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**Search for the exotic state $X(5568)$ decaying
into $B_s^0 \pi^\pm$ at the CMS Experiment**

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*Dedicated to my sweet mom,
to my brother and sisters.*

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Resumen

Recientemente, la Colaboración D0 anunció la observación de una nueva estructura resonante en la distribución de masa invariante $B_s^0\pi^\pm$, llamada $X(5568)$. El $X(5568)$ es un buen candidato para ser un estado tetraquark, y ha despertado gran interés de las comunidades teórica y experimental.

Este trabajo presenta la búsqueda del estado $X(5568)$ en el sistema $B_s^0\pi^\pm$ en el Experimento CMS usando 19.7 fb^{-1} de colisiones pp a 8 TeV colectados en 2012. Con cerca de 50000 mesones B_s^0 reconstruidos, ninguna señal es encontrada alrededor de la masa reclamada por la Colaboración D0 y límites superiores a la producción relativa de la posible partícula exótica son calculados para diferentes condiciones cinemáticas sobre el B_s^0 , tanto como para la masa y ancho del estado.

Abstract

Recently, the D0 Collaboration announced the observation of a new resonant structure in the $B_s^0\pi^\pm$ invariant mass distribution, named $X(5568)$. The $X(5568)$ is a good candidate to be a tetraquark state, and has raised a lot of interest from the theoretical and experimental communities.

This work presents the search of the $X(5568)$ state in the $B_s^0\pi^\pm$ system at the CMS Experiment using 19.7 fb^{-1} of pp collisions at 8 TeV collected in 2012. With about 50000 reconstructed B_s^0 mesons, no signal is found around the mass claimed by the D0 Collaboration and upper limits to the production of the possible exotic particle is calculated for different kinematics requirements on the B_s^0 , as well as for the mass and width of the state.

Chapter 1

Introduction

The answer to the ultimate question of life, the universe and everything else is: 42. This was a very funny reply of a fictitious super-powerfull computer, the Deep Thought, in the movie “The Hitchhiker’s Guide to the Galaxy” [1], that took 7.5 millions of years to figure out. Because real life is so different and it does not seem to be easy to solve, humanity has tried along history to explain its nature.

So, in order to understand “what is everything made of?”, the matter was considered made of elementary substances (water, fire, air and ground), the indivisible atoms, atoms with different properties, etcetera, until today, when matter is described in terms of particles which are considered elementary and their interactions. This is the Standard Model of Particles Physics and their interactions (SM).

The SM is a successful theory whose the most fundamental predictions have been corroborated by experiments with impressive accuracy. Nevertheless it is not the final theory, because there are still some problems to solve (neutrino mass, mass hierarchy, matter-antimatter asymmetry, dark-matter, etcetera).

In the last two decades, non-conventional “particles” have been discovered that seem composed of more than three quarks and antiquarks. Usually, the observed particles are composed of a quark-antiquark pair or a quark (antiquark) triplet, and recent discoveries show states with four or five (anti)quarks. Sometimes, these exotics states are due to statistical fluctuations or they are result of bad analysis. A lot of work is needed in order to recognize which signals are real states or which are unfortunate events.

In the begining of 2016, the D0 Collaboration announced the observation of a new state composed of four quarks and its properties caught the interest of the community.

Fermionic sector $S = \frac{1}{2}$			
	1 st family	2 nd family	3 rd family
Quarks	u	c	t
	d	s	b
Leptons	ν_e	ν_μ	ν_τ
	e	μ	τ
Gauge sector $S = 1$			
Electromagnetic	Weak		Strong
γ	$W^\pm$	Z^0	g
Escalar sector $S = 0$			
H			

Table 1.1: Particles in the Standard Model

This work presents results of the search for this state at the CMS experiment with the Large Hadron Collider (LHC), the most powerful particle acelerator in the world. Chapter 1 will present a review to the current status of the D0 state, Chapter 2 a description of the experiment, Chapter 3 the data selection, Chapter 4 and 5 the data analysis and Chapter 6 the conclusions.

1.1 The Standard Model of particle physics

The matter is understood as a set of structured particles. The most fundamental particles create structures by interacting. These exist in four kinds of them: gravitational, electromagnetic, weak and strong. The electric charge permits electromagnetic interactions, weak charge permits quantum weak interactions and color charge the strong interactions. In an unknown way particles with energy have gravitational interactions.

The Standard Model (SM) describes three of the four fundamental forces (interactions) by a relativistic quantum field theory using the symmetry group

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

This formulation combines the Quantum Chromodynamics, QCD, with the Electro-Weak

theory, and explains the electromagnetic, the weak and the strong interactions by particles carriers of the interaction: the gauge bosons. Gravitational interactions are excluded from this model.

The particles in the SM, Table 1.1, can be clasified in three different sectors depending on their spin: the fermionic sector is formed by particles with spin $\frac{1}{2}$, the gauge sector by particles with spin 1 and the scalar sector or Higgs sector by the particle with spin 0, the Higgs boson.

As said before, gauge bosons are the carriers of the interaction. The strong interaction is carried by gluons (particles without mass, without electric charge, with color and self-interacting). The electromagnetic interaction is carried by photons (non self-interacting particles, without mass, electric charge and color). The weak interaction is carried by three massive self-interacting particles (charged particles $W^\pm$ and the neutral particle Z^0).

Likewise, fermions can be clasified in leptons and quarks. Leptons have lepton number different from zero and do not have color charge, while quarks have color charge and leptonic number zero.

There are leptons with and without electric charge. Charged leptons have mass and electric charge -1 . These are the electron e , the muon μ and the tau τ . Neutral leptons are the neutrinos and come in three different flavors: ν_e , ν_μ and ν_τ . In the SM neutrinos do not have mass, but currently it is known that these must to have a very small mass.

On the other hand, all quarks have mass and fractional electric charge: $\frac{2}{3}$ for up quarks and $-\frac{1}{3}$ for down quarks. Up-type quarks are up u , charm c and top t ; down-type quarks are down d , strange s and bottom b . Quarks have an exclusive property shared with gluons: the color charge, responsible for strong interactions. This color property is not observed on isolated particles. Quarks are confined on hadrons, particles made of quarks, with null average color.

Also fermions can be classified in generations or families. An up-type quark with a down-type quark, or a charged lepton with its respective neutrino, form families. Families properties are similar, except for the mass increasing in every generation.

The only particle in the scalar sector is the Higgs boson. This massive particle without electric charge is responsible to give mass to other particles in the SM. The discovery of this particle in recent years, at the CMS [2] and ATLAS [3] experiments, is the most important achievement of the LHC and gives a strong support to the validity of the SM.

Every particle in the SM has a corresponding anti-particle, with same mass and fermion spin but opposite quantum numbers. These particles form the anti-matter.

Protons and neutrons are made of quarks (u, d) and, together with electrons, form atoms. So, almost all matter is made of the first generation of particles in the SM. In general these hadrons are classified in mesons and baryons. A meson is a particle formed by a quark-antiquark pair ($q\bar{q}$), and baryons are particles with three quarks (qqq) or three antiquarks ($\bar{q}\bar{q}\bar{q}$). This classification is a result of several observations in nature. The occurrence of new particles beyond this classification is a possibility.

1.2 The exotic states

Beyond the existence of $q\bar{q}$ mesons and qqq baryons, and even since the beginning of quarks model [4, 5], QCD allows the existence of mesons with more than two quarks ($q\bar{q}q\bar{q}$, $qqq\bar{q}\bar{q}\bar{q}$, ...), and baryons with more than three quarks ($qqqq\bar{q}$, $qqqqq\bar{q}\bar{q}$, ...): states is allowed if the difference on their number of quarks and their number of antiquarks is multiples of three (including zero). Also, states with any number of valence gluons can exist, gluons contributing to quantum numbers of the hadron. Then, conventional mesons and baryons are states $q\bar{q}$ and qqq , respectively; more exotic states are $q\bar{q}q\bar{q}$ tetraquarks and $qqqqq\bar{q}$ pentaquarks; states formed by quarks and gluons are called hybrid hadrons (i.e. $q\bar{q}g$ is a hybrid meson); and states composed only by gluons are called glue-balls. All these particles are called exotics except for conventional mesons and baryons.

In the last decades new unexpected particles or states have been observed beyond the conventional meson and baryon paradigm [6].

Recently, a new state with four flavour of quarks was observed and reached the international interest due to its unprecedent, the $X(5568)$.

1.3 The $X(5568)$

In February 24, 2016, the D0 Collaboration announced the observation of a new state in the invariant mass spectrum of a system formed by a B_s^0 meson and a $\pi^\pm$, the $X(5568)$ [7]. (details are described in section 1.3.2).

A resonance-like structure was observed with mass $m = 5567.8 \pm 2.9$ (stat) MeV/c² and natural width $\Gamma = 21.9 \pm 6.4$ (stat) MeV/c². This new particle, decaying to $B_s^0 \pi^\pm$, would be made of four different flavours of quarks (u , b , s and d), the first one of its kind. For this reason, this state is so relevant and a lot of efforts are ongoing in order to understand its nature.

On the other hand, the $X(5568)$ could be decaying into $B_s^* \pi^\pm$, $B_s^* \rightarrow B_s^0 \gamma$, with an undetectable low energetic γ , because the mass difference between the B_s^* and B_s^0 mesons is less than 50 MeV [8]. In this case, the structure is shifted, and the actual mass of the particle is around 5616 MeV.

1.3.1 Interpretations

A lot of theoretical work was performed in order to explain the nature of this new state [11, 12]:

The molecular state

Two mesons can be bounded together forming a molecular state. A lot of new particles are candidates to be explained by such a model: $X(3872)$, $Z_c^\pm(4430)$, $Z_b^\pm(10610, 10650)$, $Z_c^\pm(3900)$ and $Z_c^\pm(4020)$.

In the best case, the $X(5568)$ could be composed by B_d and K^- mesons, but the observed mass would be around 200 MeV less than the sum of the masses of the B_d and the K^- . Due to the energy binding being too high to be considered as a real molecular state, some authors tried to save the model making use of very unusual requirements [11, 13].

Threshold effects

Because the observed mass of the $X(5568)$ is near to the mass threshold, around 5506 MeV, some weak coupling could occur that depends on the relative angular momentum between the final states B_s^0 and $\pi^\pm$. The rate enhancements of the two particles grows with phase space but is attenuated due to overlaps of the relevant hadronic wave-functions.

Comparing the signal shape with data from D0, and the shape result from S-wave and P-wave threshold models, Ref. [11] shows that threshold effects can not explain the observed structure.

Cusp effects

Loops diagrams in the relevant process can have singularities that produce peaks in the invariant mass, mainly when the production mechanism involves large mass intermediate states.

For the $X(5568)$, the cusp effect model requires special considerations to give a good explanation of the signal shape and, as result, different structures are predicted than these observed.

Tetraquark

A state composed by four (anti)quarks is allowed in QCD. Nevertheless, the unclear observation of such states raises questions. The reference [11] explored this scenario and found that the $X(5568)$ mass is unexpectendly light for a tetraquark candidate.

On the other hand, tetraquarks models, applied to the $X(5568)$, predict new particles in the $B_s^0\pi^\pm$ spectrum.

At this moment, there is not a good explanation about the nature of the particle observed by the D0 Collaboration.

1.3.2 The D0 observation

Using the Fermilab Tevatron Collider, the D0 Collaboration found evidence of a new resonant state in the $B_s^0\pi^\pm$ invariant mass distribution (see Fig. 1.1). With 10.4 fb^{-1} of $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96 \text{ TeV}$, and reconstructing the decay chain $X \rightarrow B_s^0\pi^\pm$, $B_s^0 \rightarrow J/\psi\phi$, $J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$, D0 measures a mass of $m = 5567.8 \pm 2.9(\text{stat})_{-1.9}^{+0.9}(\text{syst}) \text{ MeV}/c^2$ and natural width of $\Gamma = 21.9 \pm 6.4(\text{stat})_{-2.5}^{+5.0}(\text{syst}) \text{ MeV}/c^2$ for the X particle. The signal has a significance of 5.1σ [7], including systematic uncertainties and look-elsewhere effects. The relative production ρ of the $X(5568)$ with respect the B_s^0 meson, times the branching ratio $\mathcal{B}(X(5568) \rightarrow B_s^0\pi^\pm)$, is measured to be $8.6 \pm 2.4\%$ for $p_T(B_s^0) > 10 \text{ GeV}$ and $8.2 \pm 3.1\%$ for $p_T(B_s^0) > 15 \text{ GeV}$.

The D0 study considers a special requirement on the angle between the B_s^0 meson and the $\pi^\pm$, $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$, where η is the pseudorapidity and ϕ the azimuthal angle. This cut suppresses background in the $B_s^0\pi^\pm$ mass spectrum. Without this “cone cut” the signal significance is 3.9σ .

Because of the observed mass of the $X(5568)$, this state can be interpreted as a tetraquark state with four different flavours and the properties already mentioned.

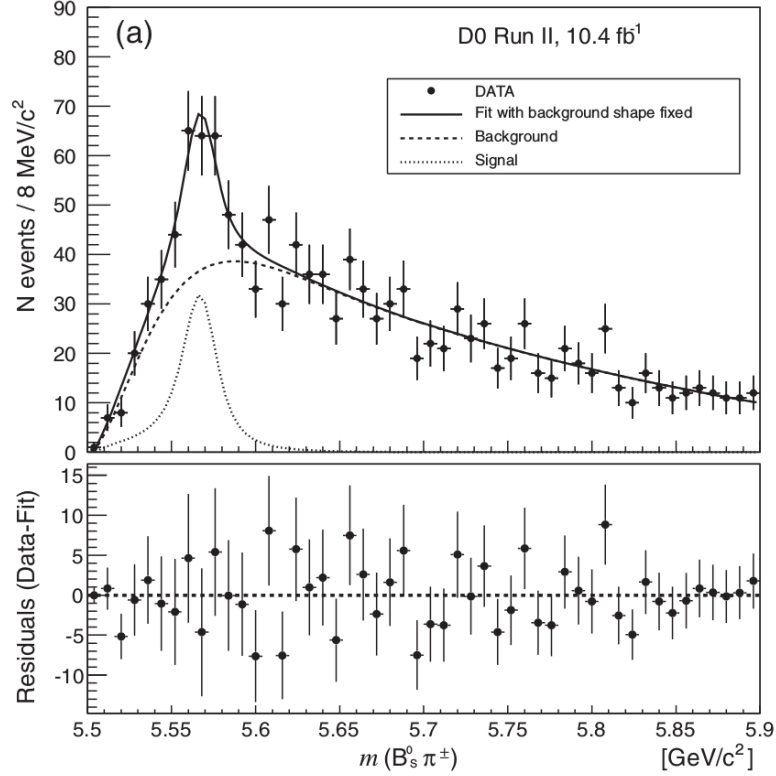


Figure 1.1: D0 observation of the $X(5568)$ state in the $B_s^0\pi^\pm$ invariant mass distribution [7]. The cone cut requirement is applied on this distribution.

1.3.3 The LHCb result

On August 2, 2016, the LHCb Collaboration announced the non-observation of any significant excess in the $B_s^0\pi^\pm$ invariant mass spectrum (see Fig. 1.2) and reported upper limits to the relative production [9]. LHCb, using 3 fb^{-1} of pp collisions at $\sqrt{s} = 7$ and 8 TeV, searched for the $X(5568)$ state decaying into $B_s^0\pi^\pm$ in two different decay channels of the B_s^0 meson: $B_s^0 \rightarrow D_s^- \pi^+$, $D_s^- \rightarrow K^+ K^- \pi^-$ and $B_s^0 \rightarrow J/\psi \phi$, $J/\psi \rightarrow \mu^+ \mu^-$, $\phi \rightarrow K^+ K^-$. With around 7 times more B_s^0 mesons than D0 in the same kinematic region, LHCb did

not find evidence of the claimed $X(5568)$ state and its existence is not confirmed. Even more, the LHCb experiment can extend the kinematic region, including low energetic B_s^0 mesons, resulting in around 20 times more B_s^0 mesons but without clues of the $X(5568)$ state. The limits to the relative production ρ_X , estimated by integration of the likelihood in the positive region whose value is equivalent to 90(95)% of confidence level (CL) are:

$$\rho_X < 1.1(1.2)\% \text{ for } p_T(B_s^0) > 5 \text{ GeV},$$

$$\rho_X < 2.1(2.4)\% \text{ for } p_T(B_s^0) > 10 \text{ GeV},$$

$$\rho_X < 1.8(2.0)\% \text{ for } p_T(B_s^0) > 15 \text{ GeV}.$$

In addition, no significant signal is found at different values of mass and width of a possible state in the $B_s^0\pi^\pm$ invariant mass.

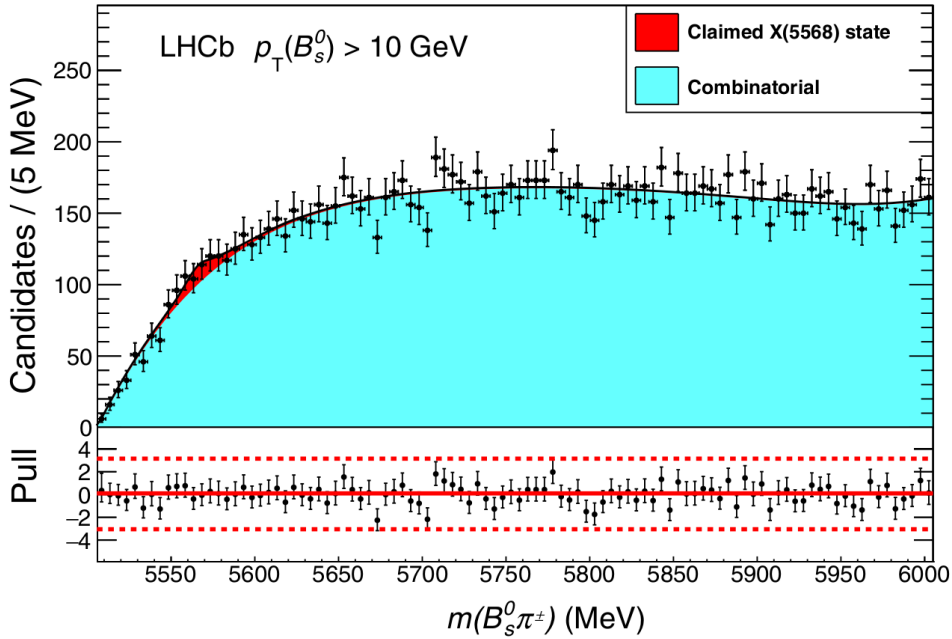


Figure 1.2: The LHCb $B_s^0\pi^\pm$ invariant mass distribution [9].

1.3.4 The CMS result

Recently, on December 17 (2017), CMS results became available to the public: the CMS Collaboration announced the non-observation of the $X(5568)$ state, or any excess, in the $B_s^0\pi^\pm$ invariant mass distribution [10]. With 19.7 fb^{-1} of pp collisions at $\sqrt{s} = 8 \text{ TeV}$, the

CMS experiment searched for the decay $X(5568) \rightarrow B_s^0 \pi^\pm$ ($B_s^0 \rightarrow J/\psi \phi$, $J/\psi \rightarrow \mu^+ \mu^-$, $\phi \rightarrow K^+ K^-$) in the same kinematic region used by D0. The results of this search are documented in the following chapters, with details on the data selection, reconstruction, and analysis.

1.4 Goal

The purpose of this thesis is to describe in detail the search for the $X(5568)$ state at the CMS experiment by investigating the $B_s^0 \pi^\pm$ invariant mass distribution.

The final goal is to report the relative production of the $X(5568)$ with respect to the B_s^0 meson, times the branching fraction of the $X(5568) \rightarrow B_s^0 \pi^\pm$ decay,

$$\begin{aligned} \rho &\equiv \frac{\sigma(pp \rightarrow X(5568) + \text{anything})}{\sigma(pp \rightarrow B_s^0 + \text{anything})} \times \mathcal{B}(X(5568) \rightarrow B_s^0 \pi^\pm) \\ &= \frac{N_{X(5568)}}{N_{B_s^0} \times \epsilon_{rel}} \end{aligned} \quad (1.2)$$

with

$$\epsilon_{rel} \equiv \frac{\epsilon_{X(5568)}}{\epsilon_{B_s^0}}, \quad (1.3)$$

where $N_{X(5568)}$ and $N_{B_s^0}$ are the number of $X(5568)$ and B_s^0 candidates, respectively; $\epsilon_{X(5568)}$ and $\epsilon_{B_s^0}$ are the reconstruction efficiency of each decay channel. All details about the estimation of these parameters are described in this thesis.

Chapter 2

The experiment

Trying to understand the structure of matter, scientist have gone to higher and higher energies to probe the smallest scales of all. With experiments as Rutherford's, the particles are colliding at growing energies and their products give information about the inner structure and, moreover, about how particles are interacting between themselves.

Because the required energies are higher time to time, more powerfull accelerators and more efficient detectors are developed to be able to investigate in depth the nature of the underlying processes.

Currently, the Large Hadron Collider (LHC) is the most powerful particle accelerator in the world and, with its four main experiments, is trying to extend the frontiers of knowledge.

2.1 The LHC

Aiming to find the Higgs particle and study rare events at very high energies, the European Organization for Nuclear Research (CERN) approved by the end of 1994 the construction of the most powerful particle accelerator of the world: the Large Hadron Collider (LHC) [14].

Located at the border of France and Switzerland, near to Geneva city, the LHC is a circular accelerator, Fig. 2.1, built in the tunnel of the old Large Electron-Positron collider (LEP). With around 27 km of circumference and 100 m underground, the LHC collides two counterwise proton beams, injected from the Super Proton Synroton (SPS), at center-of-mass energies of up to 14 TeV and instant luminosity of $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The

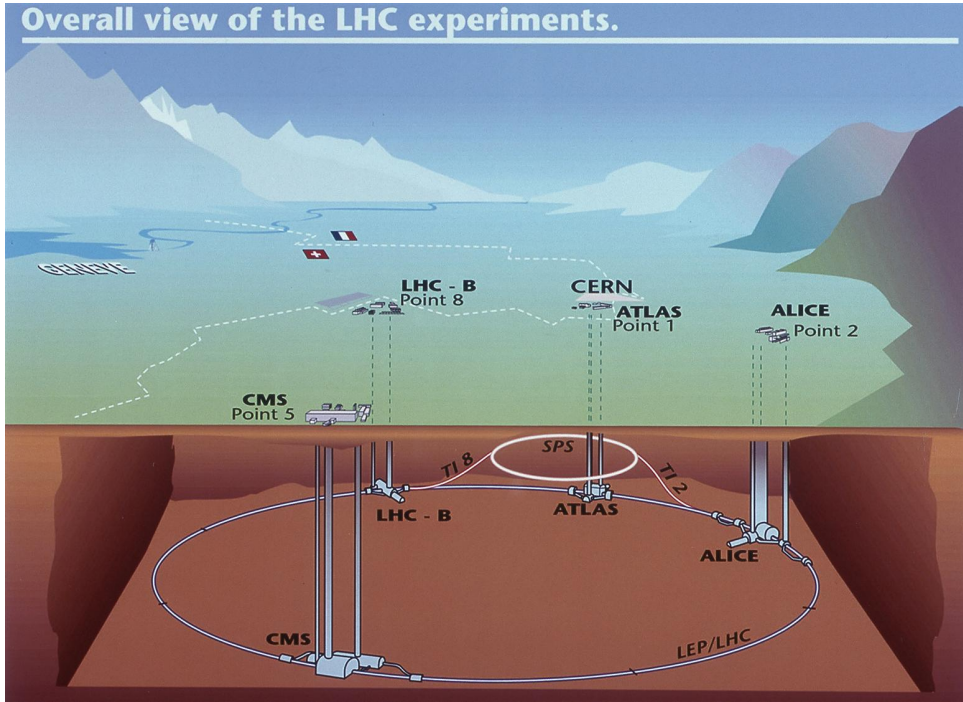


Figure 2.1: Experiments at the Large Hadron Collider (LHC).

LHC also collides heavy ions (Pb nuclei) at an accumulated energy of up to 1150 TeV and instantaneous luminosity of $1 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$.

The first collisions were produced in November of 2009 with a center-of-mass energy of $\sqrt{s} = 0.9 \text{ TeV}$. In March 30, 2010, the LHC started collisions at $\sqrt{s} = 7 \text{ TeV}$; $\sqrt{s} = 8 \text{ TeV}$ in 2012; and currently, since June 3, 2015, at $\sqrt{s} = 13 \text{ TeV}$, starting the second stage of the LHC operation.

The LHC is designed to collide proton beams, with around 1.15×10^{11} particles and every 24.95 ns, in four main experiments along the accelerator: CMS, ATLAS, ALICE and LHCb. Also, two small independent detectors were included in order to give complementary information to other experiments: LHCf and TOTEM.

The *Compact Muon Solenoid* (CMS) and *A Thoroidal LHC Apparatus* (ATLAS) are multi-purpose experiments capable of studying all the physics of interest at the highest energies of the LHC. On the other hand, *A Large Ion Collider Experiment* (ALICE) is an experiment designed to study the quark-gluon state, by ion collisions, in order to understand the conditions at the early universe. Finally, the *Large Hadron Collider beauty experiment* (LHCb) studies b-hadrons in order to understand CP-Violation, matter-antimatter asymmetry, etcetera.

The recent Higgs boson discovery in July 4, 2012, by CMS [10] and ATLAS [3] experiments, shows the great importance of this machine and gives strong support to the SM. Nevertheless, fundamental questions in particle physics and beyond are still pending such as dark-matter, the matter-antimatter asymmetry, the hierarchy problem, extra-dimensions, the neutrino mass, etcetera. So, in order to reach beyond, the LHC is preparing for the next major upgrade: the High Luminosity LHC (HL-LHC) [15], [16]. This new stage of the LHC will reach the $\sqrt{s} = 14$ TeV and a larger instant luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

2.2 The CMS experiment

The Compact Muon Solenoid, CMS, is one of the biggest experiments of the world, and the heaviest, whose purpose is to investigate all the physics reachable by the LHC [17], [18].

Approved on January 1997, the CMS experiment is located near to Cessy village at France in a cavern, 100 m underground, with dimensions of 53 m (length) $\times$ 26.5 m (width) and 24 m of height. CMS weighs 12500 Tons and measures 21.6 m in length and 14.6 m in diameter, and can study both pp and ion collisions.

The CMS detector has a very simple design, shown in Fig. 2.2. The detector is composed by a set of specialized detectors in concentric cylinders (barrels) and disks (endcaps), and with a powerful solenoid. Properties of each subdetector allow a very precise tracking in the inner rings and very fast triggering on muons.

2.2.1 Tracker System

Closer to the interaction point, in the core of the detector, the Inner Tracker System is entirely based on silicon technologies in order to have very high granularity, fast response and radiation hardness. This also provides a very precise and efficient detection of the tracks of charged particles coming from the LHC collisions.

With 5.8 m in length and 2.5 m in diameter, the tracker system is composed by a pixel detector (cell size: $100 \times 150 \mu\text{m}^2$) and a silicon strip tracker.

The pixel detector covers a pseudorapidity region of $|\eta| < 2.5$ by an arrangement of three cylindrical layers surrounding the interaction point with radii 4.4, 7.3 and 10.2 cm, and two disks (endcaps) with radii from 6 to 15 cm located at $z = \pm 34.5$ cm and $z = \pm 46.5$ cm.

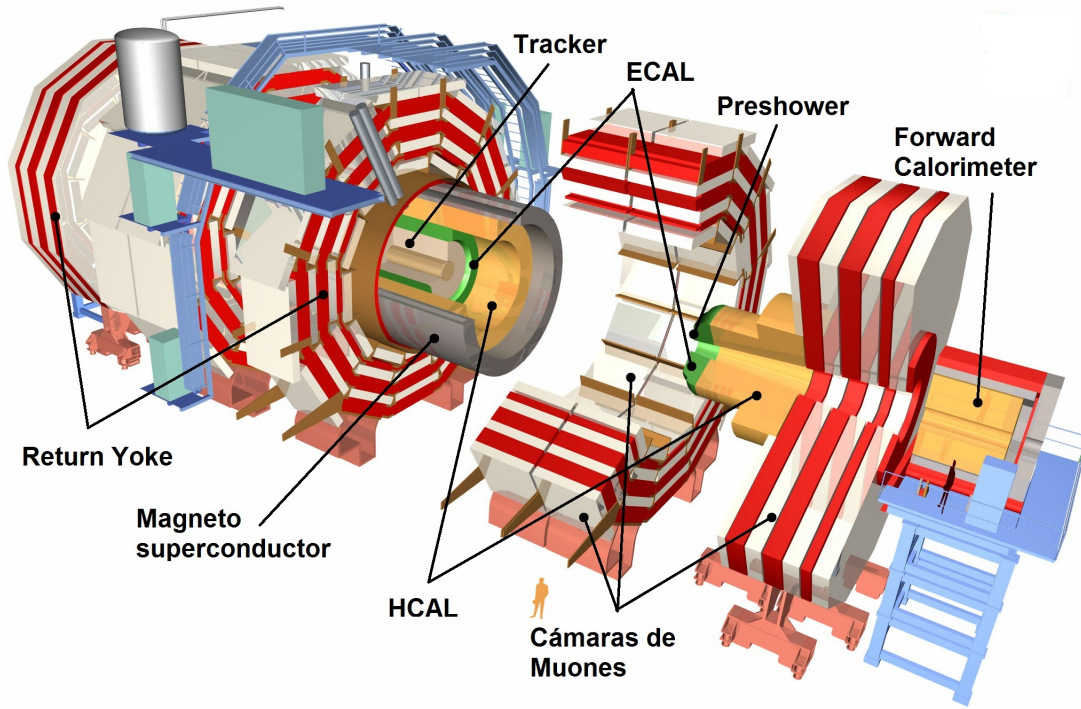


Figure 2.2: The Compact Muon Solenoid (CMS).

cm from the interaction point. This system allows to have three precise tracking points in $r - \phi$ and z directions with enough resolution to reconstruct secondary vertices.

The silicon strip tracker is composed by three different subsystems: the Tracker Inner Barrel and Disks (TIB/TID), which have 4 barrels placed at radii of 25 to 50 cm, and three disks at each end; the Tracker Outer Barrel (TOB) that surrounds the TIB with 6 barrel layers; and the Tracker EndCaps (TEC) that have 9 disks with up to 7 rings of silicon micro-strip detectors each one. The first two layers and rings of TIB, TID and TOB, and rings 1, 2 and 5 of TEC, have a second micro-strip detector in back-to-back way with estereo angle of 100 mrad in order to have a second coordinate. Altogether, the silicon strip tracker covers the region $|\eta| < 2.5$.

2.2.2 ECAL

Surrounding the tracker system, the **Electromagnetic Calorimeter** (ECAL) is designed to measure the energy of electrons, positrons and photons, by using lead tungstate (PbWO_4) crystals in a hermetic homogeneous calorimeter. This allows a good energy resolution to be able to detect the “two-photon decay” of the Higgs boson. The PbWO_4

has a very high density (8.28 g/cm²), a short radiation length (0.98 cm) and a small Molière radius (2.2 cm), needed to obtain good granularity. About 80% of the produced light is emitted in 25 ns, the bunch crossing time of the LHC.

The ECAL is divided in a barrel part and endcaps. The barrel has 61200 crystals, covering a pseudorapidity region $|\eta| < 1.479$, with 23 cm in length each one, and a cross-section of 22×22 mm² (26×26 mm²) in the inner (outer) face. The center of each inner face is located at radius 1.29 m from the beam line. The endcaps have 7324 crystals, covering the region $1.479 < |\eta| < 3.0$ and grouped in units of 5×5 (supercrystals or SCs), with 22 cm in length each one, and cross-section of 28.62×28.62 mm² (30×30 mm²) in the inner (outer) face. With the endcap envelope at 315.4 cm, crystals are focused 130 cm beyond the interaction point, resulting in off-pointing angles between 2-8 degrees. Photons produced in crystals are amplified by Avalanche photodiodes (APDs) in the barrel and by vacuum phototriodes (VPTs) in the endcaps.

In order to reach a better precision, a preshower detector is placed in-front of the endcaps. The main goal is to identify neutral pions toward endcaps in the region $1.653 < |\eta| < 2.6$. It helps to identify electrons against minimum ionizing particles and improves the position determination of electrons and photons.

2.2.3 HCAL

The **Hadron Calorimeter** (HCAL) surrounds the ECAL. It is designed to measure hadronic jets, as well as neutrinos or exotic particles as apparent missing transverse energy. The HCAL is composed by three main parts: barrel (HB), endcaps (HE) and outer (HO).

The HB is placed between the ECAL barrel and the magnet coil, radii in 1.77 and 2.95 m, covering a region of $|\eta| < 1.3$. The HE is designed to minimize cracks between HB and HE and to keep a self-supporting hermetic construction. It is composed by two identical rings (HB+, HB-), each one segmented in 18 parts, each one divided by 4 in ϕ direction. Each part is made of 14 flat brass absorber plates bolted together with scintillator material, divided in tails covering 16 η regions, and stainless steel plates at the ends. The HE covers the rapidity range $1.3 < |\eta| < 3$ with 17 scintillator layers, in 14 η regions, bolted together with brass plates. The HE granularity is $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for $|\eta| < 1.6$ and $\Delta\eta \times \Delta\phi = 0.17 \times 0.17$ for $|\eta| \geq 1.6$.

Because EB and HB do not have enough containment power for hadron showers, the

hadronic calorimeter is extended outside the solenoid with the HO. This employs the magnet coil as absorber and measures the shower energy after HB. It is composed of five rings of scintillators tails, with double layer of scintillator for center ring.

In forward regions, there is a main energy deposition coming from charged hadrons above the Cherenkov threshold. So, the Forward Calorimeter (HF) is located at $z = \pm 11.2$ m. This detector is composed by two cylindrical steel structures with inner/outer radius of 12.5/130 cm from the beam line. It is divided in 18 sectors in the ϕ direction, and uses bundles of quartz-fibers in the beam direction forming towers of an active material with granularity $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$.

2.2.4 The magnet

The superconducting magnet is the main part of the detector. Designed to reach 4 T, is composed by 4 layer of reinforced NbTi conductor in a 6.3 m cold bore, with 12.5 m length and 220 Tons of weight. This allows to have an operational current of 19.14 kA, a stored energy of 2.6 GJ, and inductance of 14.2 H.

The magnetic flux is returned by a 10000 Tons iron-yoke in 5 barrel wheels and 6 endcaps disks, interspersed with muon detectors. The barrel measures 13 m in length, with iron layers thickness of 30, 63 and 63 cm, and the outer layer has a diameter of 14 m. Disks have thickness of 25, 60 and 60 cm.

2.2.5 The Muon System

Located at the most external region, the muon system is the main detector of the experiment. Because muon detection provides good opportunities to study interesting processes at the very high background rate of the LHC, the muon system has three functions: identification, momentum measurement and triggering of muons.

Following the cylindrical design detector, the muon system has a barrel section and two endcaps using three different muon detectors based on gas: Drift Tubes (DTs), Cathode Strip Chambers (CSCs) and Resistive Plate Chambers (RPCs). These detectors are interspersed with the layers of the return yoke.

DTs are gas tubes with wires inside in order to collect the generated charge when muons travel through them. They are located in the barrel region inside and outside the 5 wheels of the return yoke, forming 4 cylindrical layers, and covering a pseudorapidity

region of $|\eta| < 1.2$. For each wheel, the first 3 internal layers have 8 chambers in groups of 4 forming superlayers (SL), to measure the $r - \phi$ coordinate, and 4 chambers to provide the z direction. The external layer only has 8 chambers for the $r - \phi$ coordinate. In total, there are 60 chambers in each internal layer and 70 in the external one. The number of chambers in each layer and their orientation was chosen to match with muons hits from different stations in a single muon track and to reject background hits. The drift cells of each chamber are offset by a half-cell width respect to their neighbor to eliminate dead spots in the efficiency and provides good time resolution.

The CSCs are multiwire chambers between 6 anode wire planes interleaved among 7 cathode panels, wires going in the ϕ direction. They are located in the endcaps covering a region of $0.9 < |\eta| < 2.4$. Each endcap has 4 stations of CSCs with trapezoidal chambers in concentric rings, perpendicular to the beam line and spanning 10° or 20° on ϕ . The CSCs system provides a precise muon measurement and muon triggering with high background rejection and efficient matching of hits to those in other stations and to the inner tracker.

In order to ensure a fast triggering and good p_T resolution measurement, a Resistive Plate Chambers System (RPCs) was added in the barrel and endcap regions, covering a region of $|\eta| < 1.6$. RPCs are gaseous parallel-plate detectors in double-gap chambers operating in avalanche mode to produce fast response and good time resolution at high rates. Although RPCs have larger spatial resolution than CSCs and DTs, this system allows to solve ambiguities with tracks reconstructed from multiple hits in chambers. In the barrel region, there are 6 layers of RPCs, 2 in each of the first 2 stations, and 1 in each of the last 2 stations. In endcaps, there is a RPCs plane in each of the 3 stations. RPCs can recognize the arrival time between 2 consecutive LHC bunch crossings, less than 25 ns.

2.3 The detection process

At these very energetic collisions, a lot of secondary particles are produced that in turn produce more particles by interactions or by decays. Particles go out from the interaction point, and reach the first part of the detector, the tracker. This detects the trace of particles, allowing to reconstruct the trajectory of particles with good accuracy. With the magnetic field, the spiral trajectories give information about the momentum of charged particles passing through the detector.

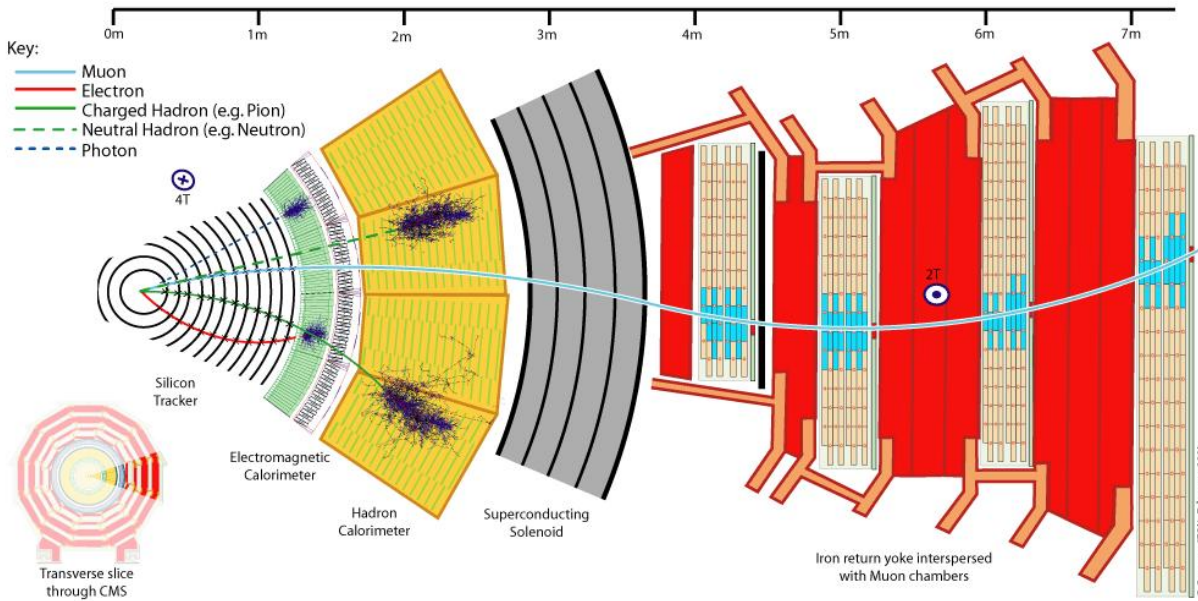


Figure 2.3: Particle detection at CMS.

In the next layers, some particles are absorbed and the energy is measured. In the ECAL, proton, electrons and photons are absorbed; while the HCAL absorbs the energy of hadrons.

In general, only neutrinos and muons can reach the Muon System. Only muons are detected and their trajectories are reconstructed. As mentioned before, RPCs provide a good temporal resolution to use muon signals as trigger. Because neutrinos are weakly interacting and neutrally charged, its presence is inferred as missing momentum in the reconstruction process.

2.4 The Data acquisition

The LHC provides proton-proton and heavy-ions collisions at very high rates. Each collision produces a lot of particles and the number increases with the instantaneous luminosity. With collisions each 25 ns (40 MHz), the LHC generates a large amount of data imposible to store and process. For this reason, the data are reduced in real time selection by the trigger system.

2.4.1 The trigger system

The trigger system is the first part of the physics event selection process, and is divided in two steps: Level-1 Trigger (L1) and High-Level Trigger (HLT). The L1 is based on the detector design and the HLT is on real time analysis in around one thousand commercial processors.

The L1 trigger employs information from the calorimeters and the muon system with local, region and global components. The local triggers, or Trigger Primitive Generators (TPG), are based on energy deposits in calorimeters and on track segments or hit patterns in muon chambers. The regional trigger combines this information to sort out trigger objects, as muon or electron candidates, in limited spatial regions. The rank is determined as function of energy or momentum and quality. The Global Calorimeter and Global Muon Triggers take the highest-rank calorimeter and muon objects and transfer them to the Global Trigger. The global trigger takes the decision to reject or accept an event based on algorithm calculations and the readiness of the sub-detectors and the Data Acquisition system (DAQ). This process reduces the data acquisition up to 100 KHz.

In the HLT, all the events passing the L1 trigger are sent to the computer farm (Event Filter) that performs basic consistency checks and physics selections, using faster versions of the offline reconstruction software, reducing the data rate by a factor of 1000. This stage also generates, collects and distributes the Data Quality Monitoring (DQM) information of the event.

Chapter 3

Data selection

3.1 The decay reconstruction

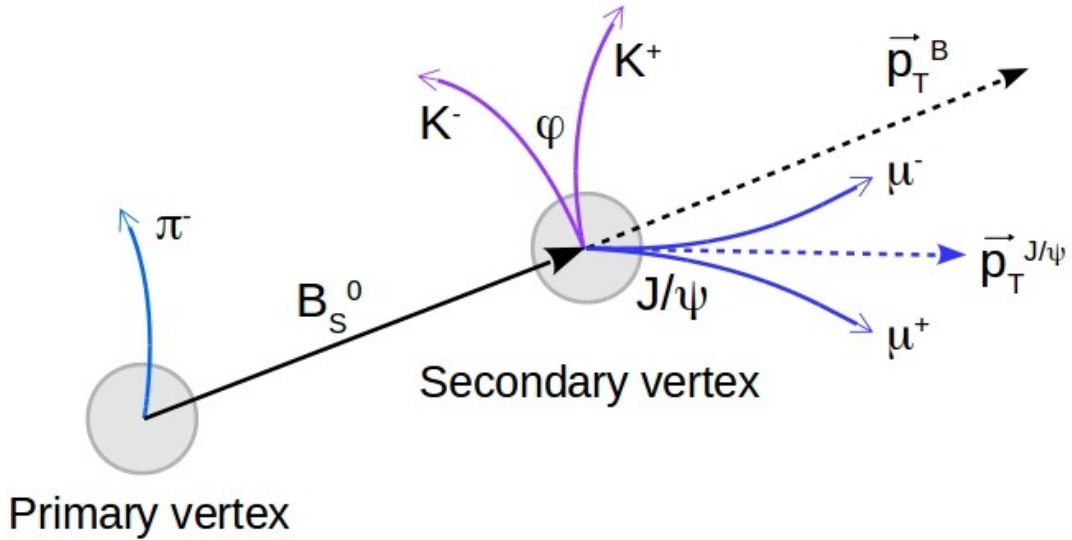


Figure 3.1: Decay channel of the $X(5568) \rightarrow B_s^0 \pi^\pm$.

Our goal is to study the invariant mass distribution of the $B_s^0 \pi^\pm$ candidates collected by the CMS experiment. We assume that the proton-proton collisions produce the $X(5568)$ state decaying through the chain $X(5568) \rightarrow B_s^0 \pi^\pm$, $B_s^0 \rightarrow J/\psi \phi$, $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$, as shown in Fig. 3.1.

Only five final particles are detected: muons, kaons and the pion. The L1 triggers filter events with at least one muon, and the HLT triggers filter events for different kind

of physics. For B-physics studies, processes involving hadrons with b-quark content are of interest. There exist a special HLTs to select events with a dimuon system $\mu^+\mu^-$, since some B-hadrons decaying to $J/\psi \rightarrow \mu^+\mu^-$.

For each event, muons are detected by the muon system and matched to hits in the tracker system. These objects are the muon track candidates and are stored in the muon-track collection of the event. Tracks without connection to the muon system are stored in a generic track collection. Some of these tracks are used as kaons and pions. Some kinematic and quality criteria are applied to reject background events. At the end, particles are reconstructed in each step of the decay chain by forming vertices with the tracks.

3.2 MC samples

Simulated Monte Carlo (MC) samples are necessary to calculate the detector reconstruction efficiency of the decay channels used in this analysis.

An inclusive MC sample of $B_s^0 \rightarrow J/\psi\phi$ ($J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$), at $\sqrt{s} = 8$ TeV, was available with about 4M of events. This was generated with kinematic requirements of $p_T(\mu^\pm) > 3.5$ GeV, $|\eta(\mu^\pm)| < 2.5$, $p_T(K^\pm) > 0.4$ GeV and $|\eta(K^\pm)| < 2.5$.

Also, $X(5568)$ events are produced for this analysis using PYTHIA v6.424 [19]. The $X(5568)$ is simulated as a spinless particle of mass and width equal to the D0 measurement: 5568 MeV and 21.9 MeV, respectively, and is decayed to a B_s^0 meson and a charged pion using EVTGEN [20]. EVTGEN generates masses values according to a non-relativistic Breit-Wigner function, from the threshold up to the value that leaves a symmetric distribution, as shown in Fig. (3.2). For the B_s^0 signal generation, the EVTPVVCPLH module in EVTGEN simulates the double vector decay considering mixing and CP-violating effects. Final-state radiation is included using PHOTOS [21], [22]. The generated events are passed to a detailed simulation of the CMS detector using GEANT4 [23], including additional interactions due to peripheral pp collisions in each bunch crossing (pileup).

The $X(5568) \rightarrow B_s^0\pi^\pm$ MC sample, generated using a phase space decay model (PHSP) to decay the $X(5568)$ and realistic decay models for $B_s^0 \rightarrow J/\psi\phi$, $J/\psi \rightarrow \mu^+\mu^-$, $\phi \rightarrow K^+K^-$ as described in detail in Appendix A, has around 18 M events with the following kinematic requirements: $p_T(\mu^\pm) > 3.5$ GeV, $|\eta(\mu^\pm)| < 2.7$, $p_T(K^\pm) > 0.4$ GeV, $|\eta(K^\pm)| < 2.5$ and $|\eta(\pi^\pm)| < 3.5$.

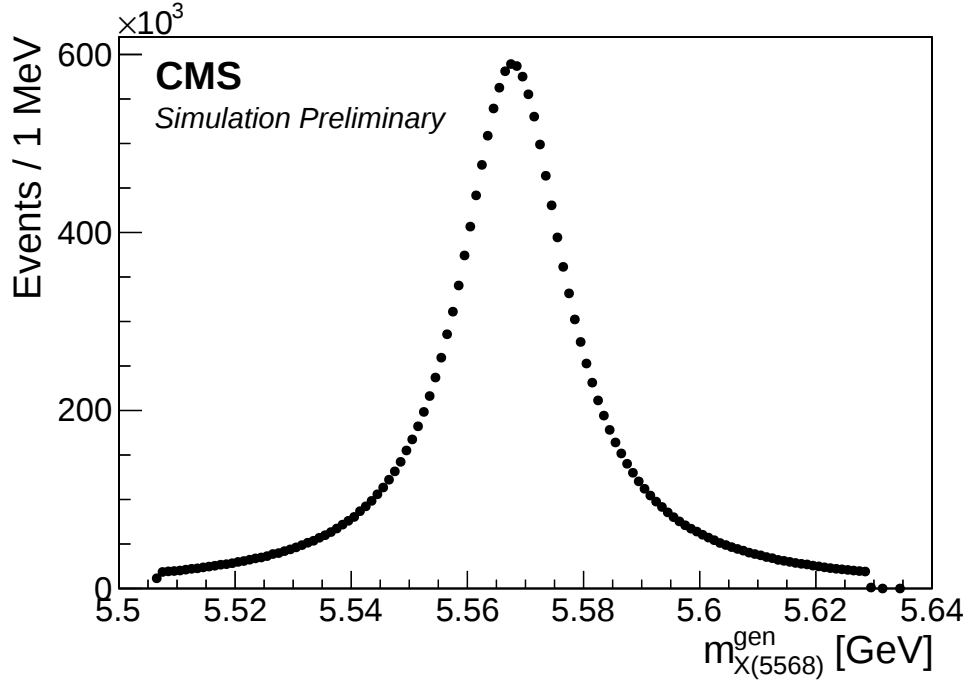


Figure 3.2: The $X(5568)$ mass distribution at generator level.

3.3 Data samples

The data employed for this analysis was collected by the CMS experiment during the LHC Run I in 2012 with a center-of-mass energy of $\sqrt{s} = 8$ TeV. This corresponds to an integrated luminosity of 19.7 fb^{-1} (see Table 3.1).

The data sample was collected using the High Level Trigger terms “HLT_DoubleMu4_JpsiDisplaced_v[9-12]”, selecting events with two muons consistent with originating from a J/ψ meson and decaying at a significant distance from the beamspot. The beamspot represents the most probable collision point in a luminous region covering 68% of the pp collisions in each dimension.

3.4 B_s^0 selection

In reference [24], CMS used the decay $B_s^0 \rightarrow J/\psi \phi$ ($J/\psi \rightarrow \mu^+ \mu^-$, $\phi \rightarrow K^+ K^-$) to measure the CP-violating phase ϕ_s . In this analysis, similar selection criteria are used to reconstruct the B_s^0 candidates.

The reconstruction requires two muons of opposite charge that must match those that triggered the event readout. Since the trigger requirements change depending on the

Samples	Inst. lumi. [fb ⁻¹]
/MuOnia/Run2012A-22Jan2013-v1/AOD	0.876
/MuOnia/Run2012B-22Jan2013-v1/AOD	4.412
/MuOnia/Run2012C-22Jan2013-v1/AOD	7.054
/MuOnia/Run2012D-22Jan2013-v1/AOD	7.363
JSON file:	
Cert-190456-208686-8TeV-22Jan2013ReReco-Collisions12-JSON.txt	

Table 3.1: Data samples for pp collisions at $\sqrt{s} = 8$ TeV by CMS

instantaneous luminosity, the muon offline selection is more restrictive:

- $p_T(\mu^\pm) > 4$ GeV,
- $|\eta(\mu^\pm)| < 2.2$,
- $p_T(\mu^+\mu^-) > 7$ GeV,
- dimuon vertex χ^2 fit probability $P_{vtx}(\mu^+\mu^-) > 10\%$,
- distance between the beamspot and the reconstructed dimuon vertex positions in the transverse plane $L_{xy}(\mu^+\mu^-) > 3\sigma_{L_{xy}(\mu^+\mu^-)}$,
- cosine of the dimuon candidate pointing angle to the beam spot
 $\cos(\vec{L}_{xy}(\mu^+\mu^-), \vec{p}_T(\mu^+\mu^-)) > 0.9$. The pointing angle is the angle between the $\mu^+\mu^-$ candidate momentum in the transverse (xy) plane and the vector from the beamspot position to the reconstructed dimuon vertex in transverse plane.
- dimuon invariant mass $M(\mu^+\mu^-)$ in the region (3.04, 3.15) GeV.

In addition, the reconstruction requires two oppositely charged tracks assumed to be kaons with $p_T(K^\pm) > 0.7$ GeV.

Muons and kaons candidates must also satisfy general muon identification and high quality track requirements, respectively. For muon and kaon tracks, these includes hits in at least six (two) strip (pixel) silicon layers; moreover, for muons they impose a minimum number of hits in a muon chamber (at least one muon segment) and a transverse (longitudinal) impact parameter $d_{xy(z)}(\mu^\pm) < 0.3$ (20) cm (determined from the associated

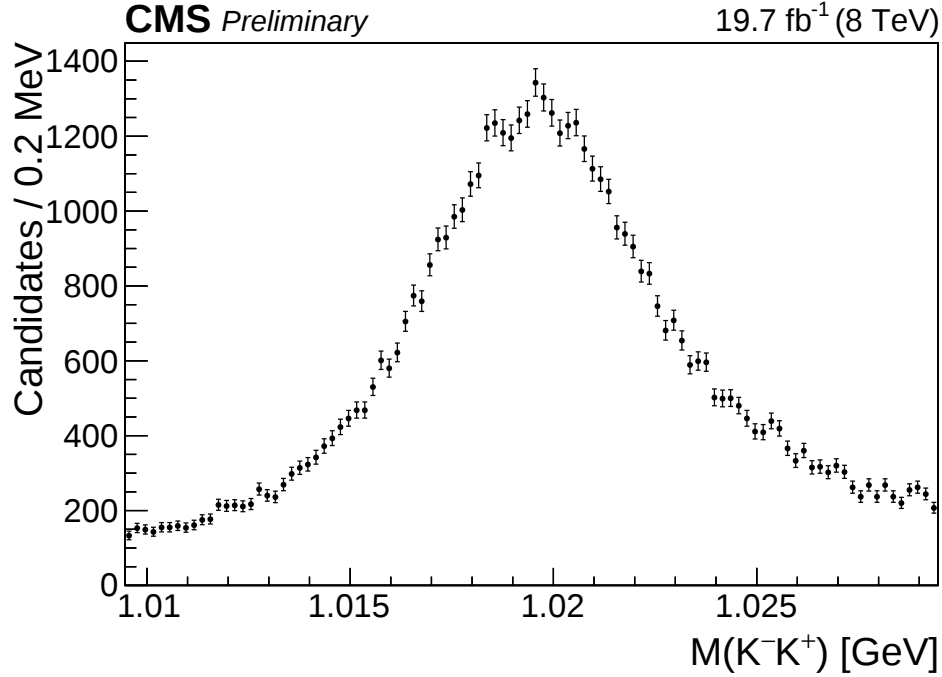


Figure 3.3: K^+K^- invariant mass distribution from the selected $B_s^0 \rightarrow J/\psi\phi$.

tracker track). Kaon candidates that are identified in the muon chambers are rejected. The invariant mass of a kaon pair, $M(K^+K^-)$, is required to be within 10 MeV of the world-average (W.A.) $\phi(1020)$ mass [8] (see Fig. 3.3).

The B_s^0 candidates are obtained by performing a kinematic vertex fit to the four muon and kaon tracks that constrains the dimuon invariant mass to the W.A. J/ψ mass [8] within the experimental energy resolution. The same criteria imposed on the distance and pointing angle of the dimuon candidates with respect to the beamspot are now required for the B_s^0 candidates with respect to the primary vertex (PV) interaction. From all reconstructed pp collision points, the PV is chosen as the one with the largest cosine of the B_s^0 pointing angle. The pointing angle is the angle between B_s^0 candidate momentum and the vector from the PV to the reconstructed B_s^0 candidate vertex. Furthermore, if in this procedure any of the four tracks used in the B_s^0 candidate reconstruction are included in the fit of the chosen PV, they are removed, and the PV is refitted. The B_s^0 candidates are required to have

- $p_T(B_s^0) > 10$ GeV,
- $P_{vtx}(\mu^+\mu^-K^+K^-) > 1\%$,

- $\cos(\vec{L}_{xy}(B_s^0), \vec{p}_T(B_s^0)) > 0.99$,
- and $M(J/\psi K^+ K^-)$ in (5.2, 5.55) GeV.

3.5 $B_s^0 \pi$ selection

The $X(5568)$ state is supposed to be produced at the PV and then strongly decaying to $B_s^0 \pi^\pm$. Thus, its production point and its decay vertex virtually coincide. Therefore, the daughter pion is required to be a track used in the PV fit. The pion candidate is required to have $p_T(\pi^\pm) > 0.5$ GeV/ c and to pass the standard high quality and purity track requirements. The invariant mass of the $B_s^0 \pi^\pm$ candidate is defined as $M^\Delta(B_s^0 \pi^\pm) = \Delta M + m_{B_s^0}^{PDG}$, where $\Delta M = M(J/\psi K^+ K^- \pi^\pm) - M(J/\psi K^+ K^-)$ and $m_{B_s^0}^{PDG}$ is the W.A. B_s^0 mass [8]. This definition improves the invariant mass resolution. Similar to D0, this analysis explores a $M^\Delta(B_s^0 \pi^\pm)$ region between 5.5 and 5.9 GeV/ c^2 .

All requirements for the $B_s^0 \pi^\pm$ candidates are summarized in Table 3.2.

Reconstructed candidate	Observable	Requirement
$J/\psi \rightarrow \mu^+\mu^-$	Muon trigger matching	True
	$p_T(\mu^\pm)$	> 4 GeV
	$ \eta(\mu^\pm) $	< 2.2
	$p_T(\mu^+\mu^-)$	> 7 GeV
	$P_{vtx}(\mu^+\mu^-)$	$> 10\%$
	$L_{xy}(\mu^+\mu^-)/\sigma_{L_{xy}(\mu^+\mu^-)}$	> 3
	$\cos(\vec{L}_{xy}(\mu^+\mu^-), \vec{p}_T(\mu^+\mu^-))$	> 0.9
	$M(\mu^+\mu^-)$	in (3.04, 3.15) GeV
	Muon-ID	Soft
$\phi \rightarrow K^+K^-$	$p_T(K^\pm)$	> 0.7 GeV
	Track quality	High-purity
	$M(K^+K^-)$	$m_{\phi(1020)}^{PDG} \pm 10$ MeV
$B_s^0 \rightarrow J/\psi\phi$	$p_T(B_s^0)$	> 10 GeV
	$P_{vtx}(\mu^+\mu^-K^+K^-)$	$> 1\%$
	$L_{xy}(B_s^0)/\sigma_{L_{xy}(B_s^0)}$	> 3
	$\cos(\vec{L}_{xy}(B_s^0), \vec{p}_T(B_s^0))$	> 0.99
	$M(J/\psi K^+K^-)$	in (5.20, 5.55) GeV
$B_s^0\pi^\pm$	$\pi^\pm$ track	Used in the PV fit
	$p_T(\pi^\pm)$	> 0.5 GeV
	Track quality ($\pi^\pm$)	High-purity
	$M(J/\psi K^+K^-)$ (signal region)	$m_{B_s^0}^{fit} \pm 2\sigma_{eff}$
	$M^\Delta(B_s^0\pi^\pm)$	in (5.5, 5.9) GeV

Table 3.2: Summary of the event selection requirements used to study the B_s^0 and the $B_s^0\pi^\pm$ invariant mass distributions.

Chapter 4

The $B_s^0\pi^\pm$ invariant mass

This chapter presents an analysis of the selected data previously described in order to investigate the $B_s^0\pi^\pm$ invariant mass distribution with the CMS experiment. Data from pp collisions at $\sqrt{s} = 8$ TeV was collected in 2012 and corresponds to an integrated luminosity of 19.7 fb^{-1} .

4.1 The B_s^0 invariant mass distribution

The selection criteria used to reconstruct the B_s^0 candidates are described in section 3.4. In this case, the B_s^0 invariant mass distribution is investigated.

Considering a double-Gaussian model for the signal, and an exponential function for the background, an extended unbinned maximum-likelihood fit to the $J/\psi K^+ K^-$ invariant mass distribution results in a yield of 49277 ± 278 B_s^0 signal candidates. The Fig. 4.1 shows the fit result. These yields can be compared to the D0 and LHCb B_s^0 yields of about 5600 and 41600 events, respectively, and for $p_T(B_s^0) > 10$ GeV [7, 9].

In addition, signal and background sidebands mass regions are defined as

- Signal: $|M(J/\psi K^+ K^-) - m_{B_s^0}^{fit}| < 2\sigma_{eff}$,
- Background: $4 < \sigma_{eff}|M(J/\psi K^+ K^-) - m_{B_s^0}^{fit}| < 10\sigma_{eff}$,

with an effective resolution given by

$$\sigma_{eff} = [(1-f)\sigma_1^2 + f\sigma_2^2]^{1/2} \simeq 14.02 \text{ MeV}, \quad (4.1)$$

where σ_1 , σ_2 , $(1-f)$ and f , are the standard deviations and fractions of the first and second B_s^0 signal Gaussian, respectively, and the $m_{B_s^0}^{fit}$ is the common fitted mean value

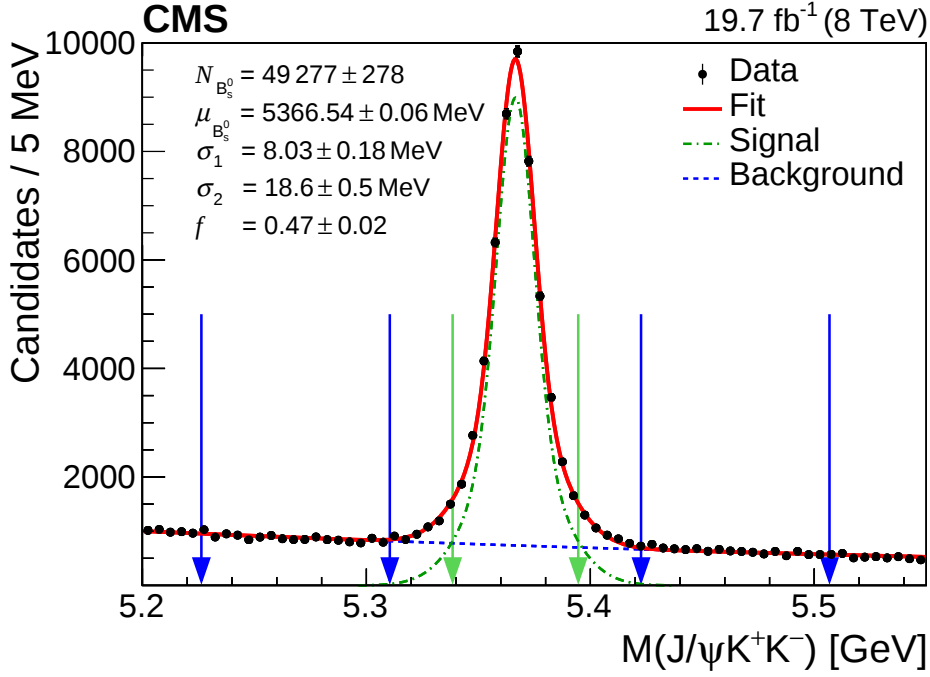


Figure 4.1: Invariant mass distribution of $B_s^0 \rightarrow J/\psi\phi$ candidates with fit results superimposed. The signal and sidebands regions are defined between green and blue lines, respectively.

of the double-Gaussian function. With 46222 ± 261 candidates in the signal region, and 8277 ± 45 in the background, the purity of this sample is about 85%.

4.2 The $B_s^0\pi^\pm$ invariant mass distribution

Now, the $B_s^0\pi^\pm$ invariant mass distribution is investigated. $B_s^0\pi^\pm$ candidates are reconstructed with the selection criteria described in section 3.5 and the invariant mass of $B_s^0\pi^\pm$ candidates is used as $M^\Delta(B_s^0\pi^\pm)$.

The $M^\Delta(B_s^0\pi^\pm)$ distribution obtained from events in the B_s^0 signal region is compared with the one obtained from sidebands regions after normalization, see Fig. 4.2. As can be seen, there are not significant differences between these two distributions. In other words, the $M^\Delta(B_s^0\pi^\pm)$ distribution using mainly real B_s^0 candidates is approximately indistinguishable from the distribution using fake B_s^0 candidates from the B_s^0 sidebands. Then, neither distribution shows any excess around the mass of the state claimed by the D0 Collaboration (which is marked by the red vertical band in Fig. 4.2).

D0 observes a peak in the $B_s^0\pi^\pm$ invariant mass distribution when a limit is imposed

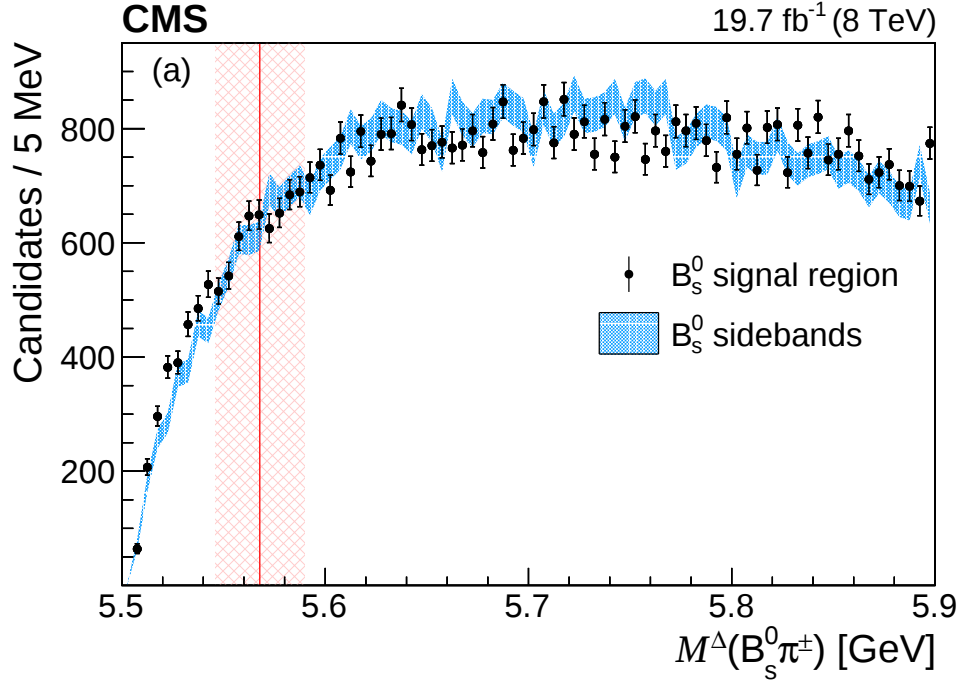


Figure 4.2: The $M^\Delta(B_s^0\pi^\pm)$ distribution for events in the B_s^0 signal (points) and sideband regions (band). The latter is normalized to the first one. The vertical band indicates the region $m_X \pm \Gamma_X$.

on the difference between the directions of the B_s^0 and pion candidates, even when this cut is not employed. This controversial cut is not considered in the baseline selection.

4.3 Validity of the reconstruction procedure

The requirement on the invariant mass $M(K^+K^-)$ avoids contaminations from $B^0 \rightarrow J/\psi K^+\pi^-$ decays to the $B_s^0\pi^\pm$ sample; the pion could be misreconstructed as a kaon. So, in order to verify the reconstruction procedure this requirement is completely removed.

Using an official simulated dataset of $B^0 \rightarrow J/\psi K^+\pi^-$ at $\sqrt{s} = 8$ TeV, the pion is misreconstructed as a kaon and it is combined with the real kaon and the J/ψ to form the $B_s^0 \rightarrow J/\psi K^+K^-$. So the Fig. 4.3 shows the contribution to the $B_s^0 \rightarrow J/\psi K^+K^-$ invariant mass distribution coming from a misidentification of the $B^0 \rightarrow J/\psi K^+\pi^-$ sample. It is clear that, while the contribution to the left B_s^0 sideband is relatively small, there are significant contributions to the signal and right sideband B_s^0 regions.

The effect of removing the $M(K^+K^-)$ requirement from the baseline selection is also investigated on data. The Fig. 4.4(a) shows the $B_s^0 \rightarrow J/\psi K^+K^-$ invariant mass distri-

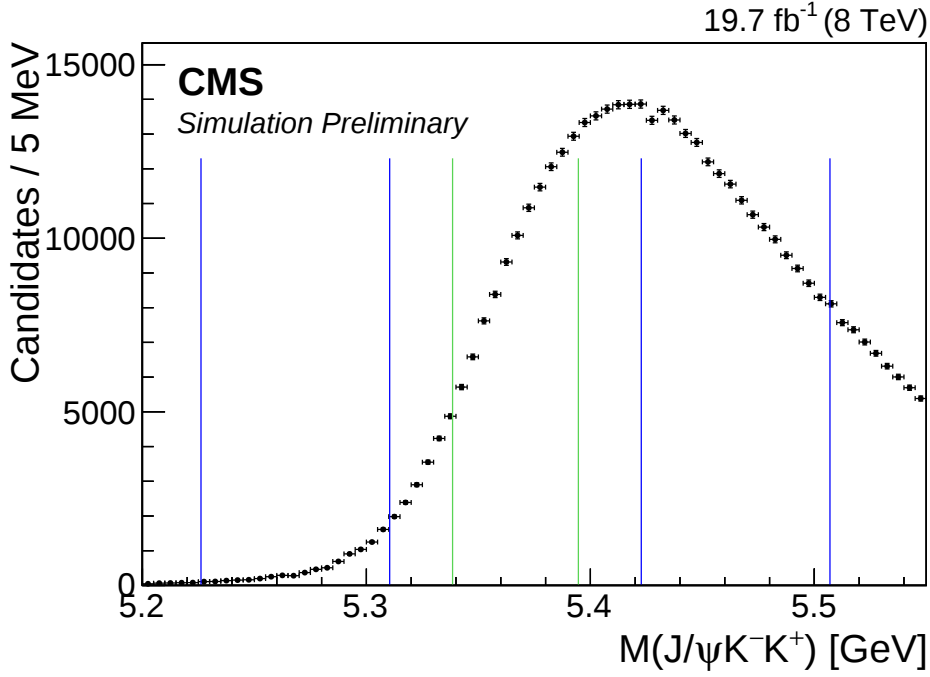


Figure 4.3: Contribution from a simulated $B^0 \rightarrow J/\psi K^+ \pi^-$ sample to the $J/\psi K^+ K^-$ invariant mass distribution. Outermost blue lines define the left and right B_s^0 sidebands, while green lines delimit the B_s^0 signal region.

bution reconstructed without the $M(K^+ K^-)$ requirement, and harder kinematic requirements are imposed in order to suppress the background component ($p_T(B_s^0) > 25$ GeV, $p_T(\pi^\pm) > 1$ GeV and $p_T(K^\pm) > 1$ GeV). So, this plot exposes a broad contribution from the $B^0 \rightarrow J/\psi K^+ \pi^-$ decay (and from the charge-conjugate decay).

On the other hand, the Fig. 4.4(b) shows $M^\Delta(B_s^0 \pi^\pm)$ distributions from signal, left and right sidebands B_s^0 regions, without the $M(K^+ K^-)$ requirement in the baseline selection, harder kinematic requirements are applied in order to make the excess more visible and to suppress the background components ($p_T(B_s^0) > 25$ GeV, $p_T(\pi^\pm) > 1$ GeV and $p_T(K^\pm)$). This excess can be explained by the decays $B_1(5721)^+ \rightarrow B^{*0} \pi^+$, $B_2^*(5747)^+ \rightarrow B^{*0} \pi^+$ and $B_2^*(5747)^+ \rightarrow B^0 \pi^+$, where the decay $B^0 \rightarrow J/\psi K^+ \pi^-$ is misreconstructed as $B_s^0 \rightarrow J/\psi K^+ K^-$ (the charge-conjugate decays are implied, and photons from $B^{*0} \rightarrow B^0 \gamma$ decays are not reconstructed). As expected, the peaks resulting from the before mentioned $B_{1,2}^{(*)+} \rightarrow B^{(*)0} \pi^+$ decays are shifted in the $M^\Delta(B_s^0 \pi^\pm)$ mass distribution by a mass difference around $m_{B_s^0} - m_{B^0}$ from their nominal positions as long as they are correctly reconstructed as $B_s^0 \pi^\pm$.

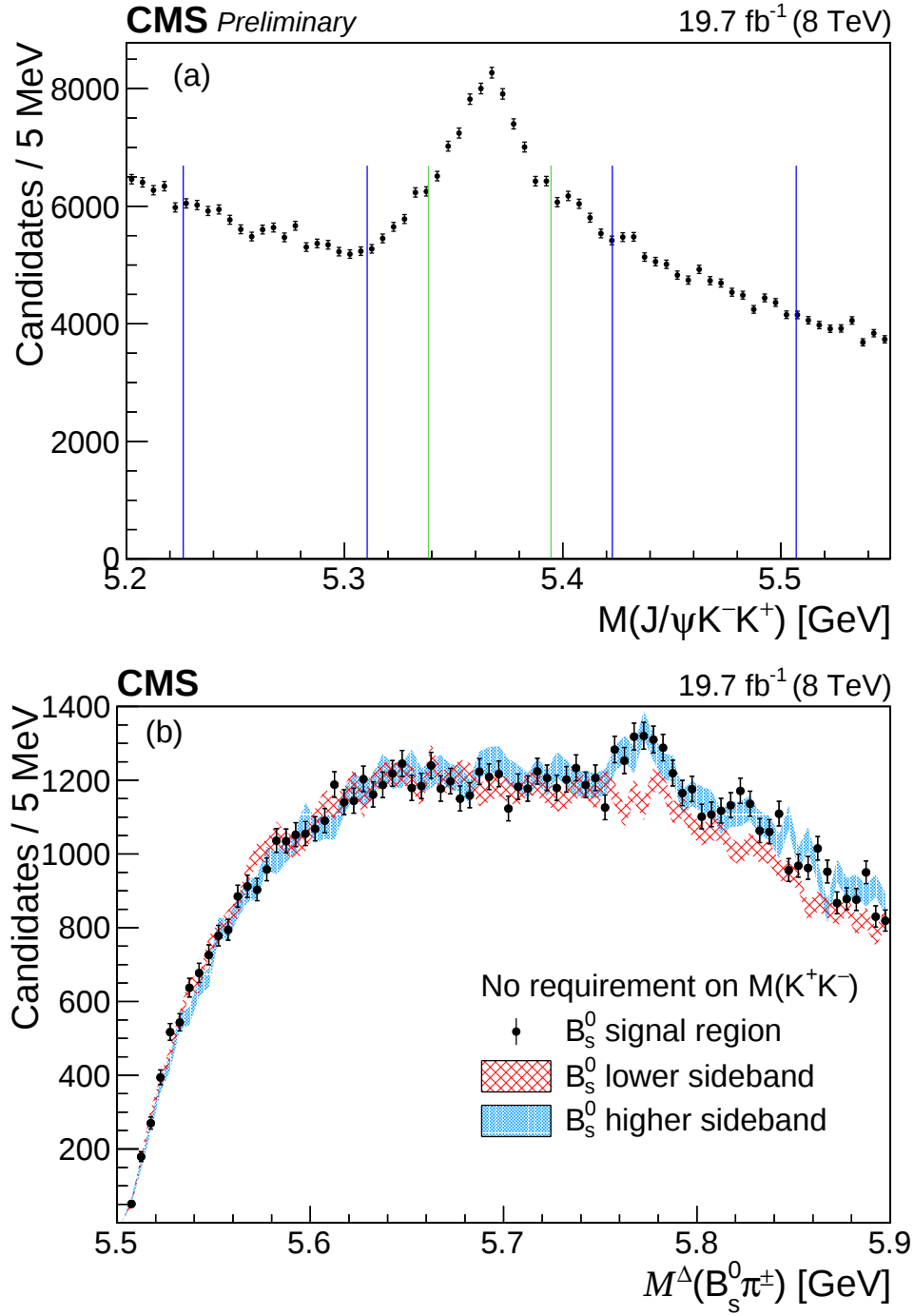


Figure 4.4: From data and without the $K^+ K^-$ invariant mass window:

(a) $J/\psi K^+ K^-$ invariant mass distribution. Outermost blue lines define the left and right B_s^0 sidebands, while green lines delimit the B_s^0 signal region. (b) $M^\Delta(B_s^0 \pi^\pm)$ distribution from signal, left sideband and right sideband B_s^0 regions. All distributions are equally normalized from the mass threshold up to 5.74 GeV. An expected contribution from $B_{1,2}^{(*)+} \rightarrow B^{(*)0} \pi^+$ decays (and the charge-conjugated ones) are clearly seen around $M^\Delta(B_s^0 \pi^\pm) \sim 5.77$ GeV and higher masses coming only from the signal and right sideband B_s^0 region. In both plots, harder kinematic requirements are imposed (see text).

4.3.1 Event multiplicity

Multiple B_s^0 candidates in an event can be excluded from the $B_s^0 \rightarrow J/\psi\phi$ selection by choosing the candidate with the largest 4-track vertex fit probability. The fit to the $J/\psi K^+K^-$ mass distribution, Fig. 4.1, results in a yield of 49277 ± 278 B_s^0 signal candidates and 49268 ± 277 after choosing only one candidate per event, Fig. 4.5(a). The B_s^0 yield decreases by less than 0.02% when multiplicity is removed. Then multiple B_s^0 entries are negligible.

The average multiplicity of $B_s^0\pi^\pm$ candidates from the B_s^0 signal region is 1.8, and it is almost entirely due to several pions combined with a single B_s^0 candidate. The multiplicity of the $B_s^0\pi^\pm$ candidates from the B_s^0 signal region is shown in Fig. 4.5(b). This multiplicity can be removed by choosing the largest $B_s^0\pi^\pm$ vertex fit probability $P_{vtx}(B_s^0\pi^\pm)$.

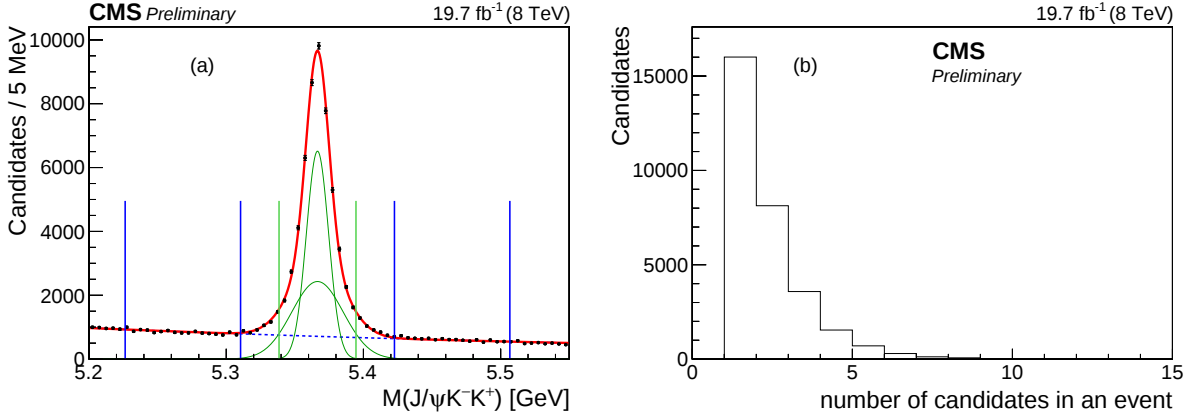


Figure 4.5: (a) Fit to $M(J/\psi K^+K^-)$ invariant mass distribution with multiple candidates removed. (b) Multiplicity of $B_s^0\pi^\pm$ candidates.

4.4 Fit to the $B_s^0\pi^\pm$ invariant mass

4.4.1 The mass resolution

The resolution distribution of the $B_s^0\pi^\pm$ invariant mass is obtained by subtracting, for each event, the generator-level $X(5568)$ mass (Fig. 3.3) from the value obtained after reconstruction: $M^\Delta(B_s^0\pi^\pm) - m_{X(5568)}^{\text{gen}}$. As shown in Fig. 4.6, this distribution is fitted with a triple-Gaussian function, resulting in an effective resolution of

$$\sigma_{eff}^{X(5568)} = [f_1\sigma_1^2 + f_2\sigma_2^2 + (1 - f_1 - f_2)\sigma_3^2]^{1/2} = 2.240 \pm 0.003 \text{ MeV}. \quad (4.2)$$

The $B_s^0\pi^\pm$ invariant mass resolution is fitted in several regions resulting that the resolution varies slowly throughout the mass region (results are presented in appendix B). Therefore, the resolution function is considered to be mass-independent in the fit to data. Alternative resolution functions are considered to evaluate a systematic uncertainty due to a mass-dependent resolution. Additionally, the resolution is basically unchanged if the cut $p_T(B_s^0) > 15 \text{ GeV}$ is applied.

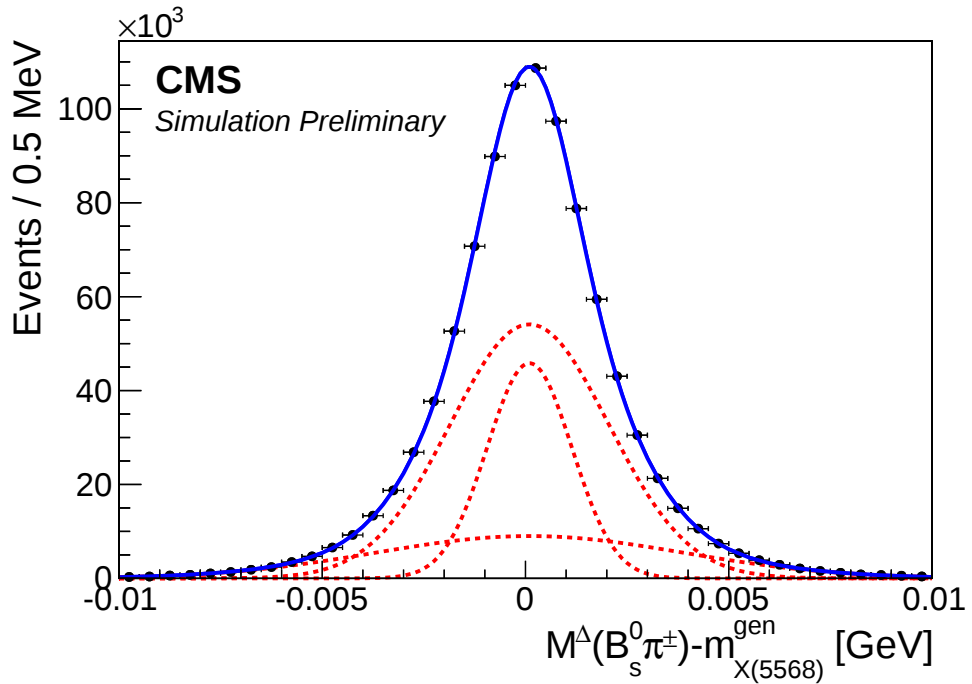


Figure 4.6: Fit of the $B_s^0\pi^\pm$ invariant mass resolution distribution with a triple-Gaussian function.

4.4.2 Mass-dependent efficiency

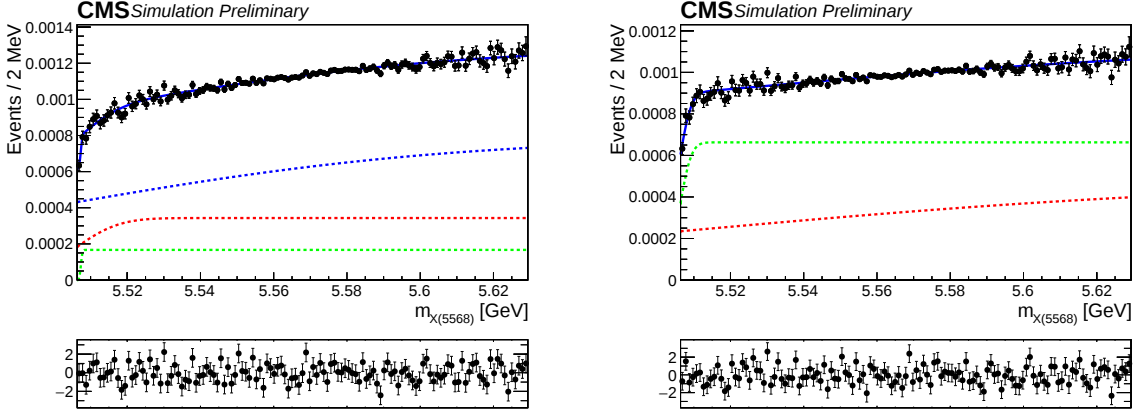


Figure 4.7: Efficiency in bins of the $B_s^0\pi^\pm$ invariant mass for (a) the baseline selection with $p_T(B_s^0) > 10$ GeV and (b) $p_T(B_s^0) > 15$ GeV. The efficiency clearly depends on $p_T(B_s^0)$.

The signal shape of a possible resonance in data must take into account the variation of the reconstruction efficiency along the $B_s^0\pi^\pm$ mass spectrum.

The efficiency is defined as the ratio of mass histograms between reconstructed events and events at generator level (without filters). Since it is possible to match the reconstructed decays to the corresponding generated particles, the true $X(5568)$ mass is used instead of the reconstructed $B_s^0\pi^\pm$ mass to avoid resolution effects. The efficiency as a function of mass obtained with the baseline selection is shown in Fig. 4.7. It is observed to fall close to the threshold and seems to saturate at high mass, faster for large values of $p_T(B_s^0)$. The efficiency is assumed to plateau at high $B_s^0\pi^\pm$ mass¹ and, hence, it is modeled by a superposition of error-functions:

$$\begin{aligned} \varepsilon(x) = f_1 \left[1 + \operatorname{erf} \left(\frac{x - a_1}{a_2} \right) \right] + f_2 \left[1 + \operatorname{erf} \left(\frac{x - a_4}{a_5} \right) \right] \\ + (1 - f_1 - f_2) \left[1 + \operatorname{erf} \left(\frac{x - a_7}{a_8} \right) \right], \end{aligned} \quad (4.3)$$

¹The efficiency shape for mass values greater than ~ 5.64 GeV cannot be determined directly from the official $X(5568)$ MC due to a cut introduced by EVTGEN (see Appendix A). Possible variations of the efficiency with respect to the curve extrapolation of Eq. (4.3) at high invariant mass are expected to have a negligible effect on the signal yield determination, since they only affect the far tail of the Breit-Wigner function.

where x is the (true) $B_s^0\pi^\pm$ invariant mass; $a_{1,2}$, $a_{4,5}$, $a_{7,8}$ are parameters of each error function, and $f_{1,2}$ fractions. Fit results are summarized in Table 4.1.

Table 4.1: Fit results of the efficiency obtained for the baseline selection ($p_T(B_s^0) > 10$ GeV) and a tighter selection with $p_T(B_s^0) > 15$ GeV.

	$p_T(B_s^0) > 10$ GeV	$p_T(B_s^0) > 15$ GeV
a_1	5.50736 ± 0.00089	5.5060 ± 0.0015
a_2	0.00048 ± 0.00081	0.0036 ± 0.0013
a_4	5.505 ± 0.013	5.505 ± 0.087
a_5	0.0137 ± 0.0079	0.17 ± 0.11
a_7	5.4946 ± 0.0517	—
a_8	0.125 ± 0.042	—
f_1	0.15 ± 0.11	0.67 ± 0.32
f_2	0.30 ± 0.35	$1 - f_1$

4.4.3 The background model

The background model can be determined from MC. A sample formed by $X(5568)$ candidates in MC which are combinations of fully matched B_s^0 candidates and tracks that do not come from the $X(5568)$ are representative of about 85% of the background found in data (the other $\sim 15\%$ corresponding to fake B_s^0). Fits to these events in the MC sample are shown in Figs. 4.8 and 4.9 for several background models composed by a power function times a polynomial function: $(x - x_0)^\alpha \times \text{Pol}n(x)$, for $n = 2, 3$ and 4; and $(x - x_0)^{(\alpha + \beta \times (x - x_0))} \times \text{Pol}1(x)$, where $x = M^\Delta(B_s^0\pi^\pm)$ and $n, 1$, are the degree of the polynomial.

The fit using a threshold function attenuated with a n -order polynomial returns a χ^2/n_{dof} of 233.4/197 for $n = 2$, 186.8/196 for $n = 3$, and 185.5/195 for $n = 4$. Since the first model does not follow the data accurately, and the fit with the last model is unstable and uses 5 parameters, the model with $n = 3$ seems a good choice. The fit using the model with a linear power times a first order polynomial returns $\chi^2/n_{dof} = 190.4/197$, and “competes” with the model with $n = 3$. At the end, the model with $n = 3$ is chosen to be the baseline fit model.

The procedure is repeated for the case where an additional requirement $p_T(B_s^0) > 15$ GeV is applied, see Appendix C. In particular, the third order polynomial is still employed.

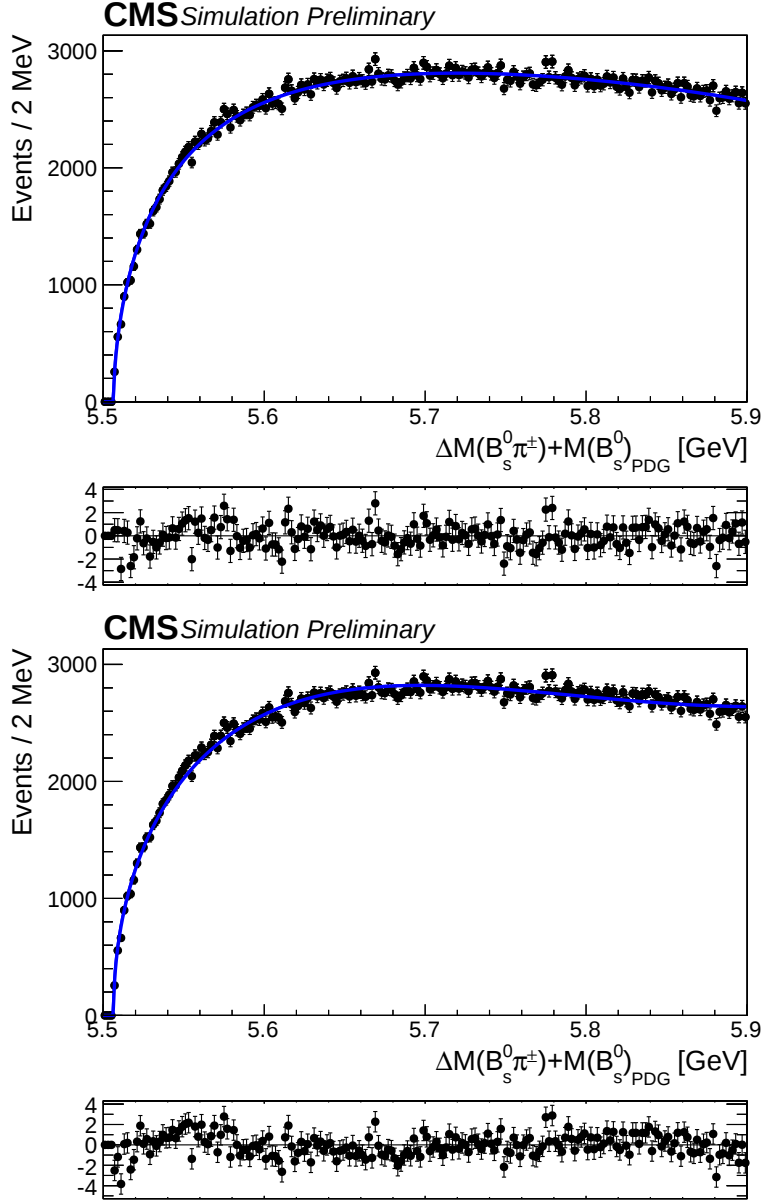


Figure 4.8: Fits to background shape of the $M^\Delta(B_s^0\pi^\pm)$ distribution obtained from MC for the baseline selection criteria. Reconstructed candidates with a “pion” track matching a generated pion coming from the $X(5568)$ are excluded. Models are the linear power function times Pol1 (up) and times 2nd-order polinomial (Pol2, down). Pulls are shown in the bottom panels.

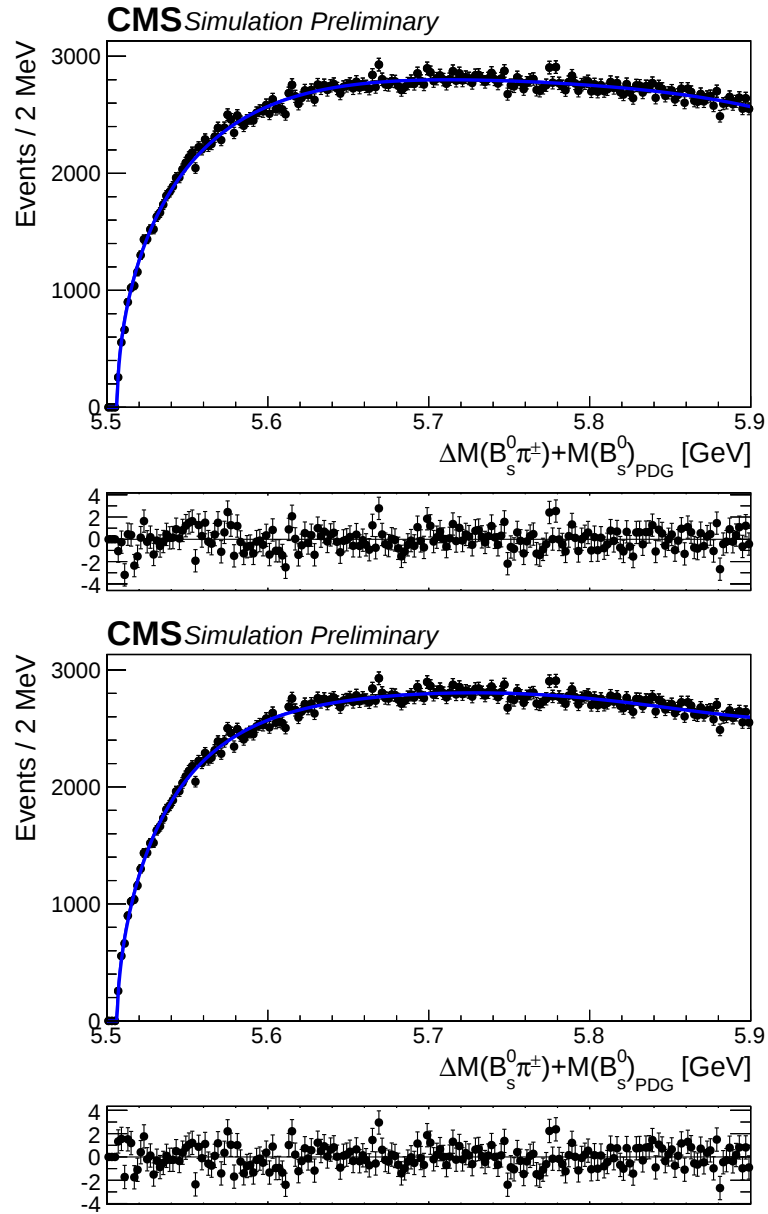


Figure 4.9: Fits to background shape of the $M^\Delta(B_s^0\pi^\pm)$ distribution obtained from MC for the baseline selection criteria. Reconstructed candidates with a “pion” track matching a generated pion coming from the $X(5568)$ are excluded. Models are the linear power function times $\text{Pol}n$ with $n = 3$ (up) and $n = 4$ (down). Pulls are shown in the bottom panels.

4.4.4 Fit to the $B_s^0\pi^\pm$ invariant mass

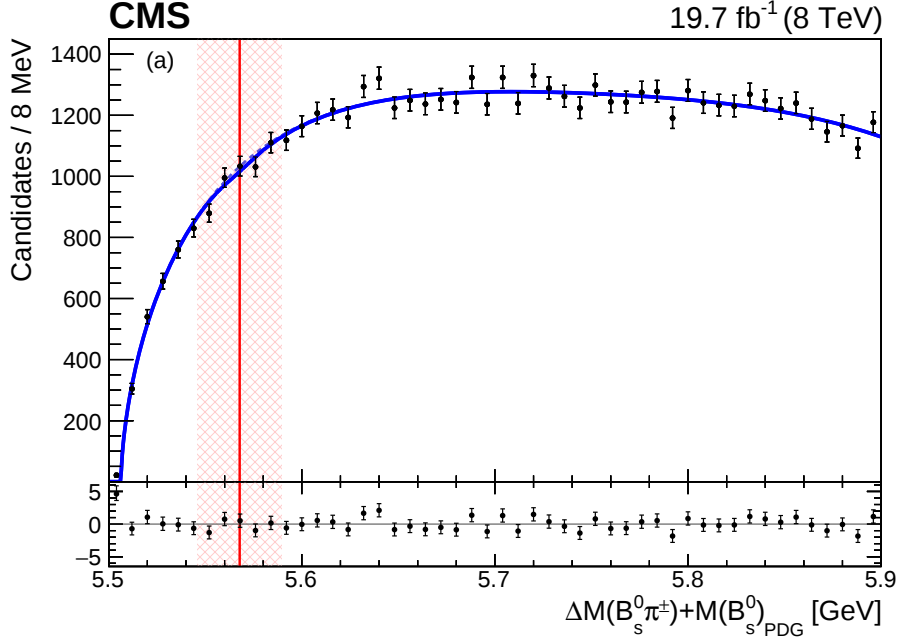


Figure 4.10: $M^\Delta(B_s^0\pi^\pm)$ distribution of events in the B_s^0 signal region (black points with error bars) with fit results superimposed (blue line). The pull distributions are shown in bottom panels. The (red) vertical band indicates the region $M_X \pm \Gamma_X$ around the mass of the claimed $X(5568)$ state.

The $B_s^0\pi^\pm$ invariant mass spectrum is modeled by a smooth “background” function of the form

$$(x - x_0)^\alpha \times \text{Pol3}(x), \quad (4.4)$$

where $x = M^\Delta(B_s^0\pi^\pm) = \Delta M + m_{B_s^0}^{PDG}$, $x_0 = m_{B_s^0}^{PDG} + m_{\pi^\pm}^{PDG}$ is the threshold value, $\text{Pol3}(x)$ represents a third order polynomial function, and $m_{\pi^\pm}^{PDG}$ is the W.A. $\pi^\pm$ mass [8].

A possible $X(5568)$ “signal” contribution is modeled by a S-wave Relativistic Breit-Wigner (BW) function, with mass and width parameters fixed to the mean values measured by the D0 Collaboration, and convolved with a triple-Gaussian resolution model obtained from MC.

An unbinned extended maximum-likelihood fit to the $M^\Delta(B_s^0\pi^\pm)$ distribution is performed, where the polynomial coefficients are free in the fit as well as the exponent α and the signal and background yields. The fit is presented in Fig. 4.10, resulting in a $X(5568)$ yield of -85 ± 160 events and shows no deviation from the background function. At the end, no evidence of the $X(5568)$ state is found.

4.5 Additional cross-checks

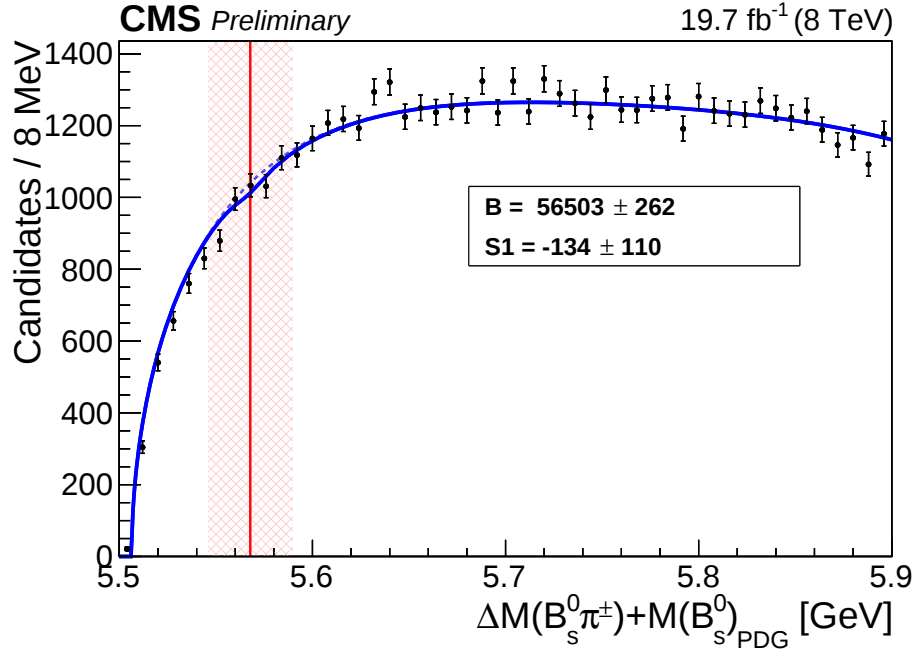


Figure 4.11: Fit to the $M^\Delta(B_s^0\pi^\pm)$ distribution of events in the B_s^0 signal region, with background shape fixed from MC.

In the previous section, the fit in Fig. 4.10 is allowed to float background parameters. Because there is not a clear division between signal and background components, in a first approximation, the background parameters could be fixed before searching for signals of the $X(5568)$ state. So the Fig. 4.11 shows the fit to data distribution of $M^\Delta(B_s^0\pi^\pm)$ with the background model fixed from MC and resulting in a $X(5568)$ yield of -134 ± 110 , consistent with zero.

In addition to fixing the background model from MC, this can be done from data. Excluding the region $[m_X - 2.5\Gamma_X, m_X + 2.5\Gamma_X]$ from the $X(5568)$ invariant mass distribution the background model is fitted on Fig. 4.12(a), where m_X and Γ_X are the mean values of mass and width reported by the D0 collaboration respectively. Then, as is shown in Fig. 4.12(b), a fit in the complete mass region (5.5 – 5.9 GeV) is performed with the signal component included and the background shape fixed to the previous fit. This cross-check is repeated with $2.0\Gamma_X$ window instead of $2.5\Gamma_X$. In both cases, the signal is consistent with zero.

Another cross-checks can be done with the $B_s^0\pi^\pm$ multiplicity, this is not considered in

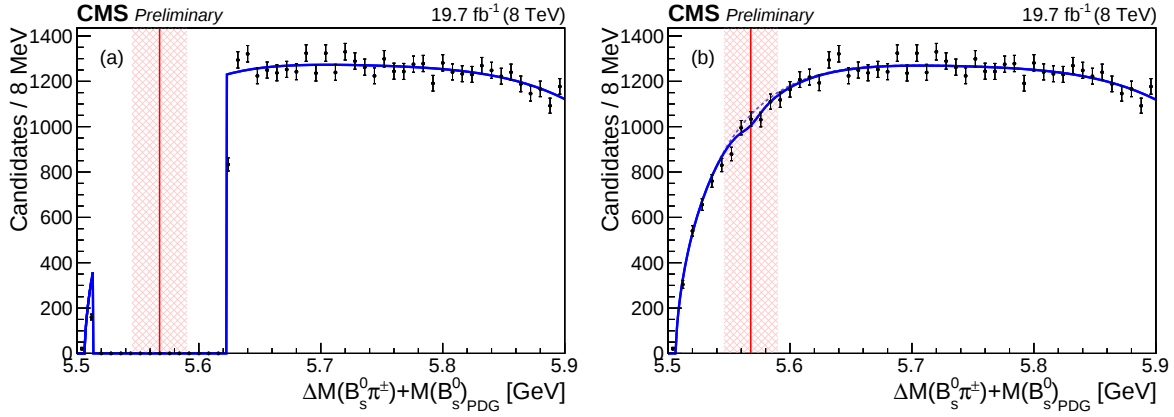


Figure 4.12: (a) Background model fitted in the $M^\Delta(B_s^0\pi^\pm)$ distribution excluding the region $[m_X - 2.5\Gamma_X, m_X + 2.5\Gamma_X]$ for events in the B_s^0 signal region. (b) Fit to the $M^\Delta(B_s^0\pi^\pm)$ distribution of events in the B_s^0 signal region with the background fixed to the obtained in (a). The vertical band indicates the region $M_X \pm \Gamma_X$ around the mass of the claimed $X(5568)$ state.

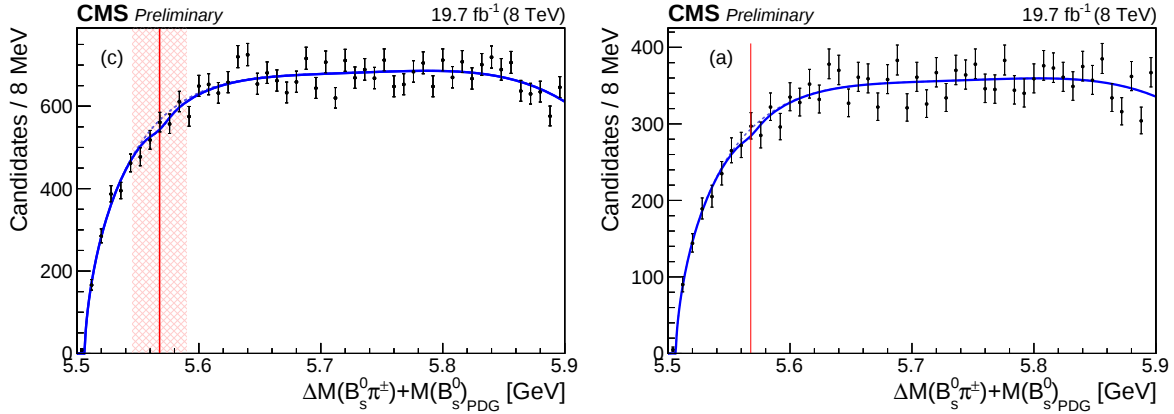


Figure 4.13: Fit to the $M^\Delta(B_s^0\pi^\pm)$ distribution for events in the B_s^0 signal region: removing the $B_s^0\pi^\pm$ multiplicity choosing the candidate with the largest $P_{vtx}(B_s^0\pi^\pm)$ (left), when only 1 candidate passes selection (right).

the baseline selection but can be removed choosing the largest $B_s^0\pi^\pm$ vertex fit probability $P_{vtx}(B_s^0\pi^\pm)$. The fit to $M^\Delta(B_s^\pm\pi^\pm)$ with multiple candidates removed is shown in the left plot of the Fig. 4.13. In addition, the fit to a $B_s^0\pi^\pm$ invariant mass distribution, for events with only one candidate passing all the selection criteria, is presented in right plot of the Fig. 4.13. In both cases results are consistent with zero, non-relativistic Breit-Wigner function is used for signal model in this last case.

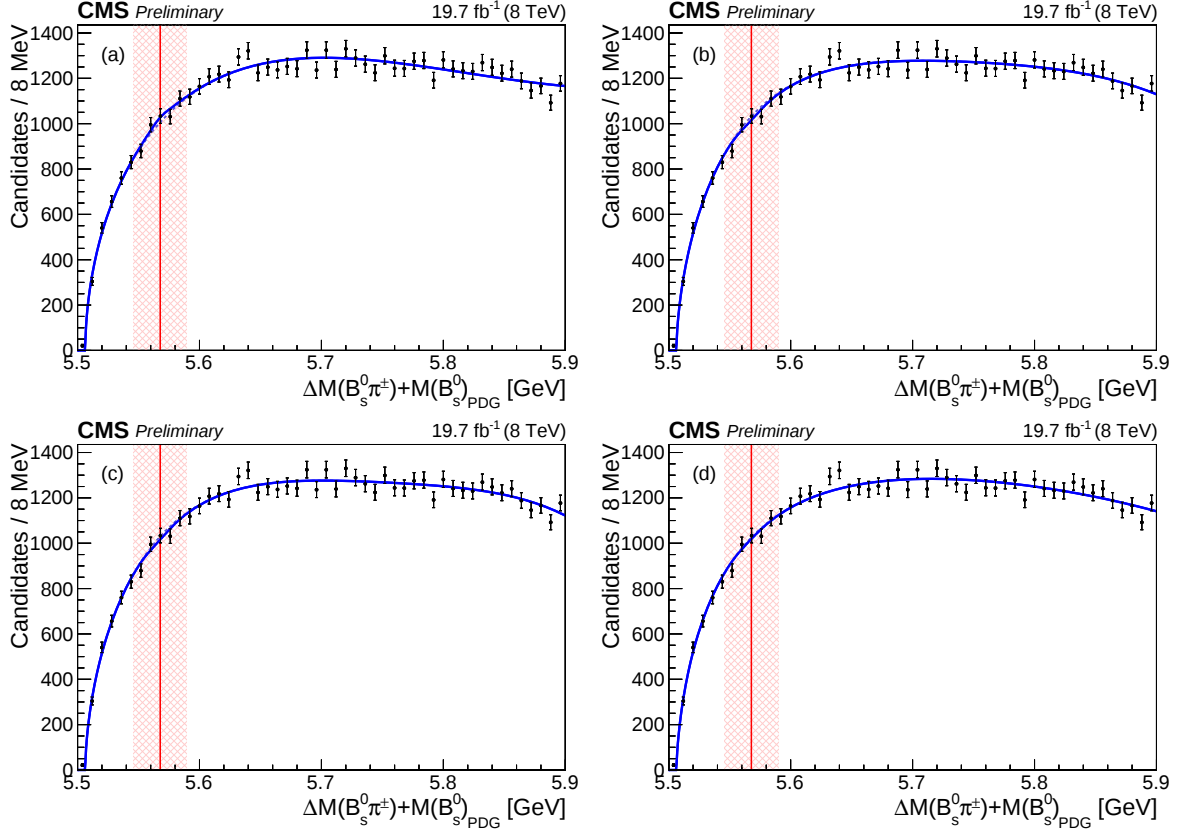


Figure 4.14: Fitted $M^\Delta(B_s^0\pi^\pm)$ distributions for events in the B_s^0 signal region. Different polynomial degrees of the polynomial factor in the nominal model are used: (a) $n = 2$, (b) $n = 3$ (nominal) and (c) $n = 4$. (d) The alternative model $(x - x_0)^{(\alpha+\beta \times (x-x_0))} \times \text{Pol1}(x)$ is used, where Pol1 is a first degree polynomial and its parameters as well as α and β are free in the fit. The vertical band indicates the region $M_X \pm \Gamma_X$ around the mass of the claimed $X(5568)$ state.

Some cross-checks are performed considering kinematic requirements and results are consistent with a negligible $X(5568)$ signal: variations on the p_T requirements of $B_s^0\pi^\pm$, B_s^0 and $\pi^\pm$ candidates are in Appendix A; requirements on the significance of the pion impact parameter are in Appendix E1; requirements on the pion weight in the PV fit (W_π^{PV}) in Appendix E2; and variations on the requirement of the $B_s^0\pi^\pm$ common vertex probability (P_{vtx}) are in Appendix E3.

Also alternative background models are investigated with data on Fig. 4.14. Fits to the $M^\Delta(B_s^0\pi^\pm)$ distribution include different polynomial degrees in the nominal model $(x - x_0)^\alpha \times \text{Pol3}(x)$ and a model $(x - x_0)^{(\alpha+\beta \times (x-x_0))} \times \text{Pol1}(x)$, where $x = M^\Delta(B_s^0\pi^\pm) =$

$\Delta M + m_{B_s^0}^{PDG}$ and $x_0 = m_{B_s^0}^{PDG} + m_{\pi^\pm}^{PDG}$. All fits result in a signal contribution consistent with zero.

In addition, the Fig. 4.15 shows fits to the $M^\Delta(B_s^0\pi^\pm)$ distribution in several mass regions. Similar to previous cases, all results are consistent with a negative observation of the $X(5568)$.

Another cross-check considers the multiplication of the signal function by a mass-dependent efficiency (see Subsection 4.4.2), in this case the actual change in the signal shape is negligible as can be seen from Appendix F and the fit returns $N_X = -88 \pm 161$.

Results of all these cross-checks are summarized in Tables 4.2 and 4.3, showing no significant signal yields.

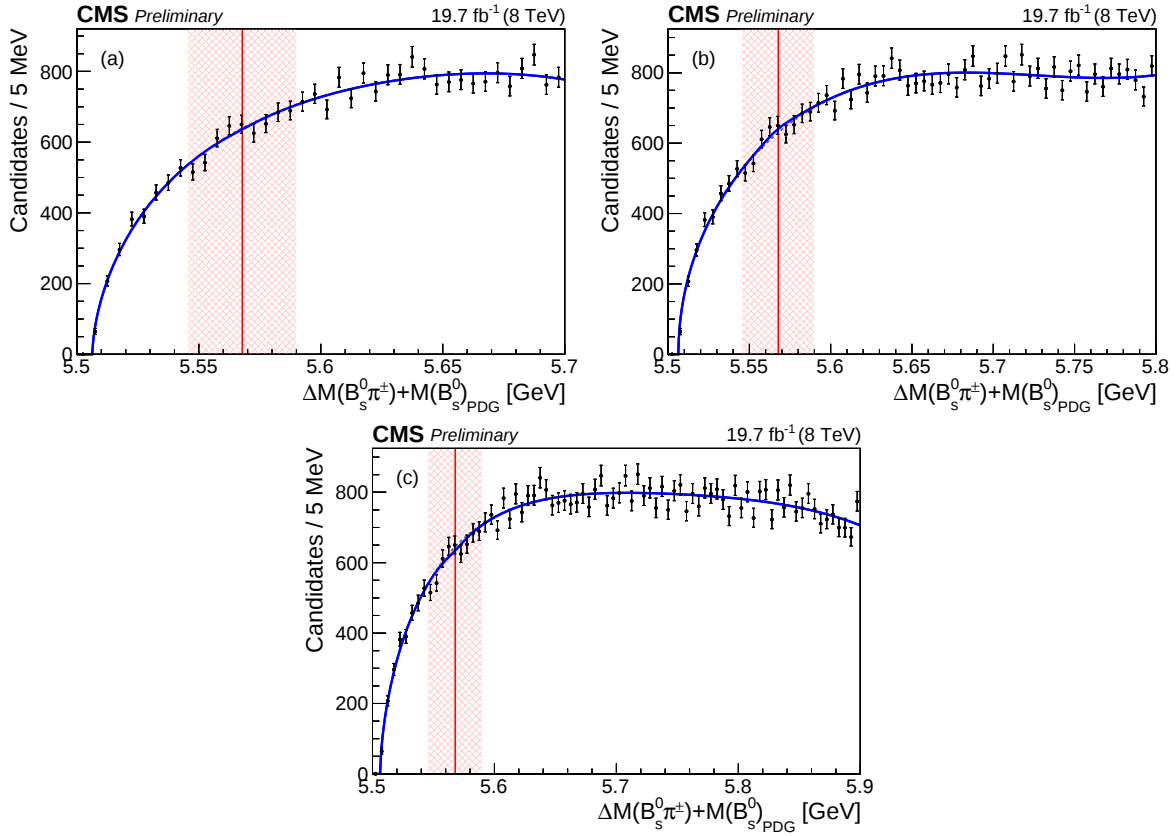


Figure 4.15: Fit to $M^\Delta(B_s^0\pi^\pm)$ distributions for events in the B_s^0 signal region. Different fit ranges are used: (a) 5.5 – 5.7 GeV, (b) 5.5 – 5.8 GeV and (c) baseline 5.5 – 5.9 GeV. The bin width in these plots is 5 MeV. The vertical band indicates the region $M_X \pm \Gamma_X$ around the mass of the claimed $X(5568)$ state.

Table 4.2: Summary of results from the fits to the $B_s^0\pi^\pm$ distributions obtained by using different kinematic and quality requirements. All variations require at least the baseline selection, which imposes $p_T(B_s^0) > 10$ GeV and $p_T(\pi^\pm) > 0.5$ GeV. P_{vtx} stands for the probability of the $B_s^0\pi^\pm$ common vertex fit. W_π^{PV} is the pion weight in the PV fit. Non-relativistic Breit-Wigner function is used for signal model as “baseline” in these cross-checks (except for the first and the last lines).

Requirements	$X(5568)$ yield	χ^2/n_{dof}
Relativistic BW	-85 ± 160	41.9/44
Non-relativistic BW	-175 ± 134	42.3/44
$p_T(B_s^0) > 15$ GeV	-170 ± 121	36.1/44
$p_T(B_s^0) > 20$ GeV	-217 ± 79	43.5/44
$p_T(B_s^0) > 30$ GeV	-45 ± 57	32.7/44
$p_T(\pi^\pm) > 1.0$ GeV	-18 ± 48	42.7/44
$p_T(B_s^0) > 20$ GeV, $p_T(\pi^\pm) > 1.0$ GeV	-22 ± 57	39.8/44
$p_T(B_s^0\pi^\pm) > 20$ GeV	-188 ± 97	41.6/44
$p_T(B_s^0\pi^\pm) > 30$ GeV	-44 ± 61	32.3/44
$d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)} < 3$	-159 ± 132	40.3/44
$d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)} < 2$	-182 ± 131	37.4/44
$d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)} < 1$	-165 ± 113	40.1/44
$P_{vtx} > 1\%$	-187 ± 132	43.5/44
$P_{vtx} > 5\%$	-199 ± 129	40.7/44
$P_{vtx} > 10\%$	-190 ± 126	43.8/44
$P_{vtx} > 20\%$	-168 ± 121	44.2/44
Multiple $B_s^0\pi^\pm$ entries in an event removed	-156 ± 144	60.6/44
Events with only one $B_s^0\pi^\pm$ candidate	-38 ± 67	48.1/44
$W_\pi^{PV} > 0.95$	-57 ± 137	39.0/44

Table 4.3: The fit results to the $M^\Delta(B_s^0\pi^\pm)$ distribution obtained by using different background models and fit regions.

Fit conditions	$X(5568)$ yield	χ^2/n_{dof}
Baseline	-85 ± 157	41.9/44
Multiply the signal pdf by efficiency(mass)	-88 ± 161	41.9/44
Fit region [5.5, 5.7] GeV	-24 ± 173	37.1/34
Fit region [5.5, 5.8] GeV	78 ± 135	67.4/54
Bkg. model: $(x - x_0)^\alpha \times \text{Pol2}(x)$	102 ± 140	49.5/45
Bkg. model: $(x - x_0)^\alpha \times \text{Pol4}(x)$	-72 ± 167	41.3/43
Bkg. model: $(x - x_0)^{(\alpha+\beta \times (x-x_0))} \times \text{Pol1}(x)$	-36 ± 149	44.2/45
Bkg. shape fixed (MC)	-134 ± 110	65.4/48
Bkg. shape fixed (without $m_X \pm 2.5\Gamma_X$ region)	-229 ± 110	44.4/48
Bkg. shape fixed (without $m_X \pm 2.0\Gamma_X$ region)	-220 ± 110	44.7/48

4.6 “Cone cut” case

The D0 Collaboration observes a peak with a significance beyond 5σ only when they impose a limit on the difference between the directions of the B_s^0 and pion candidates, $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$. Here $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal angle differences between the directions of the B_s^0 and $\pi^\pm$. This “cone cut” changes abruptly the $M^\Delta(B_s^0\pi^\pm)$ distribution shape, as shown in Fig. 4.16. It can create a peak or enhance the significance of statistical fluctuation of the data, and therefore it is not used in this analysis. The distributions with $\Delta R < 0.1$ are significantly different between B_s^0 signal region and B_s^0 sidebands.

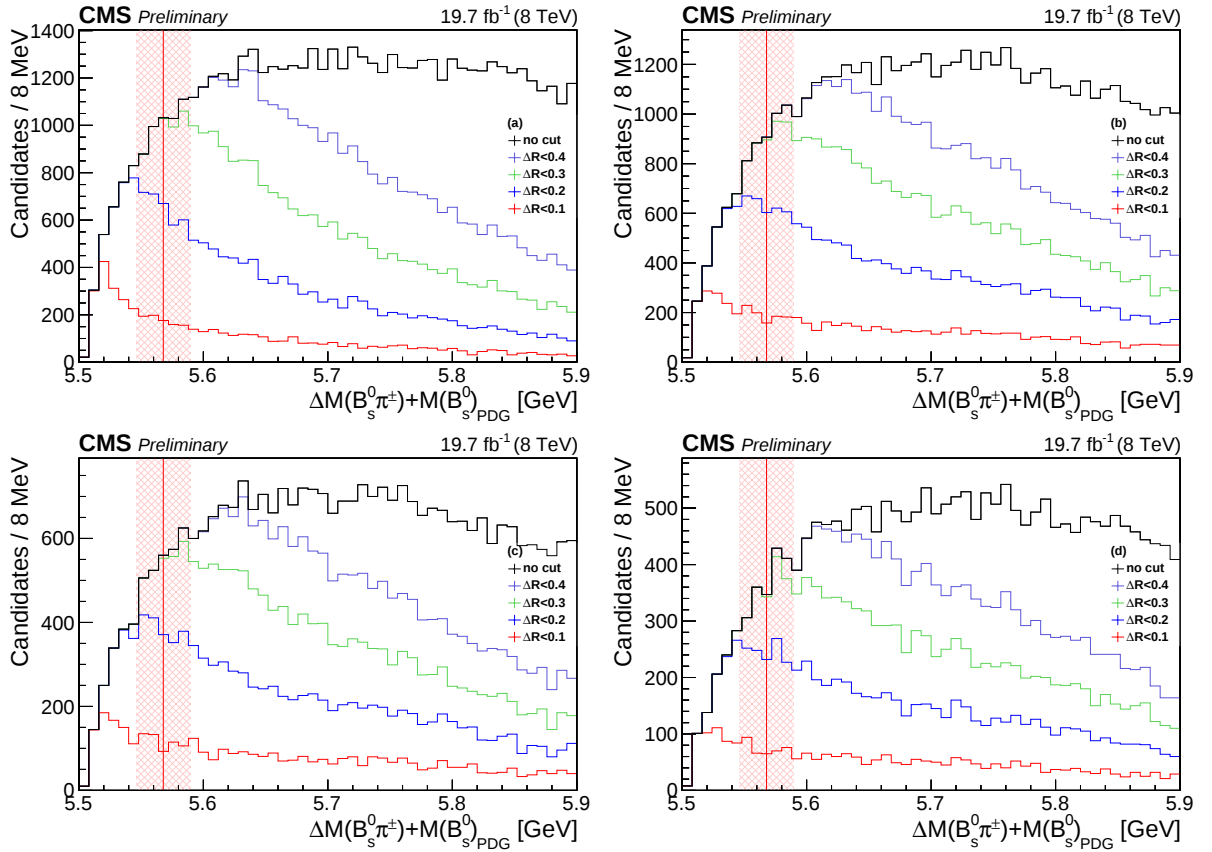


Figure 4.16: $M^\Delta(B_s^0\pi^\pm)$ distributions for (a) B_s^0 signal region, (b) B_s^0 sidebands, (c) B_s^0 left sideband and (d) B_s^0 right sideband with: no ΔR cut, $\Delta R < 0.4$, $\Delta R < 0.3$, $\Delta R < 0.2$ and $\Delta R < 0.1$. The vertical band indicates the region $M_X \pm \Gamma_X$ around the mass of the claimed $X(5568)$ state.

Chapter 5

The relative production ρ_X

5.1 The relative efficiency estimation

The efficiency is defined as the rate of reconstructed events over generated events: $\epsilon = N^{Reco} / N^{Gen}$. The total efficiency is a product of the acceptance and the combined trigger, reconstruction and selection efficiencies. Simulated samples are used to determine the total efficiency for each decay channel, $X(5568) \rightarrow B_s^0 \pi^\pm$, $B_s^0 \rightarrow J/\psi \phi$ and the inclusive $B_s^0 \rightarrow J/\psi \phi$ (in both, $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$).

As a first step the reconstructed events are investigated, generated events are known since their production. Fig. 5.1 shows the invariant mass distribution of the reconstructed B_s^0 and $X(5568)$ candidates obtained from the $B_s^0 \rightarrow J/\psi \phi$ and $X(5568) \rightarrow B_s^0 \pi^\pm$ MC samples. The B_s^0 mass resolution ($\simeq 13.7$ MeV), obtained from a fit with a double-Gaussian function, is in excellent agreement with the resolution found in data ($\simeq 14.0$ MeV). The fit in Fig. 5.1(b) uses a non-relativistic BW function convoluted with a triple-Gaussian resolution function and multiplied by the mass-dependent efficiency obtained in section 4.4.2. Natural width, resolution and efficiency parameters are fixed. The fit allows a background component due to events selected incorrectly by the matching algorithm, the matching purity is about 99.8% (see details on Appendix G).

Furthermore, the pulls between the fits and the data are slightly improved by allowing the mean mass parameter to float. The yield variations due to the small mass shifts are negligible. In the $X(5568)$ fit, the mass shift is less than 0.1 MeV; therefore, the reconstruction bias is negligible and well covered by the systematic uncertainty due to the total uncertainty on the $X(5568)$ mass measured by D0 of about 3.5 MeV.

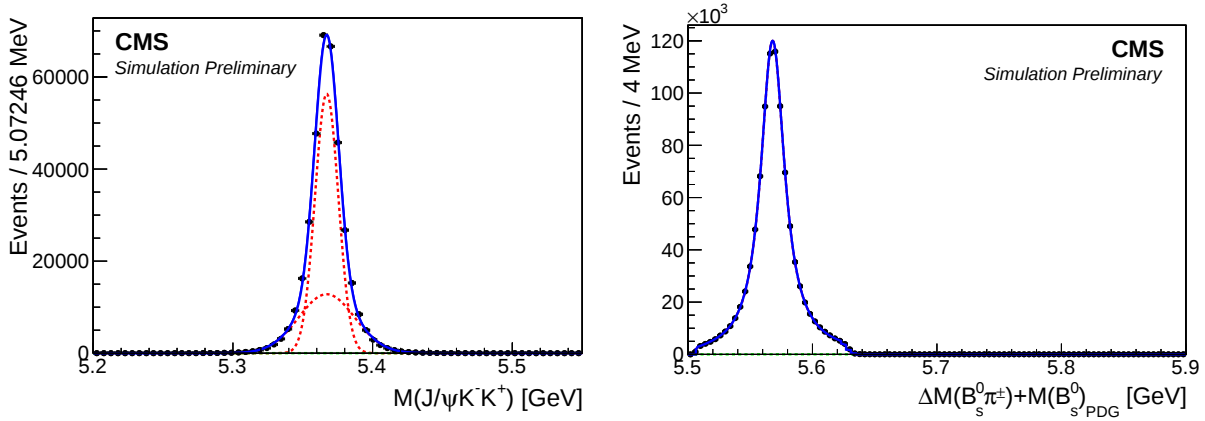


Figure 5.1: Fitted invariant mass of reconstructed (a) B_s^0 and (b) $X(5568)$ candidates in MC.

Since the official MC samples are generated with kinematic filters, the reconstruction efficiency must be multiplied by a filter efficiency in order to obtain the total one, see Eq. 5.1. The filter efficiency is obtained by generating events at truth level requiring kinematic filters, and must be corrected by the $pp \rightarrow X(5568)$ (or B_s^0) cross section in PYTHIA, evaluated using an independent generation requiring only an $X(5568)$ (or B_s^0). The calculation is reproduced below in detail for the B_s^0 :

$$\epsilon_{B_s^0} = \frac{N_{B_s^0}^{\text{reco}}}{N_{B_s^0}^{\text{gen}}} = \frac{N_{B_s^0}^{\text{reco}}}{N_{B_s^0}^{\text{gen-filters}}} \frac{N_{B_s^0}^{\text{gen-filters}}}{N_{B_s^0}^{\text{gen}}} = \epsilon_{B_s^0}^{\text{reco}} \epsilon_{B_s^0}^{\text{filters}} \quad (5.1)$$

$$\epsilon_{B_s^0}^{\text{reco}} = \frac{358,770 \pm 600}{3,975,982} = (9.02 \pm 0.02) \times 10^{-2} \quad (5.2)$$

$$\begin{aligned} \epsilon_{B_s^0}^{\text{filters}} &= \frac{\epsilon_{B_s^0}^{B_s^0 \text{ \& filters}}}{\epsilon_{B_s^0}^{B_s^0 \text{ only}}} = \frac{(4.26 \pm 0.04) \times 10^{-5}}{(1.645 \pm 0.003) \times 10^{-3}} \\ &= (2.59 \pm 0.03) \times 10^{-2} \end{aligned} \quad (5.3)$$

$$\begin{aligned} \therefore \epsilon_{B_s^0} &= (9.02 \pm 0.02) \times 10^{-2} \cdot (2.59 \pm 0.03) \times 10^{-2} \\ &= (2.34 \pm 0.02) \times 10^{-3} \end{aligned} \quad (5.4)$$

Similarly, for $X(5568)$:

$$\epsilon_{X(5568)} = \epsilon_{X(5568)}^{\text{reco}} \epsilon_{X(5568)}^{\text{filters}} = \epsilon_{X(5568)}^{\text{reco}} \frac{\epsilon_{X(5568)}^{X(5568) \text{ \& filters}}}{\epsilon_{X(5568)}^{X(5568) \text{ only}}} \quad (5.5)$$

$$\begin{aligned}
\epsilon_{X(5568)} &= \frac{942,842 \pm 971}{17,966,317} \frac{(4.00 \pm 0.01) \times 10^{-4}}{(1.8649 \pm 0.0009) \times 10^{-2}} \\
&= (5.239 \pm 0.005) \times 10^{-2} \cdot (2.148 \pm 0.007) \times 10^{-2} \\
&= (1.125 \pm 0.004) \times 10^{-3}
\end{aligned} \tag{5.6}$$

From the relations above, the relative efficiency is:

$$\epsilon_{rel} \equiv \frac{\epsilon_{X(5568)}}{\epsilon_{B_s^0}} = \frac{(1.125 \pm 0.004) \times 10^{-3}}{(2.34 \pm 0.02) \times 10^{-3}}. \tag{5.7}$$

In the evaluation of the relative efficiency, the systematic uncertainties due to the B_s^0 reconstruction efficiency cancel out in the ratio, and the remaining systematic uncertainty is connected to the tracking efficiency uncertainty. From Refs. [28, 29], the tracking efficiency uncertainty is at most 3.9% for pions between 0.4 and ~ 10 GeV. Then:

$$\epsilon_{rel} = 0.481 \pm 0.005 \text{ (MC stat)} \pm 0.019 \text{ (trk)} = 0.48 \pm 0.02 \text{ (syst)} \tag{5.8}$$

5.2 Upper limit estimation of ρ_X

An upper limit is estimated using the formalism developed by the CMS and ATLAS Collaborations in the context of the LHC Higgs Combination Group [25]. The asymptotic modified frequentist method CL_s [26, 27] is used as a statistical test, allowing a quick estimate of the observed and expected limits, which is fairly accurate when the event yields are not too small and the systematic uncertainties do not play a major role in the result.

The estimation of an upper limit on the relative production ρ_X is done using Eq. 1.2 and requires the set of $M^\Delta(B_s^0 \pi^\pm)$ measurements, the expected background yield, which is the same as the observed event yield, the approximation function and the measured $N(B_s^0) \times \epsilon_{rel}$. For the baseline selection criteria, $N(B_s^0) \times \epsilon_{rel} = (46222 \pm 261) \times (0.481 \pm 0.020) = 22233 \pm 906$ (see Sections 4.1 and 5.1). The uncertainty of this value is dominated by the pion tracking efficiency uncertainty of 3.9% [28]. The approximation function is the baseline fit function $(x - x_0)^\alpha \times \text{Pol3}(x)$ for the background and an S-wave Relativistic Breit-Wigner function, convoluted with triple-Gaussian resolution for signal. More technical details about the usage of the tool can be found in Appendix H. Without systematic uncertainties taken into account, the estimated upper limit at 95% CL is $\rho_X < 1.00\%$.

Several sources of systematic uncertainty can be considered:

1. The knowledge of the $X(5568)$ signal shape parameters is accounted for by introducing (parametric) systematic uncertainties of the mass and width, which are set to the statistical uncertainties of the D0 measurement (2.9 MeV for mean, 6.4 MeV for Γ);
2. The knowledge of the $N(B_s^0) \times \epsilon_{rel} = 22233 \pm 906$ value.

The tool output considering all these systematic uncertainties is $\rho_X < 1.05\%$ at 95% CL.

The other variations correspond to the changes in the signal and background function; in the tests described above systematic uncertainties are taken into account. Variations in the background model are explored in subsection 4.4.3. The second order polynomial multiplied by power function is not considered as an alternative background function since the fit with this option is not stable and hardly converges. Additionally, the distribution of $M^\Delta(B_s^0\pi^\pm)$ obtained in MC from not- X -decays is much better described with the use of third and higher order polynomials. The fourth order polynomial multiplied by the power function used for the background description leads to the limit $\rho_X < 0.97\%$ at 95% CL. The model $(x - x_0)^{(\alpha+\beta \times (x-x_0))} \times \text{Pol1}(x)$ is as well tested as an alternative background model, providing $\rho_X < 1.11\%$ at 95% CL. In case the background shape is fixed from MC, the limit becomes much stricter: $\rho_X < 0.64\%$ at 95% CL.

Additional cross-checks include modified signal model: the Relativistic Breit-Wigner multiplied by the efficiency dependence on mass and convoluted with the resolution results in $\rho_X < 1.07\%$ at 95% CL (if in this case the background is described by $(x - x_0)^{(\alpha+\beta \times (x-x_0))} \times \text{Pol1}(x)$, the limit becomes $\rho_X < 1.13\%$ at 95% CL). The limit does not change when the signal resolution model is varied according to subsection 4.4.2 (the narrowest and the widest resolution values are tested from those presented in Appendix B as well as mass-dependent single-Gaussian model with effective resolution). This is expected since the natural $X(5568)$ width of approximately 22 MeV is much larger than the resolution variations and its uncertainty of 6.4 MeV (it significantly exceeds the resolution variations) is already accounted for as the systematic uncertainty.

Thus the most conservative estimate for an upper limit on the relative production is

$$\rho_X < 1.1\% \text{ at } 95\% \text{ CL.}$$

5.3 Mass-dependent upper limit

Upper limits are also obtained for different values of mass and natural width of a possible $B_s^0\pi^\pm$ resonance, one should take into account the efficiency and resolution dependence of the invariant mass. The mass-dependent efficiency was obtained in Sec. 4.4.2, while the resolution as a function of the invariant mass is described in Appendix I.

Such a mass-dependent efficiency, estimated using a single $X(5568)$ MC sample, as well as its extrapolation to higher mass values, can not be considered 100% reliable for values of mass and width too far from the input values. To have 100% correct efficiency values, a dedicated MC sample is needed to be generated for each mass and natural width value. To take into account a possible bias in the efficiency extrapolation, an additional systematic uncertainty is assigned to the relative efficiency for mass values exceeding 5.63 GeV¹, equal to half of the difference $|\epsilon_{rel}(M) - \epsilon_{rel}(5.5678 \text{ GeV})|$. For example, the relative efficiency function at 5.8 GeV takes 12% higher values than at $M_X = 5.5678 \text{ GeV}$ (input mass of the official MC). Thus, the conservative estimate for the additional systematic uncertainty on the relative efficiency at $M = 5.8 \text{ GeV}$ is 6%. In general, the additional systematic uncertainty takes values between 0 and 6%. This is added in quadrature to the existing 4% systematic uncertainty assigned to the relative efficiency due to the tracking efficiency and MC statistics.

The procedure to obtain mass-dependent limit can be summarised as:

- Consider several sets of (M, Γ) points:
 - Γ is the same across each set of points. Five sets of points correspond to 5 different tested values of Γ (in MeV): [10, 20, 30, 40, 50].
 - In each set, M takes values $x_0 + \Gamma, x_0 + 2\Gamma, x_0 + 3\Gamma, \dots, x_0 + n\Gamma$, where x_0 is the threshold value and n is minimum integer value satisfying the inequality $x_0 + (n + 1.5)\Gamma > 5.9 \text{ GeV}$.
- For each (M, Γ) point, the limit is calculated using the Combine tool, as in the baseline analysis, with the following setup:
 - The signal model is a Relativistic Breit-Wigner function, convolved with a single-Gaussian resolution and multiplied by the efficiency dependence on mass.

¹Maximum value available in the official $X(5568)$ MC.

- The Gaussian resolution is fixed according to the function obtained in Appendix I.
- The background is described by the baseline $(x - x_0)^\alpha \times \text{Pol3}(x)$ function with free parameters.
- No systematic uncertainties related to mass and Γ knowledge are added.
- The relative efficiency is obtained for each value of mass (M) as the baseline efficiency ratio scaled by the ratio of the mass-dependent efficiency values:
 $\epsilon = (0.48 \pm 0.02) \times \epsilon_{rel}(M) / \epsilon_{rel}(5.5678 \text{ GeV})$.
- The additional systematic related to extrapolation of the relative efficiency, described above, is added in quadrature to the existing 4% uncertainty.

Then, Fig. 5.2 shows the upper limit on ρ_X for different values of mass and natural width.

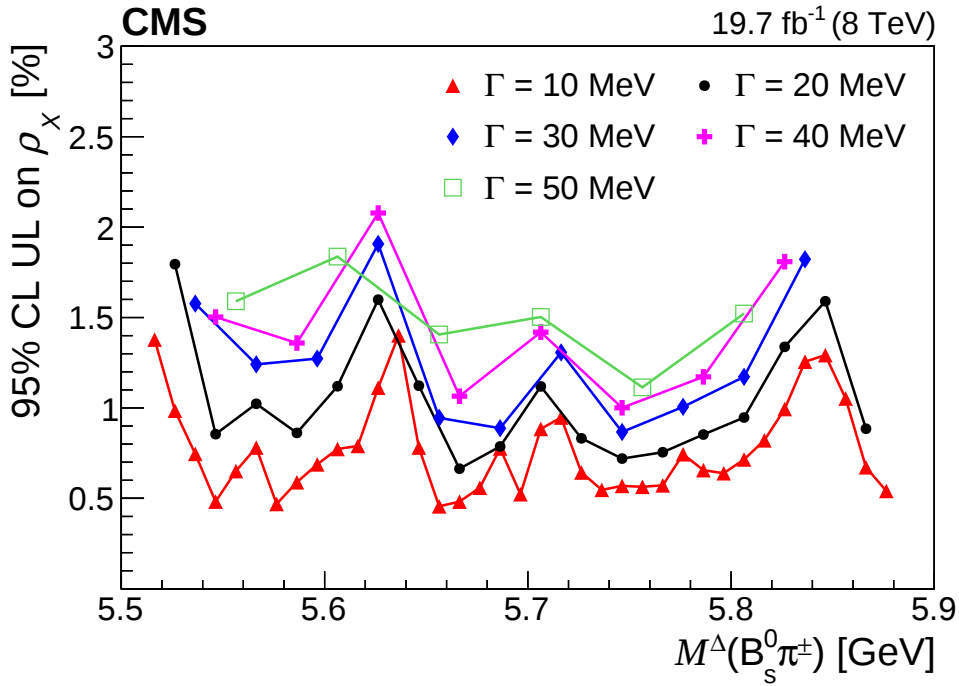


Figure 5.2: The upper limit on ρ_X at 95% CL, as a function of the mass of a possible exotic state decaying into $B_s^0 \pi^\pm$ for five different values of the natural width of the state.

5.4 Case $p_T(B_s^0) > 15$ GeV

The existence of the $X(5568)$ state is also investigated for $p_T(B_s^0) > 15$ GeV. As a first step, the Fig. 5.3(a) shows a fit to the B_s^0 invariant mass distribution for events with $p_T(B_s^0) > 15$ GeV; a double-Gaussian function is employed for the signal model and an exponential function for the background model. Fit results are presented in Table 5.1, the signal yield is 40292 ± 246 while the yield in the signal region is 37643 ± 230 .

The $M^\Delta(B_s^0\pi^\pm)$ distribution obtained after the baseline selection and an additional requirement $p_T(B_s^0) > 15$ GeV is shown in Fig. 5.3(b). The distribution is fitted with the same signal+background function as in the baseline analysis, only the fixed from simulation mass resolution is not the same (see Appendix B). Then the $X(5568)$ yield returned by the fit is -103 ± 141 , consistent with zero.

Similar to the baseline analysis, the limit on ρ_X is estimated using the HiggsAnalysis-CombinedLimit tool. Now, for the case $p_T(B_s^0) > 15$ GeV, the $N(B_s^0) \times \epsilon_{rel}$ is equal to $(37643 \pm 230) \times (0.524 \pm 0.020) = 19725 \pm 811$. The tool returns $\rho_X < 0.85\%$ at 95% CL, where the systematic uncertainties related to the B_s^0 yield and the relative efficiency are taken into account as well as the uncertainties of $X(5568)$ mass and width.

Cross-checks include variations in the signal and background model. The function $(x - x_0)^{(\alpha+\beta \times (x-x_0))} \times \text{Pol1}(x)$ is tested as an alternative background model, resulting in a value of $\rho_X < 1.02\%$ at 95% CL. The fourth order polynomial is not used as an alternative model for the case $p_T(B_s^0) > 15$ GeV due to limited size of the dataset (even the fit with the baseline function has $\chi^2/n_{dof} = 0.81$ and probability=0.8). Once the background shape is fixed from MC, the returned by the tool limit becomes $\rho_X < 1.00\%$ at 95% CL. An additional cross-check changing the signal model, the Relativistic Breit-Wigner multiplied by the efficiency dependence on mass and convoluted with the resolution results in $\rho_X < 0.86\%$ at 95% CL (if in this case the background function of the form $(x - x_0)^{(\alpha+\beta \times (x-x_0))} \times \text{Pol1}(x)$ is used, the limit is $\rho_X < 1.04\%$ at 95% CL).

Thus the most conservative estimate for an upper limit on the relative production in kinematic region $p_T(B_s^0) > 15$ GeV, is

$$\rho_X < 1.0\% \text{ at } 95\% \text{ CL.}$$

Table 5.1: Fit results to $J/\psi K^+ K^-$ invariant mass distribution for $p_T(B_s^0) > 15$ GeV: Common mean value of two signal Gaussian functions ($m_{B_s^0}^{fit}$), resolutions of Gaussians (σ_1, σ_2), fraction of the second Gaussian function (f) and signal and background yields ($N_{B_s^0}$ and N_{Bkg} , respectively).

Fit parameter	Value
$m_{B_s^0}^{fit}$ [GeV]	5.367 ± 0.070
σ_1 [MeV]	8.10 ± 0.19
σ_2 [MeV]	19.10 ± 0.54
f	0.461 ± 0.024
$N_{B_s^0}$	40292 ± 246
N_{Bkg}	35744 ± 237

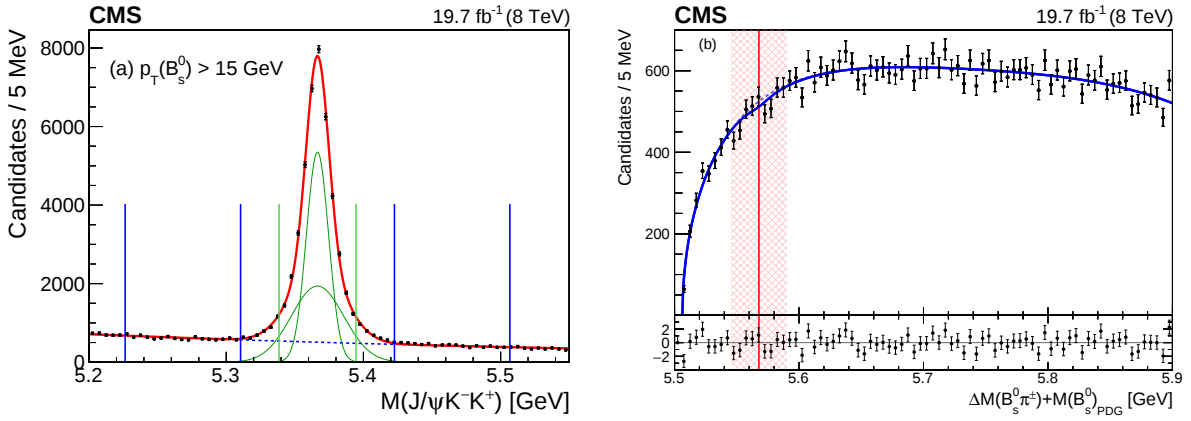


Figure 5.3: (Left) Invariant mass distribution of the B_s^0 candidates with $p_T(B_s^0) > 15$ GeV. (Right) $M^\Delta(B_s^0 \pi^\pm)$ distribution of events in the B_s^0 signal region for $p_T(B_s^0) > 15$ GeV.

Chapter 6

Conclusions and discussion

The $X(5568)$ state is searched for in the CMS experiment using 19.7 fb^{-1} of pp collision data collected at $\sqrt{s} = 8 \text{ TeV}$. With a sample of about 50,000 B_s^0 events, the $B_s^0\pi^\pm$ invariant mass spectrum is reconstructed without any clear signal of the structure observed by the D0 Collaboration.

The reconstruction procedure of $X(5568) \rightarrow B_s^0\pi^\pm$ candidates is verified with the reconstruction of the decay channels $B_{1,2}^{(*)+} \rightarrow B^{(*)0}\pi^+$, which share a similar decay topology and are prominent in data.

The absence of a peak is supported by the direct comparison with events in the B_s^0 mass sidebands; and by fits to the $B_s^0\pi^\pm$ invariant mass distribution with an $X(5568)$ component included, using different kinematic selection requirements, variants of background modeling, mass regions, and quality criteria. In all cases, the obtained yield of $X(5568)$ is consistent with zero.

An upper limit to the relative production rate ρ_X , of $X(5568)$ with respect to B_s^0 , multiplied by the unknown branching fraction of the $X(5568)^\pm \rightarrow B_s^0\pi^\pm$ decay, is calculated using the Eq. (1.2) at 95% CL:

$$\rho_X < 1.1\% \quad \text{for } p_T(B_s^0) > 10 \text{ GeV}$$

$$\rho_X < 1.0\% \quad \text{for } p_T(B_s^0) > 15 \text{ GeV}$$

Mass-dependent limits on ρ_X are obtained and they show no significant enhancements from the mass threshold up to 5.9 GeV for several values of the decay width, disfavoring predictions of more exotic states [11, 31] in this mass region.

The obtained limit values are in strong contradiction with the D0 result of $\rho_X = (8.6 \pm 2.4)\%$ for $p_T(B_s^0) > 10$ GeV at 95% CL ($\rho_X = (8.2 \pm 3.1)\%$ for $p_T(B_s^0) > 15$ GeV), [7]. In addition, they are significantly more restrictive than LHCb results of $\rho_X = 2.4\%$ for $p_T(B_s^0) > 10$ GeV at 95% CL ($\rho_X = 2.0\%$ for $p_T(B_s^0) > 15$ GeV) [9].

6.1 Comparison with very recent results

The search for the $X(5568)$ state in CMS started at the beginning of 2016, as soon as the state was announced, with the hope to confirm the D0 observation. The first results from CMS on July, 28th 2016 [35], were negative, but a lot of improvements were needed in order to support this result. In the meantime, the LHCb Collaboration published their results on October, 7th 2016 [9], in agreement with the CMS preliminary result.

Final CMS results at the end of 2017 confirm and improve the LHCb results. Few days after, the CDF Collaboration announced the non-observation of the $X(5568)$, and the following week the D0 Collaboration reported a reconfirmation in a different B_s^0 decay channel. This gives an idea about the relevance of the issue nowadays.

The CDF result

A week after the final CMS results were available, on december 27th, 2017, the CDF Collaboration presented their results on the search of the $X(5568)$ state, the first one with the same initial conditions [33]. Using the Fermilab Tevatron Collider, the CDF experiment collected 9.6 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The decay channel $X(5568) \rightarrow B_s^0 \pi^\pm$ ($B_s^0 \rightarrow J/\psi \phi$, $J/\psi \rightarrow \mu^+ \mu^-$, $\phi \rightarrow K^+ K^-$) was investigated and, with around a few B_s^0 mesons less than the D0 study (this is surprising, given the larger efficiency of the CDF detector), no evidence of the $X(5568)$ state was found.

Similar to LHCb and CMS, an upper limit to the relative production was reported at 95% of CL for $p_T(B_s^0) > 10$ GeV: $\rho_X < 6.7\%$. Our result is significantly more restrictive than CDF.

The new D0 result

Two days after the CDF announcement, on December 29th, 2017, the D0 Collaboration presented additional evidence of the $X(5568)$ state in a different decay channel [34].

Considering 10.4 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, D0 search for the $X(5568)$

state decaying into $B_s^0 \pi^\pm$ using the semileptonic decay $B_s^0 \rightarrow \mu^+ D_s^- Y$, $D_s^- \rightarrow \phi \pi^-$, $\phi \rightarrow K^+ K^-$. In this case, Y stands for an unseen neutrino, photons or pions from a D_s^* decay, or other hadrons from the B_s^0 decay. So, similar to the hadronic case, they found around 121 $X(5568)$ candidates with around 6200 B_s^0 mesons. The invariant mass and natural width of the $X(5568)$ are $m = 5566.4_{-2.8}^{+3.4}(\text{stat})_{-0.6}^{+1.5}(\text{syst})$ MeV/c² and $\Gamma = 2.0_{-2.0}^{+9.5}(\text{stat})_{-2.0}^{+2.8}(\text{syst})$ MeV/c², respectively, and the signal has a significance of 3.2σ , without the look-elsewhere effect and including systematics. At the end, these results are in agreement with the hadronic channel results within uncertainties.

In addition, hadronic and semileptonic samples were combined and fitted with common mass and natural width parameters. This results in around $131 + 147$ $X(5568)$ candidates for hadronic and semileptonic samples, with invariant mass $m = [5566.9_{-3.1}^{+3.2}(\text{stat})_{-1.2}^{+0.6}(\text{syst})]$ MeV/c² and natural width $\Gamma = [18.6_{-6.1}^{+7.9}(\text{stat})_{-3.8}^{+3.5}(\text{syst})]$ MeV/c². In this case, the signal significance including systematics and the look-elsewhere effect is 6.7σ .

6.1.1 Current status

Although the CDF Collaboration searched the $X(5568)$ state in the same conditions as D0, they did not find signals of this structure in the $B_s^0 \pi^\pm$ mass distribution. Since the number of B_s^0 candidates in CDF is about 2/3 of the number of B_s^0 candidates reconstructed in D0, their limit to the relative production can not reject the D0 observation.

On the other hand, since both experiments, LHCb and CMS, have much larger B_s^0 samples with lower background and better mass resolution compared to the D0 collaboration, it is easy to think that the peak seen by D0 could be a statistical fluctuation of their data. However, The D0 Collaboration also found evidence of the $X(5568) \rightarrow B_s^0 \pi^\pm$ with B_s^0 mesons reconstructed in a semi-leptonic decay. Then, currently the D0 Collaboration is the only experiment that can see the $X(5568)$ state.

Appendix

A.- MC simulation

The EVTGEN user decay table for the $X(5568)$ decay simulation is shown:

```
Define Hp 0.4727
Define Hz 0.7258
Define Hm 0.4998
Define pHp 3.23
Define pHz 0.0
Define pHm 3.16
Define dms 17.757e12
Define dgammas 8.2e10
yesIncoherentBsMixing dms dgammas
#
Alias myX5568+ B+
Alias myX5568- B-
ChargeConj myX5568- myX5568+
Alias MyB_s0 B_s0
Alias Myanti-B_s0 anti-B_s0
ChargeConj Myanti-B_s0 MyB_s0
Alias MyJ/psi J/psi
Alias MyPhi phi
ChargeConj MyJ/psi MyJ/psi
ChargeConj MyPhi MyPhi
#
Decay myX5568+
```

```

0.500 MyB_s0 pi+ PHSP;
0.500 Myanti-B_s0 pi+ PHSP;
Enddecay
#
Decay myX5568-
0.500 MyB_s0 pi- PHSP;
0.500 Myanti-B_s0 pi- PHSP;
Enddecay
#
Decay MyB_s0
1.000 MyJ/psi MyPhi PVV_CPLH 0.017 1 Hp pHp Hz pHz Hm pHm;
Enddecay
#
Decay Myanti-B_s0
1.000 MyJ/psi MyPhi PVV_CPLH 0.017 1 Hp pHp Hz pHz Hm pHm;
Enddecay
#
Decay MyJ/psi
1.000 mu+ mu- PHOTOS VLL;
Enddecay
#
Decay MyPhi
1.000 K+ K- VSS;
Enddecay
End

```

B.- Fit results of the $B_s^0\pi^\pm$ mass resolution in MC

Table 1: Fit results of the $B_s^0\pi^\pm$ invariant mass resolution distribution in MC with a triple-Gaussian function, and obtained in several mass regions (first column). Case with $p_T(B_s^0) > 15$ GeV is also presented.

Region MeV	σ_1 MeV	σ_2 MeV	σ_3 MeV	f_1	f_2
Full	1.05 ± 0.02	3.79 ± 0.04	1.95 ± 0.02	0.26 ± 0.01	0.18 ± 0.01
5506 – 5546	1.53 ± 0.04	0.72 ± 0.02	3.35 ± 0.10	0.51 ± 0.02	0.41 ± 0.02
5546 – 5561	1.88 ± 0.07	1.13 ± 0.04	3.63 ± 0.08	0.51 ± 0.04	0.35 ± 0.05
5561 – 5575	1.24 ± 0.03	3.73 ± 0.10	2.10 ± 0.06	0.36 ± 0.03	0.13 ± 0.02
5575 – 5590	1.26 ± 0.09	2.02 ± 0.10	3.77 ± 0.08	0.21 ± 0.07	0.54 ± 0.05
5590 – 5630	1.37 ± 0.16	2.22 ± 0.16	4.13 ± 0.15	0.17 ± 0.09	0.55 ± 0.06
Full ($p_T(B_s^0) > 15$ GeV)	1.03 ± 0.02	3.76 ± 0.04	1.93 ± 0.02	0.25 ± 0.01	0.18 ± 0.01

Table 2: Effective resolution for several mass regions.

Region [MeV]	$\sigma_{eff}^{X(5568)}$ [MeV]
Full	2.24 ± 0.003
5506 – 5546	1.504 ± 0.007
5546 – 5561	2.036 ± 0.006
5561 – 5575	2.155 ± 0.005
5575 – 5590	2.46 ± 0.06
5590 – 5630	2.81 ± 0.02
Full ($p_T(B_s^0) > 15$ GeV)	2.219 ± 0.003

C.- Fits to the background shape of the $B_s^0\pi^\pm$ invariant mass for $p_T(B_s^0) > 15$ GeV/ c from MC

Figure 1: Fits to the background shape of the $M^\Delta(B_s^0\pi^\pm)$ distribution obtained from MC for $p_T(B_s^0) > 15$ GeV/ c . The model is a linear power function (up) times Pol1, or (down) times Pol2. Pulls are shown in bottom panels. The background sample is a combination of fully matched B_s^0 candidates and “pion” tracks. Generated pions coming from the $X(5568)$ are excluded.

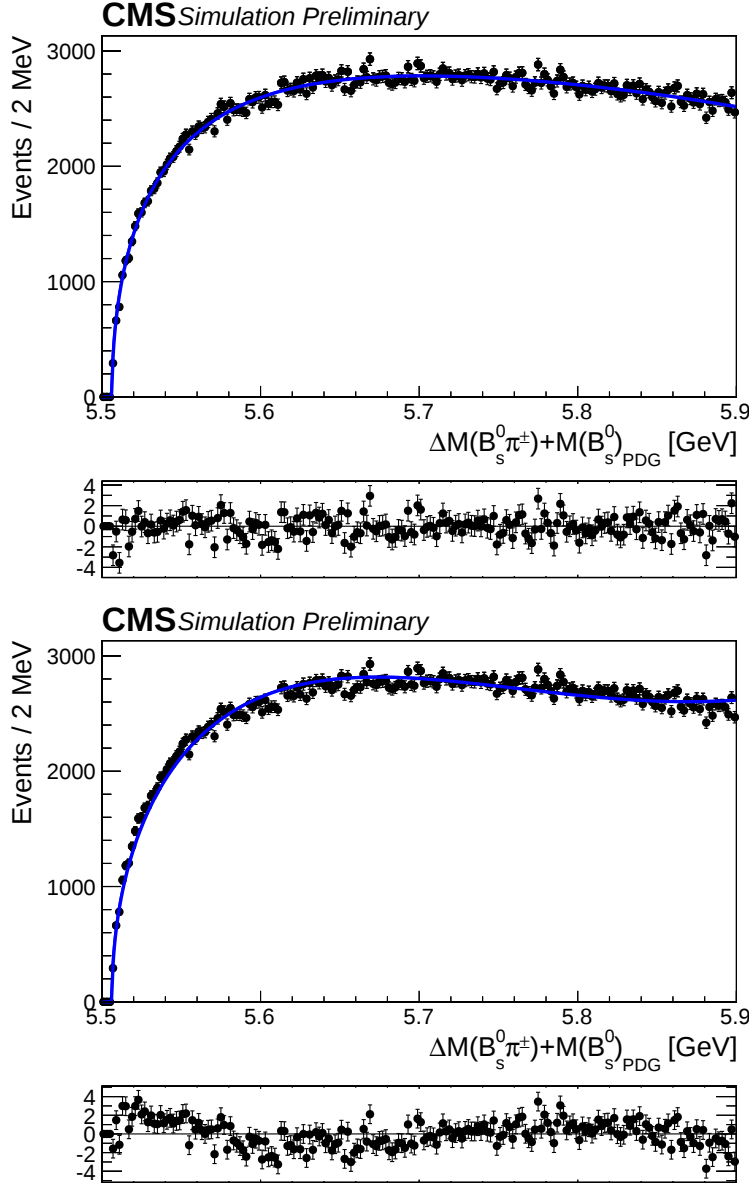
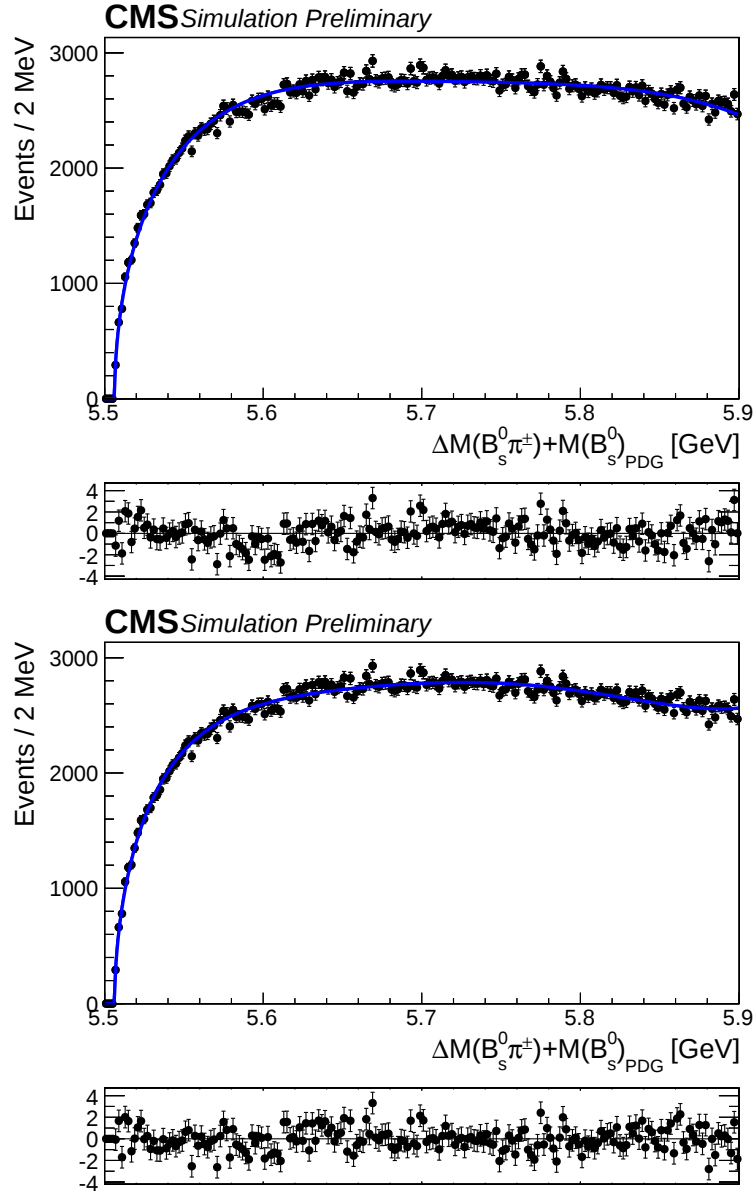


Figure 2: Fits to the background shape of the $M^\Delta(B_s^0\pi^\pm)$ distribution obtained from MC for $p_T(B_s^0) > 15$ GeV/ c . The model is a linear power function (up) times Pol3, (down) times Pol4. Pulls are shown in the bottom panels. The Background sample is a combination of fully matched B_s^0 candidates and “pion” tracks. Generated pions coming from the $X(5568)$ are excluded.



D.- Fits varying p_T requirements

Fits varying the p_T requirements of the $B_s^0\pi^\pm$, B_s^0 and $\pi^\pm$ candidates are shown in Fig. 3 and Fig. 4. Non-relativistic Breit-Wigner function is used for the signal model in these cross-checks. All results are consistent with a negligible $X(5568)$ signal (See Table 4.2).

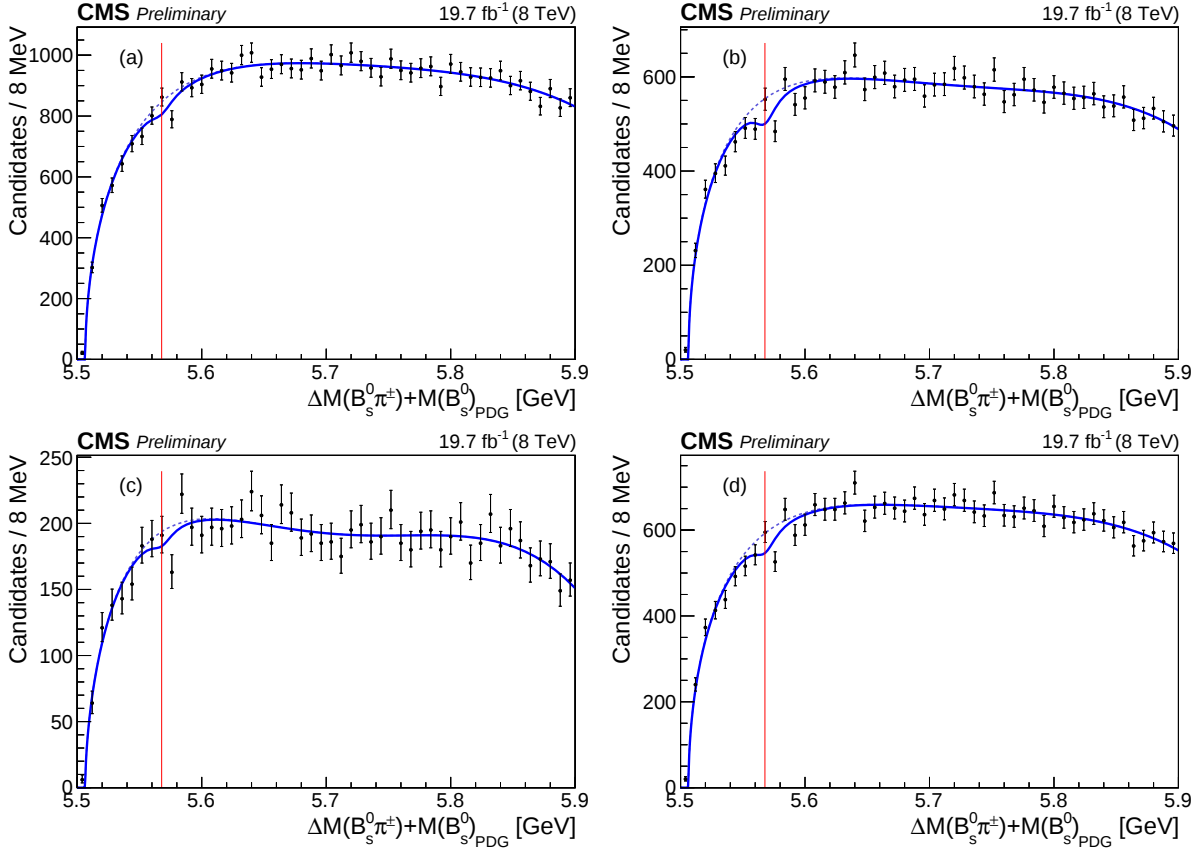


Figure 3: Fits to $M^\Delta(B_s^0\pi^\pm)$ distributions for events in the B_s^0 signal region with: (a) $p_T(B_s^0) > 15$ GeV, (b) $p_T(B_s^0) > 20$ GeV, (c) $p_T(B_s^0) > 30$ GeV, (d) $p_T(B_s^0\pi^\pm) > 20$ GeV.

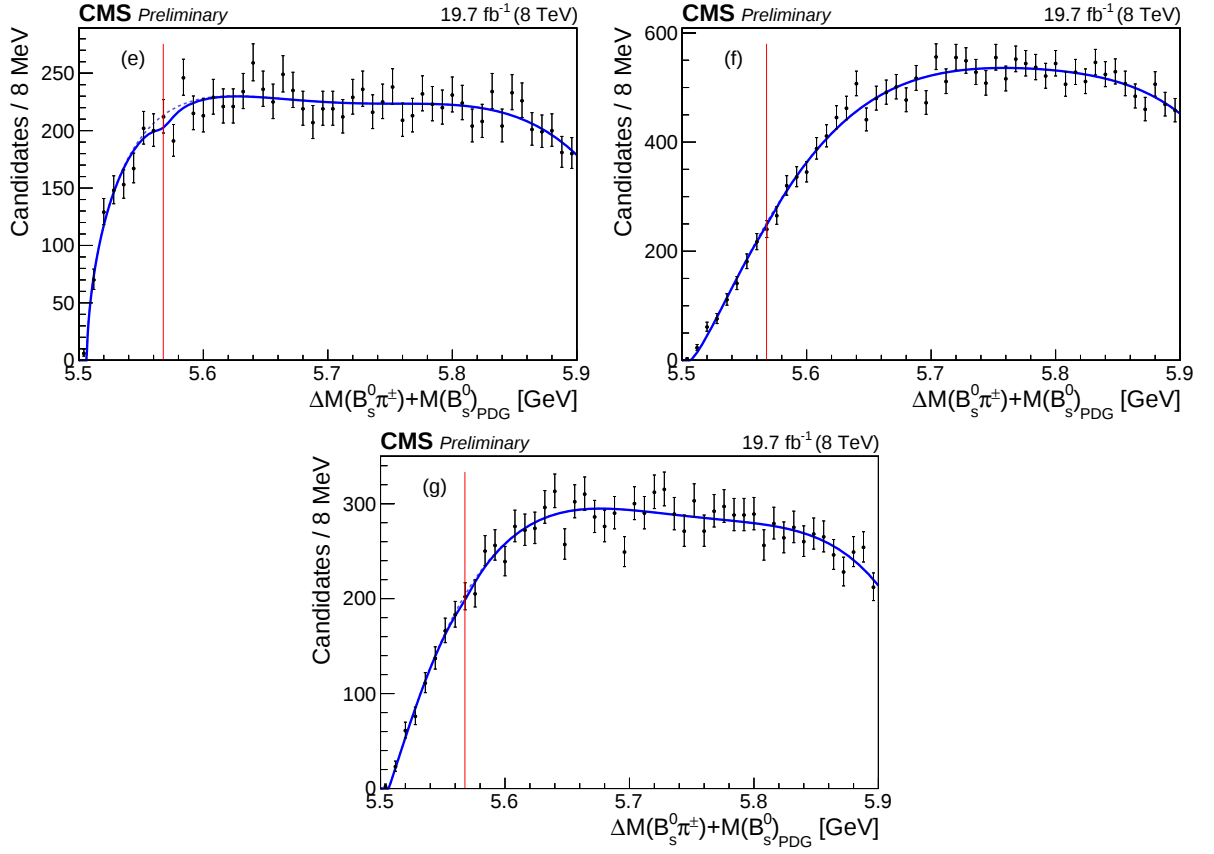


Figure 4: Fits to $M^\Delta(B_s^0 \pi^\pm)$ distribution for events in the B_s^0 signal region with: (e) $p_T(B_s^0 \pi^\pm) > 30$ GeV, (f) $p_T(\pi^\pm) > 1$ GeV, (g) $p_T(B_s^0) > 20$ GeV and $p_T(\pi^\pm) > 1$ GeV.

E.- Study on vertex requirements

The pion and B_s^0 candidate are expected to be in the PV. For this reason, the baseline requirement on the pion is to belong to the collection of tracks forming the selected PV. Other assumptions are investigated below.

E1.- Fits varying the requirement on the pion impact parameter significance

A requirement on the pion impact parameter significance, $d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)}$, is investigated. Fig. 5 shows fits to the $B_s^0\pi^\pm$ mass distribution varying this parameter. The signal model used for this cross-checks is a non-relativistic Breit-Wigner function, and all results are consistent with a negligible $X(5568)$ signal (see Table 4.2).

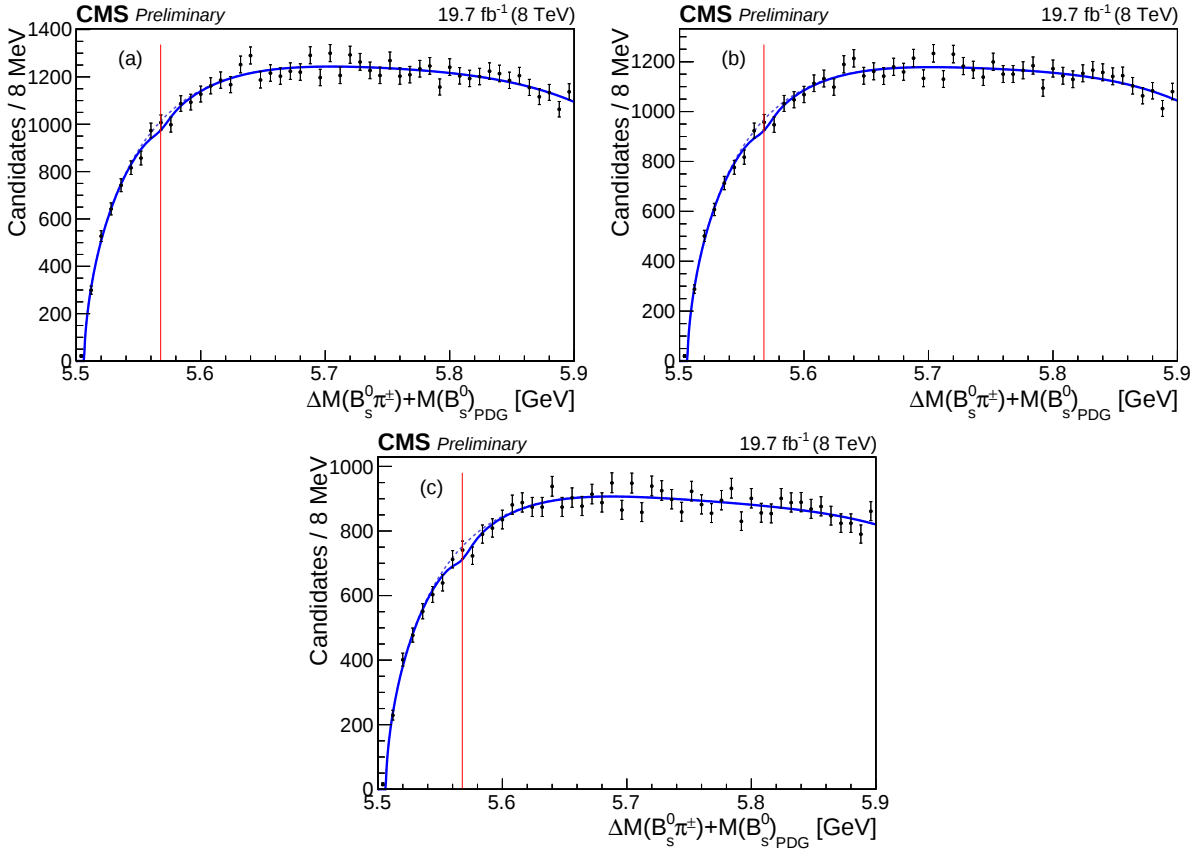


Figure 5: Fits to $M^\Delta(B_s^0\pi^\pm)$ distributions for events in the B_s^0 signal region. Additionally to the baseline selection, this requirement is imposed: (a) $d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)} < 3$, (b) $d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)} < 2$ and (c) $d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)} < 1$.

E2.- Study of the pion weight in the selected PV

Another variable not employed in the baseline selection is the pion weight in the selected primary vertex (W_π^{PV}). The distribution of the W_π^{PV} for the selected events is shown in Fig. 6(a), and the scatter plot of this variable versus $d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)}$ is presented in Fig. 6(b). These plots show that most events have high values of the W_π^{PV} , and low (< 2) values of $d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)}$. Additionally, as expected, the variables W_π^{PV} and $d_{xy}(\pi^\pm)/\sigma_{d_{xy}(\pi^\pm)}$ are negatively correlated.

The $M^\Delta(B_s^0\pi^\pm)$ distributions obtained with different requirements on W_π^{PV} are shown in Fig. 6(c). In every case there is no visible excess in the region where the $X(5568)$ was claimed, and the shape of the distribution in general is similar to the shape without a cut on W_π^{PV} . The Fig. 6(d) shows a fit $B_s^0\pi^\pm$ mass distribution with $W_\pi^{PV} > 0.95$. With a signal yield of -57 ± 137 , it shows excellent consistency with background-only hypothesis.

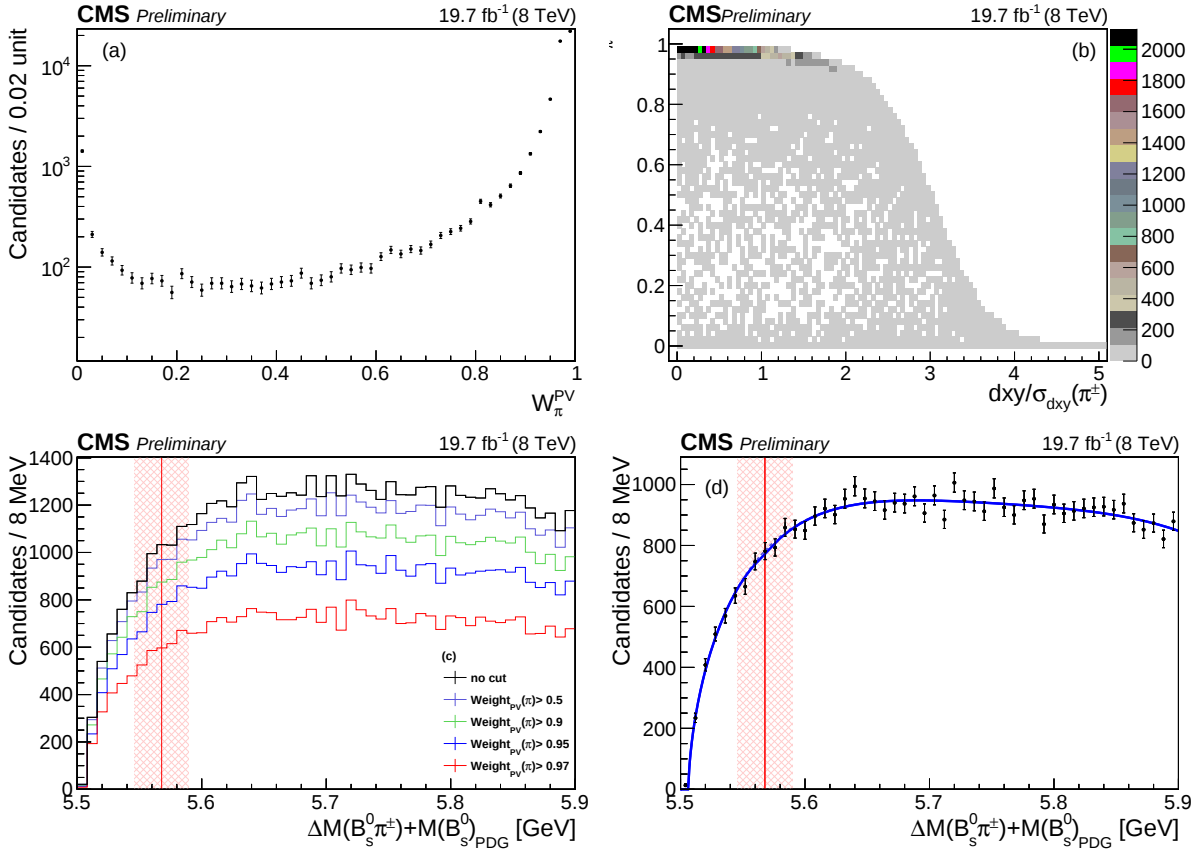


Figure 6: (a) Distribution of W_{π}^{PV} variable. (b) Scatter plot of W_{π}^{PV} : $d_{xy}(\pi^{\pm})/\sigma_{d_{xy}}(\pi^{\pm})$. (c) $M^{\Delta}(B_s^0 \pi^{\pm})$ distribution for events in the B_s^0 signal region with different cuts on W_{π}^{PV} . (d) Fit to $M^{\Delta}(B_s^0 \pi^{\pm})$ distribution for events in the B_s^0 signal region, the signal yield results in -57 ± 137 ; the $W_{\pi}^{PV} > 0.95$ requirement is imposed additionally to the baseline selection.

E3.- Fits varying the requirement on the $B_s^0\pi^\pm$ vertex probability

The requirement on the $B_s^0\pi^\pm$ vertex probability (P_{vtx}) is investigated. Fig. 7 shows fits varying this requirement with a non-relativistic Breit-Wigner function used for the signal model. All results are consistent with a negligible $X(5568)$ signal (See Table 4.2).

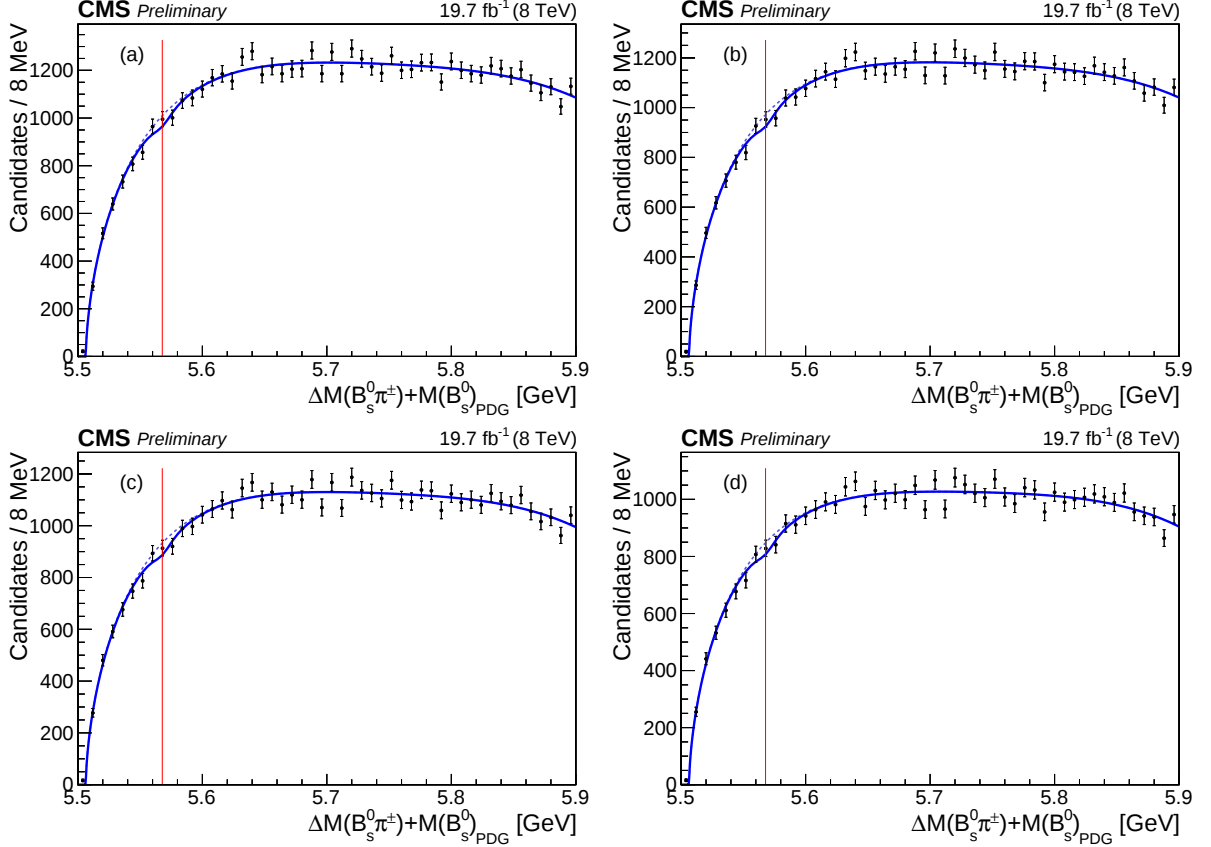


Figure 7: Fits to the $M^\Delta(B_s^0\pi^\pm)$ distributions for events in the B_s^0 signal region. Different requirements on the $B_s^0\pi^\pm$ vertex probability are imposed: (a) $P_{vtx} > 1\%$, (b) $P_{vtx} > 5\%$, (c) $P_{vtx} > 10\%$, (d) $P_{vtx} > 20\%$.

F.- The signal shape comparison

During the different stages of the analysis, different functions were used to model the $X(5568)$ signal in $B_s^0\pi^\pm$ invariant mass distribution. The Fig. 8 shows the comparison of the following shapes:

- non-relativistic Breit-Wigner function;
- Relativistic Breit-Wigner function;
- Relativistic Breit-Wigner function convolved with the triple-Gaussian resolution;
- Relativistic Breit-Wigner function multiplied by the efficiency dependence on mass and convolved with the triple-Gaussian resolution.

In all cases, the mean value and Γ are fixed to their “nominal” values, D0 measurements, of 5.5678 GeV and 0.0219 GeV, respectively. It is clearly seen that the differences between the last 3 shapes are negligibly small.

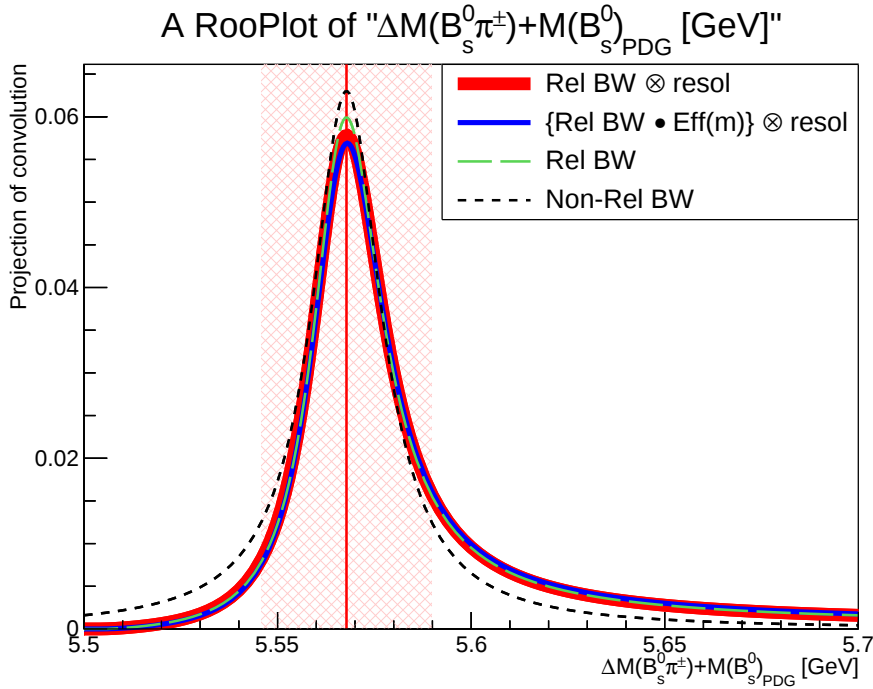


Figure 8: Different $X(5568)$ signal functions compared. The red vertical band indicates $M_X \pm \Gamma_X$.

G.- Matching and background model from MC

A matching process between the reconstructed tracks and generated particles is used to remove background from the MC samples (e.g. Fig. 5.1).

In order to match a track with a particle, the angular difference $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ must be less than 0.004 for muons and 0.03 for hadron tracks. Information about the parents of these particles (PDG Id) is also used to require the complete decay chain (e.g. $X(5568)^\pm \rightarrow B_s^0 \pi^\pm \rightarrow J/\psi \phi \pi^\pm \rightarrow \mu^+ \mu^- K^+ K^-$) in the case of fully matched signal events.

The fully matched $B_s^0 \pi^\pm$ invariant mass distribution in Fig. 5.1(b) can be compared with the same distribution without matching the pion track in Fig. 9 (matching of the B_s^0 decay chain is always required since the relative efficiency is not affected by this requirement). The MC matching efficiency is found to be 1.0007 ± 0.0002 for the baseline selection and 1.0050 ± 0.0002 for $p_T(B_s^0) > 15$ GeV; therefore, it could be considered 100% efficient. The matching purity is of about 99.8%.

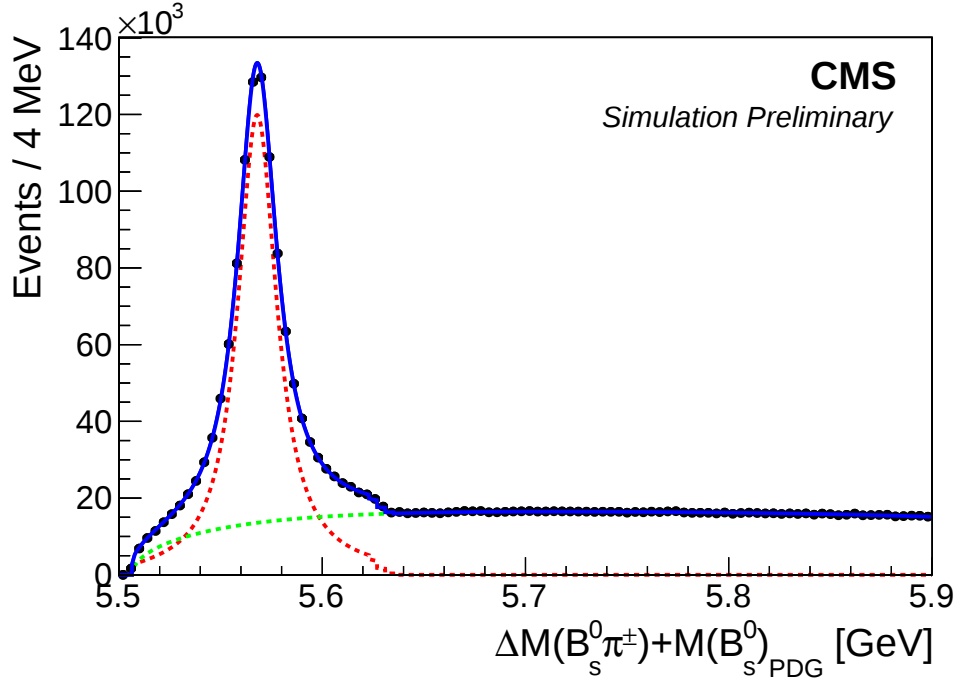


Figure 9: Fitted invariant mass of reconstructed $X(5568)$ candidates in MC. The pion track is not required to match a MC particle.

H.- HiggsAnalysisCombinedLimit tool for the upper limit estimation

The first step to use the tool is to setup the environment, as described in [32]. After that, a datacard file “datacard.txt” has to be prepared with the following content:

```
imax 1
jmax 1
kmax *
-----
shapes * * shapes.root wspace:$PROCESS
-----
bin 1
observation 56369
-----
bin      1      1
process  signal  bkgr
process   0      1
rate     2.2233  56369
-----
BsAndEff  lnN    1.041  -
S1_mean   param  5.5678  0.0029
S1_gamma  param  0.0219  0.0064
```

In this file, the line “shapes * * shapes.root wspace:\$PROCESS” refers to the file shapes.root, where the RooWorkspace named “wspace” is saved. The RooDataset with values of $M^\Delta(B_s^0\pi^\pm)$ is saved in this RooWorkspace. “Observation 56369” stands for the total number of events after the selection criteria. Names “signal” and “bkgr” correspond to the names of the signal and background RooAbsPdf’s, saved in the same RooWorkspace.

The tool result is an upper limit on the signal strength factor, r , which is the ratio of the signal to the expected signal (the latter is defined by “rate 2.2233”). In this line, 2.2233 stands for $1/10000$ of the $N(B_s^0) \times \epsilon_{rel}$ value (division by 10000 is needed to make this value negligible compared to 56369). The line “BsAndEff lnN 1.041 -” makes

the uncertainty of $N(B_s^0) \times \epsilon_{rel}$ taken into account.¹.

The systematic uncertainty due to the knowledge of $X(5568)$ mass and Γ is accounted for with the last two lines (where `S1_mean` and `S1_gamma` are names of `RooRealVar` parameters of the signal function).

The tool is launched by execution “`combine -M Asymptotic datacard.txt`” command, where `Asymptotic` stands for the method (`Asymptotic` is the advised one for calculation of limits)². The tool result “ $r < 105$ at 95% CL” is translated into an upper limit (10000 times smaller value) $\rho_X < 1.05\% @ 95\% \text{ CL}$.

¹The inclusion of these uncertainties produces almost negligible change in the limit value; however, this is the expected behavior, since the statistical uncertainty of the limit from data is already large, and the uncertainties are added in quadrature.

²Addition of “`--toysFrequentist`” option into command line produces no change since the initial parameters of background are already reasonable.

I.- Further studies

The resolution function is mainly mass-independent around the $X(5568)$ peak measured by D0, as shown in Table 1; however, far from the nominal mass value, the effective resolution can change significantly. Because the official $X(5568)$ MC only has events with masses up to about 5.563 GeV, we use the official B_s^0 MC reconstructed as $B_s^0\pi^\pm$ to obtain the mass resolution for higher $B_s^0\pi^\pm$ invariant mass values (the pion candidate must match a generated charged particle in order to obtain its true momentum, and it is assigned the mass of a pion regardless of its true mass). Fig. 10 (left) shows a comparison of effective resolutions between the $X(5568)$ and B_s^0 MCs reconstructed as $B_s^0\pi^\pm$. Distributions are fitted with a linear function and parameters are found to be statistically consistent. Therefore, points are combined in Fig. 10 (right) to obtain a single model for the effective resolution in a wide mass region.

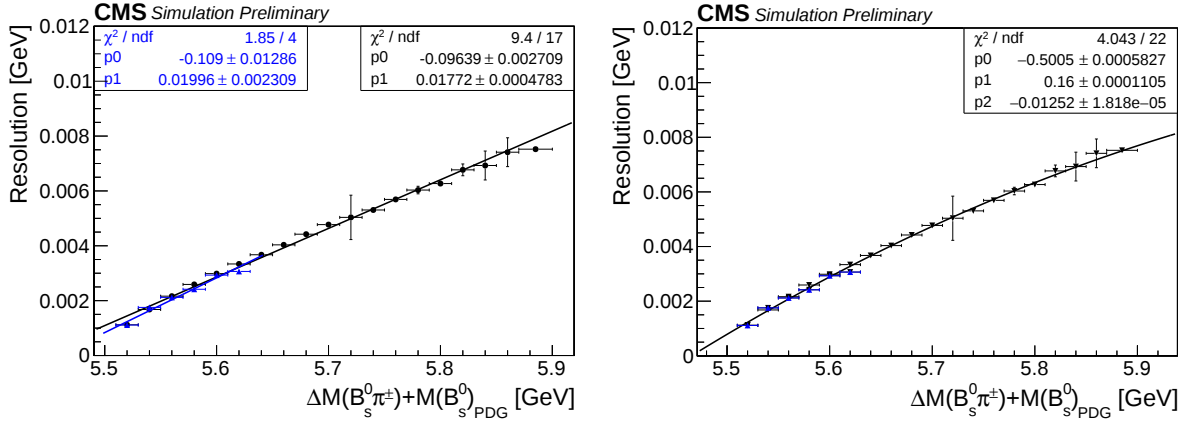


Figure 10: Effective mass resolution as a function of the $B_s^0\pi^\pm$ invariant mass. The $X(5568)$ MC sample is shown in blue and the B_s^0 MC in black. A first order polynomial is used to fit each distribution in the left plot, while a second order polynomial is used in the right plot to fit both distributions simultaneously.

As mentioned in Sec. 4.4.2, the efficiency decreases at lower mass values. This drop is mainly due to the correlation of the resonance mass with the pion p_T . This is verified in Fig. 11, that shows generator-level distributions of the pion p_T and the angle between the B_s^0 meson and $\pi^\pm$ momenta in the transverse plane, for different mass regions. It is evident that pion p_T distribution is harder at higher $B_s^0\pi^\pm$ mass values. Together with the $p_T(\pi^\pm) > 0.5$ GeV requirement at analysis level, they explain the steep drop

of the efficiency near the mass threshold. Same arguments can be used to justify the extrapolation of the efficiency to higher mass values, that assumes that the efficiency will continue to rise, but saturate at very high mass values.

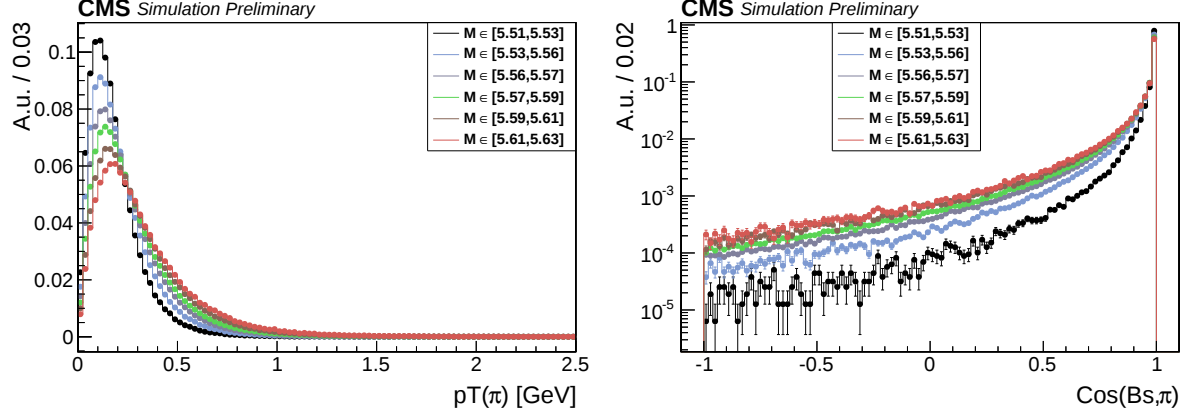


Figure 11: Distributions at generation level for different mass regions of: the pion p_T (left), the angle between the $p_T(B_s^0)$ and the $p_T(\pi^\pm)$ (right).

Bibliography

- [1] “The Hitchhiker’s Guide to the Galaxy”, Directed by Garth Jennings, Touchstone Pictures, 2005.
- [2] CMS Collaboration, “Observation of a new boson at a mass of 1225 GeV with the CMS experiment at the LHC”, Phys. Lett. B716 (2012) 30, (arXiv:1207.7235).
- [3] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, Phys. Lett. B716 (2012) 1, (arXiv:1207.7214)
- [4] M. Gell-Mann, “A SCHEMATIC MODEL OF BARYONS AND MESONS”, Phys. Lett. 8 (1964) 214.
- [5] G. Zweig, “An $SU(3)$ Model for Strong Interaction Symmetry and its Breaking”, Version 1, CERN Report CERN-TH-401, 1964.
G. Zweig, in: D. Lichtenberg, S. Rosen (Eds.), “An $SU(3)$ Model for Strong Interaction Symmetry and its Breaking”, Version 2, in: Developments in the Quark Theory of Hadrons, vol. 1, 1964, 1964-1978.
- [6] R.F. Lebed et al. , “Heavy-quark QCD exotica”, Progress in Particle and Nuclear Physics 93 (2017) 143-194.
- [7] D0 Collaboration, “Evidence for $B_s\pi^\pm$ state”, Phys. Rev. Lett. 117 (2016) 022003, (arXiv:1602.07588).
- [8] Particle Data Group, C. Patrignani et al., “Review of Particle Physics”, Chin. Phys. C 40 (2016) 100001 and 2017 update.
- [9] LHCb Collaboration, “Search for the structure in the $B_s\pi^\pm$ invariant mass spectrum”, Phys. Rev. Lett. 117 (2016) 152003, (arXiv:1608.00435)

- [10] CMS Collaboration, “Search for the $X(5568)$ state decaying in to $B_s^0\pi^\pm$ in proton-proton collisions at $\sqrt{s} = 8$ TeV”, arXiv:1712.06144v1 (2017).
- [11] T.J. Burns and E.S. Swanson, “Interpreting the $X(5568)$ ”, Phys. Lett. B 760 (2016) 627.
- [12] F.-K. Guo, U.-G. Meßner, and B.-S. Zou, “How the $X(5568)$ changes our understanding of QCD”. Commun. Theor. Phys. 65 (2016) 593.
- [13] C.J. Xiao, D.Y. Chen, “Possible $B^{(*)}\bar{K}$ hadronic molecule state”, Eur. Phys. J. A (2017) 53: 127.
- [14] O. Brüning et al. (editors), “LHC Design Report”, CERN-2004-003, 4 June 2004.
- [15] CMS Collaboration, “The Phase-2 Upgrade of the CMS Muon Detectors”, Technical Design Report CERN-LHCC-2017-012, CMS-TDR-17-003, CERN, 2017.
- [16] I. Béjar Alonso et al. (editors), “High-Luminosity Large Hadron Collider (HL-LHC)”, CERN-2017-007-M, 18 September 2017.
- [17] CMS Collaboration, “The Muon Project”, Technical Design Report CERN/LHCC 97-32, CMS TDR 3, CERN, 1997.
- [18] CMS Collaboration, “The CMS Experiment at the CERN LHC”, JINST 3 (2008) S08004.
- [19] T. Sjöstran, S. Mrenna, and P. Skands, “Pythia 6.4 physics and manual”, JHEP 05 (2006) 026.
- [20] D.J. Lange, “The EvtGen particle decay simulation package”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 462 (2001), no. 1-2, 115-128.
- [21] E. Barberio, B. van Eijik, and Z. Wąs, “Photos - a universal Monte Carlo for QED radiative corrections in decays”, Computer Physics Communications 66 (1991), no. 1, 115-128.
- [22] E. Barberio, and Z. Wąs, “PHOTOS - a universal Monte Carlo for QED radiative corrections: version 2.0”, Computer Physics Communications 79 (1994), no. 2, 291-308.

- [23] S. Agostinelli et al., “Geant4-a simulation toolkit”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 506 (2003), no. 3, 250 - 303.
- [24] CMS Collaboration, “Measurement of the CP-violating weak phase ϕ_s and the decay width difference $\Delta\Gamma_s$ using the $B_s^0 \rightarrow J/\psi\phi(1020)$ decay channel in pp collisions at $\sqrt{s} = 8$ TeV”, Phys. Lett. B757 (2016) 97-120.
- [25] The ATLAS Collaboration, The CMS Collaboration, The LHC Higgs Combination Group Collaboration, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report CMS-NOTE-2011-005. ATL-PHYS-PUB-2011-11, CERN, Geneva, Aug, 2011.
- [26] A. L. Read, “Presentation of search results: The CL_s technique”, J. Phys. G28 (2002) 2693-2704.
- [27] T. Junk, “Confidence level computation for combining searches with small statistics”, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 434 (1999), no. 2, 435-443.
- [28] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, JINST 9 (2014), no. 10, P10009.
- [29] CMS Collaboration, “Measurement of Tracking Efficiency”.
- [30] A. Esposito, A. Pilloni, and A. D. Polosa, “Hybridized tetraquarks”, Phys. Lett. B 758 (2016) 292.
- [31] A. Ali, L. Maiani, A. D. Polosa, and V. Riquer, “ $B_c^\pm$ decays into tetraquarks”, Phys. Rev. D 94 (2016) 034036.
- [32] CMS, “HiggsAnalysisCombinedLimit twiki page”.
- [33] CDF Collaboration, “A search for the exotic meson $X(5568)$ with the Collider Detector at Fermilab”, arXiv:1712.09620v1 (2017).
- [34] D0 Collaboration, “Study of the $X^\pm(5568)$ state with semileptonic decays of the B_s^0 meson”, arXiv:1712.10176v1 (2017).

- [35] CMS Collaboration, “Search for the X(5568) state in B^0_s π^{+-} decays”, Technical Report CMS-PAS-BPH-16-002, CERN, Geneva, 2016.