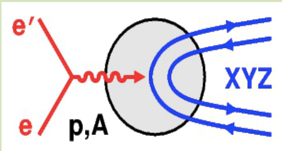
results & plans in exotic meson spectroscopy



Exotic heavy meson spectroscopy and structure with EIC

EIC Workshop @ CFNS Stony Brook

15/18 August 2022 - VIRTUAL TALK [https://indico.bnl.gov/event/14792]

Alexis Pompili

(on behalf of the CMS Collaboration)

UNIVERSITÀ degli Studi di BARI & I.N.F.N. Sezione di Bari

Introduction

- **CMS is providing significant contributions to beauty and quarkonium sectors**, mainly using final states containing muon pairs (due to trigger constraints).
  - This is possible thanks to the combination of :
    - **excellent tracking and high-purity muon identification performances**,
    - **a flexible trigger system** essential to collect data @ increasing luminosity & pile-up,
    - the large production cross-sections for heavy flavoured particles in *pp* collisions [LHC is a "quarkonium factory"; prompt production + from B decays (charmonia only)]

- **Selected relevant results integrate and/or complement the LHCb results !**

  - A complete review of **CMS results in conventional and exotic hadron spectroscopy** (WP for Snowmass2021) can be found here : arXiv:2204.06667

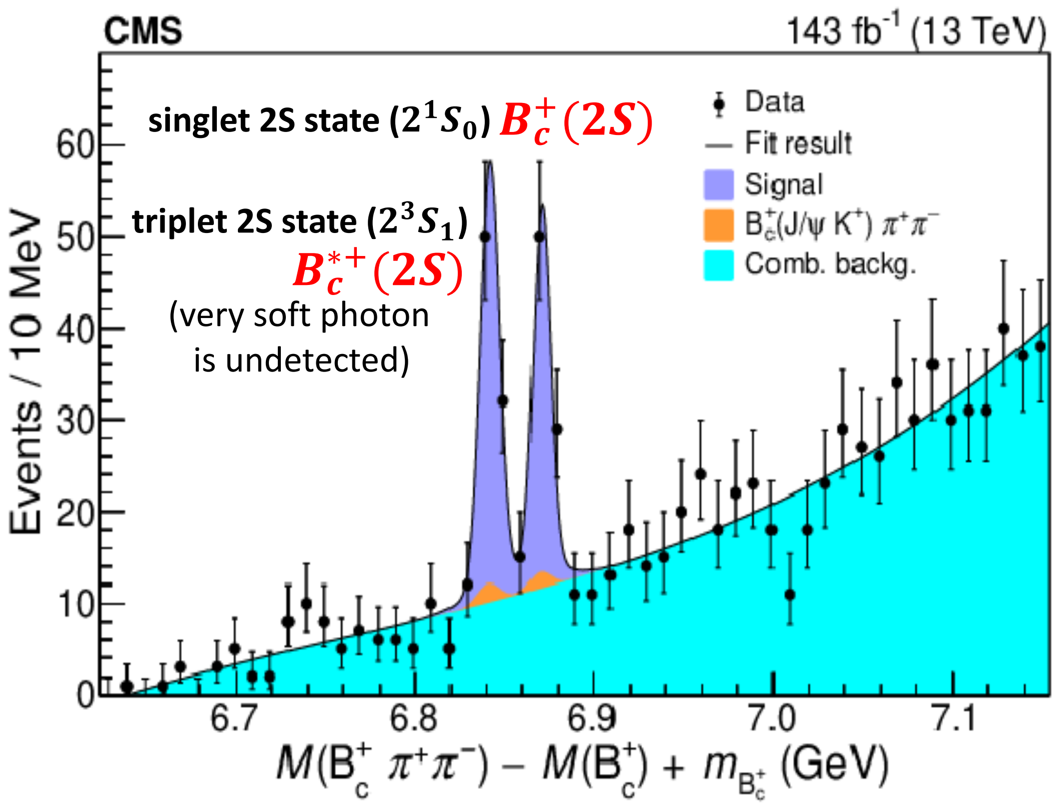
    Pointers to all CMS Heavy Flavour results can be found here: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

Conventional hadron spectroscopy

- $(\bar{b}c)$ spectroscopy : observation of *resolved* $B_c^+(2S)$ & $B_c^{*+}(2S)$ in $B_c^+\,\pi^+\,\pi^-$ spectrum

(first observation of *resolved* radially excited "doublet")

- $\Delta m = (28.9 \pm 1.5) MeV$
- mass resolution $\approx 6 MeV$

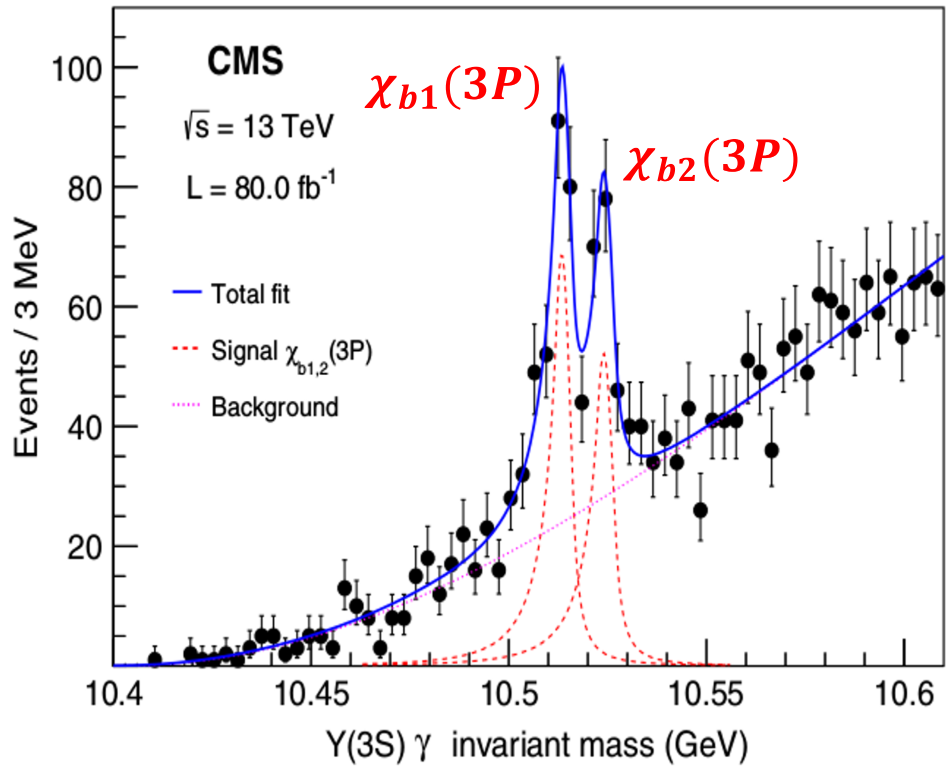


PRL 122 (2019) 132001

Conventional hadron spectroscopy

- $(\bar{b}c)$ spectroscopy : observation of *resolved* $B_c^+(2S)$ & $B_c^{*+}(2S)$ in $B_c^+ \pi^+ \pi^-$ spectrum — PRL 122 (2019) 132001
- $(\bar{b}b)$ spectroscopy : observation of *resolved* $\chi_{b1}(3P)$ & $\chi_{b2}(3P)$ in $\Upsilon(3S)\gamma$ spectrum

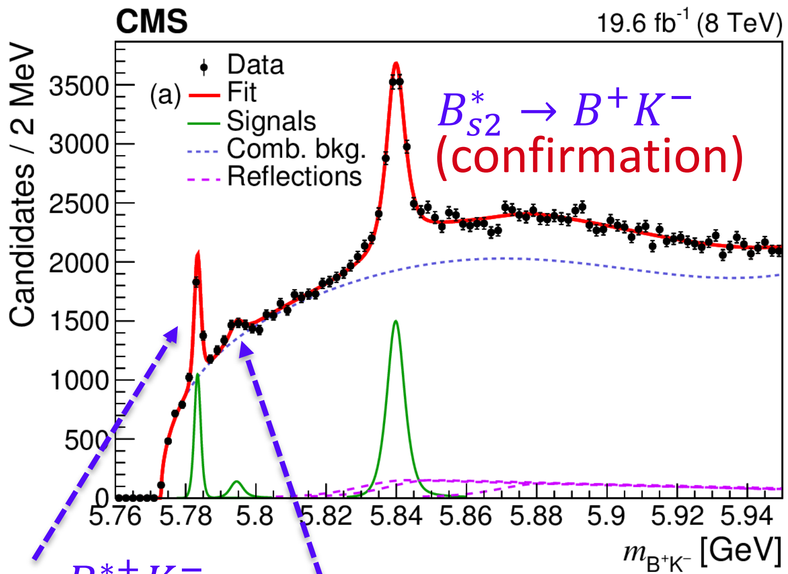
(first observation of resolved doublet)



PRL 121 (2018) 092002

Conventional hadron spectroscopy

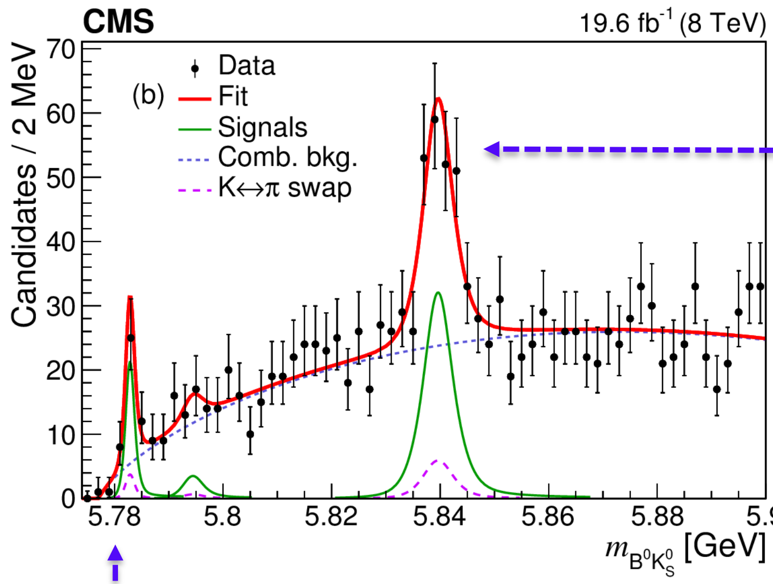
- $(\bar{b}c)$ spectroscopy : observation of *resolved* $B_c^+(2S)$ & $B_c^{*+}(2S)$ in $B_c^+\,\pi^+\,\pi^-$ spectrum — PRL 122 (2019) 132001
- $(\bar{b}b)$ spectroscopy : observation of *resolved* $\chi_{b1}(3P)$ & $\chi_{b2}(3P)$ in $\Upsilon(3S)\gamma$ spectrum — PRL 121 (2018) 092002
- $(\bar{b}s)$ spectroscopy : study of excited B_{sj}^{0*} mesons in the $B^{(*)0}K_s^0$ and $B^{(*)+}K^-$ spectra



$B_{s2}^* \to B^+K^-$ (confirmation)

$B_{s1} \to B^{*+}K^-$

$B_{s2}^* \to B^{*+}K^-$ (confirmations)



$B_{s2}^* \to B^0K_s^0$ (first observation)

$B_{s1} \to B^{*0}K_s^0$ (first evidence)

EPJ 78 (2018) 939

CMS Spectroscopy results - I / conventional

Conventional hadron spectroscopy

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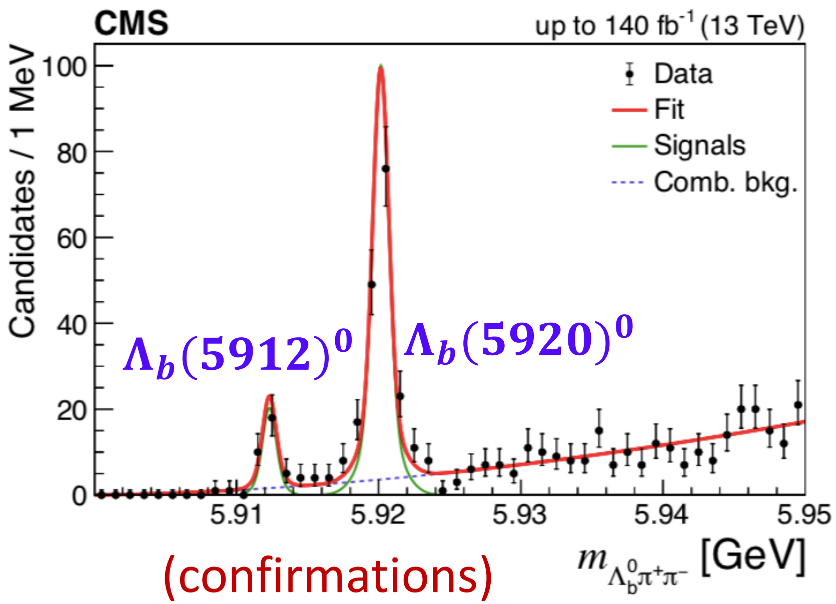
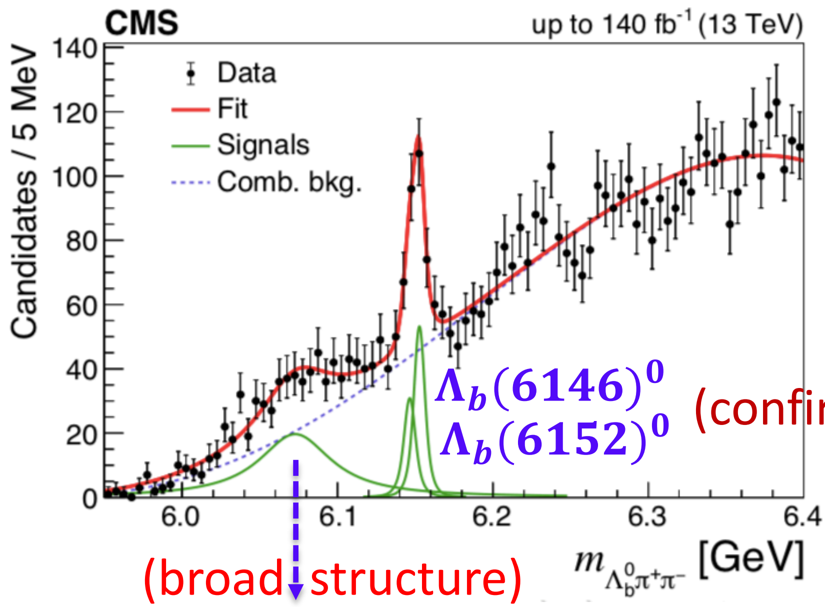
- (udb) spectroscopy : study of excited Λ_b^0 baryons in the $\Lambda_b^0\,\pi^+\,\pi^-$ spectrum



(confirmations)



(confirmations)

(broad structure)

PLB 803 (2020) 135345

[later confirmed by LHCb and interpreted as further excited state]

CMS Spectroscopy results - I / conventional

Conventional hadron spectroscopy (details in the additional material)

- $(\bar{b}c)$ spectroscopy : observation of *resolved* $B_c^+(2S)$ & $B_c^{*+}(2S)$ in $B_c^+ \pi^+ \pi^-$ spectrum — **PRL 122 (2019) 132001**
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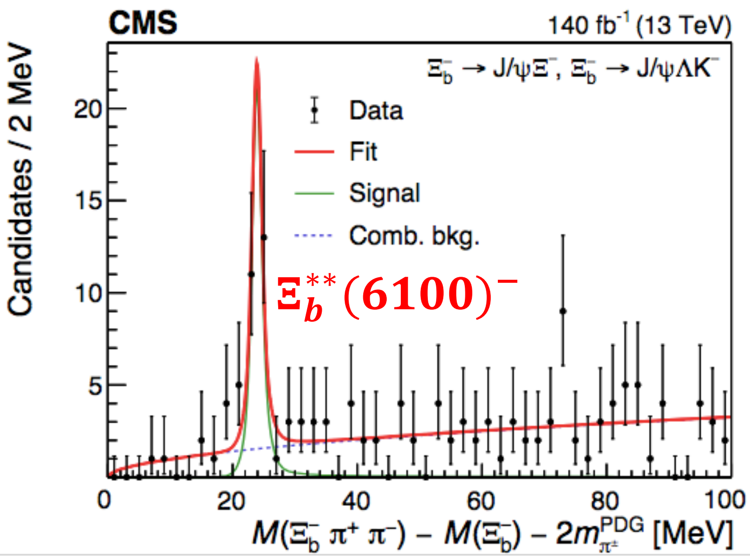
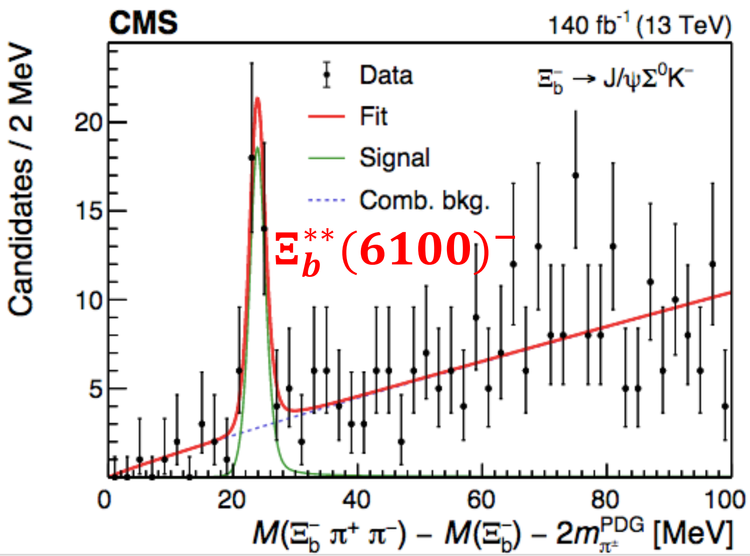
- (udb) spectroscopy : study of excited Λ_b^0 baryons in the $\Lambda_b^0 \pi^+ \pi^-$ spectrum — **PLB 803 (2020) 135345**
- (dsb) spectroscopy : observation of excited Ξ_b^{**-} baryons in the $\Xi_b^- \pi^+ \pi^-$ spectrum — **PRL 126 (2021) 252003**





(first observation in 3 different decay chains)

CMS Spectroscopy results - II / exotic / outline

Exotic hadron spectroscopy

- $X(3872)$ production properties in pp collisions — JHEP 04 (2013) 154
- First evidence of $X(3872)$ production in PbPb collisions — PRL 128 (2022) 032001
- First observation of the decay $B_s^0 \to X(3872)\phi$ — PRL 125 (2020) 152001
- Search for resonances in the $J/\psi\, J/\psi$ final state NEW! — https://cds.cern.ch/record/2815336/files/BPH-21-003-pas.pdf CMS-PAS-BPH-21-003

I will focus here on these **exotic meson spectroscopy** results interesting for this workshop.

CMS Spectroscopy results - II / exotic / outline

Exotic hadron spectroscopy

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- Search for narrow heavy bottom tetraquark decaying to $\Upsilon(1S)\,\mu^+\mu^-$ — PLB 808 (2020) 135578
- Search for the beauty partner of $X(3872)$ in the $\Upsilon(1S)\,\pi^+\pi^-$ spectrum — PLB 727 (2013) 57
- Search for pentaquark states in the $J/\psi\, p$, $J/\psi\, \bar{\Lambda}$ final states ($B^+ \to J/\psi\, \bar{\Lambda} p$) — JHEP 12 (2019) 100
- Peaking structures in the $J/\psi\, \phi$ mass spectrum in the $B^+ \to J/\psi\, \phi K^+$ decay — PLB 734 (2014) 261
- Search and Upper Limits for the $X(5568)$ in the $B_s^0\pi^+$ — PRL 120 (2018) 202005

(details in the backup material)

Production & decays @ CMS - I

- **Two main production processes of charmonia (& charmonium-like) states @ Hadron Colliders :**

  - **Prompt (inclusive):** $pp(p\overline{p}) \to (c\overline{c}) + X$
  - ***b-jets*** **(exclusive B-decays):** $B \to (c\overline{c}) + X$

  di-muons are used as trigger signatures (+ tracks for displaced topologies)

NOTE: **bottomonium explored triggering on prompt di-μs around the S-wave states** **(** $Y(nS)\,, n = 1{,}2{,}3$ **)**

- **Establishing XYZ existence with both production mechanisms would be ideal, but …**

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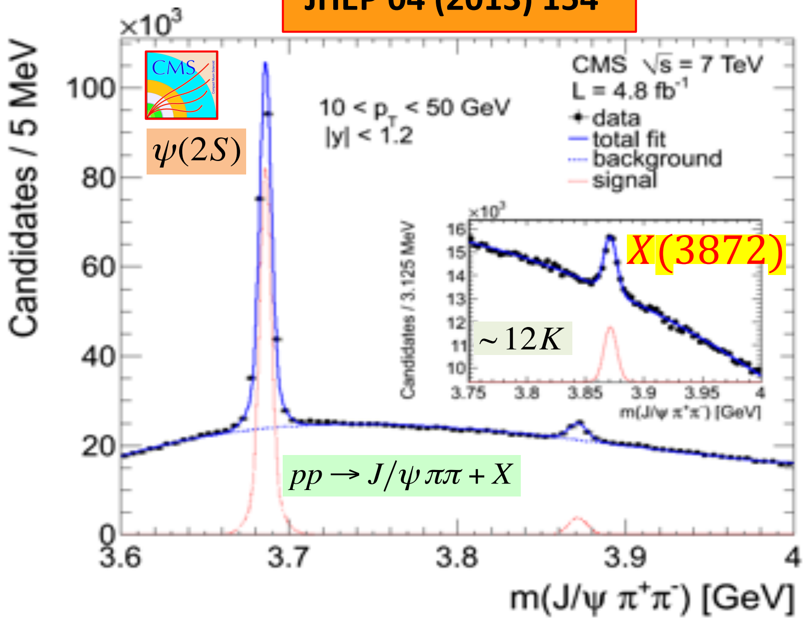
JHEP 04 (2013) 154



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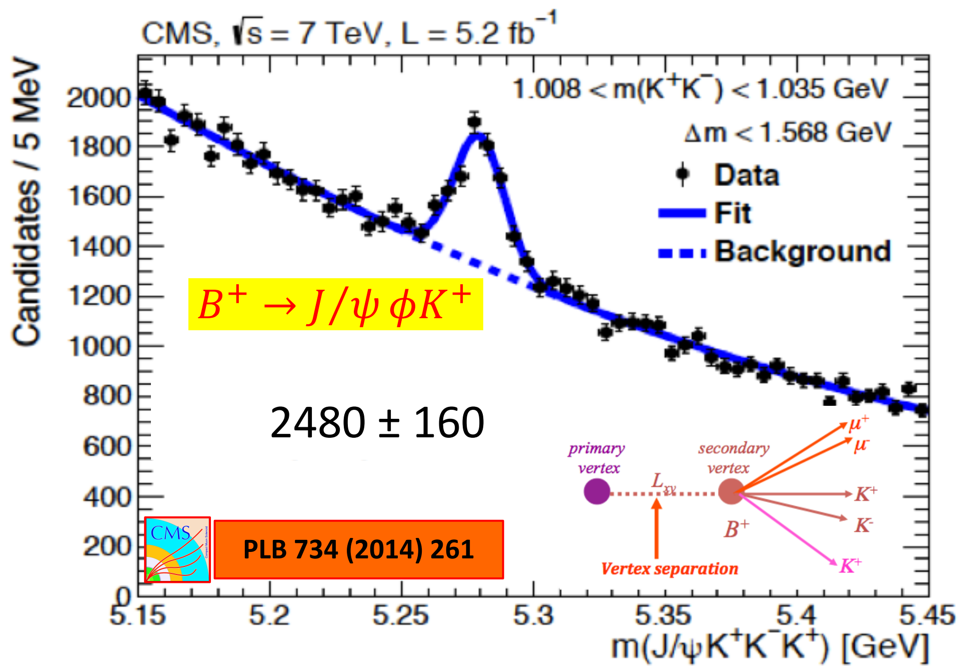
Amplitude analyses of 3-body B-decays difficult : high BKGs (low purity) due to the lack of hadronic PID



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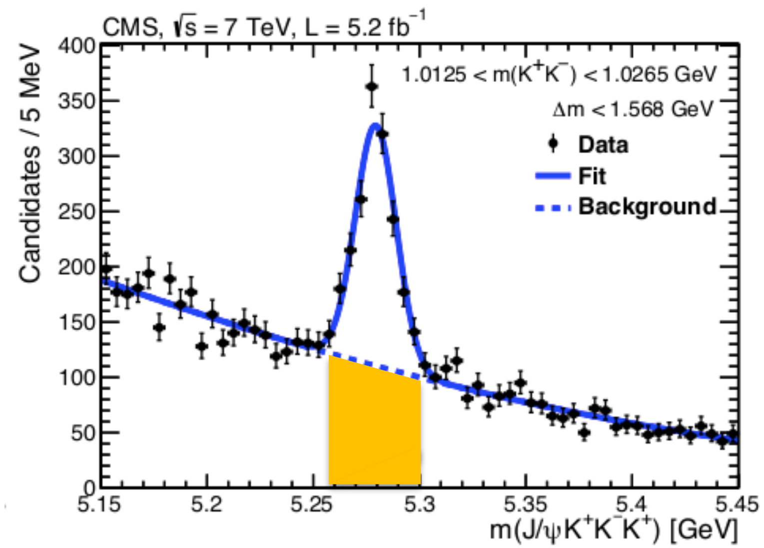
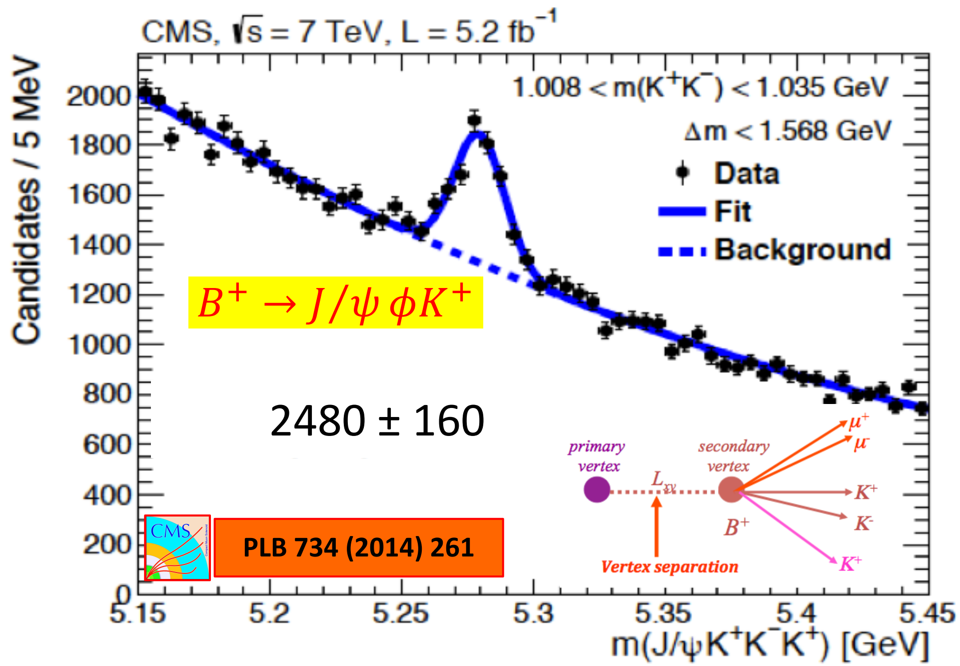


[tighter requirements]



Production & decays @ CMS - II

- **Typical decay processes (suitable when lacking *Hadron Identification* capabilities):**

  - **Hadronic transitions** to a lighter $c\bar{c}$ meson through the emission of light hadrons $[\pi, \pi\pi, K_S^0, \phi, \Lambda, \ldots]$

    - suitable for triggering on dimuon objects ($\boldsymbol{J/\psi}$, $\boldsymbol{\psi(2S)}$ - both prompt/displaced - also, **non-resonant dimuons** sharing a common vertex)

    … in the different topologies: prompt**, non-prompt, "long-lived" (**baryonic decay chains**)**

Production & decays @ CMS - II

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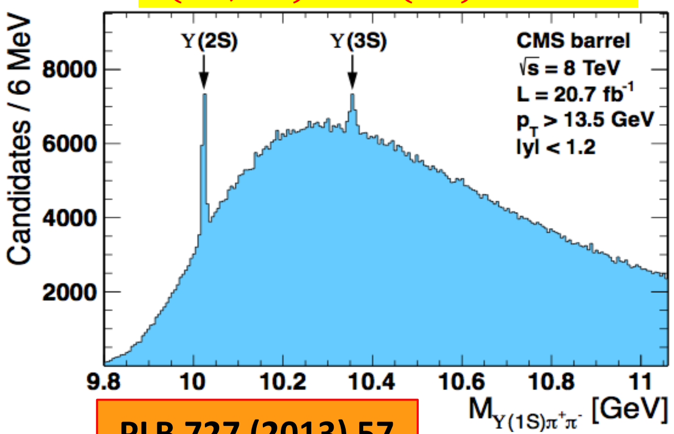
… in the different topologies: **prompt**, …

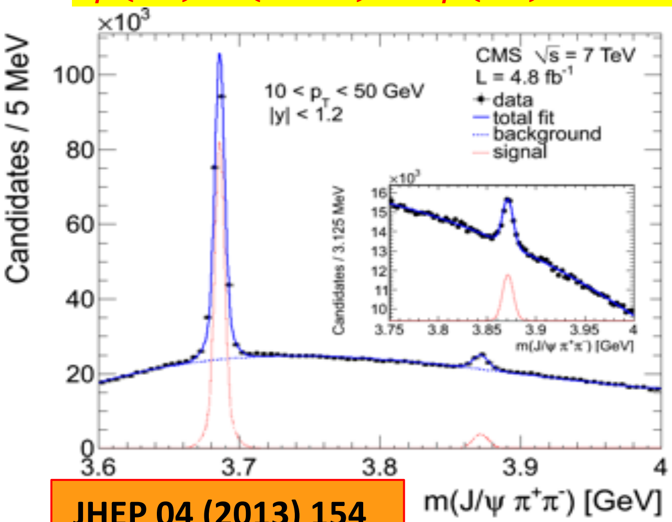
$\Upsilon(2S,3S) \to \Upsilon(1S)\,\pi^+\pi^-$



PLB 727 (2013) 57

(only prompt)

$\psi(2S), X(3872) \to \psi(1S)\,\pi^+\pi^-$

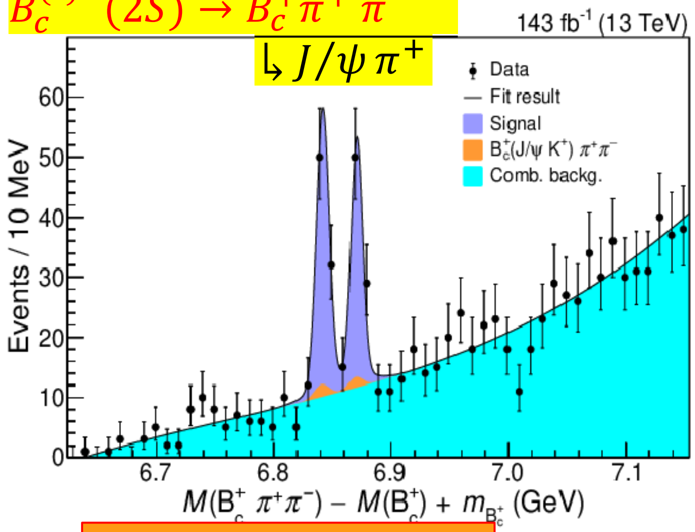


JHEP 04 (2013) 154

(inclusive = **prompt** + non-prompt)

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

$\hookrightarrow J/\psi\,\pi^+$



PRL 122 (2019) 132001

(displaced B_c + **prompt di-pion**)

Production & decays @ CMS - II

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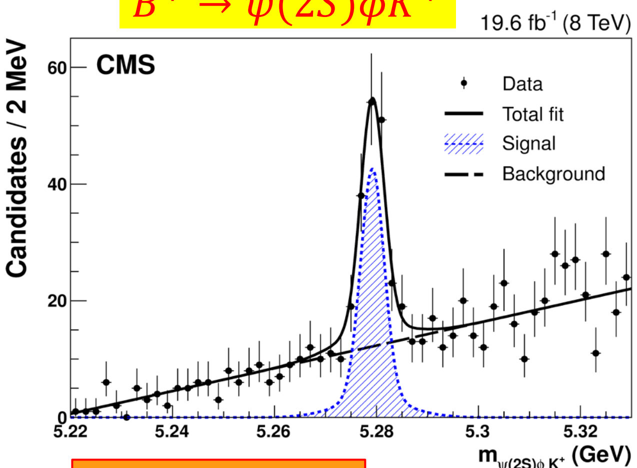
… in the different topologies: **prompt, non-prompt, …**

(first observation)

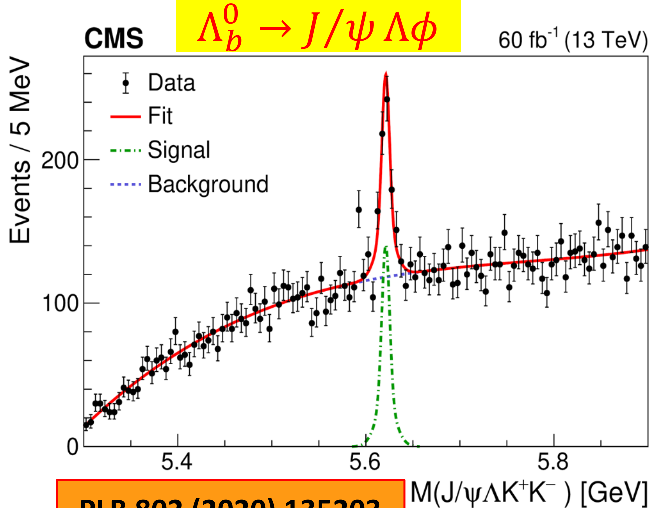
$B^+ \to \psi(2S)\phi K^+$



PLB 764 (2017) 66

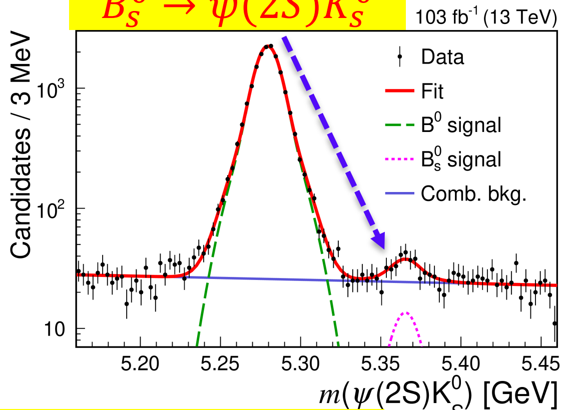
(first observation)

$\Lambda^0_b \to J/\psi\,\Lambda\phi$



PLB 802 (2020) 135203

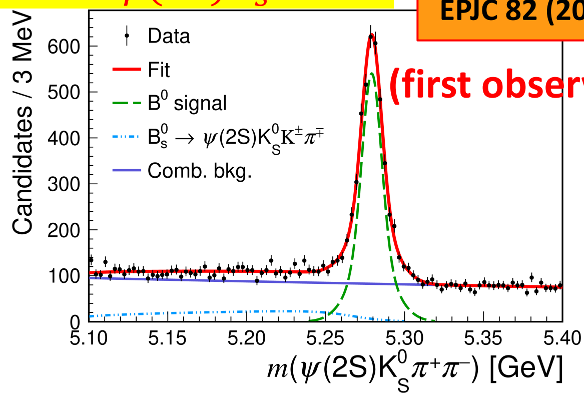
$B^0_S \to \psi(2S)K^0_S$



NEW!

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

EPJC 82 (2022) 499



(first observations)

Production & decays @ CMS - II

Typical decay processes (suitable when lacking *Hadron Identification* capabilities):

- **Hadronic transitions** to a lighter $c\bar{c}$ meson through the emission of light hadrons $[\pi, \pi\pi, K_S^0, \phi, \Lambda, \ldots]$
  - suitable for triggering on dimuon objects (J/ψ , $\psi(2S)$ - both prompt/displaced - also, **non-resonant dimuons** sharing a common vertex)

… in the different topologies: **prompt, non-prompt,** “long-lived” (baryonic decay chains)

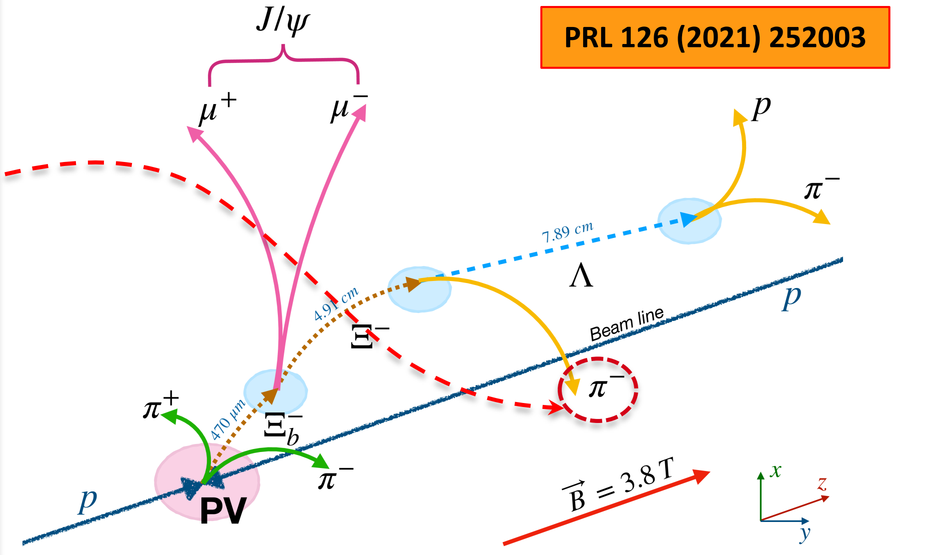
Good efficiency for low-p_T tracks, both **prompt** and more or less **displaced** from the PV.

The **displaced tracks** are crucial for the reconstruction of

- the $K_S^0 \to \pi^+\pi^-$,
- the self-flavour tagging $\Lambda^0 \to p\pi^-$ decays
- the $\Xi^- \to \Lambda^0\, \pi^-$ decays (these π^- are very soft & displaced)

Decay chain from $\Xi_b^{**}(6100)^- \to \Xi_b^-\pi^+\pi^-$

PRL 126 (2021) 252003



Production & decays @ CMS - II

- **Typical decay processes (suitable when lacking *Hadron Identification* capabilities):**
  - **Hadronic transitions** to a lighter $c\bar{c}$ meson through the emission of light hadrons $[\pi, \pi\pi, K_S^0, \phi, \Lambda, \ldots]$
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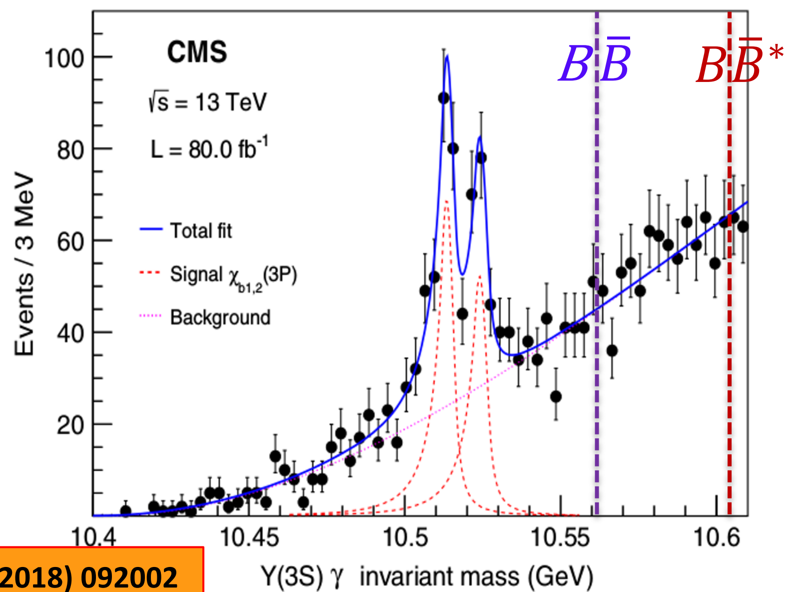
    … in the different topologies: **prompt, non-prompt, "long-lived" (**baryonic decay chains**)**

  - **Electromagnetic transitions** to a lighter $c\bar{c}$ meson through the emission of a γ
    - using ***photons converted in the tracker material*** (reco issue: *low efficiency* & for $E_\gamma > 400 MeV$)



PRL 121 (2018) 092002

- $\Delta m_{21} = (10.60 \pm 0.64 \pm 0.17) MeV$
- $\chi_{bJ}(3P)$ mass resolution $\cong$ **$2.2\ MeV$**

(first observation of resolved doublet)

There have been earlier measurements related to the $\chi_{bJ}(3P)$ mass by ATLAS, LHCb & D0, but without being able to distinguish between the candidates ($J = 1, 2$) of the $\chi_{bJ}(3P)$ multiplet

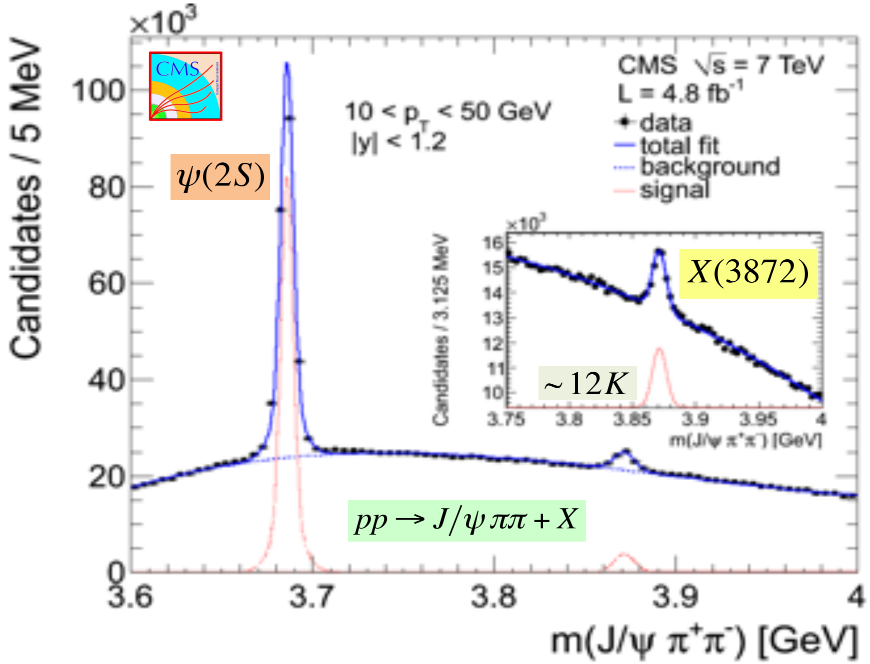
X(3872) production features

JHEP 04 (2013) 154 $\sqrt{s} = 7TeV$ (Run-I/2011)

X(3872) @ LHC

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

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



- [CMS logo] **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**

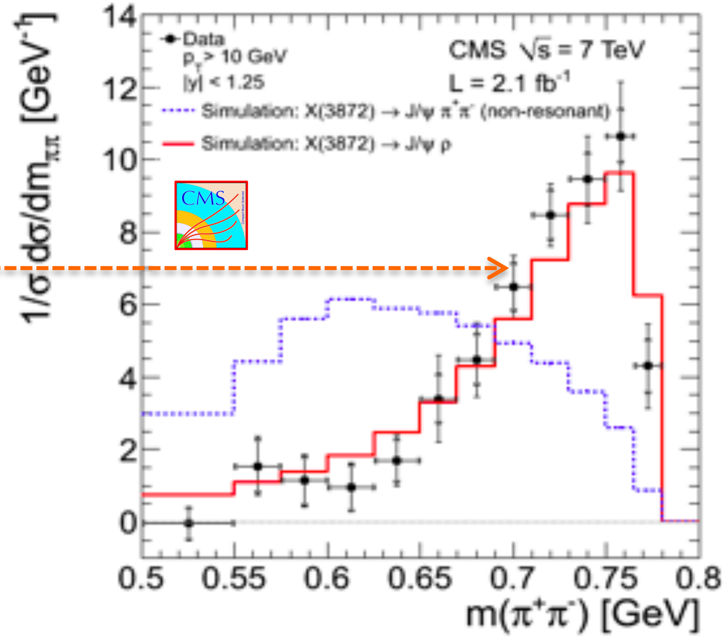
  → Will be discussed in next slides

- [ATLAS logo] **performed similar studies most recently (with** $8\ TeV$ **data) [** JHEP 01 (2017) 117 **].**
  This will be useful - later - for some comparison with theoretic calculations.

X(3872) @ CMS & ATLAS : $\pi^+\pi^-$ 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
$B^+ \to XK^+,\ X \to J/\psi\,\rho^0,\ J/\psi \to \mu\mu,\ \rho^0 \to \pi\pi$
decay chain.
Confirmed by more recent LHCb analysis
[**PRD 92 (2015) 011102** : **under general conditions :**
w/o assumption on lowest possible *L* in the *X* sub-decay]

- This is still the dominant quasi-two body intermediate decay even if LHCb found recently a sizable contribution from ω [**LHCb-PAPER-2021-045**]

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

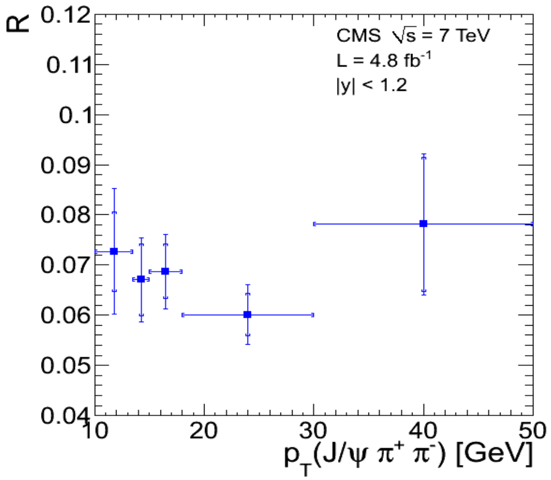
- A ratio of the cross sections has been measured to cancel out many systematic sources:

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

YIELDS from fits to data

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

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



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

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

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

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

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

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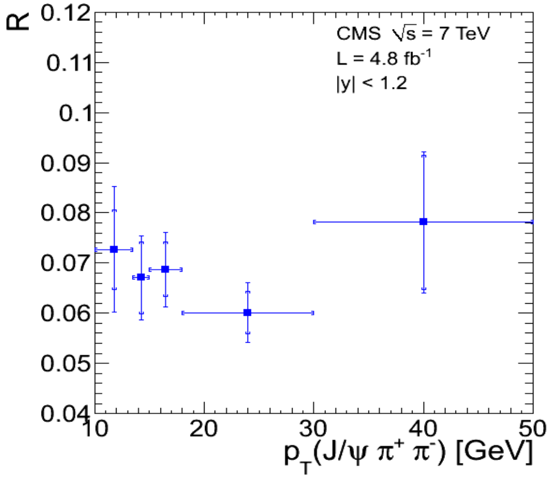


- integrating over $10 < p_T < 50 GeV$:

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

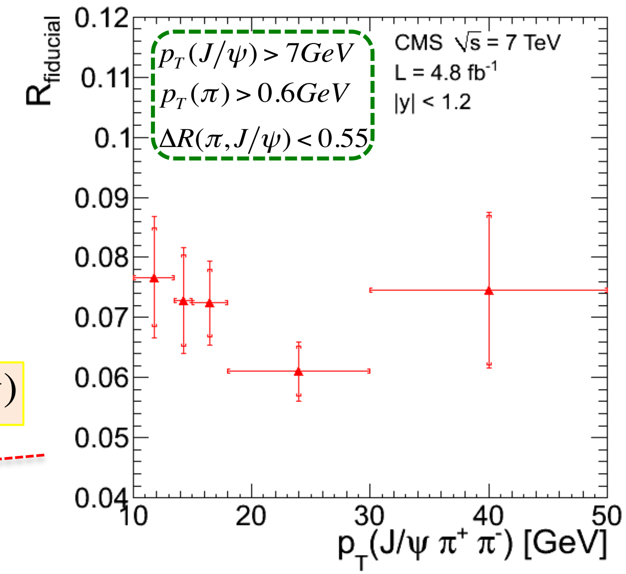
- Acceptance corrections depend on assumptions on the angular distribution of the final states (production mechanism of the X(3872) is unknown) ➡ a result without them in a fiducial region is given :

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

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

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

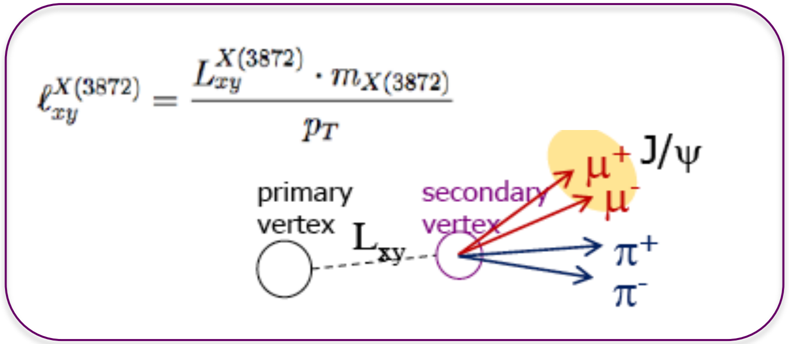
NO significant dependence on the p_T

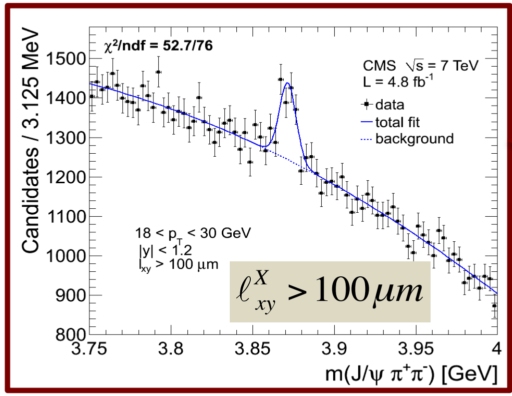


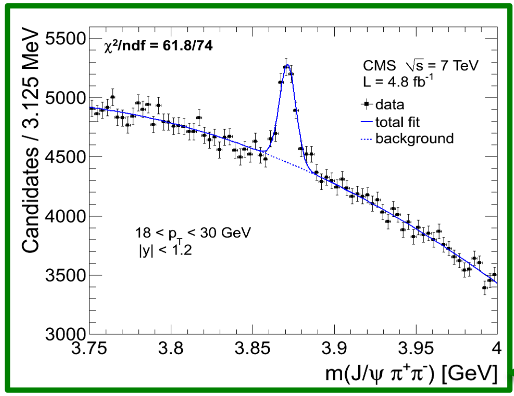
- The *X(3872)* can be produced from B hadrons' decays into a secondary vertex : prompt & non-prompt components can be separated by pseudo-proper decay length

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

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





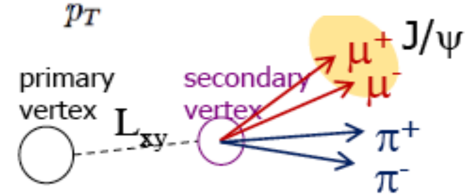


nonprompt fraction = *Nr. of X(3872) from B* / *Nr. of X(3872)*

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 pseudo-proper decay length

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



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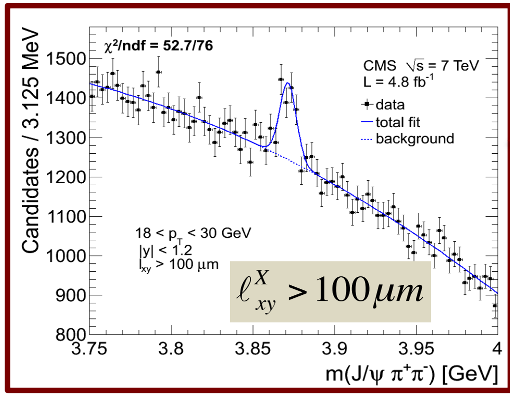

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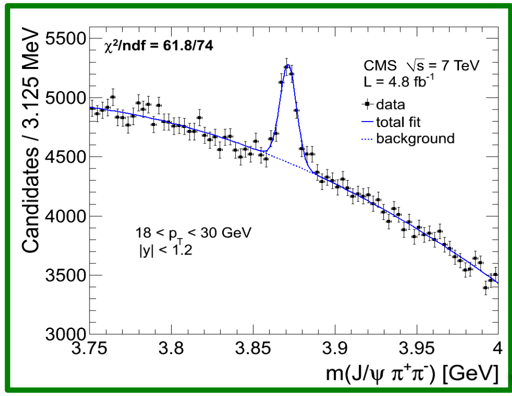
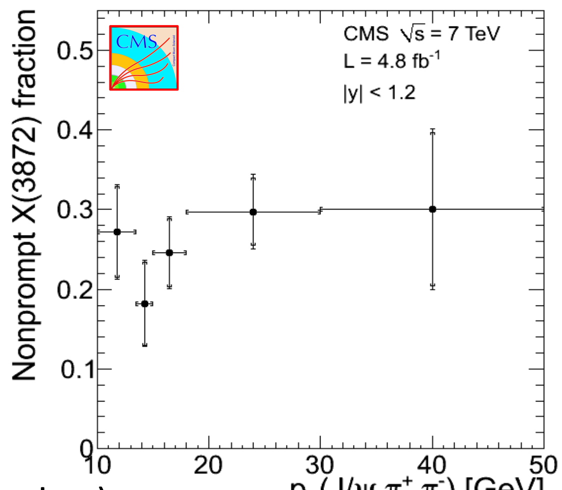


- **non-prompt fraction : NO dependence on** p_T
- integrating over $10 < p_T < 50 GeV$ (for $|y| < 1.2$): $f_{NP} \cong 0.263 \pm 0.023 \pm 0.016$

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

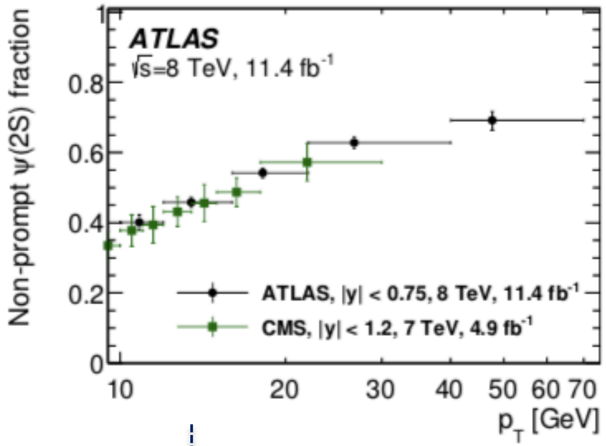


- In agreement with results by ATLAS (next slide with CMS and ATLAS results together)

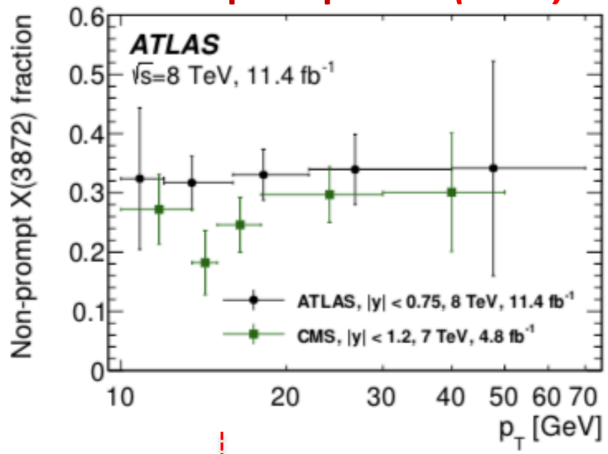
X(3872) : non-prompt fraction compared to ψ(2S)

- Indeed :

non-prompt for $\psi(2S)$



non-prompt for *X(3872)*

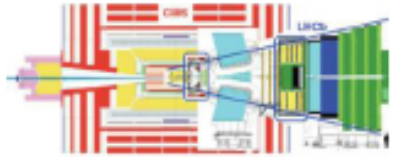


- increases with p_T
- good agreement with CMS [JHEP02 (2012) 011]

- **no sizable dependence on p_T**
- good agreement with CMS

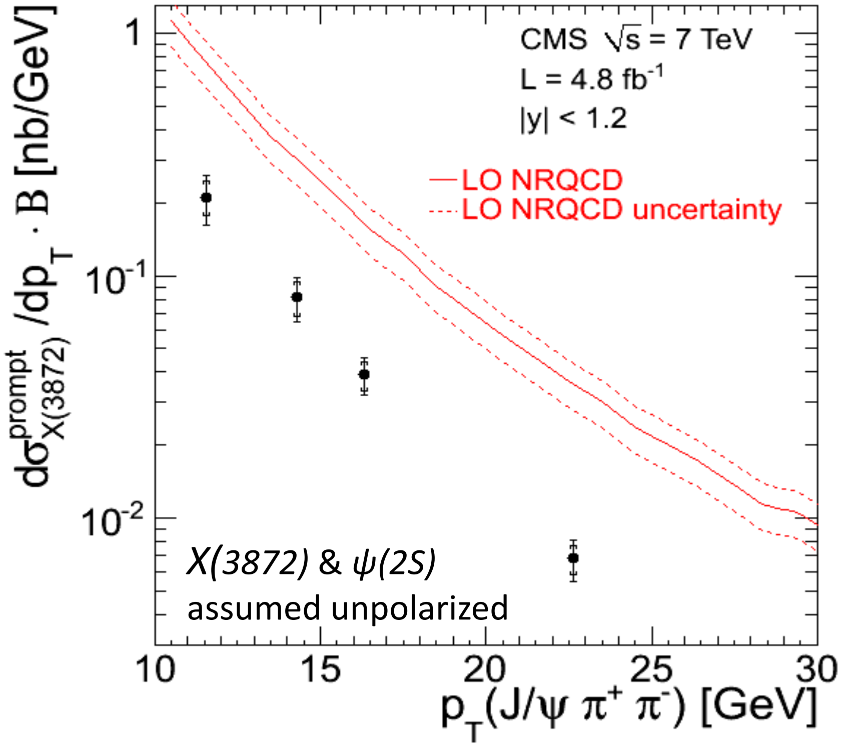
X(3872) @ CMS : prompt production Xsection

- Exploiting the previous measurements, the ***prompt production xsection*** for the *X(3872)* is measured as a function of $\boldsymbol{p_T}$ @ 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



- 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 $\boldsymbol{p_T}$]
- Integrating over p_T (10-30*GeV*) [and |y|<1.2] get the integrated cross section times the branching fraction:

$$\sigma^{prompt}_{X(3872)} \times B\left(X(3872) \to J/\psi\ \pi^+\pi^-\right) \cong (1.06 \pm 0.11 \pm 0.15)nb$$

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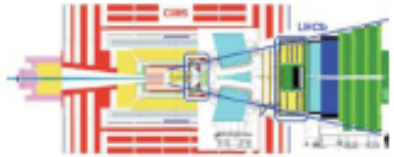
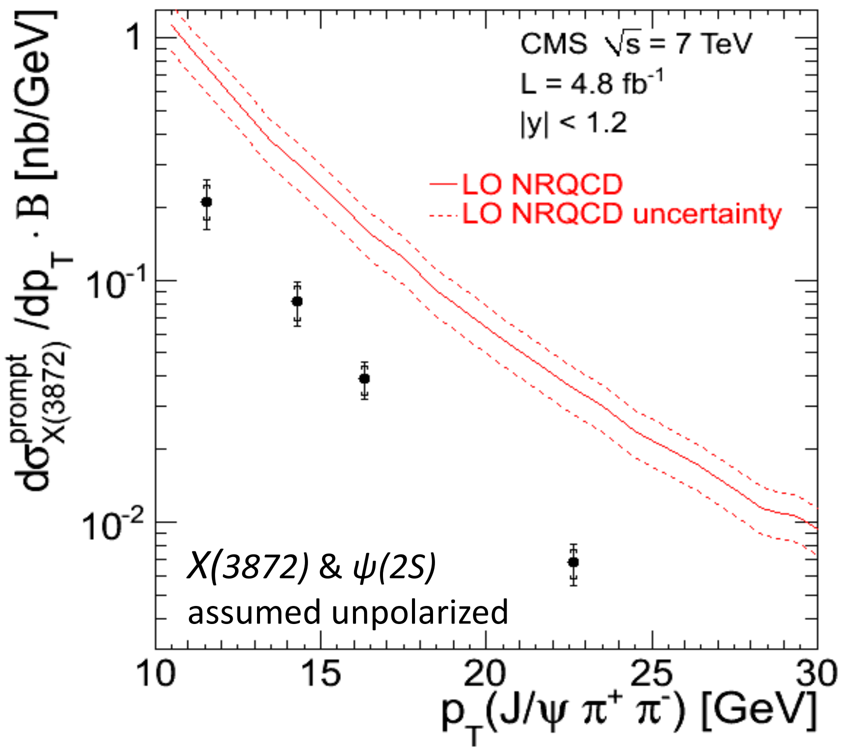


$$\sigma^{\rm prompt}_{X(3872)} \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{1 - f^B_{X(3872)}}{1 - f^B_{\psi(2S)}} \cdot R \cdot \left(\sigma^{\rm prompt}_{\psi(2S)} \cdot \mathcal{B}(\psi(2S) \to \mu^+\mu^-)\right) \cdot \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S)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

- f^B: non-prompt fraction
- R: Cross sections ratio
- $\sigma^{\rm prompt}_{\psi(2S)} \cdot \mathcal{B}(\psi(2S) \to \mu^+\mu^-)$: measured by CMS in JHEP02 (2012) 011
- $\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)/\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$: 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, an upper limit lower of one order of magnitude would imply lower prompt production rates of few orders of magnitude **[Bignamini et al., PRL 103 32009) 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 the 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) !

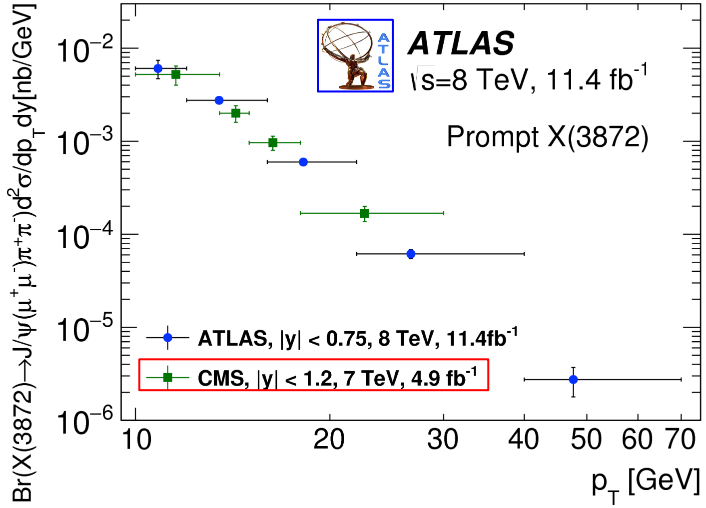
- **The previous CMS measurement is not supporting an S-wave molecular interpretation**
- **Pure molecular model** (Swanson *et al.*) **not supported by the LHCb measurement of the radiative $X(3872) \to \psi(2S)\gamma$ sub-decay in the $B^+ \to X(3872)K^+$ decays**
- **Significant *L* would hint a molecular 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]

- 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 $\bar{D}^0 D^{*0}$.**

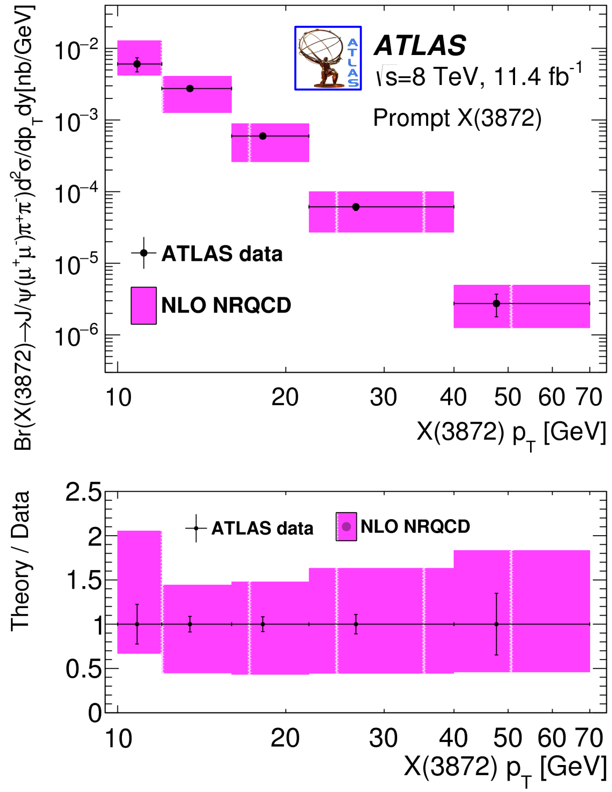
- **Results on $X(3872)$ production from** ATLAS have been compared with the latter model [next slide]

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

PRL 128 (2022) 032001

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

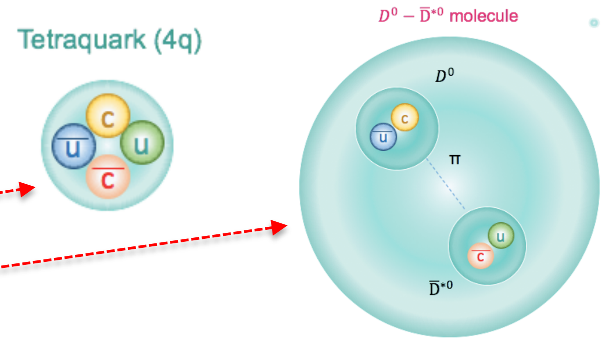
(c.o.m. energy per nucleon pair)

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

(End of Run-II / 2018)

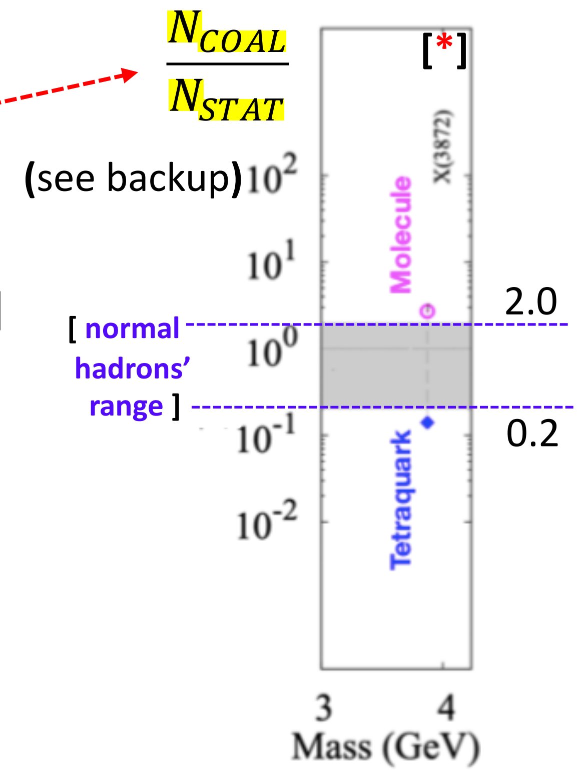
Can we learn more about X(3872) nature using HI collisions ?

- **The study of X(3872) production rate in HI collisions, with reference to a standard charmonium (ψ(2S)), may help to separate a compact tetraquark configuration (radius ≲ *1fm*) from a large-sized configuration of a molecular state (radius ~*10fm*)**



- **In relativistic HI collisions the formation of QGP** (an extended volume of deconfined quarks & gluons) **could enhance the production of the X(3872) state through the quark coalescence mechanism which depends on the spatial configuration (size) of the exotic state !**
  - Relevant parameter is the **ratio of hadron yields** calculated in the coalescence model to those in the **statistical hadronization model**

    [it assumes the produced matter being in thermodynamical equilibrium **& is known to describe the yields of hadrons in HI collisions very well]**
  -



[*] **PRL 106 (2011)** 212001

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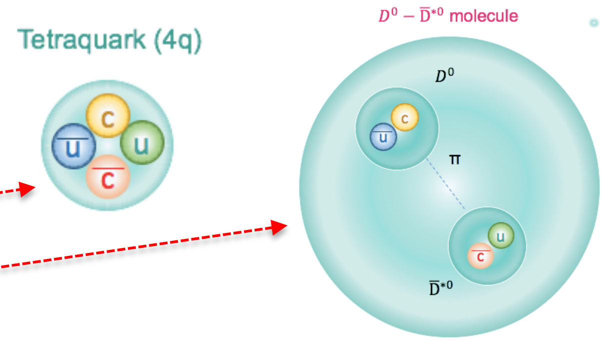

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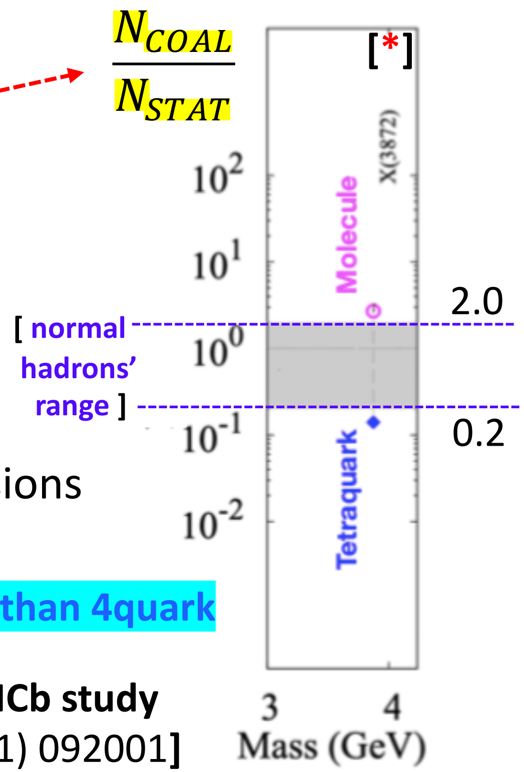
    [it assumes the produced matter being in thermodynamical equilibrium **& is known to describe the yields of hadrons in HI collisions very well]**
  - Longer distances between (anti-)quarks could also lead to **higher** X(3872) **dissociation rate** similar to suppression mechanism of quarkonia in HI collisions



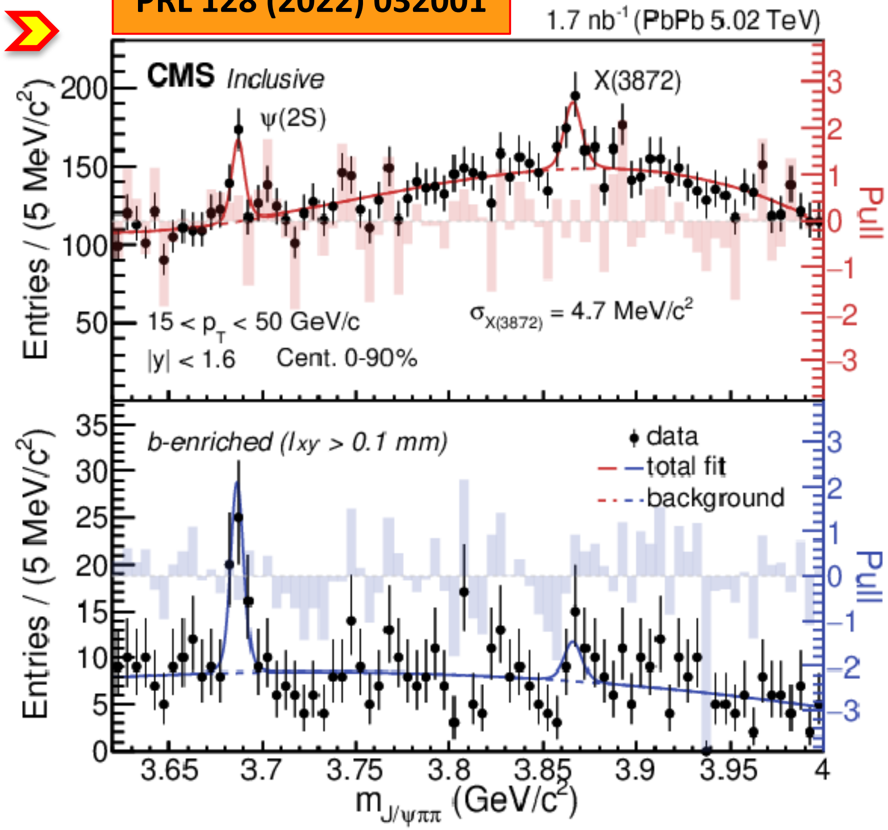
Its much larger size makes the molecule easier to be produced but also to be destroyed than 4quark

- **The *Comover Interaction Model* [EPJ C81 (2021) 669] seems to reproduce the recent LHCb study of X(3872) prompt prod. as a function of final state particle multiplicity [PRL 126 (2021) 092001]**

[*] **PRL 106 (2011)** 212001

Signals in B-enriched & inclusive samples ($J/\psi\,\pi^+\pi^-$ final state)

PRL 128 (2022) 032001



In *inclusive* data sample :

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

- **Clearly visible $X(3872)$ & $\psi(2S)$ signals to same final state**

In B-enriched data sample :

(non-prompt part, i.e., from B decays: $\ell_{xy} = \frac{L_{xy} \cdot m_{PDG}}{|\vec{p}_T|} > 0.1$ mm
it is produced outside the QGP)

- **non-prompt $\psi(2S)$ is clearly visible**

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

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

$$R = \frac{N^X_{corr}}{N^\psi_{corr}} \quad , \quad N^i_{corr} = \frac{N^i_{raw} \cdot f^i_{prompt}}{(\alpha \cdot \varepsilon_{tot})^i}$$

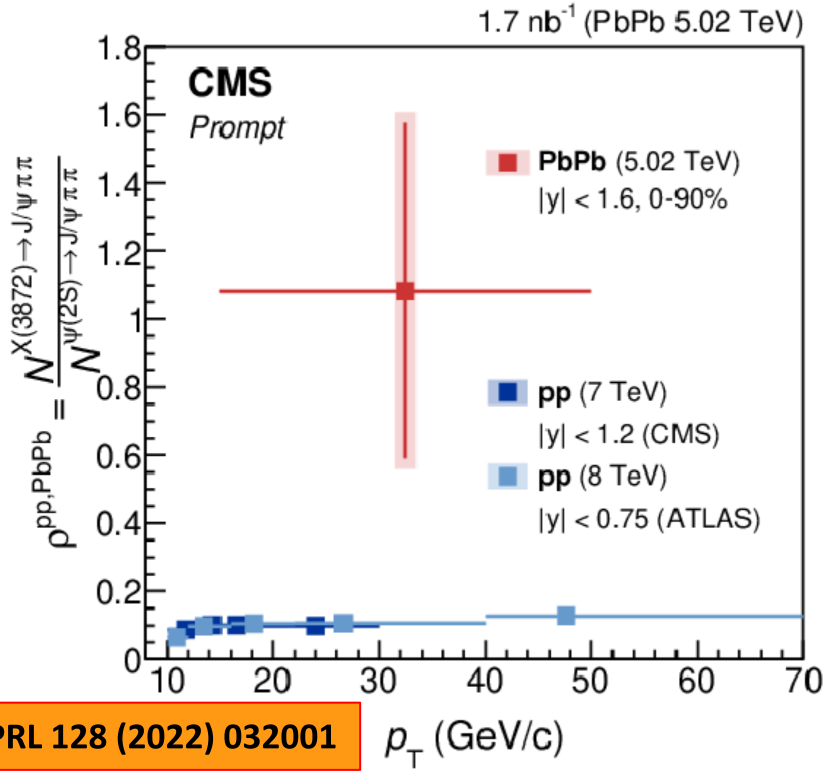
$$f_{prompt} = 1 - \frac{N_{B-enr}/f^{non-prompt}_{B-enr}}{N_{incl}}$$

[see backup]

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

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

$$R = \frac{N^X_{corr}}{N^{\psi(2S)}_{corr}}$$



PRL 128 (2022) 032001

Note: stat.err.=bars & syst.err.=boxes (not added!)

$R(PbPb) = 1.08 \pm 0.49(stat.) \pm 0.52(syst.)$

… to be compared with …

$R(pp) \sim 0.1$ (both ATLAS & CMS)

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

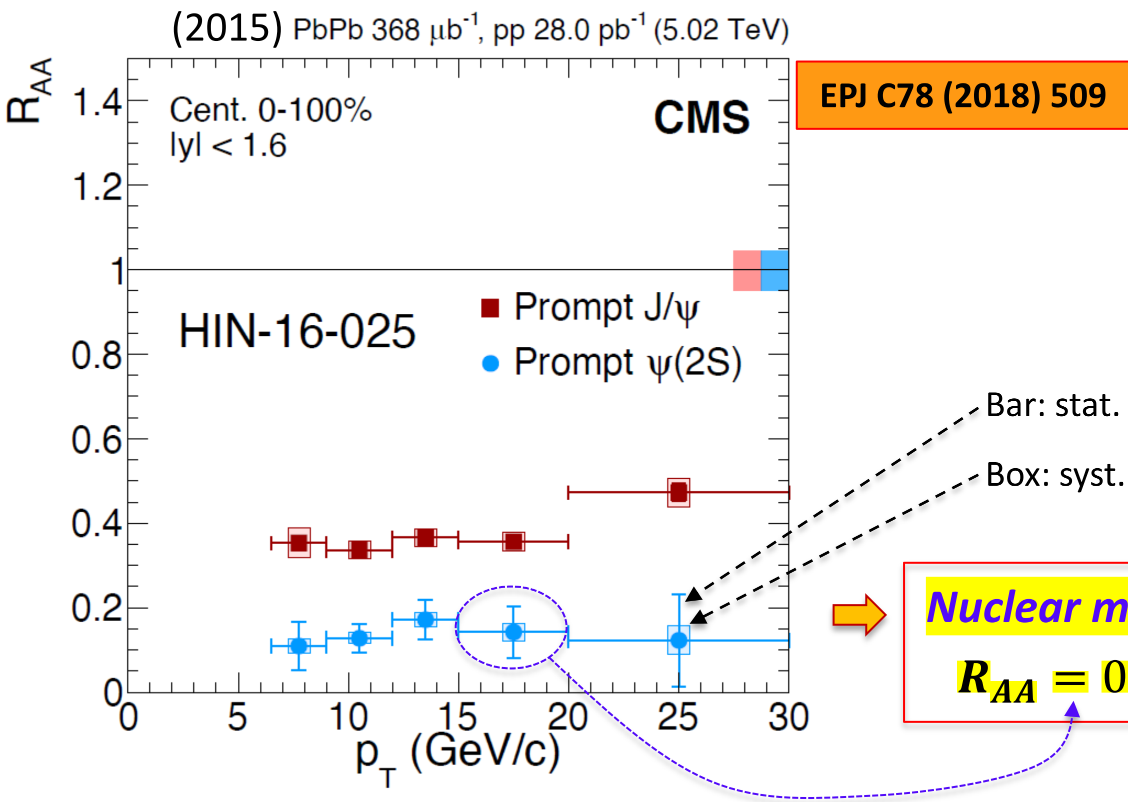
S-wave Charmonia nuclear modification factors in PbPb

- **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 :



EPJ C78 (2018) 509

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

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

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

PRL 125 (2020) 152001

$\sqrt{s} = 13TeV$

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

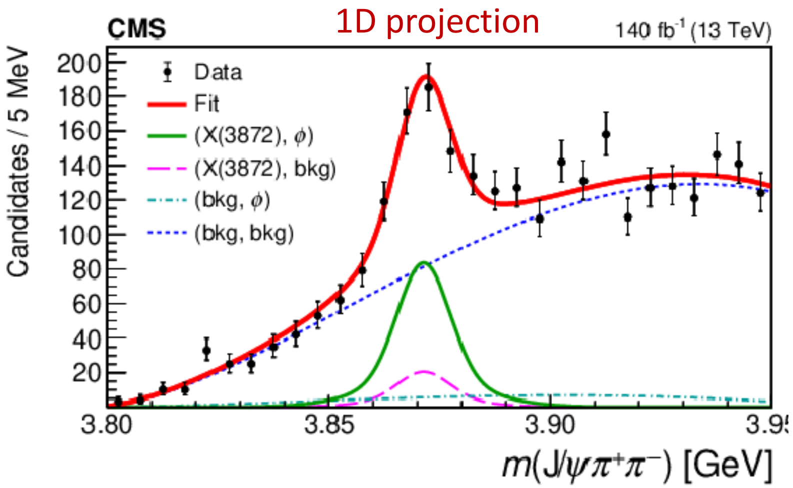
(Run-II)

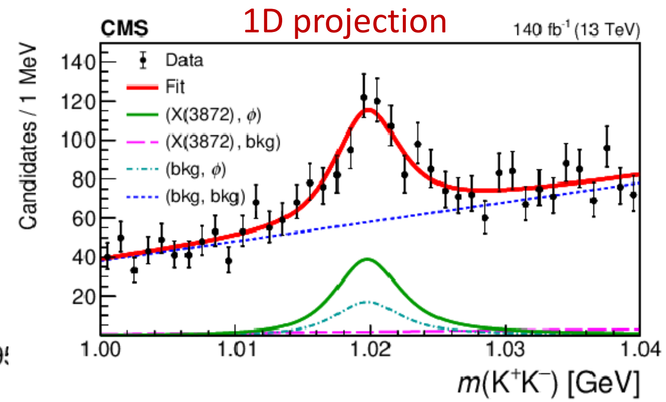
Observation of the new decay mode $B_s^0 \to X(3872)\phi$

recently observed a new decay mode involving the $X(3872)$ **reconstructed by** $X(3872) \to J/\psi\,\pi^+\pi^-$

The signal of $B_s^0 \to X(3872)\phi$ **is extracted with reference to the** control channel $B_s^0 \to \psi(2S)\phi$ (having the same decay topology and similar kinematics) **used as normalization channel for the BF measurement (**many systematic uncertainties cancel out in the ratio**)** [see next slide]

- Signal yield **determined from a** **simultaneous 2D fit** of the distributions ... $\begin{cases} m(J/\psi\,\pi^+\pi^-) \\ m(K^+K^-) \end{cases}$
  - $N(B_s^0 \to X(3872)\phi) = 299 \pm 39$
  - Stat. significance > 6σ **(systematics included)**





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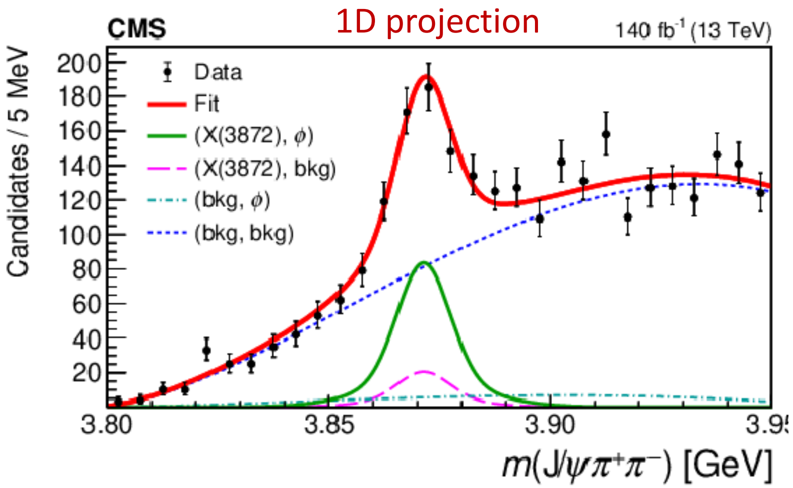
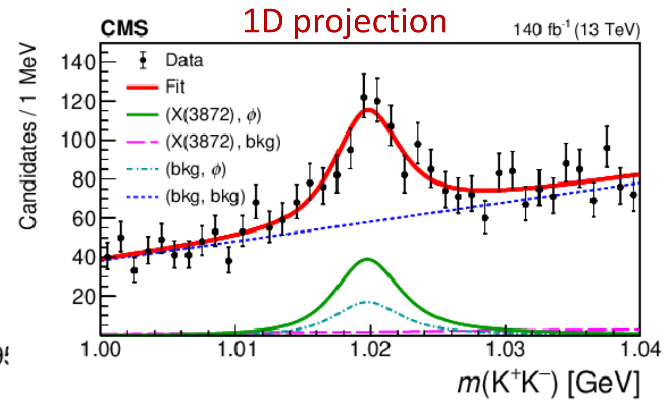
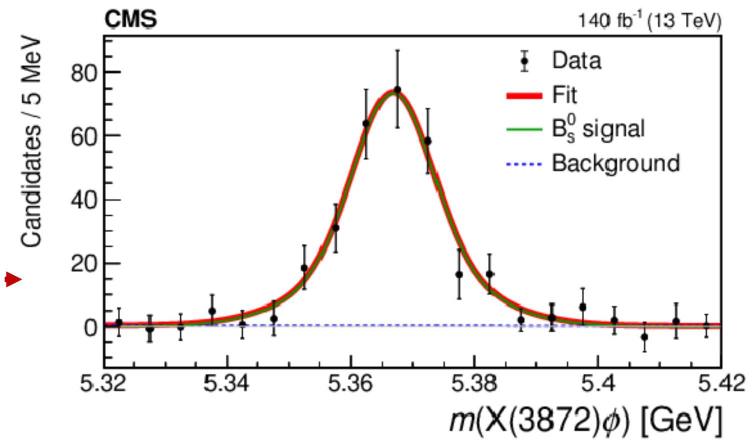




- **Evaluation of the residual non-B_s^0 background** [non-B_s^0 production of $X(3872)\phi$] **by using the non-resonant** bkg-subtracted $m(X(3872)\phi)$ **obtained by means of the *sPlot* technique.** **This bkg contribution is 1.7% (**0.5% for $\psi(2S)\phi$ **).**



Branching fraction (ratios)

Product of branching fractions for $B_s^0 \to X(3872)\phi$ measured relative to $B_s^0 \to \psi(2S)\phi$:

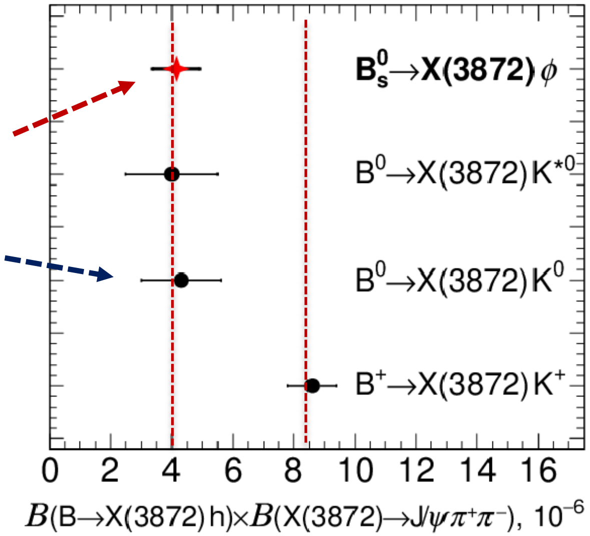
$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi)} \times \frac{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst}))\%$$

(confirmed later by LHCb [JHEP02 (2021)024]: $(2.42 \pm 0.23(\text{stat}) \pm 0.07(\text{syst}))\%$)

Branching fraction consistent with that of $B^0 \to X(3872)K^{(*)0}$:

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

$$\mathcal{B}(B^0 \to X(3872)K^0)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.3 \pm 1.3)\times 10^{-6}$$



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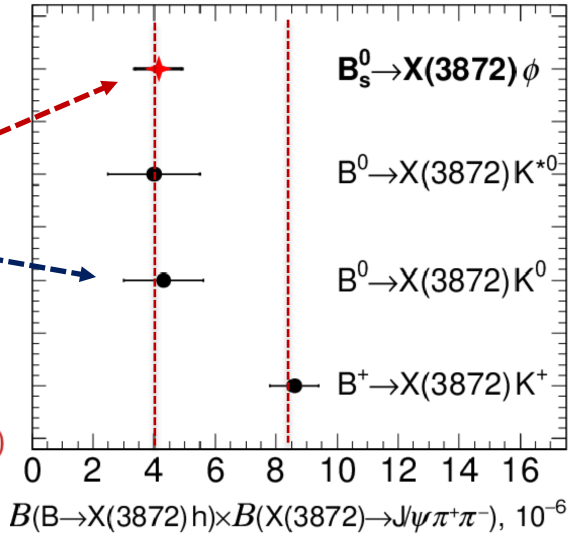
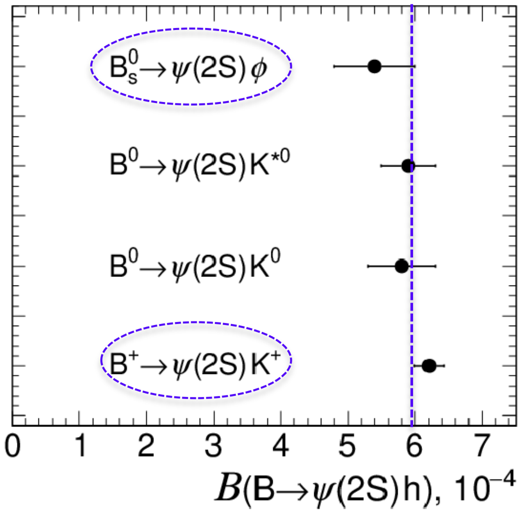


Significant difference in branching fraction ratio **(neutral-to-charged)** compared to $\psi(2S)$ modes:

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

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



Branching fraction (ratios)

- **Product of branching fractions for $B_s^0 \to X(3872)\phi$ measured relative to $B_s^0 \to \psi(2S)\phi$:**

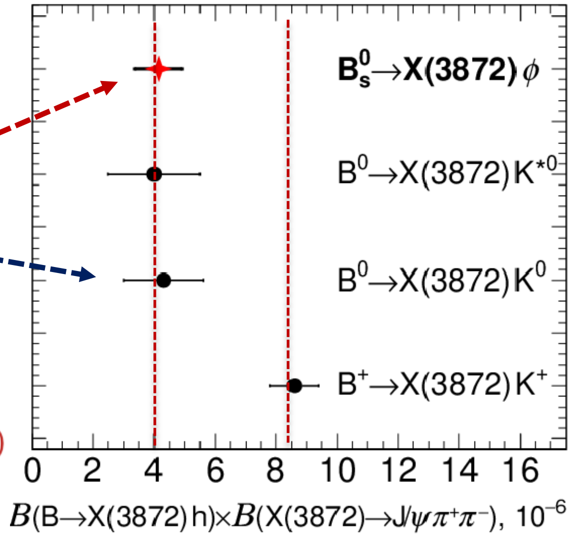
$$\frac{\mathcal{B}(B_s^0 \to X(3872)\phi)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi)} \times \frac{\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (2.21 \pm 0.29(\text{stat}) \pm 0.17(\text{syst}))\%$$

(confirmed later by LHCb [JHEP02 (2021)024]: $(2.42 \pm 0.23(\text{stat}) \pm 0.07(\text{syst}))\%$)

- **Branching fraction consistent with that of $B^0 \to X(3872)K^{(*)0}$:**

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

$$\mathcal{B}(B^0 \to X(3872)K^0)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.3 \pm 1.3)\times 10^{-6}$$



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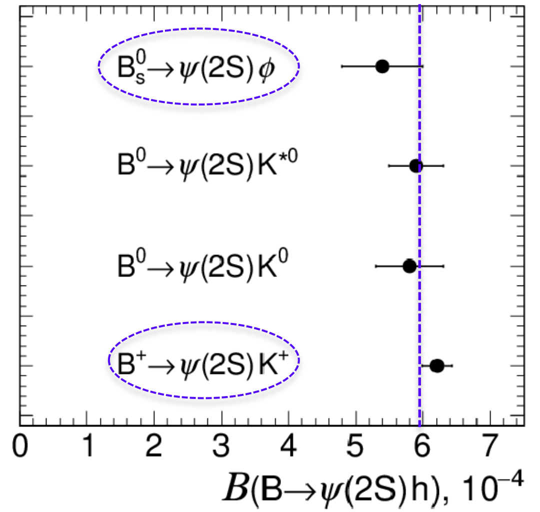


- **This suggests a difference in the production dynamics of the *exotic* $X(3872)$ in B^0 & B_s^0 decays compared to B^+ with respect to the *standard* $\psi(2S)$**

- **This observation may help in the comprehension of the nature of $X(3872)$**
  - **in the tetraquark (diquark-based) scenario this is explained by the fact that the amplitude for the charged decay gets 2 contributions of the same order instead of 1** [Maiani *et al.*, PRD 102 (2020) 034017]

Observation of new structures in the $J/\psi\, J/\psi$ mass spectrum $(T_{cc\bar{c}\bar{c}} \to J/\psi\, J/\psi \to 4\mu)$

CMS-PAS-BPH-21-003 $\sqrt{s} = 13 TeV$ $\mathcal{L} = 135 fb^{-1}$

(Run-II)

https://cds.cern.ch/record/2815336/files/BPH-21-003-pas.pdf (PAS)

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-21-003/index.html (Preliminary Plots)

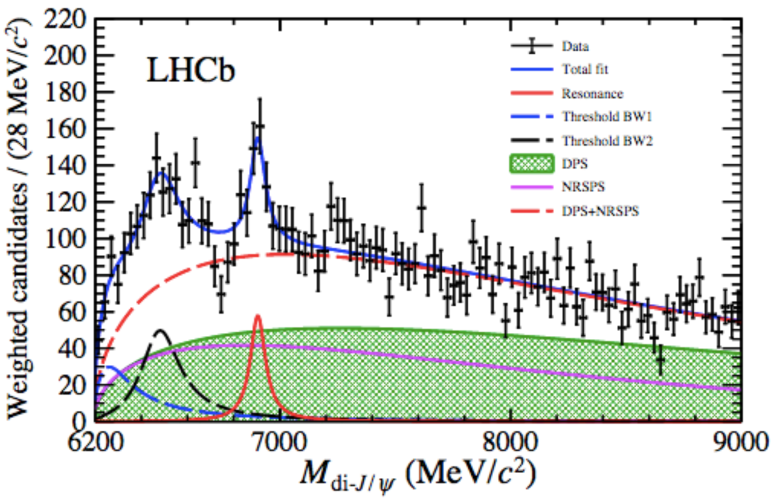
For comparison: Science Bulletin 65 (2020) 1983

https://cds.cern.ch/record/2815676/files/ATLAS-CONF-2022-040.pdf

LHCb models for the $J/\psi\, J/\psi$ mass spectrum

- In 2020 LHCb observed a peak in the $J/\psi\, J/\psi$ **mass spectrum, the $X(6900)$**, which was considered with great interest as a **possible *all-charm tetraquark*** **(**even if also alternative interpretations have been advocated**).** LHCb **reported two alternative fit models:**

- **Model-I :**



3 B.-W.s: - 1 for the signal peak $X(6900)$

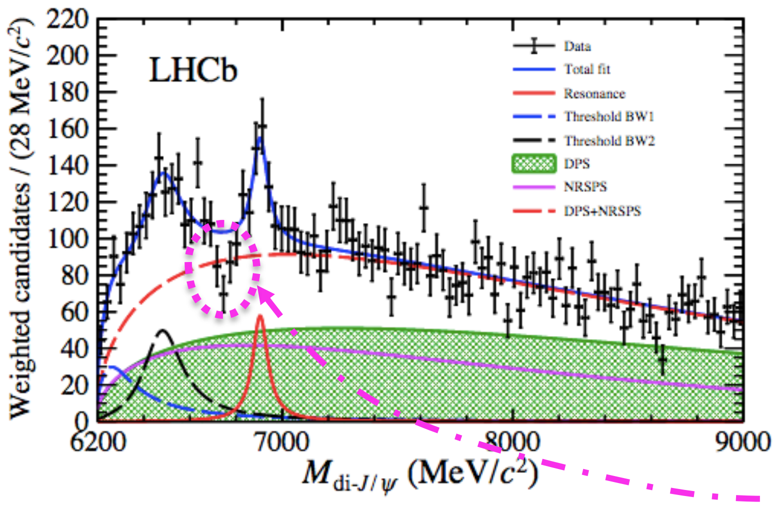
- other 2 auxiliary "threshold" B.-W.s for the initial raise and first "bump"

NRSPS+DPS shapes for the background

- **Model-II :**

- In 2020 LHCb observed a peak in the $J/\psi J/\psi$ **mass spectrum, the $X(6900)$**, which was considered with great interest as a **possible *all-charm tetraquark*** **(**even if also alternative interpretations have been advocated**).** LHCb **reported two alternative fit models:**

Model-I :

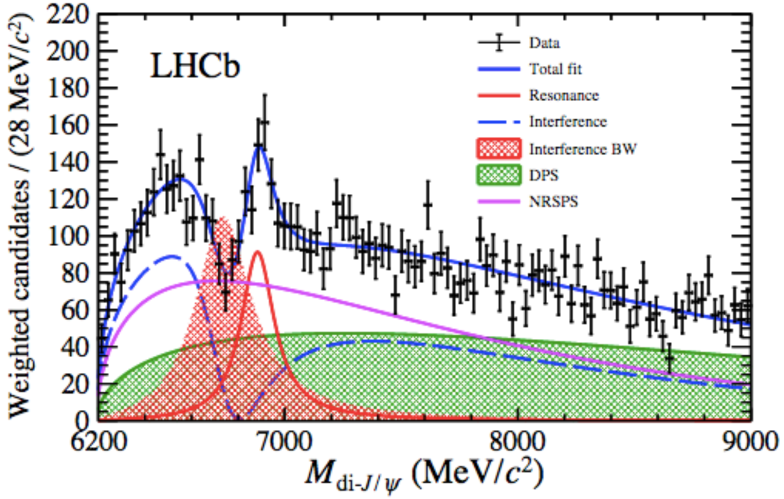


3 B.-W.s: - 1 for the signal peak $X(6900)$
- other 2 auxiliary "threshold" B.-W.s for the initial raise and first "bump"

NRSPS+DPS shapes for the background

It poorly describes the dip, suggesting to try a destructive interference of a "virtual" B.-W. with the NRSPS bkg. component, while getting rid of the "threshold B.-W.s".

Model-II :



Masses & **natural widths** for the $X(6900)$ result to be compatible in the two models.
LHCb is agnostic on which one is to prefer.

After **event selection** (4μs in final state; see backup) a **baseline model** to fit the **di-J/ψ** spectrum is built with a **minimal** number of potential structures **added to the null-hypothesis** (bkg-only) by adding - @ each subsequent step - the *most prominent* structure & keeping it in the baseline… if local statistical significance > 3σ (standard likelihood ratio method). This is repeated until no more structures can be added.

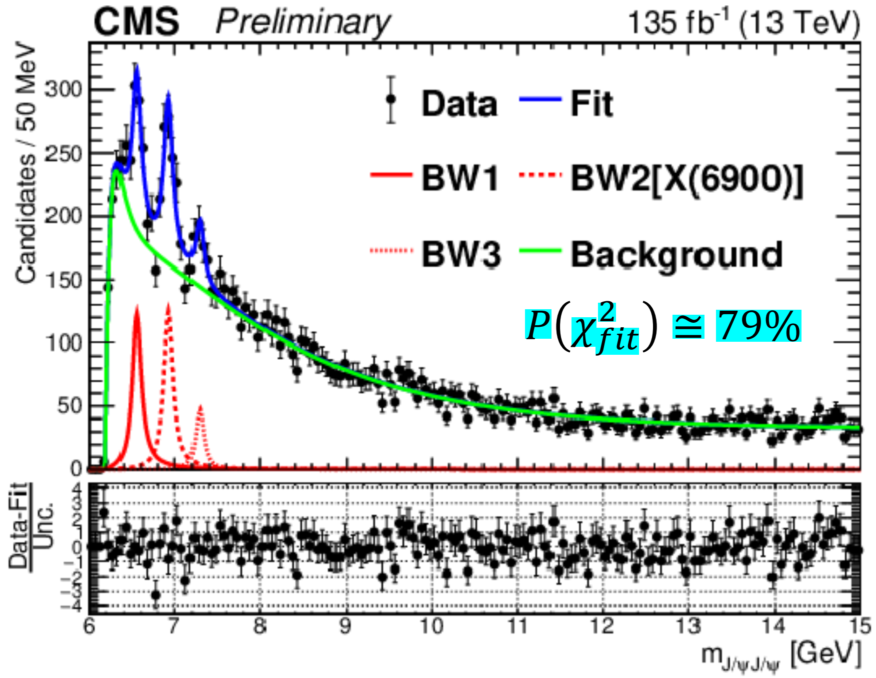
The specific followed sequence is:

1) Initial null-hypothesis model : **NRSPS + NRDPS**

- from Pythia8 distributions, parametrized by:

SPS: $threshold\ func. * poly2 * exponential$

DPS: $sqrt * poly2 * exponential$



CMS baseline model to fit the $J/\psi\, J/\psi$ mass spectrum - I

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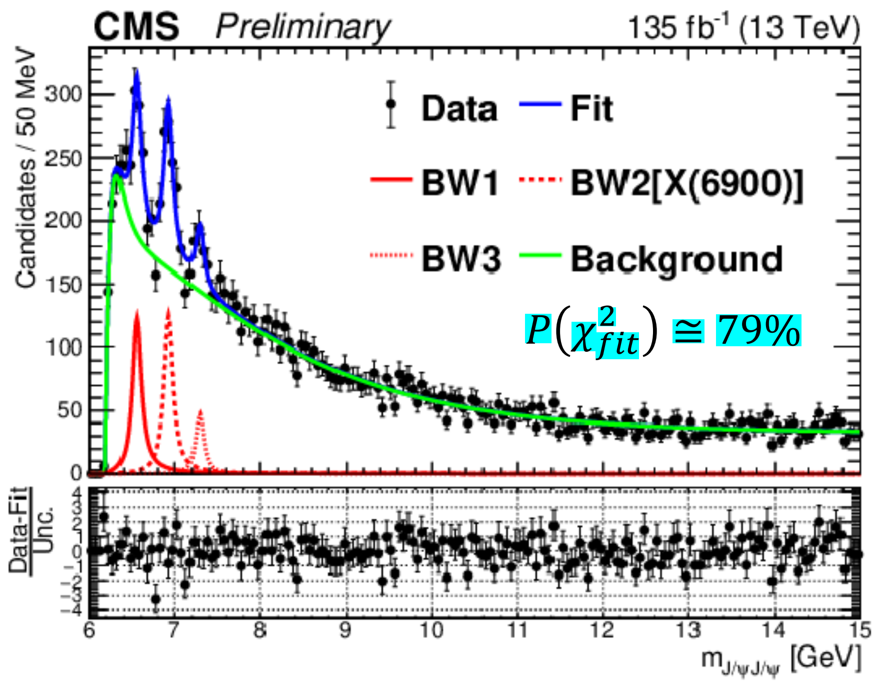
- from Pythia8 distributions, parametrized by:

$$\text{SPS: } threshold\ func. * poly2 * exponential$$
$$\text{DPS: } sqrt * poly2 * exponential$$

2) Add the most significant structure (@ threshold) modelled empirically (*ad hoc*) by a B.-W. and consider it as part of the background (**BW0**) since:

- this region is populated by feed-down from possible higher mass states (checked @MC)
- this region could be affected by possible coupled-channel interactions, final state rescattering, etc …
- the NRSPS model shaped via a unique floating parameter: it turns out to be inadequate to shape the threshold region



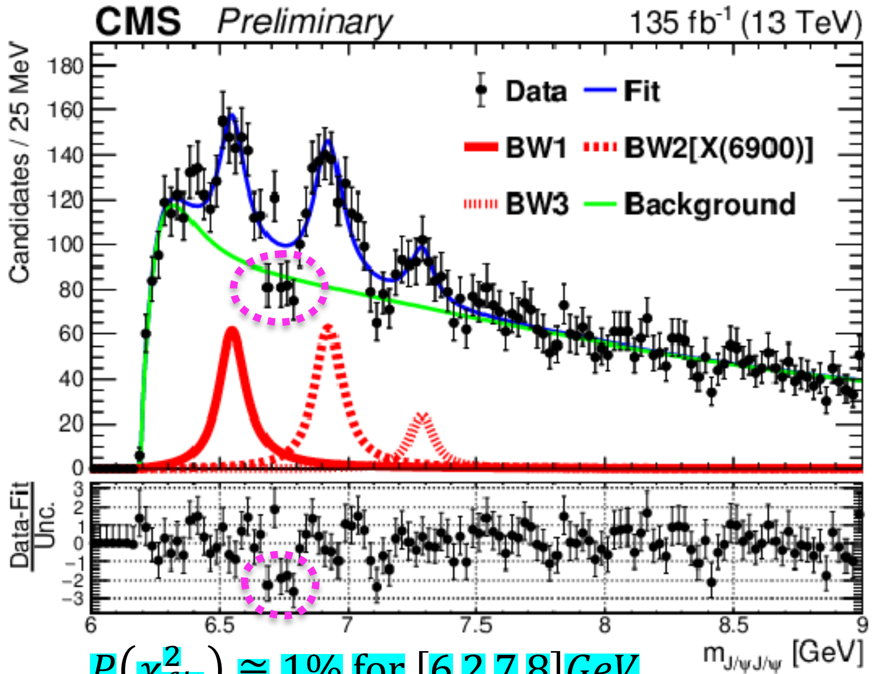
Bkg-hypothesis model :
BW0 + NRSPS + NRDPS

Note: BW0 parameters very sensitive to the additional part of the model

CMS baseline model to fit the $J/\psi\, J/\psi$ mass spectrum - II

Now, we model structures beyond bkg-hypothesis by using relativistic B.-W. functions (with $\mathrm{L} = 0$) …

- convolved with double-Gaussian resolution functions
- **not modified by acceptance & trigger/selection efficiencies**
  (varying very slowly in the search region: consider as systematics)



$P(\chi^2_{fit}) \cong 1\%$ for $[6.2, 7.8]\,GeV$

3) Add B.-W. @ $\approx 6900\,MeV$:

BW2 ($> \mathbf{9.4\sigma}$) ⇨ **CONFIRMATION of $X(6900)$**

4) Add B.-W. @ $\approx 6550\,MeV$: **BW1** ($> \mathbf{6.5\sigma}$)

⇨ **OBSERVATION of $X(6600)$**

5) Add B.-W. @ $\approx 7300\,MeV$: **BW3** ($> \mathbf{4.1\sigma}$) ⇨ **EVIDENCE for $X(7300)$**

CMS baseline model to fit the $J/\psi J/\psi$ mass spectrum - II

Now, we model structures beyond bkg-hypothesis by using relativistic B.-W. functions (with $L = 0$) …

- convolved with double-Gaussian resolution functions
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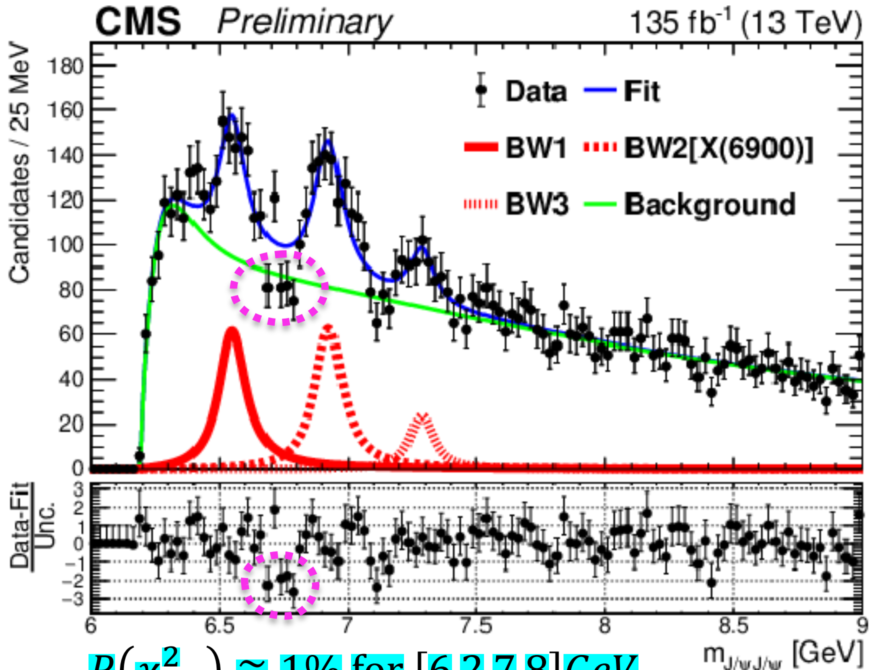

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BW2 ($> 9.4\sigma$) ⇨ **CONFIRMATION of $X(6900)$**

4) Add B.-W. @ $\approx 6550 MeV$: **BW1** (~~$> 6.5\sigma$~~) 5.7σ

⇨ **OBSERVATION of $X(6600)$**

5) Add B.-W. @ $\approx 7300 MeV$: **BW3** ($> 4.1\sigma$) ⇨ **EVIDENCE for $X(7300)$**

Fit results including also the systematic uncertainties:

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
N	474 ± 113	492 ± 75	156 ± 56

Table 2: Systematic uncertainties on masses and widths, in MeV.

Source	ΔM_{BW1}	ΔM_{BW2}	ΔM_{BW3}	$\Delta\Gamma_{BW1}$	$\Delta\Gamma_{BW2}$	$\Delta\Gamma_{BW3}$
signal shape	3	4	3	14	7	7
NRDPS	1	< 1	< 1	3	3	4
NRSPS	3	1	1	18	15	17
momentum scaling	1	3	4	-	-	-
mass resolution	< 1	< 1	< 1	< 1	< 1	1
combinatorial background	< 1	< 1	< 1	2	3	3
efficiency	< 1	< 1	< 1	1	< 1	1
feeddown shape	11	1	1	25	8	6
total	12	5	5	34	19	20

(CASCADE, HELAC-ONIA)

(Pythia8, JHUGen)

Agreement with LHCb (Model-I / non-interf.)

$m(6900)$	$\Gamma(6900)$
$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$

CMS baseline fit provides $X(6900)$ parameters in agreement with LHCb non-interference fit (Model-I).

In order to remove potential model-dependencies in a comparison between results, …
we also apply - to our data - the two LHCb main models, but using CMS-specific background shapes.
(NRSPS + NRDPS)

Compare with Model-I :

- Apply 2 auxiliary B.-W.s + $X(6900)$ + CMS Bkg. model

Note: 1) CMS data show a ***shoulder*** that helps make BW1 more distinct

2) the main dip remains undescribed as well as the dip/peak $\approx 7.2 - 7.3 GeV$

- Overall g.o.f : 2) the dip remains undescribed

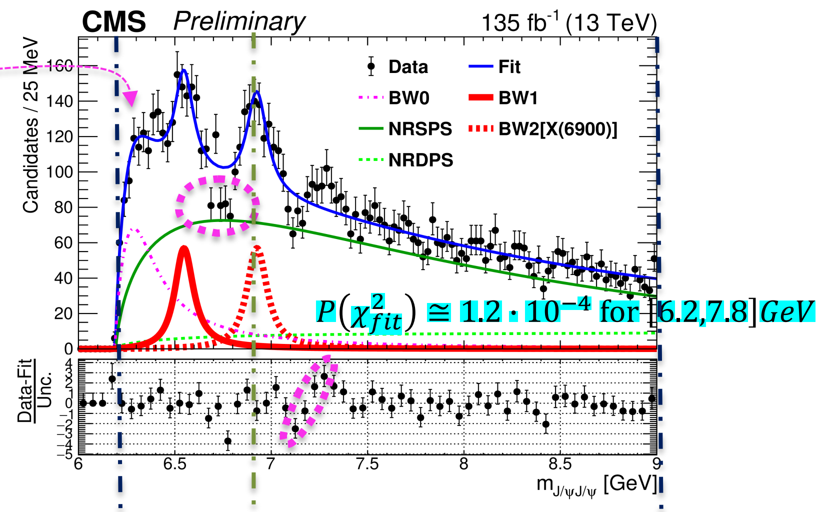
$P(\chi^2_{fit}) \cong 0.51$ for $[6.2,15] GeV$

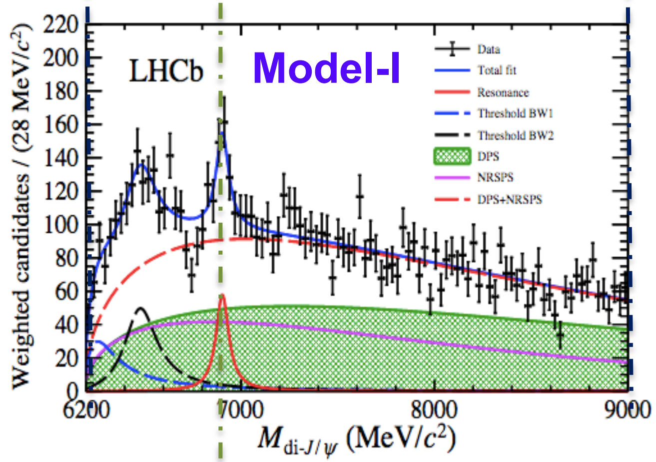
$P(\chi^2_{fit}) \cong 1.2 \cdot 10^{-4}$ for $[6.2,7.8] GeV$

⇨ **worse fit than CMS baseline fit model**

- $X(6900)$ parameters still in good agreement :

Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb	Model I	unrep.	unrep.	$6905 \pm 11 \pm 7$	$80 \pm 19 \pm 33$
CMS	Model I	6550 ± 10	112 ± 27	6927 ± 10	117 ± 24





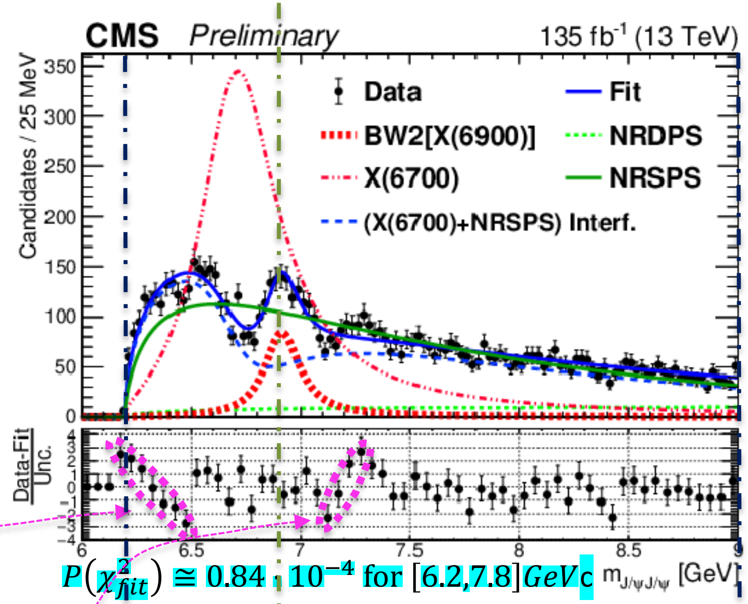
Application of LHCb fit models to the $J/\psi\, J/\psi$ mass spectrum - II

Compare with Model-II :

- Apply an **interference** between a **"virtual"** $\boldsymbol{X(6700)}$ & CMS NRSPS + $\boldsymbol{X(6900)}$ + CMS NRDPS

$(439 \pm 65)MeV$!

Note: 1) CMS data show **larger** amplitude & width for $X(6700)$
2) CMS's $X(6600)$ is "eaten" by this interference



- Overall g.o.f : the fit remains poor:

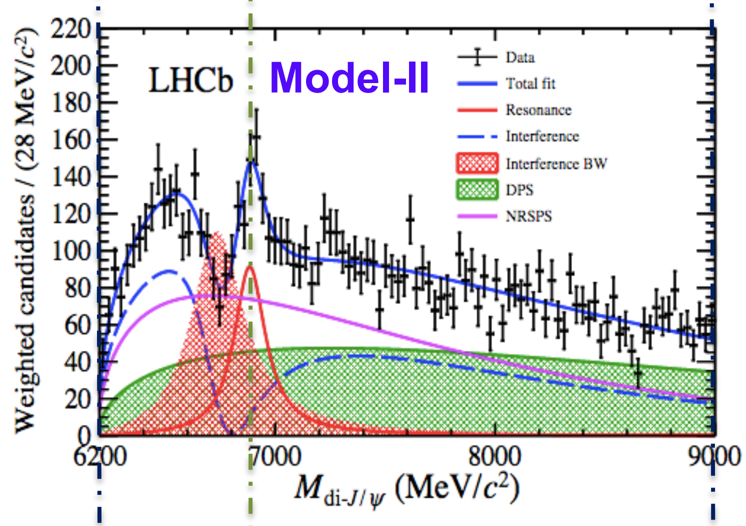
$$P(\chi^2_{fit}) \cong 0.84 \cdot 10^{-4} \text{ for } [6.2,7.8]GeV$$

worse fit than CMS baseline fit model

worse fit than LHCb fit Model- I

(region $\approx 6550 MeV$ poorly described; same for $\approx 7200 MeV$)

[unlike Model-II that better describes LHCb data]



- $\boldsymbol{X(6900)}$ parameters still consistent :

[$X(6700) \equiv BW1$]

Exp.	Fit	m(BW1)	Γ(BW1)	m(6900)	Γ(6900)
LHCb	Model II	6741 ± 6	288 ± 16	$6886 \pm 11 \pm 11$	$168 \pm 33 \pm 69$
CMS	Model II	6736 ± 38	439 ± 65	6918 ± 10	187 ± 40

Find the comparison with ATLAS **di-J/ψ** spectrum in the backup!

- CMS di-J/ψ spectrum hints a possible rich pattern of 3 structures (candidates to be all-charm tetraquarks):

	BW1	BW2	BW3
m	$6552 \pm 10 \pm 12$	$6927 \pm 9 \pm 5$	$7287 \pm 19 \pm 5$
Γ	$124 \pm 29 \pm 34$	$122 \pm 22 \pm 19$	$95 \pm 46 \pm 20$
(systematic effects included) St.Sig.	$> 5.7\sigma$	$> 9.4\sigma$	$> 4.1\sigma$
	OBSERVATION of $X(6600)$	CONFIRMATION of $X(6900)$	EVIDENCE for $X(7300)$

… under the assumption of no interference between signal components and between signal & background

- All CMS fits presented are not very good/satisfactory and …
  … other interference scenarios/models are currently under study to describe the dip(s) (that hint possible interference effects). This is mandatory to have out a paper.
  The near-threshold region needs also to be better understood (more data may be needed).

- The measurement of the production Xsections (in a fiducial region) is in our plans.

[https://arxiv.org/abs/2111.05370]

- CMS has good sensitivity to all-muon final states (see also the triple-J/ψ result), thus it is worthy to explore $J/\psi\,\psi(2S)$ and di-$\psi(2S)$ spectra.
  Run-3 will be certainly useful to afford more or enough statistics.

Perspectives & Plans - I

- Run-3 has just started (2022-24) - the plan is to approx. double the statistics collected so far.
  - Rethought tracking/vertexing needs - especially @ low p_T - for the mini-AOD data format (AOD will be only on tape)
  - Refined/improved trigger strategy for B-Physics and Quarkonia (in Run-3 harsher experimental conditions)
  - The data that are going to be collected in Run-3 can certainly help to achieve very interesting new and updated results, integrating and/or complementing LHCb results (pp) and ALICE (HI collisions), …
    … in spite of huge backgrounds, trigger constraints, particle identification limitations.

  By the way … the physics potentiality of data already collected (Run-2) is far from being fully explored (currently several analyses are still ongoing).

Perspectives & Plans - I

- Run-3 has just started (2022-25) - the plan is to approx. double the statistics collected so far.
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  By the way … the physics potentiality of data already collected (Run-2) is far from being fully explored (currently several analyses are still ongoing).

- Analysis efforts will be oriented where the specific strengths of the CMS detector and reconstruction algorithms make us competitive, both in exotics searches and in the extraction of signals of rare spectroscopic transitions.
  - Double-charmonia(bottomonia) measurements & searches can be carried out at the same(better) sensitivity compared to LHCb, thanks to **large muons' acceptance**.
  - Radiative spectroscopic transitions thanks to **precise photon conversions.**
  - Beauty hadrons rare decays (observations, Branching Fractions) thanks to the **good efficiency for low-p_T tracks**, both **prompt** and **displaced** from the Primary Vertex; especially exploting **signatures with K_S^0, Λ^0 and ϕ reconstructed mesons** to fight the overwhelming backgrounds due to huge track multiplicity.
  - QCD exotics in **HI collisions** (X(3872), …), hardly doable at ALICE.

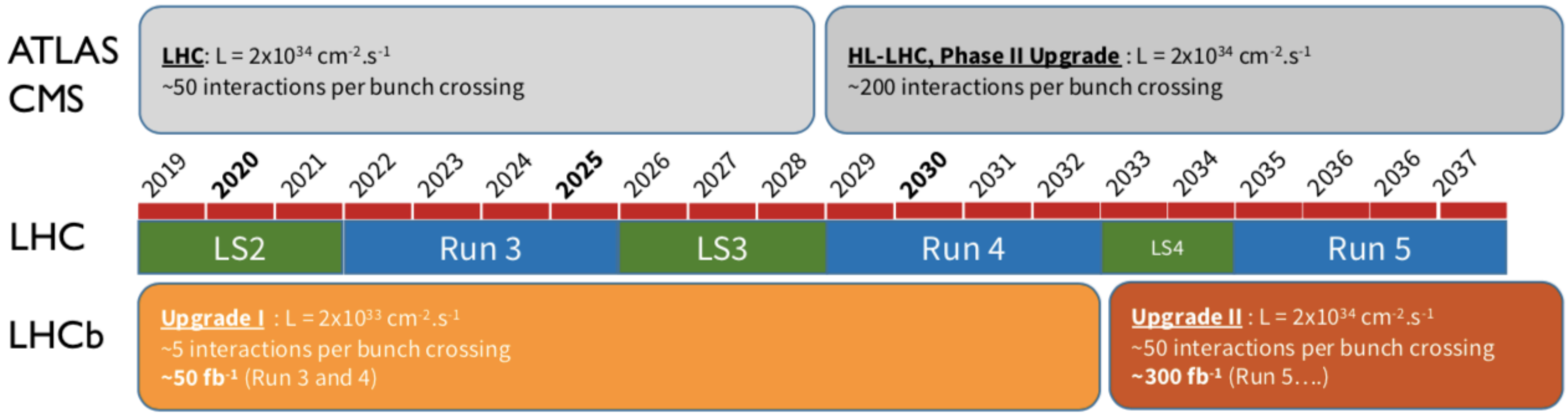
Perspectives & Plans - II

What is planned for Phase-2/HL-LHC (Run-4, …)? [focusing on this kind of Physics …]

- the **availability of tracking information at Level-1 trigger** will be crucial to retain the full physics potential when pile up conditions expected (<PU>~140-200) will hold.

- the **new additional timing layer** (**M**ip **T**iming **D**etector) will allow:
  - **some hadronic PID capabilities for the softer** ($p_T < 2\,\mathrm{GeV}$) **charged track**
  - an upgrade of the 3D vertex fit to a 4D one, thus allowing **precision timing for charged hadrons & converted photons** and - consequently - **an effective pile up mitigation**.

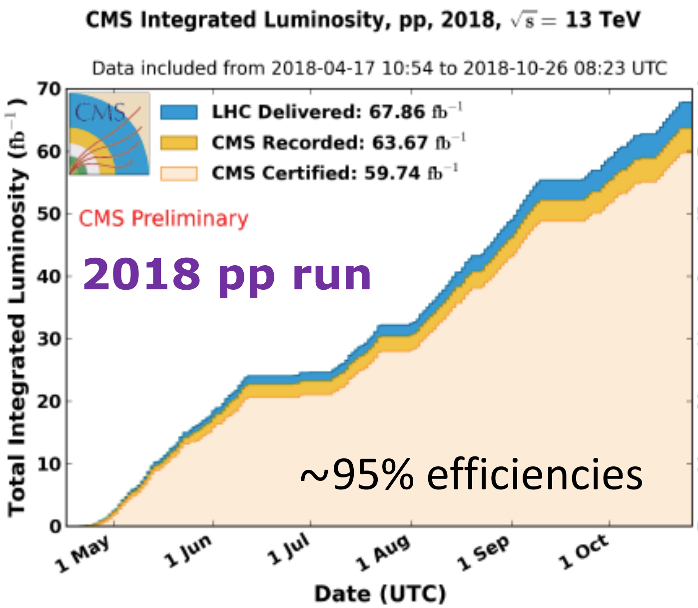
- even more **careful** ***dedicated trigger strategy*** will be needed

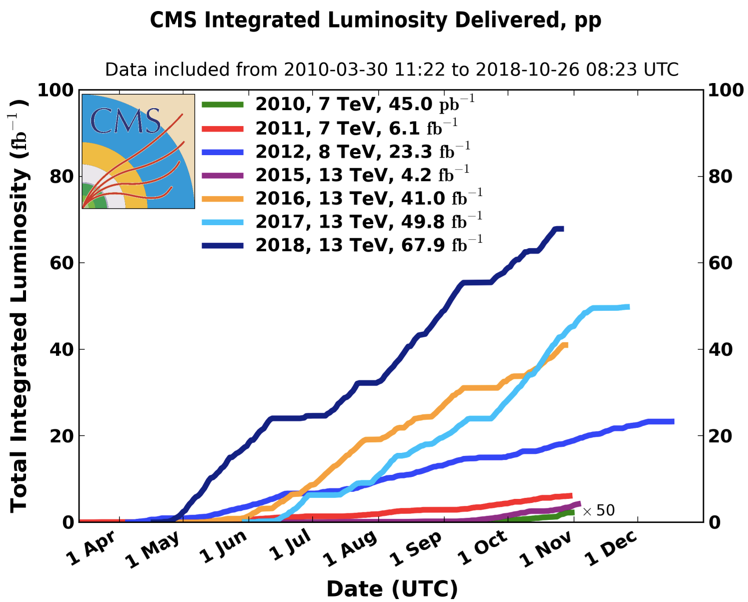


Backup material

Run-1 & Run-2 data taking

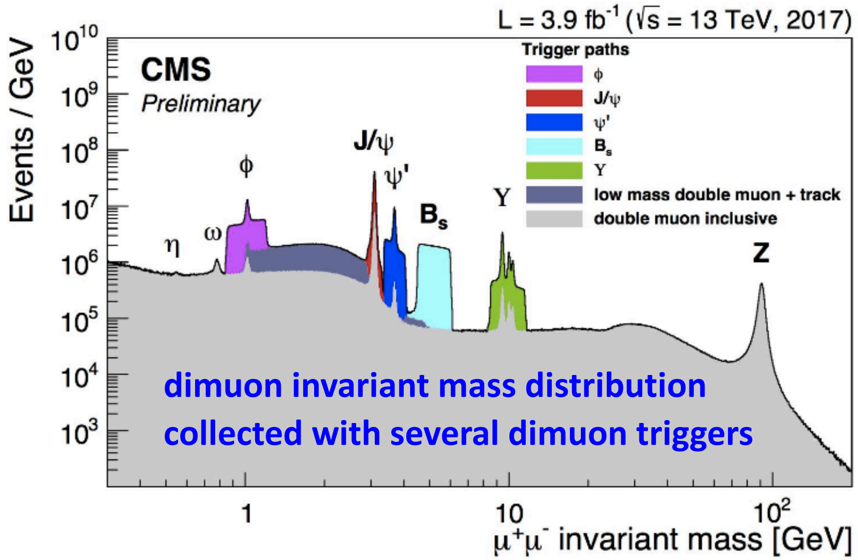
- The LHC Run-II was characterized by excellent LHC & CMS performances :





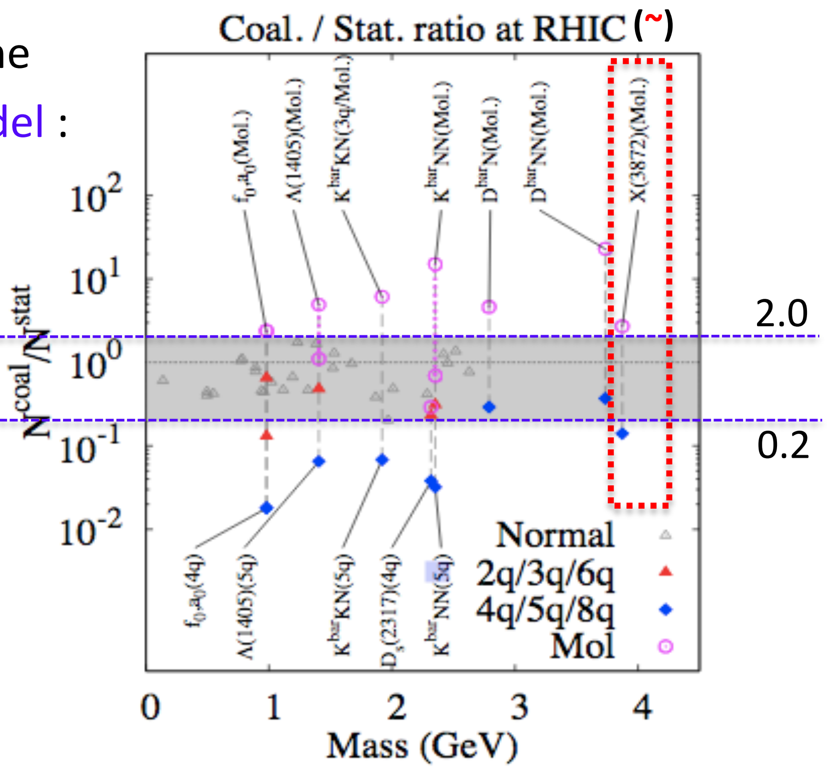
Data samples

		$L_{int} \approx$
Run-I		
$\sqrt{s} = 7TeV$	2011	5
$\sqrt{s} = 8TeV$	2012	20
Run-II		
$\sqrt{s} = 13TeV$	2015	4
	2016	38
	2017	45
	2018	60



- 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 !

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

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

- The ratio of corrected yields of prompt X(3872) to prompt $\psi(2S)$ is defined as: $R = \frac{N^{X}_{corr}}{N^{\psi}_{corr}}$ $\psi(2S)$
  - prompt yields are corrected for efficiency and acceptance from …

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

  - 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 $\ell_{xy} > 0.1mm$):

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

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

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

CMS selection of $J/\psi J/\psi$ candidates - I

Trigger requirements

	2016	2017-18
L1	at least 3 μ	at least 3 μ
		leading μ : $p_T > 5.0GeV$; sub-leading μ : $p_T > 3.0GeV$ (*)
		at least one pair of OS μs : $m < 9.0GeV$
HLT	each μ : $\|\eta(\mu)\| < 2.5$; at least one pair of OS μs : $2.95 < m < 3.25GeV$, $P(\text{vtx}) > 0.5\%$	each μ : $\|\eta(\mu)\| < 2.5$; at least one pair of OS μs : $2.95 < m < 3.25GeV$, $P(\text{vtx}) > 0.5\%$
		each μ forming the "triggering" pair (J/ψ) : $p_T(\mu) > 3.5GeV$

Offline selection

2016	2017-18
HLT bit fired	HLT bit fired
each μ : SOFT-ID, $p_T(\mu) > 2.0GeV$, $\|\eta(\mu)\| < 2.4$	each μ : SOFT-ID, $p_T(\mu) > 2.0GeV$, $\|\eta(\mu)\| < 2.4$
$J/\psi J/\psi$ candidates are built (can be more than 1/event): for each J/ψ: $2.95 < m < 3.25GeV$, $P(\text{vtx}) > 0.5\%$, kin-fit : $P(J/\psi) > 0.1\%$, $p_T(J/\psi) > 3.5GeV$	$J/\psi J/\psi$ candidates are built (can be more than 1/event): for each J/ψ: $2.95 < m < 3.25GeV$, $P(\text{vtx}) > 0.5\%$, kin-fit : $P(J/\psi) > 0.1\%$, $p_T(J/\psi) > 3.5GeV$
4μ vertex fit : $P(4\mu - \text{vtx}) > 0.5\%$, kinematic fit : $P(J/\psi J/\psi - \text{fit}) > 0.1\%$	4μ vertex fit : $P(4\mu - \text{vtx}) > 0.5\%$, kinematic fit : $P(J/\psi J/\psi - \text{fit}) > 0.1\%$
	at least 2 OS μs (forming a J/ψ) : $p_T(\mu) > 3.5GeV$
Best candidate selected if 2 $J/\psi J/\psi$ candidates are formed with the same 4μ (~ 0.2% of the cases); both conserved if they have at least 1 different μ (~ 0.2% of the cases)	Best candidate selected if 2 $J/\psi J/\psi$ candidates are formed with the same 4μ (~ 0.2% of the cases); both conserved if they have at least 1 different μ (~ 0.2% of the cases)

Overall kinematic phase-space selected: - for 2016: $p_T(\mu) > 2.0GeV$, $|\eta(\mu)| < 2.4$, $p_T(J/\psi) > 3.5GeV$

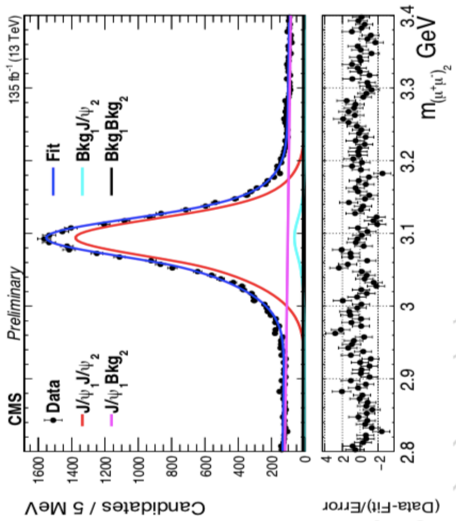
- for 2017-18: in addition: *at least* two OS μs with $p_T(\mu) > 3.5GeV$

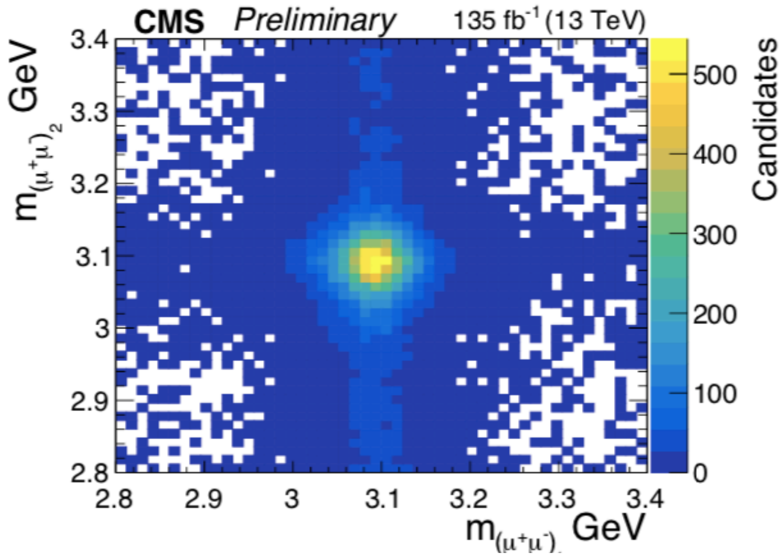
(*) These L1 requirements do not have relevant effect offline (on reconstructed efficiency and spectrum)

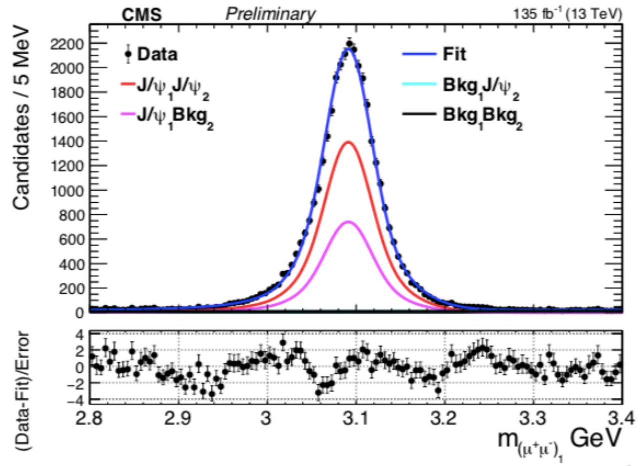
CMS selection of $J/\psi\, J/\psi$ candidates - II

- The sample has $14{,}049$ ($8{,}651$) $J/\psi\, J/\psi$ signal pairs for $m(J/\psi\, J/\psi) < 15.0(9.0) GeV$.

  The 4-muons mass resolution ranges from $\sim 10 MeV$ (@ $6.5 GeV$) to $\sim 18 MeV$(@ $7.3 GeV$).







- The offline selection in the previous slide was determined in an unbiased and model independent way: selection criteria were fixed before looking at the data in the signal region $m(J/\psi\, J/\psi) < 7.8 GeV$ and relied also on loose requirements aligned with past experience in double- J/ψ analysis. This approach is possible thanks to the high purity of the J/ψ signal.

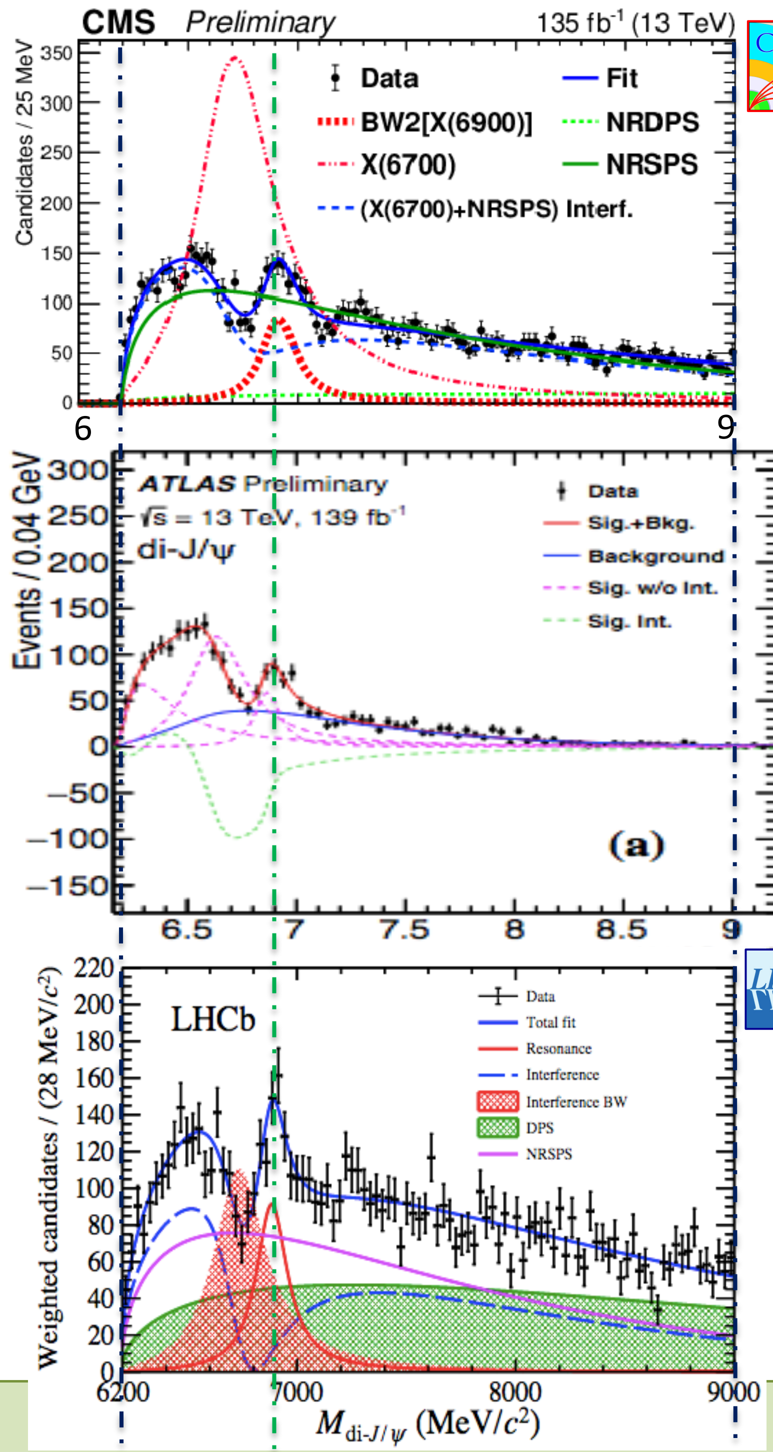
  As a cross-check, an optimization was afterwords performed by simulating a $9 GeV$ 0^+ signal meson and using backgrounds from data, yielding to a selection very similar to the original one.

Comparison of interference fit results on $J/\psi\, J/\psi$ spectrum by ATLAS, CMS & LHCb

- ATLAS model considers 3 B.-W.s and their possible interference to describe the dip @ $\approx 6800 MeV$ together with the large initial shoulder. This interference is different from that in LHCb's Model-II, thus the shown comparison is not fully meaningful.

Different binnings and vertical scales do not help the comparison of the data points.

- Note: CMS & LHCb seem to have a similar number of $X(6900)$ candidates. Evidently there is a compensation among different major factors:
  - integrated luminosity : 135/9 ~ **15X**
  - muon acceptance (pseudorapidity): $(5/3)^4$ ~ **8X**
  - muon kinematical cuts (reco efficiency): $p_T > 0.6 GeV$ (LHCb) vs. (CMS) $p_T > 3.5\ or\ 2.0 GeV$



LHCb Model-II

Model-II

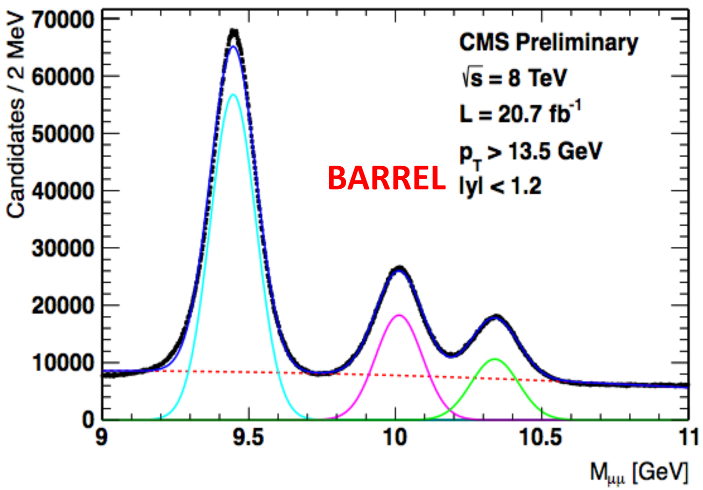
Search for X_b - I

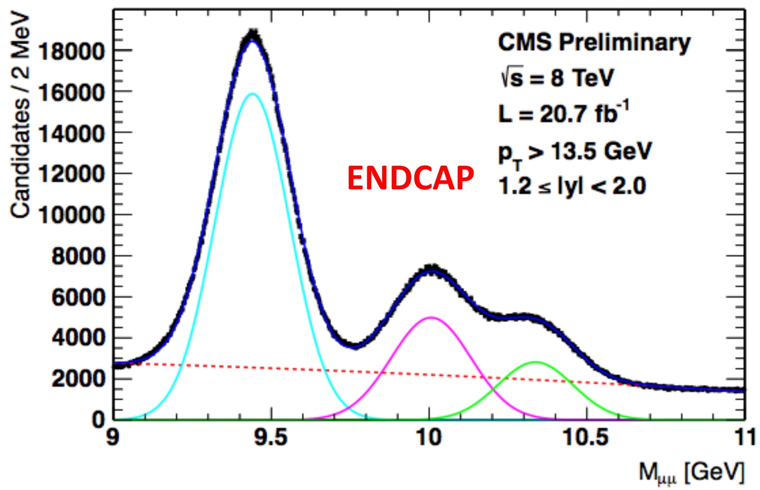
- **Heavy Quark symmetry suggests an X_b as 'bottomonium counterpart' of $X(3872)$.**
  Molecular model suggests to search close to $B\bar{B}^{(*)}$ threshold ($m \cong 10.562(604) GeV$);
  [model dependent prediction for a $B\bar{B}^{(*)}$ molecule by Swanson (2004)**]**

  CMS **looked for $X_b \to \Upsilon(1S)\ \pi^+\pi^-$ decay seemingly analogous to $X(3872) \to J/\psi\ \pi^+\pi^-$**

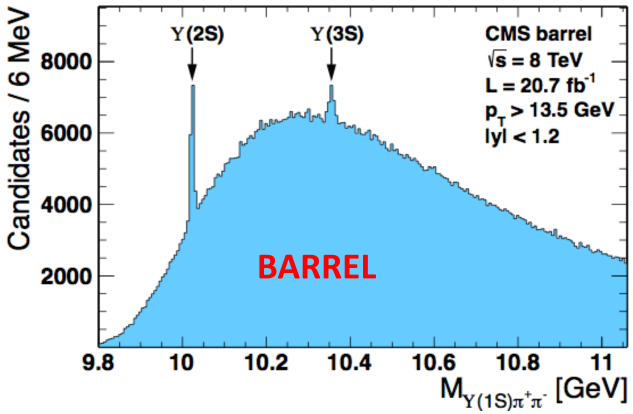
- Analysis strategy: search for a peak - other than known $\Upsilon(2S), \Upsilon(2S)$ - in the $\Upsilon(1S)\ \pi^+\pi^-$ spectrum within 10-11GeV
  [expecting **narrow width** & possibly **sizable BF** similarly to X(3872)]

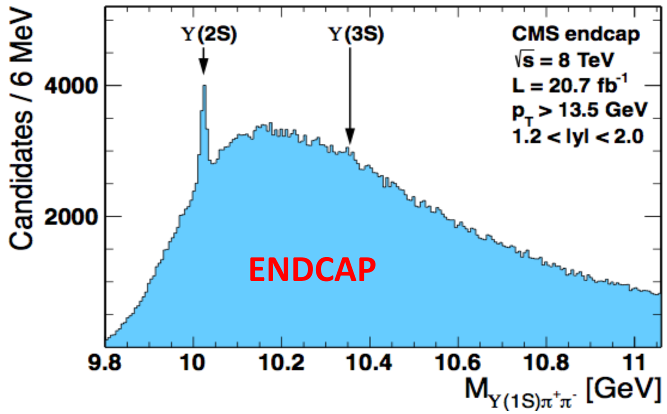
- CMS **collected (*pp@8TeV*) large sample of $\Upsilon(nS) \to \mu^+\mu^-$ [better mass resolution and lower bkg in the barrel]:**





- X_b cands are reconstructed by associating two oppositely selected charged tracks to the $\Upsilon(1S)$ cand.; the $\Upsilon(1S)\ \pi^+\pi^-$ spectrum is studied in the kinematic region $p_T > 13.5 GeV,\ |y| < 2.0$:





- Selection criteria optimized by using a genetic algorithm that maximized the expected significance of the signal in the mass region near the $\Upsilon(2S)$.
The statistical significance of the signal is expected to be $> 5\sigma$ if the following ratio that represents the X_b BF times the production Xsection relative to the $\Upsilon(2S)$ ...

$$R \equiv \frac{\sigma\left(pp \to X_b\right)}{\sigma\left(pp \to \Upsilon(2S)\right)} \cdot \frac{BF\left(X_b \to \Upsilon(1S)\pi^+\pi^-\right)}{BF\left(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-\right)}$$

... is > 6.56% [analogous to that of X(3872) relative to the $\Upsilon(2S)$].

Search for X_b - Upper Limit @ CMS

For each mass point of a mass scan (by 10*MeV*-sized steps), the mass spectrum is fitted (gaussian signal with width fixed to values from the simulation & 3rd order polynomial bkg**) and *R* is evaluated as ...**

observed YIELDS

$$R = \frac{N^{obs}_{X_b}}{N^{obs}_{\Upsilon(2S)}} \cdot \frac{\varepsilon_{\Upsilon(2S)}}{\varepsilon_{X_b}}$$

overall EFFICIENCIES estimated from SIMULATION

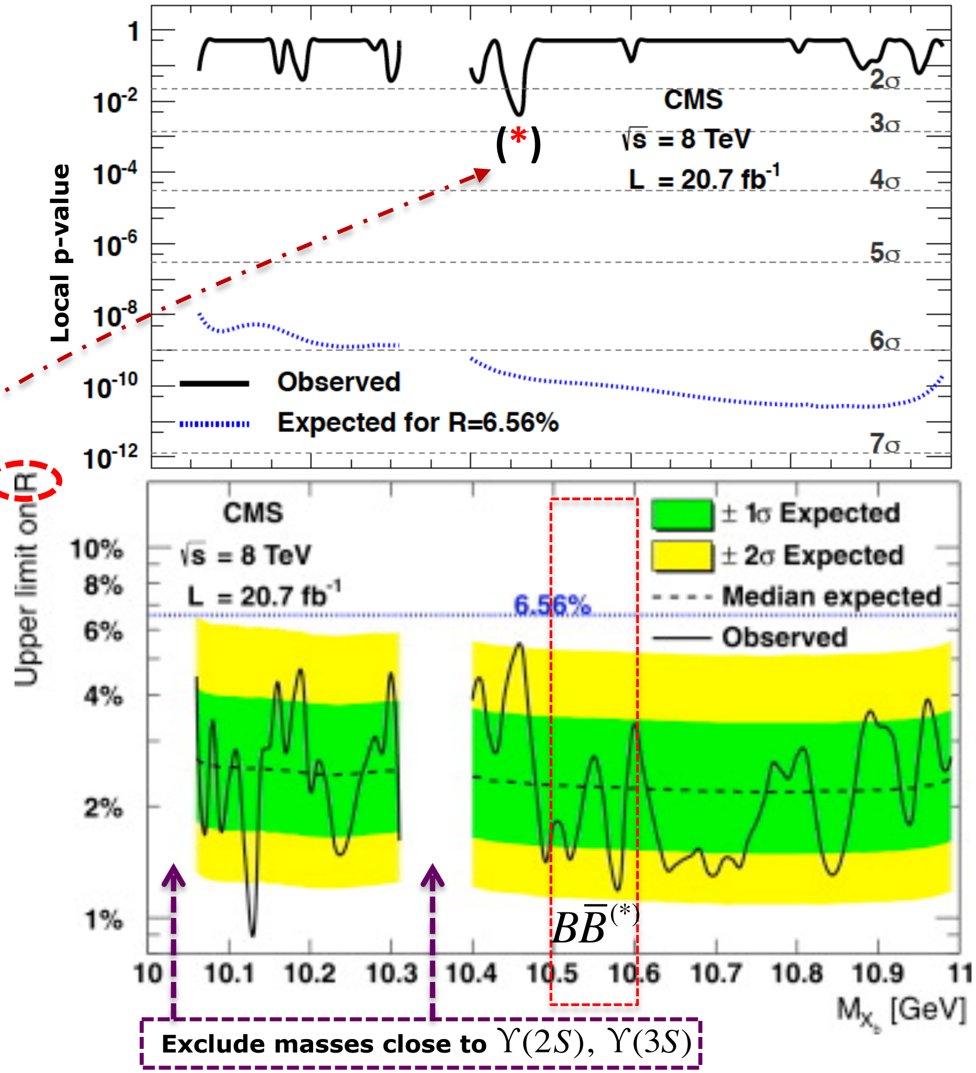
Assumptions in simulation:

- **same production mechanism for *Y(2S)* and X_b**
- **same dipion mass distribution for *Y(2S)* and X_b**
- ***Y(2S)* and X_b assumed both unpolarized**

...and a local *p-value* is calculated

(asymptotic approach & barrel/endcap combination)

[(*) : smallest *p-value* = 0.004 $\Rightarrow 2.8\sigma \xrightarrow{LEE} 0.8\sigma$]



NO significant excess observed

95% CL upper limits set on the ratio *R* :

observed UL range: 0.9% to 5.4%

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Search strategies for X_b

- According to Karliner&Rosner [PRD91 (2015) 014014], **the analogy with $X \to J/\psi\, \pi^+\pi^-$ is misguided for this particular decay channel**: $X_b \to \Upsilon(1S)\, \pi^+\pi^-$ **should be forbidden by G-parity conservation** :
  - **For the $X(3872)$ the I-conserving decay $X \to J/\psi\omega$ was kinematically suppressed, thus equally likely than the I-violating $X \to J/\psi\rho^0$:**

$$\frac{B(X \to J/\psi\, \pi^+\pi^-\pi^0)}{B(X \to J/\psi\, \pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$$

($\pi^+\pi^-\pi^0 \to \omega^0$; $\pi^+\pi^- \to \rho^0$)

  - **In the beauty sector Isospin should be well conserved & $X_b \to \Upsilon(1S)\omega$ allowed (preferred if it exists) !**

- **Thus, the search strategy for X_b should include the reconstruction of these decays with 1 or 2 photons:**

$$X_b \overset{(*)}{\to} \Upsilon(1S)\omega(\to \pi^+\pi^-\pi^0) \quad (\pi^0 \to 2\gamma)$$
$$X_b \to \chi_b(1P)\pi^+\pi^- \quad (\chi_b(1P) \to \Upsilon(1S)\gamma)$$
$$X_b \to \Upsilon(3S)\gamma$$

(*) No significant signal found by Belle in *Y(5S)* decays [PRL113, 142001 (2014)]

- **NOT easy task for CMS & ATLAS :**

  Reconstruction of SOFT photons by conversions into the tracker …

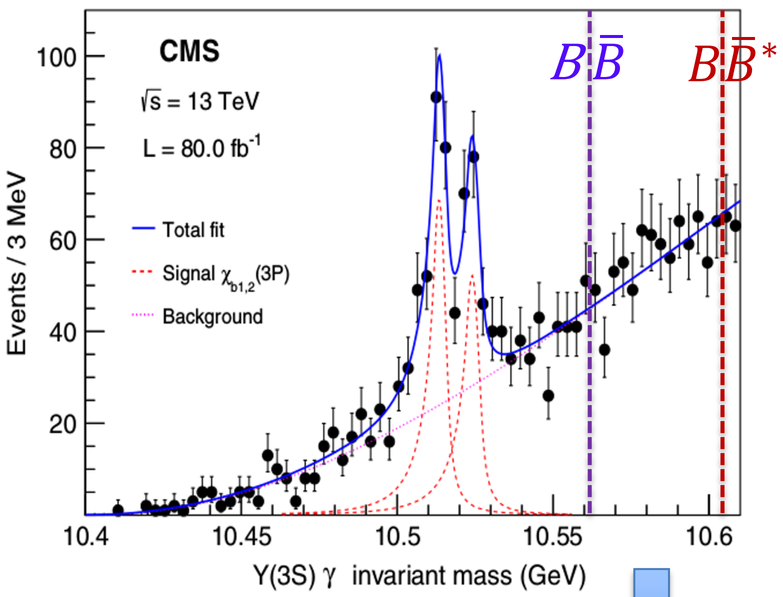
  - … provides enough mass resolution to resolve the two peaks
  - **… BUT conversion efficiency is LOW !**

- **Makes sense to use full Run-2 dataset !**

Is the hypothetical X_b seen decaying radiatively ?

- **The bottomonium *analogs* of the $\chi_{c1}(2P)$ and $X(3872)$ states …**
  would be the … $\chi_{b1}(3P)$ **and** X_b (the latter suggested by Heavy Quark symmetry)

Confirming that the $\chi_{b1}(3P)$ is well below the open-beauty threshold would suggest differences w.r.t. the charmonium: $\chi_{c1}(2P)$ is expected to be approximately 100MeV above the $D\bar{D}$ threshold



- Among the possibilities…
  - the single peak seen by LHCb could have been the X_b or a mixture of the $\chi_{b1}(3P)$ and the possible X_b state (Karliner & Rosner [PRD91 (2015) 014014] ; in analogy with the $X(3872)$ interpreted as a mixture of $\chi_{c1}(2P)$ & $D^0\bar{D}^{*0}$ molecule),
  - it could simply be the conventional (unresolved) $\chi_{bJ=1,2}(3P)$ and in this case a hypothetical X_b might exist at higher masses close to the $B\bar{B}^{(*)}$ thresholds.

- **At the level of the current statistics <u>no</u> hint of the hypothetical X_b that might exist close to the $B\bar{B}^{(*)}$ thresholds [radiatively decaying as $X_b \to \Upsilon(3S)\gamma$]**

This measurement strongly disfavours the breaking of the conventional pattern of splittings in the doublet and supports the standard hierarchy (*J=2* heavier than *J=1*) i.e. the proximity of open-beauty threshold have no relevant influence on the splitting

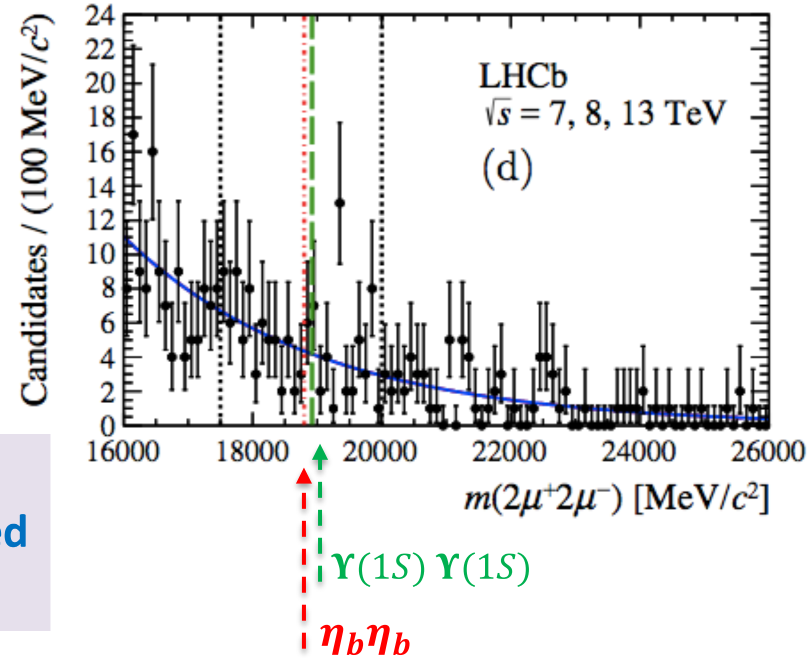
Introduction to searches in the $\Upsilon(1S)\mu^+\mu^-$ final state

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

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



- This new analysis probes a kinematical region not accessible at LHCb. CMS has also a very competitive acceptance for muons from $\Upsilon(1S)$ decays.

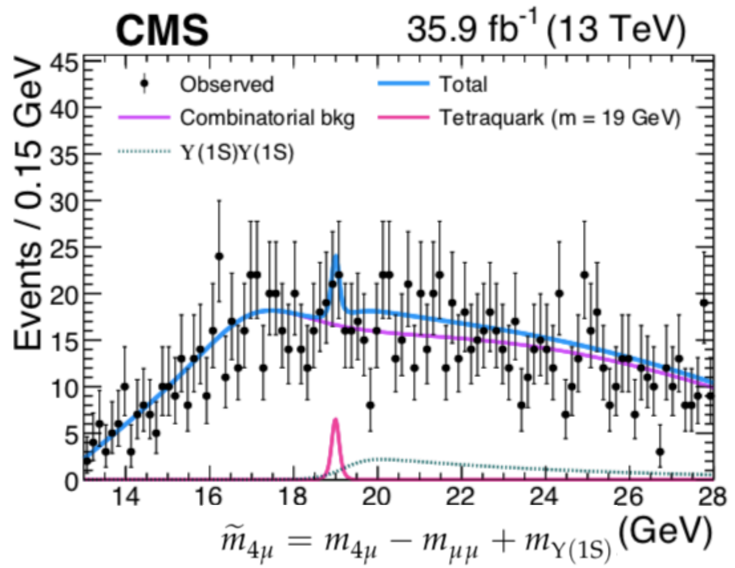
Moreover … a generic search for narrow resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ was performed in an extended mass window $16.5 \div 27$GeV .

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

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

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

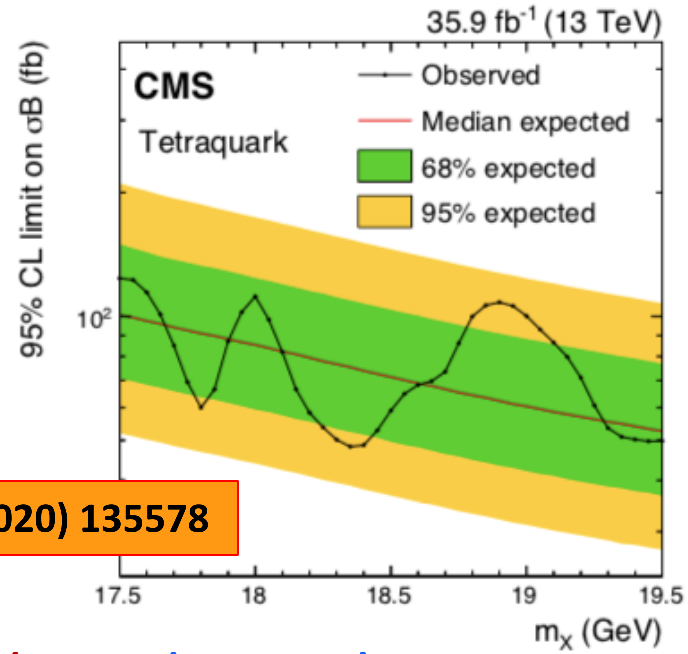
  An example of 4quark signal at 19GeV is shown
  This mass window is probed using the bottomonium model.
  In UML fits the signal has FWHM ~200MeV for a 18GeV resonance.



  Upper limits on the product of the production Xsection of a resonance & the BF to the final state of 4 muons via an intermediate $\Upsilon(1S)$, $\sigma(T_{bb\bar{b}\bar{b}})\times\mathcal{B}(T_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu^+\mu^-)$, are set @95% CL (using the modified frequentist construction CL_s in the asymptotic approx.**).**

  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).

  (*)$[79 \pm 11(stat) \pm 6(syst) \pm 3(BF)]pb$ for $|y| < 2.0$



PLB 808 (2020) 135578

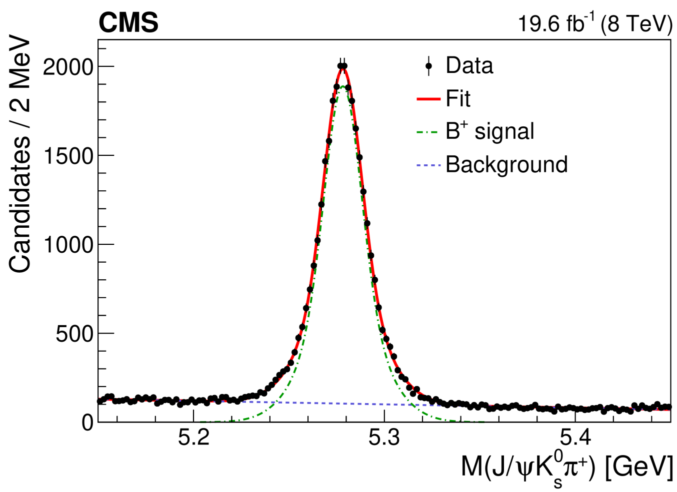
- **A further search for a light narrow resonance, such as a BSM bound state, does not show any significant narrow excess of candidates above the background expectation** (see backup).

Motivation & technique of the study of the decay $B^+ \to J/\psi\,\bar{\Lambda}p$

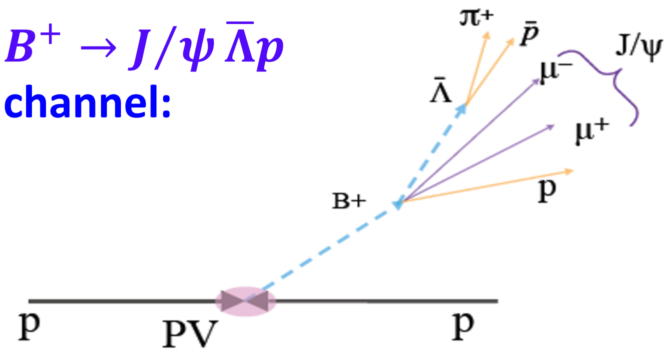
- Belle reported the observation of this decay in 2005 with low statistics [PRD 72 (2005) 051105]: it was the first observed *B* meson decay into baryons and a charmonium state.

- Studies of the intermediate inv. mass spectra in 3-body decays of *B* mesons & Λ_b baryon of the $J/\psi\, p$ system [PRL 115 (2019) 072001, 5-quarks by LHCb in $\Lambda_b \to J/\psi\, pK$] and - in general - of charmonium+baryon systems make this kind of decays rather interesting.

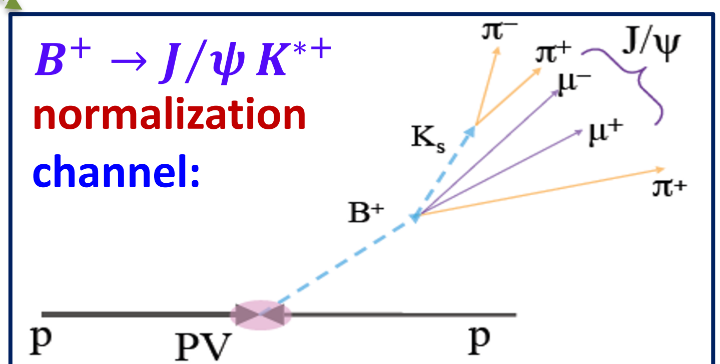
- The decay $B^+ \to J/\psi\, K^{*+}(\to K_S^0\pi^+)$ is chosen as the normalization channel, as it is measured with high precision and has similar decay topology (similar efficiency)



$B^+ \to J/\psi\,\bar{\Lambda}p$ channel:



$B^+ \to J/\psi\, K^{*+}$ normalization channel:



Signal extraction

- **Having no hadron identification: - proton mass assigned to the highest p_T track**
  - K^0_s veto applied for cleaning the Λ sample by contamination

- **UML fit to extract the B^+ signal yield :**

  signal model : 3 gaussian with a floating common mean and overall normalization (widths and rel. norm. from MC)

  bkg model : threshold polynomial

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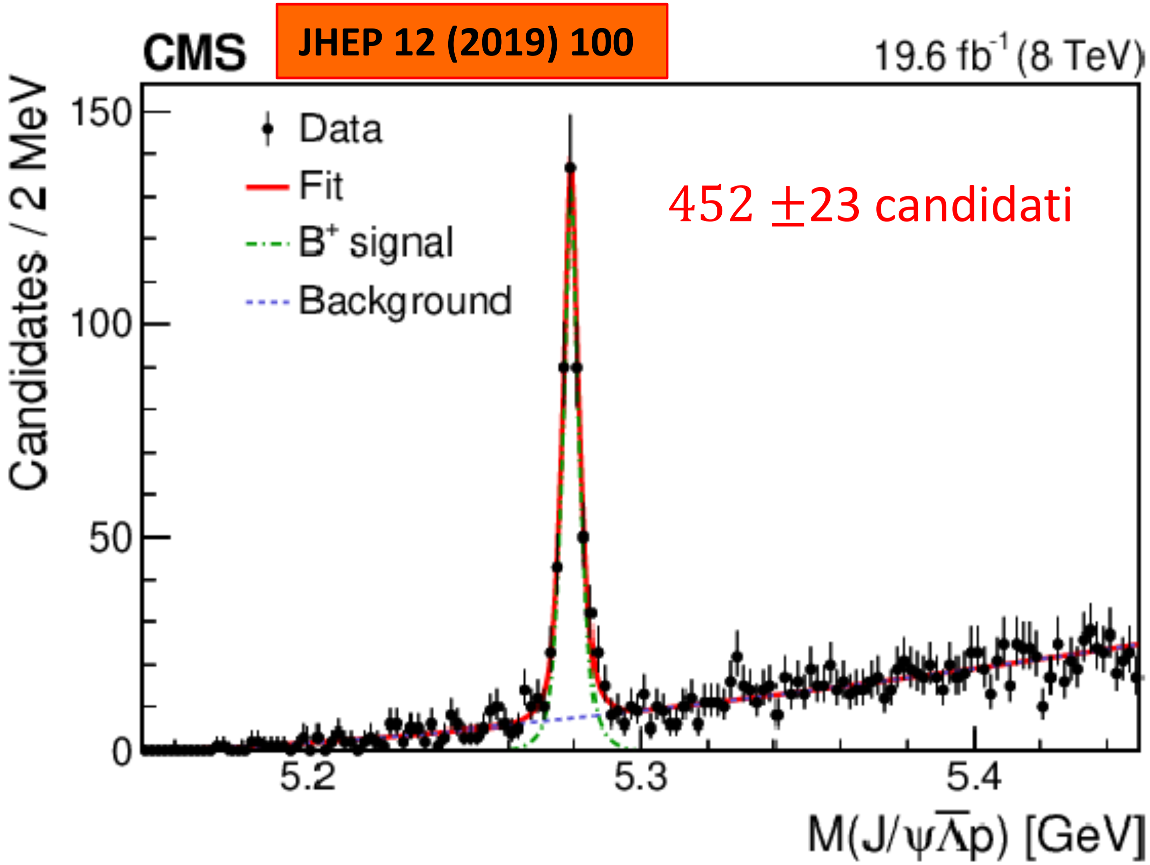


BF ratio measurement

- **The BF ratio is calculated as follows:**

$$\frac{\mathcal{B}(B^+ \to J/\psi \bar{\Lambda} p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = \frac{N(B^+ \to J/\psi \bar{\Lambda} p)\mathcal{B}(K^{*+} \to K^0_S \pi^+)\mathcal{B}(K^0_S \to \pi^+\pi^-)\epsilon(B^+ \to J/\psi K^{*+})}{N(B^+ \to J/\psi K^{*+})\mathcal{B}(\bar{\Lambda} \to \bar{p}\pi^+)\epsilon(B^+ \to J/\psi \bar{\Lambda} p)}$$

ratio of the signal yields in data

known Branching Fractions from PDG

Ratio of total efficiencies (from MC)

$$\frac{\mathcal{B}(B^+ \to J/\psi \bar{\Lambda} p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = (1.054 \pm 0.057(stat.) \pm 0.028(syst.) \pm 0.011(br.)) \times 10^{-2},$$

and using $\mathcal{B}(B^- \to J/\psi K^{*-}) = (1.43 \pm 0.08) \times 10^{-2}$

$$\mathcal{B}(B^+ \to J/\psi \bar{\Lambda} p) = (15.07 \pm 0.81(stat.) \pm 0.40(syst.) \pm 0.86(br.)) \times 10^{-6}$$

PDG mean value of $\mathcal{B}(B^+ \to J/\psi \bar{\Lambda} p) = (11.8 \pm 3.1) \times 10^{-6}$

The latest Belle measurement $\mathcal{B}(B^+ \to J/\psi \bar{\Lambda} p) = (11.7 \pm 2.8^{+1.8}_{-2.3}) \times 10^{-6}$

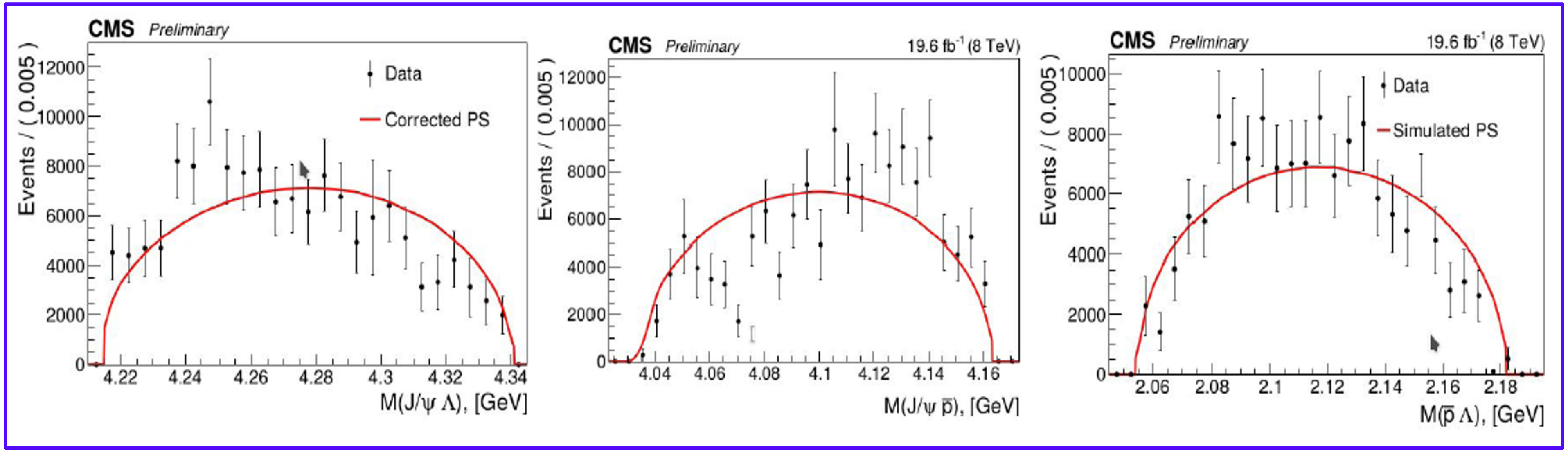
Most precise measurement to date and consistent with Belle

Study of intermediate invariant masses in the decay $B^+ \to J/\psi\,\bar{\Lambda}p$

- **Large signal yield allows CMS to try to perform a search for new exotic multiquark states in the *efficiency-corrected* two-body intermediate systems of the 3-body decay under study**

  - Background subtraction is performed using the ***sPlot*** **technique**, with the invariant mass $m(J/\psi\,\bar{\Lambda}p)$ as the discriminating variable.

The obtained bkg-subtracted distributions are compared with pure 3-body phase space shapes:



The intermediate invariant masses are found to be inconsistent with the pure 3-body phase space hypothesis with a significance more than 6.1σ, 5.5σ & 3.4σ respectively for …
… $J/\psi\,p$, $J/\psi\,\bar{\Lambda}$ & $\bar{\Lambda}p$!

Model independent approach (method of moments) - I

- **This method has been first introduced by** [PRD 79 (2009) 112001, PRD 85 (2012) 052003] **and later used by** [PRD 92 (2015) 112009, PRL 117 (2016) 082002].

  - There are at least three known **K^{*+} resonances** (excited kaons) resonances that can decay to $\bar{\Lambda}p$ (as listed in the table). This method has been used to properly account for possible contributions - due to their *reflections* - onto the other two intermediate two-body invariant mass spectra.

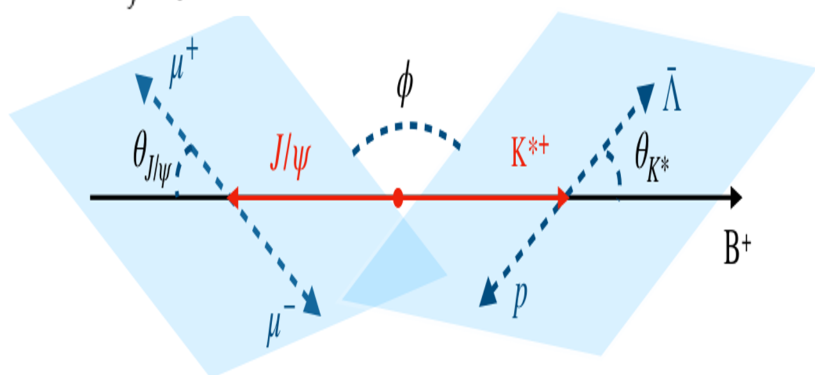
Resonance	Mass [MeV]	Natural width [MeV]	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

In each efficiency-corrected $m(\bar{\Lambda}p)$ bin [through weights calculated on the rectangular DP $m(\bar{\Lambda}p)$ vs $\cos(\vartheta_{K^*})$ and obtained by simulation] the $\cos(\vartheta_{K^*})$ distribution can be expressed as the expansion in terms of Legendre polynomial

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{j=0}^{l_{\max}} \langle P_j^U \rangle P_j(\cos\theta_{K^*}) \quad , \ell_{MAX} = 8$$

where:

- $\ell_{MAX} =$ 2 x (spin of the highest spin resonance) can describe all resonances & interferences;
- $\cos(\vartheta_{K^*})$ is the helicity angle of the K^{*+} (see fig.) in the $\bar{\Lambda}p$ system rest frame.



Model independent approach (method of moments) - II

- The simulation-based reweighting according to the observed angular structure in the $\bar{\Lambda}p$ system shows that the description of the distributions of the invariant masses $m(J/\psi\,\bar{\Lambda})$ & $m(J/\psi\,p)$ is much improved after accounting for the angular and invariant mass characterizing the $\bar{\Lambda}p$ system.

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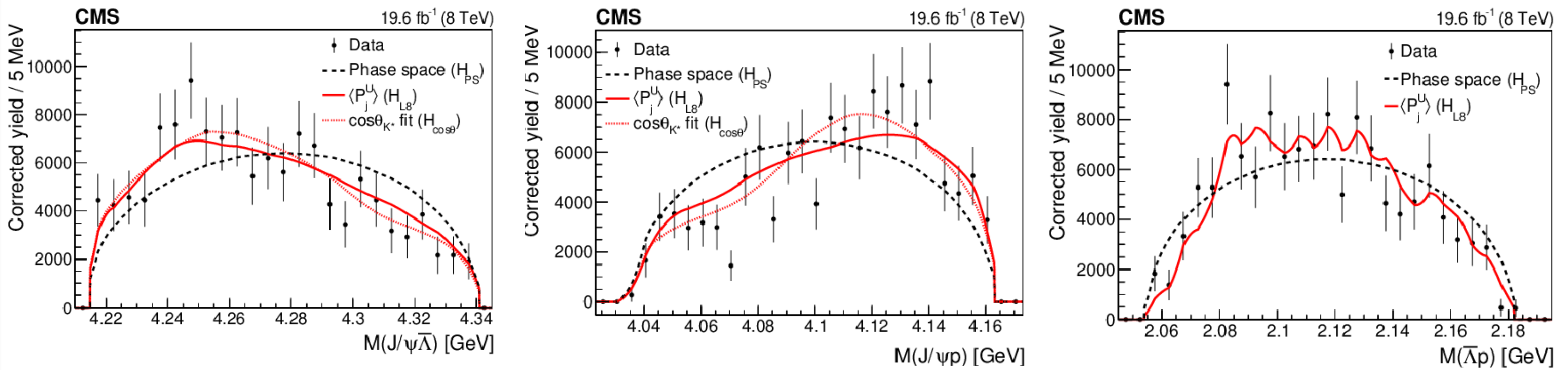


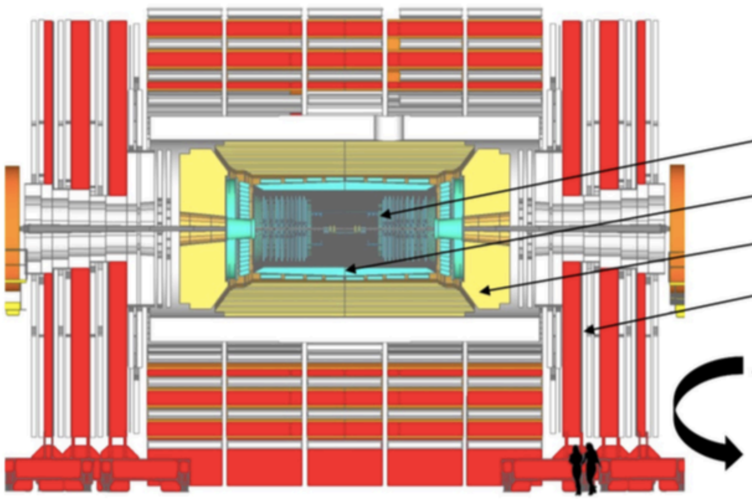
The *incompatibility* of the data with the reweighted phase-space distributions is quantified by using a likelihood ratio method and results to vary from 1.3σ to 2.8σ (2.7σ) .

Thus, there is no need to introduce exotic resonances in the $J/\psi\,p$ & $J/\psi\,\bar{\Lambda}$ systems.

- **CMS will undergo a vast upgrade designed for pile-up of 200 in pp collisions**
(pp events will be characterized by a similar multiplicity than in central PbPb collisions).

CMS will have a larger rapidity coverage and higher acquisition rate compared to current config.

[CERN-LHCC-2015-010]

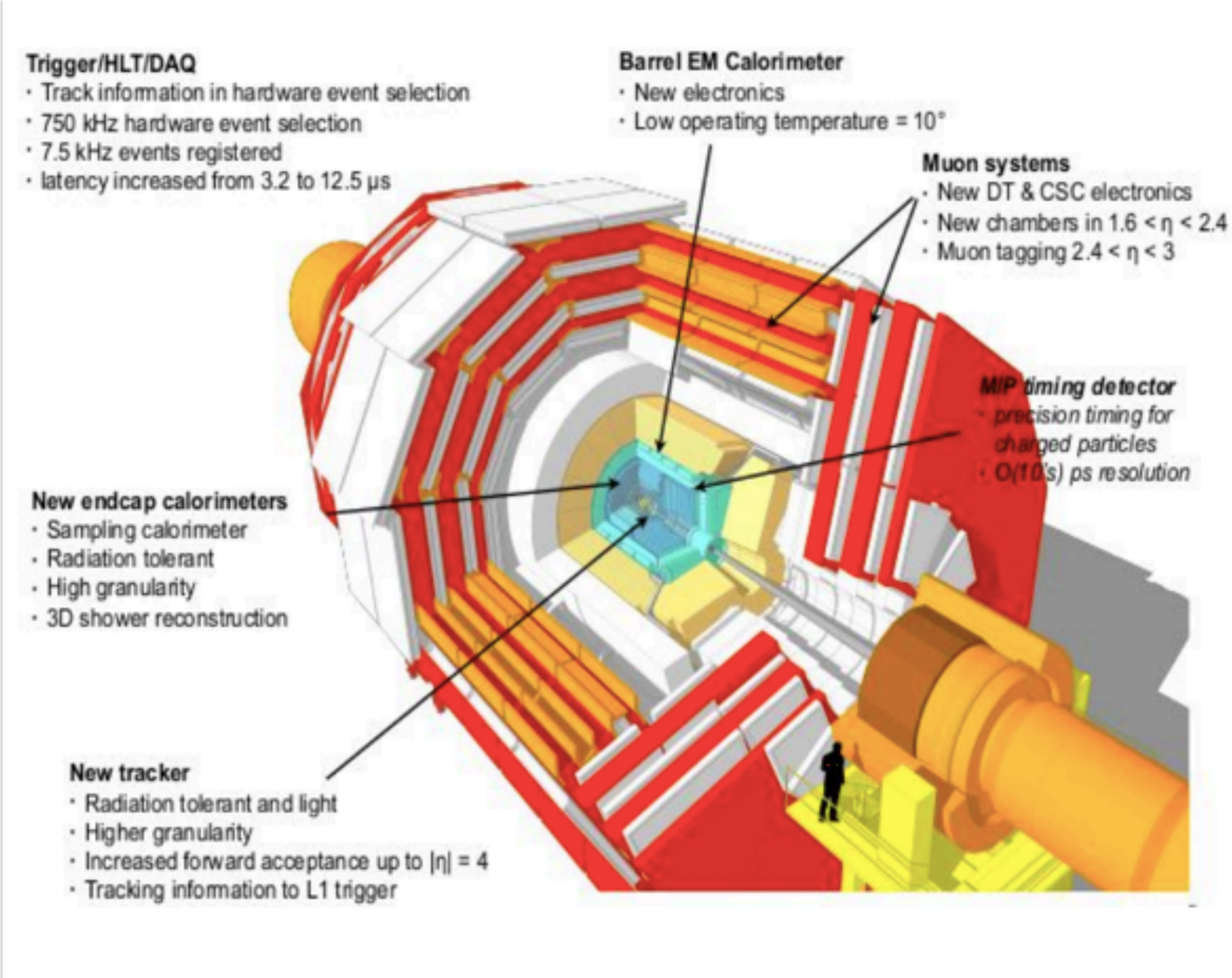


System	Present	Phase 2
Tracker	$\|\eta\| < 2.4$	$\|\eta\| < 4$
TOF	None	$\|\eta\| < 3$
Calorimeters	Standard	High granularity
Muon	$\|\eta\| < 2.4$	$\|\eta\| < 2.8$
Trigger	100 kHz	750 kHz
DAQ	6 GB/s	60 GB/s

Record **all** PbPb events (≈50% in Run 3)

CMS

Phase-II Upgrade - 2



CMS Phase-II upgrades include:

- a new tracker with improved p_T resolution and radiation hardness, lower material budget, extended coverage
- increased muon coverage
- a new forward calorimeter with high granularity and resolution
- addition of the MIP timing detector (MTD)
- increased trigger bandwidth & latencies
- inclusion of tracking information at L1 trigger
- replacement of electronics

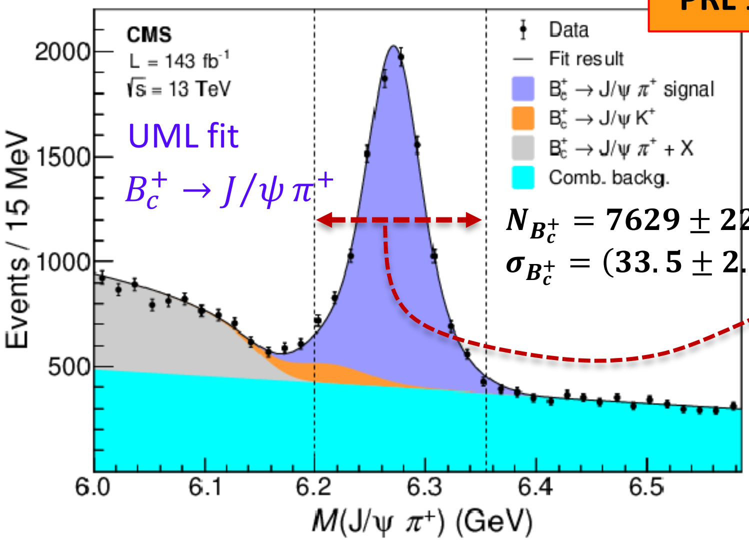
Additional material

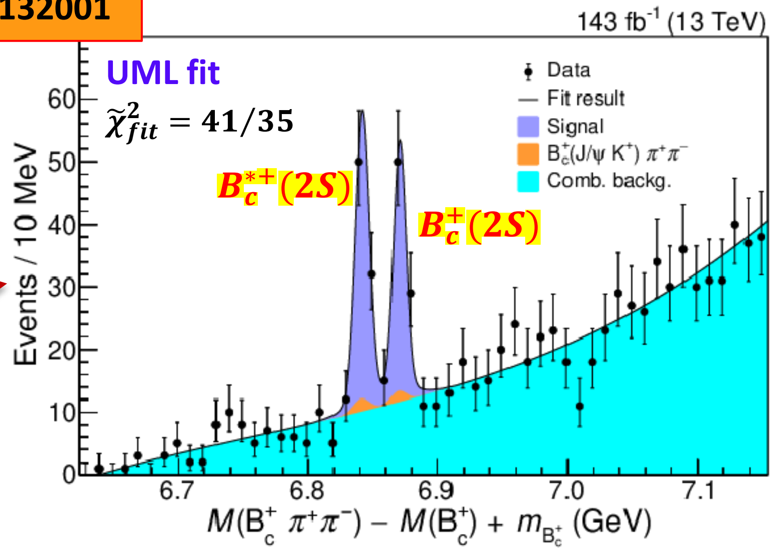
Observation of radially excited B_c^+ mesons

- CMS [PRL 122 (2019) 132001] **observed for the first time the two radially excited (hyperfine doublet)** $\{B_c^+(2S), B_c^{*+}(2S)\}$ **decaying to $B_c^+\pi^+\pi^-$ final state [** the second through a radiative decay with the emitted very soft photon undetected : $B_c^{*+}(2S) \to B_c^{*+}\pi^+\pi^-, B_c^{*+} \to B_c^+\gamma$ **]**

- Predictions $[m(B_c^{*+}(1S)) - m(B_c^+(1S))] > [m(B_c^{*+}(2S)) - m(B_c^+(2S))]$ imply that **$B_c^{*+}(2S)$ peak is the lower one :** [see next slide]

PRL 122 (2019) 132001





$N_{B_c^+(2S)} = 52 \pm 9$

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

$\Delta m = (28.9 \pm 1.5) MeV$

$m(B_c^+(2S)) = (6871.0 \pm 1.2) MeV$

- **Mass resolution agrees with MC expectations (~6MeV) and is much lower than Δm thus allowing to observe 2 peaks**
  - **Local significance exceeding 6.5σ for observing 2 peaks rather than 1. For both single peaks significance >5σ.**
  - **Natural widths (**predicted $50 \div 90 KeV$ **) much smaller than mass resolution.**

- LHCb **has later confirmed** [PRL 122 (2019) 232001] **the 2 peaks (**actually, there is an **evidence for the 2nd)**
  - $B_c^+(2S)$ mass & hyperfine splitting ΔM are in agreement between the two experiments

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**

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

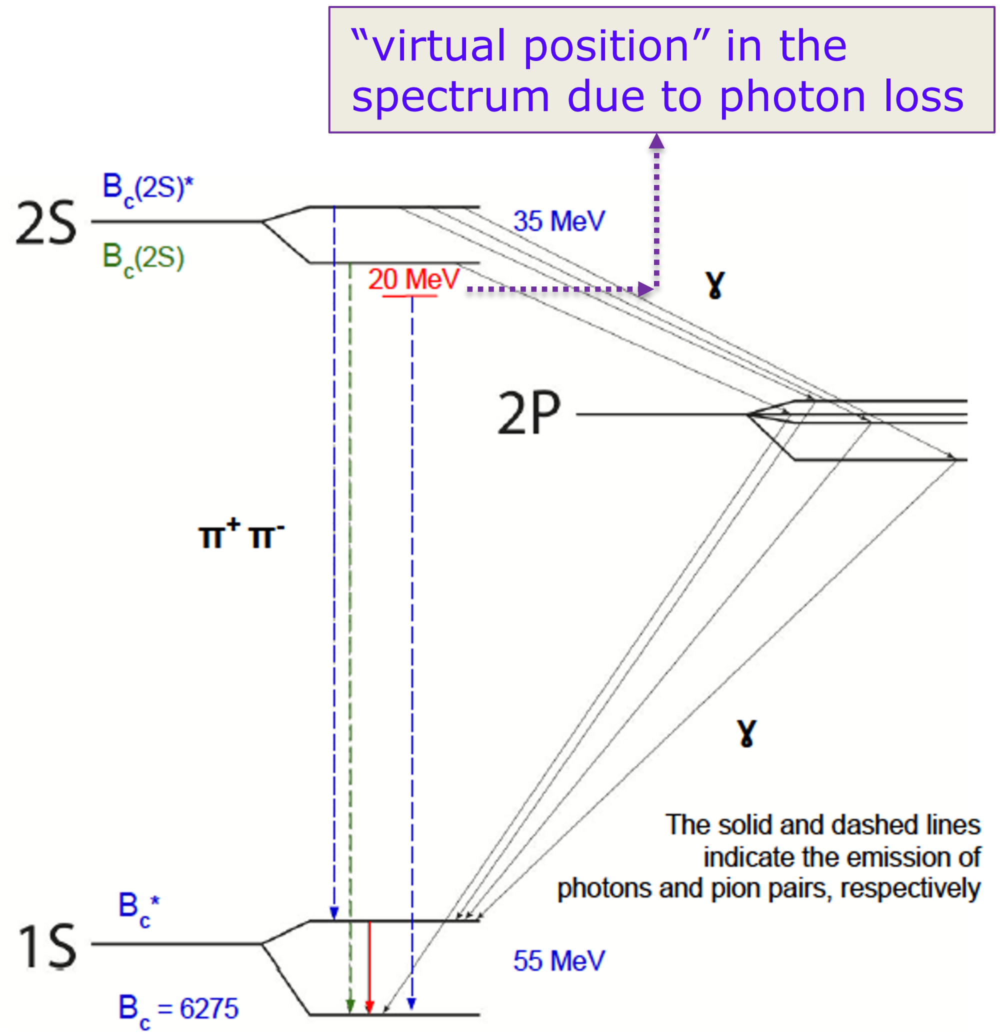
  which is predicted to be around 20 MeV.

  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**!



Differential production Xsection ratios for $B_c^+(2S)$ & $B_c^{*+}(2S)$

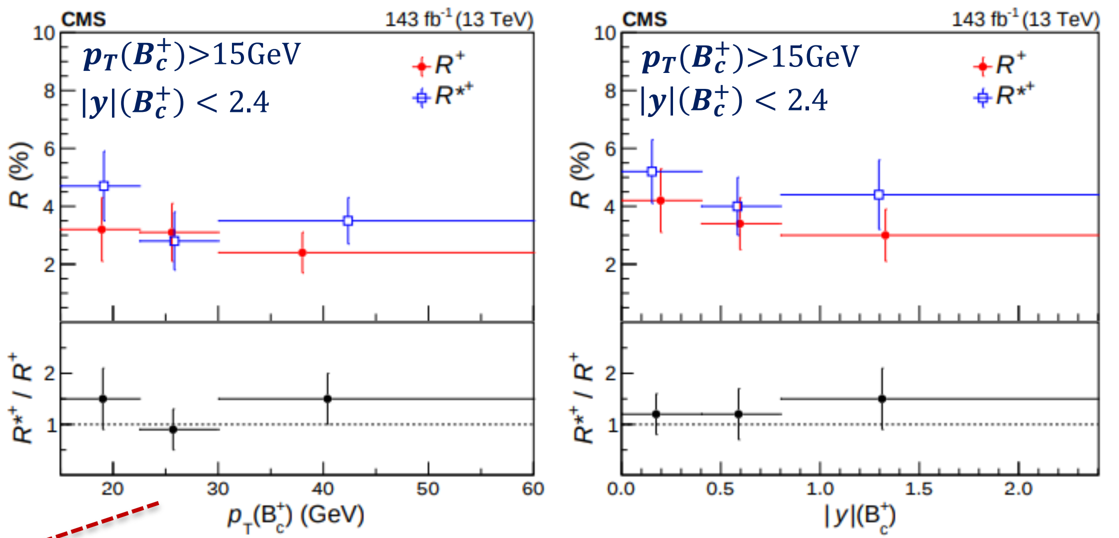
- To infer ratios of production Xsections (times BFs) from the extracted yields the latter must be corrected for detection efficiencies and acceptances. It is important to experimentally determine the ratio since different models can bring to relevantly different predictions for 2S-excitations (*).

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

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

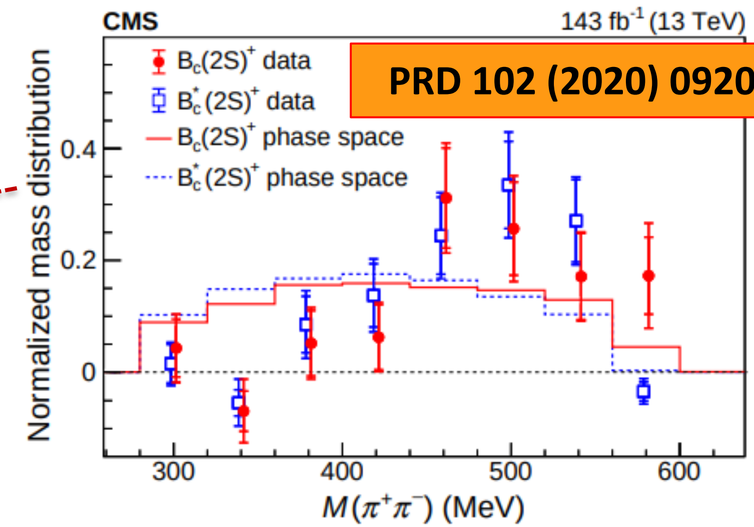
$$R^{*+}/R^+ = \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c(2S)^+)}\frac{\mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-)}{\mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-)} = \frac{N(B_c^*(2S)^+)}{N(B_c(2S)^+)}\frac{\epsilon(B_c(2S)^+)}{\epsilon(B_c^*(2S)^+)}.$$

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



- No significative dependence of these three xsection ratios on $p_T(B_c^+)$ & $|y|(B_c^+)$

- In the normalized dipion invariant mass …
… observed different shapes from ~flat phase space, not fully significant at this level of the uncertainties.



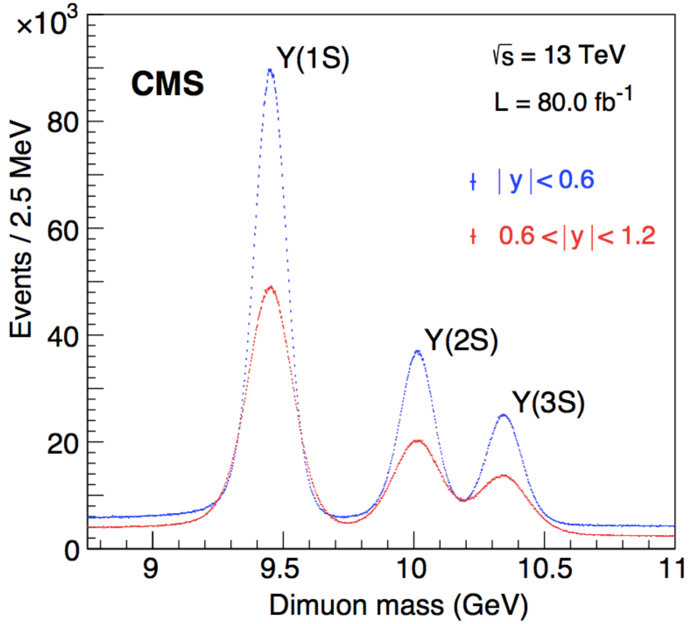
PRD 102 (2020) 092007

(*) Berezhnoy et al., Mod. Phys. Lett. A34 (2019) 1950331]; Eichten & Quigg, PRD 99 (2019) 054025]

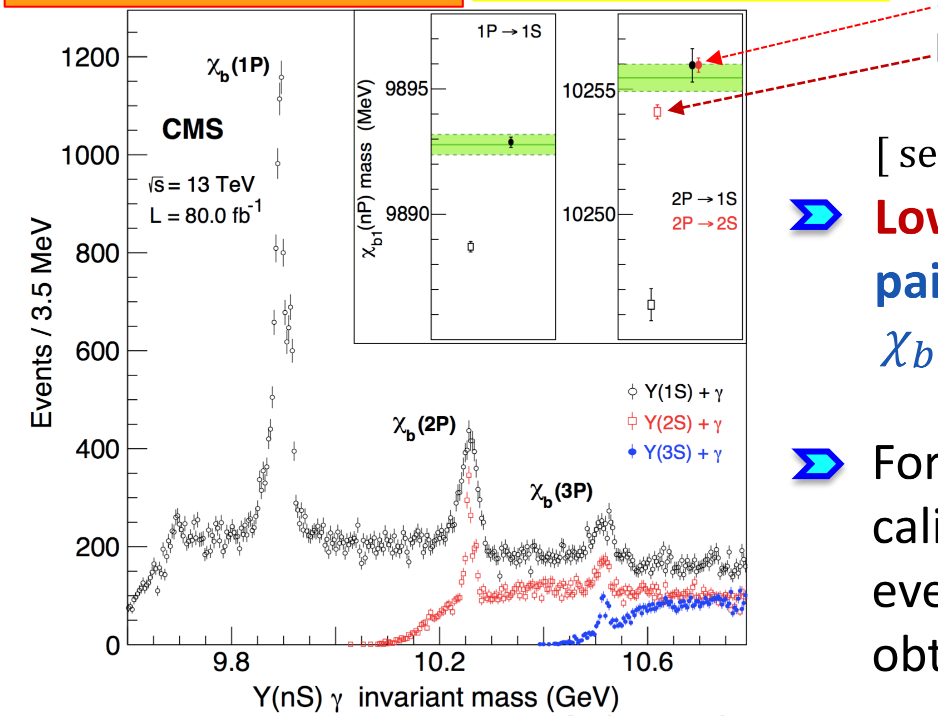
First observation of resolved $\chi_{b1}(3P)$ & $\chi_{b2}(3P)$ states - I

By CMS, through their radiative decays to $\Upsilon(3S)\gamma$ using $\sim 80 fb^{-1}$ of 2015-2017 Run-II (13TeV)

- **Dimuons** (with two oppositely charged muons coming from a common vertex) **compatible with the signals $\Upsilon(nS) \to \mu\mu, n = 1, 2, 3$ are used to trigger the events.**
- Offline $\Upsilon(3S) \to \mu^+\mu^-$ candidates: $p_T > 14GeV$ & $|y| < 1.2$



PRL 121 (2018) 092002 $\Upsilon(nS)\gamma \ [n = 1,2,3]$



[selection: p_T>500MeV , $|\eta| < 1.2$]

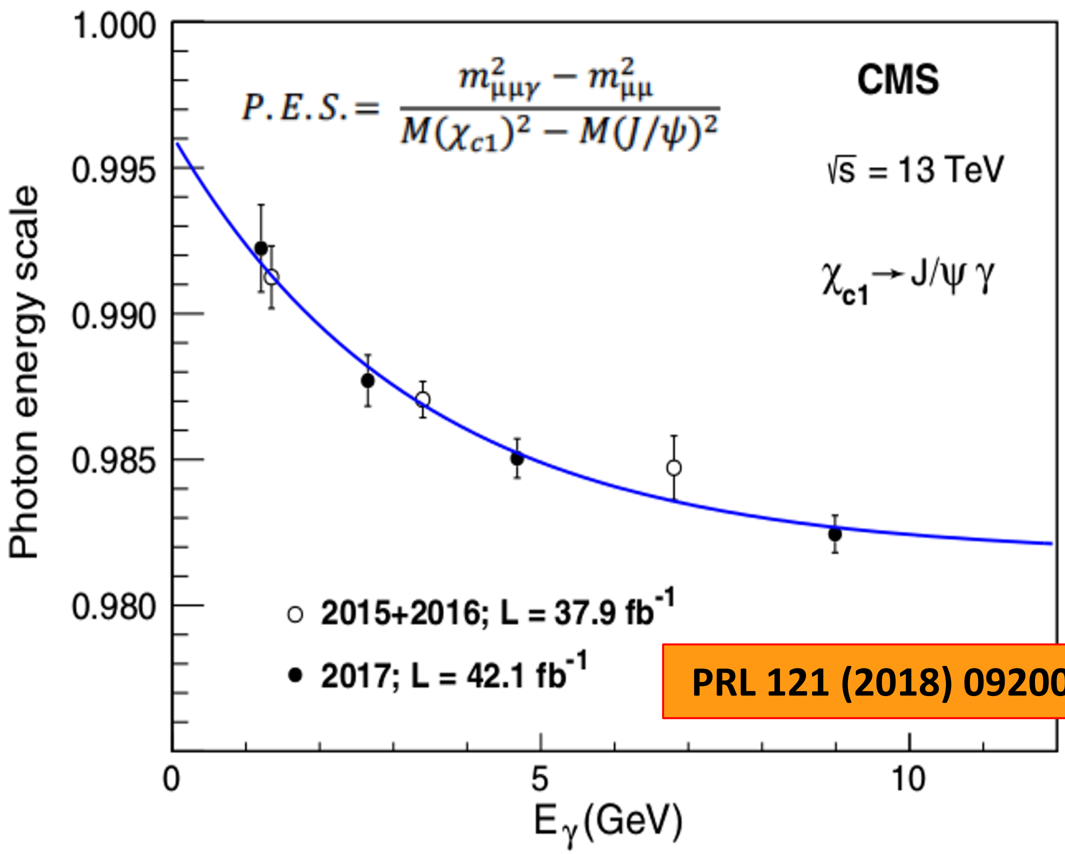
- **Low-energy photons detected after converting to e^+e^- pairs in the beam pipe and silicon tracker leading to a $\chi_b(3P)$ mass resolution of $2.18 \pm 0.32 MeV$!**
- For a more accurate measure the photon energy scale (PES) is calibrated by means of a large data sample of $\chi_{c1} \to J/\psi\,\gamma$ events (event-by-event corrections - reco/true energy - are obtained in several bins of E_γ : $P.E.S. = \frac{m^2_{\mu\mu\gamma} - m^2_{\mu\mu}}{M(\chi_{c1})^2 - M(J/\psi)^2}$).

PES correction: details

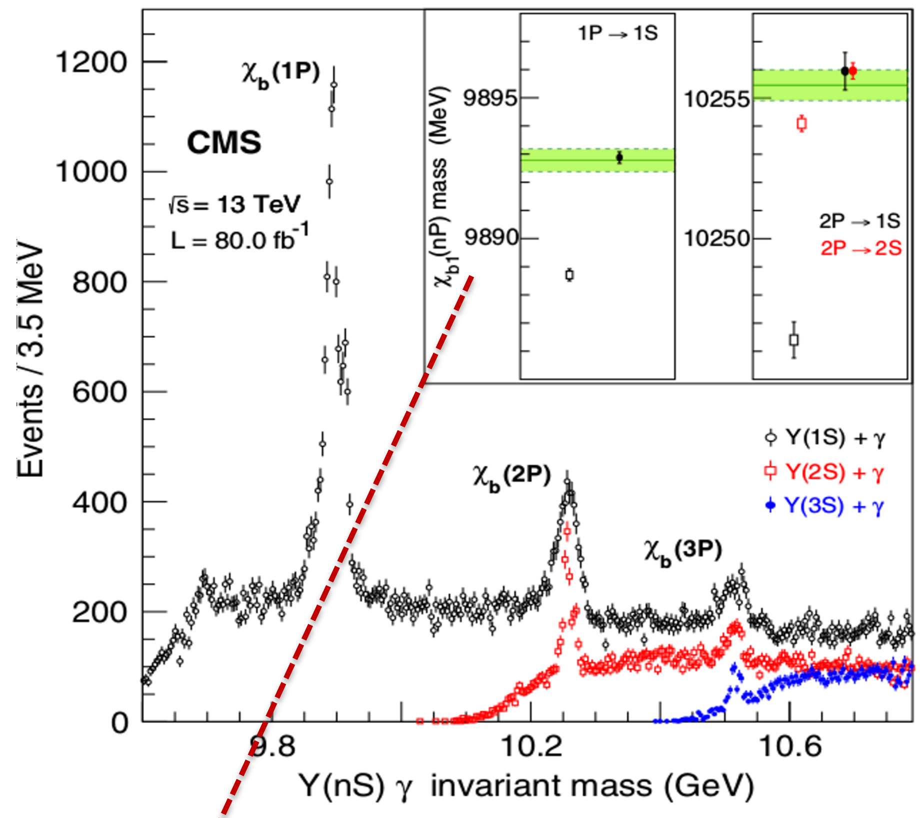
The measured photon energy might differ from the true value: $E_{true} = E_{rec} / PES$

The PES is computed using $\chi_{c1} \to J/\psi\ \gamma$ events, comparing the measured and PDG χ_{c1} masses

The J/ψ γ events were collected in the same runs, with similar dimuon triggers, and processed in the same way as the Upsilon events



PRL 121 (2018) 092002

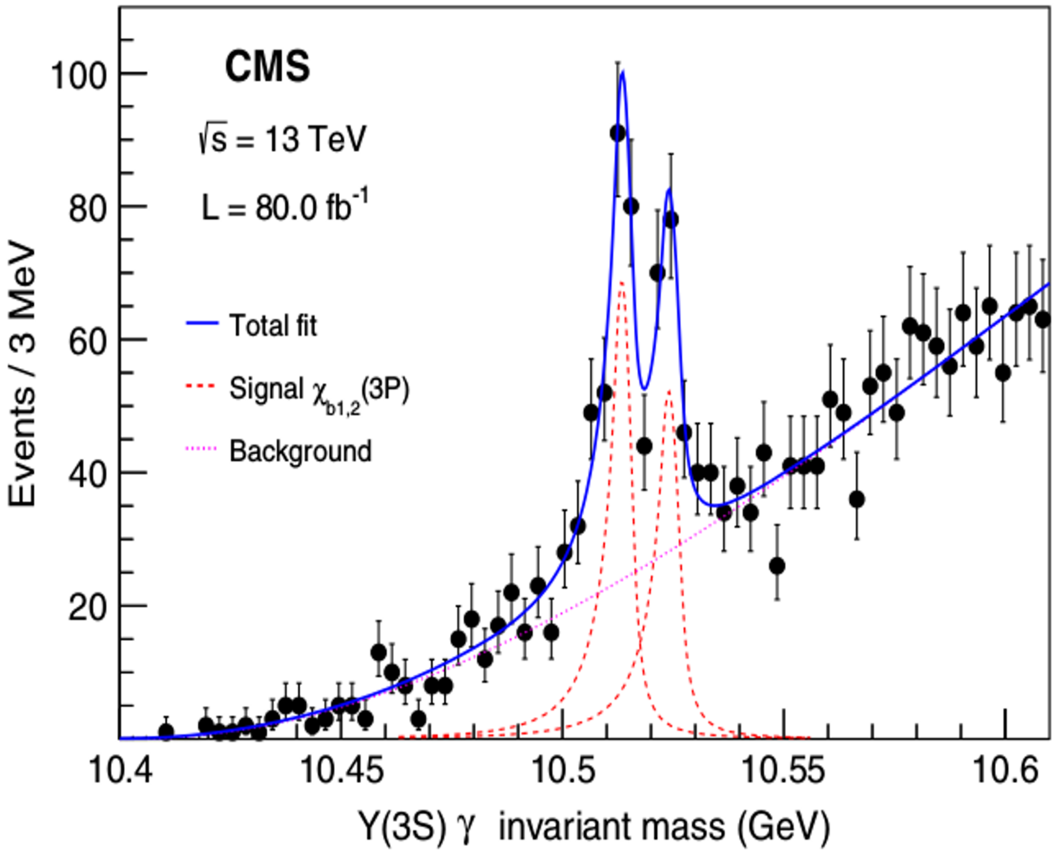


(The correction is small for $\chi_b(3P) \to Y(3S)\gamma$ because of small photon energies)

Source of uncertainty	ΔM	$M(\chi_{b1}(3P))$
Fit Model	0.05	0.05
PES correction	0.16	0.17

First observation of resolved $\chi_{b1}(3P)$ & $\chi_{b2}(3P)$ states - II

- **UML fit** to the mass spectrum with:
  - **signal peaks: double-sided Crystal Ball**
  - **bkg: (exp. × quadratic threshold)** functions
  - main systematic uncertainty from PES function
  - total (2-peaks) yield: $\mathbf{372 \pm 36}$
  - 2-peaks local stat. significance >9σ (rather than one; likelihood ratio test)



- **The two masses are *individually* measured & the Δm as well :**

PRL 121 (2018) 092002

$$M[\chi_{b1}(3P)] = (10513.42 \pm 0.41 \pm 0.18)\ \text{MeV},$$

$$M[\chi_{b2}(3P)] = (10524.02 \pm 0.57 \pm 0.18)\ \text{MeV},$$

$$\Delta m_{21} \equiv m(\chi_{b2}) - m(\chi_{b1}) = (10.6 \pm 0.64 \pm 0.17)\ \text{MeV}$$

→ **enough precise to provide an important constraint to theory models**

Reminder: *J=0* state expected to have negligible radiative decay BF !

Mass splitting : comparison with theoretical predictions

- **The high-resolution study by CMS is able to distinguish *for the first time* between the $\chi_{b1}(3P)$ & $\chi_{b2}(3P)$ candidates of the multiplet.**

- **This measurements fills the gap in the spin-dependent bottomonium spectrum below the open-beauty threshold and should contribute to the understanding of the non-perturbative spin-orbit interactions affecting quarkonium spectroscopy:**

TABLE II. Mass splitting (in MeV) of 3*P*-wave bottomonia in our UQM [12], Godfrey-Isgur (GI) model [16], modified GI model [17], and constituent quark model (CQM) [18]. The later three models are regarded as quenched quark models.

Mass splitting	Our UQM [12]	GI [16]	Modified GI [17]	CQM [18]	Experiment [1]
$\chi_{b1}(3P) - \chi_{b0}(3P)$	23	16	14	13	...
$\chi_{b2}(3P) - \chi_{b1}(3P)$	12	12	12	9	$(10.6 \pm 0.64 \pm 0.17)$

From: Anwar et al., PRD99 (2019) 094005

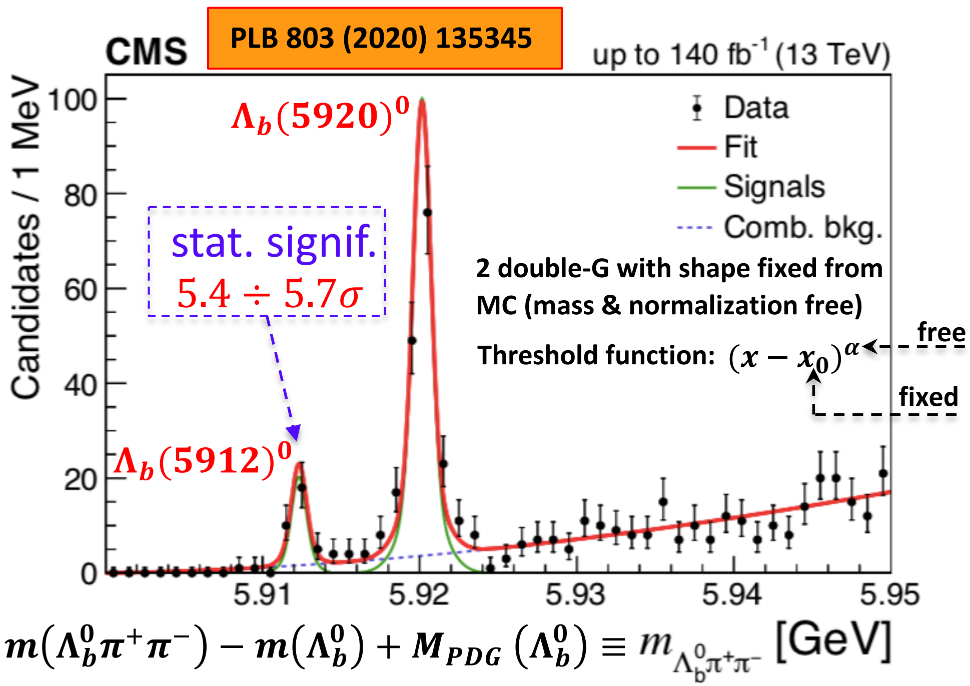
- The same authors predict **relative BF** of $\chi_{b0}(3P) \to \Upsilon(3S)\gamma$ to be slightly more than 1 order of magnitude smaller than that of $\chi_{b2}(3P) \to \Upsilon(3S)\gamma$ (slightly more than potential models). **They are all consistent with the CMS non-observation (so far).**

- **Studies of excited heavy baryon spectrum are important test of HQET.**
  There are many - not agreeing ! - predictions of excited Λ_b & Σ_b states (masses' spread in rather wide regions, most predictions without uncertainties' ranges)

- LHCb [PRL 109 (2012) 172003] **observed** for the first time **2 near-threshold excited states $\Lambda_b^{0*} \to \Lambda_b^0 \pi^+ \pi^-$**
  $(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$, $\Lambda_c^+ \to pK^-\pi^+$

- CMS can't use neither … the most copious $\Lambda_b^0 \to \Lambda_c^+ \pi^-$: no dedicated trigger, large BKG (no PID)
  …nor $\Lambda_b^0 \to J/\psi\, pK^-$: very large BKG (lack of hadronic PID)

…but… can use $\Lambda_b^0 \to J/\psi\, \Lambda$ (~85%) & $\Lambda_b^0 \to \psi(2S)\Lambda$ [with $\psi(2S) \to \mu\mu, J/\psi\,\pi\pi$] by triggering on dimuons



Confirmation of $\Lambda_b(5912)^0$

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

Mass measurements:

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

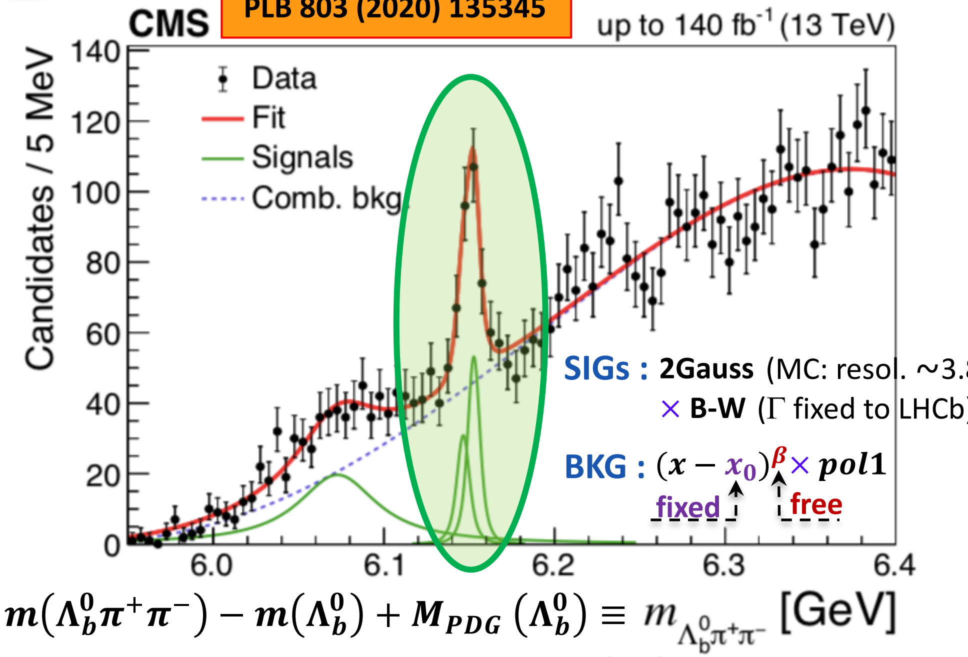
$$M(\Lambda_b(5920)^0) = [5920.16 \pm 0.07(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\text{MeV}$$

- **consistent with those by LHCb/PDG & with similar precision**

Λ_b^0 excited states in *high-mass region*

- [PRL 123 (2019) 152001] **using full Run-1+2 dataset observed 2 new excited states decaying to $\Lambda_b^0\pi^+\pi^-$**
(using $\Lambda_b^0 \to \Lambda_c^+\pi^- \& \Lambda_b^0 \to J/\psi\, pK^-$)

- **PLB 803 (2020) 135345**



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

Mass measurements:

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

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

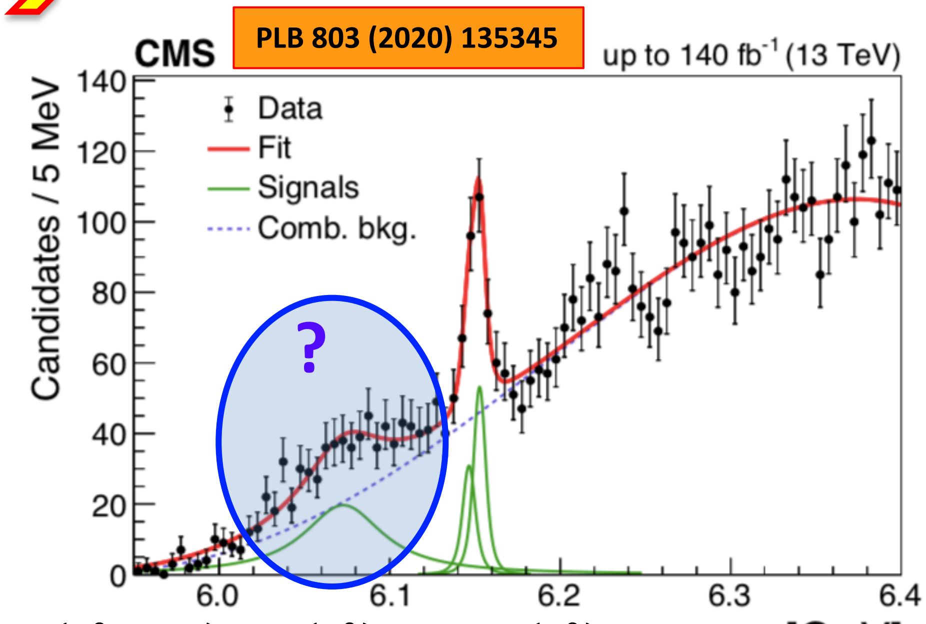
- **… in agreement with LHCb values (but not as precise as theirs)**

- **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) **: not sensitive to the splitting**
  (because of the worse mass resolution & much lower statistics w.r.t. LHCb)

Broad structure in *high-mass region*



- "bump" **not present in the SS ($\Lambda_b^0\pi^\pm\pi^\pm$) mass spectrum**
- **assuming a single broad resonance X_b the fit** with M & Γ free parameter **- provides (with stat. sig. ~ 4σ) :**

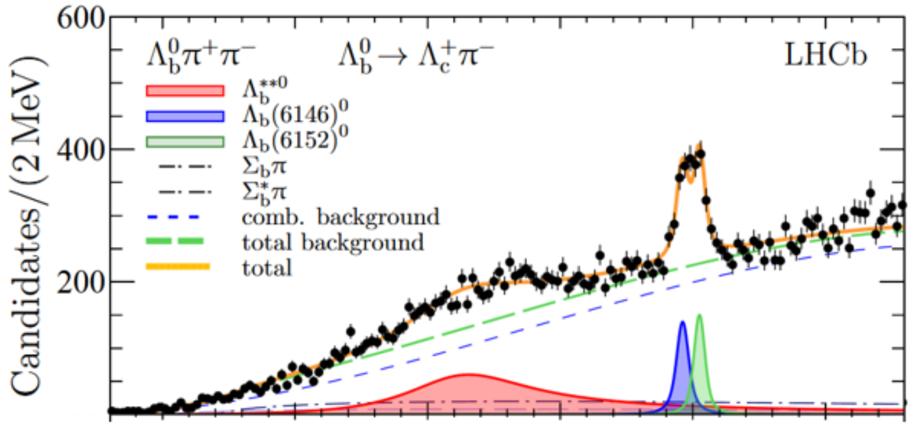
  $M(X_b) = [6073 \pm 5(stat)]MeV \quad \Gamma(X_b) = [55 \pm 11(stat)]MeV$

- **consistent with originating from a resonance in the $\Sigma_b^{(*)\pm}\pi^\mp$ system, but no firm conclusion can be made**
- **various reflections studied & excluded as the origin; but… may be due to partially reconstructed decays of higher-mass states**
- **too low statistics to try a proper interpretation of broad structure (could be also a superposition of few nearby broad states)**

Few days after CMS paper has appeared on the arXiv …
LHCb **confirmed the wide bump** with similar parameters:

$$m = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2MeV\,, \Gamma = 72 \pm 11 \pm 2MeV$$

… interpreting it as a further excited Λ_b^0 state: $\Lambda_b(6072)^{**0}$



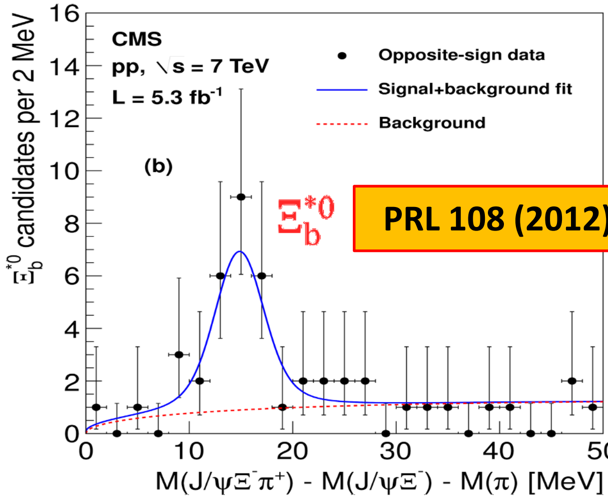
[JHEP 06 (2020) 136]

Observations of new beauty Ξ baryons

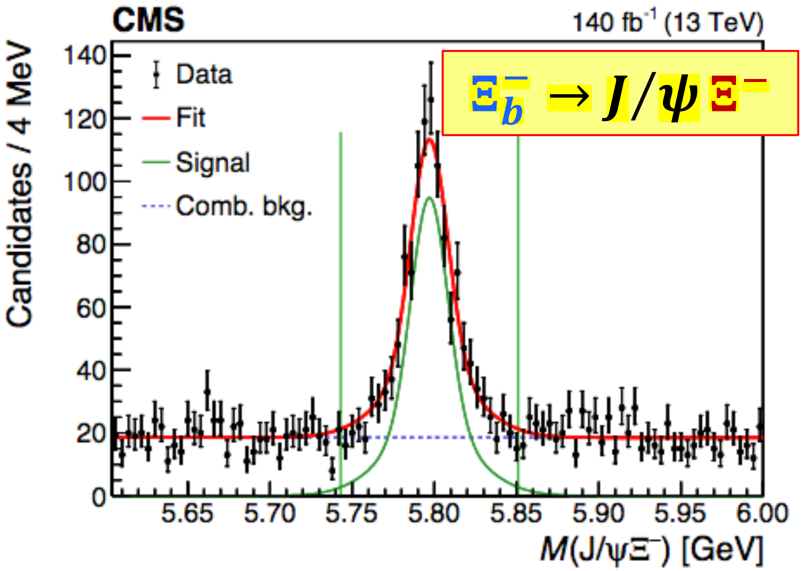
- CMS - already with 2011 data - **observed a new Ξ baryon** (Ξ_b^{*0}) [PRL 108 (2012) 252002] **via its strong decay** to $\Xi_b^{\mp}\pi^{\pm}$.

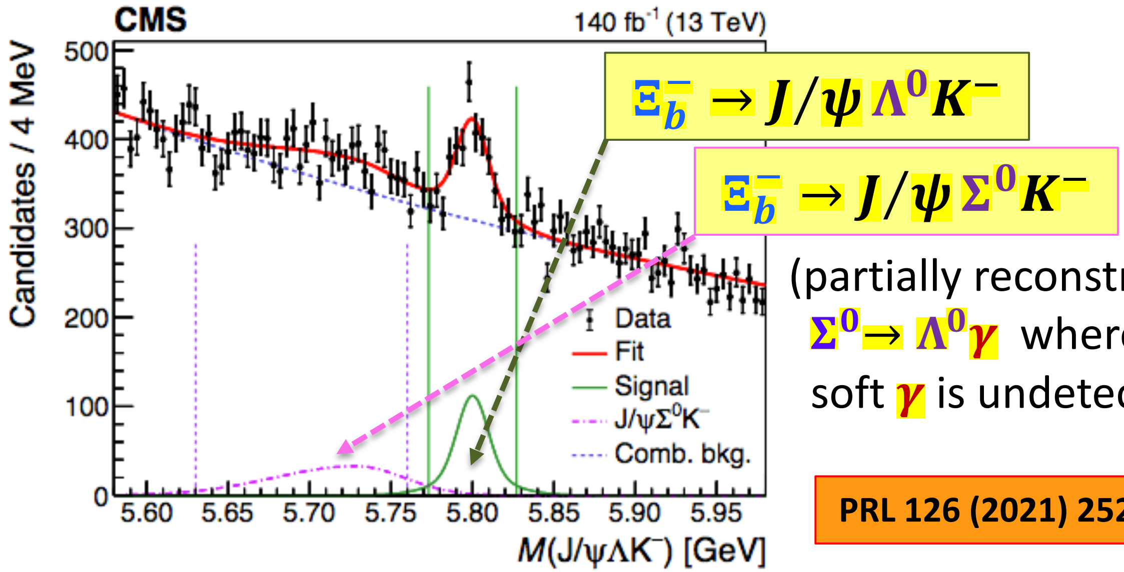
  The ground state Ξ_b baryon was reconstructed via the decay chain $\Xi_b^- \to J/\psi\, \Xi^-$, $\Xi^- \to \Lambda^0\pi^-$, $\Lambda^0 \to p\pi^-$.

  - It should correspond to the $J^P = 3/2^+$ **companion** of the Ξ_b.



- **Recently** CMS **observed the lightest orbitally excited beauty strange baryon** $\Xi_b^{**}(6100)^- \to \Xi_b^-\pi^+\pi^-$ **(including the - dominant - intermediate resonance** $\Xi_b^{*0} \to \Xi_b^-\,\pi^+$). The Ξ_b baryon was reconstructed via:



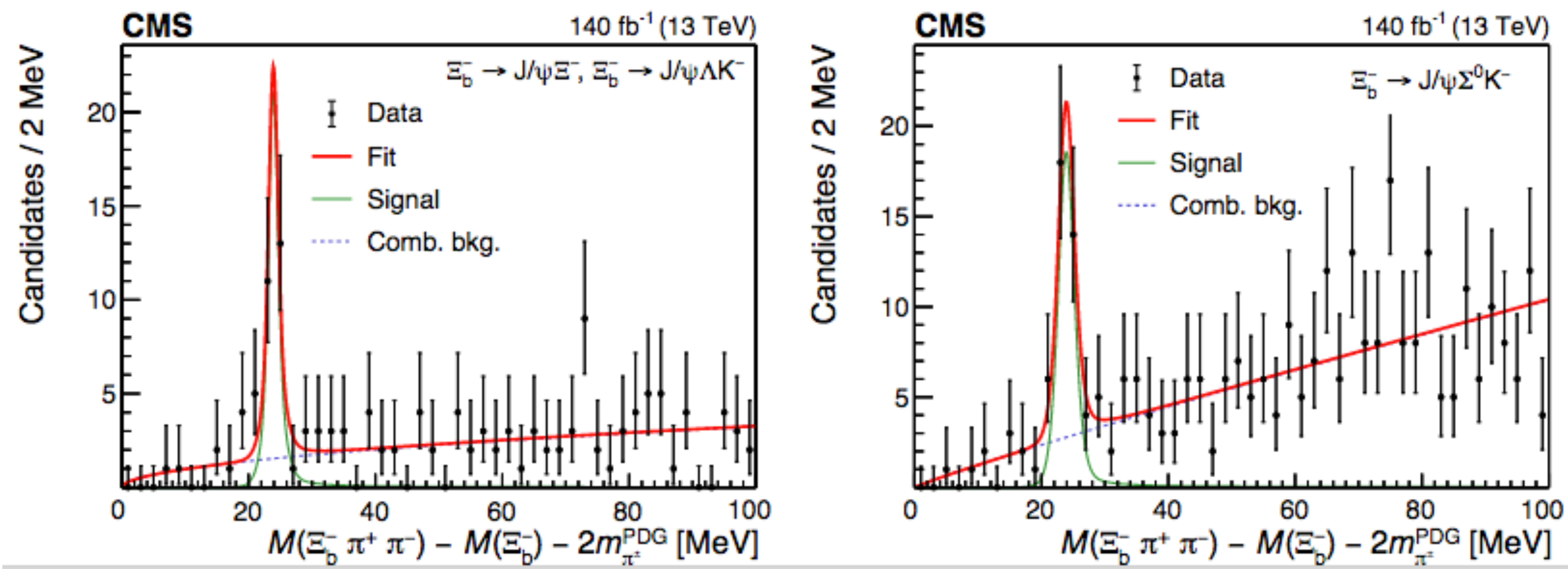


(partially reconstructed: $\Sigma^0 \to \Lambda^0\gamma$ where the soft γ is undetected)

PRL 126 (2021) 252003

Observation of the excited beauty baryon $\Xi_b^{**}(6100)^-$

- The invariant mass of the final state is build combining the fully reconstructed decays (left) with identical mass resolutions and the partially reconstructed channel (right) with a 30% larger mass resolution.
The projections of the **simultaneous** extended UML fit (mass parameter is common due to Δm definition):



(local stat. signif. ~6.2-6.7σ)

$m(\Xi_b^{**-}) = [\ 6100.3$
$\pm 0.2(\mathrm{stat}) \pm 0.1(\mathrm{sys})$
$\pm 0.6(\Xi_b^-)\ ]$ MeV

PRL 126 (2021) 252003

- **The natural width** (signal model: RBW⊗2Gauss-resolution) is **too small (consistent with 0) to be measured** with the present data sample and experimental resolution. An Upper Limit $\Gamma(\Xi_b^{**-}) < 1.9\mathrm{MeV}$ @95%CL is obtained (systematics included) through the scan of the profiled likelihood.

- The low yield does not allow a measurement of the quantum numbers.
However following analogies with the established Ξ_c baryon states …
… **the new $\Xi_b^{**}(6100)^-$ resonance is the analogue of Ξ_c(2815) and its decay sequence are consistent with lightest the orbitally excited Ξ_b^- baryon with $J^P = 3/2^-$**[L=1 between b-quark and (ds)-diquark]