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Abstract: A search for resonancelike structures in the B0s ± invariant mass spectrum is performed using proton-proton collision data collected by the CMS experiment at the LHC at √s=8 TeV, corresponding to an integrated luminosity of 19.7 fb−1. The B0s mesons are reconstructed in the decay chain B0s→J/ , with J/ → + − and →K+K−. The B0s ± invariant mass distribution shows no statistically significant peaks for different selection requirements on the reconstructed B0s and ± candidates. Upper limits are set on the relative production rates of the X(5568) and B0s states times the branching fraction of the decay X(5568)±→B0s ±. In addition, upper limits are obtained as a function of the mass and the natural width of possible exotic states decaying into B0s ±.

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Search for the $X(5568)$ State Decaying into $B_s^0\pi^\pm$ in Proton-Proton Collisions at $\sqrt{s}=8$ TeV

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A search for resonancelike structures in the $B_s^0\pi^\pm$ invariant mass spectrum is performed using proton-proton collision data collected by the CMS experiment at the LHC at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1}. The B_s^0 mesons are reconstructed in the decay chain $B_s^0 \to J/\psi\phi$, with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. The $B_s^0\pi^\pm$ invariant mass distribution shows no statistically significant peaks for different selection requirements on the reconstructed B_s^0 and $\pi^\pm$ candidates. Upper limits are set on the relative production rates of the $X(5568)$ and B_s^0 states times the branching fraction of the decay $X(5568)^\pm \to B_s^0\pi^\pm$. In addition, upper limits are obtained as a function of the mass and the natural width of possible exotic states decaying into $B_s^0\pi^\pm$.

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The evidence presented by the D0 Collaboration of a new state decaying to $B_s^0\pi^\pm$ [1] initiated considerable interest within the exotic hadron community (discussed, e.g., in Refs. [2,3] and references therein) and triggered a similar search by the LHCb Collaboration [4]. The D0 experiment reported an unexpected, narrow structure, named $X(5568)$, in the $B_s^0\pi^\pm$ invariant mass distribution and interpreted it as a hadron composed of four quarks of different flavors ($b\bar{s}u\bar{d}$; inclusion of charge-conjugate modes is implied throughout this Letter). The measured mass and natural width of this state are $5567.8 \pm 2.9(\mathrm{stat})^{+0.9}_{-1.9}(\mathrm{syst})$ MeV and $21.9 \pm 6.4(\mathrm{stat})^{+5.0}_{-2.5}(\mathrm{syst})$ MeV, respectively [1]. Possible quantum numbers for the state are $J^P = 0^+$, if the $B_s^0\pi^\pm$ is produced in an S-wave, or $J^P = 1^+$, if the decay proceeds via the chain $X(5568)^\pm \to B_s^{*0}\pi^\pm$, $B_s^{*0} \to B_s^0\gamma$ and the photon is not reconstructed. In the latter case, the mass of the new state would be shifted by $m_{B_s^{*0}} - m_{B_s^0}$ with respect to the measured $X(5568)$ mass, where $m_{B_s^0}$ and $m_{B_s^{*0}}$ are the nominal B_s^0 and B_s^{*0} masses [5].

The LHCb Collaboration searched for the $X(5568)$ state and reported a negative result [4]. Further independent searches are needed either to confirm the $X(5568)$ state or to set stronger limits on its production. In particular, the CMS detector can probe a central kinematic region of B_s^0 candidates similar to that of D0, complementing the LHCb search in the forward region. Recently, the CDF and ATLAS Collaborations reported independently negative search results for the $X(5568)$ [6,7], while the D0 Collaboration presented additional evidence for the $X(5568)$ by adding B_s^0 mesons reconstructed in semileptonic decays [8].

This Letter presents a search for the $X(5568)$ state performed by the CMS Collaboration at the LHC. The data sample corresponds to 19.7 fb^{-1} of proton-proton (pp) collisions at $\sqrt{s} = 8$ TeV collected in 2012. The $B_s^0\pi^\pm$ candidates are reconstructed through the decay $B_s^0 \to J/\psi\phi$, with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. The relative production rate of $X(5568)$, with respect to B_s^0, times the branching fraction of the $X(5568)^\pm \to B_s^0\pi^\pm$ decay is calculated using the relation

$$\rho_X \equiv \frac{\sigma(pp \to X + \text{anything})\mathcal{B}(X \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})} = \frac{N_X}{\epsilon_{\mathrm{rel}} N_{B_s^0}}, \tag{1}$$

where $X = X(5568)^\pm$, N_X ($N_{B_s^0}$) is the number of $X(5568)$(B_s^0) signal candidates reconstructed in data and $\epsilon_{\mathrm{rel}} = \epsilon_X/\epsilon_{B_s^0}$ is the relative efficiency. The D0 Collaboration measured $\rho_X = (8.6 \pm 2.4)\%$ and $(8.2 \pm 3.1)\%$ for $p_{\mathrm{T}}(B_s^0) > 10$ and 15 GeV [1].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are detected in the pseudorapidity range $|\eta| < 2.4$ in gas-ionization chambers embedded in

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the steel flux-return yoke outside the solenoid. The main subdetectors used for the present analysis are the silicon tracker and the muon detection system. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For nonisolated particles with transverse momentum $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [9]. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution for muons with $p_T < 10$ GeV of 0.8%–3.0% depending on $|\eta|$ [10]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [11].

Events of interest are selected using a two-tiered trigger system [12]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing. This analysis uses events collected with HLT algorithms requiring two muons that are consistent with originating from a J/ψ meson decaying at a significant distance from the luminous region.

The reconstruction of the B_s^0 candidates closely follows the procedure described in Ref. [13], where the CP-violating phase ϕ_s was measured using the same decay chain, $B_s^0 \to J/\psi\phi$, with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$, reconstructed from the same data set and triggered by the same L1 and HLT algorithms.

The reconstruction requires two muons of opposite charge that must match those that triggered the event readout. The offline muon selection is more restrictive than the trigger requirements and includes $p_T(\mu^\pm) > 4$ GeV, $|\eta(\mu^\pm)| < 2.2$, $p_T(\mu^+\mu^-) > 7$ GeV, soft muon identification [10], the dimuon vertex χ^2 fit probability $P_{\text{vtx}}(\mu^+\mu^-) > 10\%$, and the dimuon mass within the range 3.04–3.15 GeV. The angle $\alpha_T(\mu^+\mu^-)$ in the transverse plane between $\vec{p}_T(\mu^+\mu^-)$ and the vector $\vec{D}_{xy}(\mu^+\mu^-)$ from the beam axis to the dimuon vertex is required to satisfy $\cos\alpha_T(\mu^+\mu^-) > 0.9$. The dimuon vertex transverse displacement divided by its uncertainty, $D_{xy}(\mu^+\mu^-)/\sigma_{D_{xy}(\mu^+\mu^-)}$, must be greater than 3.

The two muons are combined with two other oppositely charged tracks in the event, neither identified as a muon and assumed to be kaons, which must each have $p_T(K^\pm) > 0.7$ GeV and satisfy high-purity track [9] requirements. The invariant mass of the kaon pair candidate, $M(K^+K^-)$, is required to be within ±10 MeV of the known $\phi(1020)$ meson mass [5].

The B_s^0 candidates are obtained using a kinematic vertex fit to the two muon and two kaon tracks, with the dimuon candidate mass constrained to the nominal J/ψ meson mass [5] [the mass of the K^+K^- candidate is not constrained because the width of the $\phi(1020)$ resonance exceeds the mass resolution]. Additional requirements imposed on the B_s^0 candidates include $p_T(B_s^0) > 10$ GeV, $P_{\text{vtx}}(B_s^0) > 1\%$, $D_{xy}(B_s^0)/\sigma_{D_{xy}(B_s^0)} > 3$, and $\cos\alpha_T(B_s^0) > 0.99$, where $D_{xy}(B_s^0)$ and $\alpha_T(B_s^0)$ are analogous to the corresponding dimuon variables and are measured with respect to the primary interaction vertex (PV). The events contain multiple pp collisions from the same or nearby bunch crossings (pileup), with an average of 16 collisions per event. The PV is chosen as the one with the smallest angle between the vector from the collision point to the B_s^0 candidate decay vertex and the B_s^0 candidate momentum.

An extended unbinned maximum-likelihood fit to the $J/\psi K^+K^-$ invariant mass, $M(J/\psi K^+K^-)$, distribution yields 49277 ± 278 B_s^0 signal candidates, where the signal and background components are modeled by a double-Gaussian and an exponential function, respectively, as shown in Fig. 1. In the fit, the common mean ($\mu_{B_s^0}$), the fraction of the second Gaussian function (f), and the widths ($\sigma_{1,2}$) of the two signal Gaussian functions (given in Fig. 1), as well as the parameter of the exponential function, are left free. Signal and lower and upper sideband mass regions are defined, respectively, by the intervals $[-2\sigma_{B_s^0}, +2\sigma_{B_s^0}]$, $[-10\sigma_{B_s^0}, -4\sigma_{B_s^0}]$, and $[4\sigma_{B_s^0}, 10\sigma_{B_s^0}]$ around $\mu_{B_s^0}$, as indicated in Fig. 1. Here, $\sigma_{B_s^0} \simeq 14$ MeV represents the standard deviation of the double-Gaussian function. In the signal region, the signal purity is about 85% and the number of multiple B_s^0 candidates in a single event is negligible.

The pion candidate from the $X(5568)^\pm \to B_s^0\pi^\pm$ decay is required to be a track used in the PV fit, with $p_T(\pi^\pm) > 0.5$ GeV, and satisfy track quality requirements [9]. The average number of $B_s^0\pi^\pm$ candidates per event in the B_s^0 signal region is 1.8. Constraints on the angle between the

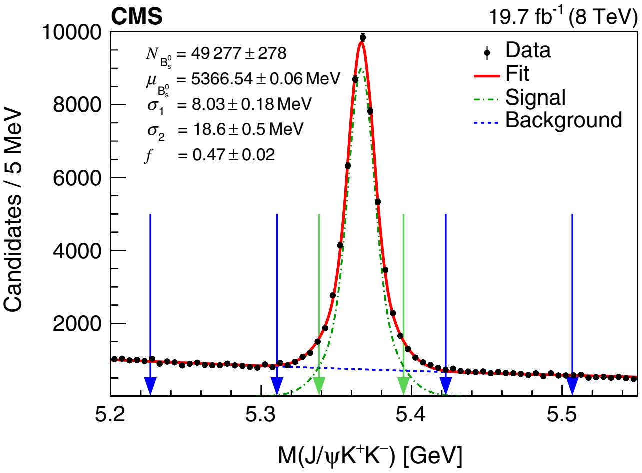

FIG. 1. Invariant mass distribution of the B_s^0 candidates with the fit result superimposed. The outermost pairs of dark vertical arrows define the lower and upper B_s^0 sidebands, while the innermost light vertical arrows delimit the signal region.

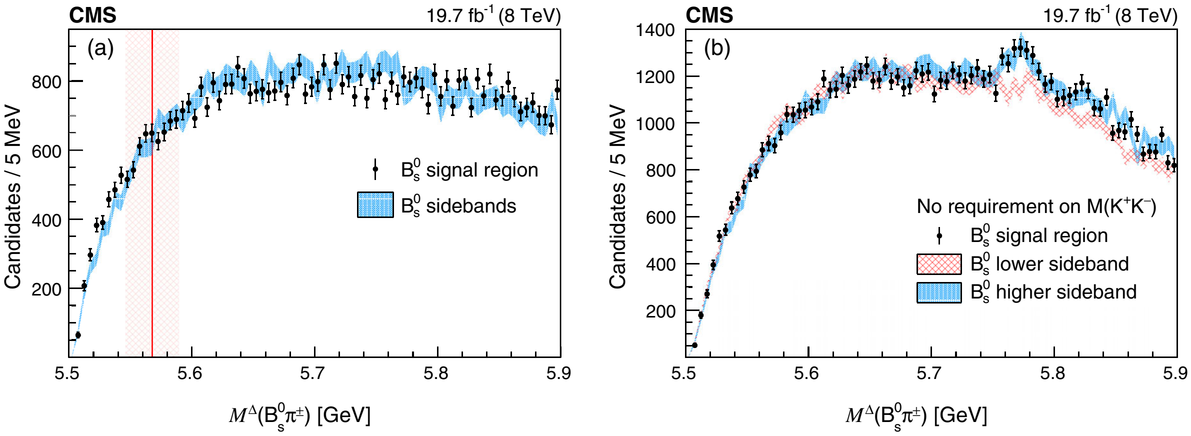

FIG. 2. (a) The $M^\Delta(B_s^0\pi^\pm)$ distribution for events in the B_s^0 signal (points) and sideband regions (bands). The latter is normalized to the former. The vertical band indicates the region $m_X \pm \Gamma_X$. (b) The $M^\Delta(B_s^0\pi^\pm)$ distribution for events in the B_s^0 signal (points) and lower and higher sideband regions (bands), when the requirement on $M(K^+K^-)$ is removed (see text for additional requirements). The three distributions are normalized from the mass threshold up to 5.74 GeV. The excess observed for events in the B_s^0 signal and higher sideband regions is due to $B_{1,2}^{(*)+} \to B^{*0}\pi^+$ decays.

momenta of the B_s^0 and $\pi^\pm$ candidates are not imposed in this analysis, because such requirements sculpt the $B_s^0\pi^\pm$ invariant mass distribution in a nontrivial way, as discussed in the Supplemental Material [14]. Motivated by the low momentum of the $\pi^\pm$ from the signal decay, together with the strong correlation between $M(J/\psi K^+K^-\pi^\pm)$ and $M(J/\psi K^+K^-)$, the invariant mass of a $B_s^0\pi^\pm$ candidate is defined as $M^\Delta(B_s^0\pi^\pm) = M(J/\psi K^+K^-\pi^\pm) - M(J/\psi K^+K^-) + m_{B_s^0}$. This improves the $B_s^0\pi^\pm$ mass resolution by a factor of 5, as found in Monte Carlo (MC) simulations.

Simulated MC events are produced with PYTHIA v6.424 [15]. The $X(5568)$ is simulated as a spin-0 particle of mass and width equal to $m_X \equiv 5567.8$ MeV and $\Gamma_X \equiv 21.9$ MeV, and is forced to decay to a B_s^0 meson and a $\pi^\pm$ using the phase-space model in EVTGEN 1.3.0 [16]. For the B_s^0 signal generation, EVTGEN simulates the $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, and $\phi \to K^+K^-$ decays, including the effects from mixing and *CP* violation. Final-state photon radiation is included in EVTGEN using PHOTOS [17,18]. The events are then passed through a detailed GEANT4-based simulation [19] of the CMS detector with the same trigger and reconstruction algorithms used on data. The simulation includes pileup effects at the same rate as observed in data.

The $M^\Delta(B_s^0\pi^\pm)$ distributions obtained from events in the B_s^0 signal and sideband regions are compared after normalization in Fig. 2(a), showing no significant differences from threshold near 5.5 GeV up to 5.9 GeV. In particular, no excess is visible near 5568 MeV.

To verify the reconstruction procedure, the requirement on $M(K^+K^-)$ is removed. This allows the $B^0 \to J/\psi K^+\pi^-$ decay to contribute to the resulting $M(J/\psi K^+K^-)$ distribution, but only in the B_s^0 signal and the higher sideband regions, as verified by simulation. Additional requirements are imposed to reduce the level of background: $p_T(B_s^0) > 25$ GeV, $p_T(\pi^\pm) > 1$ GeV, and $p_T(K^\pm) > 1$ GeV. Figure 2(b) shows the resulting $M^\Delta(B_s^0\pi^\pm)$ distributions for events in the lower and higher sideband and signal regions. Only the latter two distributions have a clear excess around 5.75–5.84 GeV. This excess is consistent with the decays $B_1(5721)^+ \to B^{*0}\pi^+$, $B_2^*(5747)^+ \to B^{*0}\pi^+$, and $B_2^*(5747)^+ \to B^0\pi^+$, where the decay $B^0 \to J/\psi K^+\pi^-$ is misreconstructed as $B_s^0 \to J/\psi K^+K^-$ (the photon from the $B^{*0} \to B^0\gamma$ decay is not reconstructed). The peaks in the $M^\Delta(B_s^0\pi^\pm)$ distribution corresponding to the decays $B_{1,2}^{(*)+} \to B^{*0}\pi^+$ are shifted by $m_{B_s^0} - m_{B^{(*)0}}$ with respect to the nominal masses of the $B_{1,2}^{(*)+}$ states [5].

A possible $X(5568)$ signal contribution in the $M^\Delta(B_s^0\pi^\pm)$ spectrum is modeled by a relativistic *S*-wave Breit–Wigner (BW) function, with mass and width parameters fixed to m_X and Γ_X, respectively. The BW is convolved with a triple-Gaussian resolution function whose parameters are obtained from the simulated data (standard deviation of the triple-Gaussian function is about 2.2 MeV in the region of interest). The background shape is approximated by a function of the form $(x - x_0)^\alpha \mathrm{Pol}_n(x)$, where $x = M^\Delta(B_s^0\pi^\pm)$, $x_0 = m_{B_s^0} + m_{\pi^\pm}$, with $m_{\pi^\pm}$ the $\pi^\pm$ mass [5], and $\mathrm{Pol}_n(x)$ represents a polynomial function of order n. For the default shape $n = 3$ is used. The polynomial coefficients, as well as the exponent α and the signal and background yields, are obtained from the unbinned extended maximum-likelihood fit shown in Fig. 3(a). The fit returns a signal yield of $N_X = -85 \pm 160$ events. The procedure is repeated requiring $p_T(B_s^0) > 15$ GeV, and the fit results displayed in Fig. 3(b) give $N_X = -103 \pm 122$ events.

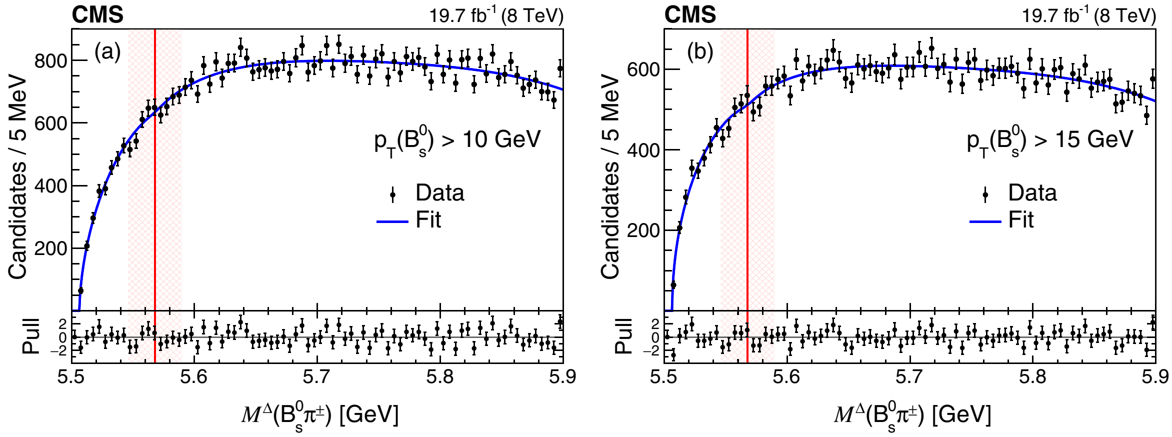

FIG. 3. The $M^{\Delta}(B_s^0\pi^{\pm})$ distribution for events in the B_s^0 signal region with the result of the fit superimposed for the baseline selection with $p_{\mathrm{T}}(B_s^0) > 10$ GeV (a) and $p_{\mathrm{T}}(B_s^0) > 15$ GeV (b). The vertical band indicates the region $m_X \pm \Gamma_X$. The lower panels display the pull (difference between the data and the fit result, divided by the statistical uncertainty in the data).

Several cross-checks are performed and in all cases the signal yield is consistent with zero. They include repeating the fit with the following variations: the background model parameters are fixed to the values obtained from the fit with the $X(5568)$ signal region excluded; the background model is fixed to the shape obtained from simulated B_s^0 mesons combined with pion candidates from the same simulated event; different kinematic requirements and reconstruction quality criteria are imposed on the $B_s^0\pi^{\pm}$, B_s^0, and $\pi^{\pm}$ candidates; collision events with multiple reconstructed candidates are removed from the data sample, and alternative background functions and fit regions are used.

An upper limit on ρ_X, defined in Eq. (1), is computed using the asymptotic CL_S [20,21] method developed in Ref. [22]. The limit takes into account the following sources of systematic uncertainty: the uncertainty in the mass and the width of the BW measured by the D0 Collaboration [1]; the uncertainty in $N(B_s^0)$; the pion tracking efficiency uncertainty of 3.9% [9]; the uncertainty in ϵ_{rel} due to the finite number of simulated events; the description of the background by alternative approximation functions, including the shape obtained from simulation; and modifications of the signal function due to variations of the resolution function and the efficiency with respect to $M^{\Delta}(B_s^0\pi^{\pm})$ (both negligible). The measured upper limit is $\rho_X < 1.1\%$ at 95% confidence level (CL) for the baseline selection criteria [$p_{\mathrm{T}}(B_s^0) > 10$ GeV] and $\rho_X < 1.0\%$ at 95% CL for the analysis requiring $p_{\mathrm{T}}(B_s^0) > 15$ GeV. Using simulations of a spin-1 state decaying to $B_s^{*0}\pi^{\pm}$, where $B_s^{*0} \to B_s^0\gamma$ and where the mass is shifted by $m_{B_s^{*0}} - m_{B_s^0}$, the upper limits were verified to differ negligibly between either the spin-1 or spin-0 assumption.

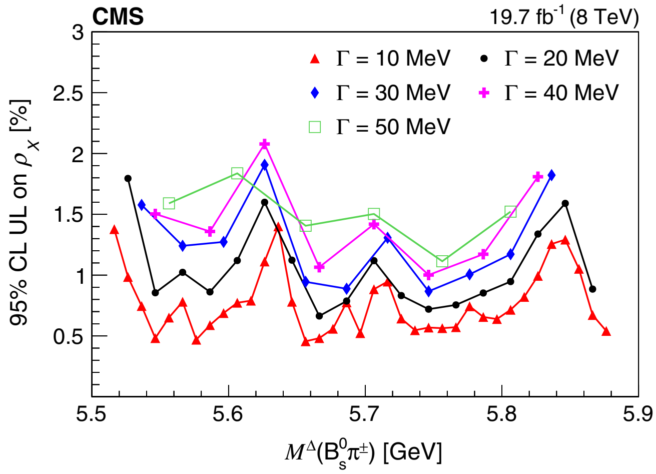

FIG. 4. The 95% CL upper limit (UL) on ρ_X, Eq. (1), as a function of the mass of a possible exotic state decaying into $B_s^0\pi^{\pm}$ for five different values of the natural width of the state.

Upper limits are also obtained for different values of mass and natural width (Γ) of a possible $B_s^0\pi^{\pm}$ resonance, as shown in Fig. 4. For these limits, no systematic uncertainties related to the mass and width of the exotic state are assigned. On the other hand, an additional systematic uncertainty in the relative efficiency of up to 6% is estimated for the extrapolation to high-mass resonances from the low-mass simulation. The limits are obtained for values of Γ from 10 to 50 MeV in 10 MeV steps, while the mass takes values from $m_{B_s^0} + m_{\pi^{\pm}} + \Gamma$ up to 5.9 GeV–1.5 Γ in order to consider a possible exotic state with higher mass decaying to the $B_s^0\pi^{\pm}$ final state [23,24]. No significant excess is found throughout the region considered.

In summary, a search for the $X(5568)$ state is performed by the CMS Collaboration using pp collision data collected at $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of 19.7 fb^{-1}. With about 50 000 B_s^0 signal candidates, no significant structure in the $B_s^0\pi^{\pm}$ invariant mass spectrum is found around the mass reported by the D0 Collaboration (nor for masses up to 5.9 GeV). The absence of a peak is supported by direct comparison with the events in the B_s^0 sidebands, and by fits to the $B_s^0\pi^\pm$ invariant mass distribution with a resonant component included, using different kinematic selection requirements, as well as variants of the background modeling, fit regions, and quality criteria.

Upper limits on the relative production rates of the $X(5568)$ and B_s^0 states, multiplied by the unknown branching fraction of the $X(5568)^\pm \to B_s^0\pi^\pm$ decay, are computed to be

$$\rho_X < 1.1\% \quad \text{at } 95\%\text{CL} \quad \text{for } p_{\mathrm{T}}(B_s^0) > 10\ \text{GeV} \quad \text{and}$$

$$\rho_X < 1.0\% \quad \text{at } 95\%\text{CL} \quad \text{for } p_{\mathrm{T}}(B_s^0) > 15\ \text{GeV}.$$

The upper limits on ρ_X presented in this Letter are a factor of 2 more stringent than the previous best limits, and do not confirm the existence of the $X(5568)$ state. These limits are also valid for a spin-1 state decaying into $B_s^{*0}\pi^\pm$. Additionally, upper limits are set for different values of mass and natural width of a hypothetical exotic resonance decaying into $B_s^0\pi^\pm$.

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