Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO

Latest spectroscopy results from CMS

HQL 2021

The XV International Conference on Heavy Quarks and Leptons

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On Behalf of the CMS Collaboration

(*) with the support of Italian MAECI (PGR 01273/2021 - CUP I94I19000060001)

Latest spectroscopy results from CMS

- ★ Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ in proton-proton 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) 25, 252003**

- ★ 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

- ★ **Observation of the $B_s^0 \rightarrow X(3872)\phi$ decay; PRL 125 (2020) 15, 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 Phys. Rev. Lett.**

- ★ **Observation of $B^0 \rightarrow \psi(2S)K_s^0\pi^+\pi^-$ and $B_s^0 \rightarrow \psi(2S)K_s^0$ 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) 9, 092007

More recent results are bold will be discussed in this talk. For others, you can find some details in the backup slides.

Observation of a new excited beauty strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$

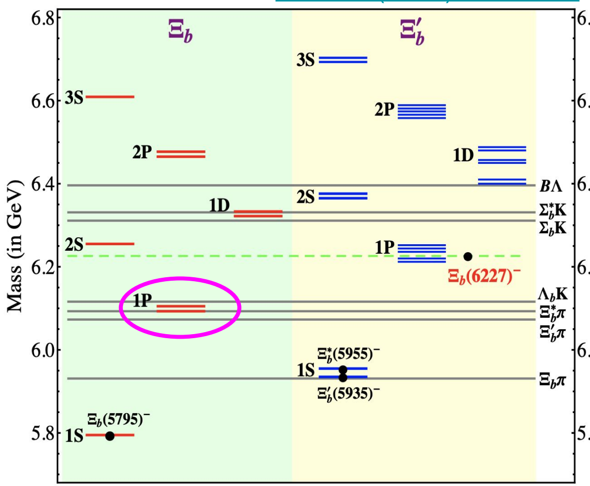
A new excited beauty strange baryon - Introduction & Topology

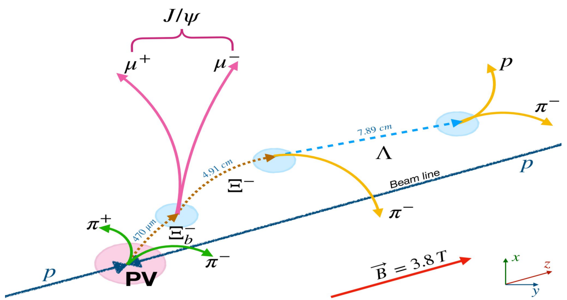
[PRD 98 (2018) 3, 031502](#)

- The Ξ_b family are **qsb** (q = u or d) isodoublets, their ground states have been observed at Tevatron for the first time.

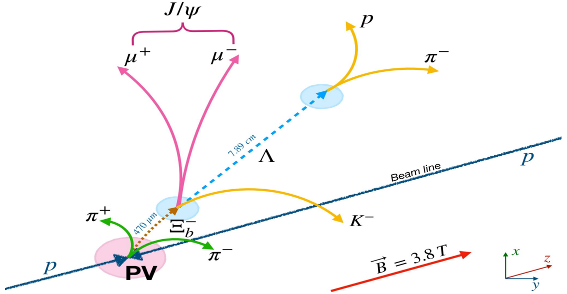
- Based on $\Xi_c \to \Xi_c\pi \to \Xi_c\pi\pi$ analogy, a new Ξ_b^{**-} excited resonance is predicted near the kinematic threshold in the $\Xi_b^-\pi^+\pi^-$ mass spectrum [with intermediate $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$].

- The mass of the Ξ_b^{**-} is expected to be around 6100-6130 MeV [PRD 96 (2017) 11, 116016; PRD 99 (2019) 9, 094016; PRD 98 (2018) 3, 031502].





- ➔ $\delta m[\Xi_b^-\pi^+] - \delta m_{PDG}[\Xi_b^{*0}] < 5$ MeV.
- ➔ PV is selected as the one with smallest 3D pointing angle.
- ➔ Ξ_b^- is combined with two soft pion tracks coming from PV.



$\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$ ➔ $\Xi_b^{**-} \to \Xi_b^-\pi^+\pi^-$

$\Xi_b^{*0} \to \Xi_b^-\pi^+$

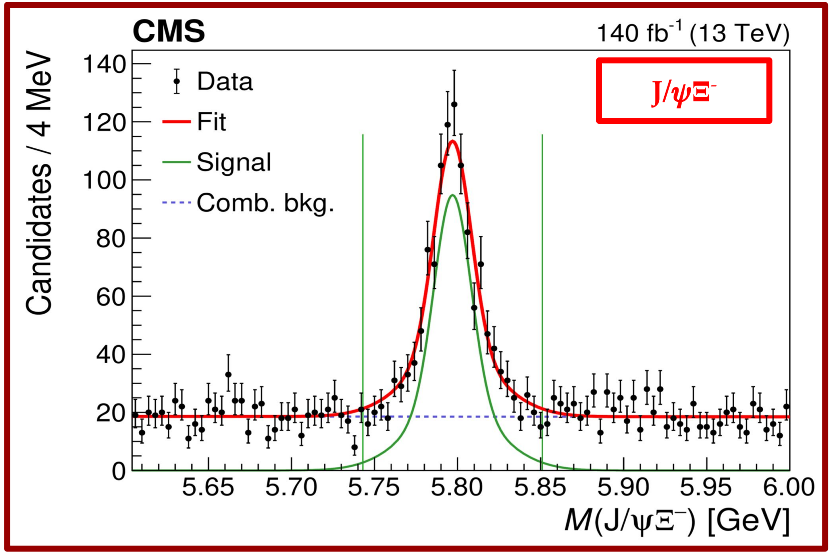
$\Xi_b^- \to J/\psi\Xi^-$ ➔ $\Xi^- \to \Lambda\pi^-$

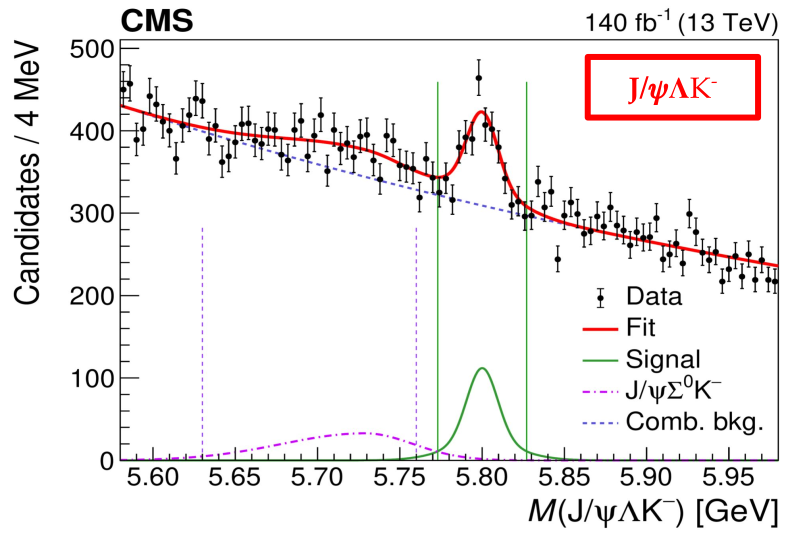
$J/\psi \to \mu^+\mu^-$

$\Xi_b^- \to J/\psi\Lambda K^-$ ➔ $\Lambda \to p\pi^-$

Charge conjugate states are implied

A new excited beauty strange baryon - Ξ_b^- signals





N = 859 ± 36

M = 5797 ± 0.7 MeV

σ = 19.0 MeV

★ Ξ_b^- signal events from green-lines mass windows are used to form **fully-reconstructed** $\Xi_b^-\pi^+\pi^-$ sample.

★ The $\Xi_b^- \to J/\psi\Sigma^0K^-$ is **partially-reconstructed** due to the soft photon in $\Sigma^0 \to \Lambda\gamma$ and its contribution is modelled with an asymmetrical gaussian.

★ **Both contributions are taken into account.**

N = 815 ± 74

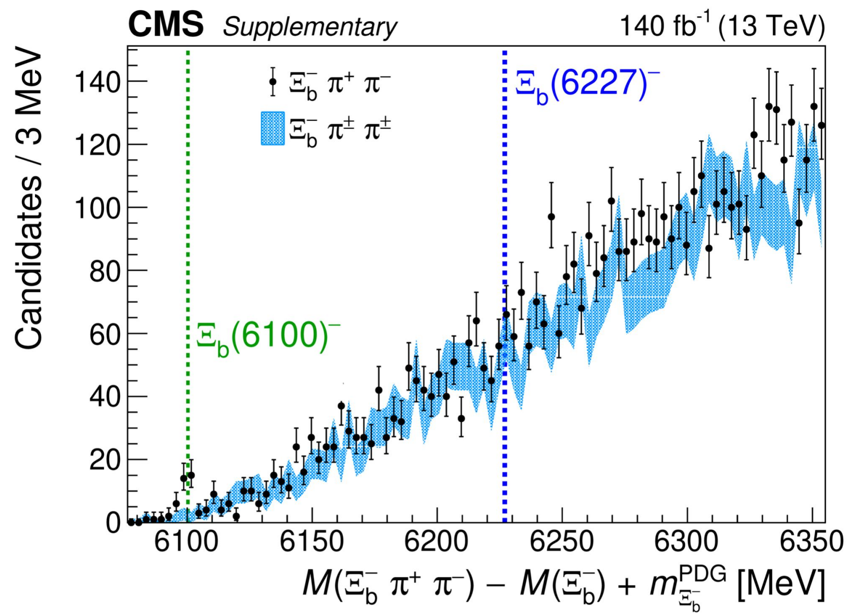
M = 5800.1 ± 1.2 MeV

σ = 14.9 MeV

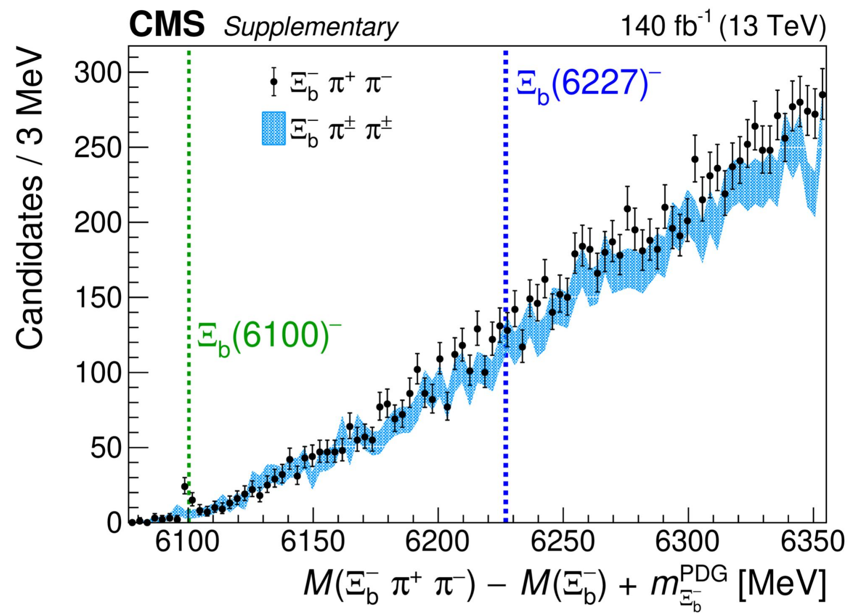
N_{refl} = 820 ± 158

A new excited beauty strange baryon - Opposite Sign & Same Sign

$\Xi_b^- \to J/\psi \Xi^-$ & $\Xi_b^- \to J/\psi \Lambda K^-$

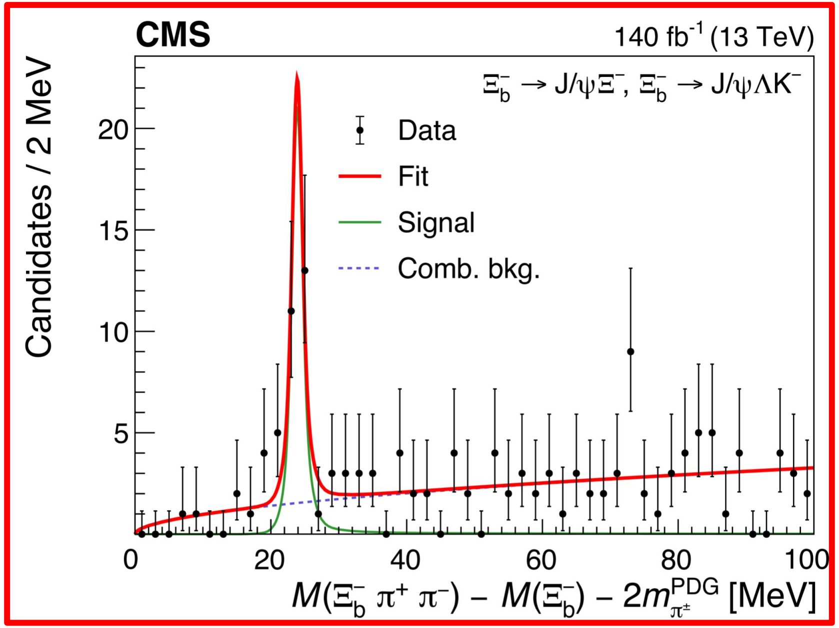


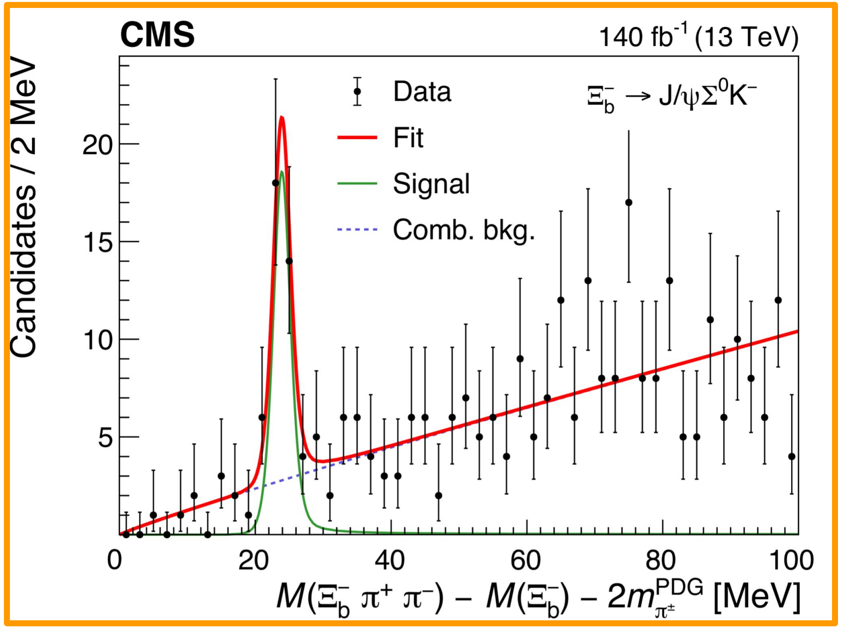
$\Xi_b^- \to J/\psi \Sigma^0 K^-$



- ➔ Plots with SS distribution overlaid w/o Ξ_b^{*0} selection.
- ➔ No signal in SS distribution.
- ➔ **Only one peak at ~ 6100 MeV.**
- ➔ There is **no excess of $\Xi_b(6227)^-$** state observed by the LHCb [*Phys.Rev.Lett.* 121 (2018) 7, 072002]

A new excited beauty strange baryon - Ξ_b^{**-} simultaneous fit & $\Xi_b(6100)^-$





➔ Signal: Relativistic Breit-Wigner ⊗ Double-Gaussian. **Background**: $(x-x_0)^\alpha$ threshold.

➔ The simultaneous fit to the two distributions with common **M** and **Γ** gives:

- ◆ M[$\Xi_b(6100)^-$] = [6100.3 ± 0.2(stat) ± 0.1(syst) ± 0.6(Ξ_b^-)] MeV
- ◆ **Γ**[$\Xi_b(6100)^-$] < 1.9 MeV @ 95% CL

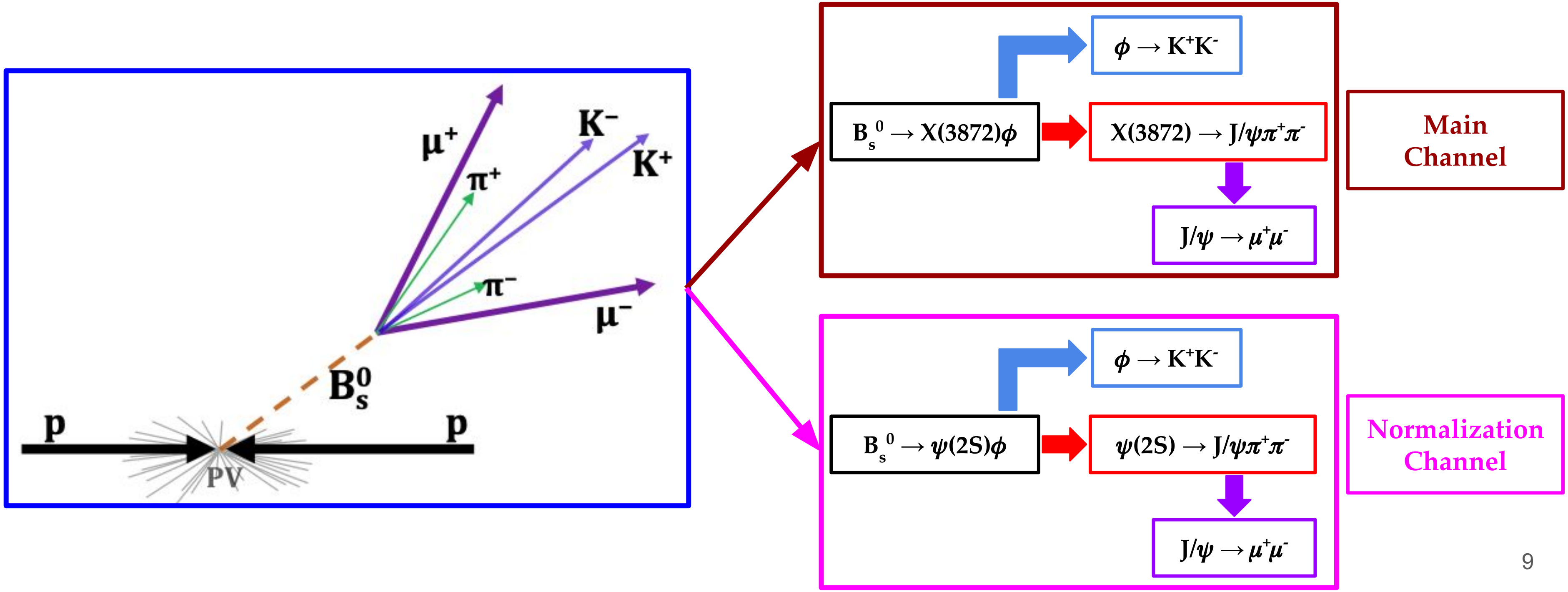
$$M(\Xi_b(6100)^-) - M(\Xi_b^-) - 2\,m_{\pi^\pm}^{\mathrm{PDG}}$$
$$= 24.14 \pm 0.22\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst})\,\mathrm{MeV}$$

➔ **Significance in 6.2σ - 6.7σ**

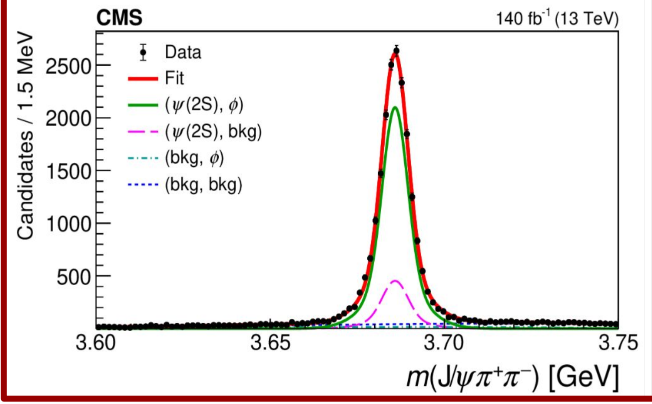
Observation of the $B_s^0 \to X(3872)\phi$ decay

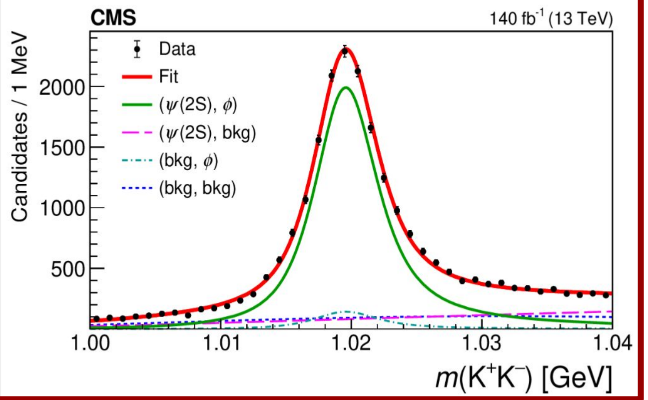
Observation of the $B_s^0 \to X(3872)\phi$ decay - Introduction & Topology

- X(3872) was observed in 2003 by Belle with a mass very near to $m(D^0D^{*0})$ threshold, $\Gamma < 1.2$ MeV and $J^{PC}=1^{++}$
- But still we don't know if it is a molecule, a tetraquark or a conventional charmonium state!!!
- X(3872) was never observed in B_s^0 decays, only promptly in pp, non-prompt from B^0, B^+, Λ_b^0 and prompt and non-prompt in PbPb collisions.



Observation of the $B_s^0 \to X(3872)\phi$ decay - Normalization & Observation





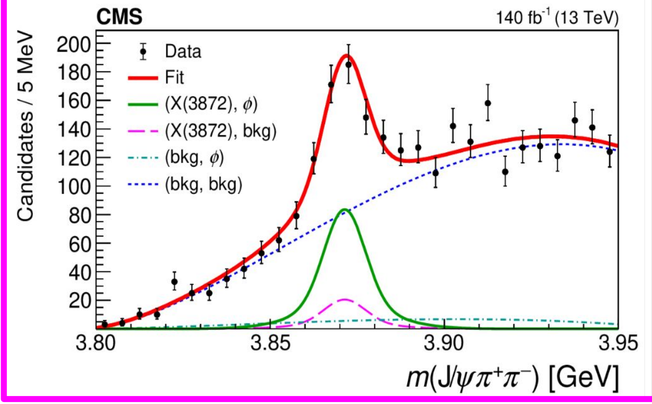
$B_s^0 \to \psi(2S)\phi$

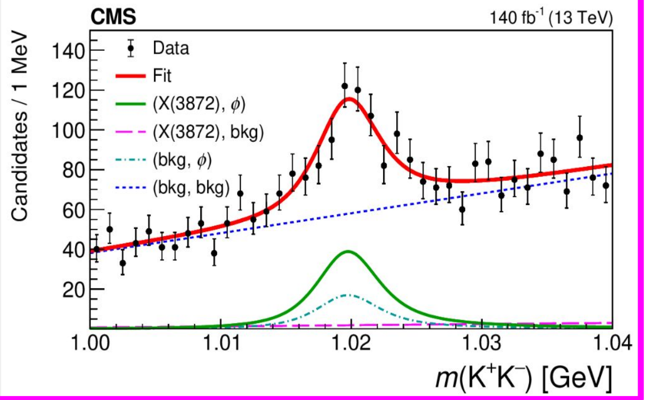
A 2D fit applied to

Left: $m(J/\psi\pi^+\pi^-)$ in the ψ(2S) mass window
Right: m(KK) in the ϕ mass window.

$N[B_s^0] = 15359 \pm 171$

[PRL 125 (2020) 15, 152001]





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

A 2D fit applied to

Left: $m(J/\psi\pi^+\pi^-)$ in the X(3872) mass window
Right: m(KK) in the ϕ mass window.

$N[B_s^0] = 299 \pm 39$

First observation with significance > 6σ

The BR ratio R is calculated correcting the yields with the relative efficiencies. See next slide!

Observation of the $B_s^0 \to X(3872)\phi$ decay - *R*; Calculations & Comparison

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

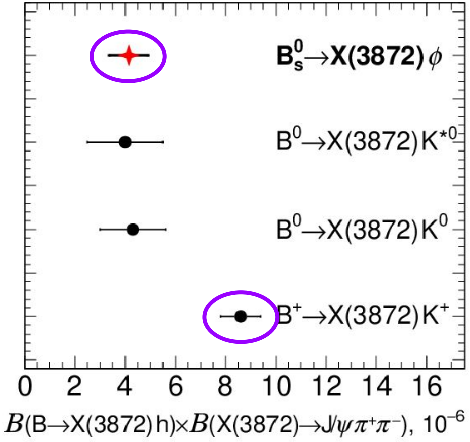
= [2.21 ± 0.29(stat) ± 0.17(syst)]%

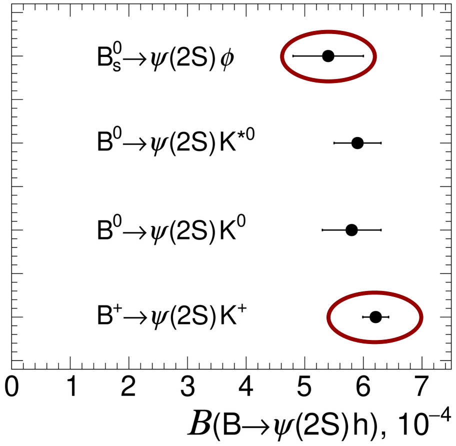
Later it has been confirmed by LHCb, JHEP 02 (2021) 024:
R = [2.42 ± 0.23(stat) ± 0.07(syst)]%

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

It is consistent with analogous B^0 decay, but two times smaller than B^+:

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





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

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

In PRD 102 (2020) 034017, this results is interpreted as favouring the **compact tetraquark hypothesis** of the **X(3872) state.**

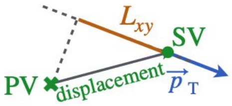
Evidence for X(3872) in PbPb collisions

Evidence for X(3872) in PbPb collisions - Signals in B-enriched & inclusive samples

In B-enriched data sample:

(non-prompt part, i.e. from B decays, it is produced **outside the QGP**)

$$l_{xy} = \frac{L_{xy} \cdot m}{|\vec{p}_{\mathrm{T}}|}$$



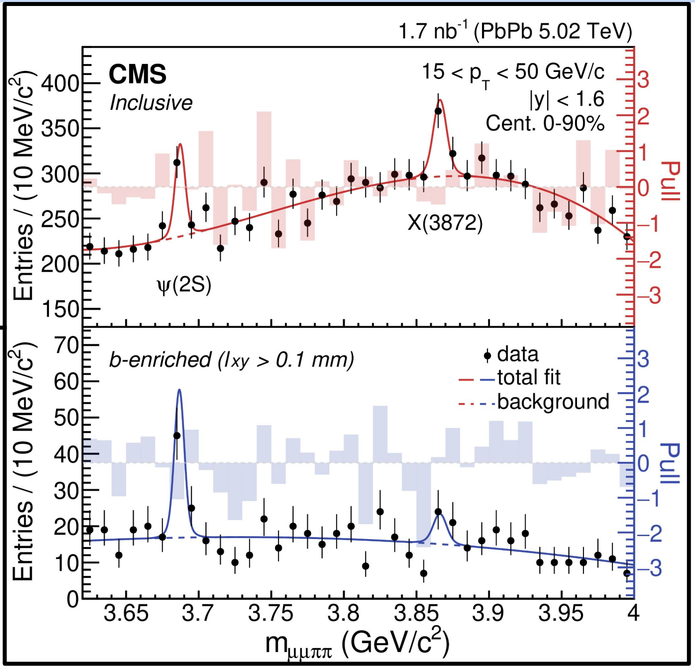
★ **Non-prompt ψ(2S) is clearly visible**

In inclusive data sample:

(interested in prompt part produced **inside the QGP**)

★ **First evidence of inclusive X(3872) production in HI collisions [statistical significance ~4.2σ]**

★ **A clear ψ(2S) signal to same final state is also visible**



To gain more insights, the prompt X(3872) to ψ(2S) ratio: arXiv:2102.13048

$$\rho^i = \frac{N_i^{X(3872)\to J/\psi\,\pi\pi}}{N_i^{\psi(2S)\to J/\psi\,\pi\pi}}$$

$$N^{i\to J/\psi\pi\pi} = N^i_{\mathrm{raw}} \boxed{f^i_{\mathrm{prompt}}} / (\alpha\, \epsilon_{\mathrm{reco}}\, \epsilon_{\mathrm{sel}})^i$$

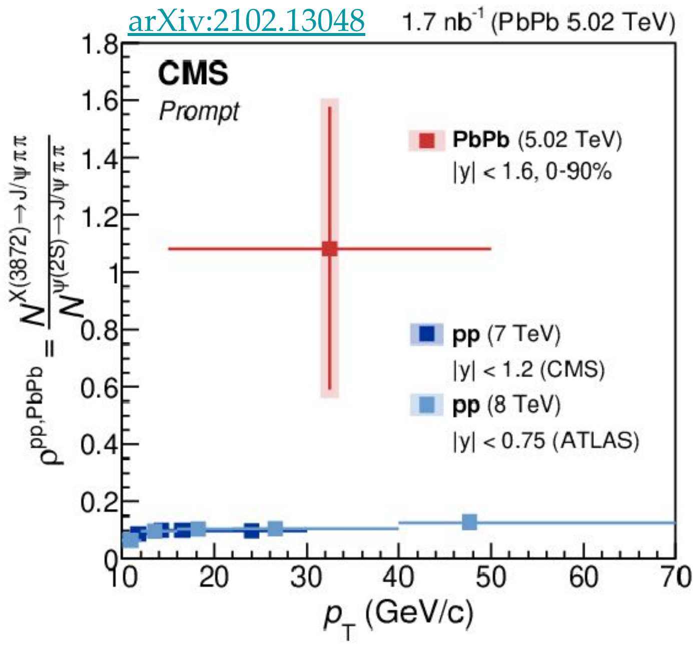
$$\boxed{f_{\mathrm{prompt}}} = 1 - \frac{N_{\text{b-enr}} / \boxed{f^{\text{b-enr}}_{\mathrm{nonprompt}}}}{N_{\mathrm{incl}}}$$

$$\boxed{f^{\text{b-enr}}_{\mathrm{nonprompt}} = N_{\mathrm{nonprompt}}(l_{xy} > 0.1\,\mathrm{mm}) / N_{\mathrm{nonprompt}}}$$

Evidence for X(3872) in PbPb collisions - Ratio of prompt X(3872) & ψ(2S) yields

- The **ratio** of **corrected** yields of prompt X(3872) to prompt ψ(2S), times their branching fractions into $J/\psi\pi^+\pi^-$:

arXiv:2102.13048



The ratios in pp and PbPb collisions are connected to the nuclear modification factors $R_{AA}^{X(3872)}$ and $R_{AA}^{\psi(2S)}$: **The meson yield ratio in nucleus-nucleus and pp interactions normalized by the number of inelastic nucleon-nucleon collisions.**

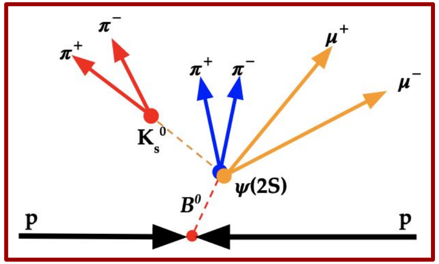
$$\boxed{\rho^{PbPb} = \rho^{pp}\frac{R_{AA}^{X(3872)}}{R_{AA}^{\psi(2S)}}} = 1.08 \pm 0.49(\text{stat}) \pm 0.52(\text{syst})$$

[to be compared with typical values of 0.1 for pp collisions]

- The **ratio measurement** is affected by several sources of sizeable systematic uncertainty, **see backup**.

Observation of $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_s^0$ decays

Observation of $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ and $B_s^0 \to \psi(2S)K_s^0$ decays- at CMS; 2017-2018 data, 13 TeV, ~103.7 fb^{-1}



$B^0 \to \psi(2S)K_s^0\pi^+\pi^-$

$\psi(2S) \to \mu^+\mu^-$ | $K_s^0 \to \pi^+\pi^-$

$B_s^0 \to \psi(2S)K_s^0$

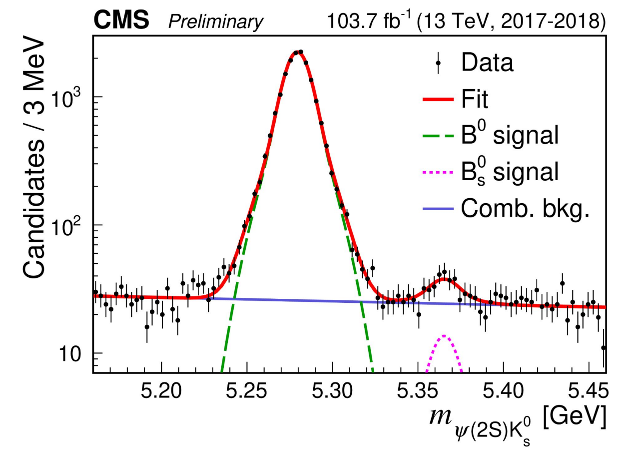
$\psi(2S) \to \mu^+\mu^-$ | $K_s^0 \to \pi^+\pi^-$

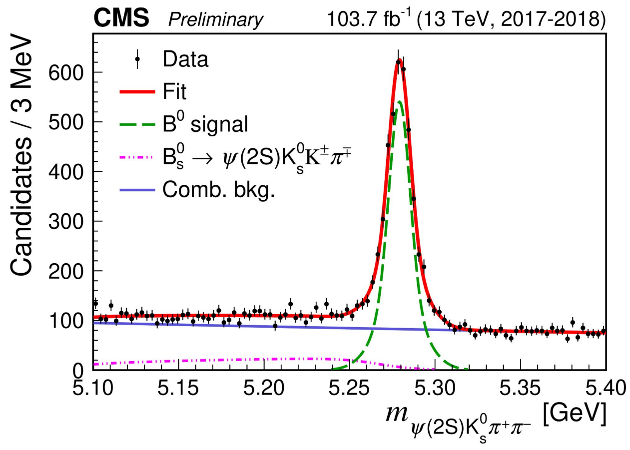
Normalization Channel

$B^0 \to \psi(2S)K_s^0$

$\psi(2S) \to \mu^+\mu^-$ | $K_s^0 \to \pi^+\pi^-$

- In the decays where final state is accessible both for B and B-bar, the interference between the **direct decay** and **the decay via oscillation** induces **time-dependent CP violation**.
- In **multibody** decays, search for **intermediate exotic resonances** [as in the last decade].
- $B^0 \to \psi(2S)K_s^0$ is the normalization channel
  - ✓ To reduce systematic uncertainties
  - ✓ the same decay topology as the $B_s^0 \to \psi(2S)K_s^0$
- $\mathbf{B_s^0 \to \psi(2S)K_s^0}$ with **5.2σ** significance.
- $\mathbf{B^0 \to \psi(2S)K_s^0\pi^+\pi^-}$ with a significance > 30σ.
- Using the *sPlot* technique, background subtracted 2-body and 3-body invariant mass distributions have been obtain.
- The mass distributions **do not present** any significant narrow peaks that could indicate a contribution from an exotic charmonium state [see backup slides].





Summary

★ The first observation of a new excited beauty strange baryon ~ $\Xi_b(6100)^-$ resonance. [PRL 126 (2021) 25, 252003]

★ A new decay mode $B_s^0 \rightarrow X(3872)\phi$ has been observed. Production of the X(3872) in B decays supports its unconventional nature. [PRL 125 (2020) 15, 152001]

★ The first evidence of X(3872) production in HI collisions has been observed. The $\rho[N^{X(3872)}/N^{\psi(2S)}]_{prompt} \times BR[\psi(2S)/X(3872)]$ into $J/\psi\pi^+\pi^-$ needs more statistics but still provides a unique experimental input to theory community. [arXiv:2102.13048]

★ In HI collisions, CMS also has several recent results, B_s^0 observation [arXiv:2109.01908], B_c^+ observation [CMS-PAS-HIN-20-004], etc.. More CMS results in HI Physics can be found here.

★ With recent results, clearly seen that, CMS has important role in the conventional and exotic hadron spectroscopy.

With Run-III data samples, CMS can provide more exciting results...

Thank you for your attention

Backup

Observation of the $B_s^0 \to X(3872)\phi$ decay - Systematic Uncertainties

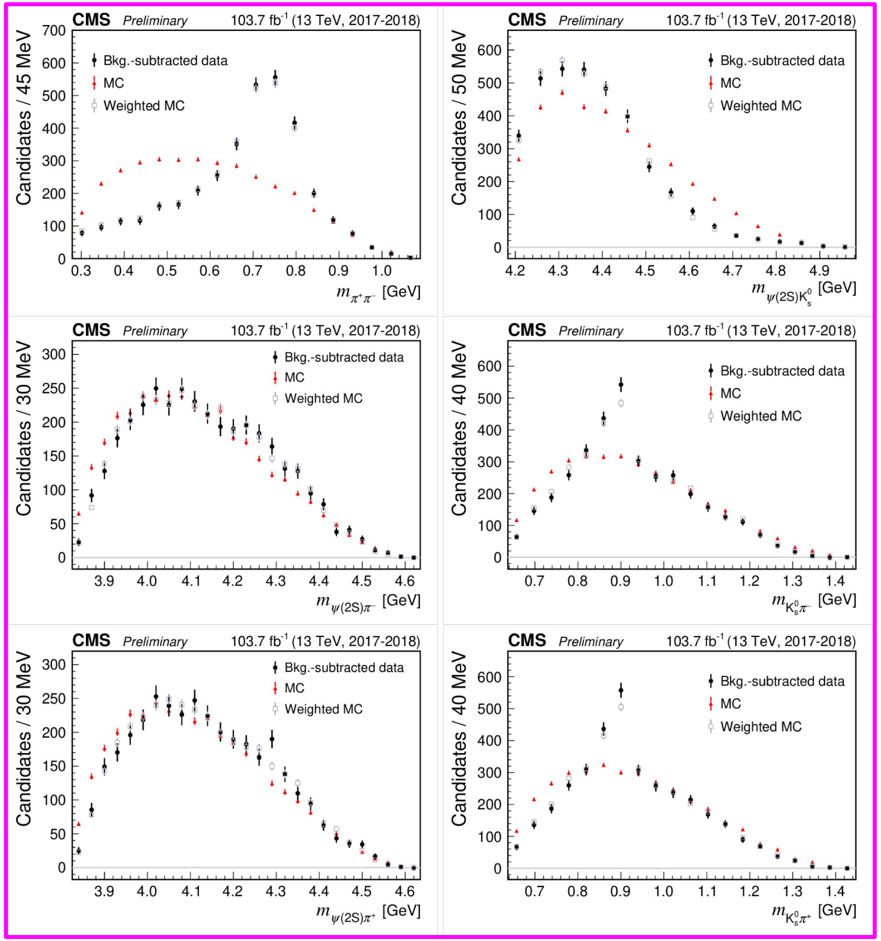
Source	Uncertainty (%)
$m(K^+K^-)$ signal model	< 0.1
$m(K^+K^-)$ background model	2.5
$m(J/\psi\pi^+\pi^-)$ signal model	5.3
$m(J/\psi\pi^+\pi^-)$ background model	4.3
Non-B_s^0 background	1.2
Simulated sample size	2.2
Total	7.7

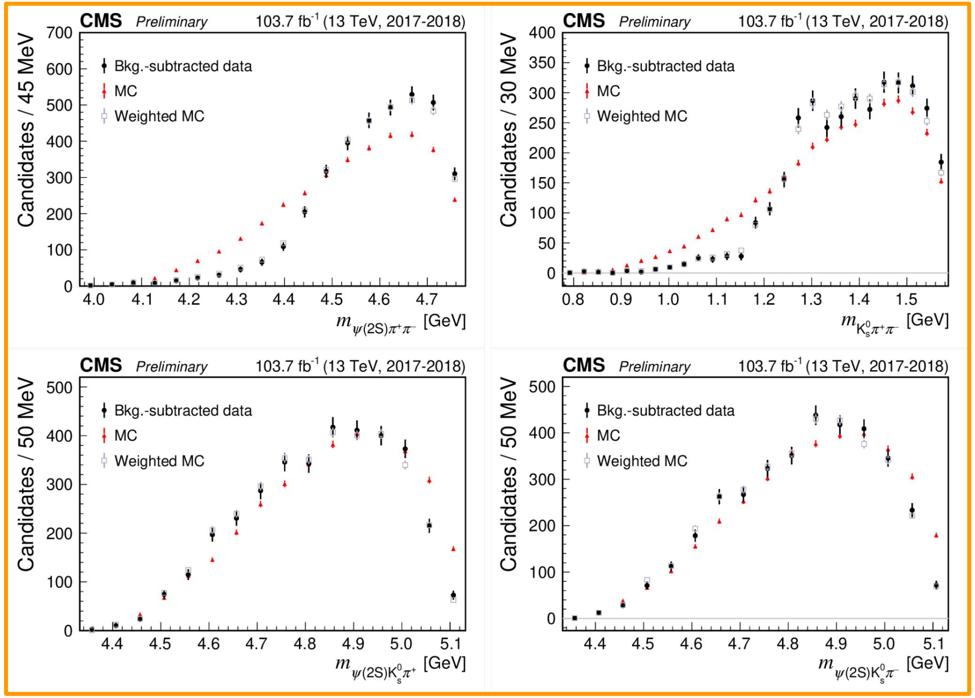
Evidence for χ_{c1}(3872) in PbPb collisions - Systematic Uncertainties

	$N(\psi(2S))$	$N(\chi_{c1}(3872))$	$N(\chi_{c1}(3872))/N(\psi(2S))$
Yield Extraction	4.6%	4.8%	8.0%
Acceptance	2.6%	0.7%	2.7%
Efficiency	27.1%	45.5%	40.3%
p_T Shape	12.4%	2.9%	12.8%
TnP	4.3%	4.0%	0.3%
Prompt Fraction	14.8%	7.9%	8.1%
Total	39.7%	48.1%	48.3%

arXiv:2102.13048

Observation of $B^0 \to \psi(2S)K_s^0\pi^+\pi^-$ and $B^0_s \to \psi(2S)K_s^0$ decays - Mass distributions of 2&3-body decays

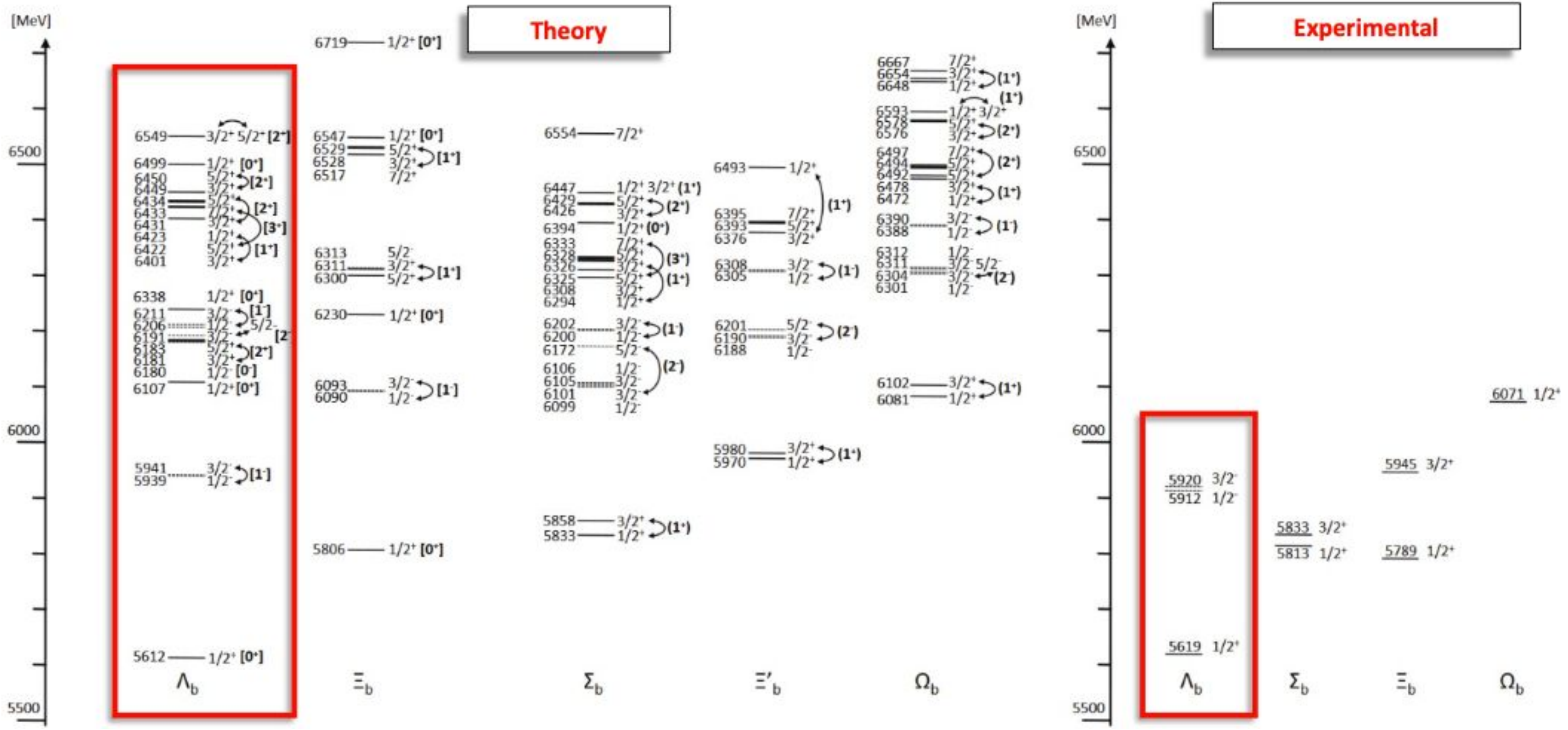




- ➔ 2-body & 3-body mass distributions obtained by sPlot bkg-subtraction technique.
- ➔ MC is reweighted to make it compatible with data.
- ➔ MC does not take into account the intermediate resonance structure.

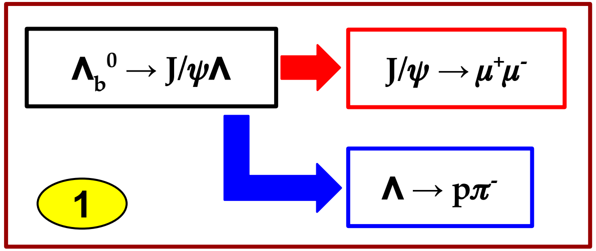
Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ - Introduction

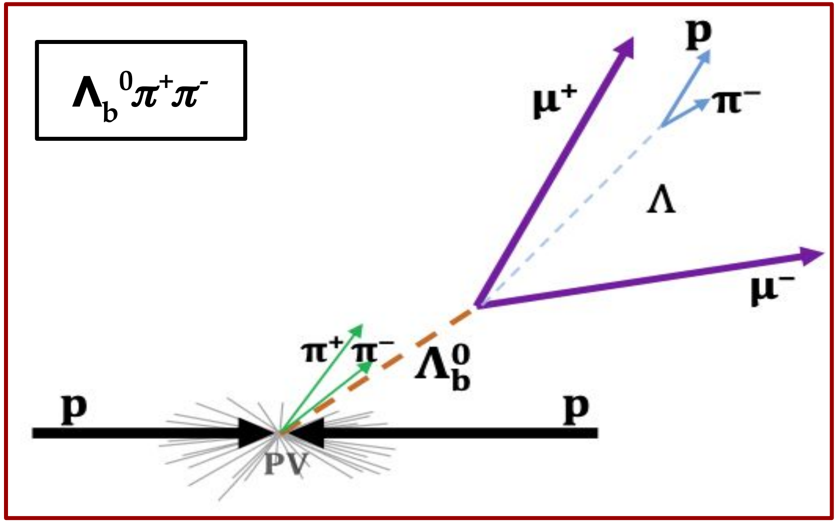
❖ The are many theoretical predictions of excited Λ_b and Σ_b states, but the predicted masses are spread in rather wide regions and do not point to any particular narrow window to search for a signal.

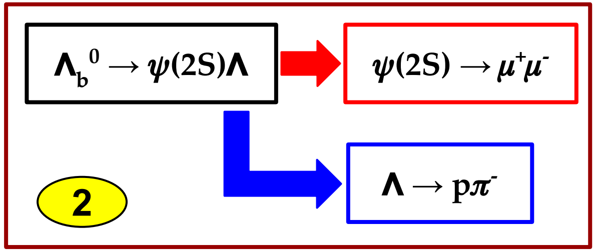


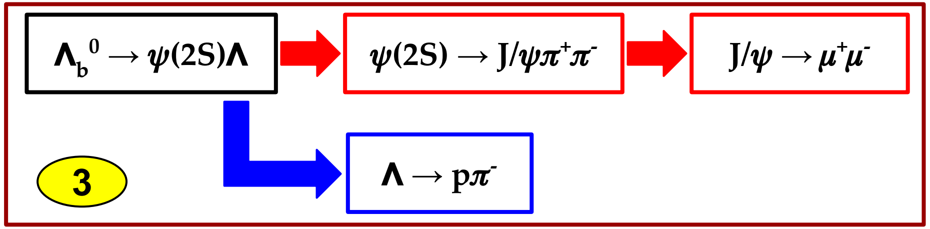
Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ - Topology at CMS

- In CMS, the $\Lambda_b^0 \to \Lambda_c^+\pi^-$ channel can not be used because there is no dedicated trigger and no hadron ID. Also $\Lambda_b^0 \to J/\psi p K^-$ is very difficult due to high background since no hadron ID.
- Therefore, to study the excited Λ_b states, CMS used $\Lambda_b^0 \to J/\psi\Lambda$ and $\Lambda_b^0 \to \psi(2S)\Lambda$ channels

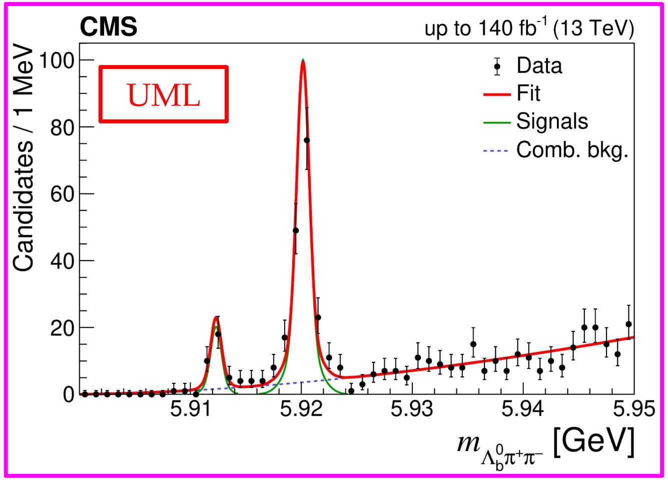


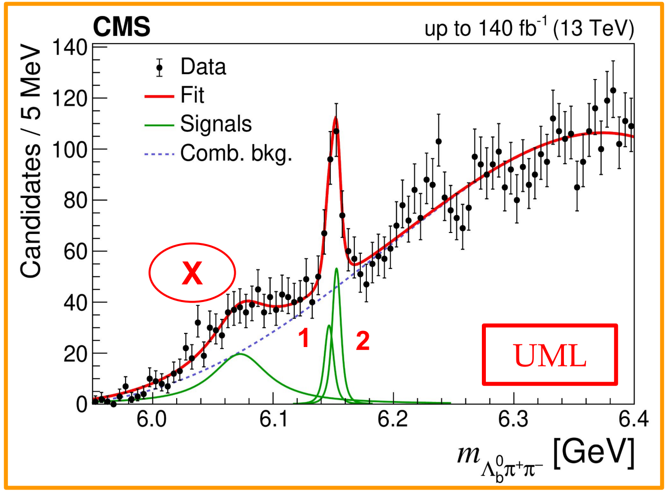






Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ - at CMS; 2016-2018 data, 13 TeV, ~140 fb^{-1}





Search has been performed in the mass window: $M(\Lambda_b^0\pi^+\pi^-) \in [5.90, 6.40]$ GeV

Low mass region

Signals: Double-Gaussian [for both signals]

Background: $(x - x_0)^\alpha$

Signal 1: confirmation of $\Lambda_b^0(5912)$ state [N = 28.4±5.8, 5.7σ]

Signal 2: confirmation of $\Lambda_b^0(5920)$ state [N = 159±14, 14.5σ]

$M[\Lambda_b^0(5912)] = [5912.32 \pm 0.12(stat) \pm 0.01(syst) \pm 0.17(m_{PDG})]$ MeV

$M[\Lambda_b^0(5920)] = [5920.16 \pm 0.07(stat) \pm 0.01(syst) \pm 0.17(m_{PDG})]$ MeV

PLB 803 (2020) 135345

High mass region

Signal 1: BW convoluted with Double-Gaussian [$\Lambda_b^0(6146)$]

Signal 2: BW convoluted with Double-Gaussian [$\Lambda_b^0(6152)$]

Signal X: BW convoluted with Double-Gaussian [excess]

Background: $(x - x_0)^\alpha \times 1^{st}$ order polynomial

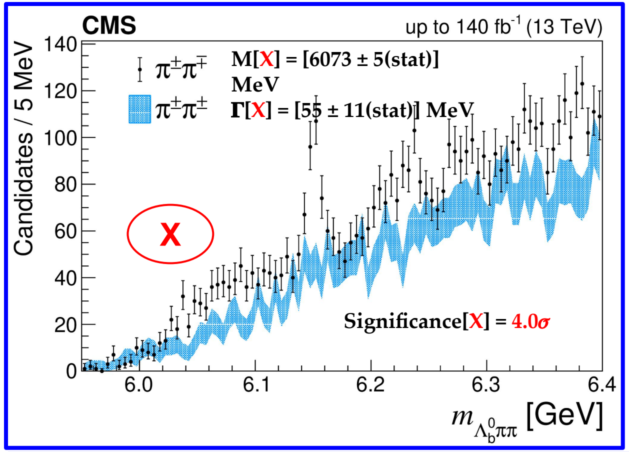
The first confirmation of $\Lambda_b^0(6146)$ and $\Lambda_b^0(6152)$ states

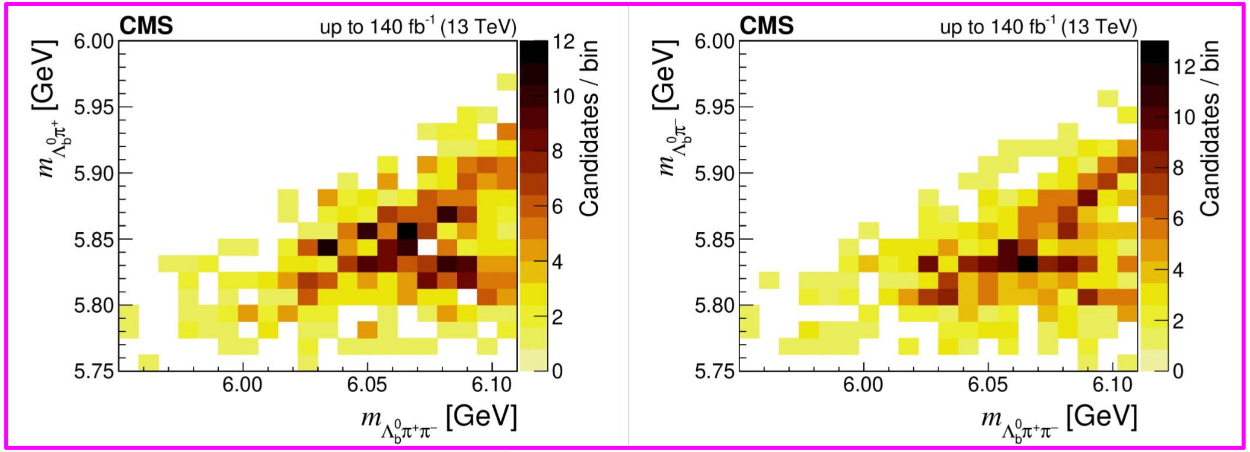
1 peak vs NO peak: 6.5σ ; 1 vs 2 peaks: 0.4σ

$M[\Lambda_b^0(6146)] = [6146.5 \pm 1.9(stat) \pm 0.8(syst) \pm 0.2(m_{PDG})]$ MeV

$M[\Lambda_b^0(6152)] = [6152.7 \pm 1.1(stat) \pm 0.4(syst) \pm 0.2(m_{PDG})]$ MeV

Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$ - an excess in [6.0, 6.1] GeV

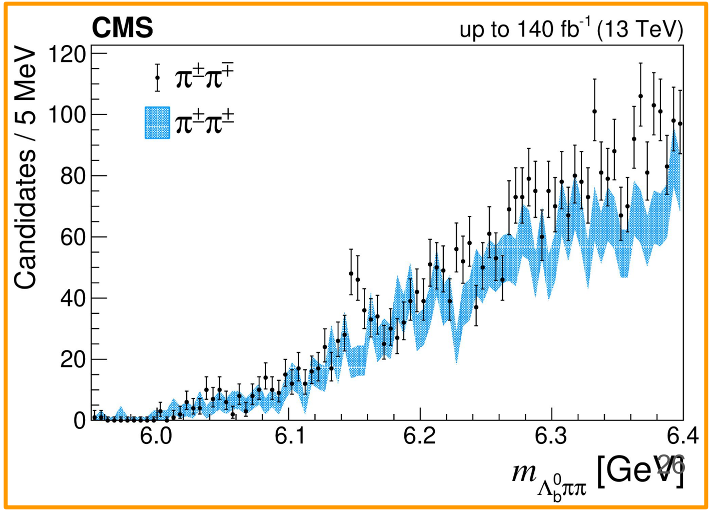




The excess below 6.1 GeV in the $\Lambda_b^0\pi^+\pi^-$ OS distribution is not seen in the SS distribution.

Looking 2D plots for [$\Lambda_b^0\pi^\pm$ vs $\Lambda_b^0\pi^\pm\pi^\mp$], it can be related to the intermediate Σ_b states decaying into $\Lambda_b^0\pi^\pm$.

If $\Sigma_b^{(*)\pm}$ are vetoed, the excess is disappear. The excess is then consistent with originating from a resonance in the $\Sigma_b^{(*)\pm}\pi^\mp$ system. But the intermediate Σ_b states cannot be tested with the current data.



Similar structure observed at LHCb, interpreting it as a further excited Λ_b^0[6072] state.
LHCb Collab, JHEP 06 (2020) 136

The search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ - Introduction

- Quarkonium pair production at LHC:
  - **Single-parton scattering** (SPS): dominant→strongly correlated→small |Δy|
  - **Double-parton scattering** (DPS): difficult to calculate→ less correlated→ large |Δy|

- Models for **tetraquark** bound states or generic resonances predicts that their **masses should be close** to **twice the Υ(1S) mass**.

- CMS performed a tetraquark $(bb\bar{b}\bar{b})$ search in $\Upsilon(1S)\mu^+\mu^-$ final states using 2016 data at $\sqrt{s}$ = 13 TeV corresponding to 35.9 fb^{-1}.

Base strategy:
- ➔ Searched a resonance in $\Upsilon(1S)\mu^+\mu^-$ final states where Υ(1S) decay to $\mu^+\mu^-$
- ➔ $p_T[\mu] > 2.5$ GeV, $P_{vtx}[4\mu] > 5\%$ and $M[\mu^+\mu^-] \in [M_{Y(1S)}-2\sigma, M_{Y(1S)}+2\sigma]$
- ➔ 4μ paired in Υ states and second $\mu^+\mu^-$ rejected if compatible with J/ψ.

Υ(1S)Υ(1S) mass distribution:
- ➔ m_{12}(top) and m_{34}(bottom) projections and the results of the 2D fit to the muon pair invariant masses.
- ➔ Each event is corrected for acceptance and efficiency using MC.
- ➔ Signal model: Double-Crystal Ball
- ➔ Background model: Gaussian for Υ(2S,3S) and 2nd order Chebychev polynomial for the combinatorics.

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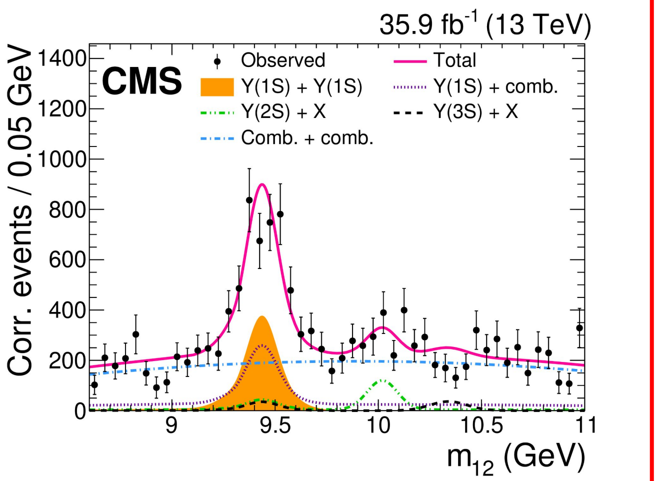
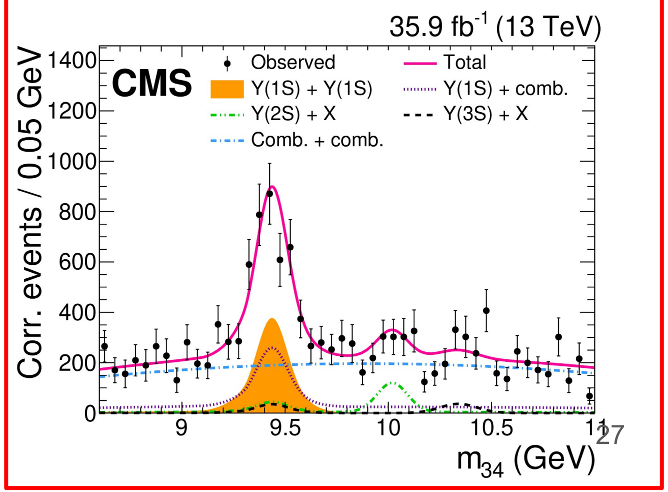
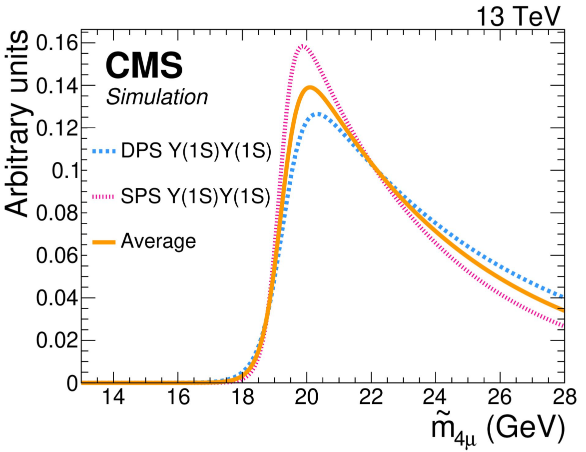




The search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ - Double Υ production as BKG source



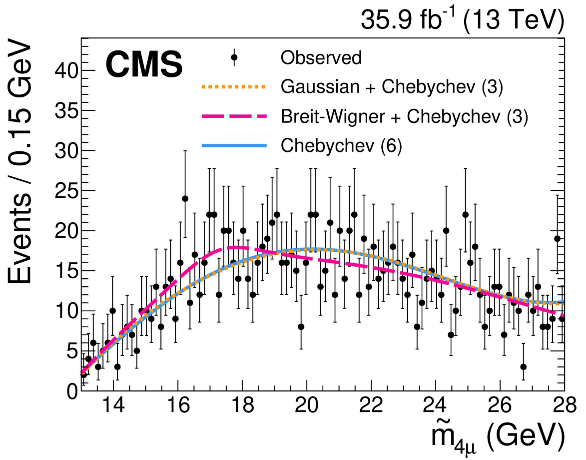
Mass difference:

PLB 808 (2020) 135578

$$\boxed{\tilde{m}_{4\mu} = m_{4\mu} - m_{\mu\mu} + m_{\Upsilon(1S)}}$$

has been used to improve the mass resolution (the improvement ~50%).

- ➔ $M[\mu^+\mu^-] \in [M_{Y(1S)}-2\sigma, M_{Y(1S)}+2\sigma]$: $N[\Upsilon\Upsilon] = 74 \pm 13$
- ➔ The shape of the $\Upsilon(1S)$ pair contribution in the $\Upsilon(1S)\mu^+\mu^-$ spectrum is estimated from MC: Sigmoid × falling exponential with f_{DPS}(DPS-to-inclusive fraction) from fiducial cross section measurement.



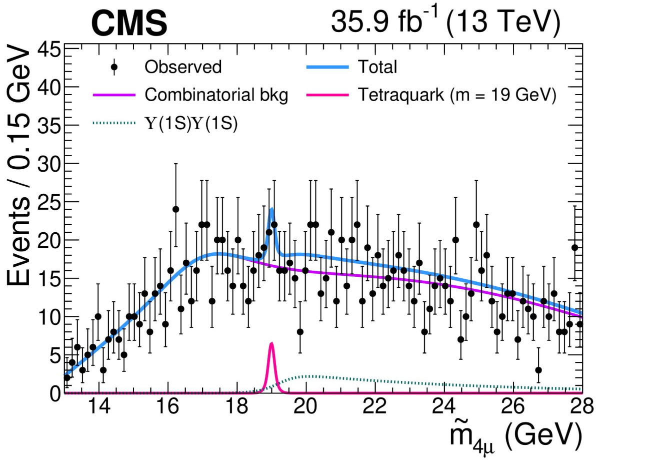
Background shape parameterization is defined using events with low 4μ vertex fit probability:

- ➔ $P_{vtx}[4\mu] \in [10^{-10}, 10^{-3}]$

Distribution of the combinatorial background has been fitted using different fit models:

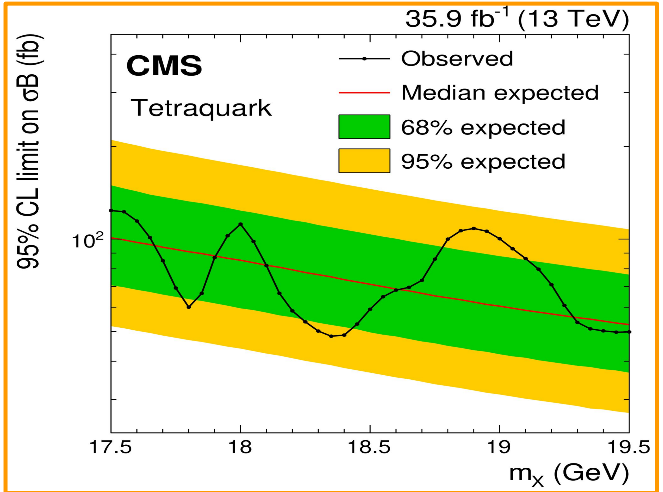
- ➔ Gaussian + 3rd order Chebychev polynomial
- ➔ Breit-Wigner + 3rd order Chebychev polynomial
- ➔ 6th order Chebychev polynomial

The search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ - An example signal at 19 GeV & Upper Limit



An example signal for the tetraquark model with a mass of 19 GeV is fitted:

- ➔ Signal model: Double-Gaussian
- ➔ $\Upsilon(1S)$ pair production is a background to the resonance search
- ➔ Significance: ~1σ

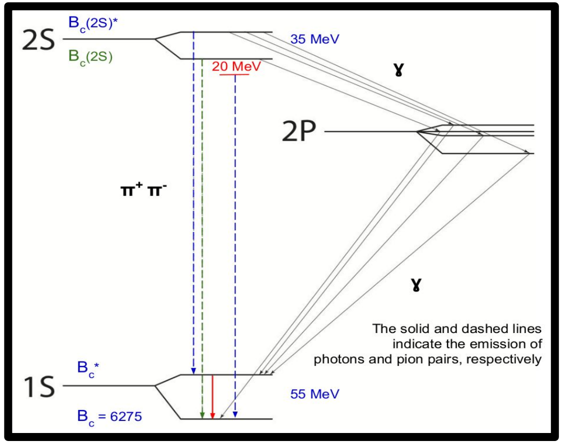


- ➔ The fiducial cross section for $\Upsilon(1S)$ pair where $|y[\Upsilon(1S)]| < 2.0$ at $\sqrt{s} = 13$ TeV is measured at CMS with 35.9 fb^{-1} data.
- ➔ Observed upper limit at 95% CL is set on the production cross section and branching fraction: $\sigma_{pp\to X}\times B[X\to\Upsilon(1S)\mu^+\mu^-\to 4\mu]$
- ➔ No significant excess is observed near $\Upsilon(1S)\Upsilon(1S)$ mass in [17.5, 19.5] GeV.
- ➔ Upper Limits are also set for scalar, pseudoscalar and spin-2 states. More details: PLB 808 (2020) 135578 & Backup

$B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios - Introduction & Topology

Particle	B_c	B_c^*	$B_c(2S)$	$B_c(2S)^*$
Predicted M(MEV)	6247-6286	6308-6341	6835-6882	6881-6914

PRD 49 (1994) 5845, PRD51 (1995) 3613, PRD 52 (1995) 5229, PRD 53 (1996) 312, PLB 382 (1996) 131, PRD 160 (1999) 074006, PRD 67 (2003) 014027, PRD 70 (2004) 054017, PRL 104 (2010) 022001, PRD 86 (2012) 094510, PRL121 (2018) 202002



⇒ 2019: Observation of two excited B_c^+ states and measurement of $B_c^+(2S)$ mass in pp collisions at √s = 13 TeV [CMS, PRL 122 (2019) 132001]

⇒ 2020: Measurement of $B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios in proton-proton collisions at √s = 13 TeV [CMS, PRD 102 (2020) 092007]

Properties of spectrum

The $B_c(2S)$ decays directly to the B_c ground state : $B_c(2S) \to B_c\pi^+\pi^-$

The $B_c(2S)^*$ decays to B_c^* state through two pions emission followed by a radiative decay of B_c^* to the B_c ground state with the emission of a soft photon (around 55 MeV in rest frame):

$B_c^*(2S) \to B_c^*\pi^+\pi^-$ → $B_c^* \to B_c\gamma$

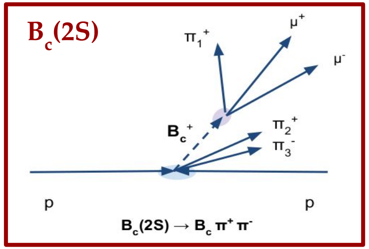
Having the emitted photon a very low energy, its detection is very challenging, and typically it is lost. Thus:

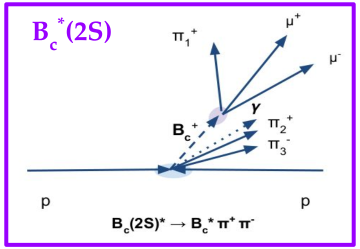
$B_c(2S) \to B_c\pi^+\pi^- + \text{"Missing Energy"}$

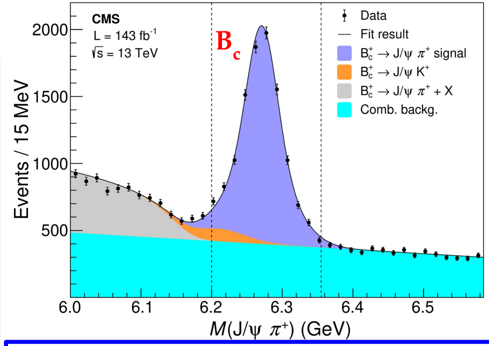
The $B_c(2S)^*$ peak should appear into $B_c\pi^+\pi^-$ mass spectrum at the mass $M(B_c(2S)) - \Delta M$

where $\Delta M = [M(B_c^*(1S)) - M(B_c(1S))] - [M(B_c^*(2S)) - M(B_c(2S))]$

which is predicted positive (ΔM~20 MeV) so that the $B_c(2S)^*$ peak will be at lower masses than the $B_c(2S)$ peak



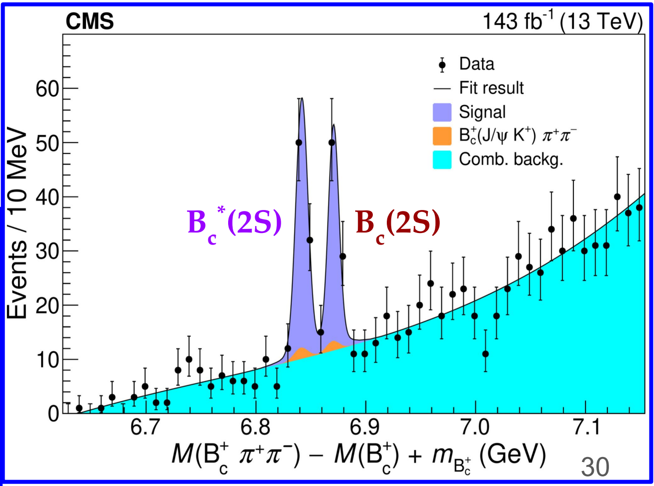




Two peak structure, well resolved:
ΔM = [29.1 ± 1.5(stat) ± 0.7(syst)] MeV

Mass of $B_c(2S)$ measured to be:
$M[B_c(2S)]$ = [6871 ± 1.2(stat) ± 0.8(syst) ± 0.8(B_c)] MeV

CMS, PRL 122 (2019) 132001



$B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios - Efficiencies & Ratio of the cross sections

- **Reconstruction efficiency:** the number of reconstructed $B_c(2S) \rightarrow B_c\pi^+\pi^-$ events after the full selection divided by the number of generated $B_c(2S) \rightarrow B_c\pi^+\pi^-$ decays in the fiducial region that $|y(B_c)| < 2.4$ and $p_T(B_c) > 15$ GeV.

$$\epsilon_{B_c(2S)^+} = \frac{N^{rec}_{B_c(2S)^+ \rightarrow B_c^+ \pi^+ \pi^-}}{N^{gen}_{B_c(2S)^+ \rightarrow B_c^+ \pi^+ \pi^-}}$$

- The **ratio R** of the $B_c(2S)^\pm$ production cross-section times the branching fraction of $B_c(2S)^\pm \rightarrow B_c^\pm\pi^+\pi^-$ diveded by the production cross-section of the $B_c^\pm$ state is then measured as:

$$\mathcal{R} = \frac{\sigma_{B_c(2S)^{(*)+}}}{\sigma_{B_c^+}} \times \mathcal{B}(B_c(2S)^{(*)+} \rightarrow B_c^+ \pi^+ \pi^-) = \frac{N_{B_c(2S)^{(*)+}}}{N_{B_c^+}} \frac{\epsilon_{B_c^+}}{\epsilon_{B_c(2S)^{(*)+}}}$$

$R[B_c(2S)^+] = [3.47 \pm 0.63(\text{stat}) \pm 0.33(\text{syst})]\%$

$R[B_c(2S)^{*+}] = [4.69 \pm 0.71(\text{stat}) \pm 0.56(\text{syst})]\%$

$R[B_c(2S)^{*+}/B_c(2S)^+] = [1.35 \pm 0.32(\text{stat}) \pm 0.09(\text{syst})]\%$

CMS, PRD 102 (2020) 092007

The new analysis on B_c meson production in HI collisions also can be find here: CMS-PAS-HIN-20-004