X(3872) production in pp & PbPb
&
Heavy Flavour spectroscopy with CMS

Heavy Flavour Hadronization in pp & HI Collisions at the LHC

Workshop @ CERN (2-3 March 2020)

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Outline

Production of $X(3872)$ in pp & PbPb collisions

- $X(3872)$: production Xsection measurement in pp collisions — **JHEP 04 (2013) 154**
- $X(3872)$: first evidence in PbPb collisions — **CMS PAS HIN-19-005** NEW!

New results in Heavy Flavour spectroscopy

- (udb) spectroscopy : study of excited Λ_b^0 baryons in the $\Lambda_b^0\,\pi^+\,\pi^-$ spectrum — **arXiv:2001.06533 accepted by PLB** NEW!
- $(\mathrm{c}\bar{b})$ spectroscopy : observation of $B_c^+(2S)$ & $B_c^{*+}(2S)$ in the $B_c\,\pi^+\,\pi^-$ spectrum — **PRL 122 (2018) 132001**
- Search for narrow resonances with mass between $16.5\text{-}27\,\mathrm{GeV}$ decaying into $\Upsilon(1S)\,\mu^+\mu^-$ — **arXiv:2002.06393 submitted to PLB** NEW!

Production features of $X(3872)$ in pp collisions

JHEP 04 (2013) 154

$\sqrt{s} = 7TeV$

(Run-I/2011)

$\mathcal{L} = 4.8fb^{-1}$

X(3872) @ LHC

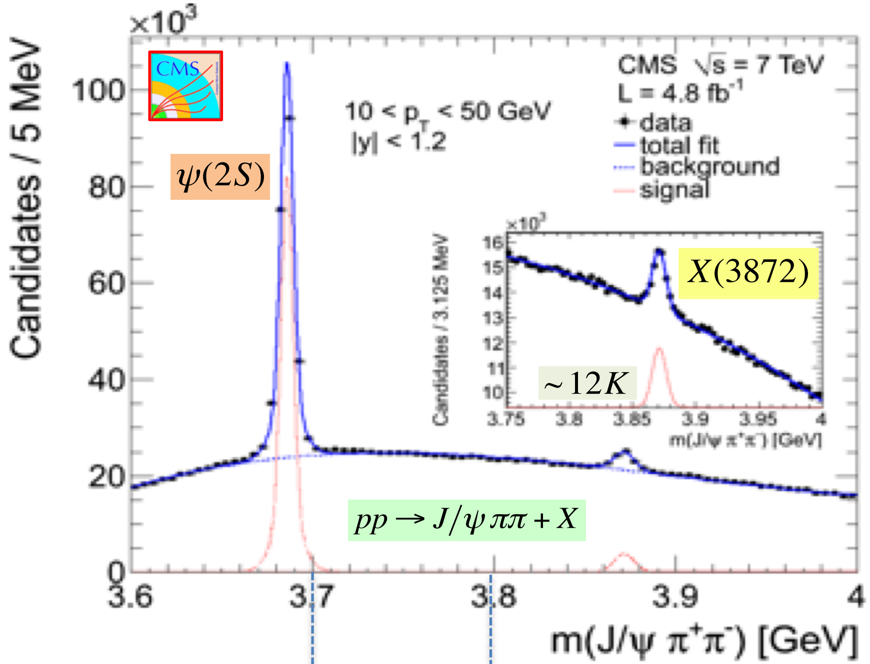
- **First exotic state discovered by** Belle **in the decays** $B^{+} \to K^{+}X(3872) \to K^{+}(J/\psi\,\pi\pi)$ **and confirmed by** CDF **with inclusive** $p\overline{p}$ **collisions (**mainly prompt production: only ~16% from *B* mesons**).**

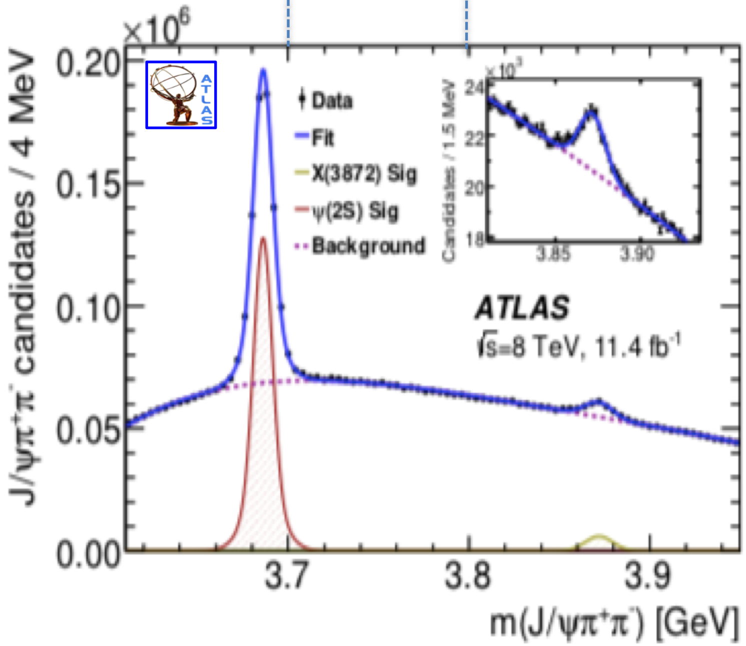
- **As soon as LHC started, quickly confirmed by** CMS **&** LHCb **, either inclusively and exclusively (**B decays**) and later by** ATLAS**.**

- CMS **inclusively reconstructed the *X(3872)* in the** $J/\psi\,\pi\pi$ **final state & studied (with** $7\ TeV$ **data) :**
  - **Xsection ratio** w.r.t $\psi(2S)$
  - **non-prompt component** *vs* p_T
  - **prompt X(3872) prod. xsection**
  - **inv. mass distrib. of the** $\pi^{+}\pi^{-}$ **system**

  next slides

- ATLAS **performed similar studies most recently (with** $8\ TeV$ **data)** **[JHEP 01 (2017) 117]**

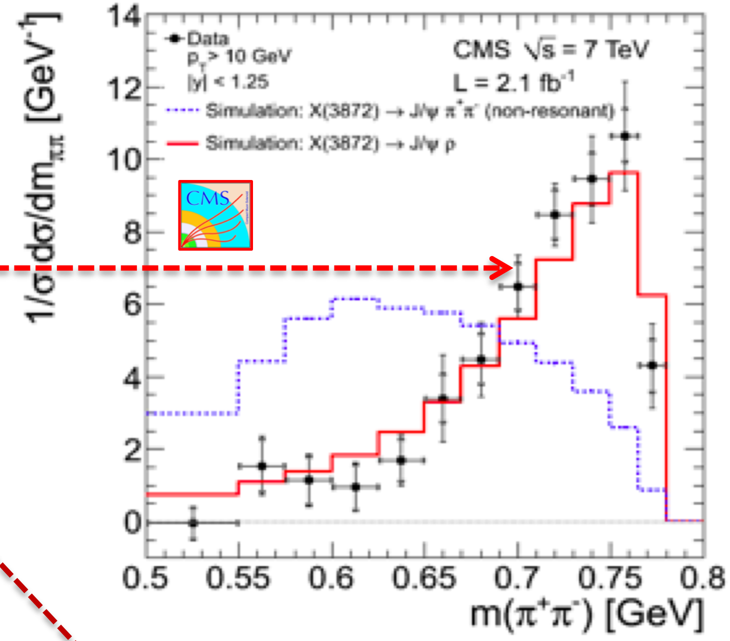




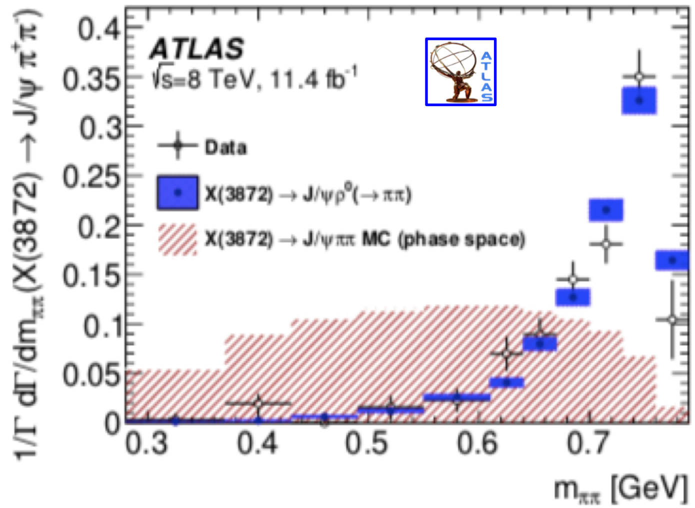
X(3872) @ CMS : $\pi^+\pi^-$ mass spectrum

- **Invariant mass distribution of the $\pi^+\pi^-$ system :**

The data spectrum compared to simulations w/ & w/o an intermediate ρ^0 in the decay shows much better agreement when assuming it (as for Belle & CDF)



- In the simulations $J_X^{PC} = 1^{++}$ is assumed.



Assumption is based on the unambiguous determination of the quantum numbers performed by LHCb **[PRL 110 (2013) 222001]**
by means of a **full angular analysis** of the decay chain $B^+ \to XK^+,\ X \to J/\psi\,\rho^0,\ J/\psi \to \mu\mu,\ \rho^0 \to \pi\pi$

Confirmed later by LHCb **[PRD 92 (2015) 011102]**
under general conditions **[w/o assumption on lowest possible *L* in the *X* sub-decay]**

X(3872) @ CMS : Xsection x BF ratio [w.r.t. $\psi(2S)$]

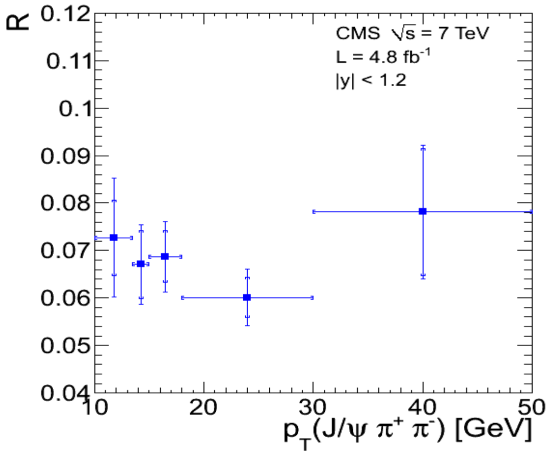
- A ratio of the cross sections has been measured to cancel out many systematic sources:

$$R \equiv \frac{\sigma\left(pp \to X(3872) + \text{anything}\right) \cdot B\left(X(3872) \to J/\psi\, \pi^+\pi^-\right)}{\sigma\left(pp \to \psi(2S) + \text{anything}\right) \cdot B\left(\psi(2S) \to J/\psi\, \pi^+\pi^-\right)} = \frac{N_{X(3872)} \cdot A_{\psi(2S)} \cdot \varepsilon_{\psi(2S)}}{N_{\psi(2S)} \cdot A_{X(3872)} \cdot \varepsilon_{X(3872)}}$$

YIELDS from fits to data

ACCEPTANCES & EFFICIENCIES from SIMULATION (and cross-checks on data)

Acceptance estimated assuming X(3872) & $\psi(2S)$ unpolarized and $J_X^{PC} = 1^{++}$



- integrating over $10 < p_T < 50 GeV$:

$$R \cong 0.0656 \pm 0.0029(stat) \pm 0.0065(syst)$$

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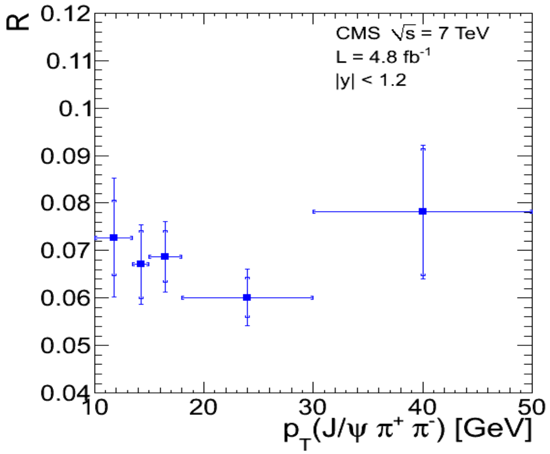


- integrating over $10 < p_T < 50 GeV$:

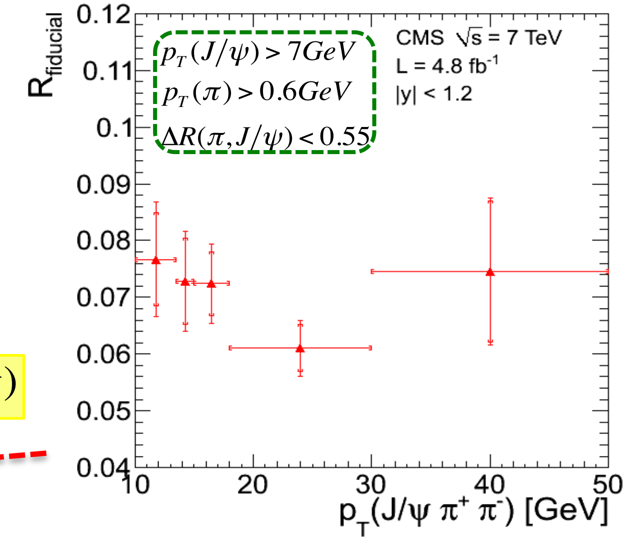
$R \cong 0.0656 \pm 0.0029(stat) \pm 0.0065(syst)$

- Acceptance corrections depend on assumptions on the angular distribution of the final states (production mechanism of the X(3872) is unknown) ⇒ a result without them in a fiducial region is given :

$$R_{fiducial} \equiv \frac{N_{X(3872)}}{N_{\psi(2S)}} \cdot \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{X(3872)}}$$

- integrating over $10 < p_T < 50 GeV$:

$R_{fiducial} \cong 0.0694 \pm 0.0029(stat) \pm 0.0036(syst)$



NO significant dependence on the p_T

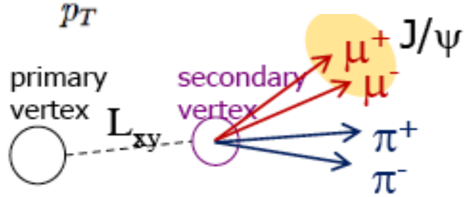
X(3872) @ CMS: non-prompt fraction

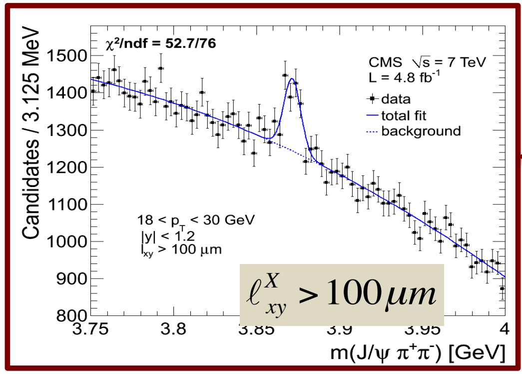
- **The *X(3872)* can be produced from B hadrons' decays into a secondary vertex :**
  prompt & non-prompt components can be separated by <u>pseudo-proper decay length</u>

X(3872) from B decays selected requiring: $\ell_{xy}^{X} > 100\,\mu m$

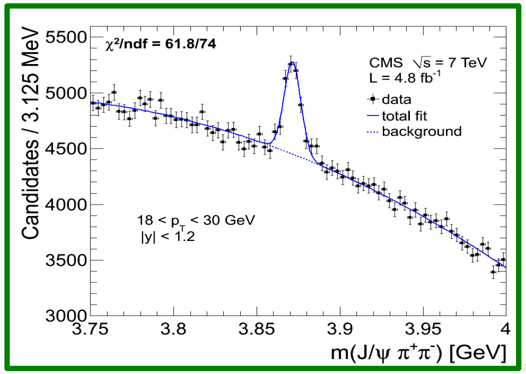
… for which prompt-fraction is negligible (<0.1%) [MC]

$$\ell_{xy}^{X(3872)} = \frac{L_{xy}^{X(3872)} \cdot m_{X(3872)}}{p_T}$$





$$\text{nonprompt fraction} = \frac{\text{Nr. of } X(3872) \text{ from B}}{\text{Nr. of } X(3872)}$$



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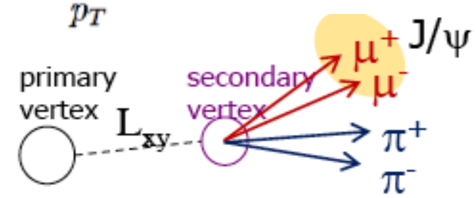

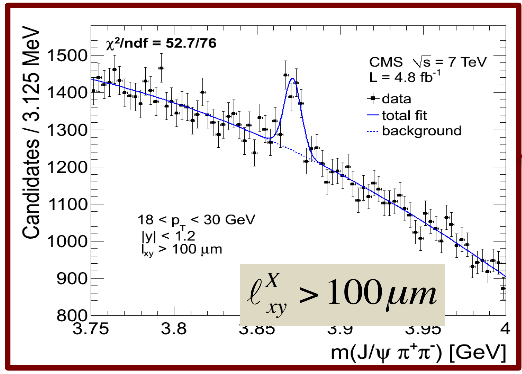

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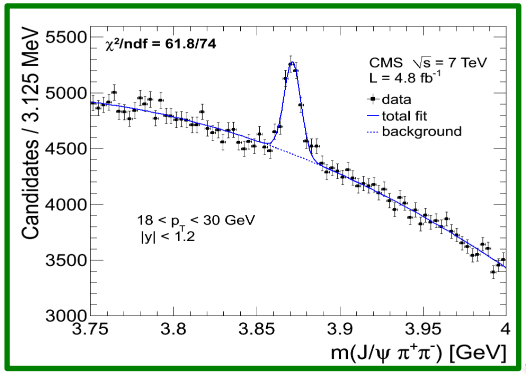
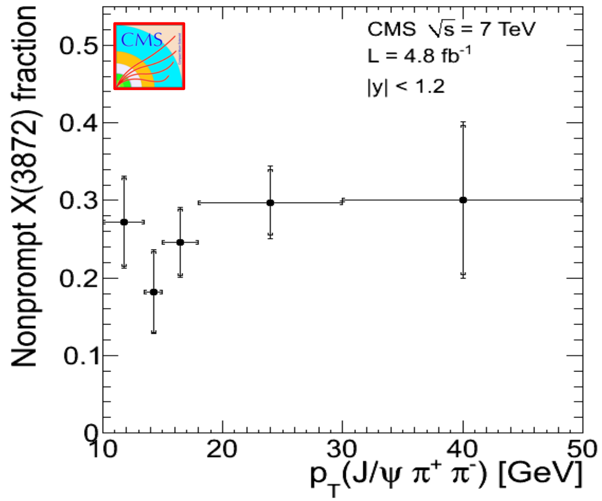


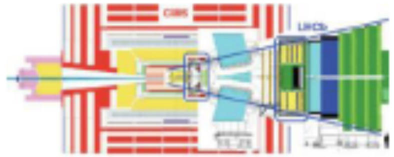
- **non-prompt fraction : NO dependence on p_T**
- integrating over $10 < p_T < 50 GeV$ (for $|y| < 1.2$): $f_{NP} \cong 0.263 \pm 0.023 \pm 0.016$

  … significantly smaller than that for the ψ(2S) (increasing with p_T)
  (measured again and in agreement with [CMS, JHEP02 (2012) 011])



- behaviour confirmed later by ATLAS

- Exploiting the previous measurements, the ***prompt production xsection*** for the *X(3872)* is measured as a function of p_T @ central rapidities (complementary to LHCb):



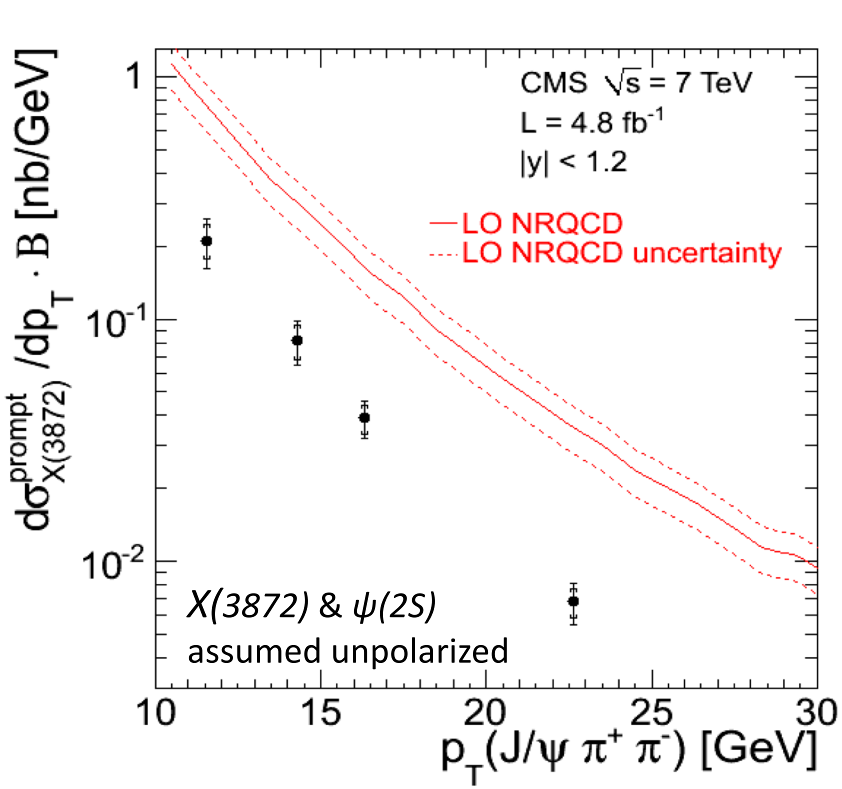
$$\sigma^{\text{prompt}}_{X(3872)} \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{1 - f^B_{X(3872)}}{1 - f^B_{\psi(2S)}} \cdot R \cdot \left(\sigma^{\text{prompt}}_{\psi(2S)} \cdot \mathcal{B}(\psi(2S) \to \mu^+\mu^-)\right) \cdot \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$$

non-prompt fraction

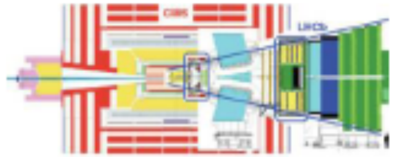
Cross sections ratio

measured by CMS in JHEP02 (2012) 011

from PDG



X(3872) @ CMS : prompt production Xsection - I



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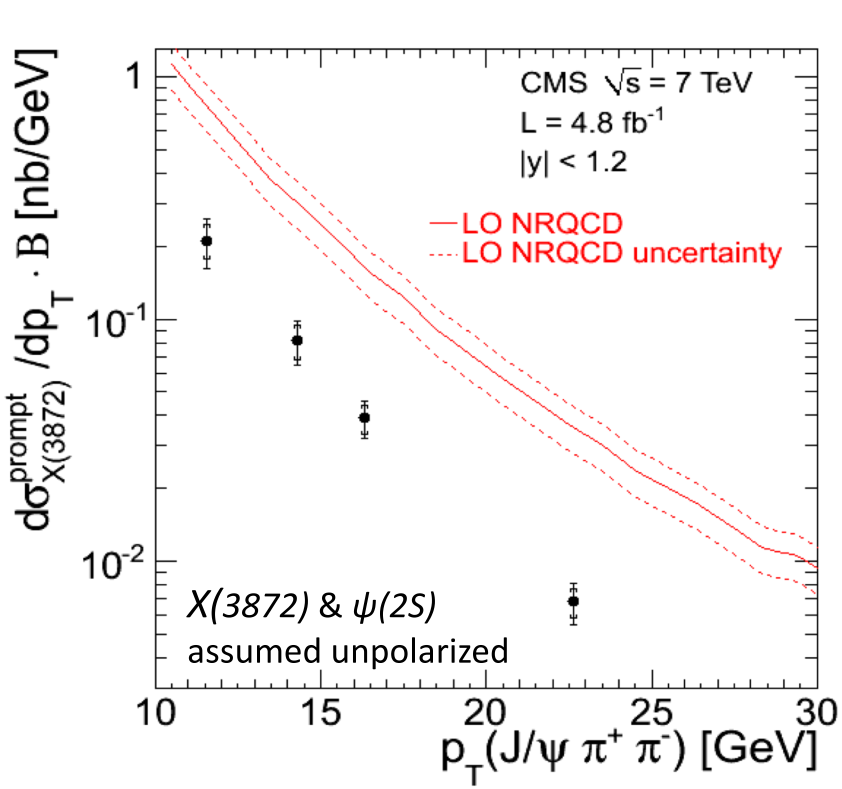


- Results are compared with a theoretical prediction based on NRQCD factorization @ LO approach by Artoisenet & Brateen [PhysRevD.81.114018] with calculations normalized using Tevatron results, modified by the authors to match CMS phase-space
- The shape is reasonably well described by the theory while the predicted cross section is overestimated by over 3σ ![the same happens with LHCb data @ low p_T]
- Integrating over p_T (10-30*GeV*) [and *|y|<1.2*] get the integrated cross section times the branching fraction:

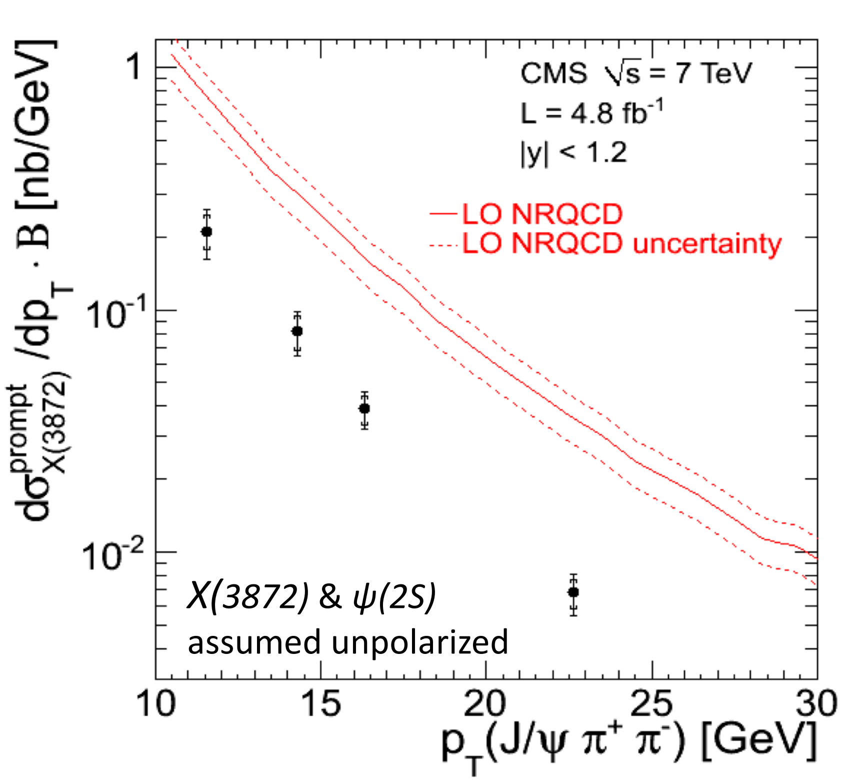
$$\sigma^{prompt}_{X(3872)} \times B\left(X(3872)\to J/\psi\ \pi^+\pi^-\right) \cong (1.06\pm0.11\pm0.15)nb$$

X(3872) @ CMS : prompt production Xsection - II

- Exploiting the previous measurements, the ***prompt production xsection*** for the *X(3872)* is measured as a function of p_T @ central rapidities (complementary to LHCb):

$$\sigma^{\text{prompt}}_{X(3872)} \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{1 - f^B_{X(3872)}}{1 - f^B_{\psi(2S)}} \cdot R \cdot \left(\sigma^{\text{prompt}}_{\psi(2S)} \cdot \mathcal{B}(\psi(2S) \to \mu^+\mu^-)\right) \cdot \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$$

non-prompt fraction | Cross sections ratio | measured by CMS in JHEP02 (2012) 011 | from PDG



Predictions by Artoisenet & Brateen assume, within an S-wave molecular model, the relative momentum of the mesons being bound by an upper limit of 400*MeV* which is quite high for a loosely bound molecule, but they assume it is possible as a result of rescattering effects.

On the other hand, one order of magnitude lower upper limit would imply lower prompt production rates of few orders of magnitude [Bignamini et al., PRL 103 (2009) 162001]

X(3872) : experimental results & interpretations

- **One crucial aspect is the possibility to discriminate experimentally between …**
  compact multiquark configuration ($c\bar{c}u\bar{u}$) & loosely bound hadronic molecule (by proximity to $D\bar{D}^{0*}$ threshold)

[conventional charmonium ($\chi_{c1}(2P)$ for $J^{PC}=1^{++}$) has been ruled out by mass value & the fact should be a pure isoscalar state]

- ***X(3872)* would be a large and fragile molecule with a miniscule binding energy (~100 *KeV*)**

$$E_{binding}^{X(3872)} \cong m(D^0 D^{*0}) - m(X) = 2m(D^0) + \Delta m(D^{*0} - D^0) - m(X) = (0.09 \pm 0.28) MeV$$

… that leads to a radius of ~*10 fm* (~5 times as large as the deuteron) !

- **The previous CMS measurement is not supporting an S-wave molecular interpretation**
- **Pure molecular model** (Swanson *et al.*) **not supported by the LHCb measurement of the radiative $X(3872) \to \psi(2S)\gamma$ sub-decay in the $B^+ \to X(3872)K^+$ decays**
- **Significant *L* would hint a molecular structure; however …**
  ***D*-wave fraction in $X(3872) \to J/\psi\ \rho^0$, for $J^{PC}=1^{++}$, results to be consistent with 0 [LHCb PRD 92 (2015) 011102]**

-

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- Alternatively to the compact tetraquark option, a possible interpretation for the $X(3872)$ is a **mixture of a charmonium state $\chi_{c1}(2\,^3P_1)$ & an S-wave molecule $\bar{D}^0 D^{*0}$.**

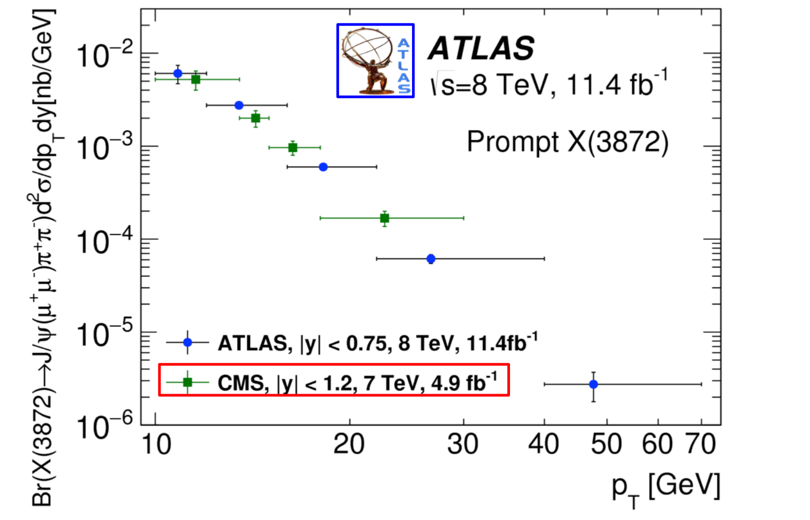
- **Results on $X(3872)$ production from ATLAS** have been compared with the latter model (next slide)

Comparison with a mixed molecule-charmonium state

- **Comparison of ATLAS with CMS results shows consistency.**

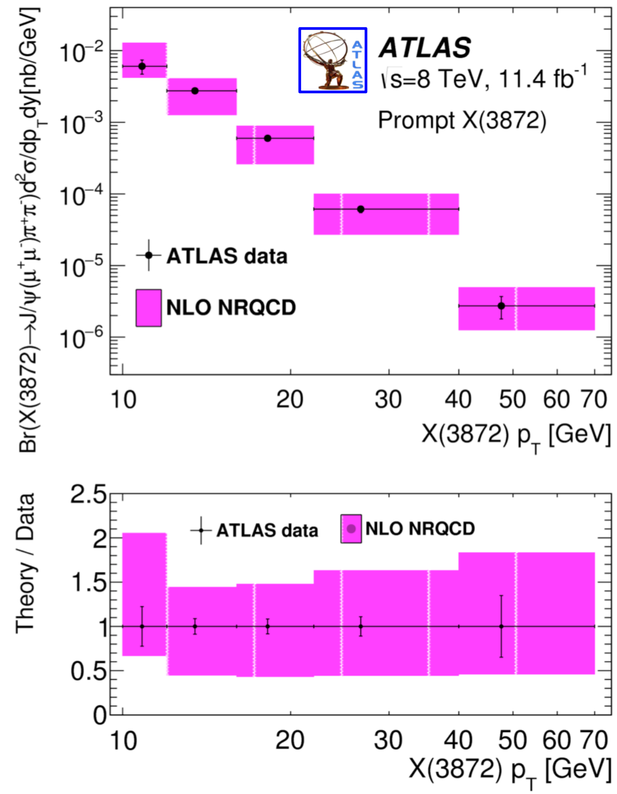
Beware that:

- ATLAS points positioned @ the mean p_T of the weighted signal events
- CMS points positioned @ the mean p_T of the theoretical predictions



- **Measured prompt production xsection (times BFs), as a function of p_T, is compared to NLO NRQCD predictions assuming the $X(3872)$ modelled as a mixture of $\chi_{c1}(2P)$ & a $\bar{D}^0 D^{*0}$ molecular state** by Meng *et al.* [PRD96 (2017) 074014].

The first would play crucial role in the short-distance production, while the second would be mainly in charge of the hadronic decays of $X(3872)$ into $DD\pi$, $DD\gamma$ as well as $J/\psi\,\rho$, $J/\psi\,\omega$.



First evidence of $X(3872)$ in PbPb collisions

CMS PAS HIN-19-005

(for QM2019)

$\sqrt{s_{NN}} = 5.02 TeV$

(c.o.m. energy per nucleon pair)

$\mathcal{L} = 1.7 nb^{-1}$

(End of Run-II / 2018)

Can we learn more about X(3872) nature using HI collisions? - I

In relativistic HI collisions the formation of the QGP (an extended volume of deconfined quarks & gluons**) could enhance the production of the X(3872) state [*] through the quark coalescence mechanism**

- Since this mechanism is based on the overlap of the Wigner functions of the quarks, the level of the X(3872) enhancement in QGP could depend on the spatial configuration (size) of this exotic state.

- The longer distance between (anti-)quarks could also lead to higher X(3872) dissociation rate similar to the mechanism of quarkonia suppression in HI collisions **[**]**

Its much larger size makes the molecule easier to be produced & destroyed than tetraquark

[*] S.Cho *et al.* (ExHIC Collab.)**, PRL 106 (2011)** 212001**, PRC84 (2011)** 064910; **A.Martinez Torres** *et al.***, PRD 90 (2014)** 114023

[**] T. Matsui *and* **H. Satz, PLB 178 (1986) 4**16

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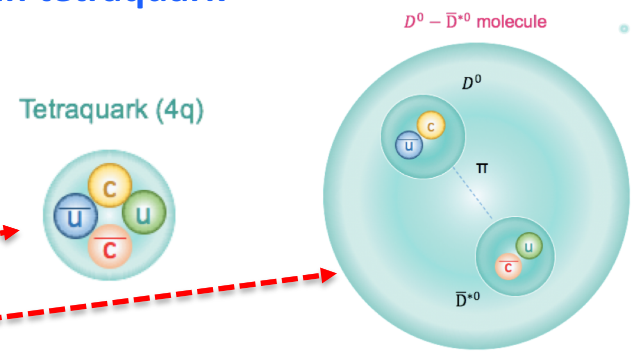
The study of X(3872) production rate in HI collisions, with reference to a standard charmonium ($\psi(2S)$), may be used to separate a compact tetraquark configuration (radius $\lesssim$ *1fm*) from a large-sized configuration of a molecular state (radius ~*10fm*), where the latter could lead to a significantly larger enhancement of the prompt production rate.



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Can we learn more about X(3872) nature using HI collisions? - II

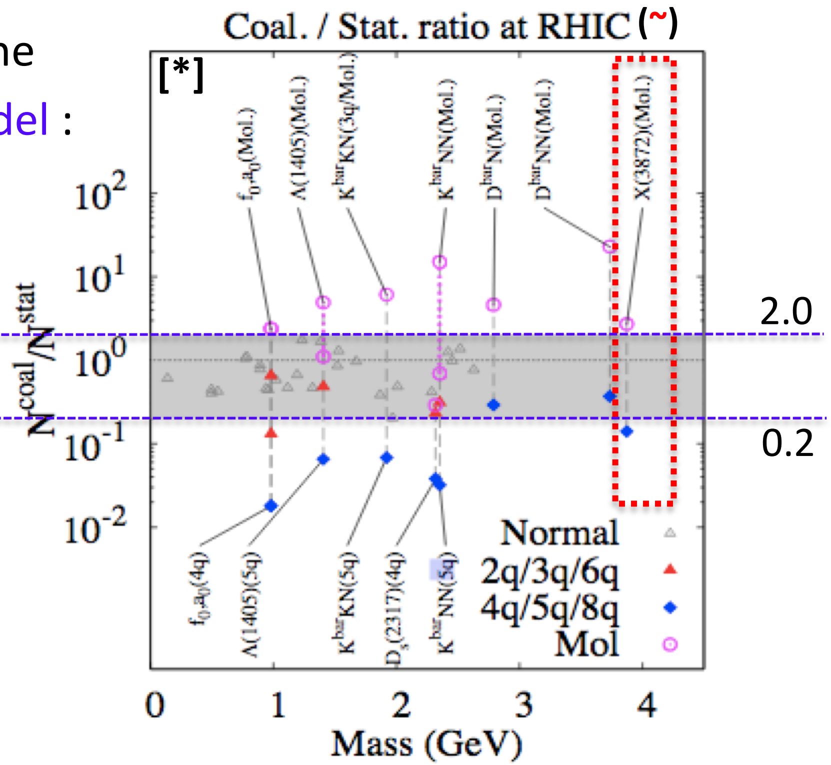
Moreover …

the measurements of inclusive prompt X(3872) could also provide a new test on the statistical hadronization model [*], that assumes the produced matter being in thermodynamical equilibrium
[the model is known to describe the yields of hadrons in HI collisions very well]

- Relevant parameter is the ratio of hadron yields calculated in the coalescence model to those in the statistical hadronization model :

$$\frac{N_{COAL}}{N_{STAT}}$$

Range of ratios for normal hadrons (2quarks/3quarks) & for crypto-exotic hadrons with usual 2q/3q configs



The yield of a hadron in relativistic HI collisions reflects its structure !

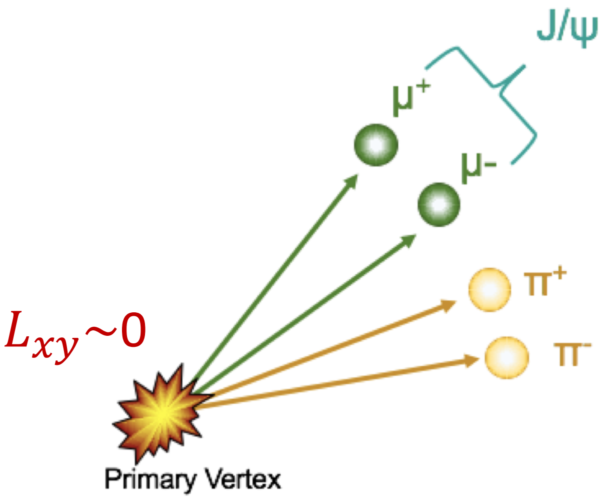
[*] A.Andronic *et al.*, NPA 772 (2006) 167-199

(~) Note: Also holds for LHC: freezout conditions similar to those @RHIC

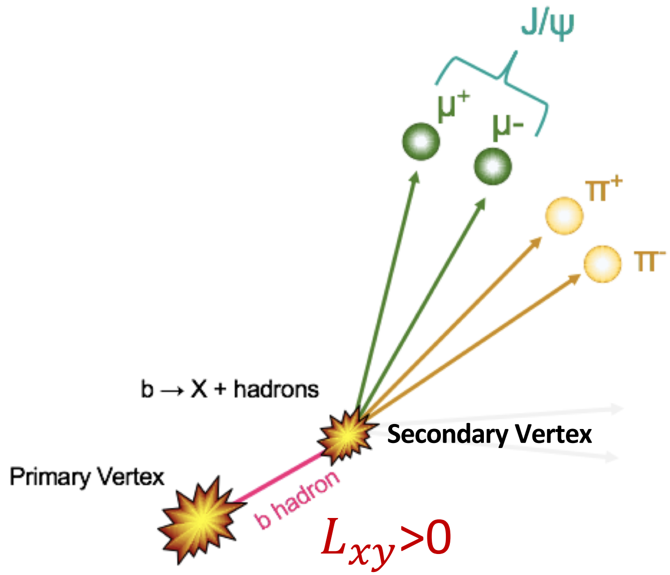
Reconstruction of prompt & non-prompt X(3872) & ψ(2S) - I

- **Reconstruction through same decay chain :** $X(3872), \psi(2S) \rightarrow \underbrace{J/\psi}_{\hookrightarrow \mu^+ \mu^-} \pi^+\pi^-$ **Vertex & kinematic fit**

J/ψ mass constraint



PROMPT component



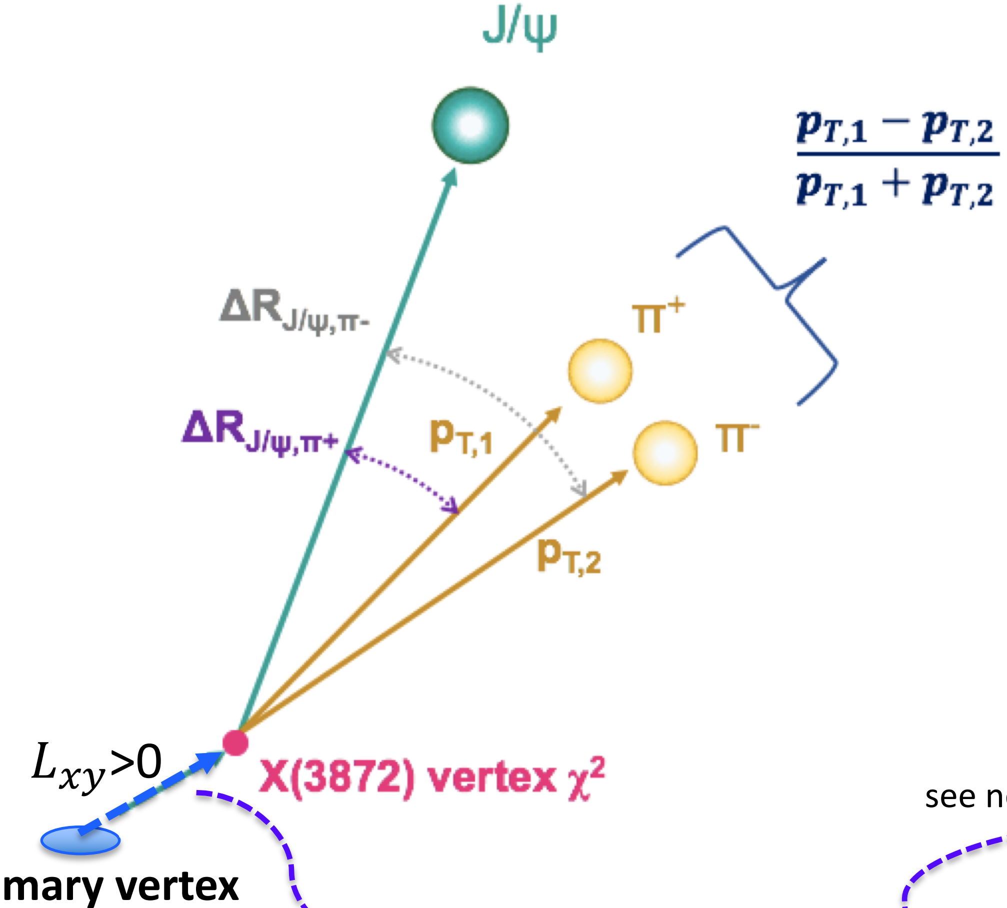
NON-PROMPT component from b-hadrons

- **Produced outside of the QGP**, it is related to the medium modification b-hadron production in HI collisions (such as beauty quark energy loss & modification of b-jet fragmentation)

A BDT algorithm is used to suppress the large combinatorial background :

5 input variables :

1) χ^2 of the 4-tracks' vertex
2) p_T balance of the pions : $\dfrac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$
3) p_{T2} of the slow pion
4) opening angle between J/ψ & p_{T1}
5) opening angle between J/ψ & p_{T2}



see next slide

Flight-length projected into the transverse plane allows to disentangle PROMPT & NON_PROMPT components

Reconstruction of prompt & non-prompt X(3872) & ψ(2S) - III

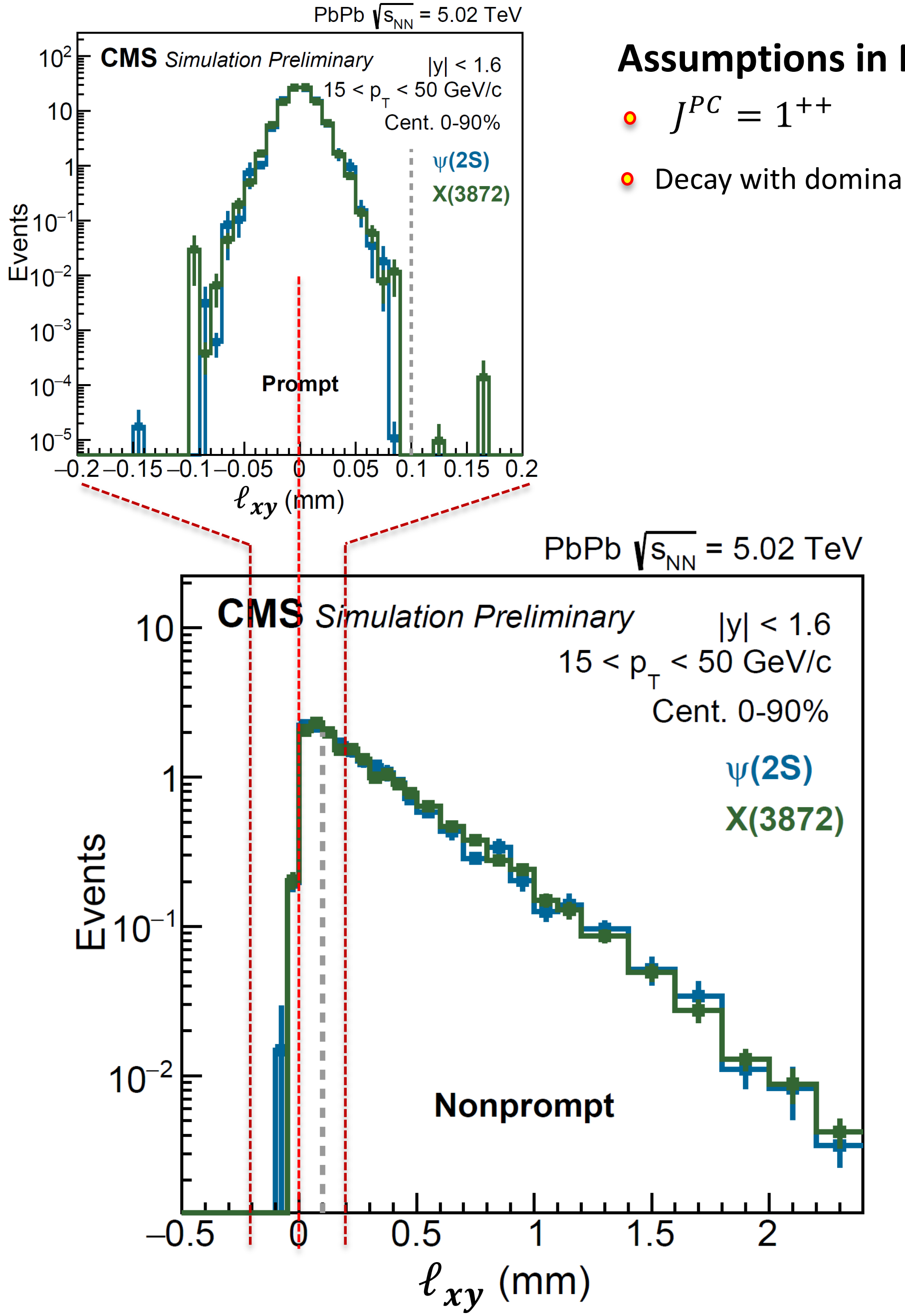
Pseudo-proper decay length $\ell_{xy} = \dfrac{L_{xy} \cdot m_{PDG}}{|\vec{p}_T|}$

is used to disentangle the 2 components:

[this criterium is derived from MC study :]

$\ell_{xy} < 0.1mm$	$\ell_{xy} > 0.1mm$
prompt data sample (i.e. from charm quarks fragmentation)	**B-enriched data sample** (non-prompt, i.e. from B hadrons' decays)

inclusive data sample



Assumptions in MC:

- $J^{PC} = 1^{++}$
- Decay with dominant ρ

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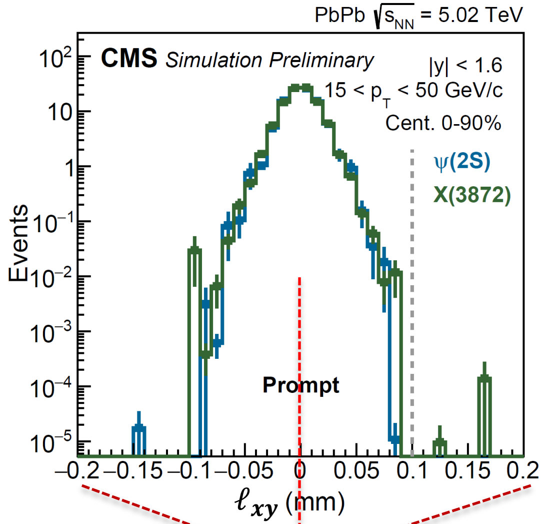

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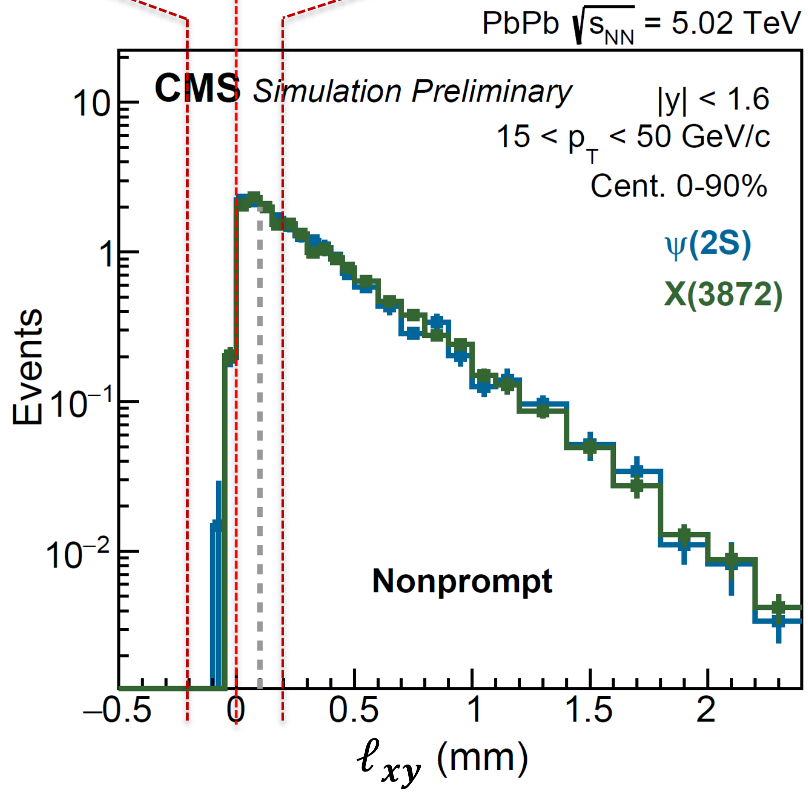
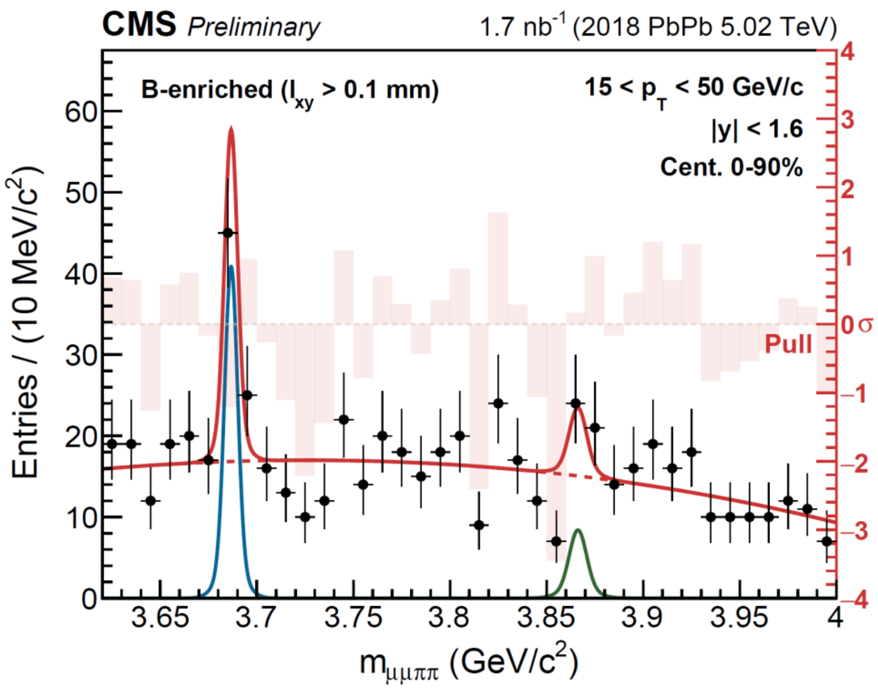


Measurements are performed in a kinematic range in which: $15 < p_T^X < 50$ GeV/c & $|y^X| < 1.6$

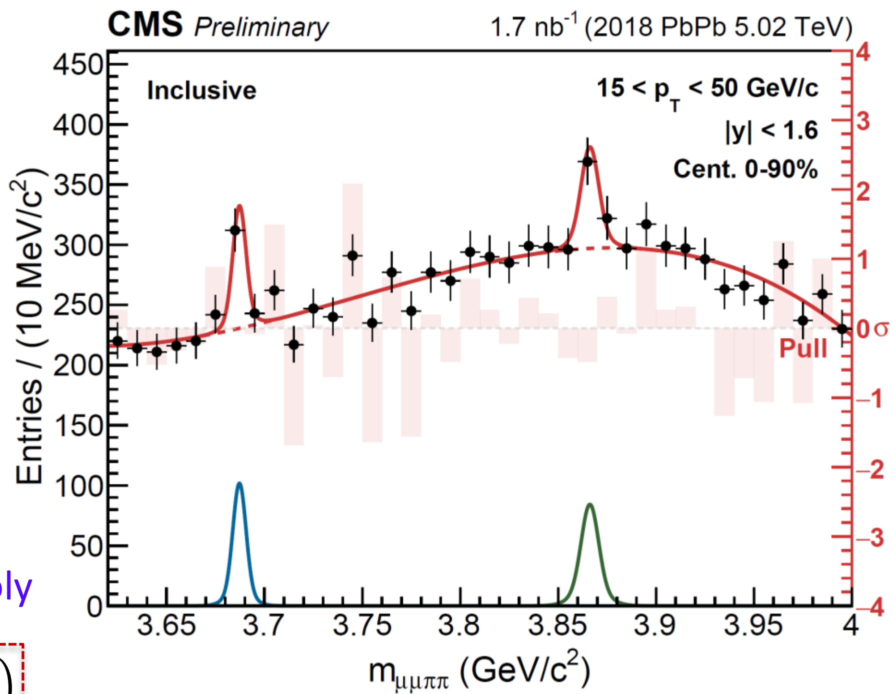
Only events with centrality 0-90% are selected

Signals in B-enriched & inclusive samples

In B-enriched data sample :



In inclusive data sample :



UML fits
2G + 4th-poly

$\left(m, \sigma_1, \sigma_2, \frac{A_2}{A_1}\right)$
from MC

- **non-prompt $\psi(2S)$ is clearly visible**
- **first evidence of inclusive $X(3872)$ production in heavy ion collisions** [statistical significance **> 3σ**]
- **a clear $\psi(2S)$ signal to the same final state is also visible**

To gain more insights we need to quantify the prompt $X(3872)$ to $\psi(2S)$ ratio (next slides**)**

Corrected prompt X(3872) & $\psi(2S)$ yields

- The ratio of corrected yields of prompt X(3872) to prompt $\psi(2S)$ is defined as: $R = \dfrac{N^{X}_{corr}}{N^{\psi}_{corr}}$

  - prompt yields are corrected for efficiency and acceptance from …

    … a PYTHIA MC embedded in HYDJET PbPb background $\quad N^{i}_{corr} = \dfrac{N^{i}_{raw} \cdot f^{i}_{prompt}}{(\alpha \cdot \varepsilon_{tot})^{i}}$

  - prompt fractions are calculated from the # of candidates of the inclusive signal (from nominal fit) and # of candidates in the B-enriched sample (from the fit to the signal after applying $\ell_{xy} > \mathbf{0.1}\boldsymbol{mm}$):

$$f^{(i)}_{prompt} = 1 - \frac{N_{B-enr} / f^{non-prompt}_{B-enr}}{N_{incl}}$$

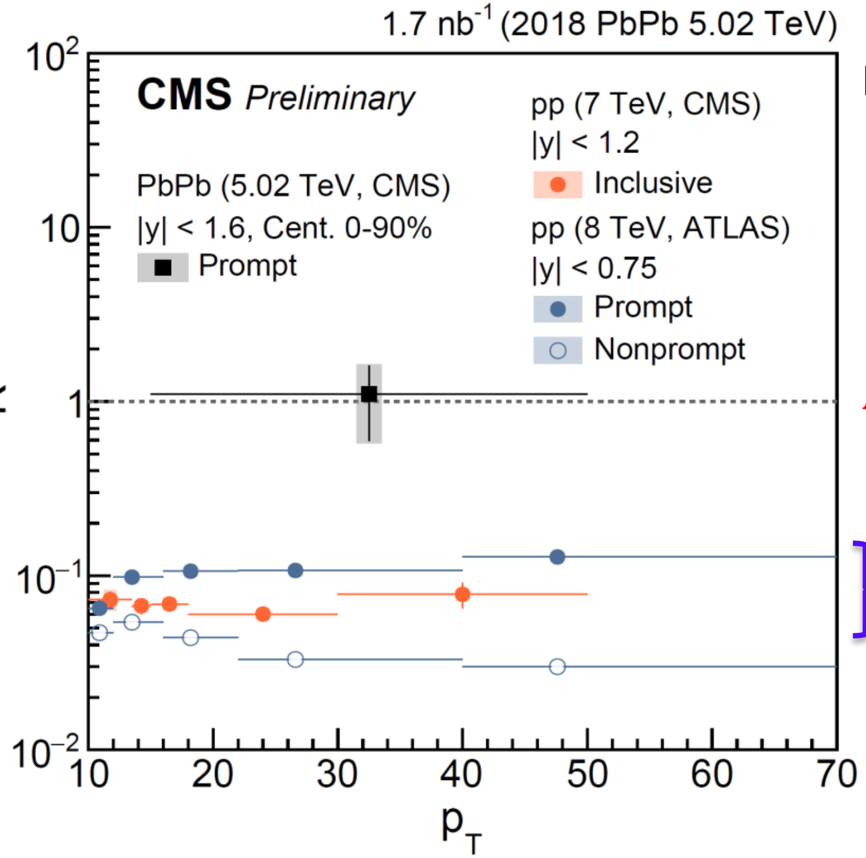
with the latter to be corrected for the non-prompt candidates with $\ell_{xy} < \mathbf{0.1}\boldsymbol{mm}$:

$$f^{non-prompt}_{B-enr} = \frac{N^{non-prompt}(\ell_{xy} < 0.1mm)}{N^{non-prompt}}$$ (obtained from MC)

Ratio of corrected prompt $X(3872)$ & $\psi(2S)$ yields

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

$$R = \frac{N^X_{corr}}{N^\psi_{corr}}$$



Note: log-scale ;
stat.err.=bars & syst.err.=boxes (not added!)

$$R(PbPb) = 1.10 \pm 0.51(stat.) \pm 0.53(syst.)$$

… to be compared with …

$$R(pp) \sim 0.04 \div 0.1$$

- **The ratio measurement is affected by several sources of sizeable systematic uncertainty** (see backup)
- **More statistic is needed to get a conclusive result**

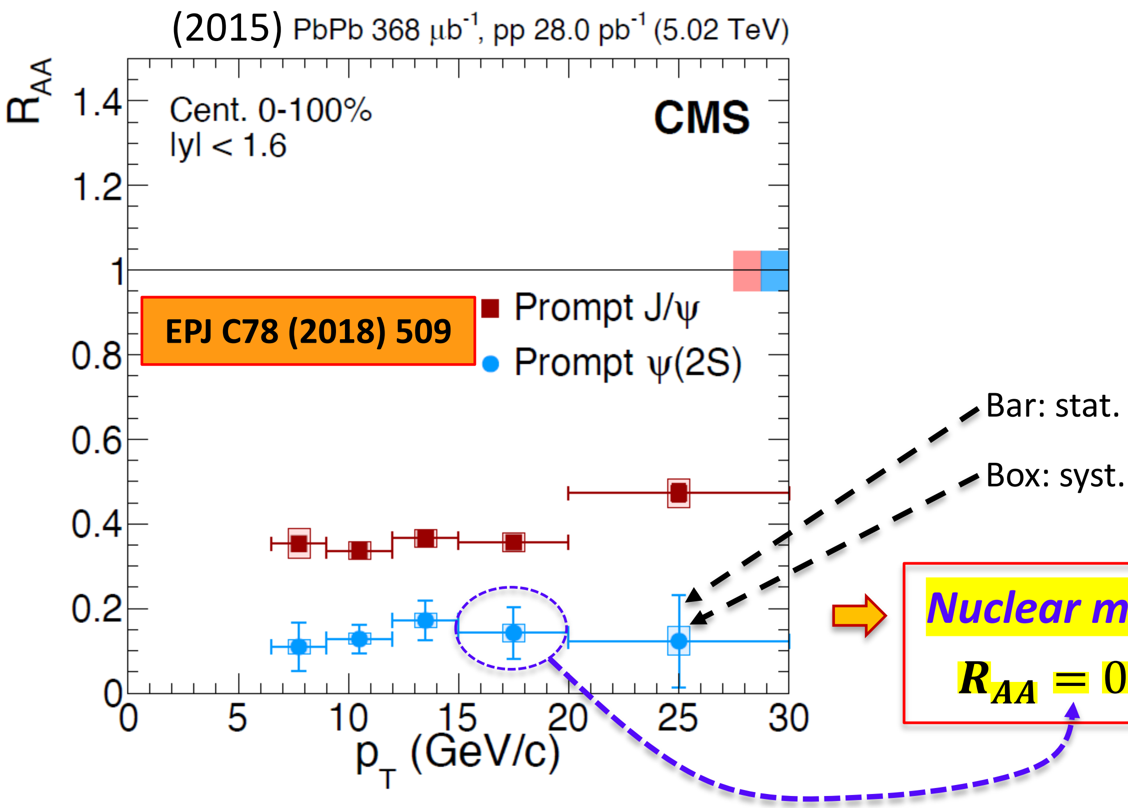
S-wave Charmonia nuclear modification factors in PbPb

- **This ratio measurement - considered alone - may hint that …**

… the X(3872) is less suppressed than $\psi(2S)$.

Whereas we have no idea about the *nuclear modification factor* of the X(3872),

CMS has already reported a significant suppression of $\psi(2S)$ in PbPb collisions :



***Nuclear modification factor* of prompt $\psi(2S)$:**

$$R_{AA} = 0.142 \pm 0.061(stat.) \pm 0.020(syst.)$$

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

CMS

arXiv:2001.06533
accepted by PLB

$\sqrt{s} = 13 TeV$

$\mathcal{L} \leq 140 fb^{-1}$

(Run-II/2016-8)

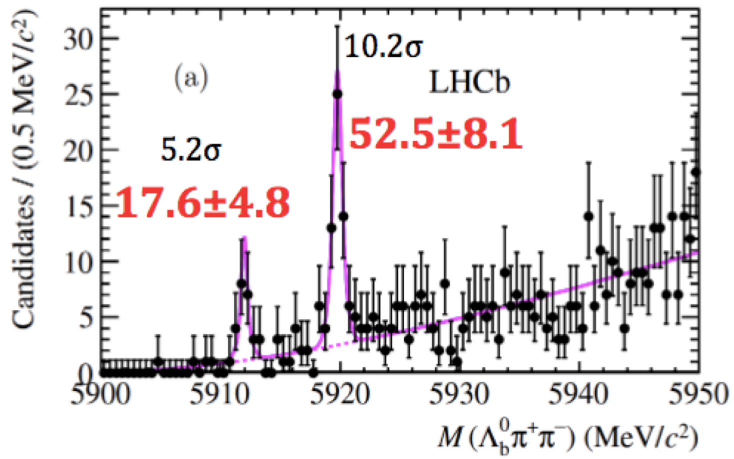
Introduction to Λ_b^0 spectroscopy

- **Studies of excited heavy baryon spectrum is an important test of HQET.**
  There are many predictions of excited Λ_b & Σ_b states that generally contradict each other (masses are spread in rather wide regions, most predictions do not have uncertainties' ranges) [see backup]

studied excited Λ_b^0 baryons in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum in a wide mass range with Run-II data triggered by the observation by **of** 2 near-threshold excited states decaying into $\Lambda_b^0\pi^+\pi^-$

[PRL 109 (2012) 172003**]:** $\Lambda_b(5912)^0$ **&** $\Lambda_b(5920)^0$

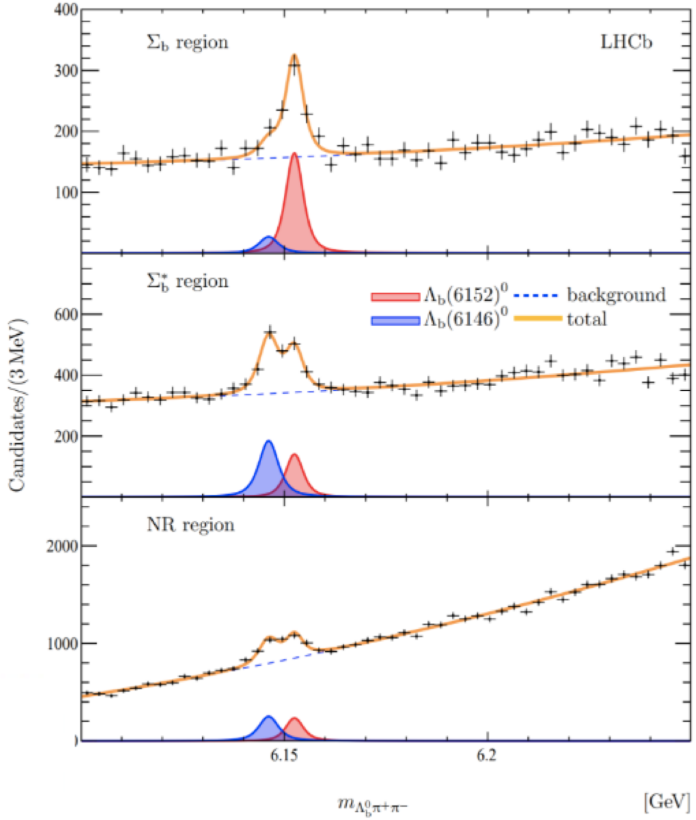
Only the latter was confirmed (3.5σ) by [PRD88 (2013) 071101]



- **Since there is** no dedicated trigger **, in order to increase efficiency, the search uses a** combination of **various $J/\psi + X$ & $\psi(2S) + X$** triggers

Λ_b^0 spectroscopy: recent results & analysis strategy

- In the meanwhile LHCb using full Run-I+II dataset observed two new excited states [PRL 123 (2019) 152001] decaying to $\Lambda_b^0\pi^+\pi^-$ final state: $\Lambda_b(6146)^0$ & $\Lambda_b(6152)^0$
  - with Λ_b^0 baryons reconstructed via both decays $\begin{cases} \Lambda_b^0 \to \Lambda_c^+\pi^- \\ \Lambda_b^0 \to J/\psi\, pK^- \end{cases}$



- In CMS we cannot use the most copious $\Lambda_b^0 \to \Lambda_c^+\pi^-$ because no dedicated trigger were configured & backgrounds are large due to the lack of hadronic PID

  Also usage of $\Lambda_b^0 \to J/\psi\, pK^-$ is very difficult due to high backgrounds due to the lack of hadronic PID

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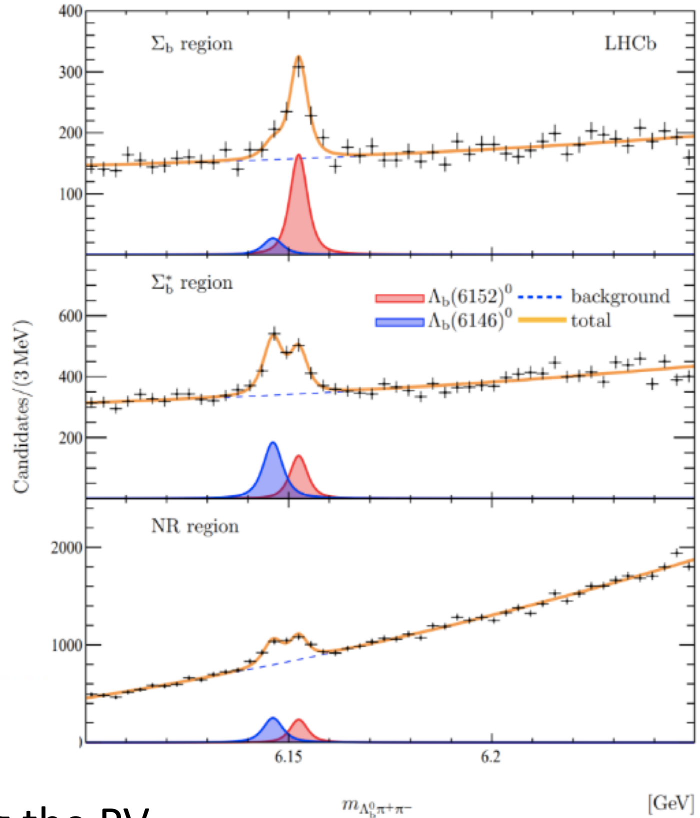

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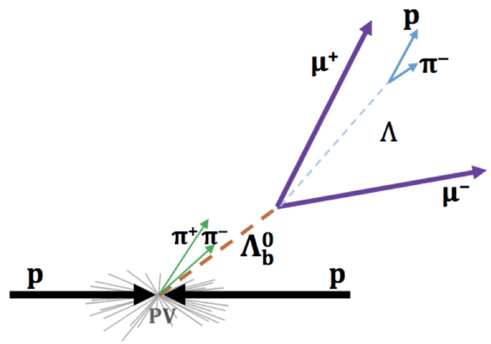
  - **However we can use $\Lambda_b^0 \to J/\psi\,\Lambda$ (~85%) and $\Lambda_b^0 \to \psi(2S)\Lambda$**

    with $\psi(2S)$ reconstructed via both decays $\begin{cases} \psi(2S) \to J/\psi\,\pi\pi \\ \psi(2S) \to \mu\mu \end{cases}$

    Additional two OS prompt tracks are selected from the tracks forming the PV (specifically the one with the smallest 3D pointing angle of the Λ_b^0 candidate).



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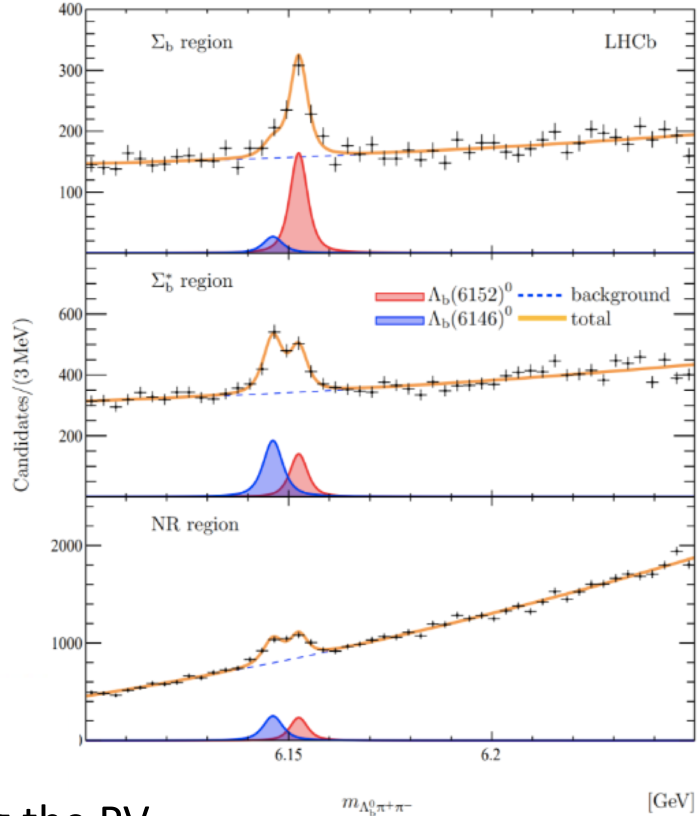

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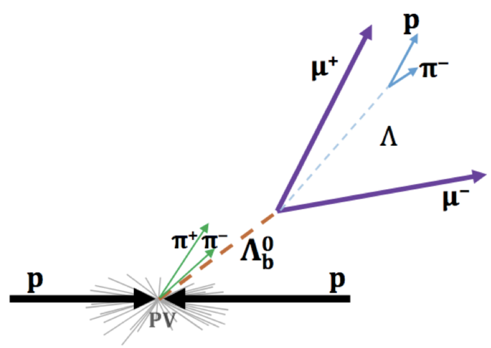
    Additional two OS prompt tracks are selected from the tracks forming the PV (specifically the one with the smallest 3D pointing angle of the Λ_b^0 candidate).

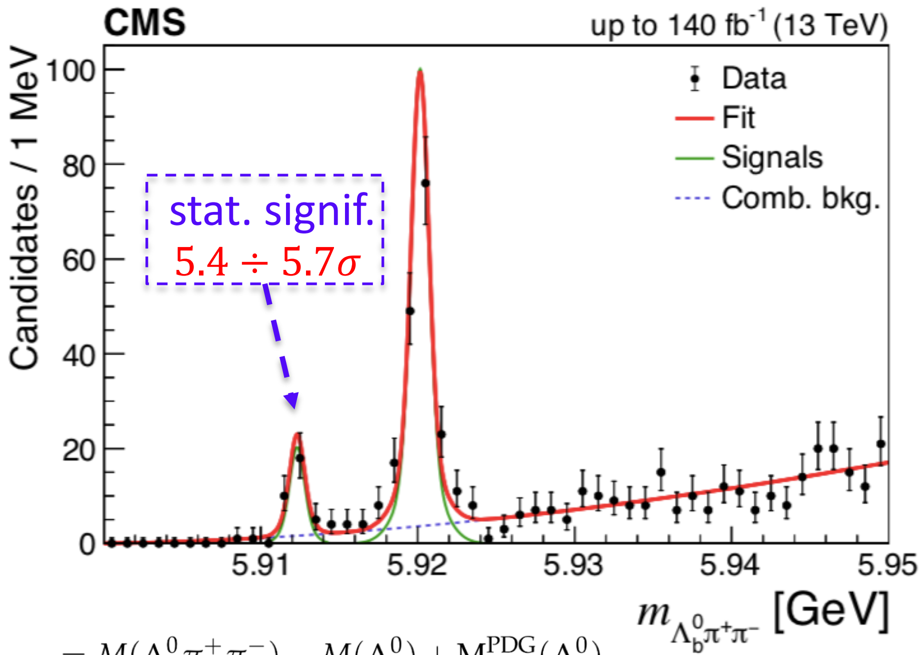
  - Combinations with SS prompt pions are used as a control channel

  - **The analysis has been optimized differently**
    - **at low masses, near threshold where BKGs are low**
    - **at high masses where BKG is large**



Excited states in low-mass region

LOW-MASS REGION (near threshold)



$m_{\Lambda_b^0\pi^+\pi^-} = M(\Lambda_b^0\pi^+\pi^-) - M(\Lambda_b^0) + M^{PDG}(\Lambda_b^0)$

2 double-G with shape fixed from MC (mass & normalization free)

Threshold function $(x - x_0)^{\alpha}$ ← free; x_0 → fixed

Confirmation of $\Lambda_b(5912)^0$

First confirmation of $\Lambda_b(5920)^0$

Mass measurements:

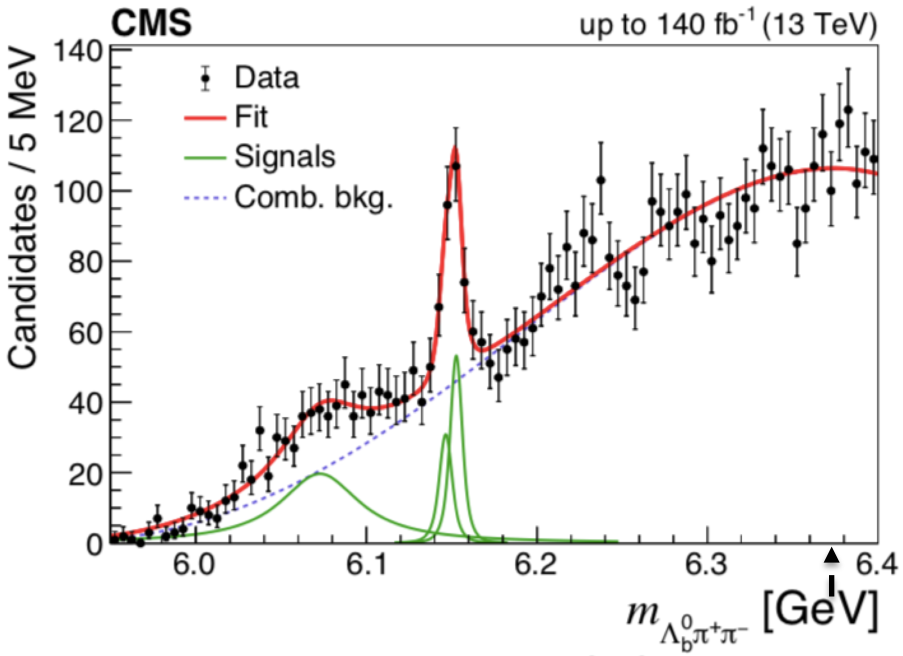
$$M(\Lambda_b(5912)^0) = [5912.32 \pm 0.12(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\mathrm{MeV}$$

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

consistent with those by LHCb/PDG & with similar precision

Excited states in high-mass region

HIGH-MASS REGION



Each of the 2 SIGs for the narrow structure :

2 double-G (with mass resolution fixed from MC within gaussian constraits) 3.8MeV

single Breit-Wigner (Γ fixed to LHCb ones within gaussian constraits)

BGK : $(x - x_0)^{\beta} \cdot poly(1)$: threshold power function x polynomial

free (β) fixed (x_0)

First confirmation of $\Lambda_b(6146)^0$ & $\Lambda_b(6152)^0$

(very recently discovered by LHCb)

- Mass measurements:

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

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

… in agreement with LHCb values but not as precise as

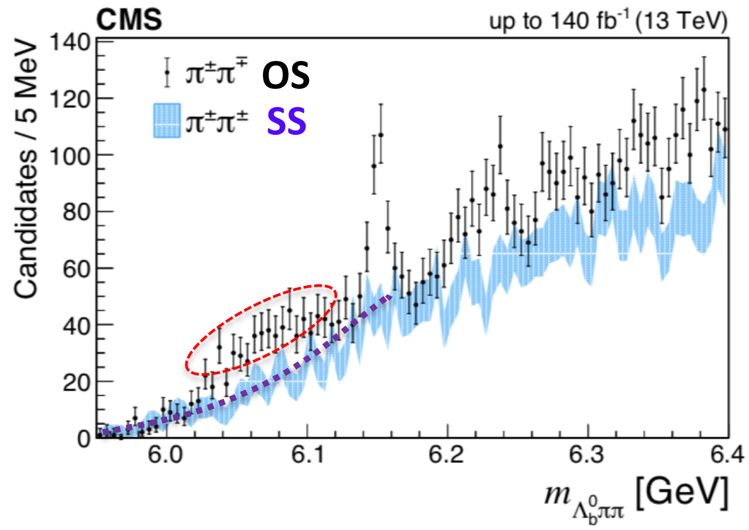
- Data are consistent with a single peak @6150MeV :

  * 1-peak hypothesis vs BKG-only has significance $> 5.4 \div 6.5\sigma$ (changing fit range & model)

  * 2-peaks vs 1-peak hypotheses (Γ free) has very low significance (0.4σ) : we are not sensitive to the splitting because of the worse mass resolution and much lower statitstics w.r.t LHCb.

Broad structure in high-mass region - I

- Firstly this "bump" is not present in the $\Lambda_b^0\pi^+\pi^-$ mass spectrum with SS dipions :



Same for SIG for the broad structure (but Γ free)

- Assuming a single broad resonance X_b the fit - with M & Γ free parameter - provides:

$$M(X_b) = [6073 \pm 5(stat)]MeV$$
$$\Gamma(X_b) = [55 \pm 11(stat)]MeV$$

.... with the stat. signif. ~ 4σ

- Various reflections have been thoroughly studied and excluded as the origin/nature of the bump

  However it may be created by partially reconstructed decays of higher-mass states

- The amount of data is too low to try a proper interpretation of the broad structure as it could be not necessarily a single state but - instead - a superposition or several nearby broad states.

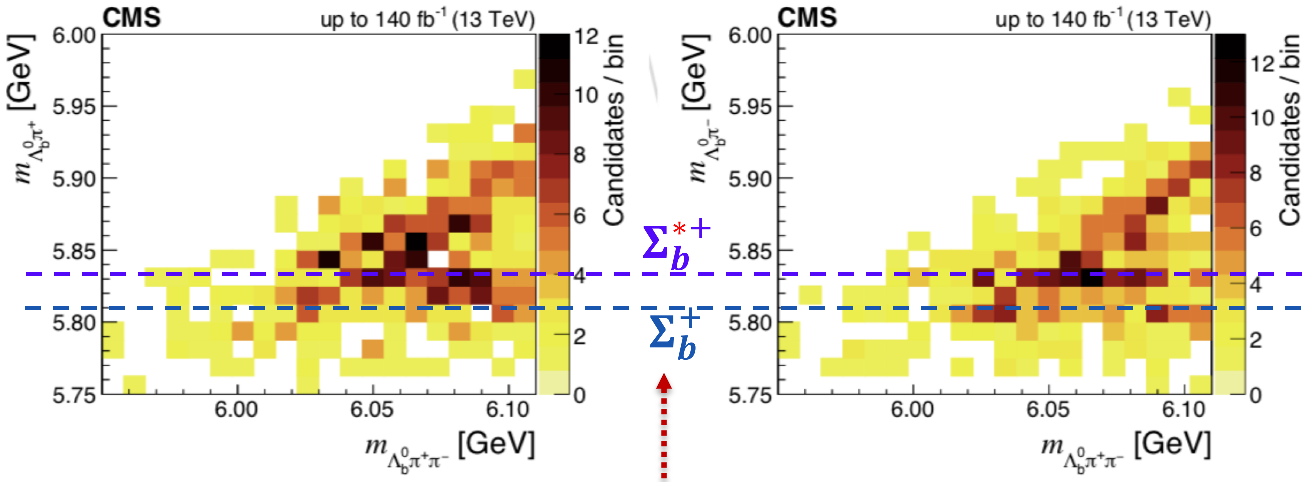
Broad structure in **high-mass region** - II

- **By inspecting the scatter plots**

  $\Lambda_b^0\pi^+$ vs. $\Lambda_b^0\pi^+\pi^-$

  $\Lambda_b^0\pi^-$ vs. $\Lambda_b^0\pi^+\pi^-$

  …. in the concerned region
  $[\ \mathrm{m}(\Lambda_b^0\pi^+\pi^-) < 6.11 GeV\ ]$



  - **Horizontal bands corresponding to $\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^\pm$ can be appreciated**

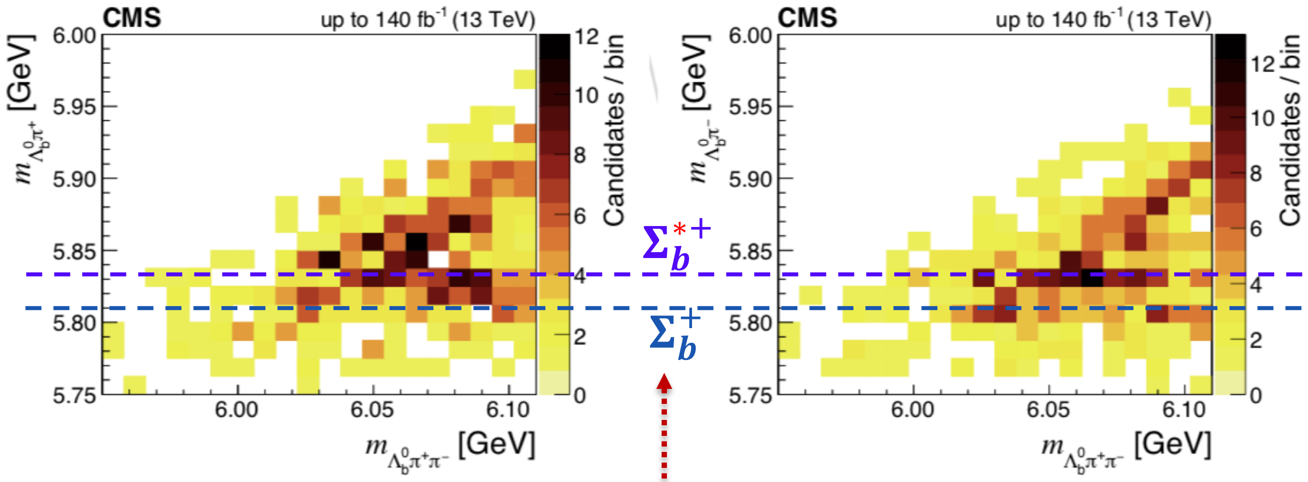
-

Broad structure in high-mass region - II

- By inspecting the scatter plots

$$\Lambda_b^0\pi^+ \text{ vs. } \Lambda_b^0\pi^+\pi^-$$
$$\Lambda_b^0\pi^- \text{ vs. } \Lambda_b^0\pi^+\pi^-$$

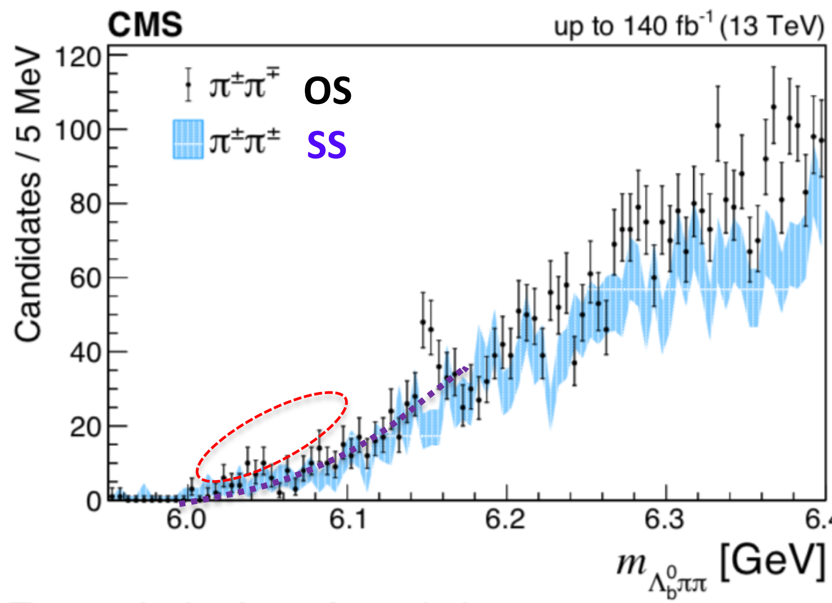
.... in the concerned region
$[\,\mathrm{m}(\Lambda_b^0\pi^+\pi^-) < 6.11 GeV\,]$



- Horizontal bands corresponding to $\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^\pm$ can be appreciated

- Comparison between OS & SS distributions of $\mathrm{m}(\Lambda_b^0\pi^+\pi^-)$ once the $\Sigma_b^\pm$ & $\Sigma_b^{*\pm}$ contributions are vetoed :

  - the "bump" is consistent with originating from a resonance in the $\Sigma_b^{(*)\pm}\pi^\mp$ system, But no firm conclusion can be made with the present data set



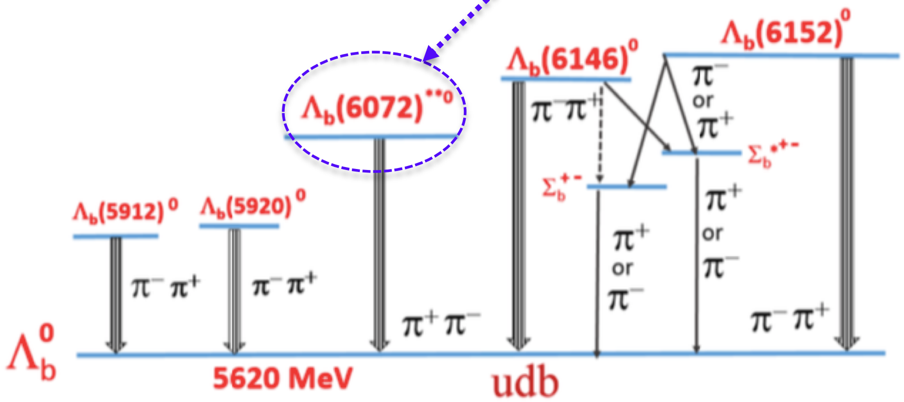
- On the day our paper has appeared on the arXiv …

  confirmed the wide bump with similar parameters

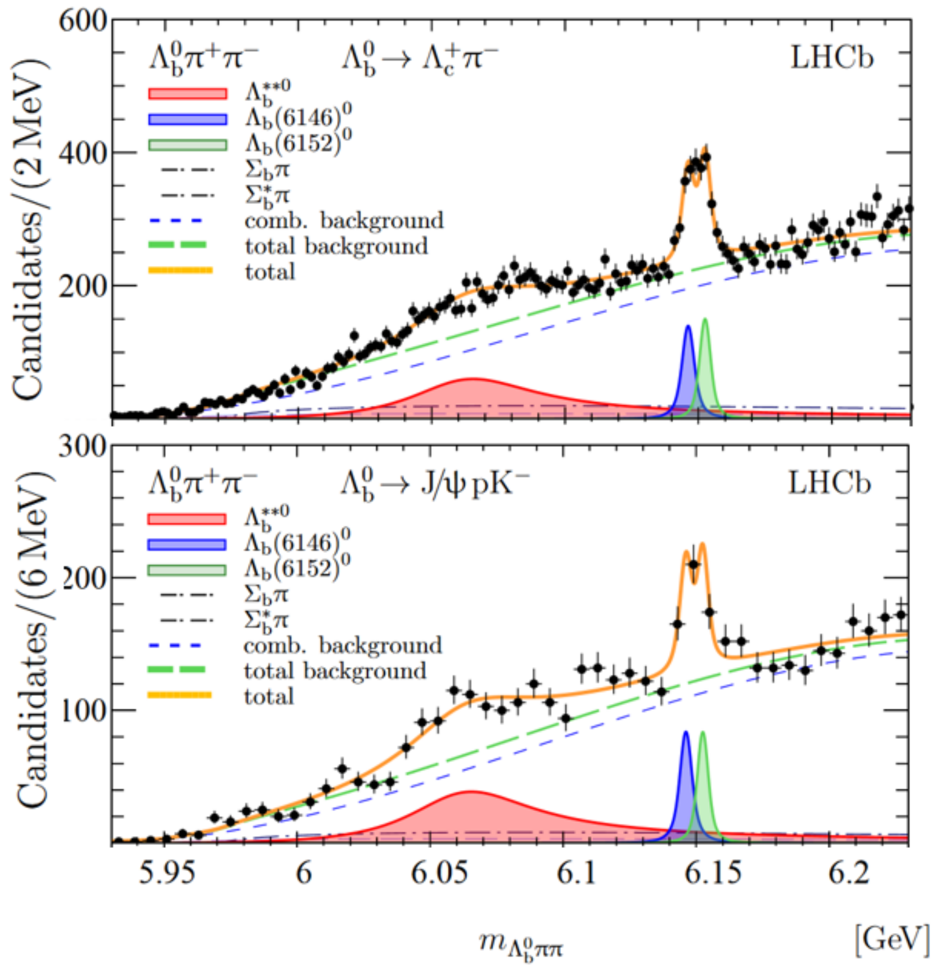
  (@Bormio workshop and some days later on arXiv)

  [arXiv:2002.05112]

- … interpreting it as a further excited Λ_b^0 state



http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#news



First observation of the excited $B_c^+(2S)$ & $B_c^{*+}(2S)$ states

PRL 122 (2019) 132001

$\sqrt{s} = 13 TeV$

$\mathcal{L} = 143 fb^{-1}$

(Full Run-II / 2015-8)

Introduction to $(c\bar{b})$ spectroscopy

- The B_c^+ meson was discovered by CDF [PRL 81 (1998) 2432]

It is the lowest-mass bound state of the family of mesons composed of a charm quark & a bottom anti-quark $(c\bar{b})$.
Absolutely stable against strong/em decays (weak dominate).

Experimental information is limited by **rare production rate**:
Xsection proportional to α_s^4 : qqbar, gg → (c-bbar) b-cbar.

Given the different heavy quark flavors, **the only allowed transitions are through photons or pion pairs**
(these mesons cannot annihilate into gluons)

Particle	Predicted mass [MeV]
B_c^+	6247-6286
B_c^{+*}	6308-6341
$B_c^+(2S)$	6835-6882
$B_c^{*+}(2S)$	6881-6914

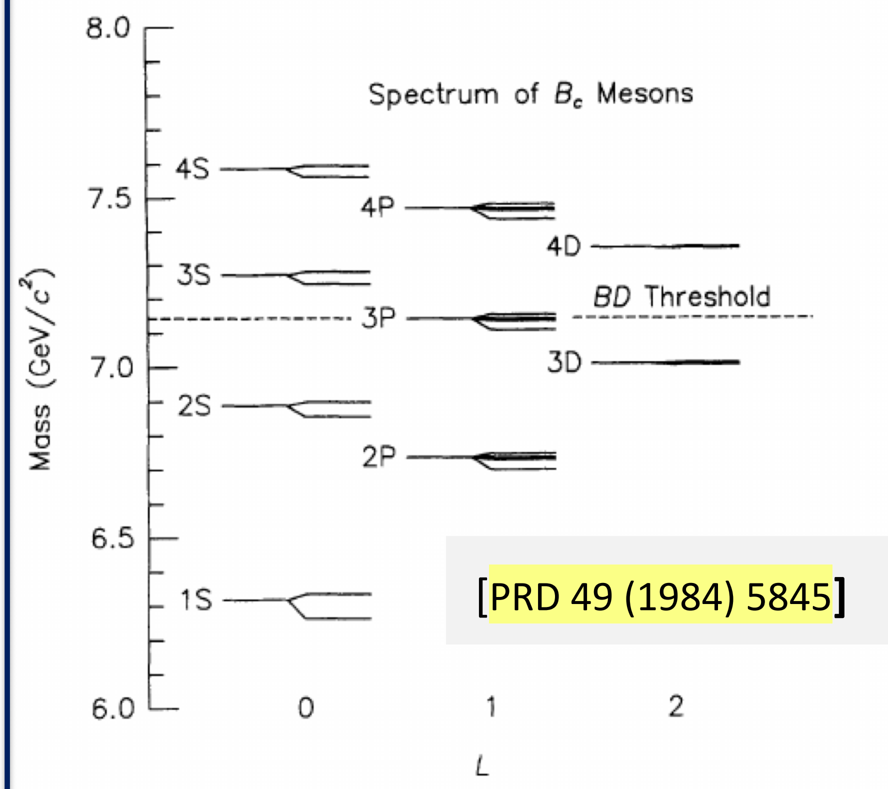
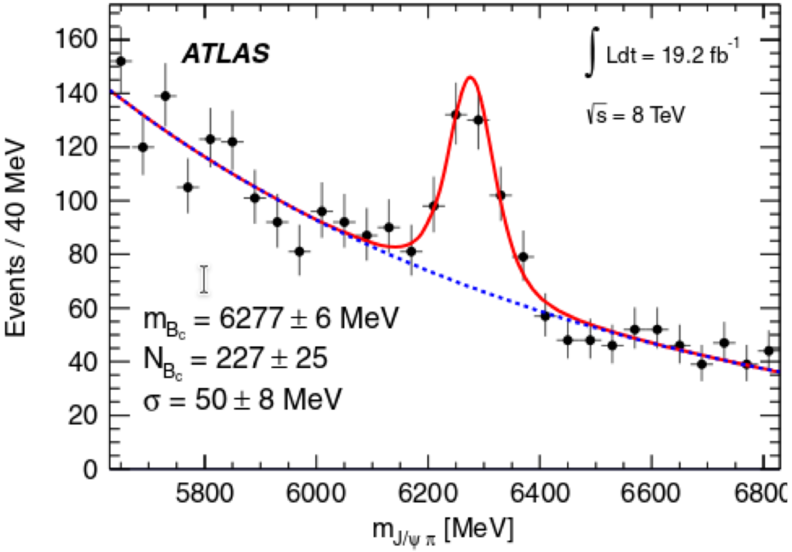


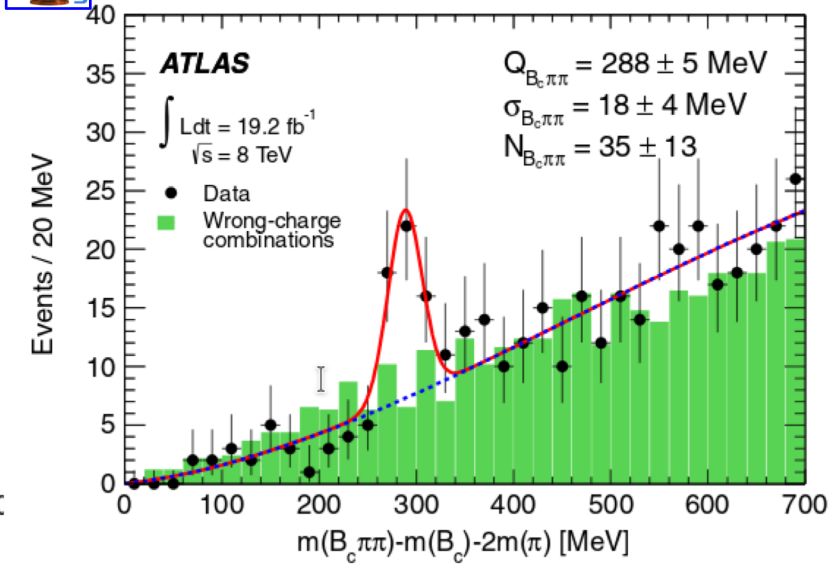
FIG. 1. The spectrum of $c\bar{b}$ states.

Spectroscopy predictions for the "B_c^+ family" :

PRD 49 (1994) 5845, PRD 51 (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, PRL 121 (2018) 202002

PRL 113 (2014) 212004

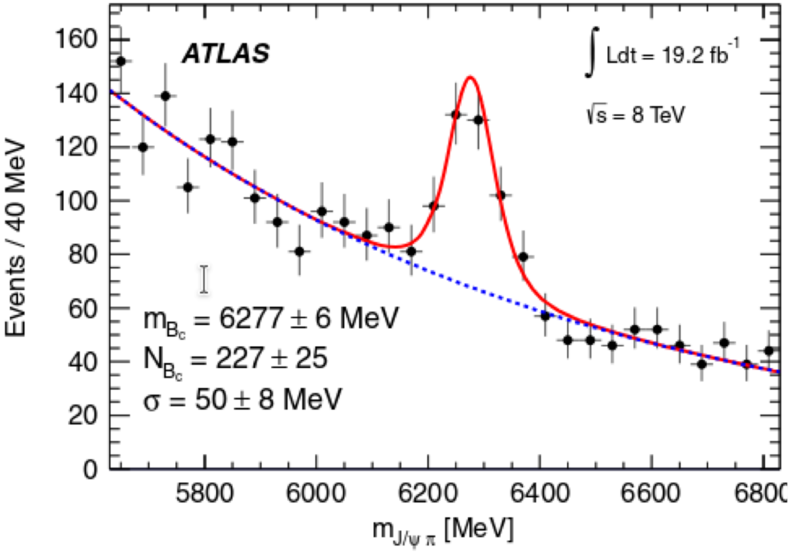


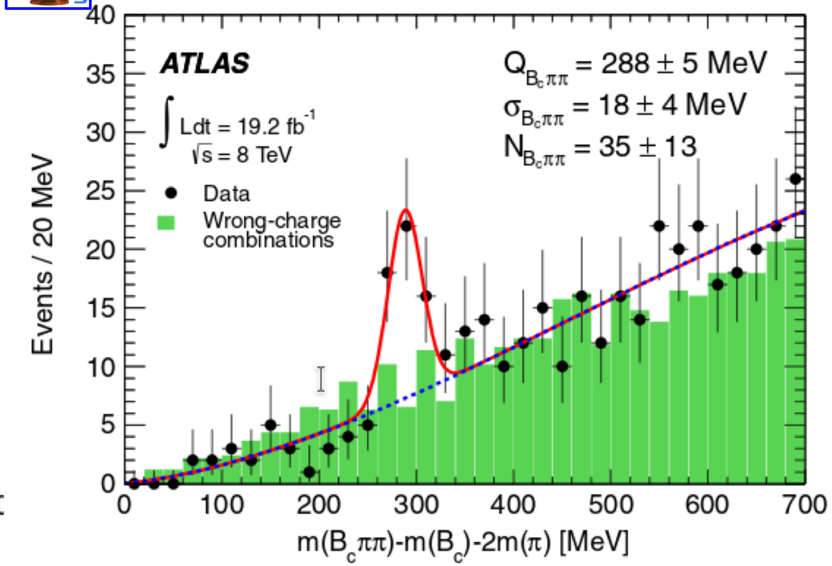


Observation of a new state with mass consistent with predictions for $B_c^+(2S)$. It's reconstructed from the decay to $B_c^+\pi\pi$ followed by $B_c^+ \to J/\psi\,\pi$ with a local significance of 5.4σ.
Can be the superposition of 2 closely spaced hyperfine partners (very soft photon is lost).

Observation/search for radially excited B_c^+ mesons

PRL 113 (2014) 212004





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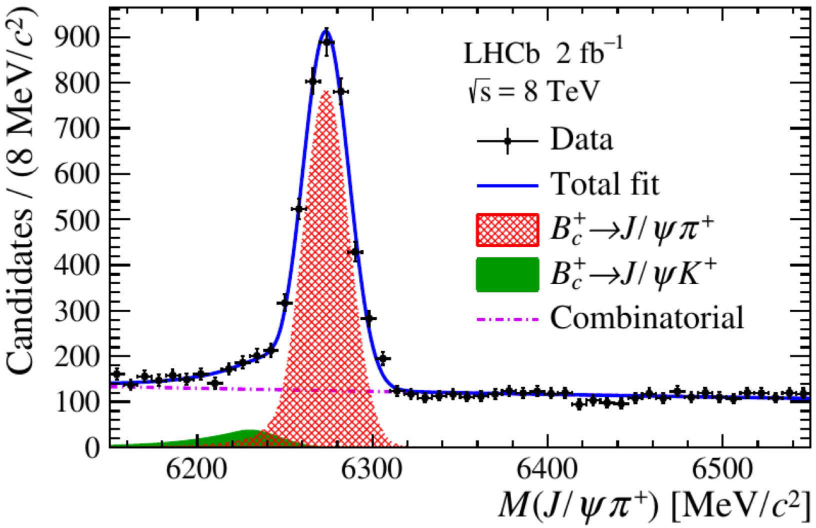
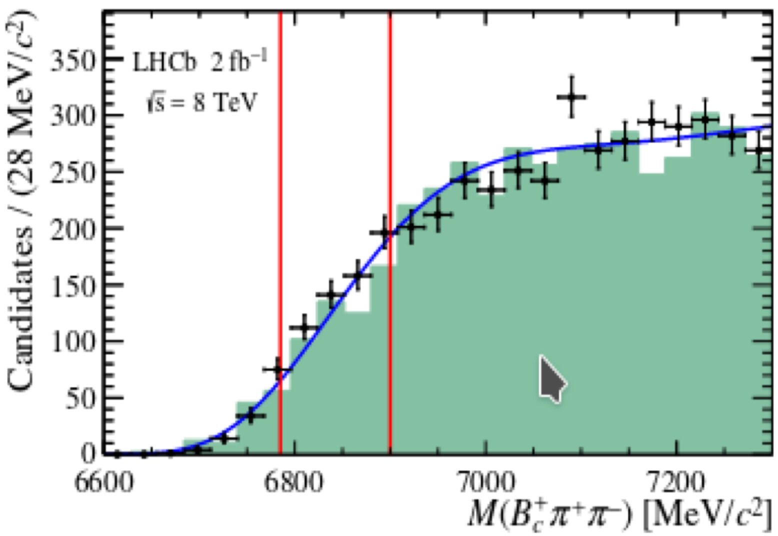




With 3325 ± 73 B_c^+ events: "No significant signal is found" in the search for the excited states $B_c^+(2S)$ & $B_c^{*+}(2S)$ in Run-I/2012

JHEP 01 (2018) 138

Reconstruction of the hyperfine partners

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

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

  Since the photon is not detected, we end up seeing

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

  Same final state as

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

  Thus, a two-peak structure in the $B_c \pi^+ \pi^-$ 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.

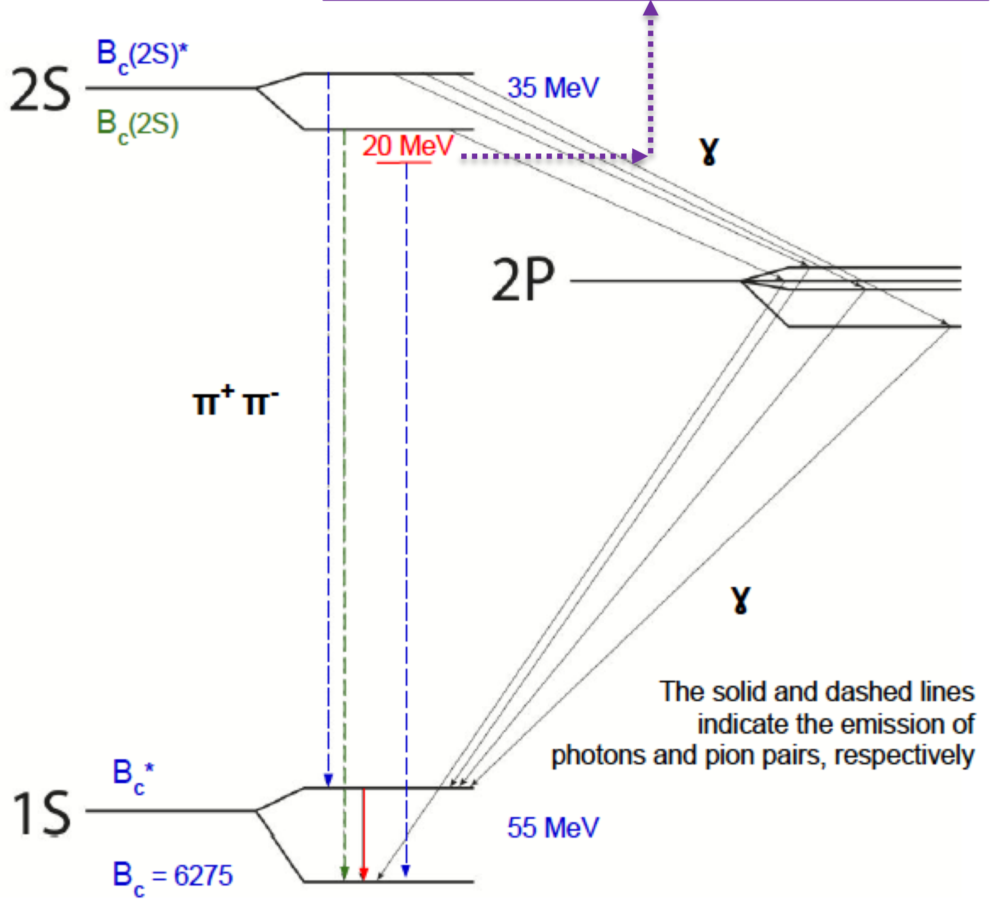
  The two-peak can be appreciated only if ΔM value is larger than experimental resolution!

  Notice that 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**!

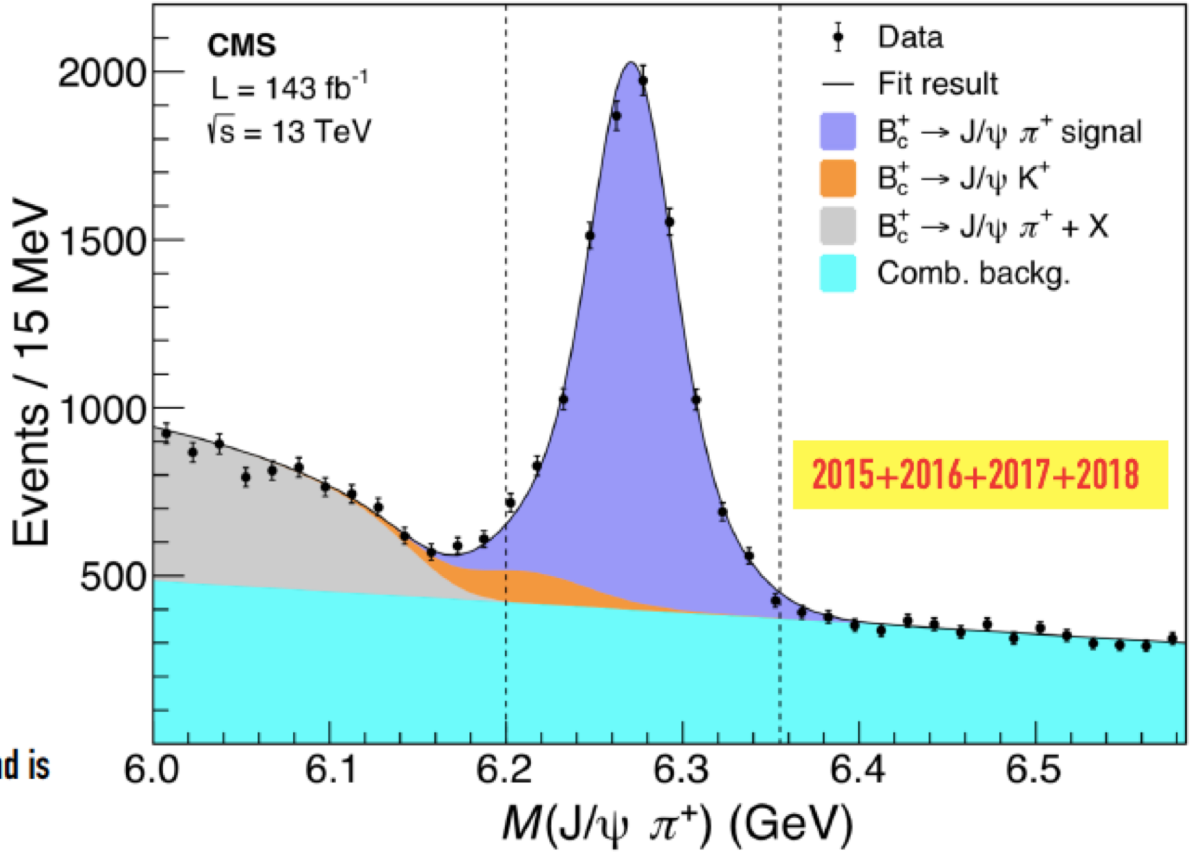
"virtual position" in the spectrum due to photon loss



B_c^+ reconstruction

The B_c^+ signal in Run-II data :

- Unbinned ML fit
- Signal modelled using a double gaussian
- Combinatorial background: first-order Chebyshev polynomial function
- $B_c^+ \to J/\psi K^+$ background: shape determined from simulation studies and a normalization fixed relative to the $B_c^+ \to J/\psi\pi^+$ yield
- $B_c^+ \to J/\psi\pi^+ + X$ background: relevant only below $6.2GeV$ and is described by a ARGUS function convolved with a Gaussian resolution

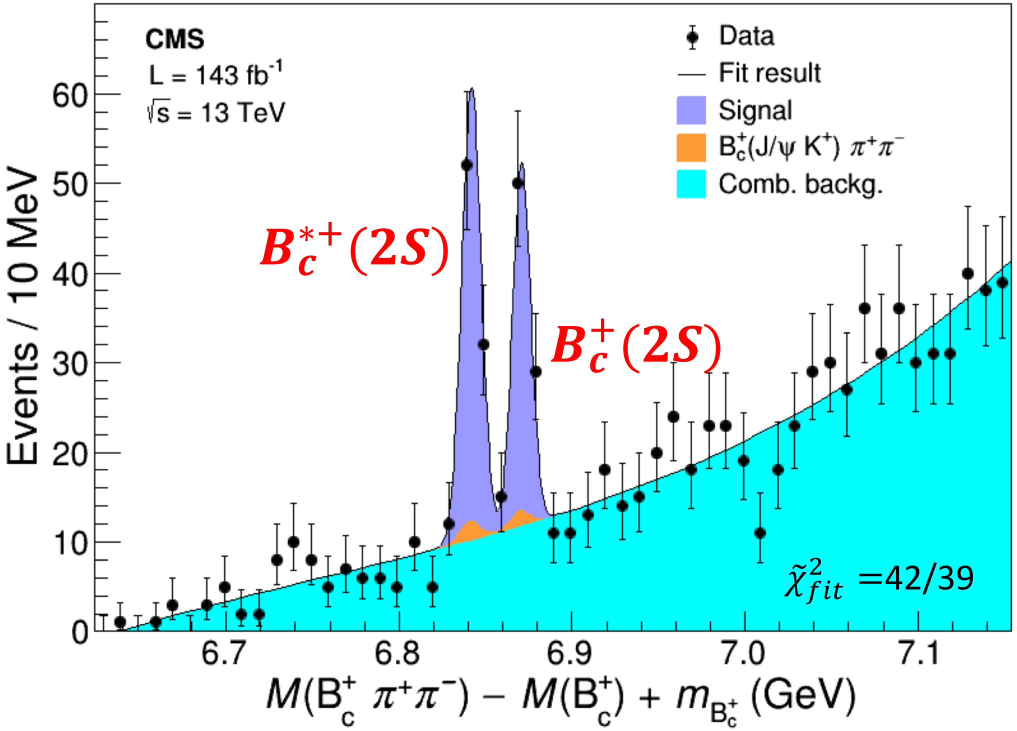


$N_{B_c^+} = 7629 \pm 225$ $M(B_c^+) = 6371.1 \pm 0.5\text{MeV}$ $\sigma(B_c^+) = 33.5 \pm 2.5\text{MeV}$ $\chi^2_{fit} = 35\ (d.o.f. = 30)$

[mass resolution]

Observation of the two-peak structure

- The $M(B_c\pi\pi) - M(B_c) + m_{PDG}(B_c)$ distribution is fitted with Gaussian functions for the peaks and a 3rd order Chebyshev polynomial for the background.
- Mass resolution agrees with MC expectations (~6MeV) and is much lower than ΔM thus allowing a two-peak structure to be observed.



$N(B_c^{*+}(2S)) = 67 \pm 10$ $\quad N(B_c^{+}(2S)) = 51 \pm 10$

- Measured two peaks' mass difference:

$$\Delta M = 29.1 \pm 1.5\,(stat) \pm 0.7(syst) MeV$$

Given the predicted mass splitting ($\Delta M_1 - \Delta M_2 > 0$), $B_c^+(2S)$ is assumed to be the right-most peak

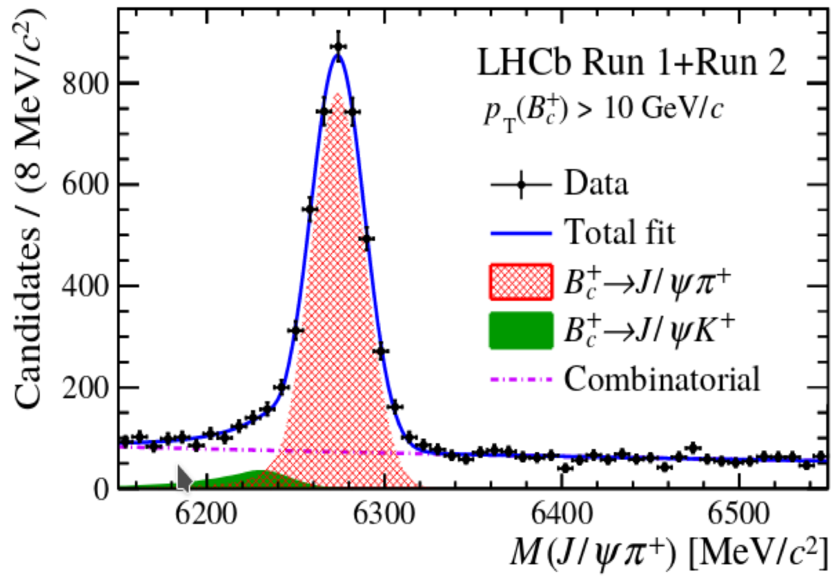
$$M(B_c(2S)) = [6871.0 \pm 1.2(stat) \pm 0.8(syst) \pm 0.8(m_{PDG}(B_c^+))]\text{MeV}$$

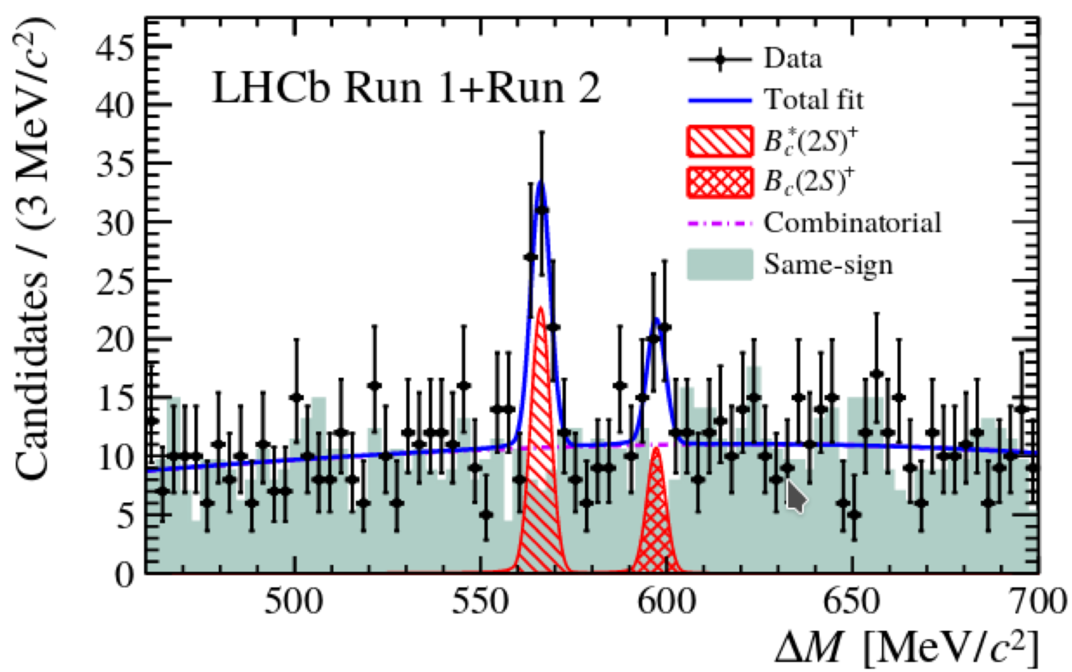
From MC studies: the low-energy γ emitted in the $B_c^{*+}(2S)$ decay has a very small reconstruction efficiency, of order 1% . The photon is not detected and the mass of the $B_c^*(2S)$ cannot be measured.

- Local significance exceeding 6.5σ for observing two peaks rather than one. For both single peaks significance is above 5σ

- When fitting each signal with a Breit-Wigner convolved with the gaussian resolution function the natural width (predicted $50 \div 90$ KeV) is consistent with zero: natural widths are much smaller than resolution.

- LHCb has recently confirmed [PRL 122 (2019) 232001] the 2 peaks (actually there is an evicence for the 2[nd]; yields seem to be smaller w.r.t. CMS)





- $B_c^+(2S)$ mass & hyperfine splitting ΔM are in agreement between the two experiments

What is next? Importance of determining the direct Xsections x BF

- The extracted yields in the observation paper are not yet corrected for detection efficiencies and acceptances, thus they cannot be used to infer ratios of production Xsections (times BFs).

Why is this important as the next step of this spectroscopy?

There are predictions for relative yields of 2S-excitations decaying w/ a dipion emission : different models can bring to relevantly different predictions, thus it is important to experimentally determine this ratio:

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

Search for narrow resonances decaying to $\Upsilon(1S)\mu^+\mu^-$

arXiv:2002.06393
submitted to PLB

$\sqrt{s} = 13TeV$

$\mathcal{L} = 36fb^{-1}$

(Run-II/2016)

Introduction to searches in the $\Upsilon(1S)\mu^+\mu^-$ final state

CMS very recently released a measurement of the $\Upsilon(1S)$ pair production Xsection @ $\sqrt{s} = 13TeV$

This process serves as a standard reference in a search for narrow resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ since the final state is the same and the event selection is similar.

The existence of an heavy bottom tetraquark [$b\bar{b}\, b\bar{b}$] predicted by few theoretical models (*) [below twice the η_b mass] is searched in a mass window between $17.5 \div 19.5\text{GeV}$ (namely around 4 times the mass of the bottom quark), within the $\Upsilon(1S)\mu^+\mu^-$ final state.

(*) Y.Chen *et al.*, PLB 705 (2013) 93 ; A.V. Berezhnoy *et al.*, PRD 86 (2012) 034004

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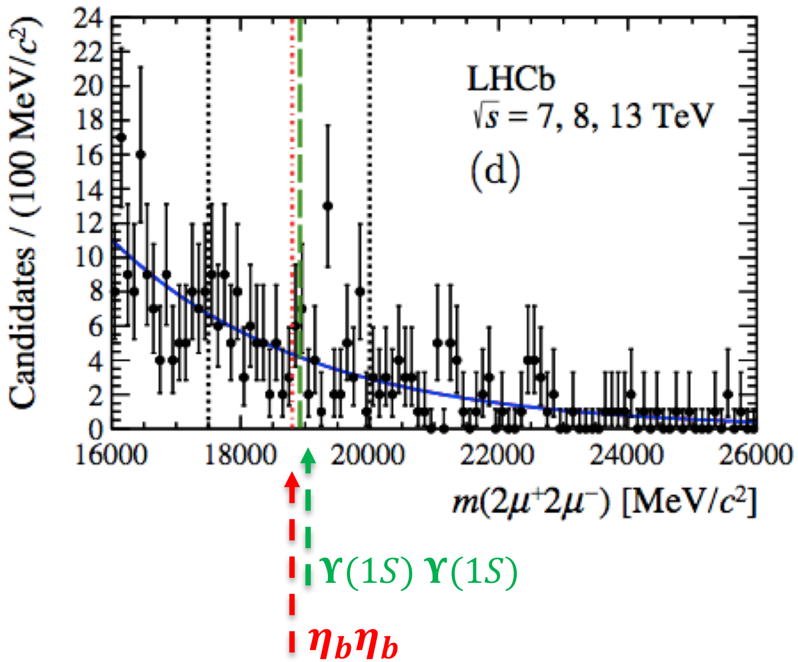
LHCb searched for such tetraquarks without finding any hint of a signal [JHEP 10 (2018) 086]



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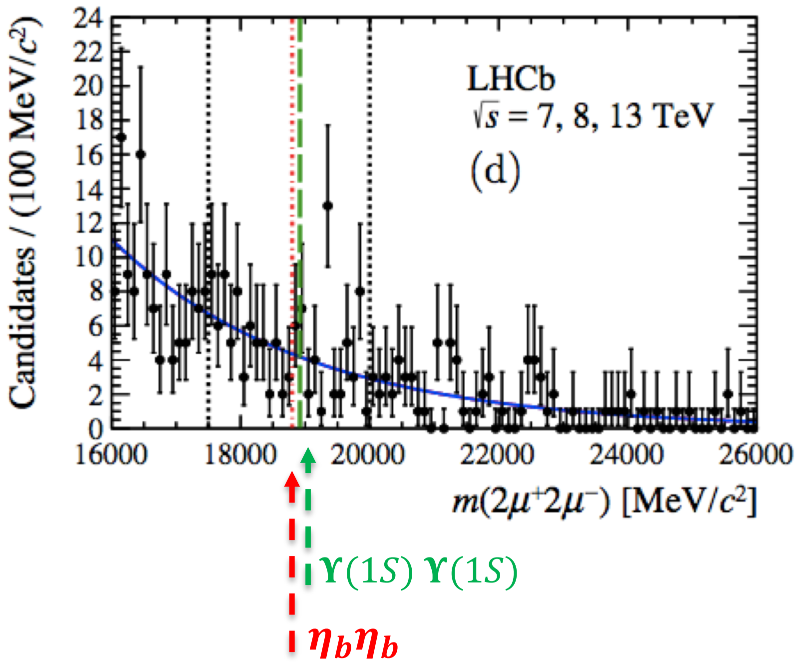


This new analysis probes a kinematical region not accessible at LHCb.

Moreover … a generic search for narrow resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ is performed in an extended mass window $16.5 \div 27\text{GeV}$

(*) Y.Chen *et al.*, PLB 705 (2013) 93 ; A.V. Berezhnoy *et al.*, PRD 86 (2012) 034004

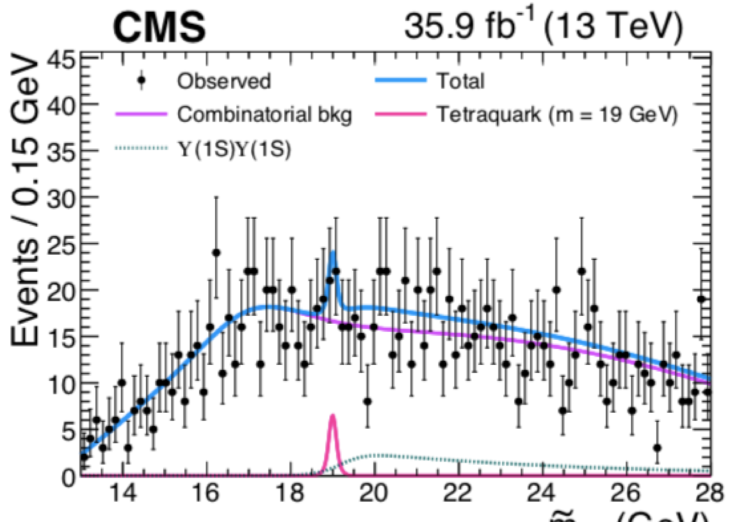
Search for a $b\bar{b}\,b\bar{b}$ tetraquark state

- No significant narrow excess of candidates is observed above the background expectation.

An example of 4quark signal at 19GeV is shown

This mass window is probed using the bottomonium model.

In UML fits the signal has FWHM ~200MeV for a 18GeV resonance.



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

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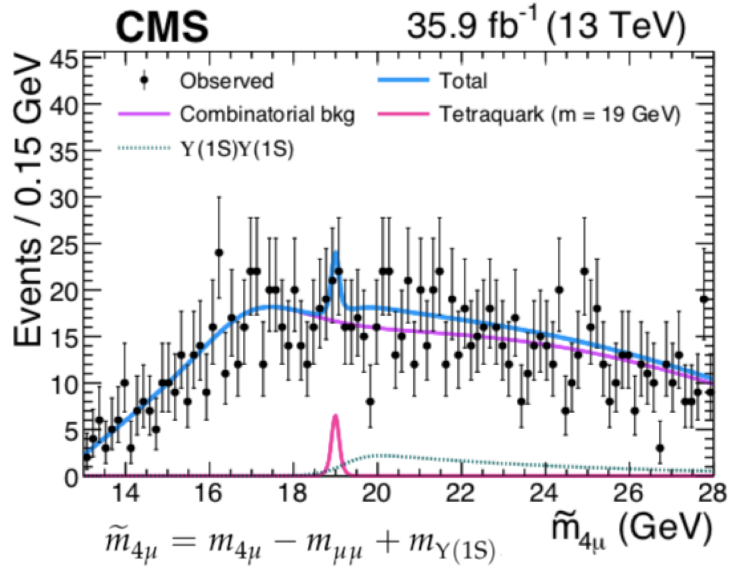
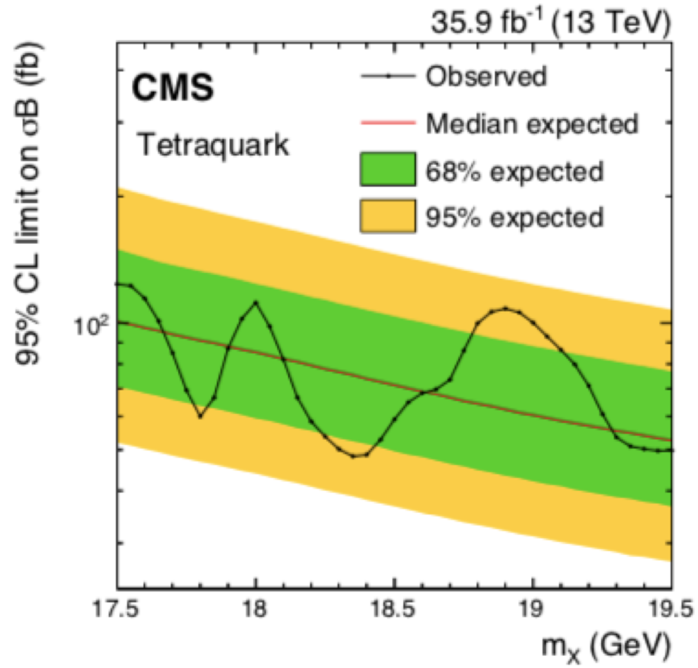


Upper limits on the product of the production Xsection of a resonance and the BF to a final state of 4 muons via an intermediate $\Upsilon(1S)$ are set @95% CL (using the modified frequentist construction CL_s in the asymptotic approx.**).**



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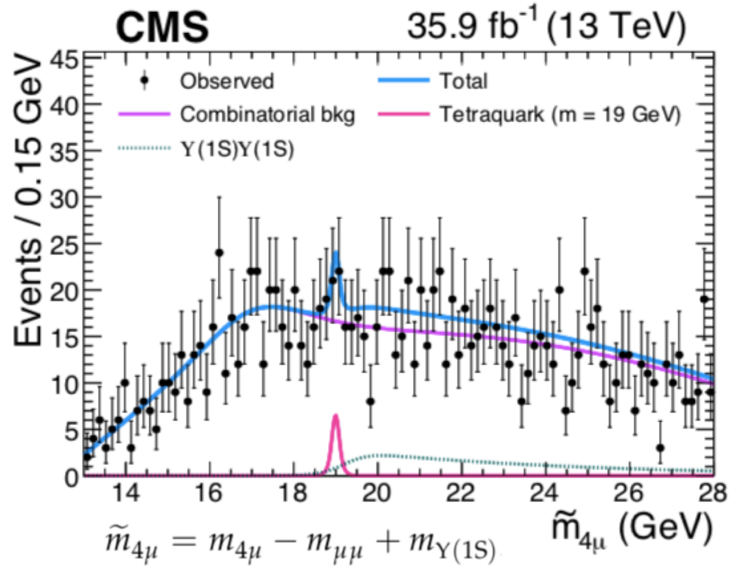

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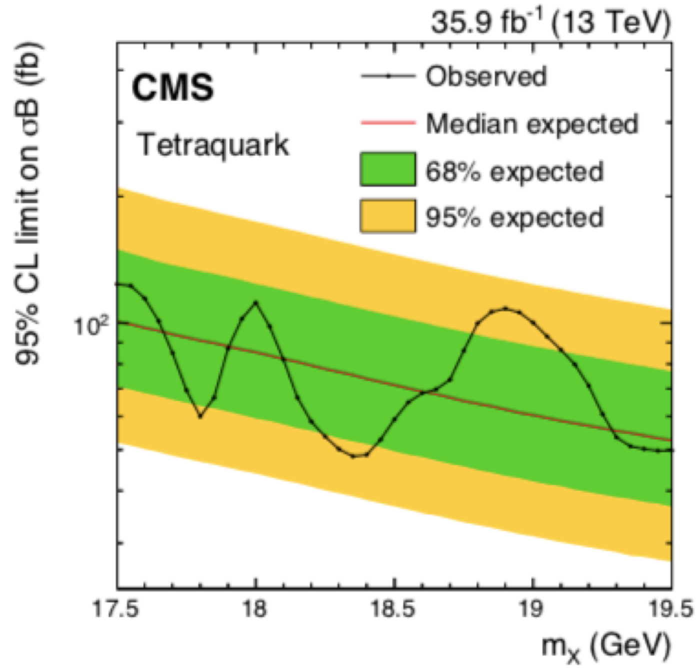


Using the number of $\Upsilon(1S)\Upsilon(1S)$ events observed in data as a reference, a resonance with a mass at ~19GeV and having a similar production Xsection (*) and BF to 4 muons as the $\Upsilon(1S)\Upsilon(1S)$ production, would produce ~100 candidates in our data sample (given the similarity between the kinematic distributions of both processes).

(*) $[79 \pm 11(stat) \pm 6(syst) \pm 3(BF)]pb$

Generic search for narrow resonances in the $\Upsilon(1S)\mu^+\mu^-$ final state

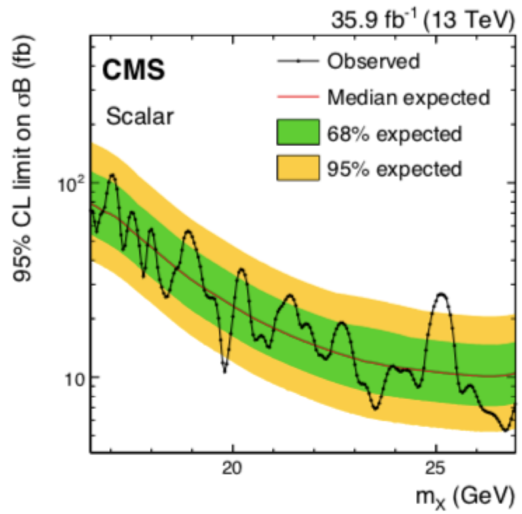
- **The results of a search for a light narrow resonance, such as a bound state beyond-the-standard model, does not show any significant narrow excess of candidates above the background expectation.**

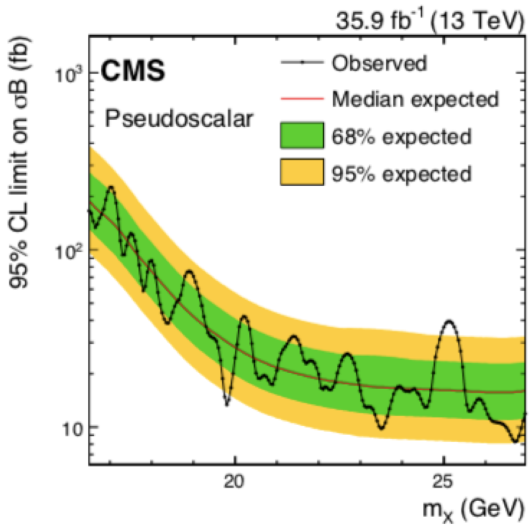
This generic search in the extended mass window is probed using the JHUGEN models.

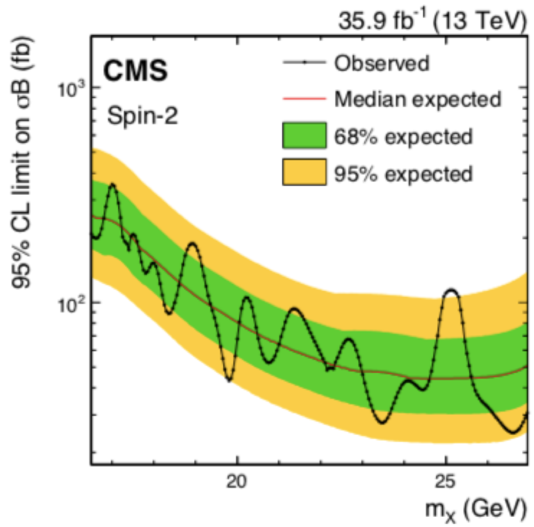
Upper limits on the product of the production Xsection of a resonance and the BF to a final state of 4 muons via an intermediate $\Upsilon(1S)$ are set @95% CL (using the modified frequentist construction CL_s in the asymptotic approx.**).**

The largest excess is observed @ 25.1GeV with a *local* stat. signif. of 2.4σ.

ULs range between $5 \div 380\text{fb}$ depending on the mass and signal model chosen (scalar, pseudoscalar, tensor)







- **These searches should be performed again with full Run-II data**

Outlook

- **The first evidence of X(3872) production in HI collisions has been found**

  The ratio of the prompt yields of X(3872) & $\psi(2S)$ times their branching fractions into $J/\psi\,\pi^+\pi^-$ needs more statistics to be conclusive but still provides a unique experimental input to theory community

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More exciting results can be obtained in the future either
- **in the understanding the nature of the X(3872) also by means of HI collisions, and**
- **in performing conventional & exotic spectroscopy searches and measurements.**

Backup & additional material

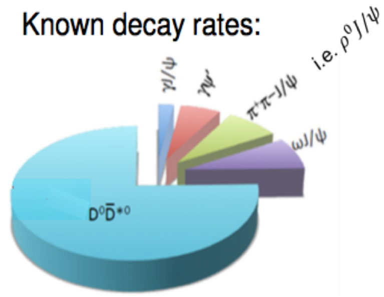
Why X(3872) can't be a conventional charmonium ?

- **What about $\chi_{c1}(2^3P_1)$ assignment ?**

Somehow ruled out by the fact that should be a pure isoscalar state:
X(3872) shows an equal amount of isospin components (I=0 & I=1): $\frac{B(X \to J/\psi\, \pi^+\pi^-\pi^0)}{B(X \to J/\psi\, \pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$

But mainly it is unlike because $c\bar{c} \to \rho J/\psi$ **violates isospin** (explanation below)

Known decay rates:



Indeed $X(3872) \to \rho^0 J/\psi,\ \rho^0 \to \pi^+\pi^-$ is **isospin violating decay!**

- Suppression of isospin **allowed** $X(3872) \to J/\psi\, \omega$ can be blamed on phase-space $\Delta m = 774.8 MeV$

- However comparing charmonium & bottomonium systems …

$c\bar{c}$: $\frac{BR(X(3872) \to \gamma J/\psi(1^3S_1))}{BR(X(3872) \to \pi^+\pi^- J/\psi(1^3S_1))} = 0.27 \pm 0.08$ LHCb, $\Delta m = 774.8$ MeV

$b\bar{b}$: $\Delta m = 795.2$ MeV

$\frac{BR(\chi_{b1}(2^3P_1) \to \gamma\Upsilon(1^3S_1))}{BR(\chi_{b1}(2^3P_1) \to \omega\Upsilon(1^3S_1))} = 6.1 \pm 1.6$

$\chi_{b1}(2^3P_1) \to \pi^+\pi^-\, \Upsilon(1^3S_1)$ not seen

… we can conclude that …

Enhancement of isospin violating $X(3872) \to \pi^+\pi^- J/\psi$ relative to radiative transitions rules out pure $\chi_{c1}(2^3P_1)$ interpretation

Systematic uncertainties on the ratio of corrected yields X(3872)/$\psi(2S)$

- **Several sources of systematic uncertainty on the ratio of corrected yields:**

	$N(\psi(2S))$	$N($ X (3872) $)$	$N($ X (3872) $)/N(\psi(2S))$
Yield Extraction	3.5%	4.3%	5.5%
Acceptance	1.8%	0.6%	1.9%
Efficiency	27.4%	43.1%	38.1%
p_T Shape	12.4%	2.9%	12.8%
TnP	+5.4%	+5.2%	+0.1%
	-5.0%	-4.8%	-0.2%
Prompt Fraction	22.4%	10.5%	15.4%
Total	+38.1%	+44.8%	+43.2%
	-38.0%	-44.8%	-43.2%

BDT is optimized to maximize the X(3872) statistical significance and not the $\psi(2S)$:
this can be a bias … to be covered by varying the cut on the BDTs' output

Alternatively to its nominal estimation (from MC, slide 19) use template fits on ℓ_{xy}

Associated to the tuning of the p_T distributions to match simulated to experimental data

Systematic uncertainties on the measurements of the 4 masses of excited Λ_b^0 states

- Systematic uncertainties (in MeV) in the measured masses ["-" = negligible] :

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 (quadratic sum)	0.009	0.011	0.77	0.41

Natural widths fixed in the baseline fit to the values by LHCb: now assign ± their uncertainty

Redo the fit once extended in the highest mass region (up to m~6650MeV)

Redo the fit only in the region m>6.1GeV (namely neglecting the broad excess)

Theoretical [Y.Yamaguchi *et al.*, PRD 91 (2014) 034034 **] (experimental status as was in 2014)**

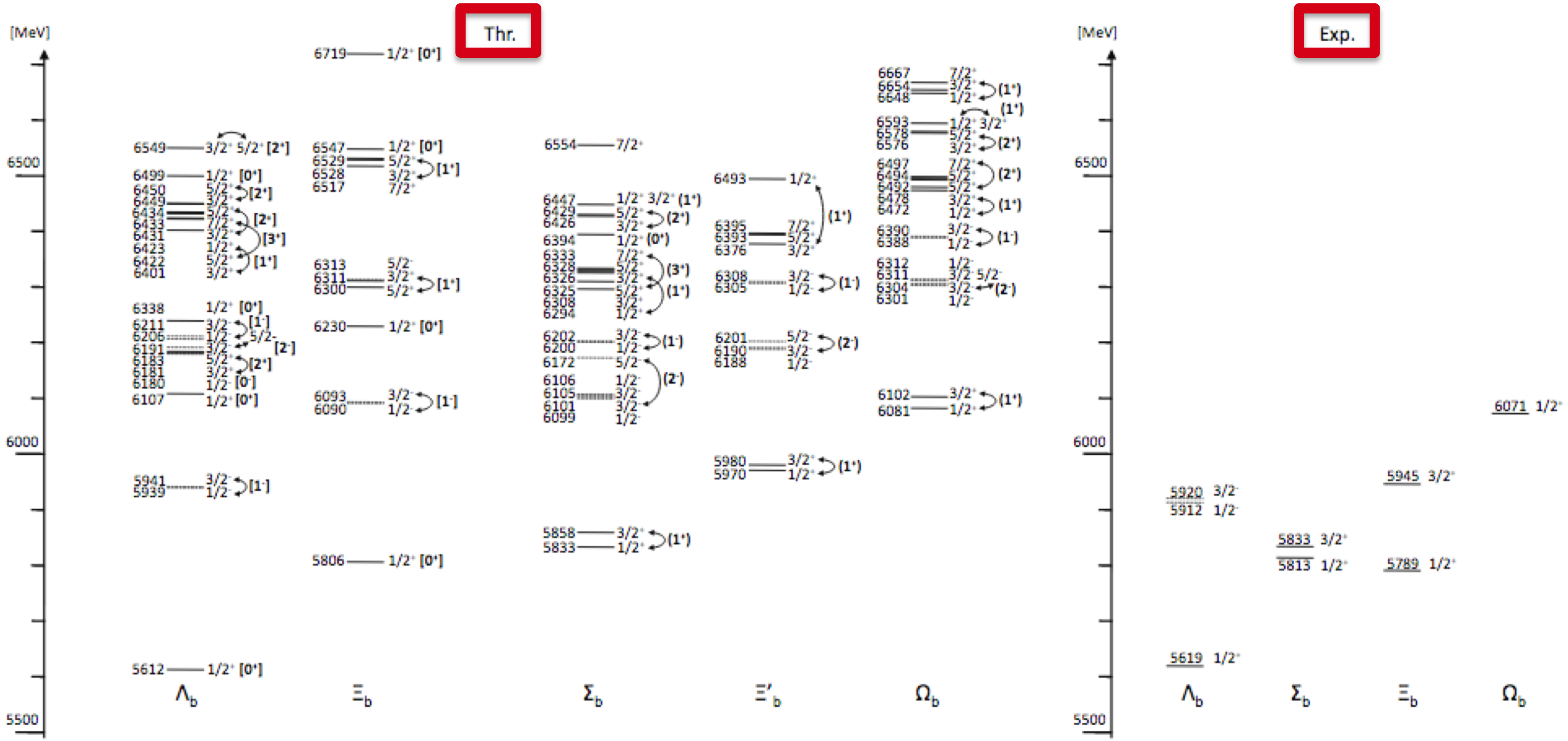
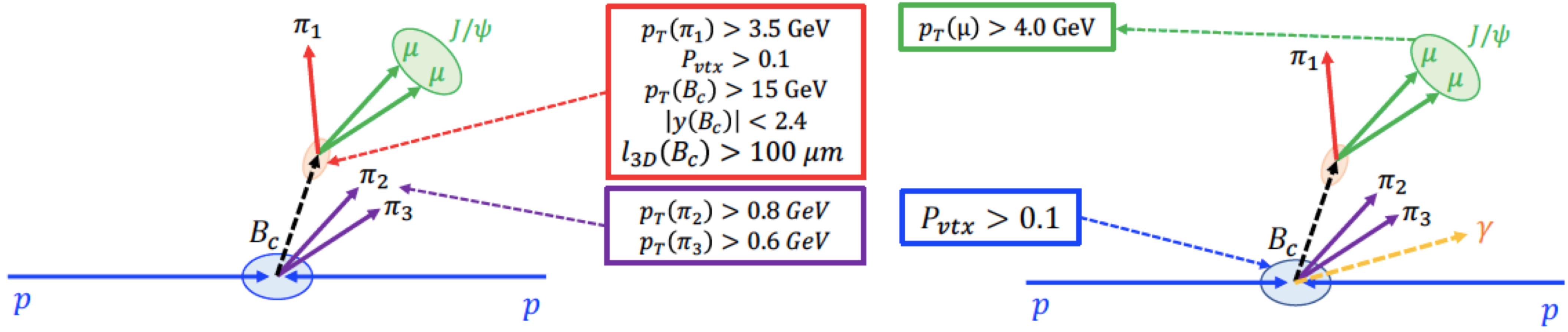


Figure 5: Comparison of the mass spectrum of the bottom baryons in the constituent quark model (CQM) [44] (left) and the experimental data [10] (right) The conventions are the same as Fig. 4.

$B_c^{(*)+}(2S)$ signals' extraction : selection criteria

Trigger preselection: two μ from J/ψ plus a track, with common vertex displaced from interaction point ($L_{xy}/\sigma_{L_{xy}} > 3.0$)



$B_c^+(2S) \to B_c^+\pi^+\pi^-$ $\qquad$ $B_c^{*+}(2S) \to B_c^{*+}\pi^+\pi^-$

- B_c^+ meson momentum required to point to PV in xy plane
- $6.2GeV < M(B_c) < 6.35$GeV
- The PV is re-fitted excluding the three B_c decay tracls ($\mu\mu\pi_1$)
- Tracks and muons satisfy high-quality requirements
- Among multiple $B_c^+\pi^+\pi^-$ candidates the highest p_T one is kept
- π_2 and π_3 are tracks from the refitted PV

Configuration of simulated samples for resonance searches

The signal of a narrow resonance decaying to a $\Upsilon(1S)$ meson and a pair of muons is modeled using different physics assumptions depending on the nature of the resonance:

- a bottomonium state with the properties of the $\chi_{b1}(1P)$, assuming a phase-space decay to a $\Upsilon(1S)$ meson and a pair of muons, using the PYTHIA 8.226 generator;
- a scalar particle produced in gluon fusion, using the JHUGEN generator [24–27];
- a pseudoscalar particle produced in gluon fusion, using the JHUGEN generator;
- a spin-2 particle produced in gluon fusion, using the JHUGEN generator.

The signals are generated assuming the narrow-width approximation. The $\chi_{b1}(1P)$ sample is used to model the tetraquark signal, for which no dedicated generator exists. The other samples correspond to the signals in the generic search over an extended mass range. For each model, four resonance mass values are simulated: 14, 18, 22, and 26 GeV. Since the signal acceptance falls steeply around and below 14 GeV in the simulated samples, the probed mass range in this analysis is restricted to stay well above this mass threshold. The different mass points are used to interpolate and extrapolate the signal model over the whole mass range.

The PYTHIA generator with the tune CUETP8M1 [28] is used to model the parton shower and hadronization processes. Generated events are processed through a simulation of the CMS detector based on GEANT4 [29].

In the UML fits:

The signal distributions are parameterized by the sum of two Gaussian functions with the same mean. The fits are performed for every resonance mass available in simulation, and the parameters of the functional forms are parameterized as a function of the resonance mass to interpolate or extrapolate the signal modeling to any mass not available in simulation. This is done separately for each signal model. The full width at half maximum is about 0.2 GeV for a resonance mass of 18 GeV.