

Search for supersymmetry with tau leptons in the CMS experiment

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ABSTRACT

This thesis is focused on the search for pair production of the supersymmetric τ lepton partners within the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). The search is performed using the data collected at a center-of-mass-energy $\sqrt{s} = 13$ TeV with the CMS detector in the years 2016-2017.

One of the most popular extensions of the Standard Model (SM) is supersymmetry (SUSY). The minimal supersymmetric standard model (MSSM) predicts the existence of fermion superpartners called sfermions. Every SM fermion has two scalar superpartners, and the superpartners of the τ leptons are called staus ($\tilde{\tau}$). The light $\tilde{\tau}$ could bring the neutralino relic density to the observed value through co-annihilation with the Lightest Supersymmetric Particle (LSP). Models describing direct $\tilde{\tau}$ -pair production, where each $\tilde{\tau}$ is expected to decay to a τ lepton and the LSP, as well as neutralino-chargino and chargino pair production with decays to τ leptons are investigated. Three scenarios of direct $\tilde{\tau}$ pair production are considered for interpretation: scenarios in which superpartners of only left-handed or right-handed τ are produced in pairs, and a mass degenerate scenario in which the partners of the left- and right handed τ leptons have the same mass and are produced simultaneously.

The analysis selection is based on final states with one hadronically decaying τ lepton, an electron or muon from the decay of the second τ , and final states with one electron and one muon from the decay of the τ leptons. To optimize the sensitivity to the new physics topologies mentioned above, a cut-based approach as well as a multivariate approach (MVA) are applied. The data are compared with the expectation from the SM background processes and with $\tilde{\tau}$ -pair production signal hypotheses. No evidence for the production of supersymmetric τ lepton partners is found. Mass and cross section limits are determined within simplified model parameters. In the case of purely left-handed production and a nearly massless neutralino, the strongest limits are obtained for a $\tilde{\tau}$ slepton mass of 125 GeV, where 1.14 times the theoretical cross section can be excluded. For the degenerate production scenario, $\tilde{\tau}$ masses up to 150 GeV are excluded when assuming a nearly massless LSP.

In addition, the sensitivity of the direct $\tilde{\tau}$ production is studied for future experiments, assuming 3 ab^{-1} of proton-proton collision data to be produced by the High Luminosity LHC (HL-LHC) at a center-of-mass energy of 14 TeV as well as assuming 15 ab^{-1} and 27 TeV energy to be delivered by the High Energy LHC (HE-LHC). The analysis is performed using the Delphes simulation of the upgraded CMS detector, where the object reconstruction performance is tuned to the one achieved with CMS Phase-2 full simulation. In the degenerate direct $\tilde{\tau}$ -pair production scenario, $\tilde{\tau}$ masses are excluded below 650 (1150) GeV, with the discovery contour of $\tilde{\tau}$ masses reaching up to 470 (810) GeV for HL-LHC (HE-LHC).

ZUSAMMENFASSUNG

Diese Dissertation behandelt die Suche nach der Paarproduktion von supersymmetrischen τ -Lepton Partnern. Die Suche erfolgt mit den Daten, die in den Jahren 2016 und 2017 mit einer Schwerpunktenenergie von $\sqrt{s} = 13$ TeV mit dem Compact Muon Solenoid (CMS) am Large Hadron Collider (LHC) aufgenommen wurden.

Eine der populärsten Erweiterungen des Standardmodells (SM) ist die Supersymmetrie (SUSY). Die minimale supersymmetrische Erweiterung des Standardmodells (MSSM) sagt das Vorhandensein von supersymmetrischen Partnern der Fermionen (Sfermions) voraus. Jedes SM-Fermion hat zwei skalare supersymmetrische Partner. Durch Ko-Annihilation der τ -Lepton-Partner ($\tilde{\tau}$) mit den leichtesten SUSY-Teilchen (LSPs) kann die gemessene Dichte an dunkler Materie durch LSPs, die gute Kandidaten für dunkle Materie sind, richtig beschrieben werden. Es werden sowohl direkte Zerfälle von $\tilde{\tau}$ Paaren in LSP und τ -Leptonen als auch Zerfälle von Neutralino/Chargino- und Chargino-Paaren in τ -Leptonen analysiert. Drei Szenarien für die direkte $\tilde{\tau}$ Paarproduktion werden für eine Interpretation der Ergebnisse herangezogen: die exklusive Produktion von Partnern der linkshändigen oder nur rechtshändigen τ -Lepton Paaren und die gleichzeitige Produktion beider Partner.

Die Ereignisselektion basiert auf dem semi-leptonischen Zerfall des τ -Leptonenpaares, wobei ein τ -Lepton hadronisch zerfällt und das zweite leptonisch in ein Elektron oder Myon und auf dem leptonischen Zerfall, in dem das τ -Leptonenpaar in ein Elektron und ein Myon zerfällt. Um die Sensitivität auf neue Physik-Topologien zu optimieren, wird eine cut-basierte Ereignisselektion sowie ein multivariater Ansatz (MVA) verwendet. Die Daten werden mit den Vorhersagen der SM-Prozesse und mit der $\tilde{\tau}$ Signalthypothese verglichen. Es wurden keine Hinweise für die Produktion supersymmetrischer τ -Leptonpartner gefunden. Für das Szenario der linkshändigen $\tilde{\tau}$ Produktion und einem nahezu masselosen Neutralino können die stärksten Ausschlussgrenzen bei einer $\tilde{\tau}$ Masse von 125 GeV gezogen werden, wobei das 1.14-fache des theoretischen Wirkungsquerschnitts ausgeschlossen werden kann. In dem Szenario mit beiden Helizitätszuständen können unter der Annahme eines nahezu masselosen LSP $\tilde{\tau}$ Massen bis zu 150 GeV ausgeschlossen werden.

Darüber hinaus wurde die Analyse der direkten $\tilde{\tau}$ Produktion von auf zukünftige LHC-Upgrades projiziert. Es wurden Projektionen unter der Annahme einer gesammelten integrierten Luminosität von 3 ab^{-1} und der Schwerpunktsenergie von 14 TeV für den High Luminosity LHC (HL-LHC) und 15 ab^{-1} mit 27 TeV für den High-Energy LHC (HE-LHC) analysiert. Im Szenario mit direkter Paarproduktion von rechts- und linkshändigen gleicher Masse $\tilde{\tau}$ können Massen bis zu 650 (1150) GeV ausgeschlossen werden, wobei eine Entdeckung von $\tilde{\tau}$ -Massen bis zu 470 (810) GeV für den HL-LHC (HE-LHC) erreicht werden kann.

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CHAPTER

1

INTRODUCTION

His job was to make sense of the world, and there were times when he wished that the world would meet him halfway

Terry Prattchet

Particle physics is one of the most fundamental physics fields, which tries to understand and to describe nature at a subnuclear level. Both theoretical and experimental developments made a significant contribution to the development of this field. Within theoretical developments, quantum field theory gave an important framework for different phenomenological theories describing subatomic processes and the fundamental interactions. As an important milestone, the standard model (SM) was built in stages throughout the second half of the 20th century to unify the electromagnetic, the weak and the strong forces in one model. Meanwhile, the evolution of experimental technologies allows us to test and confirm the SM by a long history of discoveries, starting from quark discovery in 1968 and finishing by the Higgs boson discovery in 2012.

Nowadays, the SM describes perfectly most of the experimental observations. However, a range of still unanswered questions and several experimental evidence point to the existence of physics beyond the SM. Questions like "what is the nature of the dark matter and dark energy?" and "how to describe gravity in terms of quantum fields?" need additional physics essences or change of the axiomatic base. Moreover, the neutrino oscillations, and, consequential, the existence of neutrino masses, as well as the measured value of magnetic dipole moment of muon, which is 3σ away from the SM predicted value, do not have a description in the SM. In addition, a strong belief in the existence of physics beyond the SM brings one more problem connected with the Higgs boson mass. The quantum corrections to the Higgs boson mass are quadratically sensitive to the scale of new physics. The last could be even the Planck scale, which makes the observed Higgs mass of 125 GeV look very fine tuned.

There are many extensions of the SM created to solve the aforementioned problems. One of the most attractive theories is supersymmetry (SUSY), which postulates an underlying

symmetry between bosons and fermions. SUSY can solve the fine tuning problem by introducing supersymmetric partners for SM particles with spin difference of $1/2$. Contribution from these superpartners to the quantum corrections of the Higgs boson mass can compensate those coming from SM particles. Moreover, in R-Parity conserving SUSY, the lightest SUSY particle (LSP) is stable and can be a viable dark matter candidate.

In some SUSY models, the superpartner particle of the τ lepton, the $\tilde{\tau}$ ($\tilde{\tau}$), is expected to be lighter than other lepton superpartners. In these cases, it might either be produced directly, or might appear in decay chains of heavier neutralinos or charginos with higher branching ratios. However, many SUSY models predict a relic density larger than the measured dark matter density. Light $\tilde{\tau}$ could bring the neutralino relic density to the observed value through co-annihilation with LSP.

This thesis is focused on the search for $\tilde{\tau}$ pair production within the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). The main challenge of this search is the extremely low cross section in comparison with both, SM and other SUSY processes. Therefore, a machine learning algorithm is developed to enhance the discriminating power between $\tilde{\tau}$ production and SM background. The data sample used for this search corresponds to an integrated luminosity of 77.2 fb^{-1} collected in the years 2016 and 2017. Part of the SM background with genuine τ leptons is modelled from simulations with subsequent corrections. Another part of the background component with τ leptons misidentified by jets is estimated from data in orthogonal control regions because of the lack of simulated events in the sample.

In order to fully profit from the LHC potential, an upgrade to increase the instantaneous luminosity by a factor of 5, called the High Luminosity LHC (HL-LHC), has been planned. The HL-LHC is expected to collect an integrated luminosity of 3 ab^{-1} of data in pp collisions with a centre-of-mass energy of 14 TeV . Moreover, in the perspective of pushing the LHC sensitivity even further, the LHC facility and the whole CERN accelerator infrastructure could be upgraded to reach the highest possible energy. This project is called High Energy LHC (HE-LHC) and it is expected to collect an integrated luminosity of 15 ab^{-1} with the collision energy of 27 TeV . Therefore a sensitivity study to the direct production of $\tilde{\tau}$ is developed assuming both the HL-LHC and HE-LHC conditions. Expected upper limits, as well as the discovery potential on the cross section of direct $\tilde{\tau}$ pair production, are derived for the aforementioned simplified models.

The thesis consists of seven main chapters. The first chapter gives an overview of theoretical aspects of particle physics including SM and SUSY. The second chapter introduces the LHC and the CMS detector. In the third chapter, different reconstruction algorithms of physics objects within CMS as well as event generation are presented. A performance study of missing transverse momentum in 2016 CMS data, is described in the fifth chapter. The sixth chapter reveals the details and results of the direct $\tilde{\tau}$ search with CMS Run 2 data including an overview of a boosted decision tree approach with application to the $\tilde{\tau}$ analysis. The last chapter describes the aforementioned HL-LHC and HE-LHC sensitivity projection study for the direct $\tilde{\tau}$ scenario.

CHAPTER

2

THEORETICAL FRAMEWORK

It's very hard to talk quantum using a language originally designed to tell other monkeys where the ripe fruit is.

Terry Prattchet

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Since ancient times people have been trying to reveal the underlying rules governing everything around, from the falling apple to human communication. After inventing the scientific method as an empirical approach to acquire knowledge, people tremendously improved understanding of nature, especially its physical part. Nowadays, the most fundamental concept

of the physical world consists of a set of models describing nature at different scales, from the universe to subnuclear scale. The latter is described best by the standard model (SM) [1–3] of particle physics.

The anatomy of the SM, as well as its prediction successes and current challenges, is described in Chapter 2.1. Furthermore, the supersymmetric extension of the SM is discussed in Chapter 2.2.

2.1 The Standard Model of particle physics

2.1.1 Fundamental forces of nature

The fundamental forces of nature are the interactions that cannot be reduced to more basic interactions. As of today, four fundamental forces [4] are known to exist: electromagnetism, gravity, strong and weak forces. There are a lot of new theories describing the unification of the aforementioned interactions as well as predicting new forces. Such theories are one of the primary motivations for current and future experiments in fundamental particle physics.

Gravity

The gravitation is a long-range force and governs a wide range of phenomena from Earth attraction to black hole fusion. Gravity is the weakest of the four interactions at the atomic scale, but is the only interaction acting on all particles having mass, energy and/or momentum. Since it is a long-range interaction and has an attractive nature, gravity is responsible for the motion and the interaction of the large celestial bodies, such as planets, stars, and galaxies. Our present-day understanding of gravity stems from Einstein’s General Theory of Relativity giving an accurate description for cosmological systems in terms of the space-time and its curvature. Regarding quantum scale, various theories are trying to quantize the gravitational field, resulting in different theories of quantum gravity. Currently, none of these theories have strong experimental confirmation. The main reason for this is the aforementioned weakness of gravity in comparison with the other forces preventing scientists from studying its effects in the lab for quantum systems and testing the proposed theories.

Electromagnetism

Electromagnetic interaction acts between electrically charged objects. It is a long-range force, but it repels objects of the same charge and attracts oppositely charged objects. Electromagnetic interaction determines most of the macroscopic and atomic level processes such as chemical elements bonding. Just two centuries ago, electricity and magnetism were still considered as separate phenomena, but in the 19th century James Clerk Maxwell proposed that they are two aspects of the same interaction. This hypothesis formed the basis of the Maxwell’s equations. Later on, Richard Feynman, Freeman Dyson, Julian Schwinger, and Sin-Itiro Tomonaga, quantized Maxwell’s theory and derived quantum electrodynamics (QED).

Weak interaction

The weak interaction, also known as weak nuclear force, is responsible for nuclear phenomena such as the beta decay. It has limited interaction distance of 10^{-18} m and unifies at the energy of order 90 GeV with electromagnetism forming the electroweak interaction.

Strong interaction

The strong interaction is an additional subnuclear force governing the bound states of protons and neutrons in nuclei, as well as quarks binding within hadrons. It also has a limited interaction distance of 10^{-15} m. The modern understanding of the strong interaction is given by the fundamental theory of quantum chromodynamics (QCD).

QCD together with the quantum electroweak theory forms the standard model of particle physics. The SM successfully describes many phenomena at the quantum level and is discussed below.

2.1.2 Quantum field theory framework

The Quantum Field Theory (QFT) framework combines the special relativity, classical field theory, and quantum mechanics [5] in order to describe the behavior of subatomic particles by treating all particles as excited states of their underlying fields. This leads to the conclusion that quantum fields are more fundamental than the basic particles. Quantum fields can be classified according to their particle spin, an internal degree of freedom. Here, the scalar (spin 0) and spinor (spin 1/2) fields are described. The quantum field evolution is governed by field equations, similar to the usual Schrodinger equation. For scalar particles the Klein-Gordon equation is used [6]:

$$(\partial^2 - m^2)\phi = 0, \quad (2.1)$$

where ϕ stands for scalar field operator and m is a particle mass. The Klein-Gordon equation is nothing more than an operator version of the famous relativistic relation $E^2 = m^2c^4 + \vec{p}^2c^2$. Equation (2.1), as well as the following equations, is written in “natural units” where $c = \hbar = 1$.

The spin 1/2 field evolution is described by the Dirac equation:

$$(\not{D} + im)\psi = 0, \quad (2.2)$$

where ψ is two-component **Spinor**

$$\psi \equiv \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}, \quad (2.3)$$

and ψ_L and ψ_R are left-handed and right-handed 2-dimensional spinors.

For practical purposes, it is better to rewrite equations 2.1 and 2.2 in terms of a Lagrangian. The Lagrangian formulation is convenient to derive correlation functions as a perturbation series in the interacting theory:

$$\mathcal{L}_{KG} = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m^2\phi, \quad (2.4)$$

$$\mathcal{L}_D = i\psi_L^\dagger\bar{\sigma}^\mu\partial_\mu\psi_L + i\psi_R^\dagger\sigma^\mu\partial_\mu\psi_R - m(\psi_L^\dagger\psi_R + \psi_R^\dagger\psi_L), \quad (2.5)$$

where σ^μ is a vector of Pauli matrices and the dagger represents the Hermitian conjugate, defined as $\psi_L^\dagger = (\psi_1^*, \psi_2^*)$ and $\psi_R^\dagger = (\psi_3^*, \psi_4^*)$.

2.1.3 Main building blocks of matter

By today, it is known that matter consists of twelve fundamental (non-composite) particles. These particles can be categorized into two groups: particles interacting with the strong force (quarks) and particles not interacting with the strong force (leptons). They have spin 1/2 and are called fermions, since they obey the Fermi-Dirac statistics. Every fermion has its antiparticle with exactly the same quantum numbers except for opposite electric charge. All fermions can be grouped in three generations, where for each fermion from the first generation two analog particles with the same quantum numbers but with higher mass, compose the second and third generation.

The first generation consists of up quark (u), down quark (d), electron and electron neutrino with $+\frac{2}{3}$, $-\frac{1}{3}$, -1 and 0 electric charge, correspondingly. Fermions from the first generation form most of the observed known matter in the universe. Free stable quarks cannot be observed directly and are confined in bound states.

All second and third generation fermions are unstable, except for neutrinos. Quarks from these generations cannot be observed in nature due to their short lifetime and can only be studied with accelerators. The same situation is true for the τ lepton, the third generation analog of an electron with higher mass. For a long time neutrinos were considered to be massless, as predicted by SM. However, the recent discovery of neutrino oscillations implies the existence of tiny (but nonzero) mass [7].

All fundamental interactions acquire mediator particles after quantization. All of them have integer spin and obey the Bose-Einstein statistics, therefore they are called bosons. For the electromagnetic force, it is the γ boson (photon), which is a massless particle implying the long interaction range. Massive Z and $W^\pm$ bosons are the mediators of the weak interaction and eight gluons are assigned to the strong interaction. For gravity quantization the general relativity predicts the existence of a spin-2 particle called graviton. But this particle is still not discovered and it is unlikely that it will be observed due to the weakness of gravity at the quantum level. All SM particles are summarized in Fig. 2.1 with their charge, spin and mass.

The last discovered SM particle is the Higgs boson. It was predicted by Peter Higgs in 1964 and was observed at the Large Hadron Collider in 2012 [9,10]. It is a spin-0 particle that is predicted by an extension of the SM designed to give mass to other SM particles except for neutrinos.

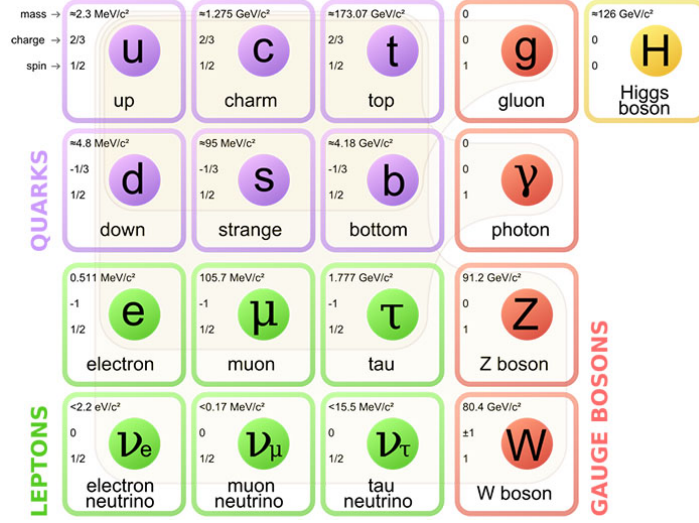


Figure 2.1: The particle content of the SM with their charge, spin and mass [8].

2.1.4 The electromagnetic interaction

QED is the first quantized field theory used for the description of the electromagnetic interaction. The interaction between charged particles can be interpreted as an exchange of virtual photons. The Lagrangian of QED is given by

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu\psi - \bar{\psi}m\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (2.6)$$

where D_μ is the covariant derivative, γ^μ is a vector of Dirac matrices and $F_{\mu\nu}$ is the field strength tensor. The covariant derivative includes vector field A_μ and is given by

$$D_\mu = \partial_\mu - iq_\psi A_\mu, \quad (2.7)$$

where q_ψ stands for the fermion electric charge. The first term in the Lagrangian is responsible for the interaction between the fermions and the electromagnetic field. The second term is a mass term contributing to fermion propagation calculations. In particular, the last term describes the photon propagation. The QED is a gauge invariant theory. In other words, the QED Lagrangian is invariant under a gauge field transformation. The Lagrangian (2.6) is constructed in a way to be gauge invariant under the $U(1)$ symmetry. The $U(1)$ symmetry field transformations are

$$A_\mu \rightarrow A_\mu - \partial_\mu\alpha(x), \quad (2.8)$$

$$\psi(x) \rightarrow e^{iq_\psi\alpha(x)}\psi, \quad (2.9)$$

where $\alpha(x)$ is a scalar phase. The $U(1)$ gauge invariance in QED intrinsically leads to

electric charge conservation according to the Noether theorem.

2.1.5 The strong interaction

The QCD theory describes strong interactions. The Lagrangian of QCD is similar to that of QED and is given by

$$\mathcal{L}_{QCD} = i\bar{\psi}\gamma^\mu D_{QCD\mu}\psi - \bar{\psi}m\psi - \frac{1}{4}G_{\mu\nu}^\alpha G_{\alpha}^{\mu\nu}, \quad (2.10)$$

with covariant derivative $D_{QCD\mu} = \partial_\mu - ig_s G_\mu$. g_s is the QCD coupling constant, α is a colour index and gluon field strength s given by

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f_{abc} [G_\mu^b G_\nu^c], \quad (2.11)$$

where f_{abc} stands for the structure constants.

The QCD Lagrangian is symmetric under $SU(3)_C$ transformation, where C is the color charge. Three dimensions of the $SU(3)_C$ lead to the three types color quantum number carried by quarks: red (R), green (G) and blue (B). Antiquarks have anticolor charges anti-red ($\bar{R}$), anti-green ($\bar{G}$) and anti-blue ($\bar{B}$).

From the equations 2.10 and 2.11 one can see that gluons can interact with each other in contrast to QED. This interaction leads to the interaction strength staying constant within two quarks with the increasing distance between them. From an energy point of view, it is more profitable to create an additional quark anti-quark pair to compensate color charge turning the original hadron into a pair of hadrons instead of leaving the color charge isolated. Such a phenomenon causes color confinement and explains the unobservability of free quarks. However, quarks form color neutral states of two (meson), three (baryon) or more quarks.

2.1.6 The weak interaction and electroweak unification

The weak interaction is unique compared to the other interactions: it can change the quark flavor, and it violates parity and charge-parity symmetry. The latter indicates weak interaction to have a chiral structure allowing only left-handed particles and right-handed antiparticles to experience the weak force. Consequently, the weak interaction mediators (Z and W bosons) couple only to left-handed field doublets.

The most straightforward symmetry group to represent the before mentioned properties is $SU(2)$. In addition, the $U(1)$ symmetry is needed for the flavor invariant part of the weak interaction. After unification with the electroweak interaction the final symmetry group can be written as $SU(2)_L \otimes U(1)_Y$, where Y is hypercharge and is defined as

$$\frac{Y}{2} = Q - T_3, \quad (2.12)$$

where T_3 is the weak isospin and Q stands for electric charge.

The electroweak Lagrangian, which is symmetric under $SU(2)_L \otimes U(1)_Y$, can be written as

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu\psi - \bar{\psi}m\psi - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}, \quad (2.13)$$

with the fields strength $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu - g[W_\mu W_\nu]$ and $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ for the $SU(2)$ three gauge fields $W_\mu^{1,2,3}$ and the $U(1)$ gauge field B_μ .

The covariant derivative in Eq. 2.13 is different from that in QED and is defined as

$$D_\mu = \partial_\mu - ig'\frac{1}{2}YB_\mu - igTW_\mu, \quad (2.14)$$

where the g' and g are the coupling constants and T is the generator of the $SU(2)$ group.

The vector fields $W_\mu^{1,2,3}$ and B_μ do not represent the physical fields, such as Z_μ , $W_\mu^\pm$ and A_μ . To do so, vector fields need to be rewritten in terms of the mass eigenstates

$$W_\mu^+ \equiv \frac{1}{\sqrt{2}}(A_\mu^1 - iA_\mu^2), \quad (2.15)$$

$$W_\mu^- \equiv \frac{1}{\sqrt{2}}(A_\mu^1 + iA_\mu^2), \quad (2.16)$$

$$Z_\mu \equiv \cos\theta_w A_\mu^3 - \sin\theta_w B_\mu, \quad (2.17)$$

$$A_\mu \equiv \sin\theta_w A_\mu^3 + \cos\theta_w B_\mu, \quad (2.18)$$

where θ_w is the weak mixing angle or the Weinberg angle.

2.1.7 The Brout-Englert-Higgs (BEH) mechanism

One significant problem of the EWK Lagrangian is that it does not contain mass terms for gauge bosons. This is not an issue for photons, since experimentally its mass is constrained to be $< 10^{-18}$ eV. However, the W and Z bosons are known to have masses of 80.4 and 91.2 GeV, correspondingly. The mass terms for these bosons in the EWK Lagrangian would violate the $SU(2)_L \otimes U(1)_Y$ symmetry. The problem can be solved by introducing an additional scalar field doublet ϕ (Higgs field) [11, 12] with the potential given by

$$V(\phi^\dagger, \phi) = \frac{1}{4}\lambda\left(\phi^\dagger\phi - \frac{1}{2}\Phi^2\right)^2, \quad (2.19)$$

and the Lagrangian defined as

$$\mathcal{L} = -\frac{1}{2}D_\mu\phi_i^\dagger D^\mu\phi_i - V(\phi^\dagger, \phi), \quad (2.20)$$

where μ and λ are the mass and the field self-interaction parameters, correspondingly. The potential is shown in Fig. 2.2 for the choice of μ^2 to be positive or negative. In the first case the vacuum of the Higgs field stays around zero, while in the second case the vacuum expectation value (VEV) acquires a nonzero value. The usual approach is to fix the gauge in

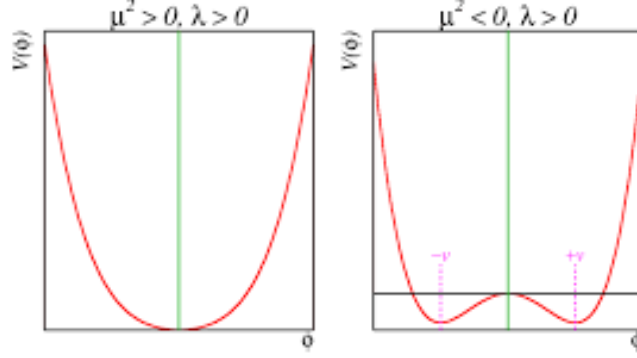


Figure 2.2: The Higgs potential for two cases of μ^2 selection: $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right)

a way that the first real component of ϕ is assigned a VEV of $v = \sqrt{\frac{-\mu^2}{2\lambda}}$. This leads to the Higgs field expansion around the VEV value in the form:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} v + h(x) \\ 0 \end{pmatrix}, \quad (2.21)$$

This mechanism is an example of spontaneous symmetry breaking, and, according to the Goldstone theorem, three associated Goldstone bosons appear. However, the gauge transformation can be used to transform these Goldstone bosons into the longitudinal degree of freedom for W and Z bosons. The final Lagrangian after the spontaneous symmetry breaking and rotation by the weak angle mentioned before can be written as:

$$\mathcal{L}_{eff} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}Z^{\mu\nu}Z_{\mu\nu} - D^{\dagger\mu}W^{-\nu}D_{\mu}W_{\nu}^{+} + D^{\dagger\mu}W^{-\nu}D_{\nu}W_{\mu}^{+} \quad (2.22)$$

$$+ie(F^{\mu\nu} + \cot\theta_w Z^{\mu\nu})W_{\mu}^{+}W_{\nu}^{-} \quad (2.23)$$

$$-\frac{1}{2}\left(\frac{e^2}{\sin^2\theta_w}\right)(W^{+\mu}W_{\mu}^{-}W^{+\nu}W_{\nu}^{-} - W^{+\mu}W_{\mu}^{+}W^{-\nu}W_{\nu}^{-}) \quad (2.24)$$

$$-(M_W^2 W^{+\mu}W_{\mu}^{-} + \frac{1}{2}M_Z^2 Z^{\mu}Z_{\mu})\left(1 + \frac{h}{v}\right)^2 \quad (2.25)$$

$$-\frac{1}{2}\partial^{\mu}h\partial_{\mu}h - \frac{1}{2}m_h^2 h^2 - \frac{1}{2}\frac{m_h^2}{v}h^3 - \frac{1}{8}\frac{m_h^2}{v^2}h^4, \quad (2.26)$$

with the following definitions is used:

$$F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu} \quad (\text{Electromagnetic field strength}) \quad (2.27)$$

$$Z_{\mu\nu} = \partial_{\mu}Z_{\nu} - \partial_{\nu}Z_{\mu} \quad (\text{Kinetic term for } Z_{\mu}) \quad (2.28)$$

$$D_{\mu} = \partial_{\mu} - ie(A_{\mu} + \cot\theta_w Z_{\mu}), \quad (2.29)$$

There is a mass term for the W and Z bosons in Eq. 2.26 with the masses defined as

$$M_W = \frac{g_2 v}{2} \quad \text{and} \quad M_Z = \frac{M_W}{\cos \theta_w} = \frac{g_2 v}{2 \cos \theta_w}. \quad (2.30)$$

Such mass generation mechanism through the spontaneous symmetry breaking was proposed almost simultaneously in 1964 by three independent groups: by Francois Englert and Robert Brout; by Peter Higgs; and by C. R. Hagen, Gerald Guralnik, and Tom Kibble.

In addition, the Higgs mechanism can generate masses also for fermions by introducing Yukawa couplings between the Higgs field and fermions. After symmetry breaking the Yukawa Lagrangian for example in the quark sector looks like:

$$\mathcal{L}_D = -\frac{1}{\sqrt{2}} \lambda' (v + h) (\psi_L^\dagger \psi_R + \psi_R^\dagger \psi_L), \quad (2.31)$$

where y' is the Yukawa coupling, which is different for every fermion.

2.1.8 SM experimental success and challenges

The combination of the aforementioned QCD and EW theory results in the SM. The SM predicted the existence of gluons as strong force mediators, that were discovered at the PETRA accelerator in 1979 by the TASSO, MARK-J and PLUTO experiments [13,14]. Weak force mediators were also predicted by the SM and were discovered in 1983 by the UA1 and UA2 experiments in proton-antiproton collisions [15–18]. After the discovery of the "strange" quark [19,20], the SM predicted the existence of a second quark within the same generation, the "charm" quark. The latter was discovered in 1974 [21,22]. The same story happened with the "bottom" and its generation partner, "top" quark. In both cases, the discovery of the corresponding quark came quite soon [23–25]. The final missing particle, the Higgs boson, was discovered in 2012 by CMS and ATLAS [9,9]. Many precision measurements are in impressive agreement with the SM prediction such as the anomalous magnetic dipole moment of the electron [26]. The SM calculations for the latter agrees with the measured value to 13 significant figures.

However, still, there are many challenges for the SM leading to the development of many theories beyond the Standard Model. These problems could be classified as theoretical and experimental.

The main theoretical problem is the unproven SM self-consistency as quantum field model. In addition, the SM has 19 parameters, exactly three quark generations and many other initial inputs that do not come from fundamental theoretical consideration but from experimental results. Therefore, many theories are trying to explain the current SM complexity from basic principles. In addition, the SM symmetry does not prohibit writing CP violating term in the strong interaction sector [27]. However, so far there is no experimental evidence of such violation. Moreover, finally, the SM does not include gravity.

After the SM Higgs boson discovery one more theoretical problem became crucial. The SM is proven to be renormalizable for all higher-order (loop) corrections. That implies the theory to be well defined up to infinite momentum in the loops. However, it is widely believed that the new physics must appear at least at the Planck scale where the quantum gravity

starts to play an important role. Therefore, an energy cut off (Λ_{cut}) is introduced in loop calculations. Taking into the account the next-to-leading order (NLO) contribution to the Higgs boson mass from fermion loops result in a physical Higgs boson mass of:

$$m_{phys}^2 \approx m_h^2 - \lambda'^2 \left(\frac{1}{8\pi^2} \Lambda_{cut}^2 - m_f^2 \ln \frac{\Lambda_{cut}^2}{m_f^2} \right), \quad (2.32)$$

where m_h is the bare Higgs boson mass and m_f is the fermion mass. In the case of Λ_{cut} to be of the order of the Planck scale the physical Higgs boson mass (125 GeV) is calculated from subtraction of two quantities of the Planck scale order (10^{18} GeV). This problem is known as the hierarchy or fine-tuning problem [28]. Different solutions to his problem were one of the main drivers of scientists' hope to find new physics at the TeV scale.

From the experimental side, there are several observations in contradiction with the SM. The first is the anomalous magnetic dipole moment of muon to be of the order of 3σ away from its predicted value [29]. The second is the discovery of the neutrino oscillations and the corresponding existence of neutrino masses [30]. Neutrinos are only left-handed and cannot have Yukawa terms with Higgs fields as other fermions. In this case, neutrino masses cannot appear from the symmetry breaking mechanism and scientists need to invent another way to give neutrino mass.

Experiments in cosmology indicate the existence of a large amount of almost non-radiating matter (Dark Matter) participating in the gravitational interaction distributed across the universe [31]. While the explanation of this phenomenon is still possible with ordinary baryonic matter through primordial black holes, the primary dark matter candidate is a new weakly interacting elementary particle that is not present in the SM. In addition, the accelerating universe inflation gives evidence for the existence of the even more mysterious Dark Energy [32, 33].

Most of the aforementioned problems can be solved by introducing beyond the Standard Model (BSM) theories. Some of these theories are just small extensions of the original SM. In these cases, it is sufficient to add a few new terms in the SM Lagrangian to solve, for example, the neutrino mass problem [34], or to introduce a Dark Matter candidate [35]. But it is also possible to change some fundamental axioms like initial symmetry [35] or the number of dimensions [36] in order to solve simultaneously several challenges of modern physics. One of these models is supersymmetry (SUSY) [37–44], which is discussed in the next chapter.

2.2 SUSY

SUSY is one of the most attractive extensions of the SM. By postulating an underlying symmetry between bosons and fermions, SUSY generators Q act on some state with the defined spin j as following:

$$J_3(Q|jm\rangle) = (m - \frac{1}{2})Q|jm\rangle, \quad (2.33)$$

where J_3 is the generator of rotations around the 3-axis and m is an eigenvalue for rotation. So, Q can lower the spin of an object similar to an annihilation operator. And $Q^\dagger$ increases

the m -value by $\frac{1}{2}$.

To construct the simplest supersymmetric Lagrangian [45, 46] one needs to introduce a supermultiplet containing just two types of particles, differing by a 1/2-unit of helicity. This leads to the necessity for SM particles to have supersymmetric partners with spin difference of $\frac{1}{2}$. Requiring exact SUSY would force superpartners to have the same mass as SM particles, which do not exist. Therefore, breaking of SUSY is obligatory at high energies. Various SUSY breaking mechanisms were developed, like the gravity-mediated, gauge-mediated or anomaly-mediated supersymmetry breaking, but to set up the general framework for SUSY particle search all possible SUSY breaking terms are independently parametrized.

2.2.1 Minimal Supersymmetric Standard Model

The Minimal Supersymmetric Standard Model (MSSM) is the simplest possible extension of the SM obeying supersymmetry with one kind of the supersymmetric transformation. The MSSM extends the SM particle content by introducing superpartners to both fermions and bosons and by combining them in supermultiplets. Vector supermultiplets describe spin-1 SM vector bosons and their superpartners spin-1/2 Weyl fermions called gauginos. Chiral supermultiplets describe SM spin-1/2 Weyl fermions and their spin-0 scalars. All of them should have the same degrees of freedom for SM model particles and their partners. Therefore, most of the fermions have two scalar superpartners for left-handed and right-handed chirality. All superpartners' symbols are written with a tilde above them. Fermion superpartners are called with the same name, but with prefix "s", for example, the tau superpartner is called stau. For boson superpartner names the suffix "ino" is added to the corresponding SM particles. All supermultiplets are listed in Table 2.1.

Particles	Supermultiplet	spin-0	spin-1/2	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
quarks and squarks	Q	$(\tilde{u}_{iL}, \tilde{d}_{iL})$	(u_{iL}, d_{iL})	3	2	+1/6
	$\bar{u}$	$\tilde{u}_{iR}^*$	$u_{iR}^\dagger$	3	1	-2/3
	$\bar{d}$	$\tilde{d}_{iR}^*$	$d_{iR}^\dagger$	3	1	+1/3
lepton and slepton	L	$(\tilde{e}_{iL}, \tilde{\nu}_i L)$	$(e_{iL}, \nu_i L)$	1	2	-1/2
	$\bar{e}$	$\tilde{e}_{iL}^*$	$e_{iR}^\dagger$	1	1	+1
Higgs, higgsino	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^-)$	1	2	+1/2
	H_d	(H_d^+, H_d^0)	$(\tilde{H}_d^+, \tilde{H}_d^-)$	1	2	-1/2
gluino, gluon	G	$\tilde{g}$	g	8	1	0
wino, W boson	W	$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$	1	3	0
bino, B boson	B	$\tilde{B}^0$	B^0	1	1	0

Table 2.1: The MSSM supermultiplets and their quantum numbers.

The fermion masses cannot be given by the BEH mechanism with only one Higgs boson doublet within the MSSM. Therefore, the minimal number of Higgs boson doublets is two: one doublet gives mass to the up-type quarks and the other gives mass to the charged leptons

and down-type quarks.

The symmetry breaking within the MSSM is similar to that in the SM. The main difference comes from using two Higgs boson doublets leading to two symmetry breaking

$$\langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_u \\ 0 \end{pmatrix} \quad \text{and} \quad \langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_d \end{pmatrix}, \quad (2.34)$$

where v_u and v_d stand for the vacuum expectation values.

The MSSM and other SUSY scenarios can solve the hierarchy problem. It is shown in Eq. 2.35, that the physical Higgs boson mass squared obtains a large correction from the fermion loop, proportional to the Yukawa coupling and cut-off energy squared. The same correction comes from the scalar loop, but with the opposite sign and two times smaller. Therefore, introducing two scalar particles with the same Yukawa coupling constant compensates the Λ^2 and leaves only the logarithmic terms in Higgs boson mass:

$$m_{phys}^2 \approx m_h^2 - \frac{\lambda'^2}{8\pi^2} (m_{\tilde{f}}^2 \ln \frac{\Lambda_{cut}^2}{m_{\tilde{f}}^2} - m_f^2 \ln \frac{\Lambda_{cut}^2}{m_f^2}) \quad (2.35)$$

where $\tilde{f}$ is a mass of the fermion's superpartner. But logarithmic terms in SUSY can give also considerable fine-tuning in the case of $m_{\tilde{f}} \gg m_f$. Hence, the mass of superpartners should be of the order of TeV to have the Higgs boson mass correction of the order of the physical Higgs boson mass.

The MSSM Lagrangian can contain terms violating lepton or baryon number conservation by one unit. This violation can lead to proton decay via channels like $e^+\pi^0$, $\mu^+\pi^0$ etc. However, the current experimental results set a lower bound on the proton lifetime of the order of 10^{29} years. Therefore, such lepton or baryon number violating terms are unnaturally very suppressed. Stating lepton and baryon number conservation as an axiom would not allow such violation by non-perturbative electroweak effects in SM, which are negligible at low energies but which might be important in the early universe evolution. Instead, an additional symmetry is introduced [47], which forbids baryon (B) and lepton (L) number violating terms. This symmetry is called the R parity and is defined as:

$$P_R = (-1)^{2S+3(B-L)}, \quad (2.36)$$

where S represents the spin. For all SM matter particles, the P_R is $+1$, while for their supersymmetric partners the P_R is -1 . There are several consequences of R_R -parity conservation: the lightest supersymmetric particle (LSP) is stable [48, 49], SUSY particles can only be produced only in pairs in SM particles collisions, and they cannot decay only to SM particles. In addition, a stable LSP is a viable dark matter candidate [50].

The last MSSM feature to be mentioned is gauge coupling unification. Gauge couplings change with increasing energy. These changes can be extrapolated from the EW scale to high energy using the renormalization group equations. In the SM, couplings do not unify at high energy, while MSSM gauge coupling running leads to gauge coupling unification with an accuracy of the order of 1% [51]. The comparison between the SM and MSSM for the running gauge coupling dependence on the energy is shown in Fig. 2.3.

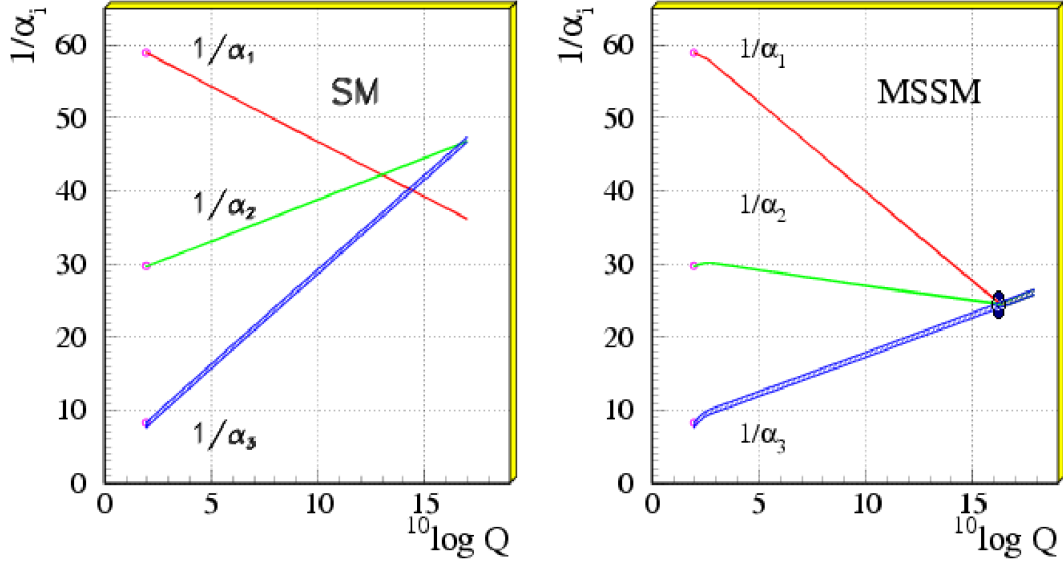


Figure 2.3: The running gauge couplings dependence from the energy for the SM (left) and MSSM (right) [51].

2.2.2 Mixing of the third generation fermions in the MSSM

In the softly broken SUSY, the third generation sfermions are usually the lightest among all generations. That makes stop and staus very attractive for collider searches. In addition, symmetry breaking introduces non-diagonal entries in the mass squared matrix. These contributions are proportional to the mass of the corresponding SM partners:

$$M_{mix}^2 = m_{f_{SM}}(A_0 - \mu \tan \beta), \quad (2.37)$$

where A_0 is a trilinear scalar coupling, $\tan \beta$ is defined as $\frac{v_d}{v_u}$ and μ is the bilinear Higgs boson coupling from the superpotential. Therefore, non-diagonal terms are most important for third generation sparticles. The most significant mixing appears in the stop sector. For sbottom and stau, the mixing term contribution becomes nonnegligible for larger values of $\tan \beta$. The mass matrix can be diagonalized by means of the orthogonal transformation

$$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_{\tilde{\tau}} & \sin \theta_{\tilde{\tau}} \\ -\sin \theta_{\tilde{\tau}} & \cos \theta_{\tilde{\tau}} \end{pmatrix} \begin{pmatrix} \tilde{\tau}_L \\ \tilde{\tau}_R \end{pmatrix}, \quad (2.38)$$

where $\tilde{\tau}_1$ and $\tilde{\tau}_2$ are mass eigenstates and $m_{\tilde{\tau}_1} > m_{\tilde{\tau}_2}$. For large mixing $\tilde{\tau}_1$ may become significantly lighter than its analogon in the first two generations.

2.2.3 Simplified model spectrum

The most general MSSM Lagrangian has more than 100 parameters coming mostly from soft SUSY breaking terms. Moreover, it also predicts more than 30 new particles to exist. It is obvious that there is no experimentally feasible approach to study this general MSSM.

One way to reduce the number of parameters is to postulate some specific SUSY breaking mechanism. For example, the gravity mediated supersymmetry breaking postulates gravity to be a mediator between MSSM particles and the hidden sector. The simplest model is minimal supergravity (mSUGRA) [44] within the $N = 1$ supergravity framework. mSUGRA requires only 4 input parameters and a sign to reconstruct phenomenology at the EW scale from the Grand Unification scale. That makes mSUGRA so attractive for experimental investigations.

Another approach for the drastic parameter space reduction is to create a Simplified Model Spectrum (SMS) [52, 53]. An SMS can be constructed from the MSSM by choosing parameters in such a way they yield a specific final state. However, most of the final states can be obtained by different SUSY particle production chains. Therefore, an SMS is adjusted to reproduce the topology of interest. For this purpose, only a few parameters are considered necessary, like masses of the SUSY particles entering the process, and other SUSY particles are set to be decoupled or too massive to contribute to the final state under study. In order not to specify all remaining possible couplings between particles in SMS, quite often, a production cross section and branching ratios are used as parameters.

In this thesis work, several simplified SUSY models are considered. Pair of $\tilde{\tau}$ can be produced either directly or indirectly, in the decay chains of charginos and neutralinos, the mixtures of the superpartners of electroweak gauge and Higgs bosons. In all cases, the $\tilde{\tau}$ decays to a τ lepton and the LSP is assumed to be 100 % branching ratio.

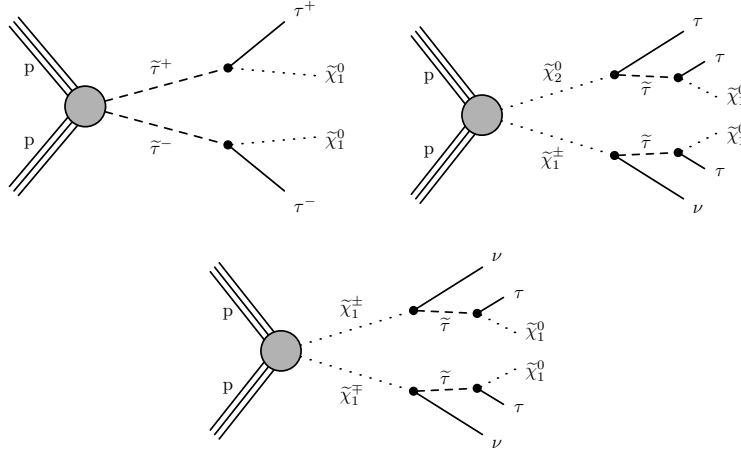


Figure 2.4: Diagrams for the simplified models studied in this paper: direct $\tilde{\tau}$ pair production followed by each $\tilde{\tau}$ decaying to a τ lepton and LSP (left), and chargino-neutralino (middle) and chargino pair (right) production with decays to τ leptons in the final state.

The cross-section of the direct $\tilde{\tau}$ pair production depends strongly on the $\tilde{\tau}$ mixing angle [54]. The experimental acceptance also changes considerably for different $\tilde{\tau}$ "helicities" due to differences in the polarization of the τ leptons. In the case of a $\tilde{\tau}$ being superpartner of a purely right-handed τ , the decay products of hadronically decaying τ leptons originating from $\tilde{\tau}$ decays have larger visible transverse momentum than in the purely left-handed scenario, while the reverse is true for leptonically decaying τ leptons. Four different scenarios of direct $\tilde{\tau}$ pair production are considered in this thesis: (i) a purely left-handed $\tilde{\tau}$ scenario, (ii) a purely right-handed $\tilde{\tau}$ scenario, (iii) maximal mixing between the right- and left-handed helicity eigenstates scenario, and (iv) a mass-degenerate scenario (superpartners

of left-handed and right-handed τ leptons have the same mass and are both produced). In addition, simplified models of mass-degenerate chargino-neutralino ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$) and chargino pair ($\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$) production are considered. The $\tilde{\chi}_2^0$ (the second-lightest neutralino mass eigenstate) is considered to decay through the chain $\tilde{\chi}_2^0 \rightarrow \tau\tilde{\tau} \rightarrow \tau\tau\tilde{\chi}_1^0$, and the $\tilde{\chi}_1^\pm$ (the lightest chargino) decays as $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu_\tau/\tilde{\nu}_\tau\tau \rightarrow \tau\nu_\tau\tilde{\chi}_1^0$, with equal branching fractions assumed for each of the two possible $\tilde{\chi}_1^\pm$ decay chains. For these indirect $\tilde{\tau}$ production mechanisms, the $\tilde{\tau}$ helicity eigenstate is assumed to be maximally mixed, and the degenerate $\tilde{\tau}$ and $\tilde{\nu}_\tau$ masses to be halfway between the mass of the produced particles ($\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$) and the LSP mass. Diagrams illustrating these models are shown in Fig. 2.4.

2.2.4 Experimental constraints

One of the main motivations for SUSY is the hierarchy problem, and the main contribution to the physical Higgs boson mass comes from the stop, the gluino, and the higgsino. Therefore, in order to reduce the Higgs boson mass corrections to the order of its physical mass, the stop and the gluino are expected to have masses of the order of 1 TeV, while the higgsino should have a mass of the order of the observed Higgs boson mass. Both the CMS and ATLAS collaborations have performed searches for stop, gluino and higgsino productions in various final states [55, 56]. Current summary tables for mass limits are shown in Figs 2.5, 2.6, 2.7 and 2.8.

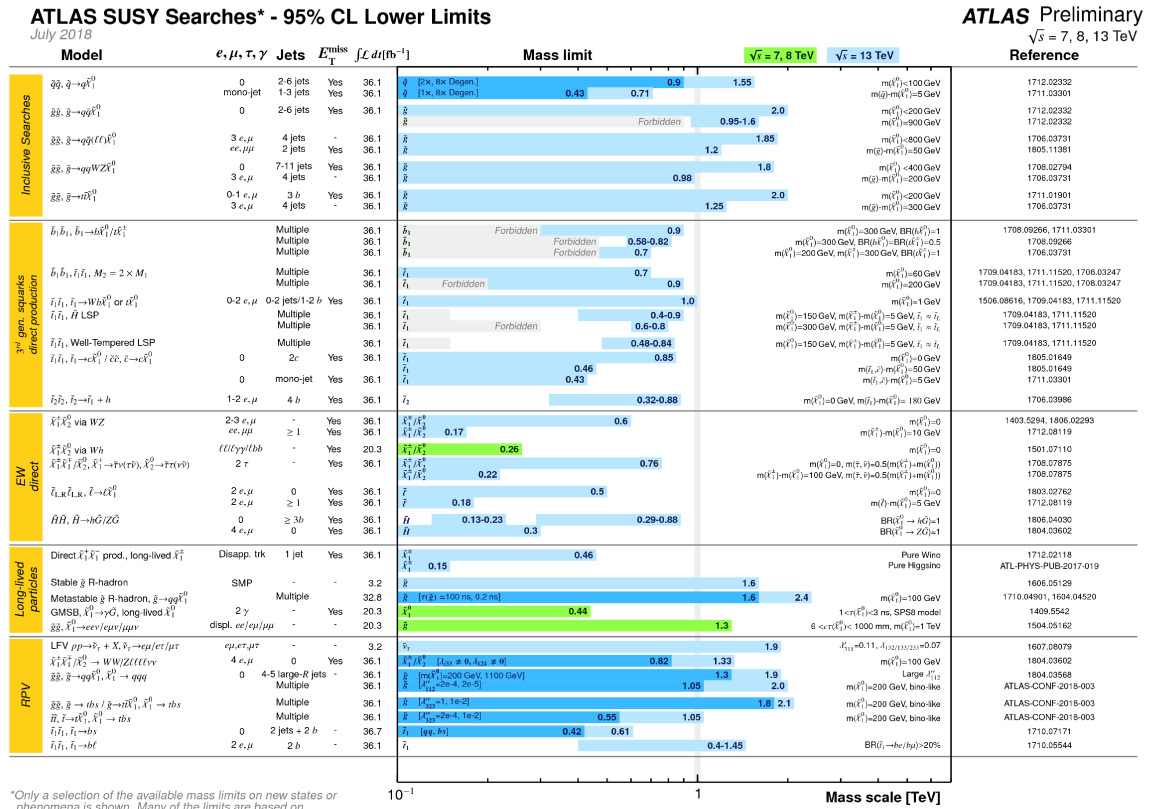


Figure 2.5: Summary table of ATLAS searches for SUSY particles [55].

Chapter 2. Theoretical Framework

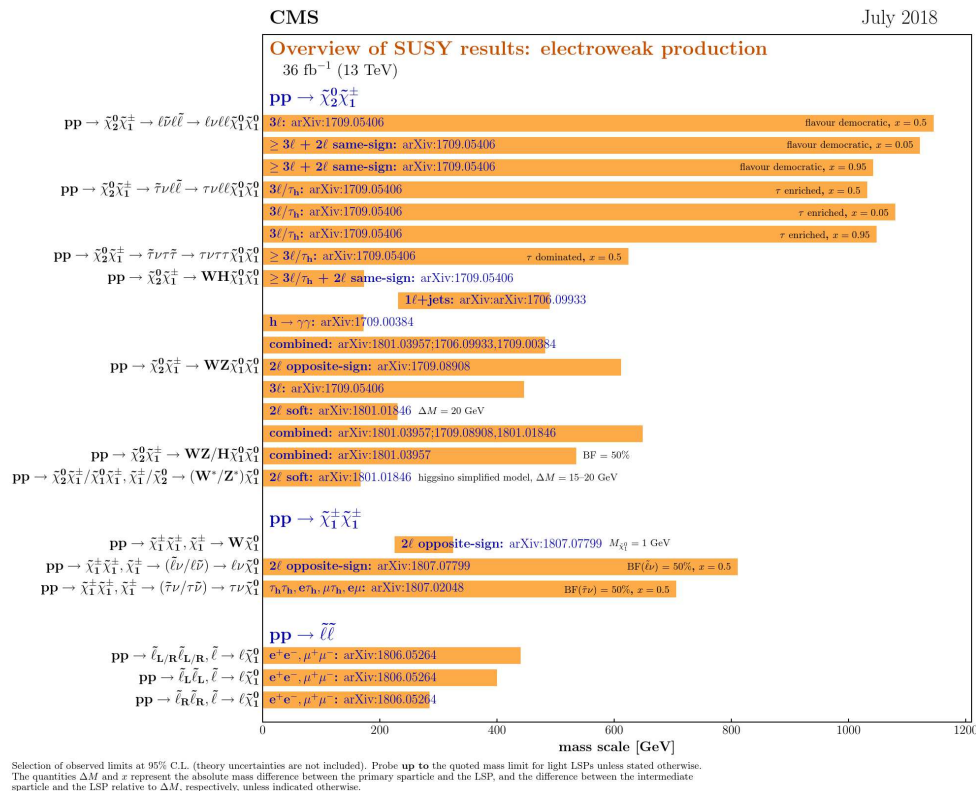


Figure 2.6: Summary tables of CMS searches for EWK SUSY particles [56].

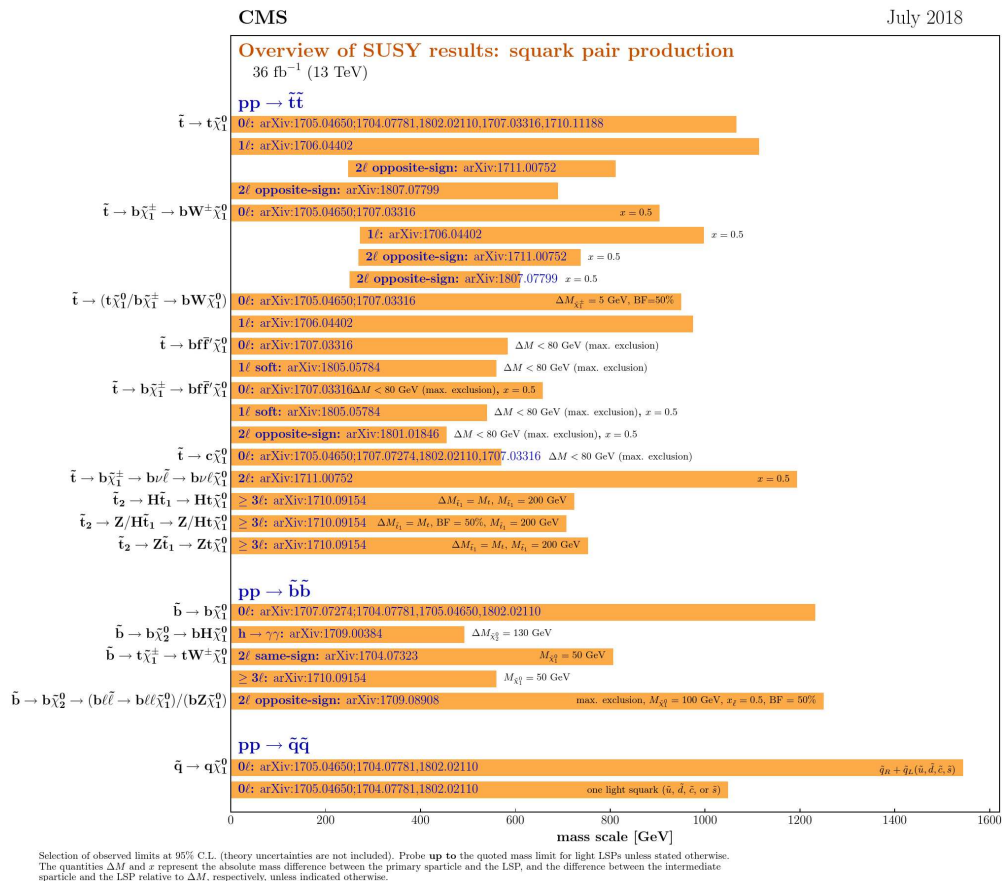


Figure 2.7: Summary tables of CMS searches for squarks [56].

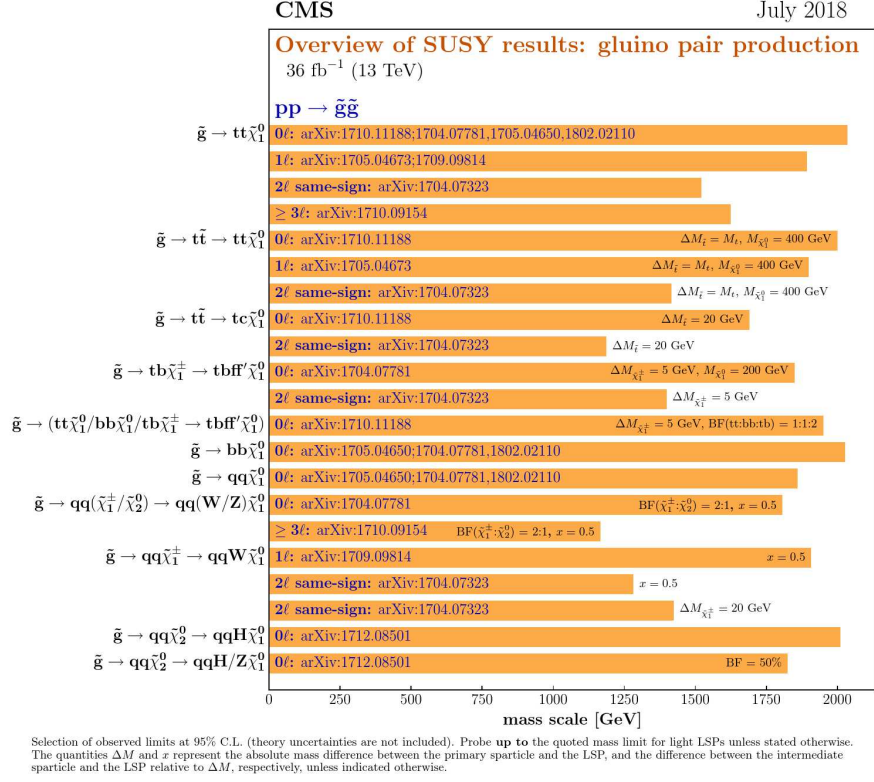


Figure 2.8: Summary tables of CMS searches for gluinos [56].

The average upper mass limits for the stop and the sbottom are around 1 TeV. The gluino upper mass limit has on average the value of 1.5 TeV with reaching a 2 TeV level for some decay channels. The chargino and neutralino masses are excluded up to 1 TeV for several decay modes. And the selectron and the smuon have an average upper mass limit of 400 GeV.

These limits constrain the most naive MSSM scenario to be more and more fine-tuned. However, there is still an unconstrained part of the parameter phase space with low fine-tuning, especially in compressed spectra, in which the studied sparticle has a mass close to a LSP mass.

For the stau, there are no strong experimental or theoretical arguments why it should have a mass within the LHC reach. However, there are several indirect hints for the light staus.

One hint comes from the DM density study. Within the current universe evolution model, it is problematic to obtain the observed DM density with only one DM particle. Coannihilation scenarios involving a light $\tilde{\tau}$ with a small mass splitting with an LSP that is almost purely bino lead to a DM relic density consistent with cosmological observations [57–62]. Since the LSP mass should be of the order of the Higgs boson mass, the stau mass could be of the same order of magnitude.

Another hint is the possibility to explain the difference between the theoretical prediction and the measurement of the anomalous magnetic dipole moment of the muon by introducing a loop contribution from light EW SUSY particles. Feynman diagrams with such contributions are shown in Fig. 2.9. The main contribution comes from the lightest chargino and smuon,

and they should be light enough to give a valuable correction. However, since the inverted mass hierarchy is preferred by most of the SUSY breaking scenarios, a light smuon also leads to a light stau.

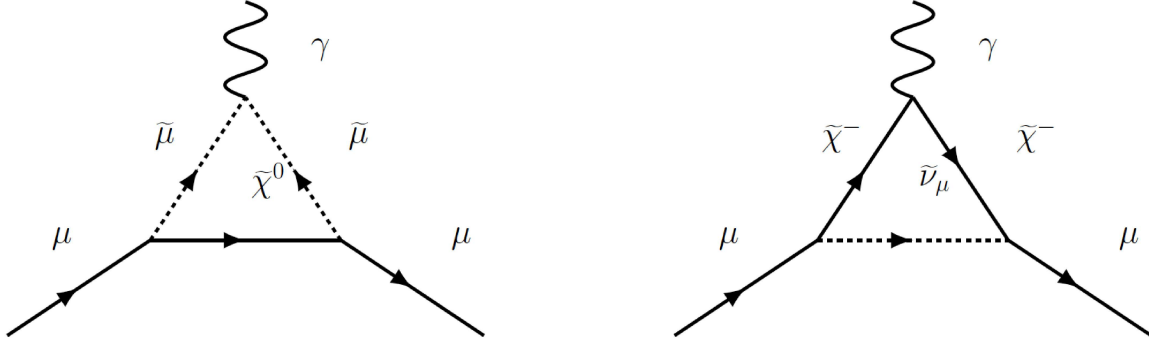


Figure 2.9: SUSY contribution to the muon anomalous magnetic dipole moment.

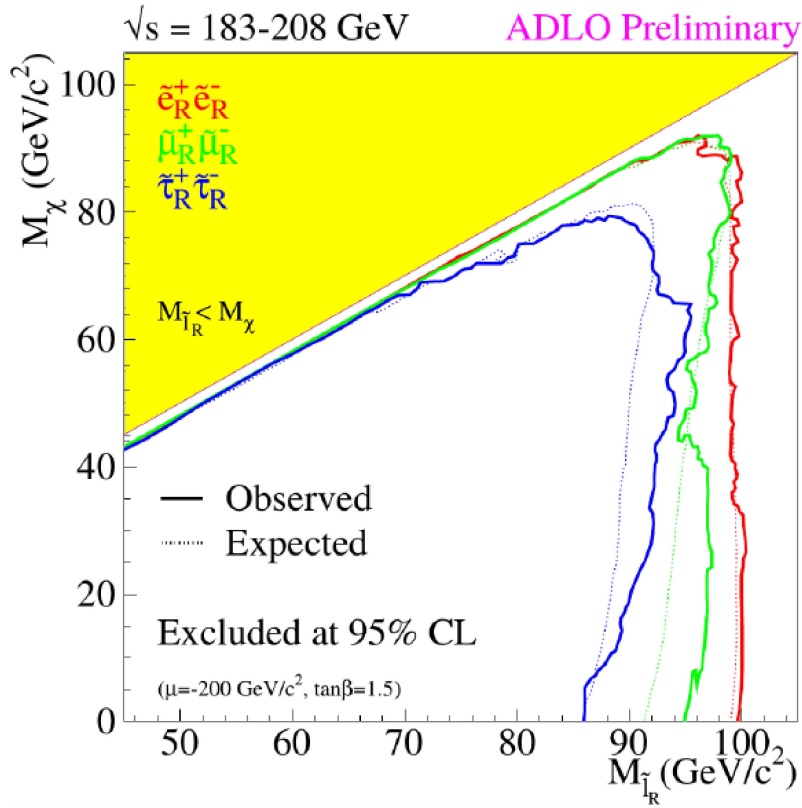


Figure 2.10: LEP limits on direct slepton production.

The most sensitive searches for direct $\tilde{\tau}$ pair production to date were performed at the CERN LEP [63–67]. LEP has excluded the direct stau production for stau mass up to 90 GeV. LEP limits on sleptons production are shown in Fig. 2.10. At the CERN LHC, the ATLAS [68, 69] and CMS [70] Collaborations have both performed searches for direct and indirect $\tilde{\tau}$ production with 8 TeV LHC data. The ATLAS Collaboration has also recently reported the results of a search for SUSY in final states with τ leptons, probing indirect $\tilde{\tau}$ production in models of chargino-neutralino and chargino pair production using data collected at $\sqrt{s} = 13$ TeV [71].

CHAPTER

3

EXPERIMENTAL SETUP

It is always useful for a university to have a Very Big Thing. It occupies the younger members, to the relief of their elders (especially if the VBT is based at some distance from the seat of learning itself) and it uses up a lot of money, which would otherwise only lie around causing trouble or be spent by the sociology department or, probably, both. It also helps if it pushes back boundaries, and it does not much matter what boundaries these are, since as any researcher will tell you that it is the pushing that matters, not the boundary.

Terry Prattchet

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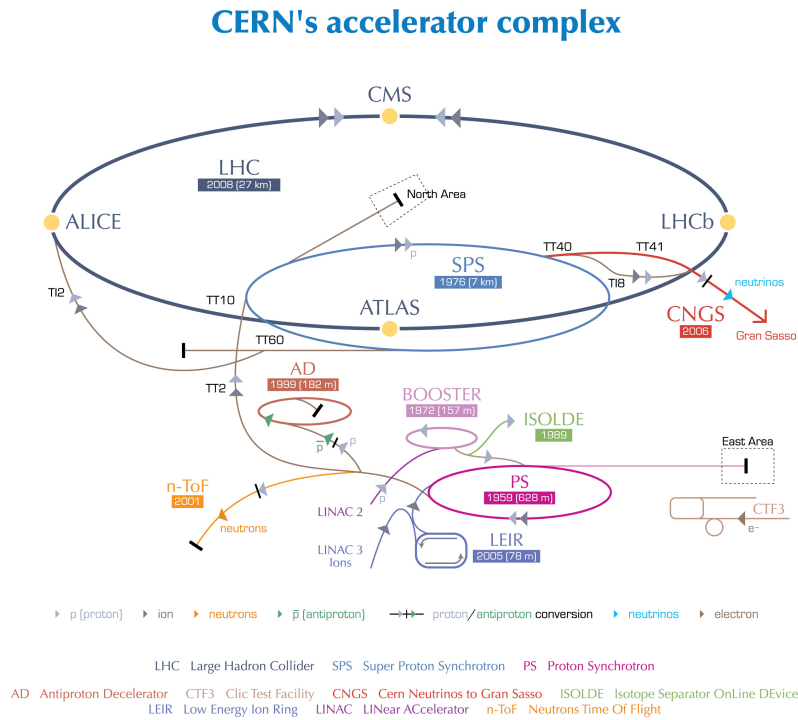
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To test a hypothesis by an experiment is the crucial part of the scientific method. Colliders are one of the main tools for such tests in particle physics for the last 60 years. However, through its development colliders went from small room based experiments to enormously

large and complicated machines built and governed by collaborations of thousands of scientists and engineers. Correspondingly, all detectors needed to detect the outcome of particle collisions are also sophisticated and composed of many subsystems.

3.1 The Large Hadron Collider and its experiments

The European Organization for Nuclear Research laboratories, known as CERN, operates one of the most advanced experimental particle physics labs in the world. It includes six accelerators, one decelerator and numerous experiments of different sizes. The accelerator complex at CERN is shown in Fig. 3.1.



European Organization for Nuclear Research | Organisation européenne pour la recherche nucléaire

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Figure 3.1: Accelerator complex at CERN, some of which are used to inject particle beams to the LHC accelerator [72].

The highest-energy accelerator built so far is the Large Hadron Collider (LHC) [73] at CERN. The LHC can accelerate and collide protons and heavy ions. Protons can currently be accelerated up to 6.5 TeV energy, resulting in a collision center-of-mass energy of up to 13 TeV. The LHC uses the former Large Electron-Positron Collider (LEP) 26.7 km long circular tunnel.

Protons for the acceleration are produced from ionized hydrogen. First, they are accelerated in the linear accelerator (LINAC2) to the energy of 50 MeV. At the second step, their energy is increased to 1.4 GeV by the Proton Synchrotron Booster. Then, they are accelerated to 26 GeV by the Proton Synchrotron (PS). Lastly, before entering the LHC tunnel, the

proton energy is increased to 450 GeV. After that, the protons are injected in the LHC and accelerated to 6.5 TeV energy.

Superconducting dipole magnets keep protons at a circular trajectory. The magnetic field of the dipole increases during the acceleration from 450 GeV to 6.5 TeV from 0.54 to 7.7 Tesla (T). Superconductivity is maintained by cooling with superfluid Helium-4 at the temperature of 1.9 K. To decrease operational costs and fit the LHC in 3.7 m diameter tunnel, a twin-bore-magnet technique is used. That means both beam pipes are constructed to be within the same magnet. The cross-section of the dipole magnet is shown in Fig. 3.2. In total, 1,232 dipole magnets are used. In addition, the 392 quadrupole magnets control the beam cross section.

LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999

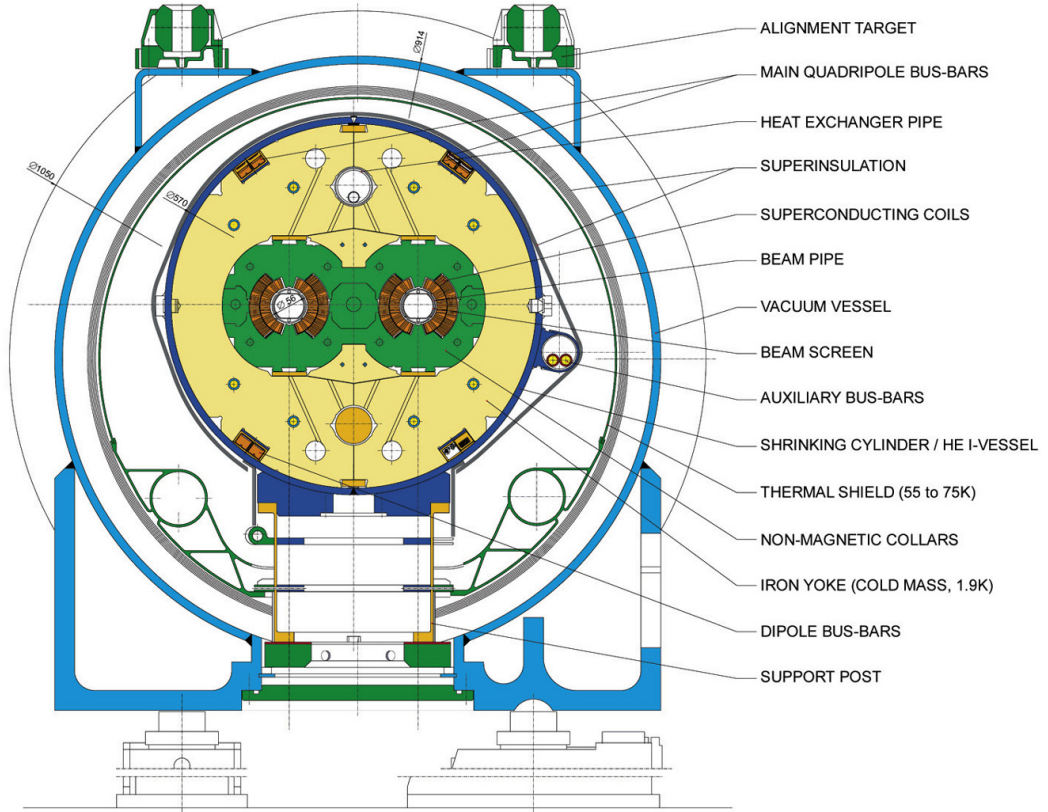


Figure 3.2: The cross-section of the LHC superconducting dipole magnet [73].

The LHC is not only a high-energy but also a high-intensity machine. The collider operates with 2808 proton bunches of approximately 10^{11} protons each. The commonly used quantity to measure the collision intensity is the instantaneous luminosity L

$$L = \frac{1}{\sigma} \frac{dN}{dt}, \quad (3.1)$$

where σ is the process cross section and $\frac{dN}{dt}$ an interaction rate. Since the LHC collides

almost identical proton beams the instantaneous luminosity can be rewritten using beam parameters:

$$L = \frac{N_p^2 n_b f_{rev} \gamma}{4\pi \epsilon_n \beta^*} F, \quad (3.2)$$

where N_p is the number of particles in each bunch, n_b is the number of bunches per beam, f_{rev} is the revolution frequency, γ is the relativistic gamma factor of the accelerated protons, ϵ_n is the normalized transverse beam emittance, β^* is the amplitude function describing beam squeezing toward the interaction point, and F is the parameter responsible for the luminosity reduction due to the beam crossing angle. The typical operating instantaneous luminosity is of the order of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

The total amount of data collected during certain data taking periods is characterized by the integrated luminosity

$$L_{\text{int}} = \int L \, dt. \quad (3.3)$$

where integration is done over the pure data taking time.

3.1.1 LHC experiments

The LHC has four main big experiments at each collision point and several smaller experiments nearby. Two large general-purpose particle detectors are ATLAS (A Toroidal LHC ApparatuS) [74] and CMS (Compact Muon Solenoid) [75]. Both consist of several concentric cylinders around the collision point. Each layer serves to measure specific features of propagating particles. The main difference between them is the magnet system: a solenoid magnet with a magnetic field strength of 3.8 T in CMS surrounds the tracker, the electromagnetic and the hadronic calorimeter, while the ATLAS solenoid magnet surrounds only the tracker and produces a 2 T magnetic field. CMS and ATLAS were designed for the Higgs boson search and study, precision measurements and new particles searches. The CMS detector is described in more detail in the next chapter.

The other two major experiments are ALICE (A Large Ion Collider Experiment) [76] and LHCb (Large Hadron Collider beauty) [77]. ALICE is created to study heavy ion collisions and the quark-gluon plasma. It uses a set of 18 subdetectors to get information about the velocity, the mass, and the charge of the particles. The two main goals of LHCb are b-physics study, in particular, CP-violating processes, and exotic hadron searches and measurements. Since b-hadrons are dominantly produced in the forward beam cone, LHCb is designed as a single arm forward spectrometer.

The three smaller experiments are LHCf (Large Hadron Collider forward) [78], MOEDAL (Monopole and Exotics Detector at the LHC) [79] and TOTEM (TOTAl Elastic and diffractive cross section Measurement) [80]. LHCf is built to study the particles generated in the region close the colliding proton beams. MoEDAL searches for magnetic monopoles and other highly ionizing massive particles with nuclear track detectors. TOTEM measures the p-p total cross section and p-p elastic scattering.

3.1.2 LHC operation

The LHC was started with the first beam in September 2008. After this, the first physics data was taken only in 2010 with 7 TeV center-of-mass energy due to a quench incident. During 2010 and 2011 6.14 fb^{-1} of data were collected by the CMS experiment. The LHC operated at a center-of-mass energy of 8 TeV in 2012 and CMS collected 23.30 fb^{-1} .

After a long shutdown, the LHC Run 2 was started at 13 TeV in 2015 and 4.22 fb^{-1} data were delivered to CMS. Further in 2016, 2017 and 2018, LHC delivered 40.8, 49.8 and 68.2 fb^{-1} of data to CMS, respectively. Different technical issues and experimental constraints do not permit to record and use all data. Therefore, CMS recorded 35.9, 41.9 and 64.0 fb^{-1} of certified data in 2016, 2017 and 2018.

Currently, Run 2 is over and a long shutdown takes place until 2020. After this, the Run 3 is planned with 14 TeV center-of-mass energy. CMS is expected to collect 300 fb^{-1} of data until 2023. As the next step, the High Luminosity LHC (HL-LHC) is planned with the same energy, but with upgraded detectors to collect 3000 fb^{-1} with five times higher instantaneous luminosity [81]. The HL-LHC and a possible future upgrade High Energy LHC with a center-of-mass energy of 27 TeV are discussed in Chapter 7 in more detail.

3.2 The CMS experiment

The Compact Muon Solenoid detector is one of the two multi-purpose experiments at the LHC. CMS has a diameter of 14.6 m and a length of 21.6 m and is about a factor of two smaller than ATLAS. A schematic view of the CMS detector with its components is shown in Fig. 3.3. CMS has a 12 m long superconducting coil to generate a homogeneous magnetic field of up to 4 T in the inner detector [82]. Currently it is operated with 3.8 T. The large field parallel to the beamline is used to curve the charged particle track. Higher field means higher track curvature, which in turn results in a better momentum resolution of the tracker.

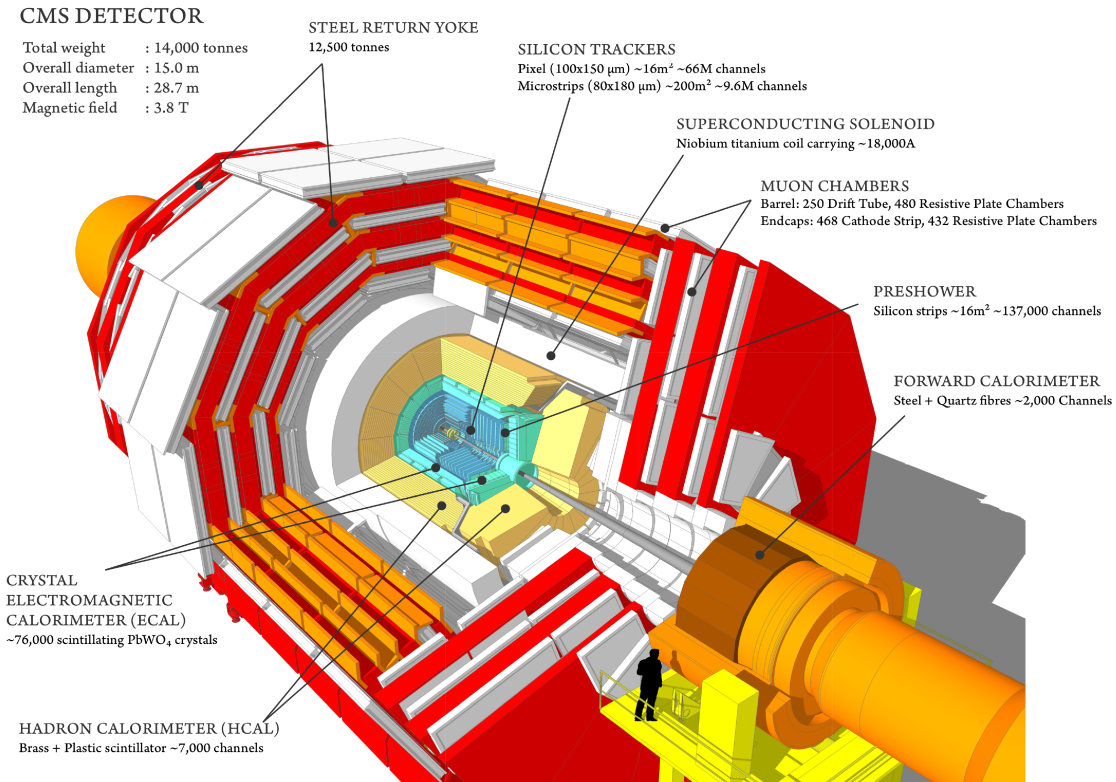


Figure 3.3: Schematic view of the CMS detector [82].

CMS consists of several layers of subdetectors with different physical purposes. The typical object propagation is shown in Fig. 3.4. The innermost part of the detector consists of the tracker system. It is placed within the inner magnetic field and detects the curvature of charged particle propagation. The next layer, the Electromagnetic Calorimeter (ECAL), absorbs photons and electrons, and it measures their energy. After this, the Hadron Calorimeter (HCAL) absorbs neutral and charged hadrons and provides information about their energy. The superconducting solenoid is placed between the HCAL and the iron return yoke. The muon chambers are integrated in the return yoke and measure the muon track curvature in the return solenoid magnetic field that goes up to 2 T.

The default CMS coordination system is defined in the following way: the origin is placed in the detector center, the x -axis is directed horizontally to the center of the LHC ring. The y -axis points vertically upwards and the z -axis is parallel to the beam axis and is directed in

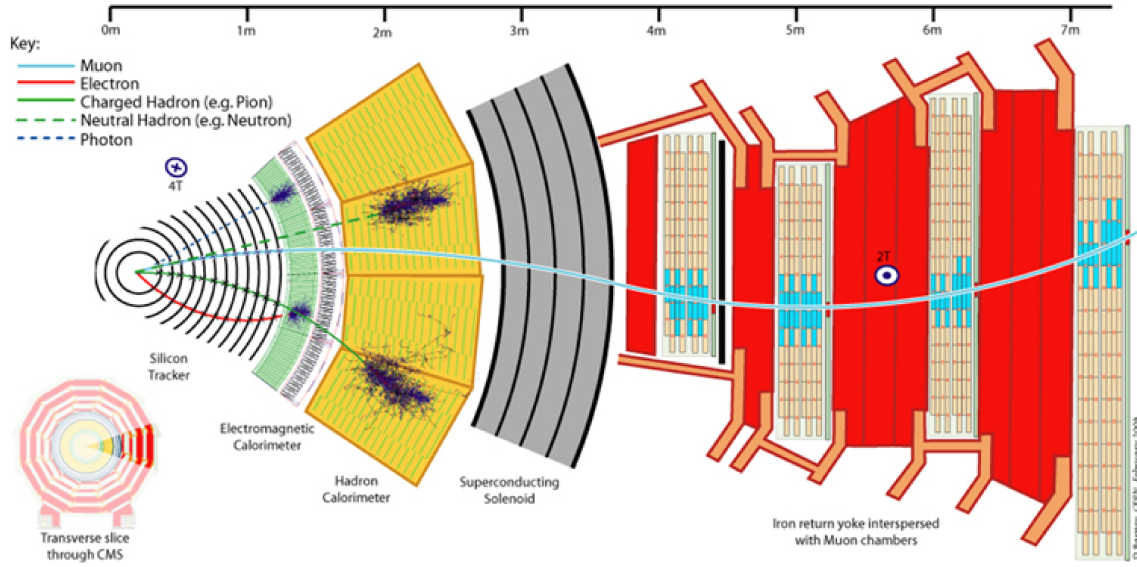


Figure 3.4: Object propagation through the CMS detector [83].

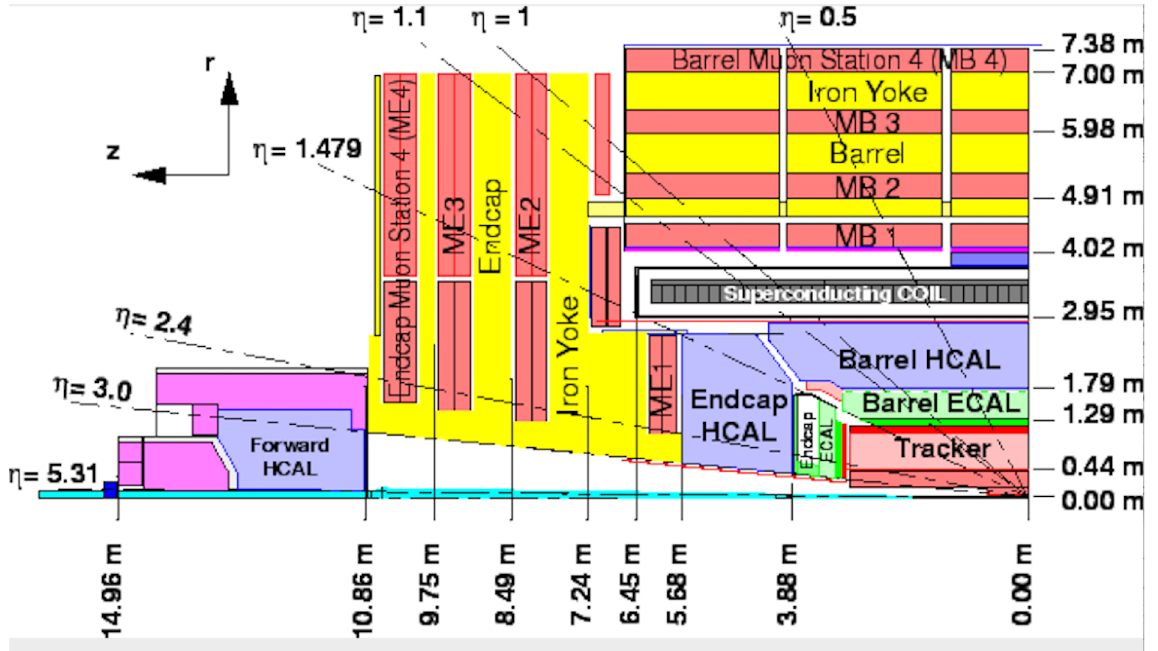


Figure 3.5: The CMS layout with the corresponding pseudorapidity values for different sub-detector parts [84].

the anti-clockwise direction of the accelerator ring. Due to the CMS symmetry around the z -axis cylindrical coordinates are widely used: the angle ϕ is set as the angle transverse to the beamline starting from the x -axis, the θ angle is defined towards positive z -axis and the transverse distance from the z -axis is denoted as r . Instead of the θ angle often pseudorapidity is used, $\eta = -\ln(\tan(\theta/2))$. The CMS layout with the corresponding pseudorapidity values for different subdetector parts is shown in Fig. 3.5.

3.2.1 The tracking system

The tracking system is used for the precise measurement of the charged particles' origin and their momentum. It consists of a pixel and a silicon strip subdetector. To increase the η coverage the sub-detectors are enclosed by the endcaps, resulting in an acceptance of up to 2.5 in pseudorapidity. The silicon tracking system with the corresponding subdetectors is shown in Fig. 3.6.

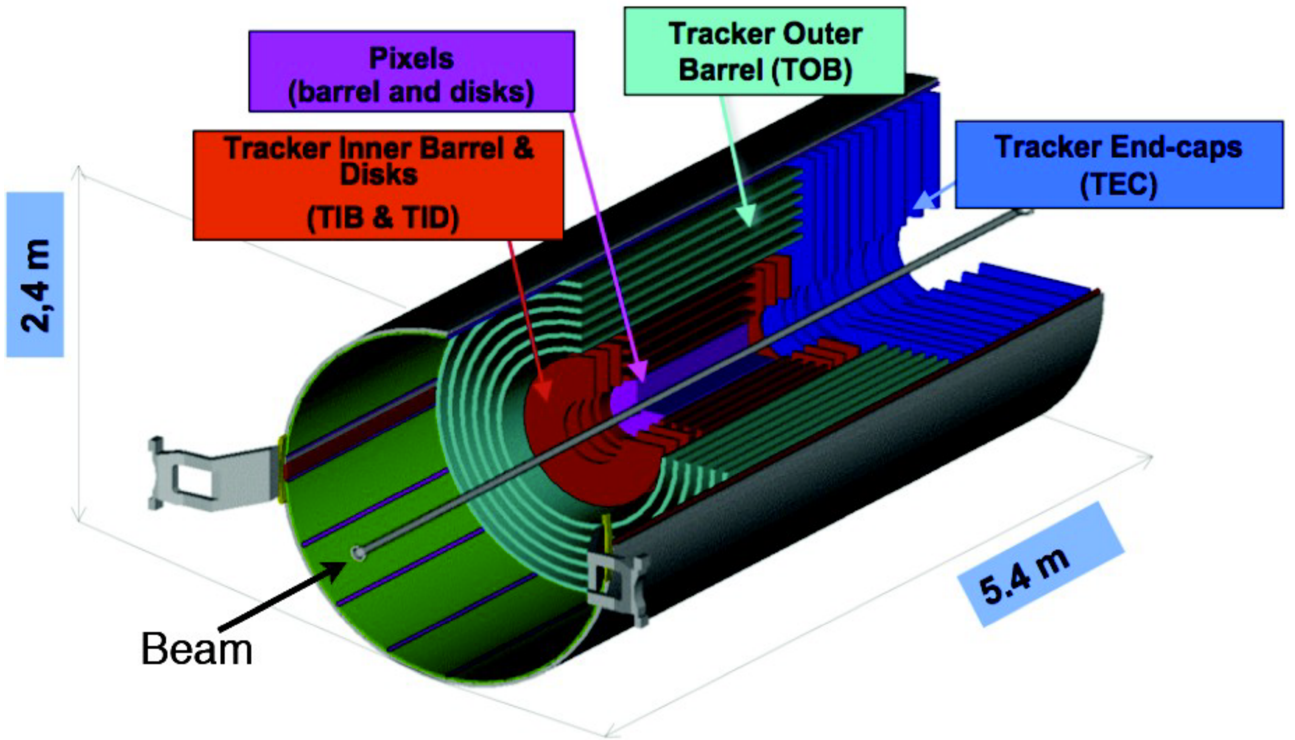


Figure 3.6: The silicon tracking system with corresponding subdetectors [85].

The pixel tracking detector is located close to the interaction point. It measures the track origin with high precision providing the main input for jets from b quark tagging, distinct vertex reconstruction and separation of prompt from secondary electrons.

The pixel detector is split in the barrel and endcap parts. The initial configuration of the pixel detector used in 2016 consisted of three concentric cylindric layers in the barrel part and two layers perpendicular to the z -axis layers in the endcap part. In 2017, the LHC delivered data to CMS with increased peak luminosity. In order to maintain good tracking performance in this condition the pixel detector was upgraded during the winter shutdown in 2016/2017. The main difference of the upgraded pixel detector is an increased number of layers in the barrel (four layers) and in the endcap (three layers). This setup provides spatial

track resolution of $10\text{--}40\,\mu\text{m}$.

The silicon strip detector is located around the pixel detector and consists of 15148 silicon strip modules. In a similar way to pixel detector, it consists of a barrel and endcap part as well. Furthermore, the barrel is split into inner and outer parts. The Tracker Inner Barrel (TIB) consists of four layers covering the radial region from 20 to 116 cm. The Tracker Outer Barrel has six layers within $55\text{ cm} < r < 116\text{ cm}$. The endcap part consists of the Tracker Inner Disk (TID) and the Tracker EndCaps (TEC) with three and nine discs at both ends, correspondingly. The spatial resolution varies from 13 to $47\,\mu\text{m}$.

3.2.2 The electromagnetic calorimeter

The next subdetector is the electromagnetic calorimeter. The ECAL layout with the corresponding subsystems is shown in Fig. 3.7. It is divided in the barrel part (EB) and the endcap part (EE) with the pseudorapidity range covering $|\eta| < 1.479$ and $1.479 < |\eta| < 3.0$, respectively. The ECAL consists of 75848 lead tungstate ($PbWO_4$) crystals used as both absorber and scintillator. Since the LHC has 25 ns delay between collisions, the crystals are designed to separate hits from different bunch crossings. Therefore, about 80% of the scintillation happens within 25 ns. The scintillator light is emitted in a visible spectrum and is detected by vacuum phototriodes in the EE and avalanche photodiodes in the EB.

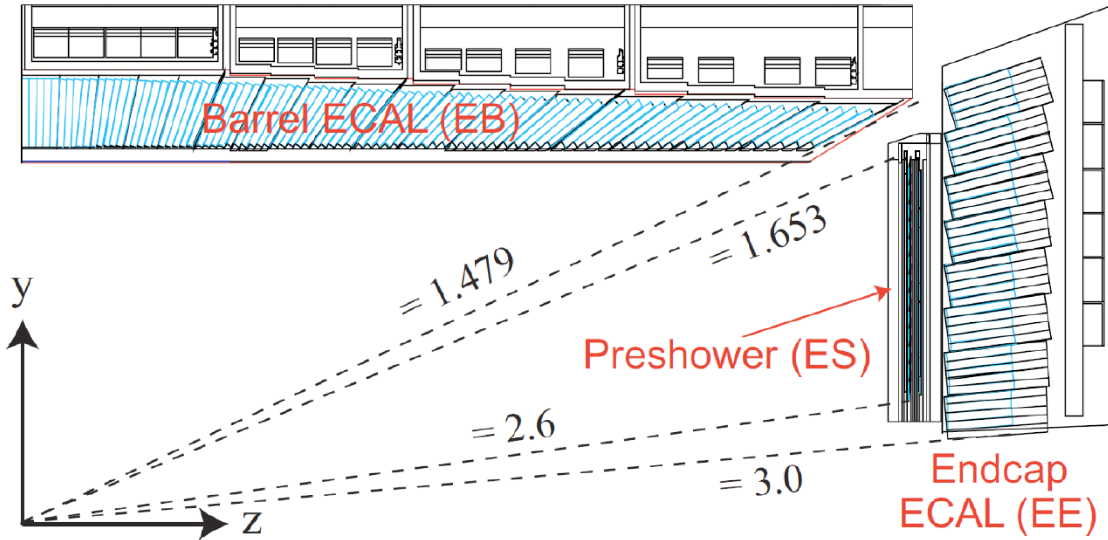


Figure 3.7: The ECAL with the corresponding subdetectors [82].

In addition, in front of the EE, the preshower detector (PS) is located within $1.653 < |\eta| < 2.6$. It consists of a lead plate to initiate electromagnetic showers and silicon sensors which measure the energy deposit and shower shape. The main goal of the PS detector is to identify neutral pions.

The approximate resolution of the ECAL is given by

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8(5)\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12(0.6)}{E}\right)^2 + (0.30\%), \quad (3.4)$$

where E is the particle energy in GeV, and the first numerical values correspond to the EB, while the values in brackets refer to the EE. The first term describes the stochastic fluctuation in the number of secondary particles within a shower. The second term is the electronic noise term, while the third one comes from calibration errors and energy leakage.

3.2.3 The hadronic calorimeter

The Hadron Calorimeter is placed between the ECAL and the magnet. The main goal of the HCAL is to measure the hadronic activity and the jet energy deposit. The detailed view of an HCAL quadrant is shown in Fig. 3.8.

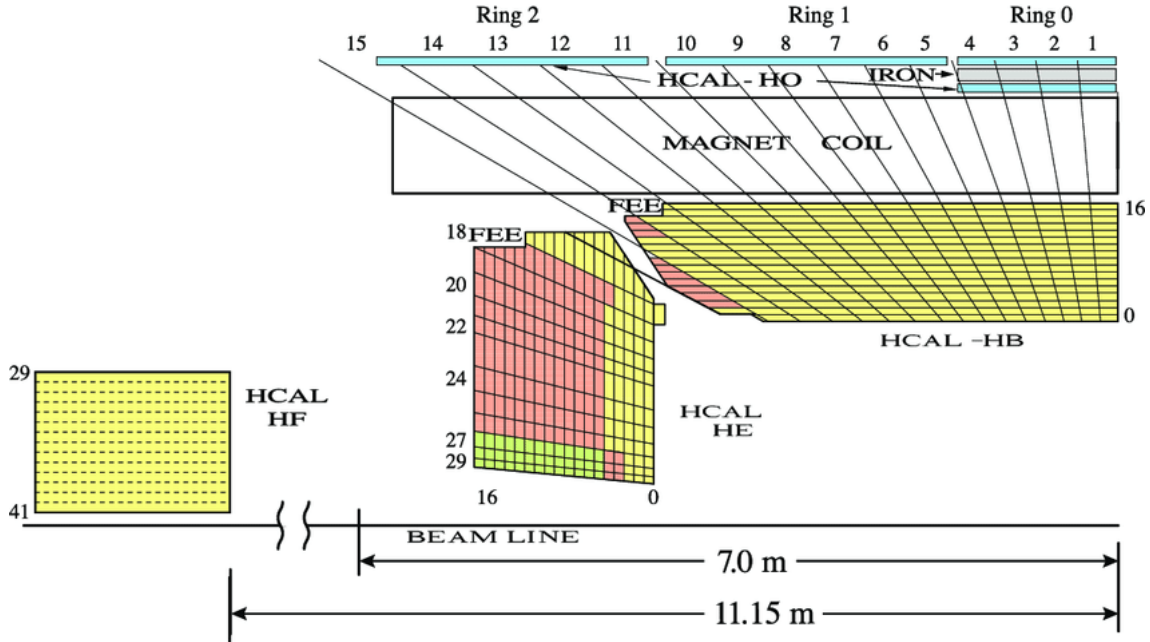


Figure 3.8: The HCAL with the corresponding subdetectors [86].

The HCAL consists of four parts: the barrel (HB), the endcap (HE), the outer (HO), and the forward calorimeter (HF). Both HB and HE are made by alternating layers of a brass absorber and a plastic scintillator. The HB consists of 16 layers of absorber plates and 17 layers of scintillator tiles covering $|\eta| < 1.3$, while the HE is designed to have 17 layers of the absorber and 18 layers of scintillators covering $1.3 < |\eta| < 3.0$. The emitted secondary light is transported by wavelength-shifting fibers to hybrid photodiodes.

The HO subdetector is located outside the solenoid magnet and has a 19.5-cm-thick iron absorber combined with two layers of plastic scintillator tiles. It is used to increase the nuclear absorption length in the central region and to measure the tails of high energy or late developing hadronic showers.

The HF is located within $3.0 < |\eta| < 5.0$ and makes use of a different technology to work

in highly radiation fluency condition. It is made of Cherenkov radiating quartz fibers as an active material, radiation-hard steel absorbers and photo-multipliers to collect light.

The hadron energy resolution of the combination of the HCAL and the ECAL can be approximated as

$$\frac{\sigma}{E} = \left(\frac{100\%}{\sqrt{E}} \right) + 5\%. \quad (3.5)$$

3.2.4 The muon system

Typical muons of interest in CMS have high enough energy to leave a minimal ionization trace in all previous detector parts and escape the inner magnet area. Therefore, the muon system is located outside the solenoid magnet. It is combined with the magnetic flux-return iron yoke providing a magnetic field up to 2 T. The muon system architecture with all components is shown in Fig. 3.9.

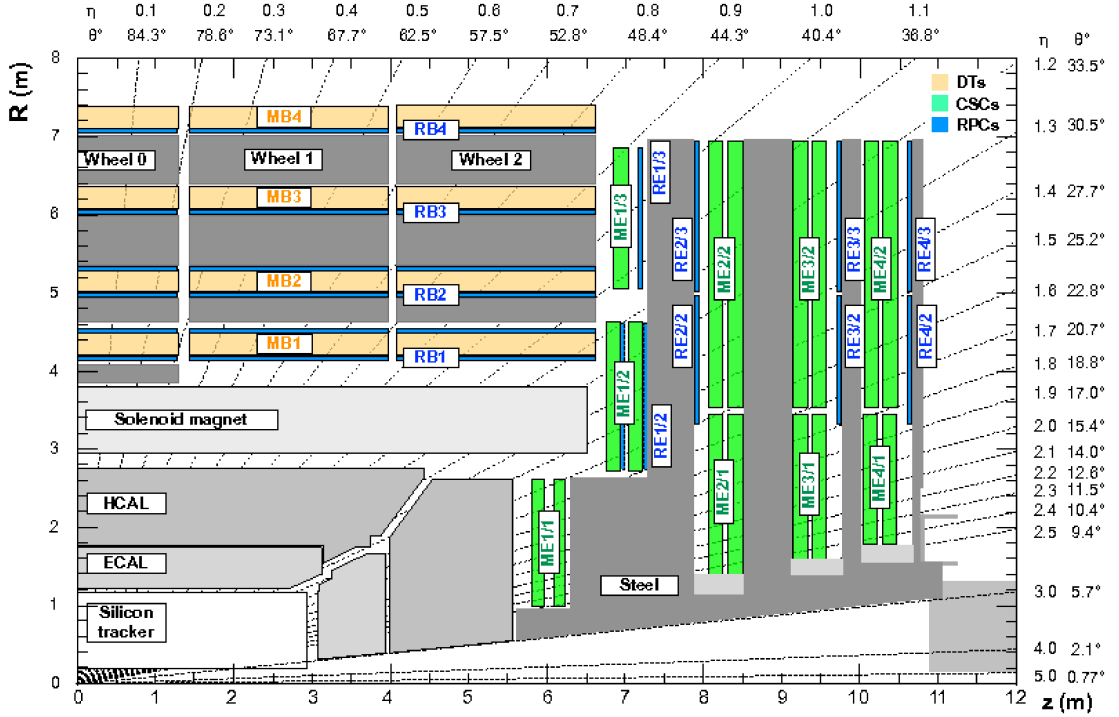


Figure 3.9: The muon system with the corresponding subdetectors [87].

Ionized gas chambers are used as detectors where muons can leave hits. The muon track then is reconstructed from the information from both the muon system and tracker. The muon system is divided into three different subsystems depending on the type of gas chambers: drift tubes (DT), cathode strip chambers (CSC) and resistive plate chambers (RPC). The DT is located in the barrel ($|\eta| < 1.2$) and consists of 4 concentric cylindrical layers with 250 drift chambers. The CSC is built as multiwire proportional chambers in the Endcap Muon system and covers the range $0.9 < |\eta| < 2.4$. The RPC is placed in both barrel and the endcap part

and is designed as parallel plate gaseous detector.

3.2.5 Trigger and data acquisition system

Protons in the current operation mode collide in CMS at a rate of 40 MHz. Each event has a size of the order of 1 MB. This leads to a data rate of 40 GB/s. It is impossible to store such a large amount of data and, moreover, most of the collisions do not contain the interesting physics events. To decrease the data stream to a manageable size and select events of interest an online triggering system is used. This triggering system has two steps: the level-1 trigger (L1T) and the high-level trigger (HLT).

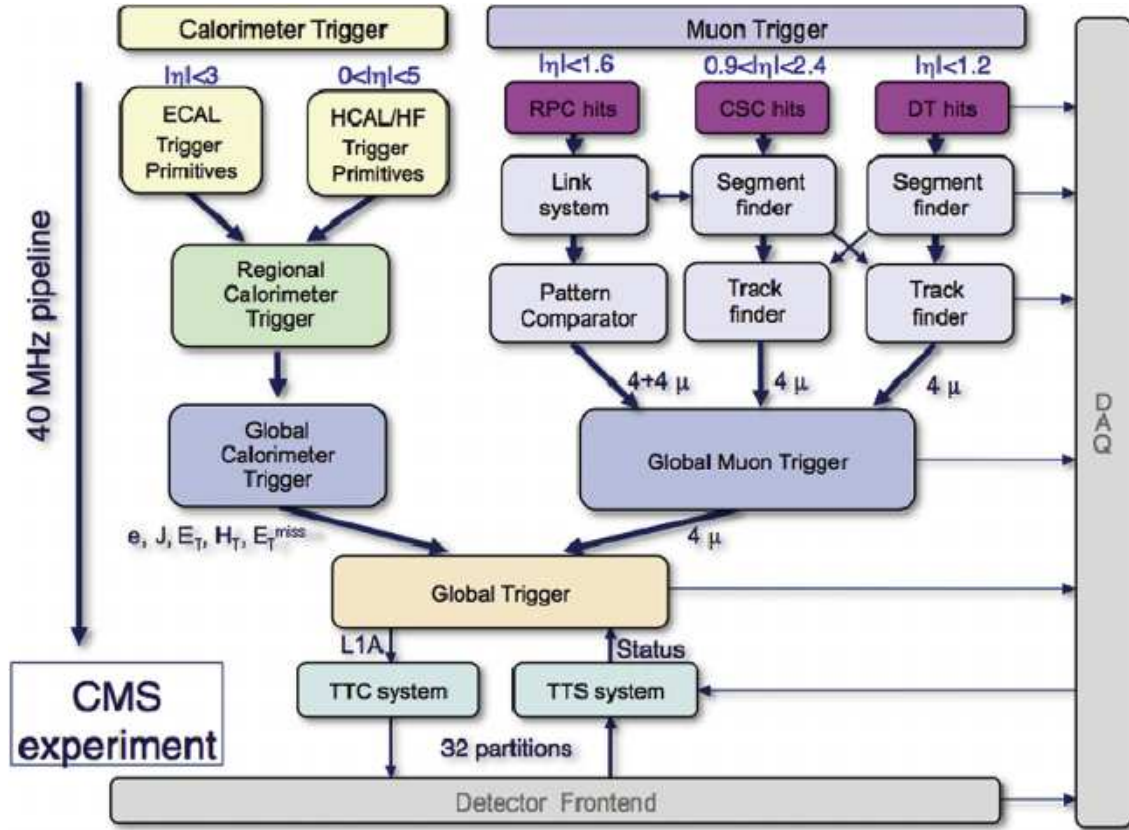


Figure 3.10: The L1T structure [73].

The main goal of the L1T is to reduce the data stream with simple operations. The L1T structure is shown in Fig. 3.10. CMS uses the L1T system based on FPGAs (Field Programming Gate Arrays) and ASICs (Application Specific Circuits). The L1T system can be split into three successive steps: local, regional and global. The calorimeter trigger obtains information from the ECAL and HCAL and locally constructs primitives from energy deposits. After this, at the regional level it combines these primitives and constructs simplified objects, like jets, electrons etc. And finally, it calculates the high-level variables at the global level such as total transverse missing energy. The muon trigger gets information from the muon system about the track segments, hit patterns, reconstructed tracks at the regional level and combines all this information into a simplified muon identification at the global level.

Information from both, muon and calorimeter trigger is transferred to the Global Trigger (GT) to make the decision about accepting an event or not. The L1T system decreases the output rate from 40 MHz to approximately 100 kHz.

The HLT system reduces the data rate by further filtering events. It takes information from L1T and performs an event reconstruction based on the full detector information. It is implemented on a computer farm and brings the event rate to 200 Hz, which leads to 350 MB/s.

The various trigger stages can initiate the event saving by the Data Acquisition (DAQ) system. The DAQ reads out the data from all subdetector buffers and stores all this information in the special format to be used by offline analysis.

3.2.6 Computing and software

The CMS experiment uses a so-called CMS software framework (CMSSW) with a modular architecture. The CMSSW provides services needed by the simulation, calibration and alignment, and reconstruction modules that process the event data to perform the analysis.

The CMSSW framework works with the different data formats and transforms one into another:

- GEN is the Monte Carlo simulated data format containing generator level events before detector simulation.
- RAW contains the detector data, the L1T result, the result of the HLT selections (HLT trigger bits) and some of the higher-level objects created during HLT processing.
- RECO data also stores the reconstructed object information.
- AOD is the reduced RECO format, which includes information important for physics analysis.
- MINIAOD and NANO AOD are even more reduced data formats for faster event processing.

CHAPTER

4

EVENT RECONSTRUCTION AND SIMULATION

One of the recurring philosophical questions is: 'Does a falling tree in the forest make a sound when there is no one to hear?' Which says something about the nature of philosophers, because there is always someone in the forest. It may only be a badger, wondering what that cracking noise was, or a squirrel a bit puzzled by all the scenery going upwards, but someone.

Terry Prattchet

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The CMS detector gives a complex set of information from each subdetector as an output event record. However, it is impossible to perform a new physics search with such raw data. Therefore, this information needs to be transformed in form of physics object properties. Such physics object reconstruction algorithms are described in Section 4.1.

In addition to reconstructed data, a set of simulated samples for SM and SUSY processes is required to be compared with. The simulation production is discussed in detail in Chapter 4.2.

4.1 Object reconstruction

Searches for new particles strongly rely on the CMS reconstruction of the well-known SM particles. On top of the online object reconstruction described in the previous chapter an offline reconstruction is applied to enhance identification performance. In the analysis described in this thesis the following reconstructed objects are used: primary vertices, electrons, muons, jets, τ leptons, and missing transverse momentum.

4.1.1 The particle flow algorithm

The Particle Flow (PF) algorithm aims at improving the particle identification beyond the reconstruction quality provided by single subdetectors [88]. This improvement is reached by combining the information from all CMS subdetectors.

The full reconstruction algorithm of physics objects including the PF algorithm consists of the following steps:

1. Charged particle tracks are reconstructed from the hit pattern in the inner tracker.
2. Energy deposits in the ECAL and HCAL are clustered by choosing seed cells with the energy above some threshold and merging surrounding cells with another minimum energy threshold.
3. Tracks and energy clusters in the HCAL and ECAL are linked together to finally reconstruct the particle candidates and reject double counting between subdetectors.
4. Muon PF candidates are reconstructed from the muon system and the tracker by removing associated tracks from the last.
5. PF electrons are constructed from the linked tracks and ECAL clusters with the possible bremsstrahlung photons. After that, the used tracks and energy clusters are removed from the list.
6. The residual ECAL clusters are identified as photons.
7. The tracks linked to the HCAL are reconstructed to be charged hadrons.
8. The remaining HCAL clusters are identified as neutral hadrons.

4.1.2 Primary vertices

The primary vertex (PV) marks the position of the interaction point in a single scattering event. As the first step, the PV reconstruction algorithm [89] groups particle tracks to form primary vertex candidates. Later, the quality and the position of these candidates are determined by the adaptive vertex fitting [90]. This method assigns a weight to every track depending on the compatibility of this track with the vertex. Then, the predefined objective function based on these weights and standardized distances of all tracks from the vertex position is minimized with respect to the vertex position. The PV is selected from the primary vertex candidates passing quality criteria with the largest transfer momentum scalar sum from the associated tracks.

However, LHC beams contain a large number of protons, such that multiple interactions occur in each bunch crossing. That typically leads to events with one interesting hard interaction point surrounded by multiple softer interactions. These additional interactions are called pile-up (PU) and the main goal of the PV reconstruction algorithm is to identify all collision vertices in the event.

4.1.3 Electron reconstruction

The electron reconstruction is done by combining input from the silicon tracker and ECAL. Since electrons lose energy through bremsstrahlung radiation, the electron reconstruction takes into account bremsstrahlung photons in the ECAL when matching the electron track to the electron energy deposit [91].

The electron energy deposit within the ECAL is formed by a supercluster algorithm. The cluster size is optimized differently for the barrel and endcap to collect energy coming from the bremsstrahlung radiation. The ECAL supercluster algorithm helps to find the seed electron track by trajectory extrapolation from the cluster position to the first layer of the tracker. Another way to find the seed track is to start from the reconstructed track and match that to the ECAL supercluster. Both electron seeding algorithms are combined. From the seed, the whole track is built by the modified Kalman filter algorithm, similar to a global least-squares minimization. Since the electron energy loss due to bremsstrahlung radiation cannot be interpolated by the Gaussian distribution assumed by the Kalman filter, a modification of the latter is used. The electron energy loss is modeled well by the Bethe-Heitler distribution. Taking this into account, the Kalman filter is modified for the electron parameter track fitting, known as Gaussian Sum Filter (GSF).

High energy electrons can also come from hadrons or other particle radiation. To separate primary from the secondary electrons, different approaches are used. For the stau search in this thesis a non-triggering MVA ID is selected, where the discriminator is trained on all electrons regardless of the trigger. For the MVA, a Boosted Decision Tree (BDT) discriminator is used, which takes track quality, shower shapes and kinematic quantities as input. The BDT was trained on a Z/γ^* Monte Carlo sample. The following variables are used as input to the BDT:

- Cluster shape variables $\sigma_{i\eta, i\eta}$ and $\sigma_{i\phi, i\phi}$, with $i\eta$ and $i\phi$ the integer label of the η and ϕ calorimeter cell. The circularity $= 1 - \frac{E_{1 \times 5}}{E_{5 \times 5}}$, with $E_{1 \times 5}$ and $E_{5 \times 5}$ the energies in a 1×5 and a 5×5 grid around the supercluster seed, respectively. Shape variable R9 =

$\frac{E_{3 \times 3}}{E_{SC}}$, with $E_{3 \times 3}$ the energy in a 3×3 grid of cells around the supercluster seed and E_{SC} the raw energy of the supercluster.

- The number of valid hits in the track fit, the χ^2 of the track fit and the χ^2 of the GSFTrack fit.
- The number of GSFtrack hits, the number of expected missing inner hits and the result of the conversion vertex fit.
- The distance $\Delta\eta$ and $\Delta\phi$ between the reconstructed supercluster and the associated track at the position of the primary vertex, and the distance in η between the supercluster and the track at the calorimeter surface.
- H/E, the ratio of the hadronic energy over the electromagnetic energy in the supercluster and E/P, the ratio of the supercluster energy over the momentum of the track associated with the electron.
- The ratio of the energy of the electron cluster and the momentum of the associated track, evaluated at the electron cluster, and $1/E_e - 1/P_e$, with E_e the energy of the electron candidate and P_e its momentum.

Another, cut based, approach is used for the electron selection for the missing transverse momentum study in the Chapter 5. The cut based identification is a simple to use and robust set of identification and selection criteria designed for analyses where ultimate performance may not be necessary. The idea is to select objects satisfying simple threshold requirements on similar to the above mentioned variables. The set of requirements is tuned in a way to provide several working points with different efficiency's and misidentification rates. The tight electron working point is selected with an average efficiency of 70% and an average misidentification rate of 1% for performance measurements.

4.1.4 Muon reconstruction

The typical muon in an interesting event has enough energy to propagate through all subdetectors and to escape from the CMS detector. Both silicon tracker and muon system can detect and recognize muons. Three different ways of muon reconstruction are used within CMS [92].

- Standalone muons are reconstructed only from the muon system hits using a Kalman filter method. This approach is fast and is used for detector studies and triggering.
- Tracker muons are built from the inner tracker trajectory reconstruction with additional loose matching to a DT or CSC segment. Such strategy picks up efficiently low momentum muons with good resolution.
- Global muons are standalone muons with additional matching to at least two reconstructed hits within different inner tracker layers, and the global muon track fit uses input information from both, inner tracker and muon system. It is the most precise approach and is used in the analysis.

The main contribution to the muon momentum reconstruction precision comes from the silicon tracker. But the global fit improves the resolution for high energy muons. To distinguish the muons of interest from the hard proton collision and background muons, for example, coming from hadrons decay, several muon identification approaches are developed in CMS. In this thesis, a cut-based approach with a medium working point is used for the stau search, resulting in identification efficiency close to unity (of the order of 98%) while keeping the misidentification rate low (of the order of 10%). For the missing transverse momentum study in Section 5 the tight working point is used. The cut-based medium (tight) ID has the following requirements:

- The muon is reconstructed by the tracker or global muon reconstruction algorithm.
- The impact parameters d_{xy} and d_z between the muon track and the primary vertex are restricted as $d_{xy} < 0.045$ cm and $d_z < 0.2$ cm to ensure the muon is associated with the primary vertex.
- At least 80% of the tracker hits have to be valid.

In addition, either of the following two sets of criteria must be satisfied:

- The muon is reconstructed by the global muon reconstruction algorithm.
- The χ^2/ndof of the global track fit is smaller than 3 (10).
- The $\chi^2/$ of the tracker-standalone position match is smaller than 12.
- The $\chi^2/$ of the track kink finder is less than 20.
- The muon segment compatibility is > 0.303 .

or

- The muon segment compatibility is > 0.451 .

Moreover, tight muons should satisfy the following requirements:

- At least one muon-chamber hit is included in the global-muon track fit.
- The muon candidate is detected in segments of at least two muon stations.
- Number of tracker layers with hits must be above five.

4.1.5 Jet reconstruction

Quarks and gluons are the main hard proton-proton collisions products. But the QCD confinement prevents them to freely propagate through the detector. Instead, initial quarks and gluons combine with quarks and antiquarks that are spontaneously created from the QCD vacuum, and form hadrons. A bunch of collimated hadrons is called jet and is the main experimental signature of the high energy gluons and quarks.

Jets can be reconstructed [93] from ECAL and HCAL information (Calo jets), from calorimeter and tracker information (Jet-plus-tracks jets) and from PF candidates (PF jets).

The first two reconstruction algorithms are fast and robust for triggering. PF jets have the best performance and are used in this analysis.

The widely used jet reconstruction method is the anti- k_T sequential algorithm [94]. It combines the PF candidates to form a jet. At the beginning, two distances are calculated for all PF candidates, between a particle (object) and the beam line $d_{i,B}$ and between two particles (objects) $d_{i,j}$ in the following way:

$$d_{i,B} = \frac{1}{p_{T,i}^2} \quad (4.1)$$

$$d_{i,j} = \min\left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2}\right) \frac{\Delta R_{ij}^2}{R^2} \quad (4.2)$$

where $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and $R = 0.4$ within the stau analysis. The clustering proceeds by identifying the smallest of the distances and if it is $d_{i,j}$ recombining objects i and j , while if it is $d_{i,B}$ calling i a jet and removing it from the list of objects. The distances are recalculated and the procedure repeated until no objects are left. An example of jets reconstruction with anti- k_T algorithm is shown in Fig 4.1.

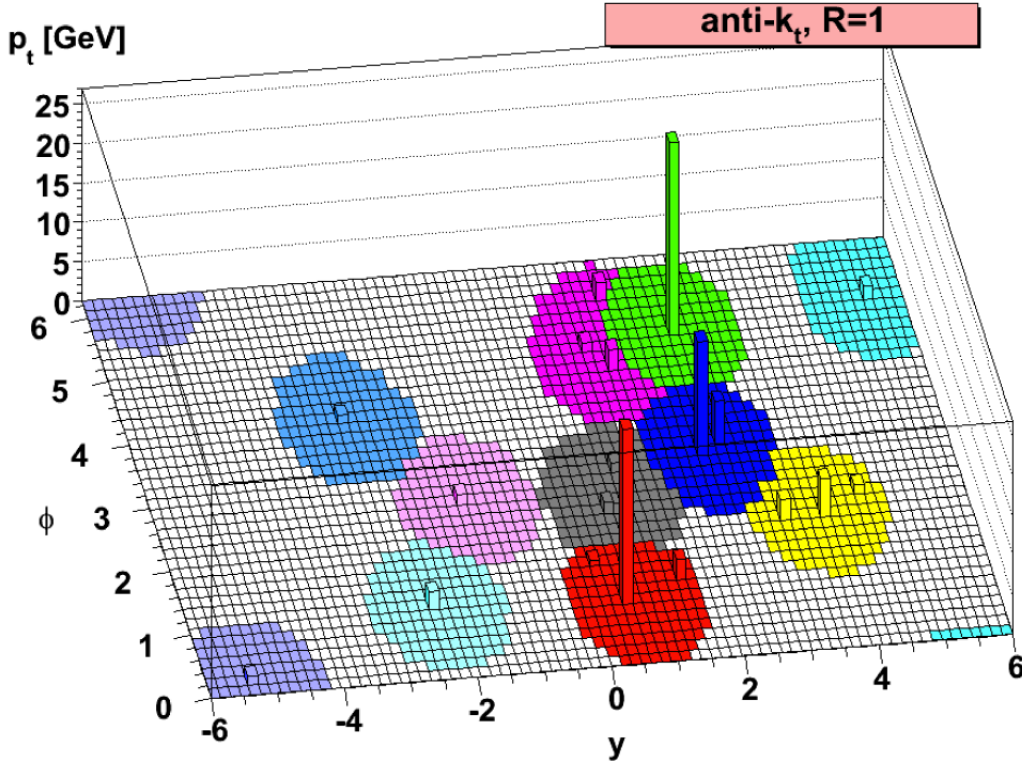


Figure 4.1: The scheme of the anti- k_T algorithm of the jet reconstruction [94].

The described approach is infrared and collinear safe. The first means adding new low energy PF candidate to the merged cluster shouldn't significantly change the result of the

algorithm. The second states correct jet reconstruction in the case when the hard PF object is split into several softer objects.

Obviously, the reconstructed jet four-momentum has some statistical and systematical deviations from the underlying parton energy. The main sources for such deviations are the PU contribution, a nonlinearity of the calorimeter response and energy response difference between jets originating from heavy and light quarks. Therefore, jets in both data and MC are corrected to neutralize these effects [93]. Moreover, data are additionally corrected to deal with the difference between data and MC. All these corrections together are known as the Jet Energy Scale (JES) corrections. In addition to the aforementioned corrections, the Jet Energy Resolution (JER) correction is also applied to simulation to smear the jet resolution in order to match the data energy resolution.

In comparison with light quarks, b and to some extent c quarks initiate jets with larger mass and higher momentum decay products. In addition, their long lifetime leads to the presence of a secondary vertex displaced with respect to the PV. This displacement can reach a few millimeters for b quarks. There are several approaches known as b-tagging algorithms. The algorithm used in the current analysis is called Combined Secondary Vertex (CSV) and is based on a multivariate technique. In the first step, the secondary vertex is reconstructed from the displaced tracks. After this, the parameters of the secondary vertex as well as the associated tracks are used as input to a neural network classifier. The classifier output is then used for b-tagged jet classification and several working points are defined based on the identification efficiency and misidentification rate. The efficiency for tagging jets originating from b quarks is measured in simulated $t\bar{t}$ + jets events to be about 63% for the working point used in the stau analysis, while the misidentification rates for jets from charm quarks, and from light quarks or gluons, are about 12% and 0.9%, respectively.

4.1.6 Missing transverse momentum

Weakly interacting neutral particles that can be produced during proton-proton collisions can travel through the detectors without leaving any trace. However, usually, such particles are produced accompanied by electromagnetically or strongly interacting particles. Since the initial momentum of the proton-proton system in the transverse plane to the beam direction is close to zero, calculating the momentum imbalance in this plane can give some information about the momentum of such invisible particles. The described momentum imbalance is described by the vector $\vec{p}_T^{\text{miss}}$ with its magnitude p_T^{miss} . In this thesis two distinct p_T^{miss} reconstruction approaches are applied, both based on PF candidates.

The first approach is PF p_T^{miss} , defined as the negative vector momentum sum of all reconstructed PF objects in the event [95, 96]. The PF p_T^{miss} is the main reconstruction algorithm used in the majority of the CMS analyses. It is a relatively simple and robust approach providing a good estimate of the p_T^{miss} . To improve the PF p_T^{miss} performance several additional corrections are applied. The first is the mitigation for the degradation of the p_T^{miss} reconstruction due to the pile-up interactions. This is achieved by removing the PU contribution from the momentum sum.

A second algorithm to be discussed is “the PU per particle identification” (PUPPI) method [97]. Its main goal is to reduce the dependence on PU. The PUPPI algorithm introduces a local shape variable α to distinguish between the collinear configuration of particles from the PV and diffuse radiation coming from PU. The α variable is computed for

each neutral particle i within the cone of R_0 in the η - ϕ space as follows:

$$\alpha_i = \log \sum_{j \neq i, \Delta R_{ij} < R_0} \left(\frac{p_{Tj}}{\Delta R_{ij}} \right)^2 \begin{cases} \text{for } |\eta_i| < 2.5, & j \text{ are charged particles from the PV} \\ \text{for } |\eta_i| > 2.5, & j \text{ are all reconstructed particles,} \end{cases} \quad (4.3)$$

where ΔR_{ij} is the distance between the particles in the η - ϕ space and j refers to the neighboring PF candidates. In addition, charged PF candidates not associated with the PV can be used if the distance between the track and the PV is $d_z < 0.3$ cm.

The momenta of the neutral PF candidates are then rescaled. The rescaling depends on their probability to originate from the PV or PU. To determine the likelihood of the different particle origin, the χ^2 is calculated:

$$\chi_i^2 = \frac{(\alpha_i - \bar{\alpha}_{\text{PU}})^2}{\text{RMS}_{\text{PU}}^2}, \quad (4.4)$$

where $\bar{\alpha}_{\text{PU}}$ is the median value of the α_i distribution for PU particles in the event and RMS_{PU} is the root-mean-square (RMS) of the α_i distribution. Within the tracker reach, $\bar{\alpha}_{\text{PU}}$ and RMS_{PU} are computed with all charged PU PF candidates, while in the forward region all particles in the event are used. The weights for scaling are derived as

$$w_i = F_{\chi^2, \text{NDF}=1}(\chi_i^2), \quad (4.5)$$

where $F_{\chi^2, \text{NDF}=1}$ is the cumulative distribution function, which approximates the χ^2 distribution with one degree of freedom of all PF candidates in the event. The weights close to zero mean PF candidates likely originating from a PU, while close to one correspond to particles mostly coming from the PV. The w_i are required to be larger than 0.01 and the minimum scaled p_T of neutral PF candidates is required to be $w_i \cdot p_{T,i} > (A + B \cdot N_{\text{vtx}})$, where N_{vtx} is the reconstructed vertex multiplicity and A and B are adjustable parameters that depend on η . An optimization of the tunable parameters to achieve the best jet p_T and p_T^{miss} resolutions is performed separately for jets in the regions $|\eta| < 2.5$, $2.5 < |\eta| < 3$, and $|\eta| > 3$. The resulting algorithm parameters are similar to those recommended in Ref. [97] for an R_0 of 0.4. The PUPPI-weighted PF candidates are used as inputs to the jet clustering algorithm. No additional pileup corrections are applied to jets clustered from these weighted inputs. Once a weight per PF candidate is determined, the p_T^{miss} can be computed using the sum of PF candidate four-vectors weighted by their w_i .

Examples of sources that can lead to an inaccurate estimation of p_T^{miss} are the nonlinearity in the calorimeter response to hadrons, the minimum energy thresholds in the calorimeters and the p_T , and inefficiencies in the track reconstruction.

The estimation of p_T^{miss} is improved by propagating the correction of the p_T of the jets, $\vec{p}_{T, \text{jet}}^{\text{corr}}$, described in Ref. [98] to p_T^{miss} in the following way:

$$\text{Corrected } \vec{p}_T^{\text{miss}} = \vec{p}_T^{\text{miss}} - \sum_{\text{jets}} (\vec{p}_{T, \text{jet}}^{\text{corr}} - \vec{p}_{T, \text{jet}}), \quad (4.6)$$

where the sum is over jets with p_T above a threshold. A jet p_T threshold of 15 GeV gives a p_T^{miss} response close to unity, reducing the contribution of jets from pileup.

4.1.7 The τ lepton reconstruction

In comparison with other leptons, the τ leptons have too short of a lifetime to reach any subdetector. They decay close to the PV and have either leptonic or hadronic decay modes. The former refers to a τ decaying to a τ neutrino and an electron (muon) and its corresponding electron (muon) antineutrino. This final state does not allow any τ lepton identification. Electron and muon decay modes have branching ratios of 17.8 % and 17.4%, correspondingly. The hadronic decay mode includes various final states with charged hadrons, a τ neutrino and various other hadrons with zero total charge. It is the dominant decay mode and allows τ identification by reconstruction of the decay products.

The reconstruction algorithm starts with the hadron-plus-strip algorithm (HPS) [99]. Since the hadronic τ decay is quite often accompanied by neutral pion creation, the feature of the HPS algorithm is to reconstruct neutral pions mostly decaying to pairs of photons or electron-positron pairs in addition to charged hadrons. The τ lepton candidates in the HPS algorithm are seeded by jets clustered with the anti- k_t algorithm with a distance parameter $\Delta R = 0.4$. To reconstruct the energy deposits from π^0 candidates in the ECAL, photon and electron constituents of the jet seeding the τ_h reconstruction are clustered into strips. The electron or γ with highest p_T that is not yet included in a strip is used to build a new strip. The η and ϕ of this candidate determine the initial position of the strip, the next highest p_T electron or γ within an $\eta \times \phi$ window centered on the strip location is added to the strip and the position is recomputed as the energy-weighted average of the electron/photon constituents in the strip. This procedure is repeated until there are no more electrons or photons with $p_T > 0.5 \text{ GeV}$ within the strip window. The $\Delta\eta$ and $\Delta\phi$ of the strip are varied based on the p_T or E_T to be added to the strip and on the energy the strip already has, as given in Eq.(4.7):

$$\begin{aligned}\Delta\eta &= f(p_T^{e/\gamma}) + f(p_T^{\text{strip}}), \\ \Delta\phi &= g(p_T^{e/\gamma}) + g(p_T^{\text{strip}}),\end{aligned}\tag{4.7}$$

where $p_T^{e/\gamma}$ is the transverse momentum of the candidate to be added to the strip and p_T^{strip} is the transverse momentum of the strip before merging a new candidate in. In addition, the strip size is restricted to $0.05 < \Delta\eta < 0.15$, $0.05 < \Delta\phi < 0.3$.

The functions $f(p_T)$ and $g(p_T)$ are defined as given in Eq.(4.8).

$$\begin{aligned}f(p_T) &= 0.2 \cdot p_T^{-0.66}, \\ g(p_T) &= 0.35 \cdot p_T^{-0.71}.\end{aligned}\tag{4.8}$$

If the Σp_T of the strip is at least 2.5 GeV, it is considered as a π^0 candidate.

To reconstruct hadronic taus, charged particles and strips are combined into different signatures which are said to be compatible with a certain decay mode if the set of cuts listed below is satisfied. If a candidate satisfies more than one of the hypotheses, the one having maximal p_T is retained.

The decay modes considered for reconstructing taus are:

- **One prong, 0 π^0 :** One charged particle, no strips.

- **One prong, 1 π^0 :** One charged particle + one strip with mass $0.3 < m_\tau < 1.3\sqrt{p_T/100}$ GeV. The mass window upper limit is constrained to lie between 1.3 and 4.2 GeV.
- **One prong, 2 π^0 :** One charged particle + two strips. The τ_h mass should be $0.4 < m_\tau < 1.2\sqrt{p_T/100}$ GeV. The upper limit on the mass window is constrained to lie between 1.2 and 4.0 GeV.
- **Three prong, 0 π^0 :** Three charged particles with mass $0.8 < m_\tau < 1.5$ GeV. The tracks are required to originate within $\Delta z < 0.4$ cm of the same vertex.

If τ lepton candidates satisfy aforementioned requirements they are defined as loose. Requiring, in addition, the reconstructed τ_h to be isolated reduces the $\text{jet} \rightarrow \tau_h$ fake rate. Both a cut-based discriminator and an MVA-based one are available, in the stau analysis the MVA-based discriminator is applied since it has a better fake rejection.

The MVA τ_h isolation discriminator combines isolation variables with τ lifetime information into a BDT to discriminate between τ_h decays and quark and gluon jets. The variables used as input are:

- The charged- and neutral-particle isolation sums.
- The reconstructed τ_h decay mode.
- The transverse impact parameter d_{xy} of the leading track of the τ_h candidate with the vertex, and its significance $d_{xy}/\sigma_{d_{xy}}$, and its sign (the projection of the impact parameter vector on the τ_h direction).
- The 3-dimensional impact parameter d_{xyz} of the leading track, and its significance.
- The distance between the τ production and decay vertices, its significance, and information about whether a decay vertex has successfully been reconstructed for a given candidate.
- p_T and η of the τ_h candidate.
- $\Delta\beta$ corrected isolation (as above).
- The $\Sigma p_T^{e/\gamma}$ included in strips used to reconstruct the τ_h , but outside the τ signal cone.
- The χ^2 value of the fit for the leading track of the τ_h candidate.
- The ratio of the total EM energy to the total energy within the τ_h signal cone.
- The total number of signal and isolation photons with $p_T > 0.5$ GeV.
- The p_T weighted ΔR of photons within the signal cone and the isolation annulus.
- The p_T weighted $\Delta\eta$ and $\Delta\phi$ of photons in strips outside of the signal cone.

Six working points ranging from very loose to very very tight are provided, where the very tight working point of the MVA-based discriminator has a τ_h efficiency between the medium and tight working points of the cut-based discriminator. The very tight working point is used in the stau analysis. This working point typically has efficiencies of around 40% for genuine τ_h , with a misidentification rate of approximately 0.01% for quark or gluon jets.

4.2 Monte-Carlo event generation

With the help of QFT differential and integral cross sections of various processes can be calculated. But, unfortunately, one cannot compare directly these cross sections with the detector output, since processes of hadronization are too complicated to compute analytically and the nonlinear CMS detector response leads to significant shape changes of the final state particle kinematic distributions. Therefore, in order to get final kinematic distributions, artificial events are generated by a stochastic technique called Monte Carlo (MC) simulation.

4.2.1 Anatomy of an event

At LHC protons collide with protons at high energy. The particles of interest can be produced in hard scattering when an interaction happens between proton components, quarks or gluons. The typical generated event is shown in Fig. 4.2 and can be split in the following steps [100]:

- **Hard scattering** in proton-proton collisions is an interaction between proton components, partons. Partons are distributed within protons and each carries a certain fraction of the total proton momentum. These distributions are called parton distribution functions and they depend on resolution scale. Cross sections of the interaction between two or more partons can be computed within QCD with a perturbative approach using matrix elements [102].
- **Parton showering** is applied after the hard scattering to take into account higher order QCD effects. Final state particles from hard scattering still could radiate via the strong interaction. In other words, the final quarks and gluons can radiate more gluons or create new quark-antiquark pairs. Such chains of the particle transformations can be well modeled by applying recursively branchings to the propagating particles. The widely used method for estimating such sequence of the branchings is the Sudakov form factor approach [100]. Parton showering happens before the final state particle reaches the hadronization scale energy, i.e the QCD coupling becomes large enough to cause non-perturbative interactions and confining quarks into hadrons.
- **Hadronization** is the process of combining hadrons out of quarks and gluons. This process happens when partons reach the hadronization scale of the order of 1 GeV. Within this energy the perturbative QFT approach can not be applied. Thus, phenomenological models are used, such as the string fragmentation hadronization model. In this model, the potential between two partons is assumed to be linear and its energy increases with the increasing distance. When the energy reaches some threshold, the connection ("string") breaks between two partons and an additional quark-antiquark pair is created from the vacuum [103]. Since the model is phenomenological, its parameters are tuned using experimental data.
- **The underlying event** is formed from multiple parton interactions and beam-beam remnants. The former originates from the remaining parts of the protons in addition to the main hard interaction. The latter is caused by proton remnants that did not participate in the hard scattering. The current approach to model the underlying event is to consider them as additional parton-parton scattering in a simplified way. However,

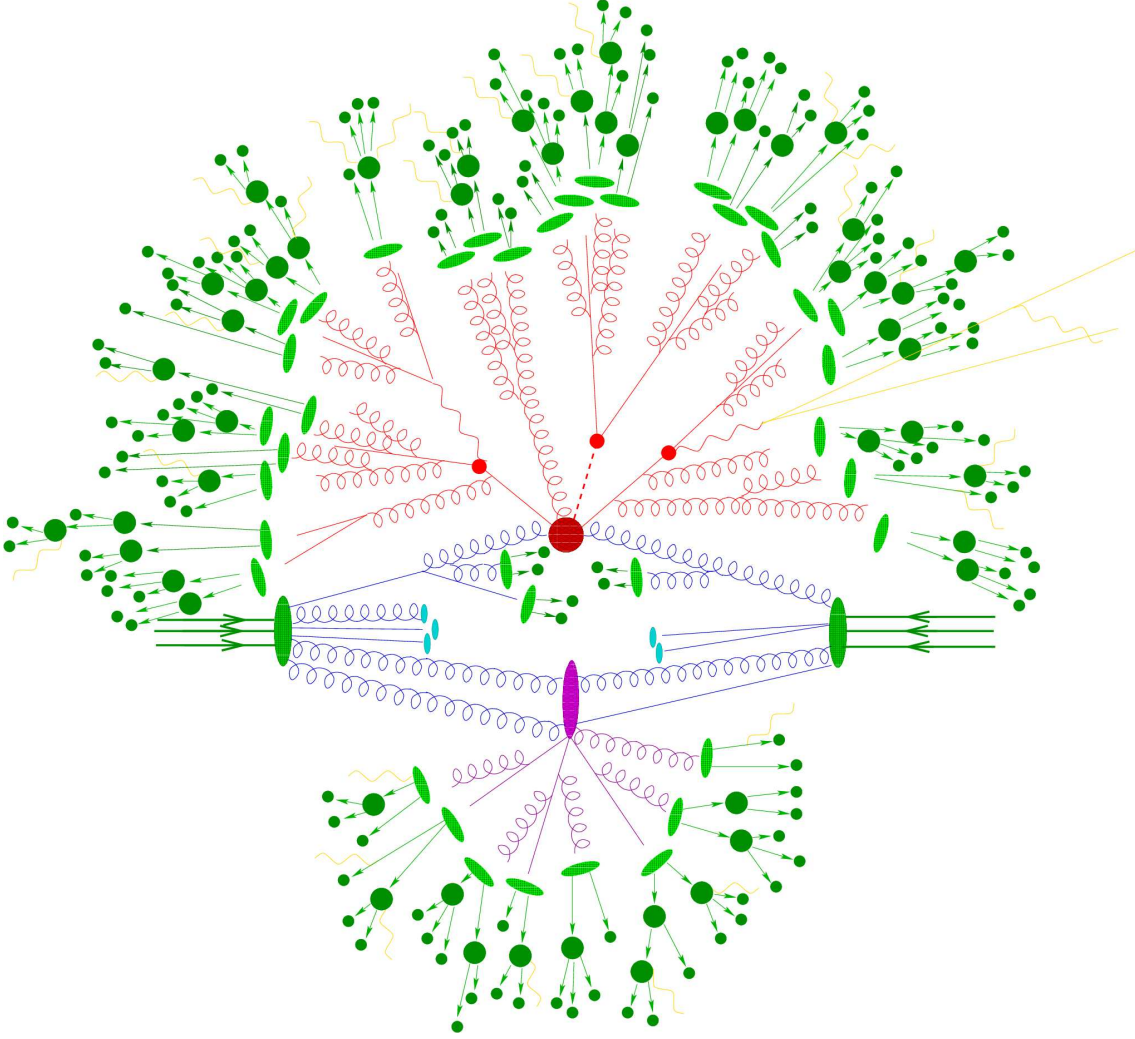


Figure 4.2: The scheme of the typical hard scattering (red spot) generator event with underlying event (purple spot) followed by parton shower (red line) and hadronization (green spots) [101]

its cross section is not computed from first principles but estimated phenomenologically with free parameters tuned with experimental data.

- **PU** is described in the previous chapter. At the current LHC conditions, each recorded event contains on average 23 additional interactions per bunch crossing in 2016 and 32 in 2017 data. PU is added to simulation by overlapping randomly the hard scattering event with separately generated PU events, which mainly contain soft QCD scattering.

After these steps, the final objects traverse the simulated detector elements leading to a similar response as in real events. The detector output is then fed into the object reconstruction described in the Chapter 4.1. There are different approaches to handle these steps. Various MC generators cover a wide range of functionality, from general purpose generators to specific ones. Modern MC generators are described in the next section.

4.2.2 Event generators

Currently, the CMS collaboration uses a variety of event generators for different purposes. In CMSSW, MC generators are incorporated as external packages, while CMS-specific software provides an interface to several packages and allows them to be tuned to generate events of the desired topology. Several widely used MC generators are mentioned below.

- **PYTHIA** [104] is a program for the generation of high-energy physics collisions between particles such as electrons and protons in various combinations. It contains theoretical leading order cross sections for SM and BSM with models for a number of physics aspects such as hard and soft interactions, multiparton interactions, parton distributions, parton showering, fragmentation, and particle decay. In addition, PYTHIA has an interface to other MC generators and tools, for instance, to use NLO generated events. Within CMS, PYTHIA is mostly used for the hadronization and showering in the majority of the SM and SUSY simulations. Moreover, to simulate τ lepton production and decay with better precision the TAUOLA package [105] is interfaced with PYTHIA. The TAUOLA package takes into account the relative QED corrections and spin correlations. Taking generator level information from PYTHIA, it calculates the form factors for tau decay.
- **MADGRAPH5_aMC@NLO** [106] is the event generator able to calculate cross sections not only in leading order but with higher order corrections. In addition, it can incorporate initial and final state radiation at the level of matrix elements. Currently, MADGRAPH is the most popular event generator in the CMS collaboration. However, hadronization and showering are not implemented in MADGRAPH. Therefore, events generated in MADGRAPH are interfaced to other MC generators, such as PYTHIA or POWHEG. An additional package within MADGRAPH called aMC@NLO [107] is used to implement the parton shower calculation reducing cross section uncertainty. One down side of this generator is the large fraction of events with negative MC weights from the interference terms in cross section calculations.
- **POWHEG** [108] stands for Positive Weight Hardest Emission Generator and is used to produce events at the NLO precision. However, it generates events with only positive weights by using the full NLO matrix elements to simulate the hardest emission.

4.2.3 Detector simulation

The next step of the MC event production is the final state particle propagation through the CMS detector. Detector simulation includes a detailed detector set up with all material properties, the external electromagnetic field, the detector readout system as well as trigger systems, and electronic noise. In general the most precise simulation, GEANT4 (GEometry ANd Tracking version 4) [109], is used. This approach, referred to as FullSim, is mostly used for SM process simulations.

A faster approach, known as FastSim, uses parameterization of material effects in the detector at the hit level. These hits information is input of the object reconstruction algorithms. FastSim is mostly used for BSM signal simulations when the ultimate precision is not needed but many benchmark points related to a different set of phenomenological parameters should be scanned. FastSim generated events are validated with FullSim and the observed

differences are implemented as corrections or systematic uncertainties in the corresponding analysis.

For more general studies the DELPHES [110] software framework is used, e.g. for studies of the future HL-LHC performance in BSM search. It includes the parametric response of all needed subdetectors, such as ECAL, HCAL tracker and muon system. The CMS model in the DELPHES framework is available also for nonCMS members to perform CMS results reinterpretation, new signature search proposals and projection studies.

CHAPTER

5

PERFORMANCE OF MISSING TRANSVERSE MOMENTUM

Humans are very good at not seeing things they know aren't there.

Terry Prattchet

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The missing transverse momentum is a key variable for many new physics searches, especially when dark matter candidates are predicted. Moreover, precise determination of p_T^{miss} is critical for standard model (SM) measurements that use final states with neutrinos, such as those containing leptonic decays of the W boson.

The reconstruction of p_T^{miss} is sensitive to the experimental resolutions, mismeasurements of the reconstructed particles, and detector artifacts. The performance of p_T^{miss} is also affected by additional pp interactions in the same or nearby bunch crossings (PU). A detailed understanding of all these effects, both in real and simulated data, is essential to achieve optimal p_T^{miss} performance.

Performance studies can be done with the SM processes without or with genuine p_T^{miss} . The former can be done with Z bosons decaying to a pair of electrons or muons, or multijet events with photon emission. A well-measured Z boson provides a unique event axis and a

precise momentum scale. Such events have little or no genuine p_T^{miss} , and the performance is measured by comparing the momenta of the Z boson or photon to that of the hadronic recoil system. The hadronic recoil system is defined as the vector p_T sum of all PF candidates except for the Z boson decay products or the photon, respectively. The procedure and the results of such an analysis can be found in Ref [111].

The second option is to study the p_T^{miss} performance with genuine p_T^{miss} events. This analysis is done by the thesis author and the results entered the aforementioned paper [111]. The details of the analysis are described below.

5.1 Performance study with genuine p_T^{miss}

The production of the W boson is chosen as a SM process with genuine p_T^{miss} for performance studies. The W boson can decay to a lepton and the corresponding lepton neutrino leading to genuine p_T^{miss} . The magnitude of the p_T^{miss} is approximately equal to the p_T of the lepton, and the hadronic recoil dominates its resolution.

This selection was used to study various p_T^{miss} reconstruction algorithms, but in the discussed analysis the best two approaches are presented, PF and PUPPI p_T^{miss} , described in the Chapter 4.1.6.

5.1.1 Simulated events and data

For comparison with data, simulated Monte Carlo (MC) events are produced for QCD multijet processes at leading order (LO) using the MADGRAPH5_aMC@NLO 2.2.2 generator with up to four additional partons in the matrix element calculations. Samples for the Z +jets and W +jets processes are also produced at next-to-leading order (NLO) using the MADGRAPH5_aMC@NLO generator with up to two additional partons in the matrix element calculations. The $t\bar{t}$ and single top quark background processes are simulated at NLO using POWHEG 2.0 and 1.0, respectively. The diboson samples (WW , WZ , and ZZ) are simulated at NLO using MADGRAPH5_aMC@NLO and POWHEG. A set of triboson samples (WWW , WWZ , WZZ , ZZZ) is simulated at NLO using MADGRAPH5_aMC@NLO.

The MC samples produced using MADGRAPH5_aMC@NLO and POWHEG generators are interfaced with PYTHIA 8.2 using the CUETP8M1 tune [112] for the fragmentation, hadronization, and underlying event description. The NNPDF3.0 [113] parton distribution functions (PDFs) are used for all samples, with the order matching the matrix element calculations. The simulated events include the effects of pileup, with the number of additional pp interactions matching that observed in data. The average number of pileup interactions per proton bunch crossing is 23 for the data sample used in this analysis.

Data samples used for the following studies were collected in 2016 in pp collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV, and correspond to an integrated luminosity of 35.9 fb^{-1} . For the single lepton selection, data sets are required to pass the single muon or single electron triggers with a p_T threshold of 24 or 25 GeV.

5.1.2 Event selection and corrections

The single-lepton samples are subdivided into two categories based on the flavor of the lepton. Candidate events are required to have a muon (electron) with p_T greater than 25

(26) GeV passing the tight cut-based identification described in Chapter 4. Events with an additional lepton with p_T greater than 10 GeV, or with a b-tagged jet, are rejected. A summary of all requirements for the selected leptons is given in Table 5.1. The leptons have to match the HLT object within $\Delta R < 0.5$.

Table 5.1: Summary of the required lepton properties.

Property	μ	e
$p_T > (\text{GeV})$	25	26
$ d_{xy} < (\text{cm})$	0.045	0.045
$ d_z < (\text{cm})$	0.2	0.2
$ \eta <$	2.4	2.1
RelIso <	0.15	0.05
Id	tight cutbased	tight cutbased
Matching to trig.	HLT_IsoMu24	HLT_Ele25_WPTight_Gsf

The trigger efficiencies are determined with tag&probe method on a $Z \rightarrow \ell\ell$ sample as function of η and p_T to correct simulation. In more details it is discussed in the next chapter.

In addition, the MC number of PV is reweighted to match PV distributions in data. Moreover, simulations are corrected by electron and muon identification scale factor to reproduce the same identification efficiency dependence on p_T and η as in data. These scale factors are computed also in Drell-Yan processes with dilepton final state by the CMS physics object group for using in analyzes.

5.1.3 Background modeling

These single-lepton samples consist mainly of W +jets events. One source of background stems from QCD multijet events containing a jet misidentified as a lepton. The simulation indicates that the magnitude of this background is small. However, since the uncertainties in simulating this background can be significant, a data control region is used to estimate it. The data control sample is selected by inverting the requirement on the relative isolation of the lepton and is dominated by QCD multijet events. Then QCD and electroweak contribution normalizations (Norm(QCD) and Norm(EWK)) are derived from a solution of the following equation:

$$\begin{pmatrix} N_{\text{Data}}(\text{Iso}) \\ N_{\text{Data}}(\text{AnIso}) \end{pmatrix} = \begin{pmatrix} N(\text{QCD}, \text{Iso}) & N(\text{EWK}, \text{Iso}) \\ N(\text{QCD}, \text{AnIso}) & N(\text{EWK}, \text{AnIso}) \end{pmatrix} \begin{pmatrix} \text{Norm}(\text{QCD}) \\ \text{Norm}(\text{EWK}) \end{pmatrix}, \quad (5.1)$$

where N_{Data} and N are numbers of data and MC events for isolated (Iso) and anti-isolated (AnIso) leptons.

To validate the agreement between data and simulation, the transverse momentum q_t of the W boson is shown in Fig. 5.1. In addition to the statistical uncertainty, the effects of the

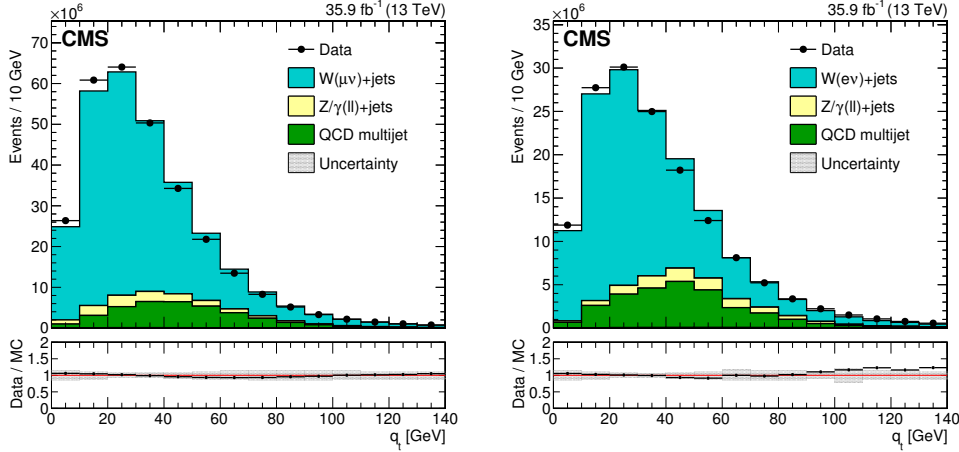


Figure 5.1: Upper panels: the W boson q_t distribution in the in single-muon (left) and single-electron (right) samples. The last bin includes all events with $q_t > 130$ GeV. Lower panels: Data to simulation ratio. The systematic uncertainties due to the JES, the JER, and variations in the E_U are added in quadrature and displayed with a band.

systematic uncertainties from the JES, JER, and in and unclustered energy (E_U) are sizable and therefore included in the total uncertainty. The E_U is the contribution from the PF candidates not associated with any of the well reconstructed physics objects, such as muons, electrons, photons, hadronically decaying taus and jets.

5.1.4 Performance of p_T^{miss} in the single lepton sample

In Fig. 5.2, the PF and PUPPI p_T^{miss} distributions are compared in the single-muon and single-electron samples. Larger discrimination between events with and without genuine p_T^{miss} is observed for the PUPPI p_T^{miss} algorithm.

The transverse mass (M_T) of the lepton- $\vec{p}_T^{\text{miss}}$ system is compared between the algorithms, as shown in Fig. 5.3. The M_T of the system is computed as:

$$M_T = \sqrt{2p_T^{\text{miss}}p_T^{\text{lepton}}(1 - \cos\Delta\phi)}, \quad (5.2)$$

where p_T^{lepton} is the p_T of the lepton, and $\Delta\phi$ is the angle between $\vec{p}_T^{\text{lepton}}$ and $\vec{p}_T^{\text{miss}}$. As in the p_T^{miss} distribution, the PUPPI algorithm has a better discrimination power between events with and without genuine p_T^{miss} . In addition, the spread of the Jacobian mass peak is smaller when M_T is computed using PUPPI p_T^{miss} . The summary of the mean and the spread of the Jacobian mass peak, calculated in simulated W +jets events, is provided in Table 5.2. Utilizing PUPPI p_T^{miss} for the M_T calculation results in a 10–15% relative improvement in the resolution of the Jacobian mass peak with respect to the PF p_T^{miss} .

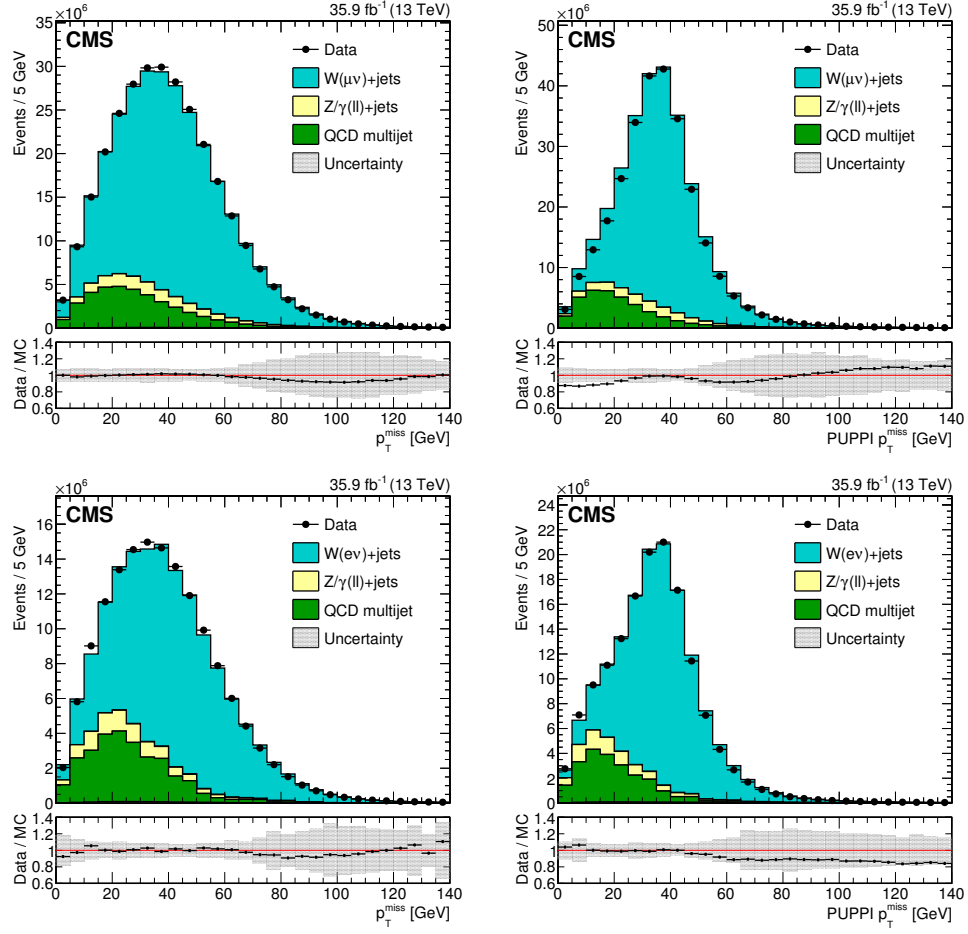


Figure 5.2: The PF (left) and PUPPI (right) p_T^{miss} distributions are shown for single-muon (upper) and single-electron (lower) events. The last bin includes all events with $p_T^{\text{miss}} > 135$ GeV. In all the distributions, the lower panel shows the ratio of data to simulation. The systematic uncertainties due to the JES, the JER, and variations in the E_U are added in quadrature and represented by the shaded band.

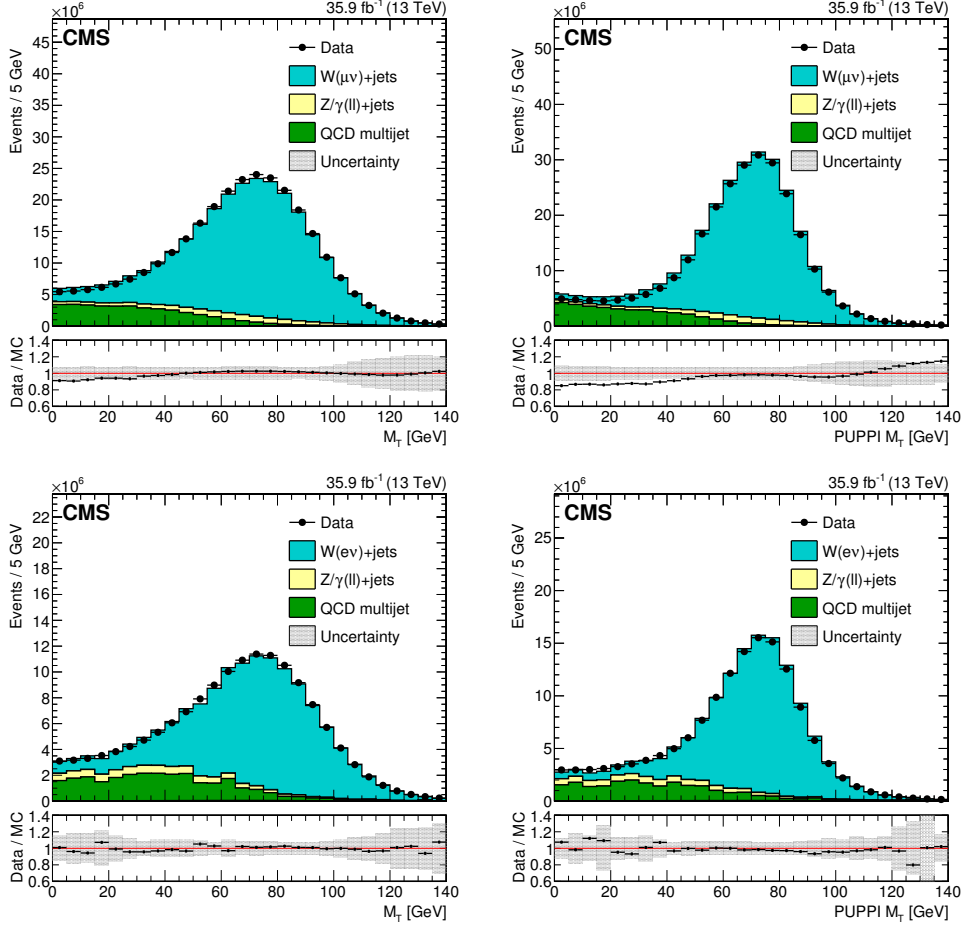


Figure 5.3: The PF (left) and PUPPI (right) M_T distributions are shown for single-muon (upper) and single-electron (lower) events. The last bin includes all events with $M_T > 135$ GeV. In all the distributions, the lower panel shows the ratio of data to simulation. The systematic uncertainties due to the JES, the JER, and variations in the E_U are added in quadrature and shown as the shaded band.

Table 5.2: The summary of the mean and the spread of the Jacobian mass peak in the M_T distribution in single-lepton events for PF and PUPPI p_T^{miss} algorithms. The results are obtained using simulated W +jets events.

Process	Mean [GeV]	RMS [GeV]	Mean [GeV]	RMS [GeV]
	PF algorithm		PUPPI algorithm	
	$0 < N_{vtx} \leq 20$			
$W \rightarrow \mu\nu$	76.26 ± 0.01	15.01 ± 0.01	73.44 ± 0.01	13.01 ± 0.01
$W \rightarrow e\nu$	77.46 ± 0.01	15.37 ± 0.01	74.61 ± 0.01	13.18 ± 0.01
	$20 < N_{vtx} \leq 30$			
$W \rightarrow \mu\nu$	78.58 ± 0.01	16.45 ± 0.01	74.21 ± 0.01	13.65 ± 0.01
$W \rightarrow e\nu$	79.96 ± 0.01	16.74 ± 0.01	75.45 ± 0.01	13.87 ± 0.01
	$N_{vtx} \geq 30$			
$W \rightarrow \mu\nu$	80.75 ± 0.02	17.47 ± 0.01	75.29 ± 0.01	14.43 ± 0.01
$W \rightarrow e\nu$	82.26 ± 0.03	17.73 ± 0.02	76.68 ± 0.02	14.70 ± 0.02

5.2 Chapter conclusion

The W selection has proven to be a practical tool for the p_T^{miss} performance studies. It allows the investigations of various p_T^{miss} corrections and their impact on simulation to data agreement. Moreover, events with genuine p_T^{miss} are an excellent tool to compare the effectiveness of various reconstruction algorithms. Within the current high PU conditions, the PUPPI p_T^{miss} approach demonstrates better resolution and discriminating power. However, using PF p_T^{miss} leads to a better agreement between data and simulation for most of the p_T^{miss} related variables as shown in Figs. 5.2 and 5.3. Therefore, the PF p_T^{miss} is used in the stau search with 2016 and 2017 data.

Similar studies were done with 2017 data and helped with tuning p_T^{miss} reconstruction recipe to overcome problems coming from the degradation tracker and HCAL. Currently, this approach is used for 2018 data to validate p_T^{miss} performance and to search for anomalies.

CHAPTER

6

$\tilde{\tau}$ SEARCH WITH 2016 AND 2017 DATA

'Oh, well, if you prefer, I can recognize handwriting,' said the imp proudly. 'I am quite advanced.'
Vimes pulled out his notebook and held it up. 'Like this?' he said. The imp squinted for a moment. 'Yep,' it said. 'That is handwriting, sure enough. Curly bits, spiky bits, all joined together. Yep. Handwriting. I would recognize it anywhere.'

Terry Prattchet

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The $\tilde{\tau}$ search in 2016 and 2017 CMS data is the core of this thesis. The analysis targets direct $\tilde{\tau}$ production with the following decay to a τ lepton and an LSP, as described in Chapter 2.2.3. A final state with one τ lepton decaying to an electron or muon (denoted as l) and neutrinos and another τ lepton decaying hadronically is the selection focus and it is referred as $\ell\tau_h$ channel. To enhance the sensitivity, an MVA boosted decision tree (BDT) approach is used. As the last step, results are combined with a second analysis using a final state with both τ leptons decaying hadronically ($\tau_h\tau_h$ channel). The observed data are found to be consistent with the Standard Model prediction, and interpreted in terms of upper limits on the stau pair production cross section. Within this chapter, first, the usual analysis steps are described such as data and simulation details, event selection, correction to simulation and background estimation technique. Second, the machine learning approach is discussed in terms of application to the stau search in Section 6.5. The analysis result with the corresponding interpretation are shown in Section 6.8. Finally, the combination of the $\ell\tau_h$ and $\tau_h\tau_h$ channels is discussed in Section 6.9. The analysis results are publicly available in Ref. [114].

6.1 Data sets and simulated samples

The background and signal samples were simulated separately for 2016 and 2017. The general description of the background MC samples is mostly the same as for the p_T^{miss} studies in Chapter 5. One difference to be mentioned is the usage of the parton distribution functions (PDFs). For the 2016 samples, the NNPDF3.0LO [113] set of PDFs is used in generating Z+jets, W+jets, and stau samples, while the newer NNPDF3.0NLO set is used for the other background processes. The NNPDF3.1 NLO PDFs set is used for all 2017 samples. Signal samples of direct stau pair production are generated with MADGRAPH5_amc@NLO at LO precision up to the production of τ leptons. In the next step, τ leptons are decayed with PYTHIA 8.212 for the 2016 analysis, and with PYTHIA 8.230 for the 2017 analysis.

Data samples used for the studies presented in this thesis were collected in 2016 (2017) in pp collisions at a centre-of-mass energy $\sqrt{s} = 13$ TeV, and correspond to an integrated

luminosity of 35.9 (41.3) fb^{-1} . The events are required to pass single muon or single electron triggers with a p_T threshold of 24 (25) or 25 (35) GeV for 2016 (2017) analysis. The selection leading to a final state with a muon is referred to as $\mu\tau_h$ channel, while the selection with an electron is named $e\tau_h$ channel.

6.2 Event selection

The main target of the analysis is the final state with two τ leptons as discussed before. To select such a final state, events are required to have one muon or one electron and one hadronically decaying τ with quality criteria discussed below. The direct $\tilde{\tau}$ production topology implies LSPs in the final state giving missing transverse momentum depending on the model parameters. Therefore, p_T^{miss} and p_T^{miss} -related variables play a crucial role in distinguishing signal from background.

6.2.1 Baseline selection

Events are required to contain an oppositely charged pair of leptons. Electrons are required to pass the 80% (90%) efficiency working point of the MVA identification optimized for 2016 (2017) working conditions in the $e\tau_h$ channel. Furthermore, to pass the selection, they must have a p_T higher than 26 (36) GeV, dictated by the corresponding electron trigger thresholds. For the $\mu\tau_h$ channel, muons are required to pass the cut-based medium ID and to have a p_T higher than 25 (28) GeV also dictated by the corresponding muon trigger thresholds. For both channels, the selected electron or muon is required to match an HLT object within $\Delta R < 0.5$. Candidates for hadronically decaying τ leptons are selected with the MVA τ ID by passing very tight working point criteria. To ensure the leptons coming from the primary vertex, their impact parameters d_{xy} and d_z are restricted to lie within the range described in Table 6.1.

As an additional quality criteria variable, an isolation variable I_{rel} is defined as the p_T sum of all objects within a cone of $\Delta R < 0.4$ around the lepton candidate (excluding the candidate itself), describing the activity around the object. An area correction is applied to remove the pileup contribution [115]. In order to reject non-prompt electrons and muons, e.g. from hadron decays, tight relative isolation is required. All object quality criteria are summarized in the Table 6.1.

For the two different event selections, exactly two leptons with opposite sign are required: an electron and a hadronically decaying τ in the $e\tau_h$ -channel, or a muon and a hadronically decaying τ in the $\mu\tau_h$ -channel. The two leptons have to be separated in ΔR by at least 0.5. Events with additional leptons passing looser selection criteria, summarized in Table 6.2, are rejected. Events with a second same-flavor electron or muon are rejected if the even looser identification given in Table 6.3 is fulfilled for these events to suppress Z +jets events. Moreover, events that contain jets with $p_T > 20$ GeV are vetoed, which significantly suppresses the background contributions from $t\bar{t}$ + jets and W +jets.

Chapter 6. $\tilde{\tau}$ search with 2016 and 2017 data

Table 6.1: Summary of the required lepton properties.

Property	μ ($\mu\tau_h$)	e ($e\tau_h$)	τ_h
$p_T > (\text{GeV})$ in 2016 (2017)	25 (28)	26 (35)	30
$ d_{xy} < (\text{cm})$	0.045	0.045	–
$ d_z < (\text{cm})$	0.2	0.2	0.2
$ \eta <$	2.4	2.1	2.3
RelIso $<$	0.15	0.1	–
Id	cut-based (medium)	MVA	MVA (very tight working point)
Pair	OS with $0.3 < \Delta R < 3.5$		
Matching to trig.	sel. lepton has to match HLT object within $\Delta R < 0.5$		

Table 6.2: Requirements for additional leptons. Events with a third lepton passing these conditions are rejected.

	Muons	Electrons
$p_T > (\text{GeV})$	10	10
$ \eta <$	2.4	2.5
$ d_{xy} < (\text{cm})$	0.045	0.045
$ d_z < (\text{cm})$	0.2	0.2
ID	Medium ID	MVA ID with efficiency of 90% and pass conversion veto
$I_{\text{rel}} <$	0.3	0.3

Table 6.3: Requirements for a second same-flavor lepton. If such a second lepton is found, the event is rejected.

	Di- μ	Di- e
$p_T > (\text{GeV})$	15	15
$ \eta <$	2.4	2.5
$ d_{xy} < (\text{cm})$	0.045	0.045
$ d_z < (\text{cm})$	0.2	0.2
ID	Global and tracker and PF muon	cut-based ID for veto
$I_{\text{rel}} <$	0.3	0.3

6.2.2 Background rejection

To suppress the background and enhance the ratio of signal over background, the following baseline selection is applied to all channels:

- Two leptons (μ and τ or e and τ) with conditions as given in Table 6.1;
- No additional leptons with looser selection;
- $N_{\text{jet}} = 0$, where jets must have $p_T > 20$ GeV and $|\eta| < 2.4$;
- $2.0 < \Delta R(\ell, \tau_h) < 3.5$ to reduce the fraction of QCD multijet events.
- $20 < m_T(\ell, E_T^{\text{miss}}) < 60$ GeV or $m_T > 120$ GeV to remove most of the W+jets events;
- $M_{\ell\tau_h} > 50$ GeV, the invariant mass of the lepton and the tau is constrained to remove low energy resonances.

Some distributions in the $\mu\tau_h$ -channel before the preselection are shown in Fig. 6.1 to endorse the aforementioned selection.

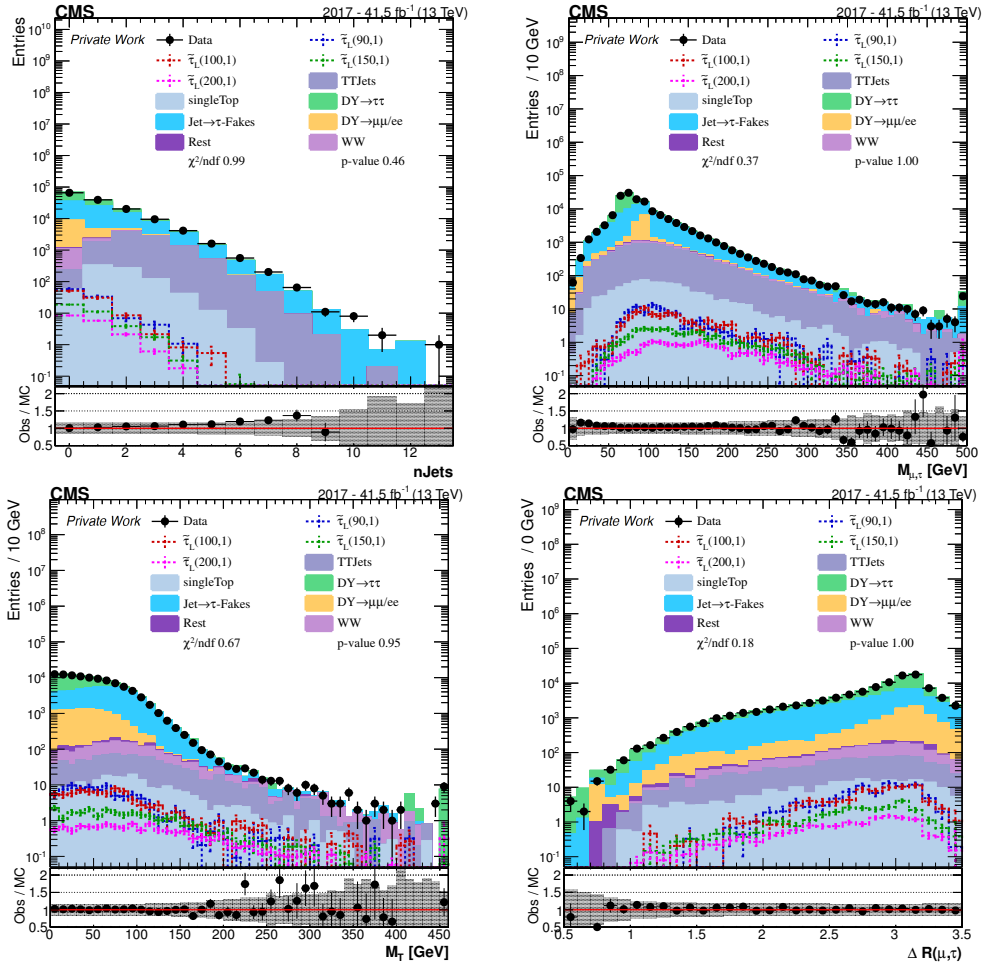


Figure 6.1: Control distributions for variables used in the preselection before the preselection requirements are applied in the $\mu\tau_h$ channel with 2016 data.

The requirement on the number of jets reduces the background with several jets from the matrix element like $t\bar{t} + \text{jets}$ by two orders of magnitude. In addition, the requirement on $\Delta R(\ell_1, \ell_2) < 3.5$ cuts away QCD multijet events without reducing signal efficiency. Furthermore, events with m_T within a mass window around the W boson mass are removed, reducing the number of W+jets events by 70%.

6.3 Corrections to simulation

Simulated background samples usually show discrepancies to real data. Therefore, studying and correcting such discrepancies is an important part of every analysis. Several corrections are applied to simulation in order to describe data as good as possible. The corrections are summarized in the following:

- PU corrections are applied to the MC sample to correct the shape of the primary vertex distribution.
- Trigger scale factors are used to improve the trigger simulation in MC.
- Lepton identification scale factors are needed to bring the lepton reconstruction and identification between simulation and data into agreement.
- The probability of a genuine lepton to pass tau identification criteria is corrected to further improve the accuracy of this identification.
- Z-boson recoil corrections are applied to Z+jets and W+jets events in simulation in order to correct the p_T^{miss} vector.
- Z-boson p_T corrections are applied to describe the disagreement of data and simulation at high Z p_T .

Most of the corrections are described below.

6.3.1 Triggers scale factors

The selected events are required to fire either a single electron or a single muon trigger. The trigger efficiencies are determined for both data and MC simulations by a tag&probe method, using a $Z \rightarrow \ell\ell$ sample as a function of η and p_T . Within this method two leptons, one as "tag" and another as "probe", are selected. The tag lepton should pass the same selection requirements as in the analysis itself. It is matched to a trigger object within a cone of size $\Delta R = 0.5$. The probe lepton is required to pass only the kinematic cuts, identification and isolation requirements. The tag-and-probe pair should be of the same flavor and have opposite charge. To select events near the Z peak, dilepton invariant mass should be greater than 50 GeV. The probe lepton is defined as passed if it matches the trigger object for the trigger scale factor calculation. Then, the efficiency is defined as a ratio of passed to the total number of probe leptons.

The bin-by-bin ratio between data and simulation is taken as correction and applied to all MC samples. The trigger efficiency is on average 0.9 for p_T after threshold. The trigger scale factor, defined as ratio of efficiencies in data and simulation, is of the order of unity.

6.3.2 Lepton identification scale factors

In the same way as for trigger simulation, an object reconstruction is not identical in data and MC simulations. Therefore, it leads to different efficiencies of leptons passing the identification and isolation criteria. These efficiencies are measured in a similar way as the trigger scale factors with a tag&probe method. The only difference is the lepton selection which, now, follows the same quality criteria as the analysis selection. The average efficiency is 0.8, while the final scale factor is of the order of unity.

6.3.3 Recoil corrections

In $Z \rightarrow \mu\mu$ events, corrections to the parallel and perpendicular parts of the E_T^{miss} vector are extracted and then applied to Z +jets and W +jets events in simulation. For the latter, the real E_T^{miss} contribution from the neutrino is subtracted before applying the correction.

Events are selected by requiring opposite-sign muon pairs passing looser identification criteria than in the main analysis selection, but using the same impact parameter selection and relative isolation criteria to be $I_{\text{rel}}^\mu < 0.15$. The leading muon must have a p_T of at least 23 GeV, while the trailing muon must have a p_T of at least 10 GeV. In addition, for data events, the leading muon must have fired the single muon trigger with a p_T threshold of 22 GeV. The requirements on the muon η are $|\eta(\mu_1)| < 2.1$ and $|\eta(\mu_2)| < 2.4$. The two muons must be separated by $\Delta R > 0.5$, and the di-muon mass must be at least 20 GeV. Pileup reweighting, the muon ID, isolation, and trigger scale factors are applied, as are the muon tracking efficiencies. To select $Z \rightarrow \mu\mu$ events, the invariant dimuon mass is required to be close to the Z mass with $70 < m_{\mu\mu} < 110$ GeV.

The corrections are performed with the variable defined as the vectorial difference between the measured missing transverse momentum and the total transverse momentum of neutrinos originating from the decay of the Z boson, $\vec{u} = \vec{p}_T^{\text{miss}} - \Sigma \vec{p}_{T,\nu}$, which can be reformulated for $Z \rightarrow \mu\mu$ events as $\vec{u} = p_T(Z) - H_T$, where H_T is the transverse momentum of the hadronic recoil. The variable $\vec{u}$ is projected onto the axes parallel ($u_{\parallel}$) and orthogonal ($u_{\perp}$) to the boson p_T for both data and simulation. A double Gaussian with the mean $\langle u_{\perp} \rangle$ symmetrically shifted away from zero is used to fit the $u_{\perp}$ component. Also, a double Gaussian is used for fitting the $u_{\parallel}$ component, but with the median parameter not fixed. These fits are performed in bins of Z p_T , (0-10, 10-20, 20-30, 30-50, and > 50 GeV), and bins of number of jets (0, 1 or at least 2).

This is shown in Figs. 6.2–6.4 where the resolution is estimated as second moment of the fitted distribution.

The recoil in simulation is then corrected as

$$u_{\parallel}^{\text{MC}'} = (u_{\parallel}^{\text{MC}} - \langle u_{\parallel}^{\text{MC}} \rangle + \langle u_{\parallel}^{\text{data}} \rangle) \cdot \frac{\sigma(u_{\parallel}^{\text{data}})}{\sigma(u_{\parallel}^{\text{MC}})}, \quad (6.1)$$

$$u_{\perp}^{\text{MC}'} = (u_{\perp}^{\text{MC}} - \langle u_{\perp}^{\text{MC}} \rangle + \langle u_{\perp}^{\text{data}} \rangle) \cdot \frac{\sigma(u_{\perp}^{\text{data}})}{\sigma(u_{\perp}^{\text{MC}})}, \quad (6.2)$$

where $\sigma(u_{\parallel,\perp})$ is the resolution of the parallel and orthogonal component, which is in the order of 15 to 25 GeV.

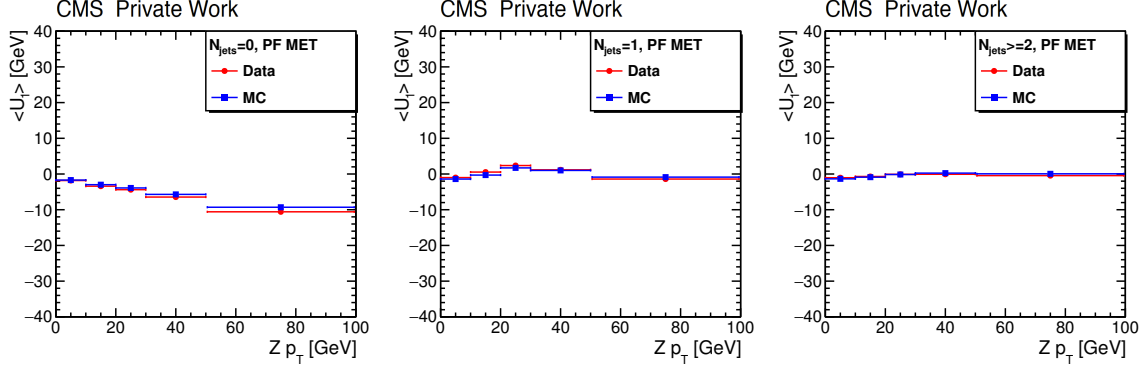


Figure 6.2: Z recoil corrections in 2016: mean value of $u_{\parallel}$ in data and simulation as a function of $Z p_T$ and jet multiplicity.

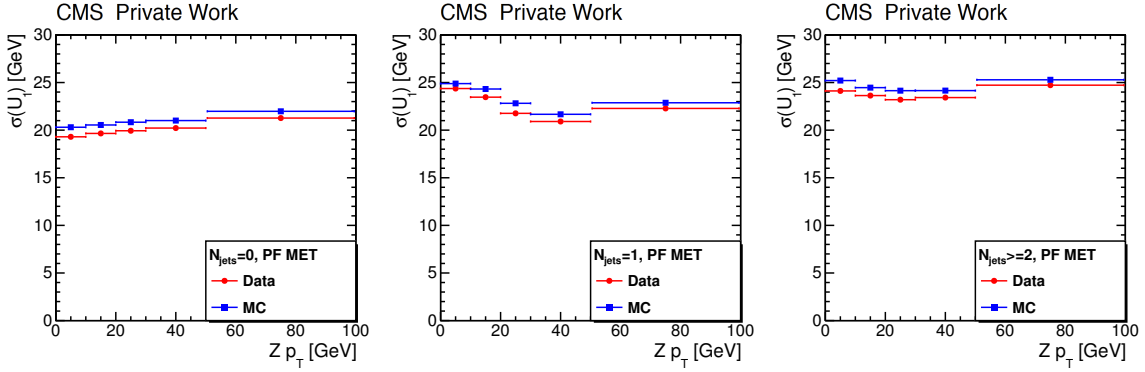


Figure 6.3: Z recoil corrections in 2016: resolution of the $u_{\parallel}$ projection in data and simulation as a function of $Z p_T$ and for jet multiplicities of $N_{\text{jets}} = 0$ (left), $N_{\text{jets}} = 1$ (middle) and $N_{\text{jets}} \geq 2$ (right).

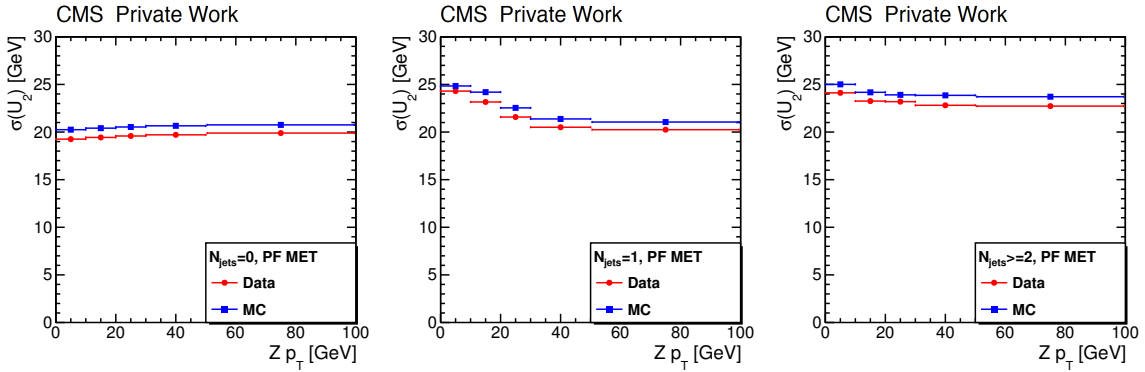


Figure 6.4: Z recoil corrections in 2016: resolution of $\langle u_{\perp} \rangle$ in data and simulation as a function of $Z p_T$ and for jet multiplicities of $N_{\text{jets}} = 0$ (left), $N_{\text{jets}} = 1$ (middle) and $N_{\text{jets}} \geq 2$ (right).

The effect of the recoil corrections on the $Z \rightarrow \mu\mu$ selection is shown in Fig. 6.5 for 2016 and in Fig. 6.6 for 2017 data. The residual differences are covered by uncertainties assigned to hadronic recoil resolution (1.5-3%) and scale (2-4%). The agreement between data and simulation is improved.

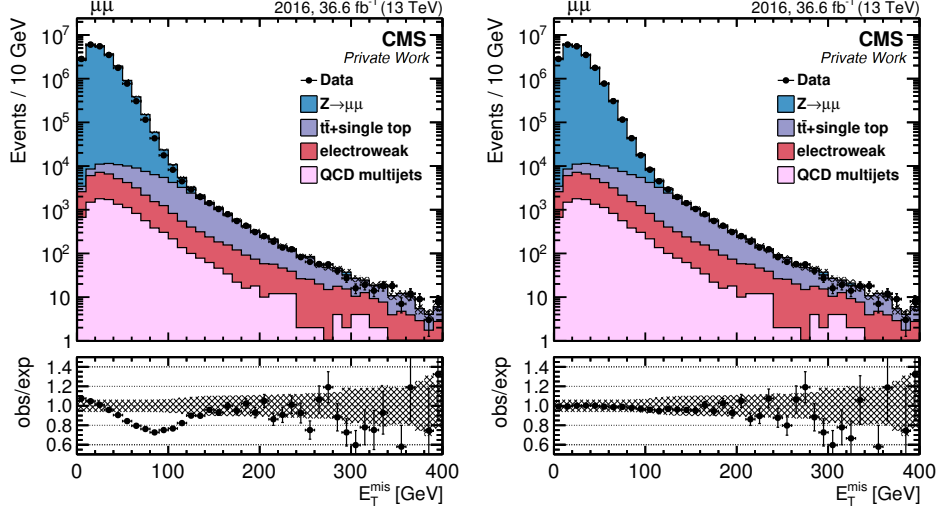


Figure 6.5: Z recoil corrections in 2016: comparison of the E_T^{miss} distribution in the $Z \rightarrow \mu\mu$ selection (left) before and (right) after recoil corrections. The agreement between data and MC is improved.

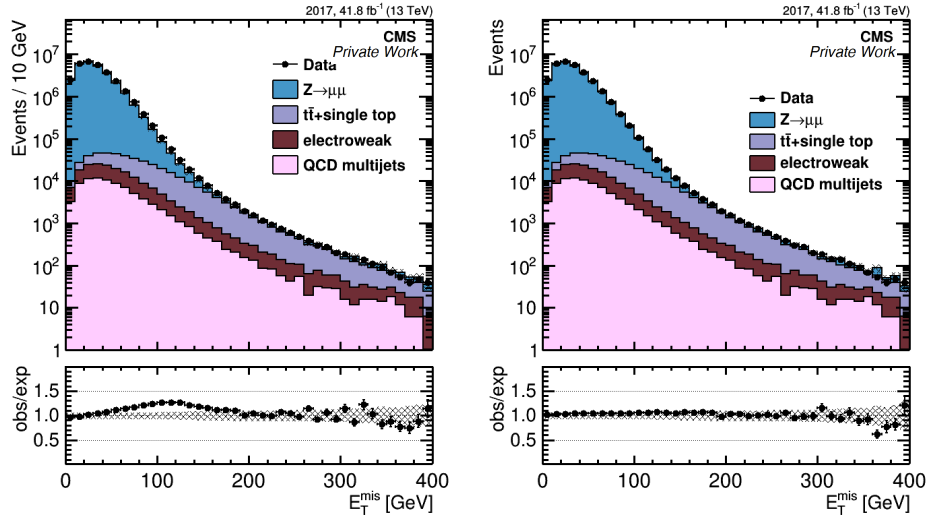


Figure 6.6: Z recoil corrections in 2017: comparison of the E_T^{miss} distribution in the $Z \rightarrow \mu\mu$ selection before (left) and after (right) recoil corrections. The agreement between data and MC is improved.

6.3.4 Drell-Yan Z p_T reweighting

It has been observed in the $H \rightarrow \tau\tau$ analysis that the generated samples for the Drell-Yan $Z \rightarrow \tau\tau$ process do not model the data well at high Z p_T and high mass [116]. This can clearly be seen in $Z \rightarrow \mu\mu$ events, as shown in Fig. 6.7. In order to correct for this effect, weights are derived using the $Z \rightarrow \mu\mu$ events in data as a control region in bins of Z p_T and dimuon mass which are then applied to the $Z \rightarrow \tau\tau$ and $Z \rightarrow \ell\ell$ events selected in the analysis.

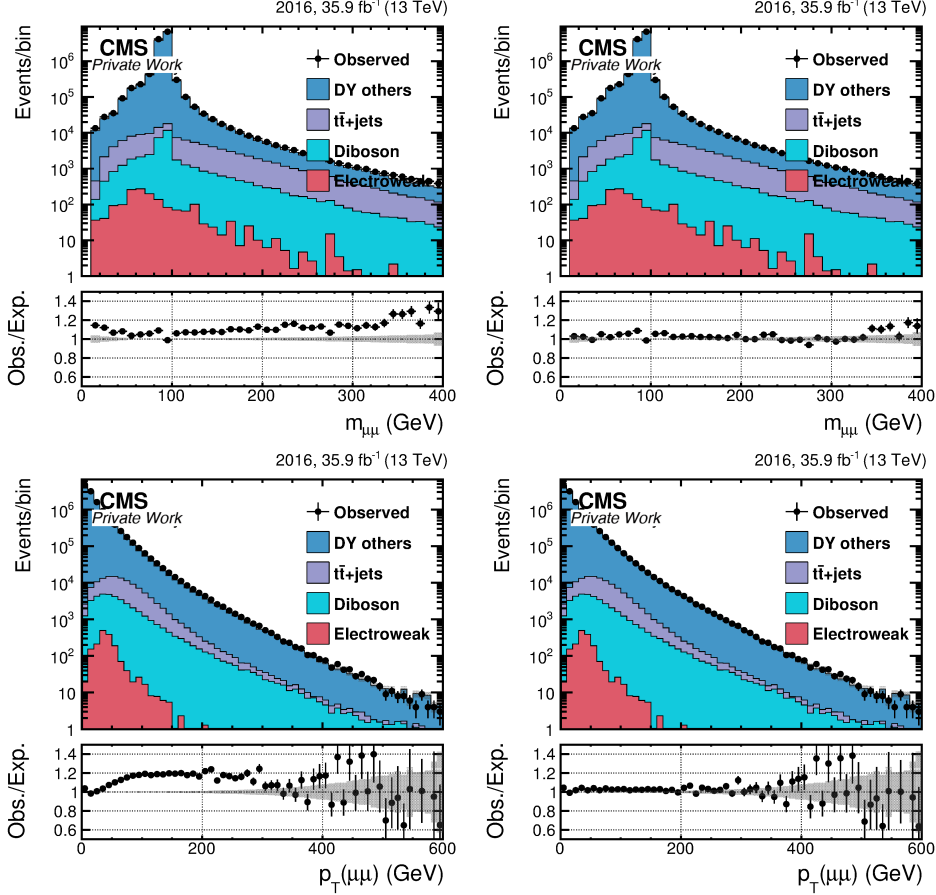


Figure 6.7: Z p_T correction: reconstructed di-muon mass and reconstructed p_T distributions in $Z \rightarrow \mu\mu$ data before (left) and after (right) the reweighting discussed in this section.

The weights are derived in such a way as to preserve the overall normalization of the DY process, such that the weights are intended to be a shape correction, whilst leaving any possible data/simulation disagreement in the overall normalization of the Drell-Yan process to be covered by a cross-section uncertainty.

The correction is produced in the $Z \rightarrow \mu\mu$ control region to reduce the shape discrepancy between data and simulation. Since for this control region (CR) the reconstructed values are close to generator values, the correction is derived as a function of reconstructed variables Z p_T and $m_{\ell\ell}$, but it is applied as a function of the generator level variables. The $m_{\ell\ell}$ is defined the same way as in the recoil correction sample. The generator-level p_T is determined by summing all generator particles coming from the hard processes. The visible p_T is found by

summing all PF candidates.

Events in the dimuon region are selected by requiring two opposite sign muons passing the medium ID and with relative isolation less than 0.15. The leading muon is required to have $p_T > 26$ GeV and the subleading muon $p_T > 15$ GeV. Events with additional identified and isolated electrons and muons are discarded. The weights are computed in such a way as to make the two-dimensional distributions of the reconstructed Z p_T and the Z boson reconstructed mass match between data and expected backgrounds. The weights are then corrected not to introduce a general yield variation of the Drell-Yan background, but to only have a shape effect. The weights are illustrated in Fig. 6.8 for the 2016 analysis as an example, whereas the $\mu\mu$ distributions before and after reweighting are shown in Fig. 6.7.

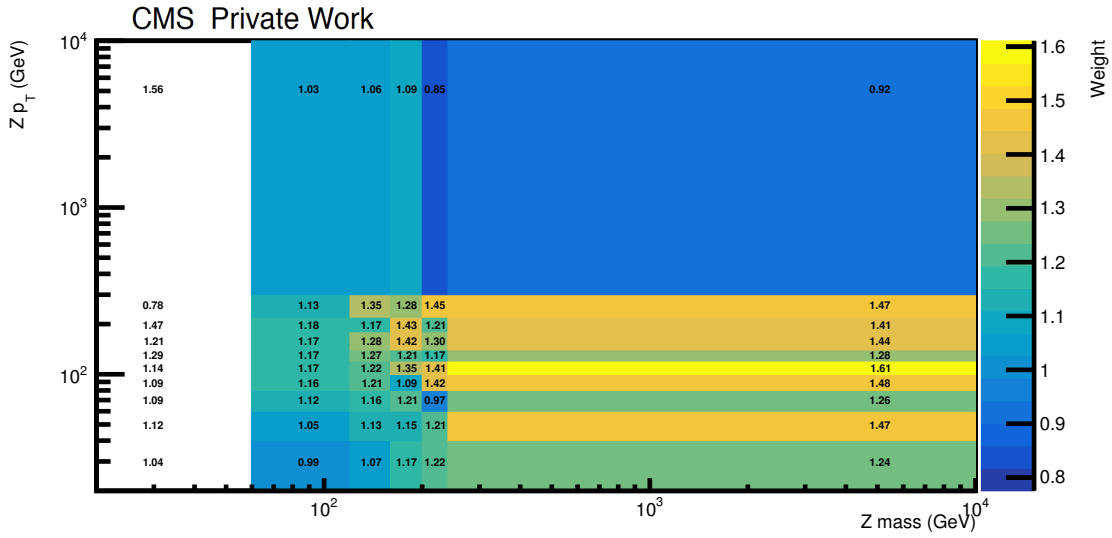


Figure 6.8: Z p_T correction for 2016: weights applied to the Drell-Yan LO MC simulation based on the generated Z boson mass and p_T . These weights correct only the shape of the distribution and do not cause a variation of the process yield.

6.4 Background estimation

After the baseline selection, the main backgrounds are W+jets, Drell-Yan and QCD, but also the contribution of diboson, $t\bar{t}$ + jets, and single top production is sizeable given the low cross section of the signal. The relative composition of background processes is shown in Fig. 6.9 and 6.10. The main contribution comes from Z+jets followed by events where the selected τ is a misidentified jet. A change in the background composition can be seen in the $e\tau_h$ channel between 2016 and 2017, caused mainly by a different electron ID and a different electron p_T threshold.

The Z+jets background mainly comes from $Z \rightarrow \tau\tau$ decays, where one tau decays hadronically and the other leptonically. The simulated Z+jets events are normalized to data in a control region as described in the following Section 6.4.1, with shape corrections as described in Section 6.3.3. For W+jets events, the lepton comes in almost all cases from the W boson decay, while a jet from the initial state radiation is misidentified as the hadronically decaying

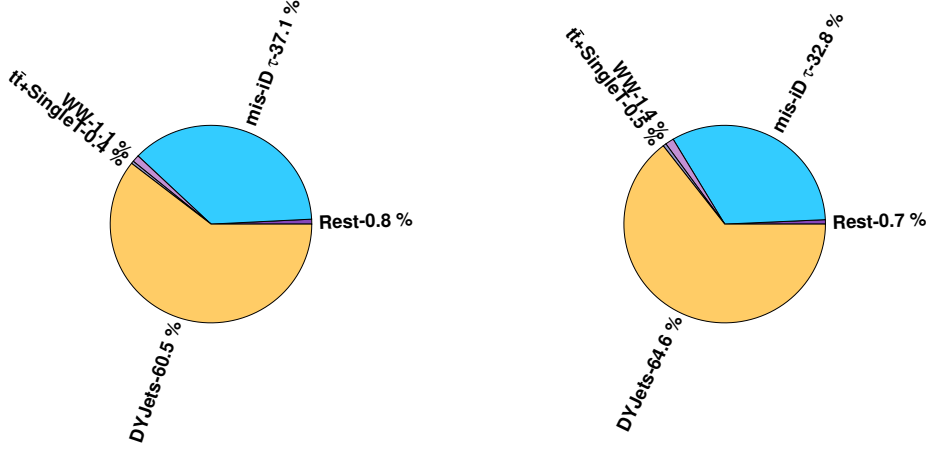


Figure 6.9: Relative composition of background processes to the total prediction for the $e\tau_h$ (left) and $\mu\tau_h$ (right) channel after the baseline selection for 2016 analysis. All background processes are taken from simulation, except for the misidentified τ , which is estimated from data control region.

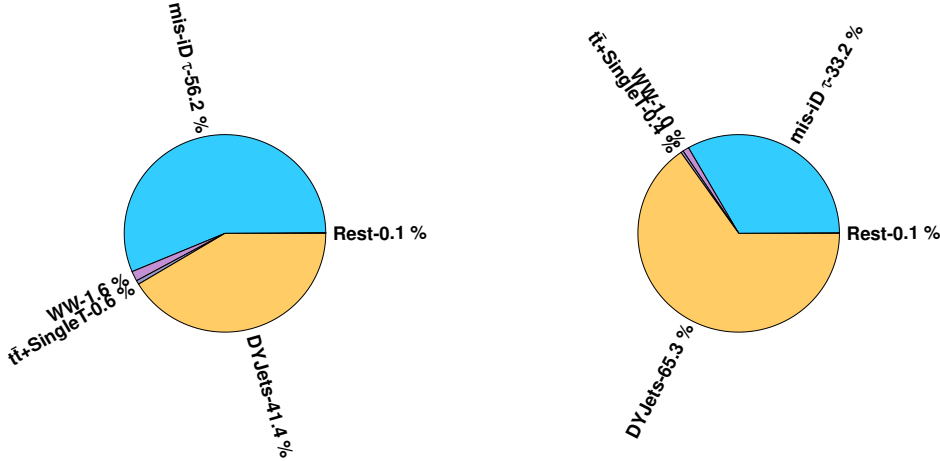


Figure 6.10: Relative composition of background processes to the total prediction for the $e\tau_h$ (left) and $\mu\tau_h$ (right) channel after the baseline selection for 2017 analysis. All background processes are taken from simulation, except for the misidentified τ , which is estimated from data control region.

tau lepton. All events with a jet misidentified as a hadronically decaying tau lepton are estimated from a control region in data, and a transfer factor is derived in a control sample that is enriched with W+jets events. All backgrounds that contain no tau lepton on generator level are removed from the simulation-based predictions of other backgrounds, like e.g. $Z \rightarrow \ell\ell$ events where one lepton will be identified, and the other one is either out of acceptance or not identified, but a jet from initial state radiation is identified as hadronically decaying tau.

For the Z+jets and $t\bar{t}$ + jets background, the shape in simulation is normalized to data

in control regions, starting with the control region that is purest, i.e. the Z+jets background control region with $> 98\%$ ($> 99\%$) purity in 2016 (2017) (discussed in Section 6.4.1), followed by the $t\bar{t}$ + jets control region with approximately 85% purity (given in Section 6.4.3). The background from jets misidentified as tau leptons, which constitutes mainly from W+jets and QCD multijet events, is determined from data, as shown in Section 6.4.2.

6.4.1 Determination of the Z+jets background

As Z+jets is expected to contribute significantly to the $e\tau_h$ and $\mu\tau_h$ channels, the normalization is determined from data in an enriched control region. The shape is taken from simulation, including the Z recoil corrections and Z p_T corrections as discussed in Section 6.3.3.

The Z+jets control region used to determine the normalization is defined as follows:

- Two μ , requiring at least one to pass the trigger, and with the rest of their conditions as given in Table 6.1.
- No additional leptons.
- $N_{\text{jet}} < 2$.
- No jets originating from b-quarks.
- $75 \text{ GeV} < M_{\mu\mu} < 105 \text{ GeV}$.

This selection results in very high purity ($> 99\%$) and the normalization is extracted from the ratio of data to simulation. After subtracting all other contributions obtained from simulation, the ratio is found to be equal to 0.96 (1.04) ± 0.02 (statistical uncertainty only) for the 2016 (2017) analysis. The shape of data in this control region is found to be in a very good agreement with simulation, which is shown in Fig. 6.11 and 6.12 before and after applying the obtained normalization. Figure 6.13 shows a comparison of data to simulation for other

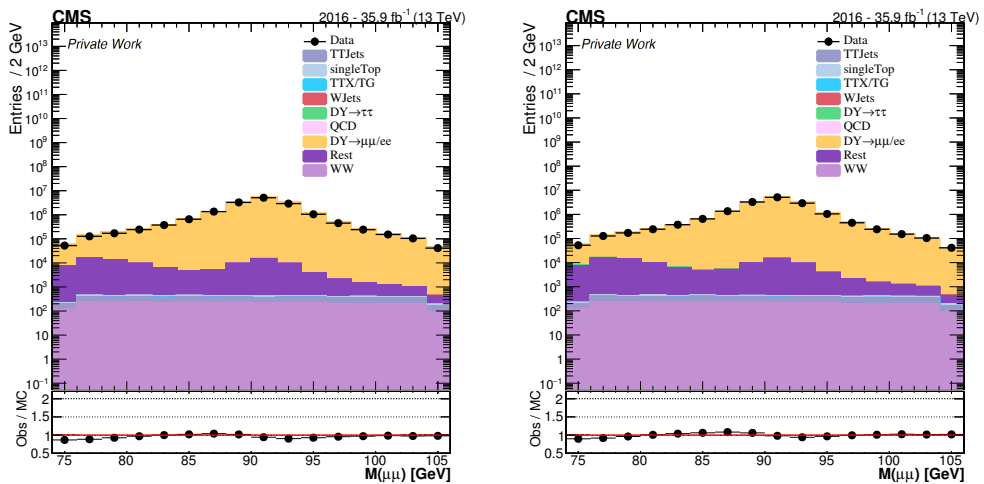


Figure 6.11: Estimation of the Z+jets background: comparison of simulation to data in the $Z \rightarrow \mu\mu$ control region for the invariant dimuon mass: (left) before and (right) after the normalization to data for the 2016 analysis.

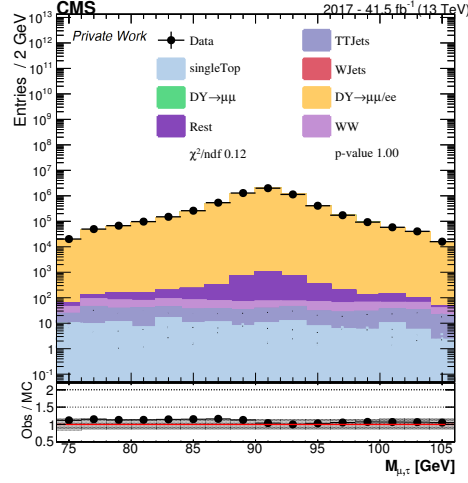


Figure 6.12: Estimation of the Z+jets background: comparison of simulation to data in the $Z \rightarrow \mu\mu$ control region for the invariant dimuon mass after the normalization to data for 2017 analysis.

variables. This normalization is applied to all simulated and shape corrected Z+jets events, except for those $Z \rightarrow \ell\ell$ events that mimic the signal by a jet misidentified as a hadronic tau, and one lepton (electron or muon) not in the acceptance or not passing ID requirements, since these events are already included in the estimate of events where jets fake hadronically decaying tau leptons, described in the following Section 6.4.2.

6.4.2 Determination of the background with jets misidentified as taus

The second main background comes from events with jets misidentified as hadronically decaying tau leptons. These are estimated from data, where the shape is taken from a control sample in data, which is selected by applying all selection requirements but requiring instead of passing a tight tau identification that the tau candidate passes a loose but not a very tight MVA identification. The transfer factor from 'loose and not very tight' ID to very tight ID is determined in a control sample in a W+jets enriched control region, which is defined as follows:

- One muon and at least one τ_h lepton with conditions as given in Table 6.1 must be present in an event. However, τ_h candidates are selected with loose ID as given by MVA discriminant.
- Events with additional electrons or muons are vetoed.
- In case of more than one τ_h lepton, the best isolated τ_h is selected.

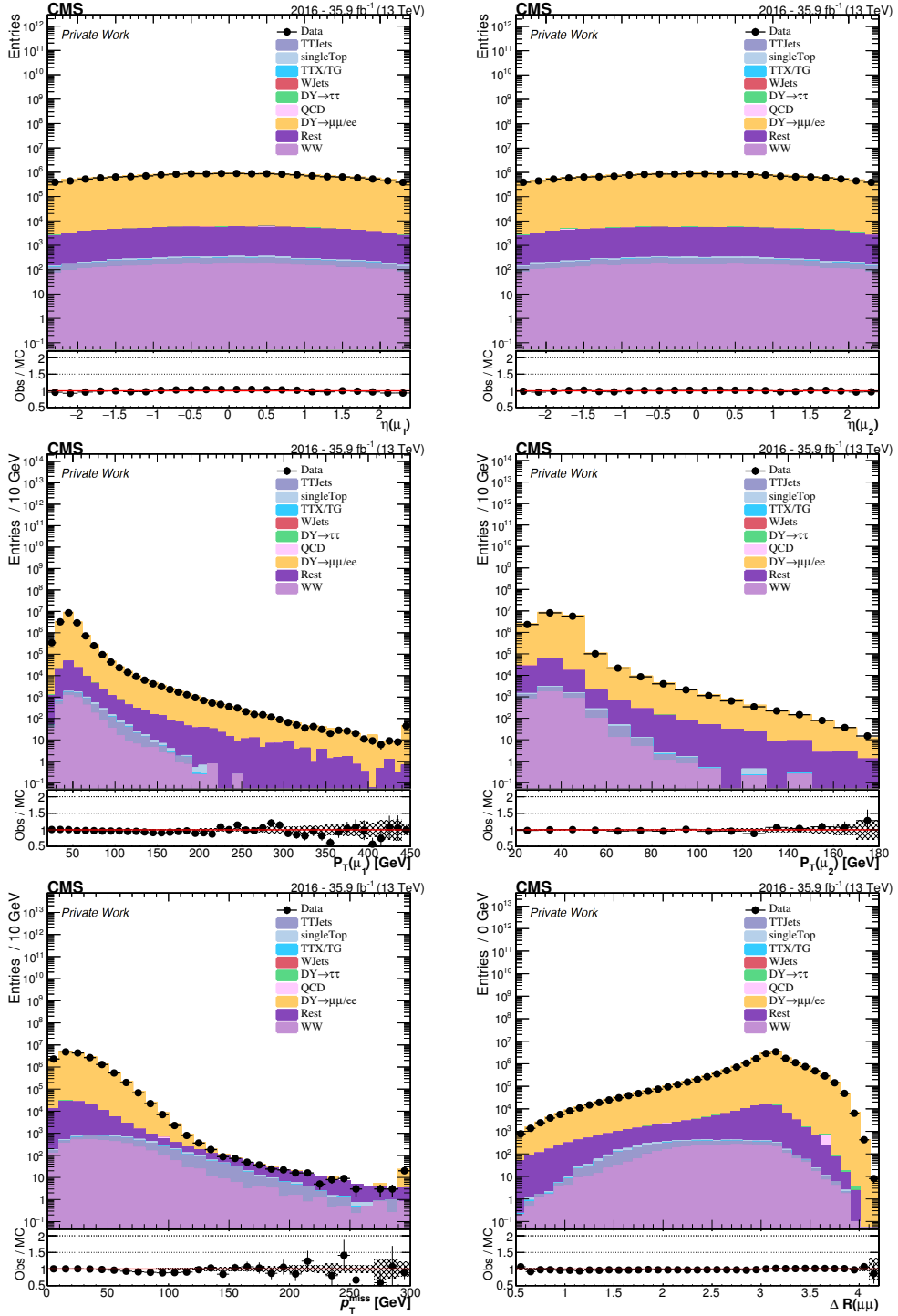


Figure 6.13: Estimation of the Z+jets background: comparison of simulation to data in the $Z \rightarrow \mu\mu$ control region after the normalization to 2016 data. Shown are (a) $\eta(\mu_1)$ (b) $\eta(\mu_2)$ (c) $p_T(\mu_1)$ (d) $p_T(\mu_2)$ (e) E_T^{miss} , and (f) $\Delta R(\mu, \mu)$.

Extra selections are imposed in order to reject contributions from multijet and $t\bar{t}$ + jets events and increase the purity of W+jets in the final sample:

- $60 \text{ GeV} < m_T < 120 \text{ GeV}$ with $m_T = \sqrt{2p_T^\mu E_T^{\text{miss}}(1 - \cos \Delta\Phi(\mu, E_T^{\text{miss}}))}$
- $\Delta\Phi(W, \text{jet}) > 2.5$ (the W boson is reconstructed from the selected μ and the E_T^{miss})
- $0 < N_{\text{jet}} < 3$
- $E_T^{\text{miss}} > 40 \text{ GeV}$

After this selection, the selected sample ($N_{\text{data}}^{\text{CS}}$) is expected to contain about 80% of W+jets events for 2016 and 2017.

The transfer factor R is then determined in this sample after subtracting the remaining 18% non-W+jets background contributions with tau candidates (denoted in the following as $N_{\text{MC w/o W+jets}}^{\text{CS}}$) as follows:

$$R = \frac{N_{\text{data}}^{\text{CS}}(\tau, VT) - N_{\text{MC w/o W+jets}}^{\text{CS}}(\tau, VT)}{N_{\text{data}}^{\text{CS}}(\tau, L\&!VT) - N_{\text{MC w/o W+jets}}^{\text{CS}}(\tau, L\&!VT)} \quad (6.3)$$

where $L\&!VT$ means loose and not very tight MVA τ ID, VT means Very tight MVA τ ID, and the corresponding transfer factors (TF) are given in Table 6.4 for 2016 and in Table 6.5 for 2017. They are comparable between 2016 and 2017 and show the same decreasing trend for increasing τ p_T . Exactly identical TFs stand for merged corresponding η bins.

Table 6.4: The transfer factors R (as shown in Eq. 6.3) as a function of p_T and η derived from the aforementioned control region for 2016. For $p_T > 40 \text{ GeV}$, the R are exactly identical because of merged corresponding η bins.

(η, p_T)	30-40 GeV	40-70 GeV	>70 GeV
$ \eta < 0.8$	0.324 ± 0.02	0.316 ± 0.03	0.251 ± 0.05
$0.8 < \eta < 1.44$	0.325 ± 0.02	0.316 ± 0.03	0.251 ± 0.05
$1.44 < \eta < 1.566$	0.387 ± 0.06	0.316 ± 0.03	0.251 ± 0.05
$1.566 < \eta < 2.3$	0.37 ± 0.03	0.316 ± 0.03	0.251 ± 0.05

Table 6.5: The transfer factors (as shown in Eq. 6.3) as a function of p_T and η derived from the aforementioned control region for 2017. For $p_T > 40 \text{ GeV}$, the R are exactly identical because of merged corresponding η bins.

(η, p_T)	30-40 GeV	40-70 GeV	40-110 GeV	>110 GeV
$ \eta < 0.8$	0.320 ± 0.02	0.281 ± 0.04	0.227 ± 0.05	0.217 ± 0.05
$0.8 < \eta < 1.44$	0.330 ± 0.02	0.281 ± 0.04	0.227 ± 0.05	0.217 ± 0.05
$1.44 < \eta < 1.566$	0.302 ± 0.05	0.281 ± 0.04	0.227 ± 0.05	0.217 ± 0.05
$1.566 < \eta < 2.3$	0.291 ± 0.04	0.281 ± 0.04	0.227 ± 0.05	0.217 ± 0.05

The backgrounds with one jet faking a hadronically decaying tau is then estimated from the sideband region defined by the main selection, but requiring instead of a tight MVA τ ID that the tau candidate passes the loose, but not the tight MVA τ ID. Therefore, event yields of the discussed background in signal region (SR) is estimated as follows:

$$N^{\text{SR}}(\text{jets} \rightarrow \tau_{\text{tight_iso}}) = R \cdot (N_{\text{data}}^{\text{SR}}(\tau_{\text{L}\&\text{!VT}}) - N_{\text{MC}}^{\text{SR}}(\tau_{\text{L}\&\text{!VT}\&\text{matched_to_gen}})) \quad (6.4)$$

The main sources for systematic uncertainties of the beforementioned R are the jet and tau energy scales. Up and down variations of these systematic sources change R by 3 to 15%. All systematic sources are taken into account by recalculating R for each up and down variation separately.

6.4.3 Determination of the $t\bar{t}$ + jets background

Similarly to the Z +jets events, the normalization of the $t\bar{t}$ +jets background is determined from data, while the shape is taken from simulated events. The aforementioned normalization for Z +jets and jets misidentified as τ leptons is also used as input. The normalization is determined in a $t\bar{t}$ + jets enriched control region in the $\mu\tau_h$ channel which is exactly the same as the selection described in Section 6.2.1, but contains in addition a requirement of at least one b-tagged jet of $N_{\text{jet}} = 1$ or 2.

With this selection, a $t\bar{t}$ + jets purity of $\approx 85\%$ is obtained and the normalization of the $t\bar{t}$ + jets events is determined from the ratio of data and simulation after subtracting the other backgrounds from the data. This normalization is found to be equal to $0.86(0.75) \pm 0.02$ (statistical uncertainty only) for 2016 (2017). The comparison of data and simulation after the extracted normalization scale factor is given in Fig. 6.14 (2016) and Fig. 6.15 (2017) for several variables.

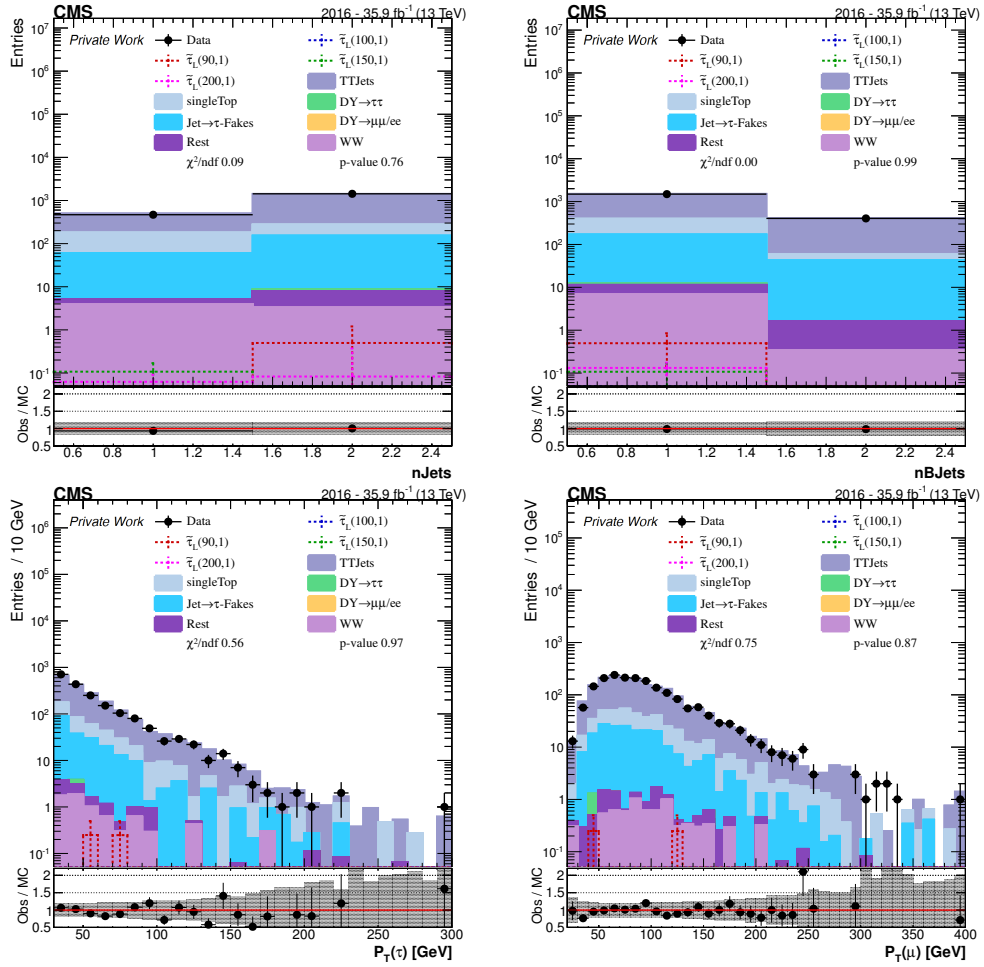


Figure 6.14: Estimation of the $t\bar{t}$ + jets background: comparison of simulation and data after the normalization to data. Shown are (a) N_{jet} , (b) $n_{\text{b-jet}}$, (c) $p_T(\tau)$, (d) $p_T(\mu)$ for 2016.

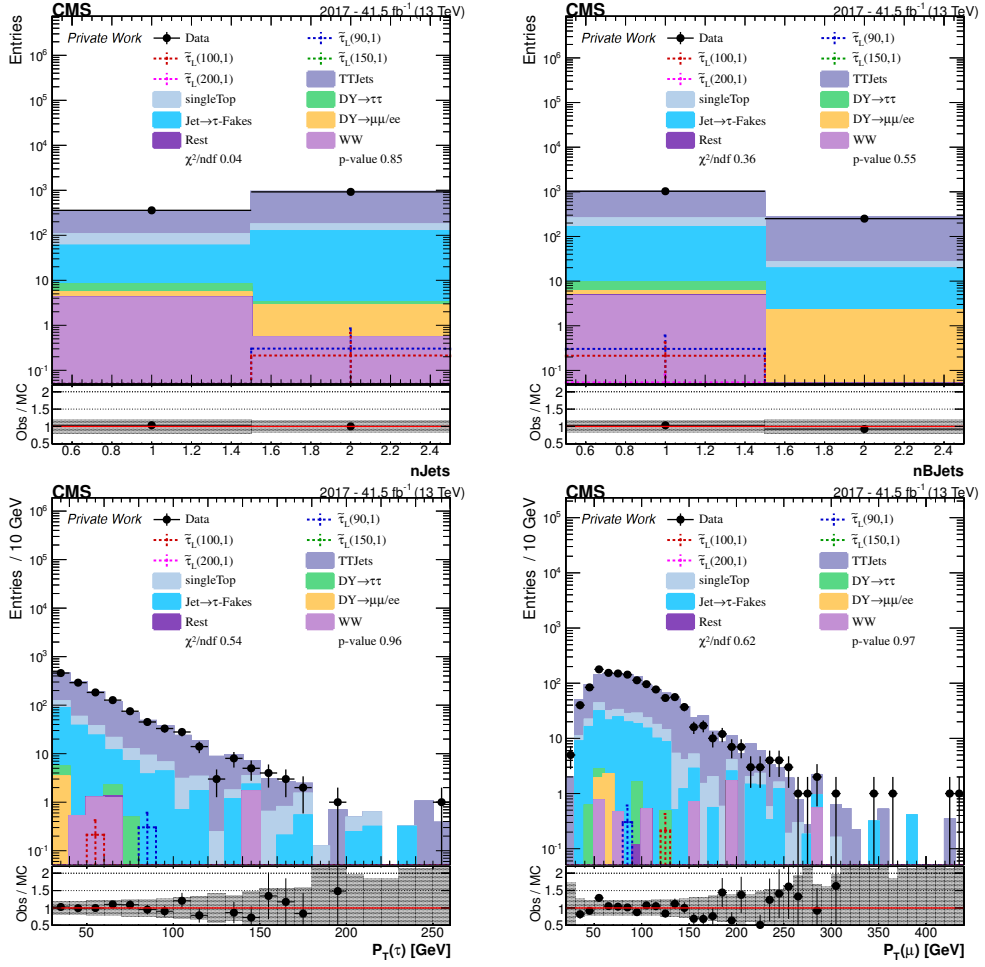


Figure 6.15: Estimation of the $t\bar{t}$ + jets background: comparison of simulation and data after the normalization to data. Shown are (a) N_{jet} , (b) $n_{\text{b-jet}}$, (c) $p_T(\tau)$, (d) $p_T(\mu)$ for 2017.

6.5 Boosted Decision Tree strategy

The direct stau pair production has an extremely low cross section in comparison to SM processes. In addition, the kinematic signature is not just a clear resonance in the invariant mass distribution, but a rather long tail in E_T^{miss} and E_T^{miss} -related variables distributions (Appendix A) because of the LSP being undetectable by CMS. Moreover, the traditional cut-based approach does not have sensitivity to direct stau production [117]. Therefore, the machine learning method is studied to gain more sensitivity for such a challenging signal.

In the first two subsections, a brief overview of the machine learning techniques and, particular, boosted decision tree (BDT) [118] approaches is given. After this, the BDT strategy, variable selection and tuning are discussed. In the end, the BDT is validated in various control regions.

6.5.1 Introduction to machine learning

The main idea of machine learning is to adjust ("train") some computer algorithm (model) with a set of data to perform a specific task. From such a description, naturally, several steps arise [119]. The first part is the preparation of the data set and splitting it for training, testing and evaluation of the computer model. The training data set is used for adjusting the free parameters of the chosen model and learning patterns within the selected data. The testing sample is needed to evaluate the performance of the already trained model and, if needed, to optimize the model or training procedure. The evaluation data set, then, is used as the final input to the trained model to reach the initial goal, for example, to make a prediction.

The second important part is to select a model for training with adjustable weights. The model can be represented as $g : X \rightarrow Y$, where X is the input feature space, Y is the output space and g is a function depending on X and the tunable weights. The most popular types of models are artificial neural networks, support vector machines and boosted decision trees. Within our studies, all aforementioned models were tested and BDT was selected as the most robust but highly efficient approach. The BDT model is described in the next subsection.

The last point to be mentioned is the type of learning (training) algorithm. While the type of model is less dependent from the original goal and can be interchangeable, the type of learning highly depends from the problem that machine learning is intended to solve. The three main types of learning are supervised, unsupervised and reinforcement learning.

- The supervised learning is used for learning that is based on training samples containing both, the input variables and the desired output. On each training iteration with given labelled input events X , the model evaluates the output Y and compares it to the desired output vector from the training sample. Based on this comparison the model weights are adjusted in order to minimize the difference between the actual and the desired output. The described approach is very useful for making a prediction based on some historical or simulated data in various fields, from the stock market to the weather forecast.
- The unsupervised learning [120] takes a training sample without the desired output and tries to cluster input data points in the feature space. Afterward, these clusters can be interpreted in terms of desired categories.

- The reinforcement learning [121] is used to train a model for actions to maximize cumulative reward. In other words, the input for such model is a set of environmental features and the output is the set of actions that should maximize in some way a defined gain calculated from the environment features.

Supervised learning is used in the stau analysis since labeled simulation samples are available. And the main goal is to classify input events into two categories, signal and background.

6.5.2 BDT introduction

A decision tree classifies data into categories by comparing shapes of input variables and putting selection requirements on these variables one after another. An example of such a tree is shown in Fig 6.16. The selection at every splitting node is done in a way that it provides the best separation between signal and background. The splitting stops if one node reaches the minimum number of events or the tree reaches a maximum number of splitting. A variety of separation criteria are available for building trees and many of them were tested for the stau search. The Gini index was selected as the separation criteria since it shows optimal performance. It is defined as $p(1 - p)$, where p is the node purity.

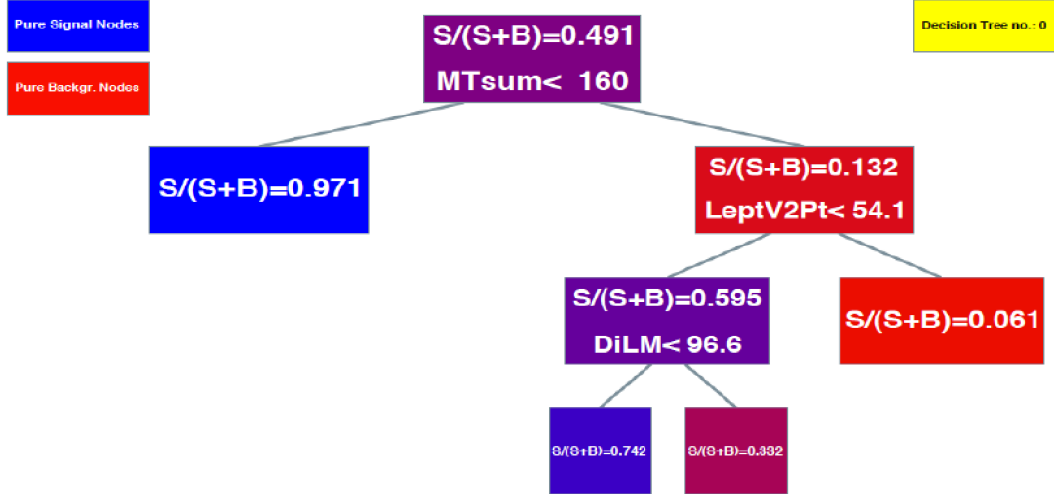


Figure 6.16: An example of a decision tree for classification between signal and background categories.

The boosting of a decision tree improves this concept and produces not only one, but a set of trees forming a forest. Every new tree is built after the previous tree using a reweighted (boosted) training data set. The final classifier is then formed by summing weighted individual tree responses. There are various boosting algorithms with different approaches for reweighting. For the stau analysis, several boosting algorithms were tested and the so-called real adaptive boost approach was selected as the most stable and highly performing approach.

The adaptive boost approach reweights a training sample for building every subsequent tree by multiplying weights of previously misclassified events by a common boost weight α . This weight is calculated from the misclassification rate (error) of the previous tree in the following way:

$$\alpha = \frac{1 - \text{error}}{\text{error}}. \quad (6.5)$$

After reweighting, all weights are normalized to give the same sum as before.

As the last step, the response $y(x)$ from such a forest is derived with

$$y(x) = \frac{1}{N_{\text{trees}}} \sum_{i=1}^{N_{\text{trees}}} \ln(\alpha_i) h_i(x), \quad (6.6)$$

where the sum is over all trees. N_{trees} is the number of the trees in the forest, x is the set of input variables, and $h_i(x)$ is the response of an individual tree. This response is defined as $h(x) = +1$ and -1 for signal and background, respectively, within standard adaptive boost. The real adaptive boost makes use of more advanced $h_i(x)$ definitions as the training purity in the leaf node is computed from the signal and background weights.

6.5.3 Analysis strategy

The BDT approach consists of three main steps: training, testing and result evaluation. In a nutshell, the whole procedure starts with a preliminary training with some default BDT options and input variables. Afterwards, the BDT performance and a possible overtraining are checked with the testing sample and, as a result, the BDT options and input variables are changed to improve sensitivity.

The performance is evaluated by calculating the Asimov significance as figure of merit (FOM) [122]. The Asimov significance considers a flat systematic uncertainty, which is taken to be 20% of the total background as an approximation of the real systematic uncertainty. When the aforementioned overtraining occurs, it implies that the model catches not only the features of the input variables, but also local statistical fluctuations in the training sample. That can lead to a significant differences in BDT sensitivity when going from testing to final evaluation. The overtraining is controlled by comparing BDT distribution shapes between the test and train samples. Finally, the BDT set up with the best balance of the overtraining and maximal Asimov significance is selected.

In the previous subsection it was mentioned, that test, train and evaluation samples should be statistically independent to not introduce biases in the final predictions. Therefore, the background samples are splitted as following: 24% of events for BDT training, 6% of events for testing and 70% of events for evaluating. And for the signal samples, 54% of events are used for training to compensate the smaller event number, 26% of events for testing and 20% of events for limit evaluation.

Different stau and LSP masses lead to different kinematic signatures. Therefore, three benchmark scenario with stau masses of 100, 150 and 200 GeV are used for training. Since a dramatic decrease in the signal acceptance occurs due to the decrease of the lepton momentum caused by a smaller mass difference between the LSP and the $\tilde{\tau}$, the training is focused only on models with an LSP mass of 1 GeV. In addition, the dissimilarity between the $\mu\tau_h$ and $e\tau_h$ channels as well as between the 2016 and 2017 object identification leads to various

noticeable differences of kinematic variables demanding separate training for each case. In total, 12 separate trainings are used for each benchmark scenario.

To reach an optimal sensitivity, a BDT parameter optimization was performed for different stau points and different years separately. For this goal, the Asimov significance for different BDT options is compared as described before. The list of final options is the following:

- Number of trees = 300-500
- Minimal node size = 0.5% (the minimal fraction of events)
- Maximal tree depth = 3-4 (maximal number of splittings)
- Boost type = real adaptive boost
- Separation type = Gini Index
- Number of bins = 35-50 (distribution binning for splitting)
- Use Randomised Trees (every tree is built not from all variables, but from randomly selected subsample)
- Number of variables for Randomised Trees = 5

Finally, the training is done with a looser requirement on the tau identification criterion, namely the identification with the tight instead of very tight working point and requirement for its $p_T > 20$ GeV to enhance the training and test statistic.

6.5.4 Variable selection and validation

The input variable selection is one of the most important parts of building the MVA model since it drives mainly the resulting prediction quality. Here, variables are selected in the following way: many variables with shape differences between signal and background enter the BDT training and the BDT ranks them according to their separation power. Then, starting from the variable with the highest separation power, they are added one by one to the training and the Asimov significance is computed with the test sample after each step. The variable selection is finished at the point, when adding a new variable does not effect the BDT performance. In this way, the following 13 variables are selected:

1. $p_T^{\ell_1}$, the muon or electron momentum.
2. $p_T^{\ell_2}$, the tau momentum.
3. E_T^{miss} .
4. $m_T = \sqrt{2p_T^{\ell_1} E_T^{\text{miss}} (1 - \cos(\Delta\Phi(\ell_1, E_T^{\text{miss}})))}$, the transverse mass of the lepton and the missing transverse momentum.
5. $\Delta\eta(\ell_1, \ell_2)$, the η angle between tau and lepton momentum.
6. $\Delta\Phi(\ell_1, E_T^{\text{miss}})$, the Φ angle between the lepton and the missing transverse momentum.
7. $\Delta\Phi(\ell_2, E_T^{\text{miss}})$, the Φ angle between the tau and missing transverse momentum.

8. $dR = \sqrt{(\Delta\Phi(\ell_1, \ell_2))^2 + (\Delta\eta(\ell_1, \ell_2))^2}$, the distance between the tau and the lepton motion direction.
9. $m_{T\text{tot}} = \sqrt{m_T^2(\ell_1) + m_T^2(\ell_2)}$, where $m_T(\ell_1)$ and $m_T(\ell_2)$ are the transverse masses of the lepton and the missing transverse momentum and of the tau and the missing transverse momentum, respectively.
10. $M_{\ell_1\ell_2}$, the invariant mass of the lepton and the tau.
11. $M_{ct}^b = \sqrt{2p_T^{\ell_1}p_T^{\ell_2}(1 + \cos(\Delta\Phi(\ell_1, \ell_2)))}$, the contranverse mass combined from visible decay products [123,124]. It is expected to have an end-point around $(m_{stau}^2 - m_{LSP}^2)/m_{LSP}^2$ for the signal.
- 12.

$$M_{T2}(m_s, \vec{s}, m_t, \vec{t}, \vec{p}_T^{\text{miss}}; \chi_1, \chi_2) = \min_{\vec{p}, \vec{q}; \vec{p} + \vec{q} = \vec{p}_T^{\text{miss}}} \left\{ \max[M_T(m_s, \vec{s}, \chi_1, \vec{p}), M_T(m_t, \vec{t}, \chi_2, \vec{q})] \right\}, \quad (6.7)$$

the tranverse mass M_{T2} [125–127], in which $\vec{s}$, $\vec{t}$, $\vec{p}$, $\vec{q}$ and $\vec{p}_T^{\text{miss}}$ are all real two-vectors in x-y plane, and the remaining quantities are real scalars which may all be assumed to be non-negative as they only enter through their squares. As input for the visible particles ($\vec{s}$ and $\vec{t}$) the 4-vectors of the two leptons is given, and the choice of $\chi_1 = \chi_2 = 0$ is made. The tranverse mass for the signal is expected to have an end-point around stau mass.

13. $D_\zeta = p_{\zeta, \text{miss}} - 0.85p_{\zeta, \text{vis}}$, a variable [128] that is used by the CMS $H \rightarrow \tau\tau$ analyses [116], where $p_{\zeta, \text{miss}} = \vec{p}_T^{\text{miss}} \cdot \vec{\zeta}$ and $p_{\zeta, \text{vis}} = (\vec{p}_T^{\ell_1} + \vec{p}_T^{\ell_2}) \cdot \vec{\zeta}$, and $\vec{\zeta}$ is a unit vector along the ζ axis, defined as the bisector of the lepton directions in the transverse plane. The value of α has been optimized to 0.85 to center the D_ζ distribution for Z+jets around 0. This variable gives separation power between Z+jets like events, where visible decay products mostly move in the same direction as invisible decay products, and W+jets like events with more independent visible decay product from invisible decay products flight direction. A sketch of this variable is given in Fig. 6.17.

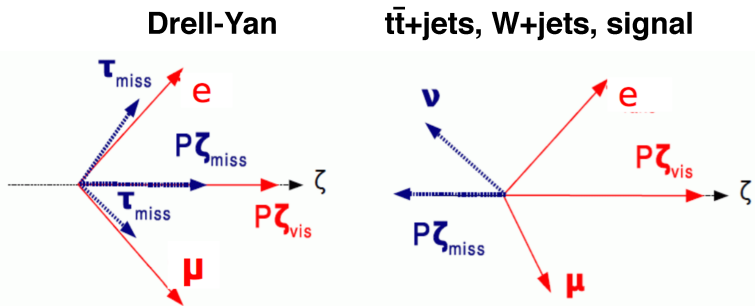


Figure 6.17: Sketch of the D_ζ variable and its features for different processes. τ_{miss} stands for invisible τ decay products.

All variables normalized to unity are shown in Fig. 6.18 for signal and background to illustrate their separation power. For all selected variables shape differences are observed, which help to distinguish signal from background.

The linear correlation coefficients of all variables for the background and the signal samples are shown in Fig. 6.19. It is important to notice, that many of the highly correlated variables do have different correlations for the signal and background models, e.g. M_{T2} and $m_{T\text{tot}}$ have a correlation of about 60% for background and only about 30% for signal events, while $m_{T\text{tot}}$ and $p_T^{\ell_2}$ have a correlation of about 40% for background and above 70% for signal events. The MVA approach is expected to exploit such correlation differences to improve background and signal separation.

The final BDT predictions are expected to be computed for both, data and background samples to compare them. However, some discrepancy between data and background model could be injected by putting into the MVA approach the badly modeled kinematic variables. Therefore, all input kinematic variables should be validated in order to ensure a good description of the data by the background model. Moreover, the BDT is trained after application of the corrections to simulation and with the data-driven estimate of jets faking tau leptons. The BDT input variables distributions are shown in Figs. 6.20 and 6.21 for the $\mu\tau_h$ channel, and in Figs. 6.22 and 6.23 for the $e\tau_h$ channel. All plots include 15% flat uncertainty for illustrative purposes as an approximation of bin dependent systematic uncertainty. In addition, the χ^2 is computed for each distribution to validate the data to background agreement. Based on these values, a sufficient quality of background modeling is confirmed.

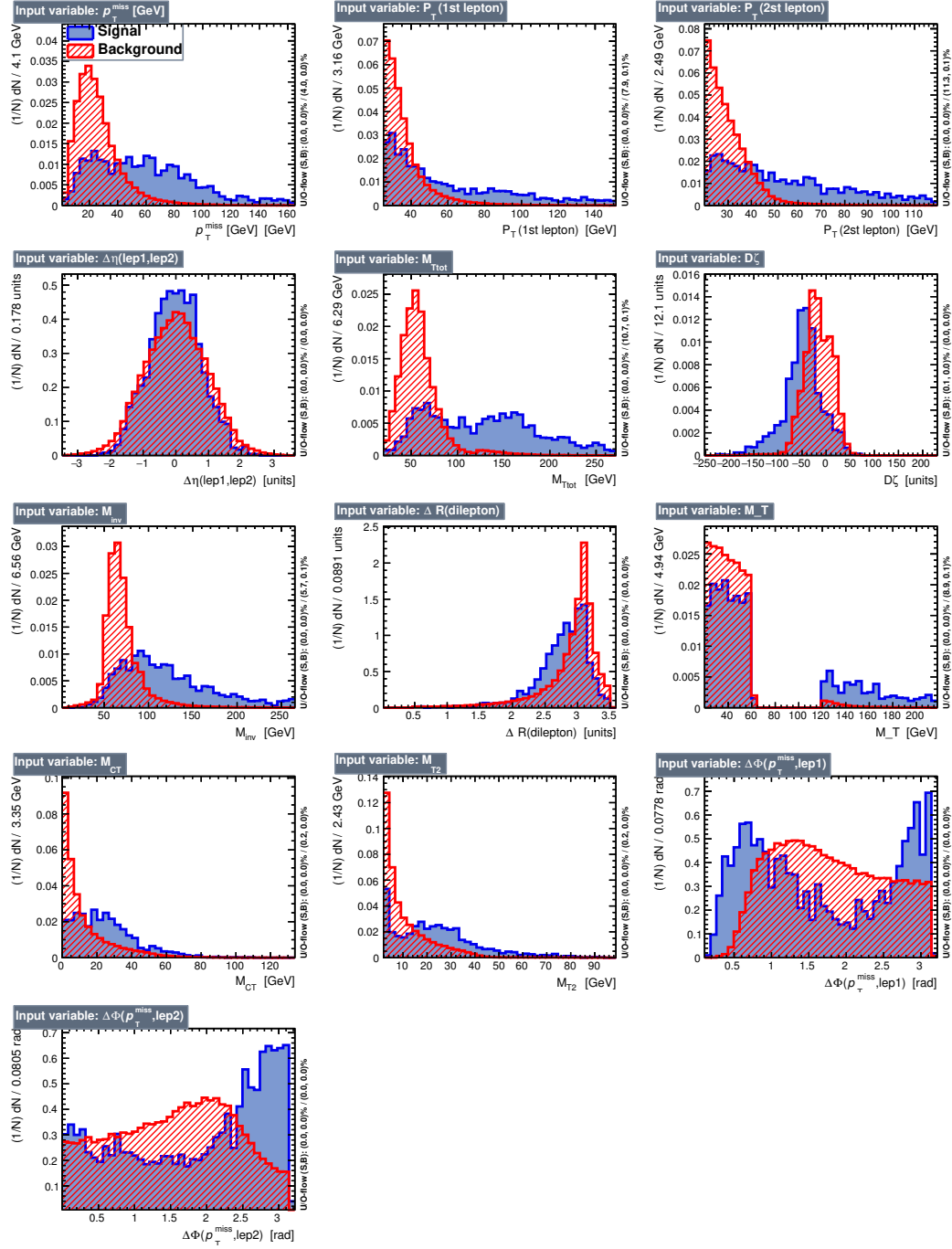


Figure 6.18: Shape comparison between background and signal for the main variables with a stau mass of 100 GeV and an LSP mass of 1 GeV. All distributions are normalized to unity.

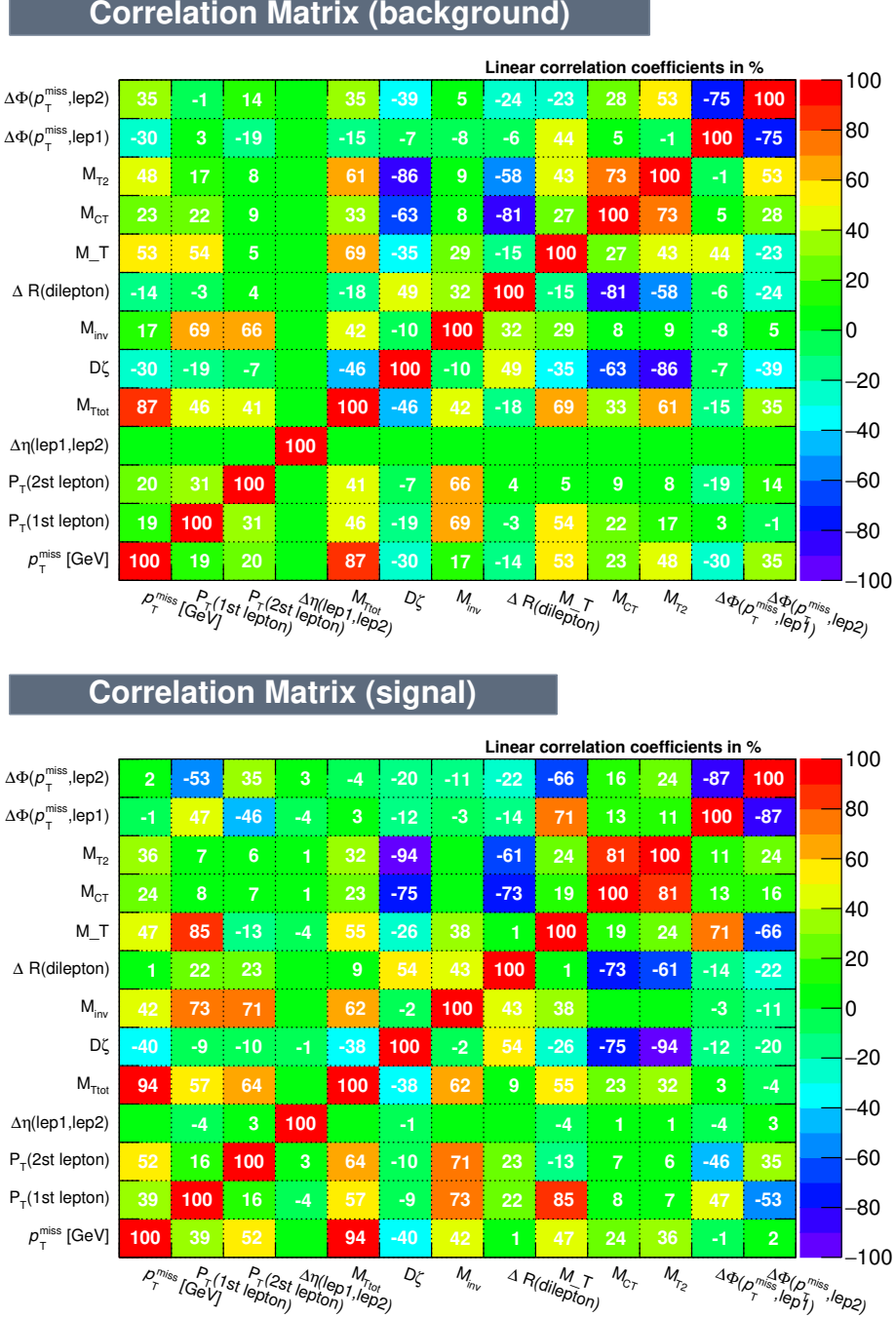
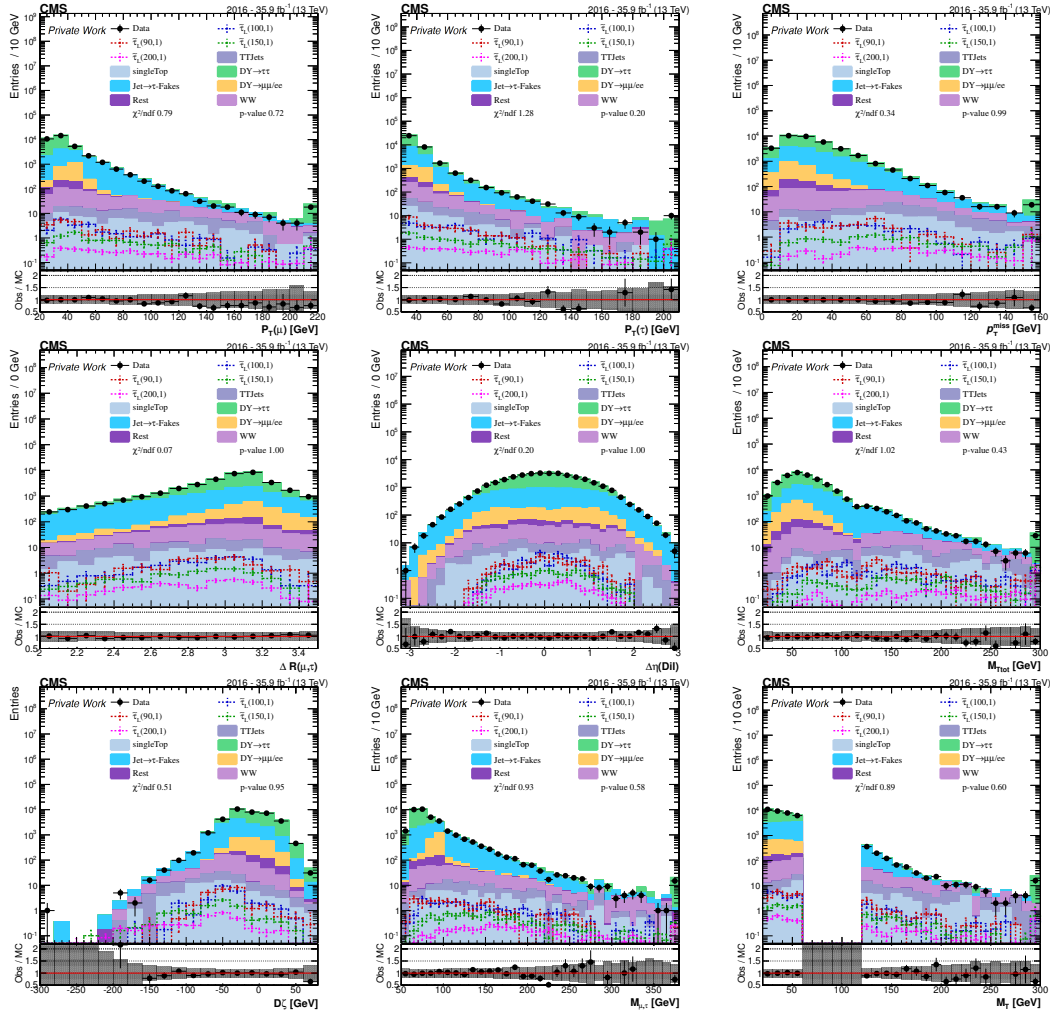
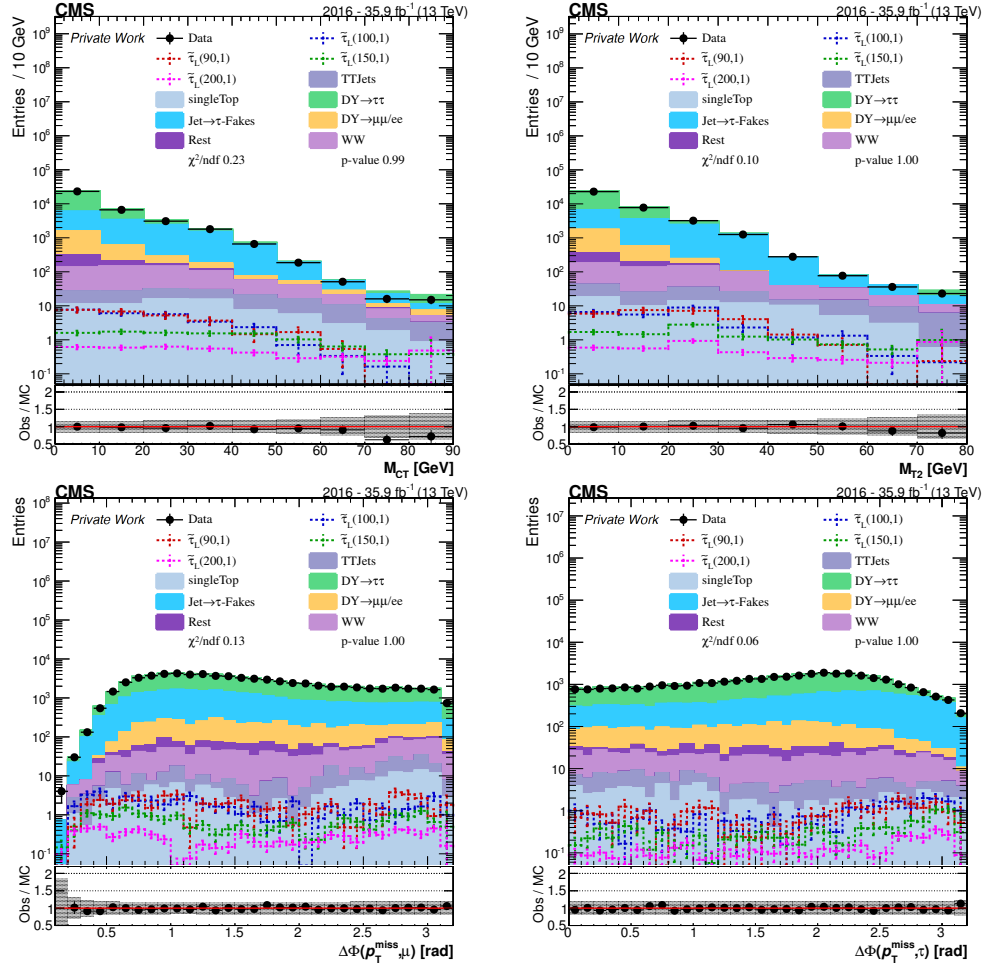


Figure 6.19: The linear correlation coefficients for all backgrounds (top) and a signal point (bottom) with a $\tilde{\tau}$ mass of 100 GeV and an LSP mass of 1 GeV.


 Figure 6.20: Control plots for the $\mu\tau_h$ channel for 2016.


 Figure 6.21: Control plots for the $\mu\tau_h$ channel for 2016.

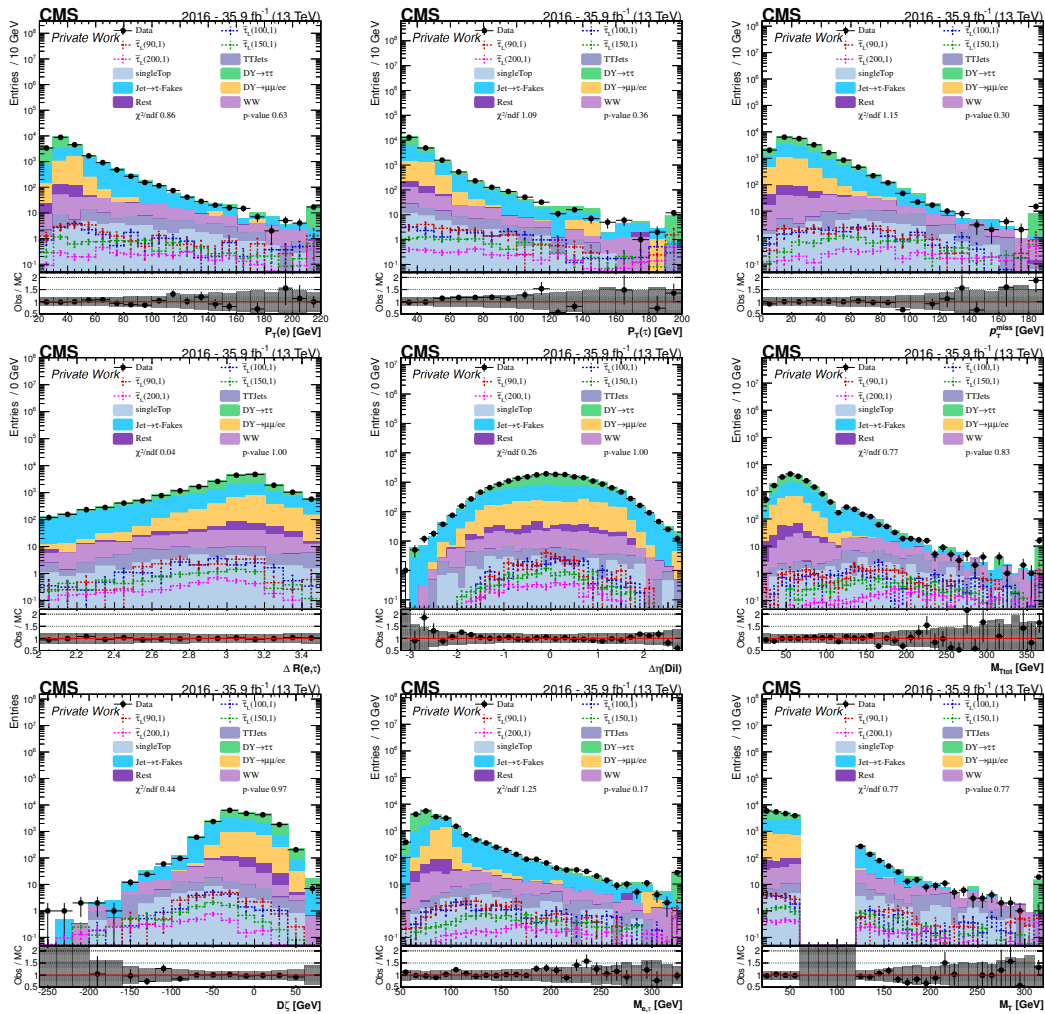
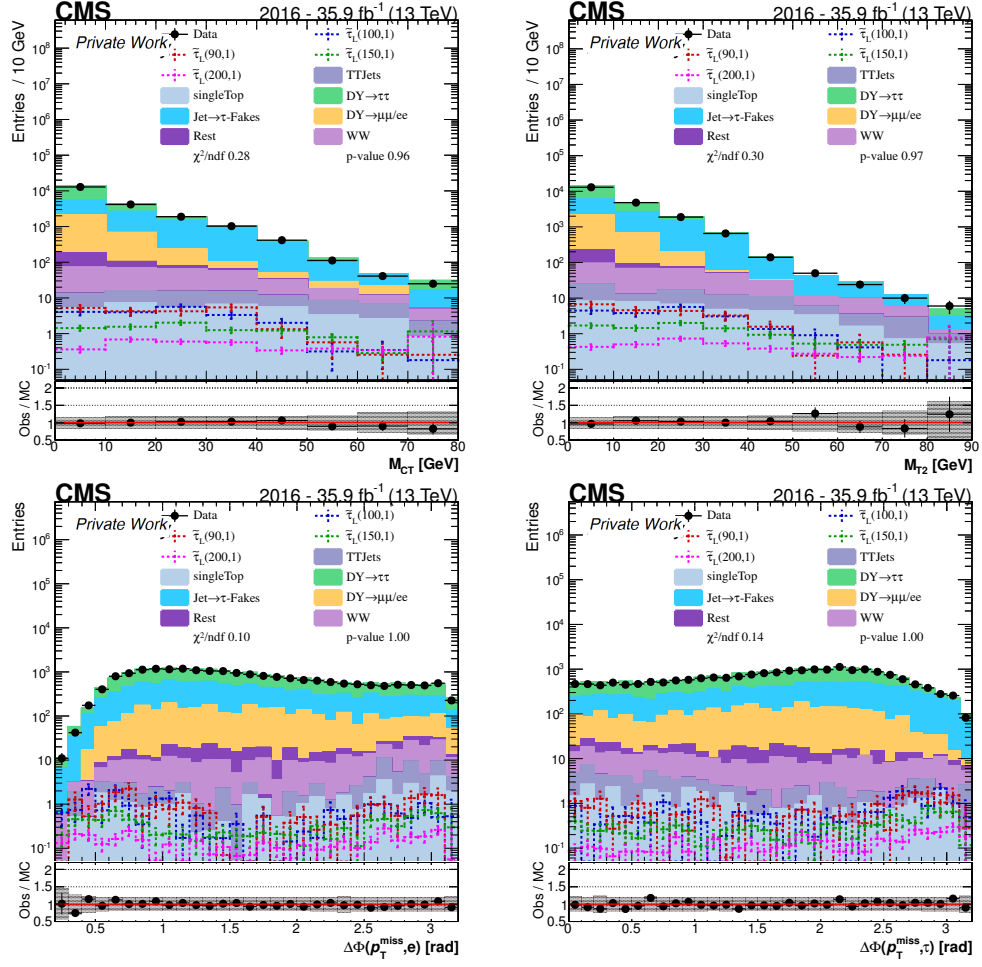
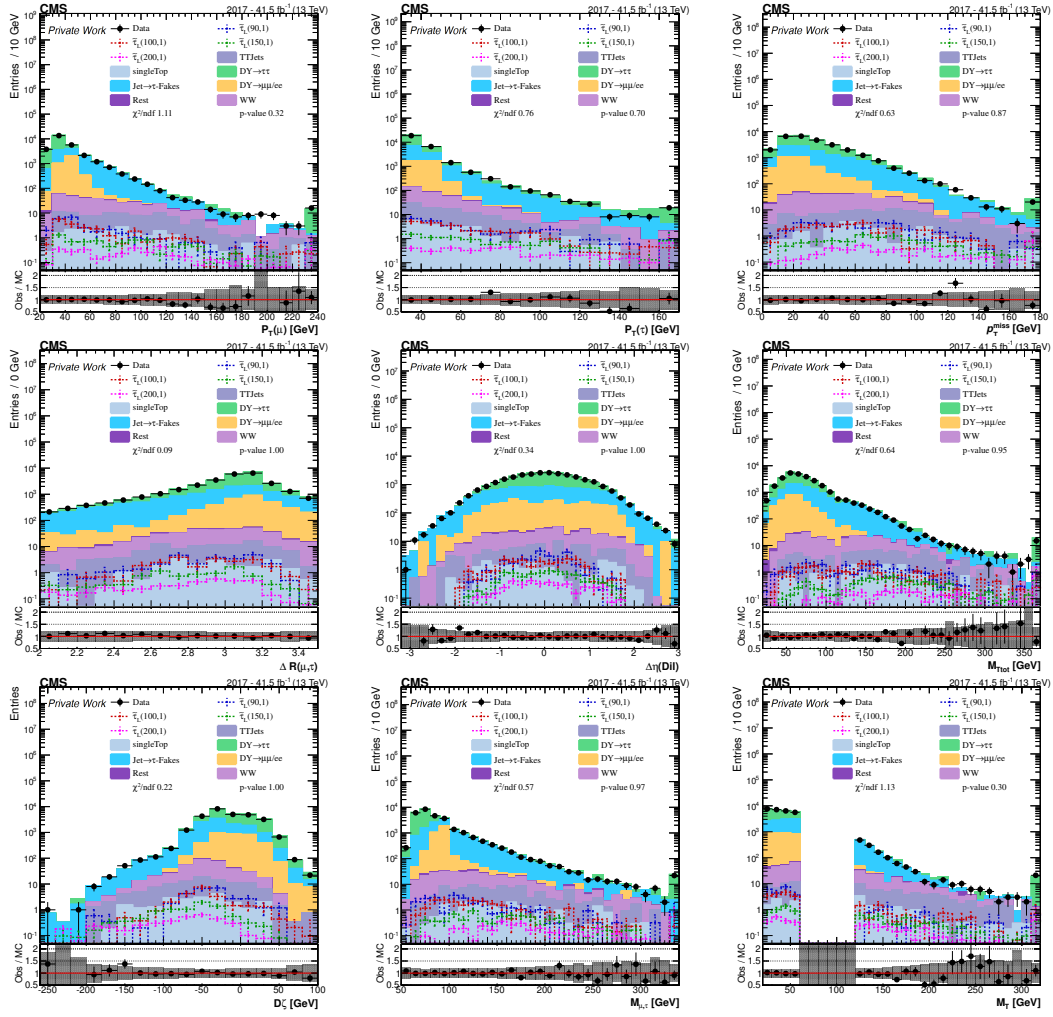
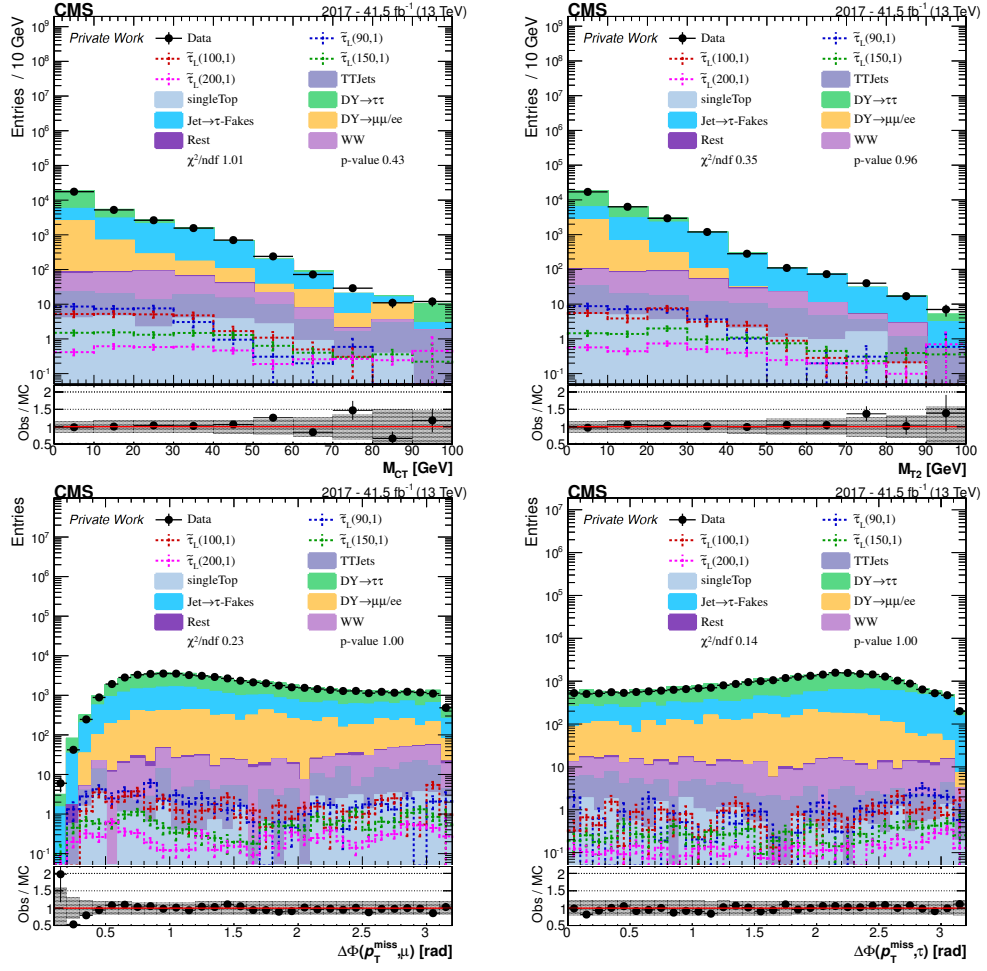
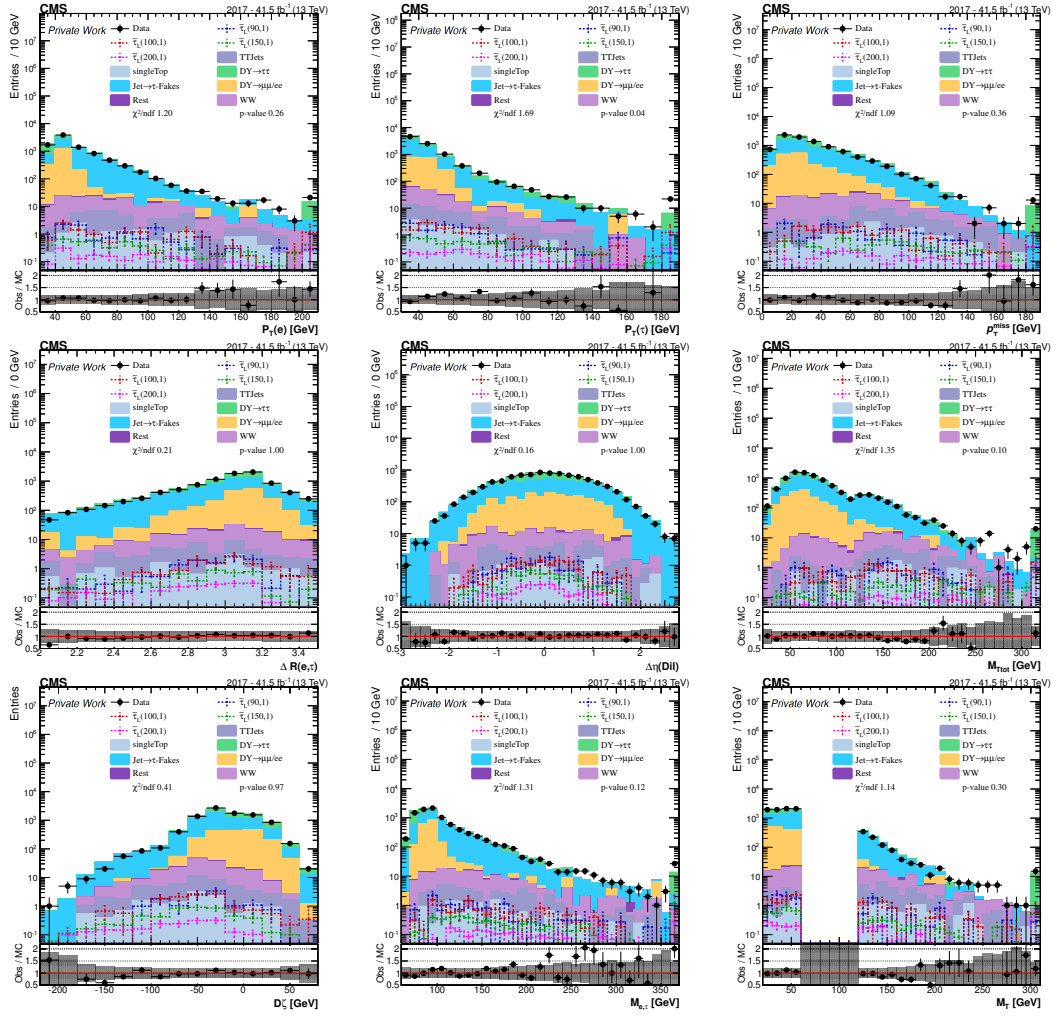


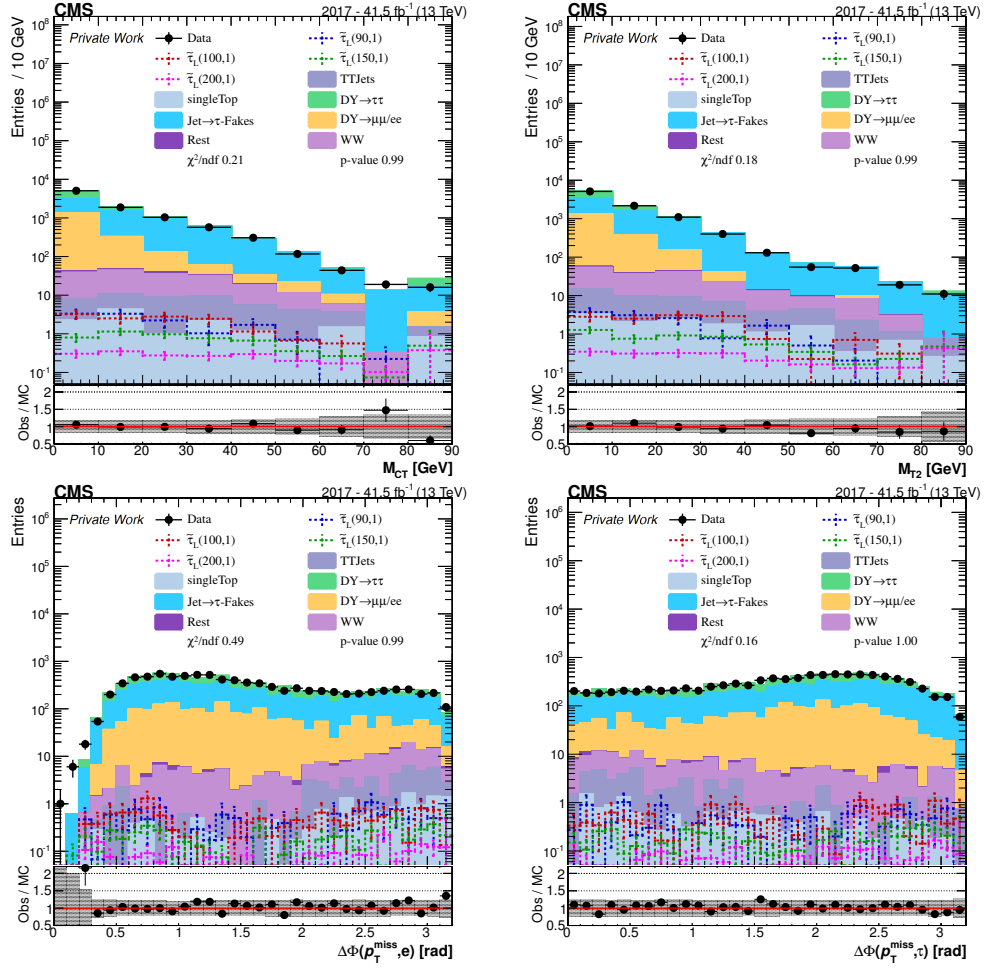
Figure 6.22: Control plots for the $e\tau_h$ channel for 2016.


 Figure 6.23: Control plots for the $e\tau_h$ channel for 2016.


 Figure 6.24: Distributions of the kinematic variables for the $\mu\tau_h$ channel for 2017.


 Figure 6.25: Distributions of the kinematic variables for the $\mu\tau_h$ channel for 2017.


 Figure 6.26: Distributions of the kinematic variables for the $e\tau_h$ channel for 2017.


 Figure 6.27: Distributions of the kinematic variables for the $e\tau_h$ channel for 2017.

6.5.5 BDT binning optimization

The main sensitivity for the stau analysis is expected to come from events with the high BDT score. Therefore, the binning optimization in the region with high BDT score is particularly important.

In the first step, the Asimov significance dependence on BDT selection requirement is plotted. An example of this distribution is shown together with the simple formula $s/\sqrt{s+b+(0.2b)^2}$, where s is the signal and b the background number of events after certain BDT election requirement, in Fig. 6.28 for training with $\tilde{\tau}$ mass of 100 GeV and LSP mass of 1 GeV. In addition, background rejection probability and signal efficiency are shown as well as the positions where three (and one) signal events are expected given the luminosity of the 2016 data-taking. The final optimization is done by combining the region starting from the Asimov significance maximum up to the BDT equal to one into one bin. In other words, the last bin is merged from bins after the BDT selection with maximum significance.

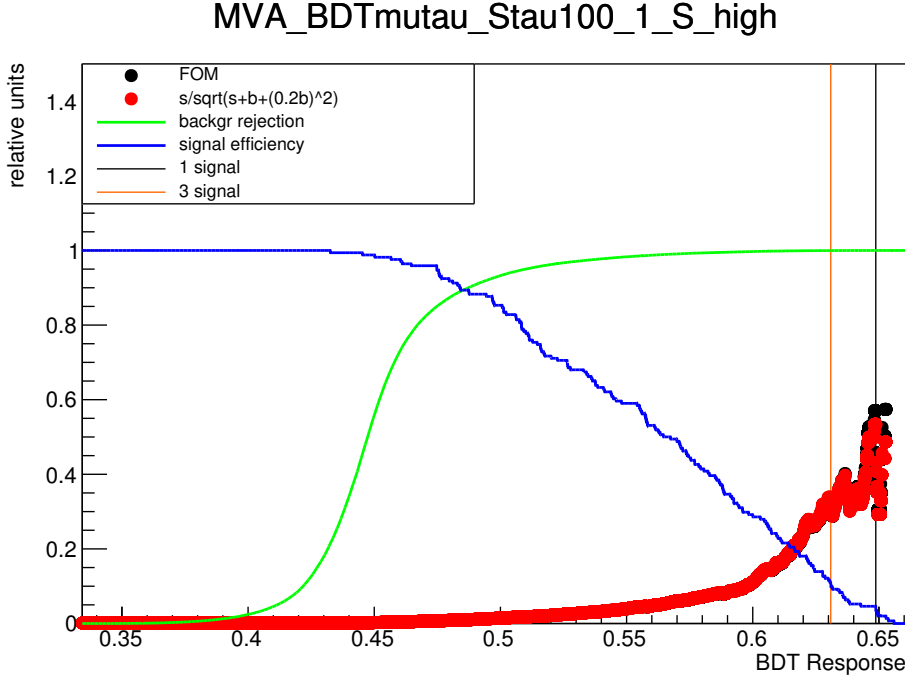


Figure 6.28: Asimov significance dependence from BDT selection requirement for training with $\tilde{\tau}$ mass of 100 GeV and LSP mass 1 GeV, in the channel for 2016. The 1 signal and 3 signal lines represent the BDT selection, after which 1 and 3 signal events weighted to proper luminosity and cross section are expected.

6.5.6 BDT validation

In the following sections, the BDT discriminant is validated in several control regions, to show the performance for each of the main backgrounds separately and to derive the BDT shape systematic uncertainty.

Control region with inverted b-quark tagging requirement

As an additional validation region, a control region orthogonal to the signal region was constructed to validate the BDT distribution for $t\bar{t}$ + jets and single top events, especially in the SR with high BDT values. The event selection for this CR is the same as the one used for the $t\bar{t}$ + jets background normalization. The BDT distributions for several trainings are shown in Fig. 6.29 and 6.30. The background composition, as well as the agreement between data and simulation look reasonable.

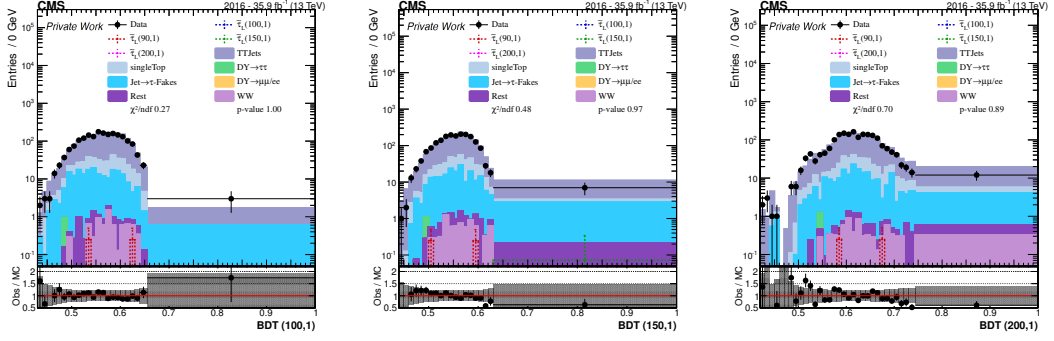


Figure 6.29: BDT distributions in an orthogonal CR obtained by requiring at least one b-tagged jet for 2016.

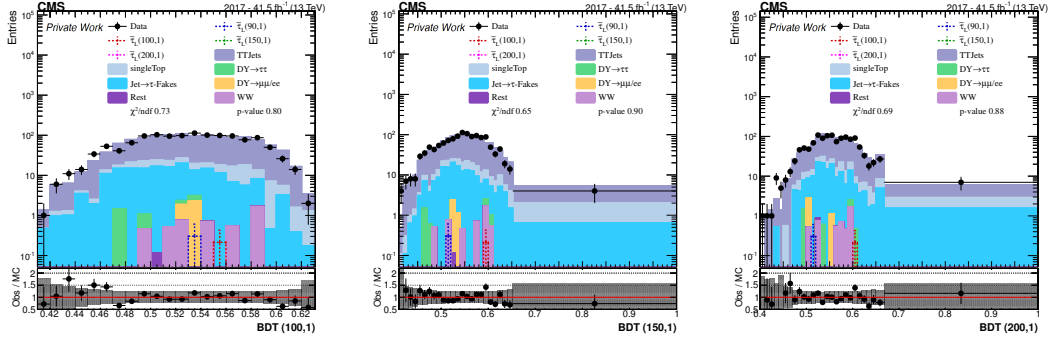


Figure 6.30: BDT distributions in an orthogonal CR obtained by requiring at least one b-tagged jet for 2017.

Control region with inverted m_T selection

To validate the fake estimation coming mostly from W+jets and background with genuine taus coming from WW events, an additional control region is constructed by inverting the m_T selection. The contribution from WW is increased by putting an additional selection on m_T calculated with tau and E_T^{miss} , $60 < m_T < 120$. Moreover, the selection on $\Delta\Phi(\text{W}, \text{jet}) > 2.5$ is used to make this CR fully orthogonal to the fake derivation region. However, an additional CR with higher WW purity is discussed below. The BDT distributions for the three trainings with different $\tilde{\tau}$ masses are shown in Fig. 6.31.

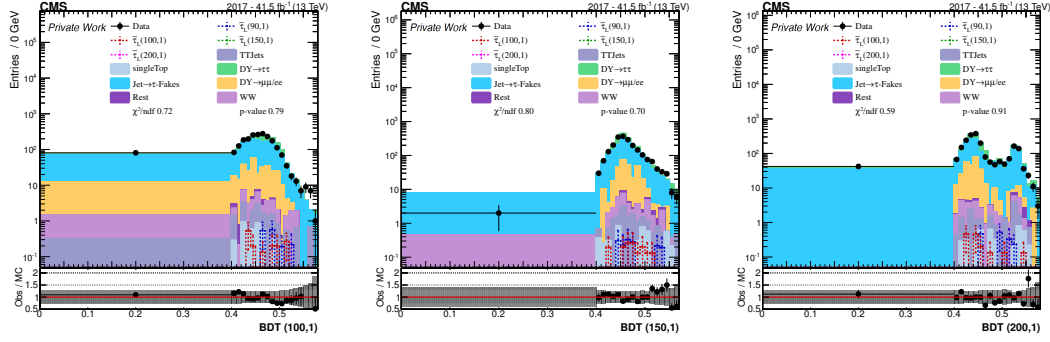


Figure 6.31: BDT distributions in an orthogonal CR obtained by inverting the m_T selection for 2017.

Additional control region for the WW background

The WW background prediction is validated in a CR constructed with oppositely charged muon-electron pair selection. An additional selection on $M_{\mu e} > 90$ and $N_{\text{jet}} = 0$ is applied to increase the WW purity. The BDT distributions for relevant trainings are shown in Fig. 6.32.

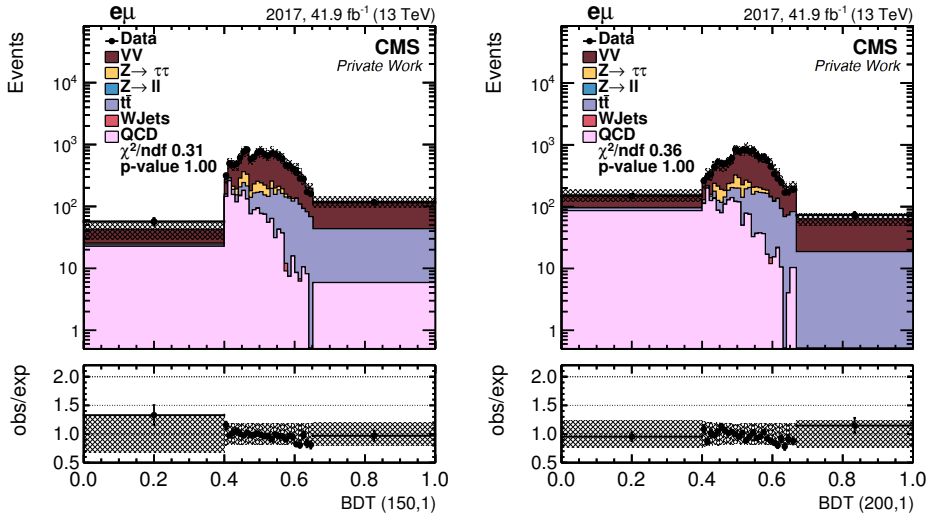


Figure 6.32: BDT distributions in an orthogonal CR obtained with the muon-electron pair selection for 2017.

Control region for the DY background.

The DY background prediction is validated by constructing a CR with m_T calculated with μ and E_T^{miss} , and $m_T > 20 \text{ GeV}$ to be orthogonal with SR.

An additional selection on $50 < M_{\ell\tau_h} < 80 \text{ GeV}$ and $N_{\text{jet}} = 0$ is applied to increase DY purity. The BDT distributions for relevant trainings are shown in Fig. 6.33.

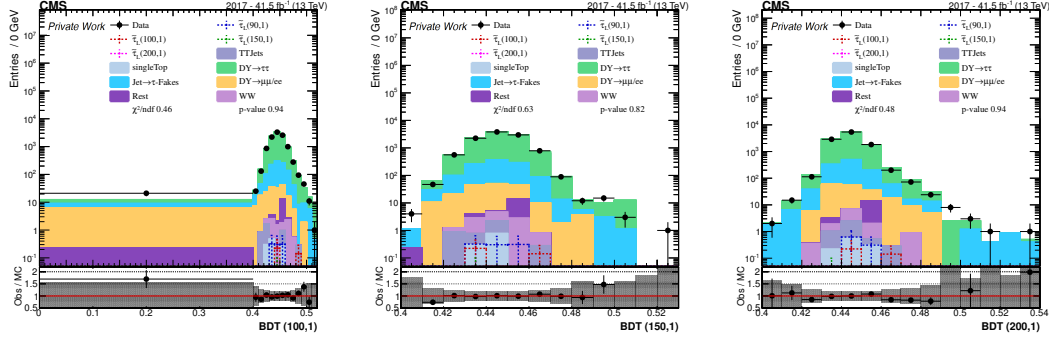


Figure 6.33: BDT distributions in an orthogonal CR obtained by inverting the m_T selection for 2017.

6.6 Systematic uncertainty

The analysis sensitivity to new-physics models is highly dependent on the uncertainties on the background and signal modeling, which is divided into statistical and systematic uncertainty. While the statistical error gives the dominant contribution to the sensitivity due to low occupancy in significant BDT regions, the estimation of systematic uncertainties is also substantial. The sources of the systematic uncertainties, in turn, can be further categorized as the reconstructed object related uncertainties, the background modeling uncertainties, and other sources.

The physics object reconstruction and identification uncertainties are related to an imperfect modeling of the real detector response and/or inaccuracy of the reconstructed objects properties. The values of such uncertainties are given by the corresponding CMS physics object groups in terms of percents from the central value or some values of upward and downward 1σ fluctuations. For example, the muon energy is varied by 1% and the impact on the BDT distribution is propagated as an uncertainty. As an another example, the jet energy uncertainty depends on the jet p_T , therefore up and down variation is also done in p_T dependent way. However the final uncertainties on the jet energy scale are below 3% for the energies considered in this analysis. All systematic uncertainties are summarized in Table 6.6.

The uncertainties coming from the background modeling have the following sources:

- The uncertainty on the Z+jets scale factor derived in control region in the Section 6.4.1 is estimated by monitoring the variation of the scale factor taking into account the upwards and downwards fluctuation within aforementioned object reconstruction uncertainties. The final value is estimated as 2% from the central value.

- The uncertainty source coming from $t\bar{t}$ normalization is assigned based on the corresponding control region purity (86%). Approximately half of the impurity is taken as an uncertainty (5%), that is applied to act as the normalization uncertainty for $t\bar{t}$ background in the final exclusion limits evaluation.
- For the WW normalization uncertainty estimation, a corresponding control region defined in Section 6.5.6 is taken. The average purity of a WW event in the high BDT region is around 75%. Therefore an uncertainty of 25% from the central value is assigned as WW normalization uncertainty.
- For the estimation of the misidentified τ background uncertainty, the purity in the sideband regions used to extract the transfer factor is 85%. That leads to a systematic uncertainty of 15%. Furthermore, each sufficient physics object related to systematic uncertainty is propagated to the transfer factor calculation.
- The cross section uncertainties for other rare background processes are taken to be 25%. This conservative value is taken to cover the uncertainty on the cross section of processes like single top production [129].

In addition, a BDT shape uncertainty is assigned based on the CRs mentioned in Section 6.5.6. This is done by constructing the χ^2 test in all CRs taking into account additional flat systematic uncertainty with a floating value of this uncertainty. Then, this uncertainty is estimated by requiring a p-value $> 68\%$ in all CRs. From this study, the BDT shape uncertainty is assigned to be 9%.

The uncertainty on the integrated luminosity measurement is taken into account for all background estimates based on simulation, as well as for signal processes. This uncertainty corresponds to 2.5% and 2.3% for the 2016 [130] and 2017 [131] data, respectively. In addition, the renormalization and factorization scales and PDF related uncertainties are also propagated to the limit setting.

Between the 2016 and 2017 data analyses, all uncertainties arising from statistical limitations are uncorrelated. All systematic uncertainties are treated as correlated except the uncertainty in the integrated luminosity, which is assumed to be uncorrelated.

Since bins with high BDT score contain only a few events, the statistical uncertainty is found to be dominant in the analysis. From the systematic uncertainty sources, the most dominant is the WW background normalization uncertainty, since the WW background has similar topology as the signal, and contributes significantly to the high BDT bins. The τ energy uncertainty is the second dominant systematic uncertainty source, since it significantly influences the selection efficiency.

6.7 Limit setting methodology

Every measurement in physics should come with uncertainties showing our imperfection in knowing reality. In a similar way, it's impossible to say definite "yes" or "no" while talking about the existence of new particles. Therefore, the conclusion about the study is set in terms of the probability of one or another theory model to describe the data.

If data is well described by the SM, the exclusion on the range of the parameters of a new model is set. The current approach accepted in most modern high energy physics analyses is to use a modified frequentist method [132, 133] referred to as CL_s . The new physics model is

Table 6.6: Systematic uncertainties considered for background and signal.

Systematic	Background	Signal	Variation
$t\bar{t}$ normalization	✓	-	3%
Z+jets normalization	✓	-	5%
Normalization of other background processes	✓	-	10-25%
Luminosity	✓	✓	2.5%
$\mu(e)$ identification and isolation	✓	✓	2(3)%
Jets misidentified as hadr. τ leptons	✓	-	10%
Leptons misidentified as hadr. τ leptons	✓	-	10%
Tau identification	✓	✓	5%
BDT shape uncertainty	✓	✓	9%
Zp_T	✓	-	1-8%
Muon Energy Scale (MES)	✓	✓	$\pm 1\%$
Electron Energy Scale (EES)	✓	✓	1 (2.5)% for Barrel (EndCap)
Tau Energy Scale	✓	✓	$\pm 3\%$
Jet Energy Scale (JES)	✓	✓	$\pm 1\sigma$
MET Recoil	✓	-	1-10%
Unclustered MET	✓	-	$\pm 1\sigma$
PDF	✓	✓	max variation
Q^2	✓	✓	max variation
Bin-by-bin uncert.	✓	✓	uncorrelated
Jets mis/ed as hadr. with varied JES	✓	-	$\pm 1\sigma$
Jets mis/ed as hadr. with varied MES	✓	-	$\pm 1\%$
Jets mis/ed as hadr. with varied EES	✓	-	1 (2.5)% for Barrel (EndCap)

considered to be rejected when $CL_s \leq \alpha$, where $1 - \alpha$ is called confidence level and usually is taken as 95%. The CL_s is defined as following:

$$CL_s = \frac{p_\mu}{1 - p_b} = \frac{P(t \geq t_{obs}|s + b)}{P(t \geq t_{obs}|b)}, \quad (6.8)$$

where p_b and p_μ are p-values for the background-only hypothesis, and the combined signal and background hypothesis with the signal strength of μ , respectively. The signal strength is a multiplication factor applied to signal normalization. The conditional probabilities of the test statistic (t) to have higher value than the observed test statistic (t_{obs}) are determined as $P(t \geq t_{obs}|s + b)$ and $P(t \geq t_{obs}|b)$. The first probability is defined with respect to the assumption that the combined signal and background hypothesis is true, while the second one implies the background only hypothesis is true. The aforementioned equation can be intuitively interpreted as saying that a particular signal model is excluded because it is α times less probable than to observe the collected data when background only hypothesis is true than it is when the background combined with signal hypothesis is true.

The most precise way of calculating the aforementioned conditional probabilities is to estimate the probability density function of the test statistics by generating a large number of MC toy pseudo-experiments. However, this approach is not feasible in terms of computing power for computing limits with a big number of signal models, which is the typical situation in SUSY search. Therefore, the test statistic can be analytically approximated to avoid toy pseudo-experiments simulation under the assumption of relatively large data sample size. Such approach is referred as an asymptotic approximation [134,135] of the CL_s and is widely used in the new physics search.

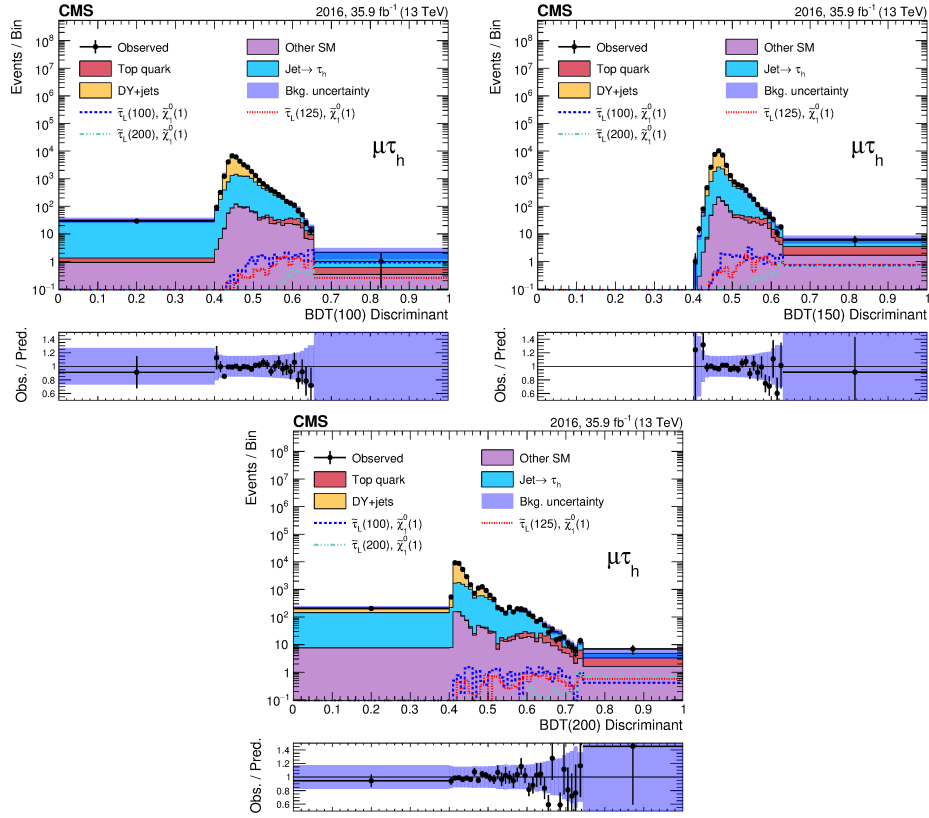
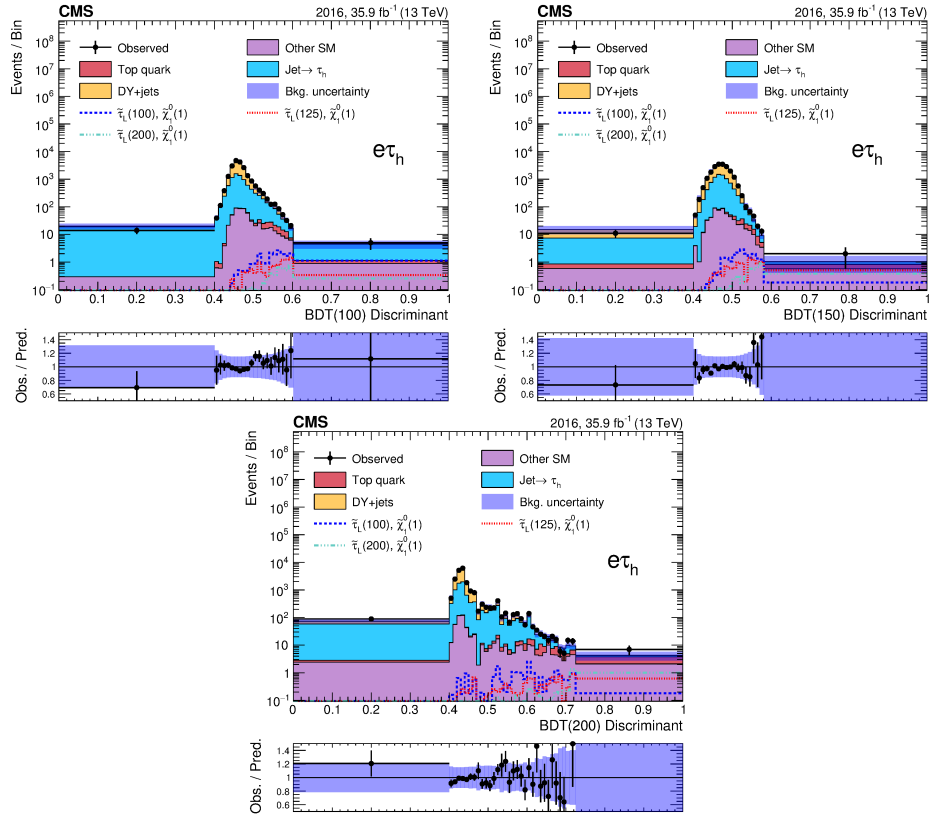
Within the stau search, CL_s is evaluated with the full BDT discriminator binned shape after the preliminary background model is fit to data. Including bins highly populated by background benefits the sensitivity by constraining nuisance parameters.

6.8 BDT analysis results with 2016 and 2017 data

The accuracy of the background modeling is validated in the distributions of the kinematic variables after the main selection and the BDT distributions in the CRs. As a next step, the BDT distributions are used for setting exclusion limits on stau model parameters. Distributions of the BDT trained for all benchmark signal models are shown in Figs. 6.34 and 6.35 for the 2016 analysis, and in Figs. 6.36 and 6.37 for the 2017 analysis. As before, all error bars of the BDT distributions are drawn with an additional flat systematic uncertainty of 15%. The overall agreement between data and the SM background model looks consistent within the given uncertainty, therefore, the upper limits on the stau production signal strength are evaluated.

Before applying the CL_s approach on the whole BDT distribution, the whole background shape is fitted to data. To monitor the fit outcome, the distributions of the BDT trained for a $\tilde{\tau}$ mass of 100 GeV and an LSP mass of 1 GeV are shown before and after the maximum likelihood fit to the data in Fig. 6.38 for the $\mu\tau_h$ final state.

The data is consistent with the prediction for the SM background for the all 6 discriminators. The predicted and observed event yields in the last BDT bins, which are the most sensitive to signal, are summarized in Tables 6.7-6.8. For the statistical interpretation of these results, normalization uncertainties affecting background and signal predictions are generally


 Figure 6.34: BDT distributions for the $\mu\tau_h$ channel for 2016 in the SR.

 Figure 6.35: BDT distributions for the $e\tau_h$ channel for 2016 in the SR.

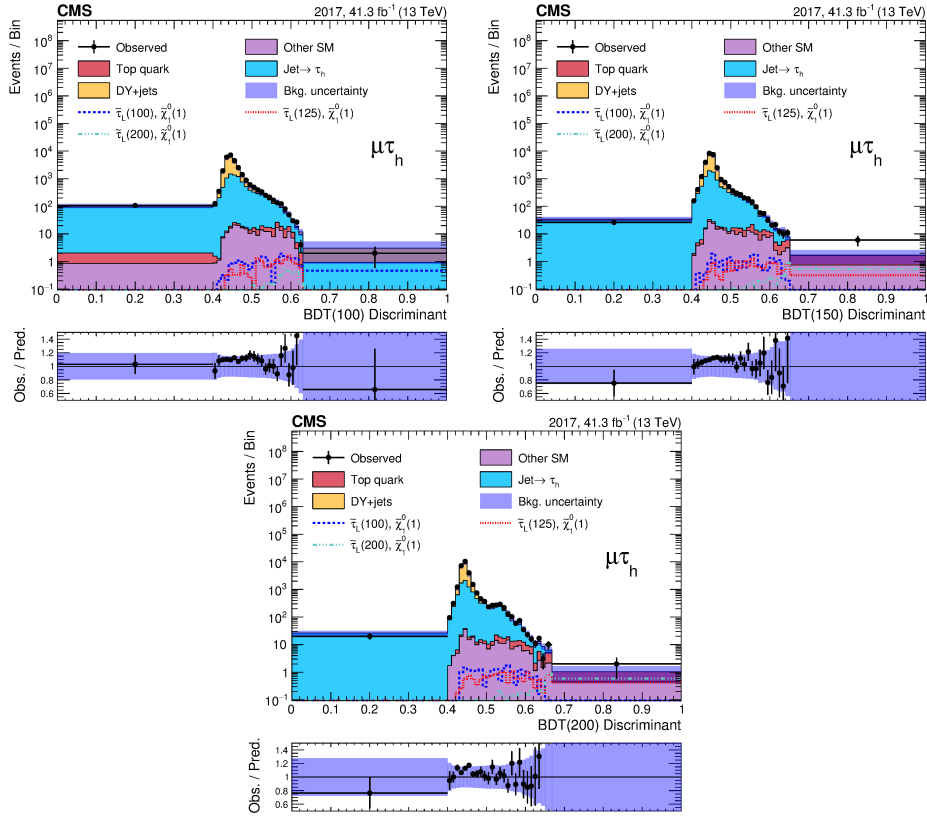


Figure 6.36: BDT distributions for the $\mu\tau_h$ channel for 2017 in the SR.

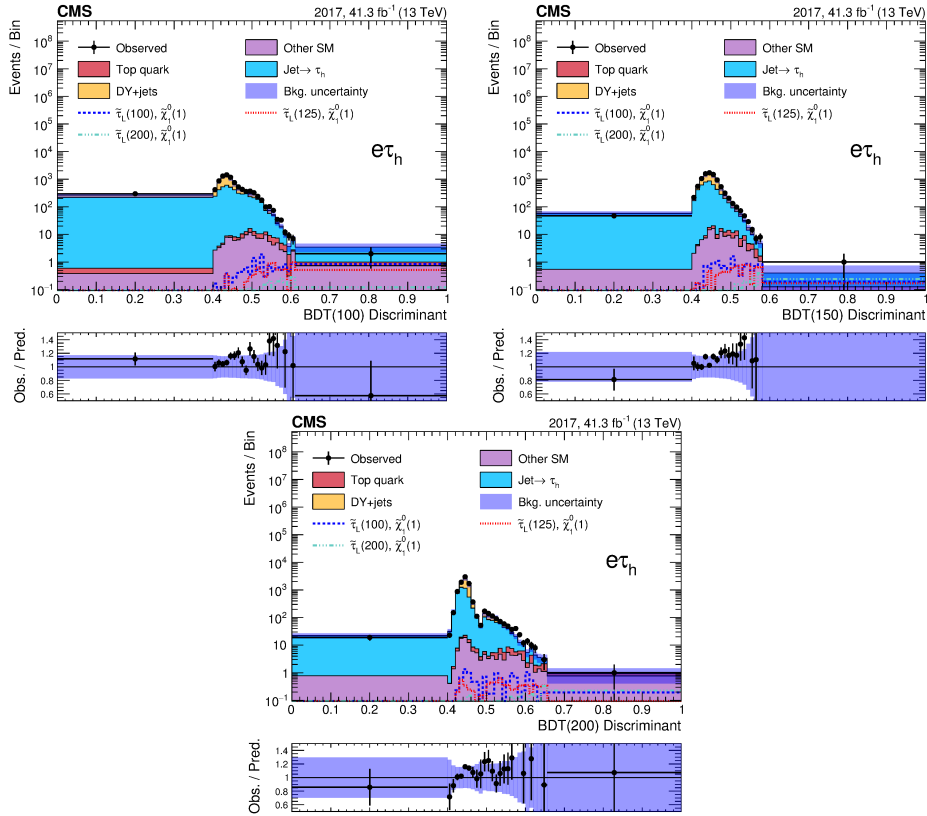


Figure 6.37: BDT distributions for the $e\tau_h$ channel for 2017 in the SR.

assumed to be log-normal distributed.

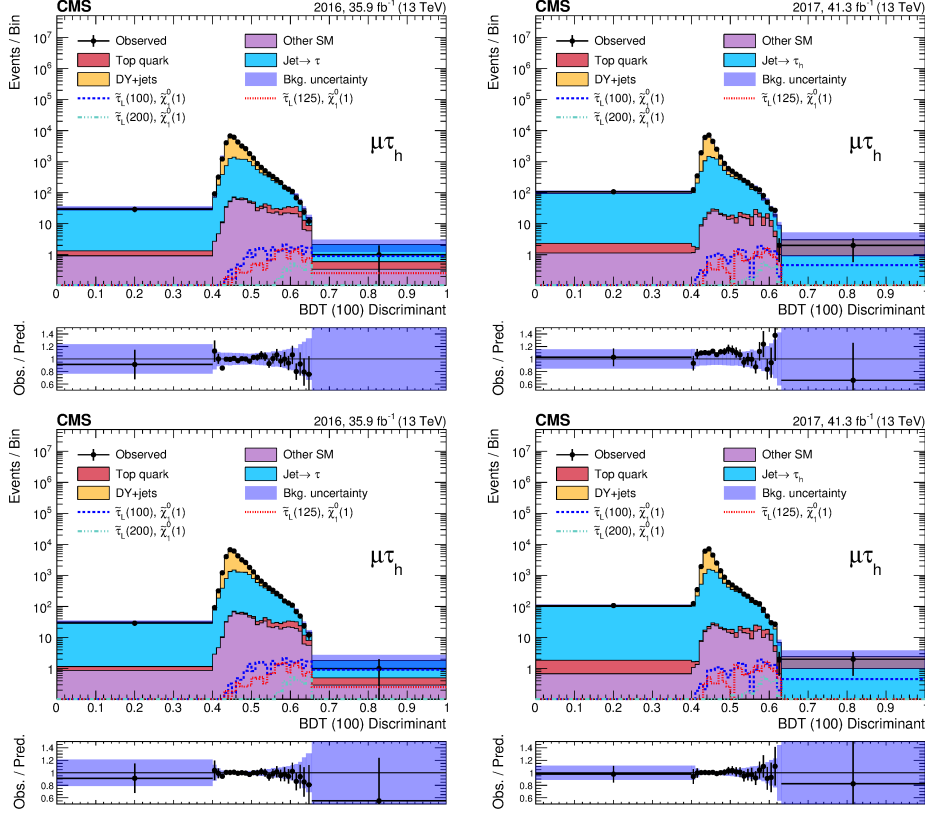


Figure 6.38: Distributions of the BDT discriminant for the BDT trained for a $\tilde{\tau}$ mass of 100 GeV and an LSP mass of 1 GeV (BDT (100)) in the $\mu\tau_h$ final state for the 2016 (left) and 2017 (right) datasets, before (top) and after (bottom) the maximum likelihood fit to the data. Predicted signal yields are also shown for benchmark models with $m(\tilde{\tau}) = 100, 125$, and 200 GeV, $m(LSP) = 1$ GeV.

Table 6.7: Predicted background yields and observed event counts in the most sensitive last bins of the BDT distributions for each training, for the $e\tau_h$ and $\mu\tau_h$ final states, corresponding to 36.9fb^{-1} of data collected in 2016. The numbers in parentheses in the first row are the $\tilde{\tau}$ and LSP masses corresponding to the signal model of left-handed $\tilde{\tau}$ pair production used to train each BDT. In the bottom row, the list of the corresponding predicted signal yields in the last bin of the BDT distribution is show.

BDT training	BDT($\mu\tau_h, 100, 1$)	BDT($\mu\tau_h, 150, 1$)	BDT($\mu\tau_h, 200, 1$)	BDT($e\tau_h, 100, 1$)	BDT($e\tau_h, 150, 1$)	BDT($e\tau_h, 200, 1$)
Misidentified τ_h	$1.6 \pm 0.8 \pm 0.3$	$2.3 \pm 1.0 \pm 0.4$	$1.5 \pm 0.8 \pm 0.3$	$3.3 \pm 1.1 \pm 0.5$	$0.2 \pm 0.4 \pm 0.1$	$0.5 \pm 0.7 \pm 0.3$
DY+jets	< 0.1	$0.8 \pm 0.8 \pm 0.1$	< 0.1	< 0.1	< 0.1	$0.1 \pm 0.1 \pm 0.1$
Top quark	$0.3 \pm 0.3 \pm 0.1$	$1.8 \pm 1.2 \pm 0.2$	$1.7 \pm 1.2 \pm 0.6$	$0.2 \pm 0.2 \pm 0.1$	$0.2 \pm 0.2 \pm 0.1$	$1.4 \pm 0.8 \pm 2.0$
Other SM	$0.3 \pm 0.3 \pm 0.1$	$1.4 \pm 0.6 \pm 0.5$	$1.5 \pm 0.6 \pm 0.4$	$0.9 \pm 0.5 \pm 0.4$	$0.6 \pm 0.4 \pm 0.5$	$2.0 \pm 0.7 \pm 1.0$
Total prediction	$2.1 \pm 0.9 \pm 0.4$	$6.4 \pm 1.8 \pm 1.0$	$4.6 \pm 1.6 \pm 0.9$	$4.5 \pm 1.3 \pm 0.8$	$1.0 \pm 0.6 \pm 0.5$	$4.2 \pm 1.3 \pm 1.8$
Observed	1	6	7	5	2	7
Signal	$1.3 \pm 0.4 \pm 0.2$	$0.9 \pm 0.2 \pm 0.1$	$0.7 \pm 0.1 \pm 0.5$	$1.5 \pm 0.4 \pm 0.2$	$0.4 \pm 0.1 \pm 0.1$	$1.0 \pm 0.1 \pm 0.2$

Table 6.8: Predicted background yields and observed event counts in the most sensitive last bin of each of the BDT distributions for each training, for the $e\tau_h$ and $\mu\tau_h$ final states, corresponding to 41.3 fb^{-1} of data collected in 2017. The numbers in parentheses in the first row are the $\tilde{\tau}$ and LSP masses in the signal model of left-handed $\tilde{\tau}$ pair production used to train each BDT. In the bottom row, the list of the corresponding predicted signal yields in the last bin of the BDT distribution is show.

BDT training	BDT($\mu\tau_h,100,1$)	BDT($\mu\tau_h,150,1$)	BDT($\mu\tau_h,200,1$)	BDT($e\tau_h,100,1$)	BDT($e\tau_h,150,1$)	BDT($e\tau_h,200,1$)
Misidentified τ_h	$0.9 \pm 0.5 \pm 0.4$	<0.1	<0.1	$2.5 \pm 0.9 \pm 1.3$	$0.3 \pm 0.3 \pm 0.1$	<0.1
DY+jets	$2.1 \pm 2.1 \pm 3.3$	<0.1	<0.1	<0.1	<0.1	<0.1
Top quark	<0.1	$0.9 \pm 0.4 \pm 0.8$	$0.6 \pm 0.5 \pm 0.5$	$0.3 \pm 0.3 \pm 0.1$	<0.1	$0.2 \pm 0.2 \pm 0.2$
Other SM	<0.1	$1.0 \pm 0.7 \pm 1.6$	$0.6 \pm 0.6 \pm 1.1$	$1.0 \pm 0.7 \pm 1.5$	$0.2 \pm 0.2 \pm 0.5$	$1.0 \pm 0.6 \pm 1.6$
Total prediction	$3.0 \pm 2.2 \pm 3.1$	$2.0 \pm 1.0 \pm 2.0$	$1.2 \pm 0.7 \pm 1.3$	$3.7 \pm 1.1 \pm 2.3$	$0.4 \pm 0.4 \pm 0.5$	$1.2 \pm 0.7 \pm 1.6$
Observed	2	6	2	2	1	1
Signal	$0.6 \pm 0.3 \pm 0.1$	$0.4 \pm 0.1 \pm 0.8$	$0.6 \pm 0.1 \pm 0.3$	$1.0 \pm 0.4 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$	$0.2 \pm 0.1 \pm 0.1$

6.8.1 Direct $\tilde{\tau}$ production interpretation

The results are used to set limits on the cross section for the production of $\tilde{\tau}$ pairs in the context of simplified models using BDT distributions in a statistical combination between 2016 and 2017 analysis, and the $\mu\tau_h$ and $e\tau_h$ channels. The assumption of the $\tilde{\tau}$ decaying with a branching fraction of 100% to a τ lepton and an LSP is considered. For the 95% confidence level (CL) upper limits setting the aforementioned CL_s criterion is used.

For the signal points with $\tilde{\tau}$ masses of 100, 150 and 200 GeV, the BDT discriminant trained with the corresponding $\tilde{\tau}$ mass is used for limit evaluation. However, limit evaluation with other mass points is done with the BDT discriminant giving the best expected limit value. With this methodology, the following combinations of stau masses and the BDT discriminants were obtained: limits for the signal with stau masses of 90 and 125 GeV were evaluated with BDT discriminant trained with stau mass of 100 GeV and the signal with a stau mass of 175 GeV is processed with the BDT distribution trained with a stau mass 200 GeV. The expected and observed limits on cross section ratio for direct left-handed and degenerate $\tilde{\tau}$ production are shown in Fig 6.39.

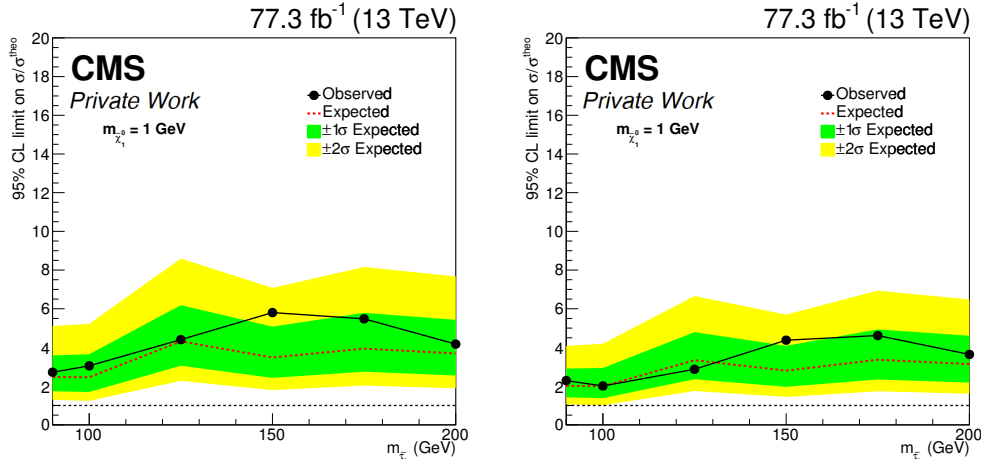


Figure 6.39: Expected and observed limits for direct $\tilde{\tau}$ production derived with the BDT approach for left-handed (left) and degenerate (right) $\tilde{\tau}$ scenario.

The best sensitivity is achieved for the signal point with a stau mass of 90 GeV and an LSP mass of 1 GeV, for which a cross section larger than 2.4 times the predicted cross section for the left-handed $\tilde{\tau}$ and 2.1 for the mass-degenerate scenario is excluded. The observed limit line lies within the expected uncertainty, which means no evidence of any significant deviation from the SM.

6.9 Combination with $\tau_h\tau_h$ channel

The $\ell\tau_h$ final states cover only 46% of the τ pair decay branching. However, another analysis can be designed to target $\tau_h\tau_h$ final state and to cover another 42% of the τ pair decays [114]. Such an analysis is designed within the CMS SUSY group for 2016 and 2017 data, and the results are combined with the $\ell\tau_h$ channel to improve the sensitivity to the direct stau production.

6.9.1 Brief $\tau_h\tau_h$ analysis description

The main feature of the $\tau_h\tau_h$ analysis is that the dominant background originates from the misidentification of jets as τ_h . In order to further improve the suppression of this background in comparison with the MVA τ ID, a new approach for improved τ_h isolation is introduced. This approach is based on the application of a Deep Neural Network (DNN) using the properties of PF candidates within an isolation cone ($\Delta R < 0.5$) around the τ_h candidate. Charged PF candidates consistent with the PV, photon candidates, and neutral hadron candidates, with $p_T > 0.5$, 1, and 1.25 GeV, respectively, provide the inputs to the DNN isolation algorithm. The list of particle features incorporated for each candidate further includes the candidate p_T relative to the τ_h jet, $\Delta R(\text{candidate}, \tau_h)$, particle type, track quality information, d_{xy} , d_z , and the corresponding uncertainties, $\sigma(d_{xy})$ and $\sigma(d_z)$. A convolutional DNN is trained using simulated signal and background event samples. Signal τ_h candidates are truth-matched to generator-level τ leptons from a mixture of processes that give rise to genuine τ leptons. Background candidates that fail the truth-matching are taken from simulated W+jets and QCD multijet event samples. The DNN output is averaged with the nominal MVA discriminant to obtain the final discriminator value for the optimal performance. The working point for the DNN isolation is chosen to maintain a flat efficiency of $\approx 50\%$, 56% , and 56% vs p_T for the three reconstructed τ_h decay modes: one charged hadron, one charged hadron with neutral pions, and three charged hadrons, respectively. The overall misidentification rate for jets not originating from τ leptons ranges from 0.15% to 0.4%.

The data used for this search are selected with triggers that require the presence of isolated electrons, muons, τ_h candidates, or E_T^{miss} . The data used for the $\tau_h\tau_h$ analysis are collected with two sets of triggers. Events with $E_T^{\text{miss}} \geq 200$ GeV are selected with a trigger that also requires the presence of two τ_h candidates, each with $p_T > 35$ (40) GeV in 2016 (2017).

Beyond the trigger selection, the baseline event selection requires the presence of exactly two isolated τ_h candidates of opposite charge satisfying the aforementioned DNN selection described with $p_T > 40$ (45) GeV in 2016 (2017), and no additional τ_h candidates with $p_T > 30$ GeV satisfying the very loose working point of the MVA discriminant. Events with additional electrons or muons are vetoed, where leptons satisfy the criteria of $p_T > 20$ GeV and $|\eta| < 2.5$ (2.4) for electrons (muons). In addition, any events with a jet originating from a b-quark are rejected in order to suppress top quark backgrounds. A requirement

of $|\Delta\phi(\tau_{h1}, \tau_{h2})| > 1.5$ helps to suppress backgrounds originating from DY+jets and QCD multijet processes while retaining high signal efficiency. Finally, a requirement on $p_T^{\text{miss}} > 50$ GeV is made in order to suppress the QCD multijet background.

The background modeling is very similar to that in $\ell\tau_h$ channel. The main background coming from τ_h misidentified from jets is estimated purely from data control regions, while Z+jets and other backgrounds are modeled by MC simulations corrected in corresponding control regions.

Events satisfying the baseline selection criteria are subdivided into exclusive search regions by means of several discriminating variables: m_{T2} , Σm_T , and the number of reconstructed jets in an event (N_j). The selection requirement is optimized to maximize sensitivity to various direct stau production signal points. The final selection of sensitive bins is summarized in Table 6.9. Distributions of Σm_T and m_{T2} after the baseline selection are shown in Fig. 6.40.

Table 6.9: Ranges of m_{T2} , Σm_T , and N_j used to define the search regions used in the $\tau_h\tau_h$ analysis.

m_{T2} [GeV]	> 50						25–50					
Σm_T [GeV]	> 300		250–300		200–250		> 300		250–300		200–250	
N_j	0	≥ 1	0	≥ 1	0	≥ 1	0	≥ 1	0	≥ 1	0	≥ 1

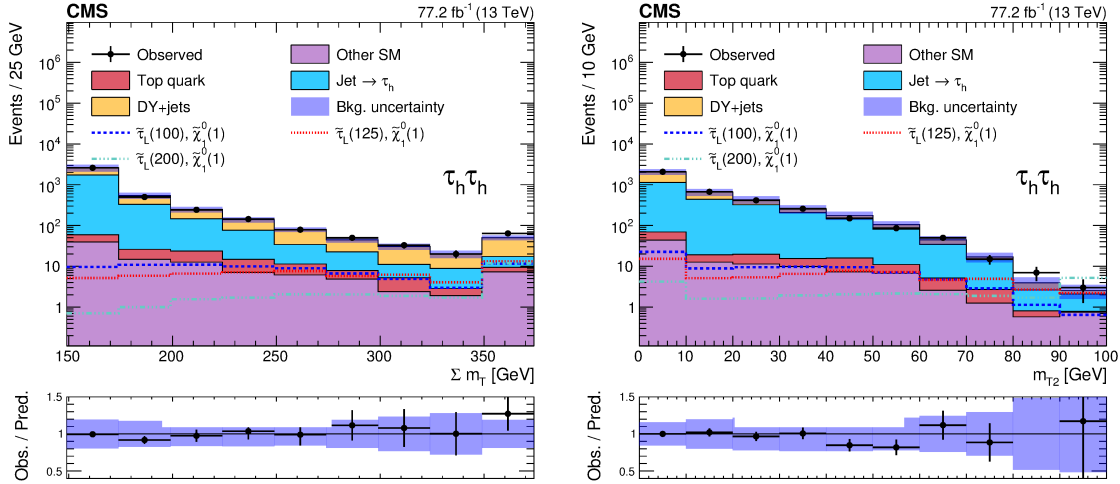


Figure 6.40: Distributions of Σm_T (left) and m_{T2} (right) for events in the combined 2016 and 2017 datasets passing the baseline selection in the $\tau_h\tau_h$ final state, along with the corresponding prediction for the SM background and three benchmark signal models of $\tilde{\tau}$ pair production. The numbers within parentheses in the legend correspond to the masses of the $\tilde{\tau}$ and LSP in GeV. The shaded uncertainty band represents the combined statistical and systematic uncertainty in the background [114].

The search bins occupancy is presented in Fig. 6.41 for both 2016 and 2017 analysis before and after the fit of the background model to data.

The background model is found to be in good agreement with data. Therefore, the upper limits on signal strength are set in the same way as in the $\ell\tau_h$ analysis.

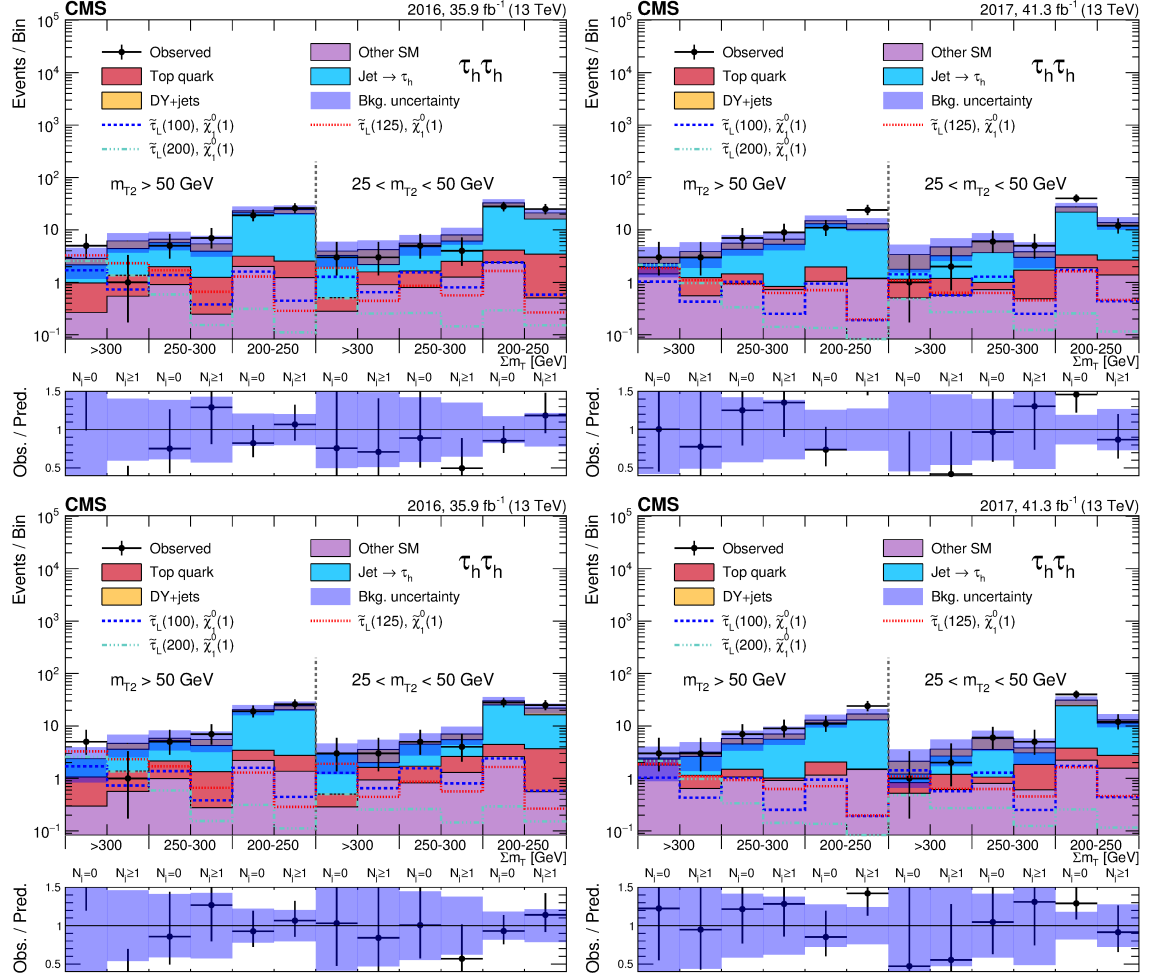


Figure 6.41: Observed event counts and predicted yields for the SM background in the $\tau_h\tau_h$ analysis for the 2016 (left) and 2017 (right) datasets, before (top) and after (bottom) the maximum likelihood fit to the data. Predicted signal yields are also shown for benchmark signal models with $m(\tilde{\tau}) = 100, 125$, and 200 GeV, $m(LSP) = 1$ GeV.

6.9.2 Combined results

For the combination of the $\tau_h\tau_h$ and $\ell\tau_h$ analyses, uncertainties related to object reconstruction are correlated, with the exception of the τ_h selection efficiency, which is treated as uncorrelated between the two analyses due to the use of different isolation algorithms.

The combination is done at the level of constructing a test statistic for the 95% CL_s upper limit calculation. Figure 6.42 shows the limits obtained in the scenario of purely left-handed $\tilde{\tau}$ pair production, while Fig. 6.43 shows the limits obtained for the degenerate $\tilde{\tau}$ scenario. The strongest limits are observed in the case of a nearly massless LSP. In general, the constraints are reduced for higher values of the LSP mass, due to smaller experimental acceptances. In the purely left-handed scenario, the strongest limits are observed for a $\tilde{\tau}$ mass of 125 GeV. In this model, the exclusion limit for a $\tilde{\tau}$ pair production cross section reaches a value of 132 fb, which is 1.14 times the theoretical cross section. In the degenerate $\tilde{\tau}$ scenario, $\tilde{\tau}$ masses between 90 and 150 GeV are excluded under an assumption of a nearly massless LSP.

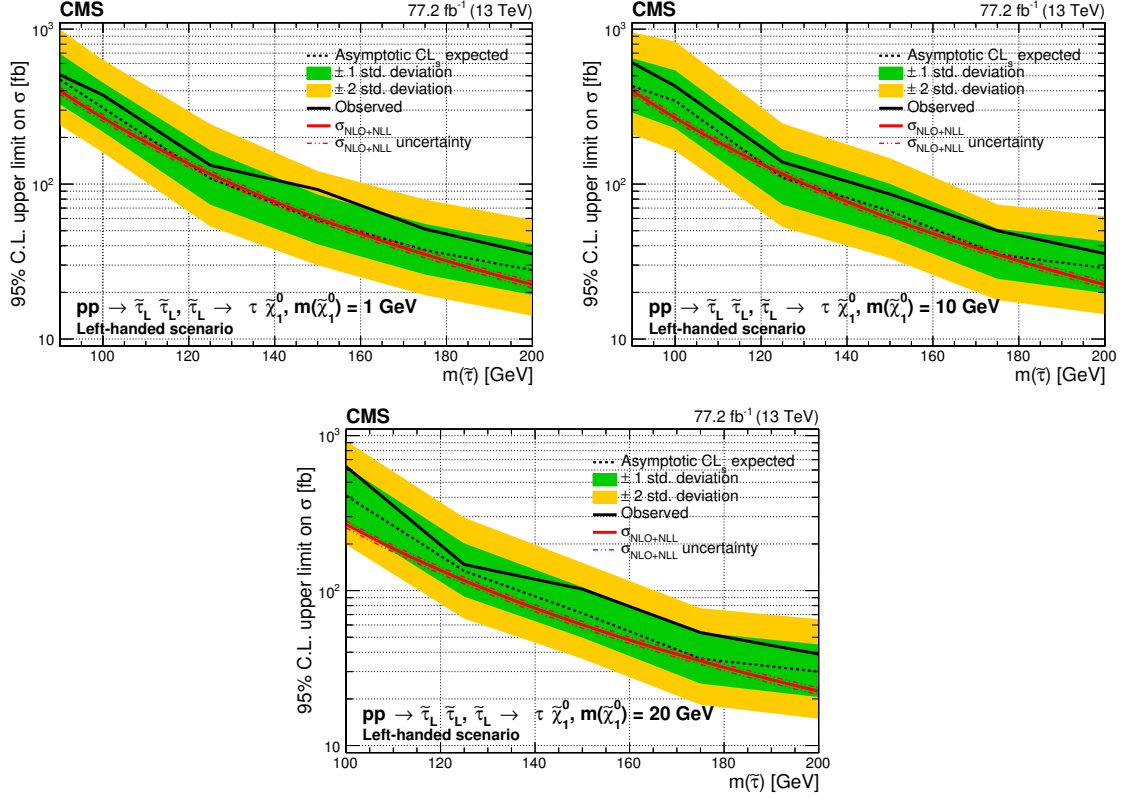


Figure 6.42: Cross section of $\tilde{\tau}$ pair production excluded at 95% CL as a function of the $\tilde{\tau}$ mass in the purely left-handed $\tilde{\tau}$ scenario for an LSP mass of 1 GeV (top left), 10 GeV (top right) and 20 GeV (bottom). The results shown are for the statistical combination of the 2016 and 2017 datasets for the $\tau_h\tau_h$ and $\ell\tau_h$ analyses. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The red line indicates the NLO+NLL prediction for the signal production cross section calculated with RESUMMINO [54], while the barely visible red dashed lines represent the uncertainty in the prediction. The bottom plot has an axis starting from 100 GeV because of an absence of signal sample with the $\tilde{\tau}$ mass of 1 GeV and an LSP mass of 20 GeV.

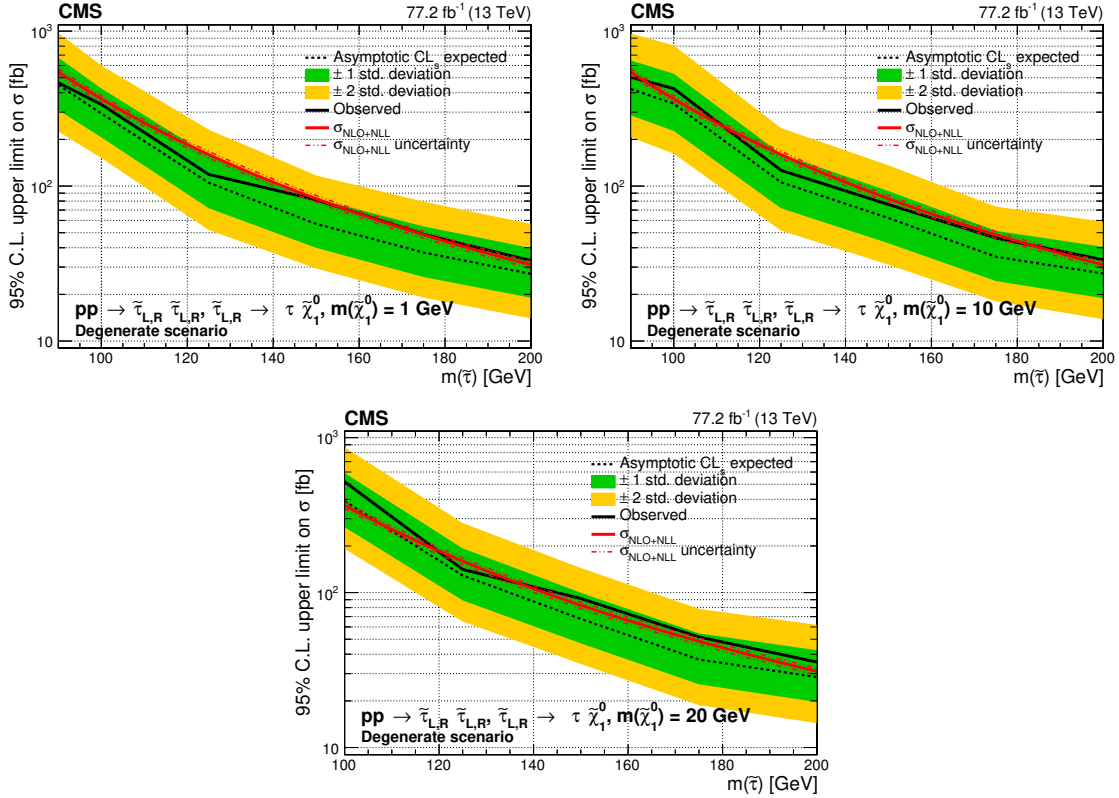


Figure 6.43: Cross section of $\tilde{\tau}$ pair production excluded at 95% CL as a function of the $\tilde{\tau}$ mass in the degenerate $\tilde{\tau}$ scenario for an LSP mass of 1 GeV (top left), 10 GeV (top right) and 20 GeV (bottom). The results shown are for the statistical combination of the 2016 and 2017 datasets for the $\tau_h\tau_h$ and $\ell\tau_h$ analyses. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The red line indicates the NLO+NLL prediction for the signal production cross section calculated with RESUMMINO [54], while the barely visible red dashed lines represent the uncertainty in the prediction. The bottom plot has an axis starting from 100 GeV because of an absence of signal sample with the $\tilde{\tau}$ mass of 1 GeV and an LSP mass of 20 GeV.

6.10 Comparison with 2016 analysis

The search with 2016 CMS data in more details can be found in Appendix A or in Ref. [117]. This analysis uses 35.9 fb^{-1} of data collected in 2016. The main difference of the $\ell\tau_h$ channel is the application of a cut-based approach instead of using MVA technique. The $\tau_h\tau_h$ channel makes use of the standard τ MVA ID for the 2016 analysis, which is less effective compared to the DNN identification developed for the combined 2016 and 2017 analysis. Further details are omitted within this thesis and, in the followings, only the interpretation is discussed below.

The 2016 results are interpreted as limits on the cross section for the production of $\tilde{\tau}$ pairs with the CL_s criterion. Figures with the cross section upper limits obtained for the $\tilde{\tau}$ pair production for the left-handed, maximally mixed, and right-handed scenarios as a function

of the $\tilde{\tau}$ mass for different LSP mass hypotheses, namely 1, 10, 20, 30, 40, and 50 GeV can be found in Appendix A. This analysis is most sensitive to scenarios with a left-handed $\tilde{\tau}$ and a nearly massless LSP, in which production rates larger than 1.26 (1.34) times the expected SUSY cross section is excluded for a $\tilde{\tau}$ mass of 90 (125) GeV.

An additional interpretation is done in terms of exclusion limits in simplified models of mass-degenerate chargino-neutralino ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$) and chargino pair ($\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$) production with decays to τ leptons. Figure 6.44 shows the 95% CL exclusion limits in the mass plane of $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ versus LSP mass obtained for the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ scenario. The exclusion in $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses goes up to around 710 GeV for a nearly massless LSP hypothesis in this scenario. Figure 6.45 shows the corresponding limits for the $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ signal scenario in the plane of $\tilde{\chi}_1^\pm$ versus LSP mass. In this scenario, $\tilde{\chi}_1^\pm$ masses up to around 630 GeV are excluded for a nearly massless LSP hypothesis.

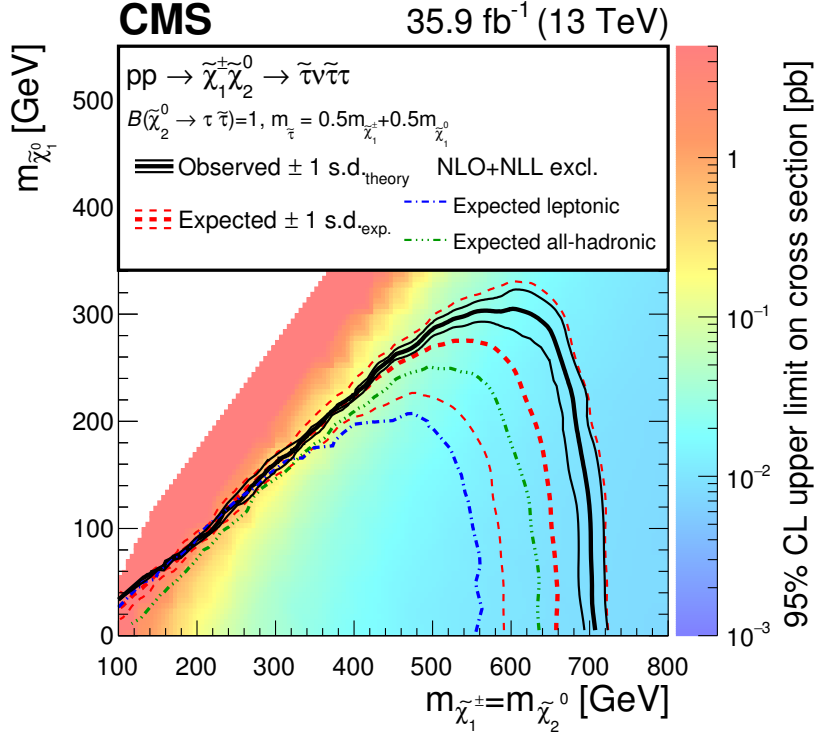


Figure 6.44: Exclusion limits at 95% CL for chargino-neutralino production with decays through $\tilde{\tau}$ to final states with τ leptons. The production cross sections are computed at NLO+NLL precision assuming mass-degenerate wino $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, light bino LSP, and with all the other particles assumed to be heavy and decoupled [54]. The regions enclosed by the thick black curves represent the observed exclusion at 95% CL , while the thick dashed red line indicates the expected exclusion at 95% CL . The thin black lines show the effect of variations of the signal cross sections within theoretical uncertainties on the observed exclusion. The thin red dashed lines indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The green and blue dashed lines show separately the expected exclusion regions for the analyses in the all-hadronic and leptonic final states, respectively.

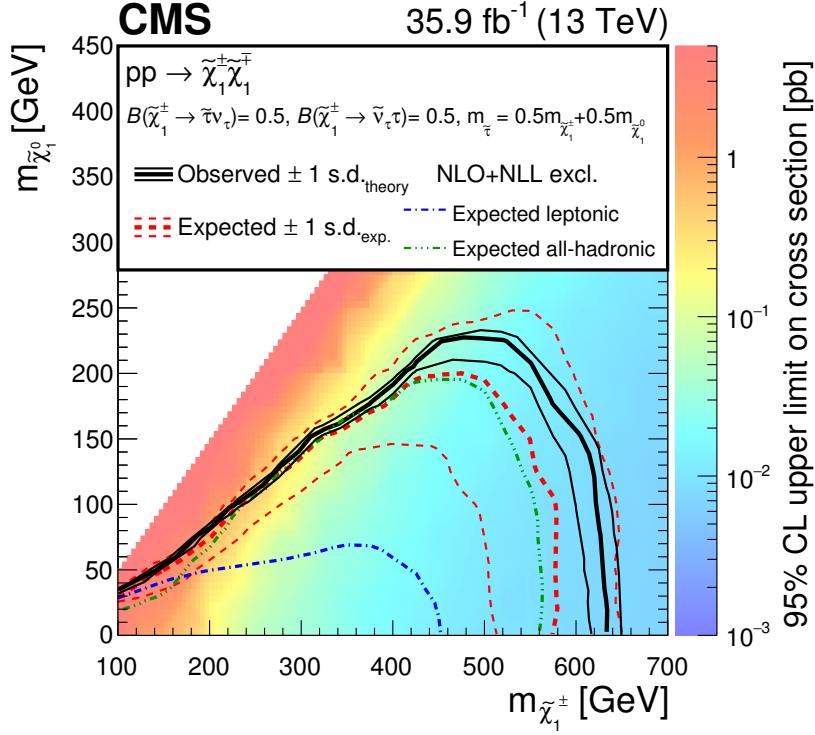


Figure 6.45: Exclusion limits at 95% CL for chargino pair production with decays through $\tilde{\tau}$ to final states with τ leptons. The production cross sections are computed at NLO+NLL precision assuming a wino-like $\tilde{\chi}_1^+$, light bino LSP, and with all the other sparticles assumed to be heavy and decoupled [54]. The regions enclosed by the thick black curves represent the observed exclusion at 95% CL , while the thick dashed red line indicates the expected exclusion at 95% CL . The thin black lines show the effect of variations of the signal cross sections within theoretical uncertainties on the observed exclusion. The thin red dashed lines indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The green and blue dashed lines show separately the expected exclusion regions for the analyses in the all-hadronic and leptonic final states, respectively.

No sensitivity to the direct $\tilde{\tau}$ interpretation is reached in the 2016 analysis. In spite of this, strong constraints on the indirect $\tilde{\tau}$ production are made. This result was the main reason to focus only on the direct $\tilde{\tau}$ production and upgrade the analysis technique. However, a direct comparison of the 2016 analysis with the two years combination is problematic, mainly, because of different signal simulation procedures. The FastSim is used for the 2016 signal simulation to produce the SUSY signal with a wide range of parameters, SUSY particle masses. In contrast, for the 2016 and 2017 analysis, the focus is shifted to the direct $\tilde{\tau}$ production within a narrow range of $\tilde{\tau}$ and LSP masses. Therefore, it was decided to use the FullSim approach for better physics object modeling in SUSY signal. It turns out, that the FastSim introduced a systematic bias in the τ_h identification leading to enhanced signal yields and optimistic limit results. Therefore, the presented exclusion limits on the left-handed $\tilde{\tau}$ scenario in the recent analysis are not as good as expected from the 2016 analysis sensitivity. However, the benefits from the application of the MVA approach partially compensated the aforementioned loss of signal efficiency.

6.11 Chapter conclusion

In this chapter the search for direct τ slepton ($\tilde{\tau}$) pair production is presented in proton-proton collisions at a center-of-mass energy of 13 TeV with the CMS detector. The data sample used for this search corresponds to an integrated luminosity of 77.2 fb^{-1} collected in the years 2016 and 2017. No excess above the expected SM background has been observed. Upper limits on the cross section of direct $\tilde{\tau}$ pair production are derived for simplified models in which the both $\tilde{\tau}$ decay to a τ lepton and LSP. The bulk of the sensitivity in the combined result comes from the $\tau_h\tau_h$ channel, while the $\ell\tau_h$ channel visibly enhances the sensitivity to the low $\tilde{\tau}$ masses.

Searching for direct stau production is very challenging due to its extremely low cross section. With the here presented analysis it is the first time the CMS collaboration reaches sensitivity to this SUSY simplified model. Despite the fact that the degenerate $\tilde{\tau}$ scenario is less theoretically motivated in comparison with other helicity scenarios, they are widely used as a standard candle useful for further phenomenological reinterpretation. Since the left-handed scenario has a lower cross section than the degenerate scenario, the interpretation in terms of this scenario leads to a reduced sensitivity. Even though, the left handed stau scenario could not be excluded with this analysis, it is also the first time a search starts to become sensitive to this helicity scenario.

CHAPTER

7

HL-LHC AND HE-LHC $\tilde{\tau}$ SEARCH

It's not enough to know what the future is. You have to know what it means.

Terry Prattchet

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It was shown in the previous chapter, that the increasing amount of data by combining the results from 2016 and 2017 improves the sensitivity for direct $\tilde{\tau}$ production. However, what will be the limit one can get from the maximum planned LHC luminosity? In order

to fully profit from the LHC potential, an upgrade giving increase of the instantaneous luminosity [136, 137], together with the corresponding upgrades of the major experiments [138, 139], has been approved by the CERN Council [140]. The High Luminosity LHC (HL-LHC) upgrade is expected to collect an integrated luminosity of 3 ab^{-1} of data in pp collisions with a centre-of-mass energy of 14 TeV. Such an upgrade will maximize the LHC sensitivity to new phenomena. The established timeline for the HL-LHC project is shown in Fig. 7.1. Moreover, in the perspective of pushing the LHC sensitivity even further, the LHC facility and the whole CERN infrastructure could be upgraded to reach the highest possible energy. This project is called High Energy LHC (HE-LHC) [141] and is currently under investigation. HE-LHC could collect an integrated luminosity of 15 ab^{-1} with the collision energy of 27 TeV.

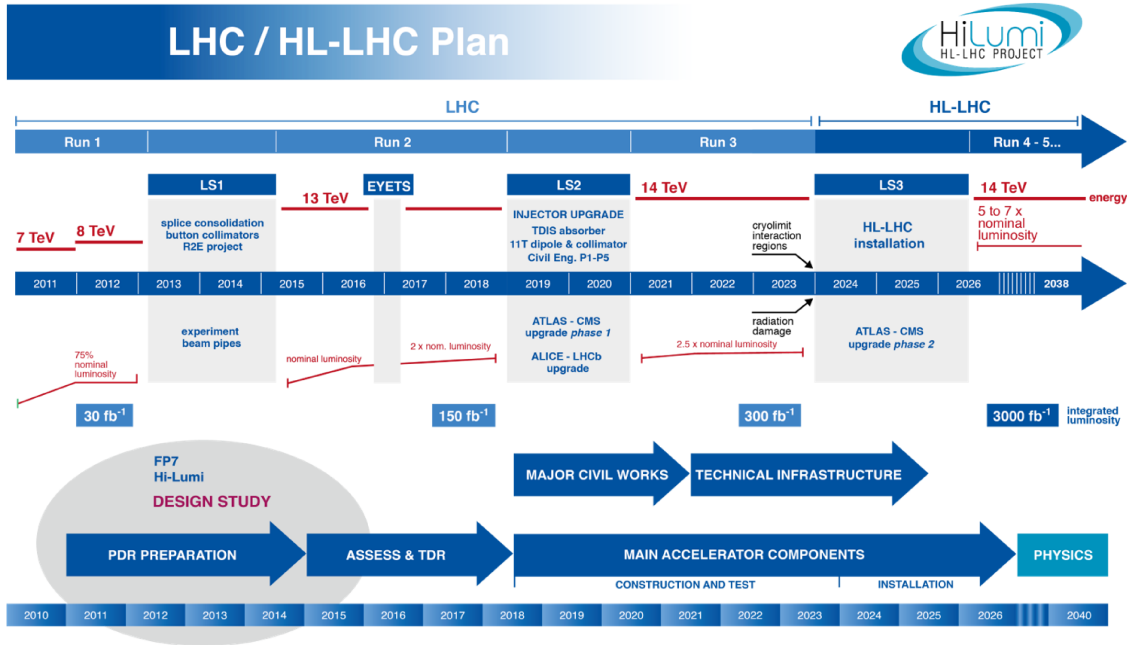


Figure 7.1: Timeline for the LHC and HL-LHC projects [142].

The CMS detector will be substantially upgraded in order to exploit the physics potential provided by the increase in luminosity at the HL-LHC and to cope with the demanding operational conditions [143–147]. This upgrade is referred to as the CMS Phase-2 Upgrade.

The last is discussed in Section 7.1. The HL-LHC stau search in the $\ell\tau_h$ channel is described in Section 7.2, while the subsequent combination with the $\tau_h\tau_h$ channel is shown in Section 7.3. Finally, the projection study for the HE-LHC is given in Section 7.4. The HL-LHC and HE-LHC analyses is public and can be found in Refs. [148] and [149].

7.1 Phase-2 CMS detector upgrade

The Phase-2 detector upgrade is vital for CMS to operate in the high-PU environment and radiation conditions of the HL-LHC. It touches on all the CMS subsystems. The current timeline for the CMS detector upgrade is shown in Fig. 7.2.

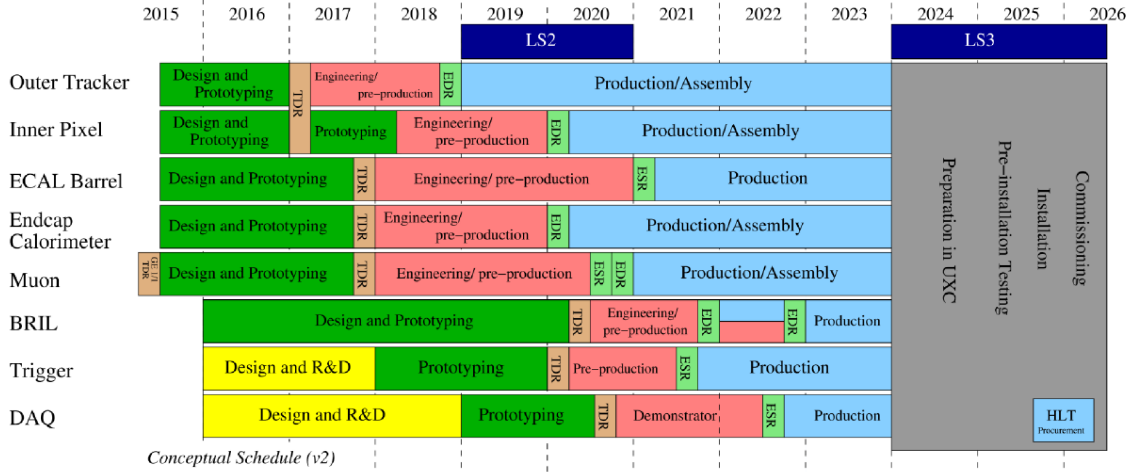


Figure 7.2: The CMS detector subsystems upgrade timeline [150].

The main problem is the increase in radiation levels that requires improved radiation hardness, followed by the larger PU and associated increase in particle density. To solve this problem higher detector granularity is needed, which reduces the average channel occupancy. In addition, an improved trigger capability is needed to keep the trigger rate at an acceptable level.

The first level hardware triggers are expected to be upgraded to allow an increase of event rate to about 750 kHz (The current operating value is 100 kHz). Moreover, the HLT is planned to reduce the event rate to 7.5 kHz (current value is 1 kHz).

The entire strip and pixel tracker detectors are scheduled to be replaced by a similar system with the increased granularity and improved radiation hardness. In addition, the new pixel and strip trackers will have extended geometrical coverage to provide particle tracking in the forward region, up to pseudorapidities of about $|\eta| = 4$.

The muon system will be improved by upgrading the electronics of the current drift tubes, resistive plate chambers and cathode strip chambers. A few new muon subdetectors based on the improved RPC and gas electron multiplier technologies will be added. That will extend the geometrical coverage up to $|\eta| = 2.8$ and improve the reconstruction performance in the forward region.

For the barrel electromagnetic calorimeter (ECAL) it is planned to upgrade the front-end electronics. Such an upgrade is expected to exploit information from the single ECAL crystal at the L1 trigger level providing 160 MHz sampling rate in order to allow photon timing measurement with high precision. The endcap hadron and electromagnetic calorimeters will be removed and replaced with a new combined sampling calorimeter, which will collect highly segmented transverse and longitudinal information with precision timing.

The last upgrade to be mentioned is a new timing detector for minimum ionizing par-

ticles (MTD) in the endcap and barrel region. The MTD is planned to make significant contributions to the 4-dimensional reconstruction of interaction vertices allowing operation in high-PU conditions.

A full overview of the CMS detector upgrade can be found in Ref. [143–147].

7.1.1 Object performance and definition

The performance of the reconstructed physics objects is evaluated based on the GEANT4 upgraded detector simulation. The event reconstruction uses the particle-flow (PF) algorithm mentioned in Chapter 4. The detailed expected performance of the reconstruction algorithms is described in Ref. [151].

Electrons are reconstructed by the multivariate technique with the Boosted Decision Tree (BDT) estimator, trained on $Z \rightarrow ee$ events with PU corresponding to the HL-LHC condition. The background rejection as a function of the electron reconstruction efficiency is shown in the Fig. 7.3. For electron candidates with $p_T > 20$ GeV, 95% signal efficiency is achieved for a background rejection of 99%, and for $10 \text{ GeV} < p_T < 20 \text{ GeV}$ - with a reduced background rejection of 90%.

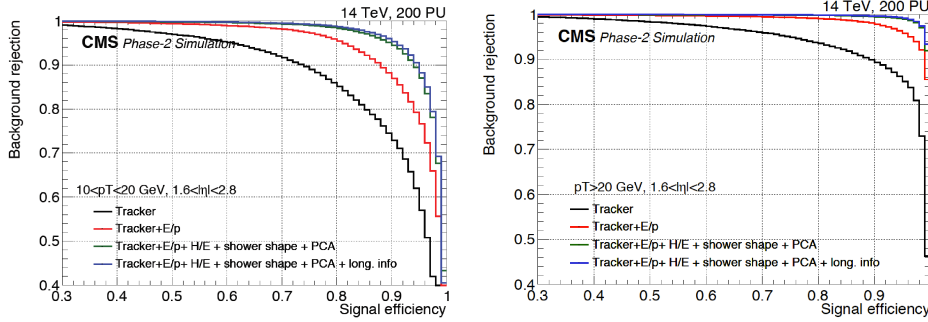


Figure 7.3: The purity as a function of the efficiency for electrons with $10 < p_T < 20$ GeV (left) and with $p_T > 20$ GeV (right), for different sets of input variables in the BDT multivariate estimator [151].

Muons are reconstructed with the PF algorithm, similar to Run 2 analysis. The muon reconstruction and identification efficiency as a function of the pseudorapidity in the high- η region for different detector settings is shown in Fig. 7.4. The efficiency of the future muon system is expected to be resilient to the HL-LHC high-PU conditions.

The efficiency to identify prompt muons from Z +jets events and nonprompt muons from $t\bar{t}$ is shown in Fig. 7.5. The effect of including timing information with the nominal timing resolution of 30 ps is also shown. A significant improvement is observed in terms of a reduced nonprompt efficiency. Overall, the muon isolation efficiency at high-PU condition with timing is equivalent to that in the Run 2 LHC conditions without timing.

For the stau analysis, electrons (muons) are required to have a transverse momentum $p_T > 30$ GeV and pseudorapidity $|\eta| < 1.6(2.4)$. The aforementioned lepton identification criteria are used with 50% to 90% efficiency for muons and 25% to 80% efficiency for electrons, depending on the lepton p_T and η . Both muons and electrons are required to have a relative isolation smaller than 0.05.

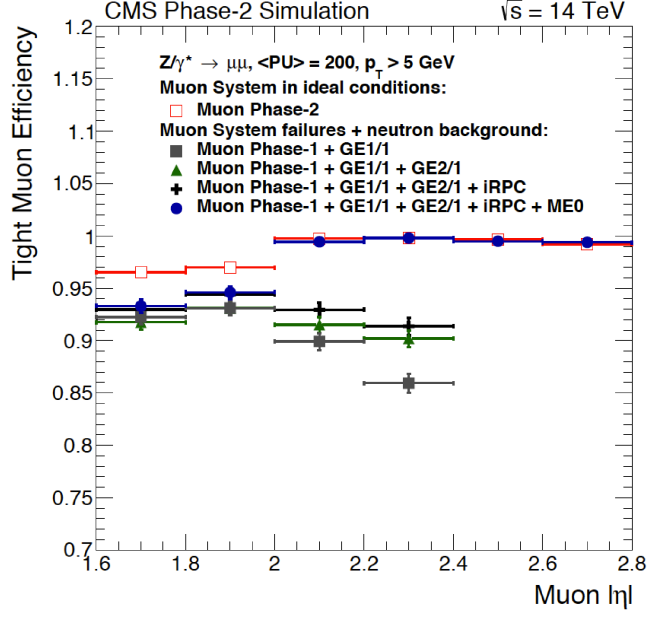


Figure 7.4: The muon reconstruction and identification efficiency with statistical uncertainty in Z +jets events, as a function of a simulated muon η , for tight muon selection criteria. Results for different detector configurations are shown. The solid points assume 200 PU, HL-LHC neutron background, and a model of the muon system aging. The open squares show the results for the un-aged muon system and without the neutron-induced background [151].

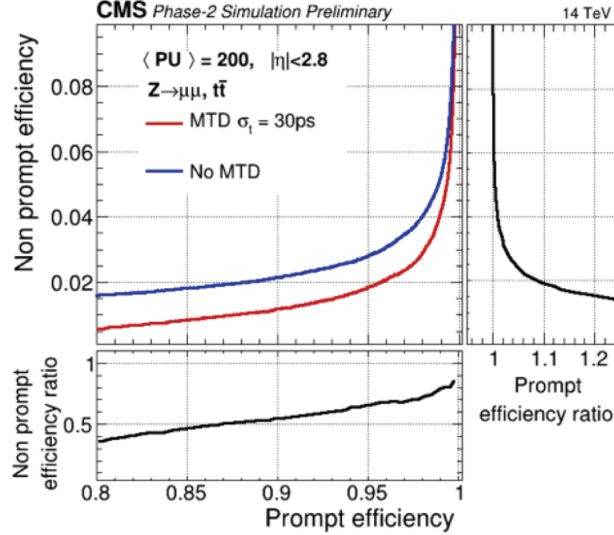


Figure 7.5: The efficiency for identifying prompt muons from Z +jets events and nonprompt muons from $t\bar{t}$ events using charged isolation with and without precision timing from the MTD for charged particles with a nominal timing resolution of 30 ps [151].

Jets are reconstructed using the anti- k_t algorithm, with a distance parameter of 0.4. For this study, PUPPI jets are used, which are required to have $p_T > 30$ GeV and $|\eta| < 2.7$. From the performance point of view, only a small degradation in the jet energy resolution is observed with the increased PU density. It is achieved by including timing in the reconstruction procedure.

Jets originating from b quarks are identified with the loose working point of the combined secondary vertex algorithm, which corresponds to an efficiency of about 60–65%. In very high-PU conditions, the secondary vertex identification algorithm is degraded by the formation of secondary vertices caused by PU tracks. However, timing information helps to restore the efficiency of the algorithm, which is shown in Fig. 7.6.

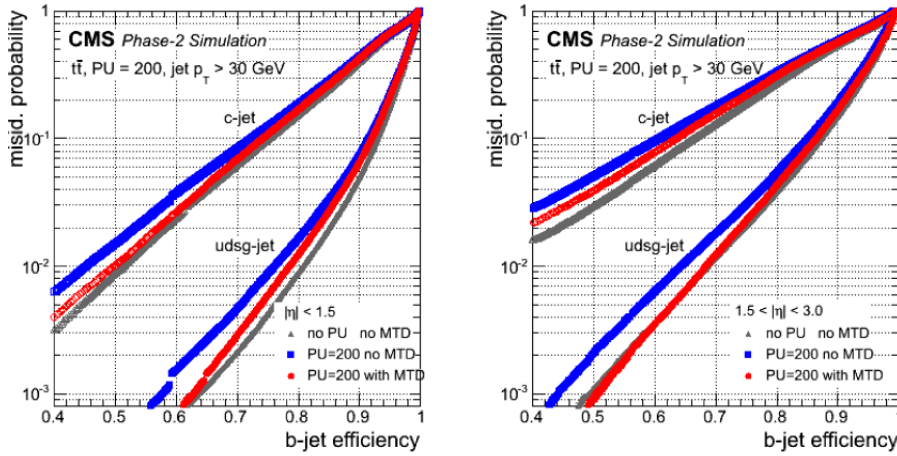


Figure 7.6: The secondary vertex tagging misidentification probability as a function of the b tagging efficiency, for light and charm jets for $|\eta| < 1.5$ (left) and for $1.5 < |\eta| < 3.0$ (right). Results with and without the MTD precision timing are compared to the 0 PU case [151].

The τ_h candidates must satisfy the requirement of $p_T > 40$ GeV. Since the main background in this analysis is due to events with jets misidentified as τ_h leptons, a tight working point with a small misidentification rate is chosen for τ_h identification. The τ_h reconstruction efficiency for this working point is about 30%, with a misidentification rate of about 0.08% assuming a multivariate analysis optimization. The performance of the τ_h reconstruction is found to be similar to that achieved in the recent Run 2 CMS data taking.

Within high-PU HL-LHC conditions, it is decided to use PUPPI p_T^{miss} in order to correct strong PU contribution. The p_T^{miss} performance is shown in Figs. 7.7 and 7.8. With the upgraded detector a resolution of about 25 GeV can be achieved in the perpendicular component using PUPPI p_T^{miss} . The dotted magenta line shows the corresponding resolution in the current LHC condition for comparison reason. The modest degradation of the resolution is observed with increasing PU for PUPPI p_T^{miss} .

7.2 HL-LHC $\tilde{\tau}$ search

The search for direct $\tilde{\tau}$ pair production is one the most challenging SUSY analysis due to the relatively small production cross section compared to other SUSY processes. For

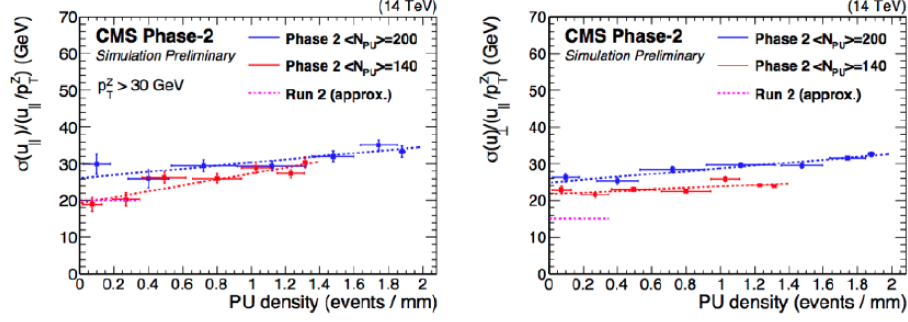


Figure 7.7: Parallel (left) and perpendicular (right) PUPPI p_T^{miss} resolution is shown as a function of PU density. The blue points indicate the Phase-2 detector performance within HL-LHC PU condition with a mean of 200, the red points indicate the Phase-2 performance with a mean PU of 140, and the pink dashed line indicates the current CMS performance with a mean PU of 27 [151].

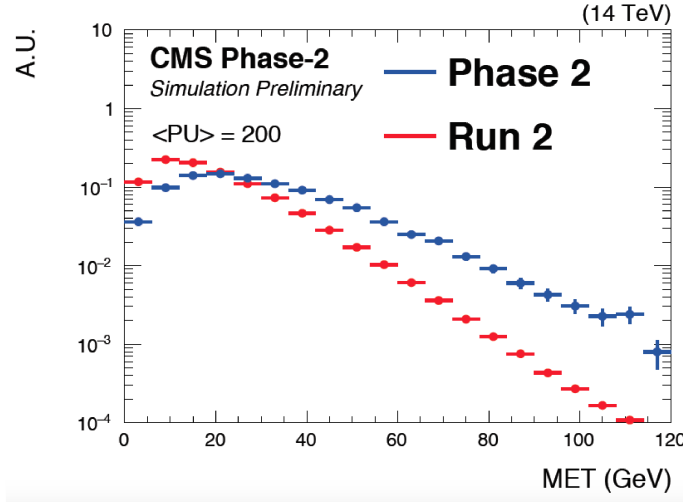


Figure 7.8: The PUPPI p_T^{miss} distribution for the Phase-2 detector within high-PU condition. The PUPPI p_T^{miss} distribution for current LHC setup is shown in red [151].

example, the cross section in the mass degenerate scenario for a $\tilde{\tau}$ mass of 100 GeV is 0.41 pb, for 300 GeV it is reduced to 0.0071 pb, and for $\tilde{\tau}$ mass of 500 GeV only a cross section of 0.79 fb is calculated [54]. The large data set expected at the HL-LHC provides an unprecedented opportunity to detect $\tilde{\tau}$ pair production. An analysis is developed for events where one of the τ leptons decays hadronically and the other one to a muon or electron and neutrinos in the same way as in Run 2 analysis.

The direct $\tilde{\tau}$ production is chosen as the simplified model used for the optimization of the search and for the interpretation of the results, since it is the most challenging scenario. Moreover, for projection studies, only the mass degenerate $\tilde{\tau}$ production is used. The cross sections have been computed at next-to-leading order (NLO) for $\sqrt{s} = 14$ TeV using the Prospino code [152]. The branching ratio of the $\tilde{\tau}$ into the τ lepton and LSP is assumed to be 100%.

7.2.1 MC simulation

The MADGRAPH5_aMC@NLO 2.3.3 generator is used to produce the parton-level background processes at leading order (LO), with the parton showering and hadronization provided by PYTHIA 8.212. Signal models of direct $\tilde{\tau}$ pair production are generated with MADGRAPH5_aMC@NLO at LO precision in perturbative quantum chromodynamics (QCD) up to the production of τ leptons, which are then decayed with PYTHIA 8.212. The NNPDF3.0LO set of parton distribution functions is used in the generation of all signal models.

The potential effect of pileup is estimated by overlaying the hard scattering event with minimum bias events drawn from a Poisson distribution with a mean of 200.

The generated signal and background events are processed with the fast-simulation package Delphes in order to simulate the expected response of the upgraded CMS detector. The object reconstruction and identification efficiencies, as well as the detector response and resolution, are parameterized in Delphes using the detailed simulation of the upgraded CMS detector based on the GEANT4 package.

The detailed simulation of the upgraded CMS detector and objects performance at HL-LHC include the effects of aging in the barrel calorimeter that correspond to an integrated luminosity of 1000 fb^{-1} .

7.2.2 Event selection and search region definition

Candidate events are expected to contain at least two leptons: one τ_h and one muon or electron from τ lepton decay. Overlaps between the two reconstructed leptons are avoided by requiring them to have a minimum separation in ΔR of 0.3.

In order to ensure orthogonality between the different final states and suppress background, events with additional electrons or muons beyond the two selected leptons are rejected. These leptons should satisfy slightly less stringent selection criteria and transverse momentum of $p_T > 20 \text{ GeV}$ and $|\eta| < 2.7$.

The object selection requirements implemented in the analysis are satisfying criterion summarized in Table 7.1.

Table 7.1: Summary of the object selection requirements for the analysis.

Selection parameter	requirement
Muon (electron) p_T	$> 30 \text{ GeV}$
Muon (electron) p_T (veto)	$> 30 \text{ GeV}$
Muon (electron) $ \eta $	$< 2.4(1.6)$
Muon (electron) $ \eta $ (veto)	< 2.7
τ_h p_T	$> 40 \text{ GeV}$
τ_h $ \eta $	< 2.3
jet p_T (veto)	$> 30 \text{ GeV}$
jet $ \eta $ (veto)	< 2.7
b jet p_T (veto)	$> 20 \text{ GeV}$

All events with at least one jet are rejected to suppress all background sources with additional jets. Due to kinematical constraints in the signal, the QCD multijet background is reduced by requiring a maximum separation of the two leptons in ΔR of 3.5. In addition, m_T is constrained to be $m_T(\ell, p_T^{\text{miss}}) > 120 \text{ GeV}$, which significantly reduces the W+jets background. The baseline events are then used for further selection based on kinematic variables to improve the sensitivity of the search to a range of sparticle masses.

Table 7.2: Search region requirements.

Variable	SR- $\ell\tau_{h_1}$	SR- $\ell\tau_{h_2}$	SR- $\ell\tau_{h_3}$	SR- $\ell\tau_{h_4}$
M_{T2}	$M_{T2} > 120 \text{ GeV}$	$M_{T2} > 120 \text{ GeV}$	$80 < M_{T2} < 120 \text{ GeV}$	$80 < M_{T2} < 120 \text{ GeV}$
$p_T(\tau_h)$	$> 200 \text{ GeV}$	$40 < p_T(\tau_h) < 200 \text{ GeV}$	$> 200 \text{ GeV}$	$40 < p_T(\tau_h) < 120 \text{ GeV}$
p_T^{miss}	$> 150 \text{ GeV}$	$> 150 \text{ GeV}$	$> 150 \text{ GeV}$	$> 150 \text{ GeV}$

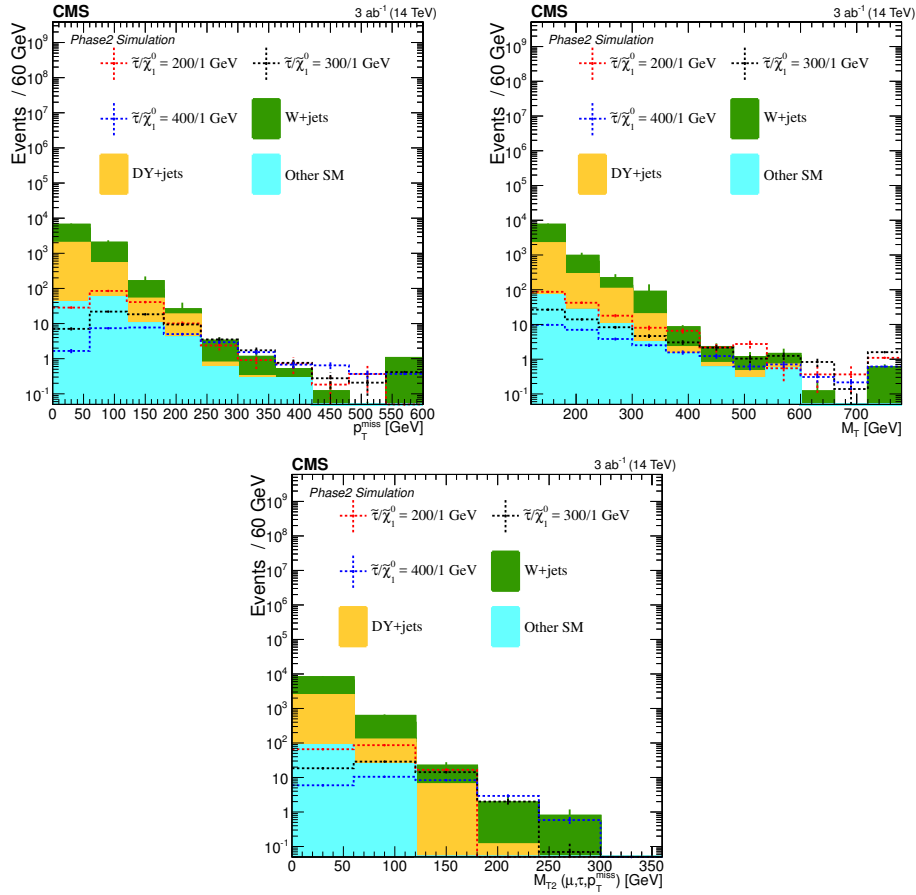


Figure 7.9: The variables used to determine the search regions in the $e\tau_h$ analysis after the baseline selection: (upper left) the p_T^{miss} distribution, (upper right) the m_T distribution, and (lower) the M_{T2} distribution using p_T^{miss} after the baseline selection. "Other SM" refers to processes with a low number of events after the baseline selection and includes diboson, triboson, $t\bar{t}$ and single top quark production.

An additional selection is required to suppress the SM background and to define the search regions. To further suppress the SM background, p_T^{miss} is required to be at least 150 GeV, which mainly reduces QCD multijets and Drell-Yan events. Finally, requirements on M_{T2} and the $\tau_h p_T$ are applied to define the search bins, as summarized in Table 7.2. Figures 7.9 and 7.10 show the distributions of p_T^{miss} , m_T , and M_{T2} before the signal region selection for the $e\tau_h$ and $\mu\tau_h$ channels, respectively. Processes with a low number of events after the baseline selection (diboson, triboson, $t\bar{t}$, and single top) are referred to as "Other SM".

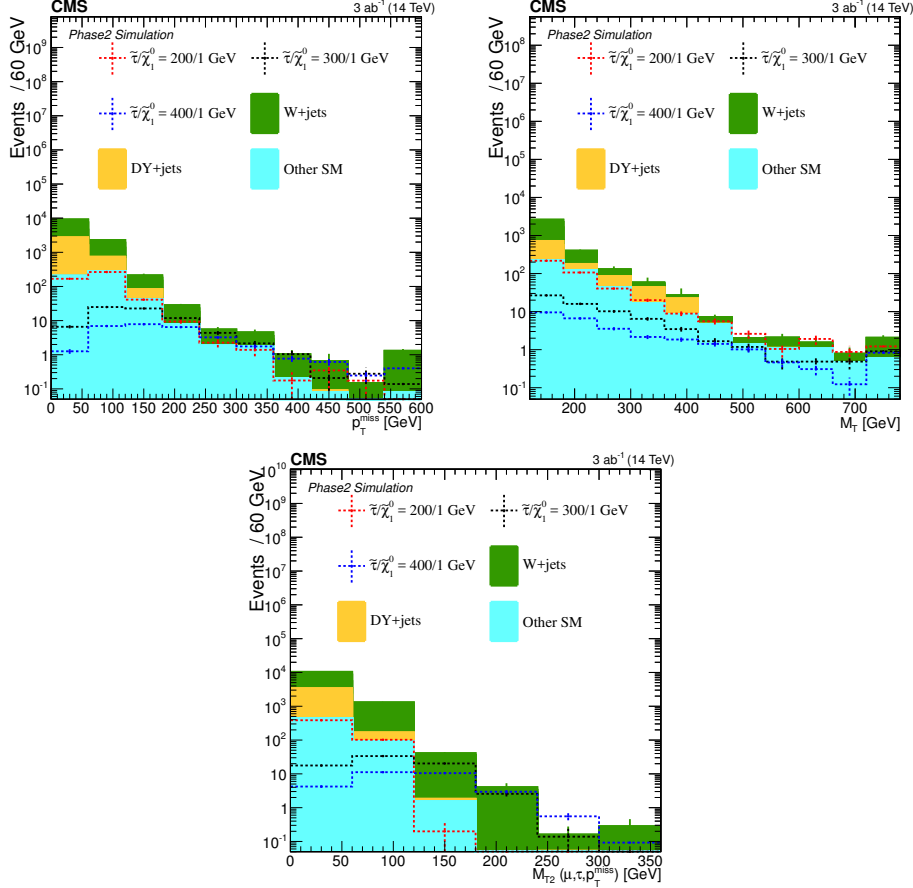


Figure 7.10: The variables used to determine the search regions in the $\mu\tau_h$ analysis after the baseline selection: (upper left) the p_T^{miss} distribution, (upper right) the m_T distribution, and (lower) the M_{T2} distribution using p_T^{miss} after the baseline selection. "Other SM" refers to processes with a low number of events after the baseline selection and includes diboson, triboson, $t\bar{t}$ and single top quark production.

7.2.3 Systematic uncertainties

The dominant experimental uncertainties arise from jets misidentified as τ_h , the lepton efficiency, the jet energy scale and resolution, b tagging efficiency and integrated luminosity. These systematic uncertainties are correlated between the signal and the irreducible background yields. The sources of the systematic uncertainties and their values are reported in Table 7.3.

Table 7.3: Summary of the experimental systematic uncertainties.

Source of systematic uncertainty	Value
τ_h efficiency	2.5%
τ_h misidentification rate	15%
Muon efficiency	0.5%
Electron efficiency	1%
Jet energy scale	1–3.5%
Jet energy resolution	3–5%
b tagging	1%
Integrated luminosity	1%

7.2.4 Results and interpretation

The expected yields for the $e\tau_h$ and the $\mu\tau_h$ analyses are given in Tables 7.4 and 7.5, respectively, for all signal regions.

Table 7.4: Signal region yields for background and signal simulation in the $e\tau_h$ channel. The three rightmost columns show the signal predictions in the degenerate scenario, for masses given in the form of $(m_{\tilde{\tau}}/m_{LSP})$ in GeV.

SR name	DY	W+Jets	Other SM	Sum	(200/1)	(300/1)	(400/1)
SR- $e\tau_{h_1}$	0.18 ± 0.07	6.83 ± 1.45	0.03 ± 0.06	7.03 ± 1.45	3.13 ± 0.78	6.83 ± 0.71	2.54 ± 0.24
SR- $e\tau_{h_2}$	0.44 ± 0.11	10.06 ± 1.52	0.98 ± 0.13	11.00 ± 1.53	8.60 ± 1.30	7.42 ± 0.74	2.36 ± 0.23
SR- $e\tau_{h_3}$	0.15 ± 0.06	10.11 ± 1.41	0.62 ± 0.10	10.57 ± 1.41	5.86 ± 1.07	3.71 ± 0.52	1.30 ± 0.17
SR- $e\tau_{h_4}$	0.10 ± 0.05	3.42 ± 0.87	0.38 ± 0.08	4.31 ± 0.97	4.10 ± 0.90	2.60 ± 0.44	0.58 ± 0.11

Table 7.5: Signal region yields for background and signal simulation in the $\mu\tau_h$ channel. The three rightmost columns show the signal predictions in the degenerate scenario, for masses given in the form of $(m_{\tilde{\tau}}/m_{LSP})$ in GeV.

SR name	DY	W+Jets	Other SM	Sum	(200/1)	(300/1)	(400/1)
SR- $\mu\tau_{h_1}$	0.06 ± 0.02	7.82 ± 1.27	0.12 ± 0.13	7.94 ± 1.28	4.57 ± 0.91	9.50 ± 0.81	7.14 ± 0.47
SR- $\mu\tau_{h_2}$	0.13 ± 0.04	20.51 ± 2.11	0.76 ± 0.29	21.62 ± 2.16	7.49 ± 1.17	9.43 ± 0.81	5.02 ± 0.39
SR- $\mu\tau_{h_3}$	0.07 ± 0.03	12.02 ± 1.65	0.72 ± 0.19	12.53 ± 1.66	6.76 ± 1.11	6.03 ± 0.65	2.68 ± 0.29
SR- $\mu\tau_{h_4}$	0.03 ± 0.02	3.19 ± 0.74	1.88 ± 0.31	4.86 ± 0.87	4.38 ± 0.89	1.25 ± 0.29	0.68 ± 0.14

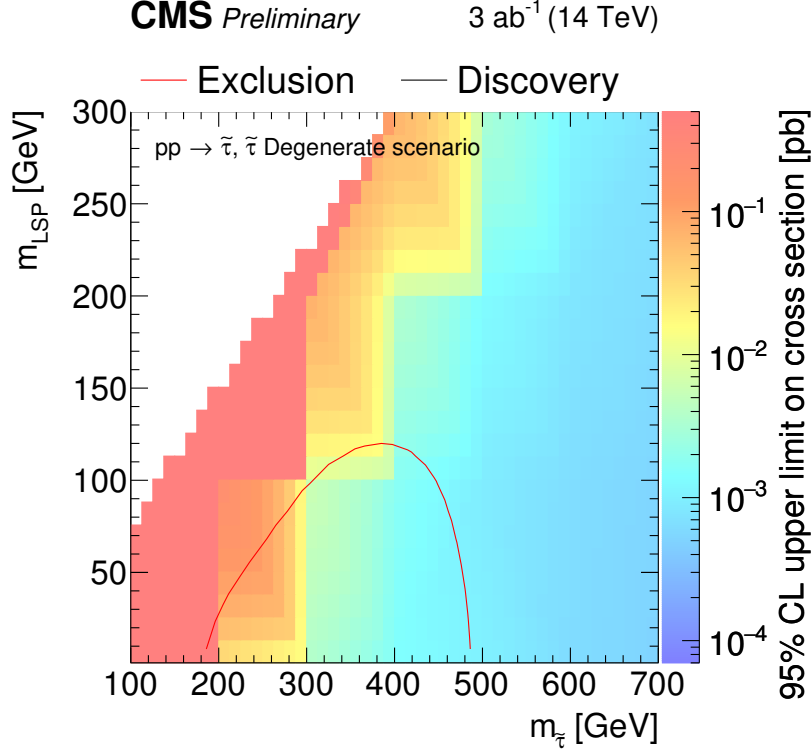


Figure 7.11: Expected upper limits at the 95% CL_s for the $\ell\tau$ channels.

The limit setting procedure is the same as in the Run 2 analysis in Chapter 6. The expected upper limits and the discovery potential are given in Fig. 7.11 for mass-degenerate scenarios.

7.3 Combination with $\tau_h\tau_h$

In the same way, as it was done for the Run 2 analysis, results for the $\tau_h\tau_h$ and $\ell\tau_h$ channels are combined to enhance the sensitivity to the direct stau production [149]. For the combination purposes, all aforementioned systematic uncertainty sources are assumed to be correlated.

7.3.1 Brief $\tau_h\tau_h$ analysis description

The object reconstruction for the $\tau_h\tau_h$ is the same as for the $\ell\tau_h$ channel. For the $\tau_h\tau_h$ channel the pair of oppositely charged τ_h is selected. The τ_h candidates must satisfy a slightly higher threshold of $p_T > 50$ GeV, driven by the trigger thresholds foreseen for the HL-LHC. In addition, di- τ_h system is required to have $p_T > 50$ GeV. All other selection is the same or similar to $e\tau_h$ channel and is given in Table 7.6.

The main background for the $\tau_h\tau_h$ final state after this selection consists of QCD multijet events, W +jets, DY +jets, and top quark events. The background is separated into prompt τ_h events, where both reconstructed τ leptons are matched to a generator τ_h , and events where one or more non-generator matched jets have been misidentified as prompt τ_h . It is

Table 7.6: Summary of object selection requirements for the analysis.

Selection parameter	requirement
Muon (electron) p_T (veto)	> 20 GeV
Muon (electron) $ \eta $ (veto)	< 2.7
τ_h p_T	> 50 GeV
τ_h $ \eta $	< 2.3
p_T (τ_h τ_h)	> 50 GeV
jet p_T (veto)	> 30 GeV
jet $ \eta $ (veto)	< 2.7
b jet p_T (veto)	> 30 GeV

found that the misidentified background dominates the search regions. To reduce the QCD contribution, $\Delta\phi(\ell_1, \ell_2) > 1.5$ is required in the same way as in the $\ell\tau_h$ analysis.

The main variables that are used to define the search regions are Σm_T and M_{T2} , which are shown for the baseline selection in Fig. 7.12. All processes with top quarks are referred to as "Top Quark", while "Other SM" consists of the background processes with a low cross section, namely diboson and triboson production.

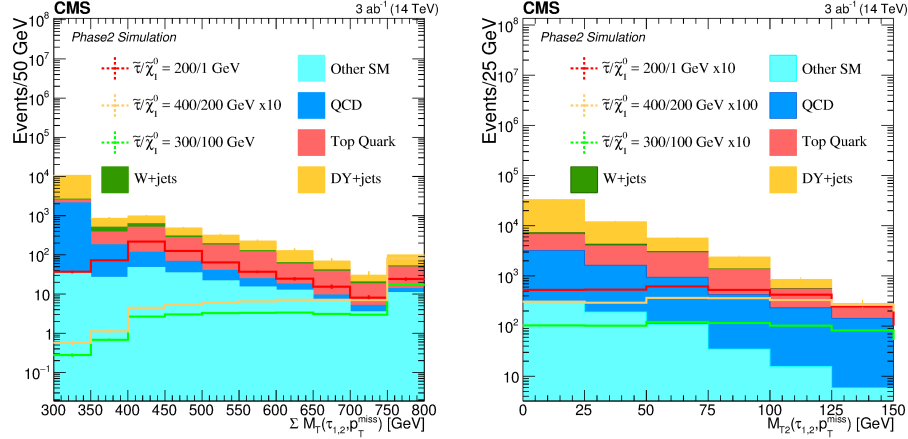


Figure 7.12: The main search variables for the $\tau_h\tau_h$ analysis, (left) Σm_T and (right) M_{T2} , both after the baseline selection. Scaled signal yields for direct $\tilde{\tau}$ production with the mass-degenerate cross section are shown for three separate scenarios of $\tilde{\tau}$ and LSP masses. All processes containing top quarks, i.e. $t\bar{t}$, single top quark, and $t\bar{t} + X$ production are combined and referred to as "Top Quark" in the Figures, while "Other SM" corresponds to background processes with a low number of events, diboson and triboson production.

A stringent requirement of at least $\Sigma m_T > 400$ GeV and $M_{T2} > 50$ GeV is applied to suppress most of the SM background events. The search regions, binned in M_{T2} , Σm_T , and the number of jets n_{jet} , are summarized in Table 7.7 and provide 24 search bins in total.

The expected yields in the $\tau_h\tau_h$ final state after all selection requirements are given in Table 7.8.

Table 7.7: Definition of the search regions (SR) for the $\tau_h\tau_h$ channel. Signal depleted bins (low Σm_T , high M_{T2}) are omitted.

Variable	SR- $\tau_h\tau_h$ _1	SR- $\tau_h\tau_h$ _2	SR- $\tau_h\tau_h$ _3	SR- $\tau_h\tau_h$ _4
M_{T2}	$50 < M_{T2} < 100$ GeV	$100 < M_{T2} < 150$ GeV	$150 < M_{T2} < 200$ GeV	$M_{T2} > 200$ GeV
Σm_T	$400 < \Sigma m_T < 500$ GeV	$500 < \Sigma m_T < 600$ GeV	$\Sigma m_T > 600$ GeV	
n_{jet}	= 0	> 0		

Table 7.8: Signal region yields for background and signal simulation in the $\tau_h\tau_h$ channel for the HL-LHC. The three rightmost columns show the signal predictions in the degenerate scenario, for masses given in the form of $(m_{\tilde{\tau}}/m_{LSP})$ in GeV.

Bin	DY+jets	W+jets	$t\bar{t}$	QCD	Other SM	Sum	(200/100)	(500/200)
SR- $\tau_h\tau_h$ - $M_{T2_0_mT_0_Nj_0}$	79.67 ± 32.14	58.80 ± 43.95	13.21 ± 3.86	5.41 ± 0.17	2.92 ± 2.35	160.00 ± 54.63	104.79 ± 4.62	1.19 ± 0.05
SR- $\tau_h\tau_h$ - $M_{T2_0_mT_0_Nj_1}$	57.76 ± 15.39	5.07 ± 0.52	104.54 ± 11.30	28.19 ± 0.33	8.78 ± 2.62	204.33 ± 19.28	56.96 ± 3.40	0.79 ± 0.04
SR- $\tau_h\tau_h$ - $M_{T2_0_mT_1_Nj_0}$	9.86 ± 6.28	3.96 ± 0.29	4.53 ± 2.24	1.26 ± 0.09	3.70 ± 1.54	23.31 ± 6.85	26.51 ± 2.32	0.72 ± 0.04
SR- $\tau_h\tau_h$ - $M_{T2_0_mT_1_Nj_1}$	1.36 ± 0.06	1.33 ± 0.13	31.25 ± 6.01	3.84 ± 0.11	2.79 ± 1.54	40.57 ± 6.21	18.99 ± 1.96	0.62 ± 0.04
SR- $\tau_h\tau_h$ - $M_{T2_0_mT_2_Nj_0}$	0.51 ± 0.04	2.85 ± 0.25	2.61 ± 1.79	0.38 ± 0.05	-	6.35 ± 1.81	21.82 ± 2.11	1.33 ± 0.06
SR- $\tau_h\tau_h$ - $M_{T2_0_mT_2_Nj_1}$	9.69 ± 6.28	0.86 ± 0.10	26.11 ± 5.56	0.86 ± 0.03	2.77 ± 1.54	40.28 ± 8.53	15.32 ± 1.76	1.11 ± 0.05
SR- $\tau_h\tau_h$ - $M_{T2_1_mT_0_Nj_0}$	32.60 ± 11.17	6.15 ± 0.53	16.36 ± 4.32	2.89 ± 0.18	4.99 ± 1.85	62.98 ± 12.13	83.71 ± 4.13	1.14 ± 0.05
SR- $\tau_h\tau_h$ - $M_{T2_1_mT_0_Nj_1}$	2.03 ± 0.10	1.34 ± 0.25	66.90 ± 8.74	18.17 ± 0.33	1.44 ± 1.62	89.89 ± 8.90	40.00 ± 2.84	0.74 ± 0.04
SR- $\tau_h\tau_h$ - $M_{T2_1_mT_1_Nj_0}$	19.59 ± 9.63	1.14 ± 0.20	3.96 ± 2.19	1.52 ± 0.11	0.56 ± 0.89	26.78 ± 9.92	25.73 ± 2.29	1.26 ± 0.05
SR- $\tau_h\tau_h$ - $M_{T2_1_mT_1_Nj_1}$	0.47 ± 0.05	0.56 ± 0.44	13.32 ± 3.91	5.19 ± 0.15	2.70 ± 1.36	22.24 ± 4.17	12.93 ± 1.62	0.91 ± 0.05
SR- $\tau_h\tau_h$ - $M_{T2_1_mT_2_Nj_0}$	9.08 ± 6.28	0.28 ± 0.06	0.05 ± 0.01	0.68 ± 0.07	2.11 ± 1.03	12.20 ± 6.37	10.83 ± 1.48	2.13 ± 0.07
SR- $\tau_h\tau_h$ - $M_{T2_1_mT_2_Nj_1}$	3.79 ± 2.51	0.06 ± 0.02	5.65 ± 2.53	1.37 ± 0.06	1.18 ± 1.03	12.05 ± 3.71	9.03 ± 1.35	1.78 ± 0.06
SR- $\tau_h\tau_h$ - $M_{T2_2_mT_1_Nj_0}$	0.17 ± 0.03	0.32 ± 0.10	0.05 ± 0.01	0.55 ± 0.08	1.03 ± 0.73	2.12 ± 0.74	2.69 ± 0.73	0.63 ± 0.04
SR- $\tau_h\tau_h$ - $M_{T2_2_mT_1_Nj_1}$	3.73 ± 2.51	0.22 ± 0.07	8.71 ± 3.13	1.84 ± 0.11	1.06 ± 0.73	15.57 ± 4.08	1.71 ± 0.58	0.39 ± 0.03
SR- $\tau_h\tau_h$ - $M_{T2_2_mT_2_Nj_0}$	0.23 ± 0.04	0.17 ± 0.05	0.04 ± 0.01	0.73 ± 0.07	0.02 ± 0.73	1.18 ± 0.73	2.48 ± 0.71	2.95 ± 0.08
SR- $\tau_h\tau_h$ - $M_{T2_2_mT_2_Nj_1}$	0.19 ± 0.02	0.04 ± 0.01	5.59 ± 2.53	1.51 ± 0.07	0.06 ± 0.73	7.38 ± 2.64	1.52 ± 0.54	2.19 ± 0.07
SR- $\tau_h\tau$ - $M_{T2_3_mT_2_Nj_0}$	53.02 ± 30.56	0.03 ± 0.02	0.02 ± 0.00	0.27 ± 0.03	0.03 ± 0.02	53.36 ± 30.56	0.24 ± 0.20	3.61 ± 0.09
SR- $\tau_h\tau_h$ - $M_{T2_3_mT_2_Nj_1}$	0.06 ± 0.01	0.02 ± 0.01	2.52 ± 1.59	0.50 ± 0.03	0.54 ± 0.51	3.66 ± 1.67	0.90 ± 0.41	3.17 ± 0.09

7.3.2 Combined results

The expected upper limits at the 95% confidence level (CL), calculated using the asymptotic formulae of the CL_s criterion, and the 5σ discovery potential are given in Fig. 7.13.

The $\tau_h\tau_h$ analysis is found to drive the sensitivity, but adding the $\ell\tau_h$ channel enlarges the exclusion bounds by about 60–80 GeV. The exclusion goes in stau masses up to 650 GeV, while the discovery potential reaches the 470 GeV.

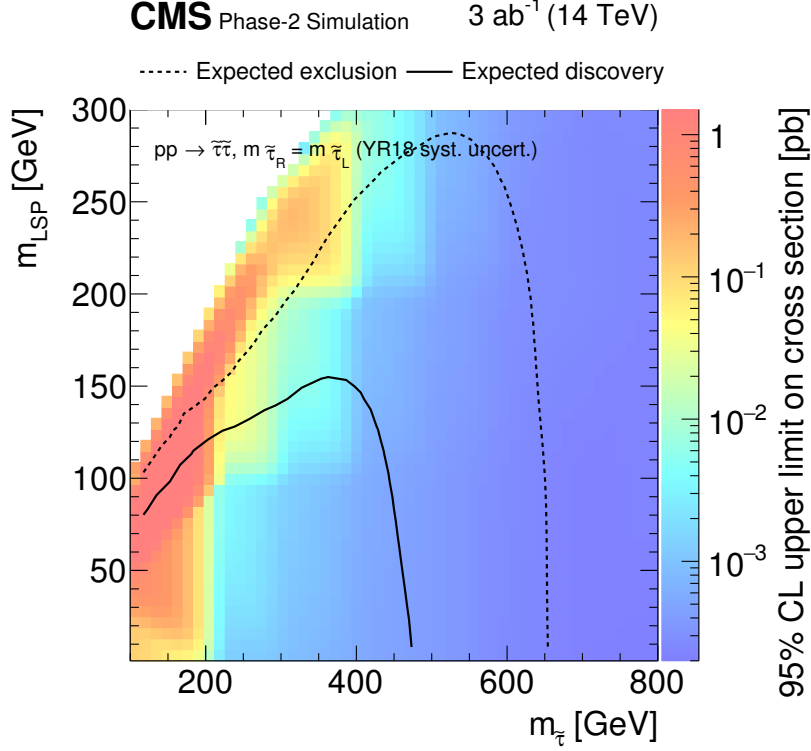


Figure 7.13: The expected upper limits at the 95% CL and the 5σ discovery potential for the combination of the results of the $\tau_h\tau_h$ and $\ell\tau_h$ channels for the HL-LHC.

7.4 HE-LHC $\tilde{\tau}$ search

On top of the CMS HL-LHC analysis, the potential of HE-LHC [153] is studied with the increased cross section for 27 TeV collisions and the increased luminosity of 15 ab^{-1} . Briefly speaking, the HE-LHC can be realized by replacing the LHC's 8.33 T niobium-titanium dipole magnets with 16 T niobium-tin magnets developed for the Future Circular Collider (FCC) [154].

7.4.1 HE-LHC description

The HE-LHC can provide proton-proton collisions with a centre-of-mass energy of 27 TeV [154]. It is expected to collect around 15 ab^{-1} of integrated luminosity over 20 years of operation. The plan is to use dipole magnets with a field of 16 T to allow such high energy.

The HE-LHC can be built in the existing LHC tunnel with a typical diameter of 3.8 m. Therefore, the dipole magnets can have an outer diameter up to 1.2 m. In addition, the HE-LHC will need up to eight new cryoplants, each with 1.5 times the capacity of the currently used LHC plants. The HE-LHC could have two high-luminosity interaction-points (IPs) 1 and 5, at the locations of the present ATLAS and CMS experiments. In addition, secondary experiments or a lepton-hadron collision point combined with an injection could be placed in IPs 2 and 8.

The LHC injector is expected to be upgraded in 2020 to deliver brighter proton beams. There are three possible injection sources: the present SPS at 450 GeV, a new fast ramping

single-layer coil superconducting (SC) synchrotron in the SPS tunnel or a double-layer coil SC synchrotron at 1.3 TeV.

The HE-LHC operation condition will lead to a photon flux and synchrotron radiation power that is 5-20 times higher in the LHC. Therefore, significant radiation damping is needed, which can be provided by an FCC-hh beam screen design with high-pumping capacity and low impedance. Also, several novel elements could be used from HL-LHC such as low-impedance collimators and crab cavities.

7.4.2 Analysis strategy

For this study the cross sections of all backgrounds and signal contributions are recalculated for $\sqrt{s} = 27$ TeV at NLO using Prospino. The signal region definition and kinematic distributions are the same as described in Sec. 7.2 for the HL-LHC study, but are scaled with the new cross sections and luminosity. The main gain in sensitivity comes from the increased luminosity since the cross section increase for the signal is of the same order as that for the background. The applied uncertainties are the same as for HL-LHC study described in Sec. 7.2. The search bin statistic uncertainty is omitted since the available MC statistics are not comparable with the expected future data and MC statistic.

Signal events were generated up to a neutralino mass of 300 GeV and up to a stau mass of 800 GeV. The stau mass range is extended towards higher values by rescaling signal region yields from the signal point with stau mass of 800 GeV by the corresponding cross section ratio.

7.4.3 Interpretation

The expected upper limits and the discovery potential are given in Fig. 7.14. In the mass-degenerate scenario, τ slepton production is excluded up to 1150 GeV with the discovery contour reaching up to 810 GeV for a massless neutralino. For high $\tilde{\tau}$ and low LSP masses, the kinematic shape is found to not depend much on the $\tilde{\tau}$ mass. Therefore, the limit on the absolute value of the cross section (color coding) does not change with the increase of $\tilde{\tau}$ mass in the aforementioned region.

7.5 Chapter conclusion

In this chapter the sensitivity projection for direct τ slepton ($\tilde{\tau}$) pair production has been presented in proton-proton collisions at a centre-of-mass energy of 14 TeV with the upgraded CMS detector and HL-LHC conditions. The study is fully based on MC simulations. Expected upper limits, as well as the discovery potential on the cross section of direct $\tilde{\tau}$ pair production, are derived for the simplified models in which each $\tilde{\tau}$ decays to a τ lepton and LSP.

The combination of 2016 and 2017 analysis shows the sensitivity to the degenerate scenario for the stau range within 100-175 GeV and light LSP, while the HL-LHC projection study predicts a significant improvement of the sensitivity, mainly, due to the increased amount of data. It is expected to exclude or, possibly, discover staus within a wide range of its masses and probe higher LSP masses. The projected sensitivity region even partially overlaps with

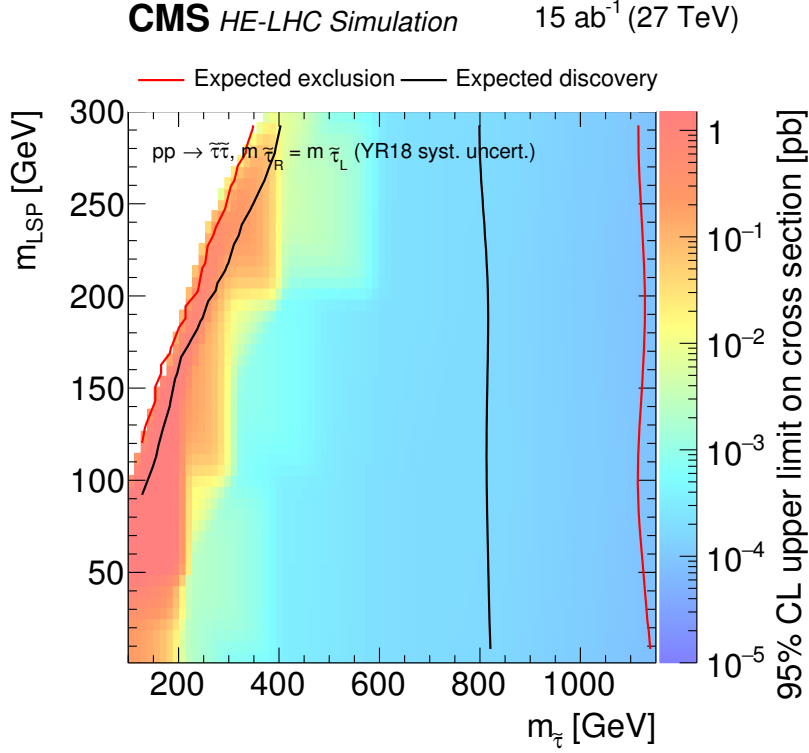


Figure 7.14: Expected upper limits at the 95% CL (red line) and the 5σ discovery potential (black line) for the combination of the results of the $\tau\tau$ and $\ell\tau$ channels for HE-LHC.

the compressed spectrum region, which is theoretically highly motivated due to providing the stau-LSP coannihilation mechanism.

In addition, the HL-LHC projection study is extended to cover the expected HE-LHC energy and luminosity. In this case, the sensitivity is pushed even further, mostly by the increased amount of data, and expected exclusion limits on stau mass exceed 1 TeV. Both HL-LHC and HE-LHC are exciting in terms of discovery potential for direct stau production despite its very low cross section. It is remarkable that the LHC is designed as a hadron machine and, usually, physicists attention is drawn by strong QCD, but its future upgrades show an unprecedented promise for possible EWK SUSY discoveries. Such a sensitivity is comparable with possible future leptonic colliders such as the International Linear Collider.

CHAPTER

8

SUMMARY AND OUTLOOK

It was such a relief to be right, even though you knew you'd only got there by trying every possible way to be wrong.

Terry Prattchet

The Standard Model (SM) is a surprisingly successful theory, which is in agreement with most of the experimental observations in particle physics. However, there are many open questions which remain unaddressed by the SM. Therefore, various new theories endeavor to provide such answers, and supersymmetry (SUSY) is a good candidate. By construction, the scientific method does not allow us to accept any of these theories without a corresponding set of experimental proofs. To this day, no strong evidence of new theories beyond the SM have been found in numerous measurements at the Large Hadron Collider.

One piece of evidence could be the discovery of a stau slepton, the superpartner of a τ lepton. The search for the stau pair production in various helicity scenarios is performed in experimentally related channels using the data collected by the Compact Muon Solenoid (CMS) detector at the LHC. The main conclusion of this thesis is that no evidence for stau production is found. Therefore, the data are interpreted in terms of upper limits on the production cross section. The combination of 2016 and 2017 analysis can exclude staus within the degenerate scenario with stau masses within 100-175 GeV and light LSP. The left-handed stau scenario can not be excluded with the current analysis, but it is also the first time a search starts to become sensitive to this helicity scenario.

Within this thesis study, a new machine learning approach using boosted decision trees is applied. It is in the context of the global tendency of using machine learning in high energy physics, which takes place in various research levels, from the track reconstruction to discriminating SUSY from SM events. Machine learning boosts the performance of many algorithms, and it has the potential to spread even further its applicability in particle physics. For example, the CMS triggering based on neural network is now in development. Moreover,

machine learning methods combined with quantum computing are already being tested for event classification.

Despite the negative SUSY search results at the LHC, there is still a large open window in parameter space to be investigated. The LHC delivered 68.18 fb^{-1} of data in 2018, which still need to be calibrated and analyzed. Currently, the stau analysis team works hard to make use of these data and to combine the full Run 2 data. Moreover, the team develops the neural network approach for both, τ identification and event classification to SUSY signal and SM background categories.

Moreover, the LHC is planned to deliver 300 fb^{-1} of data until 2023, providing a significant boost for most of the new physics searches. But this is not the end, since the High Luminosity LHC project (HL-LHC) upgrade is already scheduled and will deliver 3000 fb^{-1} of data. Therefore, the sensitivity projection for direct τ slepton pair production has been studied in proton-proton collisions at a centre-of-mass energy of 14 TeV with the upgraded CMS detector and HL-LHC conditions. The study is fully based on MC simulations. Expected upper limits, as well as the discovery potential on the cross section of direct $\tilde{\tau}$ pair production, are derived. The discovery potential reaching the stau masses of 470 GeV illustrates the unprecedented opportunity, that HL-LHC will give for stau search and for all SUSY searches.

Furthermore, the High Energy LHC project with a collision energy of 27 TeV is currently under discussion. It could provide 15 ab^{-1} of data. Therefore, the HL-LHC projection study is extended to cover the expected HE-LHC energy and luminosity. The HE-LHC analysis sensitivity on stau mass reaches an important psychological barrier of 1 TeV. In this regard, the future of the LHC looks promising in terms of open possibilities for technology developments and new physics searches. In any case, at least several discoveries of the Higgs boson coupling to the second generation fermions are guaranteed within the experimental reach in the near future. If supersymmetry or any other new physics particles providing a solution to the fine tuning problem at the TeV scale exists, there is reasonable motivation it can be discovered in the next decades.

Appendices

APPENDIX

A

$\tilde{\tau}$ SEARCH ANALYSIS WITH 2016 DATA

This Chapter described the $\tilde{\tau}$ analysis with 2016 data collected by the CMS detector. The work is documented in [117] and the whole paper is reported at the end of this Appendix.

The 2016 $\tilde{\tau}$ search is an important step before the $\tilde{\tau}$ analysis presented in the Chapter 6. Within this analysis, the background modeling strategy is developed and tuned. The signal regions are defined as a number of selection requirements on kinematic variables for $\ell\tau_h$ channel as well as for the $\tau_h\tau_h$ channel. Interpretation is done for both, the direct and indirect $\tilde{\tau}$ production scenarios. Results for indirect $\tilde{\tau}$ scenario are presented in terms of exclusion area in $\tilde{\chi}_1^+/\tilde{\chi}_2^0$ and LSP mass plane. However, no sensitivity to the direct $\tilde{\tau}$ interpretation is reached with 2016 data.



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Search for supersymmetry in events with a τ lepton pair and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV



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ABSTRACT: A search for the electroweak production of supersymmetric particles in proton-proton collisions at a center-of-mass energy of 13 TeV is presented in final states with a τ lepton pair. Both hadronic and leptonic decay modes are considered for the τ leptons. Scenarios involving the direct pair production of τ sleptons, or their indirect production via the decays of charginos and neutralinos, are investigated. The data correspond to an integrated luminosity of 35.9 fb^{-1} collected with the CMS detector in 2016. The observed number of events is consistent with the standard model background expectation. The results are interpreted as upper limits on the cross section for τ slepton pair production in different scenarios. The strongest limits are observed in the scenario of a purely left-handed low mass τ slepton decaying to a nearly massless neutralino. Exclusion limits are also set in the context of simplified models of chargino-neutralino and chargino pair production with decays to τ leptons, and range up to 710 and 630 GeV, respectively.

KEYWORDS: Hadron-Hadron scattering (experiments), Supersymmetry

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1 Introduction

Supersymmetry (SUSY) [1–8] is an attractive extension of the standard model (SM) of particle physics. It potentially provides solutions to some of the shortcomings affecting the SM, such as the need for fine tuning [9–14] to explain the observed value of the Higgs boson mass [15–20], and the absence of a dark matter (DM) candidate. Supersymmetric models are characterized by the presence of a superpartner for every SM particle with the same quantum numbers except that its spin differs from that of its SM counterpart by half a unit. The cancellation of quadratic divergences in quantum corrections to the Higgs boson mass from SM particles and their superpartners could resolve the fine-tuning problem. In SUSY models with R -parity conservation [21], the lightest supersymmetric particle (LSP) is stable [22, 23] and could be a DM candidate [24]. The superpartners of the electroweak gauge and Higgs bosons, namely the bino, winos, and Higgsinos, mix to

form neutral and charged mass eigenstates, referred to as the neutralinos ($\tilde{\chi}_i^0$) and charginos ($\tilde{\chi}_i^\pm$), respectively. In this paper we assume $\tilde{\chi}_1^0$, the lightest neutralino, to be the LSP.

The analysis reported in this paper investigates the production of the hypothetical τ slepton ($\tilde{\tau}$), the superpartner of the τ lepton. Supersymmetric scenarios in which the $\tilde{\tau}$ is light lead to the possibility of τ lepton rich final states [25, 26]. Coannihilation scenarios involving a light $\tilde{\tau}$ that has a small mass splitting with an LSP that is almost purely bino lead to a DM relic density consistent with cosmological observations [27–32], making the search for new physics in these final states particularly interesting. In this analysis, we examine simplified SUSY models [33–36] in which the $\tilde{\tau}$ can be produced either directly, through pair production, or indirectly, in the decay chains of charginos and neutralinos. In all cases, we assume that the $\tilde{\tau}$ decays to a τ lepton and $\tilde{\chi}_1^0$. The most sensitive searches for direct $\tilde{\tau}$ pair production to date were performed at the CERN LEP collider [37–41]. At the CERN LHC, the ATLAS [42, 43] and CMS [44, 45] collaborations have both performed searches for direct and indirect $\tilde{\tau}$ production with 8 TeV LHC data. The ATLAS collaboration has also recently reported the results of a search for SUSY in final states with τ leptons, probing indirect $\tilde{\tau}$ production in models of chargino-neutralino and chargino pair production, using data collected at $\sqrt{s} = 13$ TeV [46].

The cross section for direct $\tilde{\tau}$ pair production depends strongly on the chirality of the SM partner [47], while the experimental acceptance also changes considerably due to differences in the polarization of the τ leptons. We use the terms left- or right-handed $\tilde{\tau}$ to refer to a $\tilde{\tau}$ that is the superpartner of a left- or right-handed chiral state, respectively. In the case of a purely right-handed $\tilde{\tau}$, the decay products of hadronically decaying τ leptons originating from $\tilde{\tau}$ decays have larger visible transverse momentum (p_T) than in the purely left-handed scenario, while the reverse is true for leptonically decaying τ leptons. Three different scenarios of direct $\tilde{\tau}$ pair production are considered in this paper: (i) a purely left-handed $\tilde{\tau}$ ($\tilde{\tau}_L$), (ii) a purely right-handed $\tilde{\tau}$ ($\tilde{\tau}_R$), and (iii) maximal mixing between the right- and left-handed eigenstates. We also consider simplified models of mass-degenerate chargino-neutralino ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$) and chargino pair ($\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$) production. We assume that $\tilde{\chi}_2^0$ (the second-lightest neutralino mass eigenstate) decays through the chain $\tilde{\chi}_2^0 \rightarrow \tau \tilde{\tau} \rightarrow \tau \tau \tilde{\chi}_1^0$, and that $\tilde{\chi}_1^\pm$ (the lightest chargino) decays as $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau} \nu_\tau / \tilde{\nu}_\tau \tau \rightarrow \tau \nu_\tau \tilde{\chi}_1^0$, with equal branching fractions assumed for each of the two possible $\tilde{\chi}_1^\pm$ decay chains. For these indirect $\tilde{\tau}$ production mechanisms, we assume the $\tilde{\tau}$ to be in the maximally mixed state, and the degenerate $\tilde{\tau}$ and $\tilde{\nu}_\tau$ masses to be halfway between the mass of the produced particles ($\tilde{\chi}_1^\pm / \tilde{\chi}_2^0$) and the $\tilde{\chi}_1^0$ mass. Diagrams illustrating these simplified models of direct and indirect $\tilde{\tau}$ production are shown in figure 1.

The results reported in this paper are based on data collected with the CMS detector at the LHC during 2016 in proton-proton (pp) collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1} . We study events with two τ leptons in the final state, taking into account both hadronic and leptonic decay modes of the τ lepton. The following reconstructed visible final states are considered: $e\mu$, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$, where τ_h denotes a hadronically decaying τ lepton. For the purposes of this paper, we will occasionally refer to the $\tau_h\tau_h$ final state as the all-hadronic final state, and the $e\mu$, $e\tau_h$, and $\mu\tau_h$ final states collectively as the leptonic final states. In most cases, we

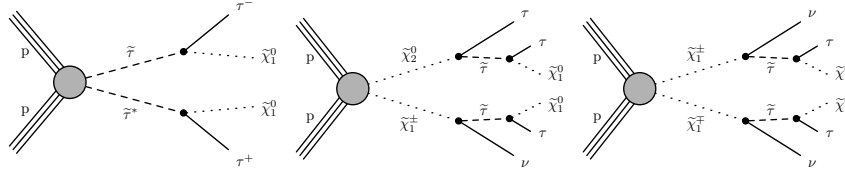


Figure 1. Diagrams for the simplified models studied in this paper: direct $\tilde{t}$ pair production followed by each $\tilde{t}$ decaying to a τ lepton and $\tilde{\chi}_1^0$ (left), and chargino-neutralino (middle) and chargino pair (right) production with subsequent decays leading to τ leptons in the final state.

require the presence of significant missing transverse momentum, which can arise from the presence of stable neutralinos produced at the end of the SUSY particle decay cascades, as well as from the neutrinos produced in τ lepton decays.

The structure of this paper is as follows. A brief description of the CMS detector is presented in section 2, followed by a discussion of the event reconstruction and simulation in section 3. We describe the event selection for the search in section 4, the background estimation strategy in section 5, and the systematic uncertainties affecting the analysis in section 6. Finally, the results of the search and their statistical interpretation are presented in section 7, followed by a summary in section 8.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [48]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μ s. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [49].

3 Event reconstruction and simulated samples

Event reconstruction uses a particle-flow (PF) algorithm [50], combining information from the tracker, calorimeter, and muon systems to identify charged and neutral hadrons, photons, electrons, and muons in an event. The missing transverse momentum, $\vec{p}_T^{\text{miss}}$, is computed as the negative vector sum of the p_T of all PF candidates reconstructed in an event,

and its magnitude p_T^{miss} is an important discriminator between signal and SM background. Events selected for the search are required to pass filters [51] designed to remove detector- and beam-related noise and must have at least one reconstructed vertex. Usually more than one such vertex is reconstructed, due to pileup, i.e., multiple pp collisions within the same or neighboring bunch crossings. The reconstructed vertex with the largest value of summed physics-object p_T^2 is selected to be the primary pp interaction vertex. The physics objects are the jets, clustered using a jet finding algorithm [52, 53] with the tracks assigned to the vertex as inputs, and the associated $\vec{p}_T^{\text{miss}}$.

Charged particles that originate from the primary vertex, photons, and neutral hadrons are clustered into jets using the anti- k_T algorithm [52] with a distance parameter of 0.4, as implemented in the FASTJET package [53]. The jet energy is corrected to account for the contribution of additional pileup interactions in an event and to compensate for variations in detector response [53, 54]. Jets considered in the searches are required to have their axes within the tracker volume, within the range $|\eta| < 2.4$. We also require them to have $p_T > 20$ GeV. Jets are required to be separated from electron, muon, or τ_h candidates that are selected for the analysis by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$ in order to avoid double counting of objects.

Jets originating from the hadronization of b quarks are identified, or “tagged”, with the combined secondary vertex (CSV) algorithm [55, 56] using two different working points, referred to as “loose” and “medium”. The b tagging efficiency for jets originating from b quarks is measured in simulation to be about 81 (63)% for the loose (medium) working point, while the misidentification rates for jets from charm quarks, and from light quarks or gluons, are about 37 and 9% (12 and 1%), respectively.

Electron candidates are reconstructed by first matching clusters of energy deposited in the ECAL to reconstructed tracks. Selection criteria based on the distribution of the shower shape, track-cluster matching, and consistency between the cluster energy and track momentum are then used in the identification of electron candidates [57]. Muon candidates are reconstructed by requiring consistent measurement patterns in the tracker and muon systems [58]. Electron and muon candidates are required to be consistent with originating from the primary vertex by imposing restrictions on the magnitude of the impact parameters of their tracks with respect to the primary vertex in the transverse plane (d_{xy}), and on the longitudinal displacement (d_z) of those impact points. To ensure that the electron or muon candidate is isolated from any jet activity, the relative isolation quantity (I_{rel}), defined as the ratio of the scalar p_T sum of the particles in an η - ϕ cone around the candidate to the candidate p_T , is required to be below a threshold appropriate for the selection under consideration. An area-based estimate [54] of the pileup energy deposition in the cone is used to correct I_{rel} for contributions from particles originating from pileup interactions.

The τ_h candidates are reconstructed using the CMS hadron-plus-strips algorithm [59, 60]. The constituents of the reconstructed jets are used to identify individual τ lepton decay modes with one charged hadron and up to two neutral pions, or three charged hadrons. The presence of extra particles within the jet, not compatible with the reconstructed decay mode, is used as a criterion to discriminate τ_h decays from other jets. A multivariate

discriminant [61], which contains isolation as well as lifetime information, is used to suppress the rate for quark and gluon jets to be misidentified as τ_h candidates. The working point used for the analysis in the $e\tau_h$ and $\mu\tau_h$ final states, referred to as the “tight” working point, typically has an efficiency of around 50% for genuine τ_h , with a misidentification rate of approximately 0.03% for light-quark or gluon jets. A more stringent (“very tight”) working point is used for the analysis in the $\tau_h\tau_h$ final state in order to suppress the background from SM events comprised uniquely of jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events. The very tight working point corresponds to typical efficiencies of around 40% for genuine τ_h , and a misidentification rate of approximately 0.01% for light-quark or gluon jets. We also employ a relaxed (“loose”) working point in the extrapolation procedures used to estimate the contributions of events to the background in which light-quark or gluon jets are misidentified as τ_h . The loose working point corresponds to an efficiency of $\approx 65\%$ for genuine τ_h , and a misidentification rate of $\approx 0.07\%$. Electrons and muons misidentified as τ_h are suppressed using dedicated criteria based on the consistency between the measurements in the tracker, calorimeters, and muon detectors [60, 61].

Significant contributions to the SM background for this search originate from Drell-Yan+jets (DY+jets), W+jets, $t\bar{t}$, and diboson processes, as well as from QCD multijet events. Smaller contributions arise from rare SM processes such as triboson and Higgs boson production, single top quark production, and top quark pair production in association with vector bosons. We rely on a combination of data control samples and Monte Carlo (MC) simulations to estimate the contributions of each background source. MC simulations are also used to model the signal processes.

The MADGRAPH5_aMC@NLO 2.3.3 [62] event generator is used at leading order (LO) precision to produce simulated samples of the W+jets and DY+jets processes, based on the NNPDF3.0LO [63] set of parton distribution functions (PDFs). Top quark pair production, diboson and triboson production, and rare SM processes like single top production or top quark pair production with associated bosons, are generated at next-to-leading order (NLO) precision with MADGRAPH5_aMC@NLO and POWHEGv2.0 [64–67], using the NNPDF3.0NLO [63] set of PDFs. Showering and hadronization are carried out by the PYTHIA 8.205 package [68], while a detailed simulation of the CMS detector is based on the GEANT4 [69] package. Finally, renormalization and factorization scale and PDF uncertainties have been derived with the use of the SYSCALC package [70].

Signal models of direct $\tilde{\tau}$ pair production are generated with MADGRAPH5_aMC@NLO at LO precision up to the production of τ leptons, which are then decayed with PYTHIA 8.212. For the models of chargino-neutralino pair production that are also studied, PYTHIA 8.212 is used to describe the decays of the parent charginos and neutralinos produced by MADGRAPH5_aMC@NLO at LO precision. The NNPDF3.0LO set of PDFs is used in the generation of all signal models. The CMS fast simulation package [71] is used to simulate the CMS detector for the signal samples.

Event reconstruction in simulated samples is performed in a similar manner as for data. A nominal distribution of pileup interactions is used when producing the simulated samples. The samples are then reweighted to match the pileup profile observed in the

collected data. The signal production cross sections are calculated at NLO with next-to-leading logarithmic (NLL) soft-gluon resummation calculations [47, 72, 73]. The most precise cross section calculations that are available are used to normalize the SM simulated samples, corresponding most often to next-to-next-to-leading order (NNLO) accuracy.

4 Event selection

The data used for this search are selected with various triggers that require the presence of isolated electrons, muons, or τ_h candidates. In the case of the $e\tau_h$ final state, the trigger used relies on the presence of an isolated electron with $p_T > 25$ GeV satisfying stringent identification criteria, while for the $\mu\tau_h$ final state, the trigger is based on the presence of an isolated muon with $p_T > 24$ GeV. A combination of triggers is used for the events selected in the $e\mu$ final state, requiring the presence of an electron and a muon. These triggers require the leading lepton to have p_T greater than 23 GeV and the subleading lepton to have p_T greater than 8 or 12 GeV for an electron or muon, respectively. Data in the $\tau_h\tau_h$ final state are selected with a trigger requiring the presence of two τ_h candidates, each with $p_T > 35$ GeV. Trigger efficiencies are measured in data and simulation. We apply scale factors accounting for any discrepancies, parameterized in the p_T and η of the reconstructed electrons, muons, and τ_h candidates, to the simulation. The efficiencies measured in data are applied directly as correction factors to simulated signal samples, which are produced using the fast simulation package and for which the trigger simulation is not available. The trigger efficiencies range from 60 to 95%, depending on the final state and the p_T and η range under consideration.

Subsequent to the trigger criteria, the event selection for each final state requires the presence of exactly two reconstructed leptons with opposite charges, corresponding to the $e\mu$, $e\tau_h$, $\mu\tau_h$, or $\tau_h\tau_h$ final states. The various lepton selection requirements implemented in the analysis are summarized in table 1. The p_T and $|\eta|$ thresholds implemented when selecting these objects are dictated by the corresponding trigger thresholds described above. We require all selected leptons to be isolated. In the case of electron and muon candidates, the isolation requirement is enforced by placing an upper bound on the relative isolation quantity, I_{rel} . For τ_h candidates, we use a multivariate discriminant. In order to ensure consistency with the primary vertex, upper bounds are placed on the absolute values of the electron and muon d_{xy} and d_z . We avoid overlaps between the two reconstructed leptons in the mixed final states ($e\mu$, $e\tau_h$, and $\mu\tau_h$) by requiring them to have a minimum separation in ΔR of at least 0.3. In order to ensure orthogonality between the different final states and suppress background, we reject events with additional electrons or muons beyond the two selected leptons that satisfy slightly less stringent selection criteria. These criteria are summarized in table 2.

A subsequent set of selection criteria is imposed for each final state to further suppress background and enhance the search sensitivity. Differences in the background compositions between the different final states play a role in the determination of the corresponding selection criteria which, together with the selection requirements described above, define the “baseline selection”.

Selection requirement	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
Electron p_T [GeV]	>24 (13)	>26	—	—
Electron $ \eta $	<2.5	<2.1	—	—
Electron $ d_{xy} $ [cm]	<0.045	<0.045	—	—
Electron $ d_z $ [cm]	<0.2	<0.2	—	—
Electron I_{rel}	<0.1	<0.1	—	—
Muon p_T [GeV]	>24 (10)	—	>25	—
Muon $ \eta $	<2.4	—	<2.4	—
Muon $ d_{xy} $ [cm]	<0.045	—	<0.045	—
Muon $ d_z $ [cm]	<0.2	—	<0.2	—
Muon I_{rel}	<0.15	—	<0.15	—
τ_h p_T [GeV]	—	>20	>20	>40
$\tau_h \eta $	—	<2.3	<2.3	<2.1
τ_h isolation working point	—	Tight	Tight	Very tight

Table 1. Summary of lepton selection requirements for the analysis. Entries with a second value in parentheses refer to the lepton with the higher (lower) p_T .

Selection requirement	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
Electron p_T [GeV]	>15	>15	>10	>20
Electron $ \eta $	<2.5	<2.5	<2.5	<2.5
Electron $ d_{xy} $ [cm]	<0.045	<0.045	<0.045	<0.1
Electron $ d_z $ [cm]	<0.2	<0.2	<0.2	<0.2
Electron I_{rel}	<0.3	<0.3	<0.3	<0.175
Muon p_T [GeV]	>15	>10	>15	>20
Muon $ \eta $	<2.4	<2.4	<2.4	<2.4
Muon $ d_{xy} $ [cm]	<0.045	<0.045	<0.045	<0.045
Muon $ d_z $ [cm]	<0.2	<0.2	<0.2	<0.2
Muon I_{rel}	<0.3	<0.3	<0.3	<0.25

Table 2. Summary of requirements for identifying additional electrons and muons.

In all final states, we require $|\Delta\phi(\ell_1, \ell_2)| > 1.5$, with additional requirements of $\Delta R(\ell_1, \ell_2) < 3.5$ and $|\Delta\eta(\ell_1, \ell_2)| < 2$ being applied for the leptonic final states to suppress the QCD multijet background. Here ℓ_1 and ℓ_2 represent the leading and trailing reconstructed electrons, muons, or τ_h candidates, respectively. In order to suppress backgrounds with top quarks, we veto events containing any b-tagged jet with $p_T > 30$ GeV identified with the loose CSV working point in the $\tau_h\tau_h$ final state. In the leptonic final states, these backgrounds are reduced by vetoing any event that contains either more than

one jet with $p_T > 20$ GeV, or any such jet that is b tagged using the medium CSV working point. One-jet events in these final states are required to have a separation in $|\Delta\eta|$ of less than 3 between the jet and the reconstructed leptons and, in the case of the $e\tau_h$ and $\mu\tau_h$ final states, a separation in ΔR of less than 4 between the jet and the τ_h . Background events from low-mass resonances are removed in these final states by requiring the invariant mass of the two leptons, $m(\ell_1, \ell_2)$, to exceed 50 GeV. In the $e\mu$ final state, $m(\ell_1, \ell_2)$ is required to lie in the window 90–250 GeV in order to suppress Z+jets events with $Z \rightarrow \tau\tau$, while the electron and muon p_T are required to be less than 200 GeV in order to suppress $t\bar{t}$ and WW events, since the signal processes targeted are not expected to produce leptons with higher p_T .

In order to further improve discrimination against the SM background, we take advantage of the expected presence of two $\tilde{\chi}_1^0$ in the final state for signal events, which would lead to additional p_T^{miss} . While background processes such as W+jets with $W \rightarrow \ell\nu$ can also produce genuine p_T^{miss} , the correlations between $\vec{p}_T^{\text{miss}}$ and the reconstructed leptons are expected to be different between signal and background processes, and these differences can be exploited. In particular, mass observables that can be calculated from the reconstructed leptons and the $\vec{p}_T^{\text{miss}}$ provide strong discriminants between signal and background. For a mother particle decaying to a visible and an invisible particle, the transverse mass (m_T), calculated using only the $\vec{p}_T$ of the decay products, should have a kinematic endpoint at the mass of the mother particle. Assuming that the p_T^{miss} corresponds to the p_T of the invisible particle, we calculate the m_T observable for the visible particle q and the invisible particle as follows:

$$m_T(q, \vec{p}_T^{\text{miss}}) \equiv \sqrt{2p_{T,q}p_T^{\text{miss}}[1 - \cos \Delta\phi(\vec{p}_{T,q}, \vec{p}_T^{\text{miss}})]}. \quad (4.1)$$

By requiring $20 < m_T(\ell, \vec{p}_T^{\text{miss}}) < 60$ GeV or $m_T(\ell, \vec{p}_T^{\text{miss}}) > 120$ GeV where ℓ here represents the electron (muon) in the $e\tau_h$ ($\mu\tau_h$) final state, the W+jets background is significantly reduced. To further suppress the SM background in the leptonic final states, we require the sum of the transverse masses, Σm_T , to be at least 50 GeV. The Σm_T is defined as the scalar sum of $m_T(\ell_1, \vec{p}_T^{\text{miss}})$ and $m_T(\ell_2, \vec{p}_T^{\text{miss}})$.

The baseline selection criteria described above are summarized in table 3. We apply these criteria to obtain an optimized sample of events in each final state. These events are then further subdivided using discriminating kinematic variables into exclusive search regions (SRs) to improve the sensitivity of the search to a range of sparticle masses. One of these discriminating variables is the “stransverse mass” m_{T2} [74, 75]. This kinematic mass variable is a generalization of the variable m_T for situations with multiple invisible particles. It serves as an estimator of the mass of pair-produced particles in situations in which both particles decay to a final state containing the same invisible particle. For direct $\tilde{\tau}$ pair production, with both $\tilde{\tau}$ decaying to a τ lepton and a $\tilde{\chi}_1^0$, m_{T2} should be correlated with the $\tilde{\tau}$ mass. Large values of m_{T2} can therefore be used to discriminate between models with large $\tilde{\tau}$ masses and the SM background. This variable is again calculated using the $\vec{p}_T$ of the different particles:

$$m_{T2} = \min_{\vec{p}_T^{X(1)} + \vec{p}_T^{X(2)} = \vec{p}_T^{\text{miss}}} \left[\max \left(m_T^{(1)}, m_T^{(2)} \right) \right], \quad (4.2)$$

Selection requirement	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$ \Delta\phi(\ell_1, \ell_2) $	>1.5	>1.5	>1.5	>1.5
$ \Delta\eta(\ell_1, \ell_2) $	<2	<2	<2	—
$\Delta R(\ell_1, \ell_2)$	<3.5	<3.5	<3.5	—
b-tagged jet veto	$p_T > 20 \text{ GeV},$ medium CSV	$p_T > 20 \text{ GeV},$ medium CSV	$p_T > 20 \text{ GeV},$ medium CSV	$p_T > 30 \text{ GeV},$ loose CSV
Additional jet veto	$>1 \text{ jet}, p_T > 20 \text{ GeV}$	$>1 \text{ jet}, p_T > 20 \text{ GeV}$	$>1 \text{ jet}, p_T > 20 \text{ GeV}$	—
$ \Delta\eta(\text{jet}, \ell_i) $ (1-jet events)	<3	<3	<3	—
$\Delta R(\text{jet}, \tau_h)$ (1-jet events)	—	<4	<4	—
$m(\ell_1, \ell_2)$ [GeV]	90–250	>50	>50	—
e/μ p_T upper bound [GeV]	<200	—	—	—
$m_T(e/\mu, \vec{p}_T^{\text{miss}})$ [GeV]	—	20–60 or >120	20–60 or >120	—
Σm_T [GeV]	—	>50	>50	—

Table 3. Summary of baseline selection requirements in each final state.

where $\vec{p}_T^{\text{X}(i)}$ (with $i=1,2$) are the unknown transverse momenta of the two undetected particles and $m_T^{(i)}$ are the transverse masses obtained by either pairing of the two hypothetical invisible particles with the two leptons. The minimization is done over the possible momenta of the invisible particles, which should add up to the $\vec{p}_T^{\text{miss}}$ in the event.

Another variable that is used to distinguish signal from background, D_ζ , is defined as:

$$D_\zeta = P_{\zeta, \text{miss}} - 0.85 P_{\zeta, \text{vis}}, \quad (4.3)$$

where $P_{\zeta, \text{miss}} = \vec{p}_T^{\text{miss}} \cdot \vec{\zeta}$ and $P_{\zeta, \text{vis}} = (\vec{p}_T^{\ell_1} + \vec{p}_T^{\ell_2}) \cdot \vec{\zeta}$, with $\vec{\zeta}$ being the bisector between the directions of the two leptons. The D_ζ variable helps to discriminate events in which p_T^{miss} originates from the decay of two τ leptons from other processes [76, 77]. Different background processes are characterized by different ranges of D_ζ . For instance, the DY+jets background is largely expected to have positive D_ζ values, while W+jets and $t\bar{t}$ events may have negative values.

The more restrictive trigger requirements in the $\tau_h\tau_h$ final state significantly reduce the signal acceptance, and the very low cross sections of the targeted $\tilde{\tau}\tilde{\tau}$ signal models result in very small expected signal event yields after the baseline selection. Events surviving the baseline selection in this final state are therefore categorized into only three SRs. These three SRs are exclusive and are optimized for sensitivity to different $\tilde{\tau}$ mass ranges. For higher values of the $\tilde{\tau}$ mass, a requirement of large m_{T2} significantly improves the discrimination of signal from background. We therefore define a search region, designated SR1, by selecting events with $m_{T2} > 90 \text{ GeV}$. For lower $\tilde{\tau}$ masses, Σm_T is found to be a more powerful discriminant than m_{T2} . Two additional SRs, designated SR2 and SR3, are therefore defined by selecting events with moderate m_{T2} ($40 < m_{T2} < 90 \text{ GeV}$), and further subdividing them into high and moderate Σm_T ranges: $>350 \text{ GeV}$ and 300–350 GeV, respectively. For these two SRs, we place a further requirement of $p_T^{\text{miss}} > 50 \text{ GeV}$ to sufficiently suppress the QCD multijet background.

Bin name	p_T^{miss} [GeV]	m_{T2} [GeV]	D_ζ [GeV]
0j-1	<40	<40	< -100
0j-2		>40	> -500
0j-3	[40,80]	<40	< -100
0j-4			>50
0j-5		[40,80]	< -100
0j-6			> -100
0j-7		>80	> -500
0j-8	[80,120]	<40	< -100
0j-9			> -100
0j-10		[40,80]	< -150
0j-11			> -150
0j-12		>80	> -500
0j-13	[120,250]	<40	< -100
0j-14			> -100
0j-15		[40,80]	< -150
0j-16			[-150, -100]
0j-17			> -100
0j-18		[80,100]	> -500
0j-19		[100,120]	> -500
0j-20		>120	> -500
0j-21	>250	>0	> -500

Table 4. Definition of SRs in the 0-jet category for the $e\tau_h$ and $\mu\tau_h$ final states.

In the leptonic final states, events satisfying the baseline selection criteria are categorized into SRs based on a series of thresholds applied to the values of the discriminating observables p_T^{miss} , m_{T2} , and D_ζ . The SR binning is defined to be slightly different for events in the 0- and 1-jet categories and is chosen such that there are small variations in the relative background contributions in the different bins. This allows us to obtain stronger constraints on the background predictions in the final result, obtained from a simultaneous maximum likelihood fit to the data in all SRs. Tables 4 to 7 list the criteria used to define the SRs in the 0- and 1-jet categories, respectively. While the same binning is chosen for the $e\tau_h$ and $\mu\tau_h$ final states, the SR bins chosen in the $e\mu$ final state are slightly different because of the different background composition.

Bin name	p_T^{miss} [GeV]	m_{T2} [GeV]	D_ζ [GeV]
1j-1	<40	<40	< -150
1j-2			[-150,100]
1j-3			> -500
1j-4	[40,80]	<40	< -100
1j-5			>50
1j-6			< -100
1j-7		[40,80]	> -100
1j-8			> -500
1j-9			< -100
1j-10	[80,120]	[40,80]	< -150
1j-11			> -150
1j-12			> -500
1j-13		[80,120]	> -500
1j-14			>120
1j-15			>120
1j-16	[120,250]	<40	< -150
1j-17			[-150,-100]
1j-18			> -100
1j-19		[40,80]	> -100
1j-20			< -150
1j-21			[-150,-100]
1j-22		[80,100]	> -100
1j-23			> -500
1j-24			> -500
1j-25		[100,120]	> -500
1j-26			> -500
1j-27			> -500
1j-28	>250	>80	> -500
1j-29			> -500
1j-30			> -500

Table 5. Definition of SRs in the 1-jet category for the $e\tau_h$ and $\mu\tau_h$ final states.

5 Background estimation

The dominant background sources for this search are DY+jets, W+jets, QCD multijet, $t\bar{t}$, and diboson processes. These background sources have different relative contributions in the different final states. For the $\tau_h\tau_h$ final state, the dominant background consists of QCD multijet and W+jets processes, where one or more of the τ_h candidates originates from a parton and is misidentified as a prompt τ_h . This background is predicted using a data-driven method relying on a control region with a loose isolation requirement. For the $e\tau_h$ and $\mu\tau_h$ final states, the main backgrounds after the baseline selection are DY+jets ($\approx 50\%$), W+jets ($\approx 30\%$), and QCD multijet ($\approx 10\%$) events. The DY+jets background

Bin name	p_T^{miss} [GeV]	m_{T2} [GeV]	D_ζ [GeV]
0j-1	<40	<40	< -100
0j-2			>0
0j-3			> -500
0j-4	[40,80]	<40	< -100
0j-5			>50
0j-6			< -100
0j-7		[40,80]	> -100
0j-8			> -500
0j-9			< -100
0j-10	[80,120]	<40	> -100
0j-11			< -150
0j-12			> -150
0j-13		>80	> -500
0j-14			< -100
0j-15			> -100
0j-16	[120,250]	[40,80]	< -150
0j-17			[-150,-100]
0j-18			> -100
0j-19		[80,100]	> -500
0j-20			> -500
0j-21			> -500
0j-22	>250	>0	> -500

Table 6. Definition of SRs in the 0-jet category for the $e\mu$ final state.

contribution, which usually consists of events with two prompt leptons, is determined from simulation after applying shape and normalization corrections that are determined from data. The W+jets and QCD multijet backgrounds usually contain a jet that is misidentified as τ_h , and are determined from a sideband sample using a data-driven method similar to the one used in the $\tau_h\tau_h$ case. The main backgrounds in the $e\mu$ final state originate from $t\bar{t}$ ($\approx 45\%$) and WW ($\approx 35\%$) events, and are estimated from simulation after applying corrections derived from data. A detailed description of the procedures used to estimate the background contributions from the different sources follows.

5.1 Estimation of the Drell-Yan+jets background

The DY+jets background mainly originates from $Z \rightarrow \tau\tau$ decays. We estimate the contribution of this background from simulation after corrections based on control samples in

Bin name	p_T^{miss} [GeV]	m_{T2} [GeV]	D_ζ [GeV]
1j-1	<40	<40	< -150
1j-2			[-150,100]
1j-3			>0
1j-4			> -500
1j-5	[40,80]	<40	< -100
1j-6			>50
1j-7			> -100
1j-8			> -500
1j-9	[80,120]	<40	< -100
1j-10			< -100
1j-11			> -500
1j-12			> -500
1j-13	[120,250]	<40	< -150
1j-14			[-150,-100]
1j-15			> -100
1j-16			< -150
1j-17		[40,80]	[-150,-100]
1j-18			> -100
1j-19			> -500
1j-20			> -500
1j-21		>120	> -500
1j-22			> -500

Table 7. Definition of SRs in the 1-jet category for the $e\mu$ final state.

data. If the Z boson mass shape or p_T spectrum are poorly modeled in the simulation, then distributions of the discriminating kinematic variables can differ significantly between data and simulation, especially at the high-end tails that are relevant for the SRs. We therefore use a high-purity $Z \rightarrow \mu\mu$ control sample to compare the dimuon mass and p_T spectra between data and simulation and apply the observed differences as corrections to the simulation in the search sample in the form of two-dimensional weights parameterized in the generator-level Z boson mass and p_T . The correction factors range up to 30% for high mass and p_T values. The full size of this correction is propagated as a systematic uncertainty. The known differences in the electron, muon, and τ_h identification and isolation efficiencies, jet, electron, muon, and τ_h energy scales, and b tagging efficiency between data and simulation are taken into account. The uncertainties corresponding to these cor-

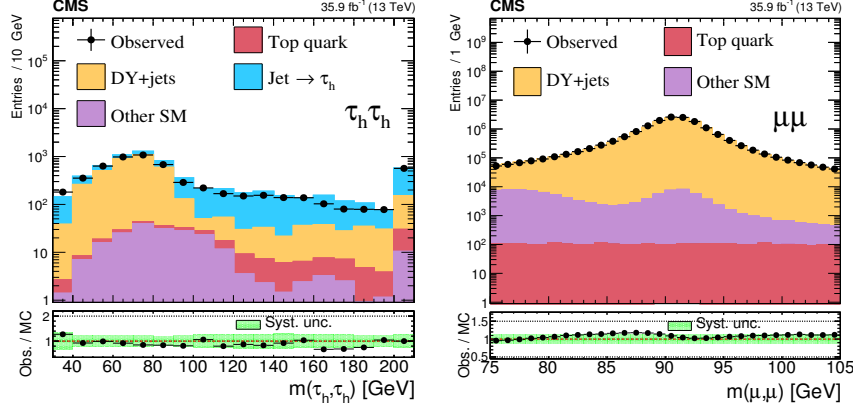


Figure 2. Left: visible mass spectrum used to validate the modeling of the DY+jets background in the $\tau_h\tau_h$ final state in a $Z \rightarrow \tau\tau$ control sample selected with low m_{T2} or Σm_T and a minimum $\tau_h\tau_h$ system p_T of 50 GeV. The last bin includes overflows. Right: dimuon mass distribution in the high-purity $Z \rightarrow \mu\mu$ control sample after all estimated correction factors have been applied to the simulation. In the legend, “Top quark” refers to the background originating from $t\bar{t}$ and single top quark production.

rections are also propagated to the final background estimate. The corrected simulation is validated in the $\tau_h\tau_h$ final state using a $Z \rightarrow \tau\tau$ control sample selected by inverting either the m_{T2} or Σm_T requirements used to define the SRs. Additionally requiring a p_T of at least 50 GeV for the $\tau_h\tau_h$ system reduces the QCD multijet background and improves the purity of this control sample. Figure 2 (left) shows that the corrected simulation agrees with the data within the experimental uncertainties in this sample.

Finally, for the analysis in the leptonic final states, a normalization scale factor as well as corrections to the $Z p_T$ distribution in the simulation are derived from a very pure $Z \rightarrow \mu\mu$ control sample in data. Events in this sample are selected by requiring two isolated muons and no additional leptons, fewer than two jets, no b-tagged jets, and a dimuon mass window of 75–105 GeV to increase the probability that they originate from $Z \rightarrow \mu\mu$ decays to >99%. After subtracting all other contributions estimated from simulation, a normalization scale factor of 0.96 ± 0.05 is extracted from the ratio of data to simulated events. The uncertainty in the scale factor is dominated by the systematic uncertainty. Figure 2 (right) shows a comparison of the dimuon mass distribution in data and simulation after all the corrections, including the normalization scale factor, have been applied.

5.2 Estimation of the background from misidentified jets

5.2.1 Estimation in the $\tau_h\tau_h$ final state

After requiring two high- p_T τ_h candidates, the dominant background for the search in the $\tau_h\tau_h$ final state consists of QCD multijet and W+jets events, in which one or both of the

τ_h candidates originate from a jet and are misidentified as prompt τ_h . This background is predicted using a method relying on extrapolation from a data sample selected with a loose isolation requirement. We estimate how frequently nonprompt or misidentified τ_h candidates that are selected with the loose isolation working point also pass the very tight isolation requirement applied in the SRs by studying a multijet-enriched control sample where we require both τ_h candidates to have the same charge. The same-charge $\tau_h\tau_h$ event sample is collected with the same trigger as the search sample, in order to take into account any biases from the isolation requirement present at the trigger level, which is not identical to the isolation requirement that corresponds to the final analysis selection criteria. We also require m_{T2} to be small (<40 GeV) to reduce any potential contributions from signal and $W+\text{jets}$ events.

The final rate measured in this sample for misidentified τ_h selected with the loose isolation working point to pass the very tight isolation requirement is around 25%, but it depends considerably on the p_T and the decay mode (one- or three-prong) of the τ_h candidate, and the parent jet flavor. The extrapolation is measured in bins of $\tau_h p_T$ and separately for the different decay modes to reduce any dependence on these factors. A systematic uncertainty of around 30% is evaluated that accounts for the dependence of the misidentification rate on the jet flavor, based on studies performed in simulation. We also noticed that the extrapolation is affected by whether or not the τ_h candidate other than the one for which the extrapolation is being applied is isolated. A correction and a corresponding systematic uncertainty are derived for this effect.

Since the isolation efficiency for prompt τ_h candidates is only around 65%, processes with genuine τ_h may leak into the data sideband regions and need to be taken into account when calculating the final estimate for the background processes with misidentified τ_h . To take this correctly into account, we define three categories for events that have at least two loosely isolated τ_h candidates: events with both τ_h candidates passing the very tight isolation requirement, events with one passing and one failing the very tight isolation requirement, and finally events with both τ_h candidates failing the very tight isolation requirement. We then equate these observable quantities with the expected sum totals of contributions from events with two prompt τ_h candidates, two misidentified τ_h candidates, or one prompt and one misidentified τ_h candidate to each of these populations. The contributions of background events with one or two misidentified τ_h candidates in the SRs can then be determined analytically by inverting this set of equations. A closure test is performed in events with two oppositely charged τ_h candidates, where the m_{T2} or Σm_T requirements used to define the SRs are explicitly inverted to avoid any overlap with the SRs. Figure 3 (left), which shows the m_{T2} distribution in this sample, confirms that the background estimation method is able to predict the background with misidentified τ_h candidates within the systematic uncertainties.

5.2.2 Estimation in the $e\tau_h$ and $\mu\tau_h$ final states

The misidentification of jets as τ_h candidates also gives rise to a major source of background for the search in the $e\tau_h$ and $\mu\tau_h$ final states, mainly from $W+\text{jets}$ events with leptonic W boson decays. We estimate this background from a sideband sample in data selected by

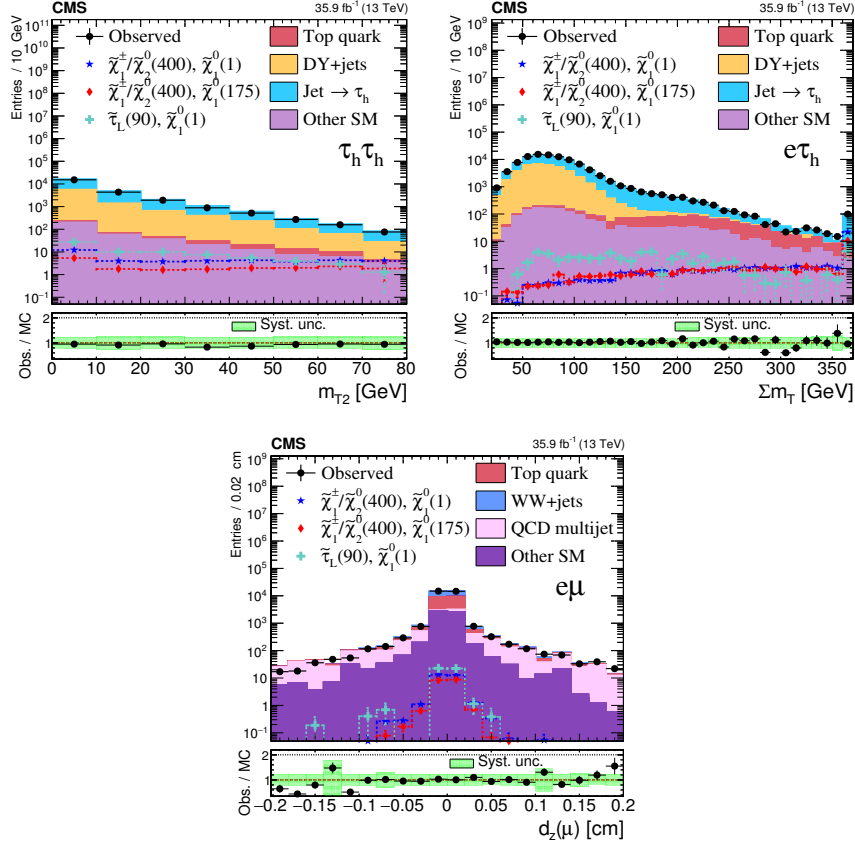


Figure 3. Top left: closure test for the method used to estimate the τ_h misidentification rate for the $\tau_h \tau_h$ final state in a data control sample where the m_{T2} or Σm_T requirements used in the SRs are inverted. Top right: Σm_T distribution for events in the $e \tau_h$ final state after the baseline selection, showing the estimation of the background with a jet misidentified as a τ_h , which is determined in a signal depleted control region. The last bin includes overflows. Bottom: distribution of the muon d_z in the $e \mu$ final state after the baseline selection, showing the estimation of the QCD multijet background using the matrix method. In the legend, “Top quark” refers to the background originating from $t\bar{t}$ and single top quark production. In all cases, the predicted and observed yields show good agreement. Distributions for two benchmark models of chargino-neutralino production, and one of direct left-handed $\tilde{\tau}$ pair production, are overlaid. The ratio of signal to background is expected to be small for these selections. The numbers within parentheses in the legend correspond to the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$ in GeV for these benchmark models.

(η , p_T)	20–30 GeV	30–40 GeV	>40 GeV
$ \eta < 0.80$	0.74 ± 0.07	0.66 ± 0.01	0.56 ± 0.02
$0.80 < \eta < 1.44$	0.68 ± 0.01	0.61 ± 0.01	0.39 ± 0.03
$1.44 < \eta < 1.57$	0.68 ± 0.03		0.64 ± 0.08
$1.57 < \eta < 2.30$	0.59 ± 0.02		0.61 ± 0.01

Table 8. Transfer factor R determined from the W+jets control sample according to eq. (5.1), as a function of p_T and η of the τ_h candidate. The uncertainties are statistical only.

applying the SR selections, with the exception that the τ_h candidates are required to satisfy the loose but not the tight isolation working point. A transfer factor for the extrapolation in τ_h isolation is determined from a W+jets control sample selected from events with one muon and at least one τ_h candidate that passes the loose isolation requirement. In events with more than one τ_h candidate, the most isolated candidate is used in the determination of the transfer factor. Events with additional electrons or muons satisfying the criteria listed in table 2 are rejected. In order to increase the purity of W+jets events in this sample by reducing the contribution of $t\bar{t}$ and QCD multijet events, we require $60 < m_T < 120$ GeV, $p_T^{\text{miss}} > 40$ GeV, no more than two jets, and an azimuthal separation of at least 2.5 radians between any jet and the W boson reconstructed from the muon and the $\vec{p}_T^{\text{miss}}$. The remaining sample has an expected purity of 82% for W+jets events. The transfer factor, R , is then determined from this control sample, after subtracting the remaining non-W+jets background contributions estimated from simulation, as follows:

$$R = \frac{N_{\text{data}}^{\text{CS}}(\text{T}) - N_{\text{MC no W}}^{\text{CS}}(\text{T})}{N_{\text{data}}^{\text{CS}}(\text{L\&!T}) - N_{\text{MC no W}}^{\text{CS}}(\text{L\&!T})}. \quad (5.1)$$

Here, $N_{\text{data}}^{\text{CS}}$ corresponds to the number of events in the control sample in data. The parenthetical arguments T and L\&!T denote events in which the τ_h candidate satisfies the tight isolation working point, and the loose but not the tight working point, respectively. The transfer factor is determined in bins of p_T and η of the τ_h candidate, as tabulated in table 8.

The contribution of the background originating from a jet misidentified as a τ_h candidate in each SR is then determined from the corresponding data sideband region selected by requiring the τ_h candidate to satisfy the loose but not the tight isolation working point as follows:

$$N^{\text{SR}}(\text{jet} \rightarrow \tau) = R(N_{\text{data}}^{\text{sideband}} - N_{\text{MC}}^{\text{sideband}}(\text{genuine } \tau)), \quad (5.2)$$

where $N_{\text{data}}^{\text{sideband}}$ represents the number of data events in the sideband region, from which $N_{\text{MC}}^{\text{sideband}}(\text{genuine } \tau)$, the expected contribution of events with genuine τ leptons determined from simulation with generator-level matching, is subtracted. Figure 3 (middle) shows a comparison of the data with the background prediction in the $e\tau_h$ final state for the Σm_T distribution for the baseline selection, where the ratio of signal to background is expected to be small.

5.3 Estimation in the $e\mu$ final state

Jets may also be misidentified as electrons or muons, although the misidentification probabilities for these objects are smaller than for τ_h . The contribution of the background from misidentified jets in the $e\mu$ final state is determined from data using a matrix method. For each SR selection we define four regions A , B , C , and D , which contain events with two leptons of either the same or opposite charge. We designate two categories for the leptons: well-isolated (electrons with $I_{\text{rel}} < 0.1$, muons with $I_{\text{rel}} < 0.15$), or loosely-isolated ($0.1 < I_{\text{rel}} < 0.2$ for electrons, $0.15 < I_{\text{rel}} < 0.30$ for muons). In order to enrich the QCD multijet contribution in events in the loosely-isolated category, we also invert the baseline selection requirements affecting the separation between the two leptons, i.e., we now require $\Delta R(\ell_1, \ell_2) > 3.5$ and $|\Delta\eta(\ell_1, \ell_2)| > 2$. We use the designations A (B) for the regions with two well-isolated leptons of the same (opposite) charge, and C (D) for the corresponding regions with a loosely-isolated lepton. Region B constitutes the search region. The purity of the C and D regions in QCD multijet events is $>90\%$, while that of the A regions is $\approx 55\%$ after the SR selections.

The charge and the isolation of misidentified leptons are expected to be uncorrelated. However, we expect a correlation to be present for the other backgrounds in these regions, e.g., prompt leptons from $t\bar{t}$ events are expected to have opposite charge. In order to account for this effect, we subtract the contributions expected from simulation for all other backgrounds from the observed numbers of events in the A , C , and D regions to obtain the estimate of the background originating from misidentified leptons in the SRs, N_B , as follows:

$$N_B = (N_A^{\text{data}} - N_A^{\text{MC}}) \frac{N_D^{\text{data}} - N_D^{\text{MC}}}{N_C^{\text{data}} - N_C^{\text{MC}}}. \quad (5.3)$$

The distribution of the muon d_z is shown in figure 3 (right) for events in the $e\mu$ final state and illustrates the estimation of the QCD multijet background using the matrix method. The data agree well with the predicted background.

5.4 Estimation of other backgrounds

Smaller contributions exist from other SM backgrounds, including other diboson processes, such as WZ +jets, triboson, and Higgs boson processes. There are also contributions from top quark processes: $t\bar{t}$ and single top quark production, or top quark pair production in association with vector bosons. These are estimated from simulation, using the known efficiency and energy scale corrections and evaluating both experimental and theoretical uncertainties as described in section 6. The shape of the top quark p_T spectrum is known to be different between simulation and data from studies of the differential $t\bar{t}$ cross section [78, 79]. The simulation is therefore reweighted by a correction factor parameterized in the top quark p_T to improve the modeling of the $t\bar{t}$ background, and the full size of the correction is propagated as a systematic uncertainty. The normalization of this background is checked in an $e\mu$ control sample enriched in $t\bar{t}$ events, selected by requiring the presence of at least two jets, at least one of which should be b tagged. The ratio of data to simulation for $t\bar{t}$ events is found to be 1.00 ± 0.05 (syst) ± 0.01 (stat), i.e., consistent with unity.

6 Systematic uncertainties

We rely on control samples in data in various ways for the estimation of the major backgrounds in the analysis. The dominant uncertainties affecting these estimates are therefore often statistical in nature, driven by the limited event yields in the corresponding control samples. For the estimates that rely on simulation, we also propagate systematic uncertainties corresponding to the different corrections that are applied, as well as statistical uncertainties related to the limited size of simulated samples. A more detailed discussion of the assessment of systematic uncertainties affecting the individual background sources follows.

In the $\tau_h\tau_h$ final state, we rely on an extrapolation in the τ_h isolation to obtain an estimate of the background with misidentified τ_h candidates. The uncertainty in this extrapolation is driven by the uncertainty introduced by the dependence of the isolation on the jet flavor. It also includes the statistical uncertainty in the control regions from which this extrapolation is measured. The uncertainty in the identification and isolation efficiency for prompt τ_h candidates is also propagated to the final estimate. Finally an additional uncertainty is assessed for the fact that the extrapolations for both τ_h candidates are correlated, leading to an overall systematic uncertainty of 30–37% for this background estimate, depending on the SR. In the estimation of the background from jets misidentified as τ_h in the $e\tau_h$ and $\mu\tau_h$ final states, for which the transfer factor is estimated in a W+jets control sample, the purity of this control sample is $\approx 85\%$, and the remaining $\approx 15\%$ is propagated as a systematic uncertainty. A systematic uncertainty of up to 5% is considered for the rate of leptons misidentified as τ_h candidates in the leptonic final states.

The effects of different sources of uncertainty, such as uncertainties related to the jet energy scale; unclustered energy contributing to p_T^{miss} ; and muon, electron, and τ_h energy scales that affect the simulated event samples used in the evaluation of the transfer factor are also propagated to the final background estimate. In the $e\mu$ final state, the largest source of uncertainty in the estimation of the background with misidentified leptons is the contamination from other background processes in the control regions A , C , and D used for the background estimation. While the C and D regions are quite pure in QCD multijet events ($>90\%$), the level of contamination can be as high as $\approx 45\%$ in the A region. A 50% uncertainty is assigned to the QCD multijet background prediction in this final state to cover the potential effects of this contamination.

We rely mostly on simulation to obtain estimates of the other background contributions and the signal yields. We propagate uncertainties related to the b tagging, trigger, and selection efficiencies, renormalization and factorization scale uncertainties, PDF uncertainties, and uncertainties in the jet energy scale, jet energy resolution, unclustered energy contributing to p_T^{miss} , and the energy scales of electrons, muons, and τ_h . For the DY+jets background, we have an additional uncertainty related to the corrections applied to the mass shape and p_T distribution, while for the $t\bar{t}$ background, we propagate an uncertainty arising from the corrections to the top quark p_T spectrum. In the leptonic final states, we derive normalization scale factors for the DY+jets and $t\bar{t}$ backgrounds in high-purity control samples. We assess uncertainties in these scale factors arising from the various

systematic effects mentioned above and propagate them to the corresponding background estimates. We also monitor the trends of these scale factors by applying a series of selection requirements on the discriminating kinematic variables that are as close as possible to the selections applied in the SRs. In the $\tau_h\tau_h$ final state, where the SRs are selected with stringent criteria applied to kinematic variables, we assign a 20% normalization uncertainty for the production cross sections of these backgrounds, as well as for other SM processes. In the leptonic final states, an uncertainty of 10% is assigned to the normalization of rare SM backgrounds to cover potential variations between the different SRs. As the WW background contribution can be sizeable in the leptonic final states and in particular for the $e\mu$ final state, a normalization uncertainty of 25% is considered for this contribution. These uncertainties have been determined from sideband regions that are defined by the same baseline cuts as those that define the search bins, except considering only those bins of the search variables that are not used in the fit for the signal extraction.

The uncertainty of 2.5% [80] in the integrated luminosity measurement is taken into account in all background estimates for which we do not derive normalization scale factors in dedicated data control samples, as well as for signal processes. In the case of the signal models we assign additional uncertainties due to differences between the fast simulation used for the signal models and the full simulation used for the background estimates that affect the p_T^{miss} resolution and lepton efficiencies. We also checked the effects of possible mismodeling of the initial-state radiation (ISR), which affects the total transverse momentum (p_T^{ISR}) of the system of SUSY particles, for the signal processes by reweighting the p_T^{ISR} distribution of simulated signal events. This reweighting procedure is based on studies of the transverse momentum of Z boson events [81]. However these effects were found to be negligible for our SR definitions. The main systematic uncertainties for the signal models and background estimates are summarized in table 9.

7 Results and interpretation

The results of the analysis in the $\tau_h\tau_h$ final state are summarized in table 10. The background estimates for the different SM processes are shown with the full uncertainty, the quadratic sum of the statistical and systematic uncertainties. As discussed in section 6, the uncertainties in the $\tau_h\tau_h$ final state are dominated by the statistical uncertainties in the data control regions and the number of simulated events produced. These uncertainties are modeled in the likelihood function used for the statistical interpretation of the results with gamma distributions [82]. If there is no event in the control region used to obtain a given background estimate for any SR or no event in the simulated sample surviving the SR selection criteria, then the one standard deviation (s.d.) upper bound evaluated for that background contribution is presented in the table. No significant excess is observed in any of the SRs.

A comparison of the observed data with the background prediction for the search variables p_T^{miss} and Σm_T is shown for the all-hadronic final state in figure 4 after the baseline selection. Similar comparisons are shown for the three search variables p_T^{miss} , m_{T2} , and D_ζ used in the leptonic final states ($e\tau_h$, $\mu\tau_h$, and $e\mu$) in figures 5–7. The background

Uncertainty (%)	Signal	Misidentified $e/\mu/\tau_h$	DY+jets	Top quark backgrounds	Rare SM
τ_h efficiency	5–11	0.1–5	5–10	4–10	0.1–10
Electron efficiency ($e\mu$, $e\tau_h$)	3	—	3	3	3
Muon efficiency ($e\mu$, $\mu\tau_h$)	2	—	2	2	2
Isolation extrapolation ($e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$)	—	15–35	—	—	—
Misidentified τ_h correlations ($\tau_h\tau_h$)	—	8–13	—	—	—
QCD multijet normalization ($e\mu$)	—	50	—	—	—
τ_h energy scale ($e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$)	0.1–23	—	1–34	0.1–24	0.1–33
Jet energy scale	0.1–45	—	0.5–24	0.5–39	0.1–67
Jet energy resolution	1–4	—	29–61	3–10	11–31
Unclustered energy	0.1–41	—	2–42	0.1–41	0.1–100
Electron energy scale ($e\mu$, $e\tau_h$)	0.1–22	—	0.5–5	0.1–13	0.1–100
Muon energy scale ($e\mu$, $\mu\tau_h$)	0.1–11	—	0.1–18	0.1–11	0.1–100
b tagging	0.5–3	1–4	0.1–3	4–20	0.1–2
Drell-Yan mass and p_T	—	—	0.5–29	—	—
Background cross sections	—	—	2–20	5–20	10–20
Fast vs. full simulation	1–30	—	—	—	—
Integrated luminosity	2.5	—	—	—	2.5

Table 9. Systematic uncertainties in the analysis for the signal models and the different SM background predictions. The uncertainty values are evaluated separately for each signal model and mass hypothesis studied and are listed as percentages.

	SR1	SR2	SR3
Nonprompt and misidentified τ_h	$0.68^{+0.90}_{-0.68}$	2.49 ± 1.83	<1.24
Drell-Yan+jets background	$0.80^{+0.97}_{-0.80}$	<0.71	<0.71
Top quark backgrounds	$0.02^{+0.03}_{-0.02}$	0.73 ± 0.31	1.76 ± 0.68
Rare SM processes	0.72 ± 0.38	0.20 ± 0.15	$0.20^{+0.25}_{-0.20}$
Total background	$2.22^{+1.37}_{-1.12}$	$4.35^{+1.75}_{-1.53}$	$3.70^{+1.52}_{-1.08}$
Left (150,1)	1.25 ± 0.40	2.91 ± 0.59	1.53 ± 0.33
Right (150,1)	1.09 ± 0.26	1.27 ± 0.20	0.74 ± 0.17
Mixed (150,1)	1.04 ± 0.22	1.39 ± 0.27	0.92 ± 0.15
Observed	0	5	2

Table 10. Final predicted and observed event yields in the three SRs defined for the $\tau_h\tau_h$ final state with all statistical and systematic uncertainties combined. For the background estimates with no event in the corresponding data control region or in the simulated sample after the SR selection, the predicted yield is indicated as being less than the one standard deviation upper bound evaluated for that estimate. The central value and the uncertainties for the total background estimate are then extracted from the full pre-fit likelihood. Expected yields are also given for signal models of direct $\tilde{\tau}$ pair production in the purely left- and right-handed scenarios and in the maximally mixed scenario, with the $\tilde{\tau}$ and $\tilde{\chi}_1^0$ masses in GeV indicated in parentheses.

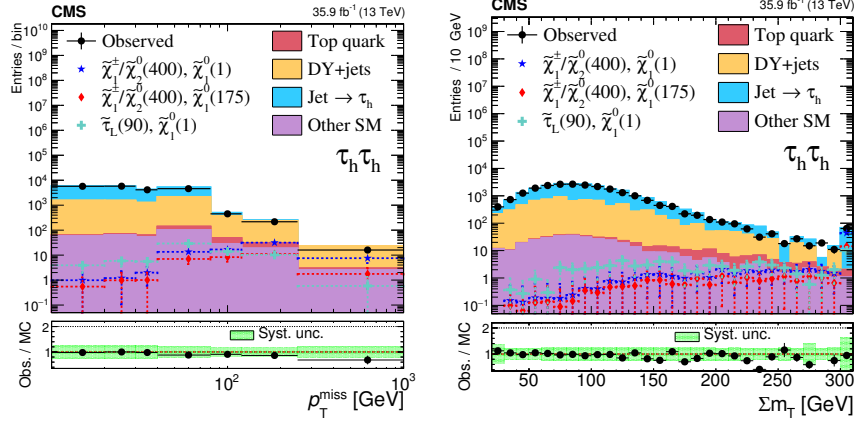


Figure 4. Distributions of the search variables p_T^{miss} (left) and Σm_T (right) for the $\tau_h \tau_h$ final state for events after the baseline selection. The black points show the data. The background estimates are represented with stacked histograms. Distributions for two benchmark models of chargino-neutralino production, and one of direct left-handed $\tilde{\tau}$ pair production, are overlaid. The numbers within parentheses in the legend correspond to the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$ in GeV for these benchmark models. In both cases, the last bin includes overflows.

estimates derived for all the SRs in the leptonic final states, as defined in tables 4 and 5, together with their uncertainties, are used as inputs to a simultaneous maximum likelihood fit to the observed data. The results for the SR bins that are used for the signal extraction in the final statistical interpretation procedure are shown in figures 8–10. Both histograms before the simultaneous fitting of all SRs (pre-fit) and after fitting (post-fit) are shown. The numbers of expected and observed events in each SR are also reported in tables 12–14 in appendix A.

No significant deviations from the expected SM background are observed in this search. The results are interpreted as limits on the cross section for the production of $\tilde{\tau}$ pairs in the context of simplified models. The produced $\tilde{\tau}$ is assumed to always decay to a τ lepton and a $\tilde{\chi}_1^0$. The 95% confidence level (CL) upper limits on SUSY production cross sections are calculated using a modified frequentist approach with the CL_s criterion [83, 84] and asymptotic approximation for the test statistic [82, 85]. Since the cross section of direct $\tilde{\tau}\tilde{\tau}$ production and the τ lepton decay are strongly dependent on chirality, the results are shown for three different scenarios. Figures 11–13 show the cross section upper limits obtained for $\tilde{\tau}\tilde{\tau}$ production for the left-handed, maximally mixed, and right-handed scenarios as a function of the $\tilde{\tau}$ mass for different $\tilde{\chi}_1^0$ mass hypotheses, namely 1, 10, 20, 30, 40, and 50 GeV. It can be seen that the constraints are reduced for higher $\tilde{\chi}_1^0$ masses due to the smaller experimental acceptance. The stronger than expected limits observed at low $\tilde{\tau}$ mass values for a $\tilde{\chi}_1^0$ mass of 50 GeV in the purely left- and right-handed scenarios are driven by a deficit in the $\mu\tau_h$ final state in the 0-jet category, leading to strong constraints on the

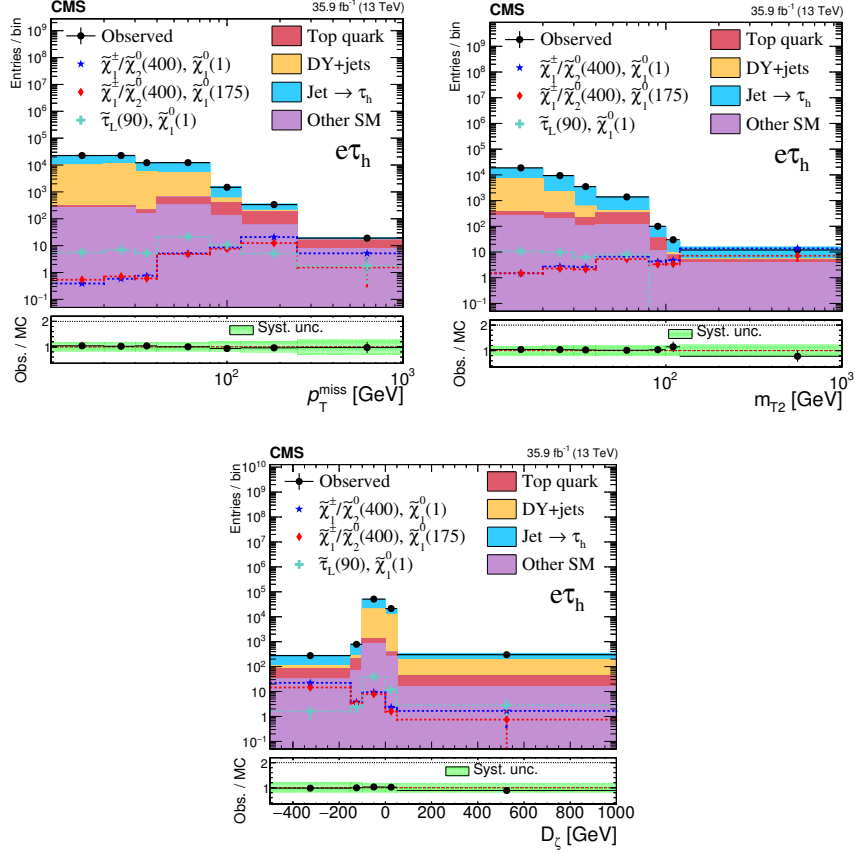


Figure 5. Distributions of the search variables p_T^{miss} (top left), m_{T2} (top right), and D_ζ (bottom) for the $e\tau_h$ final state for events after the baseline selection. The black points show the data. The background estimates are represented with stacked histograms. Distributions for two benchmark models of chargino-neutralino production, and one of direct left-handed $\tilde{\tau}$ pair production, are overlaid. The numbers within parentheses in the legend correspond to the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$ in GeV for these benchmark models. In all cases, the last bin includes overflows.

predicted background contribution in SRs sensitive to these signal models. The extremely small $\tilde{\tau}\tilde{\tau}$ production cross sections make this scenario in general very challenging. This analysis is most sensitive to scenarios with a left-handed $\tilde{\tau}$ and a nearly massless $\tilde{\chi}_1^0$, in which we exclude production rates larger than 1.26 (1.34) times the expected SUSY cross section for a $\tilde{\tau}$ mass of 90 (125) GeV.

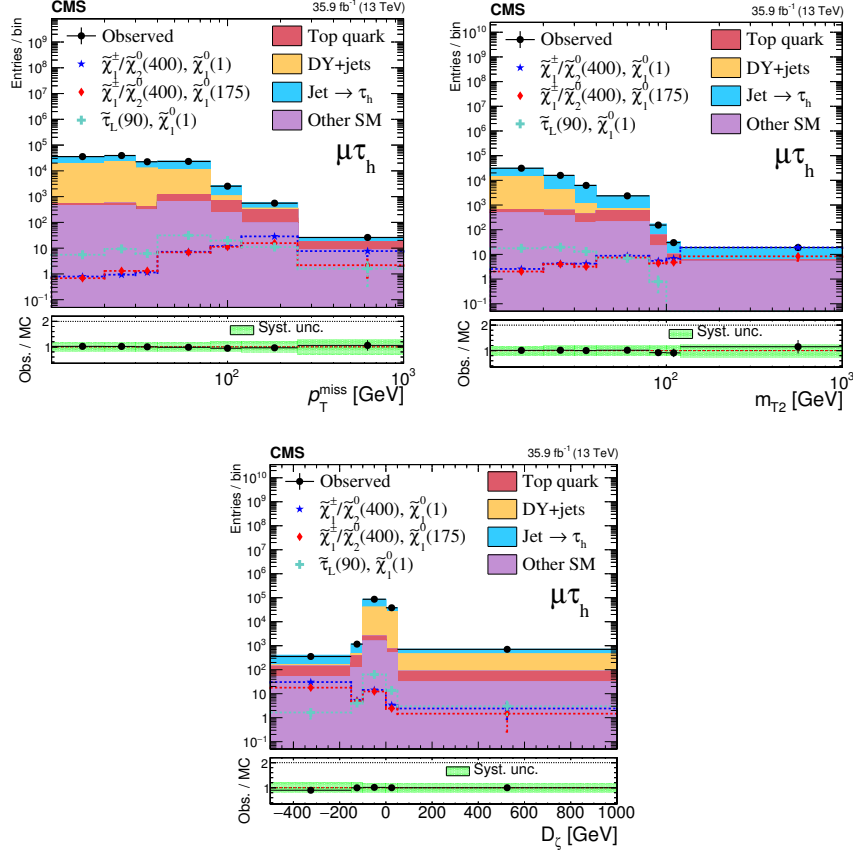


Figure 6. Distributions of the search variables p_T^{miss} (top left), m_{T2} (top right), and D_χ (bottom) for the $\mu\tau_h$ final state for events after the baseline selection. The black points show the data. The background estimates are represented with stacked histograms. Distributions for two benchmark models of chargino-neutralino production, and one of direct left-handed $\tilde{\tau}$ pair production, are overlaid. The numbers within parentheses in the legend correspond to the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$ in GeV for these benchmark models. In all cases, the last bin includes overflows.

We also interpret the results as exclusion limits in simplified models of mass-degenerate chargino-neutralino ($\tilde{\chi}_1^\pm \tilde{\chi}_2^0$) and chargino pair ($\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$) production with decays to τ leptons in the final state via the decay chains $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu_\tau/\tilde{\nu}_\tau\tau \rightarrow \tau\nu_\tau\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \rightarrow \tau\tilde{\tau} \rightarrow \tau\tau\tilde{\chi}_1^0$. Equal branching fractions are assumed for each of the two possible $\tilde{\chi}_1^\pm$ decay chains considered. The $\tilde{\tau}$ and $\tilde{\nu}_\tau$ masses are assumed to be degenerate in these models and to have a value halfway between the mass of the parent particles and the $\tilde{\chi}_1^0$ mass. Figure 14 shows the

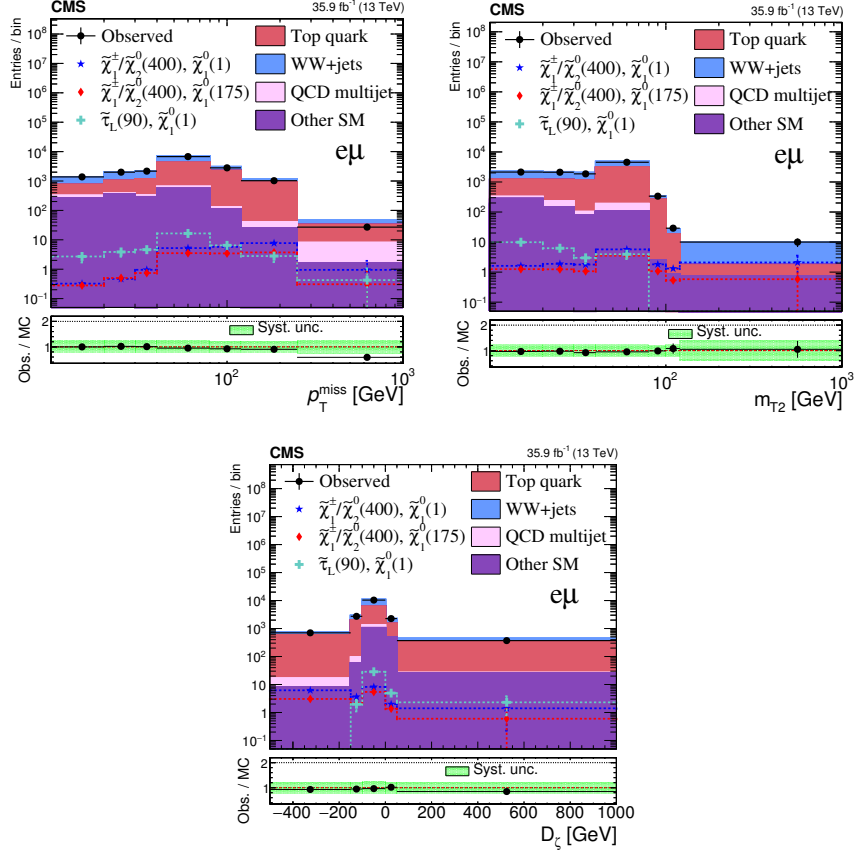


Figure 7. Distributions of the search variables p_T^{miss} (top left), m_{T2} (top right), and D_ζ (bottom) for the $e\mu$ final state for events after the baseline selection. The black points show the data. The background estimates are represented with stacked histograms. Distributions for two benchmark models of chargino-neutralino production, and one of direct left-handed $\tilde{\tau}$ pair production, are overlaid. The numbers within parentheses in the legend correspond to the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$ in GeV for these benchmark models. In all cases, the last bin includes overflows.

95% CL exclusion limits in the mass plane of $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ versus $\tilde{\chi}_1^0$ mass obtained for the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ scenario. We exclude $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses up to around 710 GeV for a nearly massless $\tilde{\chi}_1^0$ hypothesis in this scenario. Figure 15 shows the corresponding limits for the $\tilde{\chi}_1^\pm/\tilde{\chi}_1^0$ signal scenario in the plane of $\tilde{\chi}_1^\pm$ versus $\tilde{\chi}_1^0$ mass. In this scenario, we exclude $\tilde{\chi}_1^\pm$ masses up to around 630 GeV for a nearly massless $\tilde{\chi}_1^0$ hypothesis.

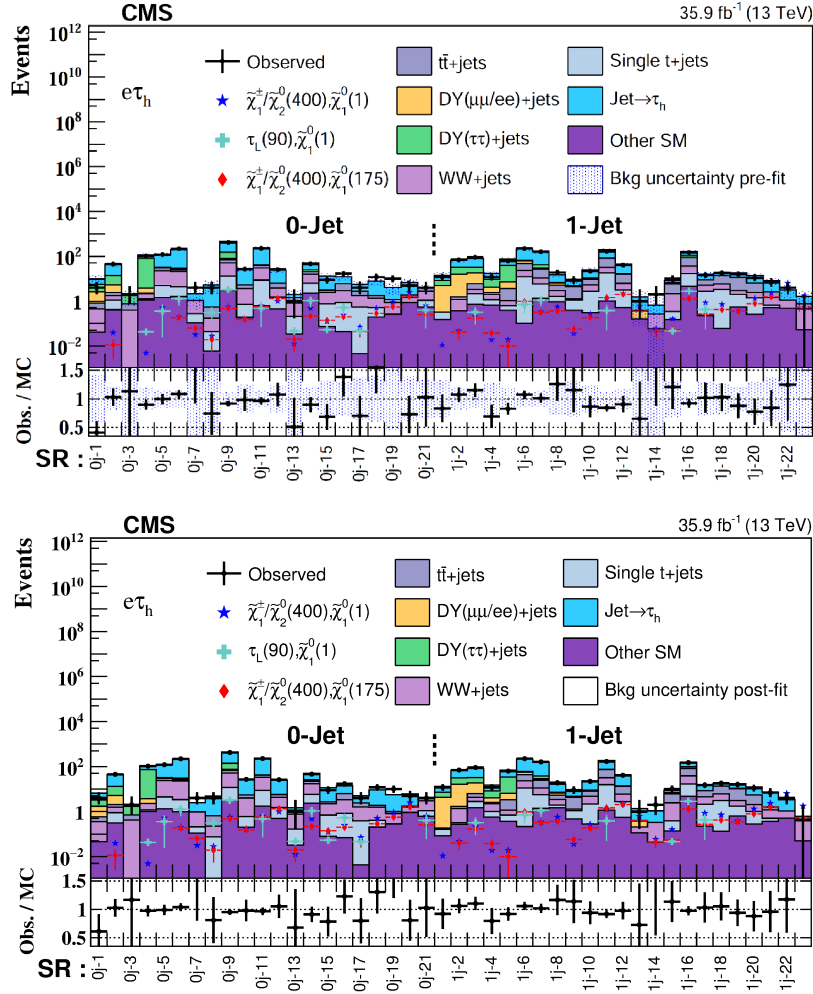


Figure 8. Pre-fit (upper) and post-fit (lower) results for the SRs used for the final signal extraction in the $e\tau_h$ final state. Distributions for two benchmark models of chargino-neutralino production, and one of direct left-handed $\tilde{\tau}$ pair production, are overlaid. The numbers within parentheses in the legend correspond to the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$ in GeV for these benchmark models. In the ratio panels, the black markers indicate the ratio of the observed data in each SR to the corresponding pre-fit or post-fit SM background prediction.

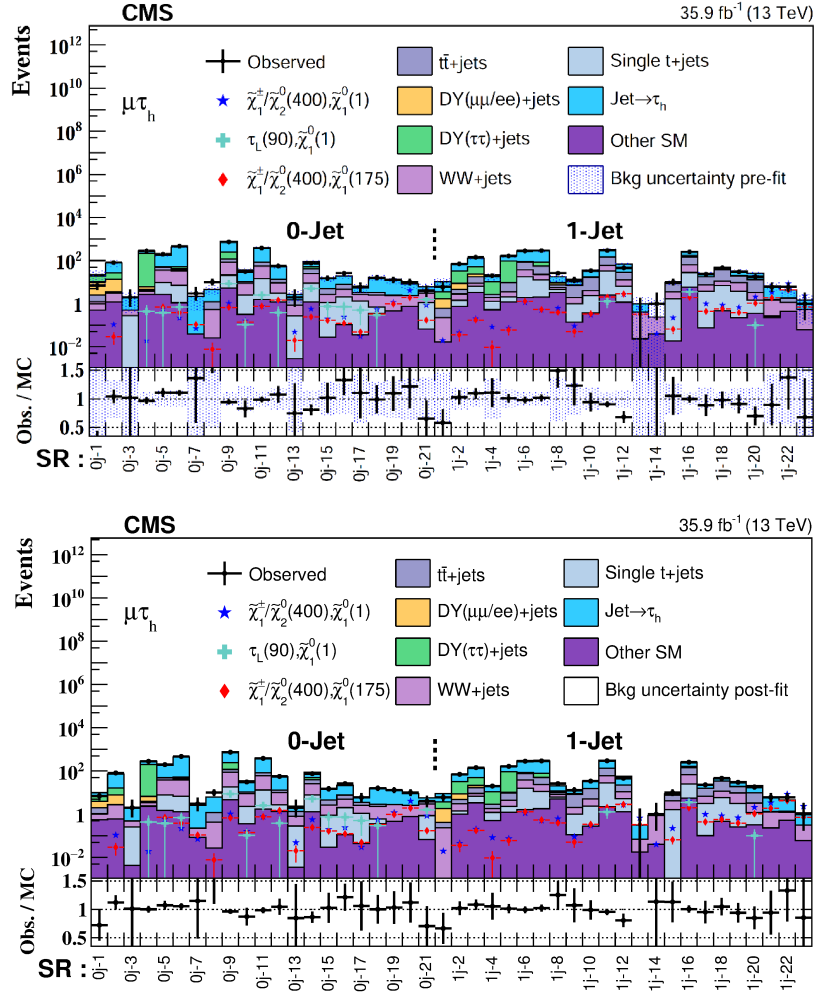


Figure 9. Pre-fit (upper) and post-fit (lower) results for the SRs used for the final signal extraction in the $\mu\tau_h$ final state. Distributions for two benchmark models of chargino-neutralino production, and one of direct left-handed $\tilde{\tau}$ pair production, are overlaid. The numbers within parentheses in the legend correspond to the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$ in GeV for these benchmark models. In the ratio panels, the black markers indicate the ratio of the observed data in each SR to the corresponding pre-fit or post-fit SM background prediction.

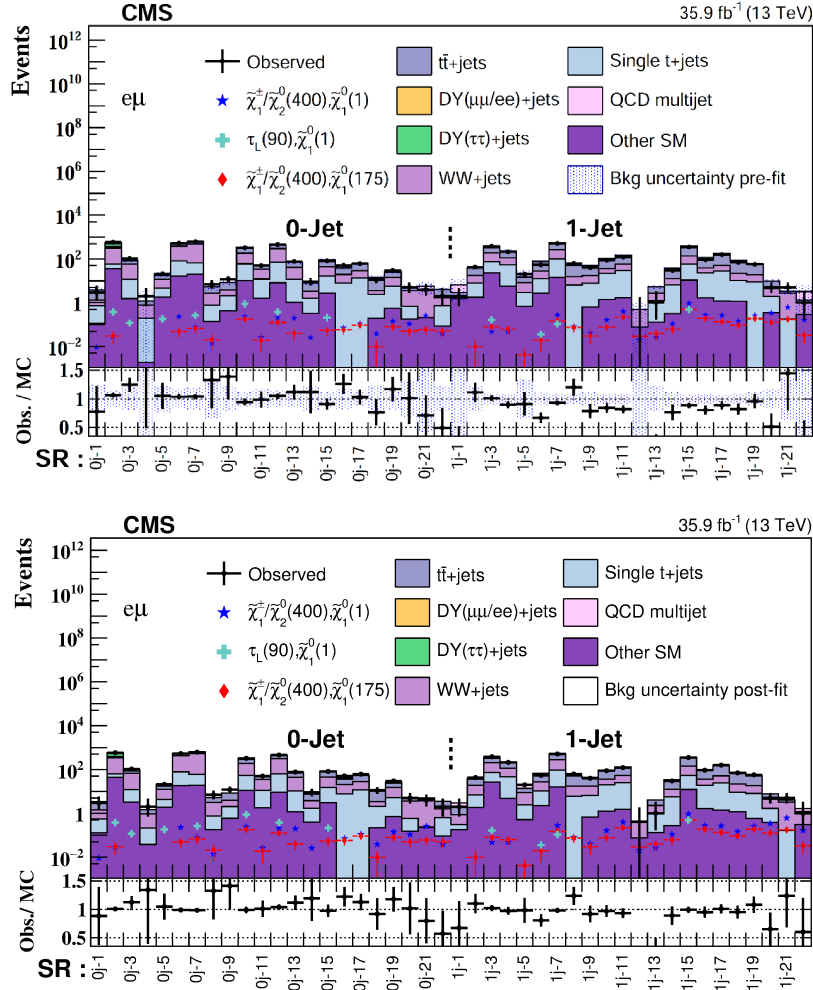


Figure 10. Pre-fit (upper) and post-fit (lower) results for the SRs used for the final signal extraction in the $e\mu$ final state. Distributions for two benchmark models of chargino-neutralino production, and one of direct left-handed $\tilde{\tau}$ pair production, are overlaid. The numbers within parentheses in the legend correspond to the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$ in GeV for these benchmark models. In the ratio panels, the black markers indicate the ratio of the observed data in each SR to the corresponding pre-fit or post-fit SM background prediction.

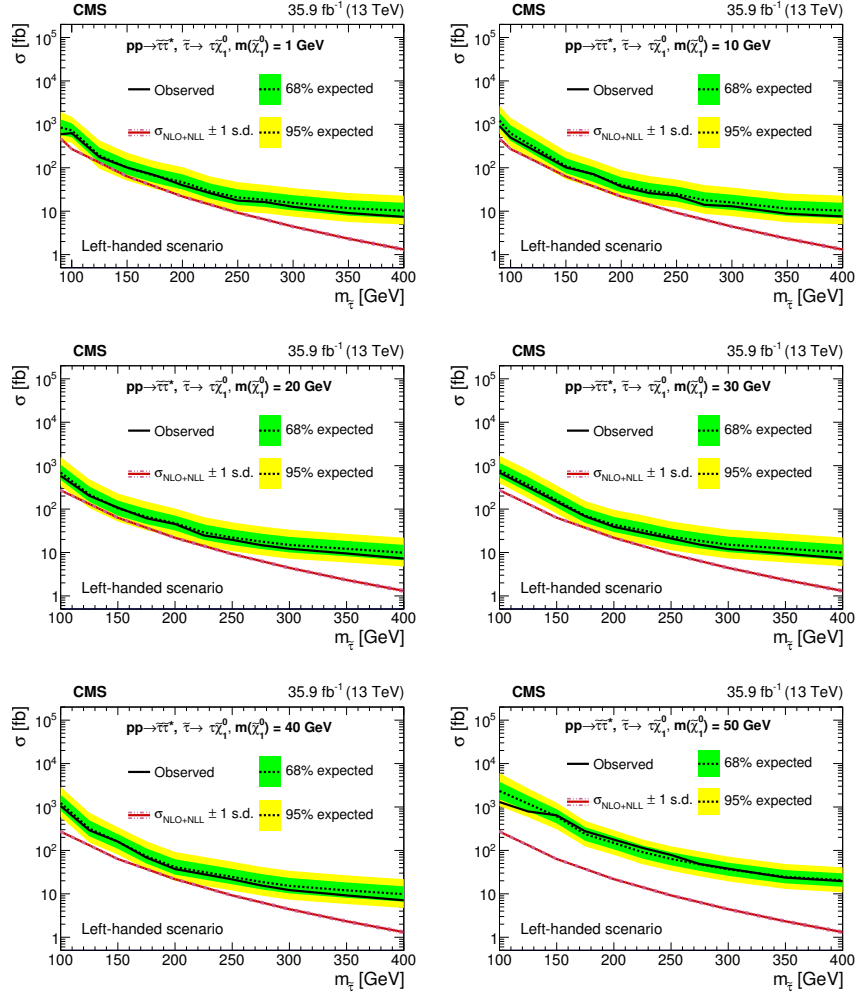


Figure 11. Excluded $\tilde{\tau}$ pair production cross section as a function of the $\tilde{\tau}$ mass for the left-handed $\tilde{\tau}$ scenario, and for different $\tilde{\chi}_1^0$ masses of 1, 10, 20, 30, 40, and 50 GeV from upper left to lower right, respectively. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The red line indicates the NLO+NLL prediction for the signal production cross section calculated with RESUMMINO [47], while the red hatched band represents the uncertainty in the prediction.

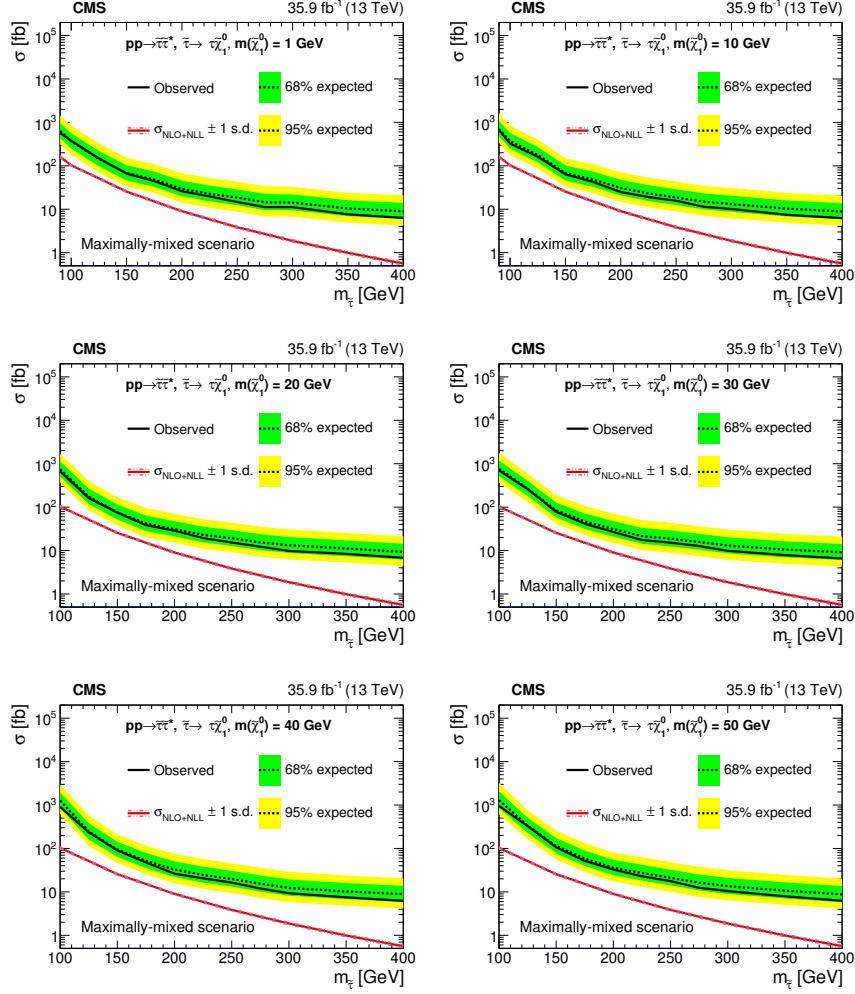


Figure 12. Excluded $\tilde{\tau}$ pair production cross section as a function of the $\tilde{\tau}$ mass for the maximally-mixed $\tilde{\tau}$ scenario, and for different $\tilde{\chi}_1^0$ masses of 1, 10, 20, 30, 40, and 50 GeV from upper left to lower right, respectively. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The red line indicates the NLO+NLL prediction for the signal production cross section calculated with RESUMMINO [47], while the red hatched band represents the uncertainty in the prediction.

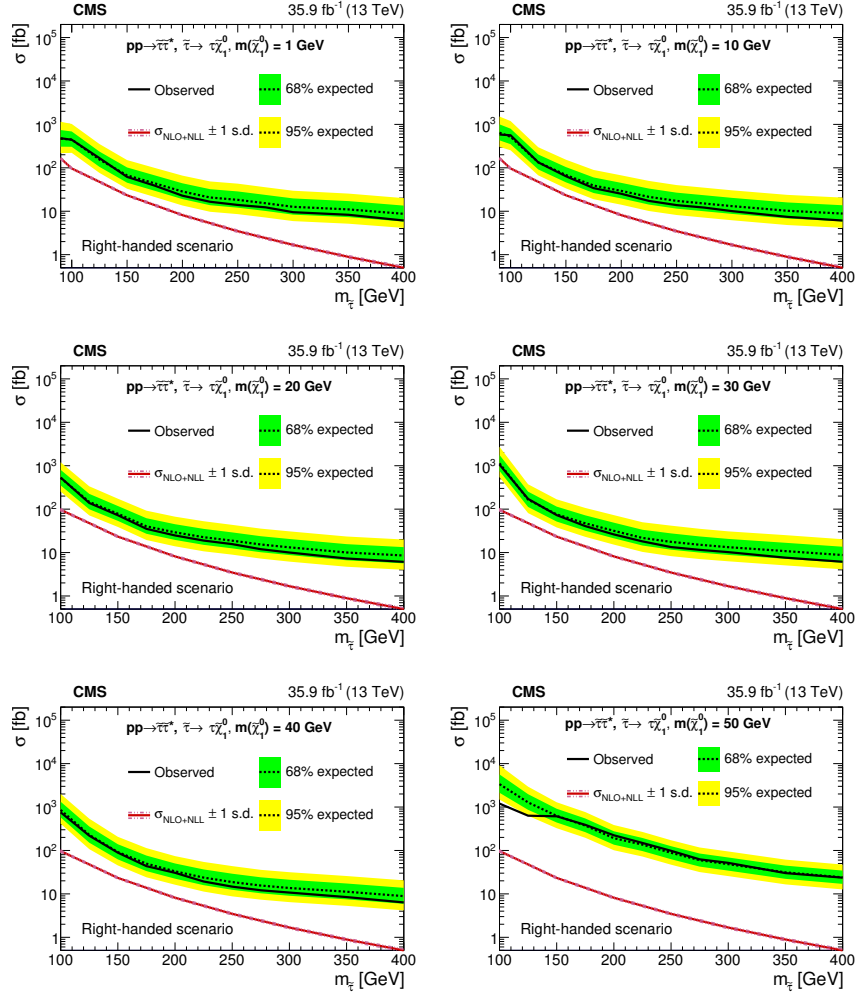


Figure 13. Excluded $\tilde{\tau}$ pair production cross section as a function of the $\tilde{\tau}$ mass for the right-handed $\tilde{\tau}$ scenario, and for different $\tilde{\chi}_1^0$ masses of 1, 10, 20, 30, 40, and 50 GeV from upper right to lower right, respectively. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The red line indicates the NLO+NLL prediction for the signal production cross section calculated with RESUMMINO [47], while the red hatched band represents the uncertainty in the prediction.

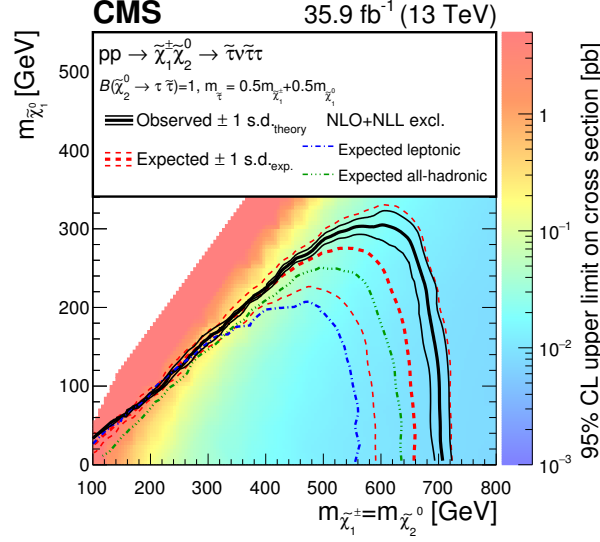


Figure 14. Exclusion limits at 95% CL for chargino-neutralino production with decays through $\tilde{\tau}$ to final states with τ leptons. The production cross sections are computed at NLO+NLL precision assuming mass-degenerate wino $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, light bino $\tilde{\chi}_1^0$, and with all the other sparticles assumed to be heavy and decoupled [72, 73]. The regions enclosed by the thick black curves represent the observed exclusion at 95% CL, while the thick dashed red line indicates the expected exclusion at 95% CL. The thin black lines show the effect of variations of the signal cross sections within theoretical uncertainties on the observed exclusion. The thin red dashed lines indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The green and blue dashed lines show separately the expected exclusion regions for the analyses in the all-hadronic and leptonic final states, respectively.

In order to simplify the reinterpretation of the results obtained in the leptonic final states using other signal models, we define a small set of aggregate SRs by combining subsets of the SRs. These aggregate SRs are chosen to have sensitivity to a range of signal models. Since they are not exclusive, the results obtained for these aggregate SRs cannot be statistically combined. These results are tabulated in table 11.

8 Summary

A search for the direct and indirect production of τ sleptons has been performed in proton-proton collisions at a center-of-mass energy of 13 TeV in events with a τ lepton pair and significant missing transverse momentum in the final state. Both leptonic and hadronic decay modes of the τ leptons are considered. Search regions are defined using discriminating kinematic observables that exploit expected differences between signal and background. The data sample used for this search corresponds to an integrated luminosity of 35.9 fb^{-1} .

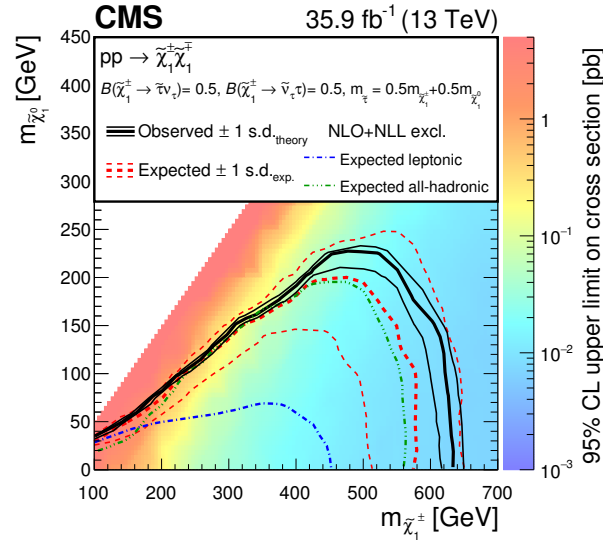


Figure 15. Exclusion limits at 95% CL for chargino pair production with decays through $\tilde{\tau}$ to final states with τ leptons. The production cross sections are computed at NLO+NLL precision assuming a wino-like $\tilde{\chi}_1^\pm$, light bino $\tilde{\chi}_1^0$, and with all the other sparticles assumed to be heavy and decoupled [72, 73]. The regions enclosed by the thick black curves represent the observed exclusion at 95% CL, while the thick dashed red line indicates the expected exclusion at 95% CL. The thin black lines show the effect of variations of the signal cross sections within theoretical uncertainties on the observed exclusion. The thin red dashed lines indicate the region containing 68% of the distribution of limits expected under the background-only hypothesis. The green and blue dashed lines show separately the expected exclusion regions for the analyses in the all-hadronic and leptonic final states, respectively.

No excess above the expected standard model background has been observed. Upper limits on the cross section of direct $\tilde{\tau}$ pair production are derived for simplified models in which each $\tilde{\tau}$ decays to a τ lepton and the lightest neutralino, with the latter being assumed to be the lightest supersymmetric particle (LSP). The analysis is most sensitive to a $\tilde{\tau}$ that is purely left-handed. For a left-handed $\tilde{\tau}$ of 90 GeV decaying to a nearly massless LSP, the observed limit is 1.26 times the expected production cross section in the simplified model. The limits obtained for direct $\tilde{\tau}$ pair production represent a considerable improvement in sensitivity for this production mechanism with respect to previous ATLAS and CMS measurements. Exclusion limits are also derived for simplified models of chargino-neutralino and chargino pair production with decays to τ leptons that involve indirect $\tilde{\tau}$ production via the chargino and neutralino decay chains. In the chargino-neutralino production model, in which the parent chargino and second-lightest neutralino are assumed to have the same mass, we exclude chargino masses up to 710 GeV under the hypothesis of a nearly massless LSP. In the chargino pair production model, we exclude chargino

Channel	N_{jet}	$p_{\text{T}}^{\text{miss}}$ [GeV]	$m_{\text{T}2}$ [GeV]	Background	Observed
$e\tau_{\text{h}}$	0	>120	>100	$10.8 \pm 2.1 \pm 2.5$	9
$e\tau_{\text{h}}$	1	>120	>120	$4.9 \pm 1.5 \pm 1.9$	4
$e\tau_{\text{h}}$	1	>250	>80	$1.6 \pm 0.9 \pm 1.2$	0
$\mu\tau_{\text{h}}$	0	>120	>100	$14.4 \pm 2.5 \pm 3.1$	14
$\mu\tau_{\text{h}}$	1	>120	>120	$5.8 \pm 1.8 \pm 2.7$	7
$\mu\tau_{\text{h}}$	1	>250	>80	$1.5 \pm 0.9 \pm 1.1$	1
$e\mu$	0	>120	>100	$9.7 \pm 2.4 \pm 3.0$	6
$e\mu$	1	>120	>120	$6.8 \pm 2.2 \pm 2.7$	6
$e\mu$	1	>250	>80	$3.3 \pm 2.0 \pm 2.3$	1

Table 11. Definition of the aggregate SRs to be used for easier reinterpretation of the results in the $e\tau_{\text{h}}$, $\mu\tau_{\text{h}}$, and $e\mu$ final states. In all of these regions, a selection requirement of $D_{\text{C}} > -500$ GeV is applied.

masses up to 630 GeV under the same hypothesis. In both cases, we significantly extend the exclusion limits with respect to previous CMS measurements.

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SR label	tt	DY+jets	WW+jets	WW+jets	Rest	Jet $\rightarrow \tau_h$	Total Bkg	$\tilde{\chi}_1^0 \tilde{\chi}_2^0$ (400,1)	$\tilde{\chi}_1^0 \tilde{\chi}_2^0$ (400,175)	$\tilde{\tau}_h$ (90,1)	Observed
0-1	$0.4 \pm 0.4 \pm 0.4$	$4.8 \pm 2.2 \pm 2.4$	<0.1	$0.4 \pm 0.3^{+0.6}_{-0.4}$	<0.1	$4.2 \pm 1.6 \pm 1.7$	$9.8 \pm 2.8 \pm 3.0$	<0.1	<0.1	<0.1	4
0-2	$0.7 \pm 0.5 \pm 0.7$	$11.4 \pm 4.1 \pm 4.4$	$0.7 \pm 0.4^{+0.9}_{-0.7}$	$0.6 \pm 0.4 \pm 0.6$	$0.4 \pm 0.4^{+0.9}_{-0.4}$	$29.8 \pm 3.2 \pm 5.5$	$43.7 \pm 5.2 \pm 7.2$	<0.1	<0.1	<0.1	45
0-3	$0.4 \pm 0.4 \pm 0.4$	$1.0 \pm 0.7 \pm 0.8$	<0.1	$0.4 \pm 0.3^{+0.6}_{-0.4}$	<0.1	<0.1	$1.8 \pm 0.8 \pm 1.0$	<0.1	<0.1	<0.1	2
0-4	<0.1	$80.3 \pm 9.1 \pm 17.3$	$0.2 \pm 0.2^{+0.4}_{-0.2}$	$0.9 \pm 0.4 \pm 0.7$	$1.1 \pm 0.8^{+1.7}_{-1.1}$	$33.3 \pm 6.3 \pm 8.0$	$115.8 \pm 11.1 \pm 19.4$	<0.1	<0.1	$0.0 \pm 0.0^{+0.7}_{-0.0}$	104
0-5	$7.4 \pm 1.7 \pm 2.3$	$2.5 \pm 1.8 \pm 1.8$	$3.6 \pm 0.8 \pm 1.5$	$17.8 \pm 1.9 \pm 6.2$	$1.4 \pm 0.3 \pm 0.9$	$88.7 \pm 7.8 \pm 15.4$	$121.5 \pm 8.4 \pm 16.9$	$0.5 \pm 0.1 \pm 0.2$	$0.4 \pm 0.1 \pm 0.3$	$0.4 \pm 0.3^{+1.0}_{-0.4}$	121
0-6	$3.9 \pm 1.2 \pm 2.4$	$4.8 \pm 1.9 \pm 2.0$	$2.6 \pm 0.7 \pm 1.3$	$16.3 \pm 1.8 \pm 6.5$	$1.7 \pm 0.9^{+1.6}_{-1.3}$	$171.9 \pm 10.4 \pm 26.2$	$204.2 \pm 10.8 \pm 29.5$	$0.2 \pm 0.0 \pm 0.1$	$0.2 \pm 0.0 \pm 0.2$	$1.3 \pm 0.6^{+2.0}_{-1.3}$	221
0-7	<0.5	<0.1	$0.2 \pm 0.2^{+0.3}_{-0.2}$	$0.8 \pm 0.4^{+1.2}_{-0.4}$	$0.1 \pm 0.1 \pm 0.1$	$1.1 \pm 0.8 \pm 0.8$	$2.2 \pm 0.9 \pm 1.0$	<0.1	<0.1	<0.1	4
0-8	$0.4 \pm 0.4^{+0.9}_{-0.4}$	<0.1	$0.0 \pm 0.0^{+0.3}_{-0.0}$	$0.1 \pm 0.1^{+0.6}_{-0.1}$	<1.9	$4.8 \pm 1.8 \pm 1.9$	$5.4 \pm 1.8 \pm 2.9$	<0.1	<0.1	$0.3 \pm 0.2^{+0.7}_{-0.3}$	4
0-9	$19.4 \pm 2.7 \pm 3.0$	$82.0 \pm 9.3 \pm 17.7$	$9.9 \pm 1.3 \pm 3.0$	$36.9 \pm 2.7 \pm 11.5$	$3.1 \pm 1.4 \pm 3.1$	$308.8 \pm 14.6 \pm 48.5$	$460.1 \pm 17.8 \pm 53.4$	$0.6 \pm 0.1 \pm 0.2$	$0.5 \pm 0.1 \pm 0.2$	$3.3 \pm 1.0^{+1.5}_{-3.3}$	421
0-10	$1.7 \pm 0.8^{+1.2}_{-0.7}$	<0.1	$0.5 \pm 0.3^{+0.7}_{-0.3}$	$3.0 \pm 0.8 \pm 1.5$	$0.2 \pm 0.1 \pm 0.1$	$22.1 \pm 1.0 \pm 5.2$	$27.5 \pm 1.1 \pm 5.9$	$0.2 \pm 0.0^{+0.2}_{-0.2}$	<0.2	<0.1	27
0-11	$9.2 \pm 1.8 \pm 4.8$	$1.3 \pm 1.3^{+1.4}_{-1.3}$	$8.0 \pm 1.2 \pm 3.5$	$21.8 \pm 2.1 \pm 9.1$	$0.6 \pm 0.1^{+1.4}_{-0.6}$	$104.2 \pm 11.5 \pm 31.3$	$235.2 \pm 12.0 \pm 33.5$	$0.6 \pm 0.1 \pm 0.2$	$0.6 \pm 0.1 \pm 0.3$	$0.5 \pm 0.4^{+1.5}_{-0.5}$	227
0-12	$2.3 \pm 0.9 \pm 2.0$	<0.1	$1.1 \pm 0.4 \pm 0.7$	$2.4 \pm 0.7 \pm 1.4$	$0.5 \pm 0.1 \pm 0.2$	$18.0 \pm 3.5 \pm 4.4$	$24.2 \pm 3.7 \pm 5.1$	$1.0 \pm 0.1 \pm 0.2$	$1.3 \pm 0.1 \pm 0.3$	<0.1	26
0-13	$0.6 \pm 0.4^{+0.7}_{-0.4}$	<0.1	$0.2 \pm 0.2^{+0.2}_{-0.2}$	$0.6 \pm 0.4 \pm 0.5$	<0.1	$0.5^{+0.2}_{-0.1} \pm 0.8$	$2.0 \pm 1.0 \pm 1.2$	<0.1	<0.1	$0.0 \pm 0.0^{+0.7}_{-0.0}$	1
0-14	$5.2 \pm 1.3 \pm 3.5$	$4.3 \pm 2.1 \pm 2.3$	$4.0 \pm 0.8 \pm 1.5$	$9.5 \pm 1.4 \pm 5.5$	$2.2 \pm 1.5 \pm 1.5$	$26.1 \pm 4.3 \pm 5.8$	$51.2 \pm 5.4 \pm 9.3$	$0.5 \pm 0.1 \pm 0.2$	$0.2 \pm 0.0 \pm 0.1$	$1.1 \pm 0.5^{+1.7}_{-0.9}$	46
0-15	$0.7 \pm 0.5^{+1.1}_{-0.7}$	<0.1	$0.7 \pm 0.3 \pm 0.5$	$1.6 \pm 0.6 \pm 1.0$	$0.1 \pm 0.0^{+0.1}_{-0.1}$	$10.1 \pm 2.6 \pm 3.0$	$13.1 \pm 2.7 \pm 3.4$	<0.1	$0.1 \pm 0.0 \pm 0.1$	$0.1 \pm 0.0^{+0.8}_{-0.1}$	9
0-16	$3.1 \pm 1.0 \pm 2.1$	<0.1	$0.8 \pm 0.4 \pm 0.5$	$2.1 \pm 0.7 \pm 1.0$	<0.1	$6.2 \pm 2.3 \pm 2.5$	$12.3 \pm 2.6 \pm 3.4$	<0.2	$0.2 \pm 0.0 \pm 0.1$	$0.5 \pm 0.3^{+1.2}_{-0.6}$	17
0-17	$1.1 \pm 0.6^{+1.2}_{-0.7}$	<0.1	$0.5 \pm 0.3 \pm 0.4$	$1.2 \pm 0.5 \pm 0.7$	<0.1	$2.9 \pm 1.3 \pm 1.3$	$5.7 \pm 1.5 \pm 1.9$	$0.1 \pm 0.0^{+0.1}_{-0.1}$	<0.1	$0.0 \pm 0.0^{+1.4}_{-0.0}$	4
0-18	$0.4 \pm 0.4^{+0.9}_{-0.4}$	<0.1	$0.3 \pm 0.2^{+0.3}_{-0.3}$	$0.8 \pm 0.4 \pm 0.7$	<0.2	$6.0 \pm 2.0 \pm 2.2$	$7.8 \pm 2.1 \pm 2.4$	<0.5	$0.3 \pm 0.1 \pm 0.1$	<0.1	12
0-19	$0.3 \pm 0.3^{+0.5}_{-0.3}$	<0.1	<0.2	$0.6 \pm 0.4^{+0.7}_{-0.4}$	<0.3	$3.0 \pm 1.5 \pm 1.5$	$4.2 \pm 1.5 \pm 1.9$	$0.9 \pm 0.1 \pm 0.3$	$0.5 \pm 0.1 \pm 0.3$	<0.1	10
0-20	$0.4 \pm 0.4^{+1.0}_{-0.4}$	<0.1	<0.1	$0.6 \pm 0.4^{+0.7}_{-0.4}$	$0.9 \pm 0.2 \pm 0.3$	$5.0 \pm 1.7 \pm 1.9$	$6.9 \pm 1.8 \pm 2.3$	$2.4 \pm 0.1 \pm 0.5$	$1.6 \pm 0.1 \pm 0.2$	<0.1	5
0-21	$1.1 \pm 0.6 \pm 0.6$	<0.1	$0.5 \pm 0.3 \pm 0.3$	$1.7 \pm 0.6 \pm 0.8$	$0.6 \pm 0.4 \pm 0.4$	<0.1	$3.9 \pm 1.0 \pm 1.2$	$0.6 \pm 0.1 \pm 0.2$	$0.2 \pm 0.0 \pm 0.1$	$0.4 \pm 0.3^{+0.5}_{-0.4}$	4
1-1	<0.1	$8.0 \pm 2.4 \pm 2.6$	$0.2 \pm 0.2^{+0.4}_{-0.2}$	<0.3	$0.2 \pm 0.1^{+0.2}_{-0.2}$	$6.1 \pm 2.0 \pm 2.2$	$14.4 \pm 3.1 \pm 3.5$	<0.1	<0.1	<0.1	12
1-2	$0.3 \pm 0.3^{+0.9}_{-0.3}$	$31.2 \pm 4.5 \pm 7.1$	<0.2	$0.8 \pm 0.4 \pm 0.7$	$0.4^{+0.9}_{-0.3} \pm 1.3$	$32.5 \pm 4.8 \pm 6.8$	$65.2 \pm 6.7 \pm 10.0$	<0.1	<0.1	<0.1	70
1-3	$2.8 \pm 1.0 \pm 2.8$	$26.8 \pm 4.2 \pm 6.0$	$1.4 \pm 0.5 \pm 0.8$	$1.2 \pm 0.6^{+1.4}_{-1.2}$	$0.7^{+1.2}_{-1.2} \pm 2.1$	$46.1 \pm 5.5 \pm 8.8$	$79.1 \pm 7.1 \pm 11.3$	$0.2 \pm 0.0 \pm 0.2$	$0.2 \pm 0.0^{+0.2}_{-0.2}$	$0.3 \pm 0.2^{+0.8}_{-0.3}$	91
1-4	$0.4 \pm 0.4^{+0.9}_{-0.4}$	$7.1 \pm 1.9 \pm 2.3$	$0.5 \pm 0.3 \pm 0.5$	$0.8 \pm 0.4^{+1.4}_{-0.8}$	$0.7 \pm 0.4 \pm 0.5$	$7.8 \pm 2.4 \pm 2.6$	$17.3 \pm 3.1 \pm 3.9$	<0.1	<0.1	<0.1	12
1-5	$2.7 \pm 1.0 \pm 1.9$	$36.1 \pm 5.4 \pm 8.3$	$0.3 \pm 0.2^{+1.3}_{-0.3}$	$0.4 \pm 0.3 \pm 0.4$	$0.4 \pm 0.3^{+0.9}_{-0.4}$	$36.6 \pm 5.6 \pm 7.8$	$76.4 \pm 7.8 \pm 11.6$	<0.1	<0.1	<0.1	63
1-6	$25.8 \pm 3.1 \pm 5.9$	$16.3 \pm 3.4 \pm 4.4$	$12.6 \pm 1.5 \pm 4.1$	$10.5 \pm 1.5 \pm 3.7$	$0.1^{+1.0}_{-0.1} \pm 1.1$	$143.3 \pm 10.1 \pm 23.7$	$208.7 \pm 11.3 \pm 25.5$	$0.9 \pm 0.1 \pm 0.6$	$0.9 \pm 0.1 \pm 0.4$	$0.7 \pm 0.4^{+0.9}_{-0.7}$	224
1-7	$16.4 \pm 2.4 \pm 3.9$	$15.3 \pm 2.9 \pm 4.1$	$4.5 \pm 0.9 \pm 2.8$	$4.9 \pm 1.0 \pm 2.5$	$1.3 \pm 0.6^{+1.9}_{-1.3}$	$116.7 \pm 8.7 \pm 19.6$	$159.1 \pm 9.6 \pm 20.8$	$0.3 \pm 0.1 \pm 0.3$	$0.3 \pm 0.1 \pm 0.2$	$1.1 \pm 0.5^{+1.2}_{-1.1}$	161
1-8	$2.2 \pm 1.0 \pm 1.4$	$1.8 \pm 1.1 \pm 1.1$	$0.7 \pm 0.4^{+1.2}_{-0.7}$	$1.3 \pm 0.5 \pm 0.8$	$1.0 \pm 0.8^{+1.1}_{-1.0}$	$8.2 \pm 2.1 \pm 2.5$	$15.1 \pm 2.8 \pm 3.6$	$0.6 \pm 0.1 \pm 0.2$	$0.4 \pm 0.1 \pm 0.1$	<0.1	19
1-9	$3.3 \pm 1.1 \pm 1.3$	$0.4 \pm 0.4^{+0.5}_{-0.4}$	$0.7 \pm 0.4 \pm 0.6$	$0.2 \pm 0.2^{+0.3}_{-0.2}$	$0.4^{+0.4}_{-0.3} \pm 0.5$	$2.8 \pm 1.5 \pm 1.5$	$7.8 \pm 2.0 \pm 2.2$	<0.1	<0.1	<0.1	9
1-10	$4.4 \pm 1.3 \pm 3.9$	$0.9 \pm 0.8 \pm 0.8$	$2.5 \pm 0.7 \pm 1.2$	$2.5 \pm 0.7 \pm 1.8$	$0.3 \pm 0.1 \pm 0.2$	$15.1 \pm 3.5 \pm 4.1$	$25.5 \pm 3.9 \pm 6.2$	$0.3 \pm 0.1 \pm 0.1$	$0.2 \pm 0.0 \pm 0.1$	<0.1	22
1-11	$51.5 \pm 4.3 \pm 9.2$	$2.7 \pm 1.2 \pm 1.4$	$17.0 \pm 1.7 \pm 5.3$	$14.0 \pm 1.7 \pm 7.4$	$1.0 \pm 0.2 \pm 0.7$	$113.2 \pm 9.4 \pm 19.4$	$199.3 \pm 10.7 \pm 23.3$	$1.2 \pm 0.1 \pm 0.5$	$1.4 \pm 0.1 \pm 0.3$	$0.4 \pm 0.3^{+0.6}_{-0.4}$	168
1-12	$10.1 \pm 1.9 \pm 6.7$	$0.8 \pm 0.8^{+0.8}_{-0.8}$	$2.7 \pm 0.7 \pm 1.4$	$3.0 \pm 0.8 \pm 1.8$	$0.5 \pm 0.2 \pm 0.2$	$28.2 \pm 4.3 \pm 6.0$	$45.3 \pm 4.9 \pm 9.3$	$2.2 \pm 0.1 \pm 0.6$	$2.0 \pm 0.1 \pm 0.7$	<0.1	41
1-13	<0.1	$0.2 \pm 0.2 \pm 0.2$	<0.1	<0.2	$0.2 \pm 0.1^{+0.8}_{-0.2}$	$1.2 \pm 0.8 \pm 0.8$	$1.5 \pm 0.9 \pm 1.2$	$0.6 \pm 0.1 \pm 0.1$	$0.4 \pm 0.1 \pm 0.3$	<0.1	1
1-14	<0.4	<0.1	<0.2	$0.2 \pm 0.2 \pm 0.2$	<0.1	$0.4^{+0.9}_{-0.4} \pm 0.6$	$0.7^{+1.1}_{-0.7} \pm 0.8$	$0.1 \pm 0.0^{+0.1}_{-0.1}$	<0.1	<0.1	2
1-15	$3.7 \pm 1.2 \pm 3.0$	$0.9 \pm 0.6 \pm 0.6$	$0.2 \pm 0.2^{+0.7}_{-0.2}$	$1.8 \pm 0.6 \pm 0.9$	$0.1 \pm 0.1 \pm 0.1$	$1.5 \pm 1.5 \pm 1.5$	$8.3 \pm 2.1 \pm 3.6$	<0.2	<0.1	$0.0 \pm 0.0^{+0.7}_{-0.0}$	10
1-16	$52.4 \pm 4.3 \pm 18.7$	$19.8 \pm 3.2 \pm 6.6$	$12.6 \pm 1.5 \pm 7.9$	$18.9 \pm 1.9 \pm 9.3$	$4.7 \pm 1.9 \pm 2.0$	$54.2 \pm 6.9 \pm 10.6$	$162.5 \pm 9.2 \pm 25.7$	$2.8 \pm 0.2 \pm 0.7$	$1.3 \pm 0.1 \pm 0.5$	$2.9 \pm 0.9 \pm 2.4$	150
1-17	$3.8 \pm 1.2^{+4.2}_{-3.0}$	<0.1	$2.5 \pm 0.7 \pm 1.6$	$2.4 \pm 0.7 \pm 1.3$	$0.2 \pm 0.1 \pm 0.2$	$5.8 \pm 2.6 \pm 2.7$	$14.7 \pm 3.0 \pm 5.4$	$0.8 \pm 0.1 \pm 0.2$	$0.3 \pm 0.1 \pm 0.1$	$0.4 \pm 0.4^{+0.8}_{-0.4}$	15
1-18	$8.5 \pm 1.7 \pm 5.4$	<0.1	$3.3 \pm 0.7 \pm 1.5$	$2.5 \pm 0.7 \pm 2.2$	$0.1^{+0.1}_{-0.1} \pm 0.2$	$3.2 \pm 2.5 \pm 2.6$	$17.5 \pm 3.2 \pm 6.6$	$0.7 \pm 0.1 \pm 0.2$	$0.4 \pm 0.1 \pm 0.1$	<0.1	18
1-19	$8.3 \pm 1.7 \pm 4.9$	$0.4 \pm 0.4 \pm 0.4$	$1.5 \pm 0.5 \pm 0.9$	$1.0 \pm 0.4^{+1.5}_{-1.0}$	$0.6 \pm 0.4 \pm 0.5$	$6.5 \pm 2.1 \pm 2.3$	$18.2 \pm 2.9 \pm 5.7$	$0.4 \pm 0.1 \pm 0.1$	$0.3 \pm 0.1 \pm 0.2$	<0.1	16
1-20	$4.0 \pm 1.3 \pm 2.8$	<0.1	$1.2 \pm 0.4^{+1.3}_{-1.2}$	$1.1 \pm 0.5^{+1.2}_{-1.1}$	$0.3 \pm 0.1 \pm 0.1$	$7.7 \pm 2.5 \pm 2.7$	$14.2 \pm 2.8 \pm 4.3$	$1.3 \pm 0.1 \pm 0.2$	$0.8 \pm 0.1 \pm 0.2$	<0.1	11
1-21	$1.1 \pm 0.6^{+1.1}_{-0.6}$	<0.1	$0.2 \pm 0.2 \pm 0.2$	$0.8 \pm 0.4^{+1.0}_{-0.8}$	$0.5 \pm 0.3^{+0.8}_{-0.5}$	$5.8 \pm 2.0 \pm 2.1$	$8.3 \pm 2.1 \pm 3.5$	$2.3 \pm 0.1 \pm 0.3$	$1.5 \pm 0.1 \pm 0.2$	<0.1	7
1-22	<0.1	<0.1	<0.1	$0.7 \pm 0.4^{+0.7}_{-0.7}$	$0.5 \pm 0.1 \pm 0.2$	$2.1 \pm 1.2 \pm 1.2$	$3.2 \pm 1.2 \pm 1.4$	$6.2 \pm 0.2 \pm 0.6$	$3.9 \pm 0.2 \pm 0.6$	<0.1	4
1-23	$0.3 \pm 0.3^{+0.5}_{-0.3}$	<0.1	<0.1	$0.4 \pm 0.3 \pm 0.3$	$0.1 \pm 0.0^{+0.1}_{-0.1}$	$0.9 \pm 0.8 \pm 0.8$	$1.6 \pm 0.9 \pm 1.2$	$1.8 \pm 0.1 \pm 0.5$	$0.5 \pm 0.1 \pm 0.4$	<0.1	0

Table 12. Numbers of expected and observed events in the $e\tau_h$ channel. The total background includes the total uncertainty, while for each process the statistical and systematic uncertainties are quoted separately. The two numbers that are quoted for the benchmark signal models are the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$, respectively, in GeV. In the case of the chargino-neutralino signal models, the first number within parentheses indicates the common $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ mass in GeV.

SR label	$t\bar{t}$	DY+jets	WW+jets	WW+jets	Rest	Jet $\rightarrow \tau_h$	Total Bkg	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ (400,1)	$\tilde{\chi}_1^0 \tilde{\chi}_2^0$ (400,175)	$\tilde{\tau}_L$ (90,1)	Observed
0j-1	$1.3 \pm 0.8 \pm 1.2$	$16.2 \pm 4.4 \pm 14.2$	<0.1	$0.7 \pm 0.4^{+0.1}_{-0.2}$	$0.5 \pm 0.5^{+1.1}_{-0.5}$	$3.5 \pm 1.6 \pm 1.7$	$22.2 \pm 4.8 \pm 14.5$	<0.1	<0.1	<0.1	7
0j-2	$0.4 \pm 0.4^{+1.1}_{-0.4}$	$23.1 \pm 5.8 \pm 22.5$	<0.2	$2.0 \pm 0.7 \pm 1.5$	$1.2 \pm 0.6^{+1.5}_{-1.2}$	$51.1 \pm 5.7 \pm 49.6$	$77.7 \pm 8.2 \pm 24.5$	<0.1	<0.1	<0.1	81
0j-3	<0.1	<0.1	$0.3 \pm 0.2 \pm 0.3$	$0.2 \pm 0.2^{+0.2}_{-0.2}$	<0.1	$1.5 \pm 1.0 \pm 1.0$	$2.0 \pm 1.1 \pm 1.2$	<0.1	<0.1	<0.1	2
0j-4	$0.7 \pm 0.5^{+1.0}_{-0.7}$	$208.3 \pm 15.7 \pm 27.2$	$0.1 \pm 0.1^{+0.1}_{-0.1}$	$1.2 \pm 0.5 \pm 0.8$	$2.6 \pm 1.1 \pm 2.2$	$76.1 \pm 9.6 \pm 11.9$	$288.9 \pm 18.5 \pm 31.1$	<0.1	<0.1	$0.4 \pm 0.4^{+0.8}_{-0.4}$	279
0j-5	$12.3 \pm 2.4 \pm 5.0$	$3.3 \pm 1.6 \pm 3.2$	$7.3 \pm 1.2 \pm 3.3$	$26.3 \pm 2.5 \pm 7.6$	$2.6 \pm 1.7^{+1.1}_{-1.1}$	$125.5 \pm 9.3 \pm 21.0$	$177.4 \pm 10.2 \pm 23.7$	$0.4 \pm 0.1 \pm 0.2$	$0.6 \pm 0.1 \pm 0.2$	$0.4 \pm 0.4^{+0.8}_{-0.4}$	197
0j-6	$4.1 \pm 1.3 \pm 3.4$	$15.5 \pm 4.1 \pm 10.8$	$6.0 \pm 1.1 \pm 2.7$	$25.8 \pm 2.5 \pm 9.5$	$1.1 \pm 0.3^{+0.3}_{-0.1}$	$372.0 \pm 15.2 \pm 57.8$	$424.5 \pm 16.0 \pm 59.8$	$0.2 \pm 0.1 \pm 0.1$	$0.3 \pm 0.1 \pm 0.1$	$0.7 \pm 0.5^{+1.8}_{-0.7}$	469
0j-7	<0.1	<0.1	<0.1	<0.7	<0.1	$2.2 \pm 1.1 \pm 1.1$	$2.2 \pm 1.1 \pm 1.3$	<0.1	<0.1	<0.1	3
0j-8	$0.7 \pm 0.5^{+1.0}_{-0.7}$	<0.1	<0.2	$0.5 \pm 0.3 \pm 0.5$	<0.1	$3.4 \pm 1.6 \pm 1.6$	$4.7 \pm 1.7 \pm 2.0$	<0.1	<0.1	<0.1	10
0j-9	$35.3 \pm 3.7 \pm 10.4$	$133.9 \pm 11.9 \pm 23.8$	$16.0 \pm 1.7 \pm 4.6$	$61.8 \pm 3.7 \pm 17.7$	$5.3 \pm 1.3 \pm 2.3$	$531.1 \pm 19.4 \pm 82.0$	$783.4 \pm 23.4 \pm 88.0$	$1.2 \pm 0.1 \pm 0.2$	$0.8 \pm 0.1 \pm 0.1$	$8.7 \pm 1.8 \pm 2.3$	739
0j-10	$1.6 \pm 1.0^{+1.7}_{-1.6}$	<0.1	$2.2 \pm 0.8^{+2.2}_{-0.7}$	$6.3 \pm 1.3 \pm 2.9$	$0.3 \pm 0.1 \pm 0.3$	$27.0 \pm 4.4 \pm 6.0$	$37.5 \pm 4.7 \pm 7.3$	$0.2 \pm 0.1 \pm 0.1$	$0.1 \pm 0.1 \pm 0.1$	$0.1 \pm 0.1^{+0.4}_{-0.1}$	31
0j-11	$26.8 \pm 3.4 \pm 5.1$	$1.0 \pm 0.7^{+1.1}_{-0.6}$	$13.0 \pm 1.7 \pm 4.1$	$40.4 \pm 3.1 \pm 11.9$	$1.6 \pm 0.3 \pm 0.6$	$305.0 \pm 14.3 \pm 47.9$	$387.8 \pm 15.1 \pm 49.8$	$0.8 \pm 0.1 \pm 0.2$	$0.7 \pm 0.1 \pm 0.2$	$2.5 \pm 1.0 \pm 1.2$	383
0j-12	$3.9 \pm 1.4 \pm 2.6$	<0.1	$1.8 \pm 0.6 \pm 1.4$	$6.3 \pm 1.3 \pm 2.4$	$1.2 \pm 0.2 \pm 0.5$	$38.7 \pm 4.9 \pm 7.6$	$52.0 \pm 5.3 \pm 8.5$	$1.2 \pm 0.2 \pm 0.2$	$1.2 \pm 0.2 \pm 0.3$	$0.4 \pm 0.4^{+0.8}_{-0.4}$	56
0j-13	$0.7 \pm 0.5^{+1.0}_{-0.7}$	<0.1	$0.3 \pm 0.2^{+0.3}_{-0.1}$	$0.6 \pm 0.3 \pm 0.6$	<0.1	$1.1 \pm 0.9 \pm 0.9$	$2.7 \pm 1.1 \pm 1.5$	<0.1	<0.1	<0.1	2
0j-14	$16.1 \pm 2.5 \pm 6.5$	$11.6 \pm 3.8 \pm 5.3$	$7.7 \pm 1.2 \pm 2.5$	$16.2 \pm 1.8 \pm 5.0$	$1.2 \pm 0.5 \pm 0.6$	$40.0 \pm 5.2 \pm 8.0$	$92.8 \pm 7.3 \pm 12.9$	$0.7 \pm 0.1 \pm 0.1$	<0.4	$5.1 \pm 1.4 \pm 1.9$	75
0j-15	$2.3 \pm 0.9 \pm 1.1$	<0.1	$1.1 \pm 0.5 \pm 0.7$	$1.5 \pm 0.6 \pm 1.2$	<0.1	$9.8 \pm 2.7 \pm 3.1$	$14.7 \pm 3.0 \pm 3.5$	<0.2	<0.2	$0.8 \pm 0.5 \pm 0.6$	15
0j-16	$3.3 \pm 1.1 \pm 1.2$	<0.1	$2.0 \pm 0.6 \pm 1.0$	$2.7 \pm 0.8 \pm 1.9$	<0.1	$11.6 \pm 3.0 \pm 3.5$	$19.6 \pm 3.3 \pm 4.2$	$0.2 \pm 0.1 \pm 0.1$	<0.1	$0.7 \pm 0.5 \pm 0.7$	26
0j-17	$0.7 \pm 0.5^{+1.0}_{-0.7}$	<0.1	$1.3 \pm 0.5 \pm 0.8$	$1.3 \pm 0.5 \pm 0.8$	<0.1	$2.0 \pm 1.3 \pm 1.4$	$5.4 \pm 1.6 \pm 2.2$	<0.1	<0.1	$0.5 \pm 0.4^{+0.8}_{-0.4}$	6
0j-18	$0.7 \pm 0.5 \pm 0.6$	<0.1	$0.3 \pm 0.2 \pm 0.3$	$1.9 \pm 0.6 \pm 1.5$	$0.4 \pm 0.1 \pm 0.2$	$12.9 \pm 3.0 \pm 3.5$	$16.2 \pm 3.1 \pm 3.9$	$0.6 \pm 0.1 \pm 0.1$	$0.4 \pm 0.1 \pm 0.2$	$0.3 \pm 0.3^{+0.3}_{-0.3}$	16
0j-19	<0.1	<0.1	<0.1	$2.0 \pm 0.7 \pm 0.9$	$0.5 \pm 0.1 \pm 0.2$	$9.4 \pm 2.5 \pm 2.8$	$11.9 \pm 2.6 \pm 3.0$	$1.3 \pm 0.2 \pm 0.2$	$1.1 \pm 0.1 \pm 0.2$	<0.1	13
0j-20	<0.1	<0.1	<0.1	$1.6 \pm 0.7 \pm 0.9$	$0.8 \pm 0.1 \pm 0.3$	$5.8 \pm 1.8 \pm 2.0$	$8.2 \pm 2.0 \pm 2.3$	$4.1 \pm 0.3 \pm 0.4$	$2.0 \pm 0.2 \pm 0.3$	<0.1	10
0j-21	$0.8 \pm 0.5^{+1.1}_{-0.4}$	<0.1	$1.1 \pm 0.4 \pm 0.6$	$1.9 \pm 0.7 \pm 1.0$	<0.1	$2.3 \pm 1.2 \pm 1.3$	$6.1 \pm 1.6 \pm 2.2$	$1.0 \pm 0.1 \pm 0.2$	<0.2	$1.6 \pm 0.8 \pm 1.0$	4
1j-1	$0.4 \pm 0.4^{+1.1}_{-0.4}$	$3.0 \pm 1.4^{+1.1}_{-0.8}$	<0.1	$0.2 \pm 0.2^{+0.3}_{-0.1}$	$0.0^{+0.0}_{-0.0} \pm 0.6$	$6.7 \pm 2.1 \pm 2.3$	$10.3 \pm 2.6 \pm 4.0$	<0.1	<0.1	<0.1	6
1j-2	$1.8 \pm 0.9^{+1.9}_{-1.4}$	$28.0 \pm 3.9 \pm 9.3$	$0.7 \pm 0.4^{+0.9}_{-0.3}$	$1.4 \pm 0.6 \pm 0.8$	$0.8^{+0.9}_{-0.4} \pm 1.0$	$35.6 \pm 5.0 \pm 7.3$	$68.2 \pm 6.5 \pm 12.1$	<0.1	<0.1	<0.1	70
1j-3	$9.0 \pm 2.1 \pm 5.1$	$35.7 \pm 4.4 \pm 8.1$	$3.2 \pm 0.9 \pm 2.6$	$23.4 \pm 0.7 \pm 1.8$	$3.4 \pm 2.1 \pm 3.4$	$77.0 \pm 7.0 \pm 13.5$	$130.5 \pm 8.8 \pm 17.2$	<0.2	<0.1	<0.1	143
1j-4	$0.7 \pm 0.5^{+1.0}_{-0.7}$	$7.9 \pm 1.9 \pm 4.9$	$0.8 \pm 0.4 \pm 0.6$	$0.6 \pm 0.4 \pm 0.6$	$0.5 \pm 0.4^{+0.6}_{-0.4}$	$7.5 \pm 2.2 \pm 2.5$	$18.1 \pm 3.0 \pm 6.0$	<0.1	<0.1	<0.1	20
1j-5	$5.9 \pm 1.6 \pm 2.3$	$86.1 \pm 8.9 \pm 18.4$	$0.9 \pm 0.4^{+0.9}_{-0.3}$	$1.6 \pm 0.6 \pm 1.1$	$1.2 \pm 0.6^{+1.2}_{-0.5}$	$67.0 \pm 8.3 \pm 13.0$	$102.6 \pm 12.5 \pm 22.8$	<0.1	<0.1	<0.1	164
1j-6	$44.8 \pm 4.3 \pm 9.5$	$9.3 \pm 2.3 \pm 4.8$	$15.8 \pm 1.8 \pm 3.5$	$19.9 \pm 2.2 \pm 6.3$	$1.9 \pm 0.7^{+1.5}_{-1.0}$	$197.5 \pm 11.9 \pm 31.9$	$290.2 \pm 13.2 \pm 34.7$	$0.7 \pm 0.1 \pm 0.2$	$0.9 \pm 0.1 \pm 0.2$	<0.1	283
1j-7	$31.7 \pm 3.7 \pm 7.2$	$31.4 \pm 3.8 \pm 6.7$	$10.5 \pm 1.5 \pm 3.8$	$10.2 \pm 1.6 \pm 5.4$	$2.0 \pm 0.7 \pm 1.4$	$201.1 \pm 11.5 \pm 32.3$	$286.9 \pm 12.9 \pm 34.4$	$0.5 \pm 0.1 \pm 0.1$	$0.3 \pm 0.1 \pm 0.1$	<0.1	292
1j-8	$1.8 \pm 0.8 \pm 1.4$	$2.3 \pm 1.7^{+2.8}_{-0.8}$	$1.3 \pm 0.5 \pm 0.8$	$1.2 \pm 0.6^{+1.2}_{-0.5}$	$3.3 \pm 3.0 \pm 3.0$	$7.6 \pm 2.2 \pm 2.4$	$17.4 \pm 4.2 \pm 5.5$	$0.6 \pm 0.1 \pm 0.2$	$0.3 \pm 0.1 \pm 0.1$	<0.1	26
1j-9	$5.2 \pm 1.6^{+2.1}_{-1.2}$	$0.5 \pm 0.4^{+0.8}_{-0.3}$	$0.9 \pm 0.4 \pm 0.8$	$0.9 \pm 0.4^{+0.8}_{-0.3}$	$0.1 \pm 0.1^{+0.2}_{-0.1}$	$3.0 \pm 1.7 \pm 1.7$	$10.5 \pm 2.5 \pm 6.5$	<0.1	<0.1	<0.1	13
1j-10	$13.2 \pm 2.6 \pm 3.6$	<0.1	$2.0 \pm 0.7 \pm 1.5$	$1.6 \pm 0.6^{+1.2}_{-0.5}$	$0.4 \pm 0.2^{+0.3}_{-0.1}$	$18.8 \pm 3.9 \pm 4.8$	$36.0 \pm 4.8 \pm 7.0$	$0.3 \pm 0.1 \pm 0.1$	$0.3 \pm 0.1 \pm 0.2$	<0.1	34
1j-11	$86.2 \pm 6.1 \pm 24.6$	$2.3 \pm 1.0 \pm 1.4$	$29.7 \pm 2.5 \pm 10.4$	$28.5 \pm 2.6 \pm 9.7$	$2.5 \pm 0.6 \pm 1.1$	$178.0 \pm 11.6 \pm 29.1$	$327.2 \pm 13.6 \pm 40.7$	$1.9 \pm 0.2 \pm 0.3$	$1.9 \pm 0.2 \pm 0.3$	$1.3 \pm 0.7 \pm 0.8$	296
1j-12	$15.4 \pm 2.8 \pm 4.5$	<0.1	$5.4 \pm 1.1 \pm 3.1$	$6.0 \pm 1.2 \pm 2.6$	$1.2 \pm 0.3 \pm 0.4$	$39.6 \pm 5.1 \pm 7.8$	$67.6 \pm 6.0 \pm 9.9$	$2.5 \pm 0.2 \pm 0.3$	$3.0 \pm 0.2 \pm 0.4$	<0.1	46
1j-13	<0.8	<0.1	<0.1	$0.4 \pm 0.4^{+0.8}_{-0.4}$	<0.1	$0.6^{+0.8}_{-0.4} \pm 0.6$	$1.0 \pm 0.7 \pm 1.1$	$0.8 \pm 0.1 \pm 0.2$	$0.3 \pm 0.1 \pm 0.1$	<0.1	0
1j-14	<0.1	<0.1	<0.1	$0.2 \pm 0.2^{+0.3}_{-0.1}$	<0.1	<0.1	$0.2 \pm 0.2 \pm 1.5$	<0.1	<0.1	<0.1	1
1j-15	$5.0 \pm 1.5 \pm 2.6$	$0.5 \pm 0.5 \pm 0.5$	$1.7 \pm 0.6 \pm 1.0$	$1.8 \pm 0.7 \pm 1.4$	<0.1	$0.6^{+1.0}_{-0.6} \pm 1.0$	$9.5 \pm 2.1 \pm 3.3$	<0.2	<0.1	<0.1	10
1j-16	$81.0 \pm 5.6 \pm 30.0$	$25.2 \pm 3.6 \pm 7.8$	$22.0 \pm 2.0 \pm 7.9$	$34.5 \pm 2.7 \pm 14.8$	$5.9 \pm 1.3 \pm 1.9$	$86.3 \pm 8.5 \pm 15.5$	$255.0 \pm 11.4 \pm 38.5$	$4.4 \pm 0.3 \pm 0.6$	$2.3 \pm 0.2 \pm 0.3$	$3.6 \pm 1.3 \pm 1.6$	254
1j-17	$10.2 \pm 2.0 \pm 6.8$	<0.1	$3.7 \pm 0.9 \pm 1.5$	$3.6 \pm 0.9 \pm 1.5$	$0.1 \pm 0.0^{+0.1}_{-0.1}$	$8.4 \pm 2.9 \pm 3.2$	$25.9 \pm 3.8 \pm 7.9$	$0.9 \pm 0.1 \pm 0.2$	$0.4 \pm 0.1 \pm 0.2$	<0.1	23
1j-18	$26.8 \pm 3.6 \pm 6.3$	<0.1	$6.3 \pm 1.1 \pm 2.6$	$4.3 \pm 1.0 \pm 2.5$	$0.5 \pm 0.2 \pm 0.2$	$9.0 \pm 3.0 \pm 3.3$	$46.9 \pm 4.9 \pm 8.0$	$0.8 \pm 0.1 \pm 0.2$	$0.6 \pm 0.1 \pm 0.1$	<0.1	46
1j-19	$9.3 \pm 1.9 \pm 7.9$	$1.1 \pm 0.8^{+1.1}_{-0.7}$	$3.6 \pm 0.9 \pm 1.5$	$5.7 \pm 1.2 \pm 2.5$	$0.2 \pm 0.1 \pm 0.1$	$13.1 \pm 3.0 \pm 3.6$	$32.9 \pm 4.0 \pm 9.3$	$0.7 \pm 0.1 \pm 0.1$	$0.4 \pm 0.1 \pm 0.1$	<0.1	30
1j-20	$9.9 \pm 2.2 \pm 4.7$	<0.1	$1.1 \pm 0.4 \pm 0.9$	$1.8 \pm 0.6 \pm 1.1$	$0.4 \pm 0.1 \pm 0.2$	$12.6 \pm 3.0 \pm 3.5$	$25.7 \pm 3.8 \pm 6.1$	$2.0 \pm 0.2 \pm 0.3$	$1.1 \pm 0.1 \pm 0.2$	$0.1 \pm 0.1^{+0.2}_{-0.1}$	18
1j-21	$0.0 \pm 0.0^{+0.4}_{-0.0}$	<0.1	$0.0 \pm 0.0^{+0.4}_{-0.0}$	$1.2 \pm 0.5 \pm 0.9$	<0.2	$5.2 \pm 1.9 \pm 2.0$	$6.7 \pm 2.0 \pm 2.3$	$3.6 \pm 0.3 \pm 0.6$	$1.9 \pm 0.2 \pm 0.3$	<0.1	6
1j-22	$0.7 \pm 0.7^{+1.9}_{-0.7}$	<0.1	<0.1	$0.7 \pm 0.4 \pm 0.7$	$0.4 \pm 0.1 \pm 0.3$	$2.5 \pm 1.3 \pm 1.4$	$4.4 \pm 1.6 \pm 2.5$	$8.7 \pm 0.4 \pm 0.8$	$4.4 \pm 0.3 \pm 0.5$	<0.1	6
1j-23	<0.1	<0.1	<0.1	$0.5 \pm 0.3^{+0.5}_{-0.3}$	<0.1	$0.9 \pm 0.8 \pm 0.8$	$1.5 \pm 0.9 \pm 1.1$	$2.7 \pm 0.2 \pm 0.3$	$0.9 \pm 0.1 \pm 0.2$	<0.1	1

Table 13. Numbers of expected and observed events in the $\mu\tau_h$ channel. The total background includes the total uncertainty, while for each process the statistical and systematic uncertainties are quoted separately. The two numbers that are quoted for the benchmark signal models are the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$, respectively, in GeV. In the case of the chargino-neutralino signal models, the first number within parentheses indicates the common $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ mass in GeV.

SR label	$\tilde{t}^*$	DY+jets	WW+jets	WW+jets	Rest	QCD	Total Bkg	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ (400,1)	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ (400,175)	$\tilde{\tau}_1$ (90,1)	Observed
0j-1	$2.5 \pm 1.0 \pm 1.6$	<0.1	$0.6 \pm 0.3 \pm 0.4$	$0.6 \pm 0.4^{+0.3}_{-0.2}$	$0.1 \pm 0.1 \pm 0.1$	<0.1	$3.9 \pm 1.1 \pm 1.8$	<0.1	<0.1	<0.1	3
0j-2	$40.0 \pm 3.8 \pm 12.9$	$155.4 \pm 13.5 \pm 20.7$	$21.1 \pm 1.9 \pm 6.0$	$248.7 \pm 7.1 \pm 64.4$	$37.3 \pm 11.6 \pm 22.4$	$35.0 \pm 16.2 \pm 23.8$	$537.5 \pm 25.4 \pm 76.4$	<0.1	<0.1	$0.4 \pm 0.0^{+0.3}_{-0.2}$	584
0j-3	$21.3 \pm 2.8 \pm 7.1$	<0.1	$9.9 \pm 1.3 \pm 3.8$	$47.2 \pm 3.1 \pm 13.3$	$1.6^{+1.4}_{-1.1} \pm 3.9$	$4.3^{+1.1}_{-1.1} \pm 5.5$	$84.2 \pm 6.9 \pm 16.9$	<0.1	<0.1	$0.1 \pm 0.0^{+0.8}_{-0.4}$	105
0j-4	$0.4 \pm 0.4^{+0.4}_{-0.4}$	<0.1	$0.2 \pm 0.2^{+0.2}_{-0.2}$	$0.6 \pm 0.4 \pm 0.6$	$0.0^{+0.0}_{-0.0} \pm 2.3$	<0.1	$1.2 \pm 0.6 \pm 2.5$	<0.1	<0.1	<0.1	2
0j-5	$5.7 \pm 1.4 \pm 2.8$	$2.4 \pm 1.5 \pm 1.6$	$2.9 \pm 0.7 \pm 1.2$	$7.1 \pm 1.2 \pm 2.2$	$1.8 \pm 1.5^{+1.4}_{-1.1}$	<0.1	$20.0 \pm 2.9 \pm 4.8$	<0.1	<0.1	$0.2 \pm 0.0^{+0.3}_{-0.2}$	21
0j-6	$105.3 \pm 6.2 \pm 33.2$	<0.1	$66.2 \pm 3.4 \pm 18.8$	$302.9 \pm 7.8 \pm 79.8$	$10.1 \pm 5.6 \pm 10.7$	$22.6 \pm 11.2 \pm 15.9$	$513.1 \pm 16.4 \pm 90.6$	$0.2 \pm 0.0^{+0.6}_{-0.2}$	<0.1	<0.1	531
0j-7	$32.9 \pm 5.5 \pm 29.4$	$1.4 \pm 1.4^{+1.5}_{-1.4}$	$46.0 \pm 2.8 \pm 13.1$	$424.6 \pm 9.3 \pm 110.0$	$19.9 \pm 6.2 \pm 16.1$	$19.6 \pm 13.8 \pm 16.9$	$594.4 \pm 18.4 \pm 116.9$	$0.1 \pm 0.0^{+0.2}_{-0.1}$	<0.1	$0.3 \pm 0.0^{+1.3}_{-0.5}$	618
0j-8	$2.9 \pm 0.9^{+0.7}_{-0.7}$	<0.1	$0.6 \pm 0.3 \pm 0.6$	$1.9 \pm 0.6 \pm 1.5$	$0.1 \pm 0.1^{+0.2}_{-0.1}$	<0.1	$5.3 \pm 1.1 \pm 3.4$	<0.1	<0.1	<0.1	7
0j-9	$4.9 \pm 1.3 \pm 1.9$	<0.1	$1.6 \pm 0.5 \pm 0.8$	$1.7 \pm 0.6 \pm 1.4$	$0.4 \pm 0.3^{+0.7}_{-0.4}$	<0.1	$8.6 \pm 1.5 \pm 2.6$	<0.1	<0.1	<0.1	12
0j-10	$119.2 \pm 6.5 \pm 33.4$	$28.3 \pm 5.9 \pm 8.0$	$49.7 \pm 2.9 \pm 13.2$	$123.9 \pm 5.0 \pm 36.1$	$10.2 \pm 3.9 \pm 8.8$	$13.0 \pm 10.3 \pm 12.2$	$344.2 \pm 15.2 \pm 53.7$	$0.2 \pm 0.0^{+0.6}_{-0.4}$	<0.4	$0.9 \pm 0.0^{+0.4}_{-0.6}$	324
0j-11	$17.0 \pm 2.5 \pm 6.6$	<0.1	$10.5 \pm 1.3 \pm 3.4$	$21.4 \pm 2.1 \pm 6.3$	$1.6 \pm 1.0^{+1.2}_{-1.0}$	<0.1	$50.7 \pm 3.6 \pm 10.3$	<0.1	<0.1	<0.1	50
0j-12	$129.0 \pm 6.8 \pm 36.9$	$0.5 \pm 0.5 \pm 0.5$	$61.3 \pm 3.2 \pm 16.5$	$224.7 \pm 6.7 \pm 58.9$	$8.2 \pm 3.2 \pm 3.4$	$11.6 \pm 7.9 \pm 9.8$	$435.3 \pm 13.2 \pm 72.2$	$0.2 \pm 0.0^{+0.6}_{-0.2}$	<0.2	$0.4 \pm 0.0^{+0.4}_{-0.6}$	457
0j-13	$27.9 \pm 3.2 \pm 8.8$	<0.1	$10.7 \pm 1.3 \pm 3.7$	$29.2 \pm 2.4 \pm 8.9$	$1.0 \pm 0.2^{+1.5}_{-1.0}$	<0.1	$68.8 \pm 4.2 \pm 13.1$	$0.2 \pm 0.0^{+0.5}_{-0.2}$	<0.1	<0.1	77
0j-14	$4.6 \pm 1.2 \pm 2.1$	<0.1	$1.3 \pm 0.5 \pm 1.1$	$1.8 \pm 0.6 \pm 1.0$	$0.3 \pm 0.3^{+0.5}_{-0.3}$	<0.1	$8.1 \pm 1.5 \pm 2.6$	<0.1	<0.1	<0.1	9
0j-15	$40.2 \pm 3.7 \pm 12.7$	$4.8 \pm 2.3 \pm 2.4$	$14.3 \pm 1.5 \pm 4.0$	$27.8 \pm 2.3 \pm 7.6$	$2.8 \pm 1.4 \pm 1.9$	$0.7^{+1.1}_{-0.9} \pm 4.2$	$90.5 \pm 6.8 \pm 16.2$	$0.2 \pm 0.0^{+0.5}_{-0.2}$	<0.1	$0.2 \pm 0.0^{+1.6}_{-0.6}$	82
0j-16	$18.0 \pm 2.5 \pm 5.6$	<0.1	$8.1 \pm 1.2 \pm 2.8$	$11.4 \pm 1.5 \pm 3.4$	<0.1	$2.9^{+3.4}_{-1.9} \pm 3.7$	$40.5 \pm 4.7 \pm 8.1$	$0.1 \pm 0.0^{+0.2}_{-0.1}$	<0.1	<0.1	51
0j-17	$30.5 \pm 3.2 \pm 10.4$	<0.1	$13.5 \pm 1.5 \pm 4.0$	$15.2 \pm 1.7 \pm 4.9$	<0.1	<0.1	$59.3 \pm 4.0 \pm 12.2$	$0.1 \pm 0.0^{+0.3}_{-0.1}$	<0.2	<0.1	61
0j-18	$9.0 \pm 1.8 \pm 3.7$	<0.1	$2.2 \pm 0.6 \pm 1.0$	$1.1 \pm 0.5^{+1.1}_{-0.7}$	$0.2 \pm 0.1 \pm 0.1$	$1.9^{+1.9}_{-1.0} \pm 2.1$	$14.5 \pm 2.7 \pm 4.5$	<0.1	<0.1	<0.1	11
0j-19	$10.5 \pm 1.9 \pm 3.7$	<0.1	$5.1 \pm 0.9 \pm 1.7$	$8.7 \pm 1.3 \pm 3.2$	$0.6 \pm 0.4 \pm 0.5$	$0.7^{+2.0}_{-0.7} \pm 2.0$	$25.6 \pm 3.2 \pm 5.5$	$0.1 \pm 0.0^{+0.1}_{-0.1}$	<0.2	<0.1	30
0j-20	$1.4 \pm 0.7 \pm 1.0$	<0.1	$0.5 \pm 0.3 \pm 0.5$	$2.8 \pm 0.8 \pm 1.3$	$0.2 \pm 0.1 \pm 0.2$	<0.1	$4.9 \pm 1.1 \pm 1.7$	$0.1 \pm 0.0^{+0.1}_{-0.1}$	<0.1	<0.1	5
0j-21	$0.4 \pm 0.4^{+0.4}_{-0.4}$	<0.1	<0.1	$3.5 \pm 0.8 \pm 1.4$	$0.2 \pm 0.1 \pm 0.1$	$1.6^{+1.9}_{-1.2} \pm 2.1$	$5.6 \pm 2.1 \pm 2.6$	$0.3 \pm 0.0^{+0.3}_{-0.3}$	<0.1	<0.1	4
0j-22	$2.4 \pm 0.9 \pm 1.3$	<0.1	$0.7 \pm 0.3 \pm 0.5$	$0.9 \pm 0.4 \pm 0.5$	<0.1	<0.1	$4.1 \pm 1.0 \pm 1.4$	<0.1	<0.1	<0.1	2
1j-1	$1.0 \pm 0.6^{+0.7}_{-0.7}$	<0.1	$0.2 \pm 0.2^{+0.2}_{-0.2}$	$0.2 \pm 0.2^{+0.2}_{-0.2}$	$1.6 \pm 1.4^{+2.8}_{-1.4}$	$3.6 \pm 2.7 \pm 3.3$	$6.5 \pm 3.2 \pm 4.5$	<0.1	<0.1	<0.1	2
1j-2	$20.2 \pm 2.7 \pm 7.6$	<0.1	$6.3 \pm 1.0 \pm 2.4$	$10.1 \pm 1.4 \pm 3.1$	$1.8 \pm 0.5 \pm 1.0$	$0.3^{+3.3}_{-1.3} \pm 5.3$	$38.6 \pm 6.2 \pm 10.1$	<0.1	<0.1	<0.1	43
1j-3	$138.1 \pm 7.0 \pm 40.1$	$50.5 \pm 6.2 \pm 10.4$	$52.3 \pm 3.0 \pm 15.0$	$114.1 \pm 4.8 \pm 29.6$	$21.0 \pm 7.0 \pm 10.5$	<0.1	$378.0 \pm 13.0 \pm 54.1$	$0.0 \pm 0.0^{+0.2}_{-0.0}$	$0.2 \pm 0.1 \pm 0.1$	$0.2 \pm 0.0^{+1.1}_{-0.5}$	382
1j-4	$121.1 \pm 6.6 \pm 36.9$	$1.2 \pm 0.7 \pm 0.8$	$48.0 \pm 2.9 \pm 13.8$	$59.4 \pm 3.5 \pm 16.6$	$5.7 \pm 2.0 \pm 4.2$	<0.1	$235.3 \pm 8.3 \pm 43.0$	<0.1	$0.1 \pm 0.1 \pm 0.1$	<0.1	211
1j-5	$6.6 \pm 1.5 \pm 3.3$	$0.5 \pm 0.5^{+0.6}_{-0.5}$	$2.2 \pm 0.6 \pm 1.0$	$5.3 \pm 1.0 \pm 2.4$	$0.7 \pm 0.4 \pm 0.7$	$6.6 \pm 4.2 \pm 5.3$	$22.0 \pm 4.7 \pm 6.8$	<0.1	<0.1	<0.1	20
1j-6	$49.3 \pm 4.2 \pm 15.3$	$3.2 \pm 1.8 \pm 1.9$	$9.7 \pm 1.3 \pm 3.3$	$15.9 \pm 1.8 \pm 4.8$	$2.8 \pm 1.1^{+5.0}_{-2.4}$	<0.1	$89.8 \pm 5.2 \pm 17.3$	<0.1	<0.1	$0.0 \pm 0.0^{+0.2}_{-0.0}$	54
1j-7	$266.9 \pm 9.8 \pm 79.3$	$0.5 \pm 0.4 \pm 0.4$	$86.1 \pm 3.8 \pm 23.4$	$165.0 \pm 5.8 \pm 42.5$	$14.2 \pm 4.5 \pm 6.5$	$17.7 \pm 11.7 \pm 14.6$	$550.3 \pm 17.3 \pm 49.3$	$0.3 \pm 0.1^{+0.7}_{-0.3}$	<0.3	$0.1 \pm 0.0^{+0.7}_{-0.1}$	511
1j-8	$35.9 \pm 3.6 \pm 11.5$	<0.1	$6.4 \pm 1.0 \pm 3.0$	$9.4 \pm 1.4 \pm 3.0$	<0.1	<0.1	$51.7 \pm 4.0 \pm 12.3$	$0.1 \pm 0.0^{+0.2}_{-0.1}$	<0.1	<0.1	62
1j-9	$31.5 \pm 3.3 \pm 10.5$	<0.1	$7.1 \pm 1.1 \pm 2.9$	$9.9 \pm 1.4 \pm 3.1$	$0.6 \pm 0.5 \pm 0.6$	$2.0^{+2.8}_{-1.0} \pm 3.0$	$51.1 \pm 4.8 \pm 11.8$	$0.0 \pm 0.0^{+0.2}_{-0.0}$	<0.1	<0.1	40
1j-10	$68.1 \pm 4.9 \pm 21.3$	$0.4 \pm 0.4 \pm 0.4$	$20.7 \pm 1.9 \pm 5.9$	$14.1 \pm 1.7 \pm 4.1$	$1.4^{+1.4}_{-1.1} \pm 2.7$	<0.1	$104.8 \pm 5.8 \pm 22.7$	$0.2 \pm 0.0^{+0.4}_{-0.1}$	<0.1	<0.1	88
1j-11	$93.2 \pm 5.8 \pm 30.3$	<0.1	$28.8 \pm 2.2 \pm 9.0$	$25.8 \pm 2.3 \pm 7.4$	$1.7 \pm 0.7 \pm 1.7$	<0.1	$149.5 \pm 6.6 \pm 32.5$	$0.4 \pm 0.1^{+1.6}_{-0.4}$	$0.4 \pm 0.1 \pm 0.1$	<0.1	122
1j-12	<0.4	<0.1	<0.1	$0.4 \pm 0.3 \pm 0.4$	<0.1	<0.1	$0.5 \pm 0.3 \pm 0.6$	<0.1	<0.1	<0.1	0
1j-13	$2.6 \pm 0.9 \pm 1.2$	<0.1	$1.1 \pm 1.4 \pm 0.5$	$1.5 \pm 0.6 \pm 0.8$	<0.1	<0.1	$5.4 \pm 1.2 \pm 1.6$	<0.1	<0.1	<0.1	1
1j-14	$23.7 \pm 2.8 \pm 7.0$	<0.1	$6.1 \pm 1.0 \pm 2.0$	$6.4 \pm 1.1 \pm 2.1$	$0.3 \pm 0.1 \pm 0.3$	$2.8 \pm 2.8^{+3.1}_{-2.2}$	$39.4 \pm 4.2 \pm 8.2$	$0.1 \pm 0.0^{+0.3}_{-0.1}$	<0.1	<0.1	30
1j-15	$250.0 \pm 9.2 \pm 73.0$	$6.4 \pm 1.8 \pm 3.1$	$48.0 \pm 2.8 \pm 12.8$	$81.0 \pm 4.0 \pm 21.2$	$10.6 \pm 2.4 \pm 7.9$	$3.9^{+1.5}_{-1.1} \pm 7.3$	$399.8 \pm 13.0 \pm 77.9$	$0.9 \pm 0.1^{+2.1}_{-0.9}$	$1.0 \pm 0.1 \pm 0.2$	$0.5 \pm 0.0^{+1.3}_{-0.5}$	353
1j-16	$74.3 \pm 5.0 \pm 21.1$	<0.1	$21.1 \pm 1.9 \pm 6.1$	$15.9 \pm 1.8 \pm 4.6$	$1.7 \pm 0.7 \pm 0.7$	$2.8^{+3.1}_{-1.4} \pm 4.4$	$115.8 \pm 7.0 \pm 22.9$	$0.3 \pm 0.0^{+0.6}_{-0.3}$	<0.1	<0.1	93
1j-17	$124.7 \pm 6.6 \pm 35.9$	<0.1	$27.0 \pm 2.1 \pm 7.5$	$23.3 \pm 2.2 \pm 6.8$	$1.2 \pm 0.3 \pm 0.4$	$2.0^{+2.2}_{-0.6} \pm 5.8$	$178.2 \pm 9.2 \pm 37.7$	$0.3 \pm 0.0^{+0.7}_{-0.3}$	$0.3 \pm 0.1 \pm 0.1$	<0.1	158
1j-18	$40.7 \pm 4.6 \pm 17.8$	<0.1	$9.1 \pm 1.2 \pm 2.8$	$11.8 \pm 1.5 \pm 3.6$	$1.1 \pm 0.4 \pm 0.5$	$2.8^{+3.6}_{-1.2} \pm 3.9$	$85.5 \pm 6.2 \pm 18.8$	$0.1 \pm 0.0^{+0.1}_{-0.1}$	$0.2 \pm 0.1 \pm 0.1$	<0.1	70
1j-19	$39.4 \pm 3.6 \pm 12.2$	<0.1	$8.8 \pm 1.2 \pm 3.0$	$10.0 \pm 1.4 \pm 3.6$	<3.6	$1.3^{+2.9}_{-1.2} \pm 3.0$	$59.7 \pm 5.0 \pm 13.9$	$0.3 \pm 0.0^{+0.7}_{-0.3}$	<0.4	<0.1	57
1j-20	$5.2 \pm 1.3 \pm 3.3$	<0.1	$1.6 \pm 0.5 \pm 0.7$	$2.6 \pm 0.7 \pm 1.2$	$0.4 \pm 0.1 \pm 0.2$	<0.1	$9.8 \pm 1.6 \pm 3.6$	$0.3 \pm 0.1^{+0.4}_{-0.1}$	<0.2	<0.1	5
1j-21	$0.7 \pm 0.5^{+0.5}_{-0.5}$	<0.1	$0.2 \pm 0.2 \pm 0.2$	$2.6 \pm 0.7 \pm 1.0$	<0.1	<0.1	$3.6 \pm 0.9 \pm 1.3$	$0.6 \pm 0.1^{+1.2}_{-0.6}$	$0.3 \pm 0.1 \pm 0.1$	<0.1	5
1j-22	$0.4 \pm 0.4^{+0.4}_{-0.4}$	<0.1	<0.1	$0.7 \pm 0.4 \pm 0.5$	$0.3 \pm 0.1 \pm 0.2$	$1.9 \pm 1.9^{+2.1}_{-1.0}$	$3.3 \pm 2.0 \pm 2.3$	$0.2 \pm 0.0^{+0.4}_{-0.2}$	<0.1	<0.1	1

Table 14. Numbers of expected and observed events in the $e\mu$ channel. The total background includes the total uncertainty, while for each process the statistical and systematic uncertainties are quoted separately. The two numbers that are quoted for the benchmark signal models are the masses of the parent SUSY particle and the $\tilde{\chi}_1^0$, respectively, in GeV. In the case of the chargino-neutralino signal models, the first number within parentheses indicates the common $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ mass in GeV.

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References

- [1] P. Ramond, *Dual Theory for Free Fermions*, *Phys. Rev. D* **3** (1971) 2415 [[INSPIRE](#)].
- [2] Y.A. Golfand and E.P. Likhtman, *Extension of the Algebra of Poincaré Group Generators and Violation of p Invariance*, *JETP Lett.* **13** (1971) 323 [[INSPIRE](#)] and online pdf version at http://www.jetpletters.ac.ru/ps/1584/article_24309.pdf.
- [3] A. Neveu and J.H. Schwarz, *Factorizable dual model of pions*, *Nucl. Phys. B* **31** (1971) 86 [[INSPIRE](#)].
- [4] D.V. Volkov and V.P. Akulov, *Possible universal neutrino interaction*, *JETP Lett.* **16** (1972) 438 [[INSPIRE](#)].
- [5] J. Wess and B. Zumino, *A Lagrangian Model Invariant Under Supergauge Transformations*, *Phys. Lett. B* **49** (1974) 52 [[INSPIRE](#)].
- [6] J. Wess and B. Zumino, *Supergauge Transformations in Four-Dimensions*, *Nucl. Phys. B* **70** (1974) 39 [[INSPIRE](#)].
- [7] P. Fayet, *Supergauge Invariant Extension of the Higgs Mechanism and a Model for the electron and Its Neutrino*, *Nucl. Phys. B* **90** (1975) 104 [[INSPIRE](#)].
- [8] H.P. Nilles, *Supersymmetry, Supergravity and Particle Physics*, *Phys. Rept.* **110** (1984) 1 [[INSPIRE](#)].
- [9] G. 't Hooft, *Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking*, *NATO Sci. Ser. B* **59** (1980) 135 [[INSPIRE](#)].
- [10] E. Witten, *Dynamical Breaking of Supersymmetry*, *Nucl. Phys. B* **188** (1981) 513 [[INSPIRE](#)].
- [11] M. Dine, W. Fischler and M. Srednicki, *Supersymmetric Technicolor*, *Nucl. Phys. B* **189** (1981) 575 [[INSPIRE](#)].
- [12] S. Dimopoulos and S. Raby, *Supercolor*, *Nucl. Phys. B* **192** (1981) 353 [[INSPIRE](#)].
- [13] S. Dimopoulos and H. Georgi, *Softly Broken Supersymmetry and SU(5)*, *Nucl. Phys. B* **193** (1981) 150 [[INSPIRE](#)].
- [14] R.K. Kaul and P. Majumdar, *Cancellation of Quadratically Divergent Mass Corrections in Globally Supersymmetric Spontaneously Broken Gauge Theories*, *Nucl. Phys. B* **199** (1982) 36 [[INSPIRE](#)].
- [15] ATLAS collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [[arXiv:1207.7214](#)] [[INSPIRE](#)].
- [16] CMS collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [[arXiv:1207.7235](#)] [[INSPIRE](#)].
- [17] CMS collaboration, *Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV*, *JHEP* **06** (2013) 081 [[arXiv:1303.4571](#)] [[INSPIRE](#)].

-
- [18] ATLAS collaboration, *Measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels with the ATLAS detector using 25 fb⁻¹ of pp collision data*, *Phys. Rev. D* **90** (2014) 052004 [[arXiv:1406.3827](#)] [[INSPIRE](#)].
 - [19] CMS collaboration, *Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV*, *Eur. Phys. J. C* **75** (2015) 212 [[arXiv:1412.8662](#)] [[INSPIRE](#)].
 - [20] ATLAS and CMS collaborations, *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments*, *Phys. Rev. Lett.* **114** (2015) 191803 [[arXiv:1503.07589](#)] [[INSPIRE](#)].
 - [21] G.R. Farrar and P. Fayet, *Phenomenology of the Production, Decay and Detection of New Hadronic States Associated with Supersymmetry*, *Phys. Lett. B* **76** (1978) 575 [[INSPIRE](#)].
 - [22] C. Boehm, A. Djouadi and M. Drees, *Light scalar top quarks and supersymmetric dark matter*, *Phys. Rev. D* **62** (2000) 035012 [[hep-ph/9911496](#)] [[INSPIRE](#)].
 - [23] C. Balázs, M. Carena and C.E.M. Wagner, *Dark matter, light stops and electroweak baryogenesis*, *Phys. Rev. D* **70** (2004) 015007 [[hep-ph/0403224](#)] [[INSPIRE](#)].
 - [24] G. Jungman, M. Kamionkowski and K. Griest, *Supersymmetric dark matter*, *Phys. Rept.* **267** (1996) 195 [[hep-ph/9506380](#)] [[INSPIRE](#)].
 - [25] G. Bélanger, S. Biswas, C. Boehm and B. Mukhopadhyaya, *Light Neutralino Dark Matter in the MSSM and Its Implication for LHC Searches for Staus*, *JHEP* **12** (2012) 076 [[arXiv:1206.5404](#)] [[INSPIRE](#)].
 - [26] E. Arganda, V. Martin-Lozano, A.D. Medina and N. Mileo, *Potential discovery of staus through heavy Higgs boson decays at the LHC*, *JHEP* **09** (2018) 056 [[arXiv:1804.10698](#)] [[INSPIRE](#)].
 - [27] WMAP collaboration, G. Hinshaw et al., *Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results*, *Astrophys. J. Suppl.* **208** (2013) 19 [[arXiv:1212.5226](#)] [[INSPIRE](#)].
 - [28] K. Griest and D. Seckel, *Three exceptions in the calculation of relic abundances*, *Phys. Rev. D* **43** (1991) 3191 [[INSPIRE](#)].
 - [29] D. Albornoz Vasquez, G. Bélanger and C. Boehm, *Revisiting light neutralino scenarios in the MSSM*, *Phys. Rev. D* **84** (2011) 095015 [[arXiv:1108.1338](#)] [[INSPIRE](#)].
 - [30] S.F. King, J.P. Roberts and D.P. Roy, *Natural dark matter in SUSY GUTs with non-universal gaugino masses*, *JHEP* **10** (2007) 106 [[arXiv:0705.4219](#)] [[INSPIRE](#)].
 - [31] M. Battaglia et al., *Proposed post-LEP benchmarks for supersymmetry*, *Eur. Phys. J. C* **22** (2001) 535 [[hep-ph/0106204](#)] [[INSPIRE](#)].
 - [32] R.L. Arnowitt, B. Dutta, A. Gurrrola, T. Kamon, A. Krislock and D. Toback, *Determining the Dark Matter Relic Density in the Minimal Supergravity Stau-Neutralino Coannihilation Region at the Large Hadron Collider*, *Phys. Rev. Lett.* **100** (2008) 231802 [[arXiv:0802.2968](#)] [[INSPIRE](#)].
 - [33] CMS collaboration, *Interpretation of Searches for Supersymmetry with simplified Models*, *Phys. Rev. D* **88** (2013) 052017 [[arXiv:1301.2175](#)] [[INSPIRE](#)].
 - [34] J. Alwall, P. Schuster and N. Toro, *Simplified Models for a First Characterization of New Physics at the LHC*, *Phys. Rev. D* **79** (2009) 075020 [[arXiv:0810.3921](#)] [[INSPIRE](#)].

- [35] J. Alwall, M.-P. Le, M. Lisanti and J.G. Wacker, *Model-Independent Jets plus Missing Energy Searches*, *Phys. Rev. D* **79** (2009) 015005 [[arXiv:0809.3264](#)] [[INSPIRE](#)].
- [36] LHC NEW PHYSICS Working Group, D. Alves, *Simplified Models for LHC New Physics Searches*, *J. Phys. G* **39** (2012) 105005 [[arXiv:1105.2838](#)] [[INSPIRE](#)].
- [37] ALEPH collaboration, A. Heister et al., *Search for scalar leptons in e^+e^- collisions at center-of-mass energies up to 209 GeV*, *Phys. Lett. B* **526** (2002) 206 [[hep-ex/0112011](#)] [[INSPIRE](#)].
- [38] DELPHI collaboration, J. Abdallah et al., *Searches for supersymmetric particles in e^+e^- collisions up to 208 GeV and interpretation of the results within the MSSM*, *Eur. Phys. J. C* **31** (2003) 421 [[hep-ex/0311019](#)] [[INSPIRE](#)].
- [39] L3 collaboration, P. Achard et al., *Search for scalar leptons and scalar quarks at LEP*, *Phys. Lett. B* **580** (2004) 37 [[hep-ex/0310007](#)] [[INSPIRE](#)].
- [40] OPAL collaboration, G. Abbiendi et al., *Search for anomalous production of dilepton events with missing transverse momentum in e^+e^- collisions at $\sqrt{s} = 183$ GeV to 209 GeV*, *Eur. Phys. J. C* **32** (2004) 453 [[hep-ex/0309014](#)] [[INSPIRE](#)].
- [41] LEP SUSY Working Group, ALEPH, DELPHI, L3 and OPAL collaborations, *Combined LEP Selectron/Smuon/Stau Results, 183–208 GeV*, LEPSUSYWG/04-01.1 (2004) and online at http://lepsusy.web.cern.ch/lepsusy/www/sleptons_summer04/slep_final.html.
- [42] ATLAS collaboration, *Search for the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying taus and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *JHEP* **10** (2014) 096 [[arXiv:1407.0350](#)] [[INSPIRE](#)].
- [43] ATLAS collaboration, *Search for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, *Phys. Rev. D* **93** (2016) 052002 [[arXiv:1509.07152](#)] [[INSPIRE](#)].
- [44] CMS collaboration, *Search for electroweak production of charginos in final states with two τ leptons in pp collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **04** (2017) 018 [[arXiv:1610.04870](#)] [[INSPIRE](#)].
- [45] CMS collaboration, *Search for supersymmetry in the vector-boson fusion topology in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **11** (2015) 189 [[arXiv:1508.07628](#)] [[INSPIRE](#)].
- [46] ATLAS collaboration, *Search for the direct production of charginos and neutralinos in final states with tau leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, *Eur. Phys. J. C* **78** (2018) 154 [[arXiv:1708.07875](#)] [[INSPIRE](#)].
- [47] B. Fuks, M. Klasen, D.R. Lamprea and M. Rothering, *Revisiting slepton pair production at the Large Hadron Collider*, *JHEP* **01** (2014) 168 [[arXiv:1310.2621](#)] [[INSPIRE](#)].
- [48] CMS collaboration, *The CMS trigger system, 2017 JINST* **12** P01020 [[arXiv:1609.02366](#)] [[INSPIRE](#)].
- [49] CMS collaboration, *The CMS Experiment at the CERN LHC, 2008 JINST* **3** S08004 [[INSPIRE](#)].
- [50] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector, 2017 JINST* **12** P10003 [[arXiv:1706.04965](#)] [[INSPIRE](#)].
- [51] CMS collaboration, *Performance of missing energy reconstruction in 13 TeV pp collision data using the CMS detector, CMS-PAS-JME-16-004* (2016) [[INSPIRE](#)].

-
- [52] M. Cacciari, G.P. Salam and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
 - [53] M. Cacciari, G.P. Salam and G. Soyez, *FastJet User Manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
 - [54] CMS collaboration, *Pileup Removal Algorithms*, CMS-PAS-JME-14-001 (2014) [[INSPIRE](#)].
 - [55] CMS collaboration, *Identification of b -quark jets with the CMS experiment*, 2013 *JINST* **8** P04013 [[arXiv:1211.4462](#)] [[INSPIRE](#)].
 - [56] CMS collaboration, *Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV*, 2018 *JINST* **13** P05011 [[arXiv:1712.07158](#)] [[INSPIRE](#)].
 - [57] CMS collaboration, *Performance of Electron Reconstruction and Selection with the CMS Detector in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV*, 2015 *JINST* **10** P06005 [[arXiv:1502.02701](#)] [[INSPIRE](#)].
 - [58] CMS collaboration, *Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV*, 2012 *JINST* **7** P10002 [[arXiv:1206.4071](#)] [[INSPIRE](#)].
 - [59] CMS collaboration, *Performance of τ -lepton reconstruction and identification in CMS*, 2012 *JINST* **7** P01001 [[arXiv:1109.6034](#)] [[INSPIRE](#)].
 - [60] CMS collaboration, *Reconstruction and identification of τ lepton decays to hadrons and ν_τ at CMS*, 2016 *JINST* **11** P01019 [[arXiv:1510.07488](#)] [[INSPIRE](#)].
 - [61] CMS collaboration, *Performance of reconstruction and identification of tau leptons in their decays to hadrons and tau neutrino in LHC Run-2*, CMS-PAS-TAU-16-002 (2016) [[INSPIRE](#)].
 - [62] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
 - [63] NNPDF collaboration, R.D. Ball et al., *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [[arXiv:1410.8849](#)] [[INSPIRE](#)].
 - [64] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [[hep-ph/0409146](#)] [[INSPIRE](#)].
 - [65] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [[arXiv:0709.2092](#)] [[INSPIRE](#)].
 - [66] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [[arXiv:1002.2581](#)] [[INSPIRE](#)].
 - [67] E. Re, *Single-top Wt -channel production matched with parton showers using the POWHEG method*, *Eur. Phys. J. C* **71** (2011) 1547 [[arXiv:1009.2450](#)] [[INSPIRE](#)].
 - [68] T. Sjöstrand et al., *An Introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].
 - [69] GEANT4 collaboration, S. Agostinelli et al., *GEANT4: A Simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
 - [70] A. Kalogeropoulos and J. Alwall, *The SysCalc code: A tool to derive theoretical systematic uncertainties*, [arXiv:1801.08401](#) [[INSPIRE](#)].

- [71] CMS collaboration, *The fast simulation of the CMS detector at LHC*, *J. Phys. Conf. Ser.* **331** (2011) 032049 [[INSPIRE](#)].
- [72] B. Fuks, M. Klasen, D.R. Lamprea and M. Rothering, *Gaugino production in proton-proton collisions at a center-of-mass energy of 8 TeV*, *JHEP* **10** (2012) 081 [[arXiv:1207.2159](#)] [[INSPIRE](#)].
- [73] B. Fuks, M. Klasen, D.R. Lamprea and M. Rothering, *Precision predictions for electroweak superpartner production at hadron colliders with Resummino*, *Eur. Phys. J. C* **73** (2013) 2480 [[arXiv:1304.0790](#)] [[INSPIRE](#)].
- [74] C.G. Lester and D.J. Summers, *Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders*, *Phys. Lett. B* **463** (1999) 99 [[hep-ph/9906349](#)] [[INSPIRE](#)].
- [75] A. Barr, C. Lester and P. Stephens, *A variable for measuring masses at hadron colliders when missing energy is expected; m_{T2} : the truth behind the glamour*, *J. Phys. G* **29** (2003) 2343 [[hep-ph/0304226](#)] [[INSPIRE](#)].
- [76] C. Cuenca Almenar, *Search for the neutral MSSM Higgs bosons in the $\tau\tau$ decay channels at CDF Run II*, Ph.D. Thesis, Departament de Física Atòmica, Molecular i Nuclear and IFIC, Universidad de València, València Spain (2008) [FERMILAB-THESIS-2008-86] [<https://doi.org/10.2172/953708>] [[INSPIRE](#)].
- [77] CMS collaboration, *Search for neutral MSSM Higgs bosons decaying to a pair of tau leptons in pp collisions*, *JHEP* **10** (2014) 160 [[arXiv:1408.3316](#)] [[INSPIRE](#)].
- [78] CMS collaboration, *Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J. C* **75** (2015) 542 [[arXiv:1505.04480](#)] [[INSPIRE](#)].
- [79] CMS collaboration, *Measurement of normalized differential $t\bar{t}$ cross sections in the dilepton channel from pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **04** (2018) 060 [[arXiv:1708.07638](#)] [[INSPIRE](#)].
- [80] CMS collaboration, *CMS Luminosity Measurements for the 2016 Data Taking Period*, *CMS-PAS-LUM-17-001* (2017) [[INSPIRE](#)].
- [81] CMS collaboration, *Search for top-squark pair production in the single-lepton final state in pp collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J. C* **73** (2013) 2677 [[arXiv:1308.1586](#)] [[INSPIRE](#)].
- [82] ATLAS, CMS collaborations and THE LHC HIGGS Combination Group, *Procedure for the LHC Higgs boson search combination in Summer 2011*, *CMS-NOTE-2011-005* (2011) [[INSPIRE](#)].
- [83] T. Junk, *Confidence level computation for combining searches with small statistics*, *Nucl. Instrum. Meth. A* **434** (1999) 435 [[hep-ex/9902006](#)] [[INSPIRE](#)].
- [84] A.L. Read, *Presentation of search results: The CL_s technique*, *J. Phys. G* **28** (2002) 2693 [[INSPIRE](#)].
- [85] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [*Erratum ibid.* **C 73** (2013) 2501] [[arXiv:1007.1727](#)] [[INSPIRE](#)].

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CHAPTER

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BIBLIOGRAPHY

- [1] S. Glashow, “Partial-symmetries of weak interactions”, *Nucl. Phys.* **22** (1961) 579, doi:10.1016/0029-5582(61)90469-2. 16
- [2] S. Weinberg, “A Model of Leptons”, *Phys. Rev. Lett.* **19** (1967) 1264, doi:10.1103/PhysRevLett.19.1264. 16
- [3] P. W. Higgs, “Broken symmetries and the masses of gauge bosons”, *Phys. Rev. Lett.* **13** (1964) 508, doi:10.1103/PhysRevLett.13.508. 16
- [4] D. Griffiths, “Introduction to Elementary Particles”. Wiley-VCH, 2009. 16
- [5] M. Peskin and D. Schroeder, “An Introduction to Quantum Field Theory”. Westview Press, 1995 edition, 1995. 17
- [6] M. B. Robinson, K. R. Bland, G. B. Cleaver, and J. R. Dittmann, “A Simple Introduction to Particle Physics. Part I - Foundations and the Standard Model”, arXiv:0810.3328. 17
- [7] B. Pontecorvo, “Neutrino Experiments and the Problem of Conservation of Leptonic Charge”, *Soviet Journal of Experimental and Theoretical Physics* **26** (May, 1968) 984. 18
- [8] “The Standard Model of Particle Physics: A Lunchbox’s Guide”. 19
- [9] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30. 18, 23
- [10] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1. 18

- [11] P. Higgs, “Broken symmetries, massless particles and gauge fields”, *Phys. Lett.* **12** (1964) 132, doi:10.1016/0031-9163(64)91136-9. 21
- [12] F. Englert and R. Brout, “Broken symmetry and the mass of gauge vector mesons”, *Phys. Rev. Lett.* **13** (1964) 321, doi:10.1103/PhysRevLett.13.321. 21
- [13] PLUTO Collaboration, “Jet Analysis of the Υ (9.46) Decay Into Charged Hadrons”, *Phys. Lett.* **82B** (1979) 449–455, doi:10.1016/0370-2693(79)90265-X. 23
- [14] PLUTO Collaboration, “Topology of the Υ Decay”, *Z. Phys.* **C8** (1981) 101, doi:10.1007/BF01547873. 23
- [15] UA1 Collaboration, “Experimental observation of isolated large transverse energy electrons with associated missing energy at $s=540$ GeV”, *Phys. Lett. B* **122** (1983) 103. 23
- [16] U. Collaboration, “Observation of single isolated electrons of high transverse momentum in events with missing transverse energy at the CERN pp collider”, *Phys. Lett. B* **122** (1983) 476. 23
- [17] UA1 Collaboration, “Experimental Observation of Lepton Pairs of Invariant Mass Around $95\text{-GeV}/c^2$ at the CERN SPS Collider”, *Phys. Lett. B* **126** (1983) 398. 23
- [18] UA2 Collaboration, “Evidence for $Z^0 \rightarrow e^+ e^-$ at the CERN anti-p p Collider”, *Phys. Lett.* **B129** (1983) 130–140, doi:10.1016/0370-2693(83)90744-X. [7.69(1983)]. 23
- [19] E. D. Bloom et al., “High-Energy Inelastic e p Scattering at 6-Degrees and 10-Degrees”, *Phys. Rev. Lett.* **23** (1969) 930–934, doi:10.1103/PhysRevLett.23.930. 23
- [20] M. Breidenbach et al., “Observed Behavior of Highly Inelastic Electron-Proton Scattering”, *Phys. Rev. Lett.* **23** (Oct, 1969) 935–939, doi:10.1103/PhysRevLett.23.935. 23
- [21] J. E. Augustin et al., “Discovery of a Narrow Resonance in e^+e^- Annihilation”, *Phys. Rev. Lett.* **33** (Dec, 1974) 1406–1408, doi:10.1103/PhysRevLett.33.1406. 23
- [22] J. J. Aubert et al., “Experimental Observation of a Heavy Particle J ”, *Phys. Rev. Lett.* **33** (Dec, 1974) 1404–1406, doi:10.1103/PhysRevLett.33.1404. 23
- [23] S. W. Herb et al., “Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions”, *Phys. Rev. Lett.* **39** (Aug, 1977) 252–255, doi:10.1103/PhysRevLett.39.252. 23
- [24] D0 Collaboration Collaboration, “Search for High Mass Top Quark Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV”, *Phys. Rev. Lett.* **74** (Mar, 1995) 2422–2426, doi:10.1103/PhysRevLett.74.2422. 23
- [25] CDF Collaboration Collaboration, “Observation of Top Quark Production in $p\bar{p}$ Collisions with the Collider Detector at Fermilab”, *Phys. Rev. Lett.* **74** (Apr, 1995) 2626–2631, doi:10.1103/PhysRevLett.74.2626. 23

-
- [26] D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, “Cavity control of a single-electron quantum cyclotron: Measuring the electron magnetic moment”, *Phys. Rev. A* **83** (May, 2011) 052122, doi:10.1103/PhysRevA.83.052122. 23
 - [27] T. Mannel, “Theory and Phenomenology of CP Violation”, *Nuclear Physics B Proceedings Supplements* **167** (May, 2007) 170–174, doi:10.1016/j.nuclphysbps.2006.12.083. 23
 - [28] S. P. Martin, “A Supersymmetry primer”, doi:10.1142/9789812839657_0001, 10.1142/9789814307505_0001, arXiv:hep-ph/9709356. [Adv. Ser. Direct. High Energy Phys.18,1(1998)]. 24
 - [29] D. Giusti et al., “Strange and charm HVP contributions to the muon ($g - 2$) including QED corrections with twisted-mass fermions”, *JHEP* **10** (2017) 157, doi:10.1007/JHEP10(2017)157, arXiv:1707.03019. 24
 - [30] R. Davis, D. S. Harmer, and K. C. Hoffman, “Search for Neutrinos from the Sun”, *Phys. Rev. Lett.* **20** (May, 1968) 1205–1209, doi:10.1103/PhysRevLett.20.1205. 24
 - [31] F. Zwicky, “Die Rotverschiebung von extragalaktischen Nebeln”, *Helv. Phys. Acta* **6** (1933) 110. 24
 - [32] “Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Interpretation”, *Astrophys. J. Suppl* **192** (2011) 18. 24
 - [33] “Planck 2015 results. XIII. Cosmological parameters”, *arXiv:1502.01589* (2015). 24
 - [34] R. N. Mohapatra and J. W. F. Valle, “Neutrino mass and baryon-number nonconservation in superstring models”, *Phys. Rev. D* **34** (Sep, 1986) 1642–1645, doi:10.1103/PhysRevD.34.1642. 24
 - [35] P. J. Fox, G. Jung, P. Sorensen, and N. Weiner, “Dark matter in light of the LUX results”, *Phys. Rev. D* **89** (May, 2014) 103526, doi:10.1103/PhysRevD.89.103526. 24
 - [36] L. Randall and R. Sundrum, “Large Mass Hierarchy from a Small Extra Dimension”, *Phys. Rev. Lett.* **83** (Oct, 1999) 3370–3373, doi:10.1103/PhysRevLett.83.3370. 24
 - [37] P. Ramond, “Dual theory for free fermions”, *Phys. Rev. D* **3** (1971) 2415, doi:10.1103/PhysRevD.3.2415. 24
 - [38] Y. A. Gol’fand and E. P. Likhtman, “Extension of the algebra of Poincaré group generators and violation of P invariance”, *JETP Lett.* **13** (1971) 323. 24
 - [39] A. Neveu and J. H. Schwarz, “Factorizable dual model of pions”, *Nucl. Phys. B* **31** (1971) 86, doi:10.1016/0550-3213(71)90448-2. 24
 - [40] D. V. Volkov and V. P. Akulov, “Possible universal neutrino interaction”, *JETP Lett.* **16** (1972) 438. 24

- [41] J. Wess and B. Zumino, “A Lagrangian model invariant under supergauge transformations”, *Phys. Lett. B* **49** (1974) 52, doi:10.1016/0370-2693(74)90578-4. 24
- [42] J. Wess and B. Zumino, “Supergauge transformations in four dimensions”, *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1. 24
- [43] P. Fayet, “Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino”, *Nucl. Phys. B* **90** (1975) 104, doi:10.1016/0550-3213(75)90636-7. 24
- [44] H. P. Nilles, “Supersymmetry, supergravity and particle physics”, *Phys. Rep.* **110** (1984) 1, doi:10.1016/0370-1573(84)90008-5. 24, 28
- [45] I. J. R. Aitchison, “Supersymmetry and the MSSM: An Elementary introduction”, arXiv:hep-ph/0505105. 25
- [46] S. K. Vempati, “Introduction to MSSM”, arXiv:1201.0334. 25
- [47] G. R. Farrar and P. Fayet, “Phenomenology of the Production, Decay, and Detection of New Hadronic States Associated with Supersymmetry”, *Phys. Lett. B* **76** (1978) 575, doi:10.1016/0370-2693(78)90858-4. 26
- [48] C. Boehm, A. Djouadi, and M. Drees, “Light scalar top quarks and supersymmetric dark matter”, *Phys. Rev. D* **62** (2000) 035012, doi:10.1103/PhysRevD.62.035012, arXiv:hep-ph/9911496. 26
- [49] C. Balázs, M. Carena, and C. E. M. Wagner, “Dark matter, light stops and electroweak baryogenesis”, *Phys. Rev. D* **70** (2004) 015007, doi:10.1103/PhysRevD.70.015007, arXiv:hep-ph/403224. 26
- [50] G. Jungman, M. Kamionkowski, and K. Griest, “Supersymmetric dark matter”, *Phys. Rept.* **267** (1996) 195, doi:10.1016/0370-1573(95)00058-5, arXiv:hep-ph/9506380. 26
- [51] S. Raby, “Grand Unified Theories”, in *2nd World Summit: Physics Beyond the Standard Model Galapagos, Islands, Ecuador, June 22-25, 2006*. 2006. arXiv:hep-ph/0608183. 26, 27
- [52] J. Alwall, P. Schuster, and N. Toro, “Simplified Models for a First Characterization of New Physics at the LHC”, *Phys. Rev. D* **79** (2009) 075020, doi:10.1103/PhysRevD.79.075020. 28
- [53] LHC New Physics Working Group, “Simplified Models for LHC new physics searches”, *J. Phys. G* **39** (2012) 105005, doi:10.1088/0954-3899/39/10/105005, arXiv:1105.2838. 28
- [54] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, “Revisiting slepton pair production at the Large Hadron Collider”, *JHEP* **01** (2014) 168, doi:10.1007/JHEP01(2014)168, arXiv:1310.2621. 28, 120, 121, 122, 123, 131

-
- [55] “Summary plots from the ATLAS Supersymmetry physics group”. 29
 - [56] “CMS Supersymmetry Physics Results”. 29, 30, 31
 - [57] G. Hinshaw et al., “Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: cosmological Parameter Results”, *Astrophys. J. Suppl.* **208** (2013) 19, doi:10.1088/0067-0049/208/2/19, arXiv:1212.5226. 31
 - [58] K. Griest and D. Seckel, “Three exceptions in the calculation of relic abundances”, *Phys. Rev. D* **43** (1991) 3191, doi:10.1103/PhysRevD.43.3191. 31
 - [59] D. A. Vasquez, G. Belanger, and C. Boehm, “Revisiting light neutralino scenarios in the MSSM”, *Phys. Rev. D* **84** (2011) 095015, doi:10.1103/PhysRevD.84.095015, arXiv:1108.1338. 31
 - [60] S. F. King, J. P. Roberts, and D. P. Roy, “Natural Dark Matter in SUSY GUTs with Non-universal Gaugino Masses”, *JHEP* **10** (2007) 106, doi:10.1088/1126-6708/2007/10/106, arXiv:0705.4219. 31
 - [61] M. Battaglia et al., “Proposed post-LEP benchmarks for supersymmetry”, *Eur. Phys. J. C* **22** (2001) 535, doi:10.1007/s100520100792, arXiv:hep-ph/0106204. 31
 - [62] R. L. Arnowitt et al., “Determining the Dark Matter Relic Density in the Minimal Supergravity Stau-Neutralino Coannihilation Region at the Large Hadron Collider”, *Phys. Rev. Lett.* **100** (2008) 231802, doi:10.1103/PhysRevLett.100.231802, arXiv:0802.2968. 31
 - [63] ALEPH Collaboration, “Search for scalar leptons in e^+e^- collisions at center-of-mass energies up to 209 GeV”, *Phys. Lett. B* **526** (2002) 206, doi:10.1016/S0370-2693(01)01494-0, arXiv:hep-ex/0112011. 33
 - [64] DELPHI Collaboration, “Searches for supersymmetric particles in e^+e^- collisions up to 208 GeV and interpretation of the results within the MSSM”, *Eur. Phys. J. C* **31** (2003) 421, doi:10.1140/epjc/s2003-01355-5, arXiv:hep-ex/0311019. 33
 - [65] L3 Collaboration, “Search for scalar leptons and scalar quarks at LEP”, *Phys. Lett. B* **580** (2004) 37, doi:10.1016/j.physletb.2003.10.010, arXiv:hep-ex/0310007. 33
 - [66] OPAL Collaboration, “Search for anomalous production of dilepton events with missing transverse momentum in e^+e^- collisions at $\sqrt{s} = 183$ GeV to 209 GeV”, *Eur. Phys. J. C* **32** (2004) 453, doi:10.1140/epjc/s2003-01466-y, arXiv:hep-ex/0309014. 33
 - [67] LEP SUSY Working Group (ALEPH, DELPHI, L3, OPAL), “Combined LEP Selectron/Smuon/Stau Results, 183-208 GeV”, (2004). LEPSUSYWG/04-01.1. 33
 - [68] ATLAS Collaboration, “Search for the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying taus and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *JHEP* **10** (2014) 96, doi:10.1007/JHEP10(2014)096, arXiv:1407.0350. 33

- [69] ATLAS Collaboration, “Search for the electroweak production of supersymmetric particles in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector”, *Phys. Rev. D* **93** (2016) 052002, doi:10.1103/PhysRevD.93.052002, arXiv:1509.07152. 33
- [70] CMS Collaboration, “Search for electroweak production of charginos in final states with two tau leptons in pp collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **04** (2017) 018, doi:10.1007/JHEP04(2017)018, arXiv:1610.04870. 33
- [71] ATLAS Collaboration, “Search for the direct production of charginos and neutralinos in final states with tau leptons in $\sqrt{s} = 13$ TeV *pp* collisions with the ATLAS detector”, *Eur. Phys. J. C* **78** (2018) 154, doi:10.1140/epjc/s10052-018-5583-9, arXiv:1708.07875. 33
- [72] C. Lefèvre, “The CERN accelerator complex. Complexe des accélérateurs du CERN”, (Dec, 2008). <https://cds.cern.ch/record/1260465>. 36
- [73] L. Evans and P. Bryant, “LHC machine”, *JINST* **3** (2008), no. S08001, 46. 36, 37, 46
- [74] the ATLAS Collaboration, “The ATLAS experiment at the CERN Large Hadron Collider”, *JINST* **3** (2008), no. S08003, 47. 38
- [75] the CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008), no. S08004, 51. 38
- [76] the ALICE Collaboration, “The ALICE experiment at the CERN LHC”, *JINST* **3** (2008), no. S08002, 96. 38
- [77] the LHCb Collaboration, “The LHCb detector at the LHC”, *JINST* **3** (2008), no. S08005, 58. 38
- [78] LHCf collaboration, “The LHCf detector at the CERN Large Hadron Collider”, *JINST* **3** (2008), no. S08006, 87. 38
- [79] MoEDAL collaboration, “Technical design report of the MoEDAL experiment”, technical report, CERN, 2009. 38
- [80] TOTEM collaboration, “The TOTEM Experiment at the CERN Large Hadron Collider”, *JINST* **3** (2008), no. S08007, 76. 38
- [81] J. Butler et al., “CMS Phase II upgrade scope document”, Technical Report CERN-LHCC-2015-019, CERN, 2015. 39
- [82] CMS Collaboration, “CMS Physics: Technical Design Report”, Technical Report CERN-LHCC-2006-001, 2006. 40, 43
- [83] G. Bayatian et al., “CMS physics technical design report: Addendum on high density QCD with heavy ions”, *J.Phys.* **G34** (01, 2007) 2307–2455. 41
- [84] D. M. Friedl, “The CMS Silicon Strip Tracker and its Electronic Readout”. PhD thesis, Vienna University of Technology, 2001. 41

-
- [85] F. R. Schilling, “Track Reconstruction and Alignment with the CMS Silicon Tracker”, 2006. 42
 - [86] S. Chatrchyan et al., “Identification and Filtering of Uncharacteristic Noise in the CMS Hadron Calorimeter”, *Journal of Instrumentation*, vol 5, pp. T03014. (05, 2019). 44
 - [87] CMS Collaboration, “The CMS muon system in Run2: preparation, status and first results”, *PoS EPS-HEP2015* (2015) 237, doi:10.22323/1.234.0237, arXiv:1510.05424. 45
 - [88] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017), no. P10003, 83. 50
 - [89] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *J. Instrum.* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009. 51
 - [90] R. Fruhwirth, W. Waltenberger, and P. Vanlaer, “Adaptive vertex fitting”, *J. Phys.* **G34** (2007) N343. 51
 - [91] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015), no. P06005, 72. 51
 - [92] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528. 52
 - [93] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017), no. P02014, 84. 53, 55
 - [94] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_t jet clustering algorithm”, *JHEP* **04** (2008) 063. 54
 - [95] CMS Collaboration, “Missing transverse energy performance of the CMS detector”, *JINST* **6** (2011) P09001, doi:10.1088/1748-0221/6/09/P09001, arXiv:1106.5048. 55
 - [96] CMS Collaboration, “Performance of the CMS missing transverse momentum reconstruction in pp data at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P02006, doi:10.1088/1748-0221/10/02/P02006, arXiv:1411.0511. 55
 - [97] D. Bertolini, P. Harris, M. Low, and N. Tran, “Pileup per particle identification”, *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013. 55, 56
 - [98] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663. 56

- [99] CMS Collaboration, “Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018), no. 10, P10005, doi:10.1088/1748-0221/13/10/P10005, arXiv:1809.02816. 57
- [100] A. Buckley et al., “General-purpose event generators for LHC physics”, *Phys. Rept* **504** (2011) 145. 59
- [101] T. Gleisberg et al., “Event generation with SHERPA 1.1”, *JHEP* **0902** (2009) 7. 60
- [102] R. K. Ellis, et al., “QCD and collider physics”, *Camb. Monogr. Part. Phys. Nucl. Phys. Cosmol* **8** (1996) 1. 59
- [103] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, “Parton fragmentation and string dynamics”, *Phys. Rept.* **97** (1983) 31, doi:10.1016/0370-1573(83)90080-7. 59
- [104] T. Sjöstrand, et al., “An Introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159. 61
- [105] Z. Was, “TAUOLA for simulation of tau decay and production: perspectives for precision low energy and LHC applications”, *Nucl. Phys. B* **218** (2011) 249. 61
- [106] J. Alwall et al., “MadGraph 5: Going Beyond”, *JHEP* **1106** (2011) 128. 61
- [107] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079. 61
- [108] P. Nason and B. Webber, “Next-to-Leading-Order Event Generators”, *Annual Review of Nuclear and Particle Science* **62** (2012) 187. 61
- [109] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8. 61
- [110] DELPHES 3 Collaboration, “DELPHES 3, A modular framework for fast simulation of a generic collider experiment”, *JHEP* **02** (2014) 057, doi:10.1007/JHEP02(2014)057, arXiv:1307.6346. 62
- [111] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *Submitted to: JINST* (2019) arXiv:1903.06078. 64
- [112] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J.* **C76** (2016), no. 3, 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815. 64
- [113] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849. 64, 72
- [114] CMS Collaboration, “Search for direct τ slepton pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-SUS-18-006, 2019. 72, 117, 118

-
- [115] CMS Collaboration, “Study of pileup removal algorithms for jets”, CMS Physics Analysis Summary CMS-PAS-JME-14-001, 2014. 73
 - [116] CMS Collaboration, “Search for neutral MSSM Higgs bosons decaying to a pair of tau leptons in pp collisions”, *JHEP* **10** (2014) 160, doi:10.1007/JHEP10(2014)160, arXiv:1408.3316. 80, 94
 - [117] CMS Collaboration, “Search for supersymmetry in events with a τ lepton pair and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **11** (2018) 151, doi:10.1007/JHEP11(2018)151, arXiv:1807.02048. 90, 121, 147
 - [118] J. R. Quinlan, “Induction of decision trees”, *Machine Learning* **1** (Mar, 1986) 81–106, doi:10.1007/BF00116251. 90
 - [119] A. Hoecker et al., “TMVA: Toolkit for Multivariate Data Analysis”, *PoS ACAT* (2007) 040, arXiv:physics/0703039. 90
 - [120] G. Hinton, “Unsupervised learning : foundations of neural computation”. MIT Press, Cambridge, Mass, 1999. 90
 - [121] L. P. Kaelbling, M. L. Littman, and A. W. Moore, “Reinforcement Learning: A Survey”, *arXiv e-prints* (Apr, 1996) cs/9605103, arXiv:cs/9605103. 91
 - [122] G. Cowan, “Discovery sensitivity for a counting experiment with background uncertainty”, 04, 2018. 92
 - [123] D. Tovey, “On measuring the masses of pair-produced semi-invisibly decaying particles at hadron colliders”, *JHEP* **04** (2008) 034, doi:10.1088/1126-6708/2008/04/034, arXiv:0802.2879. 94
 - [124] G. Polesello and D. Tovey, “Supersymmetric particle mass measurement with boost-corrected contranverse mass”, *JHEP* **03** (2010) 030, doi:10.1007/JHEP03(2010)030, arXiv:0910.0174. 94
 - [125] C. G. Lester and D. J. Summers, “Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders”, *Phys. Lett. B* **463** (1999) 99, doi:10.1016/S0370-2693(99)00945-4, arXiv:hep-ph/9906349. 94
 - [126] A. Barr, C. Lester, and P. Stephens, “ m_{T2} : the truth behind the glamour”, *J. Phys. G* **29** (2003) 2343, doi:10.1088/0954-3899/29/10/304, arXiv:hep-ph/0304226. 94
 - [127] C. G. Lester and B. Nachman, “Bisection-based asymmetric M_{T2} computation: a higher precision calculator than existing symmetric methods”, *JHEP* **03** (2015) 100, doi:10.1007/JHEP03(2015)100, arXiv:1411.4312. 94
 - [128] C. Cuenca Almenar, “Search for the neutral MSSM Higgs bosons in the ditau decay channels at CDF Run II”. PhD thesis, Valencia U., IFIC, 2008. doi:10.2172/953708. 94
 - [129] CMS Collaboration, “Cross section measurement of t-channel single top quark production in pp collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **772** (2017) 752. 110

- [130] CMS Collaboration, “CMS Luminosity Measurements for the 2016 Data Taking Period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017. 110
- [131] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, Technical Report CMS-PAS-LUM-17-004, CERN, Geneva, 2018. 110
- [132] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006. 110
- [133] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313. 110
- [134] The ATLAS Collaboration, The CMS Collaboration, The LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011. 112
- [135] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. 112
- [136] “The High-Luminosity LHC”, technical report. [WEBPAGE]. 126
- [137] G. Apollinari et al., “High-Luminosity Large Hadron Collider (HL-LHC)”, *CERN Yellow Report* **004** (2017) doi:10.23731/CYRM-2017-004. [INSPIRE]. 126
- [138] ATLAS Collaboration, “Expected performance of the ATLAS detector at the HL-LHC”, technical report, 2018. 126
- [139] CMS Collaboration, “Expected performance of the physics objects with the upgraded CMS detector at the HL-LHC”, technical report, 2018. [CDS]. 126
- [140] “HL-LHC CERN Council approval”, technical report. [WEBPAGE]. 126
- [141] “FCC Conceptual Design Report: Volume 4: The High-Energy LHC (HE-LHC)”. , 2018. [INDICO]. 126
- [142] “HL-LHC Project Schedule”. 126
- [143] D. Contardo et al., “Technical Proposal for the Phase-II Upgrade of the CMS Detector”, technical report, 2015. 126, 128
- [144] K. Klein, “The Phase-2 Upgrade of the CMS Tracker”, technical report, 2017. 126, 128
- [145] C. Collaboration, “The Phase-2 Upgrade of the CMS Barrel Calorimeters Technical Design Report”, Technical Report CERN-LHCC-2017-011. CMS-TDR-015, CERN, Geneva, Sep, 2017. This is the final version, approved by the LHCC. 126, 128
- [146] C. Collaboration, “The Phase-2 Upgrade of the CMS Endcap Calorimeter”, Technical Report CERN-LHCC-2017-023. CMS-TDR-019, CERN, Geneva, Nov, 2017. Technical Design Report of the endcap calorimeter for the Phase-2 upgrade of the CMS experiment, in view of the HL-LHC run. 126, 128

-
- [147] C. Collaboration, “The Phase-2 Upgrade of the CMS Muon Detectors”, Technical Report CERN-LHCC-2017-012. CMS-TDR-016, CERN, Geneva, Sep, 2017. This is the final version, approved by the LHCC. 126, 128
 - [148] Working Group 3 Collaboration Collaboration, “Beyond the Standard Model Physics at the HL-LHC and HE-LHC”, Technical Report arXiv:1812.07831, CERN, Geneva, 2018. * Temporary entry *. 126
 - [149] CMS Collaboration Collaboration, “Search for supersymmetry with direct stau production at the HL-LHC with the CMS Phase-2 detector”, Technical Report CMS-PAS-FTR-18-010, CERN, Geneva, 2019. 126, 136
 - [150] “HL-LHC Project Schedule”. 127
 - [151] CMS, “CMS Phase 2 object performance”, Technical Report CMS-PAS-FTR-18-012, in preparation. 128, 129, 130, 131
 - [152] W. Beenakker, R. Hopker, and M. Spira, “PROSPINO: A Program for the production of supersymmetric particles in next-to-leading order QCD”, arXiv:hep-ph/9611232. 131
 - [153] CMS Collaboration, “Search for supersymmetry with direct stau production at the HL-LHC with the CMS Phase-2 detector”, technical report, 2018. [INSPIRE]. 139
 - [154] F. Zimmermann et al., “High-Energy LHC Design”, in *Proc. 9th International Particle Accelerator Conference (IPAC’18), Vancouver, BC, Canada, April 29-May 4, 2018*, number 9 in International Particle Accelerator Conference, pp. 269–272. JACoW Publishing, Geneva, Switzerland, June, 2018.
<https://doi.org/10.18429/JACoW-IPAC2018-MOPMF064>.
doi:doi:10.18429/JACoW-IPAC2018-MOPMF064. 139