

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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³⁶⁵ **Chapter 1**

³⁶⁶ **Introduction**

³⁶⁷ The Standard Model is the current prevailing theoretical framework that encompasses
³⁶⁸ all known elementary particles to date and describes their interactions, yet falls short
³⁶⁹ of describing open problems in physics. Here, we describe the history of the Standard
³⁷⁰ Model and its particle content (Section 1.1), and provide a mathematical motivation of
³⁷¹ the SM as a gauge theory (Section 1.2). We introduce the Higgs mechanism (Section
³⁷² 1.3), and outline two groups of theoretical extensions to the Standard Model that
³⁷³ feature extended Higgs sectors (Sections 1.4 and 1.5).

³⁷⁴ **1.1 History of the Standard Model**

³⁷⁵ The building blocks of our modern-day understanding of particle physics were estab-
³⁷⁶ lished over the course of many decades by experimental discoveries and theoretical
³⁷⁷ advances, culminating in the development of a theoretical framework known as the
³⁷⁸ Standard Model (SM). In the 1880s, the electron was the first subatomic particle to
³⁷⁹ be identified, through measurements of particles produced by ionizing gas. By the
³⁸⁰ 1930s, atoms were known to consist mostly of empty space, with protons and neutrons
³⁸¹ concentrated at the center and orbited by electrons. Spurred by advances in parti-
³⁸² 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

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

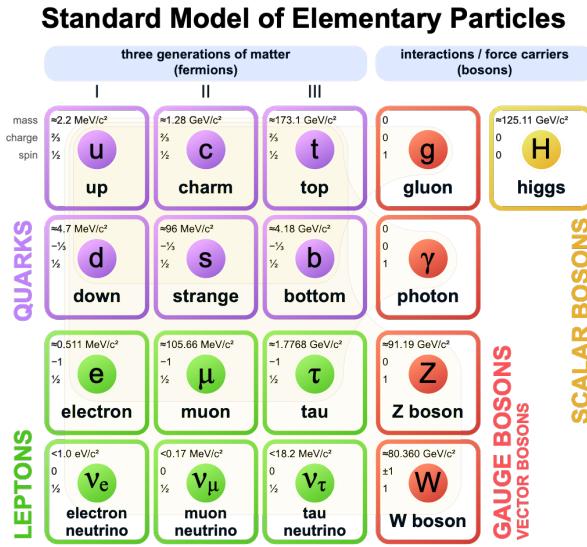


Figure 1.1: Table of Standard Model particles showing the grouping of the fermions into three generations of matter and the bosons, responsible for carrying the three fundamental forces in the Standard Model. The masses, charges, and spins of the particles are shown. The antimatter counterparts of the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

415 1.2 The Standard Model as a gauge theory

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

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

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

423 An example of this gauge invariance is classical physics is the electromagnetic
424 interaction, where the fundamental field is the four-vector potential A^μ [4]. The
425 physical electromagnetic fields and Maxwell's equations arise from the elements of
426 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
427 transformation of the form

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

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

431 One important consequence of gauge symmetry comes from the application of
432 Noether's theorem, which states that for every global transformation under which the
433 Lagrangian density is invariant, there exists a conserved quantity. If $\mathcal{L}(\Psi(x), \partial_\mu \Psi(x))$
434 is invariant under the transformation of the wave function $\Psi(x) \rightarrow \Psi'(x)$, where
435 $\Psi'(x) = \Psi(x) + \delta\Psi(x)$, then there exists a conserved current

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

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

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

⁴⁴⁴ transformation $\Psi'(x) = \exp(ie\chi)\Psi(x)$, and allow the phase χ to be a function of
⁴⁴⁵ spacetime [4]. A wave function of the form

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

⁴⁴⁶ can be verified to *not* be a solution to the Dirac equation for free particles: $(i\gamma^\mu\partial_\mu -$
⁴⁴⁷ $m)\Psi(x) = 0$. This necessitates a modified Dirac equation, where the derivative takes
⁴⁴⁸ into account that the vector field $V(x)$ needs to be compared at two displaced space-
⁴⁴⁹ time points in a curvilinear coordinate system:

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

⁴⁵⁰ We define a covariant derivative,

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

⁴⁵¹ where $A_\mu(x)$ is a 4-vector potential. Thus the modified Dirac equation reads:

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

⁴⁵² The simultaneous gauge transformation $A'_\mu(x) = A_\mu(x) - \partial_\mu\chi(x)$ and wavefunction
⁴⁵³ transformation $\Psi'(x) = \exp(ie\chi(x))\Psi(x)$ leaves the covariant-derivative form of the
⁴⁵⁴ Dirac equation (Eqn 1.1) invariant.

⁴⁵⁵ The generalization of this result is as follows: if a theory is invariant for unitary
⁴⁵⁶ transformations U of the particle states according to

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

457 One must define a derivative of the form

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

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

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

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

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

465 • 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-
466 potentials. $\tau/2$ are the Pauli matrices, generators of the $SU(2)$ transformation.

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

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

471 1.3 The Higgs Mechanism

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

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

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

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

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

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

493 The minimal self-interacting Higgs potential that is invariant under $SU(2)_L \times$
 494 $U(1)_Y$ is given by

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

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

496 energy is minimized at

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

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

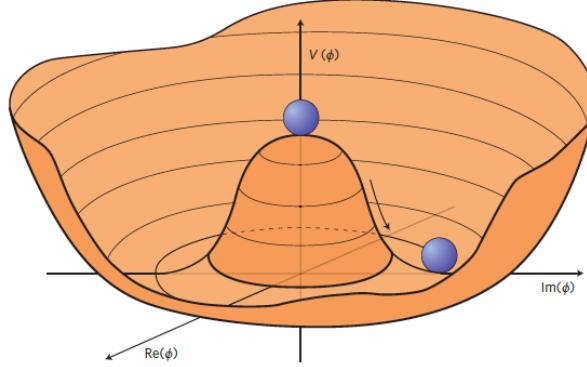


Figure 1.2: An illustration of the Higgs potential [5]. Choosing any of the points at the bottom of the potential breaks spontaneously the rotational $U(1)$ symmetry.

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

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

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

505 1.4 Two-Higgs Doublet Models

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

508 with hypercharge $Y = +\frac{1}{2}$, denoted here as $H \sim 2_{+1/2}$. These extensions are found
 509 in several theories such as supersymmetry. A general 2HDM can be extended with a
 510 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:

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

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

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

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

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

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

518 We assume that the 2HDM is near or in the decoupling limit: $\alpha \rightarrow \pi/2 - \beta$, where
 519 the lightest state in the 2HDM is h , which we identify as the 125 GeV Higgs particle
 520 [6]. In this limit, the fermion couplings of h become identical to the Standard Model

521 Higgs, while the gauge boson couplings are very close to Standard Model-like for
 522 $\tan \beta \gtrsim 5$. All of the properties of h can be determined by just two parameters: $\tan \beta$
 523 and α , and the fermion couplings to the two Higgs doublets.

524 2HDM can be extended by a scalar singlet (2HDM+S) [6]:

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

525 If this singlet only couples to the Higgs doublets $H_{1,2}$ and has no direct Yukawa
 526 couplings, all of its couplings to SM fermions result from mixing with $H_{1,2}$. Under
 527 these simple assumptions, exotic Higgs decays $h \rightarrow ss \rightarrow X\bar{X}Y\bar{Y}$ or $h \rightarrow aa \rightarrow$
 528 $X\bar{X}Y\bar{Y}$, and $h \rightarrow aZ \rightarrow X\bar{X}Y\bar{Y}$ are permitted, where $s(a)$ is a (pseudo)scalar mass
 529 eigenstate mostly composed of $S_R(S_I)$, and X, Y are Standard Model fermions or
 530 gauge bosons. There are two pseudoscalars in the 2HDM+S, and the mostly singlet-
 531 like pseudoscalar can be chosen to be the one lighter than the SM-like Higgs. For
 532 $m_a < m_h - m_Z \sim 35$ GeV, the exotic Higgs decay $h \rightarrow Za$ is possible, and for
 533 $m_a < m_h/2 \approx 63$ GeV, the exotic Higgs decay $h \rightarrow aa$ is possible.

534 In 2HDM, and by extension 2HDM+S, there are four types of fermion couplings
 535 commonly discussed in the literature that forbid flavor-changing neutral currents at
 536 tree level [6]. These are referred to as Type I (all fermions couple to H_2), Type II
 537 (MSSM-like, d_R and e_R couple to H_1 , u_R to H_2), Type III (lepton-specific, leptons
 538 and quarks couple to H_1 and H_2 respectively) and Type IV (flipped, with u_R , e_R
 539 coupling to H_2 and d_R to H_1). The exact branching ratios of the pseudoscalars to
 540 Standard Model particles vary depending on the 2HDM+S model and the value of
 541 $\tan \beta$ (e.g. Fig. 1.3).

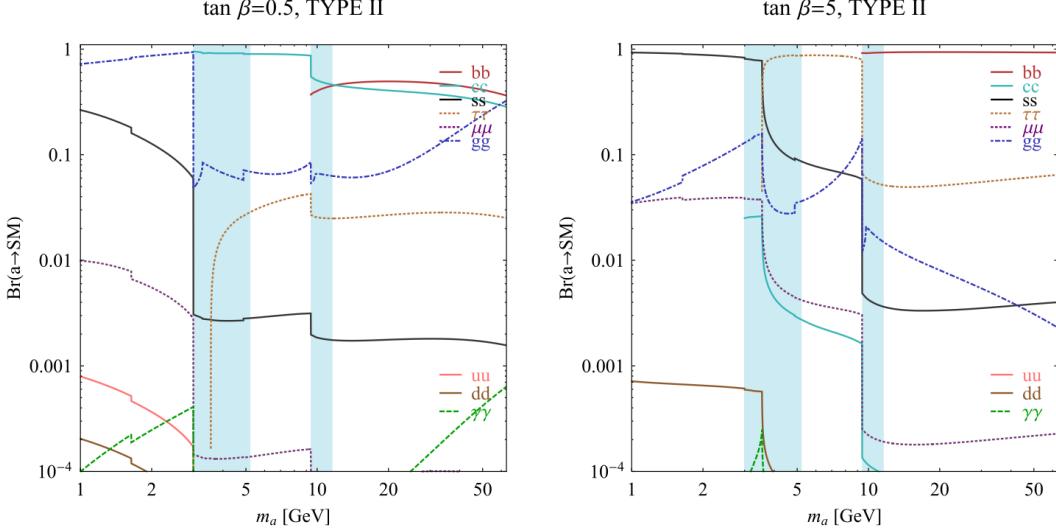


FIG. 7 (color online). Branching ratios of a singletlike pseudoscalar in the 2HDM + S for type-II Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.

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.

552 The mass eigenstates $h_{1,2,3}$ are related to the fields $\phi_{h,S,X}$ through a 3×3 orthogonal
553 mixing matrix denoted R . The mass eigenstates are assumed to be ordered $M_1 \leq$
554 $M_2 \leq M_3$. R is parameterized by the three mixing angles θ_{hS} , θ_{hX} , θ_{SX} . The nine
555 parameters of the scalar potential can be expressed in terms of the three physical
556 Higgs masses, the three mixing angles, and the three vacuum expectation values.

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

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

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

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

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

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

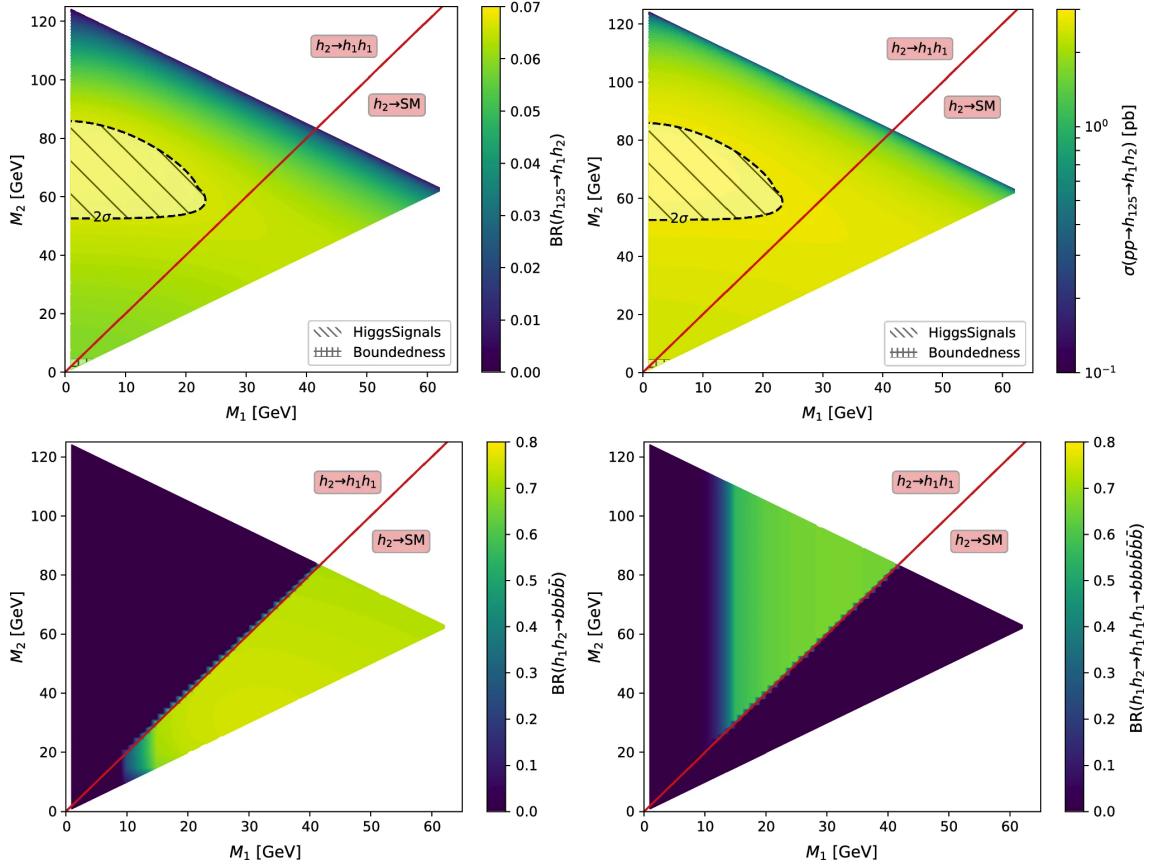


Figure 1.4: Benchmark plane BP1 for benchmark scenario 1 from [7], for the decay signature $h_{125} \rightarrow h_1 h_2$ with $h_{125} \equiv h_3$, defined in the (M_1, M_2) plane. The color code shows $\text{BR}(h_3 \rightarrow h_1 h_2)$ (*top left*) and the 13 TeV LHC signal rate for $pp \rightarrow h_3 \rightarrow h_1 h_2$ (*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.

⁵⁸¹ **Chapter 2**

⁵⁸² **The Large Hadron Collider and the**
⁵⁸³ **CMS Experiment**

⁵⁸⁴ This chapter introduces the key aspects of the CERN Large Hadron Collider (LHC)
⁵⁸⁵ and the Compact Muon Solenoid (CMS) experiment where the work for this thesis was
⁵⁸⁶ conducted. Section 2.1 describes the history of accelerator developments at CERN
⁵⁸⁷ that led to the construction of the LHC, the current LHC configuration, and the
⁵⁸⁸ largest experiments located at the LHC. The concepts of beam luminosity and pileup,
⁵⁸⁹ which are critical for understanding and measuring high-energy particle collisions,
⁵⁹⁰ are described in Section 2.2 and discussed in the context of the High-Luminosity
⁵⁹¹ LHC (HL-LHC) upgrade in Section 2.3. Lastly, Section 2.4 describes the design
⁵⁹² and function of CMS and its subdetectors, and terminates in a description of data
⁵⁹³ processing at CMS, beginning from online event filtering in the Level-1 Trigger, to
⁵⁹⁴ processing in the High-Level Trigger, to offline particle reconstruction, and finally
⁵⁹⁵ long-term storage and processing of measured events.

596 2.1 The Large Hadron Collider

597 CERN, the European Organization for Nuclear Research, is an international organiza-
598 tion based in Meyrin, Switzerland which operates the world's largest particle physics
599 laboratory, and is the site of the Large Hadron Collider (LHC) [8]. The very first
600 accelerator built at CERN was the 600 MeV Synchrocyclotron (SC), which initially
601 provided beams for CERN's first experiments. The newer and more powerful Proton
602 Synchrotron (PS), which could accelerate particles to an energy of 28 GeV, began op-
603 erations in 1959 and is still in use today. The first hadron collider at CERN was the
604 Intersecting Storage Rings (ISR), which consisted of two interlaced rings each with a
605 diameter of 200. The ISR collided protons at a center-of-mass energy of 62 GeV and
606 began measuring collisions in 1971. In 1968 CERN began to accelerate heavy ions
607 in the Super Proton Synchrotron (SPS), which is 7 kilometers in circumference and
608 was the first of CERN's giant underground rings to be built. The SPS became the
609 forefront of CERN's particle physics program in 1976, and in 1981 was converted into
610 a proton-antiproton collider. The final and largest underground ring constructed at
611 CERN was the Large Electron-Positron (LEP) collider, which was commissioned in
612 July 1989 and hosted 5176 magnets and 128 accelerating cavities located around a
613 27-kilometer circumference. Over 11 years of research, four detectors, ALEPH, DEL-
614 PHI, L3, and OPAL measured the collisions, with collision energies reaching up to
615 209 GeV in the year 2000. In November 2000, LEP was closed down to make way for
616 the construction of the LHC in the same tunnel.

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

623 the Proton Synchrotron (PS), and 450 GeV in the Super Proton Synchrotron (SPS).
624 The protons are transferred to the two beam pipes of the Large Hadron Collider
625 (LHC). The LHC is a 27-kilometer ring of superconducting magnets, inside which
626 one beam circulates clockwise and the other counterclockwise. Each LHC ring takes
627 4 minutes and 20 seconds to fill, and it takes about 20 minutes for the protons to
628 reach their maximum energy. During normal operating conditions, beams circulate
629 for many hours inside the LHC ring.

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

642 2.2 Luminosity and pileup

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

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

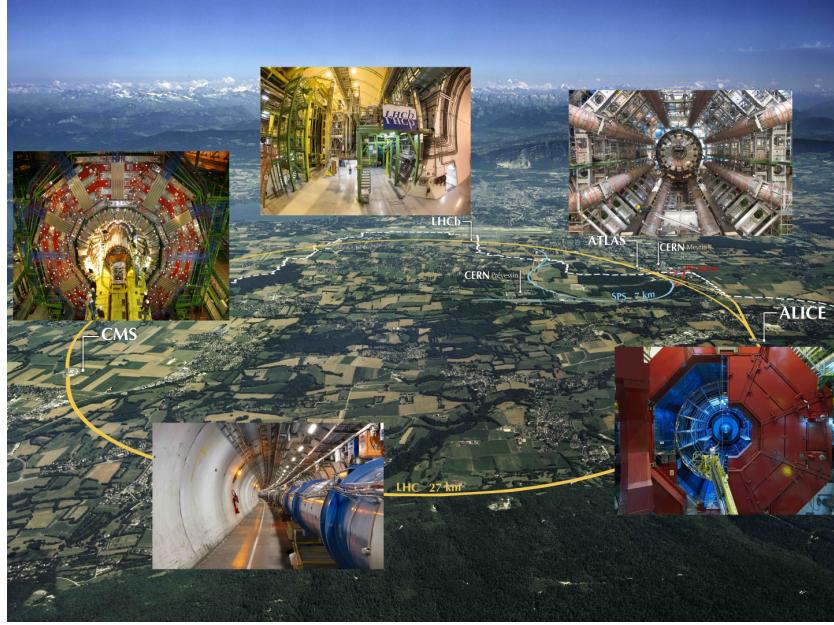


Figure 2.1: Aerial view of the Large Hadron Collider (LHC) spanning the border of France and Switzerland, and the four major experiments located around the ring: CMS (Compact Muon Solenoid), LHCb (LHC beauty), ATLAS (A Toroidal LHC Apparatus), and ALICE (A Large Ion Collider Experiment) [11].

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,

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

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

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

The LHC’s nominal beam luminosities are sufficiently large for multiple proton-proton collisions to occur in the same time window of 25 nanoseconds in which proton bunches collide [18]. These multiple collisions will lead to particle interactions overlapping in the detector. To measure a proton-proton collision, the single collision must be separated from overlapping collisions, which are called “pileup” collisions. A distribution of pileup in the data-taking years 2016-2018 is shown in Fig. 2.2. The pileup is defined as the average number of pp collisions per bunch crossing.

CMS reports an inelastic pp cross section of $\sigma_{\text{inel}} = 68.6$ millibarns at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ [19], which can be used to estimate pileup as follows:

$$\text{Pileup} = \frac{\mathcal{L} \times \sigma_{\text{inel}}}{n_b \cdot f} \quad (2.3)$$

With the example values above, pileup can be estimated to be ~ 22 .

679 While useful in the search for rare physics processes, higher luminosities create
 680 more intense pileup conditions, posing a greater challenge to detector performance
 681 and particle reconstruction and identification.

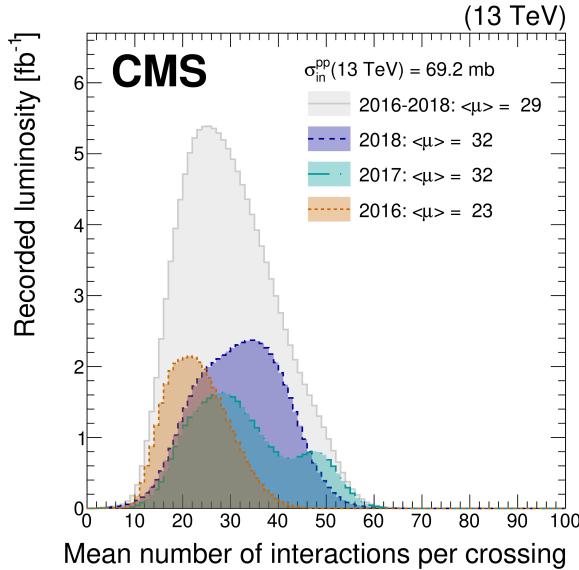


Figure 2.2: Distribution of the mean number of inelastic collisions per bunch crossing (pileup) in data [18], for proton-proton collisions in 2016 (*dotted orange*), 2017 (*dotted light blue*), 2018 (*dotted dark blue*), and integrated over 2016-2018 (*solid grey*). A cross-section of inelastic proton-proton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

682 2.3 The High-Luminosity LHC

683 The High-Luminosity LHC (HL-LHC) is a major upgrade of the LHC scheduled
 684 to take place in the late 2020s, that will increase the instantaneous luminosity by
 685 a factor of five beyond the original design value, and the integrated luminosity
 686 by a factor of ten [20]. This will be accomplished through accelerator technological
 687 advances: for instance, reduction of the interaction point β^* from 0.55 m down to 0.15
 688 m by installation of new final-focusing magnets, and improvements in the geometric
 689 luminosity loss factor $F \approx 1$ through the installation of crab cavities that optimize

690 the orientation of colliding bunches. A further discussion of the HL-LHC upgrades
691 for the CMS detector follows in Chapter 3.

692 2.4 The CMS Detector

693 The Compact Muon Solenoid (CMS) experiment was conceived to study proton-
694 proton and lead-lead collisions at a center-of-mass energy of 14 TeV (5.5 TeV nucleon-
695 nucleon) and at luminosities up to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ($10^{27} \text{ cm}^{-2} \text{ s}^{-1}$) [21] [22]. Starting
696 from the beam interaction region at the center of the CMS detector, particles first
697 pass through a silicon pixel and strip tracker, in which charged-particle trajectories
698 (tracks) and origins (vertices) are reconstructed from signals (hits) in the sensitive
699 layers. The tracker is immersed in a high-magnetic-field superconducting solenoid
700 that bends the trajectories of charged particles, allowing the measurement of their
701 electric charge and momenta. Electrons and photons are then absorbed in an electro-
702 magnetic calorimeter (ECAL) comprised of lead-tungstate scintillating-crystals. The
703 corresponding electromagnetic showers are detected as clusters of energy recording in
704 neighboring cells, from which the direction and energy of the particles can be deter-
705 mined. Charged and neutral hadrons may initiate a hadronic shower in the ECAL
706 as well, which is then fully absorbed in the hadron calorimeter (HCAL). The result-
707 ing clusters are used to estimate their direction and energies. Muons and neutrinos
708 pass through the calorimeters with little to no interactions. Neutrinos escaped un-
709 detected; muons produce hits in additional gas-ionization chamber muon detectors
710 housed in the iron yoke of the flux-return. A sketch of example particle interactions
711 in a transverse slice of the CMS detector is shown in Fig. 2.3. The collision data is
712 recorded with the use of the Level-1 (L1) trigger (discussed in greater detail in 2.5.5),
713 the High-Level Trigger (HLT), and data acquisition systems ensuring high efficiency
714 in selecting physics events of interest.

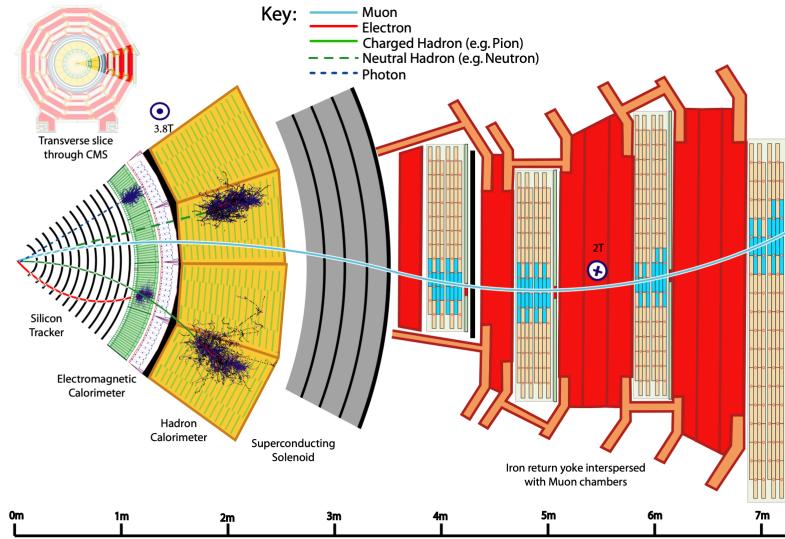


Figure 2.3: Sketch of particle trajectories of muons, electrons, charged and neutral hadrons, and photons in a transverse cross-section of the CMS detector [22].

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

725 2.5 Sub-detectors of CMS

726 This section details the sub-detectors of CMS that operate to identify and precisely
 727 measure muons, electrons, photons, and jets over a large energy range.

728 2.5.1 Inner tracking system

729 The CMS Tracker performs robust tracking and detailed vertex reconstruction in the
730 4 T magnetic field of the superconducting solenoidal magnet. The primary sensors
731 used in the tracker are p^+ on n -bulk devices, which allow high voltage operation and
732 are radiation-resistant [23] [24]. The active envelope of the CMS Tracker extends to a
733 radius of 115 cm, over a length of approximately 270 cm on each side of the interaction
734 point [23]. Charged particles in the region $|\eta| \lesssim 1.6$ benefit from the full momentum
735 measurement precision. In this region, a charged particle with p_T of 1000 GeV has a
736 sagitta of $\sim 195 \mu\text{m}$. The Tracker acceptance extends further to $|\eta| = 2.5$, with a
737 reduced radius of approximately 50 cm.

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

742 A schematic view of the current Phase-1 CMS tracker [25], including the pixel
743 detector, is shown in Fig. 2.4. The Phase-1 pixel detector consists of three barrel
744 layers (BPIX) at radii of 4.4 cm, 7.3 cm, and 10.2 cm, and two forward/backward disks
745 (FPIX) at longitudinal positions of ± 34.5 cm and ± 46.5 cm, and extending in radius
746 from about 6 cm to 15 cm. These pixelated detectors produce 3D measurements along
747 the paths of charged particles with single hit resolutions between 10-20 μm .

748 After the pixel and on their way out of the tracker, particles pass through the
749 silicon strip tracker which reaches out to a radius of 130 cm (Fig. 2.4). The sensor
750 elements in the strip tracker are single-sided p -on- n type silicon micro-strip sensors
751 [21]. The silicon strip detector consists of four inner barrel (TIB) layers assembled
752 in shells, with two inner endcaps (TID), each composed of three small discs. The
753 outer barrel (TOB) consists of six concentric layers. Two endcaps (TEC) close off
754 the tracker on either end.

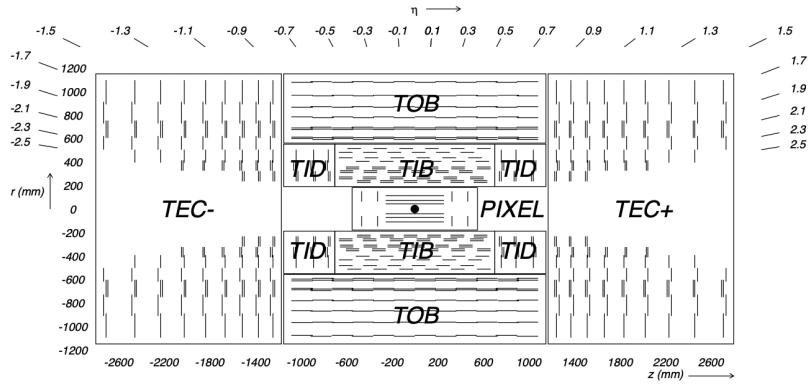


Figure 2.4: Cross section of the current Phase-1 CMS tracker [25]. Each line represents a detector module. Double lines indicate back-to-back modules which deliver two-dimensional (stereo) hits in the strip tracker.

2.5.2 ECAL

The electromagnetic calorimeter (ECAL) of CMS measures electromagnetic energy deposits with high granularity. One of the driving criteria in the design was the capability of detecting the Standard Model Higgs boson decay to two photons (in fact, the channel in which the 125 GeV Higgs boson was discovered at CMS). ECAL is a hermetic homogeneous calorimeter comprised of 61,200 lead tungstate (PbWO_4) crystals mounted in the central barrel, with 7,324 crystals in each of the two endcaps [21]. A preshower detector is located in front of the endcap crystals. Avalanche photodiodes (APDs) are used as photodetectors in the barrel and vacuum phototriodes (VPTs) in the endcaps.

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

772 by electrons and photons.

773 The barrel part of the ECAL (EB) covers the pseudorapidity range $|\eta| < 1.479$
774 [21]. The barrel granularity is 360-fold in ϕ and (2×85) -fold in η . The crystal cross-
775 section corresponds to approximately 0.0174×0.0174 in $\eta - \phi$ or $22 \times 22 \text{ mm}^2$ at the
776 front face of the crystal, and $26 \times 26 \text{ mm}^2$ at the rear face. The crystal length is 230
777 mm, corresponding to $25.8 X_0$.

778 The ECAL read-out acquires the signals of the photodetectors [21]. At each bunch
779 crossing, digital sums representing the energy deposit in a trigger tower, comprising
780 5×5 crystals in $\eta \times \phi$, are generated and sent to the Level-1 trigger system (detailed
781 in Section 2.5.5).

782 2.5.3 HCAL

783 The hadronic calorimeter (HCAL) of CMS measures hadronic energy, which is key to
784 characterizing the presence of apparent missing transverse energy which could arise
785 from hadron jets and neutrinos or exotic particles [21]. A schematic of the components
786 of HCAL are shown in Fig. 2.5. The HCAL barrel (HB) and endcaps (HE) are located
787 outside of the tracker and the ECAL, spanning a radius of 1.77 m (outer extent of
788 ECAL) up to 2.95 m (inner extent of the magnet coil). An outer hadron calorimeter
789 (HO) is placed outside the solenoid to complement the barrel calorimeter. Beyond
790 $|\eta| = 3$, the forward hadron calorimeter (HF) at 11.2 m from the interaction point
791 extend the pseudorapidity coverage to $|\eta| = 5.2$.

792 The HB is a sampling calorimeter covering the pseudorapidity range $|\eta| < 1.3$ [21].
793 It consists of 36 identical azimuthal wedges which form two half-barrels (HB+ and HB-
794), with a segmentation of $(\Delta\eta, \Delta\phi) = (0.087, 0.087)$. The HE covers pseudorapidity
795 $1.3 < |\eta| < 3$. The HB and endcap HE calorimeters are sampling calorimeters which
796 use brass as the absorber and plastic scintillator as the active material. Light from
797 the plastic scintillator is wavelength-shifted and captured in optic fibers which are

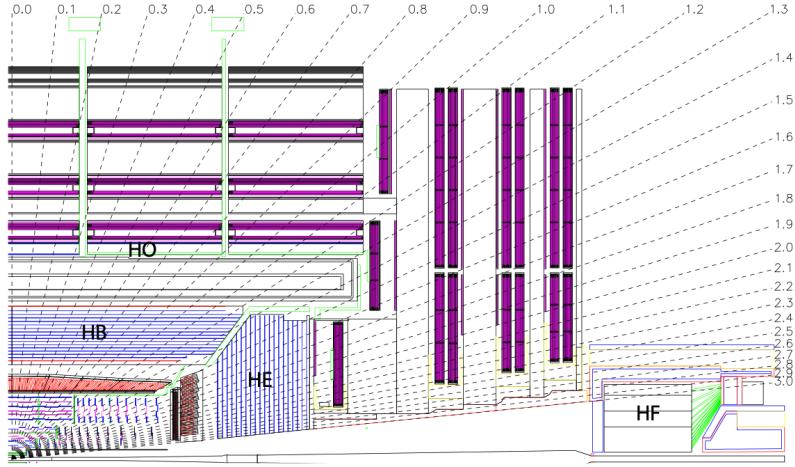


Figure 2.5: Longitudinal view of the CMS detector showing the hadron calorimeter barrel (HB), endcap (HE), outer (HO), and forward (HF) calorimeters from [21].

798 read out by front-end electronics [27].

799 In the central pseudorapidity region, the combined stopping power of EB plus the
800 HB is insufficient to contain hadron showers [21]. To ensure adequate sampling depth,
801 the hadron calorimeter is extended with a tail catcher, the HO. The size and position
802 of the tiles are designed to roughly map the layers of the HB to make towers with
803 the same granularity of 0.087×0.087 in η and ϕ . HO uses the same active material
804 as the HB and HE calorimeters, but uses the steel return yoke and magnet material
805 of CMS as absorbers [27].

806 The HF is a Cherenkov calorimeter based on a steel absorber and quartz fibers
807 which run longitudinally through the absorber and collect Cherenkov light, primarily
808 from the electromagnetic component of showers developed in the calorimeter [27].
809 Photomultiplier tubes are used to collect light from the quartz fibers. The HF is
810 designed to survive in the harsh radiation conditions and high particle flux of the
811 forward region. On average, 760 GeV per proton-proton interaction is deposited into
812 the two forward calorimeters, compared to only 100 GeV for the rest of the detector
813 [21]. Furthermore, this energy has a pronounced maximum at the highest rapidities.

814 **2.5.4 Muon detectors**

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

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

827 In the two endcap regions, the muon rates and background levels are high and the
828 magnetic field is large and non-uniform [21]. Here, the muon system uses cathode
829 strip chambers (CSCs) to identify muons between $0.9 < |\eta| < 2.4$. The cathode strips
830 of each chamber run radially outwards and provide a precision measurement in the
831 $r - \phi$ bending plane. The anode wires run approximately perpendicular to the strips
832 and are read out in order to measure η and the beam-crossing time of a muon.

833 In addition to the DT and CSC, a dedicated trigger system consisting of resistive
834 plate chambers (RPCs) in the barrel and endcap regions provide a fast, independent,
835 and highly-segmented trigger with a sharp p_T threshold over a large portion of the
836 pseudorapidity range ($|\eta| < 1.6$) of the muon system [21]. RPCs have good time
837 resolution but coarser position resolution compared to the DTs or CSCs. The RPCs
838 also play a role in resolving ambiguities in reconstructing tracks from multiple hits in
839 a chamber.

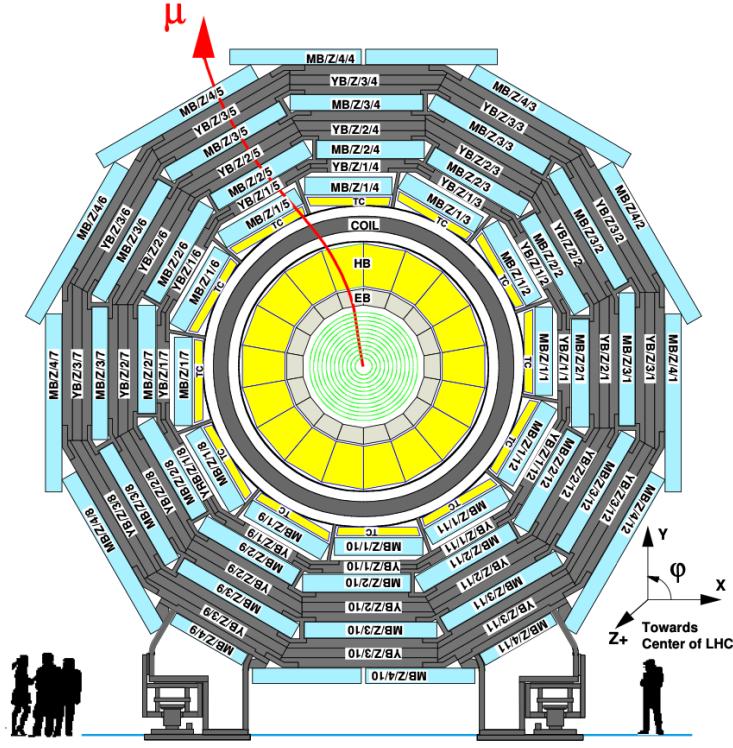


Figure 2.6: Layout of the CMS barrel muon drift tube (DT) chambers in one of the five wheels from [21]. The DTs are organized in 12 sectors of the yoke barrel (YB). In each of the 12 sectors of the yoke, there are 4 muon chambers per wheel (MB1, MB2, MB3, and MB4).

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]. The large number of minimum bias events per bunch crossing, combined with the small cross-sections of possible physics discovery signatures, necessitates a sophisticated event selection system for filtering this large event rate, as it is impossible to save all events. This data filtering system is implemented by CMS in two stages. The first stage is the Level-1 (L1) Trigger, which is deployed in custom electronic hardware systems and is responsible for reducing the event rate to around 100 kHz. The second stage is the High-Level

850 Trigger (HLT) which is described in Section 2.5.6. This section describes the Phase-1
 851 configuration of the Level-1 Trigger.

852 The L1 Trigger data flow of Phase-1 is shown in Fig. 2.7 [28], with organization
 853 into the L1 calorimeter trigger, the L1 muon trigger, and the L1 global trigger.

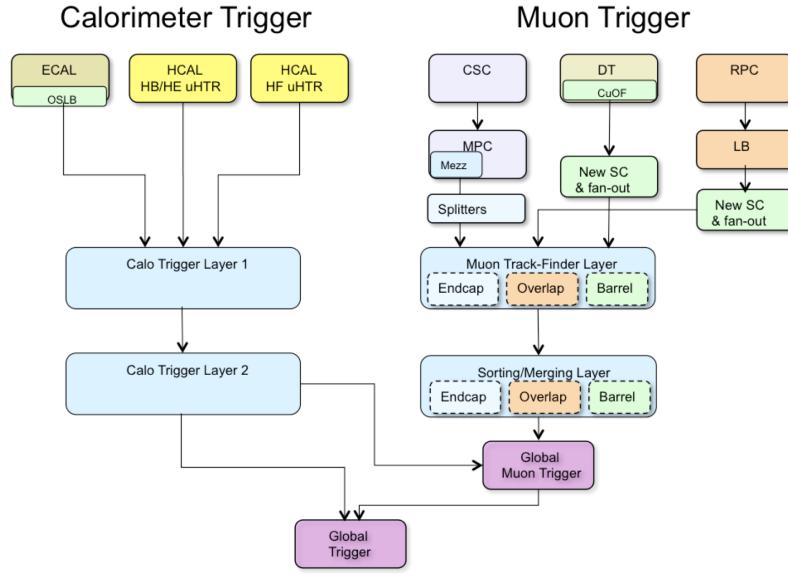


Figure 2.7: Dataflow for the Phase-1 Level-1 Trigger [28], which is implemented in custom hardware and is responsible for reducing the event rate from the LHC bunch crossing frequency of 400 MHz (bunch crossings every 25 ns) to a maximum rate of 100 kHz. In Phase-1, the Level-1 Trigger has access to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

854 The L1 calorimeter trigger begins with trigger tower energy sums formed by the
 855 ECAL, HCAL, and HF Trigger Primitive Generator (TPG) circuits from the indi-
 856 vidual calorimeter cell energies. In the original configuration, the ECAL energies
 857 were accompanied by a bit indicating the transverse extent of the electromagnetic
 858 energy deposits, and the HCAL energies were accompanied by a bit indicating the
 859 presence of minimum ionizing energy [29]. Between Long Shutdowns 1 and 2 (LS1
 860 and LS2), HF was upgraded to provide finer granularity information to the trigger,
 861 and the HCAL barrel and endcap front-end electronics were upgraded to provide
 862 high-precision timing information and depth segmentation information.

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

873 Each of the L1 muon triggers has its own trigger logic [29]. The RPC strips are
874 connected to a Pattern Comparator Trigger (PACT), which forms trigger segments
875 that are used to build tracks and calculate p_T . The RPC logic also provides some
876 hit data to the CSC trigger system to resolve ambiguities caused by two muons in
877 the same CSC. The CSCs form local charged tracks (LCTs) from the cathode strips,
878 which are combined with the anode wire information. LCTs are combined into full
879 muon tracks and assigned p_T values.

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

889 Information from the GCT and GT are sent to the Global Trigger (GT), which

890 makes the Level-1 Accept (L1A) decision to either discard or accept the bunch crossing
891 [29]. This is accomplished by sorting ranked trigger objects that are accompanied by
892 positional information in η and ϕ , permitting the trigger to applying criteria with
893 thresholds that can vary based on the location of the trigger objects, and/or to
894 require trigger objects to be close to or opposite from each other. The GT L1A
895 decision arrives at the detector front end with a $3.8\ \mu\text{s}$ latency after the interaction
896 at a rate which is required to be less than 100 kHz, and triggers a full readout of the
897 detector for further processing.

898 **2.5.6 The High-Level Trigger**

899 The HLT is implemented in software running on a large computer farm of fast com-
900 mercial processors [30] [31]. The algorithms in HLT have access to full data from
901 all CMS sub-detectors, including the tracker, with full granularity and resolution.
902 The HLT reconstruction software is similar to what is used offline for full CMS data
903 analysis. As a result, the HLT can calculate quantities with a resolution compara-
904 ble to the final detector resolution, compared to the L1 Trigger. The HLT performs
905 more computationally-intensive algorithms, such as combining tau-jet candidates in
906 the calorimeter with high- p_T stubs in the tracker, to form a hadronic tau trigger. The
907 maximum HLT input rate from the L1 Trigger is 100 kHz, and the HLT output rate
908 is approximately 100 Hz.

909 The HLT contains trigger paths, each corresponding to a dedicated trigger [32].
910 A path consists of several steps implemented as software modules. Each HLT trigger
911 path must be seeded by one or more L1 trigger bits: the first module always looks
912 for a L1 seed, consisting of L1 bit(s) and L1 object(s). Each module performs a well-
913 defined task such as unpacking (raw to digitized quantities), reconstruction of physics
914 objects (electrons, muons, jet, missing transverse energy, etc.), making intermediate
915 decisions that trigger more detailed reconstruction modules, and calculating the final

916 decision for the trigger path. If an intermediate filter decision is negative, the rest of
917 the path is not executed, and the trigger rejects the event.

918 **2.5.7 Particle reconstruction**

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

929 **2.5.8 Data storage and computational infrastructure**

930 The LHC generates over 15 petabytes (15 million gigabytes) of data every year, neces-
931 sitating a flexible computing system that can be accessed by researchers working at
932 the four main LHC experiments: ALICE, ATLAS, CMS, and LHCb. The Worldwide
933 LHC Computing Grid (WLCG) [33] is a global collaboration of computer centers that
934 links thousands of computers and storage systems in over 170 centers across 41 coun-
935 tries. These centers are arranged in “tiers”, and provide near real-time access to users
936 processing, analyzing, and storing LHC data. One of the final stages of data analy-
937 sis at LHC experiments is large-scale data processing taking place over distributing
938 computing, for instance, with the use of Condor [34], a distributed, scalable, flexible
939 batch processing system which accepts a computing job, allocates a resource to it,
940 executes it, and returns the result back to a user transparently.

941 **Chapter 3**

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

943 This chapter gives an overview of the High-Luminosity LHC upgrade of the LHC in
944 Section 3.1, and the upgrades for the Phase-2 CMS Level-1 (L1) Trigger in Section
945 3.2. One of the major upgrades is the new availability of calorimeter crystal-level
946 information to the L1 calorimeter trigger, compared to the current trigger which only
947 has access to tower-level information (a tower being 5 by 5 in crystals). To capitalize
948 on the increased spatial granularity of this information, an upgraded algorithm is
949 presented which reconstructs and identifies electron and photon candidates in the the
950 Layer-1 Calorimeter Trigger. A description of the algorithm and a validation of its
951 performance in Phase-2 conditions is given in Section 3.3.

952 **3.1 The High-Luminosity LHC**

953 In order to sustain and extend the LHC’s physics discovery program and maintain
954 operability for a decade or more, the LHC is undergoing a major upgrade to the High-
955 Luminosity LHC (HL-LHC). In its final configuration, the HL-LHC will deliver a peak
956 luminosity of $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, potentially leading to total integrated luminosity
957 of 4000 fb^{-1} after ten years of operations, scheduled to begin in 2027 [35]. This
958 integrated luminosity is about ten times the predicted luminosity reach of the LHC

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

964 3.2 The Phase-2 Level-1 Trigger

965 To achieve the goals of the HL-LHC program and to ensure the collection of information-
966 rich datasets in the HL-LHC, the Phase-2 upgrade of the CMS Level-1 Trigger [35]
967 must be upgraded in conjunction with the CMS sub-detectors and their readouts, to
968 maintain physics selectivity. The HL-LHC will produce an intense hadronic environ-
969 ment corresponding to 200 simultaneous collisions per beam crossing, necessitating
970 comprehensive upgrades of the trigger system outlined below.

971 To profit from the extended coverage and increased granularity of the upgraded
972 CMS detector, the latency of the L1 trigger system (time available to produce a L1
973 Accept signal) will be increased significantly from $3.8 \mu\text{s}$ to $12.5 \mu\text{s}$, with an increased
974 maximum output bandwidth of 750 kHz [35]. With the increased latency, in addition
975 to information from calorimeters and muon detectors (as in the Phase-1 system),
976 information from the new tracker and high-granularity endcap calorimeter can also
977 be included at L1 for the first time. This is illustrated in the functional diagram of
978 the architecture of the Phase-2 trigger system in Fig. 3.1.

979 The key feature of the Phase-2 L1 Trigger is the introduction of a correlator layer,
980 where algorithms produce higher-level trigger objects by combining information from
981 sub-detectors, with a selectivity approaching that of offline reconstruction in the
982 HLT [35]. Four independent data processing paths (grouped together in Fig. 3.1) are
983 implemented: tracking, calorimetry, muon systems, and particle-flow techniques:

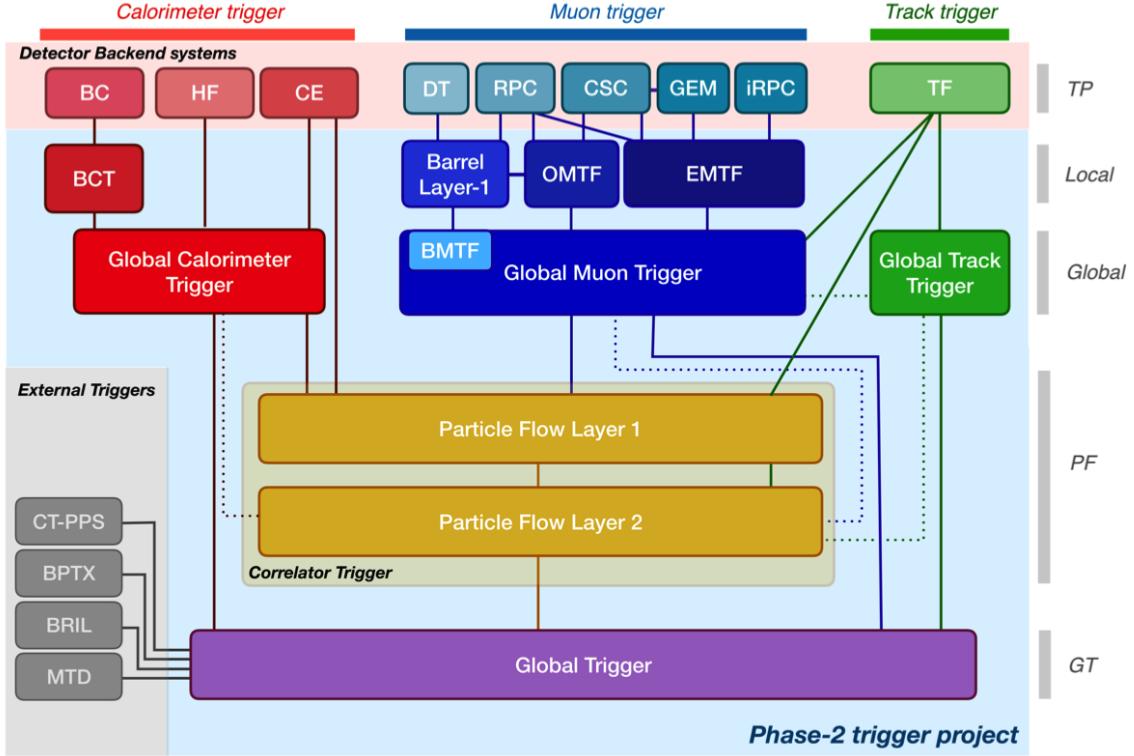


Figure 3.1: Functional diagram of the CMS L1 Phase-2 upgraded trigger design [35], showing the four trigger paths: calorimeter, muon, track, and Particle Flow. For the first time, tracking information will be available as early as the L1 Trigger.

- **Calorimeter Trigger path:** (red, Fig. 3.1) A barrel calorimeter trigger (BCT) and the HGCAL backend are used to produce high-granularity 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 [35]. 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) [36].

1017 3.3 Standalone Barrel Calorimeter electron/photon

1018 reconstruction

1019 The reconstruction and identification of electrons and photons (e/γ) begin with the
 1020 trigger primitives of the barrel ECAL and HCAL detectors and endcap HGCAL
 1021 calorimeters, covering the pseudorapidity region $|\eta| < 3$. The barrel and endcap re-
 1022 gions of the detector are intrinsically different enough to warrant different approaches
 1023 to e/γ reconstruction. This work focuses on the Standalone Calorimeter e/γ recon-
 1024 struction taking place in the barrel (Fig. 3.2).

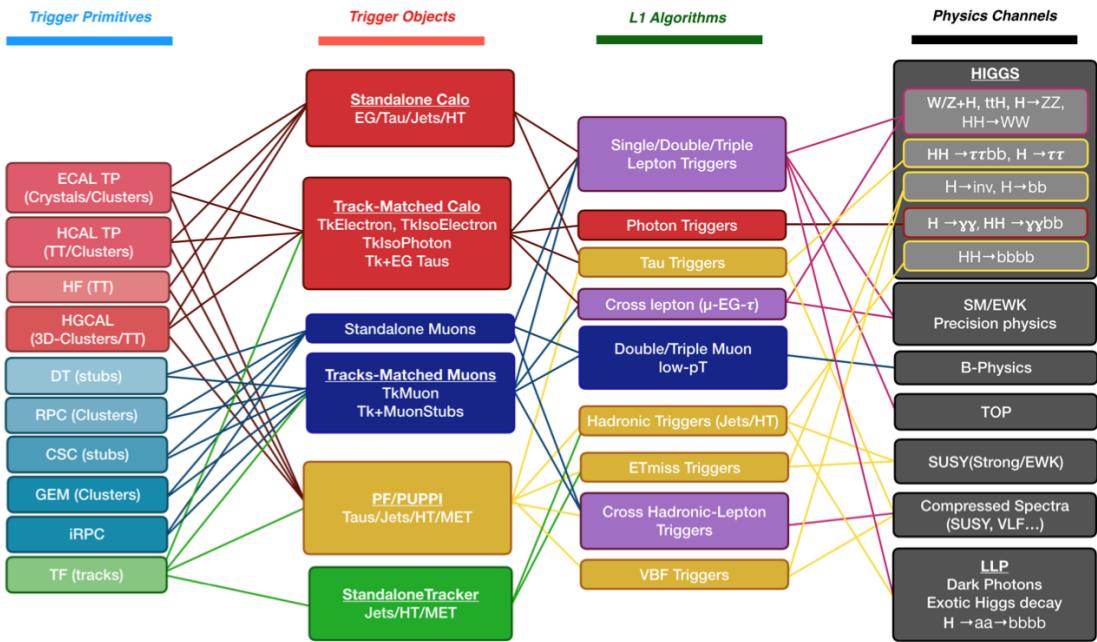


Figure 3.2: Summary of the links between the trigger primitives (*first column*), the trigger objects (*second column*), the Level-1 algorithms used in the menu (*3rd column*), and the physics channels (*4th column*), from [35], where a full description of the Phase-2 L1 algorithms can be found. This work focuses on developments for the Standalone Calorimeter electron and photon ("EG") reconstruction algorithm.

1025 **3.3.1 Phase-2 geometry of the ECAL Barrel trigger**

1026 In Phase-2, the upgrade of both on-detector and off-detector electronics for the barrel
1027 calorimeters trigger primitive generator (TPG) will stream single crystal data from
1028 the on-detector to the backend electronics, in contrast to the lower-granularity output
1029 of the Phase-1 ECAL TPG that is restricted to providing trigger tower sums of 5×5
1030 crystals [35]. A schematic representation of the geometry of the ECAL barrel in the
1031 Regional Calorimeter Trigger (RCT) is shown in Fig. 3.3. The barrel is spanned by
1032 36 RCT cards, each spanning 17×4 towers in $\eta \times \phi$. Each RCT card is subdivided
1033 into five “regions” as shown in Fig. 3.4. After initial clustering and processing, the
1034 outputs of the RCT card are sent to the Global Calorimeter (GCT) trigger, which is
1035 processed in three cards as shown in Fig. 3.5.

1036 **3.3.2 Phase-2 electron/photon reconstruction algorithm**

1037 The standalone barrel algorithm for reconstructing and identifying electrons and pho-
1038 tons in the Phase-2 Level-1 Trigger takes as input the digitized response of each crystal
1039 of the barrel ECAL, with a granularity 0.0175×0.0175 in $\eta \times \phi$, which is 25 times
1040 higher than the input to the Phase-1 trigger, which consisted of trigger towers with
1041 a granularity of 0.0875×0.0875 . In HCAL the tower size of 0.0875×0.0875 is un-
1042 changed. The trigger algorithm is designed to closely reproduce the algorithm used in
1043 the offline reconstruction, with limitations and simplifications due to trigger latency.

1044 In the RCT, an initial requirement of $p_T > 0.5$ GeV is imposed on the input
1045 trigger primitives (i.e. energies from the ECAL crystals and HCAL towers) to reject
1046 contribution from pileup. In one of the regions inside a RCT card (Fig. 3.4), the
1047 crystal containing the highest energy deposit is identified as the seed crystal, as shown
1048 in Fig. 3.6. The energy in the crystals in a window of size 3×5 in $\eta \times \phi$ around
1049 the seed cluster is added into a cluster. The energy is considered “clustered”. The
1050 process is repeated with the remaining “unclustered” energy, until up to four clusters

1051 are produced in the region.

1052 To improve e/γ identification and to reduce background contributions, identifica-
1053 tion and reconstruction algorithms are implemented at this stage:

1054 • Shower shape: The energy deposit sums around the seed crystal is computed in
1055 windows of size 2×5 and 5×5 (Fig. 3.6, *dashed lines*), with true e/γ clusters
1056 tending to produce showers that deposit most of their energy in a 2×5 region.

1057 • Bremsstrahlung recovery: e/γ tend to spread in the ϕ direction due to charged
1058 particles being bent by the magnetic field of the CMS solenoid. If sufficient
1059 energy comparable to the core 3×5 cluster is found in the adjacent 3×5
1060 windows (Fig. 3.6, *shaded yellow*), the energy is added to the core cluster and
1061 no longer considered unclustered energy.

1062 After parallel processing in the regions, the clusters in a RCT card are stitched
1063 together if they are located directly along the borders of a region (Fig. 3.3). The
1064 remaining unclustered ECAL energy is summed into ECAL towers.

1065 From each RCT card, the twelve highest-energy clusters, as well as any remaining
1066 unclustered energy, are sent to the GCT. Since each GCT card has information from
1067 sixteen RCT cards (Fig. 3.5), final stitching across the boundaries of the RCT cards
1068 is performed. One more identification algorithm is performed at this stage:

1069 • Isolation: One handle to reject backgrounds from e.g. pileup, comes from the
1070 tendency for background to be spread more uniformly across a large area in the
1071 detector, whereas genuine e/γ are expected to produce showers concentrated in
1072 the 3×5 crystal window. The energy sum in a large window of 7×7 in towers
1073 is computed and used to reject background.

1074 The performance of the standalone barrel e/γ algorithm in Phase-2 conditions is
1075 summarized in the efficiency and rates. The efficiencies are measured with a simulated
1076 Monte Carlo sample containing electrons. The rates are measured with a simulated

1077 minimum bias sample intended to closely mimic generic proton-proton collisions in
1078 the CMS detector. The performance of the Phase-2 emulator discussed in this work,
1079 which closely mimics the firmware logic and uses fixed-precision integers, is shown to
1080 be comparable to the previous emulator which used floats and idealized logic.

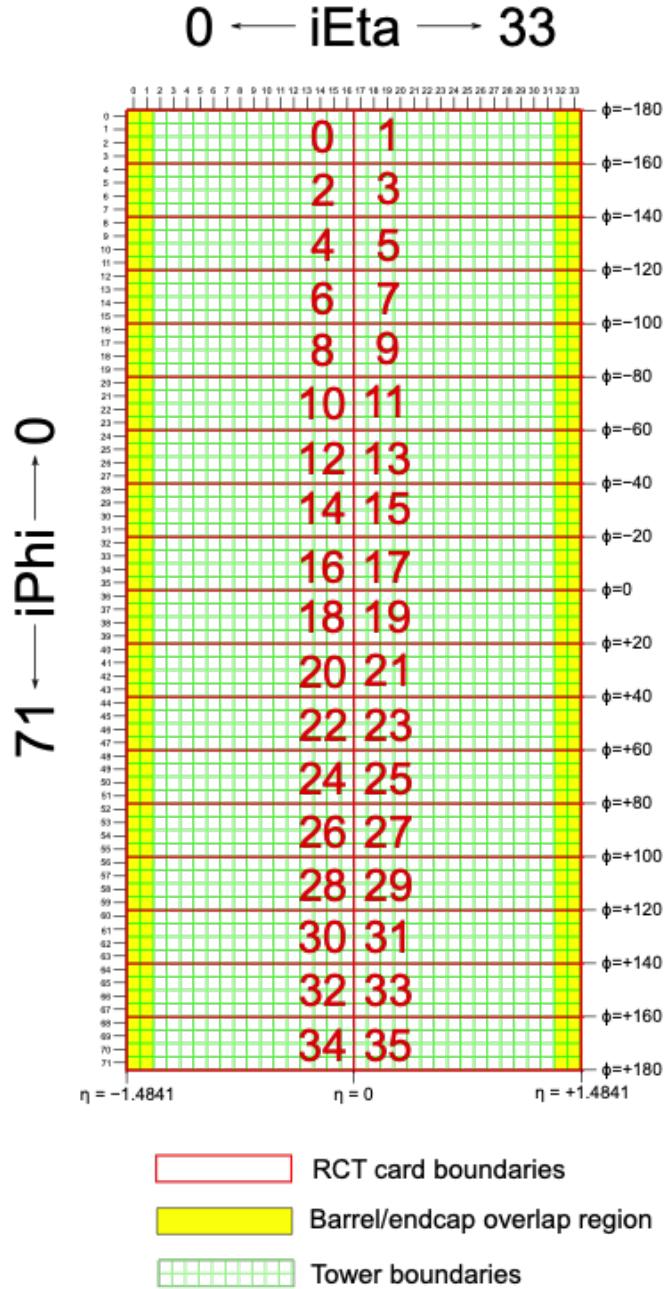


Figure 3.3: Schematic of the geometry of the Phase-2 ECAL barrel in the Regional Calorimeter Trigger (RCT), showing the division of the barrel region into 36 Regional Calorimeter Trigger (RCT) cards (*red*). Each card spans 17×4 towers in $\eta \times \phi$ (*green*), and each tower is 5×5 in single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

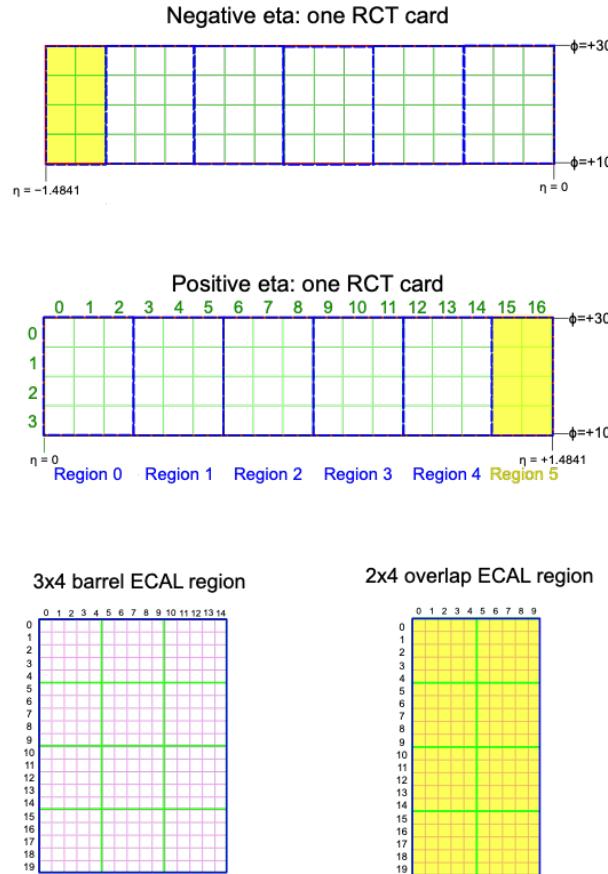


Figure 3.4: Schematic of two example RCT cards in the negative eta (*top*) and positive eta (*center*) regions of the ECAL barrel. Each RCT card is divided into five regions: four regions are of size 3×4 towers in $\eta \times \phi$ (*bottom left*), and a fifth smaller overlap region of size 2×4 towers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

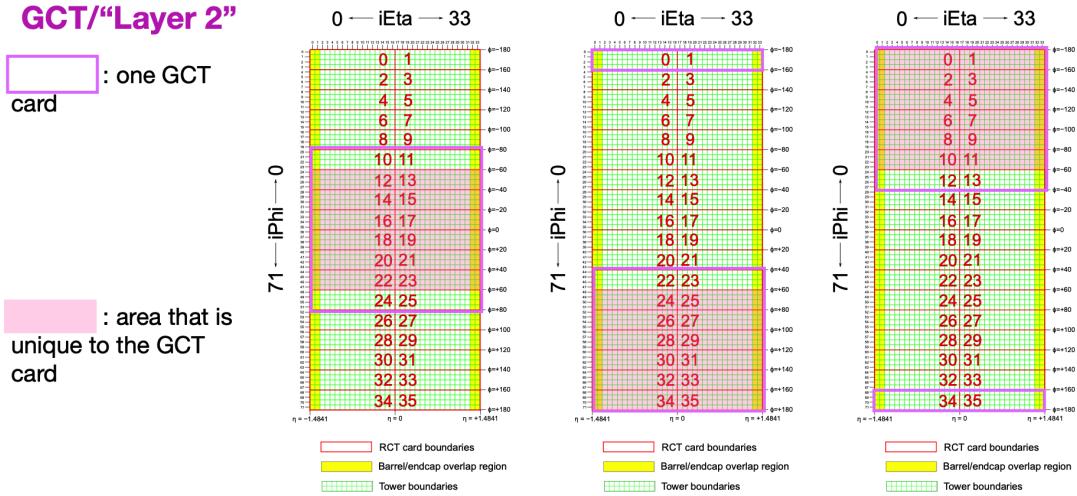


Figure 3.5: Schematic of the Phase-2 ECAL barrel in the Global Calorimeter Trigger (GCT), which will process the outputs of the Regional Calorimeter Trigger (RCT) in three cards (*magenta highlights*). Each card in the GCT processes the equivalent of sixteen RCT cards, with the center twelve being unique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

3x4 barrel ECAL region

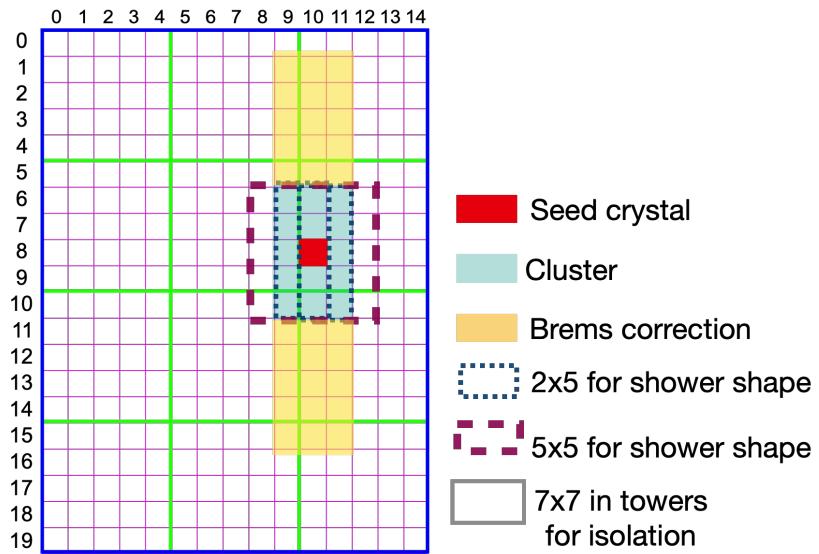


Figure 3.6: Illustration of an example electron/photon (e/γ) cluster in the Phase-2 Level-1 Trigger standalone barrel e/γ reconstruction, in a region of 15×20 crystals (3×4 towers). Each small pink square is one crystal, the highest-granularity ECAL trigger primitives available to the L1 Trigger in Phase-2. The core cluster consists of the energy sum in a 3×5 window of crystals, (*shaded light blue*) centered around the seed crystal (*red*). Bremsstrahlung corrections are checked in the adjacent 3×5 windows in the ϕ direction (*shaded light yellow*). The relative energies in windows of size 2×5 and 5×5 in crystals (*dashed dark blue and dark red*) are used to compute shower shape variables to identify true e/γ objects. Lastly, an isolation sum is computed in a window of size 7×7 in towers (not shown in figure).

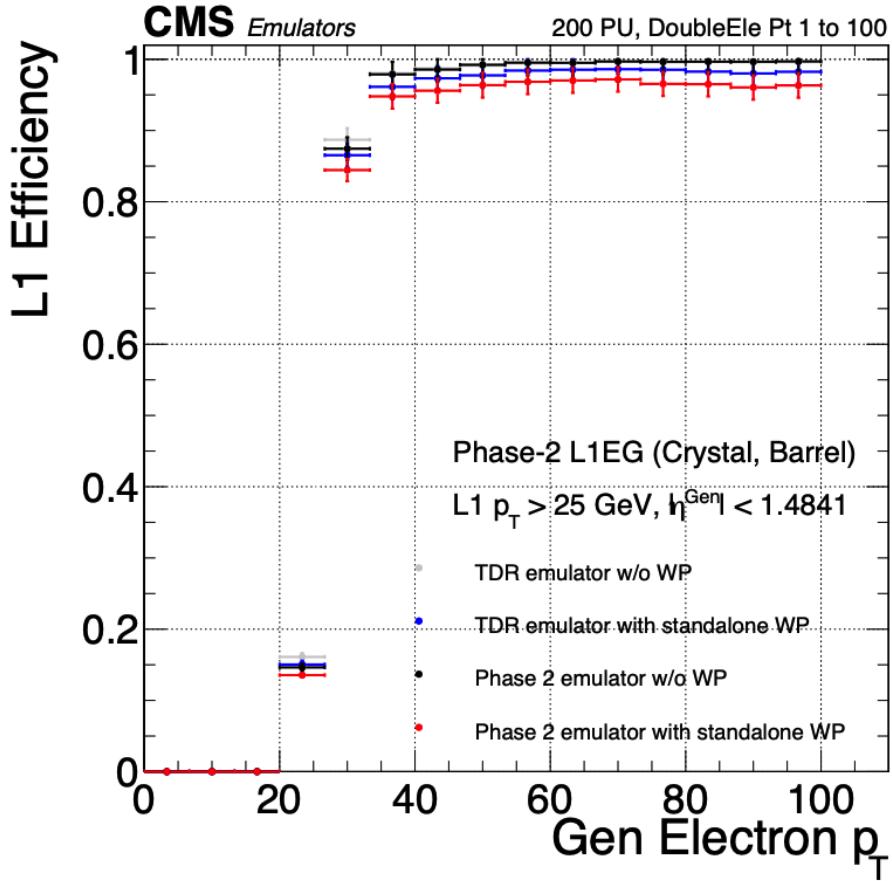


Figure 3.7: Efficiency of the standalone barrel e/γ reconstruction, measured in a simulated sample of electrons, as a function of the true electron’s transverse momentum p_T . The performance of the previous, idealized algorithm as shown in the 2021 Phase-2 TDR [35] with and without the isolation and shower shape discrimination variables (“standalone working point/ WP”) (*dark blue, grey*). The Phase-2 emulator discussed in this work with and without the same working point (*black, red*) is shown to have comparable performance.

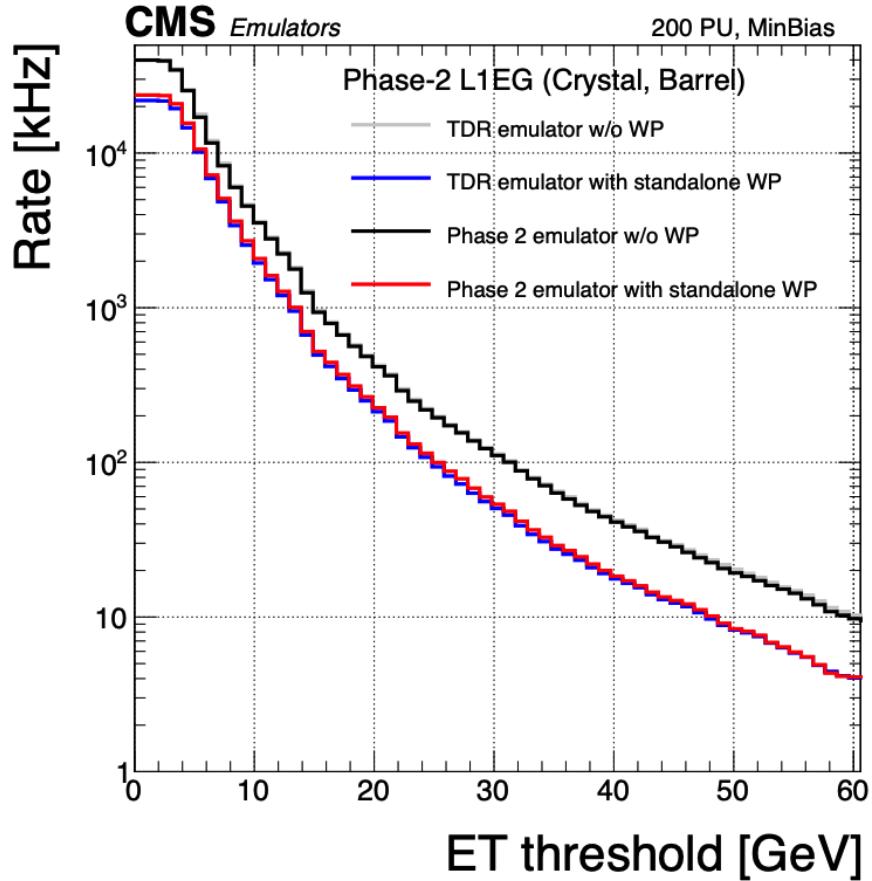


Figure 3.8: Rates of the standalone barrel e/γ reconstruction, evaluated on a minimum bias sample, measured as a function of the minimum energy (E_T) required of the reconstructed e/γ object in each event. The performance of the previous, idealized algorithm as shown in the 2021 Phase-2 TDR [35] with and without the isolation and shower shape discrimination variables (“standalone working point/ WP”) (*dark blue, grey*). The Phase-2 emulator discussed in this work with and without the same working point (*black, red*) is shown to have comparable performance.

1081 **Chapter 4**

1082 **Datasets and Monte Carlo samples**

1083 The search for the exotic decay of the 125 GeV Higgs boson to two light neutral scalars
1084 decaying to a pair of bottom quarks and a pair of tau leptons ($h \rightarrow aa \rightarrow bb\tau\tau$) is
1085 based on proton-proton collision data at a center-of-mass energy 13 TeV collected
1086 in Run-2 of data-taking, spanning the data-taking years 2016, 2017, and 2018. The
1087 datasets used and the triggers used to collect the data are described in Section 4.1.
1088 Section 4.2 describes the Monte Carlo simulated samples that are used to model the
1089 $h \rightarrow aa \rightarrow bb\tau\tau$ signal and background Standard Model processes. Lastly, in order
1090 to obtain a better description of Standard Model backgrounds that contain two tau
1091 leptons, a data-Monte Carlo hybrid technique is used to generate embedded samples
1092 which model processes with genuine $\tau\tau$ in the final state, as detailed in Section 4.3.

1093 **4.1 Datasets used**

1094 The $h \rightarrow aa \rightarrow bb\tau\tau$ analysis [37] is based on proton-proton collision data at a center-
1095 of-mass energy of 13 TeV collected in full Run-2 (2016-18) with the CMS detector.
1096 The data analyzed corresponds to a total integrated luminosity of 138 fb^{-1} (36.33 fb^{-1}
1097 for 2016, 41.53 fb^{-1} for 2017, and 59.74 fb^{-1} for 2018) [38] [39] [40]. The cumulative
1098 delivered and recorded luminosity versus time for 2015-2018 is shown in Fig. 4.1.

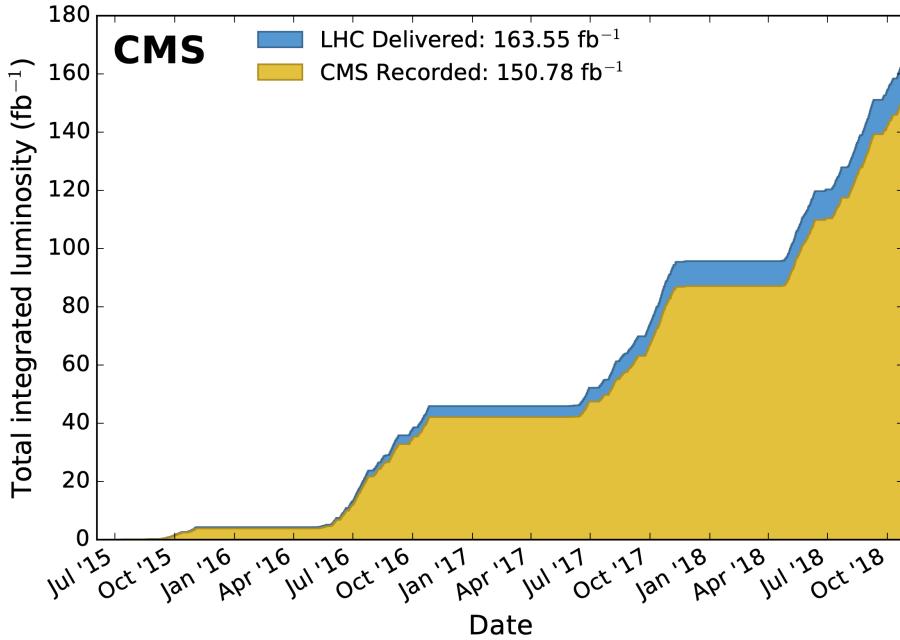


Figure 4.1: Cumulative delivered and recorded luminosity versus time for 2015-2018 at CMS, in proton-proton collision data only, at nominal center-of-mass energy [41].

1099 Data collected with the single muon trigger is used for the $\mu\tau_h$ channel. For the
 1100 $e\tau_h$ channel, data collected with the single electron trigger is used; and for the $e\mu$
 1101 channel, data collected with the electron + muon trigger is used. A more in-depth
 1102 discussion of the triggers used follows in a later section.

1103 A full list of samples used can be found in the full documentation [42] [37].

1104 4.2 Monte Carlo samples

1105 Modeling and computing observables originating from arbitrary physics processes at
 1106 the tree level and at next-to-leading order (NLO) is performed by Monte Carlo (MC)
 1107 event generators, such as Powheg and MadGraph5_amCNLO [43] [44]. The informa-
 1108 tion generated, e.g. the computation of the differential cross sections and kinematics
 1109 of the final state particles, is saved in a compressed file and used to generate MC

1110 samples that are used in physics analyses. The samples are digitized using GEANT4
1111 [45], a platform used at the LHC and other facilities to comprehensively simulate the
1112 passage of particles through matter. The digitized samples are passed through the
1113 same detector reconstruction as real data events collected in the detector.

1114 The samples for modeling the signal ($h \rightarrow aa \rightarrow 2b2\tau$ and $h \rightarrow a_1a_2$) in the
1115 2HDM+S and TRSM are generated at tree-level, for a range of masses of the light
1116 neutral scalar a . For $h \rightarrow aa$, the mass hypotheses for the a range from $m_a =$
1117 (12 GeV, 62.5 GeV). For $h \rightarrow a_1a_2$, the mass hypotheses for the two light scalars span
1118 combinations of m_{a1} , m_{a2} ranging from (12 GeV, 62.5 GeV) for the two scalars.

1119 4.3 Embedded samples

1120 An important background for Higgs boson studies and searches for additional Higgs
1121 bosons is the decay of Z bosons into pairs of τ leptons ($Z \rightarrow \tau\tau$). An embedded tech-
1122 nique was developed in the context of Standard Model Higgs to $\tau\tau$ measurements, to
1123 model $Z \rightarrow \tau\tau$ decays, and was expanded to also model all Standard Model processes
1124 that contain $\tau\tau$ [46]. The embedded technique has since been used successfully at
1125 CMS for the Standard Model $H \rightarrow \tau\tau$ measurement, as well as searches for minimal
1126 supersymmetric extensions to the Standard Model (MSSM) [47] [48].

1127 Fig. 4.2 shows a schematic of how embedded samples are produced. Data events
1128 containing $Z \rightarrow \mu\mu$ decays are selected. In these events, all energy deposits of the
1129 recorded muons are removed, and are replaced with simulated tau leptons with the
1130 same kinematic properties as the removed muons. This results in a hybrid data format
1131 containing information from both observed and simulated events, as illustrated in Fig.
1132 4.2 [46].

1133 In the selection step of the embedded technique, events are selected with at least
1134 one of a set of $\mu\mu$ trigger paths, which require $p_T > 17(8)$ GeV for the leading

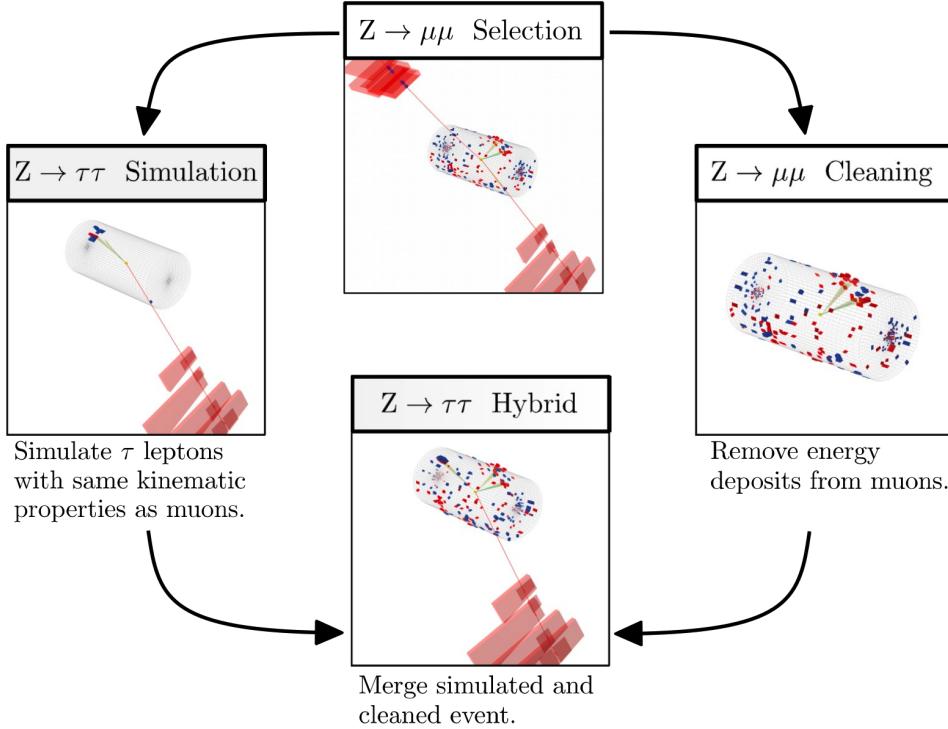


Figure 4.2: Schematic view of the four main steps of the embedding technique for τ leptons, as described in Section 4.3 [46]. A $Z \rightarrow \mu\mu$ event is selected in data ($Z \rightarrow \mu\mu$ selection), all of the energy deposits associated with the muons are removed ($Z \rightarrow \mu\mu$ 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).

(sub-leading) muons, and a minimum requirement between 3.8 and 8.0 GeV on the invariant di-muon mass $m_{\mu\mu}$ [46]. The offline reconstructed muons must match the objects at trigger level and also have offline $p_T > 17(8)$ GeV. They must have $|\eta| < 2.4$ and be located at a distance $|d_z| < 0.2$ cm to the primary vertex along the beam axis. To form a Z boson candidate, each muon is required to originate from a global muon track. The muon pairs must have opposite charges with an invariant mass of $m_{\mu\mu} > 20$ GeV. If more than two di-muon pairs are found, the pair with the invariant mass closest to the Z boson mass (91.19 GeV) is chosen.

This selection is designed to be tight enough to ensure a high purity of genuine $\mu\mu$ events, and also loose enough to minimize biases of the embedded event samples. Isolation requirements are avoided, since they would introduce a bias towards less

hadronic activity in the vicinities of the embedded leptons that will appear more isolated than expected in data. The selection results in an expected mixture of events summarized in Table 4.1 from [46]. $Z \rightarrow \mu\mu$ is the dominant process modeled by the embedded technique, with $t\bar{t}$, QCD, and diboson and single top processes becoming 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 [46], 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*).

The advantage of the embedded technique is that aspects of the event that are difficult to model and describe are directly taken from data, resulting in a better data description than can be achieved with only the $Z \rightarrow \tau\tau$ simulation [46]. The simulation must be tuned extensively to accurately model aspects of the data, such as time-dependent pileup profiles, the production of additional jets, e.g. in multijet and vector boson fusion topologies, the number of reconstructed primary interaction vertices, and the missing transverse momentum p_T^{miss} . Since all events with genuine $\tau\tau$ are estimated with samples made with the embedded technique (referred to as embedded samples from here on), events in Monte Carlo simulation with genuine $\tau\tau$ are not used, in order to avoid double-counting.

₁₁₆₁ **Chapter 5**

₁₁₆₂ **Object reconstruction and
1163 corrections applied**

₁₁₆₄ In the data processing workflow, data events and simulated events are analyzed to
₁₁₆₅ reconstruct physics objects of interest, and algorithms for distinguishing genuine par-
₁₁₆₆ ticle candidates from background, are employed. Section 5.1 describes the physical
₁₁₆₇ properties of the most important objects in the $h \rightarrow aa \rightarrow bb\tau\tau$ analysis: taus,
₁₁₆₈ muons, electrons, jets, and jets originating from b-quarks (b-flavor jets), as well as
₁₁₆₉ their reconstruction and identification in CMS. In this analysis, the full energy and
₁₁₇₀ momentum of the two tau leptons ($m_{\tau\tau}$) is estimated from the measured (i.e. visible)
₁₁₇₁ components of the tau leptons using the SVFit/FastMTT algorithm, which is de-
₁₁₇₂ scribed in Section 5.2. Corrections are applied to the simulated samples at the object
₁₁₇₃ level and the event level to account for known discrepancies between simulations and
₁₁₇₄ the data that the simulations are intended to model. These corrections are listed and
₁₁₇₅ detailed in Section 5.3.

₁₁₇₆ **5.1 Object reconstruction**

₁₁₇₇ **5.1.1 Taus**

₁₁₇₈ The tau (τ) is the heaviest known lepton. With a rest mass of 1776.86 MeV, it can
₁₁₇₉ decay to not only electrons and muons, but also hadrons. The mean lifetime of the τ
₁₁₈₀ is $\tau = 290 \times 10^{-15}$ seconds, corresponding to $c\tau = 87.03 \mu\text{m}$, which is short enough
₁₁₈₁ that taus decay in the CMS detector before reaching the detector elements.

₁₁₈₂ In two thirds of the cases, τ leptons decay hadronically, typically into one or three
₁₁₈₃ charged mesons (predominantly π^+ , π^-), often accompanied by neutral pions (that
₁₁₈₄ decay $\pi^0 \rightarrow \gamma\gamma$), and a ν_τ . These hadronic decays are denoted τ_h . In the remainder of
₁₁₈₅ the decays, the tau decays to the lighter leptons (electron or muon), termed leptonic
₁₁₈₆ decays. In all cases, at least one neutrino is produced, resulting in missing transverse
₁₁₈₇ energy in the CMS detector. The tau's largest decay branching ratios (proportional
₁₁₈₈ to probability of decay) are listed below [26]:

- ₁₁₈₉ • 17.8% decay to $e^- \bar{\nu}_e \nu_\tau$
- ₁₁₉₀ • 17.4% decay to $\mu^- \bar{\nu}_\mu \nu_\tau$
- ₁₁₉₁ • 25.5% decay to $\pi^- \pi^0 \nu_\tau$ (ρ^- resonance at 770 MeV)
- ₁₁₉₂ • 10.8% decay to $\pi^- \nu_\tau$
- ₁₁₉₃ • 9.3% decay to $\pi^- \pi^0 \pi^0 \nu_\tau$ (a_1^- resonance at 1200 MeV)
- ₁₁₉₄ • 9.0% decay to $\pi^- \pi^- \pi^+ \nu_\tau$ (a_1^- resonance at 1200 MeV)

₁₁₉₅ The neutrinos escape undetected from the CMS detector and are not considered
₁₁₉₆ in the reconstruction. Charged hadrons leave tracks in the tracking detector before
₁₁₉₇ being absorbed in the hadronic calorimeter; in CMS tau reconstruction terminology,
₁₁₉₈ they are often called “prongs”, i.e. the dominant τ_h decay modes are termed “1 prong”

₁₁₉₉ (π^\pm) , “1 prong + π^0 (s)”, and “3-prong”. Neutral pions decay to two photons which
₁₂₀₀ lose their energy in the electromagnetic calorimeter. Taus that decay to electrons
₁₂₀₁ and muons, are typically triggered on and reconstructed as electrons and muons
₁₂₀₂ respectively.

₁₂₀₃ **Hadron plus strips (HPS) reconstruction of τ_h**

₁₂₀₄ At CMS, hadronically decaying tau leptons are reconstructed with the hadron plus
₁₂₀₅ strips (HPS) algorithm [49] [50]. The HPS algorithm capitalizes on photon conversions
₁₂₀₆ in the CMS tracker material, which originate from the neutral pion (π^0) decaying
₁₂₀₇ to two photons. The bending of electron/positron tracks due to the CMS solenoid
₁₂₀₈ magnetic field leads to a spread of the neutral pions’ calorimeter signatures in the ϕ
₁₂₀₉ direction. This motivates the reconstruction of photons in “strips”: objects that are
₁₂₁₀ built out of PF photons and electrons. The strip reconstruction starts with centering
₁₂₁₁ a strip on the most energetic electromagnetic particle in a PF jet. Among other
₁₂₁₂ electromagnetic particles located in a window of size $\Delta\eta = 0.05$ and $\Delta\phi = 0.20$
₁₂₁₃ around the strip center, the most energetic one is associated with the strip and its
₁₂₁₄ momentum is added to the strip momentum. This is repeated iteratively until no
₁₂₁₅ further particles can be associated. Lastly, strips satisfying a requirement of $p_T^{\text{strip}} > 1$
₁₂₁₆ GeV are combined with charged hadrons to reconstruct individual τ_h decay modes,
₁₂₁₇ where h stands for both π and K :

- ₁₂₁₈ • *Single hadron:* $h^- \nu_\tau$ and $h^- \pi^0 \nu_\tau$ decay modes, in which the neutral pions have
₁₂₁₉ too little energy to be reconstructed as strips.
- ₁₂₂₀ • *One hadron + one strip:* $h^- \pi^0 \nu_\tau$ decay modes, where the photons from the π^0
₁₂₂₁ decay are close together in the calorimeter.
- ₁₂₂₂ • *One hadron + two strips:* $h^- \pi^0 \nu_\tau$ decay modes, where the photons from the π^0
₁₂₂₃ decay are well separated.

- 1224 • *Three hadrons:* $h^- h^+ h^- \nu_\tau$ decay modes. The three charged hadrons are re-
1225 quired to originate from the same secondary vertex.

1226 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
1227 reconstructed with the above topologies.

1228 In the HPS algorithm, the direction of the reconstructed tau momentum \vec{p}^{τ_h}
1229 is required to fall within a distance of $\Delta R = 0.1$ from the original PF jet. All
1230 charged hadrons and strips are required to be contained within a cone of size $\Delta R =$
1231 $(2.8 \text{ GeV})/p_T^{\tau_h}$, from the τ_h as reconstructed by the HPS.

1232 All charged hadrons are assumed to be pions, and they are required to be consis-
1233 tent with the masses of the intermediate meson resonances (if applicable), with the
1234 following allowed windows for candidates: 50-200 MeV for π^0 , 0.3-1.3 GeV for ρ , and
1235 0.8-1.5 GeV for a_1 . If the τ_h decay is compatible with more than one hypothesis, the
1236 one giving the highest $p_T^{\tau_h}$ is chosen. Lastly, an isolation requirement is applied: aside
1237 from the τ_h decay products, no charged hadrons or photons can be present within
1238 an isolation cone of size $\Delta R = 0.5$ around the direction of the τ_h . The outputs of
1239 the HPS algorithm are the reconstructed decay mode and the visible four-momentum
1240 (i.e. the four-momenta of all decay products excluding the neutrinos).

1241 **DeepTau for identifying τ_h**

1242 The identification of τ_h candidates in CMS has historically been divided into separate
1243 discriminators against jets, electrons, and muons. Discriminators versus jets and
1244 electrons use information from derived quantities, such as the p_T sum of particles
1245 near the τ_h axis. Building on the previous multivariate analysis (MVA) classifier [51]
1246 based on a boosted decision tree (BDT), DeepTau is a more recent classifier based on a
1247 deep neural network (DNN) that simultaneously discriminates against jets, electrons,
1248 and muons. The DNN uses a combination of high-level inputs, similar to previous
1249 algorithms, and also uses convolutional layers in η - ϕ space to process information

1250 from all reconstructed particles near the τ_h axis. Convolutional layers are based on
1251 the principle that an image can be processed independently of its position.

1252 The final DeepTau discriminators against jets, muons, and electrons are given by

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

1253 where y_τ (y_α) are estimates of the probabilities for the τ_h candidate to come from
1254 a genuine τ_h (jet, μ , e). Working points for each discriminator with different τ_h
1255 identification efficiencies are defined for D_e , D_μ , and D_{jet} , for usage in physics analyses
1256 and derivation of data-to-simulation corrections [52].

1257 5.1.2 Muons

1258 Muons are the next lightest lepton after taus, with a mass of 105.66 MeV and a
1259 mean lifetime of $\tau = 2.20 \times 10^{-6}$ seconds, or $c\tau = 658.64$ m. At CMS, muons are
1260 identified with requirements on the quality of the track reconstruction and on the
1261 number of measurements in the tracker and the muon systems [53]. In the standard
1262 CMS reconstruction, tracks are first reconstructed independently in the inner tracker
1263 (tracker track) and in the muon system (standalone-muon track). Next, these tracks
1264 are processed in two different methods.

1265 The first is Global Muon reconstruction (outside-in) [53], which fits combined hits
1266 from the tracker track and standalone-muon track, using the Kalman-filter technique.
1267 At large transverse momenta, $p_T \gtrsim 200$ GeV, the global-muon fit can improve the
1268 momentum resolution compared to the tracker-only fit.

1269 The second is Tracker Muon reconstruction (inside-out) [53], which starts with
1270 tracker tracks with $p_T > 0.5$ GeV and total momentum $p_T > 2.5$ GeV. These tracks
1271 are extrapolated outwards to the muon system and matched to detector segments
1272 there, taking into account the magnetic field, expected energy losses, and multiple

1273 Coulomb scattering in the detector material. Tracker Muon reconstruction is more
 1274 efficient than the Global Muon reconstruction at low momenta, $p \lesssim 5$ GeV, because
 1275 it only requires a single muon segment in the muon system, whereas Global Muon
 1276 reconstruction typically requires segments in at least two muon stations.

1277 To further suppress fake muons from decay in flight, isolation cuts are used. A
 1278 relative isolation variable is defined to quantify the energy flow of particles near the
 1279 muon trajectory. A relative isolation is defined similarly for muons and electrons:

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

1280 where $\sum_{\text{charged}} p_T$ is the scalar sum of the p_T of the charged particles originating from
 1281 the primary vertex and located in a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4(0.3)$
 1282 centered on the direction of the muon (electron). The sum $\sum_{\text{neutral}} p_T$ is the equivalent
 1283 for neutral particles. The sum $\sum_{\text{charged, PU}} p_T$ is the scalar sum of the p_T of the
 1284 charged hadrons in the cone originating from pileup vertices. The factor 1/2 comes
 1285 from simulation estimations, which find that the ratio of neutral to charged hadron
 1286 production in the hadronization process of inelastic pp collisions is 1/2. Thus the
 1287 subtracted term is intended to subtract contribution from pileup, from the neutral
 1288 particle contribution to the isolation sum. Finally, this is divided by the lepton
 1289 transverse momentum, p_T^ℓ .

1290 5.1.3 Electrons

1291 Electrons are the lightest lepton with a mass of 0.511 MeV. At CMS, electrons are
 1292 reconstructed by associating a track reconstructed in the silicon tracking detector
 1293 with a cluster of energy in the ECAL. Performance is maximized via a combination
 1294 of a stand-alone approach and the complementary global particle-flow approach [54].

1295 In the stand-alone approach, the electron energy, which is typically spread over

1296 several crystals of the ECAL, is clustered with the “hybrid” algorithm in the barrel
1297 and the “multi- 5×5 ” in the endcaps [54]. The hybrid algorithm collects energy in a
1298 small window in η and an extended window in ϕ . It identifies a seed crystal, and adds
1299 arrays of 5×1 crystals in $\eta \times \phi$ in a range of $N = 17$ crystals in both directions of
1300 ϕ , if their energies exceed a minimum threshold, thus forming a supercluster (SC). In
1301 the endcap, crystals are not arranged in an $\eta \times \phi$ geometry; instead clusters are build
1302 around seed crystals in clusters of 5×5 crystals that can partly overlap. Nearby
1303 clusters are grouped into a supercluster, and energy is recovered from associated
1304 deposits in the preshower.

1305 In the PF reconstruction [54], PF clusters are reconstructed by aggregating around
1306 a seed all contiguous crystals with energies two standard deviations above the elec-
1307 tronic noise observed at the beginning of a data-taking run. The energy of a given
1308 crystal can be shared among two or more clusters.

1309 The electron track reconstruction is performed in two ways [54]: the ECAL-based
1310 seeding, which begins with the SC energy and positioning, and the tracker-based
1311 seeding (part of the PF reconstruction algorithm), which uses tracks reconstructed
1312 from the general algorithm for charged particles, extrapolated towards the ECAL and
1313 matched to an SC. Kalman filter (KF) tracks with a small number of hits or that are
1314 not well-fitted, are re-fitted with a dedicated Gaussian sum Filter (GSF).

1315 A global identification variable [54] is defined using a multivariate analysis (MVA)
1316 technique that combines information on track observables (kinematics, quality of the
1317 KF track and GSF track), the electron PF cluster observables (shape and pattern),
1318 and the association between the two (geometric and kinematic observables). For
1319 electrons seeded only through the tracker-based approach, a weak selection is applied
1320 on this MVA variable. For electrons seeded through both approaches, a logical OR is
1321 taken.

1322 Electron isolation, i.e. the presence of energy deposits near the electron trajectory,

1323 is a separate key handle in rejecting significant background. Compared to isolated
 1324 electrons, electrons from misidentified jets or genuine electrons within a jet resulting
 1325 from semileptonic decays of b or c quarks tend to have significant energy deposits
 1326 near the primary trajectory [54]. Offline analyses benefit from the PF technique
 1327 for defining isolation, which sums the PF candidates reconstructed located within a
 1328 specified isolation cone around the electron candidate, as in Eqn. 5.2.

1329 **5.1.4 Jets**

1330 The vast majority of processes of interest at the LHC contains quarks or gluons in
 1331 the final state, but these particles cannot be observed directly. In a process called
 1332 hadronization, they fragment into spatially-grouped collections of particles called jets,
 1333 which can be detected in the tracking and calorimeter systems. Hadronization and
 1334 the subsequent decays of unstable hadrons can produce hundreds of nearby particles
 1335 in the CMS detector. Jets are reconstructed by the PF algorithm (PF jets), or from
 1336 the sum of the ECAL and HCAL energies deposited in the calorimeter towers (Calo
 1337 jets). In PF jets, typically used in offline analyses, jets are built using the anti- k_T
 1338 (AK) clustering algorithm [55]. The anti- k_T algorithm iterates over particle pairs and
 1339 finds the two that are closest in a distance measure d , and determines whether to
 1340 combine them:

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

1341 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-
 1342 ity, and azimuthal angle of particle i . The power -2 means that higher-momentum
 1343 particles are clustered first, leading to jets that tend to be centered on the hardest
 1344 (highest p_T) particle.

1345 There are several methods to remove contributions of pileup collisions from jet

1346 clustering [56]:

- 1347 • Charged hadron subtraction (CHS), which removes all charged hadron candidates associated with a track that is not associated with the primary vertex.
- 1349 • PileUp Per Particle Identification (PUPPI), which weighs input particles based
1350 on their likelihood of arising from pileup. QCD particles tend to have a collinear
1351 structure, compared to soft diffuse radiation coming from pileup. The local
1352 shape for charged pileup, used as a proxy for all pileup particles, is used on an
1353 event-by-event basis to calculate a weight for each particle. PUPPI is deployed
1354 in Run-2 and is more performant than CHS in high pileup scenarios.

1355 5.1.5 B-flavored jets

1356 Jets that arise from bottom-quark hadronization (b-flavor jets) have overwhelming
1357 background from processes involving jets from gluons (g) and light-flavor quarks (u, d,
1358 s), and from c-quark fragmentation. The ability to identify b-flavor jets, or b-tagging,
1359 exploits the b hadrons' relatively large masses, long lifetimes, and daughter particles
1360 with hard momentum spectra [55].

1361 The impact parameter (IP) of a track is the 3-dimensional distance between the
1362 track and the primary vertex (PV) at the point of closest approach. The IP is positive
1363 if the track originates from the decay of particles travelling along the jet axis. The
1364 resolution of the IP depends on the p_T and η of the track, motivating the use of the
1365 impact parameter significance S_{IP} (ratio of the IP to its estimated uncertainty) as an
1366 observable [55].

1367 Because of the large but finite lifetimes of the b hadrons, b hadrons tend to
1368 travel a short distance before decaying at a secondary vertex (SV), which can be
1369 measured and reconstructed separately from the primary vertex due to the excellent
1370 position resolution of the pixel detector [55]. Previous b-tagging algorithms (e.g.

1371 CSV, cMVAv2, and DeepCSV) have capitalized on variables such as the presence of
1372 a SV, the flight distance and direction (computed from the vector between the PV
1373 and the SV), and kinematics of the system of associated secondary tracks (e.g. track
1374 multiplicity, mass, and energy).

1375 The DeepJet (formerly known as DeepFlavour) algorithm [57] is a deep-neural-
1376 network multi-classification algorithm, which uses 16 properties of up to 25 charged
1377 and 6 properties of 25 neutral particle-flow jet constituents, as well as 17 properties
1378 from up to 4 secondary vertices associate with the jet. Compared to the previous clas-
1379 sifying algorithm DeepCSV, DeepJet has been demonstrated to have higher efficiency
1380 with lower misidentification probability in Phase-1 data [58].

1381 5.2 Reconstruction of the $\tau\tau$ mass

1382 The final signal extraction is done to the total $\tau\tau$ mass, which is estimated from the
1383 visible $\tau\tau$ mass using the FastMTT algorithm [59]. FastMTT is based on the SVFit
1384 algorithm, originally developed for the Standard Model $H \rightarrow \tau\tau$ analysis [60]. Both
1385 the SVFit algorithms, and the FastMTT algorithm, are described below, to give a
1386 complete picture of how tau decays are parameterized.

1387 To specify a hadronic τ decay, six parameters are needed [60]: the polar and
1388 azimuthal angles of the visible decay product system in the τ rest frame, the three
1389 boost parameters from the τ rest frame to the laboratory frame, and the invariant
1390 mass m_{vis} of the visible decay products. For a leptonic τ decay, two neutrinos are
1391 produced, and a seventh parameter, the invariant mass of the two-neutrino system, is
1392 necessary. The unknown parameters are constrained by four observables that are the
1393 components of the four-momentum of the system formed by the visible decay products
1394 of the τ lepton, measured in the laboratory frame. The remaining unconstrained
1395 parameters for hadronic and leptonic τ decays are thus:

- The fraction of the τ energy in the laboratory frame carried by the visible decay

1397 products,

- ϕ , the azimuthal angle of the τ direction in the laboratory frame,

- $m_{\nu\nu}$, the invariant mass of the two-neutrino system in leptonic τ decays (for hadronic τ decays, $m_{\nu\nu}$ is set to 0).

1401 E_x^{miss} and E_y^{miss} , the x and y components of the missing transverse energy E_T^{miss}
 1402 provide two further constraints.

1403 5.2.1 Original SVFit ‘‘standalone’’: maximum likelihood

1404 In one of the original versions of SVFit, called ‘‘standalone’’ SVFit [60], a maximum
 1405 likelihood fit method is used to reconstruct the mass $m_{\tau\tau}$ by combining the measured
 1406 observables E_x^{miss} and E_y^{miss} with a likelihood model that includes terms for the τ
 1407 decay kinematics and the E_T^{miss} resolution [60]. The likelihood function $f(\vec{z}, \vec{y}, \vec{a}_1 \vec{a}_2)$
 1408 of the parameters $\vec{z} = (E_x^{\text{miss}}, E_y^{\text{miss}})$ in an event is constructed, where the remaining
 1409 parameters are the kinematics of the two τ decays, denoted $\vec{a}_1 = (x_1, \phi_1, m_{\nu\nu,1})$ and
 1410 $\vec{a}_2 = (x_2, \phi_2, m_{\nu\nu,2})$, and the four-momenta of the visible decay products with the
 1411 measured values $\vec{y} = (p_1^{\text{vis}}, p_2^{\text{vis}})$.

1412 The likelihood f is the product of three likelihood functions. The first two likelihood
 1413 functions model the decay parameters \vec{a}_1 and \vec{a}_2 of the two τ leptons. For leptonic
 1414 decays, the likelihood function is modeled using matrix elements for τ decays,
 1415 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
 1416 hadronic τ decays, a model based on the two-body phase space is used and integrated
 1417 over $m_{\text{vis}}^2/m_{\tau\tau}^2 \leq x \leq 1$. The third likelihood function quantifies the compatibility of
 1418 a τ decay hypothesis with the reconstructed \vec{E}_T^{miss} in an event, assuming the neutrinos
 1419 are the only source of missing transverse energy. The expected \vec{E}_T^{miss} resolution

1420 is represented by a covariant matrix, estimated on an event-by-event basis using a
1421 significance algorithm [61].

1422 5.2.2 “Classic SVFit” with matrix element

1423 Classic SVFit is an improved algorithm of the original “standalone” SVFit using the
1424 formalism of the matrix element (ME) method [59]. In the ME method, an estimate
1425 for the unknown model parameter Θ (here, the mass $m_{\tau\tau}$) is obtained by maximizing
1426 the probability density \mathcal{P} . The key ingredients of the probability density are the
1427 squared modulus of the matrix element $|\mathcal{M}(\mathbf{p}, \Theta)|^2$ and the transfer function $W(\mathbf{y}|\mathbf{p})$
1428 (probability density to observe the measured observables \mathbf{y} given the phase space
1429 point \mathbf{p}). The best estimate $m_{\tau\tau}$ is obtained by computing the probability density \mathcal{P}
1430 for a range of mass hypotheses and finding the value of $m_{\tau\tau}$ that maximizes \mathcal{P} .

1431 Distributions illustrating the performance of the classic matrix element SVFit
1432 algorithm are shown in Fig. 5.1 from [59], showing the di-tau mass after and before
1433 application of SVFit to recover energy lost to neutrinos. The SVFit algorithm is
1434 found to improve the sensitivity of the Standard Model $H \rightarrow \tau\tau$ analysis performed
1435 by CMS by about 30%, compared to performing the same analysis using only the
1436 visible mass m_{vis} .

1437 5.2.3 FastMTT: optimized SVFit

1438 FastMTT [62] is a further simplification to the matrix element method of Classic
1439 SVFit which has comparable performance but is about 100 times faster. FastMTT
1440 drops the matrix element component of the computation without significant impact
1441 on the final mass resolution, and simplifies the computation of the transfer functions.
1442 The opening angle of the τ decay products with respect to the initial τ momenta ap-
1443 proaches 0 for τ with high $\gamma = E_\tau/m_\tau$, with typical τ decays from the Z boson decays
1444 already satisfying this condition. In this collinear approximation, the dimensionality

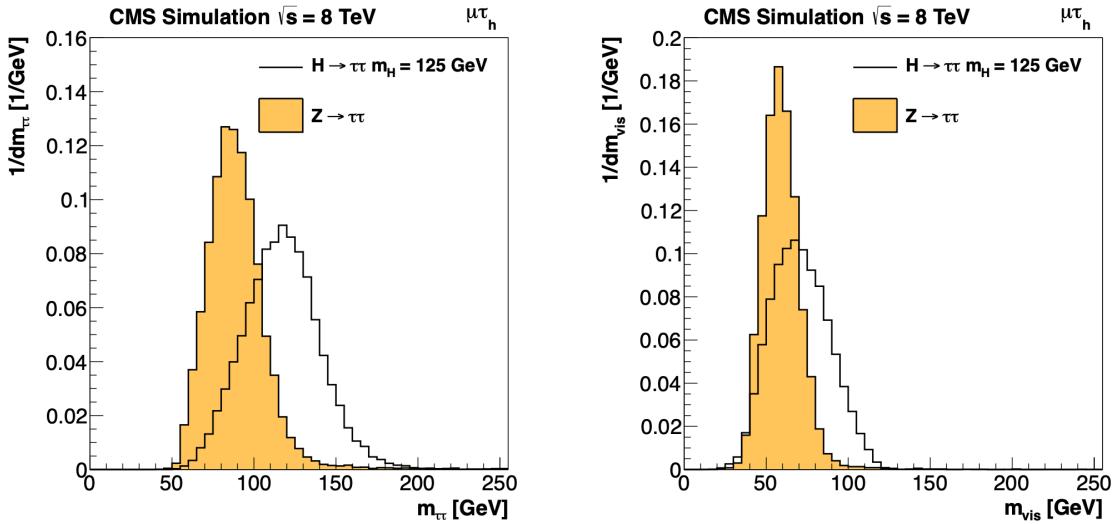


Figure 5.1: Distributions from [59], of $m_{\tau\tau}$ after reconstruction with the original SVFit algorithm (*left*), and before SVFit with only the visible tau decay products (*right*), for $H \rightarrow \tau\tau$ signal events of mass $m_H = 125$ GeV (*black line*) and the $Z/\gamma^* \rightarrow \tau\tau$ background (*orange, solid*), in the decay channel $\tau\tau \rightarrow \mu\tau_h$.

1445 of the transfer function can be reduced in the computation of FastMTT, while still
1446 yielding similar results to Classic SVFit [62].

1447 5.3 Corrections applied to simulation

1448 Corrections are applied to simulated samples to account for known effects in the event
1449 modeling and reconstruction and data-taking, and are intended to bring simulations
1450 in closer agreement with data. Corrections fall into two broad categories: *energy*
1451 *scale corrections* applied to physics objects, and *event-level corrections*. Energy scale
1452 corrections are multiplicative factors applied to the energy and transverse momentum
1453 p_T of simulated objects (e.g. leptons or jets), and bring the average reconstructed en-
1454 ergies of simulated particles into better agreement with those of objects reconstructed
1455 from data. Event-level corrections are applied as a per-event multiplicative weight,
1456 and account for effects such as mis-modeling in simulations of the underlying physics
1457 process, or changing detector operating conditions during data-taking. Event-level

1458 corrections change the shapes of the distributions of all the physical observables.

1459 Uncertainties in scale factors and corrections are also sources of systematic errors
1460 in the analysis, detailed in Chapter 8. Systematic uncertainties in the tau, muon, and
1461 electron energy scales can shift the p_T of the leptons up or down, which can change
1462 whether events pass or fail the offline p_T thresholds for the trigger paths described in
1463 the previous section, i.e. change the number of events in the signal region.

1464 5.3.1 Tau energy scale

1465 An energy scale is applied to the transverse momentum p_T and mass of the hadronic
1466 tau τ_h in the $\mu\tau_h$ and $e\tau_h$ channels, to correct for a deviation of the average recon-
1467 structed τ_h energy from the generator-level energy of the visible τ_h decay products.
1468 These correction factors are derived centrally [51], by fitting to events in $e\tau_h$ and $\mu\tau_h$
1469 final states in Z/γ^* events separately for the h^\pm , $h^\pm\pi^0$, and $h^\pm h^\mp h^\pm$ decays. The
1470 values used are shown in Table 5.1.

1471 When applying the energy scale to the τ_h , the 4-momentum of the missing trans-
1472 verse energy (MET) is adjusted such that the total 4-momenta of the τ_h and the MET
1473 remains unchanged [63].

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.

1474 **5.3.2 Muon energy scale**

1475 An energy scale is applied to the p_T and mass of genuine muons from τ decays in the
1476 $e\mu$ and $\mu\tau_h$ channels [64]. The applied values are the same for MC and embedded
1477 samples and are shown in Table 5.2. Following the SM $H \rightarrow \tau\tau$ analysis, Rochester
1478 corrections are not applied, and instead prescriptions from [65] 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 [66] [65].

1479 **5.3.3 Electron energy scale**

1480 Corrections to the electron energy scale are applied to genuine e from τ decays, and
1481 are binned in two dimensions by electron p_T and η for barrel vs. endcap [67]. The
1482 scale factors are binned in p_T and η for MC samples: e.g. values for 2018 are shown
1483 in Fig. 5.2 from [68]. For embedded samples the electron energy scale is taken as
1484 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 [69] [70] [71].

1485 **5.3.4 τ_h identification efficiency**

1486 The τ_h identification efficiency can differ in data and MC [63]. Recommended correc-
1487 tions are provided by the Tau POG, and we use the medium DeepTau vs. jet working

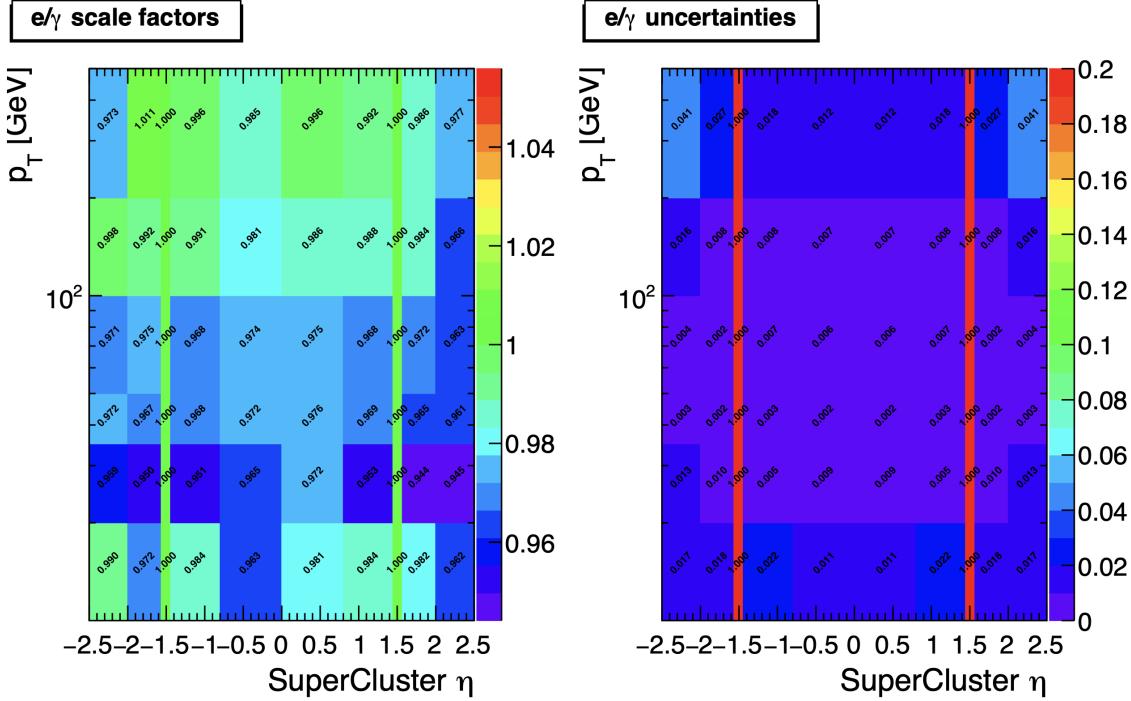


Figure 5.2: Electron/photon energy scale factors (*left*) and corresponding uncertainties (*right*) binned in the electron η and p_T , for the data-taking year 2018 [68].

¹⁴⁸⁸ point values. The identification efficiency is measured in $Z \rightarrow \tau\tau$ events in the $\mu\tau_h$
¹⁴⁸⁹ 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 [63].

¹⁴⁹⁰ 5.3.5 Trigger efficiencies

¹⁴⁹¹ Scale factors are applied to correct for differences in trigger efficiencies between MC
¹⁴⁹² and embedded vs. data, with values taken from tools provided by the Standard Model
¹⁴⁹³ $H \rightarrow \tau\tau$ working group which uses the same trigger paths [66]. In the following

1494 sections we review relevant trigger efficiencies in data, which form the basis of the
1495 trigger efficiency corrections applied to MC and embedded.

1496 **5.3.6 Tau trigger efficiencies**

1497 The efficiencies in data of the single- τ_h leg in $\mu\tau_h$, $e\tau_h$, and di- τ_h triggers is computed
1498 centrally per using a Tag and Probe (TnP) method [72] which is outlined here. In
1499 this method, $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$ are selected in data and a Drell-Yan simulated sample
1500 ($Z \rightarrow \ell\ell, \ell = e, \mu, \tau_h$) with high purity. Cuts are applied to reject events not in this
1501 final state, e.g. suppressing $Z \rightarrow \mu\mu$ by vetoing events with a single loose ID muon.
1502 An isolated muon candidate (the tag) with online $p_T > 27$ GeV and $|\eta| < 2.1$ is
1503 identified and matched to an offline μ . An offline τ_h candidate (the probe) is selected,
1504 which is separated from the tag μ , and has $p_T > 20$ GeV and $|\eta| < 2.1$. The probe
1505 τ_h must pass anti-muon and anti-electron discriminators to avoid fakes from muons
1506 and electrons, and must pass the medium MVA tau isolation to suppress fakes from
1507 QCD jets. The trigger efficiency in the TnP method is calculated as

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

1508 The efficiencies for the hadronic tau legs in the relevant channels of this analyses
1509 ($\mu\tau_h$ and $e\tau_h$) as a function of the offline tau p_T and η , are shown for data taken in
1510 2016, 2017, and 2018 in Figures 5.3a and 5.3b [72] [73]. In both figures, the different
1511 HLT thresholds and differences in the L1 seed result in higher efficiencies in 2016 and
1512 differences in shapes of the 2016 efficiencies compared to 2017 and 2018. The low
1513 pileup in 2016 also leads to higher efficiencies in that year.

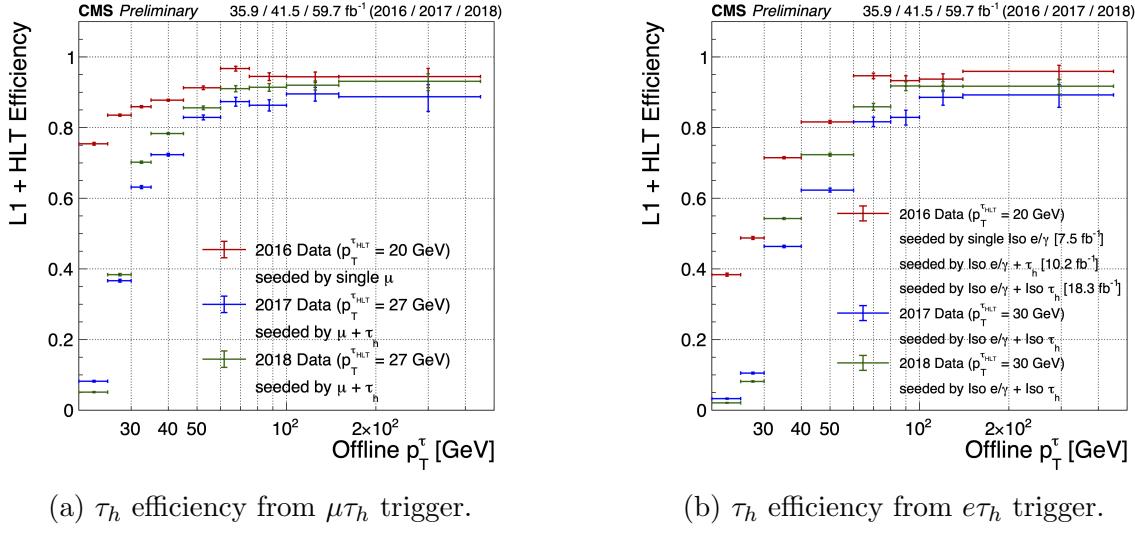


Figure 5.3: Hadronic tau leg efficiency of the cross-triggers for $\mu\tau_h$ (left) and $e\tau_h$ (right) triggers as a function of offline tau p_T for the years 2016 (red), 2017 (blue) and 2018 (green), from [73]. HLT p_T thresholds and L1 seeds are indicated in the legends.

1514 5.3.7 Single muon trigger efficiencies

1515 The efficiencies for the single isolated muon trigger with $p_T > 24 \text{ GeV}$ used in this
 1516 analysis, is shown for the data-taking year 2018 in Fig. 5.4a as a function of the muon
 1517 p_T and as a function of the muon $|\eta|$ in Fig. 5.4b from [74]. The data is split with
 1518 respect to a HLT muon reconstruction update that was deployed on 15/05/2018. A
 1519 small asymmetry in efficiencies between negative and positive η in Fig. 5.4b is due to
 1520 disabled muon chambers (CSCs). The efficiencies shown are estimated using a Tag
 1521 and Probe method using $Z \rightarrow \mu\mu$ events, with the tag being an offline muon with
 1522 $p_T > 29 \text{ GeV}$ and $|\eta| < 2.4$ passing a tight ID criteria, and the probe is an online (L1)
 1523 trigger object with $\Delta R < 0.3$ and passing tight ID and Particle Flow based isolation
 1524 requirements with $p_T > 26 \text{ GeV}$.

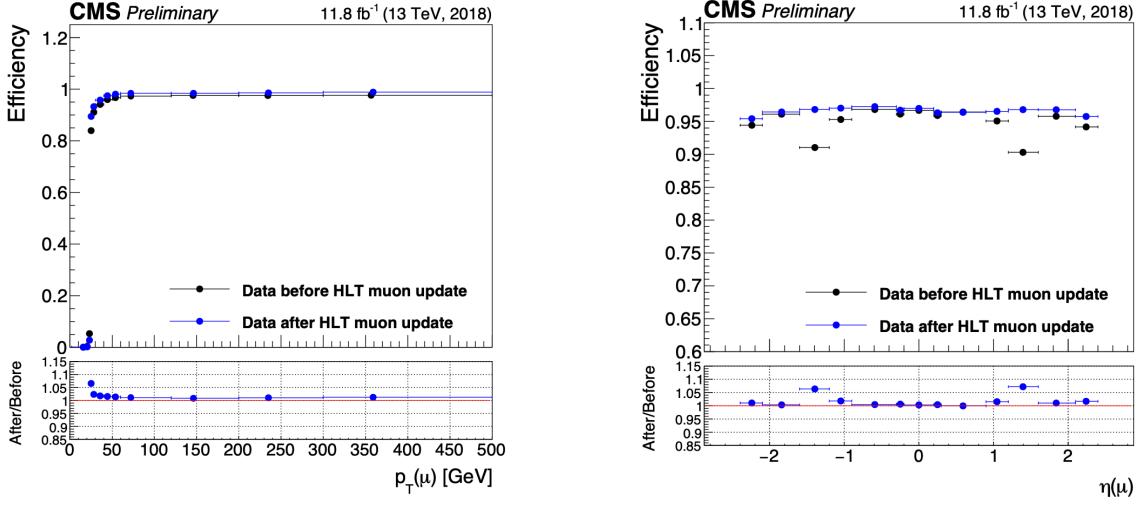
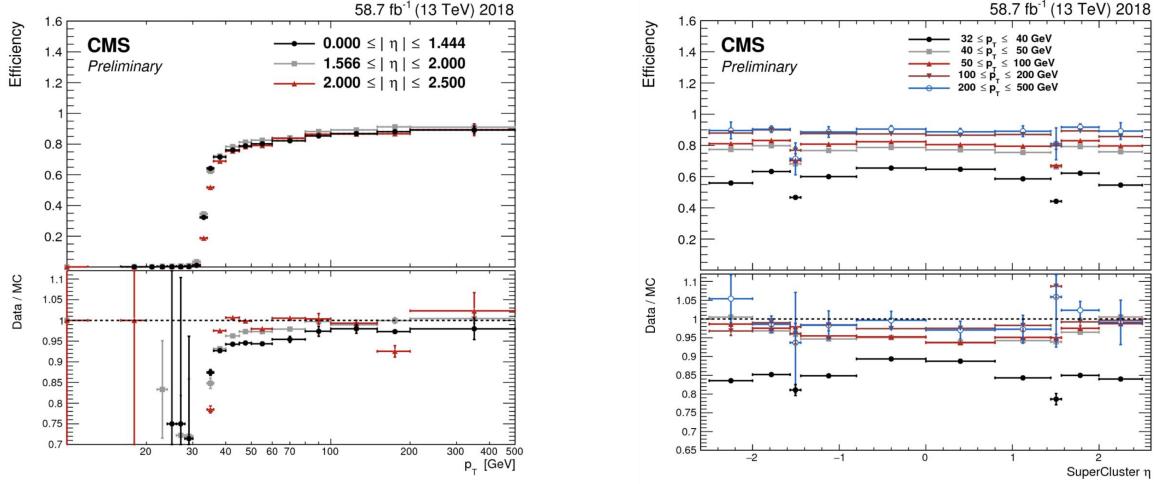
(a) Muon efficiency vs p_T for SingleMuon.(b) Muon efficiency vs $|\eta|$ for SingleMuon.

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 [74].

5.3.8 Single electron trigger efficiencies

The efficiencies in data, and the ratio between data and MC, of the single electron HLT trigger with p_T threshold 32 GeV used in this analysis are shown for 2018, as a function of the electron p_T in Fig. 5.5a and of the electron $|\eta|$ in Fig. 5.5b, from [75]. In the Tag and Probe method used for the 2018 dataset, the tag is an offline reconstructed electron with $|\eta| \leq 2.1$ and not in the barrel and endcap overlap region, with $p_T > 35$ GeV with tight isolation and shower shape requirements, firing the tag trigger. The probe is an offline reconstructed electron with $|\eta| \leq 2.5$ with $E_T^{\text{ECAL}} > 5$ GeV with no extra identification criteria [75].

The disagreement between data and MC, particularly at low transverse momentum, is in part due to detector effects that are difficult to simulate, such as crystal transparency losses in the ECAL and the evolution of dead regions in the pixel tracker [75].



(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*) [75]. 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.

1538 5.3.9 $e\mu$ cross-trigger efficiencies

1539 The efficiencies of the electron and muons for the cross-trigger with leading muon
 1540 used in the $e\mu$ channel are shown for data in 2016, 2017, and 2018 in Figures 5.6a and
 1541 5.6b [76]. These efficiencies were measured centrally using a Tag and Probe in events
 1542 with Z to dileptons with the same flavor and opposite charge, where the tags are an
 1543 isolated muon or electron, and the probe (offline) candidate is required to satisfy the
 1544 same lepton selection as that of the tag candidate, be matched within $\Delta R < 0.1$ with
 1545 a corresponding online trigger object, and also to pass the cross-trigger. The trigger
 1546 efficiency is then:

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

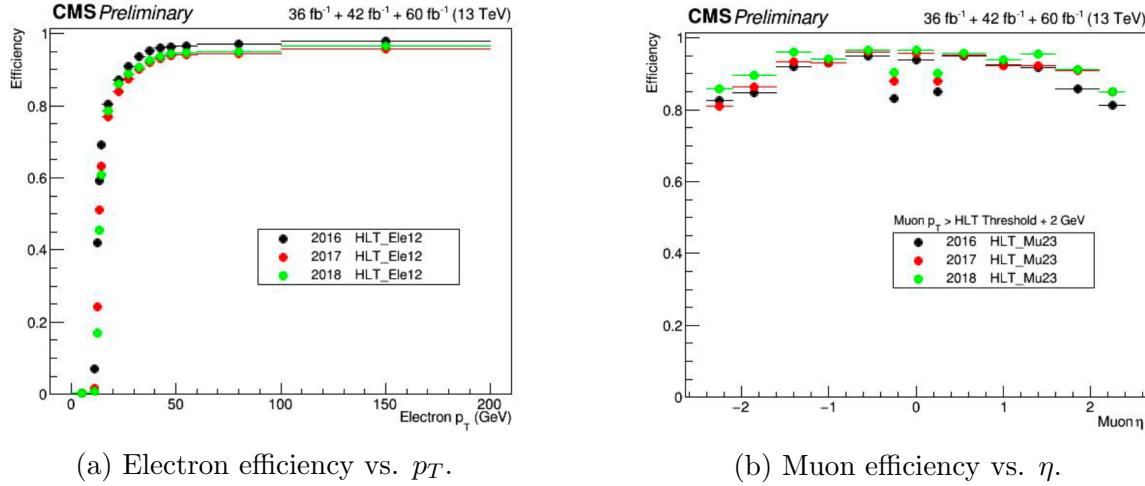
(a) Electron efficiency vs. p_T .(b) Muon efficiency vs. η .

Figure 5.6: Efficiencies of the electron leg vs. p_T (*left*) and the muon log 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*) [76].

1547 5.3.10 Electrons and muons faking τ_h : energy scales

1548 Energy scales for electrons misidentified as hadronic tau decays (e faking τ_h) are
 1549 provided by the Tau POG, and were measured in the $e\tau_h$ channel with the visible
 1550 invariant mass of the electron and hadronic tau system [66]. This energy scale is
 1551 applied for τ_h with $p_T > 20$ GeV regardless of which DeepTau vs. electron working
 1552 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 [66].

1553 No nominal energy scale is applied for muons mis-reconstructed as τ_h , and the
 1554 uncertainty is treated as $\pm 1\%$ and uncorrelated in the reconstructed decay mode
 1555 [66].

1556 **5.3.11 Electrons and muons faking τ_h : misidentification effi-**
 1557 **ciencies**

1558 Corrections on identification efficiencies are applied to genuine electrons and muons
 1559 misidentified as τ to account for differences in data and MC.

1560 The specific values depend on the vs. electron and vs. muon discriminator working
 1561 points used. For misidentified $\mu \rightarrow \tau_h$, the scale factors are split into different $|\eta|$
 1562 regions, determined by the CMS muon and tracker detector geometries, as shown in
 1563 Table 5.6 for 2018 [63].

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 $|\eta|$ [63].

1564 For misidentified $e \rightarrow \tau_h$, the scale factors are split into barrel and endcap regions,
 1565 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 $|\eta|$ [63].

1566 5.3.12 Electron ID and tracking efficiency

1567 Scale factors are applied to MC to correct for differences between MC and data in
 1568 the performance of electron identification (ID) and tracking.

1569 Electron and photon identification, as discussed earlier, use variables with good
 1570 signal vs. background discrimination power such as lateral shower shape and ratio
 1571 of energy deposited in the HCAL to energy deposited in the ECAL at the position
 1572 of the electron. The cut-based electron identification efficiencies in data and ratio of
 1573 efficiencies in data to MC are shown in Fig. 5.7a for the multivariate analysis (MVA)
 1574 identification working point.

1575 The tracking efficiencies in data and the data/MC ratio are shown in Fig. 5.7b
 1576 for the Gaussian-sum filter (GSF) tracking [77].

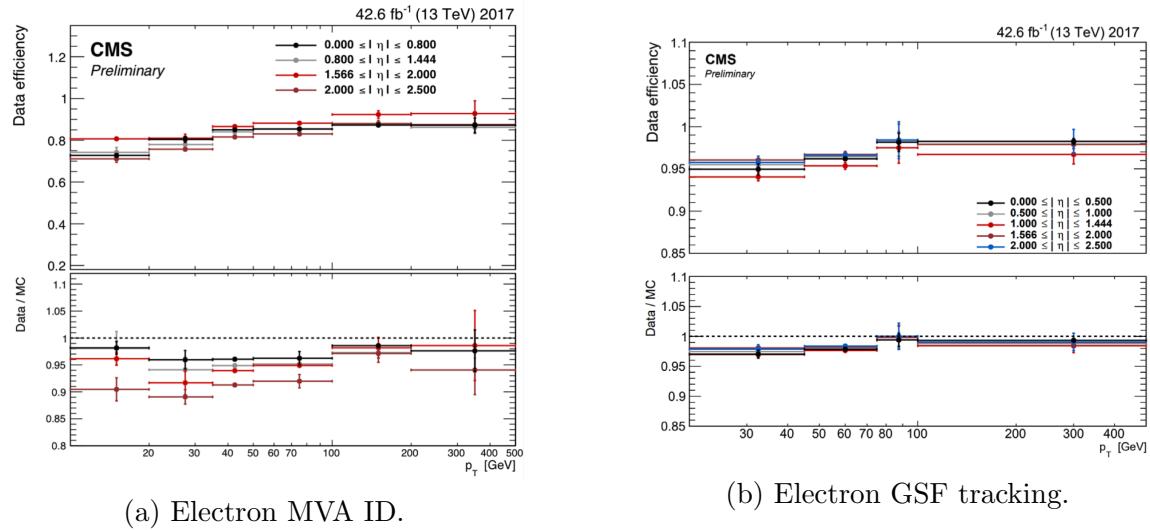


Figure 5.7: Efficiencies in data (*top panels*) and the ratio of efficiencies in data/MC (*bottom panels*), for the electron multivariate analysis (MVA) identification (*left*) and for the Gaussian-sum filter (GSF) tracking (*right*) [77]. Error bars represent statistical and systematic uncertainties.

1577 5.3.13 Muon ID, isolation, and tracking efficiencies

1578 Scale factors are applied to MC to correct for differences between MC and data in
 1579 the performance of muon identification, isolation, and tracking, as detailed below.

1580 The efficiencies for muon identification measured in 2015 data and MC simulation
 1581 are shown in Figures 5.8a and 5.8b for the loose ID and tight ID respectively [78].
 1582 The loose ID is chosen such that efficiency exceeds 99% over the full η range, and the
 1583 data and simulation agree to within 1%. The tight ID is chosen such that efficiency
 1584 varies between 95% and 99% as a function of η , and the data and simulation agree
 1585 to within 1-3%. The muon identification working point used in this analysis is the
 1586 medium ID, which has an efficiency of 98% for all η and an agreement within 1-2%
 1587 [78].

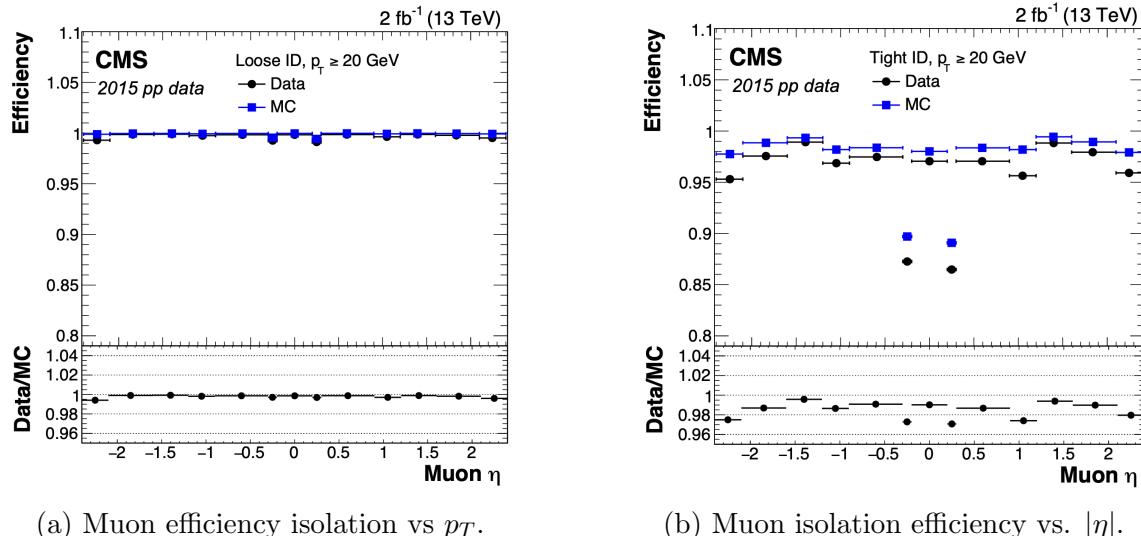
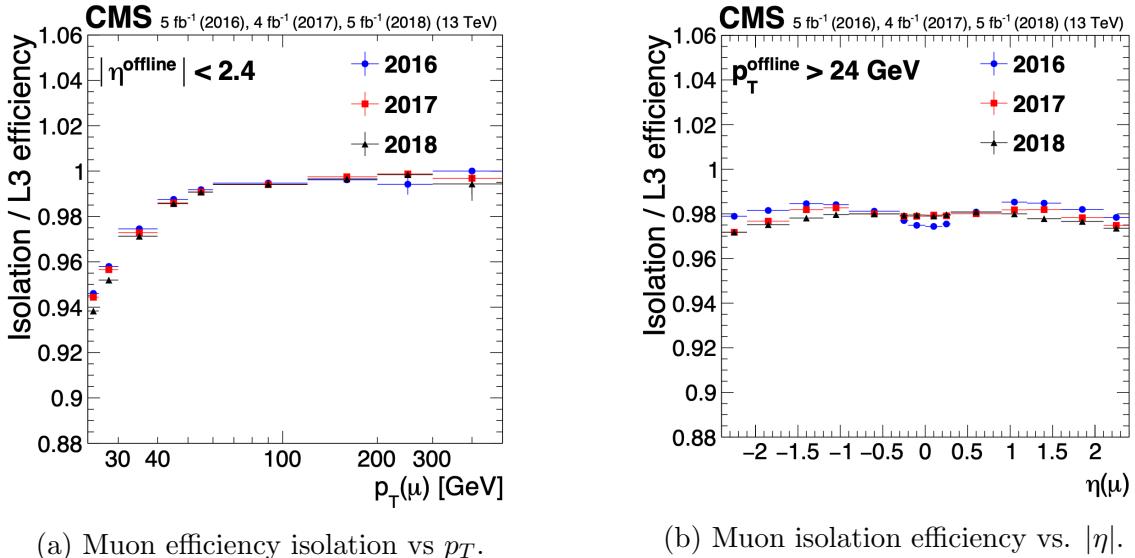


Figure 5.8: Muon identification efficiencies in 2015 data and MC as a function of the muon p_T for the loose ID (*left*) and tight ID (*right*) working points [78].

1588 The efficiencies in data for the muon isolation, as measured in Level-3 muons
 1589 (muons in one of the final stages of reconstruction in the HLT), as a function of the
 1590 muon p_T and $|\eta|$ are shown in Figures 5.9a and 5.9b [78]. The HLT muon reconstruc-
 1591 tion consists of two steps: Level-2 (L2), where the muon is reconstructed in the muon
 1592 subdetectors only, and Level-3 (L3) which is a global fit of tracker and muon hits (i.e.
 1593 the global muon reconstruction as described in Section 5.1.2) [79].

1594 The muon tracking efficiencies as a function of $|\eta|$ for standalone muons (i.e. tracks
 1595 from only the muon system, i.e. DT, CSC, and RPC, as discussed in Section 5.1.2),



(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*) [78].

1596 is shown for data and simulated Drell-Yan samples in Fig. 5.10 [80].

1597 5.3.14 Recoil corrections

1598 In proton-proton collisions, W and Z bosons are predominantly produced through
1599 quark-antiquark annihilation. Higher-order processes can induce radiated quarks or
1600 gluons that recoil against the boson, imparting a non-zero transverse momentum to
1601 the boson [81]. Recoil corrections accounting for this effect are applied to samples
1602 with W+jets, Z+jets, and Higgs bosons [66]. The corrections are performed on the
1603 vectorial difference between the measured missing transverse momentum and the total
1604 transverse momentum of neutrinos originating from the decay of the W, Z, or Higgs
1605 boson. This vector is projected onto the axes parallel and orthogonal to the boson
1606 p_T . This vector, and the resulting correction to use, is measured in $Z \rightarrow \mu\mu$ events,
1607 since these events have leptonic recoil that do not contain neutrinos, allowing the
1608 4-vector of the Z boson to be measured precisely. The corrections are binned in
1609 generator-level p_T of the parent boson and also the number of jets in the event.

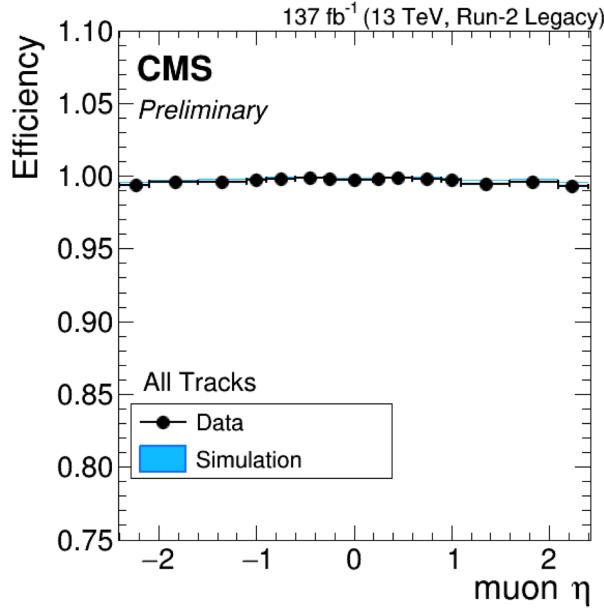


Figure 5.10: Muon tracking efficiencies as a function of $|\eta|$ for standalone muons in Run-2 data (*black*) and Drell-Yan MC simulation (*blue*) [80]. All Tracks refers to tracks which exploit the presence of muon candidates in the muon system to seed the track reconstruction in the inner tracker, 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 [82]. Per-event weights derived by the 2016 data-only version of this analysis [82] 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 Pileup reweighting

Reweighting is performed to rescale MC events to account for differences between MC and data, in the distribution of the pileup (number of additional proton-proton interactions per bunch crossing). A tool for calculating the pileup reweighting for the MC samples used is provided centrally by the Luminosity POG [83].

1621 **5.3.17 Pre-firing corrections**

1622 In 2016 and 2017 data-taking, a gradual timing shift of ECAL was not properly
1623 propagated to L1 trigger primitives (TPs), resulting in a large fraction of high η
1624 TPs being incorrectly associated with the previous bunch crossing. L1 trigger rules
1625 prevent two consecutive bunch crossings from firing, causing events to be rejected if
1626 significant ECAL energy was deposited in $2.0 < |\eta| < 3.0$. To account for this issue,
1627 MC simulations for 2016 and 2017 are corrected using an event-dependent weight.
1628 Embedded samples are not corrected [48].

1629 **5.3.18 Top p_T spectrum reweighing**

1630 In Run-1 and Run-2 it was observed that the p_T spectra of top quarks in $t\bar{t}$ data
1631 was significantly softer than those predicted by MC simulations [84]. Possible sources
1632 of this discrepancy are higher order QCD and/or electroweak corrections, and non-
1633 resonant production of $t\bar{t}$ -like final states. To account for this, corrections derived
1634 from Run-2 data by the Top Physics Analysis Group (PAG) are applied to the p_T
1635 of the top and anti-top quarks in MC simulations, computed as a function of their
1636 generator-level p_T [84].

1637 **5.3.19 B-tagging efficiency**

1638 In order to predict correct b-tagging discriminant distributions and event yields in
1639 data, the weight of selected MC events is reweighed according to recommendations by
1640 the BTV POG [85]. The reweighing depends on the jet p_T , η , and the b-tagging dis-
1641 criminant. In this method, there is no migration of events from one b-tag multiplicity
1642 bin to another.

1643 5.3.20 Jet energy resolution and jet energy smearing

1644 Calibration of jet energies, i.e. ensuring that the energy and momentum of the recon-
1645 structed jet matches that of the quark/gluon-initiated jet, is a challenging task due
1646 to time-dependent changes in the detector response and calibration and high pileup
1647 [86] [87]. Jet calibration is done via jet energy corrections (JECs) applied to the p_T
1648 of jets in MC samples, accounting successively for the effects of pileup, uniformity of
1649 the detector response, and residual data-simulation jet energy scale differences [88].
1650 Typical jet energy resolutions reported at $\sqrt{s} = 8$ TeV in the central rapidities are
1651 15-20% at 30 GeV and about 10% at 100 GeV [86]. Jet energy corrections are also
1652 propagated to the missing transverse energy.

1653 Measurements show that the jet energy resolution (JER) in data is worse than
1654 in simulation, and so the jets in MC need to be smeared to describe the data. JER
1655 corrections are applied after JEC on MC simulations, and adjust the width of the p_T
1656 distribution based on pileup, jet size, and jet flavor [89]. Tools for applying JEC and
1657 JER are provided centrally by the JER Corrections group.

1658 **Chapter 6**

1659 **Event selection**

1660 This chapter describes how events in data and simulated samples are selected in the
1661 search for $h \rightarrow aa \rightarrow bb\tau\tau$. As described in the previous chapter, the tau lepton can
1662 decay to electrons (e), muons (μ), or hadronic states (τ_h). As a result, several different
1663 final states of the $\tau\tau$ system are possible, and are here referred to as “channels” since
1664 they are mutually exclusive. The three $\tau\tau$ final states studied in this analysis are
1665 muon and hadronic tau ($\mu\tau_h$), electron and hadronic tau ($e\tau_h$), and electron and
1666 muon ($e\mu$). The procedure for dividing events into these three channels begins with
1667 checking the High-Level Trigger paths passed by the events as detailed in Section 6.1.
1668 Events are further accepted or rejected based on criteria applied to the leptons in the
1669 event. These event selections are described for the $\mu\tau_h$ channel in Section 6.2, the $e\tau_h$
1670 channel in Section 6.3, and the $e\mu$ channel in Section 6.4.

1671 **6.1 General procedure for all channels**

1672 For the search for $h \rightarrow aa \rightarrow bb\tau\tau$, three final states of the $\tau\tau$ system are considered:
1673 $\mu\tau_h$, $e\tau_h$, and $e\mu$. The $\tau_h\tau_h$ final state is not considered because signal events in the
1674 $\tau_h\tau_h$ channel would typically produce hadronic taus with momenta below data-taking
1675 trigger thresholds.

1676 In all three final states, events are required to have at least one b-tag jet passing the
1677 medium working point of the DeepFlavour tagger, with $p_T > 20$ GeV, and $|\eta| < 2.4$.
1678 A second b-tag jet is not required because such a requirement would reduce signal
1679 acceptance by 80% compared to only requiring one b-tag jet.

1680 Events in MC samples are sorted into one of the three $\tau\tau$ channels if they pass the
1681 following trigger requirements and requirements on the offline reconstructed objects
1682 in the event, first checking the HLT paths for the $\mu\tau_h$ channel, then $e\tau_h$, and finally $e\mu$.
1683 The two leading leptons (e.g. muon and hadronic tau for the $\mu\tau_h$ channel) that were
1684 determined to have originated from the $\tau\tau$ decay, are called the $\tau\tau$ “legs”. For events
1685 in data and embedded samples, the HLT paths requirements for the corresponding
1686 channel are checked.

1687 After sorting events by HLT paths and identifying the leading tau legs in the offline
1688 reconstructed objects, the p_T of the offline objects is checked against the online trigger
1689 thresholds. Trigger matching is also performed, which checks the correspondence
1690 between each offline reconstructed object used in the analysis (e.g. a muon), and a
1691 trigger object in the HLT (e.g. a HLT muon). An offline object is considered to be
1692 matched, if it corresponds to a trigger object of the same object type, with $\Delta R < 0.5$.
1693 This matched trigger object is also required to pass the filter(s) of the HLT trigger.
1694 The trigger thresholds used for the $bb\mu\mu$ final state and the $bb\tau\tau$ final state (the focus
1695 of this work) are summarized in Tables 6.1.

1696 After checking the HLT paths and trigger objects in each channel, events are
1697 subject to further selection to ensure that they contain leptons and b-tag jet(s) of in-
1698 terest. These requirements are summarized in Table 6.2, and detailed in the following
1699 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 [90], 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 on

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.

1716 track quality and muon quality. This identification criteria is designed to be highly
1717 efficiently for prompt muons and for muons from heavy quark decays. In addition to
1718 the ID, for prompt muons it is recommended to apply cuts on the impact parameter
1719 [90]: we apply $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$.

1720 In addition, a cut is applied on the muon relative isolation (defined in Section
1721 5.1.2), to be less than 0.15 in a cone size of $\Delta R = 0.4$, which corresponds to the
1722 Tight Particle Flow isolation requirement [90].

1723 The τ_h is required to pass a cut on its impact parameter of $|\Delta(z)| < 0.2$. The τ_h
1724 is also required to pass the VLoose (Very Loose) DeepTau working point vs. elec-
1725 tron, the Tight DeepTau working point vs. muons, and the VVVLoose and Medium
1726 DeepTau working point vs. jets. Events with taus reconstructed in two of the decay
1727 modes (labeled 5 and 6) are rejected, since these decay modes are meant to recover
1728 3-prong taus, but are only recommended for use in analyses where the benefits in
1729 final significance outweigh the resulting increase in background [63].

1730 For the estimation of the background from jets faking τ_h , which is described in Sec-
1731 tion 7.7, anti-isolated events are selected, by requiring events to pass all the selections
1732 described above, except failing the Medium DeepTau working point vs. jets.

1733 6.3 Event selection in the $e\tau_h$ channel

1734 The HLT trigger paths for the $e\tau_h$ channel are summarized in Tables 6.3, 6.4, and
1735 6.5. Similarly to the $\mu\tau_h$ channel, a single electron trigger is used if the electron has
1736 sufficiently high p_T in 2018 and 2017. For data taken in 2018 (2017), the OR of the
1737 single electron triggers with online p_T thresholds at 32 and 35 (27 and 32) GeV are
1738 used, with the corresponding offline electrons required to have p_T greater than 33
1739 (28) GeV. A $e + \tau_h$ cross-trigger is used for electrons with lower offline p_T between
1740 25 and 33 GeV (25 and 28 GeV). For the 2016 dataset, there is no cross trigger but

1741 only a single electron trigger with online p_T threshold at 25 GeV, which is used if the
1742 offline electron has p_T greater than 26 GeV.

1743 The electron and τ_h are required to have opposite charge and be separated by
1744 $\Delta R > 0.4$. The electron is required to be within $|\eta| < 2.3$ when no cross trigger is
1745 used, and $|\eta| < 2.1$ when the cross trigger is fired. The τ_h is required to have $|\eta| < 2.3$
1746 if no cross trigger is fired, and have $|\eta| < 2.1$ if the cross trigger is fired.

1747 The electron is required to have a relative isolation (same definition as in Section
1748 5.1.2) of less than 0.1 in a cone size of $\Delta R = 0.3$, which is the standard recommended
1749 cone size giving minimal pileup dependence and reduced probability of other objects
1750 overlapping with the cone. The isolation quantity used includes an “effective area”
1751 (EA) correction to remove the effect of pileup in the barrel and endcap parts of the
1752 detector [91].

1753 The electron is also required to pass cuts on its impact parameter of $|\Delta(z)| < 0.2$
1754 and $|\Delta(xy)| < 0.045$. It is also required to pass the non-isolated MVA working point
1755 corresponding to 90% efficiency. The electron’s number of missing hits, which are
1756 gaps in its trajectory through the inner tracker [91], must be less than or equal to
1757 1. The electron must pass a conversion veto, which rejects electrons coming from
1758 photon conversions in the tracker, which should instead be reconstructed as part of
1759 the photon [91].

1760 The impact parameter cut for the τ_h is $|\Delta(z)| < 0.2$. In contrast to the $\mu\tau_h$ event
1761 selection, the vs. electron and vs. muon DeepTau working points are flipped, to
1762 reject muons faking the τ_h leg. The τ_h is required to pass the Tight DeepTau working
1763 point vs. electrons, the VLoose DeepTau working point vs. muons, and the Medium
1764 DeepTau working point vs. jets.

1765 As in the $\mu\tau_h$ channel, for the estimation of the background from jets faking τ_h ,
1766 which is described in Section 7.7, anti-isolated events are selected, by requiring events
1767 to pass all the selections described above, except failing the Medium DeepTau working

1768 point vs. jets.

1769 6.4 Event selection in the $e\mu$ channel

1770 The HLT trigger paths for the $e\mu$ channel are summarized in Tables 6.3, 6.4, and
1771 6.5. Events are selected with the logical OR of two $e + \mu$ cross triggers, where either
1772 the electron or muon can have larger p_T : (1) leading electron, where the electron has
1773 online $p_T > 23$ GeV and muon has online $p_T > 8$ GeV, or (2) leading muon, where
1774 electron has online $p_T > 12$ GeV and muon has online $p_T > 23$ GeV.

1775 The leading and sub-leading leptons are required to have an offline p_T greater
1776 than 1 GeV above the online threshold (i.e. $p_T > 24$ GeV). If the sub-leading lepton
1777 is the electron, the offline p_T threshold is 1 GeV above the online threshold ($p_T > 13$
1778 GeV), but if it is a muon, the offline p_T threshold is required to be at least 5 GeV
1779 greater than the online threshold (i.e. $p_T > 13$ GeV). This is because of poor data
1780 and simulation agreement for low- p_T muons with p_T between 9 GeV and 13 GeV, and
1781 the higher probability of mis-identifying jets as muons at lower p_T . With no effect on
1782 the expected limits, the offline p_T threshold for muons is raised to 13 GeV instead of
1783 9 GeV, even though it may lead to loss in signal acceptance. Both the electron and
1784 muon are required to have $|\eta| < 2.4$.

1785 The electron and muon are required to have opposite charge and be separated
1786 by $\Delta R > 0.3$ (note the decreased separation requirement compared to the other
1787 two channels). The electron is required to pass the non-isolated MVA identification
1788 working point corresponding to 90% efficiency, and to have a relative isolation less
1789 than 0.1 for a cone size of $\Delta R = 0.3$ with the EA pileup subtraction correction.
1790 The electron must have one or fewer missing hits and pass the conversion veto (both
1791 described previously in Section 6.3).

1792 The muon is required to pass the medium identification working point (described

1793 earlier in 6.2), and to have a relative isolation less than 0.15 for a cone size of $\Delta R =$
1794 0.4. The muon impact parameter is required to have $|\Delta(z)| > 0.2$ and $|\Delta(xy)| < 0.045$.

1795 For the QCD multijet background estimation described in Section 7.8, the same-
1796 sign region is selected by requiring all the above selections, except the legs are required
1797 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.

1798 6.5 Extra lepton vetoes in all channels

1799 Events containing a third lepton (electron or muon) that is neither of the leading $\tau\tau$
1800 legs are rejected, and events with di-muons and di-electrons are vetoed, with criteria
1801 taken from the Standard Model $H \rightarrow \tau\tau$ working group [66].

1802 The event is vetoed if a third electron is found with the following properties:
1803 $p_T > 10$ GeV, $|\eta| < 2.5$, impact parameter $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$, passing
1804 non-isolation MVA identification with 90% efficiency, conversion veto, ≤ 1 missing

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.

1805 hits, and relative isolation < 0.3 with cone size $\Delta R = 0.3$. The event is also vetoed if
 1806 a third muon is found with the following properties: $p_T > 10$ GeV, $|\eta| < 2.4$, impact
 1807 parameter $|\Delta(z)| < 0.2$ and $|\Delta(xy)| < 0.045$, medium ID, and isolation < 0.3 with
 1808 cone size $\Delta R = 0.4$.

1809 A di-muon veto is applied, which rejects events containing a pair of muons with
 1810 opposite charge and separation of $\Delta R > 0.15$, that both pass the following selections:
 1811 $p_T > 15$ GeV, $|\eta| < 2.4$, flag for global muons, flag for tracker muon, flag for Particle
 1812 Flow muon, $|\Delta(z)| < 0.2$, $|\Delta(xy)| < 0.045$, and isolation < 0.3 with cone size $\Delta R =$
 1813 0.4. A similar di-electron veto is applied to reject events containing a pair of electrons
 1814 with opposite charge and separation of $\Delta R > 0.15$, that both pass the following
 1815 selections: $p_T > 15$ GeV, $|\eta| < 2.5$, a dedicated electron ID (cut-based) for vetoing
 1816 third leptons, $|\Delta(z)| < 0.2$, $|\Delta(xy)| < 0.045$, with pileup-corrected relative isolation
 1817 < 0.3 with cone size $\Delta R = 0.3$.

1818 These vetoes on extra leptons also ensure orthogonality of events to analyses such
 1819 as the $bb\mu\mu$ final state, whose results are combined with this $bb\tau\tau$ final state as
 1820 described in Section 10.2.

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.

₁₈₂₁ **Chapter 7**

₁₈₂₂ **Background estimation**

₁₈₂₃ This section describes methods used to estimate sources of background from Standard
₁₈₂₄ Model processes in the search for $h \rightarrow aa \rightarrow bb\tau\tau$. Similar background estimation
₁₈₂₅ methods are being used for the $h \rightarrow a_1a_2$ analysis. The background contributions
₁₈₂₆ directly taken from MC are described in Sections 7.1 to 7.6. Section 7.7 describes
₁₈₂₇ the data-driven method for estimating backgrounds from jets faking hadronic tau
₁₈₂₈ decays ($\text{jet} \rightarrow \tau_h$), which is used in the $\mu\tau_h$ and $e\tau_h$ channels. Section 7.8 describes
₁₈₂₉ the data-driven method for estimating background from quantum chromodynamic
₁₈₃₀ (QCD) processes in the $e\mu$ channel.

₁₈₃₁ **7.1 Z+jets**

₁₈₃₂ A major source of background for $\tau\tau$ analyses is the Drell-Yan (DY) process (Z+jets).
₁₈₃₃ The Z boson decays to $\tau\tau/\mu\mu/ee$ with equal probability of 3.4% each, with the dom-
₁₈₃₄ inant decay modes being to hadrons (around 70%) and neutrinos (invisible) (20%)
₁₈₃₅ [26].

₁₈₃₆ The Drell-Yan contribution with genuine taus, $Z \rightarrow \tau\tau$, is estimated using embed-
₁₈₃₇ ded samples, described in Section 4.3. To avoid double-counting between embedded
₁₈₃₈ and MC samples, in all MC samples, events with legs that originated from genuine τ

1839 are discarded.

1840 The other decays of the Z , $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$, are estimated from MC simulation,
1841 and are hereafter referred to as simply the Drell-Yan background. These MC samples
1842 are generated to leading order (LO) with different numbers of jets (jet multiplicity) in
1843 the matrix element: $Z+1$ jet, $Z+2$ jets, $Z+3$ jets, $Z+4$ jets, and inclusive $Z+jets$. The
1844 cross-sections of the samples with ≥ 1 jets are normalized to next-to-NLO (NNLO)
1845 in QCD.

1846 For the inclusive Drell-Yan sample, two samples are used with different thresholds
1847 for the di-lepton invariant mass ($m_{\ell\ell}$) at the generator level: one with $m_{\ell\ell} > 50$ GeV
1848 and the other with $10 < m_{\ell\ell} < 50$.

1849 7.2 W+jets

1850 The dominant W boson decay modes are to hadrons (67.4%), $e + \nu_e$ (10.7%), $\mu + \nu_\mu$
1851 (10.6%), and $\tau + \nu_\tau$ (11.4%) [26]. The $W+jets$ background is estimated from MC
1852 simulation. Similarly to the $Z+jets$, the $W+jets$ samples are generated with different
1853 jet multiplicities in the matrix element. LO samples are used for greater statistics
1854 and are normalized to NNLO cross sections.

1855 7.3 $t\bar{t} + jets$

1856 In hadron collisions, top quarks are produced singly with the weak interaction, or in
1857 pairs via the strong interaction, with interference between these leading-order pro-
1858 cesses possible in higher orders of the perturbation theory. The top quark is the
1859 heaviest fermion in the Standard Model and has a short lifetime ($\sim 10^{-25}$ s), decay-
1860 ing without hadronization into a bottom quark and a W boson [26], with the decay
1861 modes of the W boson as listed in the previous section. With two top quarks, the
1862 final states of the two resulting W bosons can be described as fully leptonic, semilep-

1863 tonic, and fully hadronic. These three final states are modeled separately with MC
1864 simulation in 2018 and 2017, while for 2016 the sample used is inclusive.

1865 7.4 Single top

1866 There are three main production modes of the single top in pp collisions [92]: the
1867 exchange of a virtual W boson (t channel), the production and decay of a virtual W
1868 boson (s channel), and the associated production of a top quark and W boson (tW ,
1869 or W-associated) channel. As the s channel process is rare and only 3% of the total
1870 production, the dominant production mode of the t -channel and the tW production
1871 are considered and modeled with MC.

1872 7.5 Diboson

1873 In pp collisions, the production of dibosons (pairs of electroweak gauge bosons, i.e.
1874 WW, WZ, and ZZ) is dominated by quark-antiquark annihilation, with a small con-
1875 tribution from gluon-gluon interaction [93]. MC is used to model the pair production
1876 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
1877 quarks and ℓ being leptons).

1878 7.6 Standard Model Higgs

1879 MC is used to simulate backgrounds from major production modes of the Standard
1880 Model 125 GeV Higgs boson: gluon-gluon fusion (ggH), vector boson fusion (VBF),
1881 associated production with a W or Z (WH, ZH), and associated production with a
1882 top pair (ttH) (see Fig. 7.1 for leading-order diagrams). For these production modes,
1883 samples with the Higgs decaying to $\tau\tau$ or to WW are used. Samples made with
1884 higher-order diagrams for WH and ZH that include the production of a jet, with the

1885 Higgs decaying to WW, are also used.

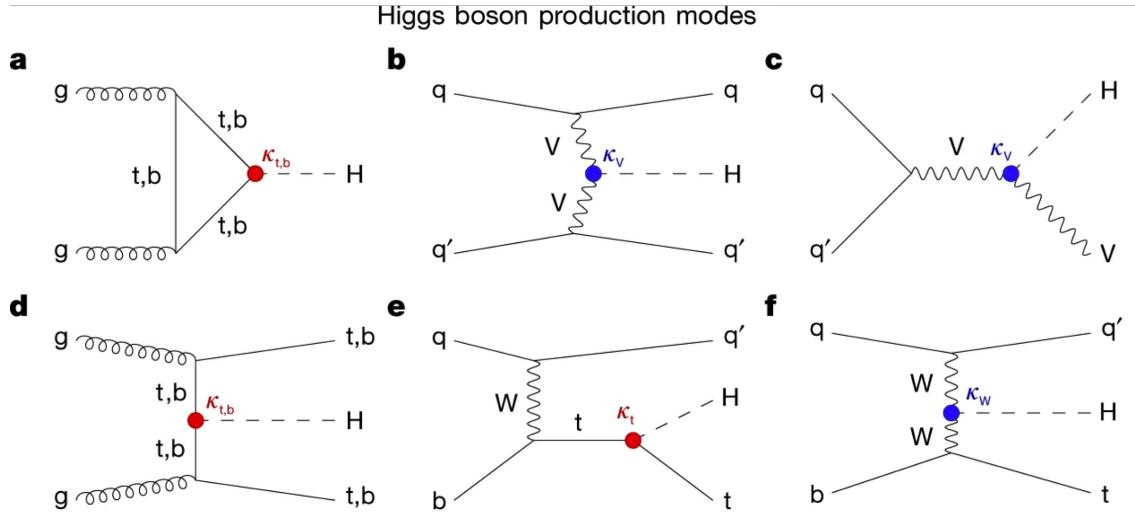


Figure 7.1: Leading-order Feynman diagrams of Higgs production from [94], in ggH (a) and vector boson fusion (VBF; b), associated production with a W or Z (V) boson (VH ; c), associated production with a top or bottom quark pair (ttH or bbH); d, and associated production with a single top quark (tH ; e, f).

1886 7.7 Jet faking τ_h

1887 Events with a jet mis-reconstructed as the hadronic tau leg τ_h are a major source of
1888 background in the $\mu\tau_h$ and $e\tau_h$ channels. The main processes contributing to jet $\rightarrow \tau_h$
1889 events are QCD multijet, $W+jets$, and $t\bar{t}$ production. These events are estimated
1890 using a data-driven method adapted from past analyses [48] [82]. This background
1891 includes contributions from $W+jets$, QCD multijets, and $t\bar{t}+jets$. To estimate this
1892 background, a sideband region is constructed, where events are required to pass all
1893 baseline $\mu\tau_h/e\tau_h$ selection criteria, but fail the τ_h isolation criteria. The events in
1894 this sideband region are reweighted with a factor $f/(1-f)$, where f is the probability
1895 for a jet to be misidentified as a τ_h . The jet $\rightarrow \tau_h$ background is the anti-isolated,
1896 reweighted MC and embedded events subtracted from the anti-isolated, reweighted
1897 data events.

1898 The fake factor is measured in $Z \rightarrow \mu\mu + \text{jets}$ events in data in the $\mu\mu\tau_h$ final
1899 state, as any reconstructed τ_h in these events must originate from a jet. The two
1900 muons are required to be isolated (< 0.15), have opposite electric charge, and have
1901 an invariant mass between 76 and 106 GeV (close to the Z mass). These events are
1902 selected with a double muon trigger, with the leading muon having offline $p_T > 20$
1903 GeV and the subleading muon $p_T > 10$ GeV. Simulated diboson (ZZ and WZ) events
1904 are subtracted to avoid contamination from events with real τ_h . The denominator of
1905 the fake rate corresponds to fake taus passing the VVVLoose working point of the
1906 discriminator vs. jets, while the numerator corresponds to those passing the Medium
1907 working point, i.e. $f = N_{\text{jet passing tight}} / N_{\text{jet passing loose}}$.

1908 f is measured as a function of the τ_h transverse momentum and is 8% - 10% in
1909 each of the data-taking years. f is derived separately for the $\mu\tau_h$ and $e\tau_h$ channels
1910 because the channels use different anti-lepton identification working points.

1911 7.8 QCD multijet background

1912 In the $e\mu$ channel, events with jets faking electrons or muons originating from QCD
1913 multijet, is estimated from data events with the same baseline selection as in the
1914 signal region, except with same-signed (SS) charged $e + \mu$, ensuring orthogonality
1915 with the signal region which requires opposite-sign (OS) $e\mu$ pairs. All same-sign MC
1916 events (both events with real and fake $e + \mu$) are subtracted from same-sign data
1917 events to remove contamination from other backgrounds. i.e. $\text{QCD}_{\text{SS}} = \text{Data}_{\text{SS}} -$
1918 MC_{SS} .

1919 Three scale factors are applied to the QCD_{SS} events to compute the QCD multijet
1920 background [82] [37]:

- 1921 • *OS-to-SS scale factor*: This scales the SS QCD to the OS region, and is mea-
1922 sured from an orthogonal region with an isolated electron and an anti-isolated

muon. Only the muon is chosen to be anti-isolated because this scale factor was observed to depend more strongly on electron isolation than that of the muon. This scale factor is treated as a function of the ΔR separation of the trajectories of the electron and muon, and is measured separately for events with 0 jets, 1, jet, and greater than 1 jet.

- *2D closure correction for the lepton p_T :* This factor accounts for subleading dependencies of the first scale factor on the p_T of the two leptons. A 2D weight is derived in a similar fashion, as a ratio of QCD_{OS} events to QCD_{SS} events, but parameterized by both electron and muon p_T , where the SS events have the previous scale factor applied.

- *Isolation correction for the muon:* The third and final factor is an isolation correction, which is a bias correction to account for the fact that the fake factor was determined for less-isolated muons. This factor is obtained as the ratio of the OS-to-SS scale factors measured in two other control regions: (1) events where the electron is anti-isolated ($0.15 < \text{iso} < 0.5$) and the muon is isolated, and (2) events where both leptons are anti-isolated.

1939 **Chapter 8**

1940 **Systematic uncertainties**

1941 The handling of systematic uncertainties is separated into normalization uncertainties
1942 (those that affect the total yield of a variables' distribution) and shape uncertainties
1943 (those that shift the distribution of events). Normalization uncertainties are expressed
1944 as multiplicative factors, while shape uncertainties are represented as up and down
1945 shifts of a variable's distribution.

1946 Up/down shifts of shape uncertainties can change the number of background
1947 events in a distribution. For instance, hadronic taus receive corrections from the
1948 nominal tau energy scale, with the nominal, up, and down energy scales provided
1949 centrally by CMS. For the $\mu\tau_h$ channel, an event could have a τ_h with p_T just below
1950 the offline threshold of 20 GeV (for instance, 19.5 GeV), so in the nominal distribution
1951 of $m_{\tau\tau}$ (or any other variable for this channel), the event is excluded. However, when
1952 we build our distributions with the tau energy scale “up” shift, the energy of this τ_h
1953 may be scaled up to, say, 20.5 GeV, and now the event passes the offline p_T threshold
1954 for the single muon trigger, leading to the event's inclusion in the distributions made
1955 with the tau energy scale “up” shift.

1956 In evaluating the up and down shifts of a specific source of uncertainty, all other
1957 corrections and scale factors are held at their nominal values, and the full chain of

1958 object and event selection and event categorization is performed to obtain the observ-
1959 able distributions. Any “downstream” variables that depend on the shifted variable,
1960 e.g. the invariant di-tau mass $m_{\tau\tau}$, must be computed for the nominal case, and then
1961 re-computed separately for each up and down shift of the tau legs’ energy scale. The
1962 objective of this process is to quantify the effect of a single source of uncertainty on
1963 the resulting observable distributions. Each scale factor and correction described in
1964 Section 5.3 has an associated uncertainty. The binning of the uncertainties follows
1965 that of the nominal scale factor value.

1966 Sections 8.1 to 8.5 describe uncertainties associated with physics objects, and
1967 Sections 8.6 and 8.7 describe uncertainties associated with sample-level effects. The
1968 pulls and impacts for the top sixty most important systematics are shown in Section
1969 8.8.

1970 8.1 Uncertainties in the lepton energy scales

1971 The uncertainties in the tau energy scales [63] are binned by the tau decay mode and
1972 are taken as shape uncertainties treated as uncorrelated across the tau decay modes
1973 and years. Same as with the application of the nominal scale factor, when applying
1974 the up or down shifts, the missing transverse energy (p_T^{miss}) of the event is adjusted
1975 so that the 4-vector sum of the tau p_T^{miss} is unchanged.

1976 The uncertainties in the muon energy scale [64] are 0.4% for $|\eta| < 1.2$, 0.9% for
1977 $1.2 < |\eta| < 2.1$, and 2.7% for $2.1 < |\eta| < 2.4$, and are treated as shape uncertainties,
1978 fully uncorrelated between embedded and MC samples.

1979 The uncertainties in the electron energy scale [67] in MC are binned in the electron
1980 $|\eta|$ and p_T , and are shown in Fig. 5.2. The uncertainties range from 0.5% to 2.2% in
1981 the barrel, and 0.3% to 4.1% in the endcap, across the p_T range. The uncertainties
1982 for the embedded sample are binned only in $|\eta|$ and are on the order of 0.5% and

1983 1.25% for the barrel and endcap [71].

1984 There are also uncertainties in the energy scales for electrons and muons misidentified as τ_h . The uncertainty for muons misidentified as τ_h is 1% [63]. For electrons misidentified as τ_h , the uncertainty is binned in barrel/endcap η and by 1-prong and 1-prong + π_0 decays. The probability for e/μ faking a 3-prong decay mode is much lower.

1989 8.2 Uncertainties from other lepton corrections

1990 Uncertainties associated with the τ_h identification efficiencies are treated as shapes, 1991 uncorrelated across the seven p_T bins and years. The shape uncertainties in the 1992 embedded samples are taken as 50% correlated with those of the MC samples.

1993 The uncertainties on electron and muon identification efficiencies are taken as 1994 normalization uncertainties of 2% each, with a 50% correlation between embedded 1995 and MC samples.

1996 In the $e\tau_h$ channel, there is an additional uncertainty for the vs. jet discrimination 1997 efficiency [63], because the analysis uses a looser anti-lepton working point (VLoose 1998 WP) than the working points used in the measurement of the efficiency (namely, 1999 VLoose WP vs e, and Tight WP vs mu). For nominal $\tau_h p_T < 100$ GeV, an additional 2000 uncertainty of 3% (5%) is used in MC (embedded), and for high p_T an uncertainty of 2001 15% is used for both.

2002 The uncertainties in trigger efficiencies are taken as shapes [63]. In the $e\tau_h$ and $\mu\tau_h$ 2003 channels, there are uncertainties for the single and cross lepton triggers, and in the 2004 $e\mu$ channel there is one uncertainty each for the two $e + \mu$ triggers, and one combined 2005 uncertainty since their trigger phase spaces are not mutually exclusive.

2006 8.3 Uncertainties from jet energy scale and reso- 2007 lution

2008 The jet energy scale uncertainties are taken as shape uncertainties: there are eleven
2009 in total, with seven correlated across years (labeled “Year” below) and the remainder
2010 uncorrelated across years. They affect the b-tag jet p_T and mass, and hence the
2011 missing transverse energy p_T^{miss} . The shifts are propagated through the b-tagging
2012 scale factor calculation and b-tag jet counting.

2013 The uncertainties in the jet energy correction and resolution [86] [95] are as follows:

- 2014 • *Absolute, AbsoluteYear*: flat absolute scale uncertainties.
- 2015 • *BBEC1, BBEC1Year*: for sub-detector regions, with barrel “BB” in $|\eta| < 1.3$
2016 and endcap region 1 “EC1”: $1.3 < |\eta| < 2.5$.
- 2017 • *EC2, EC2 year*: for sub-detector regions, with endcap region 2 “EC2” in $2.5 <$
2018 $|\eta| < 3.0$.
- 2019 • *HF, HF year*: for sub-detector regions, with hadron forward “HF” in $|\eta| > 3$.
- 2020 • *FlavorQCD*: for uncertainty in jet flavor (uds/c/b-quark and gluon) estimates
2021 based on comparing Pythia and Herwig (different MC generator) predictions.
- 2022 • *RelativeBal*: account for difference between log-linear fits of the two methods
2023 used to study the jet energy response: MPF (missing transverse momentum
2024 projection fraction) and p_T balance.
- 2025 • *RelativeSample*: account for η -dependent uncertainty due to a difference be-
2026 tween relative residuals, observed with dijet and Z+jets in Run D of 2018 data.
- 2027 • *JetResolution*: uncertainty in the jet energy resolution.

8.4 Uncertainties from b-tagging scale factors

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

- hf : contamination from heavy flavor ($b+c$) jets in the light flavor region.
 - $hfstats1, hfstats2$: linear and quadratic statistical fluctuations from b -flavor jets.
 - lf : contamination from light flavor ($udsg+c$ jets) in the heavy flavor region.
 - $lfstats1, lfstats2$: linear and quadratic statistical fluctuations from $udsg$ jets.
 - $cferr, cferr2$: uncertainty for charm jets.
- The variations for “ $lf, hf, hfstats1/2, lfstats1/2$ ” are applied to both b and $udsg$ jets. For c -flavor jets, only “ $cferr1/2$ ” is applied.

8.5 Uncertainties from MET

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

8.6 Uncertainties associated with samples used

Normalization uncertainties related to the samples used are:

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

2048 • *Uncertainties in QCD renormalization scale*: QCD scale(qqH): +0.43%-0.33%,

2049 QCD scale(WH): +0.5%-0.7%, QCD scale(ttH): +5.8%-9.2%

2050 • *Branching ratio uncertainties*: BR($H \rightarrow \tau\tau$): 1.8%, and BR($H \rightarrow WW$): 1.5%.

2051 • *Normalization uncertainties*: 2% for Drell-Yan, 4% for embedded, 20% pre-fit
2052 for the QCD multijet background in the $e\mu$ channel, 20% pre-fit for the jet
2053 faking background.

2054 The $t\bar{t}$ process has additional acceptance uncertainties from QCD scale variation
2055 and parton shower uncertainties [96]. Parton shower uncertainties originate from
2056 the modeling of perturbative and non-perturbative QCD effects handled in parton
2057 shower MC generators. The scale variations are determined from the envelope of the
2058 6 provided shapes due to variations in the factorization scale, renormalization scale,
2059 and their combined variation [96].

2060 The Z p_T reweighing uncertainty in Drell-Yan samples is taken to be 10% of the
2061 nominal value, taken as a shape uncertainty.

2062 The fake rate uncertainties are taken as shape uncertainties. For the weight ap-
2063 plied to scale up anti-isolated events in cross-trigger regions, 20% of the nominal
2064 weight is taken as a shape uncertainty.

2065 8.7 Other uncertainties

2066 A 3.6% yield uncertainty in the signal is used to cover uncertainties in the parton
2067 distribution functions, α_s (fine structure constant), and QCD scale.

2068 Normalization uncertainties from luminosity are applied to all MC samples, di-
2069 vided into those uncorrelated across years, those correlated between 2017 and 2018,
2070 and one for 2018 [83].

2071 8.8 Pulls and impacts

2072 The top impacts and pulls computed for the combination of all channels and years is
2073 shown in Fig. 8.1. The top impacts are related to uncertainty in the signal sample and
2074 cross-section of the $t\bar{t}$ cross-section, and also the yields of the jet faking τ_h background,
2075 which is a major background in all channels and expected to be constrained due to
2076 the yield uncertainty which is taken to be 20% pre-fit.

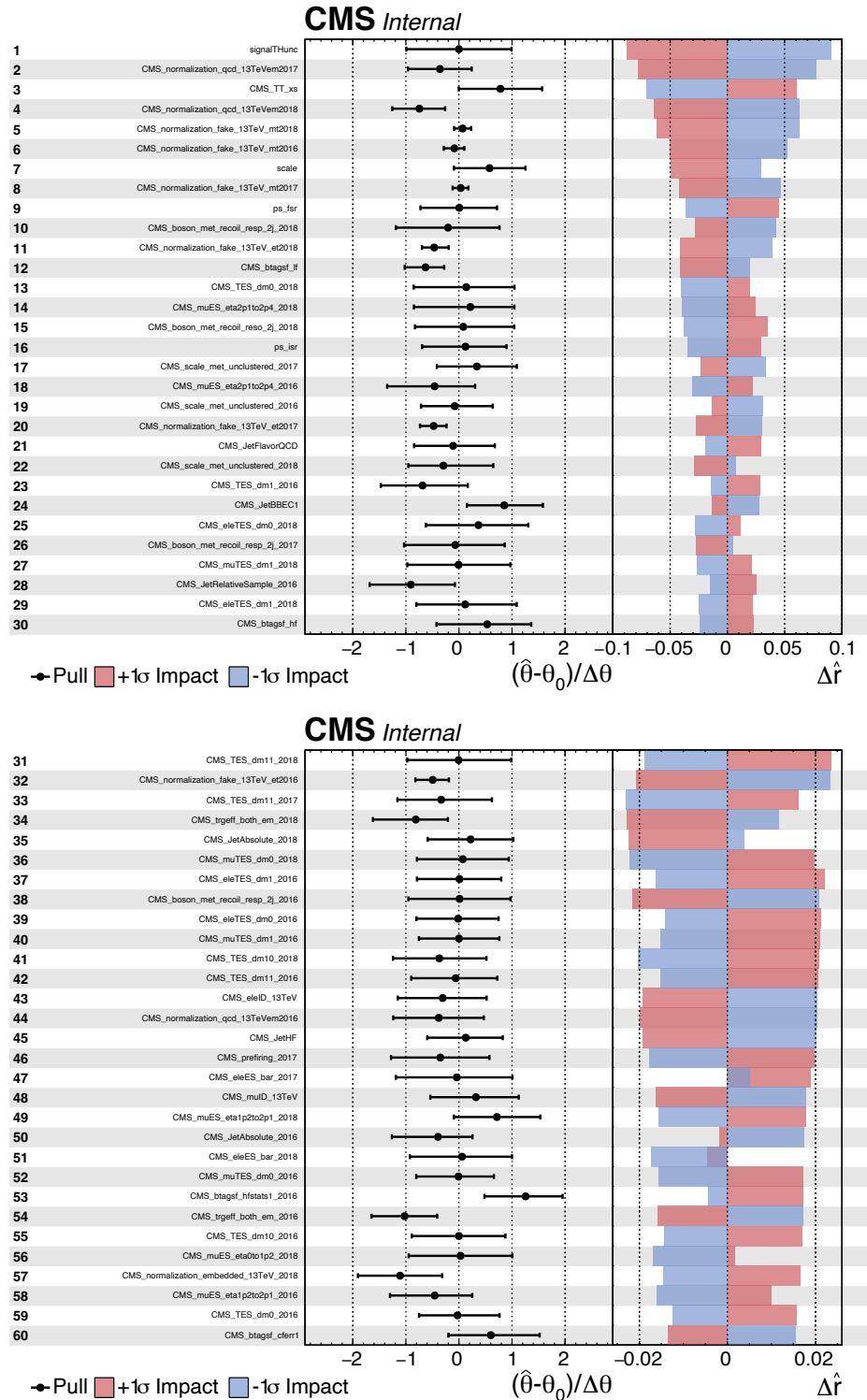


Figure 8.1: Top sixty pulls and impacts for the combination of all channels and years [42].

2077 **Chapter 9**

2078 **Event categorization and signal
extraction**2079

2080 Measured events are divided into categories, based on cuts on values of observables
2081 in the event, or some derived quantity based on the observables in the event. The
2082 objective of event categorization is to divide events into signal regions, where the
2083 signal is enhanced and the background is suppressed, and control regions, which are
2084 signal-poor and used to check that the background estimation methods employed in
2085 the analysis in fact accurately models the data. In this analysis, events in each tau-tau
2086 channel are selected to contain one or more b-tag jets reconstructed in the event as
2087 described in Section 9.1. Events are further divided into signal and control regions
2088 using a deep learning-based approach described in Section 9.2. The signal is extracted
2089 from the di-tau mass distribution in the signal region using the statistical procedure
2090 described in Section 9.3.

2091 **9.1 B-tag jet multiplicity**

2092 The increased statistics of the full Run-2 dataset enables the separation of events into
2093 events with exactly 1 b-tag jet and events with greater than 1 b-tag jet. Further event

2094 categorization is performed with deep neural networks (DNNs) described below. The
2095 DNNs are used only for separating events into signal and control regions in the 1
2096 b-tag and 2 b-tag jets scenarios. The final results are extracted from the statistical
2097 fitting to the mass of the $\tau\tau$, $m_{\tau\tau}$.

2098 9.2 DNN-based event categorization

2099 Neural networks for event categorization are trained for each of the $\mu\tau_h$, $e\tau_h$, and $e\mu$
2100 channels, for 1 and 2 b-tag jets, giving $3 \times 2 = 6$ networks in total. In the training,
2101 the signal is taken to be all of the possible pseudoscalar mass m_a hypotheses together.
2102 The backgrounds for each DNN are taken to be a representative combination of the
2103 three major backgrounds: $Z \rightarrow \tau\tau$, $t\bar{t} + \text{jets}$, and fake backgrounds. The proportions of
2104 each background for each channel and b-tag jet multiplicity are taken from the yields
2105 in the $m_{\tau\tau}$ distribution. For instance, in the $\mu\tau_h$ 1 b-tag jet category, the composition
2106 of the background for training is 17.4% from $Z \rightarrow \tau\tau$, 42.4% from $t\bar{t} + \text{jets}$, and 40.2%
2107 fakes.

2108 The input variables capture the key differences between the signal and the back-
2109 ground:

- 2110 • Transverse momentum p_T of the electron and muon in the $e\tau_h$ and $\mu\tau_h$ channels,
2111 where the signal tends to have a softer p_T spectrum (lower energy) than the
2112 background.
- 2113 • p_T of the b-tag jet(s). The signal sample b-tag jet(s) tend to have softer p_T .
- 2114 • Invariant masses of the various objects ($\tau\tau$ legs and the b-tag jet(s)), which
2115 tend to be smaller for the signal samples.
- 2116 • The angular separation ΔR between pairs of the objects, where signal samples
2117 peak at smaller ΔR values.

- 2118 • The transverse mass between the missing transverse energy p_T^{miss} and each of
 2119 the four objects [82], defined as

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

2120 where p_T^ℓ is the transverse momentum of the object ℓ , and $\Delta\phi$ is the difference
 2121 in azimuthal angle between the object and the p_T^{miss} . Events from $t\bar{t}$ +jets and
 2122 jets faking τ_h backgrounds have larger p_T^{miss} resulting in larger transverse mass
 2123 values compared to the signal, which tends to have smaller p_T^{miss} that is also
 2124 more aligned with the lepton legs.

- 2125 • The variable D_ζ [82], defined as

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

2126 where the ζ axis is the bisector of the transverse directions of the visible τ decay
 2127 products. p_ζ is the component of the p_T^{miss} along the ζ axis, and p_ζ^{vis} is the sum
 2128 of the components of the lepton p_T along the same axis. This variable captures
 2129 the fact that in signal the p_T^{miss} is small and approximately aligned with the $\tau\tau$.
 2130 In contrast, the $Z \rightarrow \tau\tau$ background tends towards large D_ζ values because the
 2131 p_T^{miss} is collinear to the $\tau\tau$, and the $t\bar{t}$ +jets events tend to have small D_ζ due to
 2132 a large p_T^{miss} not aligned with the $\tau\tau$.

- 2133 • For events with 2 b-tag jets, one additional variable is defined to capture the
 2134 difference in the invariant mass of the bb and the $\tau\tau$:

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

2135 This variable peaks at zero for the $h \rightarrow aa \rightarrow 2b2\tau$ signal.

After training, events in data, MC, and embedded are evaluated with the six DNNs
 and assigned a raw score between 0 and 1 (background-like or signal-like). In order
 to flatten the distribution of the score and define score thresholds for categorizing
 events, the raw output scores are transformed with the function $\tilde{p}(n) = \text{arctanh}(p \times$
 $\tanh(n))/n$ where n is a positive integer. The thresholds of the DNN score used for
 signal/control region definition are determined using scans 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.

9.3 Methodology for signal extraction

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

	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.

2149 analysis.

2150 **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 [97]. 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

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

2151 read “ f of x given α ”, is referred to as a probability model or model. The parameters α
 2152 typically represent parameters of the theory or an unknown property of the detector’s
 2153 response. The parameters are not frequentist in nature, unlike x . Out of all the
 2154 parameters, typically only a few are of interest, and are called the parameters of
 2155 interest (POI), labeled μ here. The remaining are referred to as nuisance parameters
 2156 (NP) [97] and are labeled $\boldsymbol{\theta}$.

2157 $f(x)$ is the probability density for the observable in one event and we wish to
 2158 describe the probability density for a dataset with many events, $\mathcal{D} = \{x_1, \dots, x_n\}$,
 2159 called the total probability model \mathbf{f} . For instance, if we also have a prediction for
 2160 the total number of events expected, called ν , we also account for the overall Poisson
 2161 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 [97]. The likelihood function is not a probability density for α
 and is not normalized to unity:

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

2162 i.e. the likelihood function is the value of f as a function of α given a fixed value of
 2163 x .

2164 To estimate the parameter α we use an estimator, which is a function of the
 2165 data. Take for example the measurement of data distributed according to a Gaussian
 2166 probability density $f(x|\mu, \sigma) = \text{Gauss}(x|\mu, \sigma)$. One possible estimator of the mean μ ,
 2167 is the mean of the measured data points $\bar{x} = \sum_{i=1}^n x_i/n$ [97].

2168 A commonly used estimator in physics is the maximum likelihood estimator
 2169 (MLE), defined as the value α which maximizes the likelihood function $L(\alpha)$. This

2170 value, labeled $\hat{\alpha}$, also maximizes $\ln L(\alpha)$ and minimizes $-\ln L(\alpha)$. By convention the
2171 $-\ln L(\alpha)$ is minimized, in a process called “fitting”, and the maximum likelihood
2172 estimate is called the “best fit value”.

2173 **9.3.2 Hypothesis testing**

2174 In this section we next introduce concepts related to hypothesis testing such as the
2175 test statistic constructed from the ratio of likelihood functions.

2176 The objective of a likelihood analysis is to distinguish different models repre-
2177 senting the various hypotheses, and determine the one that best explains the ex-
2178 perimental outcome. In a search for new physics, a signal is additive on top of the
2179 background. The background-only hypothesis is the null hypothesis, and the signal-
2180 plus-background hypothesis is the alternative.

2181 As a simple example, take the p -value test, for an experiment where we count
2182 events in the signal region, n_{SR} , and expect ν_B background events and ν_S events from
2183 the signal [97]. Then

2184 1. The null hypothesis (H_0), i.e. the background-only hypothesis in this experi-
2185 ment, with the probability modeled by $\text{Poisson}(n_{SR}|\nu_B)$.

2186 2. The alternate hypothesis (H_1), i.e. signal-plus-background hypothesis, with the
2187 probability modeled by $\text{Poisson}(n_{SR}|(\nu_B + \nu_S))$.

2188 The compatibility of the observed data n_{SR}^0 and the null hypothesis, is quantified as
2189 the probability that the background-only hypothesis would produce at least as many
2190 events as was observed. This probability is the p -value:

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

2191 If the p -value is very small, we might reject the null hypothesis. The p -value is not the

2192 probability of the null hypothesis given the data; rather, it expresses the probability
2193 that data with a certain property was obtained, assuming the null hypothesis [97].

2194 The p -value is an example of a test statistic T , which maps the data to a single
2195 real number. The Neyman-Pearson lemma states that out of the infinite possibilities
2196 of choices of test statistic, the uniformly most powerful test statistic is the likelihood
2197 ratio T_{NP} [97]:

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

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:

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

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

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

2198 where T_0 is the value of T based on the observed data, and $\theta()$ is the Heaviside
2199 function. The size of the test is conventionally chosen to be 10%, 5%, or 1%. As
2200 the p -value depends on $\boldsymbol{\alpha}$ (both the POI and NP), the null hypothesis should not be
2201 rejected if the p -value is larger than the size of the test for any value of the nuisance
2202 parameters.

2203 9.3.3 Confidence intervals

2204 In an example of the measurement of the Standard Model Higgs boson, $\boldsymbol{\alpha}_{POI} =$
2205 $(\sigma/\sigma_{SM}, M_H)$, 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 [97]. 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
 true value 95% of the time (even though we do not know the true value).

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

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

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

9.3.4 Profile likelihood ratio

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

With a multi-parameter likelihood function $L(\boldsymbol{\alpha})$, the the maximum likelihood of
 one specific parameter α_p with other parameters $\boldsymbol{\alpha}_o$ fixed, is called the conditional
 maximum likelihood estimate and is denoted $\hat{\alpha}_p(\boldsymbol{\alpha}_0)$. The process of choosing specific
 values of the nuisance parameters for a given value of μ , $\mathcal{D}_{\text{simulated}}$, and value of global

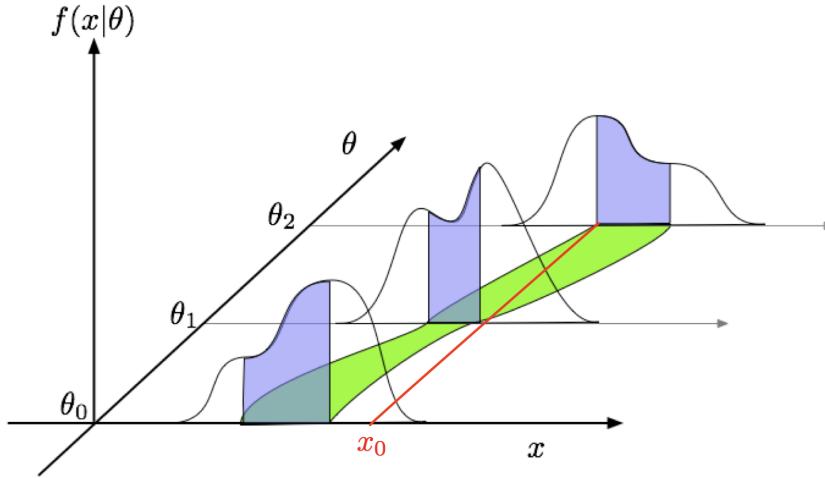


Figure 9.1: Schematic of the Neyman construction for confidence intervals [97]. For each value of θ , we find a region in x where $\int f(x|\theta)dx$ satisfies the size of the test (blue). These regions form a confidence belt (green). The intersection of the observation x_0 (red) with the confidence belt defines the confidence interval $[\theta_1, \theta_2]$ [97].

2229 observables \mathcal{G} is called profiling. From the full list of parameters $\boldsymbol{\alpha}$, we denote the
2230 parameter of interest μ , and the nuisance parameters $\boldsymbol{\theta}$.

2231 We construct the profile likelihood ratio,

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

2232 which depends explicitly on the parameter of interest μ , implicitly on the data \mathcal{D}_{sim}
2233 and global observables \mathcal{G} , and is independent of the nuisance parameters $\boldsymbol{\theta}$, which
2234 have been eliminated in profiling [97].

2235 The main conceptual reason for constructing the test statistic from the profile
2236 likelihood ratio is that asymptotically (i.e. for measurements with many events) the
2237 distribution of the profile likelihood ratio $\lambda(\mu = \mu_{\text{true}})$ is independent of the values of
2238 the nuisance parameters [97].

2239 The following p -value is used to quantify the consistency with the hypothesis of a
2240 signal strength of μ :

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

9.3.5 Modified frequentist method: CL_S

2241 In the modified frequentist method called CL_S , to test a hypothesis with signal, we
2242 define p'_μ as a ratio of p -values [97]:
2243

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

2244 where p_b is the p -value derived under the background-only hypothesis:

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

2245 The CL_S upper limit on μ , denoted μ_{up} , is obtained by solving for $p'_{\mu_{up}} = 5\%$.
2246 If testing the compatibility of the data with the background-only hypothesis, we
2247 consider the p_b value defined above and conventionally convert it into the quantile
2248 or “sigma” of a unit Gaussian. z standard deviations (e.g. $z = 5$ in “ 5σ ”) means
2249 that the probability of falling above these standard deviations, equals p_b (e.g. 3σ
2250 corresponds to $p_b = 2.7 \times 10^{-3}$ or 95.43%, and 5σ corresponds to $p_b = 5.7 \times 10^{-7}$ or
2251 99.999943%).

2252 **Chapter 10**

2253 **Results**

2254 **10.1 Results from $bb\tau\tau$**

2255 In each of the three $\tau\tau$ channels studied ($\mu\tau_h$, $e\tau_h$, and $e\mu$), events are divided based
2256 on whether they contain exactly 1 or 2 b-tag jets, and further divided into signal
2257 and control regions (SRs and CRs) using the DNN categorization score as described
2258 in Section 9.2. The control regions demonstrate good agreement between observed
2259 events in data, and the sum of the contributions from expected backgrounds that
2260 are modeled in simulated and embedded samples. The signal regions are defined to
2261 be sensitive to the $h \rightarrow aa \rightarrow bb\tau\tau$ signal. The postfit final observed and expected
2262 distributions of the di-tau invariant mass $m_{\tau\tau}$ reconstructed with SVFit (described
2263 in Section 5.2) are shown in Fig. 10.1 for the $\mu\tau_h$ channel, Fig. 10.2 for the $e\tau_h$
2264 channel, and Fig. 10.3 for the $e\mu$ channel. In all figures, the hypothesized yield for
2265 the $h \rightarrow aa \rightarrow bb\tau\tau$ signal is shown for the pseudoscalar mass $m_a = 35$ GeV and
2266 assuming a branching fraction $B(H \rightarrow aa \rightarrow bb\tau\tau) = 10\%$.

2267 The 95% CL expected and observed exclusion limits on the signal strength of the
2268 branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau)$ as a function of the pseudoscalar mass m_a
2269 ranging from 12 GeV to 60 GeV, are shown for the three $\tau\tau$ channels and all three

2270 channels combined in Fig. 10.4. The limits are shown as percentages and normalized
2271 to the production cross-section of the Standard Model Higgs boson. No excess of
2272 events above the Standard Model expectations is observed. In the limits for the three
2273 $\tau\tau$ channels combined, expected (observed) limits range from 1.4 to 5.6% (1.7 to
2274 7.6%) for pseudoscalar masses between 12 and 60 GeV.

2275 The $e\mu$ channel is the only channel that has signal sensitivity to the $m_a = 12$
2276 GeV pseudoscalar mass hypothesis, because the minimum required spatial separation
2277 $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ between the two τ legs is smaller than the other two channels
2278 ($\Delta R < 0.3$ for $e\mu$, compared to $\Delta R < 0.4$ for the other two channels). This decreased
2279 ΔR requirement results in better signal acceptance for low mass signals for the $e\mu$
2280 channel. The $\mu\tau_h$ and $e\tau_h$ channels are most sensitive to the intermediate mass points
2281 studied, since the analysis targets a resolved signature: at low mass points, the tau
2282 legs are boosted, and at high mass points, the $m_{\tau\tau}$ distributions in signal have larger
2283 overlap with background distributions. In the combination of the three $\tau\tau$ channels,
2284 the limit for $m_a = 12$ GeV comes only from the $e\mu$ channel, and the best sensitivity
2285 is attained at intermediate mass points around $m_a = 20$ GeV to 45 GeV.

2286 To set limits on the branching fraction of the 125 GeV Higgs to the two pseu-
2287 doscalars, $B(h \rightarrow aa)$, we interpret the results in four types of 2HDM+S, which were
2288 introduced in Section 1.4. In 2HDM+S, the theorized branching fraction of the pseu-
2289 doscalars depends on the 2HDM+S model type, the pseudoscalar mass m_a , and the
2290 ratio of the two Higgs doublets' vacuum expectation values $\tan\beta$. In Type I models,
2291 the branching fraction is independent of $\tan\beta$, while in Types II, III, and IV, it is
2292 a function of m_a and $\tan\beta$. Limits for the $bb\tau\tau$ final state as a function of m_a for
2293 2HDM+S Type I (valid for all $\tan\beta$ values), Type II with $\tan\beta = 2.0$, Type III with
2294 $\tan\beta = 2.0$, and Type IV with $\tan\beta = 0.6$ are overlaid and shown in Fig. 10.5a.

2295 10.2 Combination with $bb\mu\mu$ final state

2296 Results from this analysis for the $h \rightarrow aa \rightarrow bb\tau\tau$ final state are combined with the
2297 analysis for the $h \rightarrow aa \rightarrow bb\mu\mu$ final state [98]. While the predicted branching ratio
2298 for $aa \rightarrow bb\mu\mu$ is comparatively small, the $bb\mu\mu$ final state has competitive results
2299 due to the excellent di-muon resolution measured by CMS. The $bb\mu\mu$ analysis uses
2300 an unbinned fit to the data using the di-muon mass $m_{\mu\mu}$ distribution. Details can be
2301 found in [98].

2302 Combining the results is possible since the $bb\tau\tau$ analysis explicitly rejects events
2303 with extra leptons, so there is no overlap between the events studied in the $bb\tau\tau$
2304 analysis and the $bb\mu\mu$ analysis. In the statistical combination, several systematic
2305 uncertainties are treated as correlated: the integrated luminosity normalization, the
2306 b-tagging scale factor, the scale factors related to muon reconstruction, identifica-
2307 tion, and trigger efficiencies, the inefficiency in the ECAL trigger readout, and the
2308 theoretical uncertainties related to signal modeling.

2309 Since the results in both final states are statistically limited, the combination ben-
2310 efits from the additional data. For $m_a = 35$ GeV, all systematic uncertainties amount
2311 to around 6% of the total uncertainty, with the dominant systematic uncertainties
2312 coming from jet energy systematics in the $bb\mu\mu$ final state, theoretical uncertainties
2313 in the signal, and uncertainties in the QCD multijet backgrounds in the $e\mu$ channel
2314 of the $bb\tau\tau$ final state.

2315 The mass distributions of the di-muon and di-tau objects ($m_{\mu\mu}$ and $m_{\tau\tau}$) are
2316 compared to the data in a combined maximum likelihood fit to derive upper limits
2317 on $B(h \rightarrow aa)$. The observed limits at 95% CL on $B(h \rightarrow aa)$ for different 2HDM+S
2318 scenarios, are shown for the search for $h \rightarrow aa \rightarrow bb\mu\mu$ in Fig. 10.5b, and the
2319 combined analyses $h \rightarrow aa \rightarrow bb\ell\ell$ in Fig. 10.6.

2320 Exclusion limits in a two-dimensional plane as a function of $\tan\beta$ and m_a are
2321 set for 2HDM+S Types II, III, and IV in Fig. 10.7. The most stringent constraints

are observed for 2HDM+S type III because of large branching fractions predicted in theory, with predicted branching fractions between 0.47 and 0.42 for $\tan \beta = 2.0$ and values of m_a between 15 and 60 GeV, compared to the observed 95% CL upper limits which are between 0.08 and 0.03. For 2HDM+S type IV, the predicted branching fractions from theory are between 0.26 and 0.20 for $\tan \beta = 0.6$ for values of m_a between 15 and 60 GeV, and the 95% CL observed upper limits are between 0.12 and 0.05.

The combined results from $h \rightarrow aa \rightarrow bb\ell\ell$ are compared with CMS results in other final states as a function of the pseudoscalar mass m_a : for 2HDM+S type I in Fig. 10.8, type II with $\tan \beta = 2.0$ in Fig. 10.9, and type III with $\tan \beta = 2.0$ in Fig. 10.10. In other scenarios, e.g. type III with $\tan \beta = 5.0$, more stringent limits are set by analyses in other final states, $\mu\mu\tau\tau$ in this case. Other summary plots for other model types and $\tan \beta$ values can be found at [99].

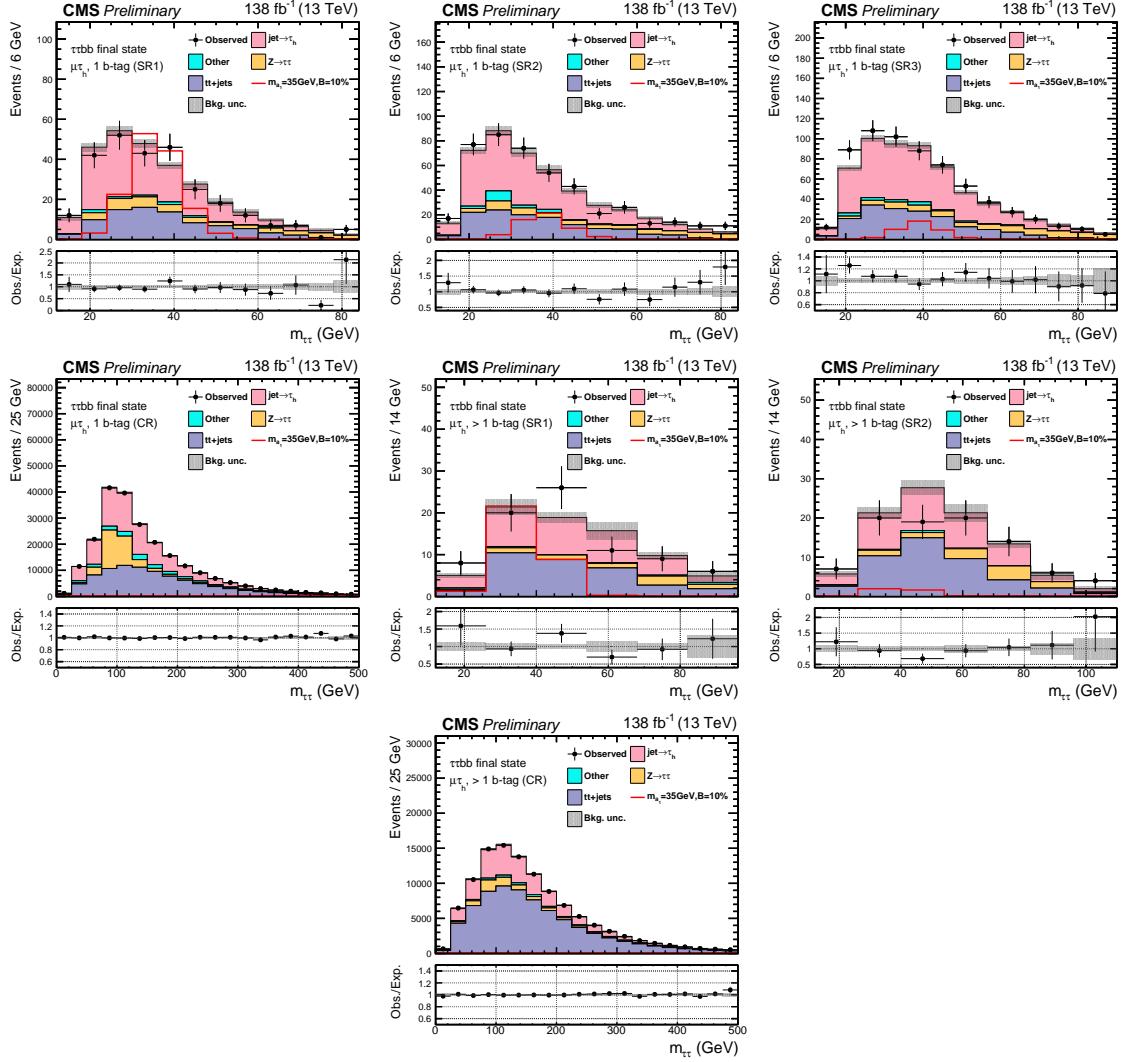


Figure 10.1: Postfit final $m_{\tau\tau}$ observed and expected distributions, and the observed/expected ratios, in the $\mu\tau_h$ channel [42]. Events are divided into the 1 b-tag jet signal regions (SR1, SR2, SR3) (*top row*), 1 b-tag jet control region (*middle row*), 2 b-tag jet signal regions (SR1, 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*).

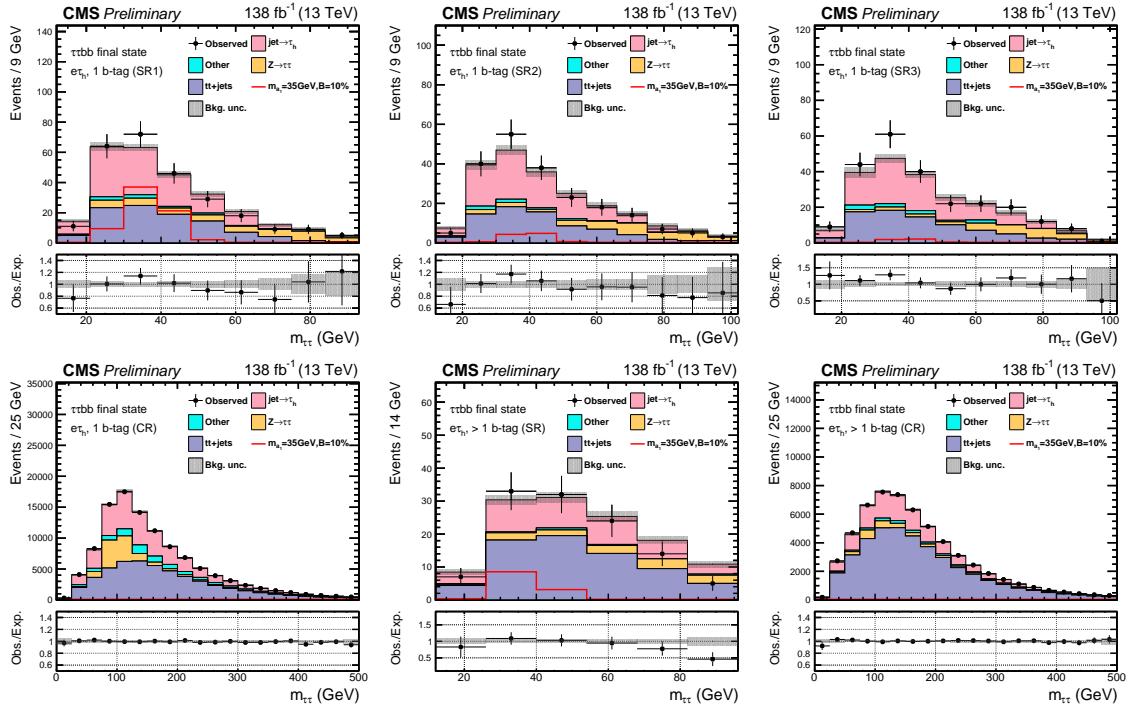


Figure 10.2: Postfit final observed and expected $m_{\tau\tau}$ distributions, and the observed/expected ratios, in the $e\tau_h$ channel [42]. Events are divided into the 1 b-tag jet signal regions (SR1, SR2, SR3) (*top row*), the 1 b-tag jet control region (CR) (*bottom row*), and 2 b-tag jet signal 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 $t\bar{t}+j$ (*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*).

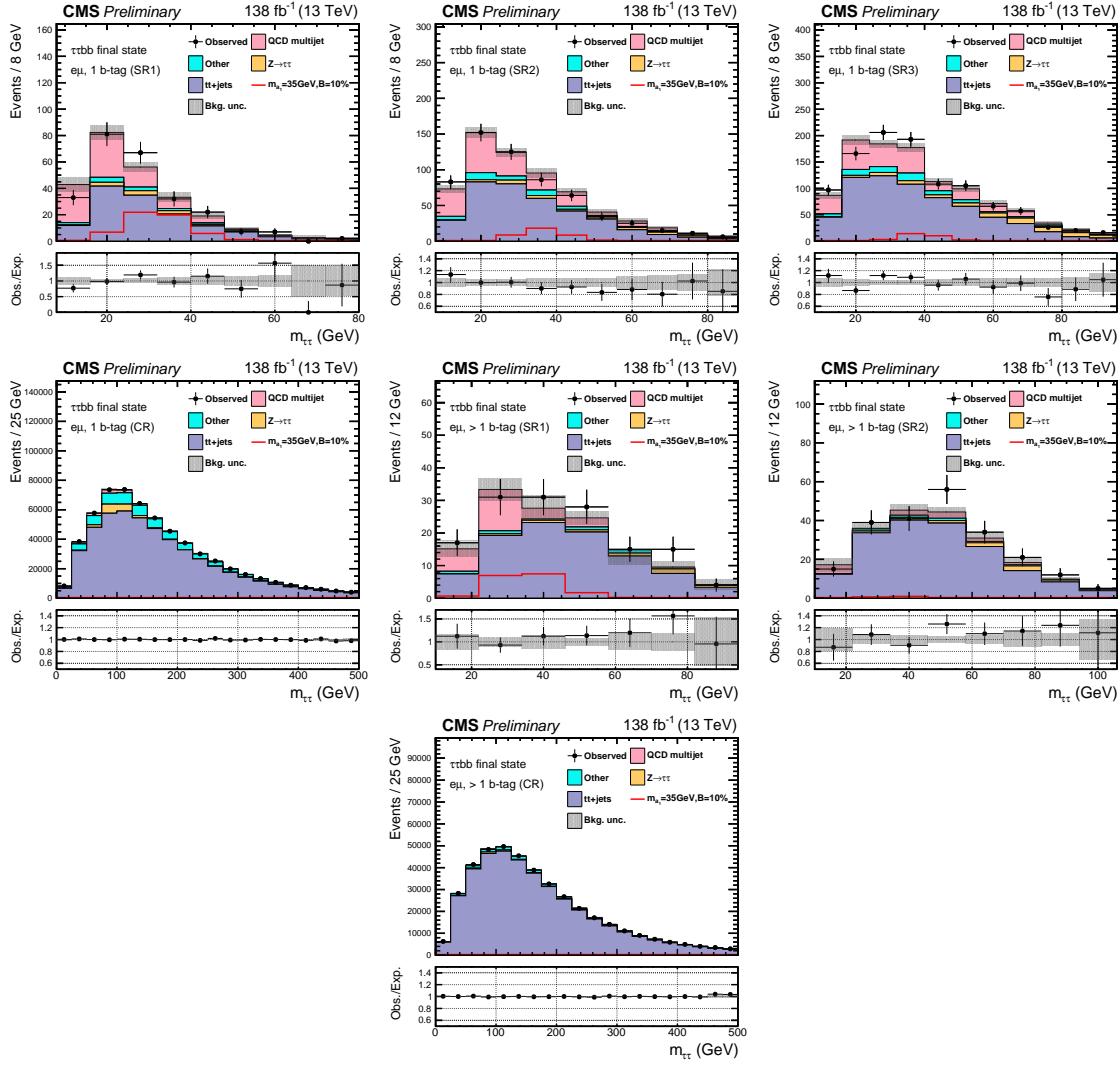


Figure 10.3: Postfit final observed and expected $m_{\tau\tau}$ distributions, and the observed/expected ratios, in the $e\mu$ channel [42]. Events are divided into the 1 b-tag jet signal regions (SR1, SR2, and SR3) (*top row*), 1 b-tag jet control region (CR) (*middle row*), 2 b-tag jet signal regions (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. TFor 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*).

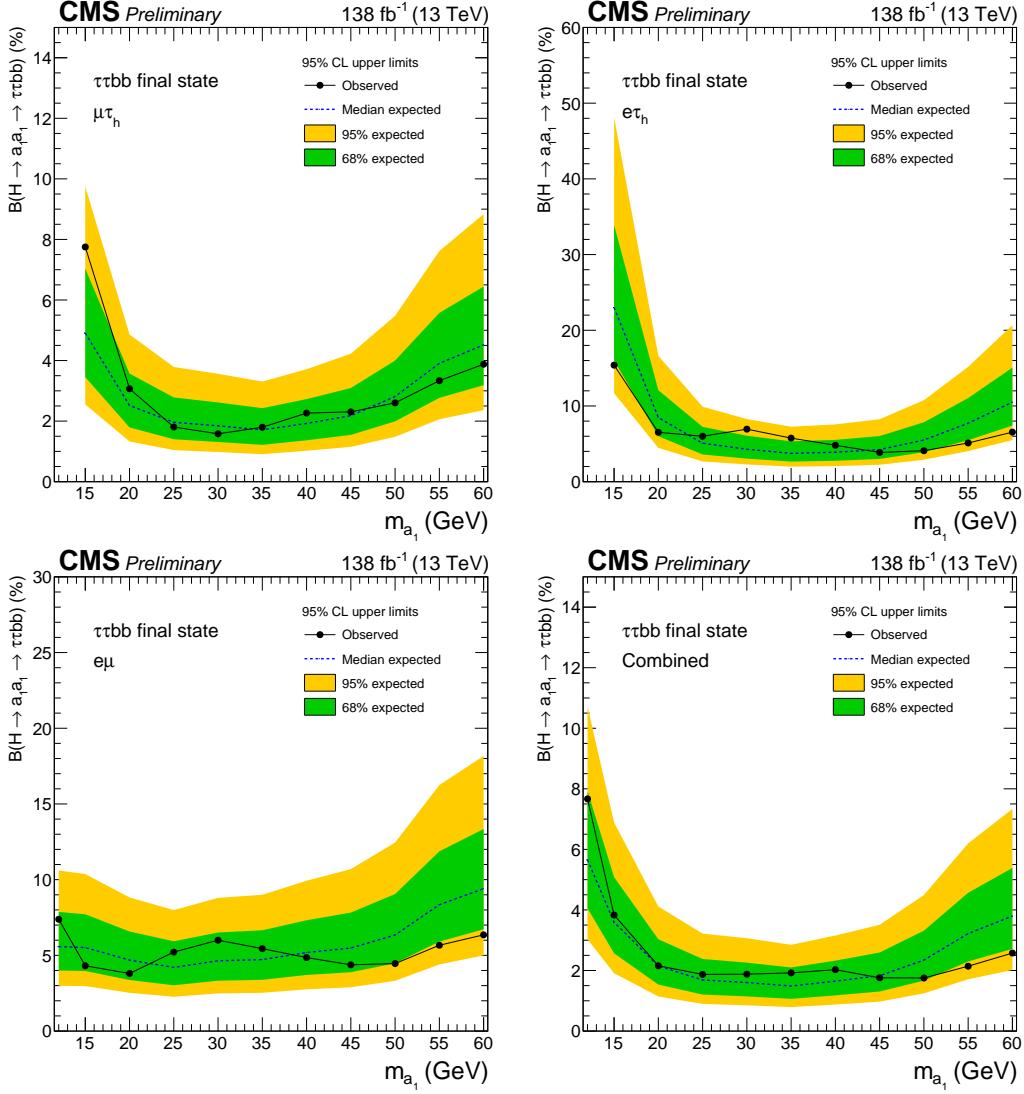


Figure 10.4: Observed 95% CL exclusion limits (*black, solid lines*) and expected 95% CL and 68% CL limits (*shaded yellow and green*) on the branching fraction $B(h \rightarrow aa \rightarrow bb\tau\tau)$ in percentages, assuming the Standard Model production for the 125 GeV Higgs (h). Limits are shown 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*) [42]. 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 $m_a = 12$ GeV. The best sensitivity is attained at intermediate mass points.

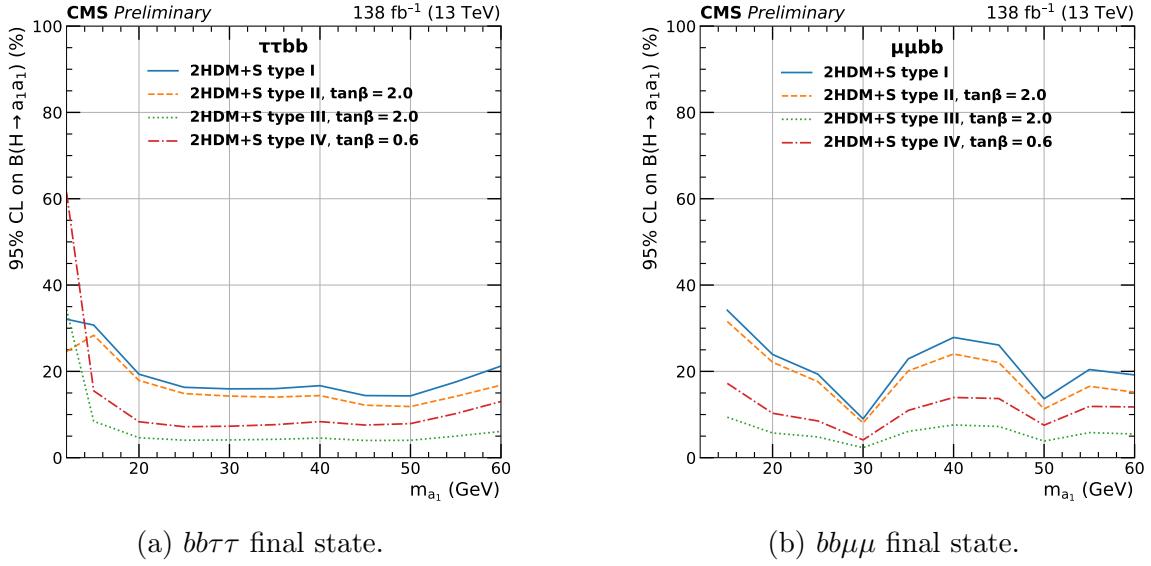


Figure 10.5: Observed 95% CL upper limits on $B(h \rightarrow aa)$ in %, for the $bb\tau\tau$ final state (*left*) and $bb\mu\mu$ final state (*right*) using the full Run 2 integrated luminosity of 138 fb^{-1} in 2HDM+S type I (blue), type II with $\tan\beta = 2.0$ (orange dashed), type III with $\tan\beta = 2.0$ (dotted green), and type IV with $\tan\beta = 0.6$ (red dashed) [42]. Linear interpolation is used between points in the graphs. The $\tan\beta$ values chosen here correspond to the most stringent limits in each model.

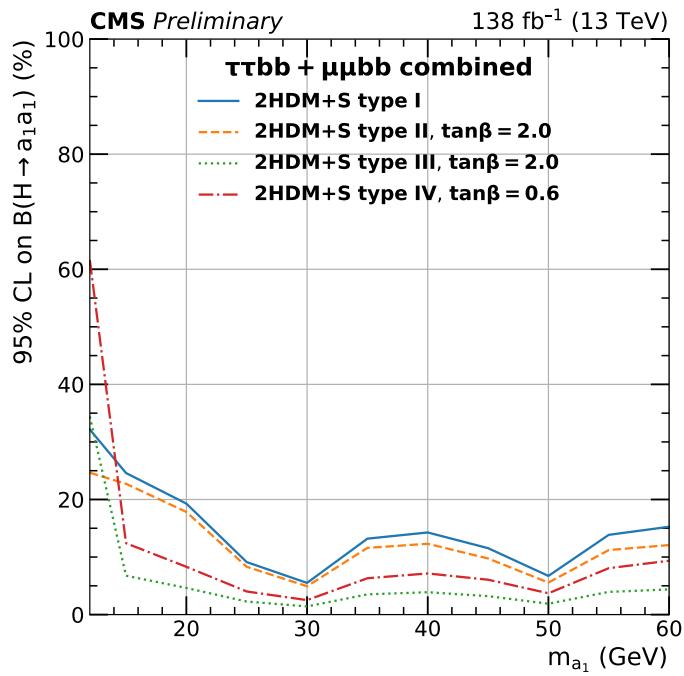


Figure 10.6: Observed 95% CL upper limits on the branching fraction of the 125 GeV Higgs boson to two pseudoscalars, $B(h \rightarrow aa)$, in percentages, as a function of the pseudoscalar mass m_a , in 2HDM+S type I (blue), type II with $\tan\beta = 2.0$ (orange dashed), type III with $\tan\beta = 2.0$ (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} [42].

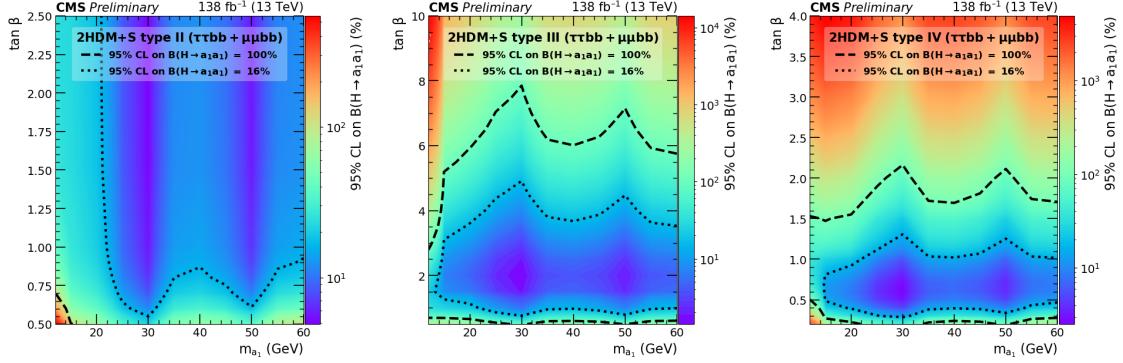


Figure 10.7: Observed 95% CL upper limits on $\mathcal{B}(h \rightarrow aa)$ in %, for the combination of $bb\mu\mu$ and $bb\tau\tau$ channels using the full Run 2 integrated luminosity of 138 fb^{-1} for Type II (*left*), Type III (*middle*), and Type IV (*right*) 2HDM+S in the $\tan \beta$ vs. m_a 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 [42].

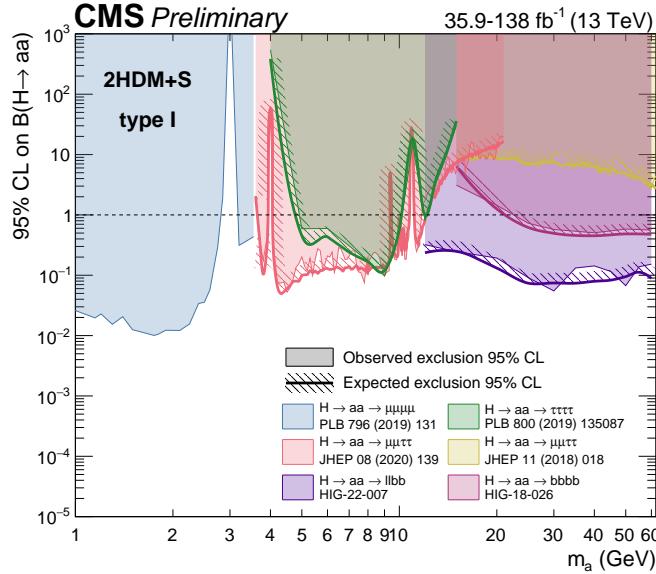


Figure 10.8: Summary plot of current 95% limits on the branching ratio of the 125 GeV Higgs boson to two pseudoscalars, normalized to the Standard Model Higgs production cross-section, $\frac{\sigma(h)}{\sigma_{\text{SM}}} \times B(h \rightarrow aa)$ in the 2HDM+S type I scenario performed with data collected at 13 TeV [99]. 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).

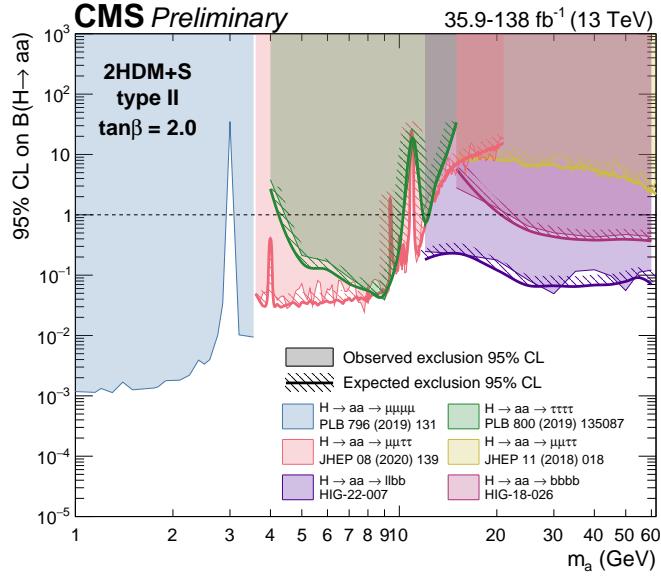


Figure 10.9: Summary plot of current observed and expected 95% CL limits on the branching ratio of the 125 GeV Higgs boson to two pseudoscalars, normalized to the Standard Model Higgs production cross-section, $\frac{\sigma(h)}{\sigma_{\text{SM}}} \times B(h \rightarrow aa)$, in the 2HDM+S type II scenario with $\tan \beta = 2.0$, obtained at CMS with data collected at 13 TeV [99]. 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).

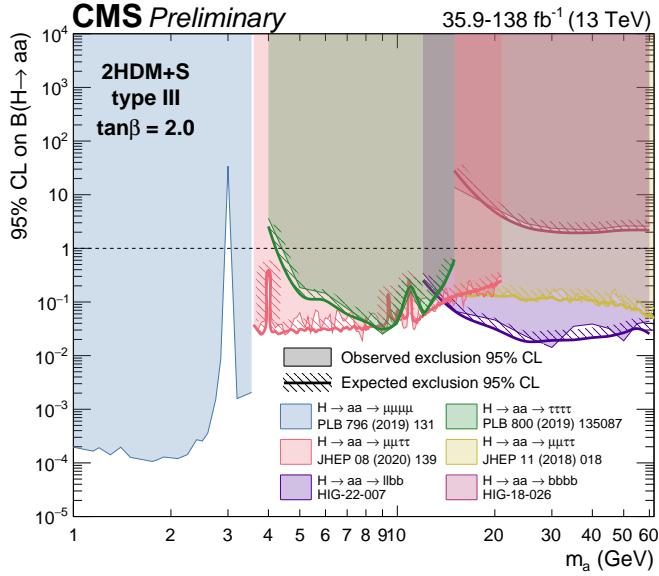


Figure 10.10: Summary plot of current observed and expected 95% CL limits on the branching ratio of the 125 GeV Higgs boson to two pseudoscalars, normalized to the Standard Model Higgs production cross section, $\frac{\sigma(h)}{\sigma_{SM}} \times B(h \rightarrow aa)$ in the 2HDM+S type-III scenario with $\tan \beta = 2.0$, obtained at CMS with data collected at 13 TeV [99]. 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 $llbb$ ($\ell = \mu, \tau$) (purple).

2335 **Chapter 11**

2336 **Asymmetric exotic Higgs decays**

2337 This chapter presents progress towards a search for exotic Higgs decays to two light
2338 scalars with unequal mass ($h \rightarrow a_1 a_2$) final states with bottom quarks and τ leptons,
2339 with plans to interpret the results in the context of Two Real Singlet Models (TRSMs),
2340 described in Section 1.5. Compared to the symmetric decay scenario $h \rightarrow aa$ which
2341 has been studied in multiple final states at CMS with stringent limits set on the
2342 various 2HDM+S scenarios, this asymmetric decay scenario has not been directly
2343 searched for at the CMS experiment. Section 11.1 lists the mass hypotheses of the
2344 new particles a_1 and a_2 that will be studied. Section 11.2 describes the studies on
2345 which channels the analysis will be carried out in. Section 11.3 shows the control
2346 plots produced using the analysis framework that will be used for this analysis.

2347 **11.1 Signal masses**

2348 As discussed in Section 1.5, $h \rightarrow a_1 a_2$ can result in a “cascade” decay if one of the
2349 scalars, a_2 is sufficiently heavy ($m_{a_2} > 2m_{a_1}$). The “non-cascade” case is where the
2350 light scalars decay directly to Standard Model particles.

2351 The mass hypotheses (mass points) (m_{a_1}, m_{a_2}) studied here are:

- *Cascade mass points:* (15, 30), (15, 40), (15, 50), (15, 60), (15, 70), (15, 80), (15, 90), (15, 100), (15, 110), (20, 40), (20, 50), (20, 60), (20, 70), (20, 80), (20, 90), (20, 100), (30, 60), (30, 70), (30, 80), and (30, 90) GeV
- *Non-cascade mass points:* (15, 20), (15, 30), (20, 30), (20, 40), (30, 40), (30, 50), (30, 60), (40, 50), (40, 60), (40, 70), (40, 80), (50, 60), and (50, 70) GeV

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

11.2 Cascade scenario signal studies

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

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

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

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

2377 and fourth b-flavor jets which have very low transverse momenta p_T . Event categories
 2378 with exactly 1 b-tag jet and ≥ 2 b-tag jets will be used.

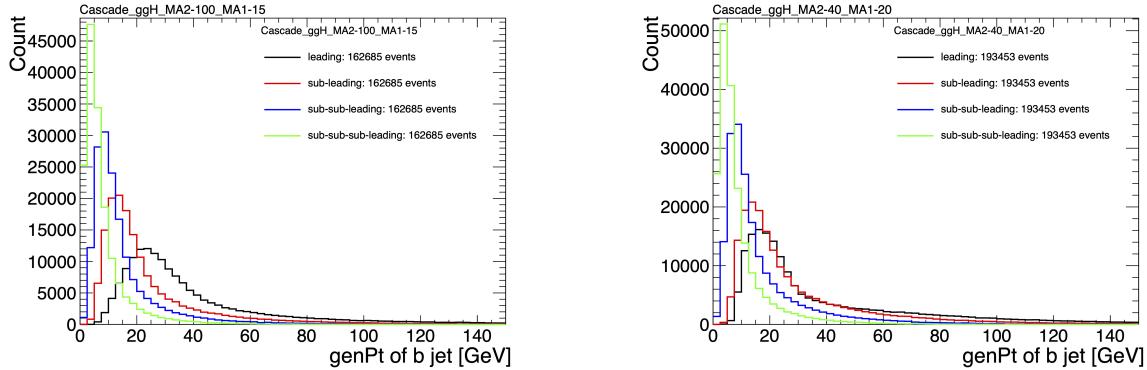


Figure 11.1: Generator-level b-flavor jet transverse momenta p_T , for $h \rightarrow a_1 a_2$ cascade scenario in the $4b2\tau$ final state, for mass hypotheses $(m_{a_1}, m_{a_2}) = (100, 15)$ GeV (*left*) and $(40, 20)$ GeV (*right*). In each plot the generator-level p_T of the leading (*black*),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

2379 In the $4b2\tau$ final state, the possibility of the leading and sub-leading b-tag jets
 2380 being sufficiently close in ΔR to require boosted jet reconstruction techniques was
 2381 explored. In the $4b2\tau$ case, the two b-flavor-jets in the generated event that were
 2382 spatially closest in ΔR were considered as one object. This two b-flavor jet object was
 2383 spatially matched in ΔR to the jets reconstructed with the standard AK4 algorithm
 2384 which uses a cone size of $\Delta R = 0.4$. The quality of the p_T resolution (computed as
 2385 $(p_{T,\text{reconstructed}} - p_{T,\text{gen}})/p_{T,\text{gen}}$) and closeness in distance ΔR of the reconstructed jet
 2386 to the nearest generator-level jets, was seen to depend on the absolute and relative
 2387 masses of the light scalars. The best (worst) performance occurred in samples with
 2388 large (small) mass differences between the heavier scalar a_2 and the lighter scalar a_1 ,
 2389 as illustrated for the mass hypotheses (m_{a_1}, m_{a_2}) (100, 15) GeV and (40, 20) GeV in
 2390 Fig. 11.2.

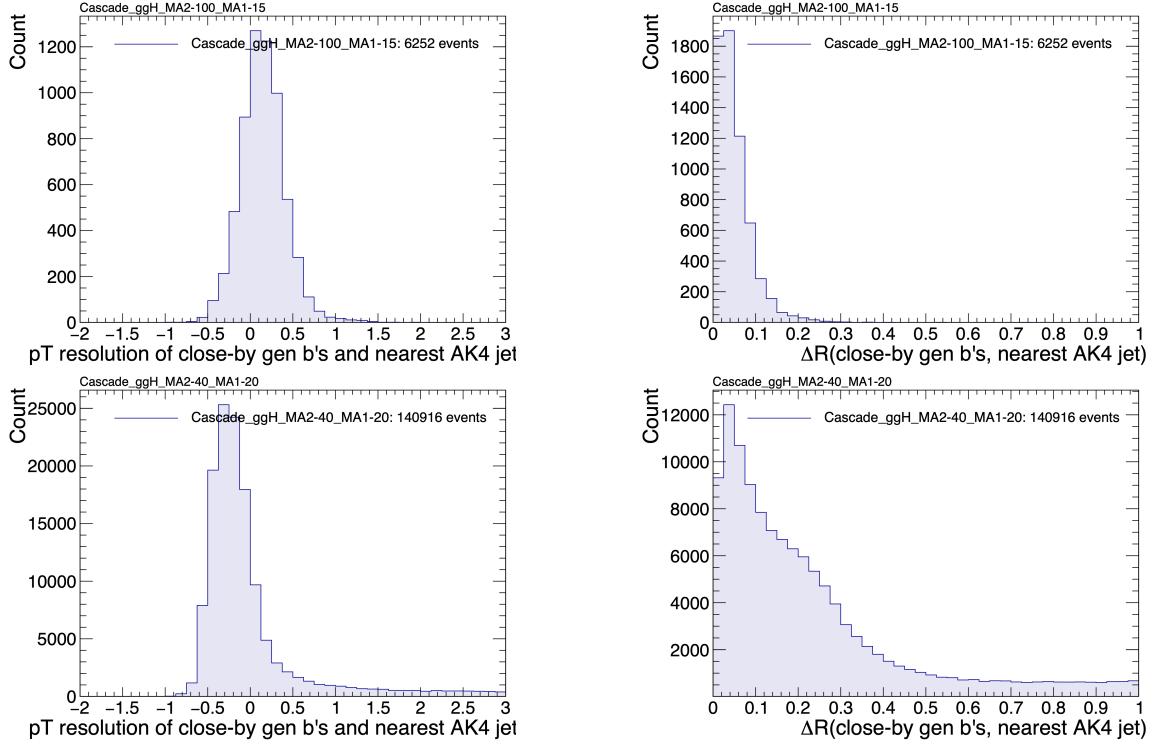


Figure 11.2: Distributions (arbitrary units) of transverse momentum p_T resolution and ΔR between the two closest generator-level b jets, treated as one object, and the nearest reconstructed AK4 jet, for two different $h \rightarrow a_1 a_2$ mass hypotheses (m_{a_1}, m_{a_2}) = (100, 15) GeV (top left, 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

The $\tau\tau$ states for the $h \rightarrow a_1 a_2$ to $4b2\tau$ analysis will be similar to those studied in $h \rightarrow aa \rightarrow bb\tau\tau$. For the $\mu\tau_h$ channel, histograms of the key kinematic variables are made for data and the sum of the expected backgrounds, which are estimated from Monte Carlo samples, embedded samples, and the data-driven method for estimating jets faking τ_h as described in Chapter 7. Nominal values of the scale factors and event reweighting are applied, as described in Chapter ???. 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,

2400 described in Sections 5.3.1, 5.3.2, and 5.3.4).

2401 The p_T , η , and ϕ of the leading muon and hadronic tau τ_h , and the di-tau visible
2402 mass m_{vis} and momentum $p_{T,\text{vis}}$, are shown in Fig. 11.3. The p_T , η , and ϕ of the the
2403 leading and sub-leading b-tag jets, and the missing transverse energy magnitude and
2404 azimuthal direction, are shown in Fig. 11.4.

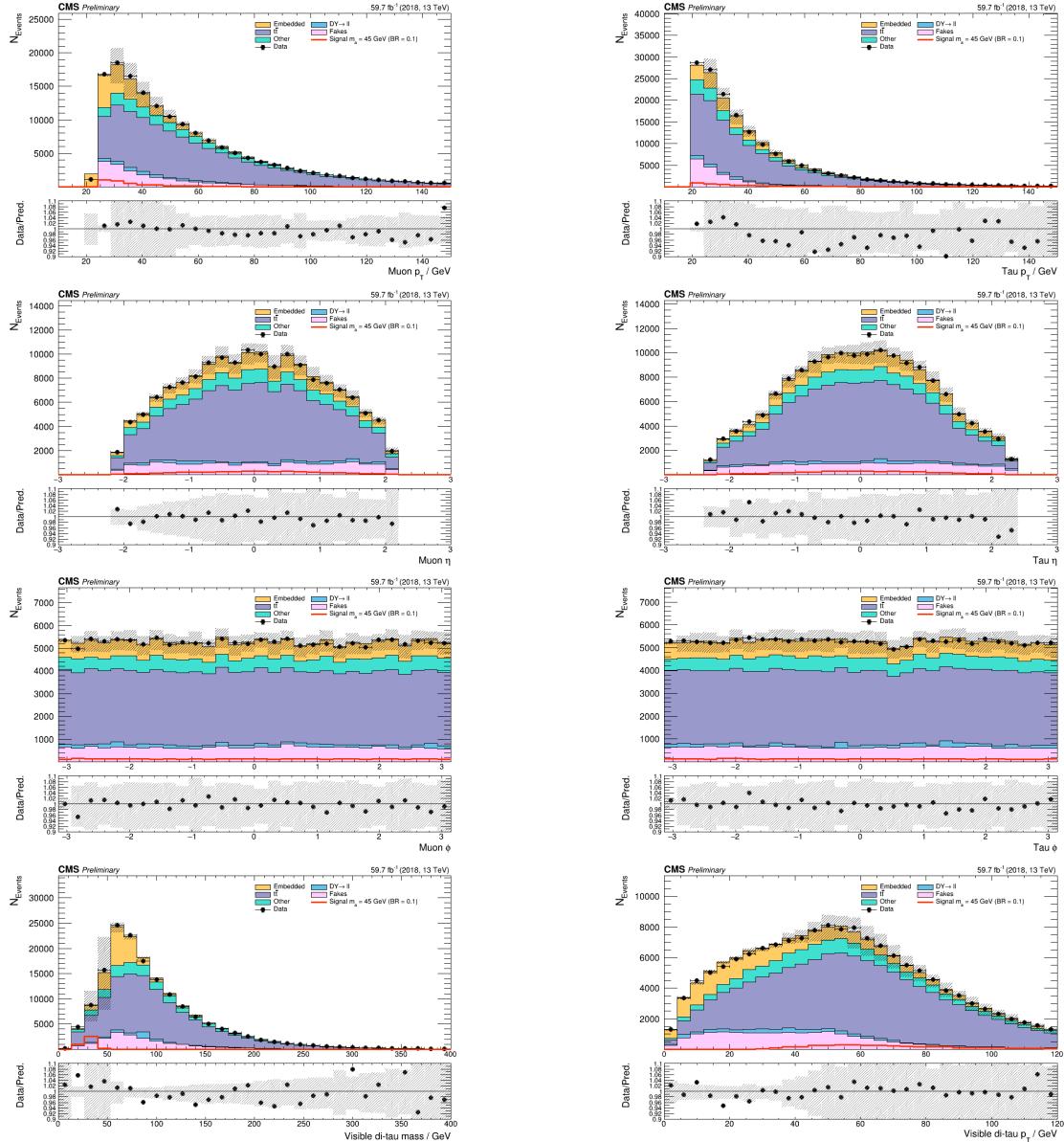


Figure 11.3: Kinematic properties of the leading muon and τ_h in the $\mu\tau_h$ channel: p_T (top row), η (second row), and ϕ (third row). The visible 4-momenta of the muon and τ_h are summed, giving the visible di-tau mass m_{vis} and transverse momentum $p_{T,\text{vis}}$. The errors shown in the 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).

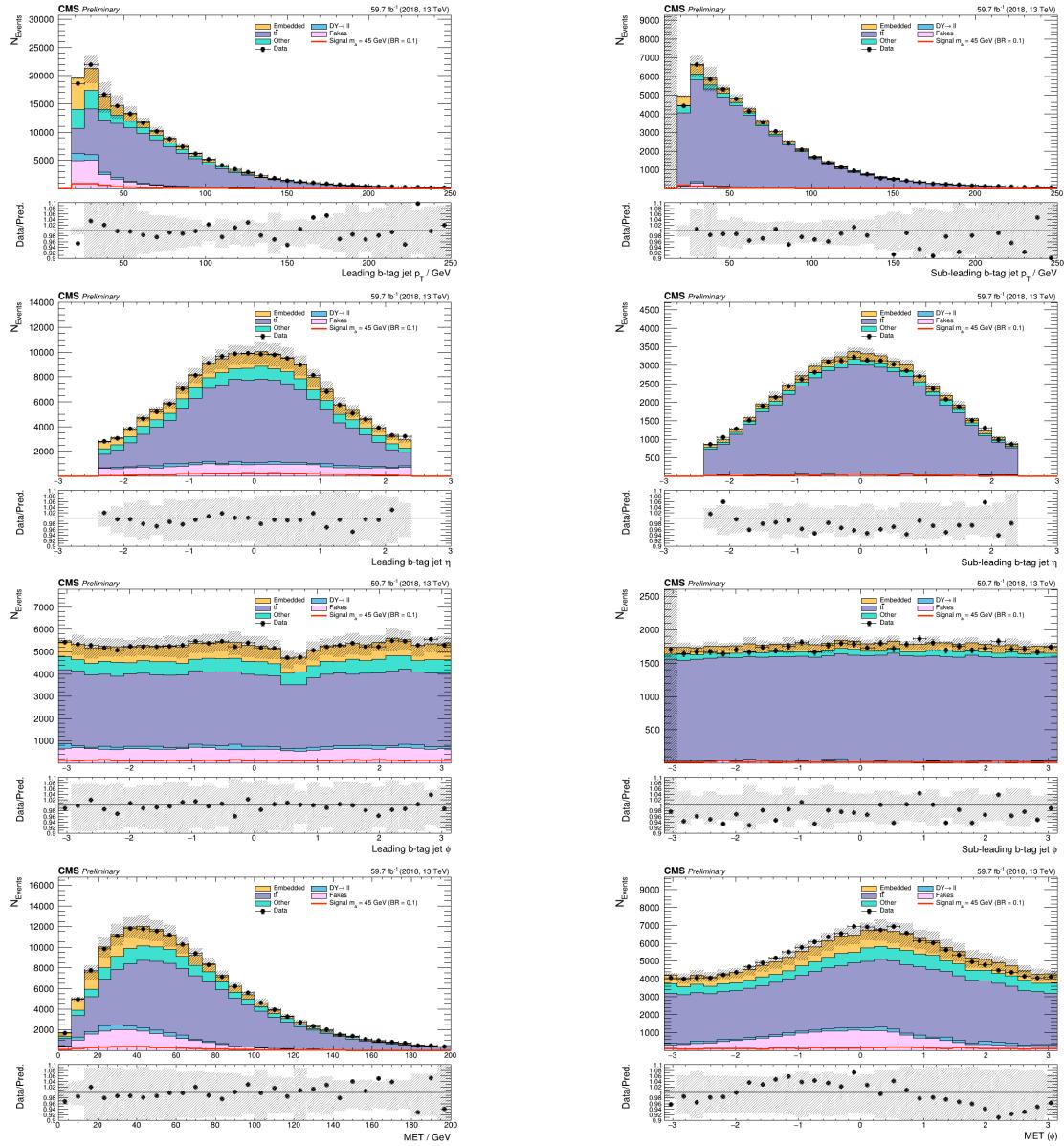


Figure 11.4: Kinematic properties of the leading and sub-leading b-tag jets in the $\mu\tau_h$ final state: jet p_T (*top row*), η (*second row*), ϕ (*third row*), as well as the missing transverse energy magnitude and azimuthal direction (*bottom row*). The errors shown in the figures only include statistical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

2405 **Chapter 12**

2406 **Conclusion and outlook**

2407 With the discovery of a Higgs boson with mass 125 GeV at the LHC in 2012, the LHC
2408 and CMS physics program has evolved to include the precise characterization of the
2409 125 GeV Higgs boson and searching for evidence of additional Higgs particles in an
2410 extended Higgs sector. This thesis presents a direct search at CMS for exotic decays
2411 of the Higgs boson with mass 125 GeV in data collected in the years 2016-2018 in
2412 proton-proton collisions at center-of-mass energy 13 TeV, to two light neutral scalar
2413 particles that decay to two bottom quarks and two tau leptons ($h \rightarrow aa \rightarrow bb\tau\tau$). The
2414 results are combined with another search that was performed in the $h \rightarrow aa \rightarrow bb\mu\mu$
2415 final state, giving the most stringent limits to date for theories with Two Higgs
2416 Doublet Models extended with a singlet scalar (2HDM+S), for pseudoscalar masses
2417 m_a ranging from 15 GeV to 60 GeV, in a number of 2HDM+S scenarios such as type
2418 II and III with $\tan\beta = 2.0$.

2419 As the rich physics program of CMS has set stringent limits on the exotic decay
2420 $h \rightarrow aa$, we turn our attention to direct searches for decays to light neutral scalars
2421 with potentially unequal mass, $h \rightarrow a_1a_2$, which has not been performed at CMS
2422 to date. Preliminary studies on $h \rightarrow a_1a_2$ signals in the Two Real Singlet Model
2423 (TRSM) are shown, and work is ongoing to develop the analysis for $h \rightarrow a_1a_2$ in final

2424 states with bottom quarks and tau leptons.

2425 To ensure the continued performance of the CMS detector and to enhance its
2426 data-taking capabilities in the intense pileup conditions of the Phase-2 upgrade of
2427 the High-Luminosity LHC, upgrades of the Level-1 Trigger are paramount for filter-
2428 ing the increased data rate of the HL-LHC. This thesis presents work on the stan-
2429 dalone barrel calorimeter algorithm for reconstructing and identifying electron and
2430 photon candidates, using high granularity crystal-level information from the ECAL
2431 subdetector. For Phase-2, the increase in the granularity of information sent from
2432 the electromagnetic calorimeter to the Level-1 trigger, from energy sums over towers
2433 (which are 5×5 in crystals) to crystal-level information, allows for the implementation
2434 of a more sophisticated clustering algorithm that can exploit the fact that genuine
2435 electrons and photons tend to leave energies concentrated a 3×5 window in crystals,
2436 and use shape and isolation information to distinguish genuine electrons and photons
2437 from noise. Electrons and photons are key to characterizing Standard Model pro-
2438 cesses and performing searches for new physics, and this represents one of the many
2439 upgrades of the CMS detector in preparation for Phase-2. With the ongoing Run-3
2440 data collecting period, and wealth of ongoing and scheduled upgrades, there remains
2441 an abundance of directions for detector development and physics at CMS heading
2442 into Phase-2 of the LHC.

- ²⁴⁴³

Bibliography
- ²⁴⁴⁴ [1] Paul H. Frampton. Journeys Beyond the Standard Model. 54(1):52–
²⁴⁴⁵ 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.
- ²⁴⁴⁶ [2] Meinard Kuhlmann. Quantum Field Theory. In Edward N. Zalta and Uri Nodelman, editors, *The Stanford Encyclopedia of Philosophy*. Metaphysics Research
²⁴⁴⁷ Lab, Stanford University, Summer 2023 edition, 2023.
- ²⁴⁴⁸ [3] Steven Weinberg. The Making of the Standard Model. *Eur. Phys. J. C*, 34:5–13,
²⁴⁴⁹ 2004. URL <https://cds.cern.ch/record/799984>.
- ²⁴⁵⁰ [4] Christopher G. Tully. *Elementary Particle Physics in a Nutshell*. Princeton
²⁴⁵¹ University Press, Princeton, 2012. ISBN 9781400839353. doi: doi:10.1515/
²⁴⁵² 9781400839353. URL <https://doi.org/10.1515/9781400839353>.
- ²⁴⁵³ [5] John Ellis. Higgs Physics. In *2013 European School of High-Energy Physics*,
²⁴⁵⁴ pages 117–168, 2015. doi: 10.5170/CERN-2015-004.117.
- ²⁴⁵⁵ [6] David Curtin, Rouven Essig, Stefania Gori, and Others. Exotic decays of the 125
²⁴⁵⁶ GeV Higgs boson. *Phys. Rev. D*, 90:075004, Oct 2014. doi: 10.1103/PhysRevD.
²⁴⁵⁷ 90.075004. URL <https://link.aps.org/doi/10.1103/PhysRevD.90.075004>.
- ²⁴⁵⁸ [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>.

- 2485 [17] Olivier S. Brning and Frank Zimmerman. Parameter space for the LHC lumi-
2486 nosity upgrade. ISBN 978-3-95450-115-1. URL <https://accelconf.web.cern.ch/IPAC2012/papers/moppc005.pdf>.
- 2488 [18] CMS Collaboration. Pileup mitigation at CMS in 13 TeV data. *JINST*, 15(09):
2489 P09018, 2020. doi: 10.1088/1748-0221/15/09/P09018.
- 2490 [19] CMS Collaboration. Measurement of the inelastic proton-proton cross section at
2491 $\sqrt{s} = 13$ TeV. *JHEP*, 07:161, 2018. doi: 10.1007/JHEP07(2018)161.
- 2492 [20] CMS Collaboration. High-Luminosity Large Hadron Collider (HL-LHC): Tech-
2493 nical design report. 10/2020, 12 2020. doi: 10.23731/CYRM-2020-0010.
- 2494 [21] CMS Collaboration. The CMS Experiment at the CERN LHC. *JINST*, 3:S08004,
2495 2008. doi: 10.1088/1748-0221/3/08/S08004.
- 2496 [22] CMS Collaboration. Particle-flow reconstruction and global event description
2497 with the CMS detector. *JINST*, 12(10):P10003, 2017. doi: 10.1088/1748-0221/
2498 12/10/P10003.
- 2499 [23] V Karimki, M Mannelli, P Siegrist, H Breuker, A Caner, R Castaldi, K Freudens-
2500 reich, G Hall, R Horisberger, M Huhtinen, and A Cattai. *The CMS tracker*
2501 *system project: Technical Design Report*. Technical design report. CMS. CERN,
2502 Geneva, 1997. URL <https://cds.cern.ch/record/368412>.
- 2503 [24] The Phase-2 Upgrade of the CMS Tracker. Technical report, CERN, Geneva,
2504 2017. URL <https://cds.cern.ch/record/2272264>.
- 2505 [25] CMS Collaboration. CMS Technical Design Report for the Pixel Detector Up-
2506 grade. 9 2012. doi: 10.2172/1151650.
- 2507 [26] R. L. Workman and Others. Review of particle physics. 2022:083C01. doi:
2508 10.1093/ptep/ptac097.

- 2509 [27] CMS Technical Design Report for the Phase 1 Upgrade of the Hadron Calorimeter. 9 2012. doi: 10.2172/1151651.
- 2510
- 2511 [28] CMS Technical Design Report for the Level-1 Trigger Upgrade. 6 2013.
- 2512
- 2513 [29] S. Dasu et al. CMS. The TriDAS project. Technical design report, vol. 1: The trigger systems. 12 2000.
- 2514
- 2515 [30] CMS Collaboration. The Phase-2 Upgrade of the CMS Data Acquisition and High Level Trigger. Technical report, CERN, Geneva, 2021. URL <https://cds.cern.ch/record/2759072>. This is the final version of the document, approved by the LHCC.
- 2516
- 2517
- 2518 [31] C. Foudas. The CMS Level-1 Trigger at LHC and Super-LHC. In *34th International Conference on High Energy Physics*, 10 2008.
- 2519
- 2520 [32] CMS Software Guide. High Level Trigger (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuideHighLevelTrigger>.
- 2521
- 2522 [33] The Worldwide LHC Computing Grid. 2012. URL <https://cds.cern.ch/record/1997398>.
- 2523
- 2524 [34] Douglas Thain, Todd Tannenbaum, and Miron Livny. Distributed computing in practice: the Condor experience. *Concurrency and Computation: Practice and Experience*, 17(2-4):323–356, 2005. doi: <https://doi.org/10.1002/cpe.938>. URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/cpe.938>.
- 2525
- 2526
- 2527
- 2528 [35] Alexandre Zabi, Jeffrey Wayne Berryhill, Emmanuelle Perez, and Alexander D. Tapper. The Phase-2 Upgrade of the CMS Level-1 Trigger. 2020.
- 2529
- 2530 [36] Technical proposal for a MIP timing detector in the CMS experiment Phase 2 upgrade. Technical report, CERN, Geneva, 2017. URL <https://cds.cern.ch/record/2296612>.
- 2531
- 2532

- 2533 [37] CMS Collaboration. Search for exotic decays of the Higgs boson to a pair of
2534 pseudoscalars in the $\mu\mu$ bb and $\tau\tau$ bb final states. *European Physical Journal C*,
2535 2 2024.
- 2536 [38] CMS Collaboration. CMS luminosity measurement for the 2016 data-taking
2537 period. CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017. URL
2538 <https://cds.cern.ch/record/2257069>.
- 2539 [39] CMS Collaboration. CMS luminosity measurement for the 2017 data-taking
2540 period at $\sqrt{s} = 13$ TeV. CMS Physics Analysis Summary CMS-PAS-LUM-17-
2541 004, 2018. URL <https://cds.cern.ch/record/2621960>.
- 2542 [40] CMS Collaboration. CMS luminosity measurement for the 2018 data-taking
2543 period at $\sqrt{s} = 13$ TeV. CMS Physics Analysis Summary CMS-PAS-LUM-18-
2544 002, 2019. URL <https://cds.cern.ch/record/2676164>.
- 2545 [41] CMS LUMI Group. CMS Luminosity Public Results (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults>.
- 2547 [42] Cécile Caillol, Pallabi Das, Sridhara Dasu, Pieter Everaerts, Stephanie Kwan,
2548 Isobel Ojalvo, and Ho-Fung Tsoi. CMS AN-20-213 (internal): Search for an
2549 exotic decay of the 125 GeV Higgs boson to light pseudoscalars, with a pair of b
2550 jets and a pair of tau leptons in the final state, 2020.
- 2551 [43] J. Alwall, R. Frederix, S. Frixione, et al. The automated computation of tree-
2552 level and next-to-leading order differential cross sections, and their matching to
2553 parton shower simulations. *Journal of High Energy Physics*, 2014(7), July 2014.
2554 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).
- 2556 [44] R. Frederix, S. Frixione, V. Hirschi, et al. The automation of next-to-leading
2557 order electroweak calculations. *Journal of High Energy Physics*, 2018(7), July

- 2558 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).
- 2559
- 2560 [45] S. Agostinelli, J. Allison, K. Amako, et al. Geant4 - a simulation toolkit. 506(3):
2561 250–303. ISSN 0168-9002. doi: 10.1016/S0168-9002(03)01368-8. URL <https://www.sciencedirect.com/science/article/pii/S0168900203013688>.
- 2562
- 2563 [46] CMS Collaboration. An embedding technique to determine $\tau\tau$ backgrounds
2564 in proton-proton collision data. *JINST*, 14(06):P06032, 2019. doi: 10.1088/
2565 1748-0221/14/06/P06032.
- 2566
- 2567 [47] CMS Collaboration. Search for neutral MSSM Higgs bosons decaying to a pair of
tau leptons in pp collisions. *JHEP*, 10:160, 2014. doi: 10.1007/JHEP10(2014)160.
- 2568
- 2569 [48] CMS Collaboration. Measurements of Higgs boson production in the decay chan-
nel 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.
- 2570
- 2571 [49] CMS Collaboration. Reconstruction and identification of tau lepton decays to
hadrons and tau neutrinos at CMS. *Journal of Instrumentation*, 11(01):P01019–
2572 P01019, January 2016. ISSN 1748-0221. doi: 10.1088/1748-0221/11/01/p01019.
2573 URL <http://dx.doi.org/10.1088/1748-0221/11/01/P01019>.
- 2574
- 2575 [50] CMS Collaboration. Performance of τ -lepton reconstruction and identification
in CMS. *Journal of Instrumentation*, 7(01):P01001, jan 2012. doi: 10.1088/
2576 1748-0221/7/01/P01001. URL <https://dx.doi.org/10.1088/1748-0221/7/01/P01001>.
- 2577
- 2578
- 2579 [51] CMS Collaboration. Performance of reconstruction and identification of τ leptons
2580 decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV. *JINST*, 13(10):
2581 P10005, 2018. doi: 10.1088/1748-0221/13/10/P10005.

- 2582 [52] CMS Collaboration. Identification of hadronic tau lepton decays using a deep
2583 neural network. *JINST*, 17:P07023, 2022. doi: 10.1088/1748-0221/17/07/
2584 P07023.
- 2585 [53] CMS Collaboration. Performance of CMS muon reconstruction in pp collision
2586 events at $\sqrt{s} = 7$ TeV. *Journal of Instrumentation*, 7(10):P10002–P10002,
2587 October 2012. ISSN 1748-0221. doi: 10.1088/1748-0221/7/10/p10002. URL
2588 <http://dx.doi.org/10.1088/1748-0221/7/10/P10002>.
- 2589 [54] CMS Collaboration. Performance of electron reconstruction and selection with
2590 the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV. *Journal of Instru-*
2591 *mentation*, 10(06):P06005, 2015. doi: 10.1088/1748-0221/10/06/P06005. URL
2592 <https://dx.doi.org/10.1088/1748-0221/10/06/P06005>.
- 2593 [55] CMS Collaboration. Identification of b-quark jets with the CMS experiment.
2594 *Journal of Instrumentation*, 8(04):P04013–P04013, April 2013. ISSN 1748-
2595 0221. doi: 10.1088/1748-0221/8/04/p04013. URL <http://dx.doi.org/10.1088/1748-0221/8/04/P04013>.
- 2597 [56] CMS Collaboration. Pileup Removal Algorithms. Technical report, CERN,
2598 Geneva, 2014. URL <https://cds.cern.ch/record/1751454>.
- 2599 [57] CMS Collaboration. CMS Phase 1 heavy flavour identification performance and
2600 developments. 2017. URL <https://cds.cern.ch/record/2263802>.
- 2601 [58] CMS Collaboration. Performance of the DeepJet b tagging algorithm using 41.9
2602 fb^{-1} of data from proton-proton collisions at 13 TeV with Phase 1 CMS detector.
2603 2018. URL <https://cds.cern.ch/record/2646773>.
- 2604 [59] Lorenzo Bianchini, John Conway, Evan Klose Friis, and Christian Veelken. Re-
2605 construction of the Higgs mass in $H \rightarrow \tau\tau$ Events by Dynamical Likelihood

- 2606 techniques. *Journal of Physics: Conference Series*, 513(2):022035, jun 2014.
2607 doi: 10.1088/1742-6596/513/2/022035. URL <https://dx.doi.org/10.1088/1742-6596/513/2/022035>.
- 2609 [60] CMS Collaboration. Evidence for the 125 GeV Higgs boson decaying to a pair
2610 of τ leptons. *JHEP*, 05:104, 2014. doi: 10.1007/JHEP05(2014)104.
- 2611 [61] CMS Collaboration. Missing transverse energy performance of the CMS detector.
2612 *JINST*, 6:P09001, 2011. doi: 10.1088/1748-0221/6/09/P09001.
- 2613 [62] Artur Kalinowski. CMS AN-19-032 (internal): Reconstruction of a τ pair invariant
2614 mass with a simplified likelihood scan, 2019.
- 2615 [63] CMS TAU POG. Tau Physics Object Group: Tau ID Recommendation For Run 2, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/TauIDRecommendationForRun2>.
- 2618 [64] CMS MUO POG. Muon Physics Object Group: Recommendations, 2024. URL
2619 <https://twiki.cern.ch/twiki/bin/view/CMS/MuonPOG>.
- 2620 [65] CMS MUO POG. Muon Physics Object Group: Reference guidelines and results
2621 for muon momentum scale and resolution in Run II, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/MuonReferenceScaleResolRun2>.
- 2623 [66] CMS HTT working group. Higgs To Tau Tau Working TWiki for the full Run-
2624 2 legacy analysis, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/HiggsToTauTauWorkingLegacyRun2>.
- 2626 [67] CMS ELE POG. Electron Physics Object Group: Recommendations,
2627 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/EgammaRunIIRecommendations>.

- 2629 [68] CMS ELE POG. Electron Physics Object Group: Recommendations for
2630 2016 to 2018 UL, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/EgammaUL2016To2018>.
2631
- 2632 [69] CMS TAU Embedding Group. Tau embedded samples using 2016
2633 data, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/TauTauEmbeddingSamples2016Legacy>.
2634
- 2635 [70] CMS TAU Embedding Group. Tau embedded samples using 2017
2636 data, 2024. URL <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TauTauEmbeddingSamples2017>.
2637
- 2638 [71] CMS TAU Embedding Group. Tau embedded samples using 2018
2639 data, 2024. URL <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TauTauEmbeddingSamples2018>.
2640
- 2641 [72] Tau Lepton Run 2 Trigger Performance. 2019. URL <https://cds.cern.ch/record/2678958>.
2642
- 2643 [73] CMS Taus High Level Trigger Studies. Tau Lepton Run 2 Trigger Performance
2644 (CMS DP-2019/012), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/HLTTauAllRun2>.
2645
- 2646 [74] Muon HLT Performance with 2018 Data. 2018. URL <https://cds.cern.ch/record/2627469>.
2647
- 2648 [75] Single and Double Electron Trigger Efficiencies using the full Run 2 dataset.
2649 2020. URL <https://cds.cern.ch/record/2888577>.
2650
- 2651 [76] Run II Trigger Performance For $e\mu$ Triggers. 2019. URL <https://cds.cern.ch/record/2687013>.

- 2652 [77] Performance of electron and photon reconstruction in Run 2 with the CMS ex-
2653 periment. 2020. URL <https://cds.cern.ch/record/2725004>.
- 2654 [78] CMS Collaboration. Performance of the CMS muon detector and muon recon-
2655 struction with proton-proton collisions at $\sqrt{s} = 13$ TeV. *JINST*, 13(06):P06015,
2656 2018. doi: 10.1088/1748-0221/13/06/P06015.
- 2657 [79] Piet Verwilligen. Muons in the cms high level trigger system. *Nuclear
2658 and Particle Physics Proceedings*, 273-275:2509–2511, 2016. ISSN 2405-6014.
2659 doi: <https://doi.org/10.1016/j.nuclphysbps.2015.09.441>. URL <https://www.sciencedirect.com/science/article/pii/S240560141500930X>. 37th Interna-
2660 tional Conference on High Energy Physics (ICHEP).
2661
- 2662 [80] Muon tracking performance in the CMS Run-2 Legacy data using the tag-and-
2663 probe technique. 2020. URL <https://cds.cern.ch/record/2724492>.
- 2664 [81] V.M. Abazov, B. Abbott, M. Abolins, et al. A novel method for modeling the
2665 recoil in W boson events at hadron colliders. *Nuclear Instruments and Methods
2666 in Physics Research Section A: Accelerators, Spectrometers, Detectors and Asso-
2667 ciated 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>.
- 2670 [82] CMS Collaboration. Search for an exotic decay of the Higgs boson to a pair
2671 of light pseudoscalars in the final state with two b quarks and two τ leptons in
2672 proton-proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Lett. B*, 785:462, 2018. doi:
2673 10.1016/j.physletb.2018.08.057.
- 2674 [83] CMS LUMI POG. Luminosity Physics Object Group: Recommendations, 2024.
2675 URL <https://twiki.cern.ch/twiki/bin/view/CMS/TWikiLUM>.

- 2676 [84] The modeling of the top quark p_T (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/TopPtReweighting>.
- 2677
- 2678 [85] CMS BTV group. Methods to apply b-tagging efficiency scale fac-
2679 tors (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/BTagShapeCalibration>.
- 2680
- 2681 [86] CMS Collaboration. Jet energy scale and resolution in the CMS experiment in
2682 pp collisions at 8 TeV. *JINST*, 12(02):P02014, 2017. doi: 10.1088/1748-0221/
2683 12/02/P02014.
- 2684 [87] Garvita Agarwal. Jet Energy Scale and Resolution Measurements in CMS. *PoS*,
2685 ICHEP2022:652, 2022. doi: 10.22323/1.414.0652.
- 2686 [88] CMS JERC group. Jet Energy Corrections (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/JECDataMC>.
- 2687
- 2688 [89] CMS JERC group. Jet Energy Resolution (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/JetResolution>.
- 2689
- 2690 [90] CMS MUO POG. Muon Physics Object Group: Baseline muon selec-
2691 tions for Run-II, 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMS/SWGuideMuonIdRun2>.
- 2692
- 2693 [91] CMS ELE POG. Electron Identification Based on Simple Cuts, 2024. URL
2694 <https://twiki.cern.ch/twiki/bin/view/CMSPublic/EgammaPublicData>.
- 2695
- 2696 [92] Jose Enrique Palencia Cortezon. Single top quark production at CMS. Technical
report, CERN, Geneva, 2018. URL <https://cds.cern.ch/record/2640578>.
- 2697
- 2698 [93] CMS Collaboration. Measurements of the electroweak diboson production cross
sections in proton-proton collisions at $\sqrt{s} = 5.02$ TeV using leptonic decays.
2699 *Phys. Rev. Lett.*, 127(19):191801, 2021. doi: 10.1103/PhysRevLett.127.191801.

- 2700 [94] CMS Collaboration. A portrait of the Higgs boson by the CMS experiment
2701 ten years after the discovery. *Nature*, 607(7917):60–68, 2022. doi: 10.1038/
2702 s41586-022-04892-x.
- 2703 [95] CMS JERC group. Jet energy scale uncertainty sources (TWiki), 2024. URL
2704 <https://twiki.cern.ch/twiki/bin/view/CMS/JECUncertaintySources>.
- 2705 [96] TOP Systematic Uncertainties (Run 2) (TWiki), 2024. URL <https://twiki.cern.ch/twiki/bin/viewauth/CMS/TopSystematics>.
- 2707 [97] Kyle Cranmer. Practical Statistics for the LHC. In *2011 European School of
2708 High-Energy Physics*, pages 267–308, 2014. doi: 10.5170/CERN-2014-003.267.
- 2709 [98] Elham Khazaie, Maryam Zeinali, Hamed Bakhshiansohi, and Abideh Jafari.
2710 CMS AN-21-058 (internal): Search for exotic decays of the Higgs boson to a
2711 pair of new light bosons with two muons and two b jets in the final states at
2712 $\sqrt{s} = 13$ TeV, 2021.
- 2713 [99] CMS Higgs Physics Analysis Group. Summary of 2HDM+S searches at 13 TeV
2714 (Run 2), 2024. URL <https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2>.