8th June 2021 - Virtual conference session
Conference on Flavour Physics and CP Violation, FPCP2021

Recent CMS results on spectroscopy of heavy flavors

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Outline

1. **Observation of the $B_s^0 \to X(3872)\phi$ decay [PRL 125 (2020) 152001]**

2. **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]**

3. **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]**

4. **Observation of a new excited beauty strange baryon in decaying to $\Xi_b^-\pi^+\pi^-$ [arXiv:2102.04524, accepted by PRL]**

5. **Measurement of the Υ(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]**

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

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

X(3872) [*aka* χ_{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 $J/\psi(\to \mu^+\mu^-)\ \pi^+\pi^-$
- **ϕ(1020)** reconstructed in K^+K^- final state
- $N[B_s^0 \to X(3872)/\psi(2S)\ \phi]$: **signal yields** for $X(3872)/\psi(2S) \to J/\psi\pi^+\pi^-$
- $\varepsilon(B_s^0 \to X(3872)/\psi(2S)\ \phi)$: **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 ψ(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:

❖ **ψ(2S)**: Double-Gaussian

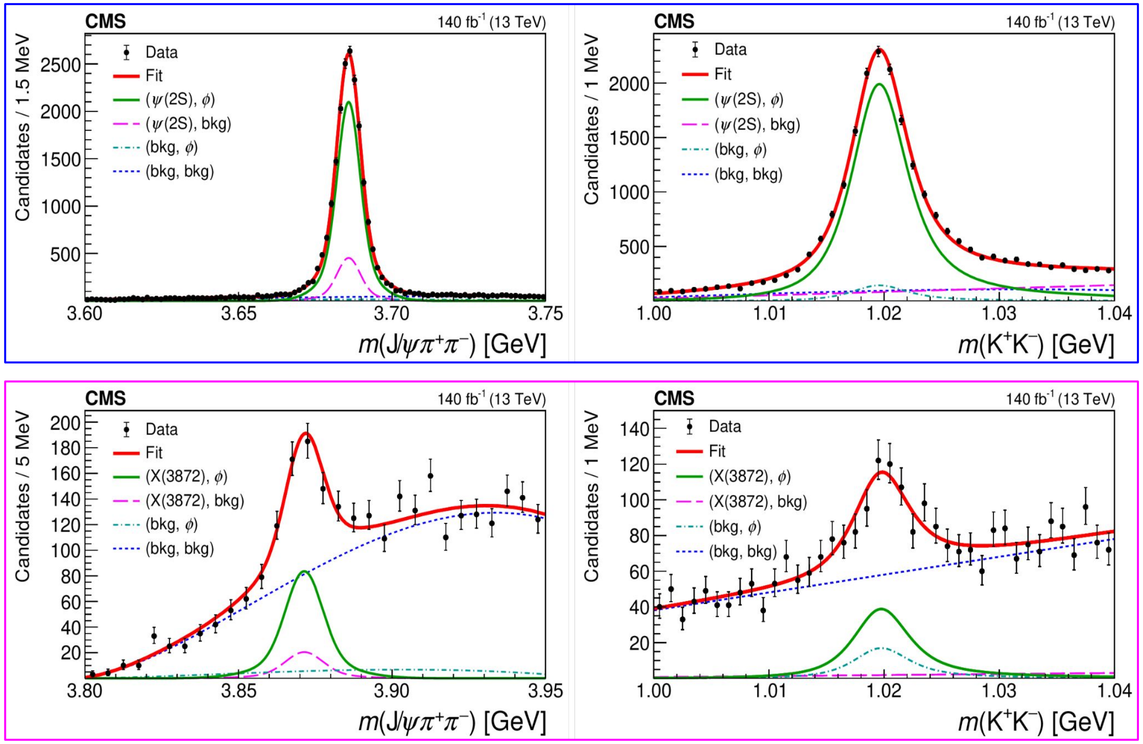
❖ **X(3872)**: Double-Gaussian (with shape fixed by ψ(2S))

❖ ϕ(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)/ψ(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]

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

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

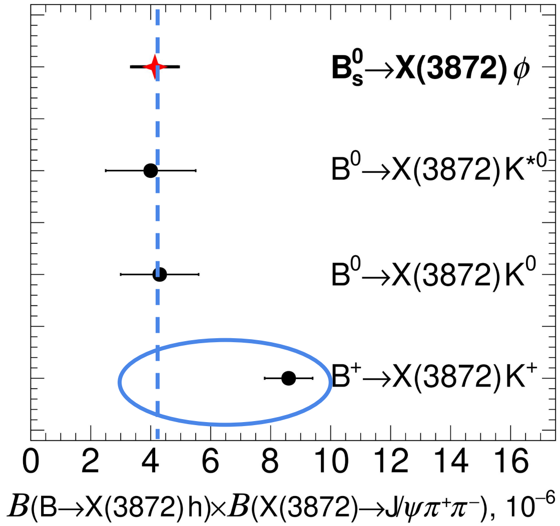
Consistent with analogous B^0 decay, but **two times smaller than B^+**

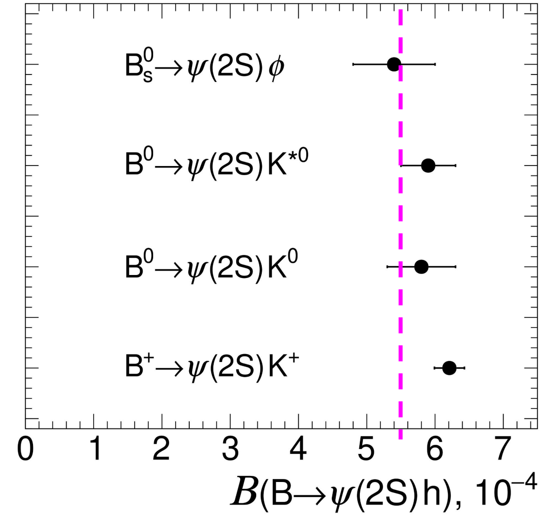
$$\frac{\mathcal{B}(B_s^0\to X(3872)\phi)}{\mathcal{B}(B^+\to X(3872)K^+)} = 0.482 \pm 0.063(syst) \pm 0.037(syst) \pm 0.070(\mathcal{B})$$

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]

$B_c(2S)$ mesons 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) [2]

[2] [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 $B_c(2S)^+$

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

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

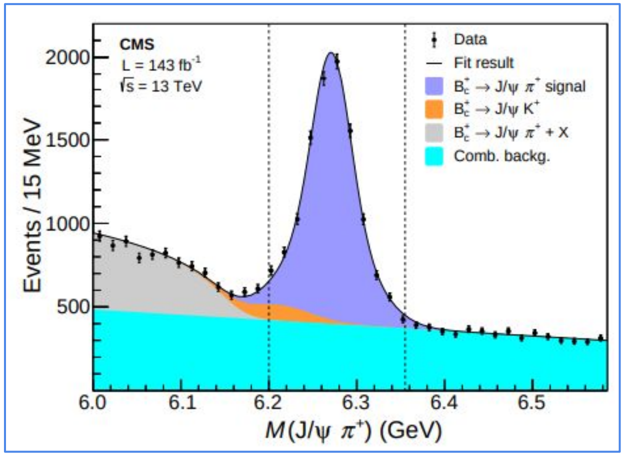
$$R^{*+}/R^+ = \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c(2S)^+)} \frac{\mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-)}{\mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-)} = \frac{N(B_c^*(2S)^+)}{N(B_c(2S)^+)} \frac{\epsilon(B_c(2S)^+)}{\epsilon(B_c^*(2S)^+)}.$$

$B_c^*(2S) \to B_c^*\pi\pi$ 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%

$B_c(2S)$ and $B_c^*(2S)$ signal yields

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

$N(B_c^+) = 7629 \pm 225$ events



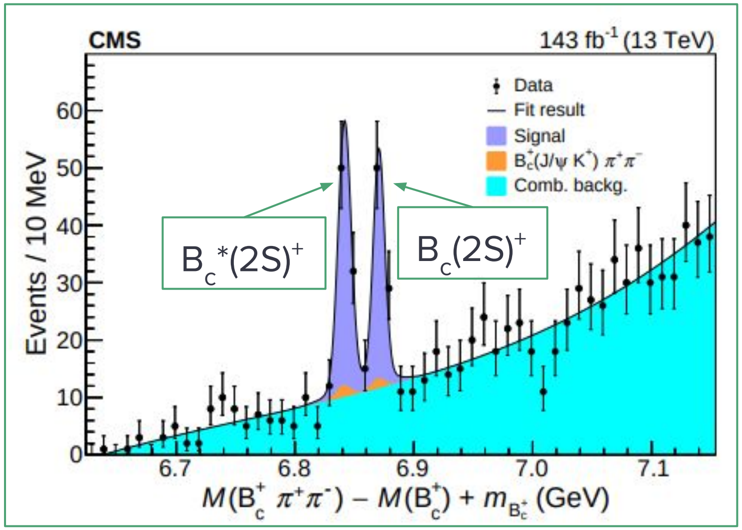
$B_c(2S)$ candidates:

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

Signal: two gaussians

Background:

- Combinatorial: Chebychev-3 polynomial
- $B_c^+ \rightarrow J/\psi K^+$ contribution: two Gaussians



$N(B_c^*(2S)^+) = 67 \pm 10$ evts

$N(B_c(2S)^+) = 52 \pm 9$ evts

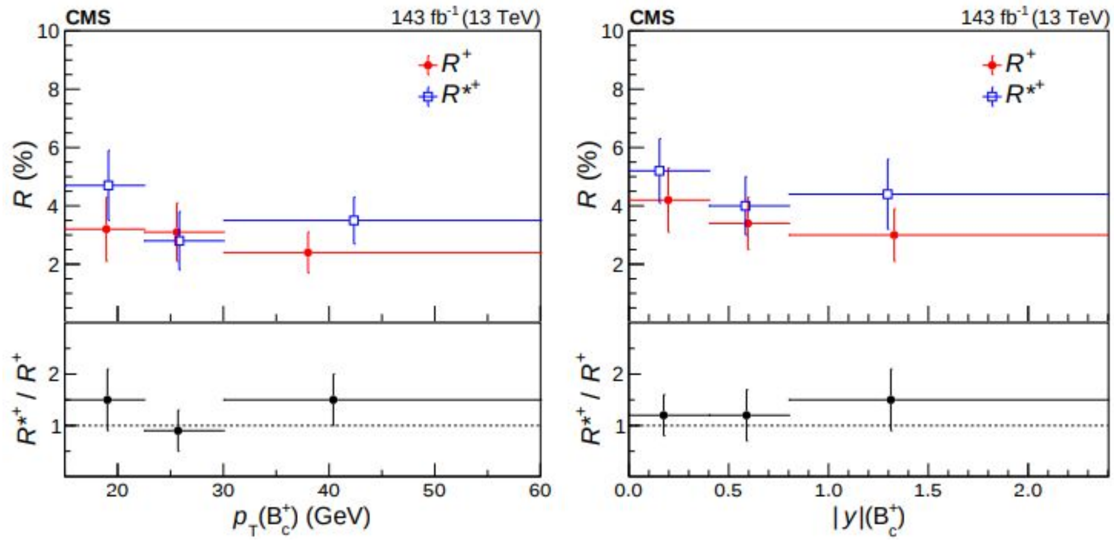
$\Delta M = 28.9 \pm 1.5$ MeV

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

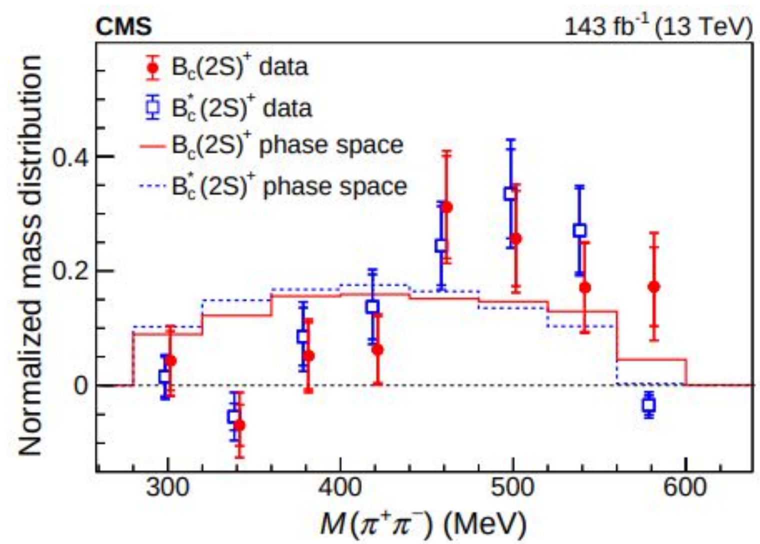
No significant dependence of the cross section on $p_T(B_c^+)$ or $\eta(B_c^+)$ observed



Invariant mass of di-pion system

Different models [3] [4] 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



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

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

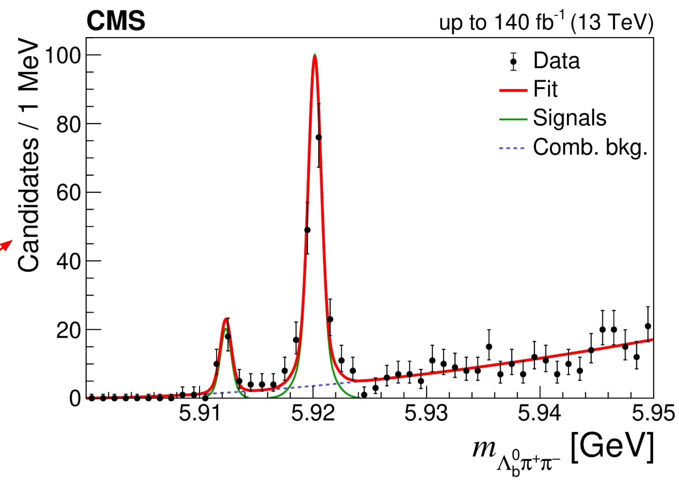
$\Lambda_b^0\pi^+\pi^-$ signal extraction

- **Λ_b^0 signal yields**: $J/\psi\Lambda$: 39k; $\psi(2S)(\to\mu^+\mu)\Lambda$: 3.4k; $\psi(2S)(\to\mu^+\mu^-\pi^+\pi^-)\Lambda$: 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**: $m_{\Lambda_b^0\pi^+\pi} \gtrless 5.95$ GeV

UML fit to data

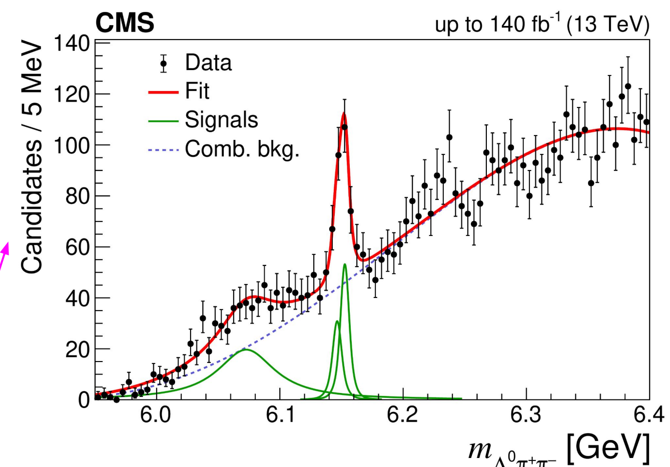
- **Signals**: Double-Gaussian (resolution from MC)
- **Background**: threshold function $(x-x_0)^\beta$

Two signals observed:
- ❑ $\Lambda_b(5912)$ (5.7σ)
- ❑ $\Lambda_b(5920)$ ($>6\sigma$)



- **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 $\Lambda_b(6146) + \Lambda_b(6152)$
2-peak / 1-peak hypothesis: $\mathcal{L}_{ratio} = 0.4\sigma$



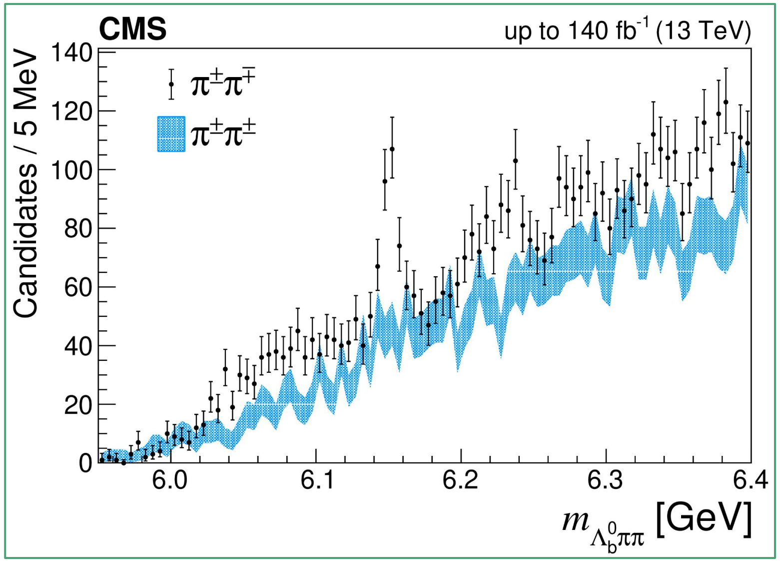
Details on event reconstruction, signal extraction and systematic uncertainties in backup

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

Broad enhancement below 6100 MeV not present in control region

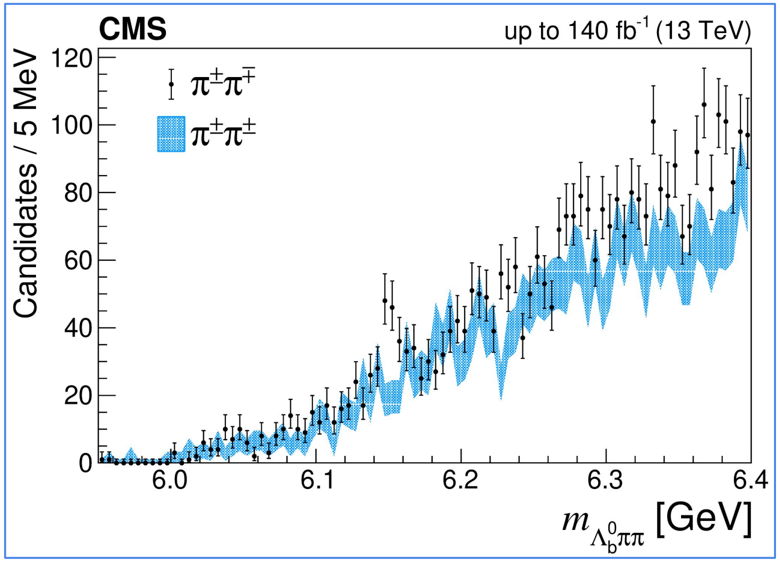
Possible sources ruled out:

- Partially reconstructed decays [e.g $\Lambda_b(6146)$, $\Lambda_b(6152) \rightarrow \Lambda_b^0\pi^+\pi^-\pi^0$, 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 [5] shortly after, interpreting it as a further excited Λ_b^0 state [$\Lambda_b^0(6072)$]

[5] [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) $\Xi_b^- \to J/\psi\Xi^-$
2) $\Xi_b^- \to J/\psi\Lambda^0K^-$
3) $\Xi_b^- \to J/\psi\Sigma^0K^-$

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

not reconstructed

Event selection for Ξ_b^- reconstruction:

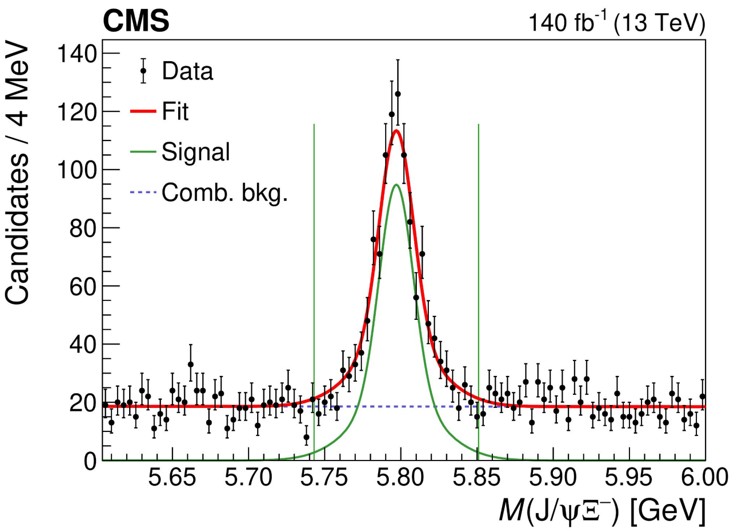
- combination of **triggers targeting $J/\psi \to \mu^+\mu^-$**
- $p_T(\mu) > 3$ GeV; $|\eta(\mu)| < 2.4$; $P_{vtx}(\mu\mu) > 1\%$; $|m(\mu\mu) - M_{J/\psi}^{PDG}| < 100$ MeV
- $|m(p\pi^-) - M_\Lambda^{PDG}| < 10$ MeV; $p_T(\Lambda) > 1$ GeV; $P_{vtx}(p\pi^-) > 1\%$
- **Further selection separately optimized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

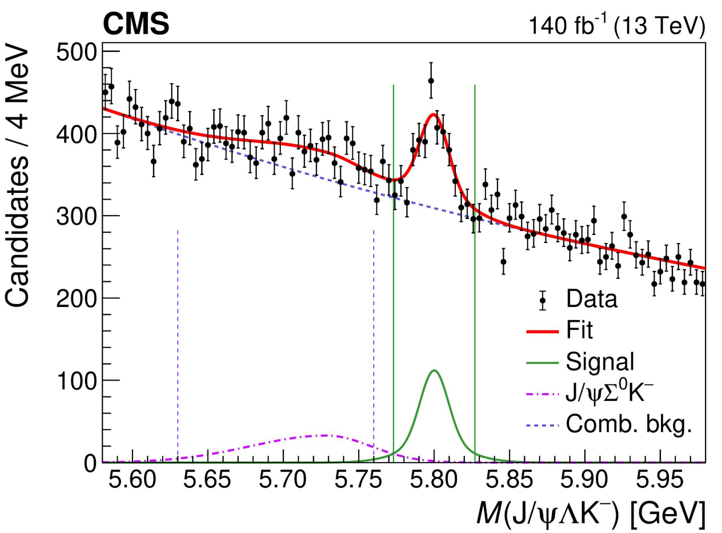
Details on event reconstruction, signal extraction and systematic uncertainties in backup

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

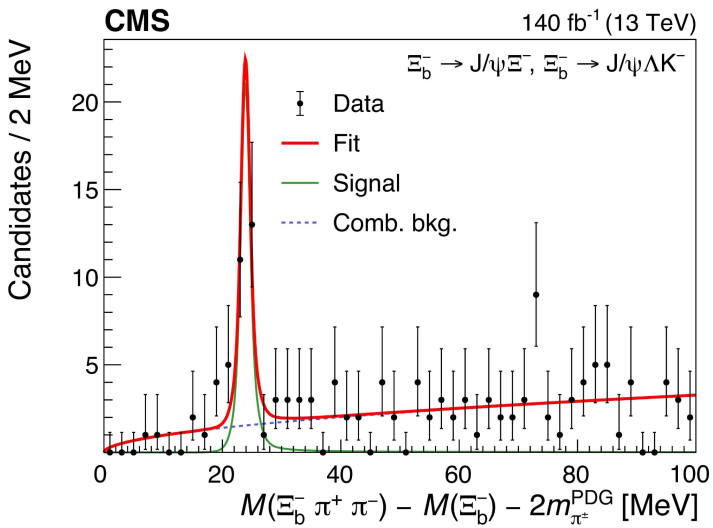
Fully reconstructed channels are combined
(same resolution, $\Xi_b^- \rightarrow J/\psi\Sigma^0K^-$ 30% larger res.)

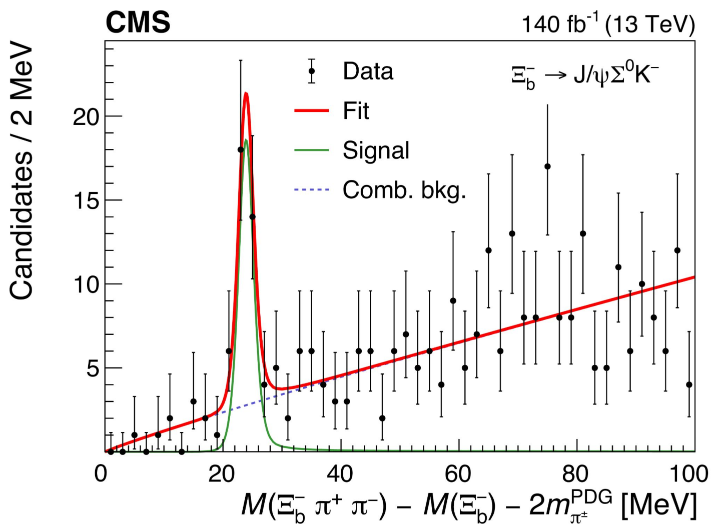
UML simultaneous fit:

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

$M(\Xi_b^{**-}) = 6100.3 \pm 0.2(stat) \pm 0.1(syst) \pm 0.6(\Xi_b^-)$ 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 Ξ_c(2815) baryon



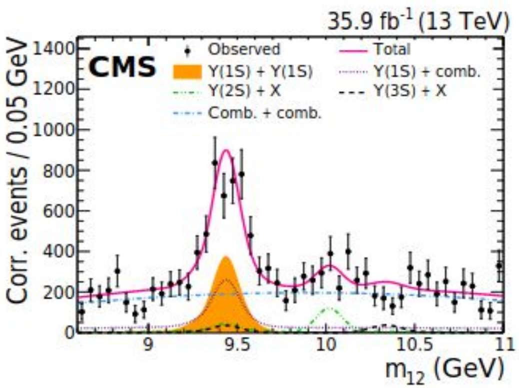


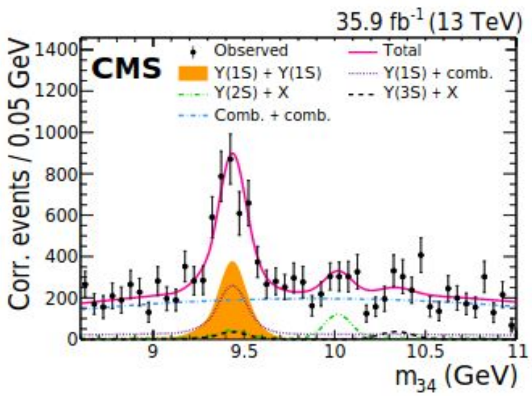
Search for narrow resonances in Υ(1S)$\mu^+\mu^-$

Measurement of fiducial cross-section for Υ(1S) pair production and search for resonances decaying to Υ(1S)μμ in pp collisions at $\sqrt{s}$ = 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|
- **Υ(1S) pair production** is standard model reference in the search for tetraquark bound state or generic narrow resonance with mass close to twice the Υ(1S) mass

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





Υ(1S)pair production fit details:

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

More details in backup

Υ(1S) pair production as background source

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

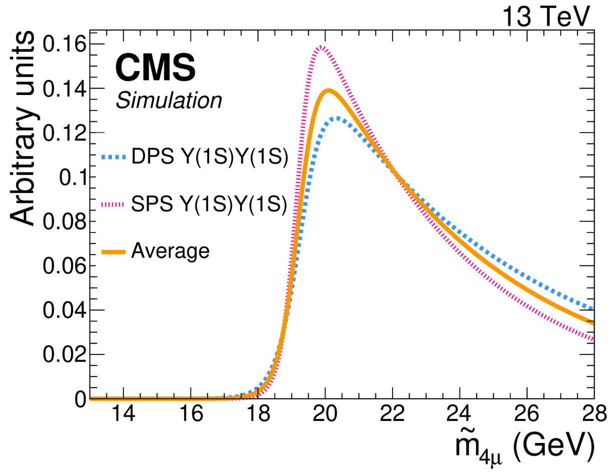
One μμ pair (from Υ(1S)) is already formed at HLT level

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



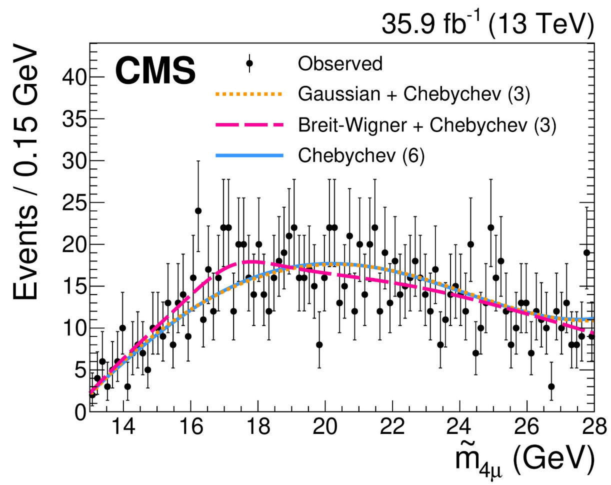
Combinatorial background

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



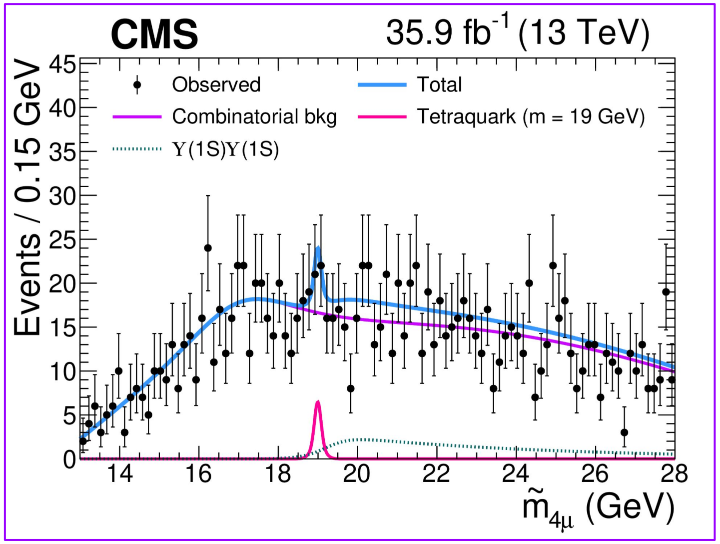
Upper limits on resonance production in $\Upsilon(1S)\mu^+\mu^-$

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

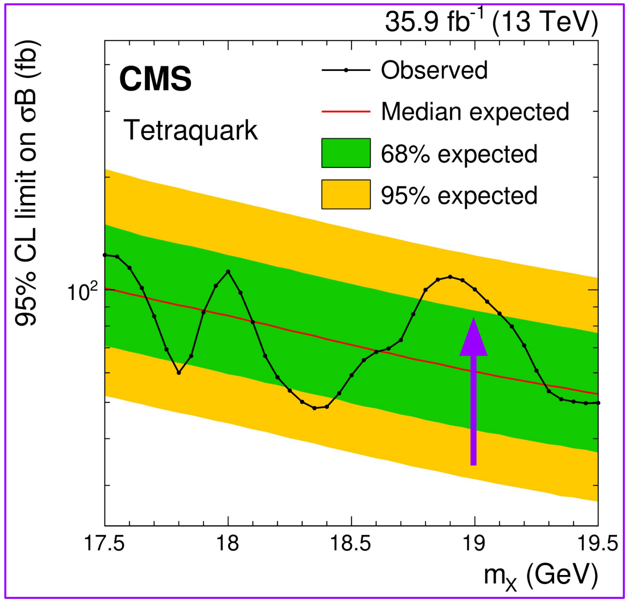
- **Signal**: DoubleGaussian
- **Significance**: ~1σ

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]

Conclusions

- **LHC provides high luminosity: heavy flavor production cross section several order of magnitudes greater than at e-e colliders**
- **CMS exploits its 4π coverage and high resolution to perform challenging measurements in Heavy Flavor physics**
- **The presented recent CMS measurements concern conventional and exotic spectroscopy in the charm (X(3872)) and beauty (B_c mesons, Λ_b and Ξ_b baryons, bottomonia) sectors**
- **Recent results from the CMS are in general good agreement with previous results from other LHC experiments (when available) and extend the current understanding of Standard Model by probing QCD phenomena**

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; $P_{vtx}(Bs) > 7\%$; $p_T(\pi) > 0.7$ 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

$B_c(2S)$: hyperfine structure

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

Soft photon (55 MeV in the rest frame) not detected, we end up seeing

$B_c^*(2S) \to B_c \pi^+ \pi^-$ plus "missing energy"

Same final state as $B_c(2S) \to B_c \pi^+ \pi^-$

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.

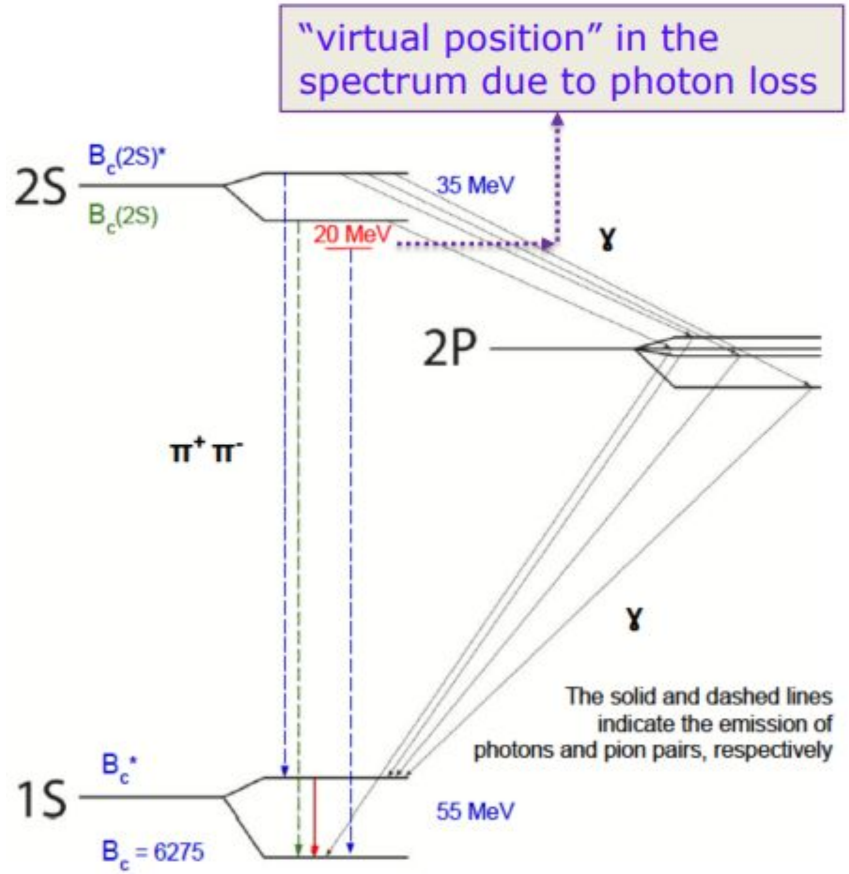
The two-peak can be appreciated only if ΔM value is larger than experimental resolution!

Predictions indicate:

$[M(B_c^*(1S)) - M(B_c(1S))] > [M(B_c^*(2S)) - M(B_c(2S))]$

that would imply that the

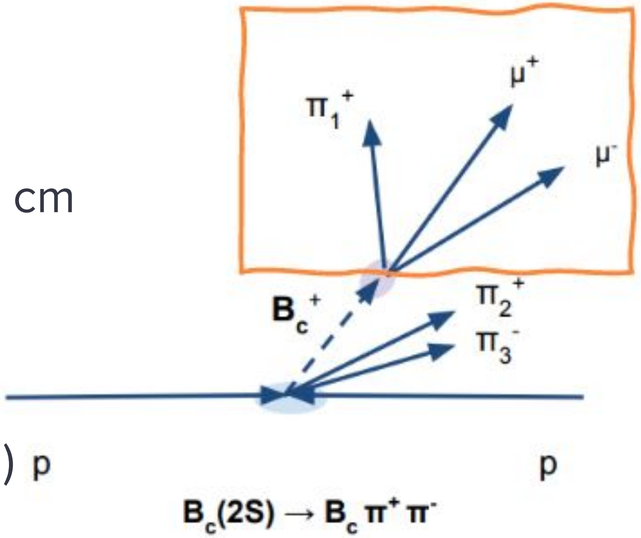
$B_c^*(2S)$ peak is the lower peak!



$B_c(2S)$: 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)



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 reconstruction

B_c candidates fit

Signal: weighted sum of two gaussians with same mean

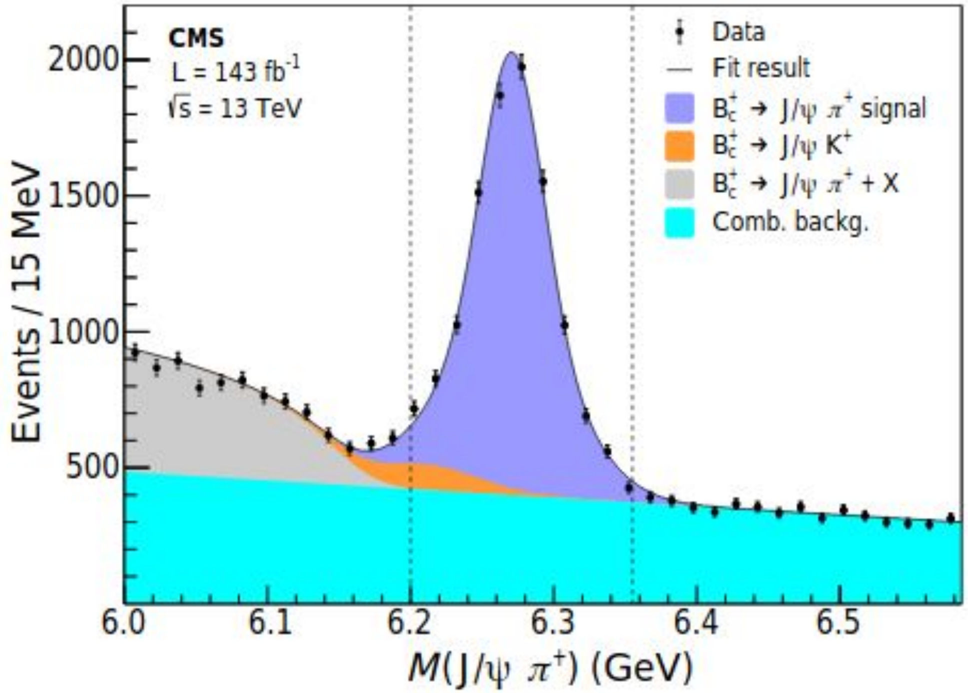
$$wG(\mu,\sigma_1) + (1-w)G(\mu,\sigma_2),$$

w = 0.47 σ_1 = 21 MeV σ_2 = 42 MeV

Background:

- Combinatorial: Chebychev polynomial
- J/ψK: shape from simulation
- J/ψπ + X: ARGUS function

N(B_c) = 7629 +/- 225 events



$B_c(2S)$ 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:

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

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 * 1st 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**

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
- μμ 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

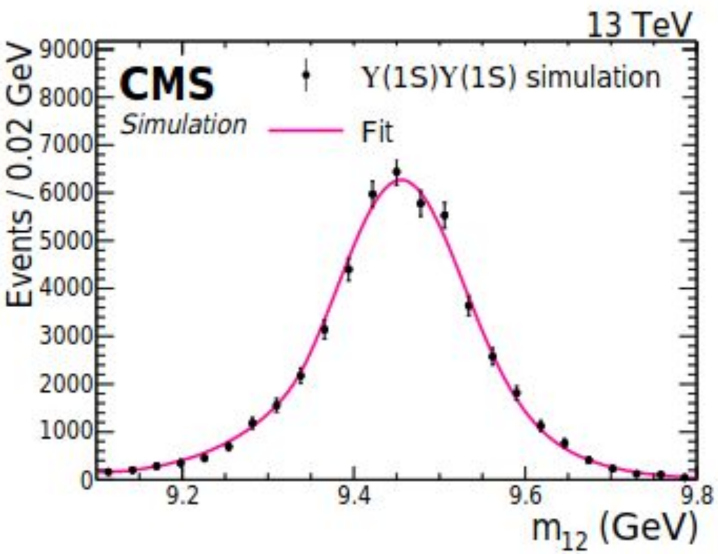
Event-by-event weight:

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

- 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



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

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

Previous measurements from CMS [A] and LHCb [B] show no polarization in single Y(1S) production

Polarization affects the angular distribution of the Y(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
$\Delta\sigma_{\mathrm{fid}}$	−60%	−22%	−12%	−3.7%	+3.4%	+9.4%	+14%	+25%

[A] [CMS Collaboration, arXiv:1209.2922]
[B] [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

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

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