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Recent CMS results in conventional and exotic hadron spectroscopy

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Hadron spectroscopy at CMS

- LHC provides high luminosity: **heavy flavor production cross section several order of magnitudes greater than at e-e colliders**

- But the hadron collisions environment is characterized by **complex initial state and high background**

- **CMS exploits its 4π coverage and high resolution to perform challenging measurements in Heavy Flavor physics using data from both proton-proton (pp) and lead-lead (PbPb) collisions**

- The presented recent CMS measurements concern both **conventional and exotic spectroscopy in the charm** (X(3872)) **and beauty** (B_c mesons, Λ_b and Ξ_b baryons, bottomonia) **sectors**

Recent CMS results

EXOTIC | CONVENTIONAL

QUARKONIA

- Measurement of the $\Upsilon(1S)$ pair production cross section and search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV [PLB 808 (2020) 135578]

  Not covered today

B MESONS

- Observation of the $B_s^0 \to X(3872)\phi$ decay [PRL 125 (2020) 152001]
- Evidence for X(3872) in PbPb collisions and studies of its prompt production at $\sqrt{s_{NN}}$ = 5.02 TeV [arXiv:2102.13048, submitted to PRL]
- Observation of $B^0 \to \psi(2S)K^0_s\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_s$ decays [CMS-PAS-BPH-18-004]
- Measurement of $B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios in proton-proton collisions at $\sqrt{s}$ = 13 TeV [PRD 102 (2020) 092007]

  See Talk by F. Simone

BARYONS

- Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ in pp collisions at $\sqrt{s}$ = 13 TeV [PLB 803 (2020) 135345]
- Observation of a new excited beauty strange baryon decaying to $\Xi_b^-\pi^+\pi^-$ [PRL 126 (2021) 252003]

Observation of $B_s^0 \rightarrow X(3872)\phi$ decay

Search on 140 fb^{-1} of pp collisions data at $\sqrt{s}$ = 13 TeV during 2016-2018 at LHC

X(3872) [*aka* $\chi_{c1}(3872)$] does not fit $c\bar{c}$ spectrum: **narrow state above $D\bar{D}$ threshold**

Investigate X(3872) production in weak decays from beauty mesons

Ratio R: production cross section measured w.r.t ψ(2S) (*normalization channel*)

$$R \equiv \frac{\mathcal{B}[B_s^0 \to X(3872)\phi]\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-]}{\mathcal{B}[B_s^0 \to \psi(2S)\phi]\mathcal{B}[\psi(2S) \to J/\psi\pi^+\pi^-]} = \frac{N[B_s^0 \to X(3872)\phi]\ \epsilon_{B_s^0 \to \psi(2S)\phi}}{N[B_s^0 \to \psi(2S)\phi]\ \epsilon_{B_s^0 \to X(3872)\phi}}$$

- **X(3872)** and **ψ(2S)** both reconstructed in same final state $J/\psi(\rightarrow \mu^+\mu^-)\ \pi^+\pi^-$
- **ϕ(1020)** reconstructed in K^+K^- final state
- $N[B_s^0 \rightarrow X(3872)/\psi(2S)\ \phi]$: **signal yields** for $X(3872)/\psi(2S) \rightarrow J/\psi\pi^+\pi^-$
- $\varepsilon(B_s^0 \rightarrow X(3872)/\psi(2S)\ \phi)$: **overall reconstruction efficiency**
- Many systematic uncertainties cancel in the ratio (*nearly identical kinematics*)

$B_s^0 \to \psi(2S)/X(3872)\phi$ signal extraction

- **HLTrigger requirements**: J/ψ+track from (common) displaced vertex
- **J/ψ+4tracks vertex**, with two OS tracks compatible with $\phi(1020) \to K^+K^-$
- **Separate $m(J/\psi\pi^+\pi^-)$ mass windows** for $\psi(2S)$ and $X(3872)$
- **Improved resolution** with $m(B_s^0) = m(J/\psi K^+K^-\pi^+\pi^-) - m(J/\psi\pi^+\pi^-) + m^{PDG}_{\psi(2S)/X(3872)}$
- **Signal extraction optimized with** (separate) **further selection** (MC-based studies)

Two separate 2D UML fits:

❖ **$\psi(2S)$**: Double-Gaussian

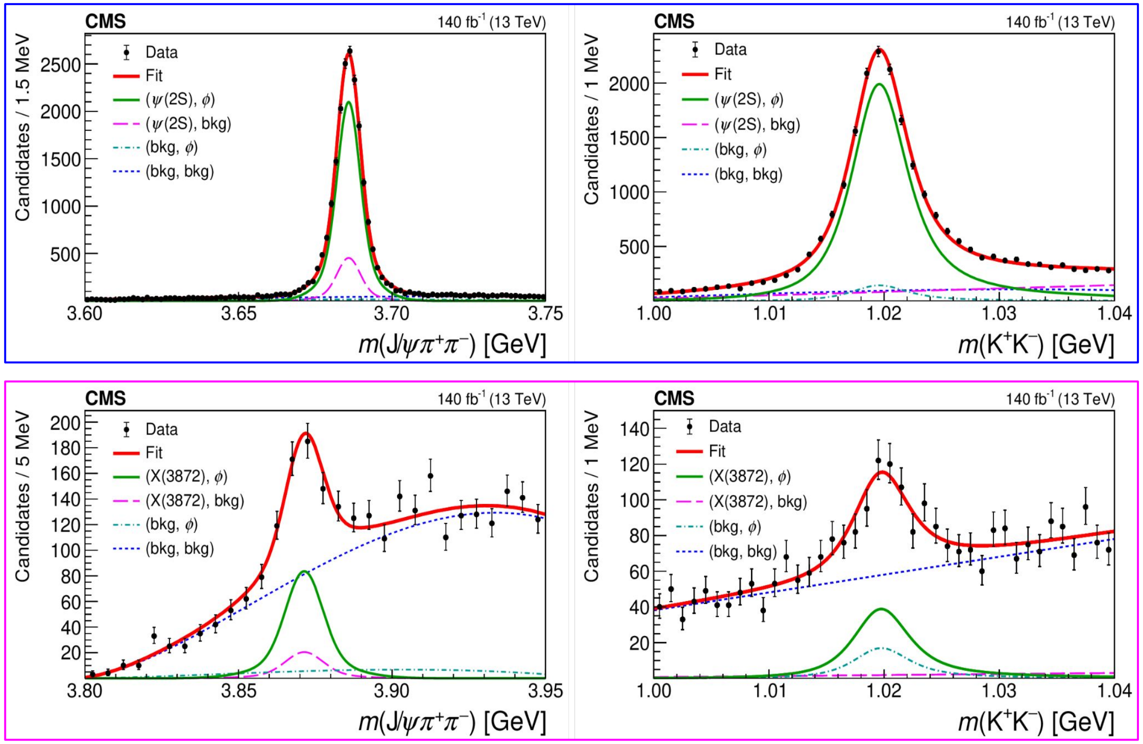
❖ **$X(3872)$**: Double-Gaussian (with shape fixed by $\psi(2S)$)

❖ $\phi(1020)$: BW⊗Gaussian

→ $N(B_s^0 \to \psi(2S)\phi) = 15359 \pm 171$

→ $N(B_s^0 \to X(3872)\phi) = 299 \pm 39$

(syst.) non-B_s^0 contribution estimated on data (background subtraction): 1.2% on $X(3872)/\psi(2S)$ yields' ratio



Details on event reconstruction, signal extraction and systematic uncertainties in backup

X(3872) production in weak decays

Efficiency correction (estimated on MC): $\frac{\epsilon_{B_s^0\to\psi(2S)\phi}}{\epsilon_{B_s^0\to X(3872)\phi}} = 1.136 \pm 0.026$

> **1**, because of tighter requirements on $m(\pi^+\pi^-)$ for X(3872)

Ratio R and X(3872) production in weak decays

(ψ(2S) decay chain well-known):

$$R = [2.21 \pm 0.29\,(stat.) \pm 0.17\,(syst.)]\%$$

[LHCb, JHEP 02 (2021) 024]

$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2}$$

$$\mathcal{B}(B_s^0 \to X(3872)\phi)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.14 \pm 0.54(stat) \pm 0.32(syst) \pm 0.46(\mathcal{B})) \times 10^{-6}$$

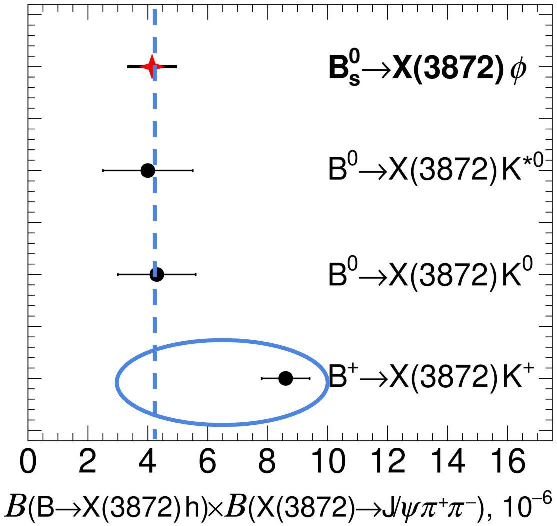
Consistent with analogous B^0 decay, but **two times smaller than B^+**

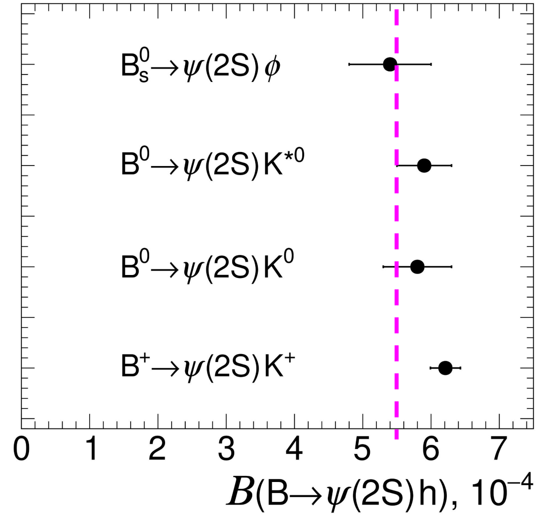
$$\frac{\mathcal{B}(B_s^0\to X(3872)\phi)}{\mathcal{B}(B^+\to X(3872)K^+)} = 0.482 \pm 0.063(syst) \pm 0.037(syst) \pm 0.070(\mathcal{B})$$

Significantly lower than the corresponding ψ(2S) decay:

$$\frac{\mathcal{B}(B_s^0\to\psi(2S)\phi)}{\mathcal{B}(B^+\to\psi(2S)K^+)} = 0.87 \pm 0.10$$

An explanation has been proposed [1] within the tetraquark model of the X(3872) state.





[1] [Maiani et al., PRD 102 (2020) 034017]

X(3872) production in PbPb collisions

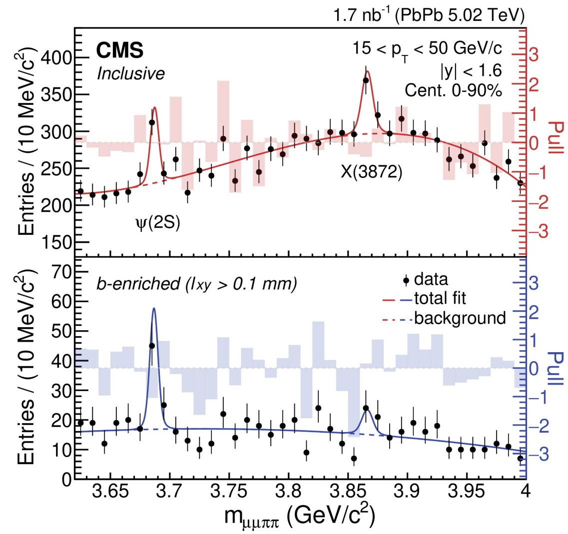
First evidence using 1.7 nb^{-1} of PbPb collisions data (2018) at CMS at $\sqrt{s_{NN}}$ = 5.02 TeV per nucleon pair

kinematical range:
$15 < p_T < 50$ GeV/c, $|y| < 1.6$

UML fit to extract signal yields for ψ(2S) and X(3872)

Final state: $J/\psi(\rightarrow \mu^+\mu^-)\,\pi^+\pi^-$

Significance for inclusive X(3872): 4.2σ

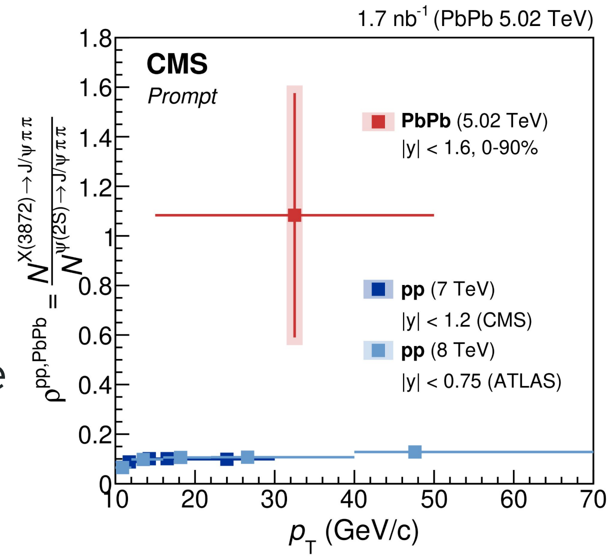


Prompt fraction estimated with MC studies

Yields corrected by acceptance and overall efficiency

Ratio of corrected yields for prompt production in PbPb collisions ρ^{pp} :

- **compatible with 1** (within 1σ)
- **compatible with $\rho^{pp} \approx 0.1$** (within 2σ)



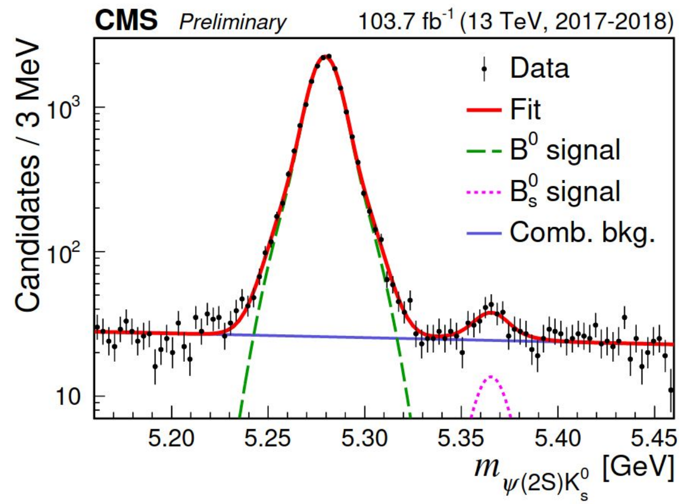
Much larger data sample expected in Run-3 at LHC in order to improve the measurement and understand the internal structure of X(3872) and the differences of its production mechanism w.r.t. ψ(2S)

Intermediate resonances in B decays

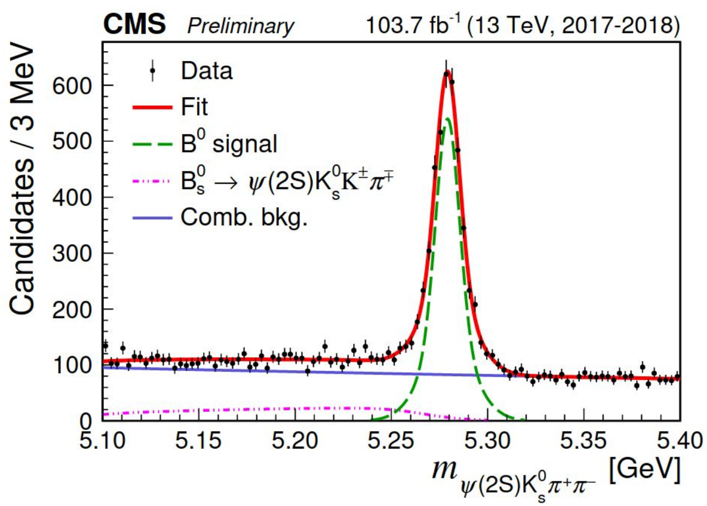
Observation of $B^0 \to \psi(2S)K^0_s\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_s$ (+ c.c) decays at CMS using 103.7 fb^{-1} of pp collisions data at $\sqrt{s}$ = 13 TeV during 2017-2018 at LHC

- ➔ Final state accessible to both B and B-bar
  - ◆ **time-dependent CP violation**
- ➔ Multi-body decays
  - ◆ **search for intermediate exotic resonances**

2- and 3-body invariant mass distributions of the $B^0 \to \psi(2S)K^0_s\pi^+\pi^-$ decay products do not show any significant exotic narrow structure in addition to the known light meson resonances ($\rho(770)$, $K^*(892)^\pm$, $K_1(1270)^0$) within the current available statistics [see backup]



- ❑ **$B^0_s \Rightarrow \psi(2S)K^0_s$: signif. 5.2σ**
- ❑ **$B^0 \Rightarrow \psi(2S)K^0_s$: control channel**



- ❑ **$B^0 \Rightarrow \psi(2S)K^0_s\pi^+\pi^-$: signif. > 30**

Study of excited Λ_b^0 states into $\Lambda_b^0\pi^+\pi^-$

Search on up to 140 fb^{-1} of pp collisions data at $\sqrt{s}$ = 13 TeV during 2016-2018 in the kinematic mass range: $m(\Lambda_b^0\pi^+\pi^-)$ in [5.90, 6.40] GeV

- Near kinematic threshold: **observation of excitations $\Lambda_b(5912)$ and $\Lambda_b(5920)$**
- Higher-mass regions: **signals consistent with $\Lambda_b(6146)$ and $\Lambda_b(6152)$**

Λ_b^0 reconstructed in:

1) $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)\Lambda^0$
2) $\Lambda_b^0 \to \psi(2S)(\to \mu^+\mu^-)\Lambda^0$
3) $\Lambda_b^0 \to \psi(2S)(\to \mu^+\mu^-\pi^+\pi^-)\Lambda^0$

- $\Lambda^0 \to p\pi^-$

Event selection (summary):

- combination of **triggers targeting $J/\psi \to \mu^+\mu^-$**
- $p_T(\mu) > 3$ GeV; $|\eta(\mu)| < 2.2$; $P_{vtx}(\mu\mu) > 1\%$; $m(\mu\mu)$ in [2.90, 3.95] GeV
- J/ψ [$\psi(2S)$] if $m(\mu\mu) <$ [>] 3.4 GeV; $m(J/\psi\pi^+\pi^-)$ in [3672, 3700] MeV
- $|m(p\pi^-) - M_\Lambda^{PDG}| < 10$ MeV; $P_{vtx}(p\pi^-) > 1\%$;
- **Primary Vertex selection** ($\tau(\Lambda_b^0)$ negligible) and **PV refitting** excluding tracks involved in the reconstructed decay chain
- Selection on Λ_b^0 flight distance and its alignment with Λ_b^0 momentum

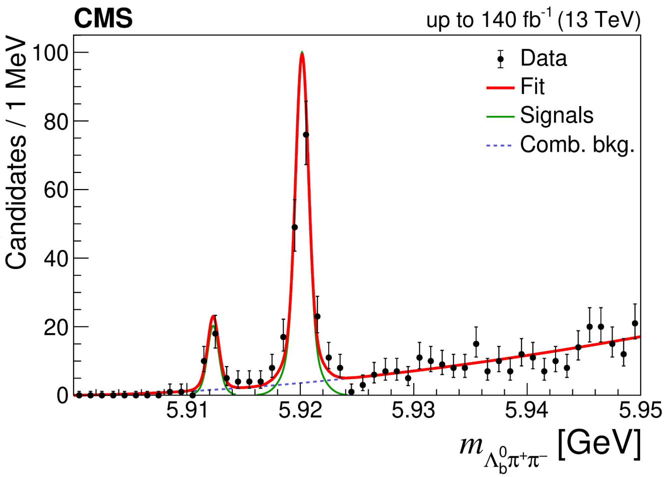
$\Lambda_b^0\pi^+\pi^-$ signal extraction

- **Λ_b^0 signal yields**: J/ψΛ: 39k; ψ(2S)(→ $\mu^+\mu$)Λ: 3.4k; ψ(2S)(→ $\mu^+\mu^-\pi^+\pi^-$)Λ: 4.3k
- **Two OS additional tracks from PV** (control region: SS tracks)
- **Mass resolution improved** with $m_{\Lambda_b^0\pi^+\pi^-} = M(\Lambda_b^0\pi^+\pi^-) - M(\Lambda_b^0) + m_{\Lambda_b^0}^{PDG}$
- **Further selection optimized for the two regions**: $m_{\Lambda_b^0\pi^+\pi} \lessgtr$ 5.95 GeV

UML fit to data

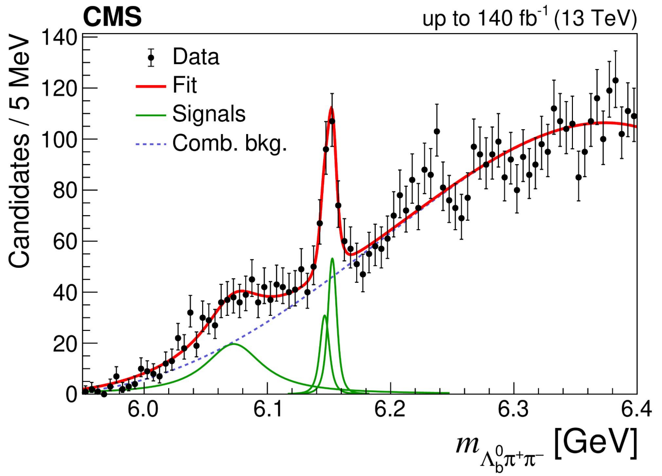
- **Signals**: Double-Gaussian (resolution from MC)
- **Background**: threshold function $(x-x_0)^\beta$

Two signals observed:
- ❑ Λ_b(5912) (5.7σ)
- ❑ Λ_b(5920) (>6σ)



- **Two Λ_b signals and broad excess**: Breit-Wigner ⊗ DoubleGaussian
- **Background**: $(x-x_0)^\beta$ * 1st-order polynomial

Single peak at 6150 MeV (σ_{res} = 3.8 MeV; signif. > 6σ)
Signal compatible with Λ_b(6146) + Λ_b(6152)
2-peak / 1-peak hypothesis: $\mathcal{L}_{ratio} = 0.4\sigma$



Details on event reconstruction, signal extraction and systematic uncertainties in backup

Investigation on $\Lambda_b^0\pi^+\pi^-$ higher-mass region

Broad enhancement below 6100 MeV not present in control region

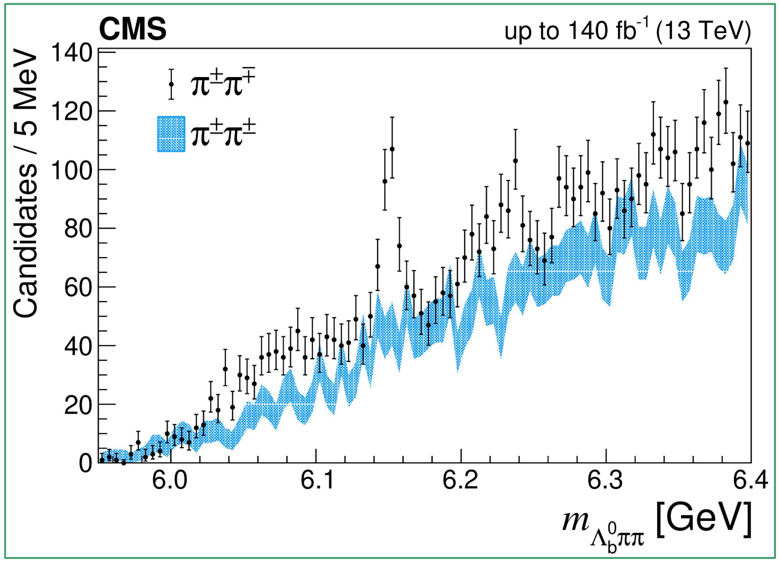
Possible sources ruled out:

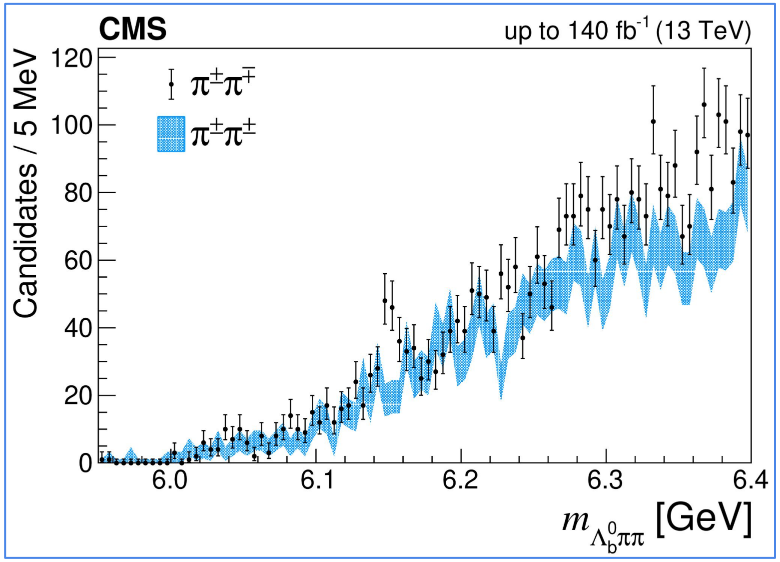
- Partially reconstructed decays [e.g $\Lambda_b(6146)$, $\Lambda_b(6152) \to \Lambda_b^0\pi^+\pi^-\pi^0$, π^0 lost]
- Excited Λ_b decaying into $\Lambda_b^0K^\pm\pi^\mp$ (by changing mass hypothesis on tracks)

Veto on $\Sigma_b^\pm$, $\Sigma_b^{*\pm}$ contribution in $\Lambda_b^0\pi^\pm$ invariant mass ranges leads to a better agreement between SS and OS mass distributions

The presence of intermediate $\Sigma_b^\pm$, $\Sigma_b^{*\pm}$ cannot be tested with the current data size

Similar structure observed at LHCb [2] shortly after, interpreting it as a further excited Λ_b^0 state [$\Lambda_b^0(6072)$]





[2] [LHCb Collab, JHEP 06 (2020) 136]

New excited beauty strange baryon into $\Xi_b^-\pi^+\pi^-$

Search on 140 fb^{-1} of pp collisions data at $\sqrt{s}$ = 13 TeV during 2016-2018 at LHC

Ξ_b baryon family: *bsq* iso-doublets (g.s.: Ξ_b, Ξ_b', Ξ_b^*, according to j_{qs} and J^P)

Search for Ξ_b^- excited states in $\Xi_b^-\pi^+\pi^-$, with Ξ_b^- reconstructed in:

1) $\Xi_b^- \rightarrow J/\psi\Xi^-$
2) $\Xi_b^- \rightarrow J/\psi\Lambda^0K^-$
3) $\Xi_b^- \rightarrow J/\psi\Sigma^0K^-$

- $J/\psi^- \rightarrow \mu^+\mu^-$
- $\Xi^- \rightarrow \Lambda^0\pi^-$
- $\Lambda^0 \rightarrow p\pi^-$
- $\Sigma^0 \rightarrow \Lambda^0\gamma_{soft}$

not reconstructed

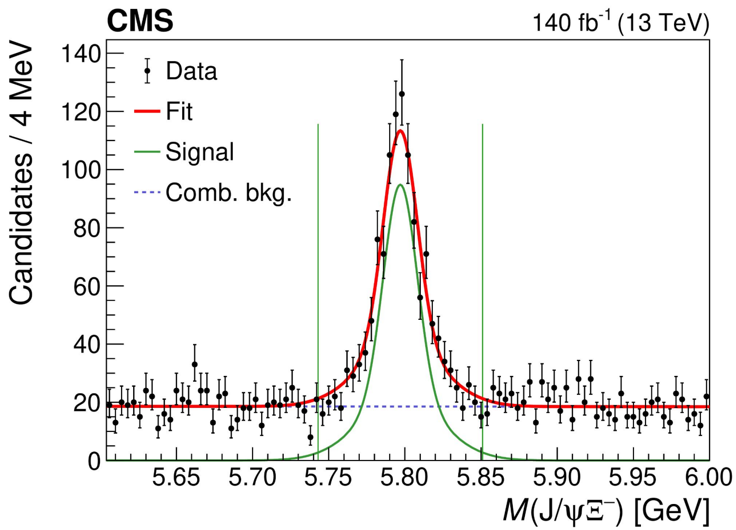
Event selection for Ξ_b^- reconstruction:

- combination of **triggers targeting $J/\psi \rightarrow \mu^+\mu^-$**
- $p_T(\mu) > 3$ GeV; $|\eta(\mu)| < 2.4$; $P_{vtx}(\mu\mu) > 1\%$; $|m(\mu\mu) - M_{J/\psi}^{PDG}| < 100$ MeV
- $|m(p\pi^-) - M_\Lambda^{PDG}| < 10$ MeV; $p_T(\Lambda) > 1$ GeV; $P_{vtx}(p\pi^-) > 1\%$
- **Further selection separately optimized for each decay channel**, including selection on Ξ_b^- flight distance and its alignment with Ξ_b^- momentum

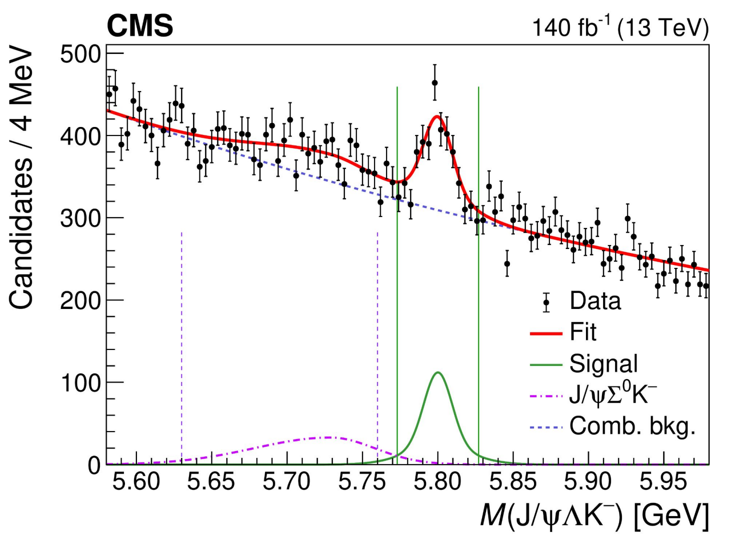
Details on event reconstruction, signal extraction and systematic uncertainties in backup

Ξ_b^- signal extraction: UML fit to data

- **Fully reconstructed signals:**
  Double-Gaussian (resolution from MC)
- **Partially reconstructed signal:**
  Asymmetric Gaussian (shape from MC)
- **Combinatorial background:**
  - $J/\psi\Xi^-$: 1st order polynomial
  - $J/\psi\Lambda K^-$: exponential function



$N(\Xi_b^- \to J/\psi\Xi^-) = 859 \pm 36$ events
$N(\Xi_b^- \to J/\psi\Lambda^0 K^-) = 815 \pm 74$ events
$N(\Xi_b^- \to J/\psi\Sigma^0 K^-) = 820 \pm 158$ events



Excited Ξ_b^- candidates' reconstruction:

- Mass windows for Ξ_b^- candidates (see plots)
- Two OS tracks from same PV as Ξ_b^-
  (negligible $\tau(\Xi_b^-) \simeq 1.6$ ps)
- Control region: SS tracks from same PV as Ξ_b^-
- Mass variable $\Delta M = m(\Xi_b^- \pi^+ \pi^-) - m(\Xi_b^-) - 2m_\pi^{PDG}$
  (insensitive to potential mass shift due to lost γ_{soft})

Excited Ξ_b^- signal extraction

Dominant contribution of intermediate Ξ_b^{*0}: $\Xi_b^{**-} \rightarrow \Xi_b^{*0}\pi^-$, $\Xi_b^{*0} \rightarrow \Xi_b^-\pi^+$ is suggested by analogy with Ξ_c family and theoretical studies

Additional cut: $m(\Xi_b^{*0}) - m(\Xi_b^-) - m_\pi^{PDG} < 20.73\,MeV$ (peak expected at 15.73 MeV)

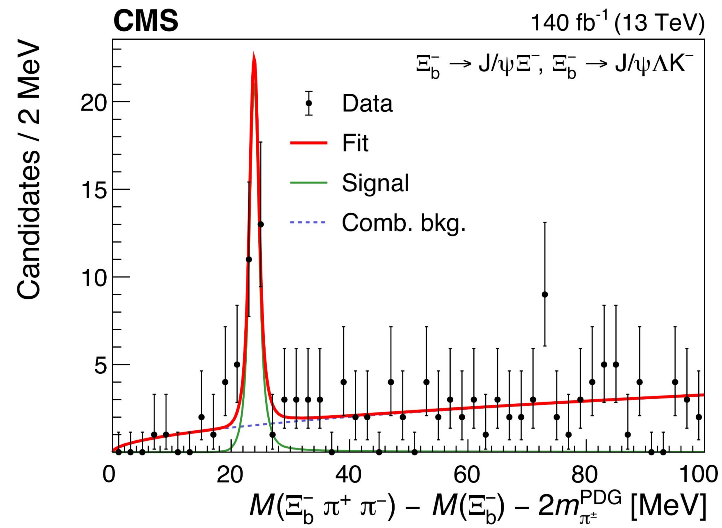
Fully reconstructed channels are combined (same resolution, $\Xi_b^- \rightarrow J/\psi\Sigma^0K^-$ 30% larger res.)

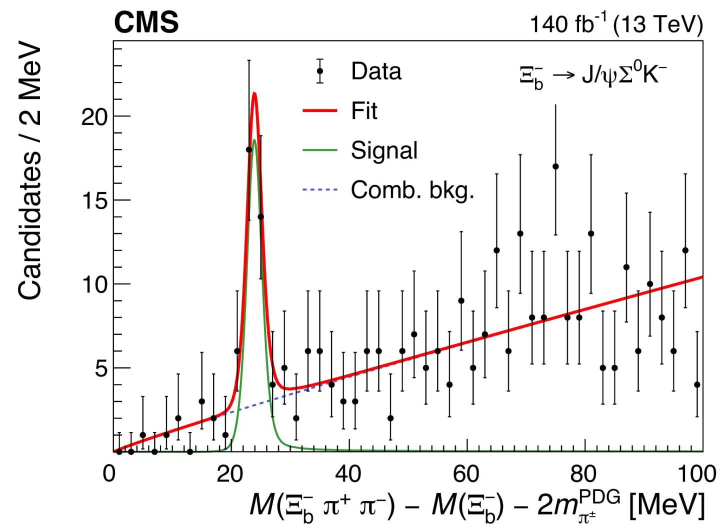
UML simultaneous fit:

- **Signal**: Relativistic BW⊗Double-Gaussian
- **Background**: $(\Delta M)^\alpha$ threshold function

$M(\Xi_b^{**-}) = 6100.3 \pm 0.2(\text{stat}) \pm 0.1(\text{syst}) \pm 0.6(\Xi_b^-)$ MeV
$\Gamma(\Xi_b^{**-}) < 1.9$ MeV @ CL=95%
(narrow resonance, 13 MeV below $\Lambda_b^0K^-$ threshold)
Local statistical significance: 6.2-6.7σ

The decay sequence suggest: $j_{qs} = 1$, $J^P = 3/2^-$
beauty partner of the charmed $\Xi_c(2815)$ baryon





Conclusions

- A **new decay involving X(3872)** has been observed, with its production suggesting a non-conventional description of the state.
  Further investigation on the nature of X(3872) can be performed on data from PbPb collisions. This will be improved with the **larger data sample expected in Run-3**.

- **Recent results from the CMS** are also in general good agreement with previous results from other LHC experiments **on conventional spectroscopy: low-mass resonances, B_c(2S) doublet, Λ_b and Ξ_b excited states**

- CMS proved to be suitable for **challenging measurements in Heavy Flavor physics**. The larger statistics available at Run-3 will improve the measurements, thus leading to **further comprehension of Standard Model and Quantum Chromo-dynamics**

THANKS FOR YOUR ATTENTION

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BACKUP

$B_s^0 \to X(3872)\phi$: event selection

HLT requirements:

- two muons compatible with J/ψ ($p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.5$, $m(\mu\mu)$ in [2.9, 3.3] GeV, $P_{vtx} > 1\%$)
- additional track ($p_T > 1.2$ GeV) from same $\mu\mu$ vertex and transverse significance > 2

Offline requirements:

- two OS muons (trigger matched) + soft-muon identification
- $\mu\mu$ kinematically constrained to J/ψ in $J/\psi KK\pi\pi$ fit
- PV chosen by minimization of B_s candidate's pointing angle
- no PID@CMS: the candidates must pass the following selection
  $m(J/\psi KK\pi\pi)$ in [3.60, 3.95] GeV; $m(KK)$ in [1.00, 1.04] GeV; $m(B_s)$ in [5.32, 5.42] GeV
- the candidate is discarded if more than one mass assignment passes the selection (MC eff 99%)

Channel optimization (Punzi figure of merit):

- $p_T(B_s) > 10$ GeV; $P_{vtx}(B_s) > 7\%$; $p_T(\pi) > 0.7$ GeV; $p_T(K) > 2.2$ / 1.5 GeV (max/min)
- decay length significance $B_s > 15$; cos(transversePointingAngle) > 0.999 (*)
- $m(\pi\pi) > 0.45$ GeV for $\psi(2S)$; > 0.7 GeV for X(3872) **only difference between channels**

(*) cosine of the angle formed by the flight direction and the momentum in the transverse plane

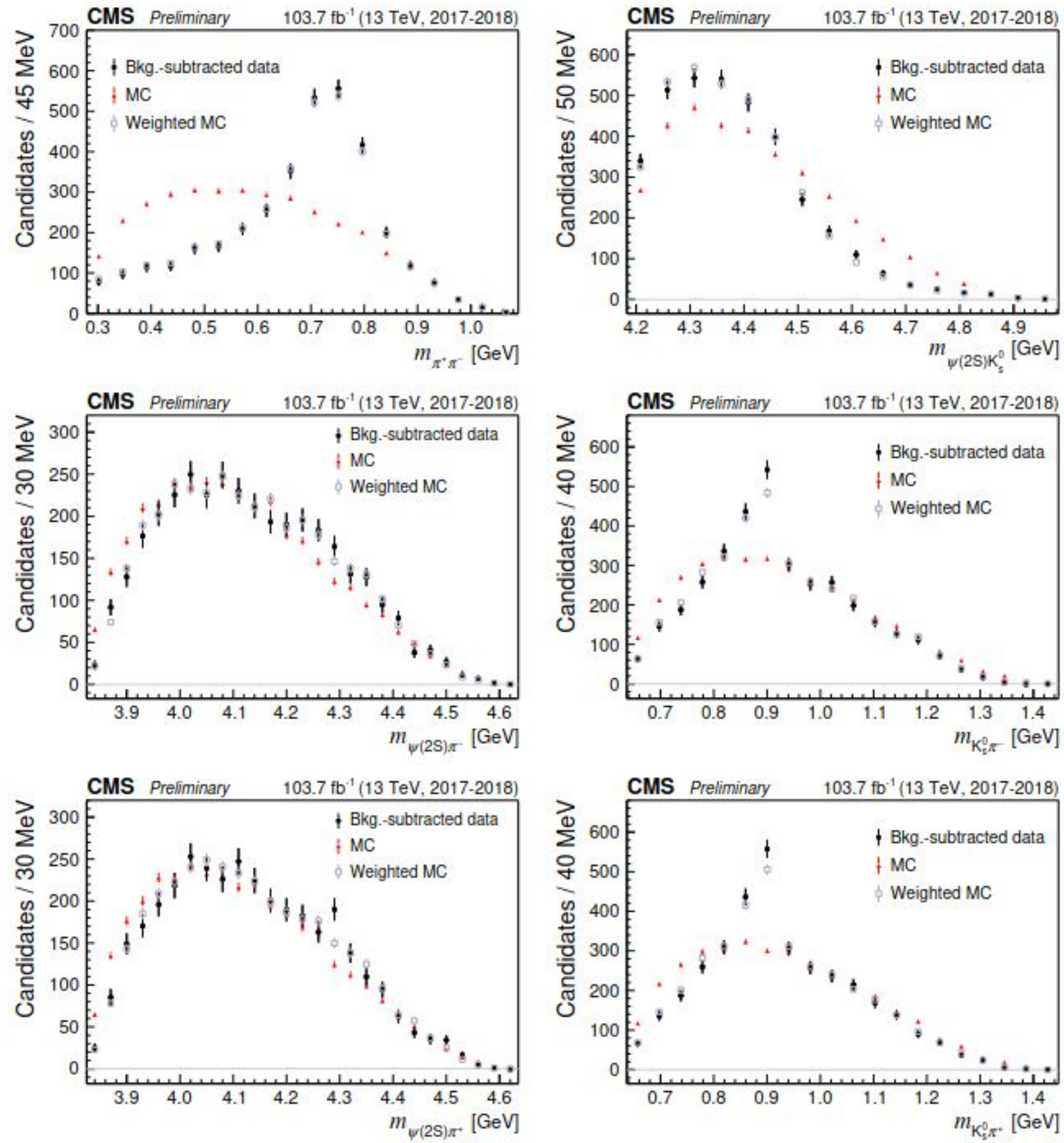
$B_s^0 \to X(3872)\phi$: systematics

Uncertainties on the **ratio R**

Source	Uncertainty (%)
$m(K^+K^-)$ signal model	<0.1
$m(K^+K^-)$ background model	2.5
$m(J/\psi\pi^+\pi^-)$ signal model	5.3
$m(J/\psi\pi^+\pi^-)$ background model	4.3
Non-B_s^0 background	1.2
Simulated sample size	2.2
Total	7.7

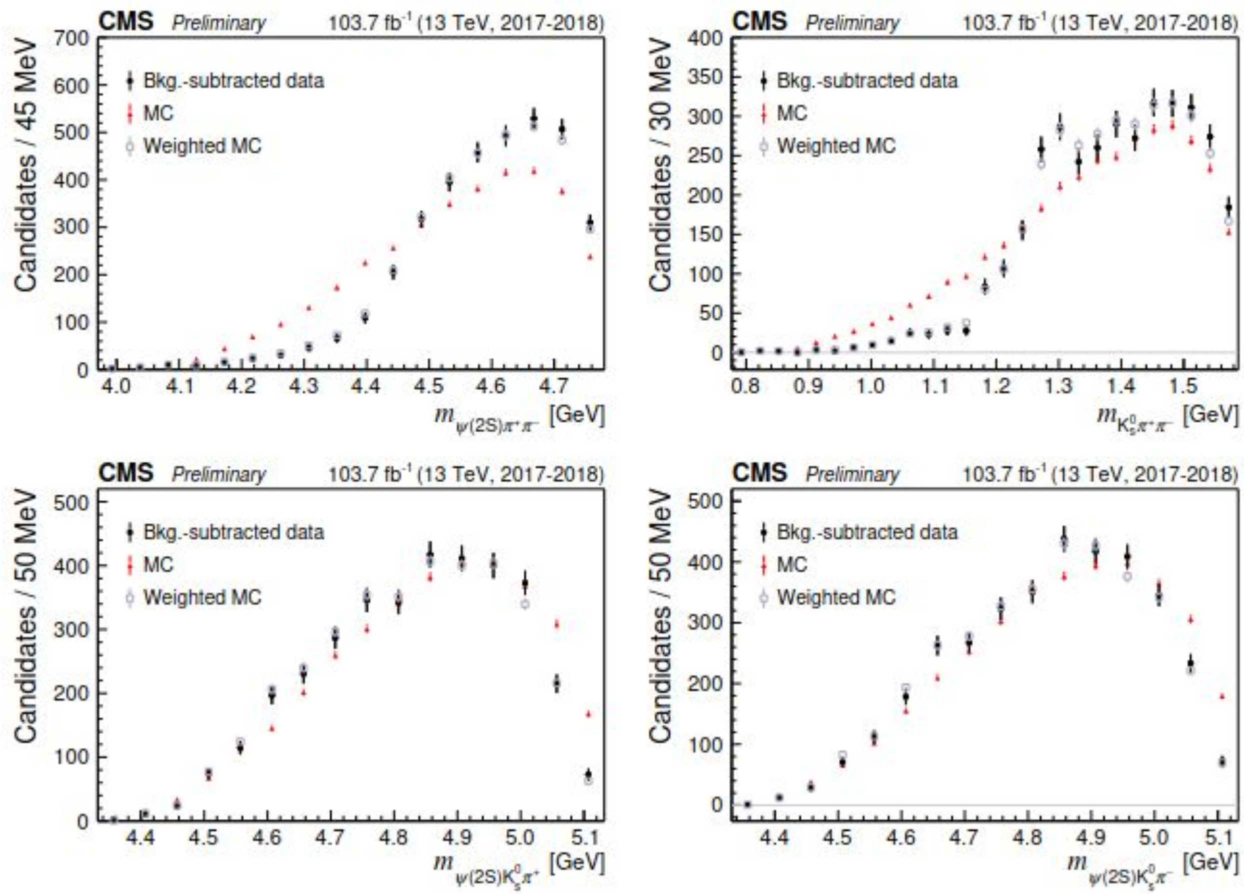
$B^0 \to \psi(2S)K^0_s\pi^+\pi^-$: 2-body mass distributions

- Data distributions bkg-subtracted (sPlot)
- MC do not take intermediate resonance structure into account, thus providing poor description of data
- MC is re-weighted in order to match data (iterative procedure on the multi-dimensional phase space)



$B^0 \to \psi(2S)K^0_S\pi^+\pi^-$: 3-body mass distributions

- Data distributions bkg-subtracted (sPlot)
- MC do not take intermediate resonance structure into account, thus providing poor description of data
- MC is re-weighted in order to match data (iterative procedure on the multi-dimensional phase space)



$B_c(2S)$: hyperfine structure

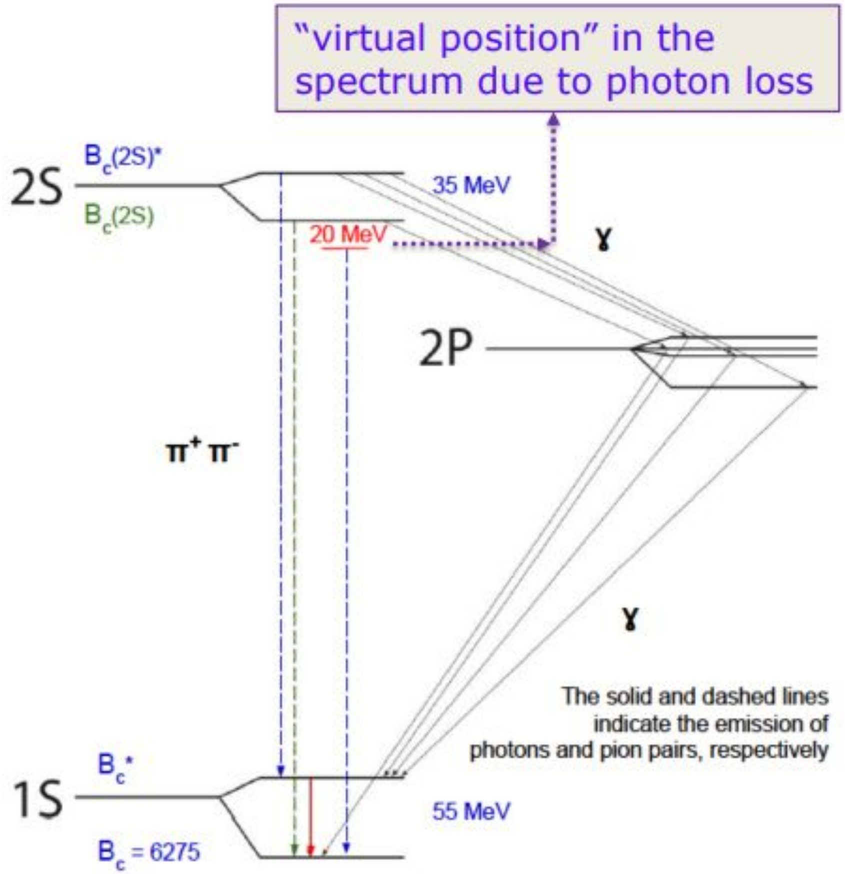
$B_c^*(2S) \rightarrow B_c^* \pi^+ \pi^-$ followed by $B_c^* \rightarrow B_c \gamma_{lost}$

Soft photon (55 MeV in the rest frame) not detected, we end up seeing
$B_c^*(2S) \rightarrow B_c \pi^+ \pi^-$ plus "missing energy"
Same final state as $B_c(2S) \rightarrow B_c \pi^+ \pi^-$

A two-peak structure in the Bc $\pi^+ \pi^-$ mass distribution is expected,
with the $B_c(2S)^*$ peak at a mass shifted by
$\Delta M = [M(B_c^*) - M(B_c)] - [M(B_c^*(2S)) - M(B_c(2S))]$
which is predicted to be around 20 MeV.

The two-peak can be appreciated only if ΔM value is larger than experimental resolution!

Predictions indicate:
$[M(B_c^*(1S)) - M(B_c(1S))] > [M(B_c^*(2S)) - M(B_c(2S))]$
that would imply that the
$B_c^*(2S)$ peak is the lower peak!



$B_c(2S)$: production ratios

★ Observation of $B_c(2S)^+$ and $B_c^*(2S)^+$ states with pp collisions at $\sqrt{s}$ = 13 TeV with 143 fb^{-1} (full Run-2 data) [A]

[A] [CMS, PRL 122 (2019) 132001]

NEW Measurement of relative cross sections:

Differential cross sections in p_T and rapidity bins

Kinematical range: $p_T(B_c^+) > 15$ GeV and $|y| < 2.4$

R^{*+}: relative cross section of $B_c^*(2S)^+$ to B_c^+
R^+: relative cross section of $B_c(2S)^+$ to B_c^+
R^{*+}/R^+: relative cross section of $B_c^*(2S)^+$ to $B_c(2S)^+$

$$R^+ \equiv \frac{\sigma(B_c(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-) = \frac{N(B_c(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c(2S)^+)},$$

$$R^{*+} \equiv \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-) = \frac{N(B_c^*(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^*(2S)^+)},$$

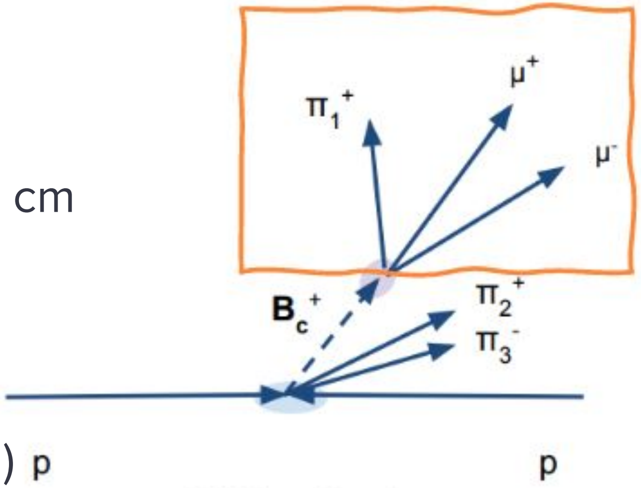
$$R^{*+}/R^+ = \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c(2S)^+)} \frac{\mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-)}{\mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-)} = \frac{N(B_c^*(2S)^+)}{N(B_c(2S)^+)} \frac{\epsilon(B_c(2S)^+)}{\epsilon(B_c^*(2S)^+)}.$$

$B_c^*(2S) \to B_c^*\pi\pi$ followed by $B_c^* \to B_c + \gamma_{lost}$ (≃ 55MeV: missing energy not detected)
The B_c^* meson is assumed to decay to the B_c ground state and a soft photon with a BF of 100%

$B_c(2S)$: event selection

HLT Requirements (DoubleMu4_JpsiTrk_displaced):

- OS muon pair in [2.9, 3.3] GeV
- dimuon vertex χ^2 probability > 10%
- distance of closest approach between muons < 0.5 cm
- significance(flight distance) > 3
- $p_T(\mu) > 4$ GeV && $|\eta(\mu)| < 2.5$
- cos(dimuon_transverse_pointing_angle) > 0.9 (*)
- third track (from μμ-vtx, $p_T > 1.2$ GeV, $\eta < 2.5$, sip > 2)



$B_c(2S) \rightarrow B_c \pi^+ \pi^-$

Offline requirements:

- Muons matching trigger muons
- High quality muons
- $|\eta(\mu)| < 2.4$ and cos(dimuon_transverse_pointing_angle) > 0.98 (*)
- muons close in angular space: $(\Delta\eta)^2 + (\Delta\phi)^2 < 1.2^2$

Integrated Luminosity per year: 2.8, 36.1, 42.1, 61.6 fb^{-1}

(*) cosine of the angle formed by the flight direction and the momentum in the transverse plane

$B_c(2S)$: B_c reconstruction

B_c candidates fit

Signal: weighted sum of two gaussians with same mean

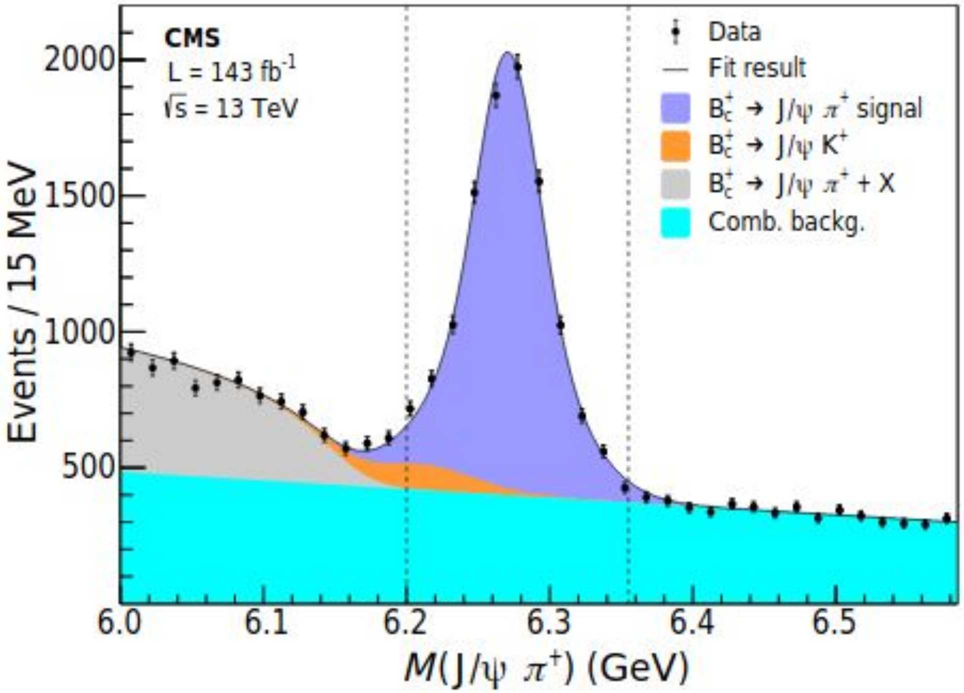
$$wG(\mu,\sigma_1) + (1-w)G(\mu,\sigma_2),$$

w = 0.47 σ_1 = 21 MeV σ_2 = 42 MeV

Background:

- Combinatorial: Chebychev polynomial
- $J/\psi K$: shape from simulation
- $J/\psi\pi + X$: ARGUS function

$N(B_c)$ = 7629 +/- 225 events



B_c(2S): signal yields

$B_c^+ \to J/\psi\pi^+$ candidates fit

$N(B_c^+)$ = 7629 +/- 225 events

B_c(2S) candidates:

- $m(J/\psi\pi^+)$ in [6.2, 6.355] GeV
- B_c^+ + two OS tracks

Signal: two gaussians

Background:

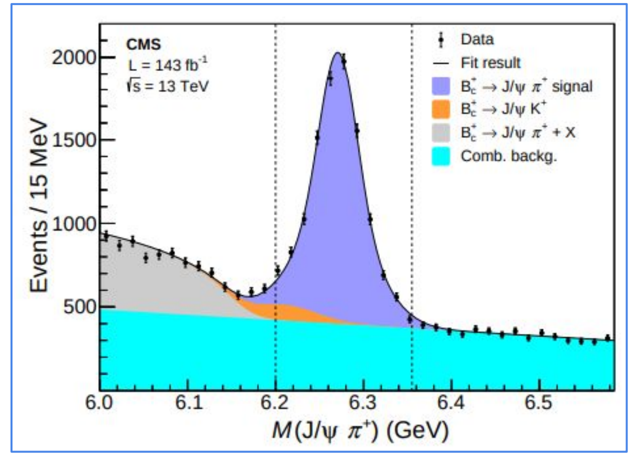
Combinatorial: Chebychev-3 polynomial

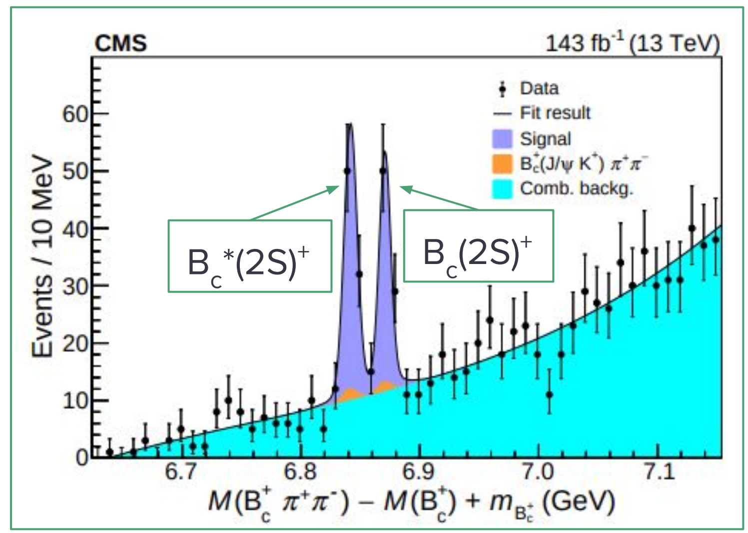
$B_c^+ \to J/\psi K^+$ contribution: two Gaussians

$N(B_c^*(2S)^+)$ = 67 +/- 10 evts

$N(B_c(2S)^+)$ = 52 +/- 9 evts

ΔM = 28.9 +/- 1.5 MeV





Yields enter the ratios once corrected by relative efficiencies

$$R^+ = (3.47 \pm 0.63\,(\text{stat}) \pm 0.33\,(\text{syst}))\%,$$
$$R^{*+} = (4.69 \pm 0.71\,(\text{stat}) \pm 0.56\,(\text{syst}))\%,$$
$$R^{*+}/R^+ = 1.35 \pm 0.32\,(\text{stat}) \pm 0.09\,(\text{syst}).$$

Details on event reconstruction and systematic uncertainties in backup

$B_c(2S)$: cross section ratios

Reconstruction efficiencies (MC studies):

- statistical: finite size of simulated events
- dispersion: average over four years
- pions: π reconstruction efficiency

	Central	Stat.	Spread	Pions
$\epsilon(B_c(2S)^+)/\epsilon(B_c^+)$	0.196	1.1%	1.8%	4.2%
$\epsilon(B_c^*(2S)^+)/\epsilon(B_c^+)$	0.187	1.0%	1.6%	4.2%
$\epsilon(B_c^*(2S)^+)/\epsilon(B_c(2S)^+)$	0.955	1.4%	0.9%	—

Systematic uncertainties:

- from signal yield
  (evaluated with different fit models)
- from efficiency
- from correlations in di-pion kinematics

	R^+	R^{*+}	R^{*+}/R^+
$J/\psi\,\pi^+$ fit model	5.5	5.5	—
$B_c^+\pi^+\pi^-$ fit model	5.9	2.9	2.9
Efficiencies: statistical uncertainty	1.1	1.0	1.4
Efficiencies: spread among years	1.8	1.6	0.9
Efficiencies: pion tracking	4.2	4.2	—
Decay kinematics	1.5	6.9	4.2
Helicity angle	1.0	6.0	3.5
Total	9.5	12.0	6.4

Results:

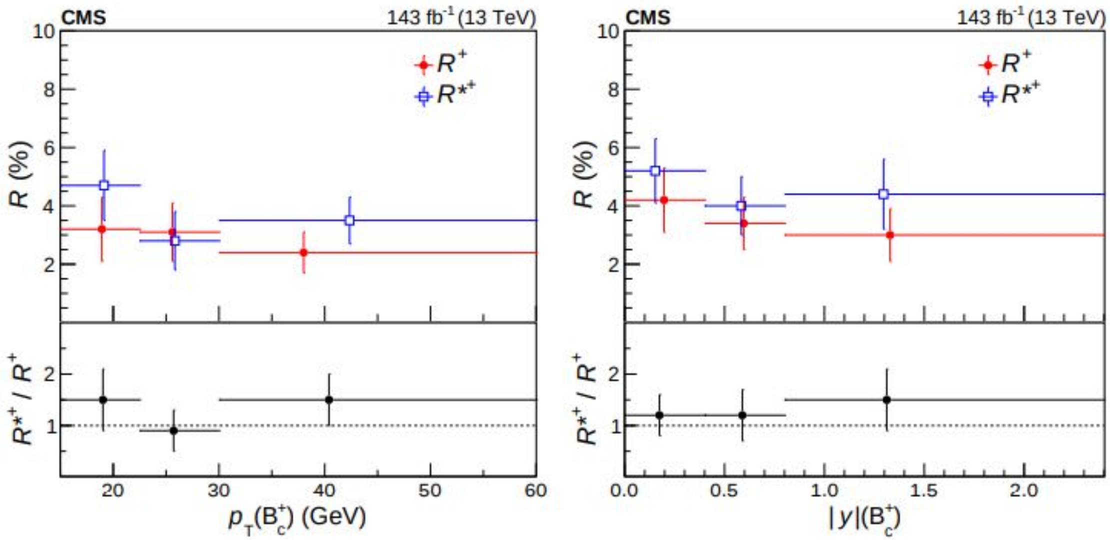
$$R^+ = (3.47 \pm 0.63\,(\text{stat}) \pm 0.33\,(\text{syst}))\%,$$

$$R^{*+} = (4.69 \pm 0.71\,(\text{stat}) \pm 0.56\,(\text{syst}))\%,$$

$$R^{*+}/R^+ = 1.35 \pm 0.32\,(\text{stat}) \pm 0.09\,(\text{syst}).$$

$B_c(2S)$: Differential cross section and ππ mass distribution

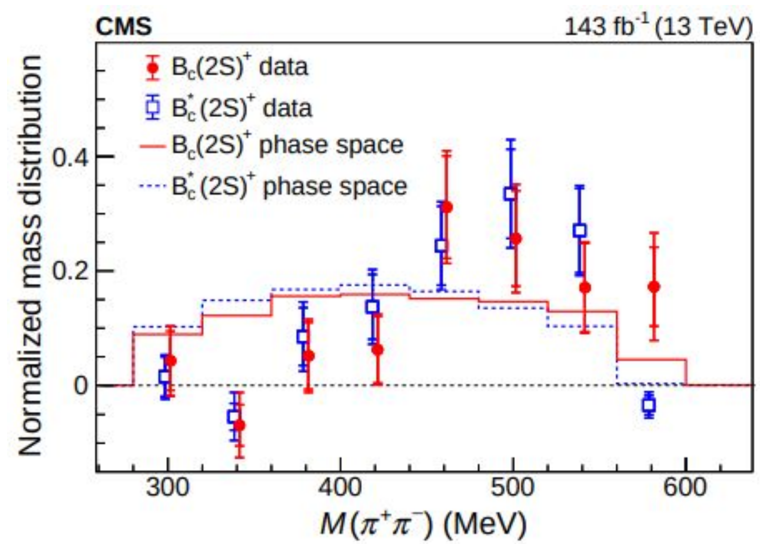
No significant dependence of the cross section on $p_T(B_c^+)$ or $\eta(B_c^+)$ observed



Invariant mass of di-pion system

Different models [B] [C] bring to different predictions on the production ratios and di-pion system

Observed shapes are consistent with each other and different from phase space, but the difference is not fully significant at the available level of statistics and uncertainties



[B] [Berezhnoy, A. V. et al. Mod. Phys. Lett. A34 (2019) 1950331]
[C] [E. Eichten, C. Quigg, PRD 99 (2019) 054025]

Excited Λ_b^0 into $\Lambda_b^0\pi^+\pi^-$: event selection

Requirements:

- two OS muons + soft-muon identification, with $p_T(\mu) > 3$ GeV, $|\eta(\mu)| < 2.2$
- $m(\mu\mu)$ in [2.90, 3.95] GeV: < 3.4 -> J/ψ > 3.4 -> $\psi(2S)$
- OS tracks (pions) with $p_T > 0.35$ GeV
- kinematic vertex fit $J/\psi\pi\pi$: $\psi(2S)$ cand. if $m(J/\psi\pi\pi)$ in [3672, 3700] MeV
- Λ candidate (to $p\pi$): $P_{vtx} > 1\%$, $|m(p\pi) - m_\Lambda| < 10$ MeV
- $J/\psi(\psi(2S))\Lambda$: $P_{vtx} > 1\%$ to form Λ_b candidate
- PV chosen by minimization of Λ_b candidate's pointing angle
- PV refitted after removing the tracks associated with the J/ψ ($\psi(2S)$) and Λ candidates
- decay length significance $\Lambda_b > 3$; cos(transversePointingAngle) > 0.99 (*)

$\Lambda_b\pi\pi$ optimization (Punzi figure of merit) - pions p_T sorted π_1, π_2

Low mass region:

- $p_T(\pi_1) > 0.3$ GeV; $p_T(\pi_2) > 0.35$ GeV;
- cos(transversePointingAngle) > 0.995
- cos(pointingAngle) > 0.995
- $p_T(\pi_{\psi(2S)}) > 0.4$ GeV

High mass region:

- $p_T(\pi_1) > 1.4$ GeV; $p_T(\pi_2) > 0.7$ GeV;
- $p_T(\Lambda_b) > 16$ GeV
- $P_{vtx}(\Lambda_b) > 2\%$
- $P_{vtx}(\Lambda_b\pi\pi) > 8\%$
- only highest p_T candidate kept

Excited Λ_b^0 into $\Lambda_b^0\pi^+\pi^-$: systematics

Source	$M(\Lambda_b(5912)^0)$	$M(\Lambda_b(5920)^0)$	$M(\Lambda_b(6146)^0)$	$M(\Lambda_b(6152)^0)$
Signal model	0.005	0.011	0.21	0.23
Background model	0.004	—	0.16	0.14
Inclusion of the broad excess region	N/A	N/A	0.35	0.14
Fit range	—	—	0.40	0.02
Mass resolution	0.007	0.001	0.01	0.09
Knowledge of Γ	N/A	N/A	0.43	0.26
Total	0.009	0.011	0.77	0.41

Excited Ξ_b^- into $\Xi_b^-\pi^+\pi^-$: event selection

Requirements:

- two OS muons + soft-muon identification, with $p_T(\mu) > 3$ GeV, $|\eta(\mu)| < 2.4$; $P_{vtx}(\mu\mu) > 1\%$
- $|m(\mu\mu) - m_{J/\psi}| < 100$ MeV;
- Λ candidate (to $p\pi$): $|m(p\pi) - m_\Lambda| < 10$ MeV; $P_{vtx} > 1\%$, $p_T(\Lambda) > 1$ GeV

Separate optimization per channel (Punzi figure of merit):

$\Xi_b^- \to J/\psi\Xi^-$; $\Xi^- \to \Lambda\pi^-$

- $p_T(\pi) > 0.25$ GeV
- $P_{vtx}(\Lambda\pi) > 1\%$
- $p_T(\Xi^-) > 3$ GeV; $|m(\Lambda\pi) - m_\Xi| < 9.5$ MeV;
- kinematic vertex fit with J/Ψ constraint
- $P_{vtx}(\Xi_b) > 1\%$; $p_T(\Xi_b) > 10$ GeV
- PV selection by minimization of Ξ_b pointing angle
- significance of transverse distance of Ξ_b vertex from PV > 3
- cos(transversePointingAngle) > 0.99
- cos(pointingAngle Ξ_b, Ξ) > 0.999
- significance of transverse displacement for pion > 0.9

$\Xi_b^- \to J/\psi\Lambda K^-$ (and $J/\psi\Sigma K$)

- $|m(p\pi) - m_\Lambda| < 9$ MeV; $p_T(\Lambda) > 2$ GeV
- $p_T(K) > 1.2$ GeV
- $p_T(\Xi^-) > 3$ GeV; $|m(\Lambda\pi) - m_\Xi| < 9.5$ MeV;
- kinematic vertex fit with J/Ψ constraint
- $P_{vtx}(\Xi_b) > 1\%$; $p_T(\Xi_b) > 15$ GeV
- PV selection by minimization of Ξ_b pointing angle
- significance of transverse distance of Ξ_b vertex from PV > 3
- cos(transversePointingAngle) > 0.993
- significance of transverse displacement of Λ from Ξ_b > 20
- significance of transverse displacement for kaon > 0.6

Excited Ξ_b^- into $\Xi_b^-\pi^+\pi^-$: systematics

Sources of systematic uncertainties:

- Alternative signal models: single/triple gaussians used to model resolution)
- Alternative background models:
  - threshold function * exponential
  - threshold function * 1^{st} order polynomial
- **Largest deviations in mass: 0.01 MeV (signal models), 0.04 MeV (background models)**

- Blatt-Weisskopf barrier factors included in Relativistic Breit-Wigner function:
  - baseline: $r = 3.5$ GeV^{-1}, $l = 1$
- Test with $r = 1$ and 5 GeV^{-1} or $l = 0$
- r variations negligible; **$l = 0$ leads to mass difference 0.01 MeV**

- Include difference in resolution between measured and simulated mass: resolution scaled up and down by 1.074 factor (obtained by comparing Ξ_b in data/MC)
- **Resolution rescaling leads to deviation of 0.02 MeV**

- **Different fit range in ΔM** (80, 120, 150 MeV instead of 100 MeV) **brings deviation of 0.02 MeV**

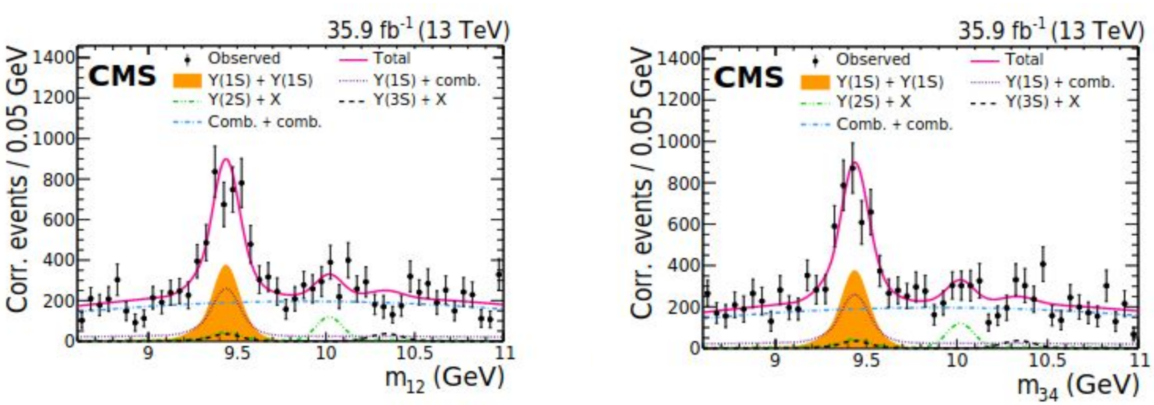
- **Total systematic uncertainty on the measured mass difference: 0.05 MeV**

Search for narrow resonances in Y(1S)$\mu^+\mu^-$

Measurement of fiducial cross-section for Y(1S) pair production and search for resonances decaying to Y(1S)μμ in pp collisions at √s = 13 TeV with 35.9 fb^{-1} (2016 data)

- **Quarkonium pair production mechanisms at LHC**:
  single-parton scattering (SPS): dominant → strongly correlated → small |Δy|
  double-parton scattering (DPS): difficult to calculate → less correlated → large |Δy|
- **Y(1S) pair production** is standard model reference in the search for tetraquark bound state or generic narrow resonance with mass close to twice the Y(1S) mass

- 4μ (final state) paired in Y states (J/ψ → $\mu^+\mu^-$ vetoed)
- fiducial region: |y(Y(1S))| < 2.0
- p_T thresholds for barrel/endcap after pairs are formed



Y(1S)pair production fit details:

- **Events corrected by efficiency and acceptance** (MC estimated)
- **Signal model** [Y(1S)]: sum of two Crystal Ball functions with common mean
- **Background model**:
  - Y(2S), Y(3S): gaussian
  - combinatorial: 2^{nd}-order Chebychev

More details in backup

Υ(1S)Υ(1S) production: event selection

HLT requirements:

- three muons
- two muons with mass in [8.5, 11.4] GeV
- dimuon vertex χ^2 probability > 0.5%

Offline requirements:

- $p_T(\mu) > 2$ GeV and $|\eta(\mu)| < 2.4$
- Best vertex-χ^2 for arbitration of best muon combination (98% eff on MC)
- Three (of four) muons must be associated with trigger muons
- $\mu\mu$ mass closest to Υ(1S) world-average for arbitration
- New p_T threshold for muons: $p_T(\mu) > 2.5$ GeV
- prob(χ^2, 4μ) > 5% and prob(χ^2, Υ(1S)) > 0.5%
- muons separated with $\Delta R > 0.02$
- on OS mixed-pairs: veto on J/ψ mass

  (window of 2σ, resolution depends on kinematics in [0.03, 0.12] GeV)

Extra requirements (Υ(1S) pair only):

- $|y(\mu\mu)| < 2.0$
- $p_T(\mu) > 3.5$ GeV for central muons, $|\eta(\mu)| < 0.9$

Extra requirements (resonance search only):

- mass of Υ(1S) candidate within 2σ, resolution depends on kinematics in [0.06, 0.15] GeV

Υ(1S)Υ(1S): shape of Υ(1S) signal

Process	Uncorrected yield
$\Upsilon(1S) + \Upsilon(1S)$	111 ± 16
$\Upsilon(2S) + \Upsilon(2S)$	$3.6\,^{+4.4}_{-3.6}$
$\Upsilon(3S) + \Upsilon(3S)$	$1.1\,^{+1.4}_{-1.1}$
$\Upsilon(1S)$ + combinatorial	166 ± 33
$\Upsilon(2S)$ + combinatorial	25 ± 18
$\Upsilon(3S)$ + combinatorial	$1.1\,^{+11}_{-1.1}$
$\Upsilon(2S) + \Upsilon(1S)$	19 ± 10
$\Upsilon(3S) + \Upsilon(1S)$	17 ± 11
Combinatorial + combinatorial	561 ± 41

Υ(1S)Υ(1S): yields

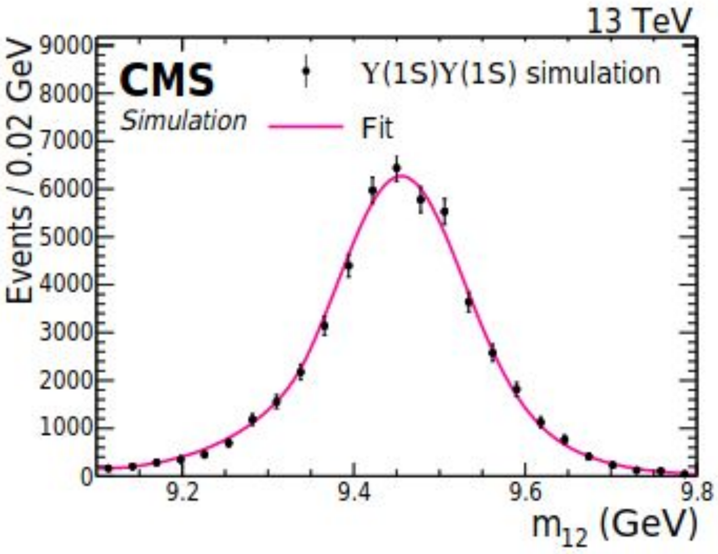
Event-by-event weight:

$$\omega = \left[A_1 A_2 \epsilon_1^{\text{reco}} \epsilon_2^{\text{reco}} \left(1 - (1 - \epsilon_1^{\text{vtx}})(1 - \epsilon_2^{\text{vtx}})\right) \epsilon^{\text{evt}}\right]^{-1},$$

- A: acceptance for Υ(1S) to μμ in fiducial region
- ε^{reco}: probability that a Υ(1S) to μμ with |y(Υ(1S))| < 2.0 and |η(μ)| < 2.4 is selected
- ε^{vtx}: probability that a selected Υ(1S) has prob(χ^2, Υ(1S)) > 0.5%
- ε^{evt}: probability that a selected event has prob(χ^2, 4μ) > 5% and cross-paired muons have invariant mass out of [m(J/ψ) - 2σ, m(J/ψ) + 2σ]

Shape of Υ(1S) signal from simulation:

- Sum of two Crystal Ball with same mean
- Different resolutions for barrel/end-cap muons



Υ(1S) pair production as background source

Mass resolution improved (by 50%) with $\tilde{m}_{4\mu} = m_{4\mu} - m_{\mu\mu} + m_{\Upsilon(1S)}$,

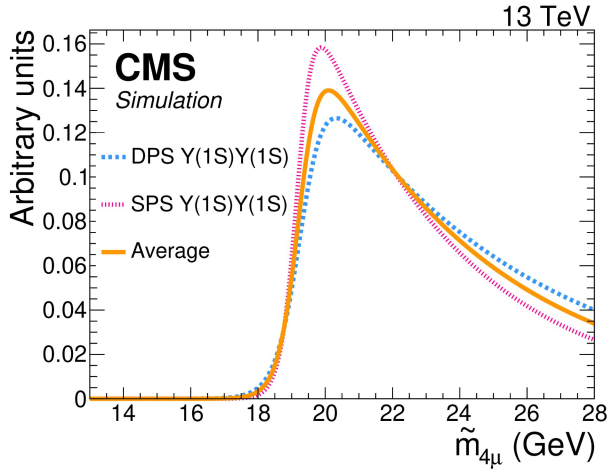
One μμ pair (from Υ(1S)) is already formed at HLT level

Υ(1S)Υ(1S) background

Yield extracted from data region

$|m(\Upsilon_{12/34}) - \Upsilon(1S)| < 2\sigma_{\Upsilon(1S)}$: N(ΥΥ) = 74 ± 13 evts

Shape from MC: sigmoid * falling exponential, with f_{DPS} (DPS-to-inclusive fraction) from fiducial cross section measurement

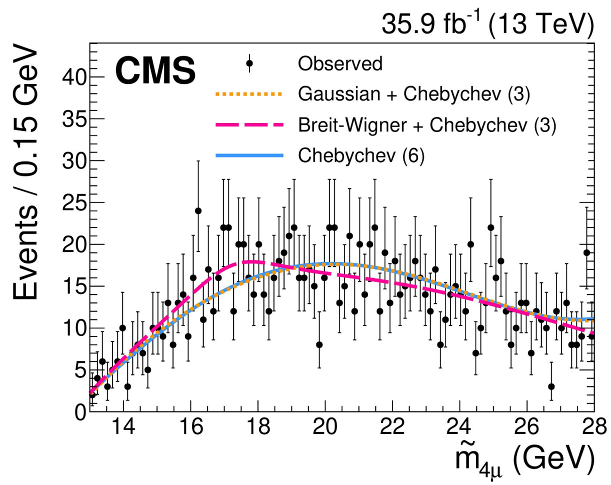


Combinatorial background

Control region: $P_{vtx}(4\mu)$ in $[10^{-10}, 10^{-3}]$

Fit with different models:

- Gaussian + 3rd-order Chebychev
- Breit-Wigner + 3rd-order Chebychev
- 6th-order Chebychev



Fit parameters are *not* used in the signal region

Υ(1S)Υ(1S): effect of the polarization

Υ(1S) pair polarization assumed to be negligible in acceptance and efficiency corrections

Previous measurements from CMS [D] and LHCb [E] show no polarization in single Υ(1S) production

Polarization affects the angular distribution of the Υ(1S) ➔ μμ decay products:

$$\frac{d^2N}{d\cos\theta\, d\phi} \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi+\lambda_{\theta\phi}\sin 2\theta\cos\phi),$$

- (θ, φ) direction of μ^+
- λ_θ, λ_φ, $\lambda_{\theta\varphi}$: angular distribution parameters

Effect of polarization on fiducial cross section:

λ_θ	−1.0	−0.5	−0.3	−0.1	+0.1	+0.3	+0.5	+1.0
$\Delta\sigma_{\text{fid}}$	−60%	−22%	−12%	−3.7%	+3.4%	+9.4%	+14%	+25%

[D] [CMS Collaboration, arXiv:1209.2922]
[E] [LHCb Collaboration, arXiv:1709.01301]

Υ(1S)Υ(1S): systematic uncertainties

Uncertainty source	Uncertainty (%)	Impact on σ_{fid} (pb)
Integrated luminosity	2.5	2.0
Muon identification	2.0	1.6
Trigger	6.0	4.7
Vertex probability	1.0	0.8
$\mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-)$	4.0	3.2
Signal and background models	1.2	1.0
Method closure	1.5	1.2
Total	8.1	6.4

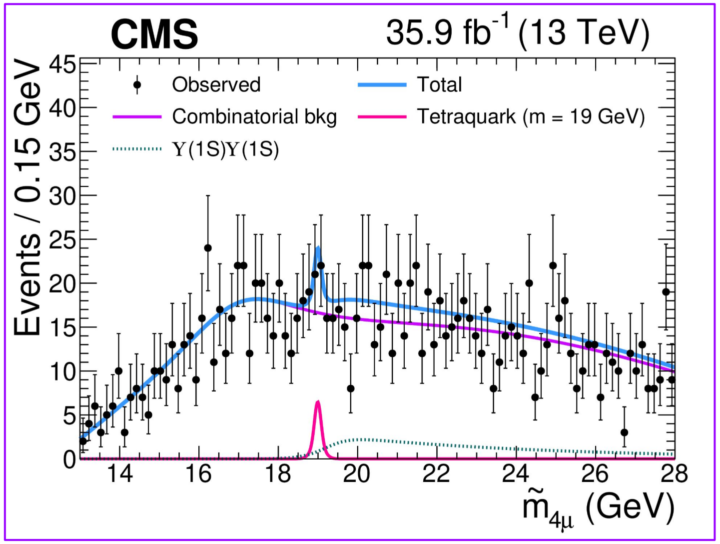
Upper limits on resonance production in $\Upsilon(1S)\mu^+\mu^-$

Fit on data with an example tetraquark signal (m_X = 19 GeV):

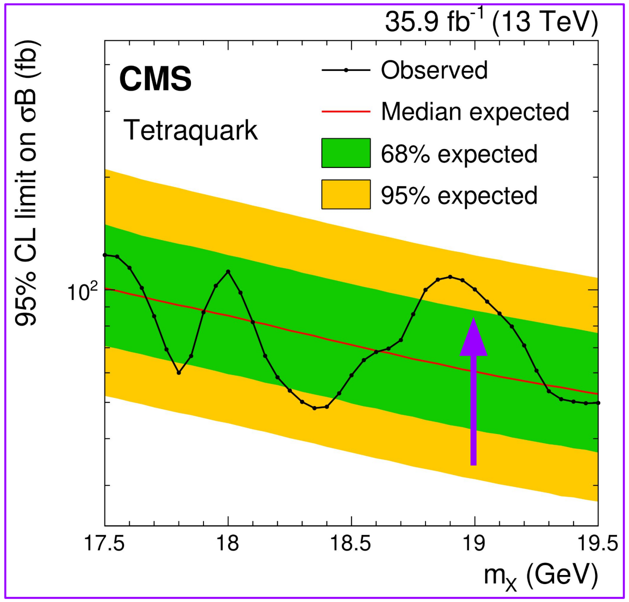
- **Signal**: DoubleGaussian
- **Significance**: ~1σ

No significant excess is observed between 17.5 and 19.5 GeV (near Υ(1S)Υ(1S) mass)

Upper limits @ CL=95 % are set



Considering similar kinematics between and Υ(1S)Υ(1S) and $b\bar{b}b\bar{b}$ resonance (same production Xsection (*) and BF into 4 muons), **a resonance with mass m_X = 19 GeV would produce around 100 candidates in our data**



(*) Υ(1S) pair production fiducial cross section (|y| < 2.0) is measured:

$$\sigma_{\text{fid}} = 79 \pm 11\,(\text{stat}) \pm 6\,(\text{syst}) \pm 3\,(\mathcal{B})\ \text{pb},$$

No significant excess compatible with a generic resonance is observed [see backup]

Search for narrow resonance in $Y(1S)\mu^+\mu^-$

Bottomonium state (χ_b(1P) as a proxy in PYTHIA 8.226) is used to model the resonance signal. Simulated mass values: 14, 18, 22, 26 GeV.

Large mass window (from 16.5 to 27 GeV) explored to search for narrow resonance

No significant excess of events compatible with a narrow resonance is observed in data

Largest excess (2.4σ) for scalar hypothesis (m_X = 25.1 GeV)

Limits on production cross section w.r.t. the resonance mass are set