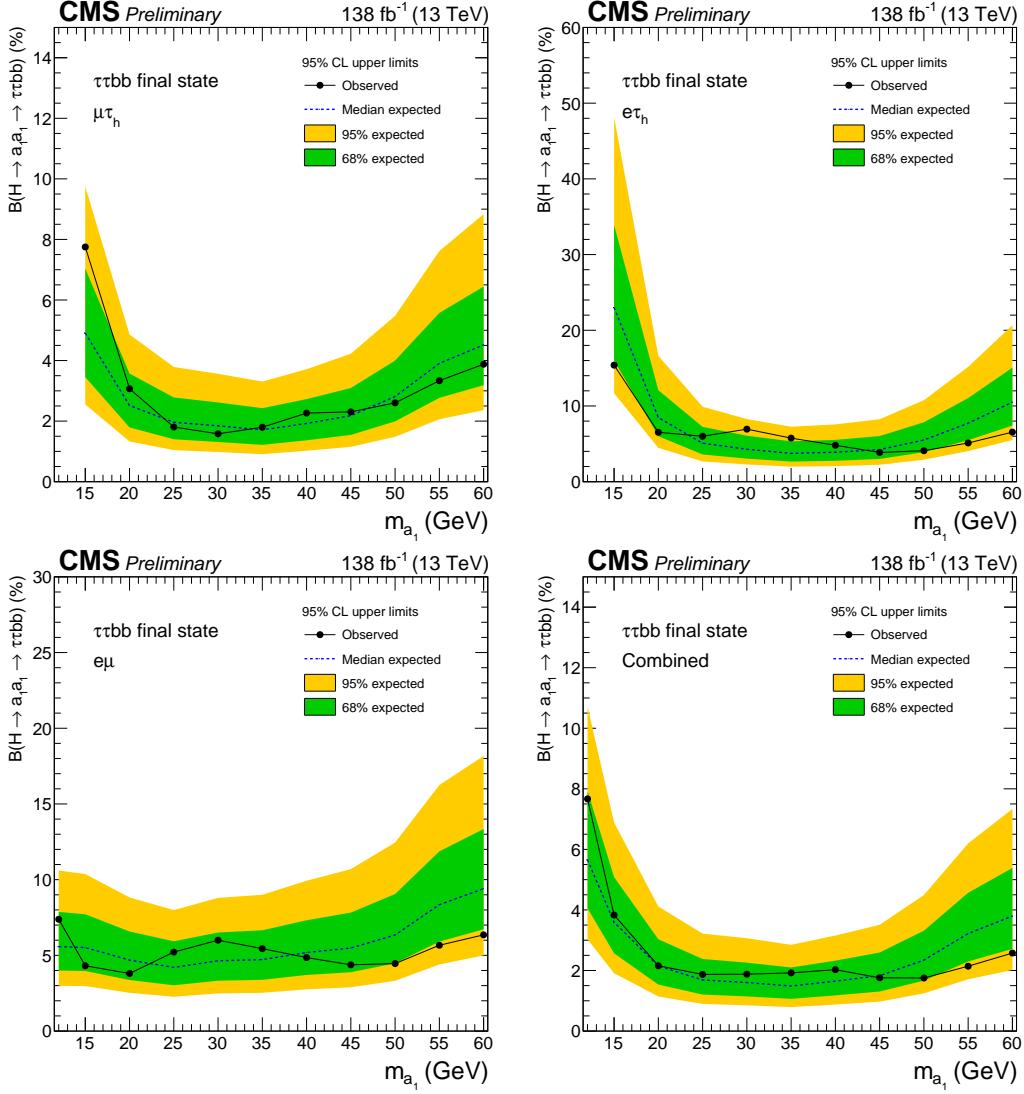
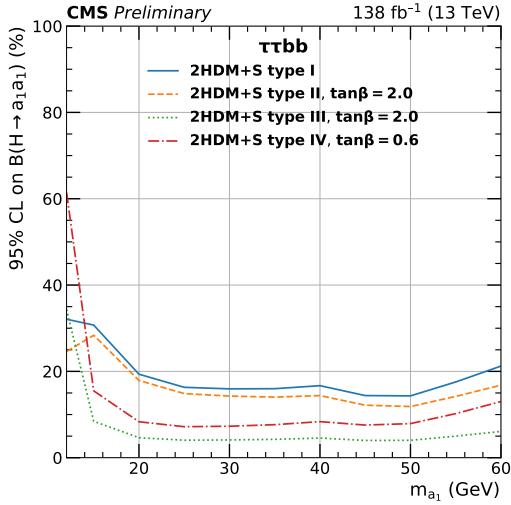
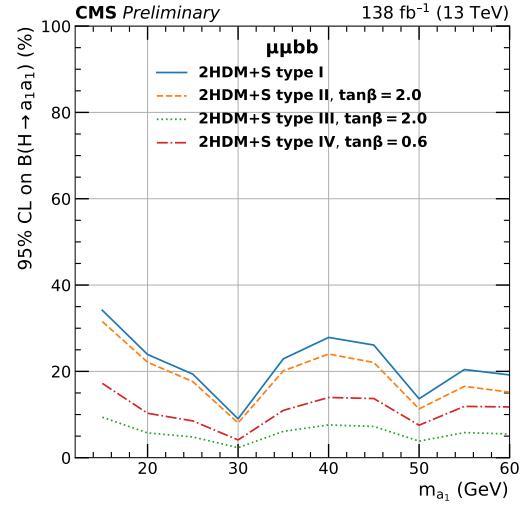


Figure 10.4: Observed 95% CL exclusion limits (*black, solid lines*) and expected 95% CL and 68% CL limits (*shaded yellow and green*) on the branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau)$ in percentages, assuming the Standard Model production for the 125 GeV Higgs (h). Limits are shown for the $\mu\tau_h$ channel (*top left*), the $e\tau_h$ channel (*top right*), and the $e\mu$ channel (*bottom left*), and lastly the combination of all three channels (*bottom right*) [101]. The dataset corresponds to 138 fb^{-1} of data collected in the years 2016-2018 at a center-of-mass energy 13 TeV. Only the $e\mu$ channel has sensitivity to the mass hypothesis $m_a = 12 \text{ GeV}$. The best sensitivity is attained at intermediate mass points.



(a) $bb\tau\tau$ final state.



(b) $bb\mu\mu$ final state.

Figure 10.5: Observed 95% CL upper limits on $B(h \rightarrow aa)$ in %, for the $bb\tau\tau$ final state (*left*) and $bb\mu\mu$ final state (*right*) using the full Run 2 integrated luminosity of 138 fb^{-1} in 2HDM+S type I (blue), type II with $\tan\beta = 2.0$ (orange dashed), type III with $\tan\beta = 2.0$ (dotted green), and type IV with $\tan\beta = 0.6$ (red dashed) [101]. Linear interpolation is used between points in the graphs. The $\tan\beta$ values chosen here correspond to the most stringent limits in each model.

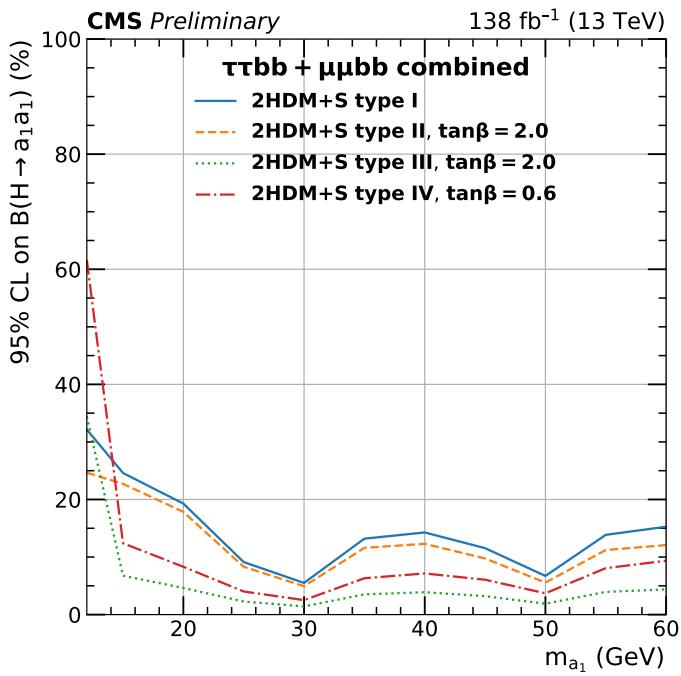


Figure 10.6: Observed 95% CL upper limits on the branching fraction of the 125 GeV Higgs boson to two pseudoscalars, $B(h \rightarrow aa)$, in percentages, as a function of the pseudoscalar mass m_a , in 2HDM+S type I (blue), type II with $\tan\beta = 2.0$ (orange dashed), type III with $\tan\beta = 2.0$ (dotted green), and type IV with $\tan\beta = 0.6$ (red dashed), for the combination of $bb\mu\mu$ and $bb\tau\tau$ channels using the full Run 2 integrated luminosity of 138 fb^{-1} [101].

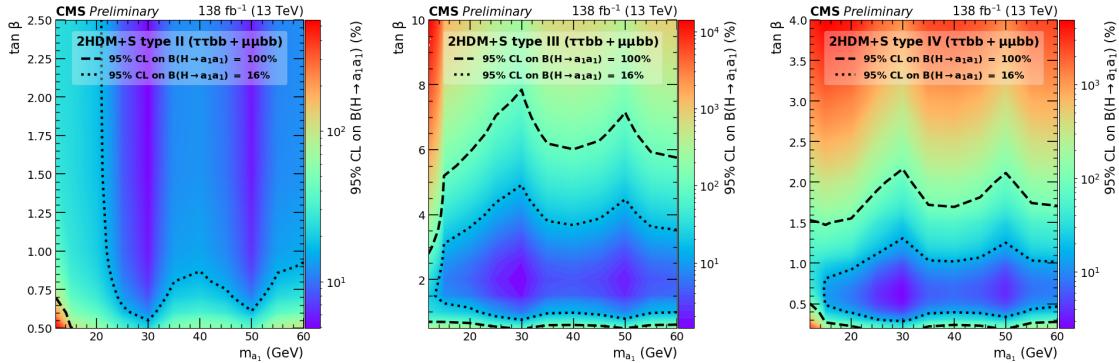


Figure 10.7: Observed 95% CL upper limits on $\mathcal{B}(h \rightarrow aa)$ in %, for the combination of $bb\mu\mu$ and $bb\tau\tau$ channels using the full Run 2 integrated luminosity of 138 fb^{-1} for Type II (*left*), Type III (*middle*), and Type IV (*right*) 2HDM+S in the $\tan \beta$ vs. m_a phase space. The contours (*dashed black*) correspond to branching fractions of 100% and 16%, where 16% is the combined upper limit on Higgs boson to undetected particle decays from previous Run-2 results. All points inside the contour are allowed within that upper limit. Linear extrapolation has been used between different points on the figures [101].

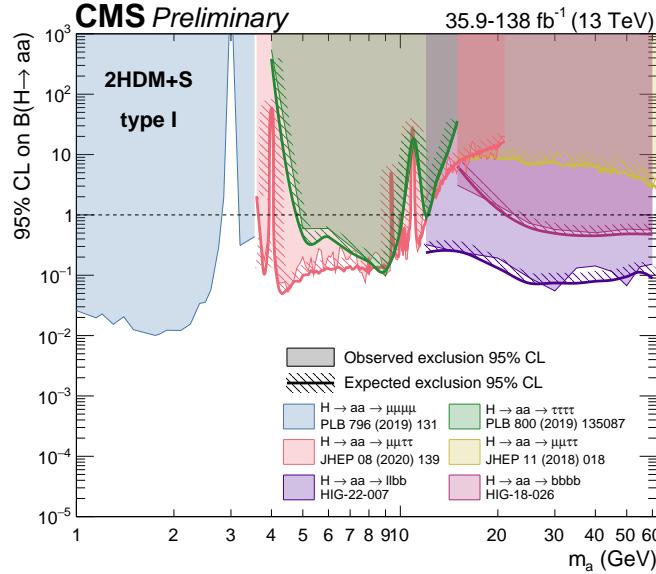


Figure 10.8: Summary plot of current 95% limits on the branching ratio of the 125 GeV Higgs boson to two pseudoscalars, normalized to the Standard Model Higgs production cross-section, $\frac{\sigma(h)}{\sigma_{SM}} \times B(h \rightarrow aa)$ in the 2HDM+S type I scenario performed with data collected at 13 TeV [104]. Results from different final states studied at CMS are overlaid on this figure: $\mu\mu\mu\mu$ (blue), $\tau\tau\tau\tau$ (green), boosted $2\mu 2\tau$ (red), resolved $2\mu 2\tau$ (yellow), $bbbb$ (magenta), and the combined result for $\ell\ell bb$ ($\ell = \mu, \tau$) (purple).

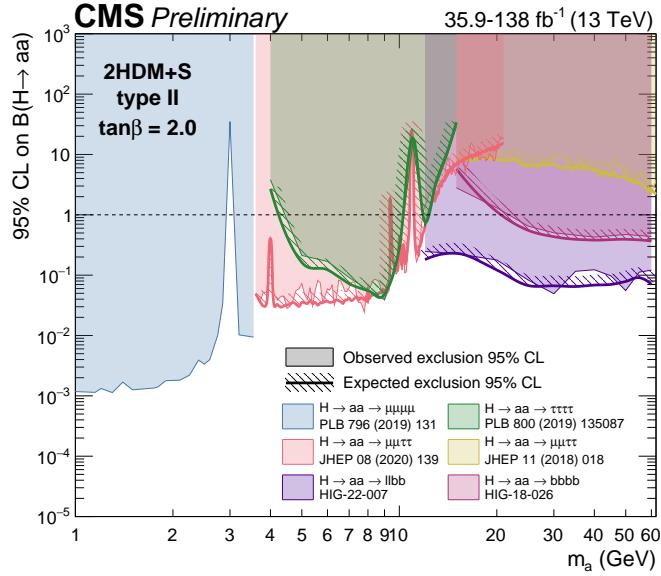


Figure 10.9: Summary plot of current observed and expected 95% CL limits on the branching ratio of the 125 GeV Higgs boson to two pseudoscalars, normalized to the Standard Model Higgs production cross-section, $\frac{\sigma(h)}{\sigma_{SM}} \times B(h \rightarrow aa)$, in the 2HDM+S type II scenario with $\tan\beta = 2.0$, obtained at CMS with data collected at 13 TeV [104]. Results from different final states studied at CMS are overlaid on this figure: $\mu\mu\mu\mu$ (blue), $\tau\tau\tau\tau$ (green), boosted $2\mu 2\tau$ (red), resolved $2\mu 2\tau$ (yellow), $bbbb$ (magenta), and the combined result for $\ell\ell bb$ ($\ell = \mu, \tau$) (purple).

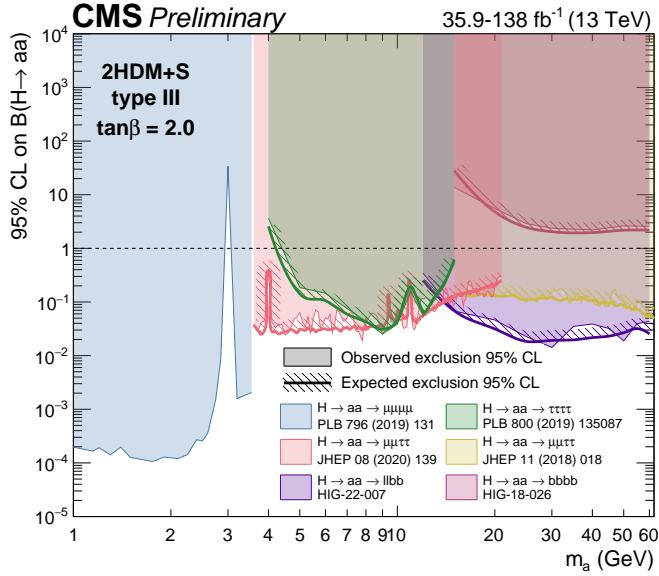


Figure 10.10: Summary plot of current observed and expected 95% CL limits on the branching ratio of the 125 GeV Higgs boson to two pseudoscalars, normalized to the Standard Model Higgs production cross section, $\frac{\sigma(h)}{\sigma_{SM}} \times B(h \rightarrow aa)$ in the 2HDM+S type-III scenario with $\tan \beta = 2.0$, obtained at CMS with data collected at 13 TeV [104]. Results from different final states studied at CMS are overlaid on this figure: $\mu\mu\mu\mu$ (blue), $\tau\tau\tau\tau$ (green), boosted $2\mu 2\tau$ (red), resolved $2\mu 2\tau$ (yellow), $bbbb$ (magenta), and the combined result for $\ell\ell bb$ ($\ell = \mu, \tau$) (purple).

2501 **Chapter 11**

2502 **Asymmetric exotic Higgs decays**

2503 This chapter presents progress towards a search for exotic Higgs decays to two light
2504 scalars with unequal mass ($h \rightarrow a_1 a_2$) final states with bottom quarks and τ leptons,
2505 with plans to interpret the results in the context of Two Real Singlet Models (TRSMs),
2506 described in Section 1.5. Compared to the symmetric decay scenario $h \rightarrow aa$ which
2507 has been studied in multiple final states at CMS with stringent limits set on the
2508 various 2HDM+S scenarios, this asymmetric decay scenario has not been directly
2509 searched for at the CMS experiment. Section 11.1 lists the mass hypotheses of the
2510 new particles a_1 and a_2 that will be studied. Section 11.2 describes the studies on
2511 which channels the analysis will be carried out in. Section 11.3 shows the control
2512 plots produced using the analysis framework that will be used for this analysis.

2513 **11.1 Signal masses**

2514 As discussed in Section 1.5, $h \rightarrow a_1 a_2$ can result in a “cascade” decay if one of the
2515 scalars, a_2 is sufficiently heavy ($m_{a_2} > 2m_{a_1}$). The “non-cascade” case is where the
2516 light scalars decay directly to Standard Model particles.

2517 The mass hypotheses (mass points) (m_{a_1}, m_{a_2}) studied here are:

- 2518 • *Cascade mass points:* (15, 30), (15, 40), (15, 50), (15, 60), (15, 70), (15, 80),
 2519 (15, 90), (15, 100), (15, 110), (20, 40), (20, 50), (20, 60), (20, 70), (20, 80), (20,
 2520 90), (20, 100), (30, 60), (30, 70), (30, 80), and (30, 90) GeV

 2521 • *Non-cascade mass points:* (15, 20), (15, 30), (20, 30), (20, 40), (30, 40), (30,
 2522 50), (30, 60), (40, 50), (40, 60), (40, 70), (40, 80), (50, 60), and (50, 70) GeV

2523 Samples were produced using the MadGraph5_aMCatNLO event generator, for each
 2524 signal mass point in the gluon-gluon fusion (ggF) and vector boson fusion (VBF)
 2525 production modes of the 125 GeV Higgs boson. In the sample generation, the decays
 2526 of a to Standard Model particles were specified to be decays to bottom quarks or τ
 2527 leptons.

2528 11.2 Cascade scenario signal studies

2529 Studies of the signal phenomenology in the cascade scenario were performed to de-
 2530 termine the viability of the $4b2\tau$ and/or $2b4\tau$ channels.

2531 Cross sections and branching fractions of the $4b2\tau$ and $2b4\tau$ final states were
 2532 compared using cross-section predictions provided by the authors of [7]. For an
 2533 example mass point $m_{a_2} = 80$ GeV, $m_{a_1} = 30$ GeV, the branching fractions to
 2534 $4b2\tau$ is ten times larger than $2b4\tau$: $B(h \rightarrow a_1 a_2 \rightarrow 3a_1 \rightarrow 4b2\tau) = 0.00857$, vs.
 2535 $B(h \rightarrow a_1 a_2 \rightarrow 3a_1 \rightarrow 2b4\tau) = 0.00068$. The $4b2\tau$ final state is chosen for this
 2536 analysis.

2537 In general the four b-flavor jets have low p_T at generator level, as illustrated for
 2538 example mass points (100, 15) GeV and (40, 20) GeV in Fig. 11.1. The p_T distribution
 2539 of the sub-leading jet peaks at an energy below 20 GeV, with the third and fourth
 2540 jets tending to have even softer energies.

2541 An event category with three or more b-tag jets was determined to be infeasible
 2542 due to low statistics in this category, due to the difficulties in reconstructing the third

2543 and fourth b-flavor jets which have very low transverse momenta p_T . Event categories
 2544 with exactly 1 b-tag jet and ≥ 2 b-tag jets will be used.

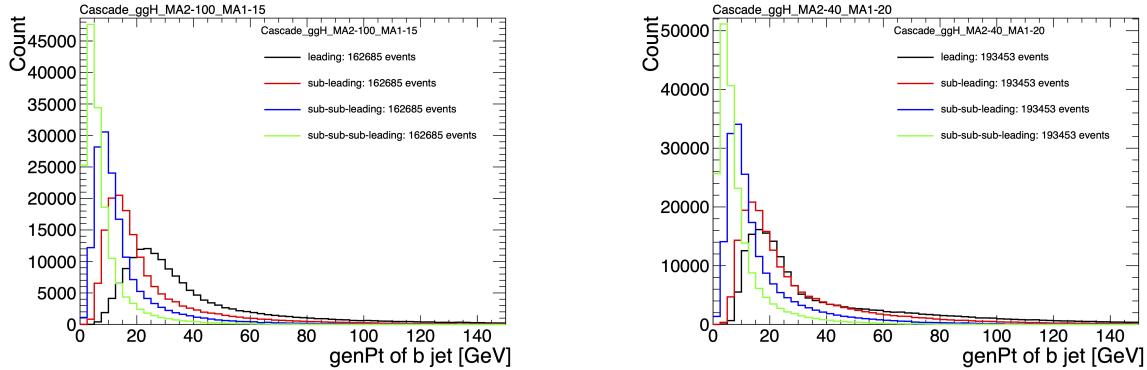


Figure 11.1: Generator-level b-flavor jet transverse momenta p_T , for $h \rightarrow a_1 a_2$ cascade scenario in the $4b2\tau$ final state, for mass hypotheses $(m_{a_1}, m_{a_2}) = (100, 15)$ GeV (*left*) and $(40, 20)$ GeV (*right*). In each plot the generator-level p_T of the leading (*black*), sub-leading (*red*), third (*blue*), and fourth (*light green*) are overlaid.

2545 In the $4b2\tau$ final state, the possibility of the leading and sub-leading b-tag jets
 2546 being sufficiently close in ΔR to require boosted jet reconstruction techniques was
 2547 explored. In the $4b2\tau$ case, the two b-flavor-jets in the generated event that were
 2548 spatially closest in ΔR were considered as one object. This two b-flavor jet object was
 2549 spatially matched in ΔR to the jets reconstructed with the standard AK4 algorithm
 2550 which uses a cone size of $\Delta R = 0.4$. The quality of the p_T resolution (computed as
 2551 $(p_{T,\text{reconstructed}} - p_{T,\text{gen}})/p_{T,\text{gen}}$) and closeness in distance ΔR of the reconstructed jet
 2552 to the nearest generator-level jets, was seen to depend on the absolute and relative
 2553 masses of the light scalars. The best (worst) performance occurred in samples with
 2554 large (small) mass differences between the heavier scalar a_2 and the lighter scalar a_1 ,
 2555 as illustrated for the mass hypotheses (m_{a_1}, m_{a_2}) (100, 15) GeV and (40, 20) GeV in
 2556 Fig. 11.2.

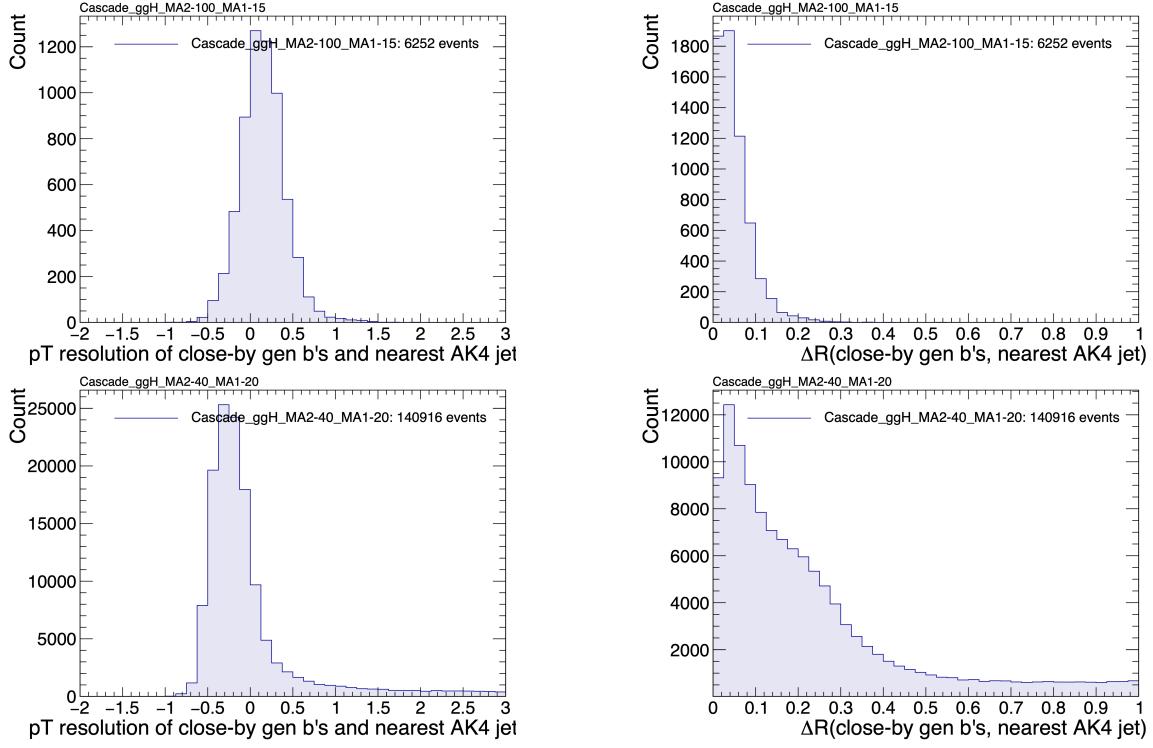


Figure 11.2: Distributions (arbitrary units) of transverse momentum p_T resolution and ΔR between the two closest generator-level b jets, treated as one object, and the nearest reconstructed AK4 jet, for two different $h \rightarrow a_1 a_2$ mass hypotheses (m_{a_1}, m_{a_2}) = (100, 15) GeV (top left, top right) and (40, 20) GeV (bottom left, bottom right) in the ggH production of the 125 GeV h . In the (40, 20) GeV mass point, the longer p_T resolution tail (bottom left) indicates that the reconstructed jet underestimates the generator b -flavor jets' energy, and the significant fraction of events with larger ΔR values (bottom right) indicate worse matching.

11.3 Current control plots for $\mu\tau_h$ channel

2558 The $\tau\tau$ states for the $h \rightarrow a_1 a_2$ to $4b2\tau$ analysis will be similar to those studied in
 2559 $h \rightarrow aa \rightarrow bb\tau\tau$. For the $\mu\tau_h$ channel, histograms of the key kinematic variables are
 2560 made for data and the sum of the expected backgrounds, which are estimated from
 2561 Monte Carlo samples, embedded samples, and the data-driven method for estimating
 2562 jets faking τ_h as described in Chapter 7. Nominal values of the scale factors and event
 2563 reweighting are applied, as described in Chapter ???. The errors shown in the figures
 2564 only include statistical errors and only several of the full set of systematic errors
 2565 (only those associated with the lepton energy scales and τ_h identification efficiency,

2566 described in Sections 5.3.1, 5.3.2, and 5.3.4).

2567 The p_T , η , and ϕ of the leading muon and hadronic tau τ_h , and the di-tau visible
2568 mass m_{vis} and momentum $p_{T,\text{vis}}$, are shown in Fig. 11.3. The p_T , η , and ϕ of the the
2569 leading and sub-leading b-tag jets, and the missing transverse energy magnitude and
2570 azimuthal direction, are shown in Fig. 11.4.

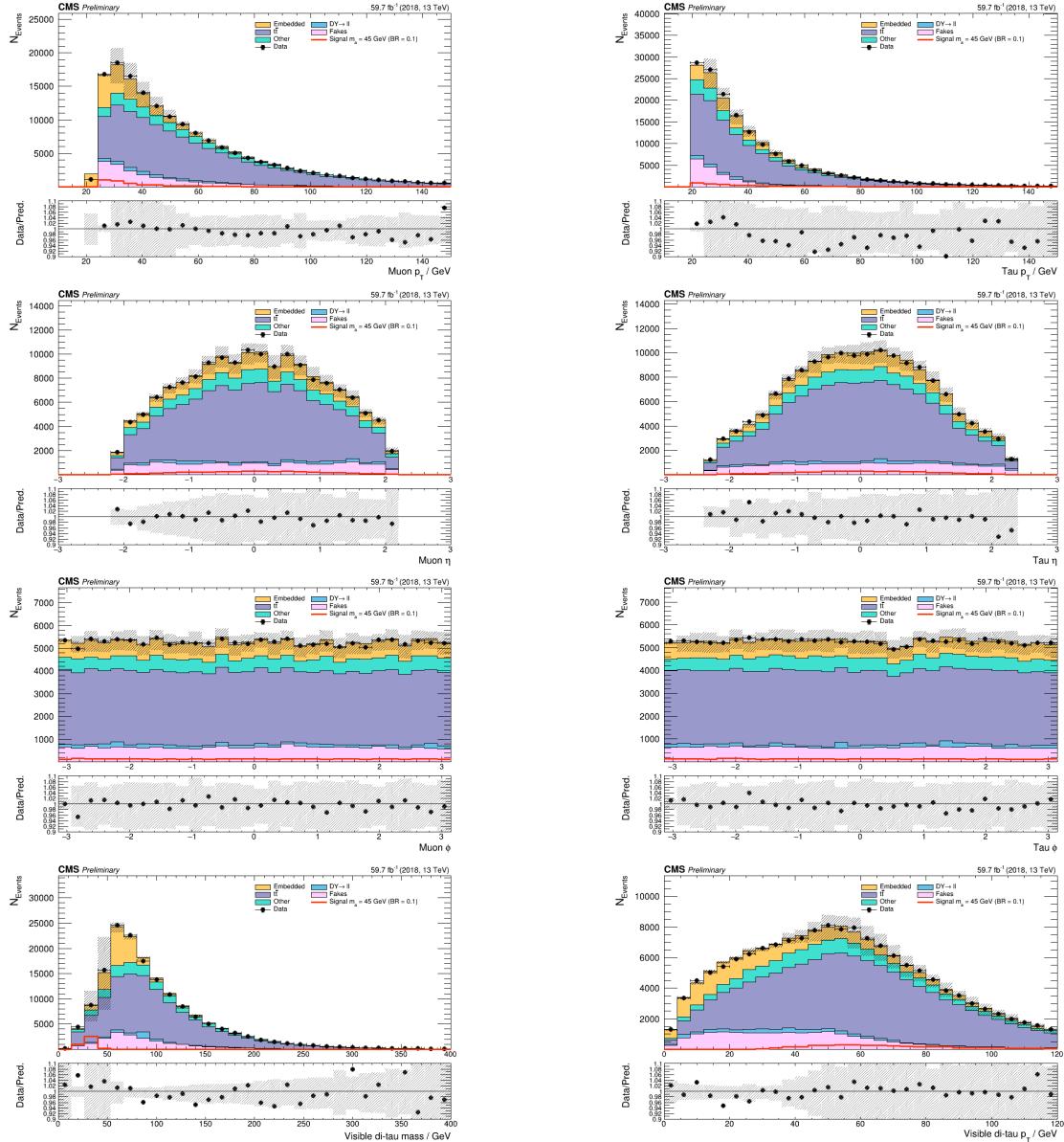


Figure 11.3: Kinematic properties of the leading muon and τ_h in the $\mu\tau_h$ channel: p_T (top row), η (second row), and ϕ (third row). The visible 4-momenta of the muon and τ_h are summed, giving the visible di-tau mass m_{vis} and transverse momentum $p_{T,\text{vis}}$. The errors shown in the figures only include statistical errors and only several of the full set of systematic errors (only those associated with the lepton energy scales and τ_h identification efficiency).

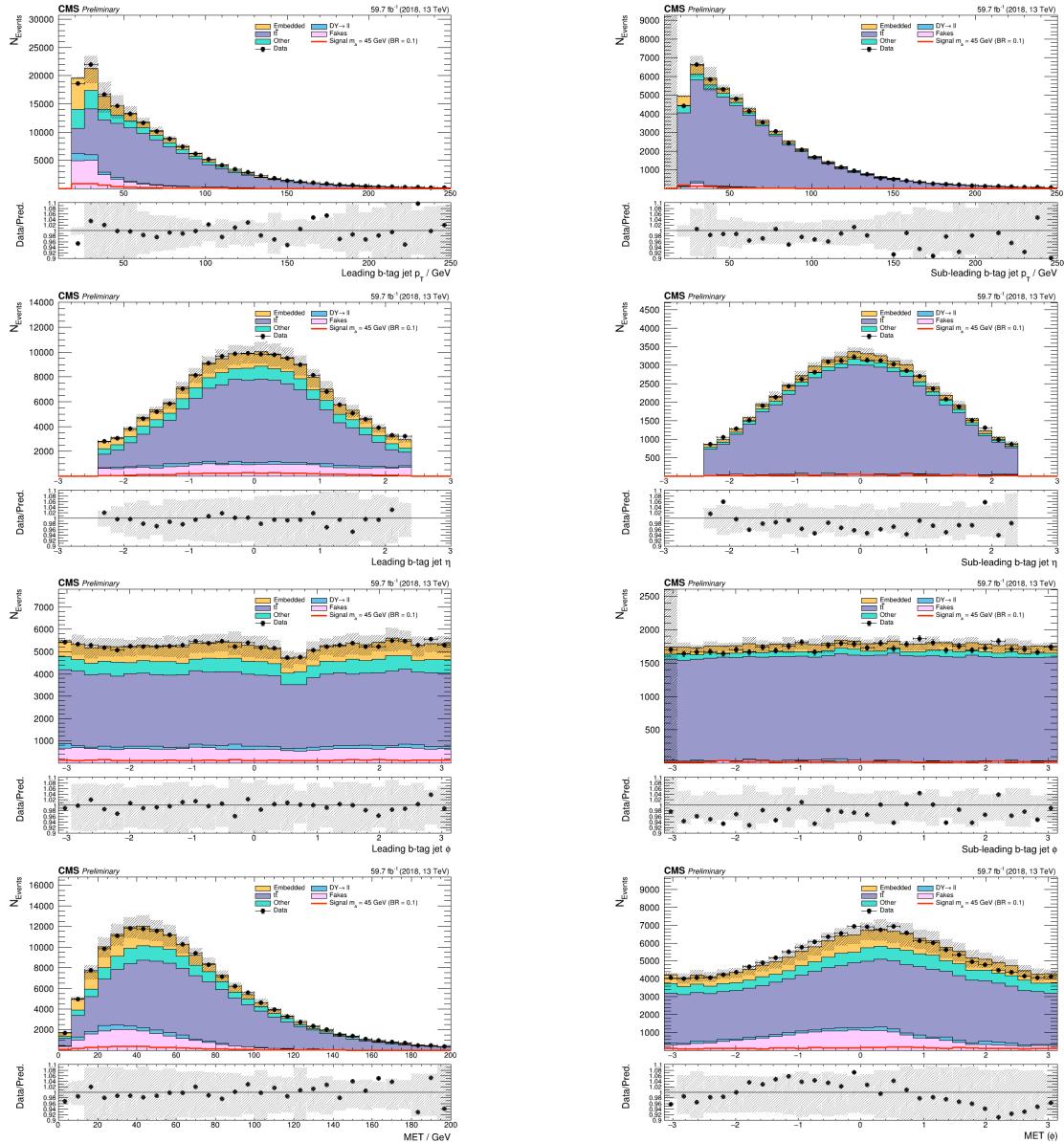


Figure 11.4: Kinematic properties of the leading and sub-leading b-tag jets in the $\mu\tau_h$ final state: jet p_T (*top row*), η (*second row*), ϕ (*third row*), as well as the missing transverse energy magnitude and azimuthal direction (*bottom row*). The errors shown in the figures only include statistical errors and only several of the full set of systematic errors (only those associated with the lepton energy scales and τ_h identification efficiency).

²⁵⁷¹

Chapter 12

²⁵⁷²

Conclusion and outlook

²⁵⁷³ With the discovery of a Higgs boson with mass 125 GeV at the LHC in 2012, the LHC
²⁵⁷⁴ and CMS physics program has evolved to include the precise characterization of the
²⁵⁷⁵ 125 GeV Higgs boson and searching for evidence of additional Higgs particles in an
²⁵⁷⁶ extended Higgs sector. This thesis presents a direct search at CMS for exotic decays
²⁵⁷⁷ of the Higgs boson with mass 125 GeV in data collected in the years 2016-2018 in
²⁵⁷⁸ proton-proton collisions at center-of-mass energy 13 TeV, to two light neutral scalar
²⁵⁷⁹ particles that decay to two bottom quarks and two tau leptons ($h \rightarrow aa \rightarrow bb\tau\tau$). The
²⁵⁸⁰ results are combined with another search that was performed in the $h \rightarrow aa \rightarrow bb\mu\mu$
²⁵⁸¹ final state, giving the most stringent limits to date for theories with Two Higgs
²⁵⁸² Doublet Models extended with a singlet scalar (2HDM+S), for pseudoscalar masses
²⁵⁸³ m_a ranging from 15 GeV to 60 GeV, in a number of 2HDM+S scenarios such as type
²⁵⁸⁴ II and III with $\tan\beta = 2.0$.

²⁵⁸⁵ As the rich physics program of CMS has set stringent limits on the exotic decay
²⁵⁸⁶ $h \rightarrow aa$, we turn our attention to direct searches for decays to light neutral scalars
²⁵⁸⁷ with potentially unequal mass, $h \rightarrow a_1a_2$, which has not been performed at CMS
²⁵⁸⁸ to date. Preliminary studies on $h \rightarrow a_1a_2$ signals in the Two Real Singlet Model
²⁵⁸⁹ (TRSM) are shown, and work is ongoing to develop the analysis for $h \rightarrow a_1a_2$ in final

2590 states with bottom quarks and tau leptons.

2591 To ensure the continued performance of the CMS detector and to enhance its
2592 data-taking capabilities in the intense pile-up conditions of the Phase-2 upgrade of
2593 the High-Luminosity LHC, upgrades of the Level-1 Trigger are paramount for filtering
2594 the increased data rate of the HL-LHC. This thesis presents work on the standalone
2595 barrel calorimeter algorithm for reconstructing and identifying electron and photon
2596 candidates, using high granularity crystal-level information from the ECAL subdetec-
2597 tor. For Phase-2, the increase in the granularity of information sent from the electro-
2598 magnetic calorimeter to the Level-1 trigger, from energy sums over towers (which are
2599 5×5 in crystals) to crystal-level information, allows for the implementation of a more
2600 sophisticated clustering algorithm that can exploit the fact that genuine electrons
2601 and photons tend to leave energies concentrated a 3×5 window in crystals, and use
2602 shape and isolation information to distinguish genuine electrons and photons from
2603 noise. Electrons and photons are key to characterizing Standard Model processes and
2604 performing searches for new physics, and this represents one of the many upgrades of
2605 the CMS detector in preparation for Phase-2. With the ongoing Run-3 data collecting
2606 period, and wealth of ongoing and scheduled upgrades, there remains an abundance
2607 of directions for detector development and physics at CMS heading into Phase-2 of
2608 the LHC.

2609

Appendix A

2610

Samples used

2611 The datasets used in the MiniAOD-based framework for the $h \rightarrow aa \rightarrow bb\tau\tau$ analysis
2612 are listed in this appendix. The NanoAOD-based framework uses the NanoAOD ver-
2613 sions of these datasets. The data used for the years 2016-2018 are listed in Tables A.1,
2614 A.2, and A.3 respectively. The embedded samples used for the years 2016-2018 are
2615 listed in Tables A.4, A.5, and A.6 respectively. The Monte Carlo simulated samples
2616 used to estimate backgrounds for the years 2016-2018 are listed in Tables A.7, A.8,
2617 and A.9 respectively.

2618 The $h \rightarrow aa \rightarrow bb\tau\tau$ signal samples are generated for 11 psuedoscalar masses
2619 between 12 GeV and 60 GeV for gluon fusion (ggF) and vector boson fusion (VBF)
2620 Higgs production. The 2016-2018 signal samples are listed in Tables A.10, A.11 and
2621 A.12 respectively. A filter is applied at the generator level for each $\tau\tau$ final state:

- 2622 • ee final state: $p_T(e_1) > 22$ GeV, $p_T(e_2) > 10$ GeV, $|\eta(e_1)| < 2.6$, and $|\eta(e_2)| <$
2623 2.6.

- 2624 • $e\tau_h$ final state: $p_T(e) > 22$ GeV, $p_T(\tau_h) > 16$ GeV, $|\eta(e)| < 2.6$, and $|\eta(\tau_h)| < 2.7$.

- 2625 • $e\mu$ final state: $p_T(e) > 11$ GeV, $p_T(\mu) > 7$ GeV, $|\eta(e)| < 2.6$, and $|\eta(\mu)| < 2.5$.

- 2626 • $\tau_h\tau_h$ final state: $p_T(\tau_{h1}) > 28$ GeV, $p_T(\tau_{h2}) > 28$ GeV, $|\eta(\tau_{h1})| < 2.5$, and

$$|\eta(\tau_{h2})| < 2.5.$$

- $\mu\tau_h$ final state: $p_T(\mu) > 19 \text{ GeV}$, $p_T(\tau_h) > 16 \text{ GeV}$, $|\eta(\mu)| < 2.5$, and $|\eta(\tau_h)| < 2.7$.

- $\mu\mu$ final state: $p_T(\mu_1) > 17 \text{ GeV}$, $p_T(\mu_2) > 8 \text{ GeV}$, $|\eta(\mu_1)| < 2.5$, and $|\eta(\mu_2)| < 2.5$.

The tables also show for each sample the filter efficiencies, which is the percentage of events that pass the above filters, and the number of events that were generated after applying the filters.

Channel	Datasets (2016)	Run range
$e\mu$	/MuonEG/Run2016B-17Jul2018_ver1-v1/MINIAOD	272760-273017
	/MuonEG/Run2016B-17Jul2018_ver2-v1/MINIAOD	273150-275376
	/MuonEG/Run2016C-17Jul2018-v1/MINIAOD	275656-276283
	/MuonEG/Run2016D-17Jul2018-v1/MINIAOD	276315-276811
	/MuonEG/Run2016E-17Jul2018-v2/MINIAOD	276831-277420
	/MuonEG/Run2016F-17Jul2018-v1/MINIAOD	277932-278808
	/MuonEG/Run2016G-17Jul2018-v1/MINIAOD	278820-280385
	/MuonEG/Run2016H-17Jul2018-v1/MINIAOD	281613-284044
$e\tau_h$	/SingleElectron/Run2016B-17Jul2018_ver1-v1/MINIAOD	272760-273017
	/SingleElectron/Run2016B-17Jul2018_ver2-v1/MINIAOD	273150-275376
	/SingleElectron/Run2016C-17Jul2018-v1/MINIAOD	275656-276283
	/SingleElectron/Run2016D-17Jul2018-v1/MINIAOD	276315-276811
	/SingleElectron/Run2016E-17Jul2018-v1/MINIAOD	276831-277420
	/SingleElectron/Run2016F-17Jul2018-v1/MINIAOD	277932-278808
	/SingleElectron/Run2016G-17Jul2018-v1/MINIAOD	278820-280385
	/SingleElectron/Run2016H-17Jul2018-v1/MINIAOD	281613-284044
$\mu\tau_h$	/SingleMuon/Run2016B-17Jul2018_ver1-v1/MINIAOD	272760-273017
	/SingleMuon/Run2016B-17Jul2018_ver2-v1/MINIAOD	273150-275376
	/SingleMuon/Run2016C-17Jul2018-v1/MINIAOD	275656-276283
	/SingleMuon/Run2016D-17Jul2018-v1/MINIAOD	276315-276811
	/SingleMuon/Run2016E-17Jul2018-v1/MINIAOD	276831-277420
	/SingleMuon/Run2016F-17Jul2018-v1/MINIAOD	277932-278808
	/SingleMuon/Run2016G-17Jul2018-v1/MINIAOD	278820-280385
	/SingleMuon/Run2016H-17Jul2018-v1/MINIAOD	281613-284044

Table A.1: Datasets used in the $h \rightarrow aa \rightarrow bb\tau\tau$ analysis for the 2016 era.

Channel	Datasets (2017)	Run range
$e\mu$	/MuonEG/Run2017B-31Mar2018-v1/MINIAOD	297047-299329
	/MuonEG/Run2017C-31Mar2018-v1/MINIAOD	299368-302029
	/MuonEG/Run2017D-31Mar2018-v1/MINIAOD	302031-302663
	/MuonEG/Run2017E-31Mar2018-v1/MINIAOD	303824-304797
	/MuonEG/Run2017F-31Mar2018-v1/MINIAOD	305040-306460
$e\tau_h$	/SingleElectron/Run2017B-31Mar2018-v1/MINIAOD	297047-299329
	/SingleElectron/Run2017C-31Mar2018-v1/MINIAOD	299368-302029
	/SingleElectron/Run2017D-31Mar2018-v1/MINIAOD	302031-302663
	/SingleElectron/Run2017E-31Mar2018-v1/MINIAOD	303824-304797
	/SingleElectron/Run2017F-31Mar2018-v1/MINIAOD	305040-306460
$\mu\tau_h$	/SingleMuon/Run2017B-31Mar2018-v1/MINIAOD	297047-299329
	/SingleMuon/Run2017C-31Mar2018-v1/MINIAOD	299368-302029
	/SingleMuon/Run2017D-31Mar2018-v1/MINIAOD	302031-302663
	/SingleMuon/Run2017E-31Mar2018-v1/MINIAOD	303824-304797
	/SingleMuon/Run2017F-31Mar2018-v1/MINIAOD	305040-306460

Table A.2: Datasets used in the $h \rightarrow aa \rightarrow bb\tau\tau$ analysis for the 2017 era.

Channel	Datasets (2018)	Run range
$e\mu$	/MuonEG/Run2018A-17Sep2018-v1/MINIAOD	315257-316995
	/MuonEG/Run2018B-17Sep2018-v1/MINIAOD	317080-319310
	/MuonEG/Run2018C-17Sep2018-v1/MINIAOD	319337-320065
	/MuonEG/Run2018D-PromptReco-v2/MINIAOD	320500-325175
$e\tau_h$	/EGamma/Run2018A-17Sep2018-v2/MINIAOD	315257-316995
	/EGamma/Run2018B-17Sep2018-v1/MINIAOD	317080-319310
	/EGamma/Run2018C-17Sep2018-v1/MINIAOD	319337-320065
	/EGamma/Run2018D-PromptReco-v2/MINIAOD	320497-325175
$\mu\tau_h$	/SingleMuon/Run2018A-17Sep2018-v2/MINIAOD	315257-316995
	/SingleMuon/Run2018B-17Sep2018-v1/MINIAOD	317080-319310
	/SingleMuon/Run2018C-17Sep2018-v1/MINIAOD	319337-320065
	/SingleMuon/Run2018D-PromptReco-v2/MINIAOD	320500-325175

Table A.3: Datasets used in the $h \rightarrow aa \rightarrow bb\tau\tau$ analysis for the 2018 eras.

Channel	Embedded samples (2016)
$e\mu$	/EmbeddingRun2016B/ElMuFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016C/ElMuFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016D/ElMuFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016E/ElMuFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016F/ElMuFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016G/ElMuFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016H/ElMuFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
$e\tau_h$	/EmbeddingRun2016B/ElTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016C/ElTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016D/ElTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016E/ElTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016F/ElTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016G/ElTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016H/ElTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
$\mu\tau_h$	/EmbeddingRun2016B/MuTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016C/MuTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016D/MuTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016E/MuTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016F/MuTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016G/MuTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5
	/EmbeddingRun2016H/MuTauFinalState-inputDoubleMu_94X_Legacy_miniAOD-v5

Table A.4: Embedded samples used in the analysis for the 2016 era.

Channel	Embedded samples (2017)
$e\mu$	/EmbeddingRun2017B/ElMuFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017C/ElMuFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017D/ElMuFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017E/ElMuFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017F/ElMuFinalState-inputDoubleMu_94X_miniAOD-v2
$e\tau_h$	/EmbeddingRun2017B/ElTauFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017C/ElTauFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017D/ElTauFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017E/ElTauFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017F/ElTauFinalState-inputDoubleMu_94X_miniAOD-v2
$\mu\tau_h$	/EmbeddingRun2017B/MuTauFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017C/MuTauFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017D/MuTauFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017E/MuTauFinalState-inputDoubleMu_94X_miniAOD-v2 /EmbeddingRun2017F/MuTauFinalState-inputDoubleMu_94X_miniAOD-v2

Table A.5: Embedded samples used in the analysis for the 2017 era.

Channel	Embedded samples (2018)
$e\mu$	/EmbeddingRun2018A/ElMuFinalState-inputDoubleMu_102X_miniAOD-v1 /EmbeddingRun2018B/ElMuFinalState-inputDoubleMu_102X_miniAOD-v1 /EmbeddingRun2018C/ElMuFinalState-inputDoubleMu_102X_miniAOD-v1 /EmbeddingRun2018D/ElMuFinalState-inputDoubleMu_102X_miniAOD-v1
$e\tau_h$	/EmbeddingRun2018A/ElTauFinalState-inputDoubleMu_102X_miniAOD-v1 /EmbeddingRun2018B/ElTauFinalState-inputDoubleMu_102X_miniAOD-v1 /EmbeddingRun2018C/ElTauFinalState-inputDoubleMu_102X_miniAOD-v1 /EmbeddingRun2018D/ElTauFinalState-inputDoubleMu_102X_miniAOD-v1
$\mu\tau_h$	/EmbeddingRun2018A/MuTauFinalState-inputDoubleMu_102X_miniAOD-v1 /EmbeddingRun2018B/MuTauFinalState-inputDoubleMu_102X_miniAOD-v1 /EmbeddingRun2018C/MuTauFinalState-inputDoubleMu_102X_miniAOD-v1 /EmbeddingRun2018D/MuTauFinalState-inputDoubleMu_102X_miniAOD-v1

Table A.6: Embedded samples used in the analysis for the 2018 era.

Process	Simulated background samples (2016)	Cross section (pb)
DY	/DY1JetsToLL_M-50_TuneCUETP8M1	1012.5 (LO)
	/DY2JetsToLL_M-50_TuneCUETP8M1	332.8 (LO)
	/DY3JetsToLL_M-50_TuneCUETP8M1	101.8 (LO)
	/DY4JetsToLL_M-50_TuneCUETP8M1	54.8 (LO)
	/DYJetsToLL_M-50_TuneCUETP8M1	4963.0 (LO)
	/DY1JetsToLL_M-10to50_TuneCUETP8M1	730.3 (LO)
	/DY2JetsToLL_M-10to50_TuneCUETP8M1	387.4 (LO)
	/DY3JetsToLL_M-10to50_TuneCUETP8M1	95.0 (LO)
	/DY4JetsToLL_M-10to50_TuneCUETP8M1	36.7 (LO)
	/DYJetsToLL_M-10to50_TuneCUETP8M1	16290.0 (LO)
Top	/TTTo2L2Nu_TuneCP5_PSweights	88.29
	/TTToHadronic_TuneCP5_PSweights	377.96
	/TTToSemiLeptonic_TuneCP5_PSweights	365.35
	/ST_t-channel_antitop_4f_inclusiveDecays [†]	26.23
	/ST_t-channel_top_4f_inclusiveDecays [†]	44.07
	/ST_tW_antitop_5f_inclusiveDecays_TuneCUETP8M1	35.6
	/ST_tW_top_5f_inclusiveDecays_TuneCUETP8M1	35.6
VV	/VVTTo2L2Nu_13TeV_amcatnloFXFX_madspin_pythia8	13.84
	/WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8	5.52
	/WZTo3LNu_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	4.43
	/ZZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8	3.38
	/ZZTo4L_13TeV-amcatnloFXFX-pythia8	1.212
W	/W1JetsToLNu_TuneCUETP8M1	8104.0 (LO)
	/W2JetsToLNu_TuneCUETP8M1	2793.0 (LO)
	/W3JetsToLNu_TuneCUETP8M1	992.5 (LO)
	/W4JetsToLNu_TuneCUETP8M1	544.3 (LO)
	/WJetsToLNu_TuneCUETP8M1	52940.0 (LO)
H	/GluGluHToTauTau_M125	48.58*0.0627
	/GluGluHToWWTo2L2Nu_M125	48.58*0.2137*0.3258*0.3258
	/GluGluZH_HToWW_M125	0.1227*0.2137
	/HWminusJ_HToWW_M125	0.5328*0.2137
	/HWplusJ_HToWW_M125	0.840*0.2137
	/HZJ_HToWW_M125	0.7612*0.2137
	/VBFHToTauTau_M125	3.782*0.0627
	/VBFHToWWTo2L2Nu_M125	3.782*0.2137*0.3258*0.3258
	/WminusHToTauTau_M125	0.5328*0.0627
	/WplusHToTauTau_M125	0.840*0.0627
	/ZHToTauTau_M125	0.7612*0.0627
	/ggZH_HToTauTau_ZToLL_M125	0.1227*0.0627*3*0.033658
	/ggZH_HToTauTau_ZToNuNu_M125	0.1227*0.0627*0.2000
	/ggZH_HToTauTau_ZToQQ_M125	0.1227*0.0627*0.6991
	/ttHToNonbb_M125_TuneCUETP8M2_ttHtranche3	0.5071*(1-0.5824)
	/ttHTobb_M125_TuneCP5	0.5071*0.5824

Table A.7: Background MC samples used in the analysis for the 2016 era. Samples marked with a [†] are generated with the powhegV2-madspin-pythia8 tag.

Process	Simulated background samples (2017)	Cross section (pb)
DY	DY1JetsToLL_M-50_TuneCP5	877.8 (LO)
	DY2JetsToLL_M-50_TuneCP5	304.4 (LO)
	DY3JetsToLL_M-50_TuneCP5	111.5 (LO)
	DY4JetsToLL_M-50_TuneCP5	44.0 (LO)
	DYJetsToLL_M-50_TuneCP5	5343.0 (LO)
	DYJetsToLL_M-10to50_TuneCP5	15810.0 (LO)
Top	TTTo2L2Nu_TuneCP5	88.29
	TTToHadronic_TuneCP5	377.96
	TTToSemileptonic_TuneCP5	365.35
	ST_t-channel_antitop_4f_inclusiveDecays_TuneCP5 [†]	80.94
	ST_t-channel_top_4f_inclusiveDecays_TuneCP5 [†]	136.02
	ST_tW_antitop_5f_inclusiveDecays_TuneCP5	35.85
	ST_tW_top_5f_inclusiveDecays_TuneCP5	35.85
VV	VVTo2L2Nu_13TeV_amcatnloFXFX_madspin_pythia8	13.84
	WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8	5.52
	WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8	4.43
	ZZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8	3.38
	ZZTo4L_TuneCP5_13TeV-amcatnloFXFX-pythia8	1.212
W	W1JetsToLNu_TuneCP5	8104.0 (LO)
	W2JetsToLNu_TuneCP5	2793.0 (LO)
	W3JetsToLNu_TuneCP5	992.5 (LO)
	W4JetsToLNu_TuneCP5	544.3 (LO)
	WJetsToLNu_TuneCP5	52940.0 (LO)
H	GluGluHToTauTau_M125	48.58*0.0627
	GluGluHToWWTo2L2Nu_M125 ^{††}	48.58*0.2137*0.3258*0.3258
	GluGluZH_HToWW_M125	0.1227*0.2137
	HWminusJ_HToWW_M125	0.5328*0.2137
	HWplusJ_HToWW_M125	0.840*0.2137
	HZJ_HToWW_M125 ^{††}	0.7612*0.2137
	VBFHToTauTau_M125	3.782*0.0627
	VBFHToWWTo2L2Nu_M125 ^{††}	3.782*0.2137*0.3258*0.3258
	WminusHToTauTau_M125	0.5328*0.0627
	WplusHToTauTau_M125	0.840*0.0627
	ZHToTauTau_M125	0.7612*0.0627
	ggZH_HToTauTau_ZToLL_M125	0.1227*0.0627*3*0.033658
	ggZH_HToTauTau_ZToNuNu_M125	0.1227*0.0627*0.2000
	ggZH_HToTauTau_ZToQQ_M125	0.1227*0.0627*0.6991
	ttHToNonbb_M125_TuneCP5	0.5071*(1-0.5824)
	ttHTobb_M125_TuneCP5	0.5071*0.5824

Table A.8: Background MC samples used in the analysis for the 2017 era. All samples use powheg, except the DYJets and WJets samples, which use madgraphMLM. Samples marked with a [†], ^{††}, or ^{†††} were produced with Powheg2 and Pythia8, and Madspin, JHUGenV714, or jhugen724 respectively.

Process	Simulated background samples (2018)	Cross section (pb)
DY	DY1JetsToLL_M-50_TuneCP5	877.8 (LO)
	DY2JetsToLL_M-50_TuneCP5	304.4 (LO)
	DY3JetsToLL_M-50_TuneCP5	111.5 (LO)
	DY4JetsToLL_M-50_TuneCP5	44.0 (LO)
	DYJetsToLL_M-50_TuneCP5	5343.0 (LO)
	DYJetsToLL_M-10to50_TuneCP5	15810.0 (LO)
Top	TTTo2L2Nu_TuneCP5	88.29
	TTToHadronic_TuneCP5	377.96
	TTToSemiLeptonic_TuneCP5	365.35
	ST_t-channel_antitop_4f_InclusiveDecays_TuneCP5 [†]	80.94
	ST_t-channel_top_5f_TuneCP5 [†]	136.02
	ST_tW_antitop_5f_inclusiveDecays_TuneCP5	35.85
VV	ST_tW_top_5f_inclusiveDecays	35.85
	VVTo2L2Nu_13TeV_amcatnloFXFX_madspin	13.84
	WZTo2L2Q_13TeV_amcatnloFXFX_madspin	5.52
	WZTo3LNu_TuneCP5_13TeV-amcatnloFXFX-pythia8	4.43
	ZZTo2L2Q_13TeV_amcatnloFXFX_madspin	3.38
W	ZZTo4L_TuneCP5_13TeV-amcatnloFXFX-pythia8	1.212
	W1JetsToLNu_TuneCP5	8104.0 (LO)
	W2JetsToLNu_TuneCP5	2793.0 (LO)
	W3JetsToLNu_TuneCP5	992.5 (LO)
	W4JetsToLNu_TuneCP5	544.3 (LO)
H	WJetsToLNu_TuneCP5	52940.0 (LO)
	GluGluHToTauTau_M125	48.58*0.0627
	GluGluHToWWTo2L2Nu_M125 ^{††}	48.58*0.2137*0.3258*0.3258
	GluGluZH_HToWW_M125	0.1227*0.2137
	HWminusJ_HToWW_M125 ^{†††}	0.5328*0.2137
	HWplusJ_HToWW_M125 ^{†††}	0.840*0.2137
	HZJ_HToWW_M125 ^{††}	0.7612*0.2137
	VBFHToTauTau_M125	3.782*0.0627
	VBFHToWWTo2L2Nu_M125 ^{†††}	3.782*0.2137*0.3258*0.3258
	WminusHToTauTau_M125	0.5328*0.0627
	WplusHToTauTau_M125	0.840*0.0627
	ZHToTauTau_M125	0.7612*0.0627
	ggZH_HToTauTau_ZToLL_M125	0.1227*0.0627*3*0.033658
	ggZH_HToTauTau_ZToNuNu_M125	0.1227*0.0627*0.2000
	ggZH_HToTauTau_ZToQQ_M125	0.1227*0.0627*0.6991
	ttHTobb_M125_TuneCP5	0.5071*(1-0.5824)
	ttHTobb_M125_TuneCP5	0.5071*0.5824

Table A.9: Background Monte Carlo samples used in the analysis for the 2018 era. All samples listed are generated for 13 TeV collisions and use pythia8. All samples use powheg, except the DYJets and WJets samples, which use madgraphMLM. Samples marked with a [†], ^{††}, or ^{†††}, were produced with Powheg and Pythia8, and Madspin, JHUGenV714, and Jhugen724 respectively.

Signal samples (2016)	# events	Filter eff.
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-12_FilterTauTauTrigger	0.4M	3.81%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-15_FilterTauTauTrigger	0.4M	3.54%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-20_FilterTauTauTrigger	1M	3.37
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-25_FilterTauTauTrigger	0.2M	3.56%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-30_FilterTauTauTrigger	0.2M	3.16%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-35_FilterTauTauTrigger	0.2M	3.30%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-40_FilterTauTauTrigger	1M	3.30%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-45_FilterTauTauTrigger	0.2M	3.23%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-50_FilterTauTauTrigger	0.2M	3.42%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-55_FilterTauTauTrigger	0.2M	3.65%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-60_FilterTauTauTrigger	1M	3.73
/SUSYVBFHToAA_AToBB_AToTauTau_M-12_FilterTauTauTrigger	0.2M	7.94%
/SUSYVBFHToAA_AToBB_AToTauTau_M-15_FilterTauTauTrigger	0.2M	7.38%
/SUSYVBFHToAA_AToBB_AToTauTau_M-20_FilterTauTauTrigger	0.2M	7.27%
/SUSYVBFHToAA_AToBB_AToTauTau_M-25_FilterTauTauTrigger	0.2M	7.21%
/SUSYVBFHToAA_AToBB_AToTauTau_M-30_FilterTauTauTrigger	0.2M	6.87%
/SUSYVBFHToAA_AToBB_AToTauTau_M-35_FilterTauTauTrigger	0.2M	6.80%
/SUSYVBFHToAA_AToBB_AToTauTau_M-40_FilterTauTauTrigger	0.2M	6.78%
/SUSYVBFHToAA_AToBB_AToTauTau_M-45_FilterTauTauTrigger	0.2M	6.56%
/SUSYVBFHToAA_AToBB_AToTauTau_M-50_FilterTauTauTrigger	0.2M	6.40%
/SUSYVBFHToAA_AToBB_AToTauTau_M-55_FilterTauTauTrigger	0.2M	6.54%
/SUSYVBFHToAA_AToBB_AToTauTau_M-60_FilterTauTauTrigger	0.2M	6.55%

Table A.10: Signal samples used in the analysis for the 2016 era. All belong to the RunIISummer16MiniAODv3 campaign and are produced with Madgraph and Pythia8. The second column is the number of events after the generator-level filter is applied, and the third column is the filter efficiency (percentage of all events that pass the generator-level filter).

Signal samples (2017)	# events	Filter eff.
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-12_FilterTauTauTrigger	0.4M	3.78%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-15_FilterTauTauTrigger	0.4M	3.55%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-20_FilterTauTauTrigger	1M	3.40%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-25_FilterTauTauTrigger	0.2M	3.32%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-30_FilterTauTauTrigger	0.2M	3.36%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-35_FilterTauTauTrigger	0.2M	3.27%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-40_FilterTauTauTrigger	1M	3.03%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-45_FilterTauTauTrigger	0.2M	3.03%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-50_FilterTauTauTrigger	0.2M	3.31%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-55_FilterTauTauTrigger	0.2M	3.56%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-60_FilterTauTauTrigger	1M	3.95%
/SUSYVBFHToAA_AToBB_AToTauTau_M-12_FilterTauTauTrigger	0.2M	7.73%
/SUSYVBFHToAA_AToBB_AToTauTau_M-15_FilterTauTauTrigger	0.2M	7.35%
/SUSYVBFHToAA_AToBB_AToTauTau_M-20_FilterTauTauTrigger	0.2M	7.33%
/SUSYVBFHToAA_AToBB_AToTauTau_M-25_FilterTauTauTrigger	0.2M	7.23%
/SUSYVBFHToAA_AToBB_AToTauTau_M-30_FilterTauTauTrigger	0.2M	6.84%
/SUSYVBFHToAA_AToBB_AToTauTau_M-35_FilterTauTauTrigger	0.2M	6.97%
/SUSYVBFHToAA_AToBB_AToTauTau_M-40_FilterTauTauTrigger	0.2M	6.17%
/SUSYVBFHToAA_AToBB_AToTauTau_M-45_FilterTauTauTrigger	0.2M	6.67%
/SUSYVBFHToAA_AToBB_AToTauTau_M-50_FilterTauTauTrigger	0.2M	6.61%
/SUSYVBFHToAA_AToBB_AToTauTau_M-55_FilterTauTauTrigger	0.2M	6.51%
/SUSYVBFHToAA_AToBB_AToTauTau_M-60_FilterTauTauTrigger	0.2M	6.71%

Table A.11: Signal samples used in the analysis for the 2017 era. All belong to the RunIIFall17MiniAODv2 campaign and are produced with Madgraph and Pythia8. The second column is the number of events after the generator-level filter is applied, and the third column is the filter efficiency (percentage of all events that pass the generator-level filter).

Signal samples (2018)	# events	Filter eff.
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-12_FilterTauTauTrigger	0.4M	3.78%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-15_FilterTauTauTrigger	0.4M	3.49%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-20_FilterTauTauTrigger	1M	3.36%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-25_FilterTauTauTrigger	0.2M	3.46%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-30_FilterTauTauTrigger	0.2M	3.18%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-35_FilterTauTauTrigger	0.2M	3.28%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-40_FilterTauTauTrigger	1M	3.10%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-45_FilterTauTauTrigger	0.2M	3.21%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-50_FilterTauTauTrigger	0.2M	3.14%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-55_FilterTauTauTrigger	0.2M	3.56%
/SUSYGluGluToHToAA_AToBB_AToTauTau_M-60_FilterTauTauTrigger	1M	3.38%
/SUSYVBFHToAA_AToBB_AToTauTau_M-12_FilterTauTauTrigger	0.2M	7.78%
/SUSYVBFHToAA_AToBB_AToTauTau_M-15_FilterTauTauTrigger	0.2M	7.52%
/SUSYVBFHToAA_AToBB_AToTauTau_M-20_FilterTauTauTrigger	0.2M	6.87%
/SUSYVBFHToAA_AToBB_AToTauTau_M-25_FilterTauTauTrigger	0.2M	7.21%
/SUSYVBFHToAA_AToBB_AToTauTau_M-30_FilterTauTauTrigger	0.2M	6.51%
/SUSYVBFHToAA_AToBB_AToTauTau_M-35_FilterTauTauTrigger	0.2M	6.95%
/SUSYVBFHToAA_AToBB_AToTauTau_M-40_FilterTauTauTrigger	0.2M	6.81%
/SUSYVBFHToAA_AToBB_AToTauTau_M-45_FilterTauTauTrigger	0.2M	6.62%
/SUSYVBFHToAA_AToBB_AToTauTau_M-50_FilterTauTauTrigger	0.2M	6.56%
/SUSYVBFHToAA_AToBB_AToTauTau_M-55_FilterTauTauTrigger	0.2M	6.64%
/SUSYVBFHToAA_AToBB_AToTauTau_M-60_FilterTauTauTrigger	0.2M	6.75%

Table A.12: Signal samples used in the analysis for the 2018 era. All belong to the RunIIIAutumn18MiniAOD campaign and are produced with Madgraph and Pythia8. The second column is the number of events after the generator-level filter is applied, and the third column is the filter efficiency (percentage of all events that pass the generator-level filter).

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Bibliography

- 2636 [1] Paul H. Frampton. Journeys Beyond the Standard Model. 54(1):52–
2637 52. ISSN 0031-9228. doi: 10.1063/1.1349615. URL <https://doi.org/10.1063/1.1349615>. eprint: https://pubs.aip.org/physicstoday/article-pdf/54/1/52/11109432/52_1_online.pdf.
- 2638
- 2639
- 2640 [2] Meinard Kuhlmann. Quantum Field Theory. In Edward N. Zalta and Uri Nodelman, editors, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research
2641 Lab, Stanford University, Summer 2023 edition, 2023.
- 2642
- 2643 [3] Steven Weinberg. The Making of the Standard Model. *Eur. Phys. J. C*, 34:
2644 5–13, 2004. URL <https://cds.cern.ch/record/799984>.
- 2645
- 2646 [4] Christopher G. Tully. *Elementary Particle Physics in a Nutshell*. Princeton
University Press, Princeton, 2012. ISBN 9781400839353. doi: doi:10.1515/
2647 9781400839353. URL <https://doi.org/10.1515/9781400839353>.
- 2648
- 2649 [5] John Ellis. Higgs Physics. In *2013 European School of High-Energy Physics*,
pages 117–168, 2015. doi: 10.5170/CERN-2015-004.117.
- 2650
- 2651 [6] David Curtin, Rouven Essig, Stefania Gori, and Others. Exotic decays of the 125
GeV Higgs boson. *Phys. Rev. D*, 90:075004, Oct 2014. doi: 10.1103/PhysRevD.
2652 90.075004. URL <https://link.aps.org/doi/10.1103/PhysRevD.90.075004>.
- 2653
- [7] Tania Robens, Tim Stefański, and Jonas Wittbrodt. Two-real-scalar-singlet

- extension of the SM: LHC phenomenology and benchmark scenarios. *Eur. Phys. J. C*, 80(2):151, 2020. doi: 10.1140/epjc/s10052-020-7655-x.
- [8] CERN. The history of CERN, 2024. URL <https://timeline.web.cern.ch/timeline-header/89>.
- [9] R. Schmidt. Accelerator physics and technology of the LHC. In *ROXIE: Routine for the Optimizazation of Magnet X-Sections, Inverse Field Calculation and Coil End Design*, pages 7–17, 1998.
- [10] J. Vollaire et al. *Linac4 design report*, volume 6/2020 of *CERN Yellow Reports: Monographs*. CERN, Geneva, 9 2020. ISBN 978-92-9083-579-0, 978-92-9083-580-6. doi: 10.23731/CYRM-2020-006.
- [11] Antonella Del Rosso. Aerial view of the LHC and the four major experiments. 2017. URL <https://cds.cern.ch/record/2253966>. General Photo.
- [12] ATLAS Collaboration. ATLAS: Detector and physics performance technical design report. Volume 1. 5 1999.
- [13] CMS Collaboration. CMS Physics: Technical Design Report Volume 1: Detector Performance and Software. 2006.
- [14] L Musa. Conceptual Design Report for the Upgrade of the ALICE ITS. Technical report, CERN, Geneva, 2012. URL <https://cds.cern.ch/record/1431539>.
- [15] S. Amato et al. LHCb technical proposal: A Large Hadron Collider Beauty Experiment for Precision Measurements of CP Violation and Rare Decays. 2 1998.
- [16] Werner Herr and B Muratori. Concept of luminosity. 2006. doi: 10.5170/CERN-2006-002.361. URL <https://cds.cern.ch/record/941318>.

- 2678 [17] Olivier S. Brning and Frank Zimmerman. Parameter space for the LHC lu-
2679 minosity upgrade. ISBN 978-3-95450-115-1. URL <https://accelconf.web.cern.ch/IPAC2012/papers/moppc005.pdf>.
- 2680
2681 [18] CMS Collaboration. Pileup mitigation at CMS in 13 TeV data. *JINST*, 15(09):
2682 P09018, 2020. doi: 10.1088/1748-0221/15/09/P09018.
- 2683 [19] CMS Collaboration. Measurement of the inelastic proton-proton cross section
2684 at $\sqrt{s} = 13$ TeV. *JHEP*, 07:161, 2018. doi: 10.1007/JHEP07(2018)161.
- 2685 [20] CMS Collaboration. High-Luminosity Large Hadron Collider (HL-LHC): Tech-
2686 nical design report. 10/2020, 12 2020. doi: 10.23731/CYRM-2020-0010.
- 2687 [21] CMS Collaboration. The CMS Experiment at the CERN LHC. *JINST*, 3:
2688 S08004, 2008. doi: 10.1088/1748-0221/3/08/S08004.
- 2689 [22] CMS Collaboration. Particle-flow reconstruction and global event description
2690 with the CMS detector. *JINST*, 12(10):P10003, 2017. doi: 10.1088/1748-0221/
2691 12/10/P10003.
- 2692 [23] V Karimki, M Mannelli, P Siegrist, H Breuker, A Caner, R Castaldi, K Freudens-
2693 reich, G Hall, R Horisberger, M Huhtinen, and A Cattai. *The CMS tracker sys-
2694 tem project: Technical Design Report*. Technical design report. CMS. CERN,
2695 Geneva, 1997. URL <https://cds.cern.ch/record/368412>.
- 2696 [24] The Phase-2 Upgrade of the CMS Tracker. Technical report, CERN, Geneva,
2697 2017. URL <https://cds.cern.ch/record/2272264>.
- 2698 [25] CMS Collaboration. CMS Technical Design Report for the Pixel Detector Up-
2699 grade. 9 2012. doi: 10.2172/1151650.
- 2700 [26] R. L. Workman and Others. Review of particle physics. 2022:083C01. doi:
2701 10.1093/ptep/ptac097.

- 2702 [27] CMS Technical Design Report for the Phase 1 Upgrade of the Hadron Calorime-
2703 ter. 9 2012. doi: 10.2172/1151651.
- 2704 [28] CMS Technical Design Report for the Level-1 Trigger Upgrade. 6 2013.
- 2705 [29] S. Dasu et al. CMS. The TriDAS project. Technical design report, vol. 1: The
2706 trigger systems. 12 2000.
- 2707 [30] Alex Tapper. The CMS Level-1 Trigger for LHC Run II. *PoS*, ICHEP2016:242,
2708 2016. doi: 10.22323/1.282.0242.
- 2709 [31] A. Zabi, F. Beaudette, L. Cadamuro, O. Davignon, T. Romantreau, T. Strebler,
2710 M. Cepeda, J.B. Sauvan, N. Wardle, R. Aggleton, F. Ball, J. Brooke, D. New-
2711 bold, S. Paramesvaran, D. Smith, J. Taylor, C. Foudas, M. Baber, A. Bun-
2712 dock, S. Breeze, M. Citron, A. Elwood, G. Hall, G. Iles, C. Laner, B. Pen-
2713 ning, A. Rose, A. Shtipliyski, A. Tapper, I. Ojalvo, T. Durkin, K. Harder,
2714 S. Harper, C. Shepherd-Themistocleous, A. Thea, T. Williams, S. Dasu,
2715 L. Dodd, R. Forbes, T. Gorski, P. Klabbers, A. Levine, T. Ruggles, N. Smith,
2716 W. Smith, A. Svetek, J. Tikalsky, and M. Vicente. The cms level-1 calorimeter
2717 trigger for the lhc run ii. *Journal of Instrumentation*, 12(01):C01065, jan 2017.
2718 doi: 10.1088/1748-0221/12/01/C01065. URL <https://dx.doi.org/10.1088/1748-0221/12/01/C01065>.
- 2720 [32] P. Klabbers et al. CMS level-1 upgrade calorimeter trigger prototype develop-
2721 ment. *JINST*, 8:C02013, 2013. doi: 10.1088/1748-0221/8/02/C02013.
- 2722 [33] CMS Collaboration. The Phase-2 Upgrade of the CMS Data Acquisition and
2723 High Level Trigger. Technical report, CERN, Geneva, 2021. URL <https://cds.cern.ch/record/2759072>. This is the final version of the document,
2724 approved by the LHCC.

- 2726 [34] C. Foudas. The CMS Level-1 Trigger at LHC and Super-LHC. In *34th Inter-*
2727 *national Conference on High Energy Physics*, 10 2008.
- 2728 [35] CMS Software Guide. High Level Trigger (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideHighLevelTrigger>.
- 2730 [36] The Worldwide LHC Computing Grid. 2012. URL <https://cds.cern.ch/record/1997398>.
- 2732 [37] Douglas Thain, Todd Tannenbaum, and Miron Livny. Distributed computing
2733 in practice: the Condor experience. *Concurrency and Computation: Practice*
2734 and Experience, 17(2-4):323–356, 2005. doi: <https://doi.org/10.1002/cpe.938>.
2735 URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/cpe.938>.
- 2736 [38] Alexandre Zabi, Jeffrey Wayne Berryhill, Emmanuelle Perez, and Alexander D.
2737 Tapper. The Phase-2 Upgrade of the CMS Level-1 Trigger. 2020.
- 2738 [39] Technical proposal for a MIP timing detector in the CMS experiment Phase 2
2739 upgrade. Technical report, CERN, Geneva, 2017. URL <https://cds.cern.ch/record/2296612>.
- 2741 [40] CMS Collaboration. Search for exotic decays of the Higgs boson to a pair of
2742 pseudoscalars in the $\mu\mu bb$ and $\tau\tau bb$ final states. *European Physical Journal C*,
2743 2 2024.
- 2744 [41] CMS Collaboration. CMS luminosity measurement for the 2016 data-taking
2745 period. CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017. URL
2746 <https://cds.cern.ch/record/2257069>.
- 2747 [42] CMS Collaboration. CMS luminosity measurement for the 2017 data-taking
2748 period at $\sqrt{s} = 13$ TeV. CMS Physics Analysis Summary CMS-PAS-LUM-17-
2749 004, 2018. URL <https://cds.cern.ch/record/2621960>.

- 2750 [43] CMS Collaboration. CMS luminosity measurement for the 2018 data-taking
2751 period at $\sqrt{s} = 13$ TeV. CMS Physics Analysis Summary CMS-PAS-LUM-18-
2752 002, 2019. URL <https://cds.cern.ch/record/2676164>.
- 2753 [44] CMS LUMI Group. CMS Luminosity Public Results (TWiki), 2024. URL
2754 <https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults>.
- 2755 [45] J. Alwall, R. Frederix, S. Frixione, et al. The automated computation of tree-
2756 level and next-to-leading order differential cross sections, and their matching
2757 to parton shower simulations. *Journal of High Energy Physics*, 2014(7), July
2758 2014. ISSN 1029-8479. doi: 10.1007/jhep07(2014)079. URL [http://dx.doi.org/10.1007/JHEP07\(2014\)079](http://dx.doi.org/10.1007/JHEP07(2014)079).
- 2760 [46] R. Frederix, S. Frixione, V. Hirschi, et al. The automation of next-to-leading
2761 order electroweak calculations. *Journal of High Energy Physics*, 2018(7), July
2762 2018. ISSN 1029-8479. doi: 10.1007/jhep07(2018)185. URL [http://dx.doi.org/10.1007/JHEP07\(2018\)185](http://dx.doi.org/10.1007/JHEP07(2018)185).
- 2764 [47] S. Agostinelli, J. Allison, K. Amako, et al. Geant4 - a simulation toolkit. 506(3):
2765 250–303. ISSN 0168-9002. doi: 10.1016/S0168-9002(03)01368-8. URL <https://www.sciencedirect.com/science/article/pii/S0168900203013688>.
- 2767 [48] CMS Collaboration. An embedding technique to determine $\tau\tau$ backgrounds
2768 in proton-proton collision data. *JINST*, 14(06):P06032, 2019. doi: 10.1088/
2769 1748-0221/14/06/P06032.
- 2770 [49] CMS Collaboration. Search for neutral MSSM Higgs bosons decaying to a pair
2771 of tau leptons in pp collisions. *JHEP*, 10:160, 2014. doi: 10.1007/JHEP10(2014)
2772 160.
- 2773 [50] CMS Collaboration. Measurements of Higgs boson production in the decay

channel with a pair of τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV.

Eur. Phys. J. C, 83(7):562, 2023. doi: 10.1140/epjc/s10052-023-11452-8.

- [51] CMS Collaboration. Reconstruction and identification of tau lepton decays to hadrons and tau neutrinos at CMS. *Journal of Instrumentation*, 11(01):P01019–P01019, January 2016. ISSN 1748-0221. doi: 10.1088/1748-0221/11/01/p01019. URL <http://dx.doi.org/10.1088/1748-0221/11/01/P01019>.

- [52] CMS Collaboration. Performance of τ -lepton reconstruction and identification in CMS. *Journal of Instrumentation*, 7(01):P01001, jan 2012. doi: 10.1088/1748-0221/7/01/P01001. URL <https://dx.doi.org/10.1088/1748-0221/7/01/P01001>.

- [53] CMS Collaboration. Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV. *JINST*, 13(10):P10005, 2018. doi: 10.1088/1748-0221/13/10/P10005.

- [54] CMS Collaboration. Identification of hadronic tau lepton decays using a deep neural network. *JINST*, 17:P07023, 2022. doi: 10.1088/1748-0221/17/07/P07023.

- [55] CMS Collaboration. Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV. *Journal of Instrumentation*, 7(10):P10002–P10002, October 2012. ISSN 1748-0221. doi: 10.1088/1748-0221/7/10/p10002. URL <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>.

- [56] CMS Collaboration. Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV. *Journal of Instrumentation*, 10(06):P06005, 2015. doi: 10.1088/1748-0221/10/06/P06005. URL <https://dx.doi.org/10.1088/1748-0221/10/06/P06005>.

- 2798 [57] CMS Collaboration. Identification of b-quark jets with the CMS experiment.
2799 *Journal of Instrumentation*, 8(04):P04013–P04013, April 2013. ISSN 1748-
2800 0221. doi: 10.1088/1748-0221/8/04/p04013. URL <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>.
2801
- 2802 [58] CMS Collaboration. Pileup Removal Algorithms. Technical report, CERN,
2803 Geneva, 2014. URL <https://cds.cern.ch/record/1751454>.
- 2804 [59] CMS Collaboration. CMS Phase 1 heavy flavour identification performance and
2805 developments. 2017. URL <https://cds.cern.ch/record/2263802>.
- 2806 [60] CMS Collaboration. Performance of the DeepJet b tagging algorithm using
2807 41.9 fb^{-1} of data from proton-proton collisions at 13 TeV with Phase 1 CMS
2808 detector. 2018. URL <https://cds.cern.ch/record/2646773>.
- 2809 [61] Lorenzo Bianchini, John Conway, Evan Klose Friis, and Christian Veelken. Re-
2810 construction of the Higgs mass in $H \rightarrow \tau\tau$ Events by Dynamical Likelihood
2811 techniques. *Journal of Physics: Conference Series*, 513(2):022035, jun 2014.
2812 doi: 10.1088/1742-6596/513/2/022035. URL <https://dx.doi.org/10.1088/1742-6596/513/2/022035>.
2813
- 2814 [62] CMS Collaboration. Evidence for the 125 GeV Higgs boson decaying to a pair
2815 of τ leptons. *JHEP*, 05:104, 2014. doi: 10.1007/JHEP05(2014)104.
- 2816 [63] CMS Collaboration. Missing transverse energy performance of the CMS detec-
2817 tor. *JINST*, 6:P09001, 2011. doi: 10.1088/1748-0221/6/09/P09001.
- 2818 [64] Artur Kalinowski. CMS AN-19-032 (internal): Reconstruction of a τ pair in-
2819 variant mass with a simplified likelihood scan, 2019.
- 2820 [65] CMS TAU POG. Tau Physics Object Group: Tau ID Recommendation

- 2821 For Run 2, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/TauIDRecommendationForRun2>.
- 2823 [66] CMS MUO POG. Muon Physics Object Group: Recommendations, 2024. URL
2824 <https://twiki.cern.ch/twiki/bin/view/CMS/MuonPOG>.
- 2825 [67] CMS MUO POG. Muon Physics Object Group: Reference guidelines and results
2826 for muon momentum scale and resolution in Run II, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/MuonReferenceScaleResolRun2>.
- 2828 [68] CMS HTT working group. Higgs To Tau Tau Working TWiki for the full Run-
2829 2 legacy analysis, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/HiggsToTauTauWorkingLegacyRun2>.
- 2831 [69] CMS ELE POG. Electron Physics Object Group: Recommendations,
2832 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/EgammaRunIIRecommendations>.
- 2834 [70] CMS ELE POG. Electron Physics Object Group: Recommendations for
2835 2016 to 2018 UL, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/EgammaUL2016To2018>.
- 2837 [71] CMS TAU Embedding Group. Tau embedded samples using 2016
2838 data, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/TauTauEmbeddingSamples2016Legacy>.
- 2840 [72] CMS TAU Embedding Group. Tau embedded samples using 2017
2841 data, 2024. URL <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TauTauEmbeddingSamples2017>.
- 2843 [73] CMS TAU Embedding Group. Tau embedded samples using 2018

- 2844 data, 2024. URL <https://twiki.cern.ch/twiki/bin/viewauth/CMS/>
2845 TauTauEmbeddingSamples2018.
- 2846 [74] Tau Lepton Run 2 Trigger Performance. 2019. URL <https://cds.cern.ch/record/2678958>.
- 2848 [75] CMS Taus High Level Trigger Studies. Tau Lepton Run 2 Trigger Performance
2849 (CMS DP-2019/012), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/HLTauAllRun2>.
- 2851 [76] Muon HLT Performance with 2018 Data. 2018. URL <https://cds.cern.ch/record/2627469>.
- 2853 [77] Single and Double Electron Trigger Efficiencies using the full Run 2 dataset.
2854 2020. URL <https://cds.cern.ch/record/2888577>.
- 2855 [78] Run II Trigger Performance For $e\mu$ Triggers. 2019. URL <https://cds.cern.ch/record/2687013>.
- 2857 [79] Performance of electron and photon reconstruction in Run 2 with the CMS
2858 experiment. 2020. URL <https://cds.cern.ch/record/2725004>.
- 2859 [80] CMS Collaboration. Performance of the CMS muon detector and muon recon-
2860 struction with proton-proton collisions at $\sqrt{s} = 13$ TeV. *JINST*, 13(06):P06015,
2861 2018. doi: 10.1088/1748-0221/13/06/P06015.
- 2862 [81] Piet Verwilligen. Muons in the cms high level trigger system. *Nuclear
2863 and Particle Physics Proceedings*, 273-275:2509–2511, 2016. ISSN 2405-6014.
2864 doi: <https://doi.org/10.1016/j.nuclphysbps.2015.09.441>. URL <https://www.sciencedirect.com/science/article/pii/S240560141500930X>. 37th Inter-
2865 national Conference on High Energy Physics (ICHEP).
- 2866

- 2867 [82] Muon tracking performance in the CMS Run-2 Legacy data using the tag-and-
2868 probe technique. 2020. URL <https://cds.cern.ch/record/2724492>.
- 2869 [83] V.M. Abazov, B. Abbott, M. Abolins, et al. A novel method for modeling
2870 the recoil in W boson events at hadron colliders. *Nuclear Instruments and*
2871 *Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors*
2872 *and Associated Equipment*, 609(2):250–262, 2009. ISSN 0168-9002. doi: <https://doi.org/10.1016/j.nima.2009.08.056>. URL <https://www.sciencedirect.com/science/article/pii/S0168900209016623>.
- 2875 [84] CMS Collaboration. Search for an exotic decay of the Higgs boson to a pair of
2876 light pseudoscalars in the final state with two b quarks and two τ leptons in
2877 proton-proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Lett. B*, 785:462, 2018. doi:
2878 [10.1016/j.physletb.2018.08.057](https://doi.org/10.1016/j.physletb.2018.08.057).
- 2879 [85] CMS LUMI POG. Luminosity Physics Object Group: Recommendations, 2024.
2880 URL <https://twiki.cern.ch/twiki/bin/view/CMS/TWikiLUM>.
- 2881 [86] The modeling of the top quark p_T (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/TopPtReweighting>.
- 2883 [87] CMS BTV group. Methods to apply b-tagging efficiency scale fac-
2884 tors (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/BTagShapeCalibration>.
- 2886 [88] CMS Collaboration. Jet energy scale and resolution in the CMS experiment in
2887 pp collisions at 8 TeV. *JINST*, 12(02):P02014, 2017. doi: [10.1088/1748-0221/12/02/P02014](https://doi.org/10.1088/1748-0221/12/02/P02014).
- 2889 [89] Garvita Agarwal. Jet Energy Scale and Resolution Measurements in CMS. *PoS*,
2890 ICHEP2022:652, 2022. doi: [10.22323/1.414.0652](https://doi.org/10.22323/1.414.0652).

- 2891 [90] CMS JERC group. Jet Energy Corrections (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/JECDataMC>.
- 2892
- 2893 [91] CMS JERC group. Jet Energy Resolution (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/JetResolution>.
- 2894
- 2895 [92] CMS MUO POG. Muon Physics Object Group: Baseline muon selec-
- 2896 tions for Run-II, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/ SWGuideMuonIdRun2>.
- 2897
- 2898 [93] CMS ELE POG. Electron Identification Based on Simple Cuts, 2024. URL
- 2899 <https://twiki.cern.ch/twiki/bin/view/CMSPublic/EgammaPublicData>.
- 2900 [94] Jose Enrique Palencia Cortezon. Single top quark production at CMS. Technical
- 2901 report, CERN, Geneva, 2018. URL <https://cds.cern.ch/record/2640578>.
- 2902 [95] CMS Collaboration. Measurements of the electroweak diboson production cross
- 2903 sections in proton-proton collisions at $\sqrt{s} = 5.02$ TeV using leptonic decays.
- 2904 *Phys. Rev. Lett.*, 127(19):191801, 2021. doi: 10.1103/PhysRevLett.127.191801.
- 2905 [96] CMS Collaboration. A portrait of the Higgs boson by the CMS experiment
- 2906 ten years after the discovery. *Nature*, 607(7917):60–68, 2022. doi: 10.1038/
- 2907 s41586-022-04892-x.
- 2908 [97] CMS JERC group. Jet energy scale uncertainty sources (TWiki), 2024. URL
- 2909 <https://twiki.cern.ch/twiki/bin/view/CMS/JECUncertaintySources>.
- 2910 [98] TOP Systematic Uncertainties (Run 2) (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TopSystematics>.
- 2911
- 2912 [99] Search for a non-standard-model Higgs boson decaying to a pair of new light
- 2913 bosons in four-muon final states. Technical report, CERN, Geneva, 2013. URL
- 2914 <https://cds.cern.ch/record/1563546>.

- 2915 [100] Michiel Botje et al. The PDF4LHC Working Group Interim Recommendations.
2916 1 2011.
- 2917 [101] Cécile Caillol, Pallabi Das, Sridhara Dasu, Pieter Everaerts, Stephanie Kwan,
2918 Isobel Ojalvo, and Ho-Fung Tsoi. CMS AN-20-213 (internal): Search for an
2919 exotic decay of the 125 GeV Higgs boson to light pseudoscalars, with a pair of
2920 b jets and a pair of tau leptons in the final state, 2020.
- 2921 [102] Kyle Cranmer. Practical Statistics for the LHC. In *2011 European School of*
2922 *High-Energy Physics*, pages 267–308, 2014. doi: 10.5170/CERN-2014-003.267.
- 2923 [103] Elham Khazaie, Maryam Zeinali, Hamed Bakhshiansohi, and Abideh Jafari.
2924 CMS AN-21-058 (internal): Search for exotic decays of the Higgs boson to a
2925 pair of new light bosons with two muons and two b jets in the final states at
2926 $\sqrt{s} = 13$ TeV, 2021.
- 2927 [104] CMS Higgs Physics Analysis Group. Summary of 2HDM+S searches at 13 TeV
2928 (Run 2), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMRun2>.