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**Study of central and exclusive production of charged Higgs
boson pairs with forward proton tagging at the LHC, and
projections for the HL-LHC**

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“It’s tempting to linger in this moment, while every possibility
still exists. But unless they are collapsed by an observer, they
will never be more than possibilities.”

—Solanum

Resumo

O Modelo Padrão (SM) de física de partículas tem-se demonstrado como sendo a teoria mais bem sucedida até à data, prevendo com precisão a maioria das observações experimentais. No entanto, deixa algumas questões fundamentais em aberto, tal como o problema da hierarquia, o problema da violação CP forte, a assimetria bariónica do Universo e a inexistência de um candidato viável para a matéria escura. Para abordar estas questões, muitas extensões teóricas do SM foram propostas, sugerindo a existência de novas partículas ou interações, razão pela qual são denominadas como cenários para além do Modelo Padrão (BSM). Uma característica de muitos destes cenários é a existência de um bóson de Higgs carregado, o que serve como motivação para estudos sobre a sua produção, sendo que a observação de tal partícula implicaria a existência de física BSM.

Com isto em mente, este projeto focou-se no estudo do processo de produção central e exclusiva (CEP) de um par de bósons de Higgs carregados utilizando o Modelo de Dois Dubletos de Higgs (2HDM), que é o cenário BSM mais simples que inclui o bóson de Higgs carregado e por isso é mais conveniente para a simulação deste processo. Neste caso, um processo de CEP foi escolhido para tirar vantagem do *Precision Proton Spectrometer* (PPS) que integra o *Compact Muon Solenoid* (CMS), mas também devido à menor quantidade de eventos de fundo associados com este tipo de processos. O *Precision Proton Spectrometer* é utilizado de forma a ser aplicado *proton tagging* para a identificação dos prótons correspondentes ao evento de sinal presentes no estado final. É ainda utilizado o *High Level Trigger* para a seleção de eventos de sinal e rejeição de eventos de fundo, uma vez que este foi desenvolvido para estudos de eventos com 4 jatos no estado final, tal como é o caso do processo de produção central e exclusiva (CEP) de um par de bósons de Higgs carregados. Esta análise foi ainda desenhada para ser o mais independente possível do modelo, de modo a continuar sensível a outras observações noutros modelos.

Este projeto começa por calcular a secção eficaz para três modos de decaimento possíveis do bóson de Higgs carregado, identificados de seguida: $H^+ \rightarrow c\bar{s}$, $H^+ \rightarrow c\bar{b}$, $H^+ \rightarrow \mu^+\nu_\mu$. A secção eficaz foi também calculada para o processo de fundo dominante que corresponde a uma interação de cromodinâmica quântica com 4 jatos no estado final do tipo $pp \rightarrow jjjj$. Foi utilizado o programa MadGraph5_aMC@NLO para simular os eventos ao nível dos partões, o programa Pythia8 para realizar a simulação dos *parton showers* e a hadronização dos eventos, e finalmente o programa Delphes para simular a interação dos eventos ao nível dos detetores.

O cálculo da secções eficazes é feito diretamente através do programa MadGraph5_aMC@NLO, tendo-se identificado qual o modo de decaimento do bóson de Higgs com maior secção eficaz, bem como o modo de decaimento com menor secção eficaz. Sendo este um estudo sobre uma partícula de massa ainda desconhecida, foram simulados vários eventos para massas diferentes do bóson de Higgs, que foram também ordenados consoante a sua secção eficaz. Neste caso, o evento de sinal, a produção central e exclusiva de um par de bósons de Higgs carregados, está associado a uma secção eficaz muito inferior à do evento de fundo correspondente, sendo este a interação de cromodinâmica quântica com 4 jatos no estado final. Consequentemente, foram gerados diversos ficheiros para o evento de fundo com intervalos de momento transversal (P_T) do jato de primeira ordem diferentes, desde um valor de 0 GeV, até ao valor de 400 GeV em intervalos de 50 GeV. Os diversos ficheiros correspondentes ao evento de fundo foram também organizados consoante a sua secção eficaz.

De seguida, a análise é dividida em duas secções, sendo que a primeira se foca na configuração dos detetores atualmente presente no *Large Hadron Collider* (LHC Run 3), e a segunda parte na configuração

projetada para a fase de alta luminosidade do *Large Hadron Collider* (HL-LHC). Em ambas as configurações, foram estudados os efeitos das interações de *pileup* nos eventos de sinal e de fundo, foi determinada a aceitação do PPS para os eventos de sinal, a eficiência do *High Level Trigger* na rejeição de eventos de fundo, e por fim a sensibilidade estatística da análise para a exclusão do evento de sinal.

A configuração do LHC Run 3 e do HL-LHC diferem nas definições do PPS, no número médio de interações de *pileup* por evento, na luminosidade integrada e na energia disponível no centro de massa. No entanto, pela ausência de um ficheiro com interações de *pileup* correspondente à energia do centro de massa projetada para o HL-LHC, foi utilizada a energia correspondente à configuração atual do LHC Run 3 ($\sqrt{s} = 13.6 \text{ TeV}$).

A análise relativamente ao modo de decaimento $H^+ \rightarrow \mu^+ \nu_\mu$ do bóson de Higgs carregado não passa para além da análise do impacto das interações de *pileup* e da determinação da aceitação do PPS para este decaimento, pois este apresenta um estado final que não se enquadra nas condições para as quais o *High Level Trigger* foi criado, o que implicaria um estudo mais complexo e demorado que não foi possível encaixar neste projeto.

Para as análises realizadas relativamente aos outros modos de decaimento, foram utilizados histogramas com as variáveis relevantes ao *High Level Trigger*, nos quais os eventos de sinal e de fundo foram normalizados de forma a preencherem a mesma área, facilitando a identificação de diferenças entre os mesmos. Foram ainda apresentadas tabelas de *cutflow*, nas quais os números de eventos que satisfazem cada condição do *High Level Trigger* estão registados, juntamente com a percentagem de eventos que sobrevive a cada corte relativamente à condição anterior, e a percentagem de eventos que sobrevive a cada corte relativamente ao número de eventos inicial. Para além das condições de seleção definidas pelo *High Level Trigger*, são ainda apresentadas tabelas de *cutflow* para três condições adicionais, com o objetivo de melhorar a rejeição de eventos de fundo. No caso da configuração para a fase de alta luminosidade do *Large Hadron Collider*, são aplicadas modificações às condições do *High Level Trigger*, que se encontram fundamentadas por dados apresentados em histogramas e tabelas de *cutflow*, sendo ainda motivado um futuro estudo sobre a aplicação do *High Level Trigger* neste cenário.

Na determinação da sensibilidade estatística da análise para a exclusão do processo de produção central e exclusiva de um par de bósons de Higgs carregados, foi utilizada a ferramenta Combine, desenvolvida e mantida pelo grupo CMS para estudos estatísticos, à qual se forneceu uma distribuição previamente identificada como sendo a mais discriminante entre eventos de sinal e de fundo. Foram obtidos os limites superiores esperados ao nível de confiança de 95% para os modos de decaimento do bóson de Higgs carregado em ambas as configurações.

Por fim, foi ainda realizada uma comparação entre as configurações do LHC Run 3 e do HL-LHC. Nesta secção foi identificado o impacto das mudanças nas definições do PPS na análise de eventos e na aceitação do PPS, mas também foi determinado o impacto do número elevado de interações de *pileup* projetado para a configuração do HL-LHC, tanto na análise dos eventos como na sensibilidade estatística da análise para a exclusão do processo de produção central e exclusiva de um par de bósons de Higgs carregados. Foram ainda feitas algumas sugestões relativamente a futuros estudos que seriam interessantes realizar para complementar os resultados obtidos.

Palavras-chave: Bóson de Higgs carregado, *Proton Tagging*, *High-Luminosity Large Hadron Collider*, Física BSM, Interações de *pileup*

Abstract

Beyond the Standard Model (BSM) scenarios suggest the existence of new particles or interactions to address some of the fundamental questions left unanswered by the Standard Model (SM). The majority of these scenarios suggest the existence of a charged Higgs boson, and its observation would directly imply the existence of BSM physics. With this in mind, this project focused on studying the central and exclusive production (CEP) of a single pair of charged Higgs bosons at the Large Hadron Collider (LHC) Run 3, including projections for the High-Luminosity LHC (HL-LHC) Phase-2, both at a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. Additionally, CEP processes are advantageous to study due to the lower number of competing background processes, but also because it's possible to perform proton tagging with the Precision Proton Spectrometer (PPS) installed at the Compact Muon Solenoid (CMS). This project also takes advantage of the first CMS jet matching High Level Trigger (HLT) designed for studying processes with a four-jet system in the final states. This study used events simulated with the tools MadGraph5_aMC@NLO, Pythia8, and Delphes. This study started with the calculation of the cross sections for the signal and background events. The next part of the analysis focused on the detector configurations for the LHC Run 3 and the HL-LHC Phase-2, and several studies were performed on the impact of pileup interactions, on the acceptance of the PPS detector, on the efficiency of the HLT, and on the statistical sensitivity to exclude the signal process. A comparison between the LHC Run 3 and HL-LHC Phase-2 configurations was also made to highlight the key differences in event analysis. Lastly, remarks were made on possible HLT improvements for the HL-LHC Phase-2, as well as on future studies that could enhance event analysis.

Keywords: Charged Higgs Boson, Proton Tagging, High-Luminosity Large Hadron Collider, BSM Physics, Pileup interactions

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List of Abbreviations and Acronyms

2HDM	Two-Higgs-Doublet Model
ALICE	A Large Ion Collider Experiment
ATLAS	A Toroidal LHC Apparatus
BDT	Boosted Decision Tree
BSM	Beyond the Standard Model
CBBAR	$H^+ \rightarrow c\bar{b}$ decay mode
CERN	European Organization for Nuclear Research
CEP	Central and Exclusive Production
CKM	Cabibbo-Kobayashi-Maskawa
CL	Confidence Level
CMS	Compact Muon Solenoid
CMSSW	CMS Software framework
CP	Charge-Parity symmetry
CSBAR	$H^+ \rightarrow c\bar{s}$ decay mode
ECAL	Electromagnetic Calorimeter
EW	Electroweak
HCAL	Hadronic Calorimeter
HEP	High Energy Physics
HL-LHC	High-Luminosity Large Hadron Collider
HLT	High Level Trigger
IP	Interaction Point
L1	Level-1 Trigger
LEP	Large Electron-Positron Collider
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty
MC	Monte Carlo
MET	Missing Transverse Energy

NLO Next-to-Leading Order

PCA Principal Component Analysis

PDF Parton Distribution Function

PMNS Pontecorvo-Maki-Nakagawa-Sakata

PPS Precision Proton Spectrometer

QCD Quantum Chromodynamics

QED Quantum Electrodynamics

QFT Quantum Field Theory

SM Standard Model

TAUNU $H^+ \rightarrow \tau^+ \nu_\tau$ decay mode

TMVA Toolkit for Multivariate Data Analysis

UPC Ultraperipheral Collision

1 Introduction

1.1 The Standard Model of particle physics

The Standard Model of particle physics (SM) describes the properties and interactions of the fundamental particles in the Universe. It uses the framework of Quantum Field Theory (QFT) and Group Theory to quantize particle and force fields [1]. The SM is based on a gauge symmetry group composed by Quantum Chromodynamics (QCD), and Electroweak (EW) theories, with the latter being the unification of Quantum Electrodynamics (QED) and weak interaction [1, 2, 3]. It's respective gauge symmetry group is:

$$SU(3)_C \times SU(2)_L \times U(1)_Y , \quad (1.1)$$

where the index letters represent the physical sectors associated with each symmetry. Here, $SU(N)$ denotes the special unitary group of degree N , the group of $N \times N$ unitary matrices with determinant equal to 1. The conservation of color charge (C) comes from the $SU(3)_C$ symmetry of the QCD theory, which leads to strong interactions mediated by gluons. The remaining $SU(2)_L \times U(1)_Y$ symmetry comes from the EW theory, and corresponds to the weak interaction only acting on left-handed (L) fermions, and to the weak hypercharge (Y). The conservation of electric charge (Q) arises after the electroweak (EW) symmetry is spontaneously broken via the Higgs mechanism, where the electromagnetic interaction (QED) emerges from the mixing of the $SU(2)_L$ and $U(1)_Y$ gauge groups [4]. In this case, the residual gauge symmetry is $U(1)_{EM}$, associated with the conserved electric charge:

$$Q = I_3 + \frac{1}{2} Y , \quad (1.2)$$

where I_3 is the third component of weak isospin and Y is the weak hypercharge. This relation is known as the Gell-Mann–Nishijima formula [5].

1.1.1 Fundamental particles

Moving away from group theory, the SM describes two fundamental types of particles: fermions, with half-integer spin, and bosons, with integer spin. Each type of particle follows a different statistical model, with fermions following Fermi-Dirac statistics, while bosons follow Bose-Einstein statistics [2].

Fermions, being particles with spin- $\frac{1}{2}$, are described by the Dirac equation [1, 2]:

$$(i\gamma^\mu \partial_\mu - m) \psi = 0 , \quad (1.3)$$

where ψ is a four-component spinor (Dirac spinor), γ^μ are the gamma matrices, and m is the mass of the particle. At first, the Dirac equation presented a problem with the existence of negative energy solutions, but, through a reinterpretation of this result, Dirac was able to solve this problem. Dirac suggested that all negative energy states are already filled, which came to be known as the Dirac sea, and that an unoccupied negative energy state would behave similarly to a positive energy particle, with same mass, but opposite charge [6]. Thanks to this reinterpretation of the negative energy solutions, the notion of antiparticle was born. This meant that for every fermion, there is a correspondent antifermion with equal properties, but opposite charge. In this case, charge is not referring only to electric charge, but to all quantum numbers, or conserved charges, that can change sign under particle $\leftrightarrow$ antiparticle exchange. However, the most modern interpretation of the concept of an antiparticle, given by Feynman-Stueckelberg, doesn't view

them as fundamentally distinct entities, but rather as particles that are propagating backwards in time [7]. In this framework, the mathematical negative energy solution evolving forwards in time is physically reinterpreted as a positive energy antiparticle evolving forwards in time. This approach eliminated the need to postulate the existence of two separate entities, integrating them within a single theoretical structure.

Fermions are further divided into two groups: leptons and quarks [1, 2]. The distinction lies in the interactions they participate in. Leptons do not carry color charge and therefore do not experience the strong force, whereas quarks do, and this interaction is described by Quantum Chromodynamics (QCD). Fermions also come in three generations, each composed of a pair of quarks and leptons, with each generation containing heavier, more unstable particles than the previous generation.

There are also two groups of leptons: electrically charged [1.1], or electrically neutral [1.2]

Table 1.1: Summary of the properties of electrically charged leptons, including their respective lepton numbers: electron (L_e), muon (L_μ), and tau (L_τ).

Symbol	Name	Mass (MeV/c^2)	Electric charge (Q)	L_e	L_μ	L_τ
e^-	Electron	0.511	-1	1	0	0
e^+	Positron	0.511	+1	-1	0	0
μ^-	Muon	105.7	-1	0	1	0
μ^+	Antimuon	105.7	+1	0	-1	0
τ^-	Tau	1777.0	-1	0	0	1
τ^+	Antitau	1777.0	+1	0	0	-1

Table 1.2: Summary of the properties of electrically neutral leptons, including their respective lepton numbers: electron (L_e), muon (L_μ), and tau (L_τ).

Symbol	Name	Mass (MeV/c^2)	Electric charge (Q)	L_e	L_μ	L_τ
ν_e	Electron neutrino	$< 0.8 \times 10^{-6}$	0	1	0	0
$\bar{\nu}_e$	Electron antineutrino	$< 0.8 \times 10^{-6}$	0	-1	0	0
ν_μ	Muon neutrino	< 0.17	0	0	1	0
$\bar{\nu}_\mu$	Muon antineutrino	< 0.17	0	0	-1	0
ν_τ	Tau neutrino	< 18.2	0	0	0	1
$\bar{\nu}_\tau$	Tau antineutrino	< 18.2	0	0	0	-1

The electrically charged leptons are the electron e^- , the muon μ^- , and the tau τ^- , and each one has an associated electrically neutral lepton, named neutrino, that come in three different flavors: electron neutrino ν_e , muon neutrino ν_μ , and the tau neutrino ν_τ [8, 9]. It is important to mention that each neutrino flavor is a linear superposition of three mass eigenstates. As these mass eigenstates propagate through space, they acquire different phases due to their distinct masses, leading to neutrino flavor oscillations, so

that upon interaction, the neutrino can be detected as a different flavor. This oscillation is described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [10, 11], which relates neutrino flavor eigenstates to their mass eigenstates. Another property of leptons is that each pair has a leptonic quantum number of +1, or -1 for antilepton pairs. This quantum number is conserved in all interactions. As mentioned earlier, leptons do not participate in the strong interaction and only interact via the weak and the electromagnetic forces, with neutrinos being an exception for the latter, as they are electrically neutral.

Similarly to leptons, quarks come in two groups: up-type-quarks, with positive electrical charge ($Q = +\frac{2}{3}$), and down-type-quarks, with negative electrical charge ($Q = -\frac{1}{3}$) [8, 9]. Quarks are the only fermions that can participate in every type of interaction, including the strong interaction. For these particles, there is also a flavor changing mechanism possible through a charged current weak interaction, where an up-type-quark can transform into a down-type-quark of the same or different generation, and vice-versa. Just like the neutrino oscillations, there is a quark-mixing matrix, known as the Cabibbo-Kobayashi-Maskawa (CKM) matrix [12, 13], that describes the probability amplitudes of such flavor changes. Quarks are also associated with multiple quantum numbers, that are summarized in table 1.3.

Table 1.3: Summary of the properties of quarks, including the quantum numbers: baryonic number (B), isospin (I_3), charm (C), strangeness (S), truth (T), and beauty (B').

Symbol	Name	Mass (MeV/c^2)	Electric charge (Q)	B	I_3	C	S	T	B'
u	Up	2.16	+2/3	+1/3	+1/2	0	0	0	0
$\bar{u}$	Antiup	2.16	-2/3	-1/3	-1/2	0	0	0	0
d	Down	4.67	-1/3	+1/3	-1/2	0	0	0	0
$\bar{d}$	Antidown	4.67	+1/3	-1/3	+1/2	0	0	0	0
c	Charm	1.27×10^3	+2/3	+1/3	0	1	0	0	0
$\bar{c}$	Anticharm	1.27×10^3	-2/3	-1/3	0	-1	0	0	0
s	Strange	93.4	-1/3	+1/3	0	0	-1	0	0
$\bar{s}$	Antistrange	93.4	+1/3	-1/3	0	0	1	0	0
t	Top	172.7×10^3	+2/3	+1/3	0	0	0	1	0
$\bar{t}$	Antitop	172.7×10^3	-2/3	-1/3	0	0	0	-1	0
b	Bottom	4.18×10^3	-1/3	+1/3	0	0	0	0	-1
$\bar{b}$	Antibottom	4.18×10^3	+1/3	-1/3	0	0	0	0	1

Quarks, being particles that carry color charge, fall under the rules of QCD, more specifically the color confinement hypothesis. In simple words, this hypothesis explains why quarks can not exist as free particles, and almost immediately decay when isolated. Since quarks transform under the representation of the $SU(3)_C$ symmetry group, they are color triplets. These can arrange themselves in combinations of quarks to create hadrons, which are color singlets with integer electric charge. These can either be baryons, which are fermions composed of three quarks with baryonic number $B = 1$, mesons, which are bosons composed of a quark-antiquark pair with baryonic number $B = 0$, or exotic hadrons, which are composed of multiple quarks or gluons.

Lastly, we must discuss bosons. These particles are responsible for mediating fundamental interactions, which is the reason why they are often referred to as force carriers [8, 9]. According to Yang-Mills theory, to every gauge symmetry generator corresponds one gauge field, therefore, the SM has 12 gauge fields: 4 EW gauge fields, including a triple of fields W_μ^i corresponding to the $SU(2)_L$ isospin generators, and a singlet B_μ to the $U(1)_Y$ hypercharge generator, and 8 QCD gauge fields G_μ^a associated with the $SU(3)_C$ generators of QCD [2, 14]. At this point, the EW sector Lagrangian is missing mass terms

for both the fermions and gauge fields, and these can not be simply added or the gauge symmetry would be explicitly broken. To solve this issue, we must have spontaneous symmetry breaking via the Higgs mechanism. In this mechanism, a complex scalar complex doublet under $SU(2)_L$ with hypercharge $\frac{1}{2}$ is introduced, which acquires a non-vanishing vacuum expectation value. Once the system falls into a particular minimum, the gauge symmetry is spontaneously broken. This means that, despite the Higgs Lagrangian remaining invariant under transformations of $SU(2)_L \times U(1)_Y$, the vacuum will only be invariant under $U(1)_{EM}$. The EW symmetry is broken down to the local EM group:

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM} . \quad (1.4)$$

This process breaks three of the four generators of the EW symmetry, giving mass to the $W^\pm$ and Z^0 bosons, while leaving the Gell-Mann–Nishijima relation unbroken. As a result, the photon remains massless. According to the Goldstone theorem, each spontaneously broken generator gives rise to a massless scalar boson, which can be removed from the spectrum by an appropriate choice of gauge, thanks to the invariance of the Higgs Lagrangian under $SU(2)_L$. By expanding the kinetic term of the Higgs Lagrangian, we discover the mass terms for the EW gauge fields in the form of a non-diagonal mass matrix, and a mass term of a physical field that corresponds to the Higgs boson. Diagonalizing this matrix, reveals that the EW gauge fields mix to form the physical fields corresponding to the photon, the Z bosons, and the $W^\pm$ bosons, as well as their masses. As mentioned earlier, the EW sector is also missing mass terms for the fermions, but this is solved by introducing Yukawa interactions between the fermions and the Higgs field, which allows the Higgs mechanism to generate mass for the fermions while preserving gauge invariance. To wrap things up, the SM contains 12 gauge bosons and 1 scalar boson. The gauge bosons include the photon, the Z and $W^\pm$ bosons, and the 8 gluons, that are responsible for mediating the electromagnetic, weak, and strong interactions, respectively. The scalar boson corresponds to the Higgs boson, that is responsible for the Higgs mechanism.

1.2 Beyond the Standard Model scenarios

The SM is the most successful theory of particle physics to date, accurately predicting the vast majority of experimental observations. However, it also contains several problems that remain unsolved [2, 3]:

- The hierarchy problem: in the SM, if no fine tuning is used, the Higgs boson mass naturally falls towards the Planck scale when quantum corrections are considered;
- The strong CP problem: despite the SM allowing for CP violation, this is yet to be measured in quantum chromodynamics (QCD);
- The baryon asymmetry of the Universe: the SM is not able to explain the observed dominance of matter over antimatter;
- Dark matter: despite the astrophysical and cosmological evidence suggesting the presence of dark matter in the Universe, the SM has no particle that can serve as a viable candidate;

To address these problems, several models with theoretical extensions of the SM were proposed. These models often suggest the existence of new interactions or particles that are not included in the SM, and for that reason are known as Beyond the Standard Model (BSM) scenarios. The study of BSM scenarios is one of the main goals of particle physics.

From all the different BSM scenarios, we are particularly interested in those involving an extra Higgs doublet. The simplest of these scenarios is the two-Higgs-doublet model (2HDM), which is predicted and motivated by supersymmetry [15, 16, 17]. Unlike in the SM, supersymmetric theories require two Higgs doublets because a single Higgs doublet cannot simultaneously give mass to up-type ($Q = +\frac{2}{3}$) and down-type ($Q = -\frac{1}{3}$) quarks. This is due to the holomorphic nature of the supersymmetric superpotential, which forbids couplings involving the complex conjugate of the Higgs field, as is done in the SM [18]. There are also other motivations, such as the Peccei-Quinn model, which suggests that if the QCD Lagrangian contained a $U(1)$ global symmetry, the CP-violating term could be rotated away, but only if there are two Higgs doublets [19, 20]. Another motivation for extended Higgs sectors is the flexibility of the Higgs scalar mass spectrum and the presence of additional sources of CP violation, which could help explain the baryon asymmetry of the Universe. In the 2HDM, the extra Higgs doublet implies five states contained in the Higgs sector: two neutral CP-even (h and H), one neutral CP-odd (A), and a pair of charged Higgs bosons ($H^\pm$) [21, 22].

1.3 The Large Hadron Collider

The Large Hadron Collider (LHC) is the world's largest particle accelerator located at CERN, near Geneva. The LHC was installed in the same tunnel used by The Large Electron-Positron Collider (LEP), whose physics focus was to explore the EW sector and make precise SM measurements, and also incorporated the pre-existing injection system. The physics motivation behind LHC was the study of the electroweak symmetry breaking mechanism, which led to the discovery of the Higgs boson, and also the search for BSM physics [23]. The main difference between the two colliders is the type of particles they accelerate and collide, since LEP was operated with light leptons (electrons and positrons), producing very clean final states, while the LHC operates with hadrons (ranging from protons to lead Pb ions), leading to more complex interactions. Moreover, LEP was only able to reach a center-of-mass energy of 209 GeV, since electrons are light particles and lose large amounts of energy to synchrotron radiation, while LHC is able to reach 13.6 TeV of center-of-mass energy, thanks to the heavier hadrons losing much less synchrotron radiation [24].

Present in figure 1.1 [25] is the LHC ring, which is divided in 8 sectors and includes four interaction points (IPs) corresponding to different experimental groups: 2 previously installed during LEP operation (ALICE [26] and LHCb [27]), and 2 new structures installed during the LHC construction (ATLAS [28] and CMS [29]). The several experimental groups focus on the study of different aspects of particle physics, with ATLAS and CMS aiming at the study of proton-proton collisions, LHCb at the study of b-flavor physics, and ALICE at the study of ion collisions. The collisions happen at each IP, where two hadron beams, moving in opposite directions, will cross and yield head-on collisions.

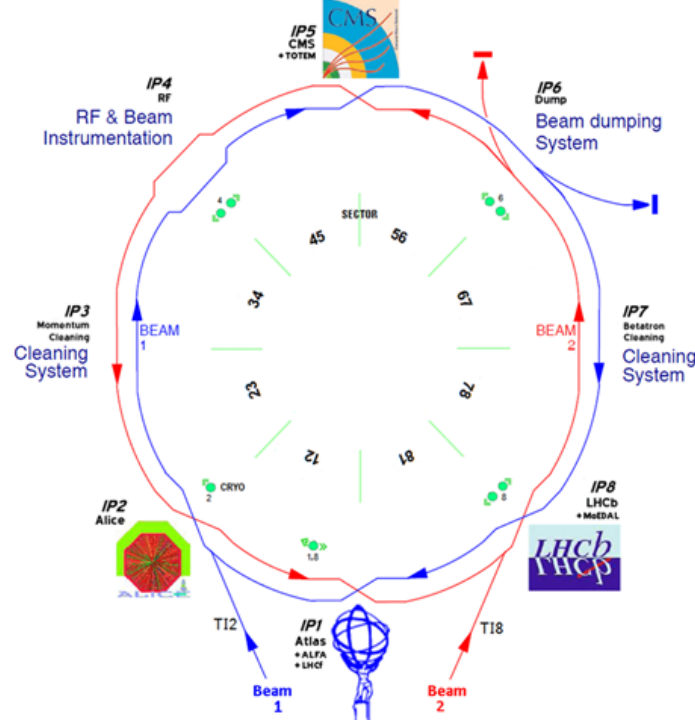


Figure 1.1: Diagram of the LHC ring, displaying its division in 8 sectors and labeling the several stations and interaction points.

Moreover, the LHC was designed to provide proton bunch crossings spaced by 25 ns , corresponding to a 40 MHz collision rate, but in certain cases, like heavy ion collisions, the spacing can go as far as 100 ns . The total number of events generated during LHC operation is given by:

$$N_{event} = L \sigma_{event} , \quad (1.5)$$

where L is the integrated luminosity, and σ_{event} is the process's cross section. The integrated luminosity is the time integral of the instantaneous luminosity $\mathcal{L}(t)$ over the period of data-taking:

$$L = \int \mathcal{L}(t) dt . \quad (1.6)$$

The instantaneous luminosity $\mathcal{L}$ is a value that solely depends on the following beam parameters: the number of particles per bunch N_b , the number of bunches per beam n_b , the revolution frequency f_{rev} , the relativistic gamma factor γ_r , the normalized transverse beam emittance ϵ_n , the beta function at the collision point β^* , and the geometric luminosity reduction factor F . Using these parameters, the instantaneous luminosity is determined as:

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F . \quad (1.7)$$

As this value depends on the beam parameters, it will not be the same for every experiment. The ATLAS and CMS, studying the head-on collision of proton beams of 7 TeV each, aim at a peak luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, while LHCb and ALICE aim at lower luminosity values of $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ and $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$, respectively. For proton-proton collisions, LHC is expected to achieve an integrated luminosity of 300 fb^{-1} during Run 3.

1.3.1 High Luminosity phase

The High-Luminosity Large Hadron Collider (HL-LHC) [30], is a performance upgrade aimed at raising the center-of-mass energy to 14 TeV and increasing the integrated luminosity by a factor of 10 beyond the original design. This will be achieved by packing more particles and focusing the beam more tightly. For proton-proton collisions, this means achieving an integrated luminosity of 3000 fb^{-1} . The higher luminosity is essential to probe rare processes and increase the sensitivity to potential signs of new physics. This upgrade depends on many technological innovations to bend and strongly focus the beam to increase the number of collisions:

- "Crab" cavities for tilting the beams;
- More powerful focusing magnets;
- Crystal collimators for increased efficiency;
- Innovative superconductive transmission lines;
- Reinforced machine protection;
- Renovated injector accelerator chain for the LHC;

1.4 The CMS detector

The Compact Muon Solenoid (CMS) is a general purpose detector system installed at the LHC [29]. This apparatus was built to take advantage of the higher-than-ever center-of-mass energy provided by the LHC and study physics at the TeV scale. These studies include the extended study of QCD under extreme conditions, of the mathematical consistency of the SM, and also the search for a unified theory, with BSM scenarios. For its approval, the CMS experiment had to satisfy a number of requirements to ensure it met the goals of the LHC physics program. The several requirements that the CMS experiment had to satisfy, which included resolution, background rejection, and particle isolation, influenced the development of CMS's main distinguishing features: a high-field superconducting solenoid, a fully silicon-based inner tracker, and a homogeneous electromagnetic calorimeter built from scintillating crystals.

1.4.1 Detector systems inside CMS

Before talking about the individual detector systems, it is useful to define the coordinate system adopted by CMS. The origin is set at the very center of the apparatus, corresponding to the collision point inside the experiment, the x-axis radially points towards the LHC ring, and the y-axis vertically upwards, setting the z-axis along the beam line pointing towards the Jura mountains, geographically speaking. From the axis a number of useful angles are also defined: the angle measured from the x-axis in the x-y plane is the azimuthal angle ϕ , and the radial coordinate set in this plane is represented by r ; the angle measured from the z-axis in the plane y-z is the polar angle θ , which is used in the definition of pseudorapidity $\eta = -\ln \tan \frac{\theta}{2}$. The full coordinate system can be visualized in figure 1.2 [29].

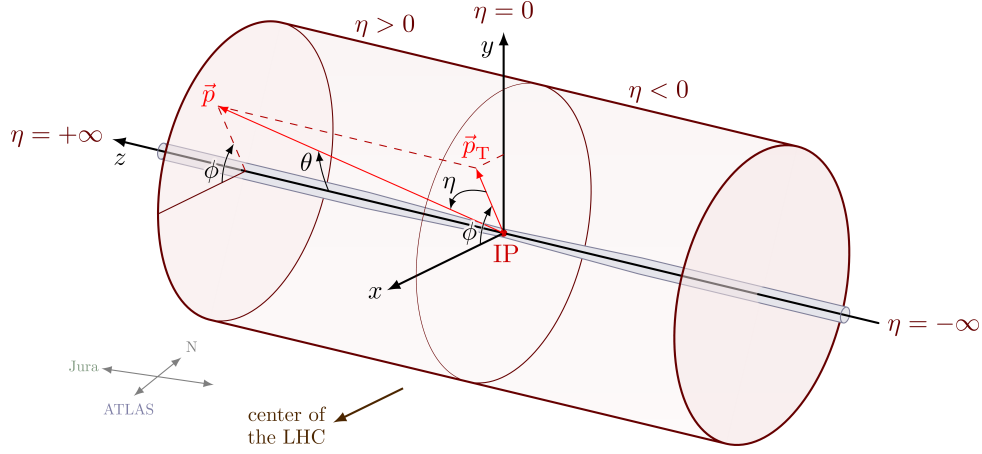


Figure 1.2: Representation of the coordinate system used by the CMS experiment. Image from https://tikz.net/axis3d_cms.

The full layout of CMS's central detector system is displayed in figure 1.3 [29].

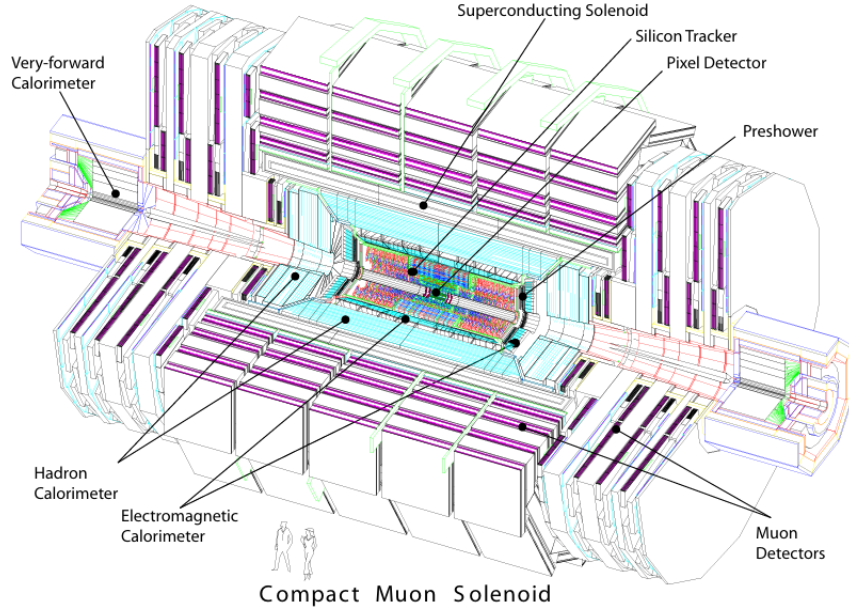


Figure 1.3: Side view of CMS's central detector system.

The superconducting solenoid's development was driven by the objective of measuring the momentum of high energy charged particles. For this particular reason, it was built with the capability of generating a 4 T magnetic field to provide a large bending power before the muons reach the muon detector system.

The region inside the superconducting solenoid contains the electromagnetic (ECAL) and hadronic (HCAL) calorimeters, as well as the silicon tracker and pixel detectors. As for the purpose of each detector: the silicon tracker is responsible for capturing particles trajectories, the pixel detectors precisely measure the impact parameter of charged particles and the position of secondary vertices, and the electronic and hadronic calorimeters measure particles' energy loss. The outer region of CMS contains the muon detector system. This system is composed of multiple gaseous detectors responsible for tracking the trajectory of muons.

At the endcaps, there is a very-forward calorimeter and additional muon detectors. These were installed to extend the pseudorapidity coverage of the central detector systems, which are limited to measuring particles within $|\eta| < 2.4$. With the inclusion of these forward detectors, the pseudorapidity coverage is increased to $|\eta| < 5.0$, with only a few efficiency drops in the transition regions between the central detector and endcap components.

The interaction of particles with the different detector systems is summarized in figure 1.4 [29].

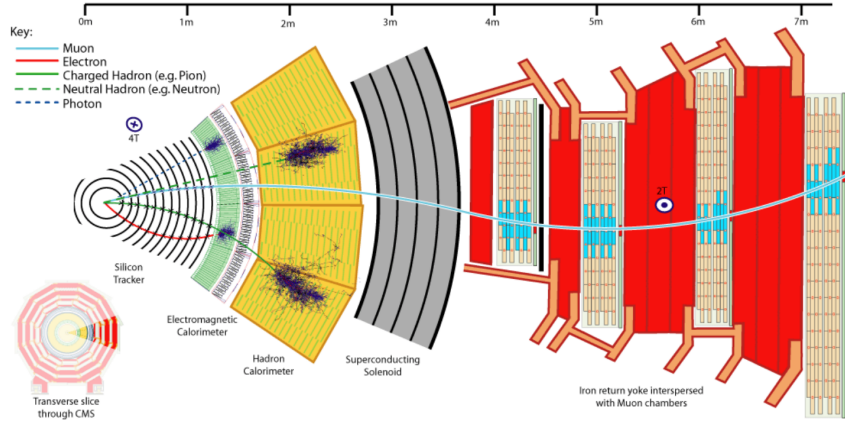


Figure 1.4: Transverse view of different particles interacting with the CMS detector.

The inner silicon tracker does not stop any particles and is only responsible for recording particles' trajectories. In the ECAL is where the first particles are stopped, which is made of elements with high atomic number to enhance electromagnetic interactions with atomic electrons. As a result, it is able to measure the energy of photons and electrons. The HCAL is responsible for stopping hadrons and is made of high-density elements, since high-energy hadrons lose energy primarily by direct interactions with atomic nuclei.

The central detector was built to study inclusive production processes. A process is inclusive when the initial state particles are not present in the final state. The Drell-Yan process [31] $pp \rightarrow l^+ l^- X$ is an example of an inclusive process, where the protons collide, dissociate, and create a lepton-antilepton pair, from the interaction of two quarks via either a virtual photon or Z boson exchange, and additional jets from decays of the remaining quarks. As the central detector is only able to measure particles within $|\eta| < 2.4$, or $|\eta| < 5.0$ using the forward detectors, it is not able to measure processes where initial/final state particles are scattered/produced at very small angles. Because of this, other detectors were developed that focused on the study of processes in the high pseudorapidity range $|\eta| \geq 5.0$.

1.4.2 Precision Proton Spectrometer

The Precision Proton Spectrometer (PPS) is a subdetector of the CMS experiment able to measure protons scattered at very small angles, with respect to the beam line. The PPS detector covers the pseudorapidity range of $|\eta| \geq 10.0$ and is installed on both sides of CMS at a distance of about 210 m from the IP [32]. It is composed of precision tracking and timing detectors encased in structures called Roman Pots (RPs). The RPs are installed on the beam pipe and use special insertions that allow the detectors to be moved closer to or further from the beam center [32]. The layout of the PPS detector system is displayed in figure 1.5 [33].

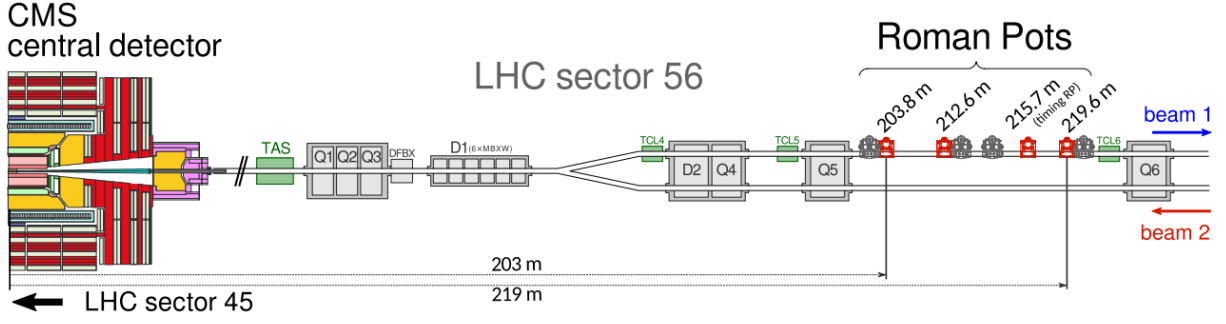


Figure 1.5: Side view of the PPS detector in LHC sector 56. The Roman Pots are colored in red. The accelerator magnets are in grey and the collimator system in green.

This detector system was built with the objective of studying Central and Exclusive Production (CEP) processes. Exclusive production processes are characterized by the presence of leading protons in the final state, while central refers to the rapidity of the central system being close to zero. Rapidity is defined by the fractional longitudinal momentum loss of the protons ($\xi_{1,2}$):

$$y = \frac{1}{2} \ln \left(\frac{\xi_1}{\xi_2} \right), \quad \xi_{1,2} = \frac{\Delta E_{1,2}}{E}, \quad (1.8)$$

where E is the initial energy of the protons, and $\Delta E_{1,2} = E - E_{1,2}$ is the energy loss by each proton during the interaction. A CEP process is therefore one in which both protons remain intact and lose a fraction of their longitudinal momentum. This type of process has the advantage of producing clean final states, making it an interesting subject of study in experimental analysis.

The PPS detector, by measuring the energy of the protons after the interaction, offers a big advantage in the study of CEP processes as, for a general process $p p \rightarrow p X p$, it is possible to reconstruct the invariant mass of the central system:

$$M_X = \sqrt{\xi_1 \cdot \xi_2 \cdot s}, \quad (1.9)$$

where $\sqrt{s}$ is the center-of-mass energy. Furthermore, the separation between signal and background can be significantly enhanced by correlating the protons, whose kinematics are reconstructed by the PPS detectors, with the events in the central CMS detector. An example would be matching the invariant mass of the central system M_X , reconstructed from the fraction of momentum loss by the protons in PPS, with the mass reconstructed from the events in the central CMS detector. Another example is the utilization of the PPS timing detectors to determine the interaction vertex of the protons and matching it with the interaction vertex reconstructed from tracks in the central CMS detector. The interaction vertex of the protons in PPS is determined by:

$$Z_{PPS} = (T_1 - T_2) \times \frac{c}{2}, \quad (1.10)$$

where $T_{1,2}$ are the times at which each proton crosses the PPS timing detectors on each side of CMS, and c is the speed of light.

1.4.3 Trigger System

As stated in [section 1.3](#), the LHC was designed to provide a proton-proton collision rate of 40 MHz . Ideally, all the collisions would be recorded and stored for analysis. In reality, this rate corresponds to about one petabyte of data per day, and LHC Run 3 is expected to generate more than 600 petabytes of data. Since it is not feasible to store this enormous amount of data in CERN's storage infrastructure, a series of data reduction systems are set in place to reduce the event rate by selecting only the most relevant collisions. The data reduction system starts with the Level-1 (L1) trigger, and is followed by a High Level Trigger (HLT) [\[34, 29\]](#). The L1 trigger uses custom-made electronics to select events at a set latency of $4 \mu\text{s}$ and at a rate of about 100 kHz . The HLT is composed of an array of processors executing an accelerated version of the event reconstruction software and reduces the event rate to roughly 1 kHz prior to data storage. There are multiple versions of these L1 and HLT triggers with different settings depending on which events are targeted.

For CEP studies, a jet matching HLT was developed to select events based on a matching between properties of the four-jet system, measured by the central detector, and of the protons, measured by PPS. This HLT was particularly designed to study processes with 4 jets in the final state, such as $pp \rightarrow pW^+W^-p$ and $pp \rightarrow pZZp$. This was the first CMS HLT using tagged protons. The conditions of the HLT are as follows:

- Number of tracks per RP < 3 ;
- Number of jets in the final state > 4 ;
- Di-jet average transverse momentum (P_T) $> 180 \text{ GeV}$;
- Matching of ξ between protons and four-jet system < 0.3 ;

In the HLT conditions, the di-jet average P_T is defined as the mean of the transverse momentum of the first and second leading jets, and the ξ matching is defined as:

$$\xi_{Matching}^{45/56} = \frac{\min(|\xi_{Jets}^{45/56} - \xi_{Proton}^{45/56}|)}{\xi_{Jets}^{45/56}} , \quad (1.11)$$

where $\xi_{Jets}^{45/56}$ provides an estimate of the proton's ξ based on the jets observed in the central detector:

$$\xi_{Jets}^{45/56} = \frac{1}{\sqrt{s}} \sum_{i=0}^{N_{Jets}} [E(j_i) \pm P_z(j_i)] . \quad (1.12)$$

In these variables, the numbers 45/56 refer to each side of CMS and have P_z with opposite sign due to the z-axis definition in CMS's coordinate system.

1.5 Charged Higgs boson pair production

An extra Higgs doublet is often present in BSM scenarios [\[16, 35, 36\]](#). Thus, the observation of a charged Higgs boson would indicate the presence of BSM physics. For this reason, the production of charged Higgs bosons has been an extensive subject of study [\[22\]](#).

Inclusive charged Higgs boson production processes are typically categorized in two regimes: light charged Higgs bosons, with $m_{H^\pm} < m_t - m_b$, and heavy charged Higgs bosons, with $m_{H^\pm} > m_t - m_b$. For a light charged Higgs boson, the dominant production mode is via top quark decays from top-antitop pair production:

$$p p \rightarrow t \bar{t}, \quad t \rightarrow b H^+, \quad \bar{t} \rightarrow \bar{b} H^- \quad (1.13)$$

In this mass range, the most significant decay channels of the charged Higgs boson are: $H^+ \rightarrow \tau^+ \nu_\tau$ and $H^+ \rightarrow c \bar{s}$. For a heavy charged Higgs boson, production occurs mainly through three mechanisms:

- Associated production with a top quark via partonic processes:

$$q\bar{q}, gg \rightarrow t b H^\pm \quad \text{or} \quad g b \rightarrow t H^\pm; \quad (1.14)$$

- Associated production with a vector or scalar boson:

$$q\bar{q}, gg \rightarrow H^\pm W^\pm \quad \text{or} \quad q\bar{q} \rightarrow H^\pm A; \quad (1.15)$$

- Pair production:

$$q\bar{q}, gg \rightarrow H^+ H^- \quad \text{or} \quad q\bar{q}, gg \rightarrow b\bar{b} H^+ H^-; \quad (1.16)$$

Due to the nature of inclusive processes and their strong coupling to colored particles, they are accompanied by large QCD backgrounds. Therefore, exclusive processes tend to be a more interesting object of study.

As for exclusive production, the dominant process is the CEP of a single charged Higgs pair [37]:

$$pp \rightarrow p H^+ H^- p, \quad (1.17)$$

where the protons remain intact and each emit a color singlet particle that is responsible for the production of the charged Higgs pair. The color singlet particle can be either a photon, a Z boson, or a Pomeron $\mathbb{P}$, which is a color singlet particle with partonic structure [38, 37].

In this study, we will focus on the CEP of a single pair of charged Higgs bosons via photon-photon fusion:

$$\gamma\gamma \rightarrow H^+ H^-. \quad (1.18)$$

This is an example of a photon induced interaction [33] in ultraperipheral proton-proton collisions (gamma-UPC). A gamma-UPC is a process where the two incoming protons, or ions, pass each other at large impact parameters, don't collide directly, and act as an electromagnetic field source, exchanging quasireal photons [39]. The photons are then able to fuse and produce a central system, in this case a pair of charged Higgs bosons $H^+ H^-$. There are also multiple decay modes for the charged Higgs boson, listed in table 1.4 [40].

Table 1.4: Possible decay modes of the charged Higgs boson in the 2HDM BSM scenario.

Mode	2HDM
$H^+ \rightarrow \tau^+ \nu_\tau$	X
$H^+ \rightarrow \mu^+ \nu_\mu$	X
$H^+ \rightarrow t \bar{b}$	X
$H^+ \rightarrow c \bar{b}$	X
$H^+ \rightarrow c \bar{s}$	X
$H^+ \rightarrow W^+ h$	X
$H^+ \rightarrow W^+ H$	-
$H^+ \rightarrow W^+ A$	-
$H^+ \rightarrow \chi_i^+ \chi_j^0$	X

From the possible decay modes, we will only focus on the following three:

$$H^+ \rightarrow c \bar{s} \quad \text{and} \quad H^+ \rightarrow c \bar{b} \quad \text{and} \quad H^+ \rightarrow \tau^+ \nu_\tau . \quad (1.19)$$

The first two decay modes correspond to a four-jet final state, falling inside the jet matching HLT category. The leptonic decay mode is particularly different from the other decay modes, as it includes both taus (τ) and neutrinos (ν) in the final state and doesn't fall within the criteria for the jet matching HLT. It should also be noted that the τ lepton, being the heaviest lepton, can decay either leptonically or hadronically. In events with 2 taus, the most commonly studied final states, omitting the neutrinos, are:

- $\tau_{hadronic} + \tau_{hadronic}$
- $\mu + \tau_{hadronic}$
- $e + \tau_{hadronic}$
- $e + \mu$

The hadronic tau $\tau_{hadronic}$ is a τ lepton that decays into quarks, subsequently hadronizing and producing a narrow jet of hadrons, mostly pions and kaons [41]. From these final states, we will only focus on the ones involving either one muon or one electron. To select one of these final states, the condition in table 1.5 has to be satisfied.

Table 1.5: Condition for selecting each final state in the leptonic decay of the charged Higgs boson.

Final state	Condition
$\mu + \tau_{hadronic}$	Single muon with $P_T > 24 \text{ GeV}$
$e + \tau_{hadronic}$	Single electron with $P_T > 30 \text{ GeV}$

1.6 Experimental analysis challenges

The main challenge in our analysis will be the separation between signal and background events. For the CEP of a single pair of charged Higgs boson, the main competing background will be a four-jet final state QCD interaction of the type $pp \rightarrow jjjj$. If we stopped right here, one could assume that separating this background from our signal events would be fairly easy with the help of the PPS detector, since the background has no protons in the final state.

However, there is an additional effect that we must take into account that creates background noise, known as pileup. There are two types of pileup:

- In-Time Pileup: when there are multiple collision within the same bunch crossing;
- Out-of-Time Pileup: due to neighboring bunch crossing collisions and caused by the finite response time of the detectors;

The consequences of pileup interactions is the introduction of additional tracks in the central detector, and of protons scattered at small angles inside the range of PPS. It's the last point that complicates the background separation, as we now have $pp \rightarrow p_{pileup} j j j j p_{pileup}$, that can be detected by PPS and looks exactly the same as our signal event. This is mainly caused by in-time pileup, and is the reason why PPS has installed timing detectors, to facilitate the distinction between protons from the signal event and protons coming from pileup interactions, by determining the interaction vertex defined in equation [1.10](#)

Regarding the leptonic decay mode of the charged Higgs boson, the primary challenge arises from the presence of neutrinos, since they are weakly interacting and their momentum can't be measured directly, complicating full event reconstruction. Instead, the missing transverse energy (MET) is typically used to deduce the presence and transverse momentum of neutrinos in such processes.

2 Methodology

2.1 Event generation

The first step of this project was the generation of the signal and background events. The signal events correspond to the three decay modes of the charged Higgs boson listed in expression [1.19](#), and the background events to a four-jet final state QCD interaction of the type $pp \rightarrow jjjj$. Simulations play a crucial role in this type of analysis, since the amount of real data collected is often very limiting for rare processes, such as the CEP of a single pair of charged Higgs bosons. By performing simulations, it is possible to bridge the gap between real detector measurements and underlying physics theory. Additionally, simulations allow control over the event properties, which permits the study of signal and background events separately, but also to test different scenarios, and optimize selection cuts.

This task was achieved using the tool MadGraph5_aMC@NLO [\[42\]](#), which is a tool designed for SM and BSM phenomenology studies, that is capable of performing Monte Carlo (MC) [\[43\]](#) simulations of hard scattering processes. It is also possible to enable the tool Pythia8 [\[44\]](#) inside MadGraph5_aMC@NLO, allowing the simulation of parton showers and hadronization of the hard scattered events. Moreover, the MadGraph5_aMC@NLO tool is able to compute cross sections, which will be an integral part of this study. The biggest advantage of this tool is that, despite performing complex computations, it is simple to set up and gives the user all the freedom to change any parameter of the simulation. Another important aspect related to this study is that MadGraph5_aMC@NLO already includes an extensive library of models, which will facilitate our study of BSM models [\[42\]](#). An example of a workflow inside MadGraph5_aMC@NLO is listed below:

1. Open the tool's terminal inside its main directory: `"/bin/mg5"`, will open the terminal with the default SM settings;
2. Choose the model: `"import model 2HDM"`, which will define the particles and parameters of the chosen model; the 2HDM model was chosen to generate the events, but the results shouldn't depend much on a specific model;
3. Define the process: `"generate a a > h+ h- > c s c s / h1 h2 h3"`, which corresponds to photon fusion and production of a single pair of charged Higgs bosons in the $H^+ \rightarrow c\bar{s}$ decay mode, excluding the processes mediated by neutral Higgs bosons (CP-even h and H , and CP-odd A);
4. Visualize the process (optional): `"display diagrams"`, to show all the possible diagrams and the respective orders of QCD/QED, for the defined process;
5. Save the process to a file: `"output /<path_to_folder>/<process_name>"`, where it's possible to define a folder for saving the simulation information and set a name for the process (the folder must be created beforehand); if this step is skipped, MadGraph5_aMC@NLO will save the process information in its main directory under a default name;
6. Launch the simulation: `"launch <path_to_folder>/<process_name> -n <name>"`, where the parameter `"-n"` is used to give a name to the specific process configuration; this parameter is particularly useful for our study, as we will be simulating the same process for different charged Higgs masses (`"launch <path_to_folder>/<process_name> -n mass80/90/100/..."`);

7. Define which tools to use in the simulation: the program will ask which tools we would like to use in the simulation, with options ranging from enabling Pythia8, to enabling MadAnalysis5 [45], which is a great tool for parton level analysis;
8. Configure the input parameters of the simulation: we will be asked if we would like to change any input parameter of the simulation, that can be directly enabled from MadGraph5_aMC@NLO, or from others tools that we have previously enabled;
9. Run the simulation: "done", which signifies the end of the input parameters configuration and initiates the simulation of the events;
10. Rerun / Close the program: "launch <path_to_folder>/<process_name> -n <name>" / "exit", to either run the simulation again, with the possibility of modifying the input parameters again, or to close the program;
11. Analysing the results: inside the process's saved results folder, MadGraph5_aMC@NLO will store all the relevant simulation information, such as the cross section of the process and the parton level events in the form of a ".lhe.gz" file [46]; if tools like Pythia8 were enabled, there will also be a ".hepmc" file [46] containing the hadron level events;

In our case study, Pythia8 will play a fundamental role, since it is responsible for simulating the parton showering and hadronization of hard scattered events. Moreover, for the study of CEP processes it is extremely important to retain the proton information after collision, which is also done by Pythia8. To keep the information of protons, when running MadGraph5_aMC@NLO, it is necessary to edit the Pythia8 card and add the following lines:

```
BeamRemnants:primordialKT = off
PartonLevel:MPI = off
SpaceShower:dipoleRecoil = on
SpaceShower:pTmaxMatch = 2
SpaceShower:QEDshowerByQ = off
SpaceShower:pTdampMatch = 1
BeamRemnants:unresolvedHadron = 3
Check:event = off
```

These commands are described in the Pythia8 documentation [44]. Here, we also change the output file type from "hepmc.gz" to "hepmc", which will facilitate the input to the tool used for detector simulation.

2.2 Detector simulation

One of the objectives of this study is to determine the acceptance of the PPS detector. For this purpose, we had to choose a tool able to simulate the CMS detector system and capable of taking hadron level events, obtained from MadGraph5_aMC@NLO with Pythia8, as input. The ideal option would be to use CMSSW [47], which stands for CMS Software and is a complex collection of software used for precise and complete simulation, calibration, and reconstruction of events for physics analysis. However, the process of learning and running this complex tool would take up much of the time available for this project, and therefore a choice was made to instead perform a more basic simulation that would still be a good approximation of the real detector behavior with a tool called Delphes [48]. For this study, we utilized a standard Delphes configuration that has been used for other CMS HL-LHC simulations.

Delphes has different run options available, depending on the type of input file, and requires a minimum bias pileup file, a card indicating the desired detector configuration, and an input file with the hadron level events. The standard output of Delphes will be in the ROOT [49] format. The tool includes some default cards for the biggest detector systems, but there is the possibility to either create a new card, or modify an existing one. Detector cards are composed by modules that define the behavior of each individual system inside the overall detector, such as particle momentum resolution, tagging efficiency, particle isolation, track merger, and pileup merger. Below there is an example of a workflow inside Delphes:

1. Prepare input file: before using Delphes, we must generate the hadron level events in MadGraph5_aMC@NLO with Pythia8 enabled, which will output a "hepmc" file;
2. Prepare a minimum bias pileup file: if the study requires the presence of pileup interactions, a minimum bias file including pileup interactions for a given center-of-mass energy must be used; this is a file usually prepared by the experimental groups, detailing the type of pileup interactions seen in the detectors;
3. Define detector configuration: inside Delphes' cards directory, assuming an already created detector card, make sure that the modules are all set up correctly, for instance with the correct value of mean pileup and PPS resolution;
4. Run Delphes: in the terminal, travel to Delphes' directory and run `"/DelphesHepMC2 cards/<detector_card> <output_file>.root <path_to_input_file>/<input_file>.hepmc"`, where "DelphesHepMC2" may change according to the type of input file, and the name of the output file can be defined;
5. Result analysis: Delphes will output the result of the simulation in the form of a root file, previously defined, on its main directory, that can then be analyzed using custom scripts;

2.3 Data analysis

Two types of files were analyzed, those being ".lhe" for parton level events, and ".root" for detector level events. For the analysis of the parton level events, the tool MadAnalysis5 [45] was used. When running MadGraph5_aMC@NLO, by enabling this tool, it is possible to obtain a simple automated analysis of the hard scattered events, such as transverse momentum and eta distributions of the final state quarks. On top of this, the same tool was used to search for correlations between the transverse momentum of quarks and the pair of quarks resulting from the decay of each charged Higgs boson.

As for detector level events, with files in ".root" format, the analysis included a C++ macro to compute the relevant properties of the events, and a Jupyter notebook [50], inside CERN SWAN [51] service, running the language Python 3 [52] together with the PyROOT interface. These tools were used to compare distributions between the different charged Higgs boson decay modes, with the objective of identifying key differences and possible correlations with their respective PPS detector acceptance efficiency, and between signal and background events, to select cuts providing the best separation. Lastly, once identified the best separating variable, the Combine tool [53] was utilized to set upper limits to each decay modes' cross section. This is a widely used tool, that takes advantage of ROOT's statistical analysis framework (RooFit and RooStats), capable of building models based on expected observations, running statistical tests, and performing model validation. This is a purely statistical tool, agnostic to any physics, that could be used for any sort of analysis, but its development is based around High Energy Physics

(HEP) cases. A simple workflow to determine the statistical sensitivity to observe or exclude a process, using the Combine tool, is listed below:

1. Prepare an histograms of the most discriminant variable for both signal and background events: a discriminant variable, presenting a good signal and background separation, must be prepared; this is usually performed during the event analysis and after applying some selection cuts; it is important to normalize the simulated events according to the number of expected events, which is determined using the process's cross section and integrated luminosity of the detector;
2. Create a datacard for the Combine tool: a text file must be created with information regarding the input file (ROOT file including the histograms of the chosen discriminant variable), and the number of bins, processes and nuisance parameters, which are sources of systematic uncertainty;
3. Convert the datacard to a ROOT workspace: `"text2workspace.py datacard.txt -m 100 -o workspace_test.root"`, this step is not strictly necessary, but is advantageous when working with many datacards and different parameters; the option `"-m 100"` is useful for studies with multiple mass values and is used to select the mass value in the presence of multiple histograms;
4. Compute the expected significance of the signal: `"combine -M Significance workspace_test.root -t -1 --expectSignal 1"`, where the option `"-t -1"` will use an Asimov dataset, in which the data is assumed to follow the model exactly, with no statistical fluctuations, and the option `"--expectSignal 1"` assumes a signal as large as the input histogram;
5. Determine the expected 95% confidence level (CL) upper limit on the signal strength: `"combine -M AsymptoticLimits workspace_test.root -t -1 --expectSignal 0"`, where `"--expectSignal 0"` assumes zero signal, and will provide the expected limit under the background-only hypothesis;

A more detailed example of usage is provided by the CMS group in the official Combine documentation [\[54\]](#).

3 Search for central and exclusive production of a single pair of charged Higgs bosons

In this project, the results were separated in four sections. The first section focuses on the study of the cross sections for the signal and background events. The second section corresponds to the results obtained using the PPS detector configuration of LHC Run 3, while the third section is dedicated to the results with the PPS detector configuration planned for the future HL-LHC upgrade. In the last section, a comparison is made between the results obtained for each detector configuration, to highlight the differences and possible improvements to future event analysis. Additionally, this analysis is designed to be as model independent as possible, by not assuming the hierarchy of the charged Higgs boson branching ratios from the 2HDM, not using any b-tagging or charm-tagging to determine the flavor of the jets, and not measuring the electrical charge of the jets to determine the actual charge of the charged Higgs boson. The 2HDM is only use for convenience when generating the events, but this analysis could also be sensitive to other signatures in other models [55].

3.1 Cross section study

The first milestone of this project was to obtain the cross section of every event being considered. In this case, the considered events were three charged Higgs boson decay modes, for different charged Higgs masses, and a general four-jet final state QCD background. Regarding signal events, the processes mediated by the neutral h , H , and A were excluded from this analysis, with the analysis being focused on the processes presented in figures 3.1, 3.2, and 3.3. In figure 3.4, there is an example of processes included in the four-jet final state.

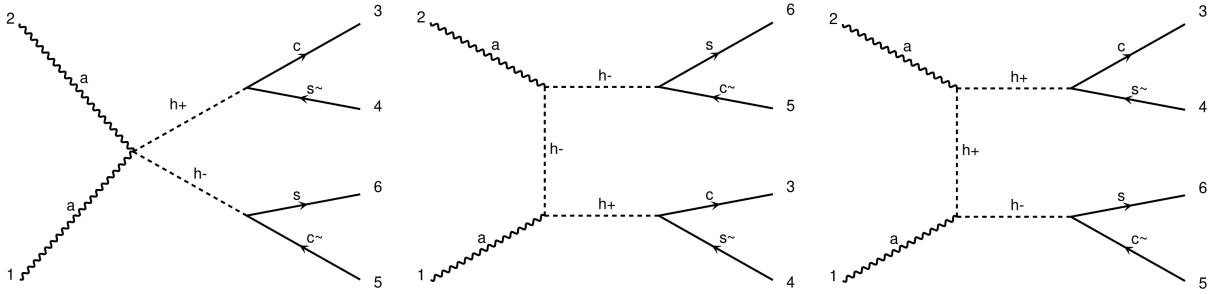


Figure 3.1: Born diagrams for the decay mode $H^+ \rightarrow c\bar{s}$.

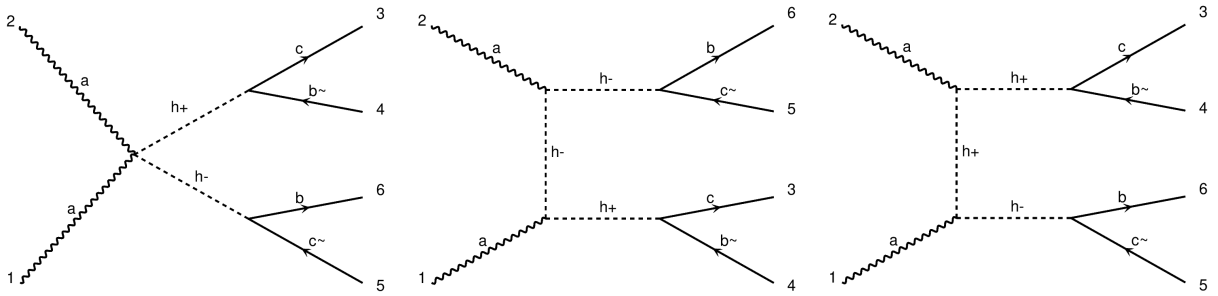


Figure 3.2: Born diagrams for the decay mode $H^+ \rightarrow c\bar{b}$.

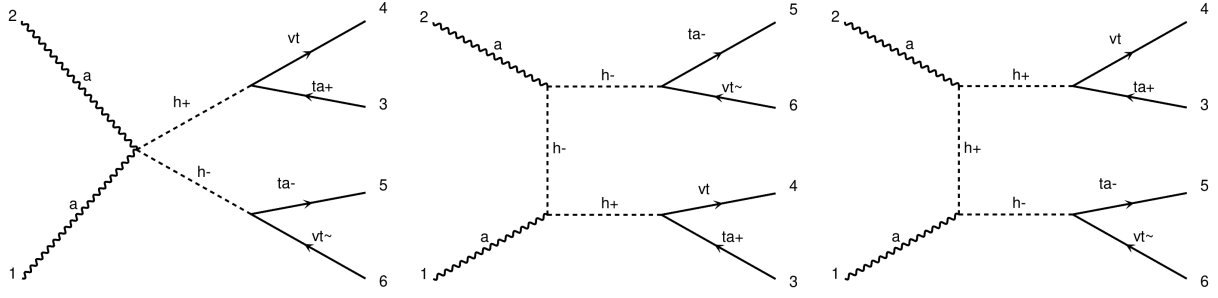


Figure 3.3: Born diagrams for the decay mode $H^+ \rightarrow \tau^+ \nu_\tau$.

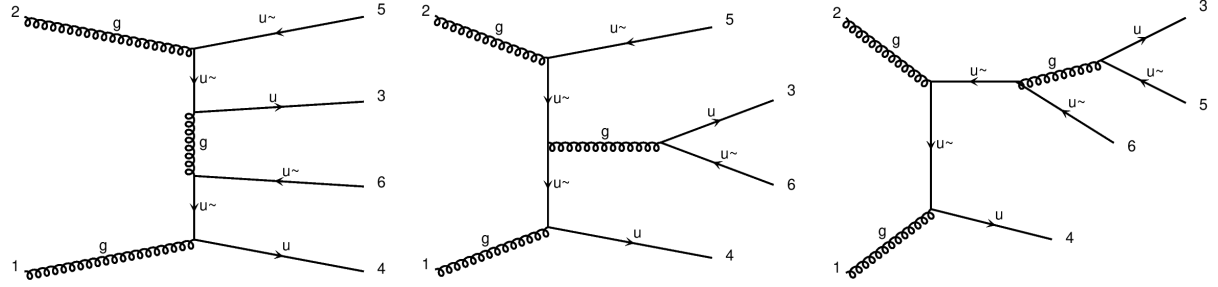


Figure 3.4: Examples of Born diagrams for the four-jet final state QCD background.

All the events were generated in MadGraph5_aMC@NLO, albeit with some minor changes to the run cards. General modifications, both for signal and background events, included the number of generated events, the selection of elastic photon from proton as the beam type, the total energy of each beam, the choice of a Parton Distribution Function (PDF) for gamma-UPC processes, and the maximum rapidity for the jets. These are listed in table [3.1](#).

Table 3.1: Set of changes applied to the run cards of all generated events.

Parameter	Value
Number of events	25000
Beam type	2
Beam energy	6800
PDF	chff
Maximum jet rapidity	2.4

The cross section times branching ratio was determined by MadGraph5_aMC@NLO after event generation and is listed in table [3.2](#) for the considered decay modes of the charged Higgs boson with different masses, and in table [3.3](#) for the total background.

Table 3.2: Cross section times branching ratio, in picobarn (pb), for each decay mode of the charged Higgs boson with different masses. Values determined by MadGraph5_aMC@NLO.

Charged Higgs Mass (GeV)	$H^+ \rightarrow c\bar{s}$	$H^+ \rightarrow c\bar{b}$	$H^+ \rightarrow \tau^+\nu_\tau$
80	$0.0294 \pm 7.6 \times 10^{-5}$	$4.029 \times 10^{-10} \pm 7.1 \times 10^{-13}$	$0.001861 \pm 3.5 \times 10^{-6}$
90	$0.02967 \pm 6.7 \times 10^{-5}$	$3.767 \times 10^{-10} \pm 6.2 \times 10^{-13}$	$0.001664 \pm 3.1 \times 10^{-6}$
100	$0.02889 \pm 6.9 \times 10^{-5}$	$3.478 \times 10^{-10} \pm 5.3 \times 10^{-13}$	$0.001494 \pm 2.8 \times 10^{-6}$
110	$0.02761 \pm 6.8 \times 10^{-5}$	$3.192 \times 10^{-10} \pm 4.7 \times 10^{-13}$	$0.001344 \pm 2.4 \times 10^{-6}$
120	$0.02615 \pm 5.9 \times 10^{-5}$	$2.917 \times 10^{-10} \pm 3.9 \times 10^{-13}$	$0.001214 \pm 2.1 \times 10^{-6}$
130	$0.02451 \pm 5.7 \times 10^{-5}$	$2.67 \times 10^{-10} \pm 3.7 \times 10^{-13}$	$0.001104 \pm 1.7 \times 10^{-6}$
140	$0.02292 \pm 4.7 \times 10^{-5}$	$2.449 \times 10^{-10} \pm 2.7 \times 10^{-13}$	$0.001006 \pm 1.7 \times 10^{-6}$
150	$0.02141 \pm 3.6 \times 10^{-5}$	$2.24 \times 10^{-10} \pm 2.9 \times 10^{-13}$	$0.0009171 \pm 1.5 \times 10^{-6}$
160	$0.01994 \pm 4.3 \times 10^{-5}$	$2.056 \times 10^{-10} \pm 2.4 \times 10^{-13}$	$0.0008393 \pm 7.8 \times 10^{-7}$
170	$0.01861 \pm 2.2 \times 10^{-5}$	$1.895 \times 10^{-10} \pm 2.3 \times 10^{-13}$	$0.0007709 \pm 1.1 \times 10^{-6}$
180	$0.01735 \pm 3.7 \times 10^{-5}$	$1.743 \times 10^{-10} \pm 2 \times 10^{-13}$	$0.0007082 \pm 1.1 \times 10^{-6}$
190	$0.01619 \pm 3.2 \times 10^{-5}$	$1.61 \times 10^{-10} \pm 2 \times 10^{-13}$	$0.0006546 \pm 1.1 \times 10^{-6}$
200	$0.01511 \pm 3.2 \times 10^{-5}$	$1.486 \times 10^{-10} \pm 1.5 \times 10^{-13}$	$0.0006053 \pm 9.3 \times 10^{-7}$
300	$0.007877 \pm 1.7 \times 10^{-5}$	$7.277 \times 10^{-11} \pm 7 \times 10^{-14}$	$0.0002992 \pm 3.9 \times 10^{-7}$
400	$0.004431 \pm 7.8 \times 10^{-6}$	$3.968 \times 10^{-11} \pm 4 \times 10^{-14}$	$0.0001658 \pm 2.3 \times 10^{-7}$
500	$0.002648 \pm 3.5 \times 10^{-6}$	$2.312 \times 10^{-11} \pm 2.3 \times 10^{-14}$	$9.734 \times 10^{-5} \pm 1.2 \times 10^{-7}$
600	$0.001643 \pm 2.7 \times 10^{-6}$	$1.411 \times 10^{-11} \pm 1.5 \times 10^{-14}$	$5.968 \times 10^{-5} \pm 6.3 \times 10^{-8}$
700	$0.001052 \pm 1.8 \times 10^{-6}$	$8.906 \times 10^{-12} \pm 9.2 \times 10^{-15}$	$3.792 \times 10^{-5} \pm 4.5 \times 10^{-8}$
800	$0.0006886 \pm 9.9 \times 10^{-7}$	$5.762 \times 10^{-12} \pm 5.9 \times 10^{-15}$	$2.469 \times 10^{-5} \pm 2.9 \times 10^{-8}$
900	$0.0004597 \pm 7.8 \times 10^{-7}$	$3.816 \times 10^{-12} \pm 3.5 \times 10^{-15}$	$1.64 \times 10^{-5} \pm 1.9 \times 10^{-8}$
1000	$0.0003114 \pm 4 \times 10^{-7}$	$2.568 \times 10^{-12} \pm 2.3 \times 10^{-15}$	$1.108 \times 10^{-5} \pm 1.3 \times 10^{-8}$

Table 3.3: Cross section, in picobarn (pb), of the four-jet final state QCD background. Value determined by MadGraph5_aMC@NLO.

Background	Cross Section (pb)
Four-jet final state QCD	$1.948 \times 10^7 \pm 2.7 \times 10^4$

From table 3.2, it can be observed that the $H^+ \rightarrow c\bar{s}$ decay mode has the highest cross section of the three being considered, with the $H^+ \rightarrow \tau^+\nu_\tau$ coming in second, and $H^+ \rightarrow c\bar{b}$ in last. This observation is specific to the 2HDM model, not being necessarily the same for other models.

Comparing the background cross section registered in table 3.3 with the highest signal cross section, which happens for the $H^+ \rightarrow c\bar{s}$ decay mode at a charged Higgs mass of 80 GeV, it is noticeable that the background is about 9 orders of magnitude larger. This fact motivated some changes to the simulation of the background events, as the large cross section would require a large number of simulated events to achieve a sufficient statistical precision. Since increasing the number of events implied a longer simulation time, the decision was made to simulate the background in several P_T ranges with intervals of 50 GeV. More specifically, the changes only targeted the minimum and maximum transverse momentum of the leading jet in each event. An example of the modified run card for the background P_T range is displayed in table 3.4, and the cross sections for each P_T range are registered in table 3.5.

Table 3.4: Example of a P_T range defined for background generation.

Parameter	Value
Minimum P_T for the leading jet	50 GeV
Maximum P_T for the leading jet	150 GeV

Table 3.5: Cross sections, in picobarn (pb), for each P_T range of the four-jet final state QCD background.

Four-jet final state QCD background	Cross Section (pb)
P_T range $[0, 50]$ GeV	$1.942 \times 10^6 \pm 4.4 \times 10^3$
P_T range $[50, 100]$ GeV	$2.366 \times 10^6 \pm 4.7 \times 10^3$
P_T range $[100, 150]$ GeV	$5.486 \times 10^5 \pm 1.1 \times 10^3$
P_T range $[150, 200]$ GeV	$1.437 \times 10^5 \pm 2.9 \times 10^2$
P_T range $[200, 250]$ GeV	$4.754 \times 10^4 \pm 94$
P_T range $[250, 300]$ GeV	$1.867 \times 10^4 \pm 36$
P_T range $[300, 350]$ GeV	8269 ± 17
P_T range $[350, 400]$ GeV	3973 ± 7.4

From the information registered in this table, it can be seen that the cross section for the background process is highest at low P_T values and lowest at high P_T values. This is expected due to the underlying dynamics of QCD and proton-proton collisions. The production of high P_T particles is less likely than distributing the energy among many soft particles, since that would require a higher center-of-mass energy to be concentrated into a single hard scattering process. Moreover, the PDFs are much larger when the partons carry a low momentum fraction of the proton’s total momentum, which favors the production of soft, low P_T interactions.

3.2 Experimental setup and detector configuration of LHC Run 3

The results presented in this section will focus on the PPS detector configuration for LHC Run 3, with a center-of-mass energy of $\sqrt{s} = 13.6$ TeV. The configuration of the PPS detector is a fundamental part of the simulations performed in Delphes, and is specifically defined as a module named "PPSProtonSmearing" inside the Delphes card selected for the analysis. This module smears the kinematic properties of the protons and only outputs those that fall inside the detector’s geometric acceptance, generating simplified detector level reconstructed protons. Inside the module, it is also possible to define the ξ resolution, the ξ range, and the time resolution of the PPS detector. The configuration of the PPS detector used during LHC Run 3 is present in table 3.6.

Table 3.6: Configuration of the PPS detector during LHC Run 3. The time resolution is given in nanoseconds. The ξ resolution is a percentage relative to the ξ value (0.05×0.03 at the minimum, and 0.05×0.15 at the maximum). The ξ minimum and maximum correspond to the percentage of proton longitudinal momentum loss.

Parameter	Value
ξ resolution	0.05 %
ξ minimum	0.03
ξ maximum	0.15
Time resolution	0.05 ns

3.2.1 The impact of pileup

Other important aspects from LHC Run 3 that must be considered include its integrated luminosity of 300 fb^{-1} , and a mean pileup value of 65, defined in the Delphes card. In this case, we used a minimum bias pileup file for a center-of-mass energy of $\sqrt{s} = 13.6$ TeV that was already prepared by the CMS group for other LHC Run 3 studies. The integrated luminosity is particularly important, since it is required to determine the expected number of events and normalize the number of simulated events. To better understand the impact of mean pileup in the analysis, two signal MC samples were simulated, one with no mean pileup, and one with the corresponding LHC Run 3 value.

The comparison between both simulations was registered in figure [3.5](#).

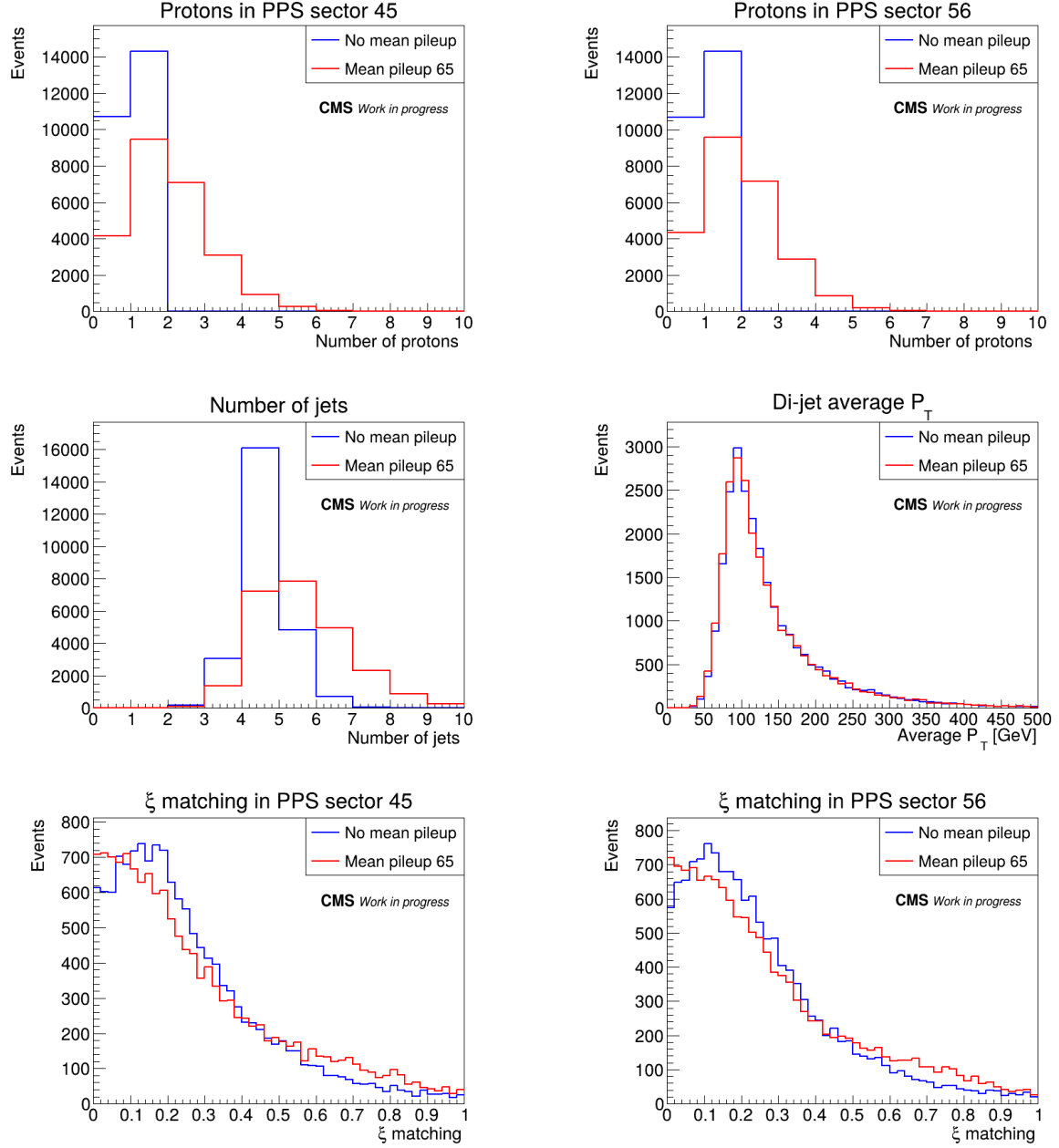


Figure 3.5: Comparison between properties of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, for a charged Higgs boson mass of 200 GeV , with a mean pileup of 65, and no mean pileup, both in the PPS detector configuration for LHC Run 3. Histograms were normalized to the area for better visualization.

The additional proton-proton collisions per bunch crossing directly increase the number of protons detected in both PPS sectors, as well as the number of jets in the central detector. Another consequence is the difference visualized in the ξ matching between protons and the four-jet system, which is composed by the four leading order jets, as the extra interactions open the possibility for mismatches with protons from pileup. The ξ matching peak seen for the signal MC events without pileup interactions, is due to this variable being relative to the ξ of the four-jet system and gives insight about the efficiency of the jet selection for the central system. This also reveals that some energy is lost in the reconstruction process of the jets, since the four-jet system is not able to fully reconstruct the ξ of the signal protons. The di-jet average P_T remains unchanged, since pileup is dominated by small-angle, low P_T scatterings that

produce low energy jets.

The effects on the $H^+ \rightarrow c\bar{b}$ decay mode were not displayed, since it also is a four-jet final state process and will be affected similarly to the $H^+ \rightarrow c\bar{s}$ decay mode. Nevertheless, the impact of pileup on the $H^+ \rightarrow \tau^+\nu_\tau$ decay mode is displayed in figure 3.6.

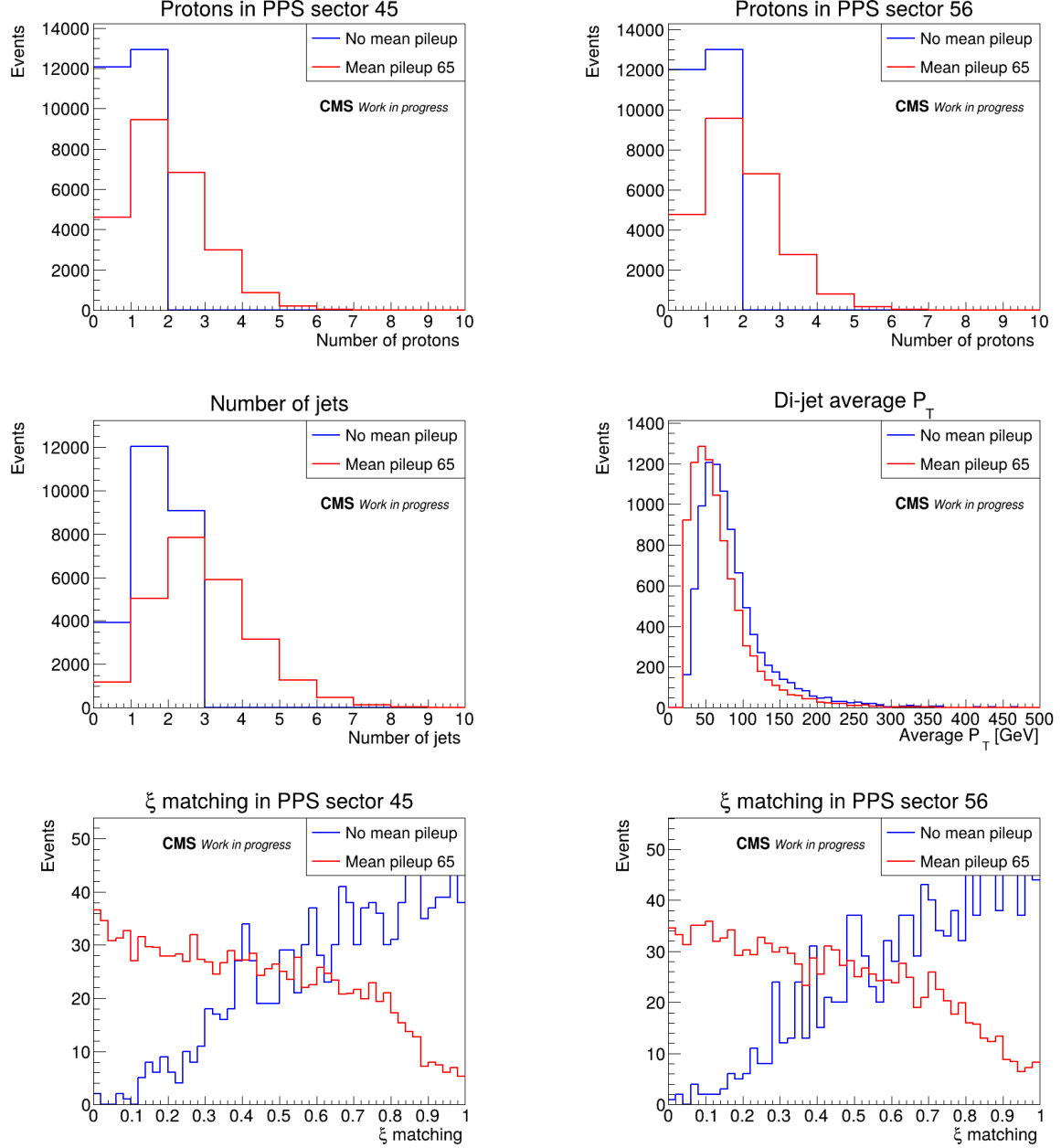


Figure 3.6: Comparison between properties of signal MC events in the $H^+ \rightarrow \tau^+\nu_\tau$ decay mode, for a charged Higgs boson mass of 200 GeV, with a mean pileup of 65, and no mean pileup, both in the PPS detector configuration for LHC Run 3. Histograms were normalized to the area for better visualization.

From these distributions, it is interesting to observe the behavior of the ξ matching values for the case without pileup. Being a final state that doesn't typically produce jets, together with the fact that the ξ matching variable was implemented for four-jet final state processes, means that it isn't possible to find a correlation between the ξ of the protons and the jets, as is indicated from the high ξ matching values. Looking at the same distributions for a mean pileup of 65, the low ξ matching values can be explained as matchings between protons and jets both originating from pileup. This is also concluded from the fact

that there is no evident peak at any particular ξ matching value. In the rest of the distributions we identify a impact from pileup similar to the $H^+ \rightarrow c\bar{s}$ decay mode, with the increase of the number of protons in each PPS sector and of the number of jets. In this case, a shift to lower values of the di-jet average P_T is visible, since this decay mode doesn't usually produce high P_T jets in the final state.

The most notorious change is seen for the background events, as protons originating from pileup interactions will be detected by PPS and allow certain background events to satisfy the HLT conditions. The histograms present in figure 3.7 show the effect of pileup on the background events.

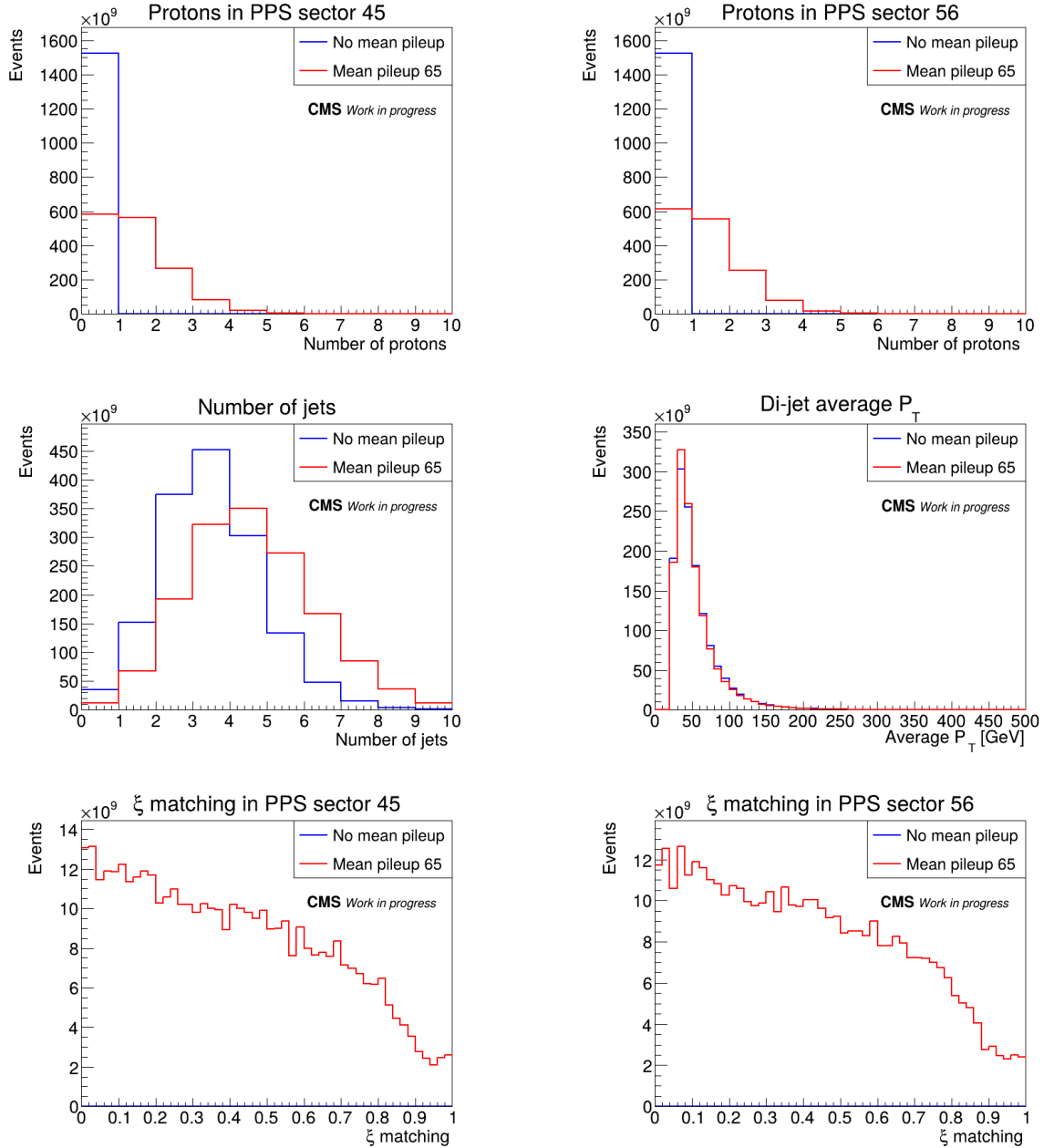


Figure 3.7: Comparison between properties of QCD background MC events in the four-jet final state with a mean pileup of 65, and with no mean pileup, both in the PPS detector configuration for LHC Run 3. Histograms were normalized to the area for better visualization.

Similarly to what was seen for the signal MC events, the pileup interactions are responsible for an increase of the number of jets in the CMS central detector and of protons in each PPS sector. By consequence, the ξ matching is now filled with wrong matchings between protons from pileup and the

jets from the central detector. In this case, the di-jet average P_T distribution also remains unchanged.

3.2.2 PPS Acceptance

Before moving to the separation of signal from background events, it is interesting to study how the different decay modes are detected by the PPS detector. The configuration of the PPS detector in the LHC Run 3 is registered in table 3.6. The acceptance of the PPS detector to the signal events can be defined as the percentage of events with at least one track in each RP or, equivalently, one proton in each PPS sector. The PPS detector's acceptance can be seen in figure 3.8 for each decay mode with no pileup, and in figure 3.9 with the inclusion of pileup.

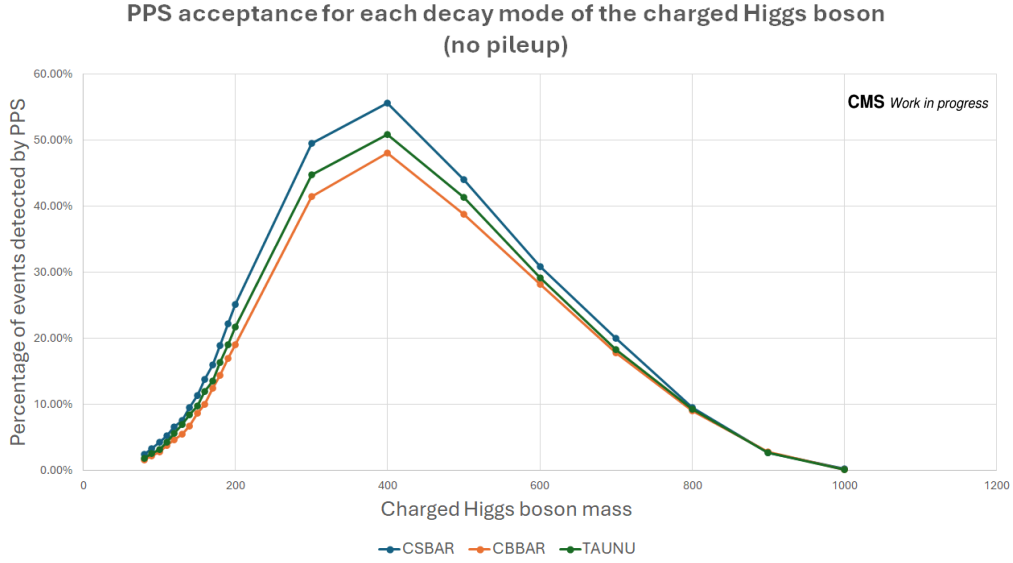


Figure 3.8: Percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) in the LHC Run 3 configuration, without pileup interactions. Each decay mode is labeled as follows: CSBAR for $H^+ \rightarrow c\bar{s}$, CBBAR for $H^+ \rightarrow c\bar{b}$, and TAUNU for $H^+ \rightarrow \tau^+\nu_\tau$.

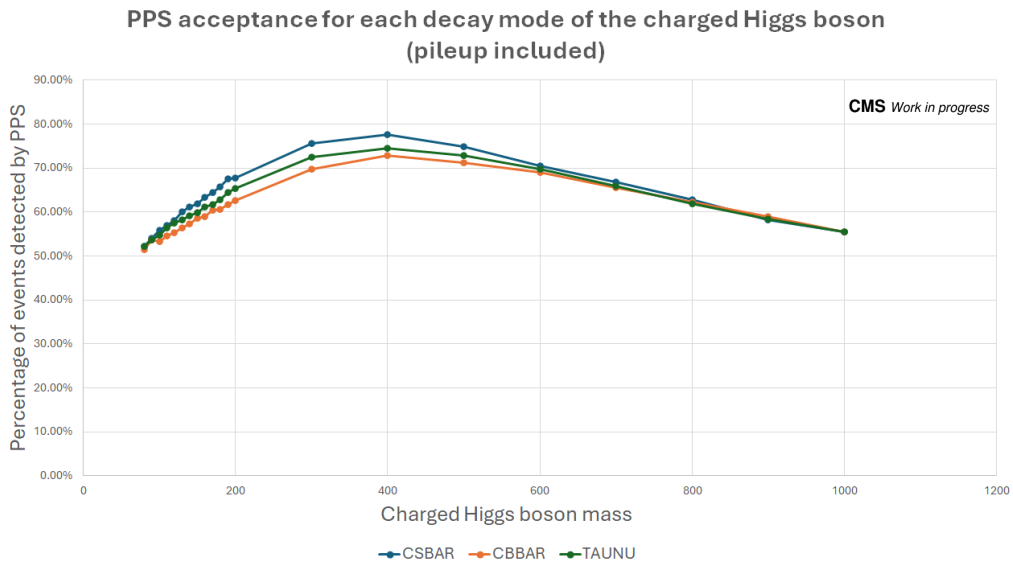


Figure 3.9: Percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) in the LHC Run 3 configuration, with pileup interactions included. Each decay mode is labeled as follows: CSBAR for $H^+ \rightarrow c\bar{s}$, CBBAR for $H^+ \rightarrow c\bar{b}$, and TAUNU for $H^+ \rightarrow \tau^+\nu_\tau$.

The obvious conclusion from figures 3.8 and 3.9 is that the extra protons from pileup interactions increase the detection rate of the signal processes. It can also be seen that the PPS acceptance peaks for every decay mode at a charged Higgs mass of 400 GeV , and it decreases for lower and higher mass values. To explain this behavior, two dimensional plots were built to show how the events are distributed in the acceptance region of the PPS detector in the LHC Run 3 configuration. The acceptance region is visualized by plotting the invariant mass ($M_X = \sqrt{\xi_1 \cdot \xi_2 \cdot s}$) versus the rapidity ($y = \frac{1}{2} \ln \left(\frac{\xi_1}{\xi_2} \right)$) central system, as well as the proton ξ_{45} against the proton ξ_{56} , where ξ_{45} corresponds to the ξ of the proton in sector 45, and ξ_{56} to the ξ of the proton in sector 56. The invariant mass of the central system ranges from the minimum value of $M_X = \sqrt{\xi_{min} \cdot \xi_{min}} \times 13600 \approx 400 \text{ GeV}$, to the maximum value of $M_X = \sqrt{\xi_{max} \cdot \xi_{max}} \times 13600 \approx 2000 \text{ GeV}$. Similarly, the rapidity of the central system ranges from the minimum value of $y = \frac{1}{2} \ln \left(\frac{\xi_{min}}{\xi_{max}} \right) \approx -0.8$, to the maximum value of $y = \frac{1}{2} \ln \left(\frac{\xi_{max}}{\xi_{min}} \right) \approx 0.8$. Both $\xi_{min} = 0.03$ and $\xi_{max} = 0.15$ are taken from the LHC Run 3 configuration of the PPS detector, present in table 3.6. The two dimensional plots for different charged Higgs masses are present in figure 3.10.

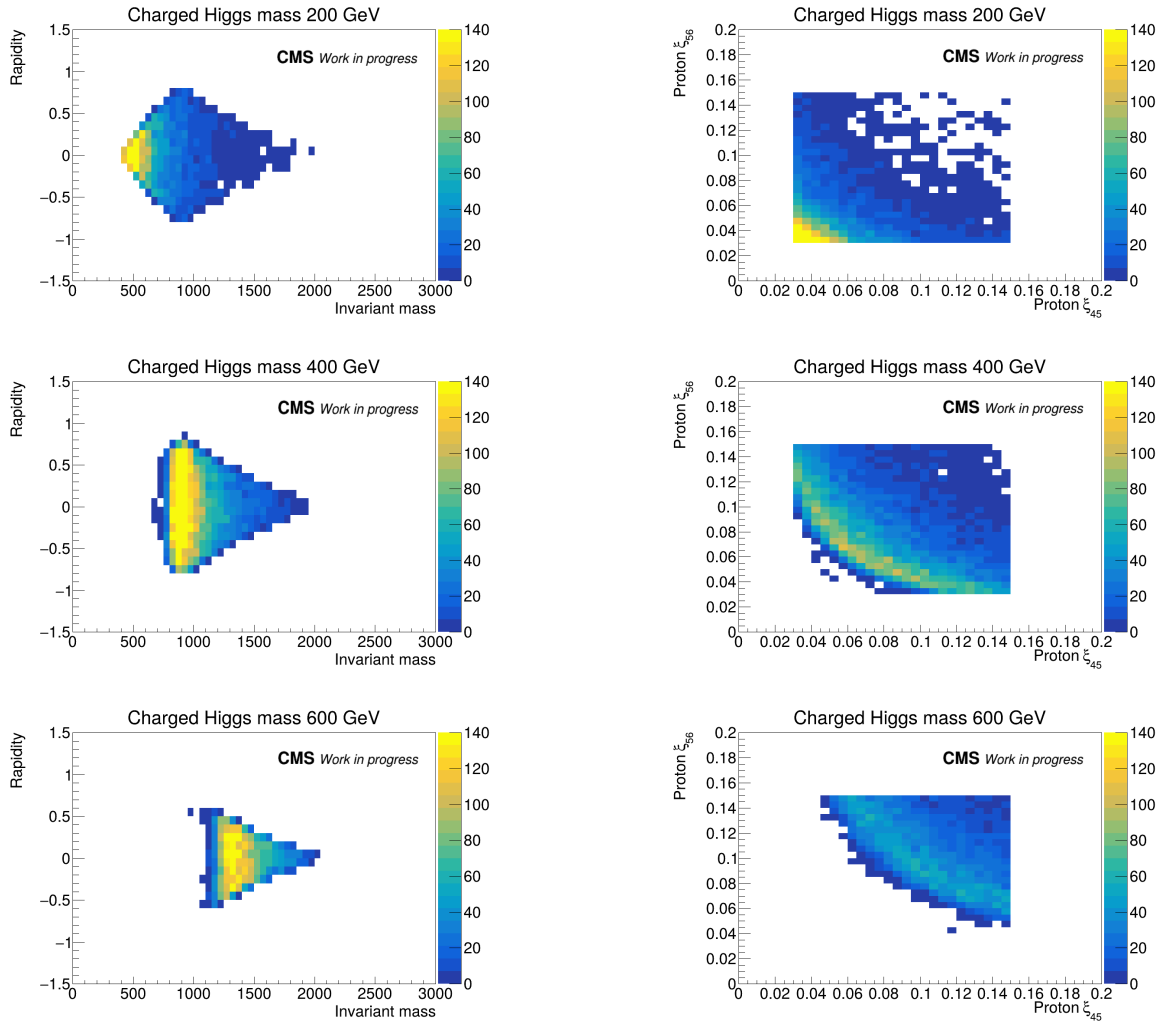


Figure 3.10: Two dimensional histograms of signal MC events detected by the PPS detector in the LHC Run 3 configuration, for the invariant mass versus rapidity of the central system, and for the proton ξ_{45} against proton ξ_{56} , where ξ_{45} corresponds to the ξ of the proton in sector 45, and ξ_{56} to the ξ of the proton in sector 56. Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

From figure 3.10 it is possible to see how signal MC events for different charged Higgs boson masses are distributed inside the acceptance region of the PPS detector in the LHC Run 3 configuration. For a charged Higgs boson mass of 200 GeV , near the minimum of the acceptance region for invariant mass, the PPS detector measures mainly events with symmetrical longitudinal momentum loss of the protons, which is made evident by the plot with both the proton ξ_{45} and ξ_{56} . Regarding the production of a single pair of charged Higgs bosons with mass of 400 GeV , the PPS detector's acceptance region is mostly filled, contrary to what is seen for the other charged Higgs masses, and explains the peaks seen in figures 3.8 and 3.9 at this specific mass. In this case, most of the events are from protons with an asymmetrical longitudinal momentum loss, noticeable by the curved shape of the proton ξ histogram. Lastly, the events for a charged Higgs boson mass of 600 GeV start falling outside the detector's acceptance region, since these approach the maximum detectable invariant mass, and the proton's ξ gets close to the ξ_{max} value. At the maximum invariant mass of the acceptance region, the events detected would again be from protons with a symmetrical longitudinal momentum loss.

Going back to figures 3.8 and 3.9, it can be observed that the decay modes are ordered such that the PPS acceptance is highest for the CSBAR decay mode and lowest for the CBBAR decay mode. The difference in acceptance seen between the decay modes was not expected, as the kinematics should be independent from the decay mode. No reasonable conclusion was achieved and, therefore the observed differences between decay modes were attributed to minor generator level differences, showering effects, and statistical fluctuations.

The same analysis was performed for two specific decay channels of the τ lepton:

1. Muon channel: $\mu + \tau_{hadronic}$, satisfying the condition of a single muon with $P_T > 24 \text{ GeV}$, registered in table 1.5;
2. Electron channel: $e + \tau_{hadronic}$, satisfying the condition of a single electron with $P_T > 30 \text{ GeV}$, registered in table 1.5;

The acceptance of the PPS detector for the τ lepton decay channels in the LHC Run 3 configuration can be seen in figure 3.11 for samples without mean pileup, and in figure 3.12 for samples with pileup included.

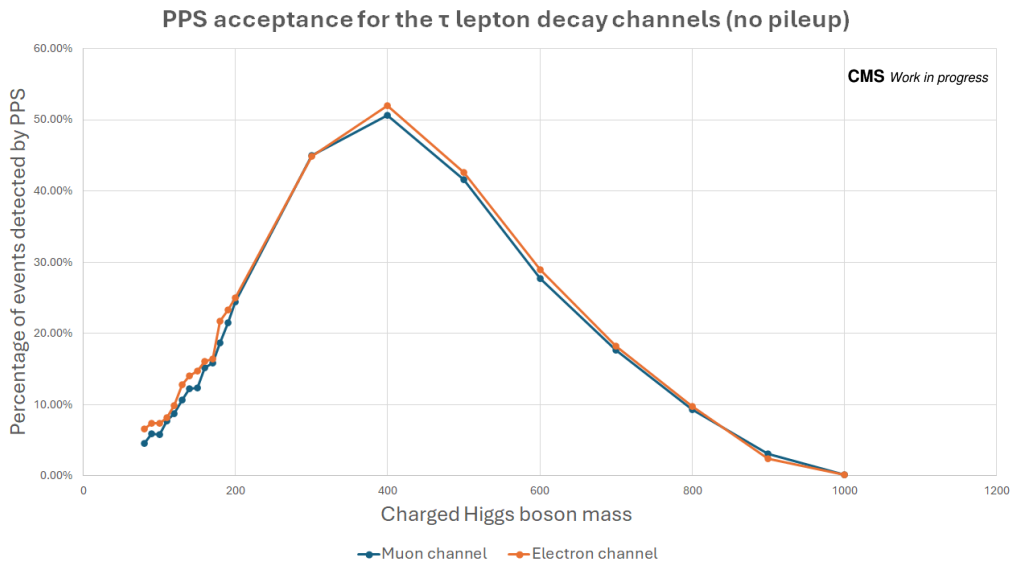


Figure 3.11: Percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) in the LHC Run 3 configuration, without pileup interactions.

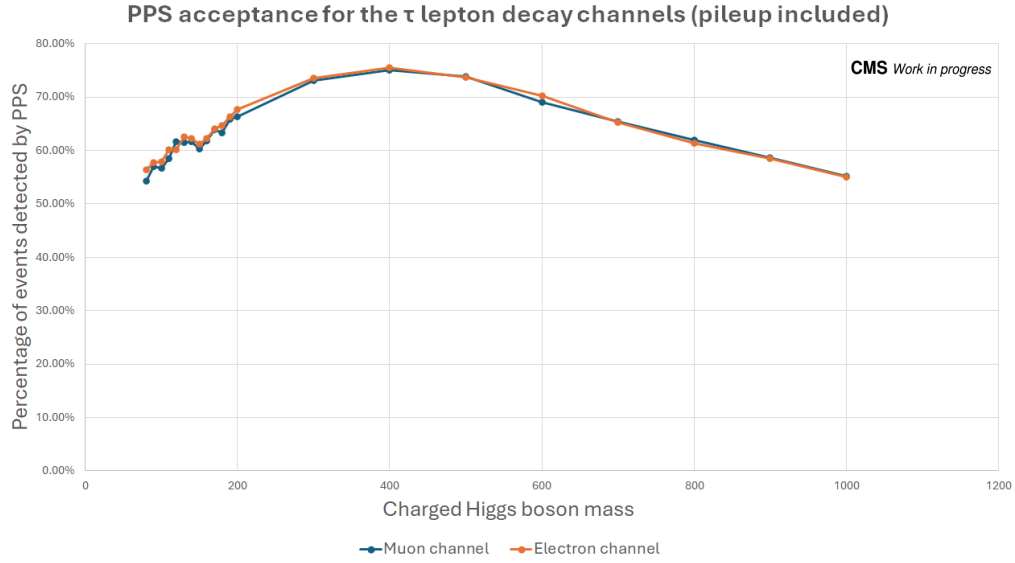


Figure 3.12: Percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) in the LHC Run 3 configuration, with pileup interactions included.

Once again, the extra protons originating from pileup interactions increase the rate of events detected by the PPS detector. However, contrary to the slight difference in acceptance seen between each decay mode, both decay channels of the τ lepton present the same percentage of events detected by the PPS detector, which is expected due to the kinematics being independent from the decay channel. Additionally, it should be noted that the acceptance for each charged Higgs boson mass is lower than what was seen for the TAUNU decay mode. This is because these two channels do not constitute the full TAUNU decay mode.

With this the PPS acceptance study is concluded, and all the events presented in the next sections will include the number of pileup interactions corresponding to the LHC Run 3 configuration, as this is the most close approximation to data collected by the CMS detector.

3.2.3 Event selection and data analysis

The primary challenge of any high energy physics (HEP) study is the separation of signal from background events. Currently, there are two main ways of accomplishing this task, that can be through manual event separation, or using machine learning algorithms. Manually separating events requires a good knowledge of the physics of both signal and background events to be able to identify key observables that provide a good separation. However, defining a good separation can be somewhat tricky, as most times signal and background distributions will have a large overlap. Nonetheless, separations are often quantified by a measure called significance (Z), which expresses how likely it is for the observed signal events to arise from background fluctuations. Significance is given in units of standard deviation (σ), not to be confused with a process's cross section. In the context of HEP studies, there is a convention that defines a significance of 5σ as the threshold for discovery. Significance is defined as follows:

$$Z = \frac{S}{\sqrt{S+B}} , \quad (3.1)$$

where S is the number of expected signal events, and B is the number of expected background events, both after the cut. To summarize, the best cut for signal versus background separation is the one with the highest significance value.

The most common tool for applying machine learning methods in HEP studies is the Toolkit for Multivariate Analysis (TMVA) that is developed and maintained by the ROOT framework team at CERN. TMVA includes machine learning methods that can be divided in two categories:

- supervised: boosted decision tree (BDT), likelihood methods, and multilayer perceptrons;
- unsupervised: clustering algorithms, and principal component analysis (PCA);

These types of methods don't explicitly encode any physics knowledge. However, supervised methods (more commonly used) are fed training sets of already labeled data from Monte Carlo (MC) simulations, while unsupervised methods use unlabeled data and perform clustering based on its similarities.

During this project, some exploration was done regarding the utilization of supervised methods for the analysis (mainly BDTs), but at the end it was decided to continue the analysis by performing manual separation of signal and background events. With this in mind, some histograms were plotted to draw a comparison between signal and background events. The comparison between the $H^+ \rightarrow c\bar{s}$ decay mode and the QCD background is present in figure [3.13](#), using the relevant HLT quantities. Figure [3.14](#) shows the same quantities but for the $H^+ \rightarrow c\bar{b}$ decay mode comparison.

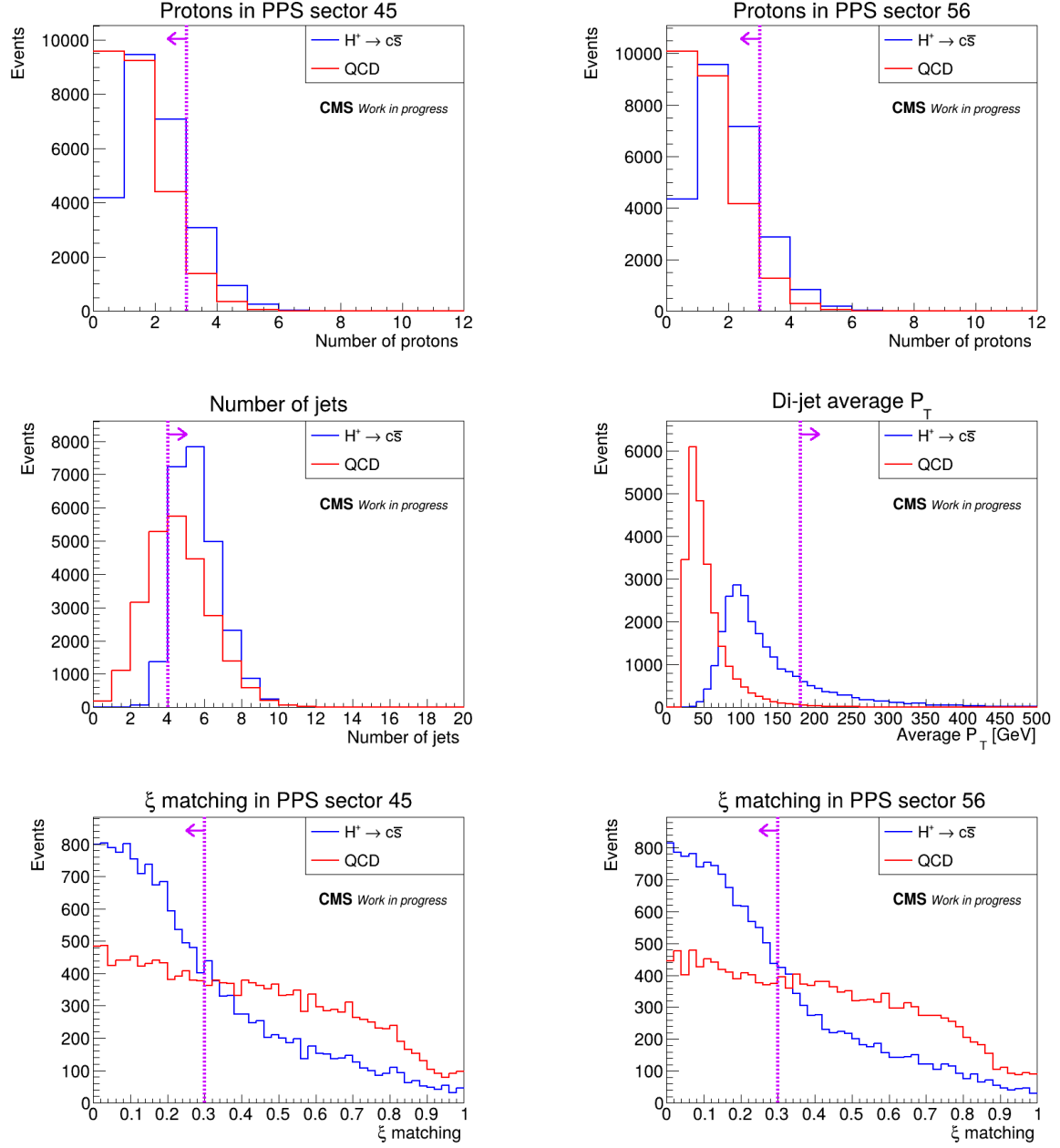


Figure 3.13: Comparison between properties of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, for a charged Higgs boson mass of 200 GeV , and QCD background MC events in the four-jet final state, both in the LHC Run 3 configuration. Histograms were normalized to the area for better visualization. The HLT conditions are displayed by the violet vertical lines.

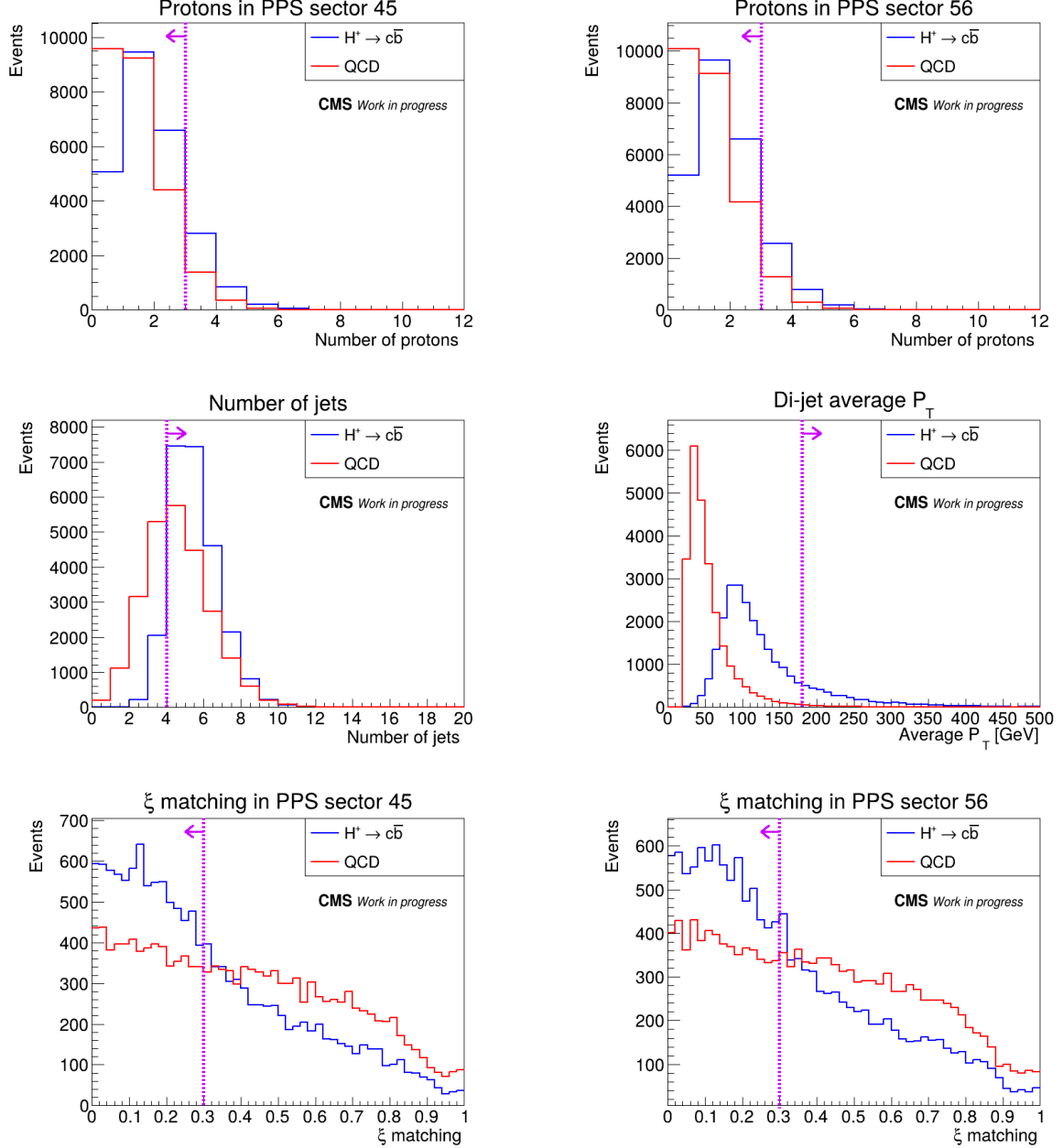


Figure 3.14: Comparison between properties of signal MC events in the $H^+ \rightarrow c\bar{b}$ decay mode, for a charged Higgs boson mass of 200 GeV , and QCD background MC events in the four-jet final state, both in the LHC Run 3 configuration. Histograms were normalized to the area for better visualization. The HLT conditions are displayed by the violet vertical lines.

The objective of figure 3.13 and 3.14 is to analyze the HLT conditions and study their efficiency at selecting signal events. The HLT conditions regarding the selection of events with less than 3 tracks per RP and with more than 4 jets in the final state come naturally, as the HLT was created to study CEP processes with a four-jet final state. From the histograms, it is possible to verify that these conditions are capable of selecting most of the signal events while rejecting areas where the background is dominant. It is also possible to identify that signal events are concentrated in the low ξ matching region, which is not true for background events and corroborates the selection condition for events with values of $\xi_{matching} \leq 0.3$. The remaining HLT condition for events with di-jet average P_T above 180 GeV is harder to explain, as this variable depends on the mass of the charged Higgs boson, which is not known.

However, it can be seen that the background events produce jets in the low P_T region, so this condition is able to provide a good background rejection and signal selection.

At this point, it should be noted that the same analysis and comparison between signal and background events was not performed for the $H^+ \rightarrow \tau^+ \nu_\tau$, since this is a special decay mode of the charged Higgs boson that does not produce a four-jet final state. Usually, studies involving processes with τ leptons in the final state focus on selecting some channels with specific τ decay products and studying them separately, since these processes require a more complex analysis due to the presence of neutrinos. It was precisely for this reason that this decay mode was not studied, as there was no available time for concluding it during this project. However, it would be interesting to study this decay mode in the future, as it has one of the highest cross sections among charged Higgs boson decay modes.

Continuing the study on HLT efficiency at selecting signal events and rejecting background events, the number of events passing each condition were registered in the cutflow table [3.7](#).

Table 3.7: Cutflow table depicting the efficiency of the HLT conditions for both signal and background MC events. Inside the parenthesis are the percentage of events surviving each cut with respect to the previous step, and the percentage of events surviving each cut with respect to the initial number of events, respectively. The events were normalized to their respective number of expected events in the LHC Run 3 configuration (integrated luminosity of 300 fb^{-1}). Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

HLT conditions	$H^+ \rightarrow c\bar{s}$	$H^+ \rightarrow c\bar{b}$	QCD background
Initial number of events	9000	9000	1.52×10^{12}
Number of tracks per RP < 3	6273 (69.70% 69.70%)	6532 (72.58% 72.58%)	1.32×10^{12} (86.84% 86.84%)
Number of jets ≥ 4	5919 (94.36% 65.77%)	5927 (90.74% 65.86%)	8.05×10^{11} (60.86% 52.85%)
Di-jet average $P_T \geq 180 \text{ GeV}$	1122 (18.96% 12.47%)	933 (15.75% 10.38%)	1.18×10^{10} (1.47% 0.78%)
$\xi_{\text{matching}} \leq 0.3$	330 (29.42% 3.67%)	232 (24.87% 2.58%)	3.44×10^8 (2.90% 0.02%)

From the results present in the cutflow table [3.7](#) it is possible to identify the two most limiting cuts as being the di-jet average P_T and the ξ_{matching} requirements. It is important to notice that these requirements are specially limiting for the background events, decreasing their selection rate to only 0.02%.

3.2.4 Statistical sensitivity to exclude the CEP of a single pair of charged Higgs bosons

The final step in this analysis was to calculate the statistical sensitivity to exclude the CEP of a single pair of charged Higgs bosons, but before doing so a decision was made to implement three extra cuts, after the HLT selection, to enhance the rejection of background events. The first cut used the information measured by the timing detectors installed in the PPS detector to determine the vertex z position of the protons, that should closely match the vertex z position of the jets reconstructed from tracks in the CMS central detector. By performing this matching the background rejection is expected to improve, as the protons present in background events are originated from pileup interactions and should be unrelated to the tracks measured by the CMS central detector. The vertex z position of protons is determined by equation [1.10](#). For the vertex z position of the jets reconstructed from tracks in the CMS central detector, Delphes provides multiple vertex z positions corresponding to different multi-jet combinations (Z_{Jets}). We select the vertex associated with the jet system that maximizes the squared sum of the jets' P_T . The matching between both vertex z position of the protons and the jets is defined by:

$$Z_{\text{Matching}} = Z_{\text{PPS}} - Z_{\text{Jets}} . \quad (3.2)$$

Moreover, we took advantage of some known properties of the jets to further improve background

rejection. These properties were the di-jet $\Delta\eta$ and ΔR distributions. In the signal process, it is expected for the charged Higgs bosons to be produced in opposite directions (back-to-back) and in the central region relative to the beam line. To look at these distributions, we took the four highest P_T jets and paired them to build two di-jet systems with similar mass, as they are supposed to be the decay products of each charged Higgs boson. Using the η and ϕ values of each di-jet system, it was possible to determine the $\Delta\eta$ and $\Delta\phi$ between each dijet system. The $\Delta\eta$ distribution between the di-jet systems is useful to determine how central is the production of the single pair of charged Higgs bosons. This quantity is also used to calculate the distance between the di-jet systems in the $\eta - \phi$ plane. This distance is given by:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} , \quad (3.3)$$

and is expected to be $\Delta R \approx \pi$ for the signal process, corresponding to back-to-back production. The three variables used to improve background rejection can be seen in figures 3.15 and 3.16, for the $H^+ \rightarrow c\bar{s}$ and $H^+ \rightarrow c\bar{b}$ decay modes, respectively.

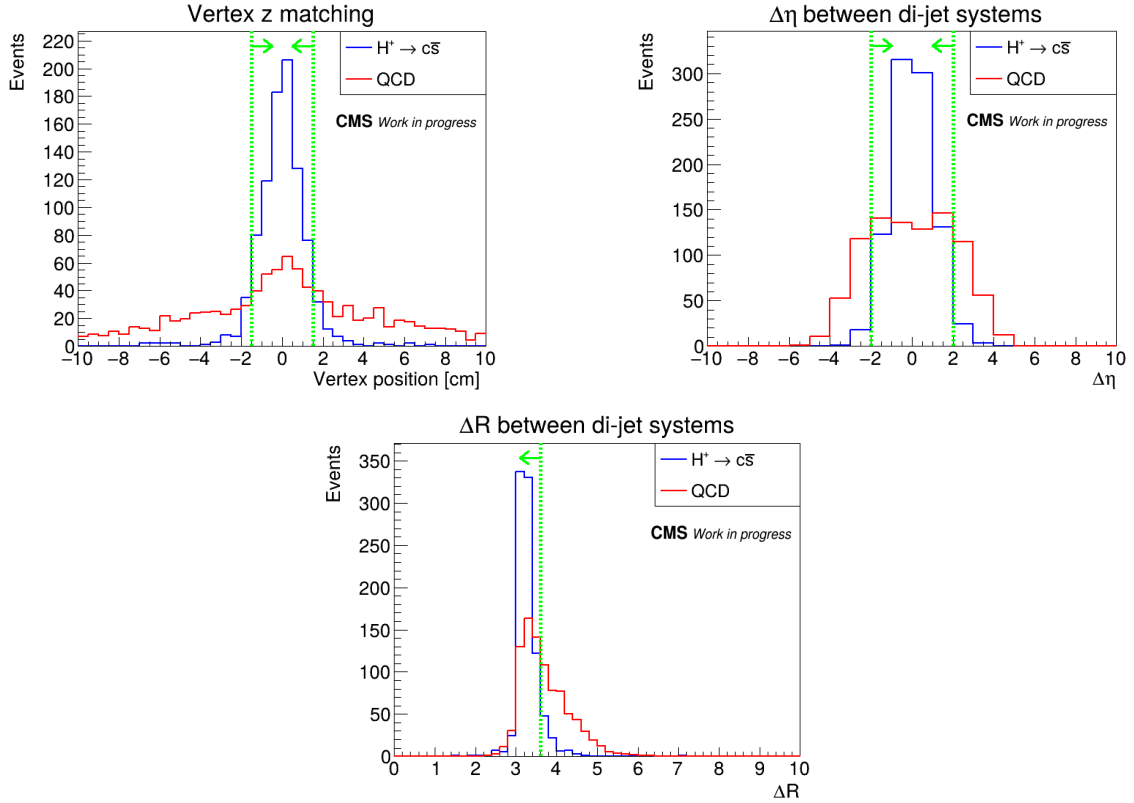


Figure 3.15: Comparison between signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, for a charged Higgs boson mass of 200 GeV , and QCD background MC events in the four-jet final state, after HLT selection cuts, with respect to the three extra variables selected to improve background rejection. Histograms were normalized to the area for better visualization. The extra selection conditions are displayed by the green vertical lines.

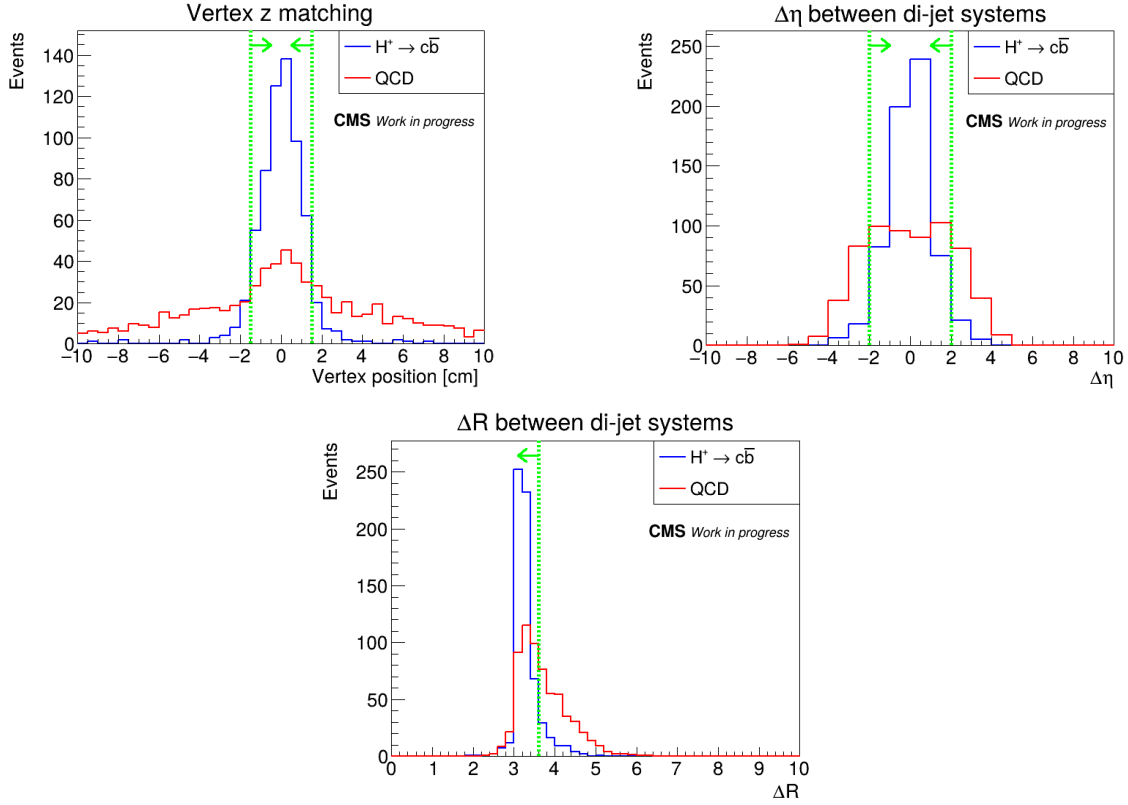


Figure 3.16: Comparison between signal MC events in the $H^+ \rightarrow c\bar{b}$ decay mode, for a charged Higgs boson mass of 200 GeV , and QCD background MC events in the four-jet final state, after HLT selection cuts, with respect to the three extra variables selected to improve background rejection. Histograms were normalized to the area for better visualization. The extra selection conditions are displayed by the green vertical lines.

From the histograms present in figures 3.15 and 3.16, we can observe that there is a much better vertex z matching for signal events than background events. The $\Delta\eta$ distribution also shows that the signal events are concentrated in the central region, and from the ΔR is possible to conclude that most charged Higgs bosons are produced back-to-back. The results from applying the cuts seen in the histograms are registered in the outflow table 3.8.

Table 3.8: Cutflow table depicting the efficiency of the extra selection conditions for both signal and background MC events, after HLT selection. Inside the parenthesis are the percentage of events surviving each cut with respect to the previous step, and the percentage of events surviving each cut with respect to the initial number of events, respectively. The events were normalized to their respective number of expected events in the LHC Run 3 configuration (integrated luminosity of 300 fb^{-1}). Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

Selection conditions	$H^+ \rightarrow c\bar{s}$	$H^+ \rightarrow c\bar{b}$	QCD background
Events after HLT	330	232	3.44×10^8
$-1.5 \leq \text{Vertex } z \text{ matching} \leq 1.5$	285 (86.37% 3.17%)	202 (87.13% 2.25%)	9.31×10^7 (27.06% 0.006%)
$-2 \leq \Delta\eta \text{ between di-jet systems} \leq 2$	242 (95.71% 3.03%)	188 (93.06% 2.09%)	5.19×10^7 (55.79% 0.003%)
$\Delta R \text{ between di-jet systems} \leq 3.4$	221 (81.13% 2.46%)	159 (84.89% 1.78%)	3.31×10^7 (63.67% 0.002%)

Starting from the signal MC events that satisfy all HLT condition, 3.67% for the $H^+ \rightarrow c\bar{s}$ decay mode and 2.58% for the $H^+ \rightarrow c\bar{b}$ decay mode, we can observe that all of the extra selection conditions have an efficiency above 80% with respect to the previous step, indicating that these are able to select most of the signal events, ending up with 2.46% of the initial events for the $H^+ \rightarrow c\bar{s}$ decay mode and with 1.78% of the initial events for the $H^+ \rightarrow c\bar{b}$ decay mode. Regarding the QCD background MC events, the vertex z position matching condition is the most restrictive, with only a 27.06% step

efficiency. Including the other two conditions, both with a step efficiency of around 60%, we are left with 0.002% of the initial background events, which is one order of magnitude smaller than the number of events that surviving the HLT cuts.

The last step before determining the statistical sensitivity to observe or exclude the signal events was to identify a discriminant variable to use as input for the Combine tool. The combine tool was used to probe the significance of several variables, where the invariant mass of the di-jet system, registered in figure 3.17, achieve the highest value of them, and was determined to be the most discriminant.

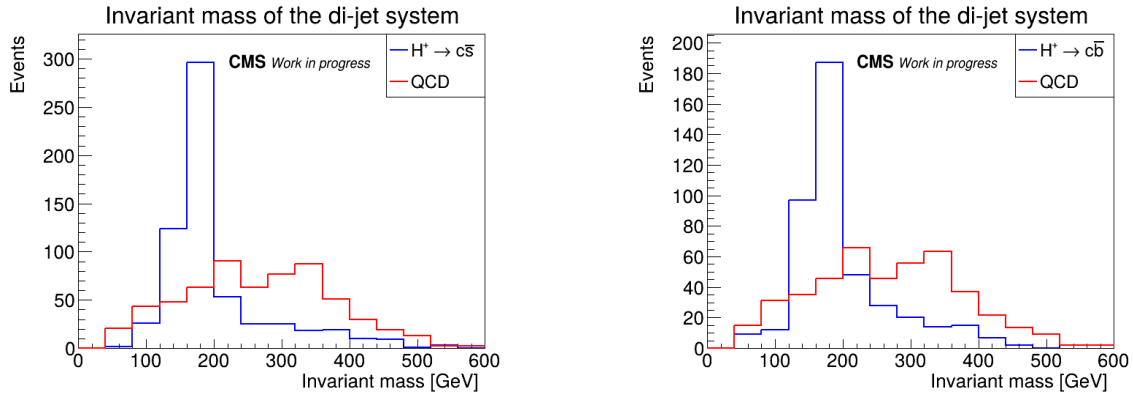


Figure 3.17: Comparison of the invariant mass of the di-jet system between signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode on the left, and in the $H^+ \rightarrow c\bar{b}$ decay mode on the right, both for a charged Higgs boson mass of 200 GeV, and QCD background MC events in the four-jet final state, after HLT and extra selection cuts. Histograms were normalized to the area for better visualization.

Here it possible to see the much higher peak present for both signal events, when compared to the background distribution. The peak's shape and position also changes according to the mass of the charged Higgs boson, which is a source of difficulty since this its mass is not known.

Afterwards, to determine the statistical sensitivity, the number of signal and background events were normalized with respect to their cross section:

$$w = \frac{N_{Expected}}{N_{Simulated}} = \frac{\sigma \times L}{N_{Simulated}} , \quad (3.4)$$

where w is the weight attributed to each event, $N_{Expected}$ is the number of events expected during LHC Run 3, $N_{Simulated}$ is the number of events simulated, σ is the process's cross section times the branching ratio for the specific decay mode in fb , and L is the integrated luminosity of 300 fb^{-1} for LHC Run 3. Nonetheless, the analysis was designed to be model independent, meaning the signal MC events could be normalized to any cross section value and wouldn't affect the statistical sensitivity calculation. For this reason, a cross section of 30 fb was assumed for the signal MC events.

Moreover, to calculate the statistical sensitivity, it is possible to use a sample of observed backgrounds events in the Combine tool, which was not available at the time of this study. Therefore, this calculation was performed for the background-only hypothesis, where the Combine tool uses Asimov models to fit the expected background distribution. A systematic uncertainty of 10% on the luminosity measurement was also considered to determine the statistical sensitivity to exclude the signal process. The expected 95% confidence level (CL) upper limits for each of the decay modes can be seen in figure 3.18.

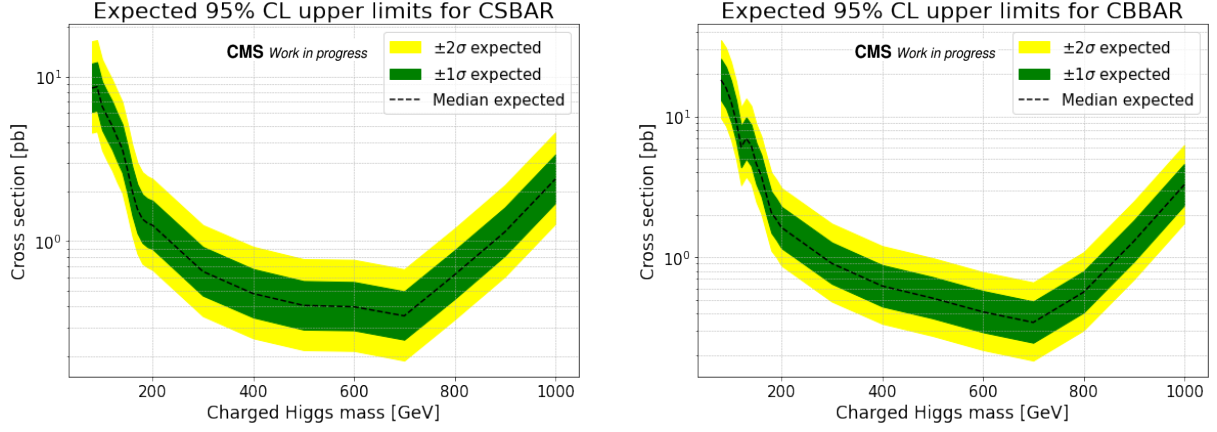


Figure 3.18: Statistical sensitivity of the analysis to exclude the CEP of a single pair of charged Higgs bosons, for signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode (CSBAR) on the left, and in the $H^+ \rightarrow c\bar{b}$ decay mode (CBBAR) on the right. The events were normalized to their respective number of expected events in the LHC Run 3 configuration (integrated luminosity of 300 fb^{-1}).

The plots present in figure 3.18 indicate that, in the absence of any signal observation, cross sections above the limit curve can be excluded. It is also possible to see that the expected 95% confidence level upper limits for the $H^+ \rightarrow c\bar{s}$ decay mode are lower than those for the $H^+ \rightarrow c\bar{b}$ decay mode.

3.3 Projections for HL-LHC

The high luminosity upgrade for the LHC aims at achieving a center-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$, and also increase the integrated luminosity up to 3000 fb^{-1} , which consequently increases the number of pileup interactions to around 200 per bunch crossing. However, at the time of this study, there was no minimum bias pileup file available for a center-of-mass energy of $\sqrt{s} = 14 \text{ TeV}$. Therefore, to conduct this study, we decided to use a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, which is currently present in the LHC Run 3 configuration. Moreover, there is a planned update to the PPS detector configuration [56], to increase its acceptance region and take advantage of the higher integrated luminosity in the HL-LHC. The results presented in the next sections include the HL-LHC planned configuration for the PPS detector, which is registered in table 3.9.

Table 3.9: Planned configuration of the PPS detector during HL-LHC operation. The time resolution is given in nanoseconds. The ξ resolution is a percentage relative to the ξ value (0.05×0.0095 at the minimum, and 0.05×0.1967 at the maximum). The ξ minimum and maximum correspond to the percentage of proton longitudinal momentum loss.

Parameter	Value
ξ resolution	0.05 %
ξ minimum	0.0095
ξ maximum	0.1967
Time resolution	0.02 ns

Despite using the current center-of-mass energy of the LHC run 3 configuration, this study may reveal to be important in the future, since there is the possibility that the HL-LHC won't raise the center-of-mass energy to $\sqrt{s} = 14 \text{ TeV}$, and stay at $\sqrt{s} = 13.6 \text{ TeV}$. With this, we will study how both the planned PPS configuration and the increased number of pileup interactions affect the event analysis, and possibly identify improvements to the current HLT.

3.3.1 The impact of pileup

The mean pileup expected during HL-LHC operation is about 200 extra proton-proton collisions per bunch crossing, which is nearly three times higher than that seen for the LHC Run 3 configuration. As explained earlier, pileup interactions introduce protons and jets that are not related to the signal process. Therefore, the higher mean pileup value is expected to have a similar impact to that seen in the LHC Run 3 configuration, but this time with even more protons and jets, and consequently a worse ξ matching result. The comparison between runs with no mean pileup and with mean pileup of 200 were registered in figures 3.19, 3.20, and 3.21, for the $H^+ \rightarrow c\bar{s}$ decay mode, $H^+ \rightarrow \tau^+\nu_\tau$ decay mode, and QCD background events, respectively.

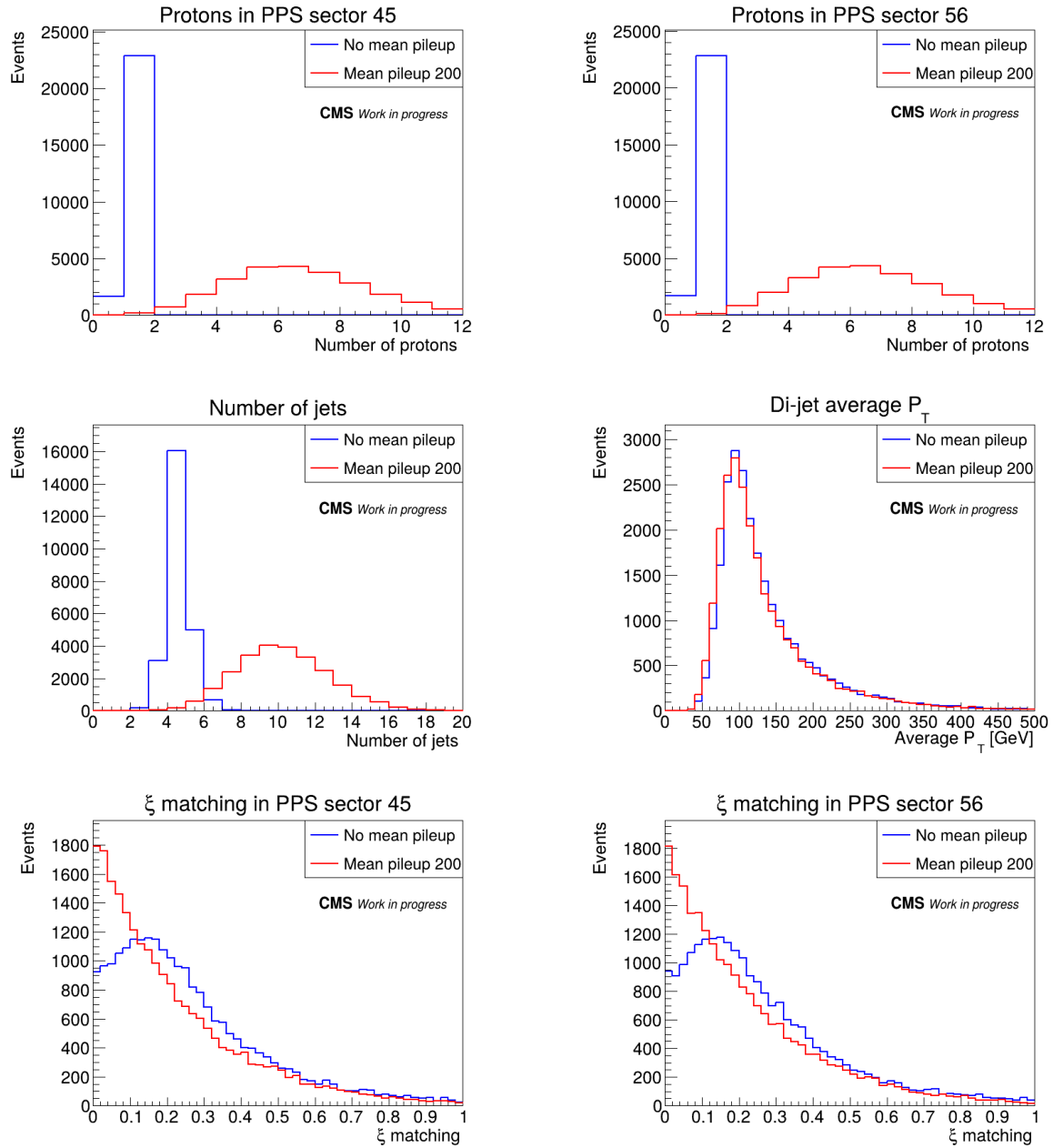


Figure 3.19: Comparison between properties of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, for a charged Higgs boson mass of 200 GeV, with a mean pileup of 200, and with no mean pileup, both in the planned PPS configuration for the HL-LHC. Histograms were normalized to the area for better visualization.

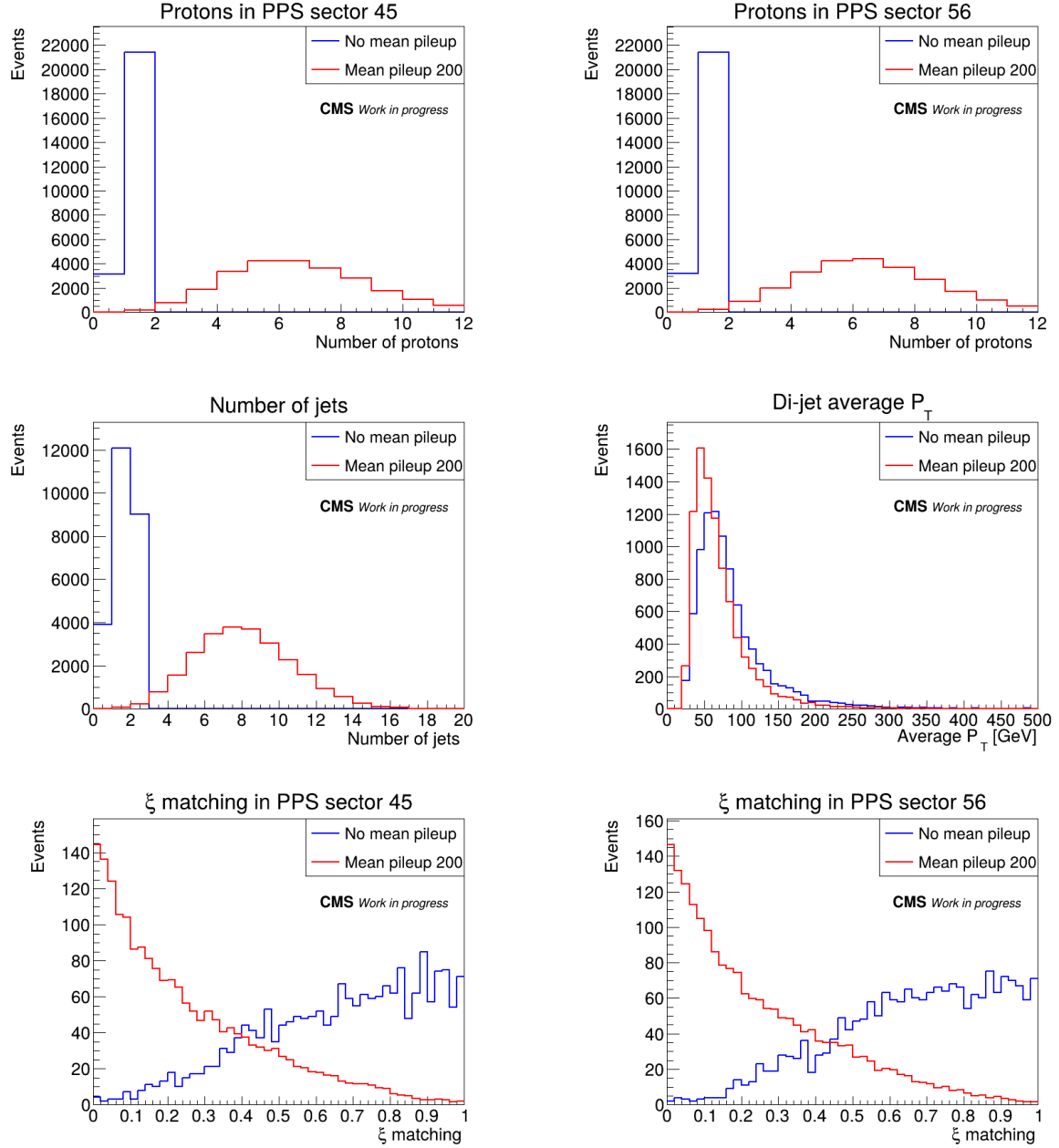


Figure 3.20: Comparison between properties of signal MC events in the $H^+ \rightarrow \tau^+ \nu_\tau$ decay mode, for a charged Higgs boson mass of 200 GeV, with a mean pileup of 200, and with no mean pileup, both in the planned PPS configuration for the HL-LHC. Histograms were normalized to the area for better visualization.

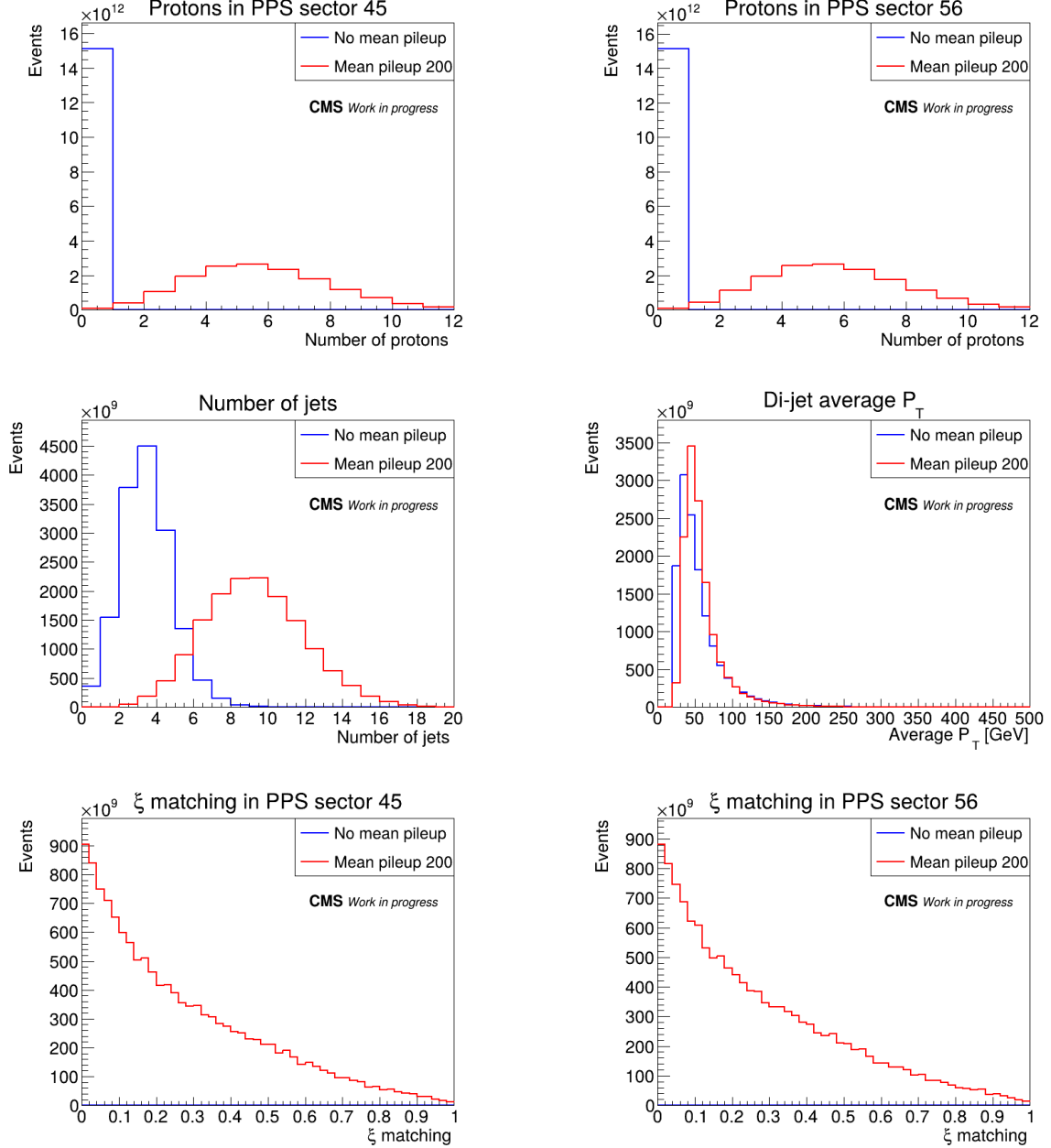


Figure 3.21: Comparison between properties of QCD background MC events in the four-jet final state with a mean pileup of 200, and with no mean pileup, both in the planned PPS configuration for the HL-LHC. Histograms were normalized to the area for better visualization.

The comparisons present in figures 3.19, 3.20, and 3.21 show similar results as the ones observed in the LHC Run 3 configuration, registered in figures 3.5, 3.6, and 3.7. Some notable differences include the number of protons peaking at around 7 in each PPS sector and the number of jets peaking at around 9 per event. Similarly to LHC Run 3, the di-jet average P_T remains unaltered for the $H^+ \rightarrow c\bar{s}$ decay mode, and also presents a shift to lower P_T values for the $H^+ \rightarrow \tau^+\nu_\tau$ decay mode. However, there is now a slight shift to higher di-jet average P_T values for the QCD background MC events. A challenging impact of pileup can be seen in the ξ matching distributions, where due to the much higher number of protons per event, there is a bigger chance of matching pileup protons with the four-jet system, resulting in ξ matching values much closer to zero. The peak seen for signal MC events without pileup around $\xi_{\text{Matching}} = 0.2$, is explained by this matching being relative to the ξ of the four-jet system and gives insight about the efficiency of this jet selection. It also reveals that some energy is lost in the reconstruction

process of the jets, since the four-jet system is not able to fully reconstruct the ξ of the signal protons.

3.3.2 PPS Acceptance

With the planned configuration for the PPS detector, listed in table 3.9, it is particularly relevant to study the detector's performance in the new scenario of increased pileup, expected during the HL-LHC operation. This study is performed by looking at the number of events with at least one track in each RP, meaning that the event is detected on both sectors of the PPS detector. This was done for each decay mode using samples without mean pileup, present in figure 3.22, and using samples with the amount of mean pileup expected for the HL-LHC, registered in figure 3.23

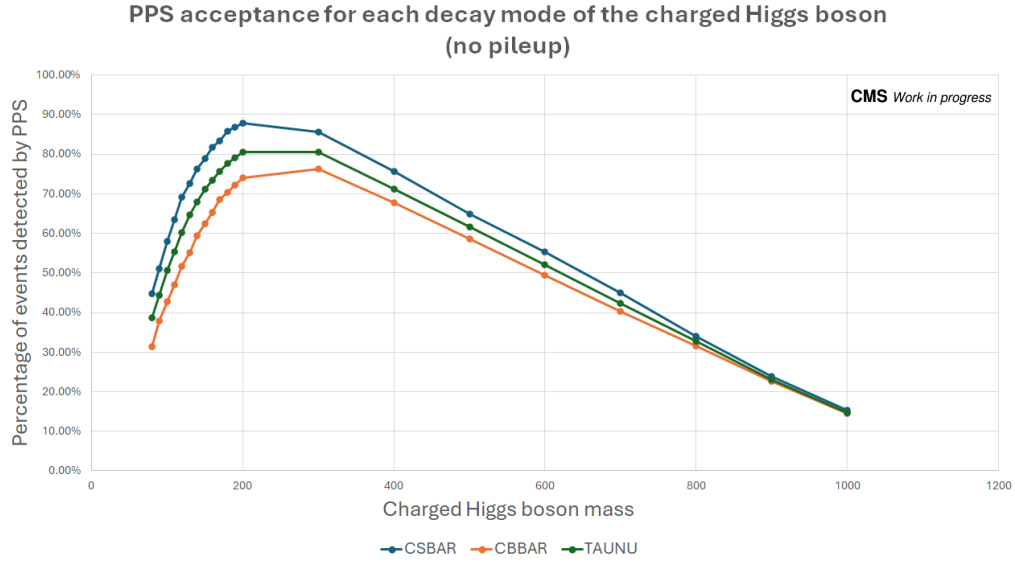


Figure 3.22: Percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) in the HL-LHC configuration, without pileup interactions, and with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. Each decay mode is labeled as follows: CSBAR for $H^+ \rightarrow c\bar{s}$, CBBAR for $H^+ \rightarrow c\bar{b}$, and TAUNU for $H^+ \rightarrow \tau^+\nu_\tau$.

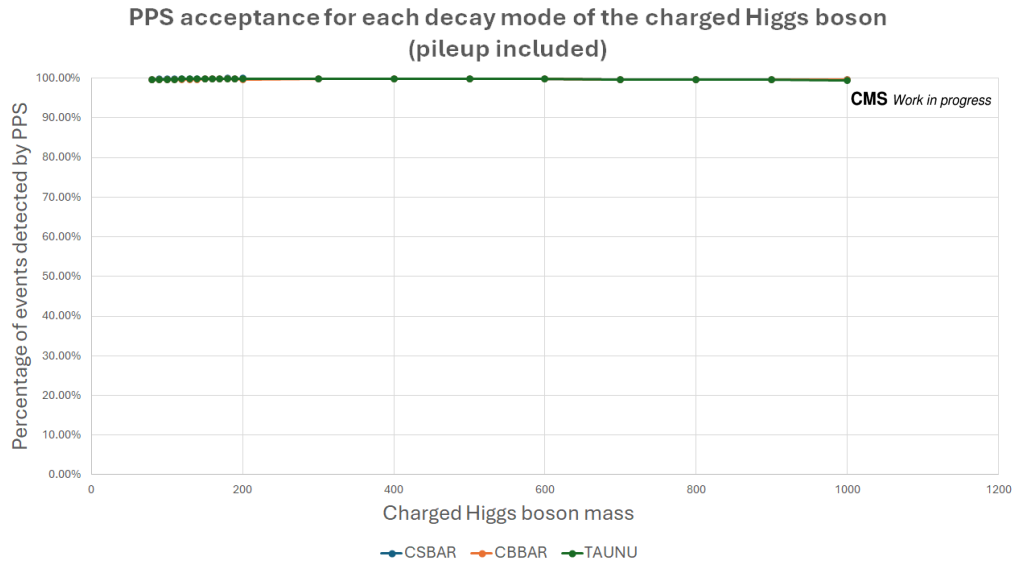


Figure 3.23: Percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) in the HL-LHC configuration, with pileup interactions included, and with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. Each decay mode is labeled as follows: CSBAR for $H^+ \rightarrow c\bar{s}$, CBBAR for $H^+ \rightarrow c\bar{b}$, and TAUNU for $H^+ \rightarrow \tau^+\nu_\tau$.

Starting by analysing the PPS acceptance in the HL-LHC configuration for each decay mode without mean pileup, figure 3.22, it is possible to see how the percentage of events detected by the PPS detector peaks around a charged Higgs boson mass of 200 GeV , and also that the three decay modes appear to be ordered such that the $H^+ \rightarrow c\bar{s}$ has the highest PPS acceptance, and the $H^+ \rightarrow c\bar{b}$ decay mode has the lowest. The ordering seen for the decay modes is not expected, and these results were attributed to statistical fluctuations between MC simulations, since the kinematics should be independent from the decay mode. When looking at the PPS acceptance for the samples including pileup, it can be seen how there is an acceptance rate of around 100% for every decay mode, which can be explained by the much higher mean pileup value, that inevitably produces protons at small scattering angles that are inside the PPS detector ξ range. To explain the shape of the curves present in figure 3.22, for the PPS acceptance of samples without pileup, we must look at how the events for each charged Higgs boson mass are distributed inside the acceptance region of the PPS detector in the HL-LHC configuration. First, we must determine the invariant mass and rapidity range for the HL-LHC configuration of the PPS detector, using $\xi_{min} = 0.0095$, and $\xi_{max} = 0.1967$, registered in table 3.9, together with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. For the invariant mass of the central system, we obtain a minimum value of $M_X = \sqrt{\xi_{min} \cdot \xi_{min}} \times 13600 \approx 130 \text{ GeV}$, and a maximum value of $M_X = \sqrt{\xi_{max} \cdot \xi_{max}} \times 13600 \approx 2700 \text{ GeV}$. Similarly, for the rapidity of the central system we obtain a minimum value of $y = \frac{1}{2} \ln \left(\frac{\xi_{min}}{\xi_{max}} \right) \approx -1.5$, and a maximum value of $y = \frac{1}{2} \ln \left(\frac{\xi_{max}}{\xi_{min}} \right) \approx 1.5$. The relevant two dimensional histograms for visualization of the PPS detector's acceptance region are present in figure 3.24

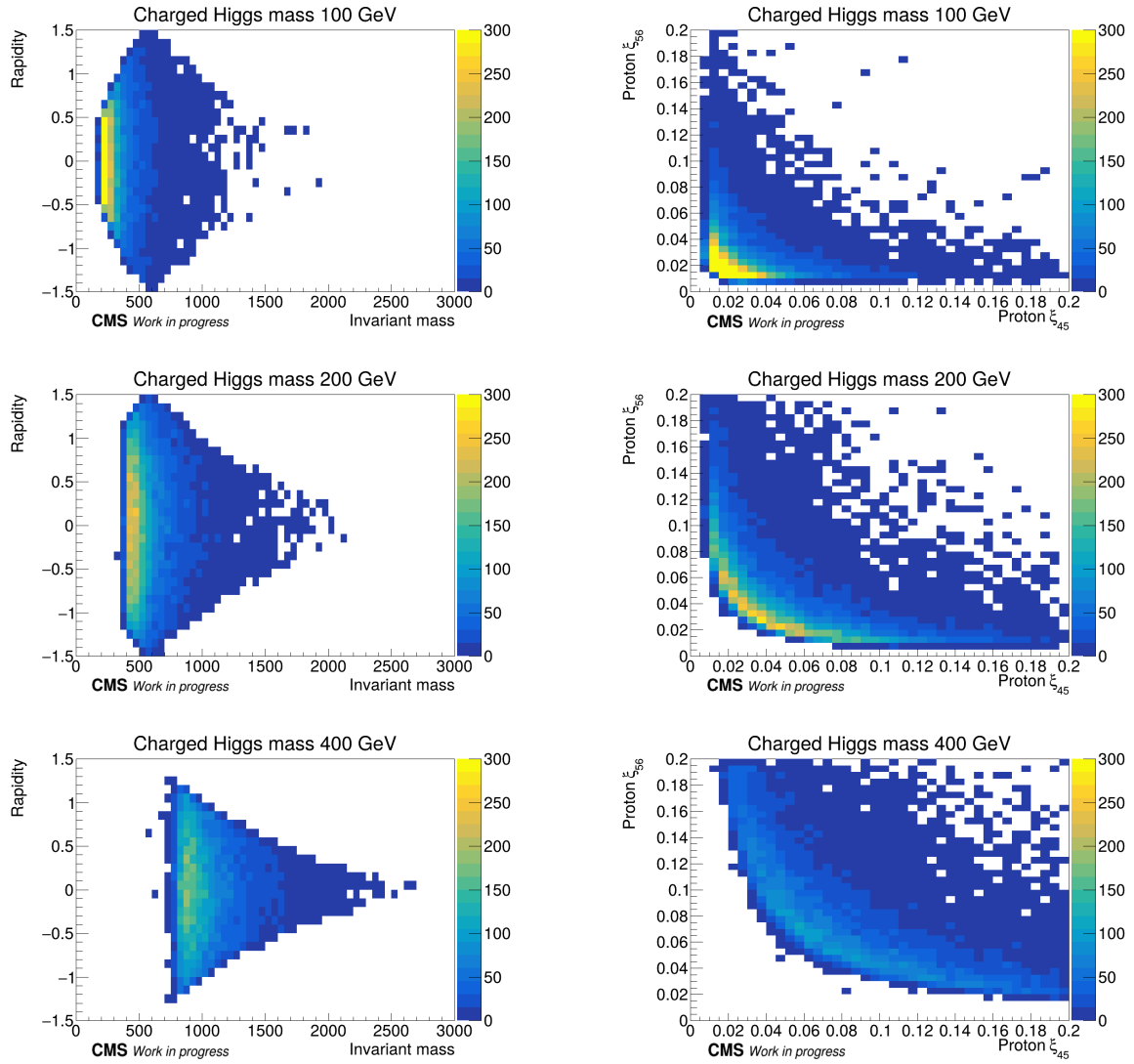


Figure 3.24: Two dimensional histograms of signal MC events detected by the PPS detector in the HL-LHC Run 3 configuration with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, for the invariant mass versus rapidity of the central system, and for the proton ξ_{45} against proton ξ_{56} , where ξ_{45} corresponds to the ξ of the proton in sector 45, and ξ_{56} to the ξ of the proton in sector 56. Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

From figure 3.24 it is possible to see how signal MC events for different charged Higgs boson masses are distributed inside the acceptance region of the PPS detector in the HL-LHC configuration, with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. The events detected by the PPS detector for a charged Higgs boson mass of 100 GeV are near the minimum of the acceptance region for invariant mass of the central system, and correspond to events where the protons lose a symmetrical amount of longitudinal momentum, visible from the histogram with the proton's ξ in each sector. The events with a charged Higgs bosons mass of 200 GeV fill the majority of the PPS detector's acceptance region, explaining the peak in acceptance seen in figure 3.22 around a mass of 200 GeV . When looking at the proton's ξ in each sector for this same charged Higgs boson mass, it is possible to see that there is a large number of events where the protons lose an asymmetrical amount of longitudinal momentum, noticeable by the curved shape of the histogram. Lastly, the events with a charged Higgs boson mass of 400 GeV start approaching the maximum of the detector's acceptance region, leading to a lower percentage of events

detected by the PPS detector. At the maximum invariant mass of the acceptance region, the events detected are expected to include protons with a symmetrical longitudinal momentum loss, similarly to what is seen at the minimum of the acceptance region.

The same analysis was then conducted for two decay channels of the τ lepton in the $H^+ \rightarrow \tau^+ \nu_\tau$ decay mode scenario, according to the conditions defined in table 1.5. The acceptance of the PPS detector for the τ lepton decay channels in the HL-LHC configuration, using a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, are presented in figure 3.25, for events without mean pileup, and in figure 3.26 for events with pileup included.

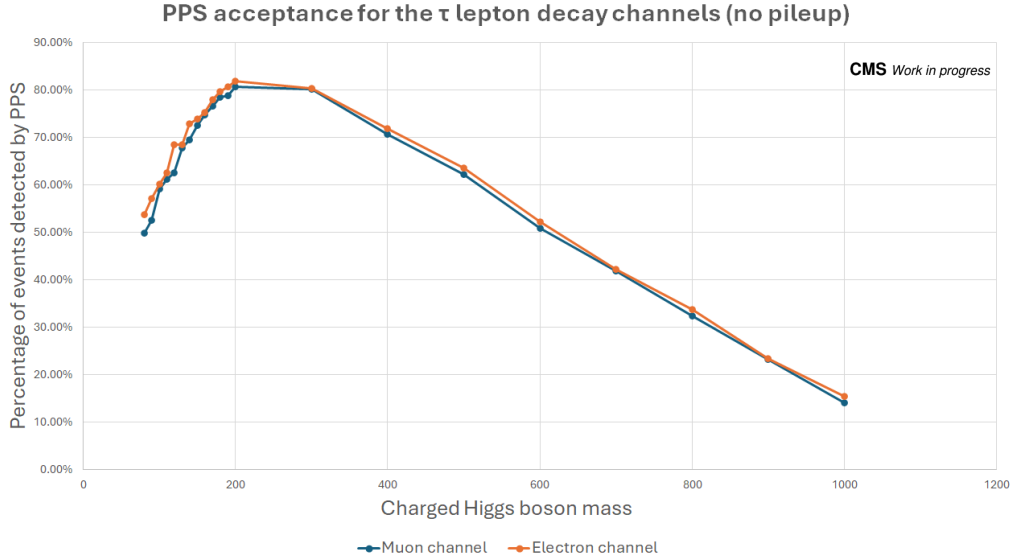


Figure 3.25: Percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) in the HL-LHC configuration, using a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, without pileup interactions.

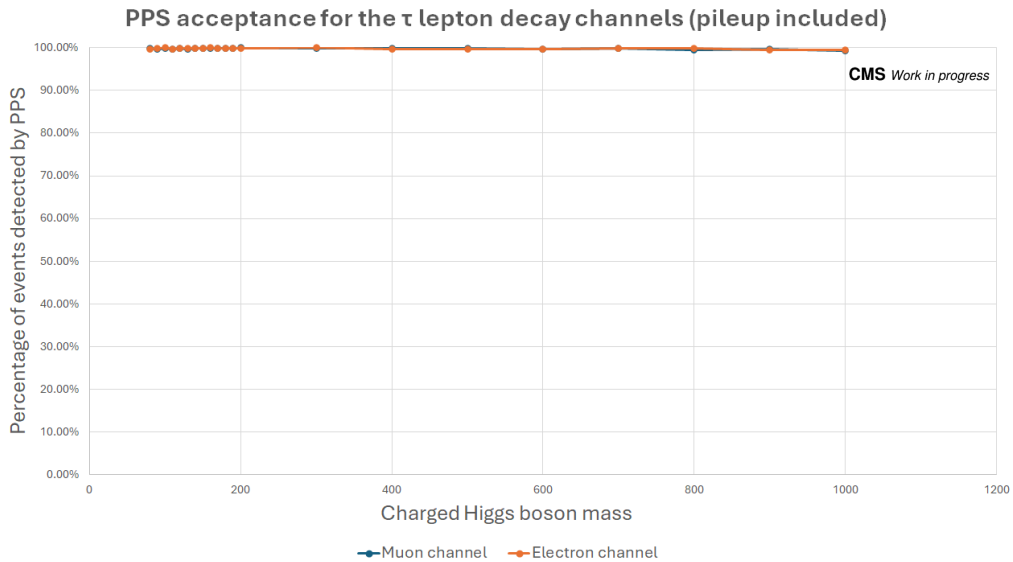


Figure 3.26: Percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) in the HL-LHC configuration, using a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, with pileup interactions included.

From figure 3.25, the same peak for the PPS acceptance at around a mass of 200 GeV can be observed. Moreover, both decay channels have similar acceptance, which makes sense since this result should only be dependent on the kinematics of the process, not on the decay mode. When looking at figure 3.26, the results are similar to those seen previously for each decay mode, where both decay channels reach near 100% acceptance due to the higher number of protons from pileup. Unfortunately, due to time constraints the analysis of the $H^+ \rightarrow \tau^+ \nu_\tau$ was not continued, being this the final result presented regarding this decay mode for the HL-LHC configuration.

This concludes the PPS acceptance study, and the events utilized for the rest of the analysis will all include the amount of mean pileup corresponding to the HL-LHC expected value of 200.

3.3.3 Event selection and data analysis

Similarly to the previous section regarding the LHC Run 3 configuration, the relevant HLT variables were plotted to compare the signal and background MC events. From the results obtained in section 3.3.1, it was predictable that some modifications would be required for the HLT conditions to account for the impact of the increased number of mean pileup interactions. Therefore, the following histograms will include both the standard HLT conditions, represented by a violet line, and the modified HLT conditions, represented by a green line. The comparison was performed for the $H^+ \rightarrow c\bar{s}$ decay mode, presented in figure 3.27, and for the $H^+ \rightarrow c\bar{b}$ decay mode, displayed in figure 3.28.

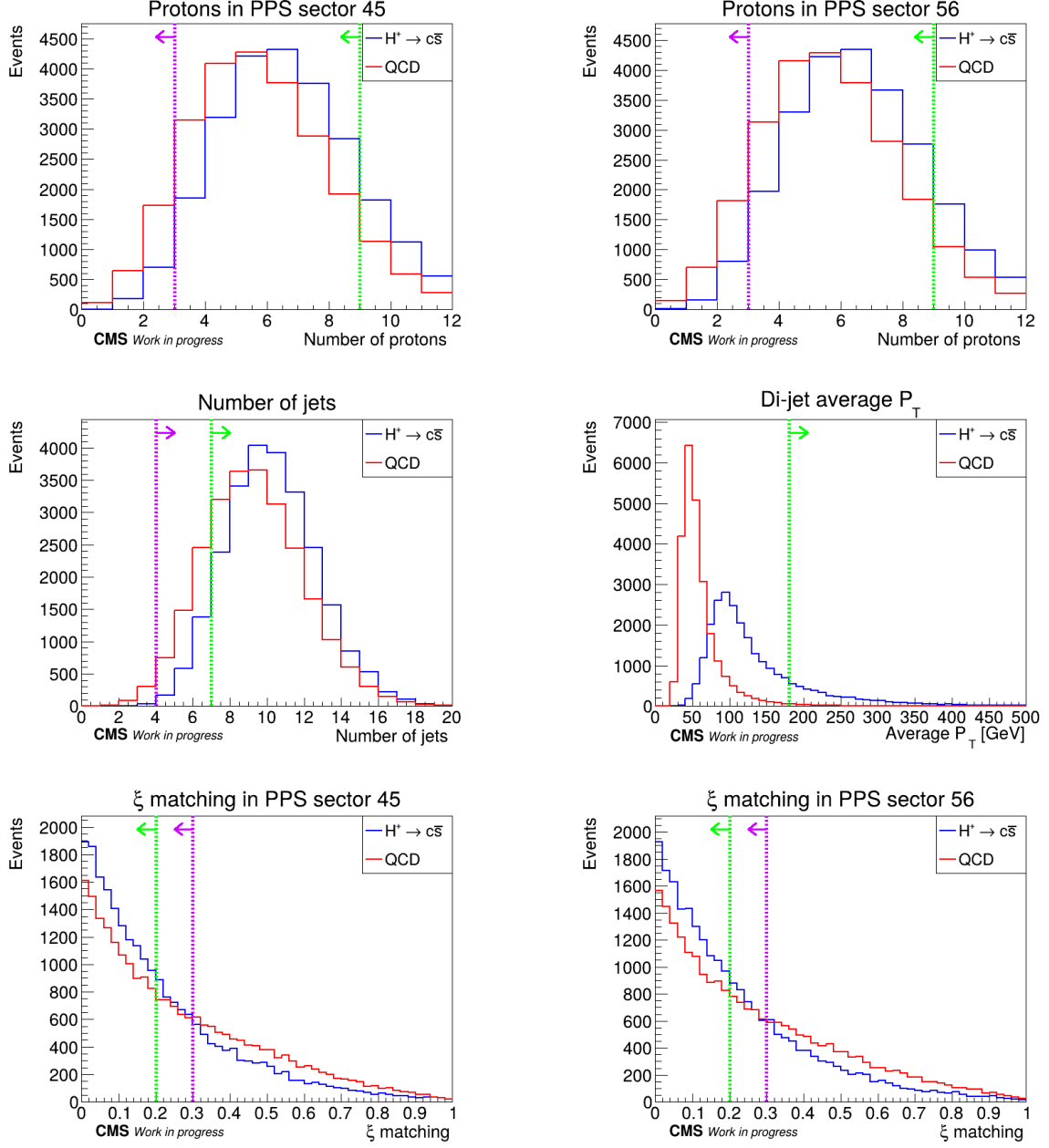


Figure 3.27: Comparison between properties of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, for a charged Higgs boson mass of 200 GeV , and QCD background MC events in the four-jet final state, both in the HL-LHC configuration, with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. Histograms were normalized to the area for better visualization. The HLT conditions are displayed by the violet vertical lines, and the modified HLT conditions by the green vertical lines.

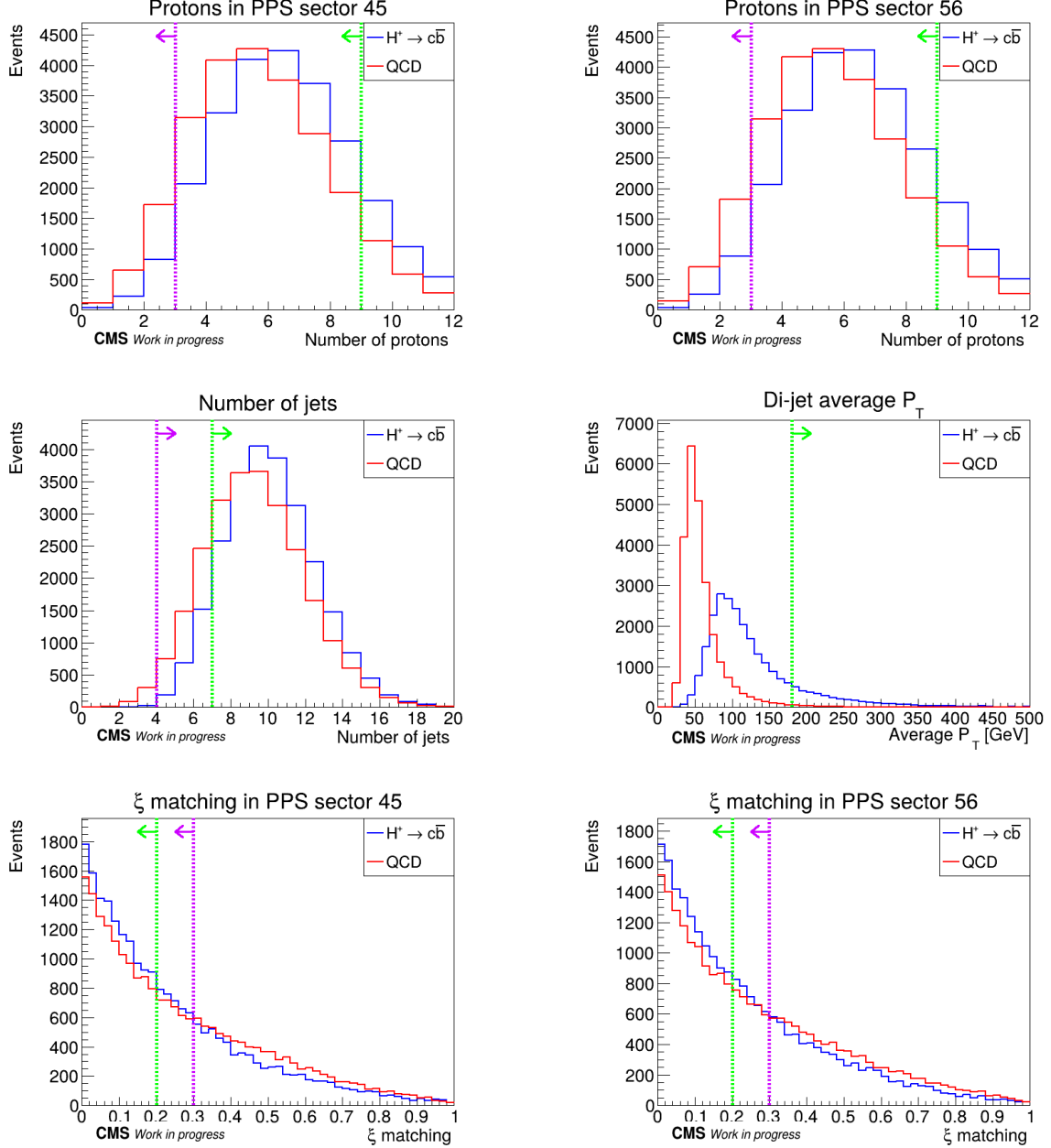


Figure 3.28: Comparison between properties of signal MC events in the $H^+ \rightarrow c\bar{b}$ decay mode, for a charged Higgs boson mass of 200 GeV , and QCD background MC events in the four-jet final state, both in the HL-LHC configuration, with a center-of-mass energy of $\sqrt{s} = 13.6\text{ TeV}$. Histograms were normalized to the area for better visualization. The HLT conditions are displayed by the violet vertical lines, and the modified HLT conditions by the green vertical lines.

Starting with the standard HLT conditions, it can be observed how the condition imposed on the number of protons per RP is very restrictive for the events in the HL-LHC configuration, since the increased number of mean pileup interactions leave few events with less than three protons in each PPS sector. The conditions on the number of jets and on the ξ matching are weak at rejecting background events, as almost every event has more than four jets, because there are more matchings between the pileup protons and the jets reconstructed from tracks in the CMS central detector. Despite the small shift caused by the pileup interactions for the di-jet average P_T distribution, seen in section 3.3.1, this was the only variable that didn't require any modification in the corresponding HLT condition. The results of applying the standard HLT conditions were registered in table 3.10.

Table 3.10: Cutflow table depicting the efficiency of the standard HLT conditions for both signal and background MC events. Inside the parenthesis are the percentage of events surviving each cut with respect to the previous step, and the percentage of events surviving each cut with respect to the initial number of events, respectively. The events were normalized to their respective number of expected events in the HL-LHC configuration (integrated luminosity of 3000 fb^{-1}), with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

Standard HLT conditions	$H^+ \rightarrow c\bar{s}$	$H^+ \rightarrow c\bar{b}$	QCD background
Initial number of events	90000	90000	1.52×10^{13}
Number of tracks per RP < 3	190 (0.21% 0.21%)	237 (0.26% 0.264%)	1.89×10^{11} (1.25% 1.247%)
Number of jets ≥ 4	190 (100.00% 0.21%)	237 (100.00% 0.264%)	1.88×10^{11} (98.98% 1.234%)
Di-jet average $P_T \geq 180 \text{ GeV}$	32 (16.98% 0.04%)	32 (13.64% 0.036%)	1.86×10^9 (0.99% 0.012%)
$\xi_{\text{matching}} \leq 0.3$	18 (55.56% 0.02%)	3 (11.11% 0.004%)	1.33×10^8 (7.18% 0.001%)

These results demonstrate the restrictiveness of the condition on the number of protons per RP, with only around 0.20% of signal MC events satisfying the condition. The most important conclusion from table 3.10 is that the standard HLT conditions are not optimal, since they greatly diminish the selection rate of signal events. Therefore, a significance study was performed for each of the selection conditions with the aim of improving both signal selection and background rejection. From this study, the best selection conditions were identified and are represented as green lines in figures 3.27 and 3.28. The new set of conditions was designated as modified HLT conditions, and their efficiency is shown in table 3.11.

Table 3.11: Cutflow table depicting the efficiency of the modified HLT conditions for both signal and background MC events. Inside the parenthesis are the percentage of events surviving each cut with respect to the previous step, and the percentage of events surviving each cut with respect to the initial number of events, respectively. The events were normalized to their respective number of expected events in the HL-LHC configuration (integrated luminosity of 3000 fb^{-1}), with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

Modified HLT conditions	$H^+ \rightarrow c\bar{s}$	$H^+ \rightarrow c\bar{b}$	QCD background
Initial number of events	90000	90000	1.52×10^{13}
Number of tracks per RP < 9	64702 (71.89% 71.89%)	65462 (72.74% 72.74%)	1.28×10^{13} (83.78% 83.78%)
Number of jets ≥ 7	58950 (91.11% 65.50%)	58953 (90.06% 65.50%)	1.02×10^{13} (79.56% 66.66%)
Di-jet average $P_T \geq 180 \text{ GeV}$	11116 (18.86% 12.35%)	9331 (15.83% 10.37%)	1.13×10^{11} (1.11% 0.74%)
$\xi_{\text{matching}} \leq 0.2$	4384 (39.44% 4.87%)	3078 (32.99% 3.42%)	2.11×10^{10} (18.63% 0.14%)

From the cutflow table 3.11, it is possible to observe that the new set of conditions is more efficient at selecting signal and rejecting background events than the standard HLT conditions. The modified HLT conditions are able to successfully select 4.87% of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, and 3.42% of signal MC events in the $H^+ \rightarrow c\bar{b}$ decay mode. Moreover, there is only 0.14% of QCD background MC events that satisfy all the modified HLT conditions. The most limiting conditions are the requirements on the di-jet average P_T and on the ξ matching. The requirement on di-jet average P_T is specially limiting for the background events, although it is also not very efficient at selecting signal events.

3.3.4 Statistical sensitivity to exclude the CEP of a single pair of charged Higgs bosons

For the sensitivity study, three extra cuts were implemented to further improve the rejection of background events. These cuts included the matching between the vertex z position of the PPS protons and of the jets reconstructed from tracks in the CMS central detector, and both the η separation and distance between the two di-jet systems, defined by the pairs formed using the four highest P_T with similar mass, as each di-jet system is supposed to represent the decay products of each charged Higgs boson. The relevant variables can be seen in figure 3.29, for the signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, and in figure 3.30, for the signal MC events in the $H^+ \rightarrow c\bar{b}$ decay mode.

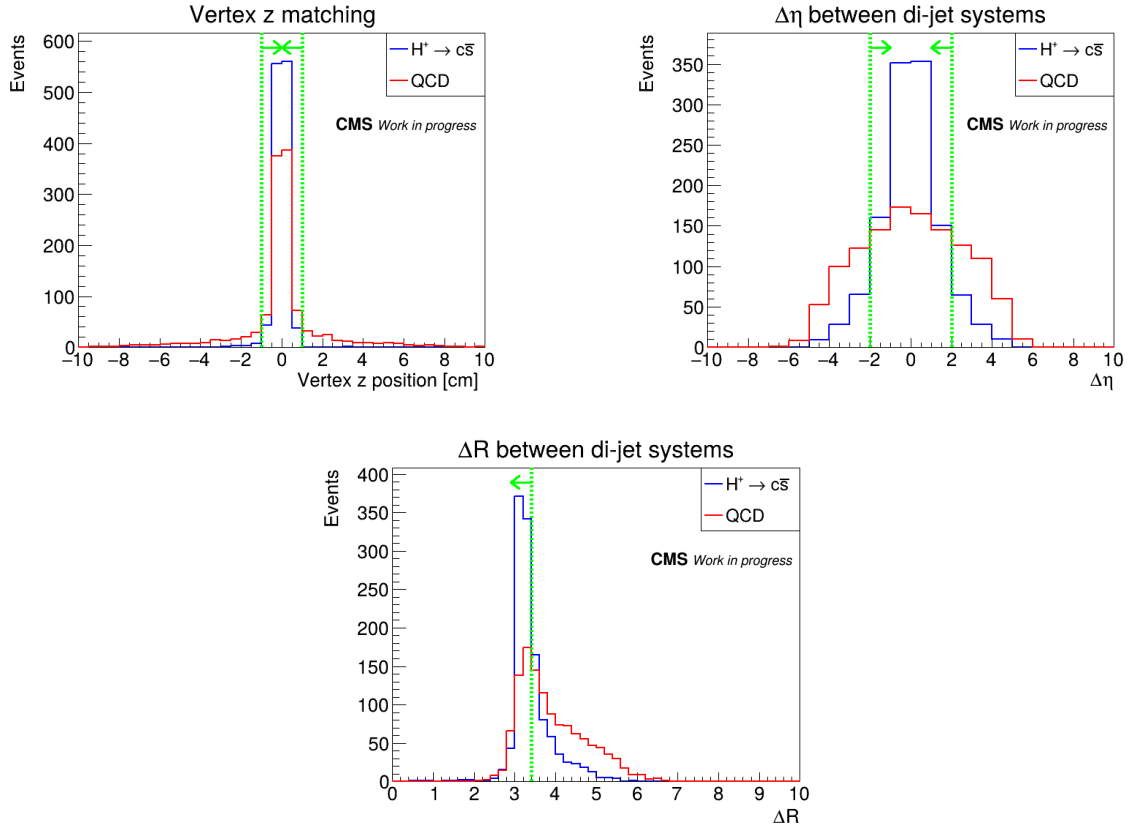


Figure 3.29: Comparison between signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, for a charged Higgs boson mass of 200 GeV , and QCD background MC events in the four-jet final state, after the modified HLT conditions, with respect to the three extra variables selected to improve background rejection. Histograms were normalized to the area for better visualization. The extra selection conditions are displayed by the green vertical lines.

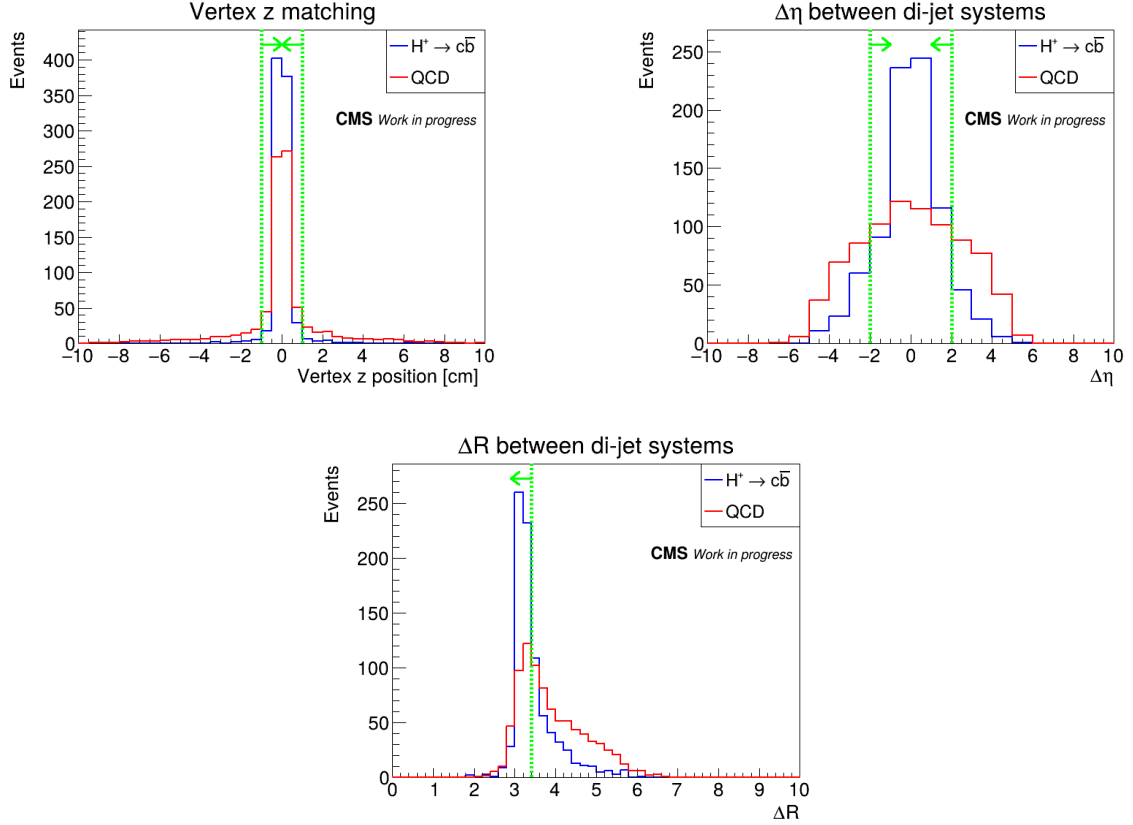


Figure 3.30: Comparison between signal MC events in the $H^+ \rightarrow c\bar{b}$ decay mode, for a charged Higgs boson mass of 200 GeV , and QCD background MC events in the four-jet final state, after the modified HLT conditions, with respect to the three extra variables selected to improve background rejection. Histograms were normalized to the area for better visualization. The extra selection conditions are displayed by the green vertical lines.

From the histograms present in figures 3.29 and 3.30, it is important to highlight how tight the matching of the vertex z position is, with both signal and background MC events centered around $z = 0$. This is opposite to what was seen in the LHC Run 3 configuration study, where the background distribution was more dispersed, and happens due to pileup protons that, by hitting the PPS timing detectors at random times, have a higher chance of matching with the vertex associated with the jet system that maximizes the squared sum of the jets' P_T . The extra cuts were applied to the events and the results are summarized in table 3.12.

Table 3.12: Cutflow table depicting the efficiency of the extra selection conditions for both signal and background MC events, after the modified HLT conditions. Inside the parenthesis are the percentage of events surviving each cut with respect to the previous step, and the percentage of events surviving each cut with respect to the initial number of events, respectively. The events were normalized to their respective number of expected events in the HL-LHC configuration (integrated luminosity of 3000 fb^{-1}), with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

Selection conditions	$H^+ \rightarrow c\bar{s}$	$H^+ \rightarrow c\bar{b}$	QCD background
Events after modified HLT	4384	3078	2.11×10^{10}
$-1 \leq \text{Vertex } z \text{ matching} \leq 1$	4312 (98.36% 4.79%)	2970 (96.49% 3.30%)	1.54×10^{10} (73.17% 0.10%)
$-2 \leq \Delta\eta \text{ between di-jet systems} \leq 2$	3607 (83.64% 4.01%)	2376 (80.00% 2.64%)	8.04×10^9 (52.07% 0.05%)
$\Delta R \text{ between di-jet systems} \leq 3.4$	2775 (76.95% 3.08%)	1850 (77.88% 2.06%)	5.07×10^9 (63.06% 0.03%)

From the results summarized in table 3.12, the extra selection cuts are satisfied by 3.08% of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, 2.06% of signal MC events in the $H^+ \rightarrow c\bar{b}$ decay mode, and

0.03% of QCD background MC events in the four-jet final state. Additionally, it can be seen how the condition applied to the vertex z matching is no longer the most limiting one, contrary to what was seen in table 3.8 for the LHC Run 3 configuration study.

The invariant mass of the di-jet system was once more utilized as the discriminant variable to calculate the statistical sensitivity to exclude the CEP of a single pair of charged Higgs bosons. Figure 3.31 displays this variable for signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, and in the $H^+ \rightarrow c\bar{b}$ decay mode.

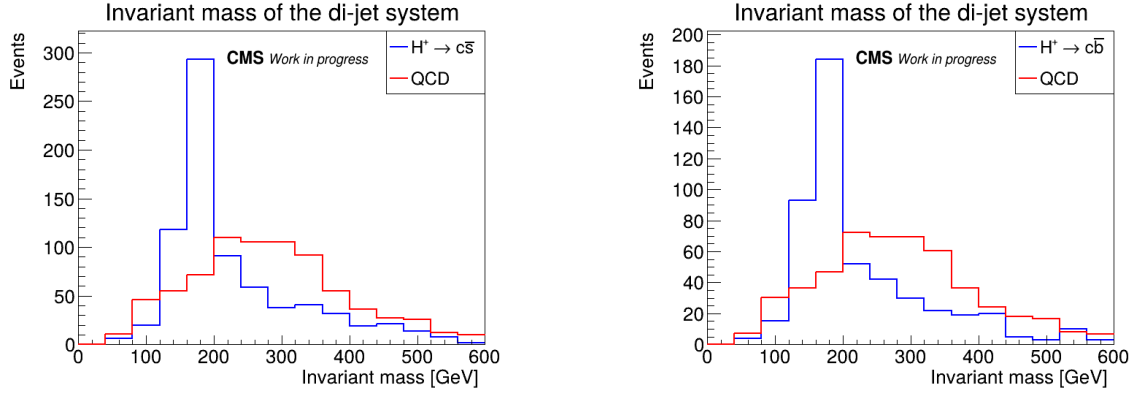


Figure 3.31: Comparison of the invariant mass of the di-jet system between signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode on the left, and in the $H^+ \rightarrow c\bar{b}$ decay mode on the right, both for a charged Higgs boson mass of 200 GeV, and QCD background MC events in the four-jet final state, after the modified HLT conditions and extra selection cuts. Histograms were normalized to the area for better visualization.

Using these variables as input for the Combine tool, the statistical sensitivity to exclude the signal process was determined in the background-only hypothesis, since this project only involved simulated data. In this process, a systematic uncertainty of 10% was also considered for the luminosity measurement. The expected 95% confidence level (CL) upper limits for both studied decay modes of the charged Higgs boson are presented in figure 3.32.

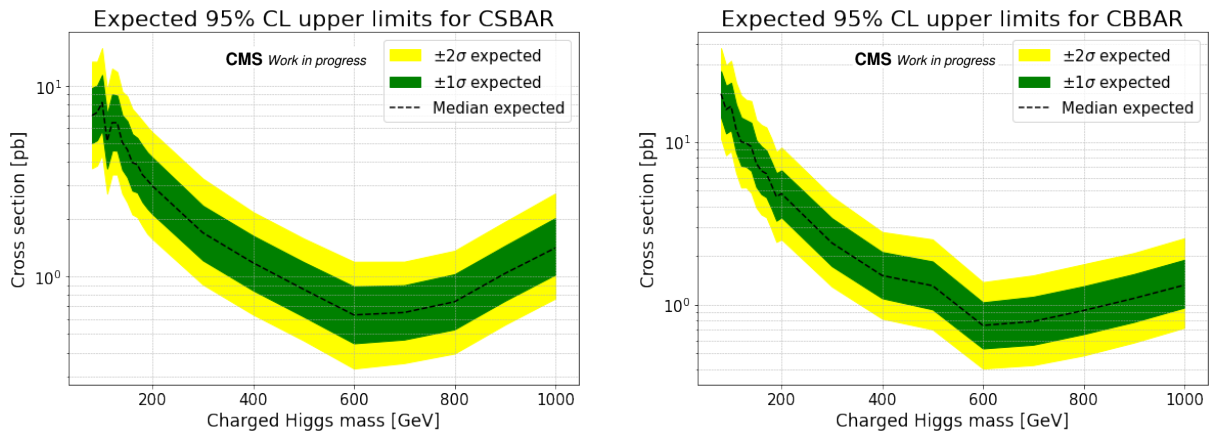


Figure 3.32: Statistical sensitivity of the analysis to exclude the CEP of a single pair of charged Higgs bosons, for signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode (CSBAR) on the left, and in the $H^+ \rightarrow c\bar{b}$ decay mode (CBBAR) on the right. The events were normalized to their respective number of expected events in the HL-LHC configuration (integrated luminosity of 3000 fb^{-1}).

The plots present in figure 3.32 indicate that, in the absence of any signal observation, cross sections above the limit curve can be excluded. It is also possible to see that the expected 95% confidence level upper limits for the signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode are lower than those in the $H^+ \rightarrow c\bar{b}$ decay mode.

3.4 Comparison of LHC Run 3 and HL-LHC configurations

This section aims at identifying the key differences between the current LHC Run 3 configuration, and the future planned HL-LHC configuration, considering an equal center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$ for both configurations. For this task, some results displayed in the previous sections will be presented together with relevant plots to highlight the differences between both configurations. Since the center-of-mass energy is considered to be the same between configurations, the main differences include the integrated luminosity, the PPS detector configuration, and the number of mean pileup interactions per event. The total number of events generated by each configuration during their operation is given by the expression 1.5, where the LHC Run 3 configuration has an integrated luminosity of 300 fb^{-1} , and the HL-LHC configuration of 3000 fb^{-1} . Therefore, the increased integrated luminosity of the HL-LHC configuration will yield about 10 times more events than the LHC Run 3 configuration. Since this would only change the height of the distributions, the events in both configurations were normalized to the same integrated luminosity, to help distinguish the impact of the additional pileup interactions and PPS configuration between the LHC Run 3 and the HL-LHC configurations. A side by side comparison of the differences in the PPS detector configuration is present in table 3.13, which was built using the information already registered in tables 3.6 and 3.9.

Table 3.13: Comparison between the LHC Run 3 and the planned HL-LHC configurations of the PPS detector. The time resolution is given in nanoseconds. The ξ resolution is a percentage relative to the ξ value. The ξ minimum and maximum correspond to the percentage of proton longitudinal momentum loss.

Parameter	Values for LHC Run 3	Values for HL-LHC
ξ resolution	0.05 %	0.05 %
ξ minimum	0.03	0.0095
ξ maximum	0.15	0.1967
Time resolution	0.05 <i>ns</i>	0.02 <i>ns</i>

The planned configuration of the PPS detector for the future HL-LHC upgrade has a higher ξ range and an improved time resolution, when compared to the current LHC Run 3 configuration. To study the impact of the planned HL-LHC configuration for the PPS detector, signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, without pileup, were used to plot variables directly related to the protons measured by the PPS detector, and are displayed in figure 3.33.

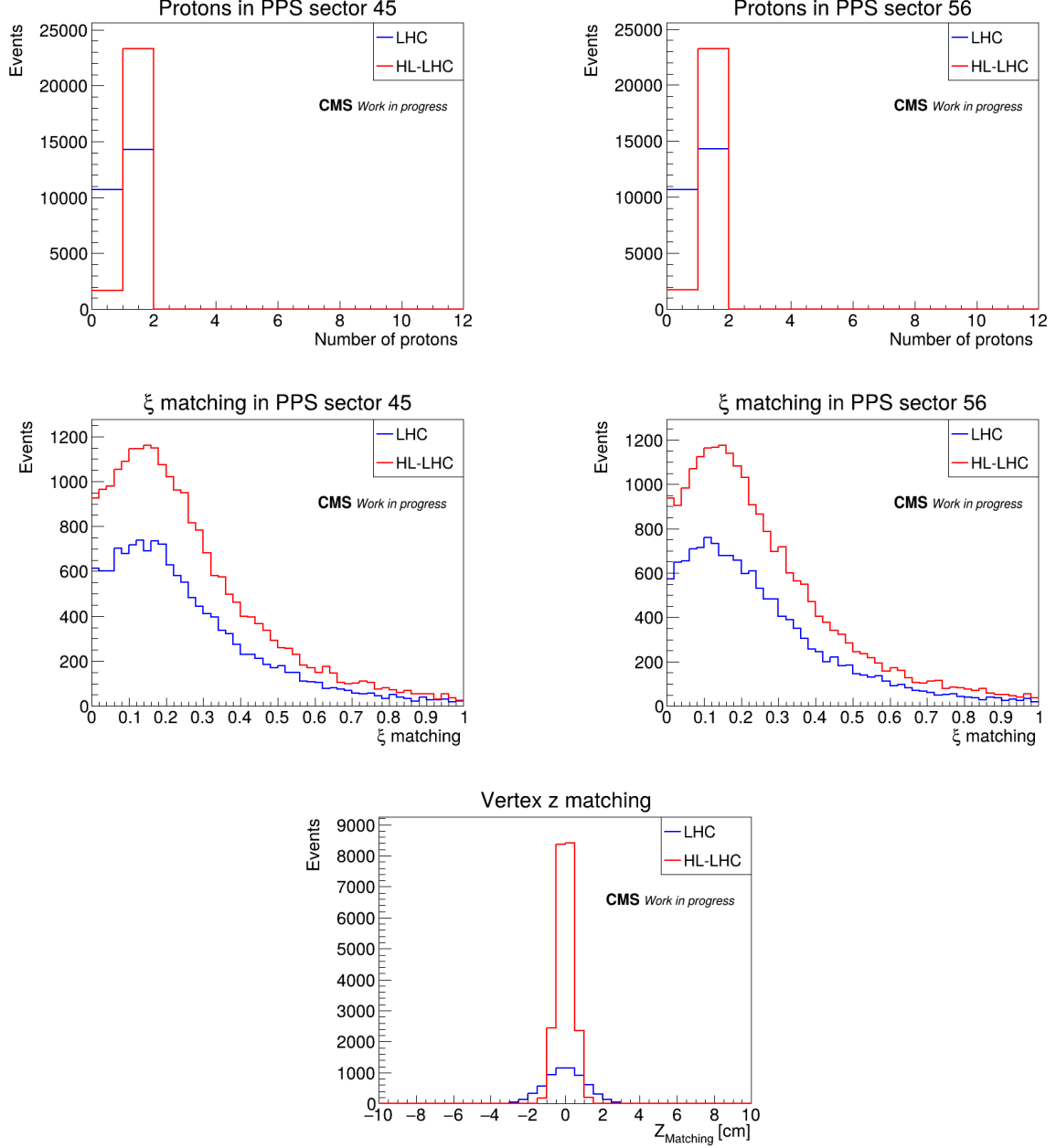


Figure 3.33: Comparison between the LHC Run 3 and the planned HL-LHC configurations, with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, using variables directly related to the protons measured by the PPS detector. Histograms built using signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, for a charged Higgs mass of 200 GeV , without pileup interactions. The events are normalized to equal integrated luminosity.

The plots present in figure 3.33 highlight the impact of the new planned HL-LHC configuration for the PPS detector. The increased ξ range of the PPS detector in the HL-LHC configuration is able to capture more protons from the signal MC events than the LHC Run 3 configuration, and is noticeable in both the distributions of the number of protons in each PPS sector, and in the distribution of ξ matching. Here, it is possible to observe the higher number of events with one proton in each PPS sector, and consequently the larger number of events present in the ξ matching distribution. Also, the improved resolution of the timing detectors is reflected by the distribution of the vertex z matching, where the HL-LHC configuration provides a tighter matching between the vertex z position of the protons and the jets reconstructed from tracks in the CMS central detector, when compared to the same distribution in

the LHC Run 3 configuration, which has fewer events and is wider.

Moreover, the impact of the planned HL-LHC configuration on the PPS detector acceptance for the several decay modes, can be seen in figure 3.37, which is a combination of figures 3.8 and 3.22.

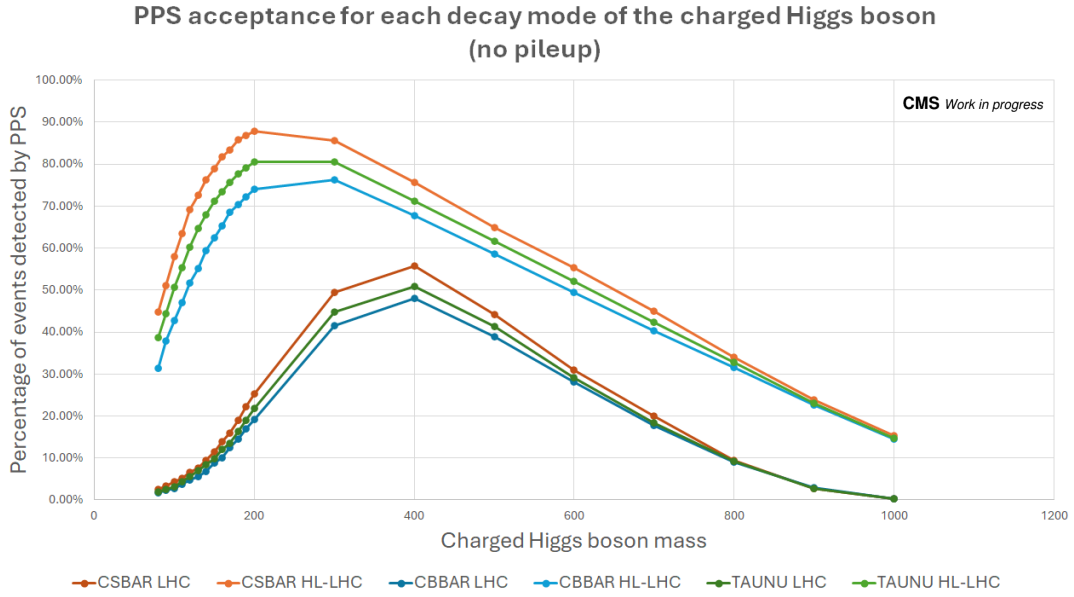


Figure 3.34: Comparison of the percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) between the LHC Run 3 and planned HL-LHC configurations, with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, without pileup interactions. The events are normalized to equal integrated luminosity. Each decay mode is labeled as follows: CSBAR for $H^+ \rightarrow c\bar{s}$, CBBAR for $H^+ \rightarrow c\bar{b}$, and TAUNU for $H^+ \rightarrow \tau^+ \nu_\tau$. The darker colors correspond to the signal MC events in the LHC Run 3 configuration, while the lighter colors correspond to the signal MC events in the planned HL-LHC configuration.

Here, the first difference can be seen on the peak in acceptance that happens at difference masses for each of the configurations. As detailed in sections 3.2.2 and 3.3.2, the peak in acceptance is explained by how the signal MC events are distributed inside the PPS detector's acceptance region for invariant mass and rapidity of the central system. Moreover, it can be seen that the percentage of events detected by PPS is higher for the HL-LHC configuration. This difference is explained by the larger ξ range of the HL-LHC configuration, which consequently is able to measure more protons, translating into a larger number of events detected by the PPS detector. This is also confirmed by the plots of the number of protons in each PPS sector, present in the previous figure 3.33, that reveals the increased number of protons in each PPS sector for the HL-LHC configuration.

The remainder of the comparison between the current LHC Run 3 and future HL-LHC configuration for the PPS detector will focus on the impact of the different values of mean pileup for the event analysis. In figure 3.35, the relevant variables used during the analysis are plotted with signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, for a charged Higgs mass of 200 GeV , and for both LHC Run 3 and HL-LHC configurations, with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$ and including pileup interactions. The same variables were plotted in figure 3.36 for the QCD background MC events in the four-jet final state under the same conditions.

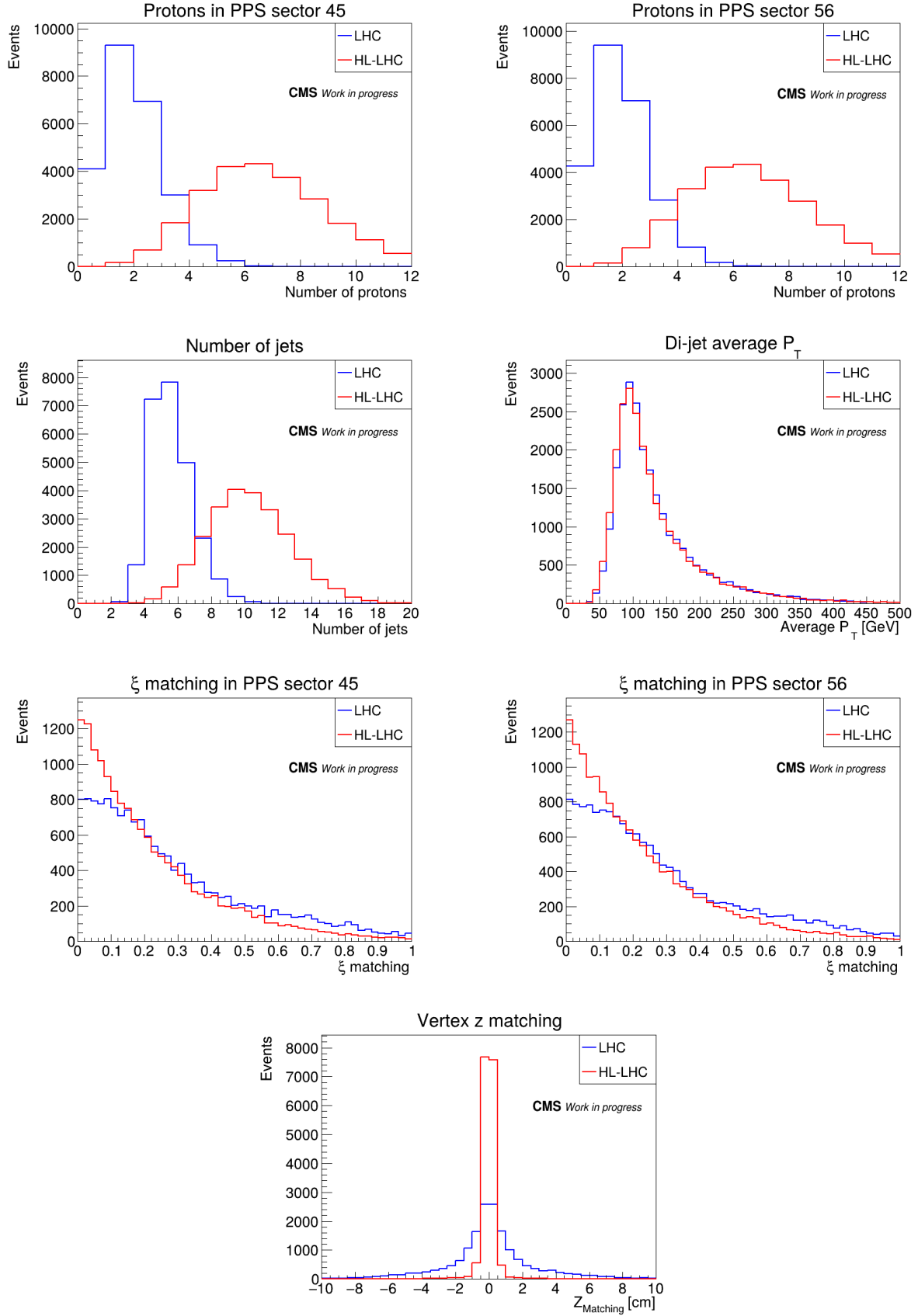


Figure 3.35: Comparison between the LHC Run 3 and planned HL-LHC configurations, with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, using variables relevant for the HLT conditions during event analysis. Histograms built using signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, for a charged Higgs mass of 200 GeV , including pileup interactions. Histograms were normalized to the area for better visualization.

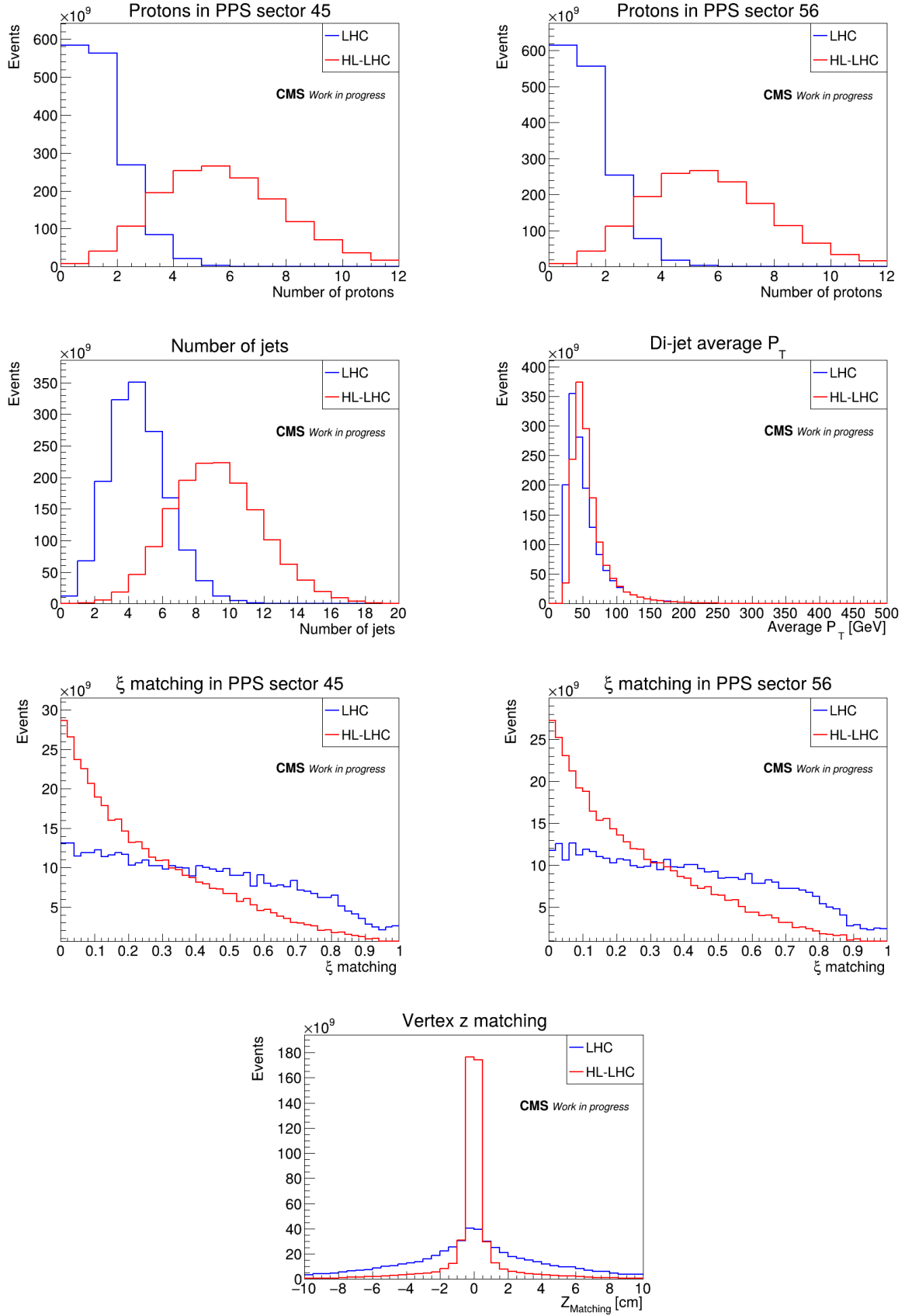


Figure 3.36: Comparison between the LHC Run 3 and planned HL-LHC configurations, with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, using variables relevant for the HLT conditions during event analysis. Histograms built using QCD background MC events in the four-jet final state including pileup interactions. Histograms were normalized to the area for better visualization.

When looking at figure 3.35, with the comparison between configurations with pileup interactions for signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, it is possible to identify the impact of the increased number of pileup interactions, since the events in the HL-LHC configuration have a higher number of jets in the CMS central detector and of protons in each PPS sector. This also means that nearly all events are measured by the PPS detector, which can be verified in figure 3.37, where a comparison is made between figures 3.9 and 3.23.

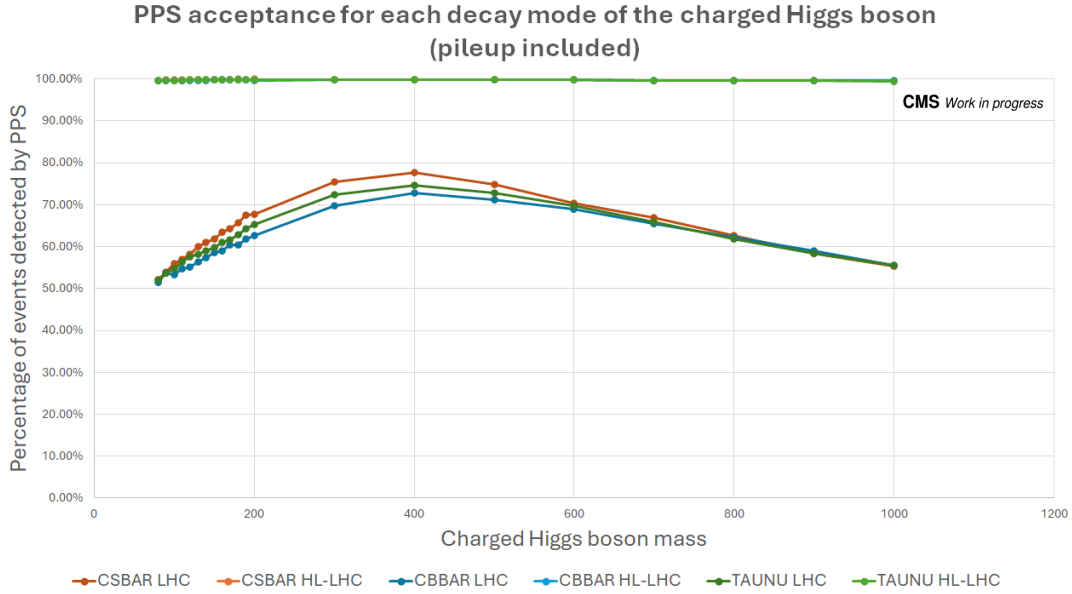


Figure 3.37: Comparison of the percentage of signal MC events measured by the PPS detector (at least 1 proton in each PPS sector) between LHC Run 3 and planned HL-LHC configurations, with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$, including pileup interactions. The events are normalized to equal integrated luminosity. Each decay mode is labeled as follows: CSBAR for $H^+ \rightarrow c\bar{s}$, CBBAR for $H^+ \rightarrow c\bar{b}$, and TAUNU for $H^+ \rightarrow \tau^+ \nu_\tau$. The darker colors correspond to the signal MC events in the LHC Run 3 configuration, while the lighter colors correspond to the signal MC events in the HL-LHC configuration.

Continuing with the analysis of figure 3.35, there is also an increase in the number of jets in the CMS central detector and in the number of protons in each sector of the PPS detector, because of the higher number of pileup interactions for the HL-LHC configuration of 200 per event, when compared to the 65 pileup interactions per event present in the LHC Run 3 configuration. The di-jet average P_T distribution remains unchanged despite the increased pileup in the HL-LHC configuration, which was also visible during the analysis on the impact of pileup with figures 3.5 and 3.19, that is explained by the fact that pileup interactions correspond to protons scattering at small angles, which produce jets in the low P_T region. The ξ matching distributions show an improvement in the matching between the protons measured by the PPS detector and the jets reconstructed from tracks in the CMS central detector for the HL-LHC configuration. The reasons behind this are the nearly zero events without protons in each of the PPS sectors, but also the increased number of pileup interactions that augment the possibility of wrong matchings between pileup protons and jets from the CMS central detector. The vertex z matching distribution highlights the impact of the improved time resolution of the PPS timing detectors, with a more tight matching for events in the HL-LHC configuration. However, in this case the peak cannot be fully attributed to correct vertex z matchings, as was noted in the analysis of figures 3.29 and 3.30.

Moving to figure 3.36, displaying the comparison between configurations for QCD background MC events with pileup interactions included, it can be seen that there are almost no events with zero protons in each PPS sector, revealing that the increase in pileup is significant enough to make the majority of QCD background events detectable by PPS. Additionally, the number of protons in each PPS sector peaks at a higher value of around 5 per event. The HL-LHC configuration also presents a higher number of jets per event than the LHC Run 3 configuration. A small shift to higher values of di-jet average P_T is visible for the HL-LHC configuration, resembling the impact of pileup interactions seen in figure 3.21, which was not noticeable in figure 3.7, because of the higher number of mean pileup, meaning that pileup interactions are able to produce jets with slightly higher P_T than the considered QCD background MC events. The highlight from the ξ matching distributions is the larger number of events present in the HL-LHC configuration, which is a result of there being almost no events with zero protons in each PPS sector. Lastly, the enhanced time resolution of the PPS timing detectors in the HL-LHC configuration is seen to bring a large improvement for the vertex z matching. These last remarks about the ξ and vertex z matchings are strongly relevant, because they reveal an increase in difficult for the background rejection rate. In principle, a good ξ and vertex z matching should be characteristic of signal events, where the final state protons are strongly correlated with the four-jet system. However, with the increase in mean pileup interactions, these same features are also visible in QCD background events, complicating their separation from signal events.

Next, a comparison is made between the statistical sensitivity achieved for each configuration, this time taking into consideration the integrated luminosity values corresponding to each configuration. Figures 3.38 and 3.39 display the expected 95% confidence level upper limits for each configuration with signal MC events in the $H^+ \rightarrow c\bar{s}$ and $H^+ \rightarrow c\bar{b}$ decay modes, respectively.

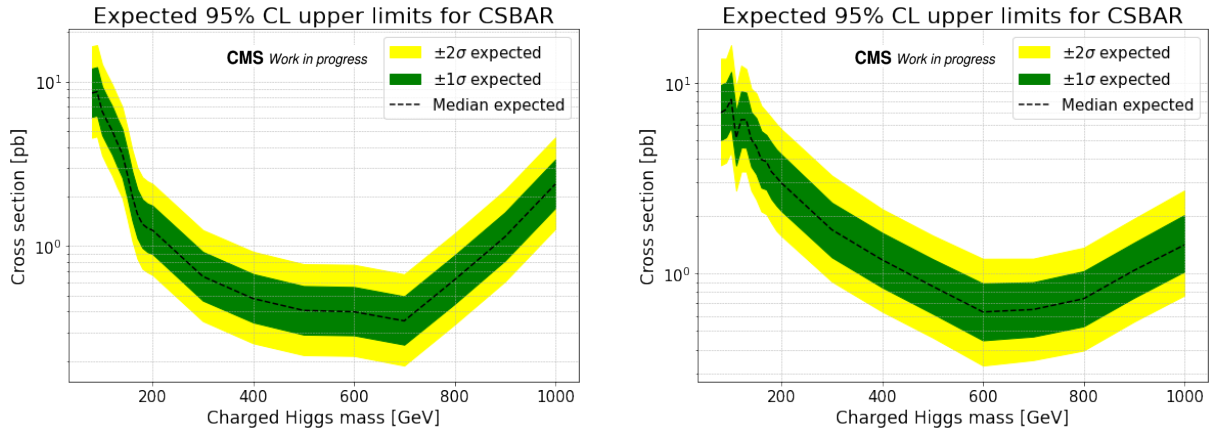


Figure 3.38: Statistical sensitivity of the analysis to exclude the CEP of a single pair of charged Higgs bosons, for signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode (CSBAR) in the LHC Run 3 configuration on the left, and in the HL-LHC configuration on the right. The events were normalized to their respective number of expected events in each configuration (integrated luminosity of 300 fb^{-1} in the LHC Run 3 configuration, and 3000 fb^{-1} in the HL-LHC configuration). Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

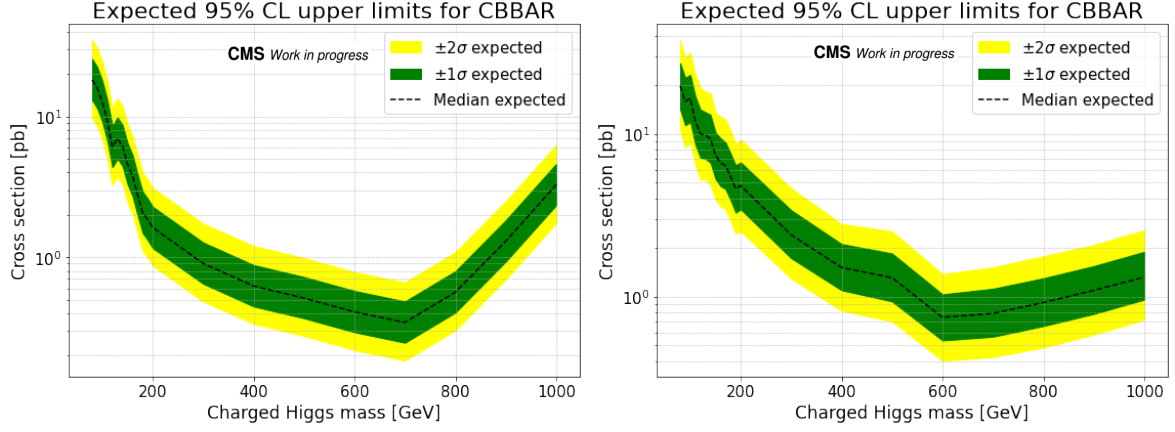


Figure 3.39: Statistical sensitivity of the analysis to exclude the CEP of a single pair of charged Higgs bosons, for signal MC events in the $H^+ \rightarrow c\bar{b}$ decay mode (CBBAR) in the LHC Run 3 configuration on the left, and in the HL-LHC configuration on the right. The events were normalized to their respective number of expected events in each configuration (integrated luminosity of 300 fb^{-1} in the LHC Run 3 configuration, and 3000 fb^{-1} in the HL-LHC configuration). Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

For both decay modes, the HL-LHC configuration obtained a worse result, since the upper limits are higher than those determined with the LHC Run 3 configuration. This is possibly due to the higher amount of background events surviving the selection conditions for the HL-LHC configuration, as can be seen in table 3.14, which is a summary of the values already presented in tables 3.8 and 3.12.

Table 3.14: Table depicting the number of events surviving the selection cuts in each configuration. The events were normalized to their respective number of expected events in each configuration (integrated luminosity of 300 fb^{-1} for the LHC Run 3 configuration, and 3000 fb^{-1} for the HL-LHC configuration), with a center-of-mass energy of $\sqrt{s} = 13.6 \text{ TeV}$. Since this analysis is model independent, a cross section of 30 fb was assumed for the signal MC events, to provide better visualization.

Configurations	LHC Run 3			HL-LHC		
	$H^+ \rightarrow c\bar{s}$	$H^+ \rightarrow c\bar{b}$	QCD	$H^+ \rightarrow c\bar{s}$	$H^+ \rightarrow c\bar{b}$	QCD
Events after selection cuts	221	159	3.31×10^7	2775	1850	5.07×10^9

The HL-LHC configuration has a larger number of signal events surviving the defined selection cuts, due to the 10 times higher integrated luminosity than the LHC Run 3 configuration. However, the number of background events is also larger by 2 orders of magnitude in the HL-LHC configuration, when compared to the LHC Run 3 configuration. This corresponds to a worse background rejection rate, and justifies the worse statistical sensitivity seen in figures 3.38 and 3.39. The larger amount of background events could also serve as a motivation for studying other decay modes of the charged Higgs boson with lower background events, such as the $H^+ \rightarrow \tau^+ \nu_\tau$ decay mode. Moreover, although not present in this study, the HL-LHC upgrade will include a number of improvements in the CMS central detector, denominated Phase-2 [57], that could provide a better efficiency for matchings between protons from signal events measured by the PPS detector and jets reconstructed from tracks in the CMS central detector.

4 Conclusion

The Standard Model (SM) of particle physics has proven to be the most successful theory to date, accurately predicting the majority of experimental observations. Nonetheless, it leaves some fundamental questions unanswered, such as the hierarchy problem, the strong CP problem, the baryon asymmetry of the Universe, and no viable dark matter candidate. To address these questions, many theoretical extensions of the SM were proposed, suggesting the existence of new particles or interactions, reason for which they are known as Beyond the Standard Model (BSM) scenarios. A key feature of many BSM scenarios is the existence of a charged Higgs boson, which serves as a great motivation for studies regarding its production, since the observation of a charged Higgs boson would directly imply the existence of BSM physics.

For that reason, this project focused on studying the central and exclusive production (CEP) of a single pair of charged Higgs bosons in the two-Higgs-doublet model (2HDM), which is the simplest BSM scenario including a charged Higgs boson. Additionally, the CEP process was chosen to take advantage of the Precision Proton Spectrometer (PPS) that is part of the Compact Muon Solenoid (CMS) general purpose detector system, but also due to the lower amount of background events associated with this type of processes. Moreover, this analysis is designed to be as model independent as possible, with the 2HDM only being used for its convenience when generating the events. Therefore, this analysis could also be sensitive to other signatures in other models.

This project started with the calculation of the cross section for three decay modes of the charged Higgs boson, those being the $H^+ \rightarrow c\bar{s}$, the $H^+ \rightarrow c\bar{b}$, and the $H^+ \rightarrow \mu^+\nu_\mu$. The cross section was also determined for the competing QCD background with four jets in the final state of the type $pp \rightarrow jjjj$. Signal and background MC hard scattered events were simulated using MadGraph5_aMC@NLO, with Pythia8 responsible for the simulation of parton showers and hadronization for those events. Multiple signal MC events were simulated, ranging from a charged Higgs boson mass of 80 GeV to 1000 GeV, since its true value is not known.

From MadGraph5_aMC@NLO, the $H^+ \rightarrow c\bar{s}$ decay mode was revealed to have the highest cross section of the considered decay modes, with the $H^+ \rightarrow \mu^+\nu_\mu$ decay mode in second, and the $H^+ \rightarrow c\bar{b}$ decay mode with the smallest. It was also visible that the cross section was highest for small charged Higgs boson masses and decreased for higher masses. Therefore, the highest signal event cross section was seen in the $H^+ \rightarrow c\bar{s}$ decay mode for a charged Higgs mass of 80 GeV, with a value of 29.4 fb, and the lowest in the $H^+ \rightarrow c\bar{b}$ decay mode for a charged Higgs mass of 1000 GeV, with a value of 2.568×10^{-9} fb. It should be noted that this hierarchy of decays is specific to the 2HDM and doesn't necessarily hold for other models with a charged Higgs boson.

The cross section for the QCD background was determined to be 1.948×10^{10} fb. Nonetheless, to achieve better statistics for the event analysis of the QCD background MC events, 8 samples were generated in different transverse momentum (P_T) ranges of the leading order jet, with intervals of 50 GeV, from zero to 400 GeV. For these samples, it was noted that the highest cross section corresponded to the lowest P_T range of [0, 50] GeV, with a value of 1.942×10^9 fb, and the lowest cross section to the highest P_T range of [350, 400] GeV, with a value of 3.973×10^6 fb.

The next part of the analysis focused on the LHC Run 3 and HL-LHC configuration, by studying the impact of pileup in the signal and background MC events, the acceptance of PPS for detection of signal events, the efficiency of the high level trigger (HLT) at rejecting background events, and finally determining the statistical sensitivity to exclude the CEP of a single pair of charged Higgs bosons. The

HL-LHC configuration includes an update to the PPS detector settings, an increased number of pileup interactions per event, a higher integrated luminosity, and a bigger center-of-mass energy. However, due to the absence of a minimum bias pileup file to use during this analysis, the center-of-mass energy used for the HL-LHC configuration was kept equal to the LHC Run 3 configuration, at a value of $\sqrt{s} = 13.6 \text{ TeV}$.

The extra pileup interactions on both signal and background MC events lead to an increased number of protons in each sector of the PPS detector, a higher number of jets reconstructed from tracks in the CMS central detector, and seemingly better ξ matchings between protons and the four-jet system. However, the protons from pileup now present in the final state for the background MC events complicate the separation of signal from background events. Additionally, the improved ξ matching is caused by wrong matchings between protons from pileup and the four-jet system, and also complicates the separation of signal from background events.

The acceptance of the PPS detector to measure signal MC events with no mean pileup, meaning that there was at least one proton in each PPS sector, was observed to peak at a charged Higgs mass of 400 GeV for the LHC Run 3 configuration, and of 200 GeV for the HL-LHC configuration of the PPS detector. The peak in acceptance is directly related to the acceptance region of the PPS detector, which is different for each of the configurations, and can be visualized by the invariant mass and rapidity of the central system. The differences in the PPS settings between configurations are a larger ξ range, and better timing resolution for the HL-LHC configuration. For events including mean pileup, both configurations saw an increase in acceptance when compared to the no mean pileup case, explained by the extra protons present in each PPS sector from the pileup interactions.

The HLT conditions were then applied to the events with mean pileup included, excluding the $H^+ \rightarrow \mu^+ \nu_\mu$ decay mode, since the HLT was designed specifically for processes with a four-jet final state, which is not the case for this decay mode. For the LHC Run 3 configuration, the HLT conditions were satisfied by 3.67% of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, 2.58% in the $H^+ \rightarrow c\bar{b}$ decay mode, and by 0.02% of QCD background MC events. For the HL-LHC configuration, the HLT conditions were satisfied by 0.02% of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, 0.004% in the $H^+ \rightarrow c\bar{b}$ decay mode, and by 0.001% of QCD background events. The lower number of events satisfying the HLT conditions can be explained by the increased value of 200 mean pileup interactions, about 3 times larger than the value of 65 present in the LHC Run 3 configuration. Since the HLT was designed to select events with less than 3 protons in each PPS sector, it is not able of selecting the events with a now much higher number of protons in each PPS sector, resulting in the low percentage of events surviving the HLT conditions. Therefore, the HLT conditions were modified for the HL-LHC configurations to select events with less than 9 protons, more than 6 jets, and less than or equal to a tighter ξ matching value of 0.2. Using the modified HLT selection, the conditions were satisfied by 4.87% of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, 3.42% in the $H^+ \rightarrow c\bar{b}$ decay mode, and by 0.14% of QCD background MC events. The results obtained in this part of the study serve as a motivation for future HLT studies, since its current conditions are not optimized for the pileup scenario of the HL-LHC configuration.

The statistical sensitivity to exclude the CEP of a single pair of charged Higgs bosons was determined for the signal MC events in the $H^+ \rightarrow c\bar{s}$ and $H^+ \rightarrow c\bar{b}$ decay mode. To obtain this results, three extra conditions were imposed on the events, taking advantage of known properties of the jets and of the timing detectors installed in the PPS detector. These were aimed at further improving the separation between signal and background events. The three imposed conditions are the matching of the vertex z position between the protons and the four-jet system, the η separation between the di-jet systems, and the distance between the di-jet systems. In the HL-LHC configuration, it was noted that, despite the

improved time resolution, the increased number of pileup interactions decreased the separation efficiency of the condition on the vertex z position matching. For the LHC Run 3 configuration, the extra conditions were satisfied by 2.46% of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, 1.78% in the $H^+ \rightarrow c\bar{b}$ decay mode, and by 0.002% of QCD background MC events. For the HL-LHC configuration, the extra conditions were satisfied by 3.08% of signal MC events in the $H^+ \rightarrow c\bar{s}$ decay mode, 2.06% in the $H^+ \rightarrow c\bar{b}$ decay mode, and by 0.03% of QCD background MC events. The Combine tool was then used, with the distribution of the invariant mass of the di-jet system as input, since it was identified as one of the most discriminant variables, and the expected 95% confidence level (CL) upper limits were obtained for both considered decay modes of the charged Higgs boson. In both configurations, the obtained upper limits for the $H^+ \rightarrow c\bar{s}$ decay mode were lower than those obtained for the $H^+ \rightarrow c\bar{b}$ decay mode.

Finally, a comparison was made between the results obtained for the LHC Run 3 and HL-LHC configurations, for events with and without pileup interactions, and for the statistical sensitivity to exclude the signal process.

Starting with the comparison of signal MC events without pileup interactions included, it was observed that the updated settings of the PPS detector in the HL-LHC configuration provided a tighter vertex z position matching, due to the better time resolution, but also a higher percentage of events detected with at least 1 proton in each PPS sector, thanks to the larger ξ minimum and maximum.

When pileup interactions are included, there is an increase in the number of protons in each PPS sector and in the number of jets reconstructed from tracks in the CMS central detector, and a better ξ matching between the protons and the four-jet system, all in the HL-LHC configuration, as a result of the much higher mean pileup number of 200 per bunch crossing, compared to the smaller 65 present in the LHC Run 3 configuration. In this case, it was also seen a higher percentage of events measured by the PPS detector for the HL-LHC configuration, resulting from both the larger ξ range of the detector and the increased number of pileup interactions.

Lastly, when looking at the statistical sensitivity to exclude the CEP of a single pair of charged Higgs bosons, it was possible to identify better results (lower upper limits) for the LHC Run 3 configuration. The main factor contributing to this result is the larger number of QCD background MC events surviving the selection conditions in the HL-LHC configuration. This could also serve as a motivation for the study of other charged Higgs boson decay modes with lower background events, such as the $H^+ \rightarrow \mu^+ \nu_\mu$ decay mode. Additionally, the HL-LHC configuration will also bring improvements for the CMS central detector, which were not included in this study, and could provide a better efficiency for matchings between protons and jets, such as the ξ and vertex z position matchings.

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