+ overview on hadron spectroscopy

Hadron Spectroscopy: the Next Big Steps - Workshop

J. Gutenberg University @ Mainz

14/18 March 2022 - VIRTUAL TALK [https://indico.mitp.uni-mainz.de/event/246/]

Alexis Pompili

(on behalf of & Collaborations)

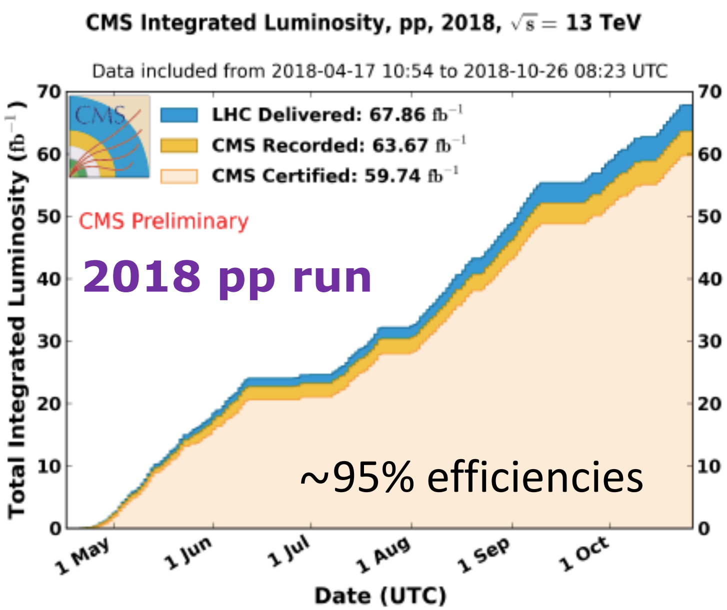
UNIVERSITÀ degli Studi di BARI & I.N.F.N. Sezione di Bari

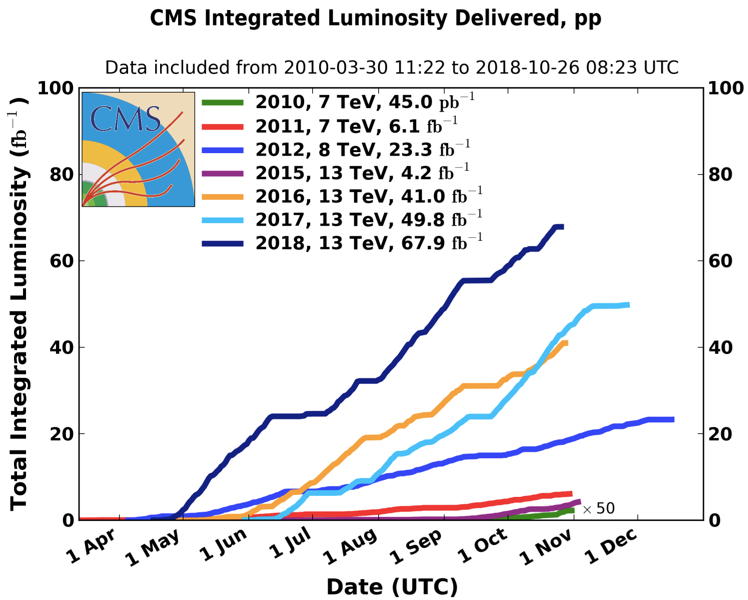
Introduction

- **CMS and ATLAS are giving significant contributions to beauty and quarkonium sectors**, mainly using final states containing muon pairs (trigger constraints). This is possible thanks to :
  - an excellent tracking and muon identification performances, combined to
  - a flexible trigger system essential to collect data @ increasing luminosity (and 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 are able to integrate and/or complement the LHCb results !**

- 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

Production & decays @ CMS (similar considerations for ATLAS)

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

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

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

… inclusive searches more difficult experimentally:

high backgrounds, too high trigger rates for prompt dimuons @ low p_T

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

- **Hadronic transition** 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 , $\psi(2S)$, non-resonant dimuon)
- **Electromagnetic transition** to a lighter $c\bar{c}$ meson through the emission of a γ
  - challenging : need converted photon (reconstructed with low efficiency)

NOTE: bottomonium is explored triggering on prompt S-wave states ($\Upsilon(nS)$, $n = 1,2,3$ **)**

Outline

Conventional hadron spectroscopy

- $(\bar{b}c)$ spectroscopy : observation of $B_c^+(2S)$ & $B_c^{*+}(2S)$ in the $B_c^+\,\pi^+\,\pi^-$ spectrum
- $(\bar{b}b)$ spectroscopy : observation of *resolved* $\chi_{b1}(3P)$ & $\chi_{b2}(3P)$ states
- (udb) spectroscopy : study of excited Λ_b^0 baryons in the $\Lambda_b^0\,\pi^+\,\pi^-$ spectrum
- (dsb) spectroscopy : observation of excited Ξ_b^{**-} baryons in the $\Xi_b^-\,\pi^+\,\pi^-$ spectrum

Exotic hadron spectroscopy

- $X(3872)$ production properties in pp collisions
- First evidence of $X(3872)$ production in PbPb collisions
- First observation of the decay $B_s^0 \to X(3872)\phi$

See also dedicated CMS talk by D. Fasanella on thursday morning (17.3)

- **Other searches** (two are provided only as **additional material** at the end):
  - Search for X_b, the beauty partner of $X(3872)$, in the $\Upsilon(1S)\,\pi^+\pi^-$ final state
  - Search for narrow heavy bottom tetraquark decaying to $\Upsilon(1S)\,\mu^+\mu^-$
  - Search for pentaquark states in the $J/\psi\,p$ final state

Conventional hadron spectroscopy

Observation of the excited $B_c^+(2S)$ & $B_c^{*+}(2S)$ states and production cross section ratios

CMS: PRL 122 (2019) 132001 | PRD, 102 (2020) 092007 | $\sqrt{s} = 13TeV$ | $\mathcal{L} = 143fb^{-1}$ (Full Run-II / 2015-8)

ATLAS: PRL 113 (2014) 212004 | $\sqrt{s} = 7 + 8TeV$ | $\mathcal{L} = 5 + 19fb^{-1}$ (Full Run-I / 2011-2)

(also: CMS JHEP 01 (2015) 063 & ATLAS arXiv:2203.01808, submitted to JHEP)

Introduction to $(c\bar{b})$ spectroscopy and B_c^+ meson

- The B_c^+ meson was discovered by CDF [PRL 81 (1998) 2432].
  It's the **lowest-mass bound state of the family of $(c\bar{b})$ mesons,**
  absolutely stable against strong/e.m. decays (weak decays dominate).

  - Experimentally the **spectrum** is poorly known since limited by **rare production rate:** x-section proportional to α_s^4 : $q\bar{q}, gg \Rightarrow c\bar{b}\ (b\bar{c})$.

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

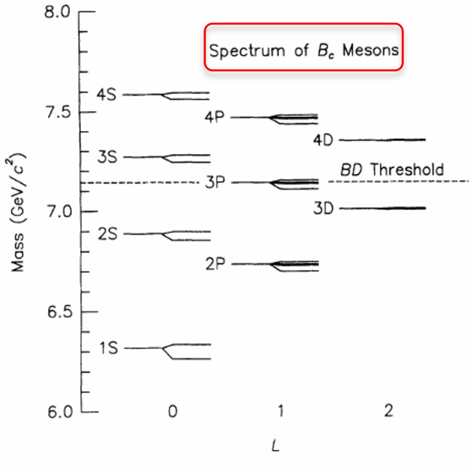


FIG. 1. The spectrum of $c\bar{b}$ states.

[Godfrey, PRD 49 (1984) 5845]

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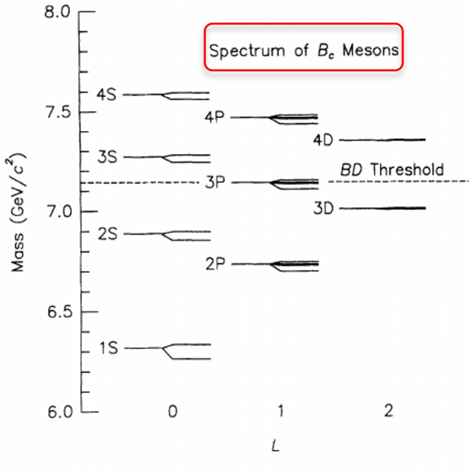

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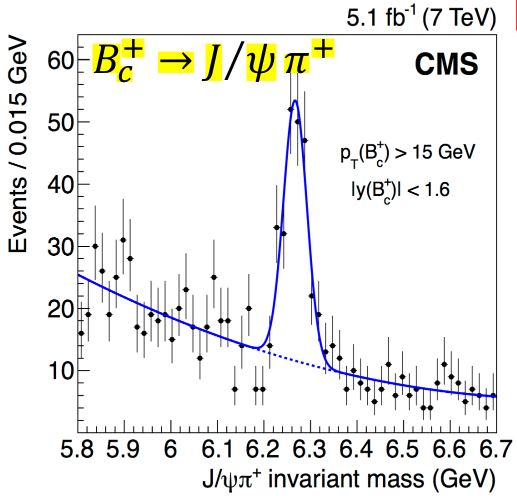
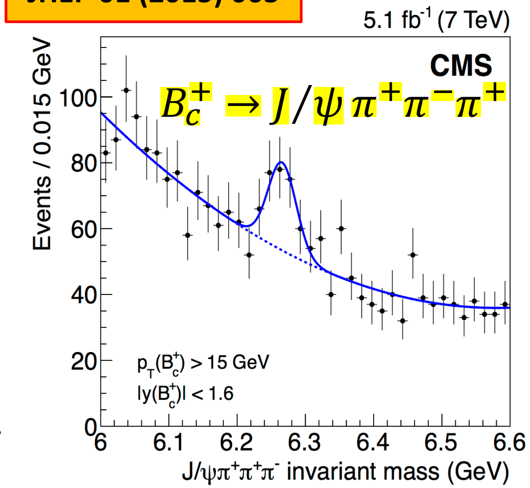
JHEP 01 (2015) 063





$$\mathcal{R} = \frac{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+\pi^-\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} \cong 2.55 \pm 0.80\,(stat) \pm 0.33(syst)$$

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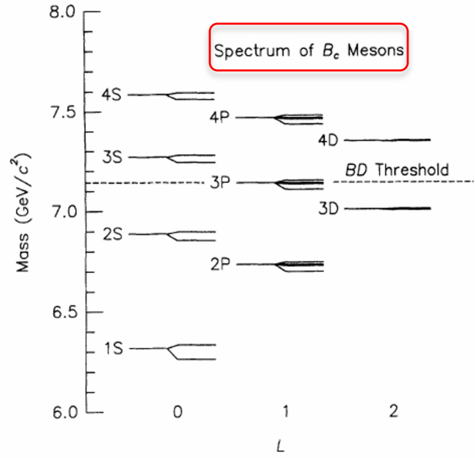

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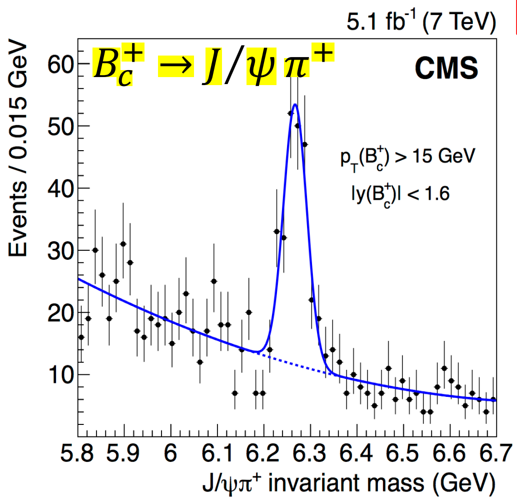
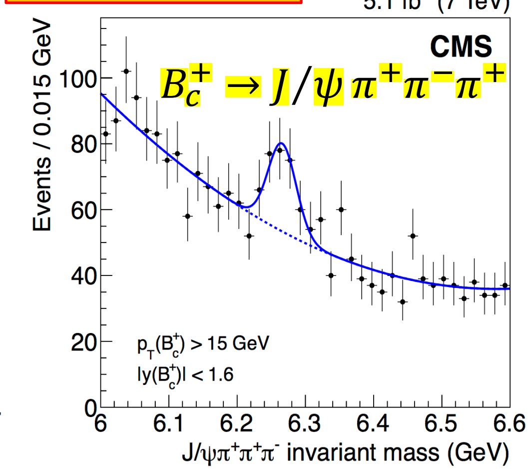


JHEP 01 (2015) 063



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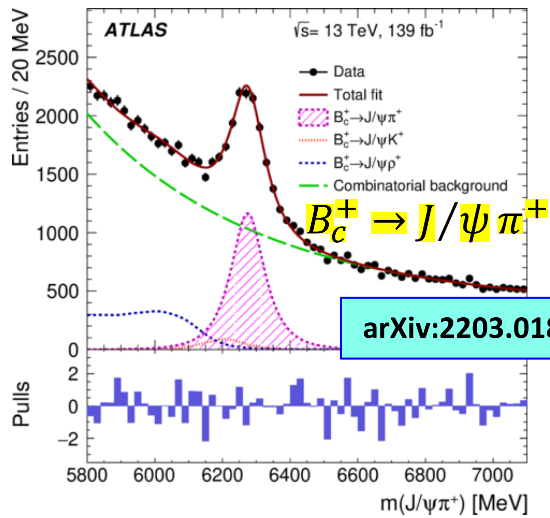
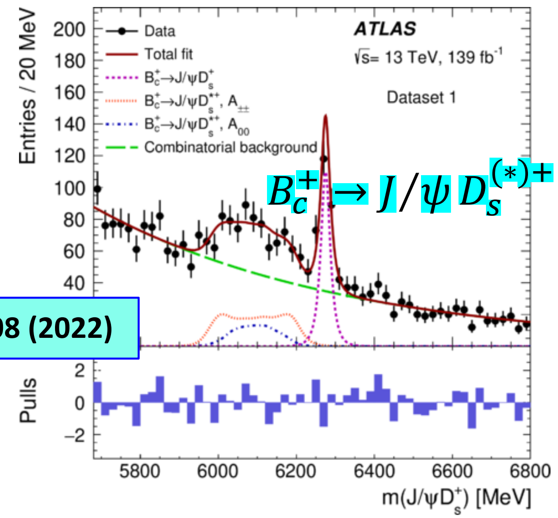


arXiv:2203.01808 (2022)

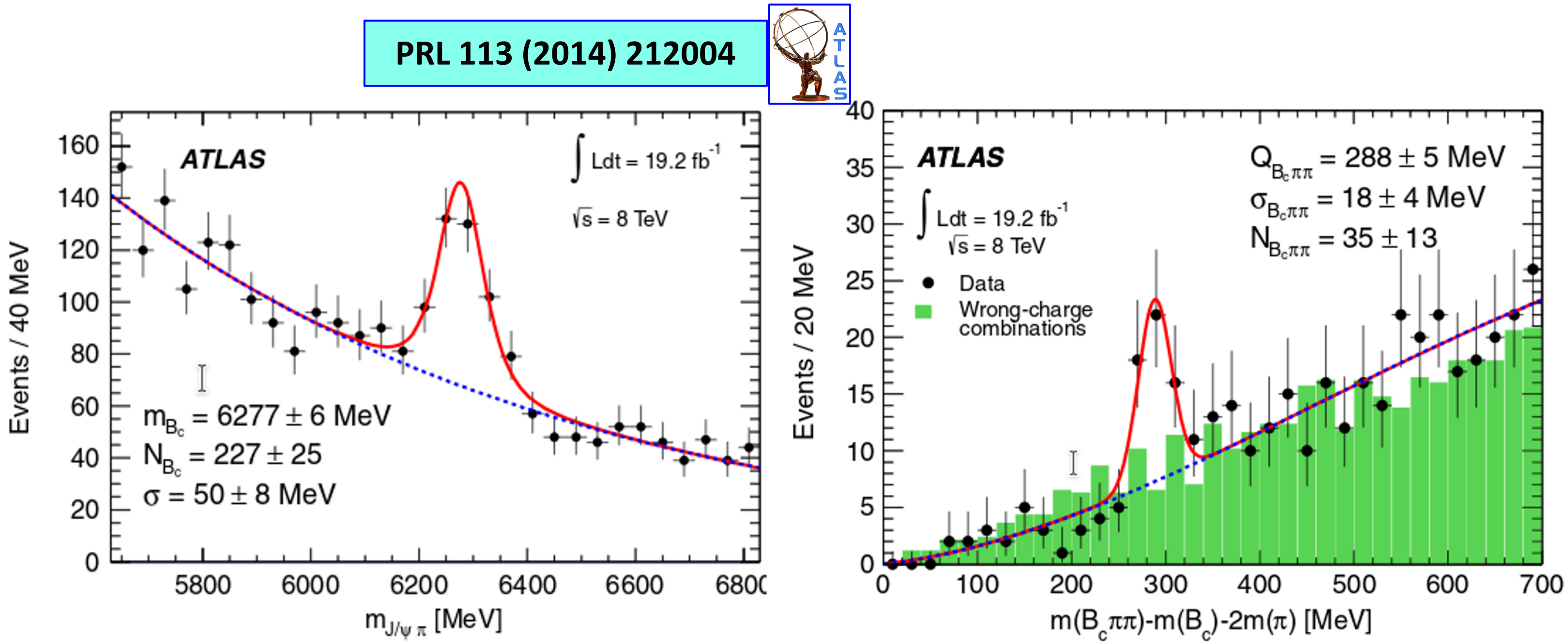


$$\mathcal{R} = \frac{\mathcal{B}(B_c^+ \to J/\psi\,D_s^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} \cong 2.76 \pm 0.47$$

$$\mathcal{R} = \frac{\mathcal{B}(B_c^+ \to J/\psi\,D_s^{*+})}{\mathcal{B}(B_c^+ \to J/\psi D_s^+)} \cong 1.93 \pm 0.26$$

Observation/search for radially excited B_c^+ mesons

PRL 113 (2014) 212004



Observation of a new state with mass consistent with predictions for $B_c^+(2S)$.
It's reconstructed from the decay to $B_c^+\pi\pi$ followed by $B_c^+ \to J/\psi\,\pi$ with a local significance of 5.4σ.

Can be likely the super-position of 2 closely spaced hyperfine partners (very soft photon is lost).

- **from the singlet 2S state (2^1S_0) :** $B_c^+(2S) \to B_c^+\pi^+\pi^-$
- **from the triplet 2S state (2^3S_1) :** $B_c^{*+}(2S) \to B_c^{*+}\pi^+\pi^-,\ \ B_c^{*+} \to B_c^+\,\gamma$
  $B_c^{*+}(2S) \to B_c^+(2S)\,\gamma,\ B_c^+(2S) \to B_c^+\pi^+\pi^-$

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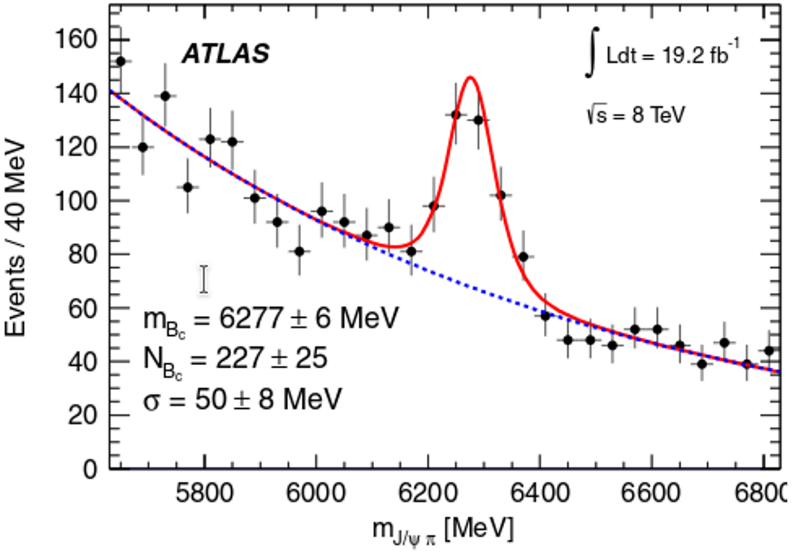

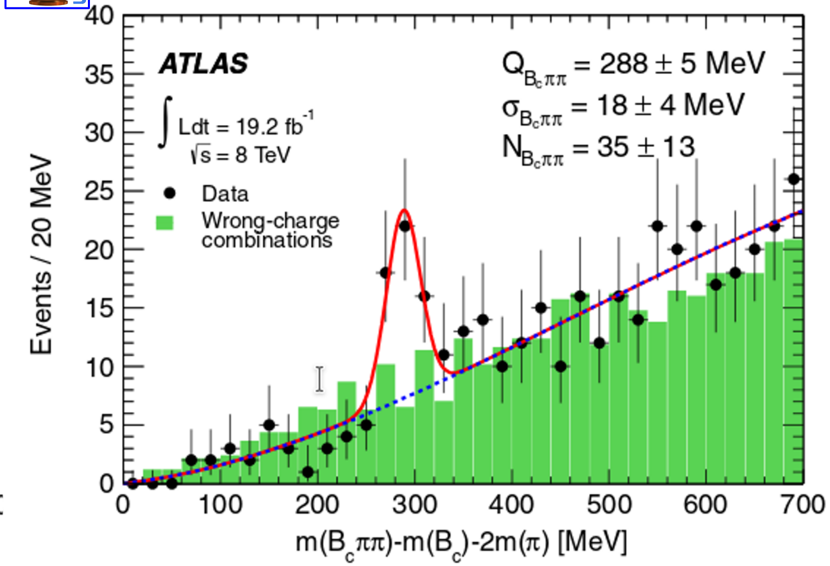

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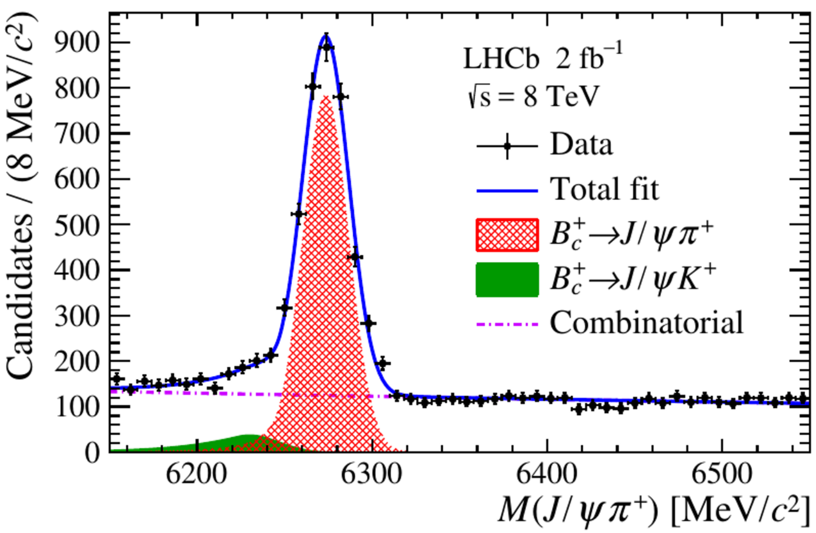
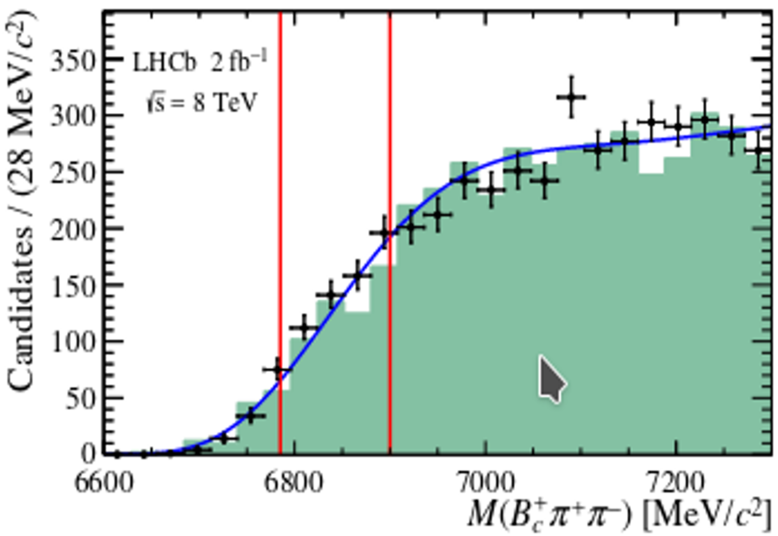




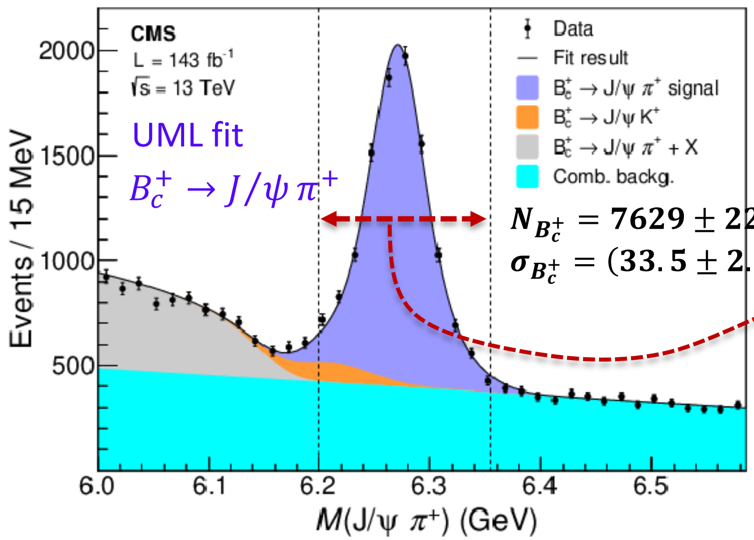
With 3325 ± 73 B_c^+ events: "No significant signal is found" in the search for the excited states $B_c^+(2S)$ & $B_c^{*+}(2S)$ in Run-I/2012

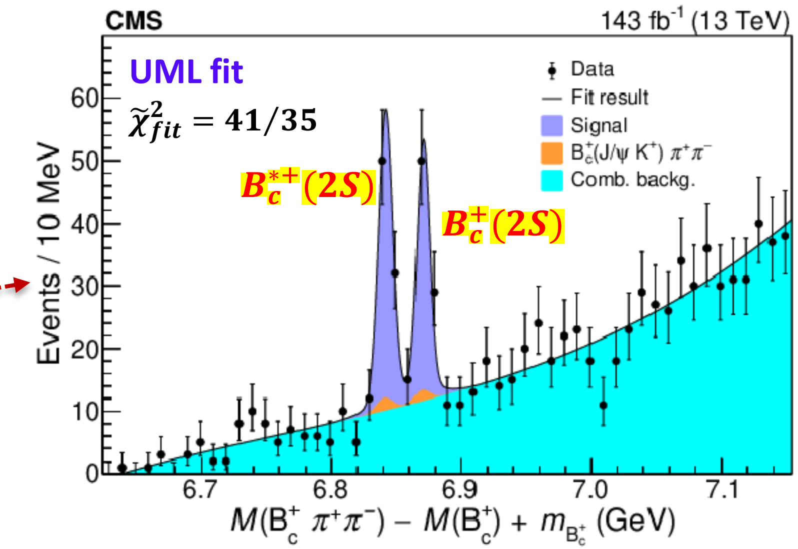
JHEP 01 (2018) 138

Observation of radially excited B_c^+ mesons

- [PRL 122 (2019) 132001] **observed for the first time the two radially excited (hyperfine doublet)** $\begin{cases} B_c^+(2S) \\ B_c^{*+}(2S) \end{cases}$ **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 backup]





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

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

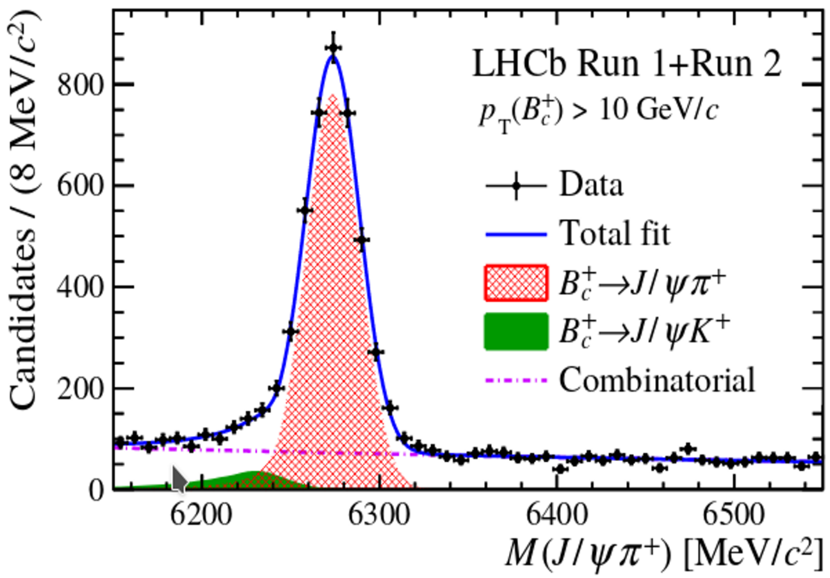
$\Delta m = (28.9 \pm 1.5)MeV$

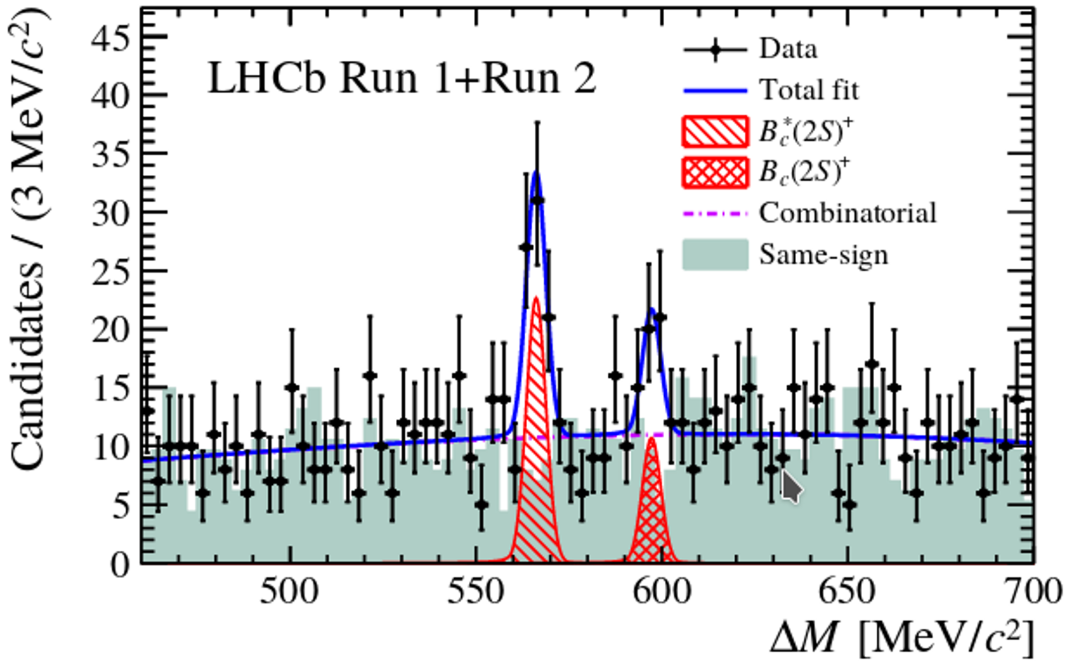
$m(B_c^+(2S)) = (6871.0 \pm 1.2)MeV$

- **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 $50 \div 90KeV$ **) much smaller than mass resolution.**

Confirmation by LHCb

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





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

Differential production Xsection ratios

- 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 (*)**.

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

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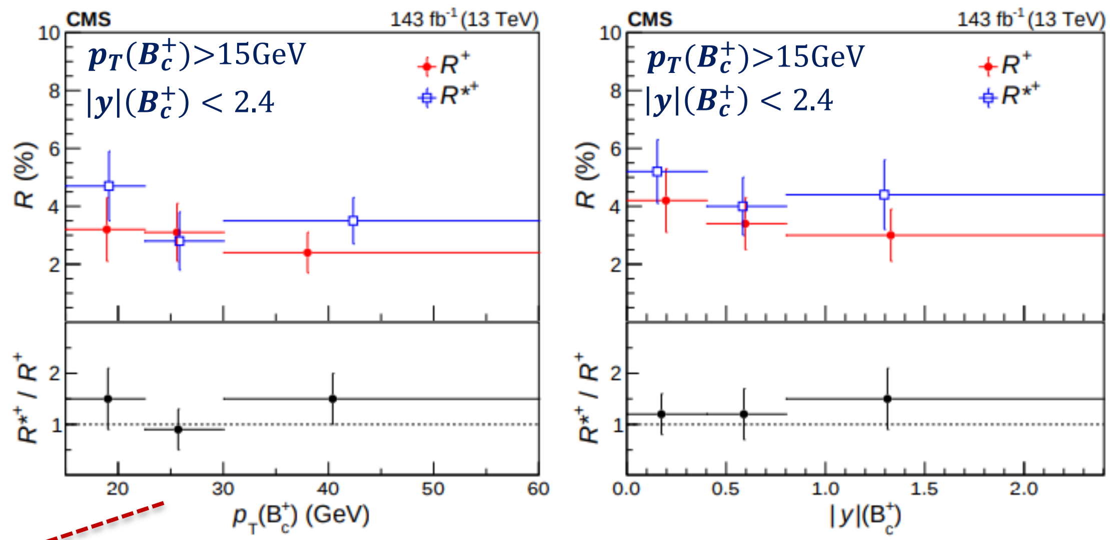
$$R^{*+}/R^{+} = \frac{\sigma(\mathrm{B_c^*(2S)^+})}{\sigma(\mathrm{B_c(2S)^+})}\,\frac{\mathcal{B}(\mathrm{B_c^*(2S)^+} \to \mathrm{B_c^{*+}}\pi^+\pi^-)}{\mathcal{B}(\mathrm{B_c(2S)^+} \to \mathrm{B_c^+}\pi^+\pi^-)} = \frac{N(\mathrm{B_c^*(2S)^+})}{N(\mathrm{B_c(2S)^+})}\,\frac{\epsilon(\mathrm{B_c(2S)^+})}{\epsilon(\mathrm{B_c^*(2S)^+})}.$$

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



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

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

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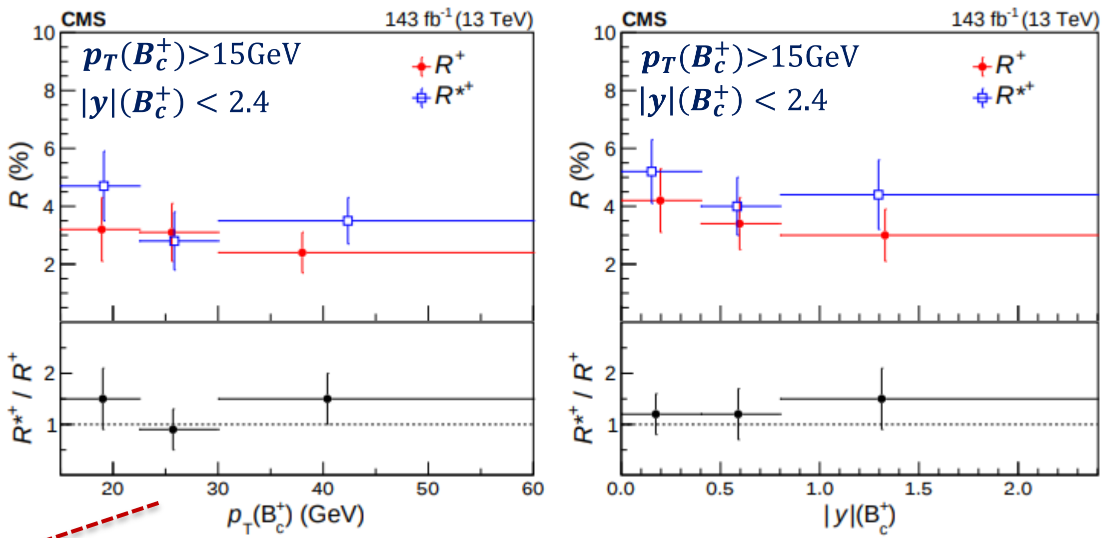
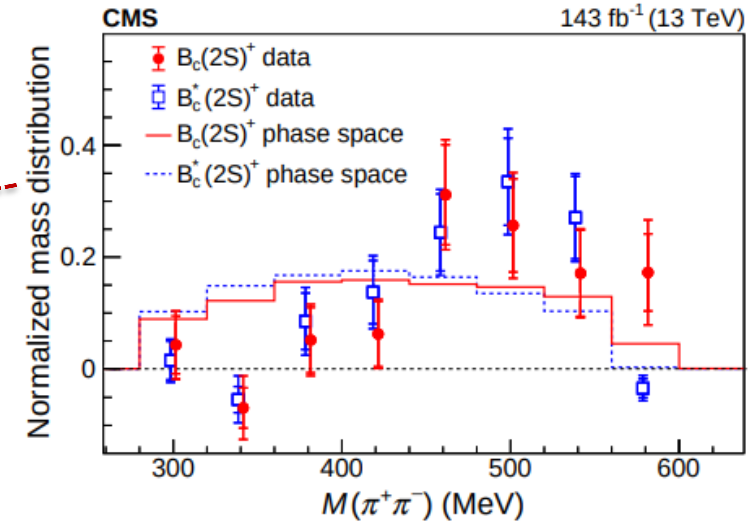


- **No significative dependence of these three xsection ratios on $p_T(B_c^+)$ & $|y|(B_c^+)$**

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



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First observation of *resolved* $\chi_{b1}(3P)$ & $\chi_{b2}(3P)$ states and measurement of their masses

PRL 121 (2018) 092002 | $\sqrt{s} = 13TeV$ | $\mathcal{L} = 80fb^{-1}$

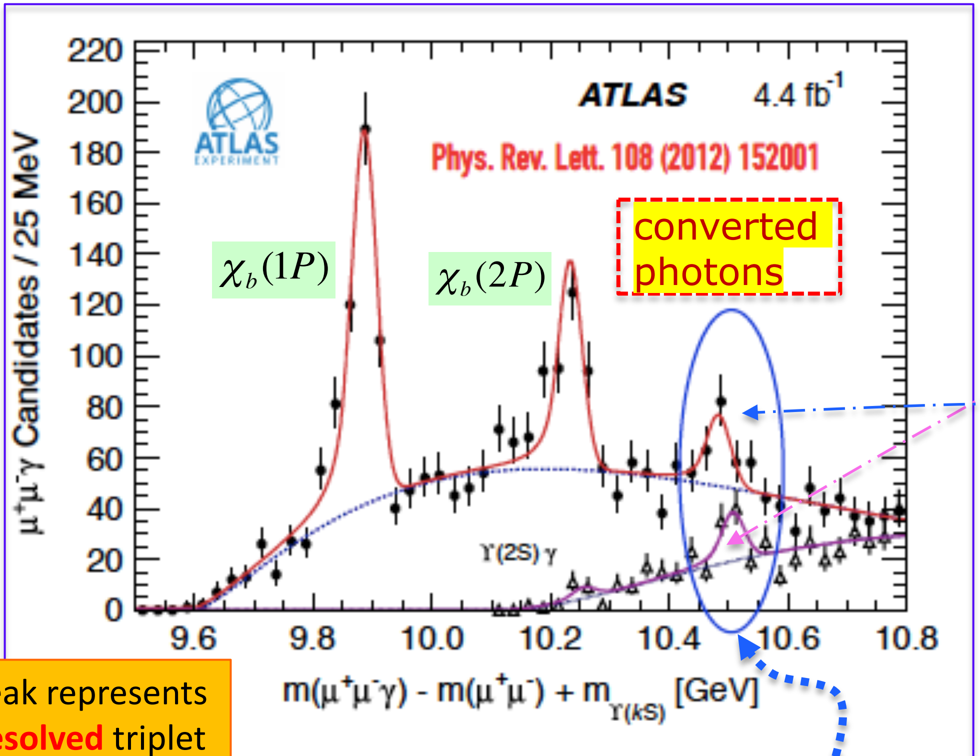
(Run-II / 2015-7)

PRL 108 (2012) 152001 | $\sqrt{s} = 7TeV$ | $\mathcal{L} = 4.4fb^{-1}$

(Run-I / 2011)

First observations of $\chi_{bJ}(3P)$ states - I

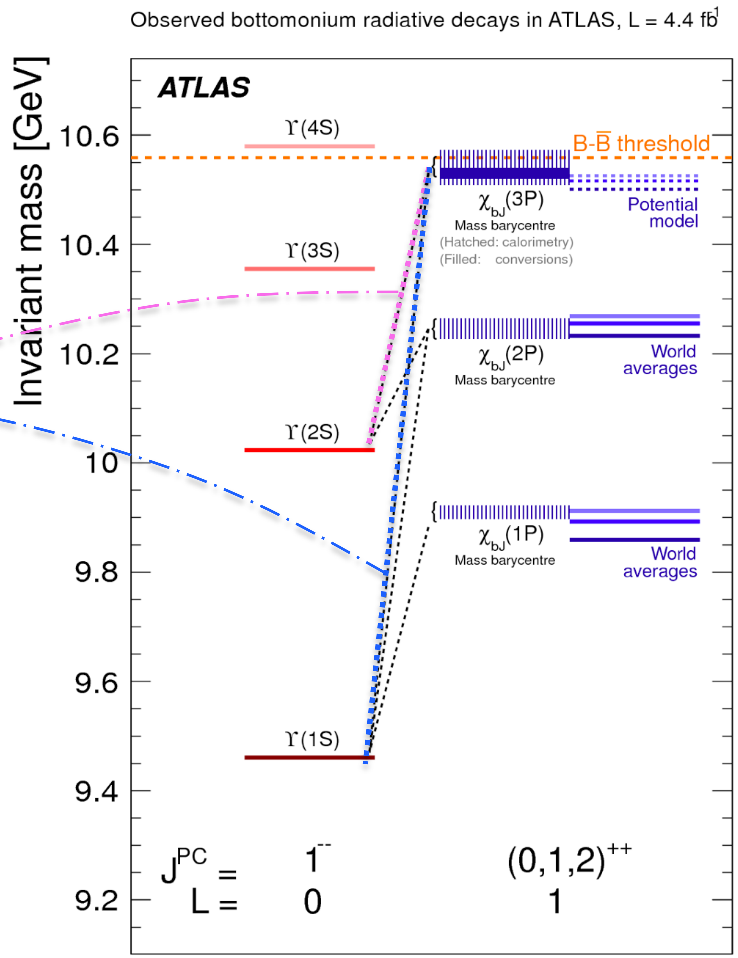
- There have been earlier measurements related to $\chi_{bJ}(3P)$ mass by ATLAS (and LHCb & D0$^{(*)}$), however without being able to distinguish between the candidates of the $\chi_{bJ}(3P)$ multiplet.



Each peak represents an **unresolved** triplet

The new structure was observed in $\chi_{bJ}(3P) \rightarrow \Upsilon(1S,2S)\gamma$ decays by

PRL 108 (2012) 152001

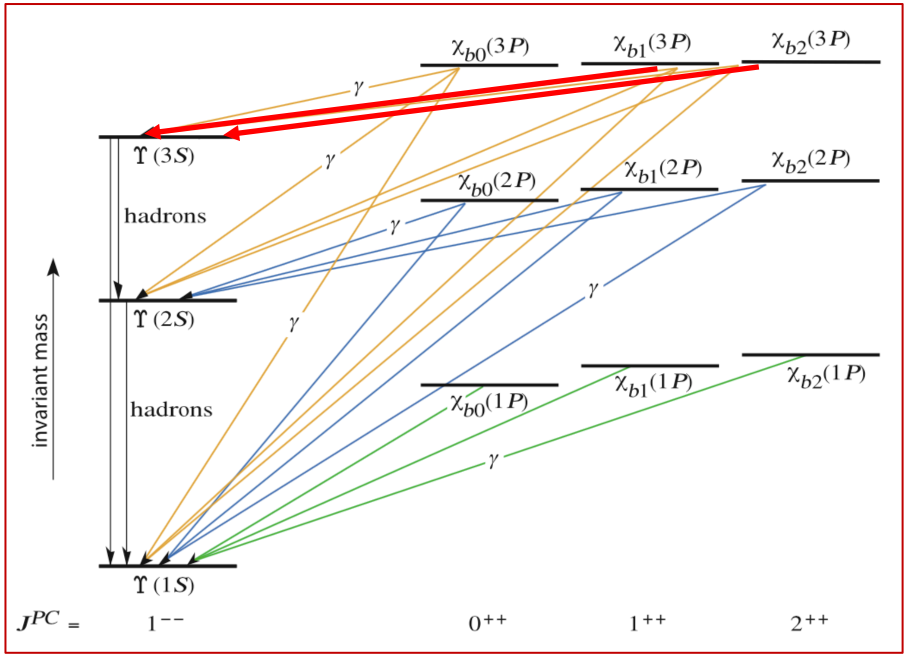


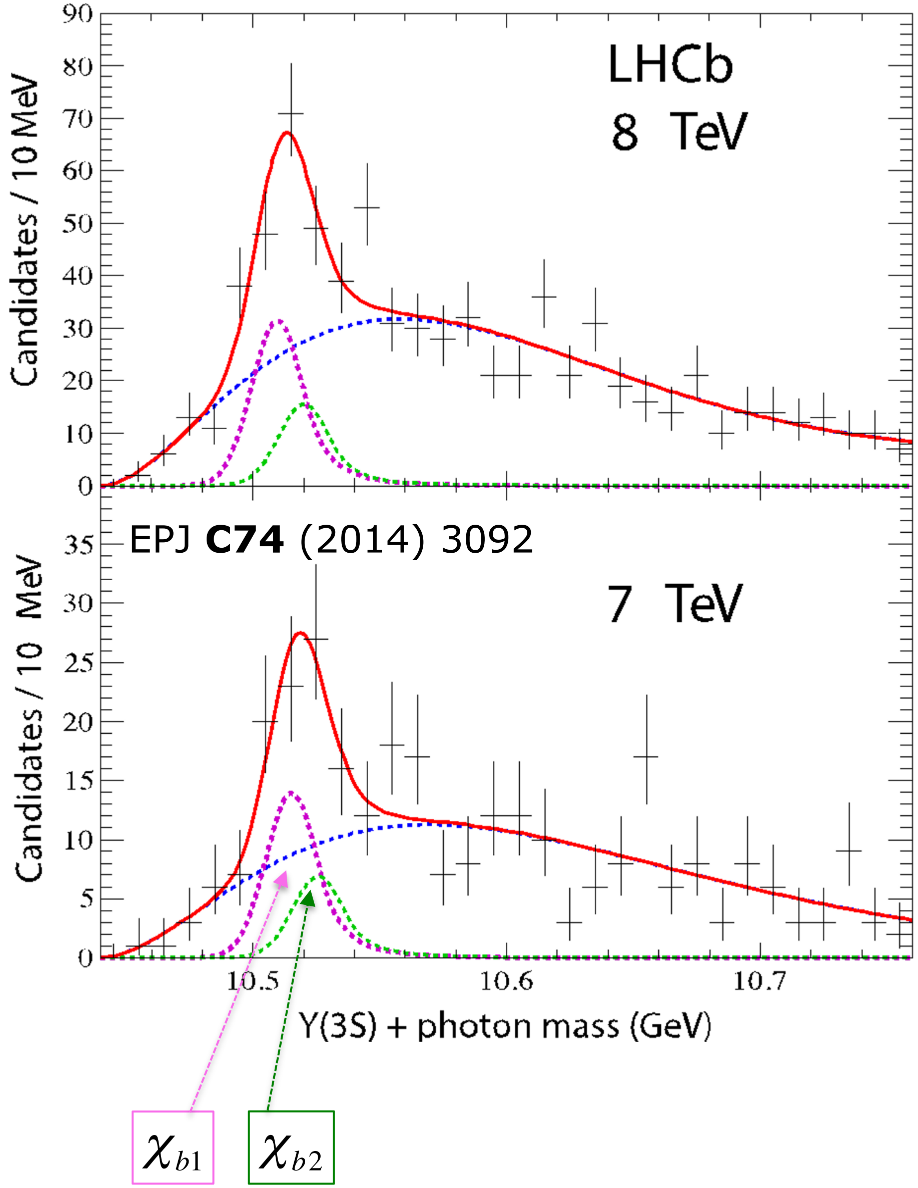
(*) PRD **86** (2012) 031103

First measurements of $\chi_{bJ}(3P)$ states - II

- The new structure was also observed by LHCb in the decays $\rightarrow \Upsilon(3S)\gamma$ and interpreted as … … the $\chi_{bJ}(3P) \rightarrow \Upsilon(nS)\gamma, n = 1, 2, 3$ triplet (J=0,1,2) state.

LHCb could not resolve the J=(1, 2) doublet (the *J=0* is expected to be suppressed).





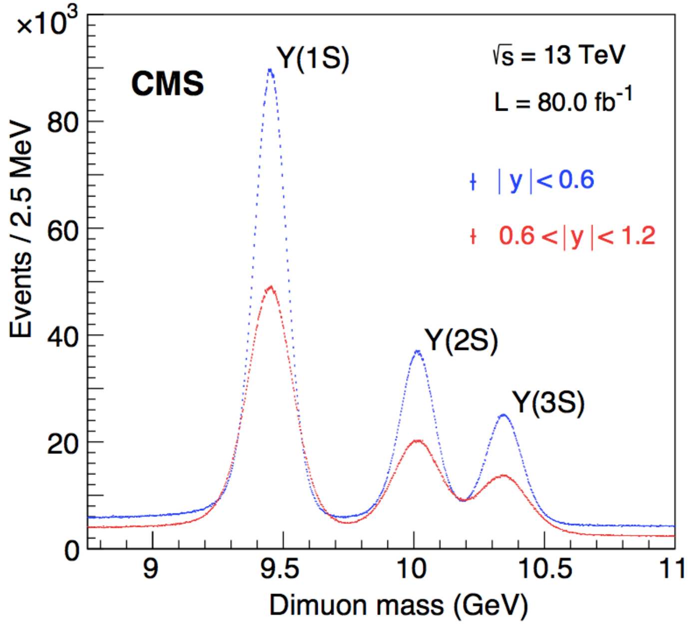
- $\chi_{bJ}(3P)$ is particularly interesting given that its properties could have been affected by the nearby open beauty thresholds $B\overline{B}^{(*)}$.

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: $p_T > 14 GeV$ & $|y| < 1.2$



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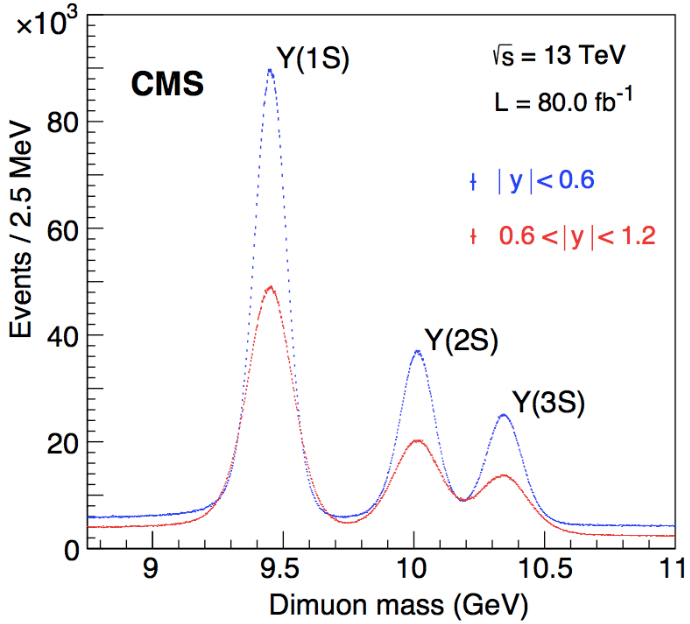
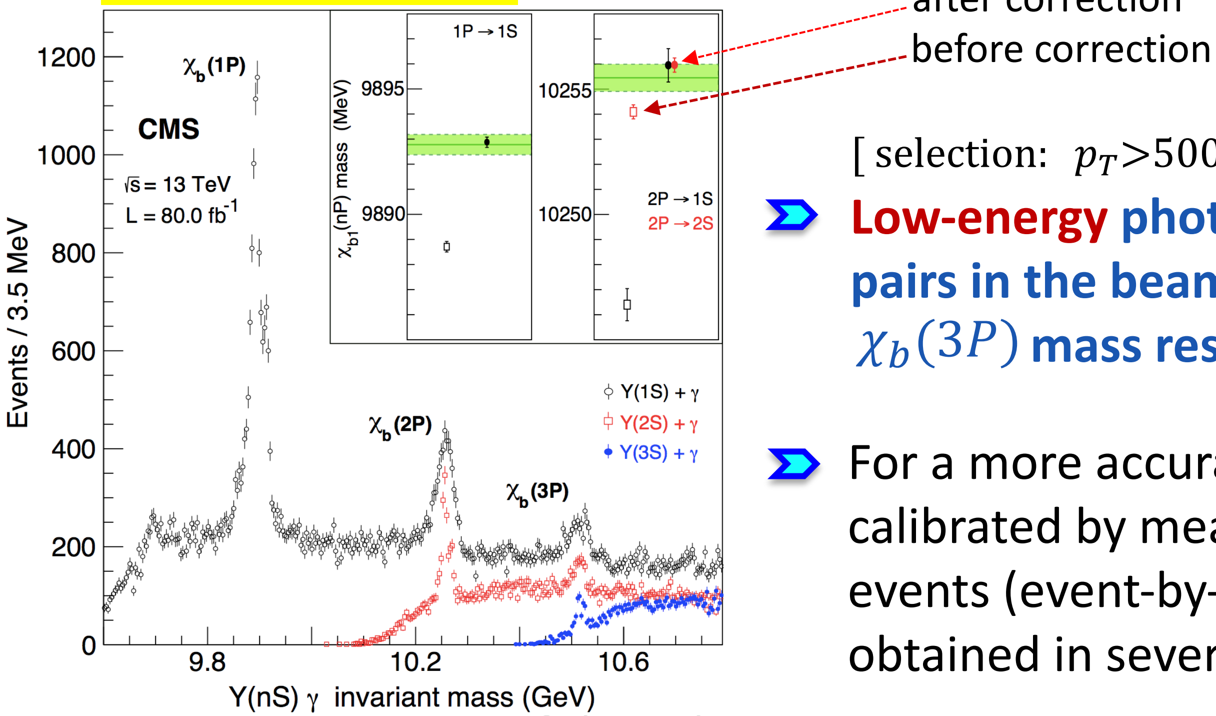


$\Upsilon(nS)\gamma \quad [n = 1,2,3]$



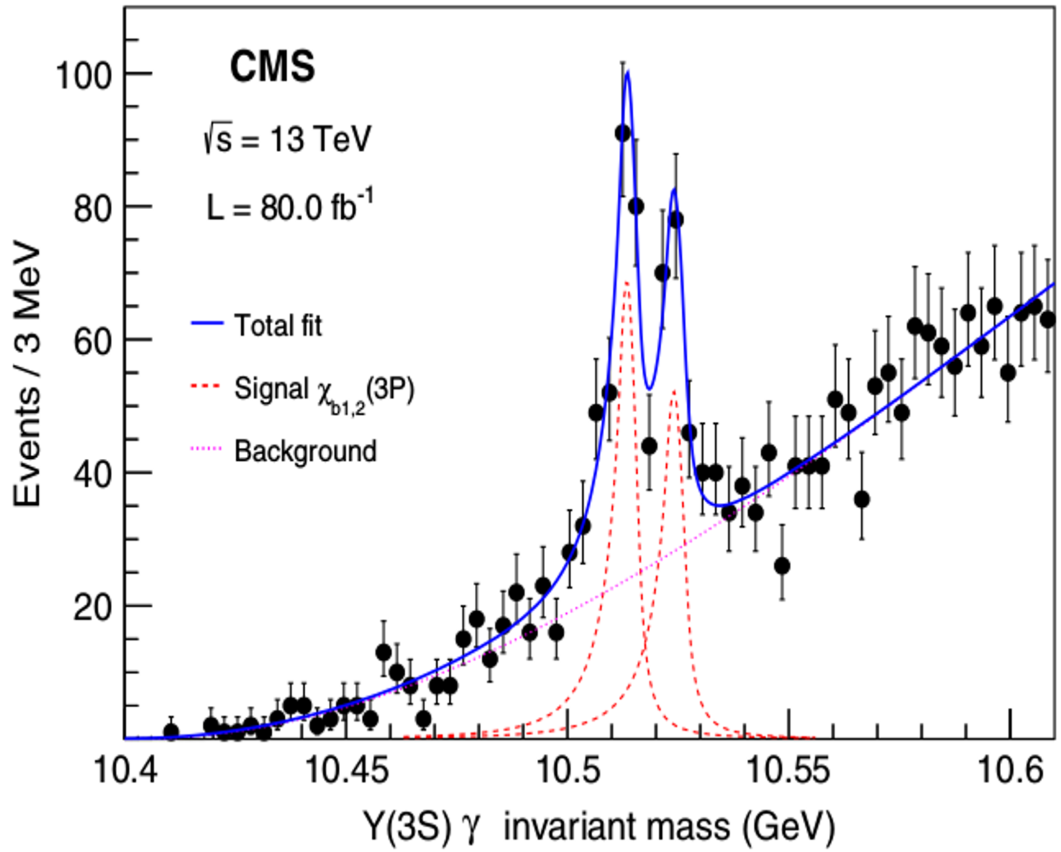
[selection: p_T>500MeV , $|\eta| < 1.2$]

- **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 : $P.E.S. = \frac{m^2_{\mu\mu\gamma} - m^2_{\mu\mu}}{M(\chi_{c1})^2 - M(J/\psi)^2}$).

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)



-

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

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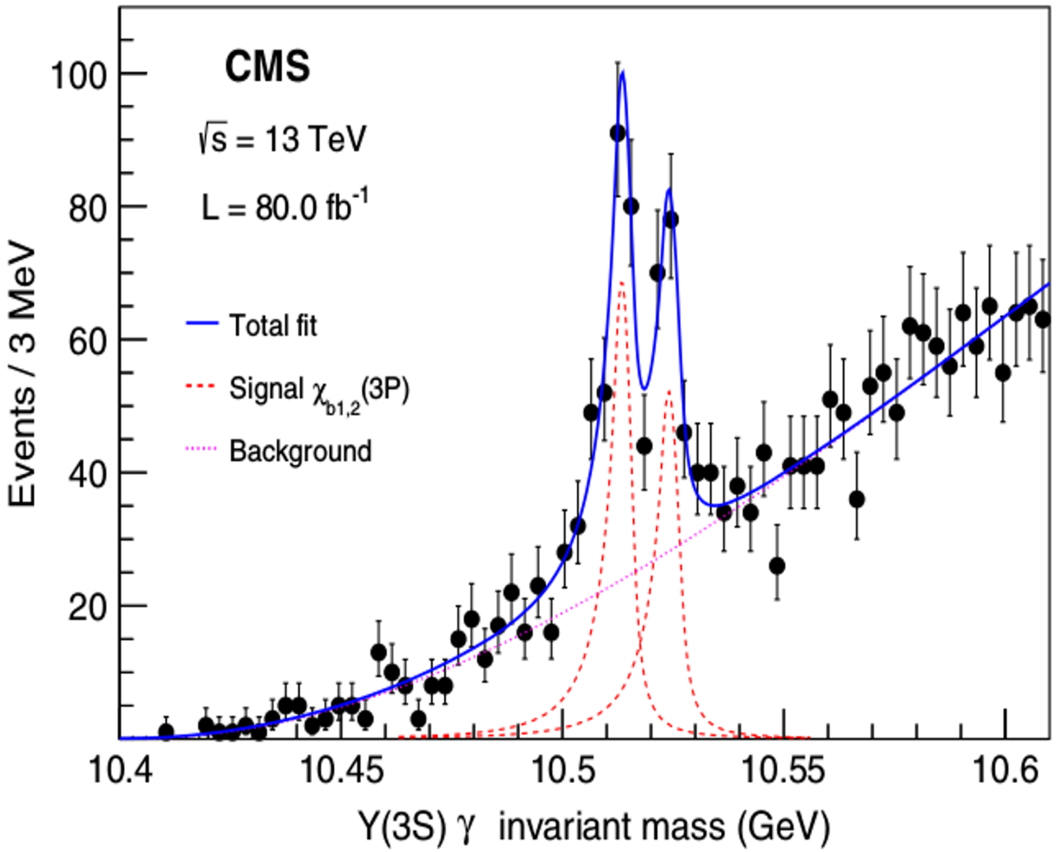


- **The two masses are *individually* measured & the Δm as well :**

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

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

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

enough precise to provide an important constraint to theory models

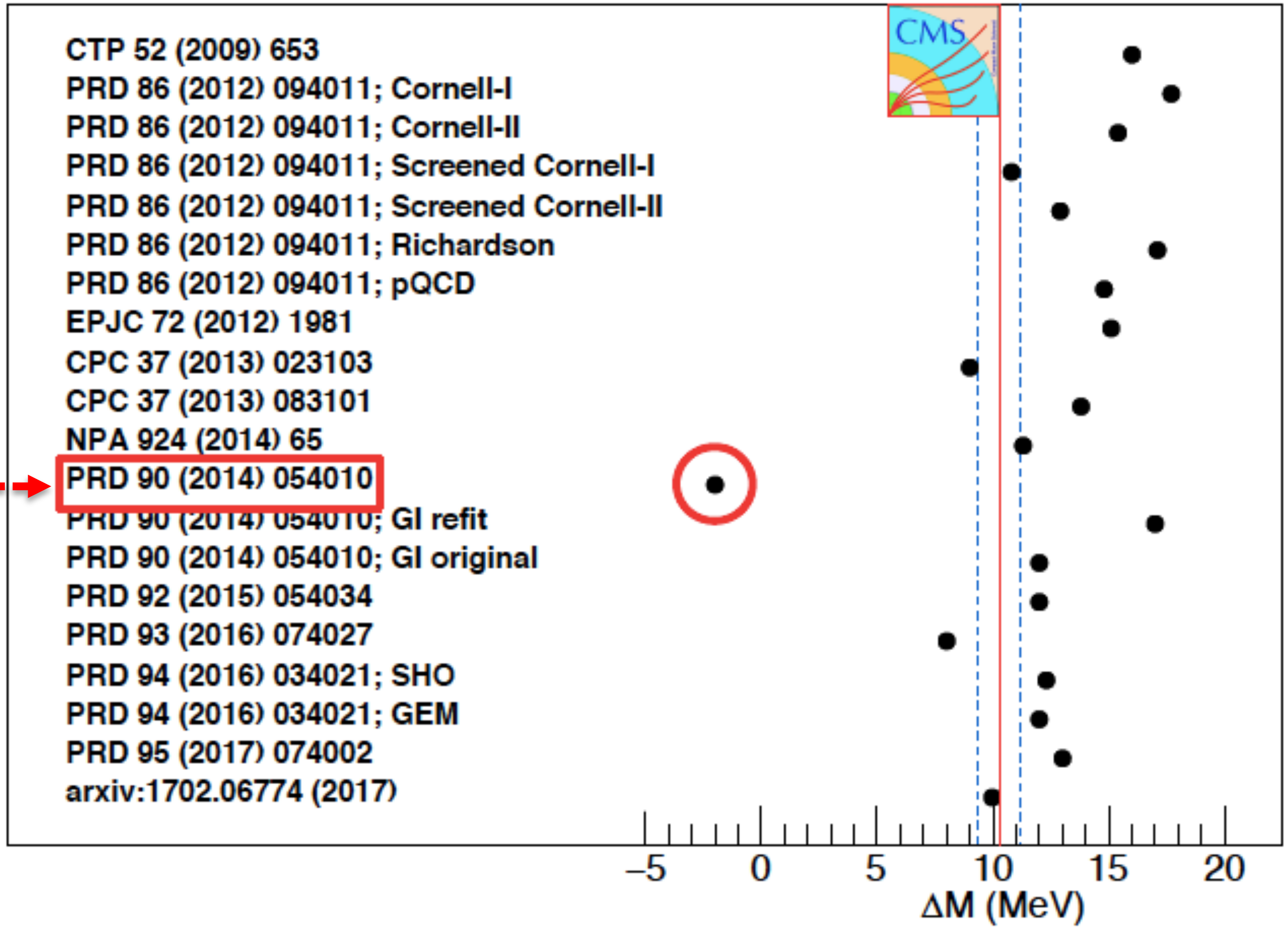
[see next slide]

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

- **There is a large number of theory predictions for the ΔM mass splitting between *J=1* & *J=2*:**

  - out of 20 predictions :
    - 19 range from 8 to 18*MeV*
    - 1 is -2*MeV*

The negative sign reflects the coupling with open-beauty threshold, whose proximity could have a striking influence on the splitting!



measurement strongly disfavours the breaking of the conventional pattern of splittings in the doublet (at least as presented in the specific calculation**) and … supports the standard hierarchy (*J=2* heavier than *J=1*)**

- **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 $3P$-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] CMS
$\chi_{b1}(3P) - \chi_{b0}(3P)$	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).**

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

PLB 803 (2020) 135345

$\sqrt{s} = 13 TeV$

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

(Run-II/2016-8)

Λ_b^0 excited states in *low-mass region* (near threshold)

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)

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

$$(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-)$$
$$\downarrow$$
$$pK^-\pi^+$$

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

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

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  $\downarrow$
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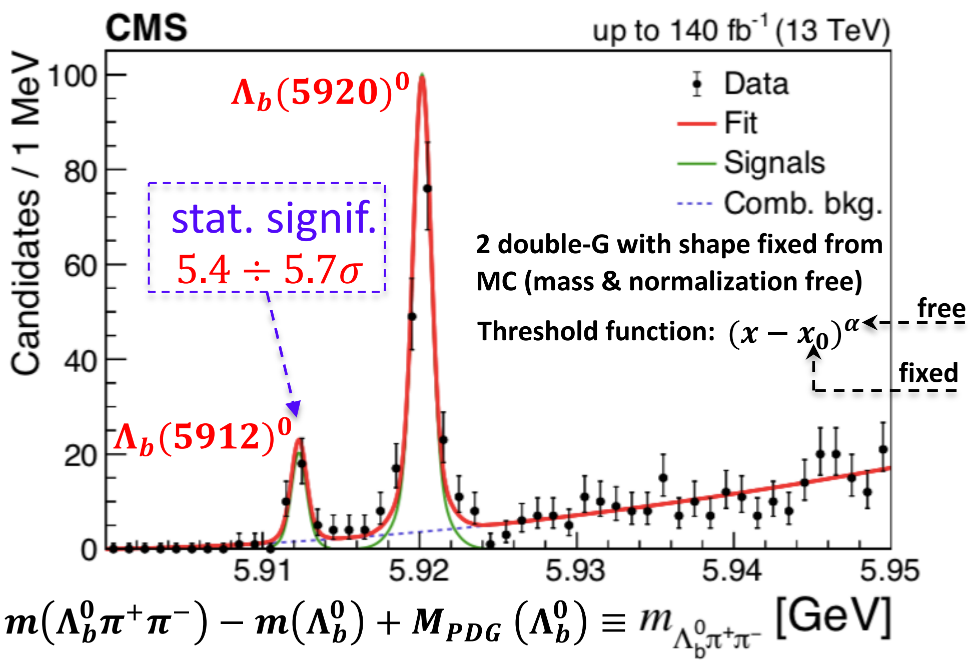


Confirmation of $\Lambda_b(5912)^0$

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

Mass measurements:

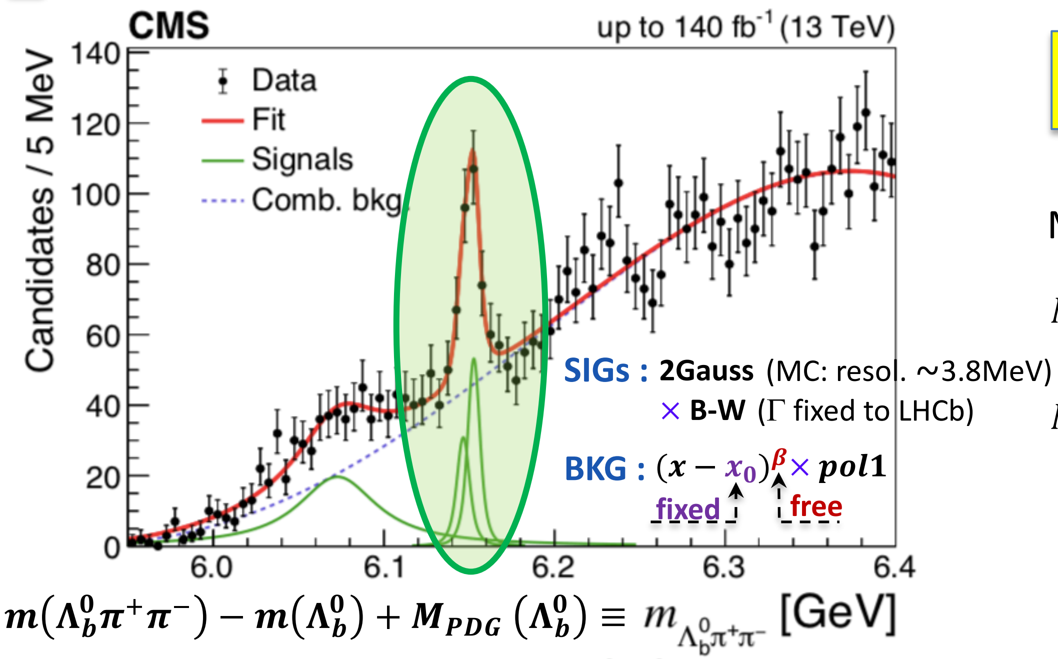
$$M(\Lambda_b(5912)^0) = [5912.32 \pm 0.12(stat) \pm 0.01(syst) \pm 0.17(m_{PDG}(\Lambda_b^0))]\mathrm{MeV}$$

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

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

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

(using $\Lambda_b^0 \to \Lambda_c^+\pi^-$ & $\Lambda_b^0 \to J/\psi\, pK^-$)



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)

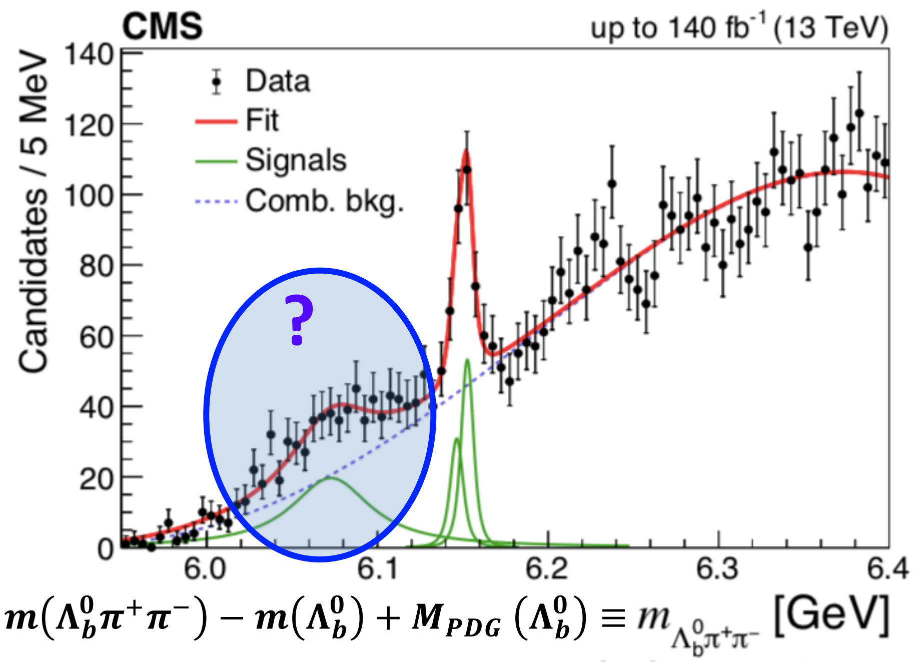
Data are consistent with a single peak @6150MeV :

* **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

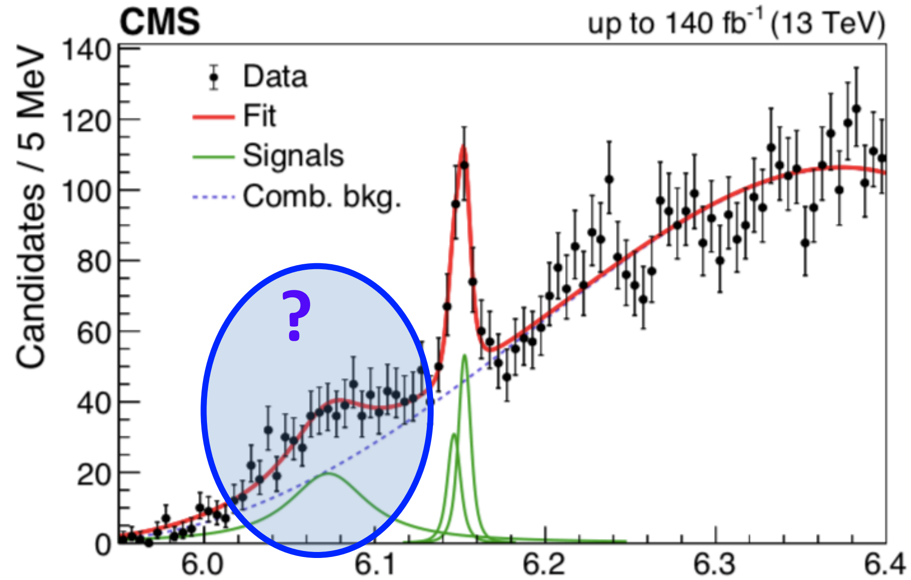
- **assuming a single broad resonance X_b the fit** with M & Γ free parameter **- provides (with stat. sig. ~ 4σ) :**

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

- **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)**



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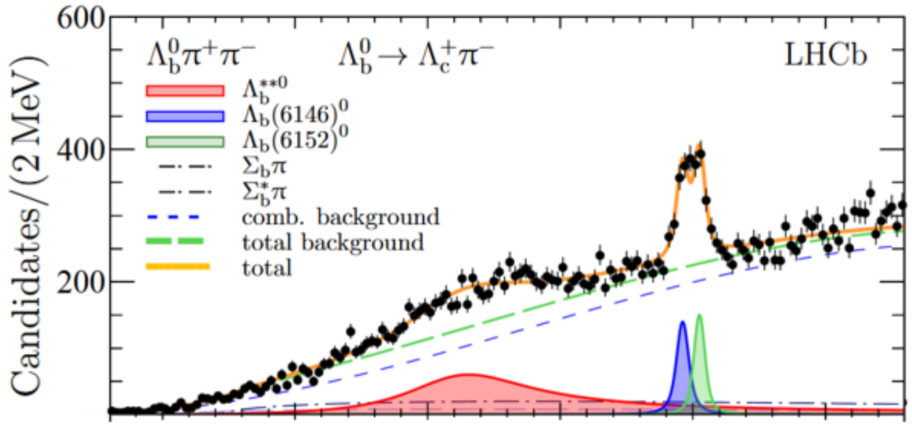
Few days after CMS paper has appeared on the arXiv …
confirmed the wide bump with similar parameters:

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

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



[JHEP 06 (2020) 136]

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

PRL 126 (2021) 252003 | $\sqrt{s} = 13 TeV$ | $\mathcal{L} = 140 fb^{-1}$

(Run-II / 2016-8)

(also: PRL 108 (2012) 252002 | $\sqrt{s} = 7 TeV$ | $\mathcal{L} = 5.3 fb^{-1}$)

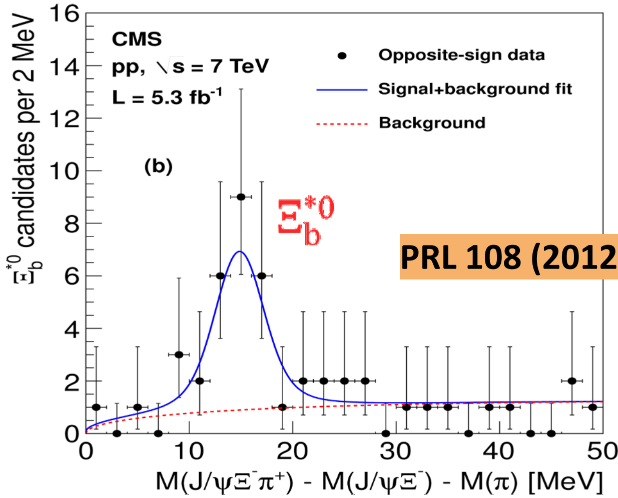
(Run-I / 2011)

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.



PRL 108 (2012) 252002

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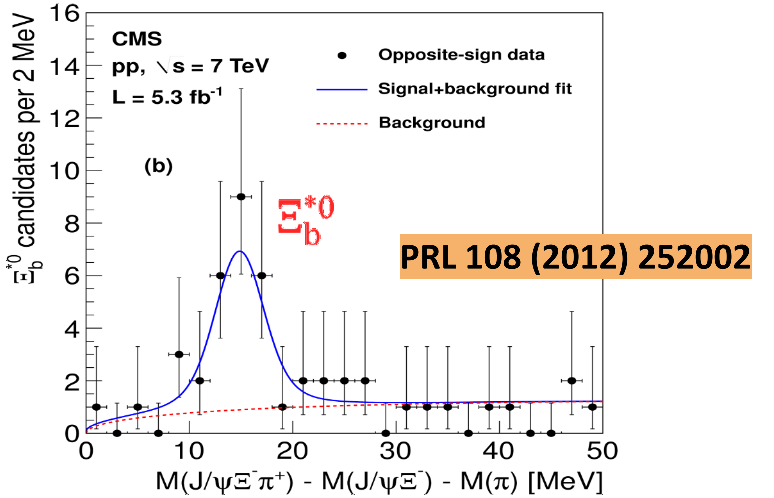
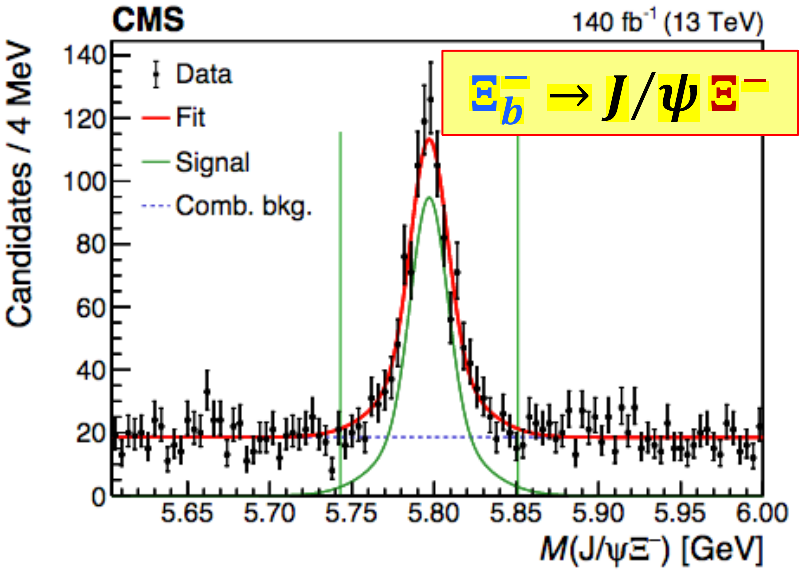
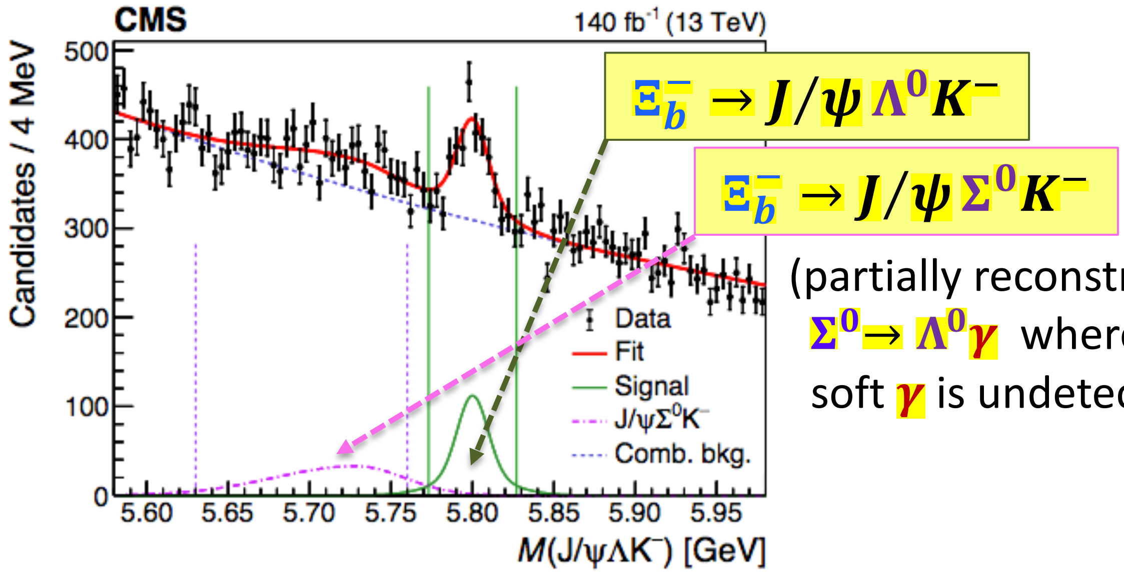


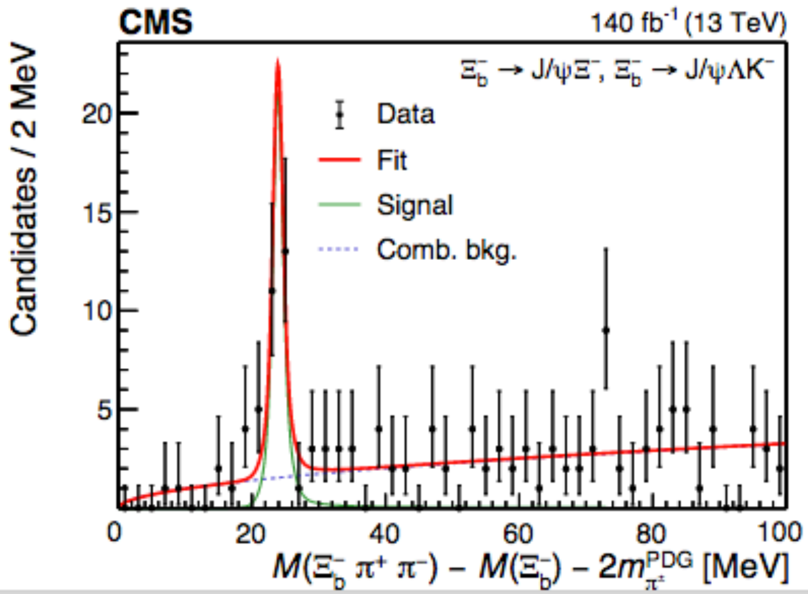
- **Recently** CMS **observed the lightest orbitally excited beauty strange baryon** $\Xi_b^{**}(6100)^- \to \Xi_b^-\pi^+\pi^-$ **(including the - dominant - intermediate resonance** $\Xi_b^{*0} \to \Xi_b^-\,\pi^+$**)**. The Ξ_b baryon was reconstructed via:

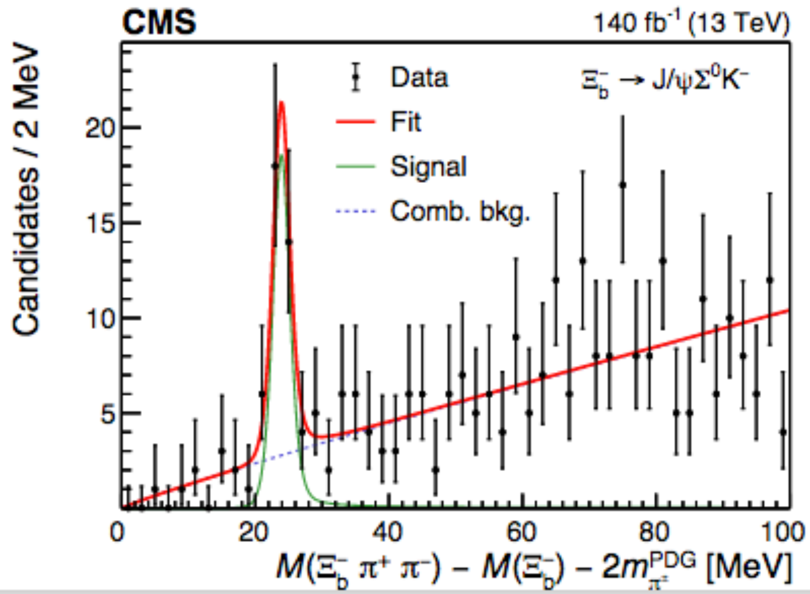




(partially reconstructed: $\Sigma^0 \to \Lambda^0\gamma$ where the soft γ is undetected)

- 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):



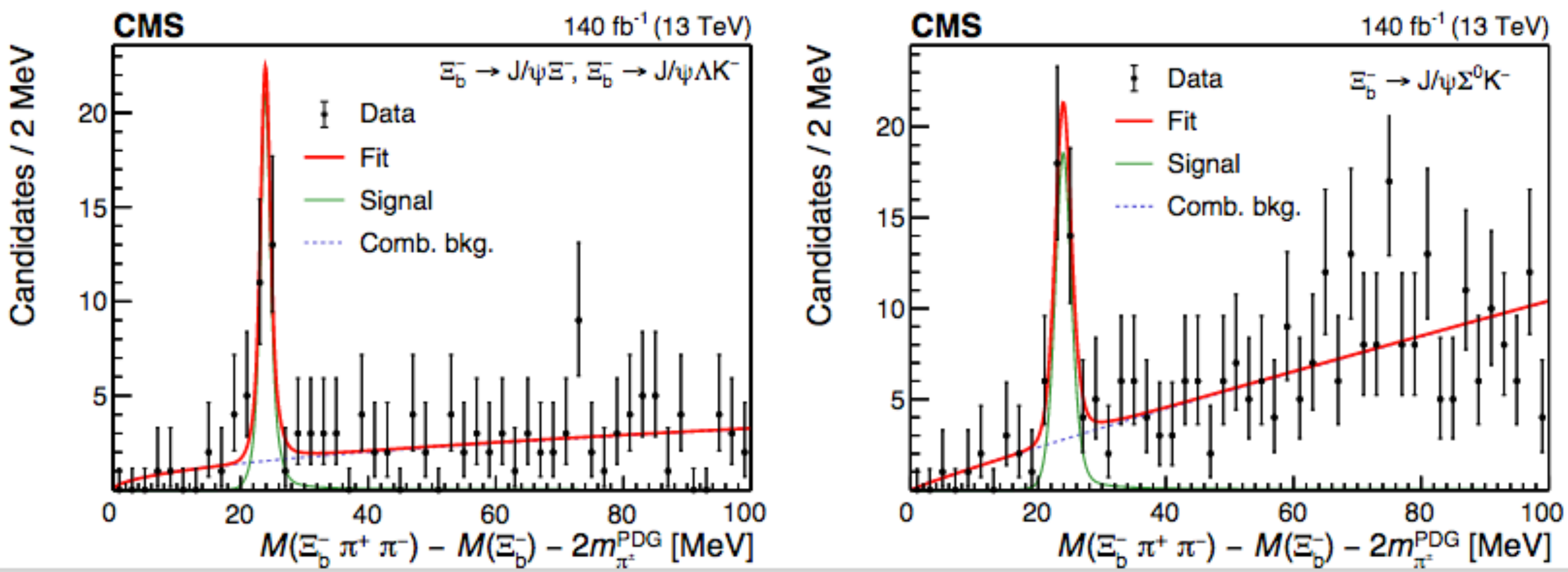


(local stat. signif. ~6.2-6.7σ)

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

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)

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

- **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 $\Gamma(\Xi_b^{**-}) < 1.9\text{MeV}$ @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]

Exotic hadron spectroscopy

X(3872) production features

JHEP 04 (2013) 154

$\sqrt{s} = 7TeV$

(Run-I/2011)

JHEP 01 (2017) 117

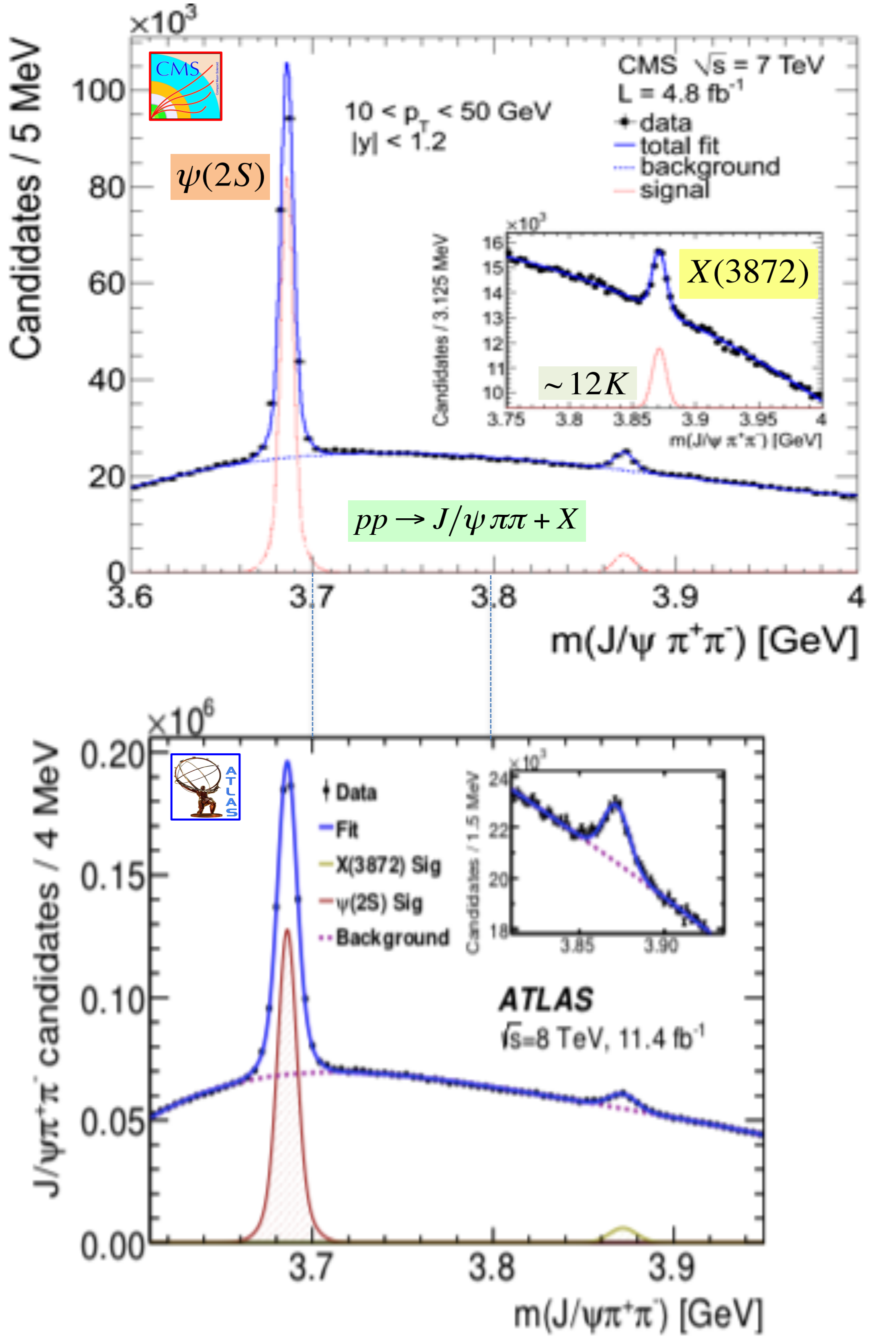
$\sqrt{s} = 8TeV$

(Run-I/2012)

[more details in the CMS talk about X(3872)]

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

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



$X(3872)$ @ LHC

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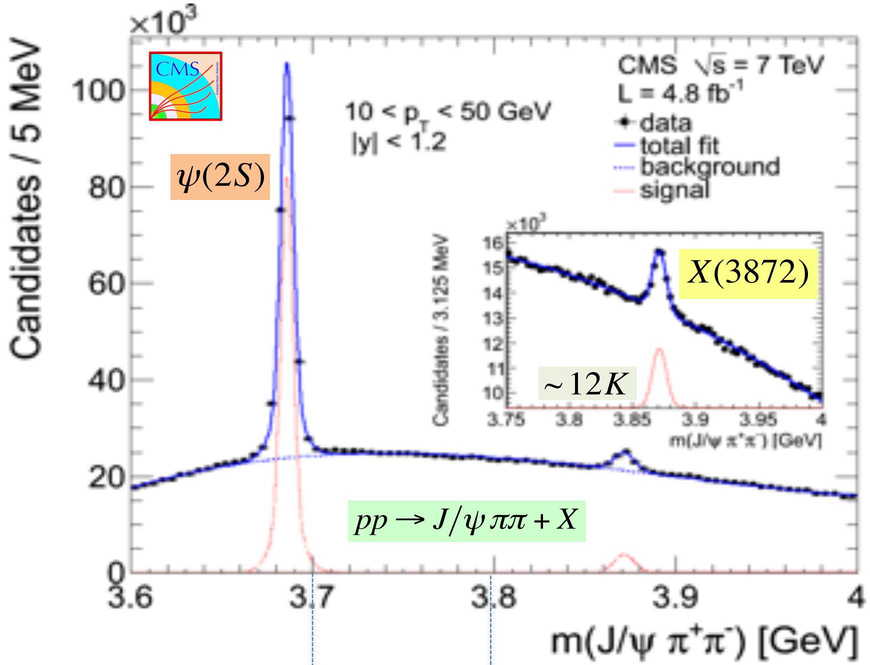
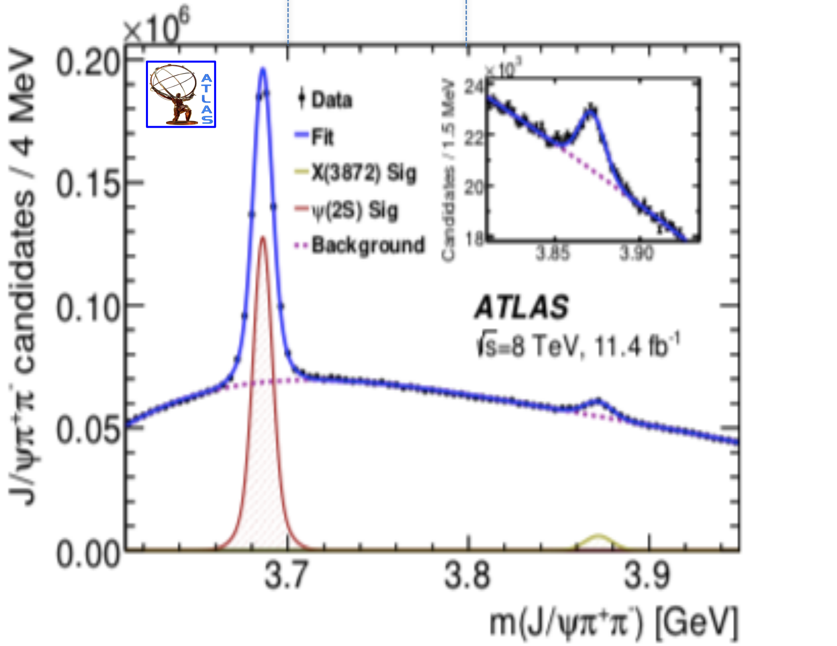
- **As soon as LHC started, quickly confirmed by & , either inclusively and exclusively (**B decays**) and later by .**

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

  next slides

  - **performed similar studies most recently (with** $8\ TeV$ **data)**

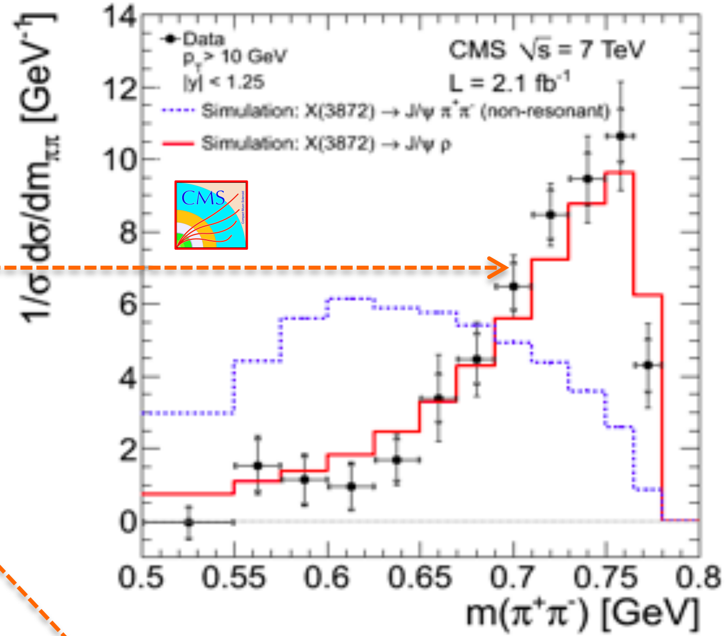




X(3872) @ CMS & ATLAS : $\pi^+\pi^-$ mass spectrum

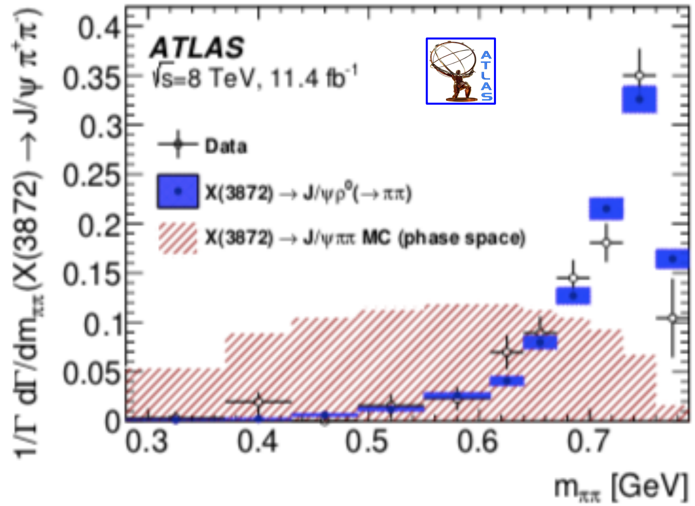
- **Invariant mass distribution of the $\pi^+\pi^-$ system :**

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]



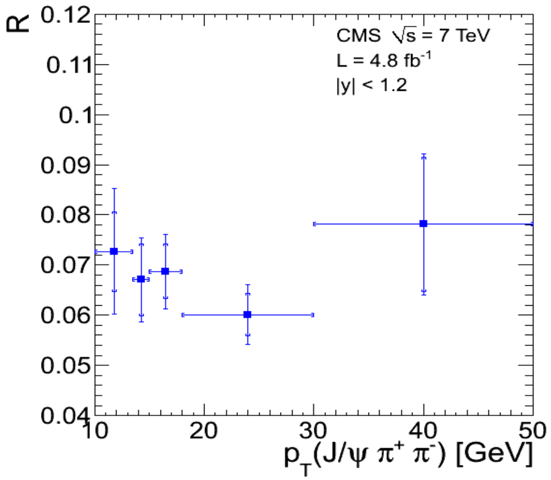
X(3872) @ CMS: Xsection x BF ratio [w.r.t. ψ(2S)]

- **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)



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

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

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

-

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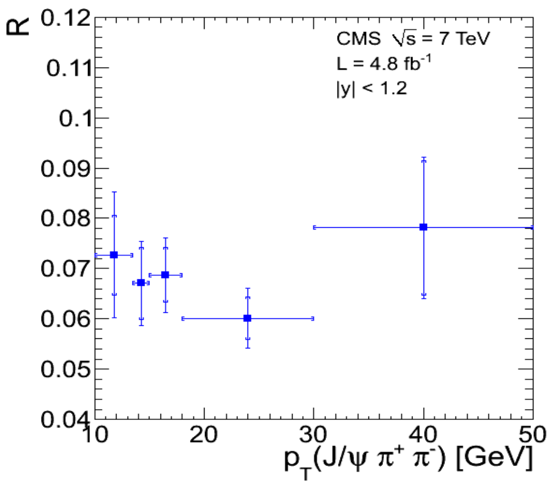
$$R \equiv \frac{\sigma\left(pp \to X(3872) + \text{anything}\right) \cdot B\left(X(3872) \to J/\psi\, \pi^+\pi^-\right)}{\sigma\left(pp \to \psi(2S) + \text{anything}\right) \cdot B\left(\psi(2S) \to J/\psi\, \pi^+\pi^-\right)} = \frac{N_{X(3872)}}{N_{\psi(2S)}} \cdot \frac{A_{\psi(2S)} \cdot \varepsilon_{\psi(2S)}}{A_{X(3872)}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

YIELDS from fits to data

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



- integrating over $10 < p_T < 50 GeV$:
  $R \cong 0.0656 \pm 0.0029(stat) \pm 0.0065(syst)$

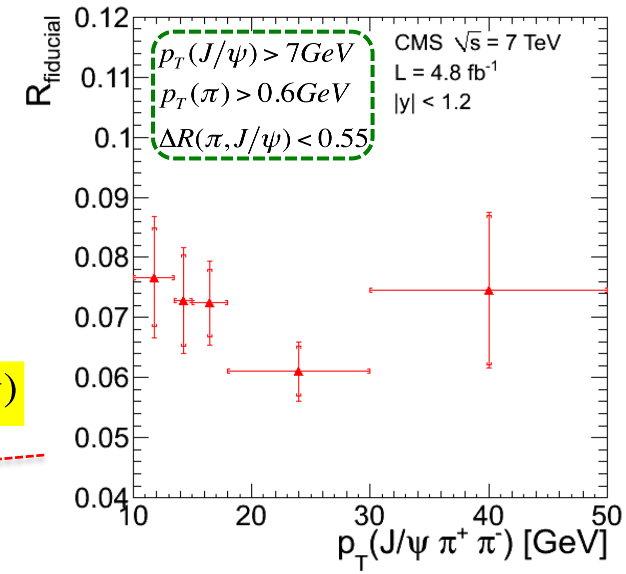
Acceptance estimated assuming *X(3872)* & *ψ(2S)* unpolarized and $J_X^{PC} = 1^{++}$

- 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 :

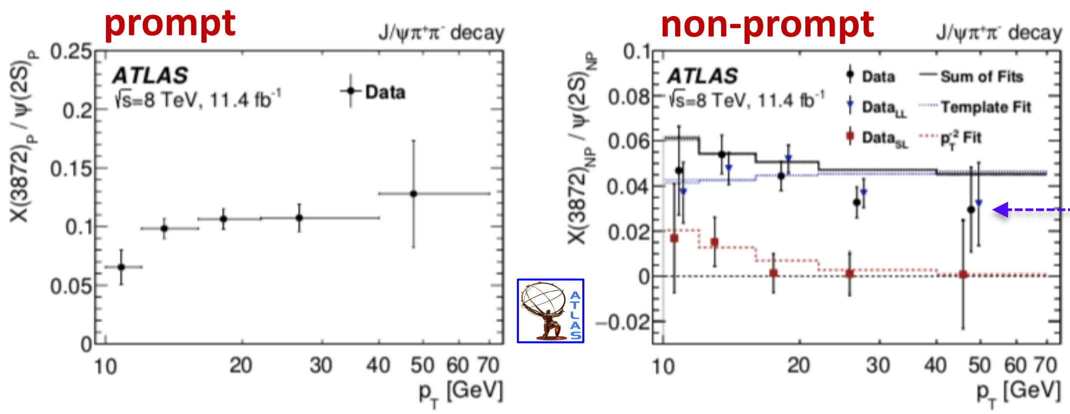
$$R_{fiducial} \equiv \frac{N_{X(3872)}}{N_{\psi(2S)}} \cdot \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{X(3872)}}$$

- 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



ATLAS provided the p_T-dependence of the same ratio **separately** for **prompt** & **non-prompt** contributions:



Non-prompt contribution is further **split** into:

long-lived: **assumed to originate from the usual mix of $B^{\pm}, B^0, B^0_s$ mesons and b-baryons**

short-lived: **assumed to originate from $B_c^{\pm}$ mesons**

Note: the statistical power of the data is insufficient to determine 2 free lifetimes: the non-prompt PDFs in the fit model is represented, in each p_T bin, by a sum of two contributions with different fixed lifetimes.

The short-lived contribution to non-prompt $\psi(2S)$ is found to be not significant.

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

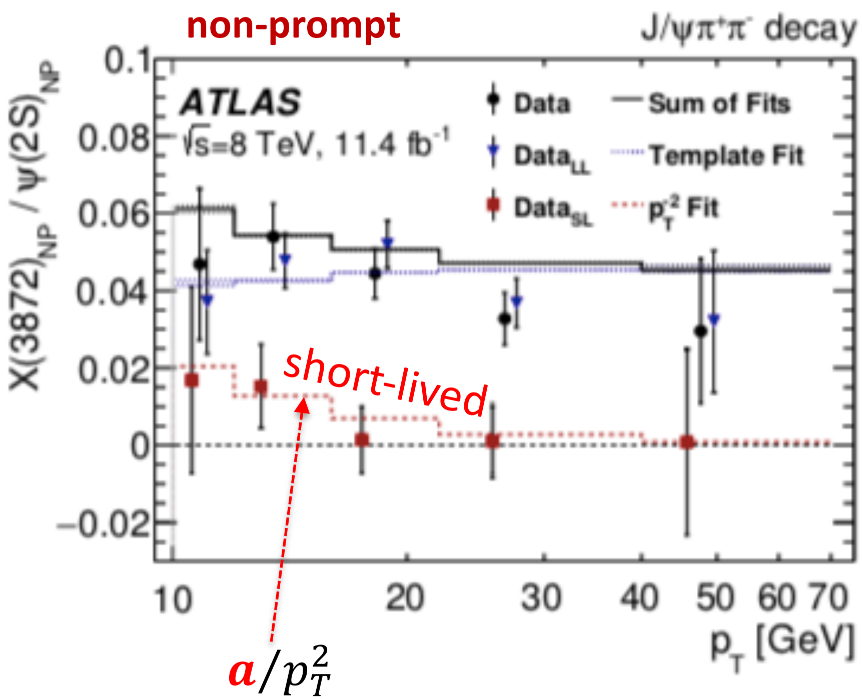
- **Production of $B_c^{\pm}$ mesons in high-energy hadronic collisions - at low p_T - is expected to be dominated by non-fragmentation processes.**

  These processes are expected to have a p_T-dependence $\propto 1/p_T^2$ relative to the fragmentation contribution that instead dominates the production of long-lived *b*-hadrons.

By fitting the ratio of short-lived non-prompt *X(3872)* to non-prompt $\psi(2S)$ with a function a/p_T^2 it is possible to derive the value of a, that together with the measured non-prompt yields of *X(3872)* & $\psi(2S)$, are used to determine the fraction of non-prompt *X(3872)* from short-lived sources:

$$\frac{\sigma(pp \to B_c)\mathcal{B}(B_c \to X(3872))}{\sigma(pp \to \text{non-prompt } X(3872))} = (25 \pm 13(\text{stat}) \pm 2(\text{sys}) \pm 5(\text{spin}))\%,$$

[for $p_T > 10 GeV$]



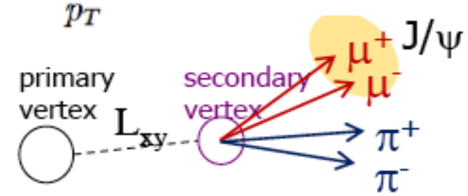
Since $B_c^{\pm}$ production is only a small fraction of the inclusive beauty production, this result could indicate that the production of ***X(3872)*** in $B_c^{\pm}$ decays is enhanced compared to its production in the decays of other ***b***-hadrons.

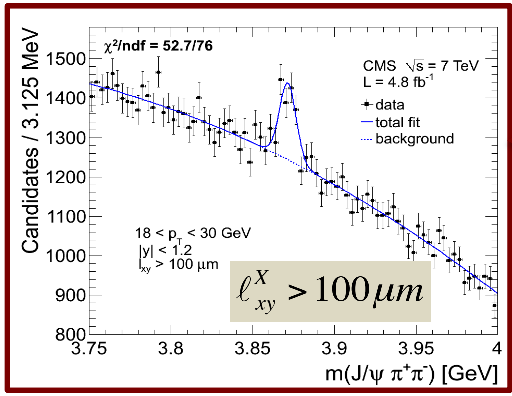
- The *X(3872)* can be produced from B hadrons' decays into a secondary vertex :
  prompt & non-prompt components can be separated by pseudo-proper decay length

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

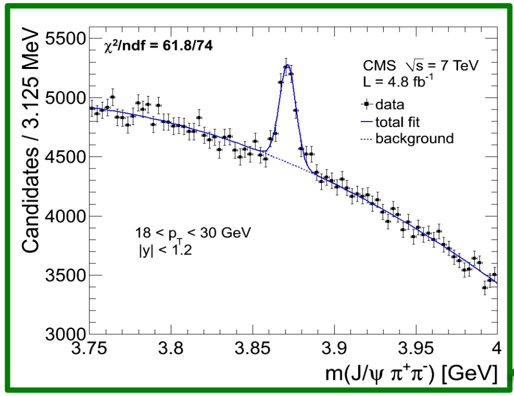
… for which prompt-fraction is negligible (<0.1%) [MC]

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





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



X(3872) @ CMS: non-prompt fraction

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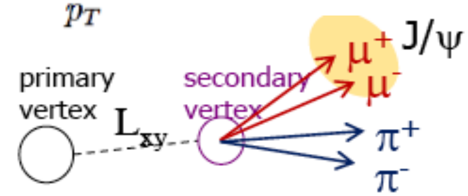
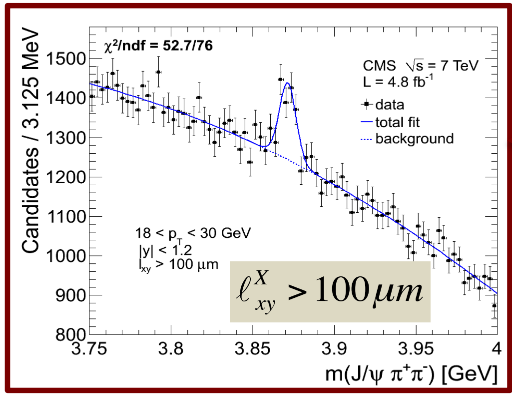
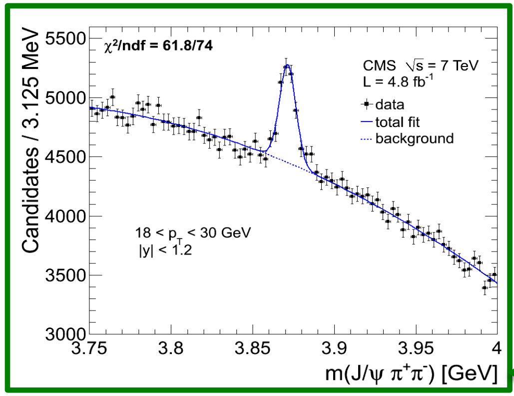
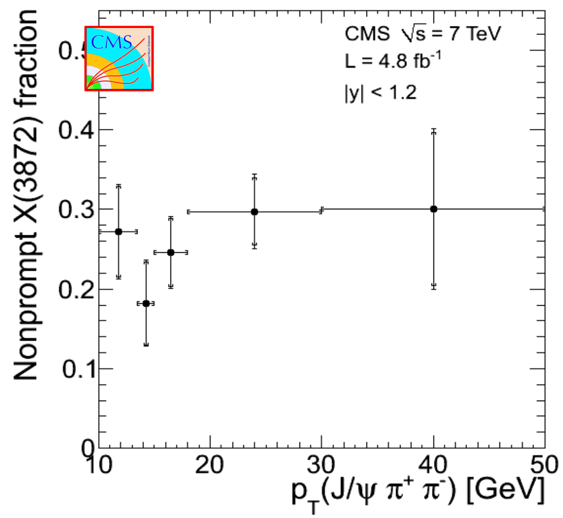




nonprompt fraction = $\frac{\text{Nr. of } X(3872) \text{ from B}}{\text{Nr. of } X(3872)}$





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

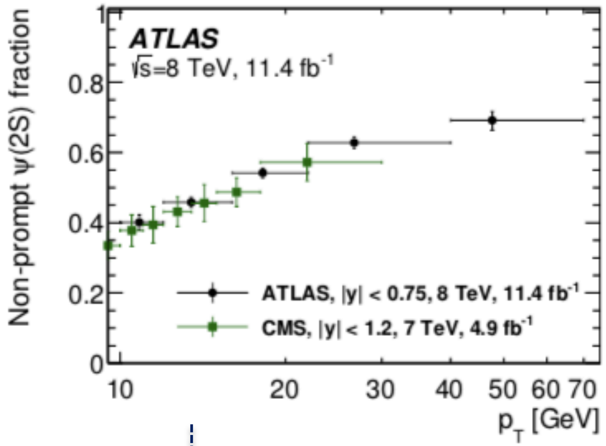
  ... significantly smaller than that for the *ψ(2S)* (increasing with p_T)
  (measured again and in agreement with [CMS, JHEP02 (2012) 011])

- In agreement with results by ATLAS (next slide)

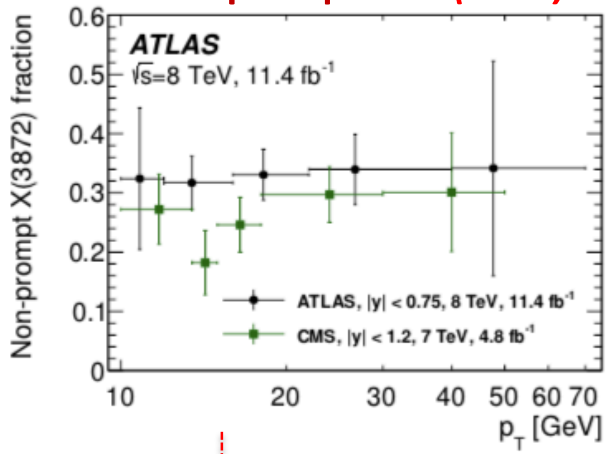
X(3872) @ ATLAS: non-prompt fraction

- Indeed :

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



non-prompt for *X(3872)*

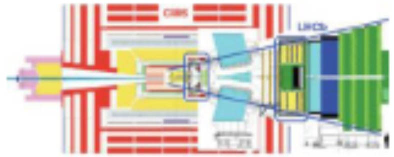


- increases with p_T
- good agreement with CMS [JHEP02 (2012) 011]

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

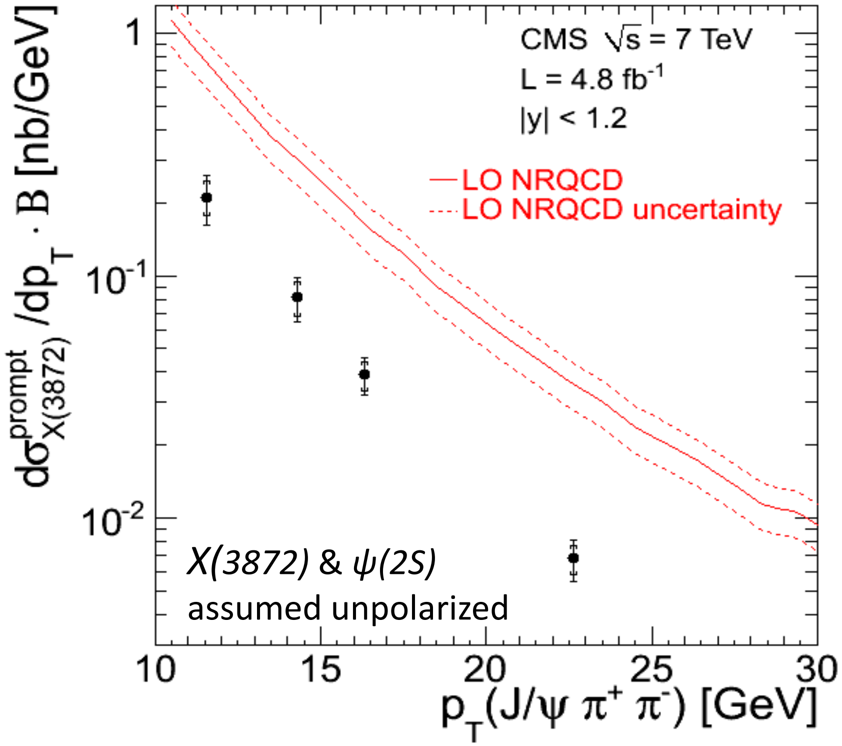
X(3872) @ CMS : prompt production Xsection

- 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):



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

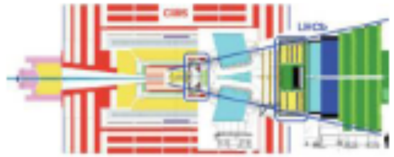
non-prompt fraction | Cross sections ratio | measured by CMS in JHEP02 (2012) 011 | from PDG



- 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:

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

X(3872) @ CMS : prompt production Xsection



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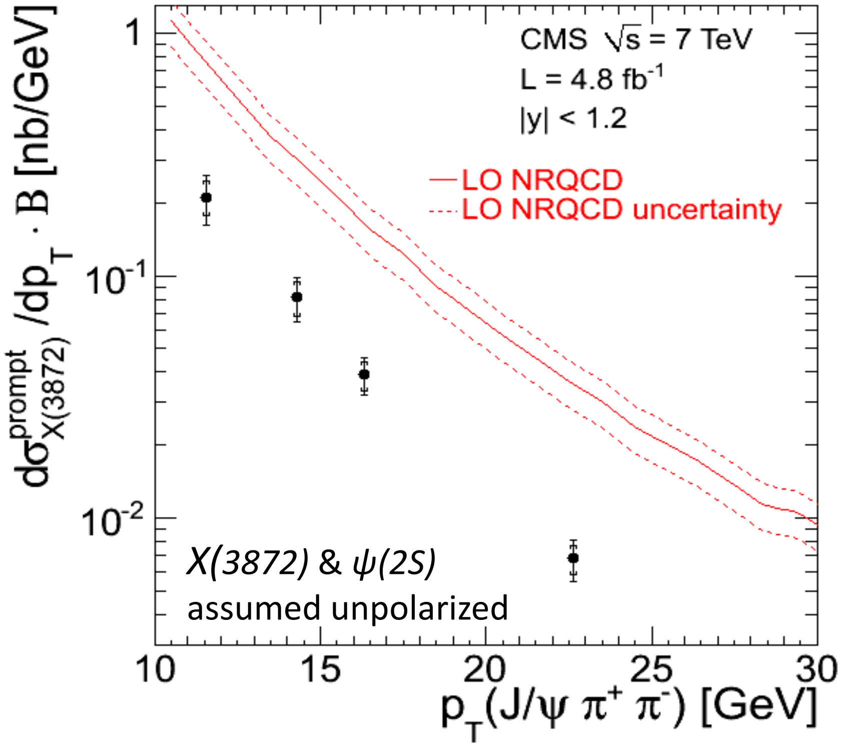
$$\sigma^{\text{prompt}}_{X(3872)} \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = \frac{1-f^B_{X(3872)}}{1-f^B_{\psi(2S)}} \cdot R \cdot \left(\sigma^{\text{prompt}}_{\psi(2S)} \cdot \mathcal{B}(\psi(2S) \to \mu^+\mu^-)\right) \cdot \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S)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

non-prompt fraction

Cross sections ratio

measured by CMS in JHEP02 (2012) 011

from PDG



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

- On the other hand, 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*)**

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

… 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]**

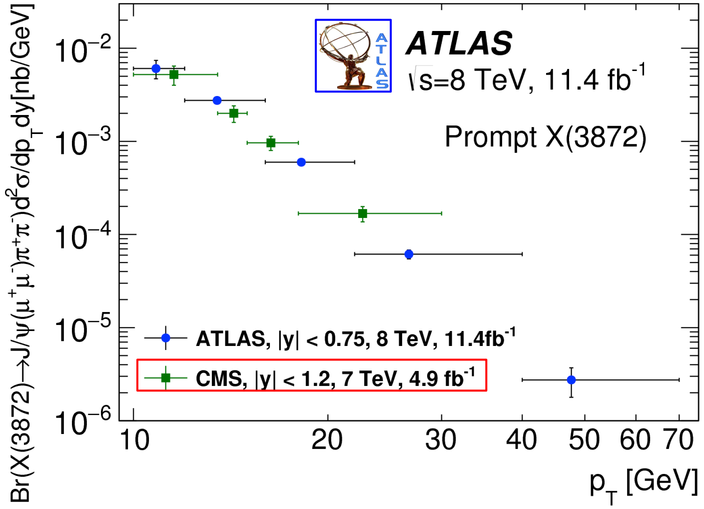
- Alternatively, to the compact tetraquark option, a possible interpretation for the $X(3872)$ is a **mixture of a charmonium state $\chi_{c1}(2\,^3P_1)$ & an S-wave molecule $\bar{D}^0 D^{*0}$.**

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

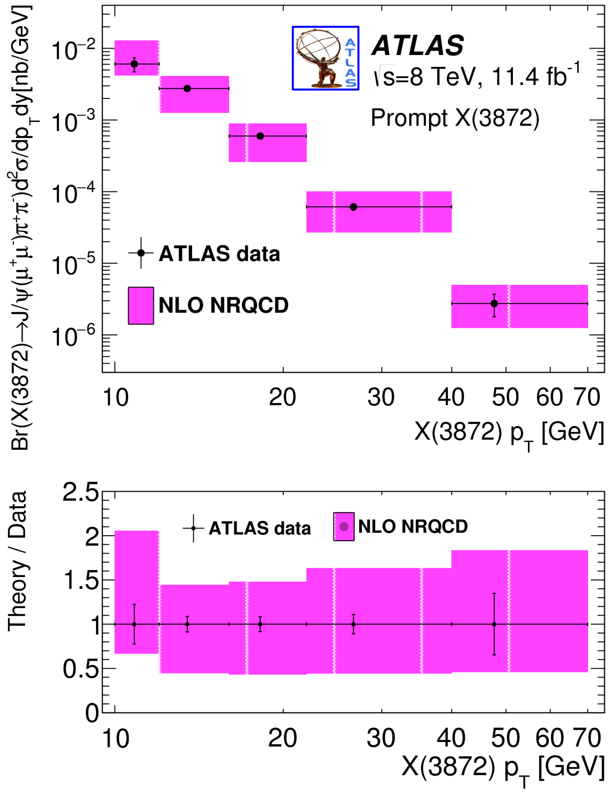
Comparison with a mixed molecule-charmonium state

- **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

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

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

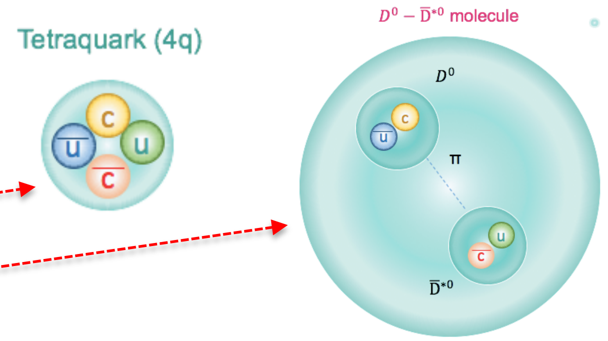
$\mathcal{L} = 1.7 nb^{-1}$

(End of Run-II / 2018)

[more details in the CMS talk about X(3872)]

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 ($\psi(2S)$), may help to separate a compact tetraquark configuration (radius $\lesssim 1fm$) from a large-sized configuration of a molecular state (radius $\sim 10fm$)**

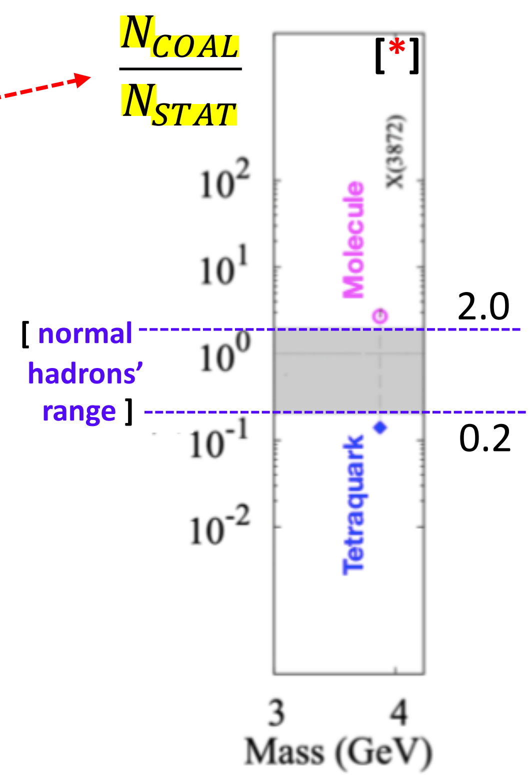


- **In relativistic HI collisions the formation of QGP** (an extended volume of deconfined quarks & gluons) **could enhance the production of the X(3872) state through the quark coalescence mechanism which depends on the spatial configuration (size) of the exotic state !**

  - 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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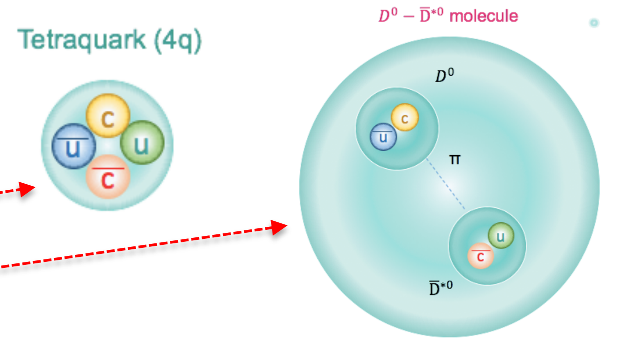
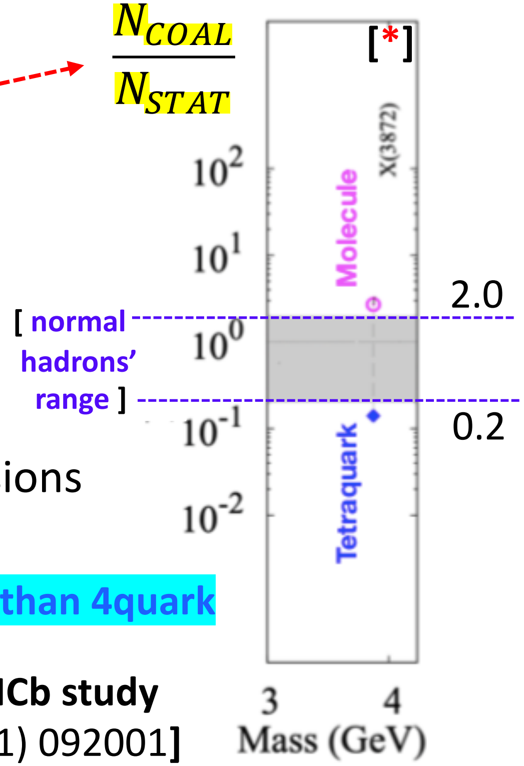


- **In relativistic HI collisions the formation of QGP (**an extended volume of deconfined quarks & gluons**) could enhance the production of the X(3872) state through the quark coalescence mechanism which depends on the spatial configuration (size) of the exotic state !**
  - Relevant parameter is the **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]**
  - Longer distances between (anti-)quarks could also lead to **higher** X(3872) **dissociation rate** similar to suppression mechanism of quarkonia in HI collisions

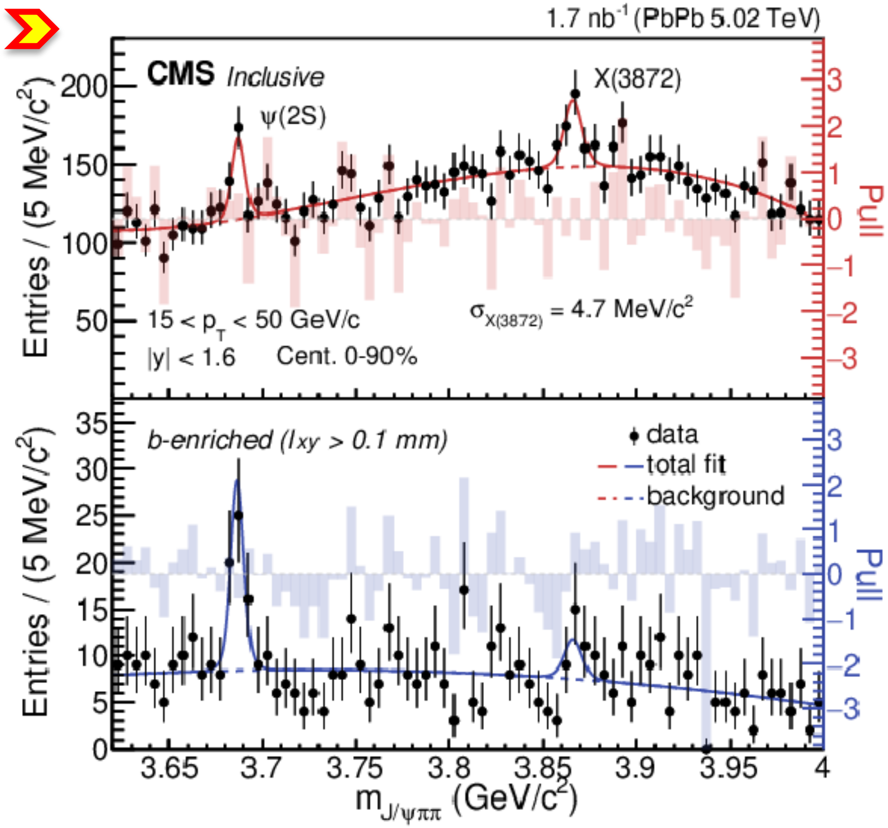
$$\frac{N_{COAL}}{N_{STAT}}$$



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



In *inclusive* data sample :

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

- a clear $\psi(2S)$ signal to same final state is also visible

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 $\mathrm{X(3872)}$ production in HI collisions [statistical significance **~4.2σ]**

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

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

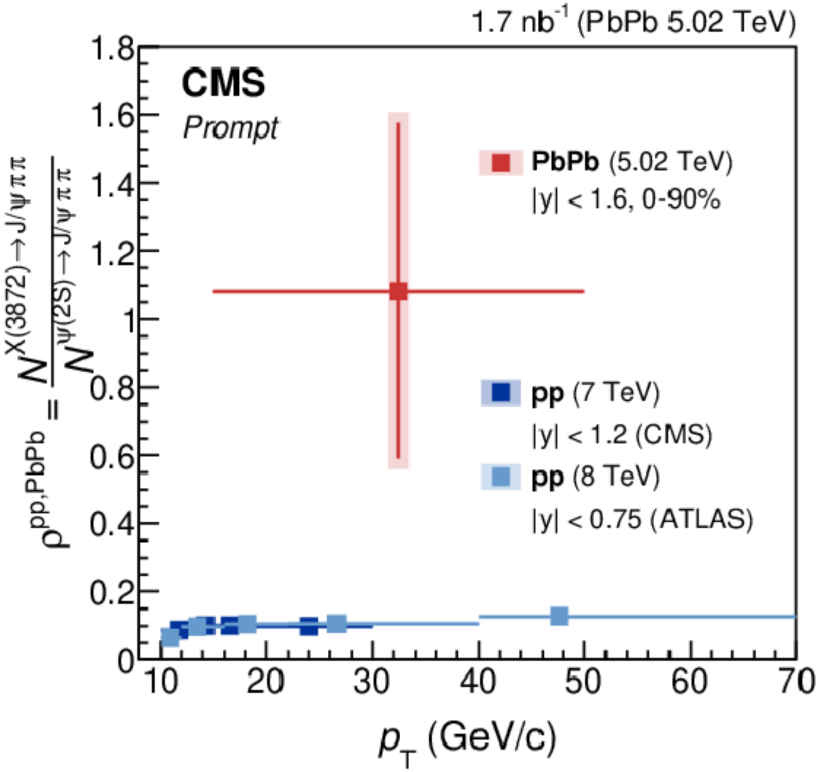
$$\boxed{1 - \frac{N_{B-enr} / f^{non-prompt}_{B-enr}}{N_{incl}}}$$

[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 $J/\psi\,\pi^+\pi^-$:

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



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 …

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

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

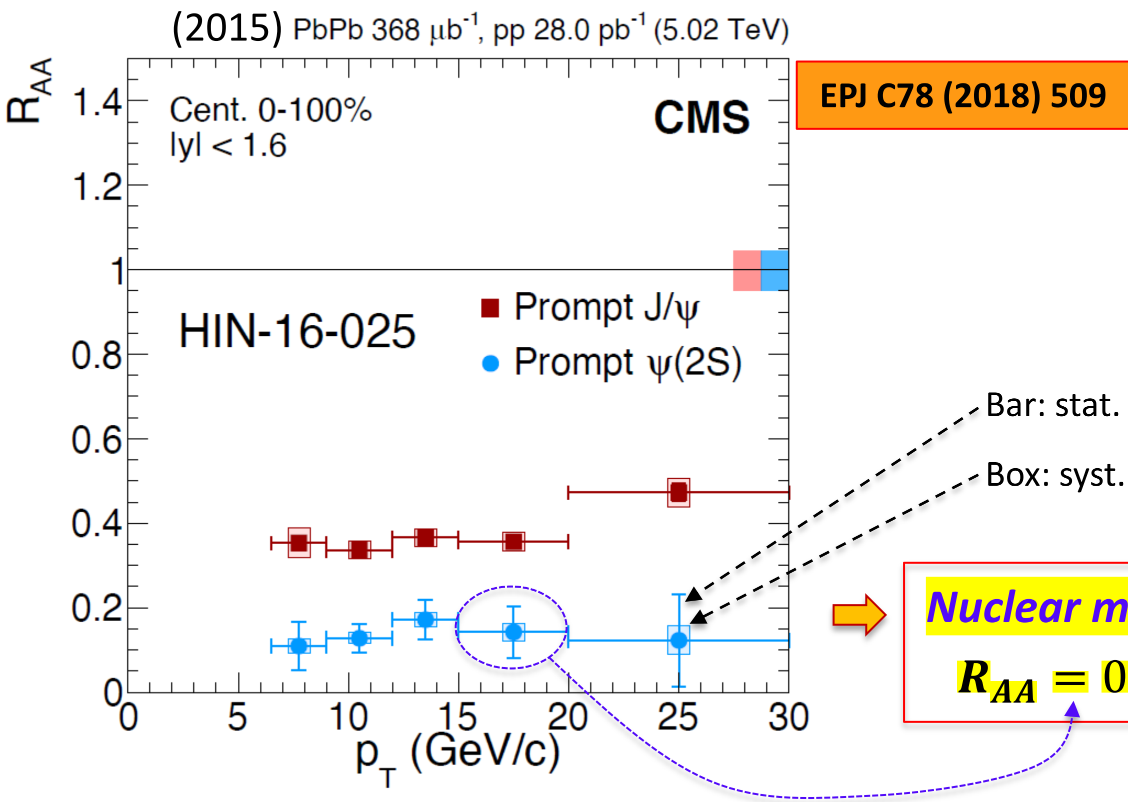
S-wave Charmonia nuclear modification factors in PbPb

- **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 $B_s^0 \rightarrow X(3872)\phi$

PRL 125 (2020) 152001

$\sqrt{s} = 13TeV$

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

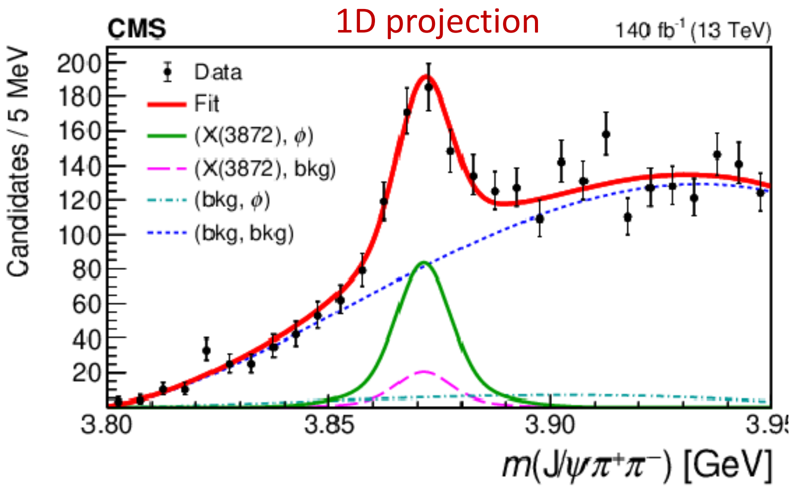
(Run-II)

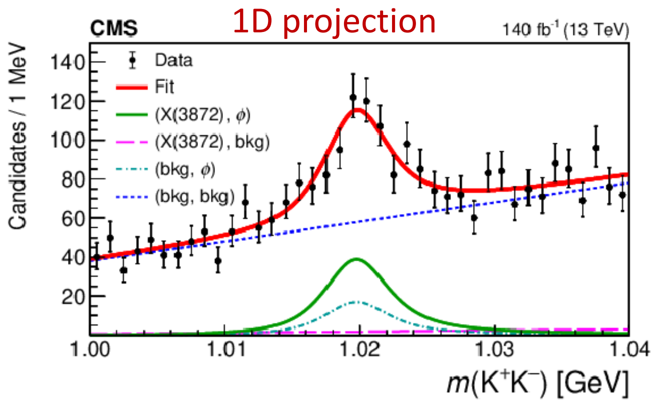
[more details in the CMS talk about X(3872)]

CMS 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)**





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

CMS 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 … $\left\{ \begin{array}{l} m(J/\psi\,\pi^+\pi^-) \\ m(K^+K^-) \end{array} \right.$
  - $N(B_s^0 \to X(3872)\phi) = 299 \pm 39$
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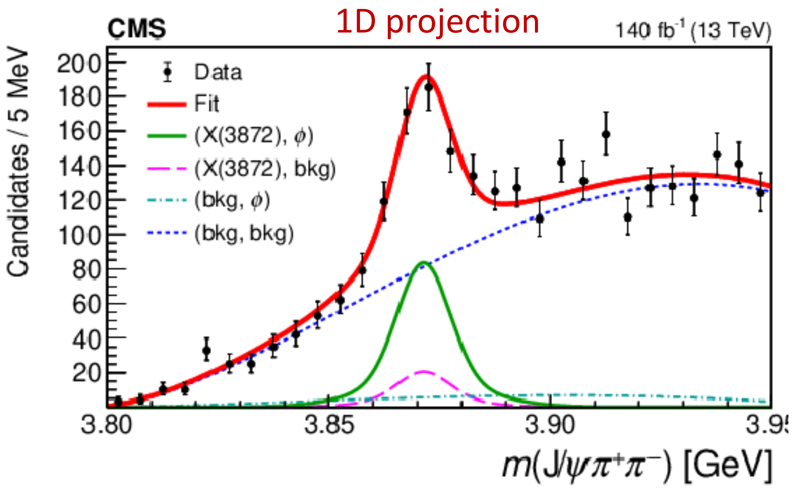
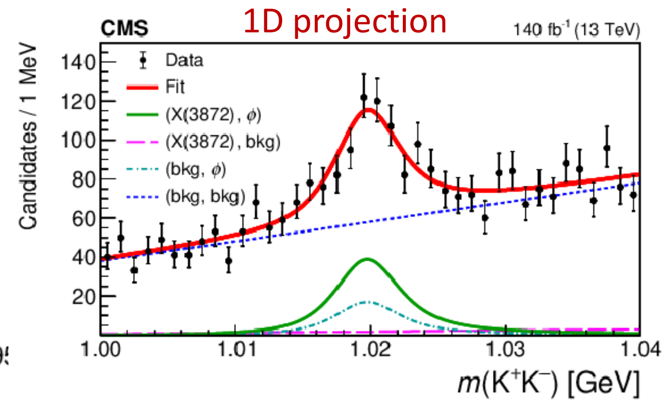
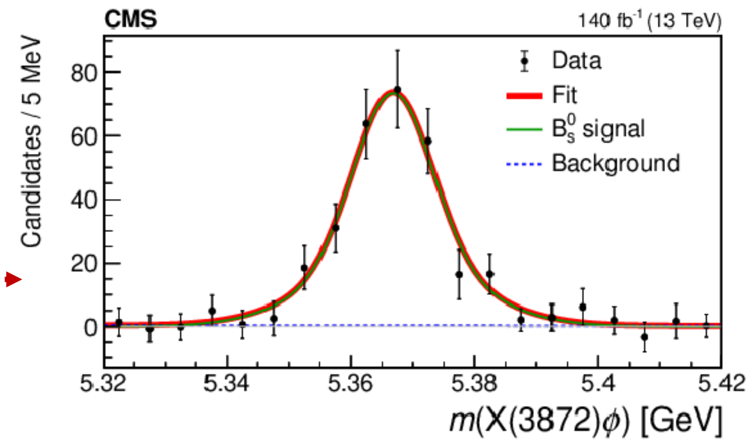




- **Evaluation of the residual non-B_s^0 background** [non-B_s^0 production of $X(3872)\phi$] **by using the non-resonant bkg-subtracted $m(X(3872)\phi)$ obtained by means of the *sPlot* technique. This bkg contribution is 1.7% (**0.5% for $\psi(2S)\phi$ **).**



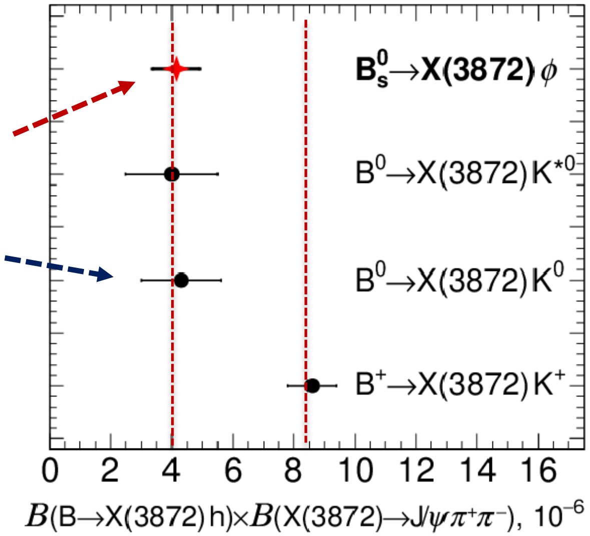
Branching fraction (ratios)

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

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

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

$$\mathcal{B}(B_s^0 \to X(3872)\phi)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.14 \pm 0.54(\text{stat}) \pm 0.32(\text{syst}) \pm 0.46(\mathcal{B}))\times 10^{-6}$$
$$\mathcal{B}(B^0 \to X(3872)K^0)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.3 \pm 1.3)\times 10^{-6}$$



Branching fraction (ratios)

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

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

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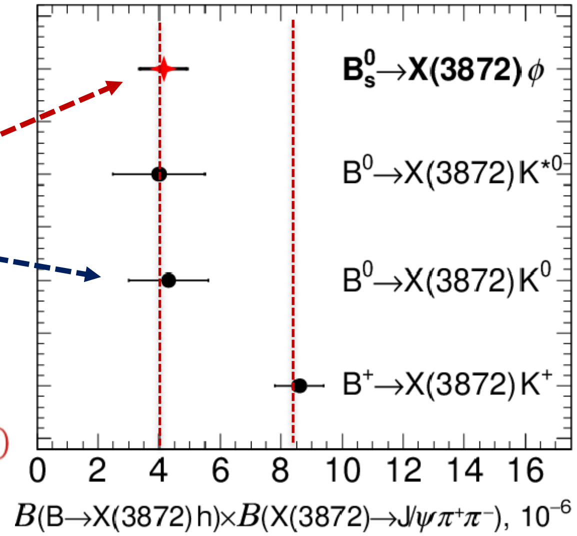
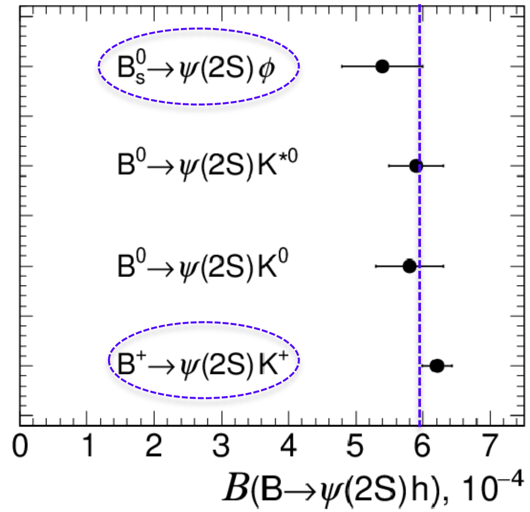
$$\mathcal{B}(B^0 \to X(3872)K^0)\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (4.3 \pm 1.3)\times 10^{-6}$$



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

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

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

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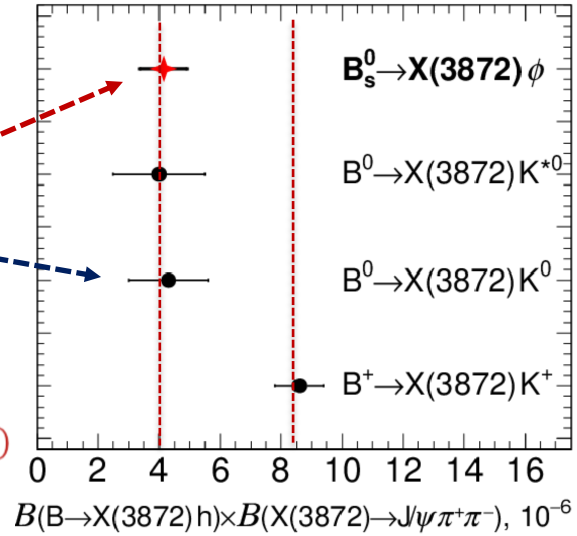

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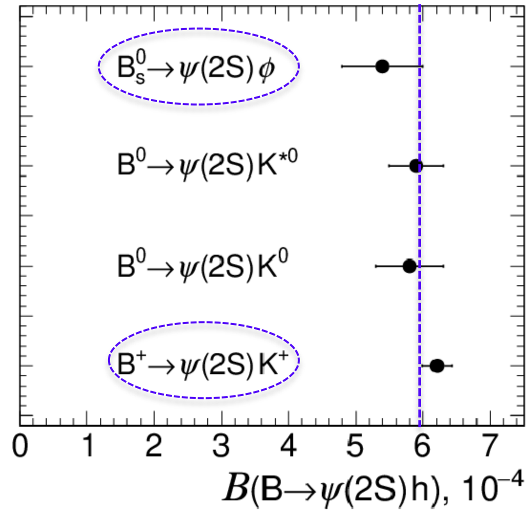
This suggests a difference in the production dynamics of the *exotic* $X(3872)$ in B^0 & B_s^0 decays compared to B^+ with respect to the *standard* $\psi(2S)$



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]

Other exotic searches

Search for X_b the bottomonium counterpart of the X(3872)

CMS — PLB 727 (2013) 57 — $\sqrt{s} = 8TeV$ — $\mathcal{L} = 20.7 fb^{-1}$ (Run-I/2012)

ATLAS — PLB 740 (2015) 199 — $\sqrt{s} = 8TeV$ — $\mathcal{L} = 16.2 fb^{-1}$ (Run-I/2012)

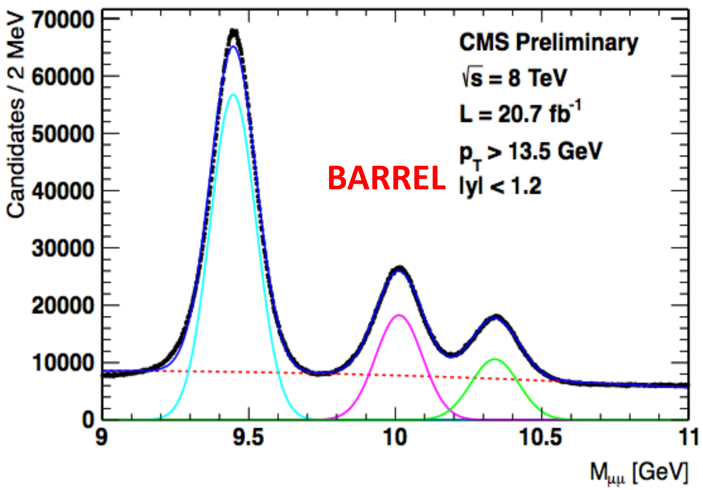
Search for X_b - I

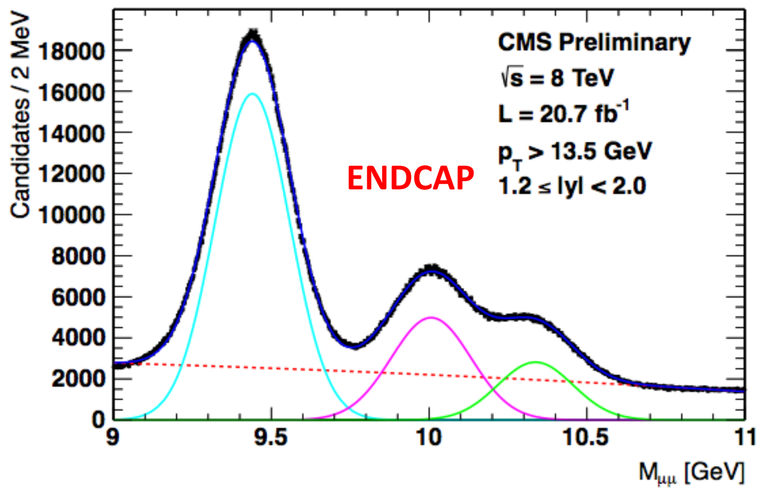
- **Heavy Quark symmetry suggests an X_b as 'bottomonium counterpart' of $X(3872)$.**
  Molecular model suggests to search close to $B\overline{B}^{(*)}$ threshold ($m \cong 10.562(604) GeV$);
  [model dependent prediction for a $B\overline{B}^{(*)}$ molecule by Swanson (2004)**]**

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

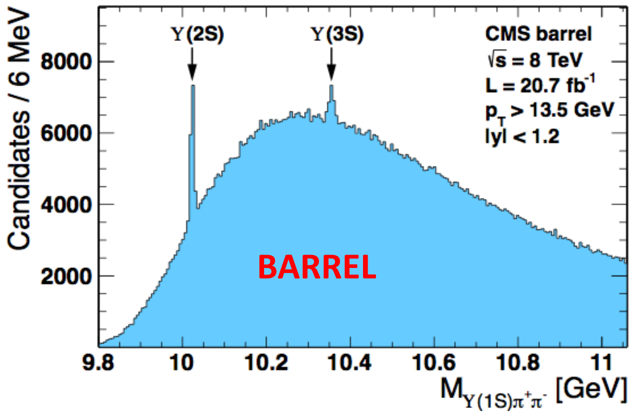
- Analysis strategy: search for a peak - other than known $\Upsilon(2S), \Upsilon(2S)$ - in the $\Upsilon(1S)\ \pi^+\pi^-$ spectrum within 10-11GeV
  [expecting **narrow width** & possibly **sizable BF** similarly to X(3872)]

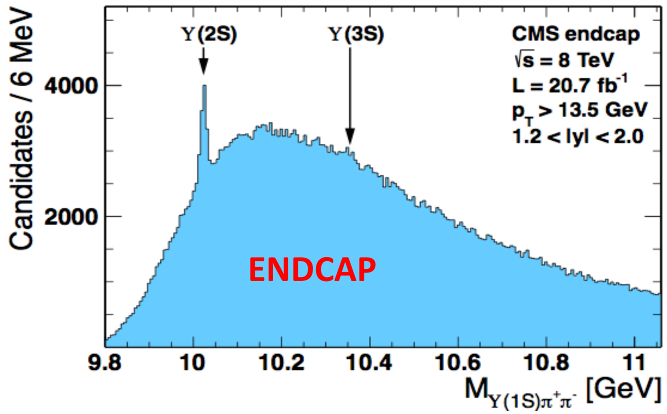
- CMS **collected ($pp@8TeV$) large sample of $\Upsilon(nS) \to \mu^+\mu^-$ [better mass resolution and lower bkg in the barrel]:**





- 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 $\Upsilon(2S)$].

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

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

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**

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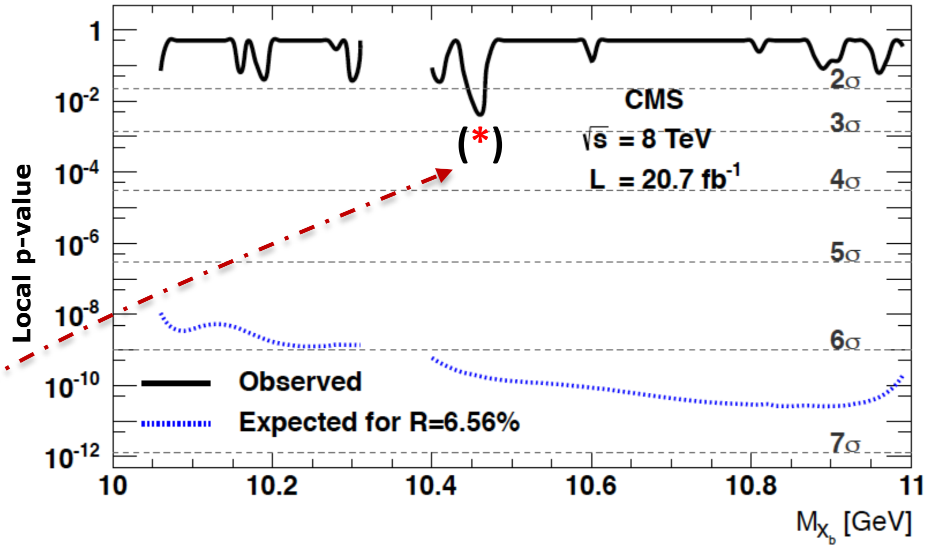

- **...and a local *p-value* is calculated (asymptotic approach & barrel/endcap combination)**

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

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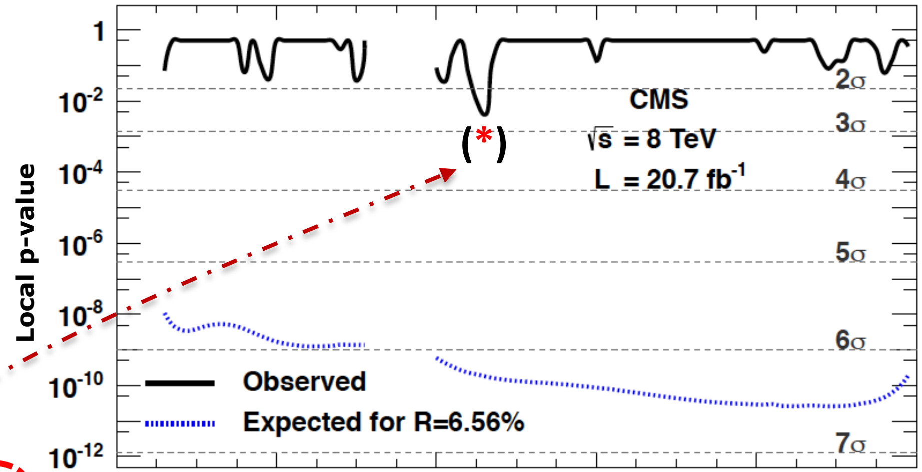
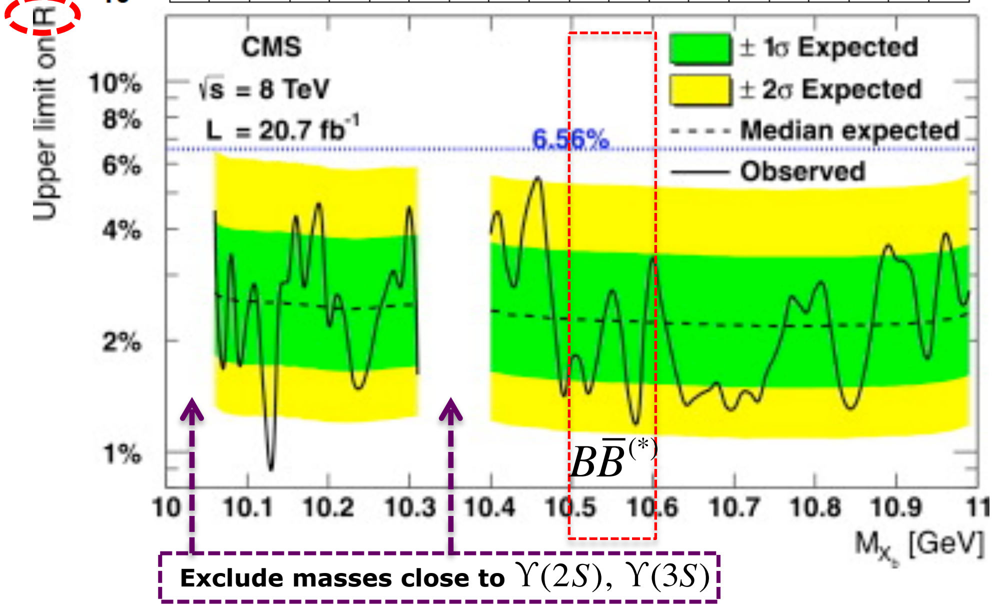
NO significant excess observed

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

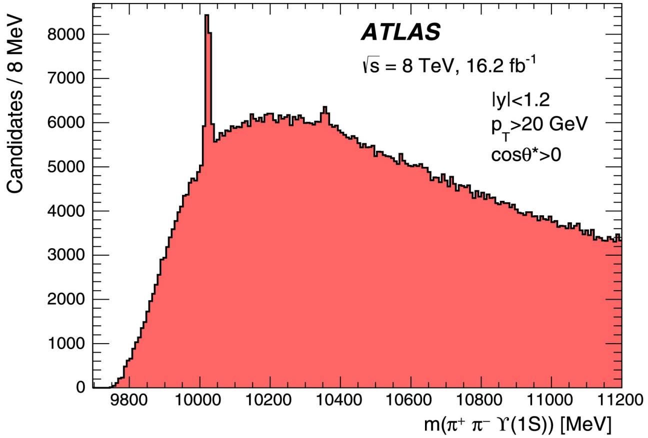
observed UL range: 0.9% to 5.4%





Search for X_b - Upper Limit @ ATLAS

- **Very similar search was later performed by** ATLAS:

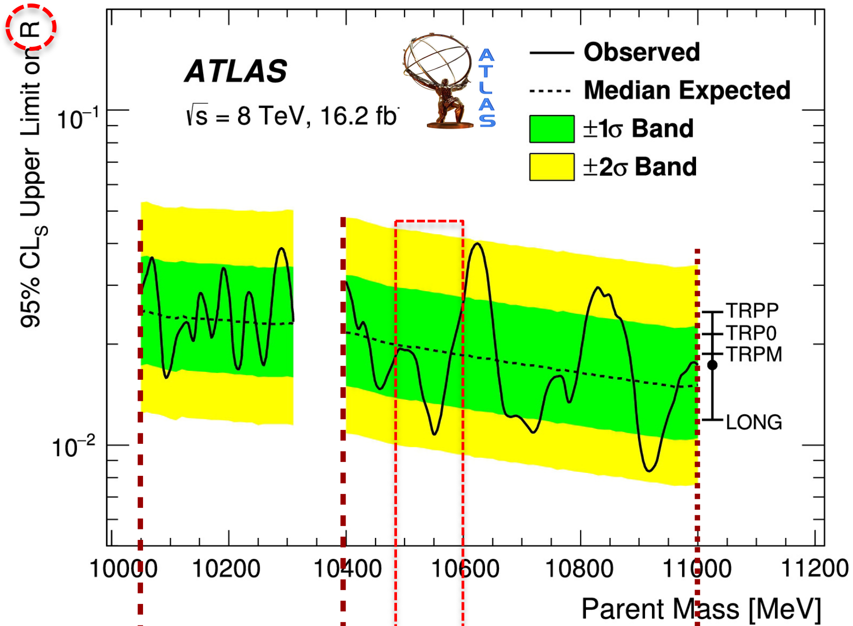


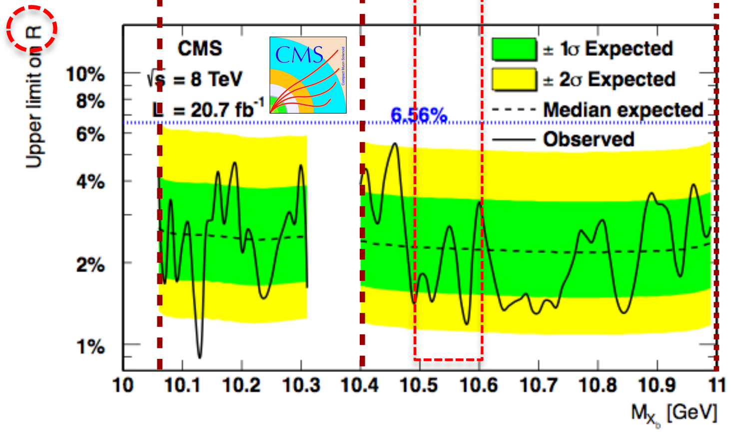
- **Fit done in 2x2x2 bins of ($|y|,\ p_T,\ \cos\vartheta^*$), where** ϑ^* is the angle between the dipion momentum & the parent momentum in the lab-frame.

- The split of the analysis into these bins take advantage of varying bin sensitivity, thus allowing for **more restrictive limits than** CMS.

- **No significant eccess found**

Observed UL range on R: 0.8% to 4.0%





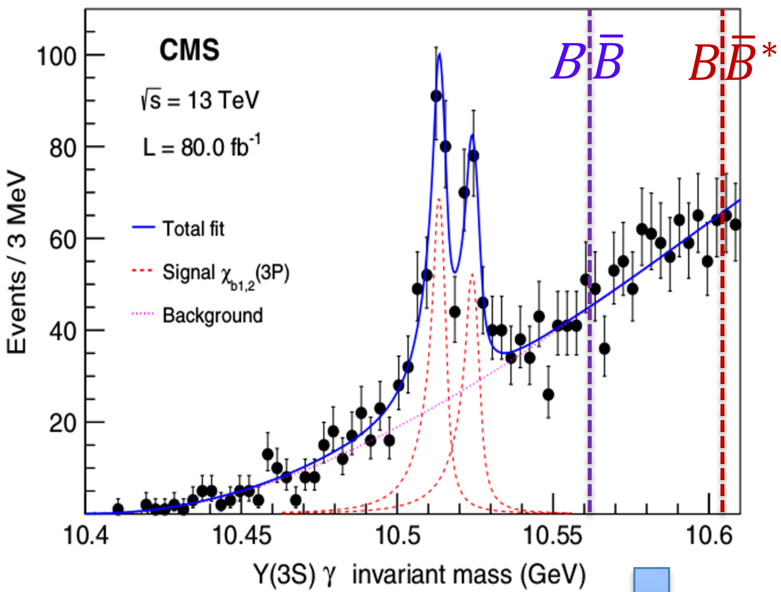
- ATLAS search for the production of the $\Upsilon(1^3D_j)$, $\Upsilon(10860)$ and $\Upsilon(11020)$ states also reveals **no signals**.

Is the hypothetical X_b seen decaying radiatively ?

$X_b \to \Upsilon(3S)\gamma$

- **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 $D\overline{D}$ 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 $\chi_{c1}(2P)$ & $D^0\overline{D}^{*0}$ 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 $B\overline{B}^{(*)}$ thresholds.

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

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

PLB 808 (2020) 135578

$\sqrt{s} = 13 TeV$

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

(Run-II/2016)

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.

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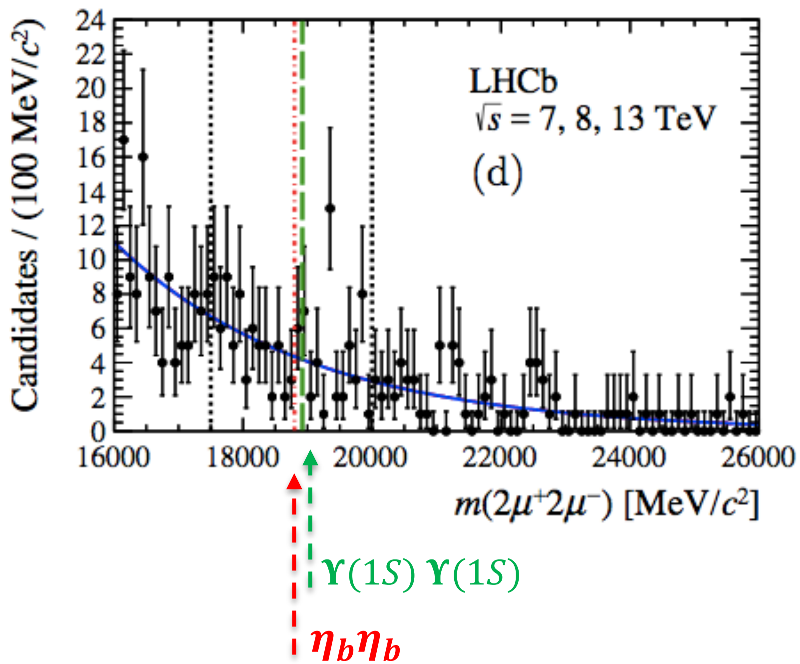
LHCb searched for such tetraquarks without finding any hint of a signal [JHEP 10 (2018) 086]



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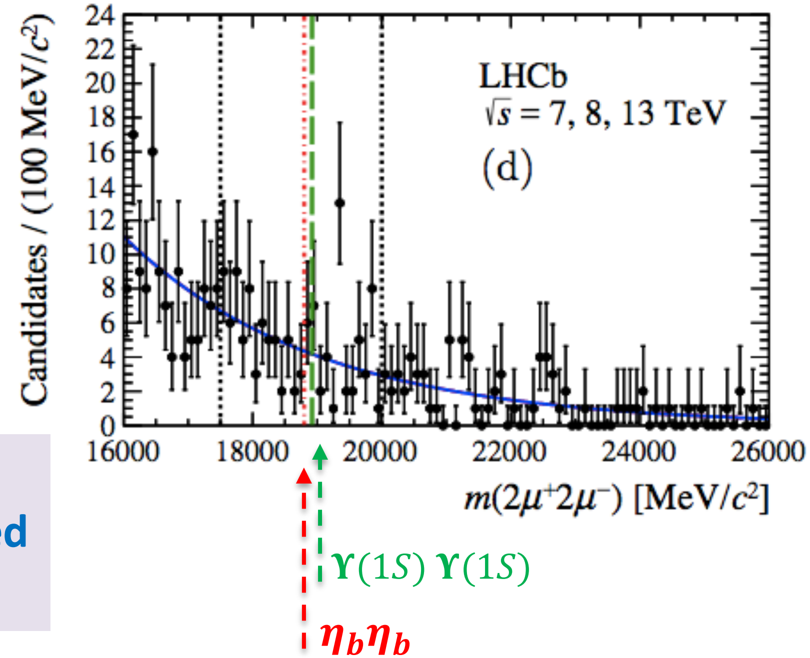

This new analysis probes a kinematical region not accessible at LHCb. CMS has also a very competitive acceptance for muons from $\Upsilon(1S)$ decays.

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 [see backup].

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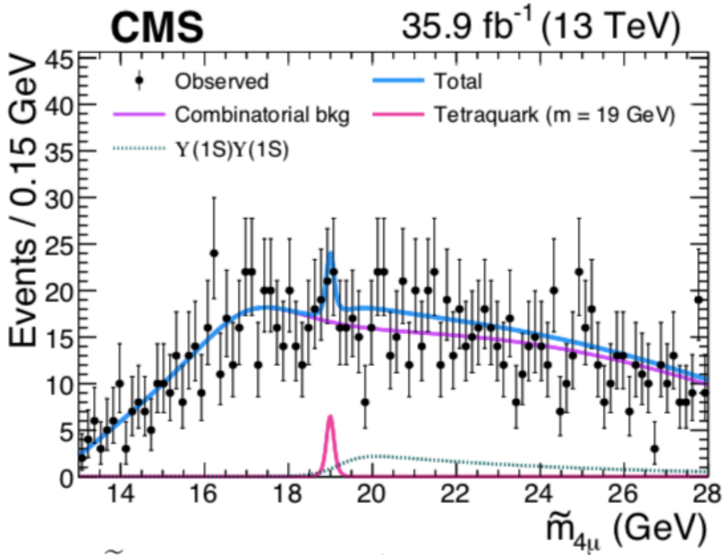
Search for a $bb\bar{b}\bar{b}$ tetraquark state

- 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.



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

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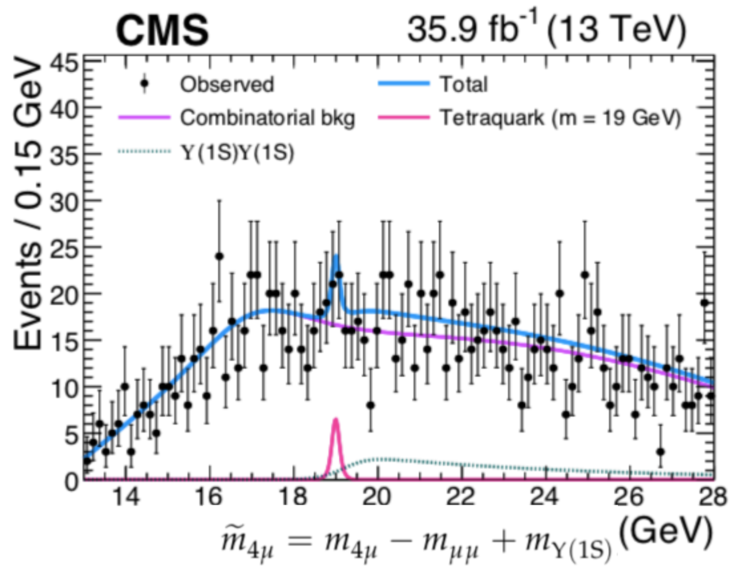

This mass window is probed using the bottomonium model.
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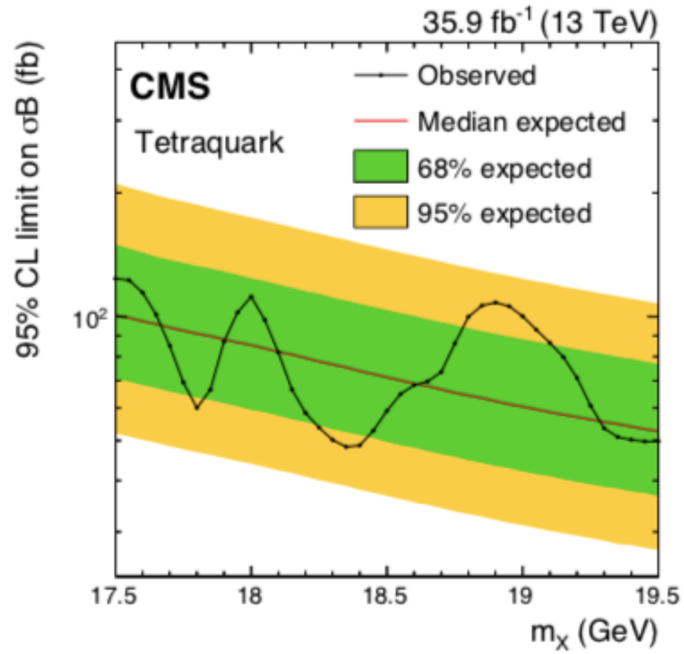
Upper limits on the product of the production Xsection of a resonance & the BF to the final state of 4 muons via an intermediate $\Upsilon(1S)$, $\sigma(T_{bb\bar{b}\bar{b}})\times\mathcal{B}(T_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu^+\mu^-)$, are set @95% CL (using the modified frequentist construction 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 $|y| < 2.0$

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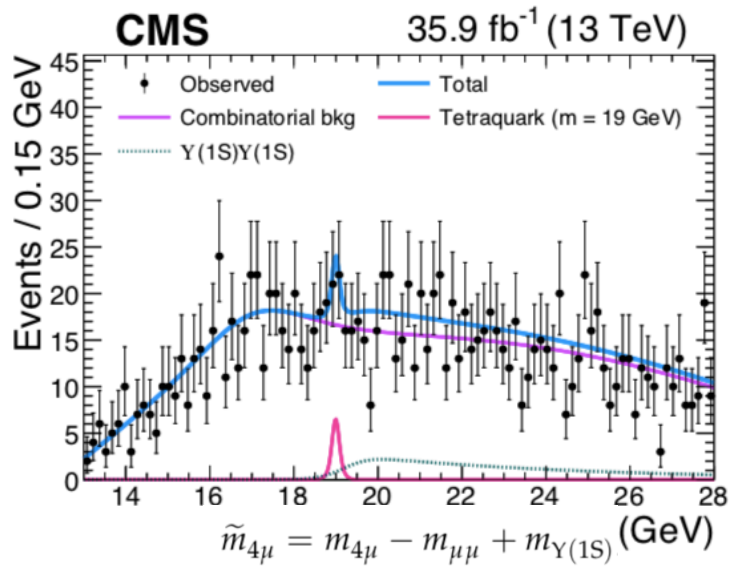

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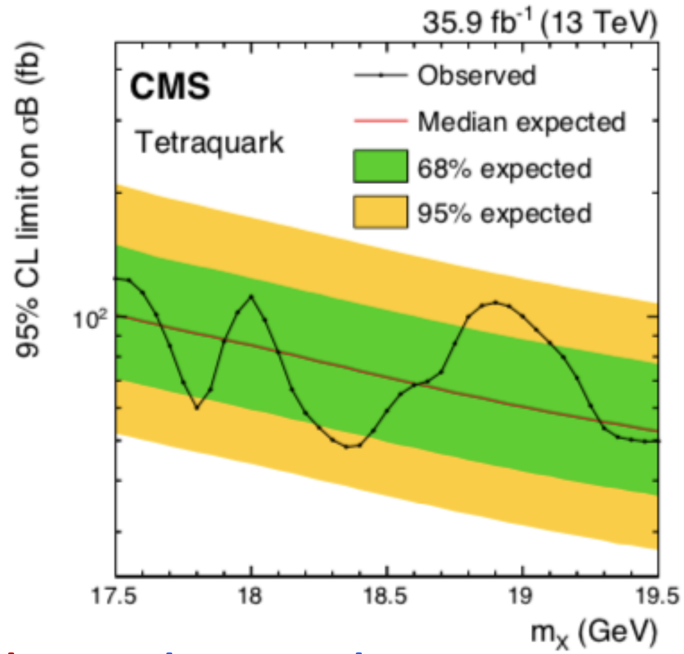


- A further search for a light narrow resonance, such as a BSM bound state, does not show any significant narrow excess of candidates above the background expectation (see backup).

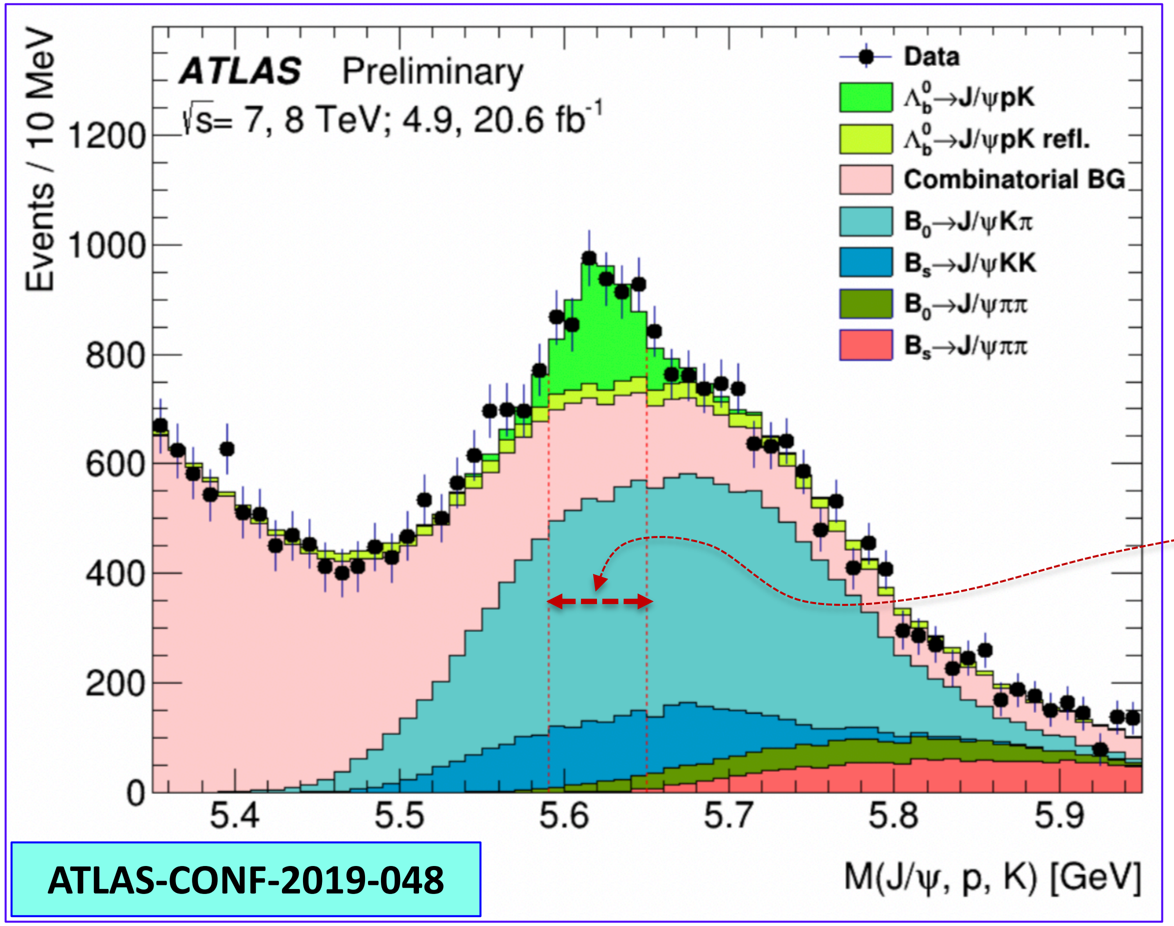
Search for pentaquark states in the final state $J/\psi\, p$

ATLAS-CONF-2019-048 $\sqrt{s} = 7 + 8 TeV$ $\mathcal{L} = 25.5 fb^{-1}$

(full Run-I)

- Motivated by the observation of pentaquark states $P_c^+(uud c\bar{c})$ in the $J/\psi\, p$ final state.

Based on full Run-I data reconstructs the decay $\Lambda_b^0 \to J/\psi\, pK^-$ dominated by backgrounds.



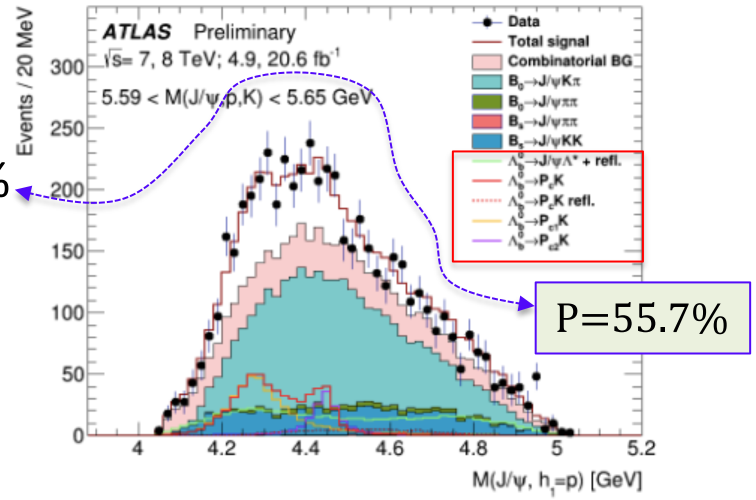
signal region

Study of $J/\psi\, p$ resonances in the $\Lambda_b^0 \to J/\psi\, pK^-$ decays - II

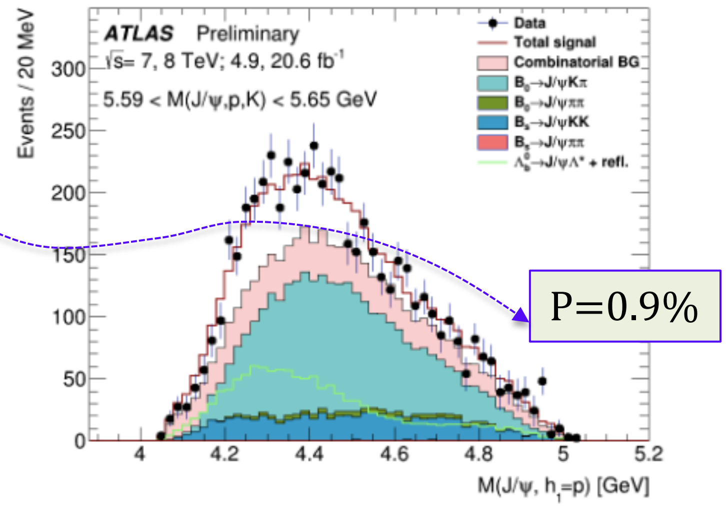
- In the **signal region** [$5.59 < m(J/\psi\, pK^-) < 5.65 GeV$] perform 1D fits of the $m(J/\psi\, p)$:
  - the 5-quark masses & width obtained using the model with two 5-quarks are consistent with the LHCb results
  - the goodness-of-fit using the model with two 5-quarks with free masses & widths corresponds to a p-value ~55.7% [table with results in *backup slide*]

    when fixing masses & widths to the LHCb values, the g.o.f. corresponds to a p-value ~24.5%
  - data are also compatible with the more recent LHCb observation of 3 narrow pentaquarks as well
- although the data prefer the model with 2 (or more) 5-quark states, the model without them is not excluded
- plans more precise studies with Run-2 data (larger statistics & improved procedure)

$2P_c^+(3/2^-, 5/2^+)$



$NO\ P_c^+$



Perspectives

NOTE: I will refer mostly to CMS ;

however many of the considerations (not all) can/may hold as well for ATLAS.

Perspectives

- LHC experiments are greatly contributing to conventional & exotic hadron spectroscopy and will continue to do it with Run-III data and beyond facing new experimental challenges.

  - CMS & ATLAS are participating to this sector with selected well thought contributions.

    Many analyses have been carried out but many others are ongoing or in the to-do list.

    Many analyses are prohibited by …
    - huge backgrounds,
    - trigger constraints,
    - particle identification limitations;

    however many other analyses can be carried out with competitive (w.r.t. LHCb) results by exploiting some excellent features of the detector and the reconstruction algorithms.

    New exciting results are still expected with the exploitation of the full Run-2 data sample. A *careful dedicated trigger strategy* can allow to collect useful new Run-3 data to extend exotics searches and the extraction of the signals of rare spectroscopic transitions.

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    New exciting results are still expected with the exploitation of the full Run-2 data sample. A *careful dedicated trigger strategy* can allow to collect useful new Run-3 data to extend exotics searches and the extraction of the signals of rare spectroscopic transitions.

  - Strategic choices must be pursued; for instance: $X(3872)$ in HI (CMS), the bottomonium spectrum, double quarkonia (CMS), B_c spectroscopy (maybe doubly heavy baryons and possibly tetraquarks), radiative transitions, prompt production of exotics (also to complement the non prompt production in B decays and find another production process, as done for the $X(3872)$), W+Z boson+quarkonium associated production (mostly ATLAS). Try the model independent approach (method of moments) for those 3-body decays where a full amplitude analysis is prohibitive due to high background level.

Particular strengths of the CMS detector and reconstruction algorithms are:

1) The large muons' acceptance, which is useful in particular for the extraction of **bottomonium** signals and more in general for all **double quarkonia**.

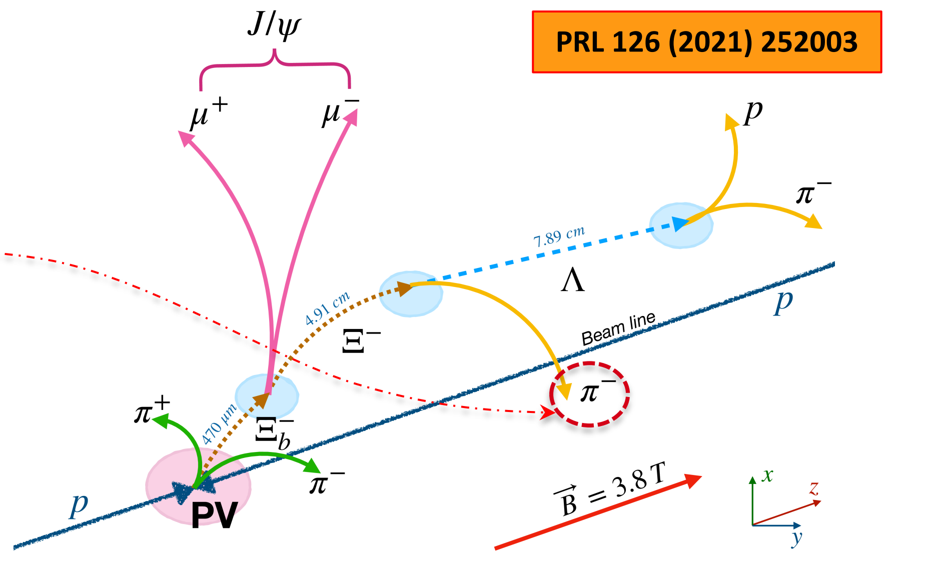
2) The precise and competitive **photon conversions** for the r**adiative spectroscopic transitions** (with photon energies larger than 400MeV). Critical issue here is the low efficiency.
Rare radiative decays can also be searched for by exploiting the usage of calorimeter photons (when resolution not crucial).

3) The **good efficiency for the low-momentum tracks,** both **prompt** and **displaced** from the Primary Vertex. 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 and the $\Xi^- \to \Lambda^0\pi^-$ decays.

For instance, the π^- from the $\Xi^- \to \Lambda^0\pi^-$ decays are **very soft** and **displaced** !

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

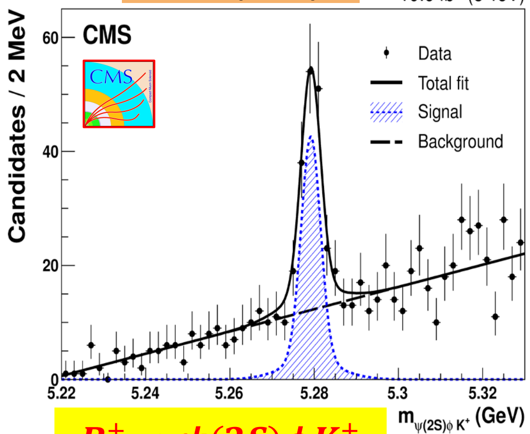
PRL 126 (2021) 252003



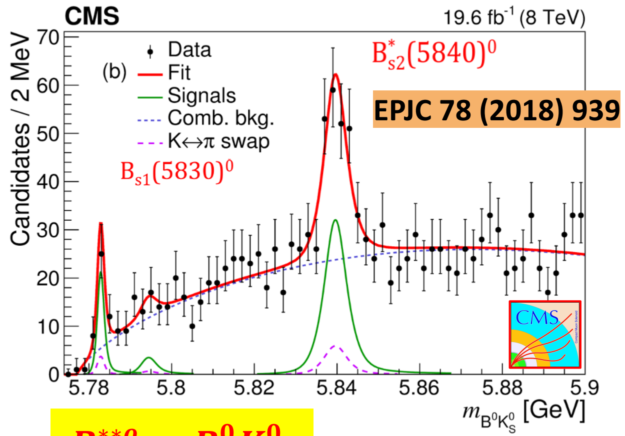
4) By lacking a hadronic particle identification, CMS is clearly more competitive when dealing with **signatures with K_s^0, Λ^0 and ϕ reconstructed mesons** that allow to fight the overwhelming backgrounds associated to a typically huge track multiplicity in the event.

Examples of observation of new decay modes:

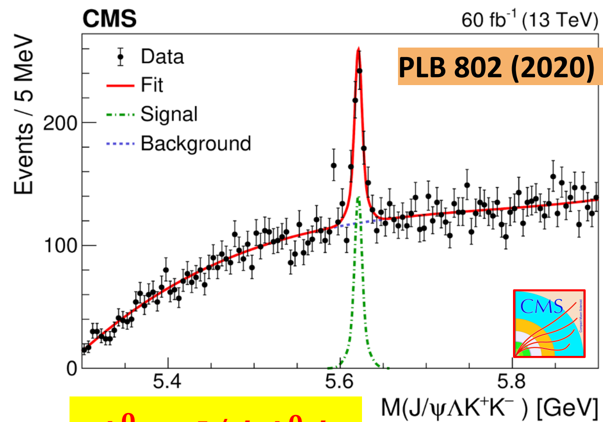
PLB 764 (2017) 66



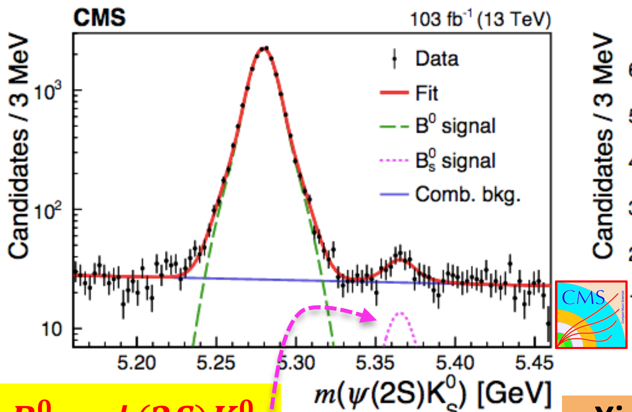
$B^+ \to \psi(2S)\phi K^+$



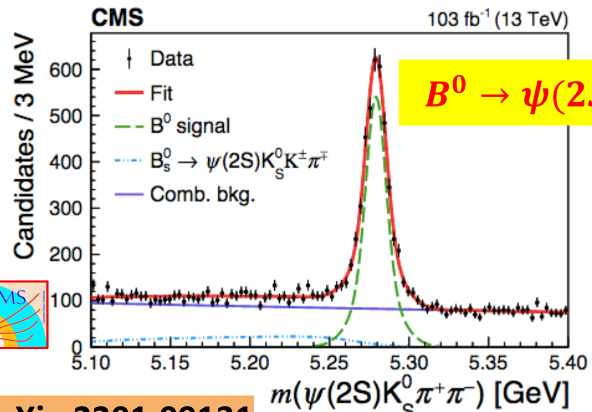
$B_s^{**o} \to B^0 K_s^0$



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



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



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

arXiv:2201.09131

Detector & Reconstruction Strenghts - III

5) In general, beauty hadrons and quarkonia production measurements will be provided in a phase-space complementary to LHCb (in pp collisions) and ALICE (in Heavy Ions collisions).
CMS will be also capable to search for QCD exotics $[X(3872), \ldots]$ in Heavy Ions collisions that will be hardly doable at ALICE.

Prospects for Phase-2 (HL-LHC)

- The data that are going to be collected in Run-3 and Run-4 can certainly help to achieve very interesting new and updated results, **integrating and/or complementing LHCb results**.
  This will be possible by carefully designing the triggers for the future data taking campaigns characterized by harsher experimental conditions.

- In Phase-2, 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.

- Moreover the new additional timing layer (CMS MTD) will allow in Phase-2:
  - not only … some hadronic PID capabilities for the softer tracks,
  - but also … an upgrade of the 3D vertex fit to a 4D one,
    thus allowing precision timing for charged hadrons & converted photons
    and an effective pile up mitigation.

Note: The ATLAS timing-detector (HGTD), since it will be covering only the forward region ($2.4<|\eta|<4.0$), will likely not be useful for improvements in B-Physics & Quarkonia sector.

Additional material

Study of the decay $B^+ \to J/\psi\,\bar{\Lambda}p$
& investigation of the intermediate two-body mass spectra (*)

CMS JHEP 12 (2019) 100

$\sqrt{s} = 8TeV$

$\mathcal{L} = 19.6fb^{-1}$

(Run-I/2012)

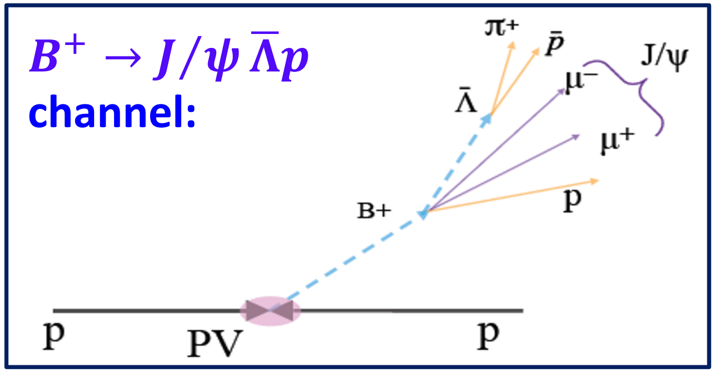
(*) intermediate $J/\psi\bar{\Lambda}$, $J/\psi p$ and $p\bar{\Lambda}$ systems

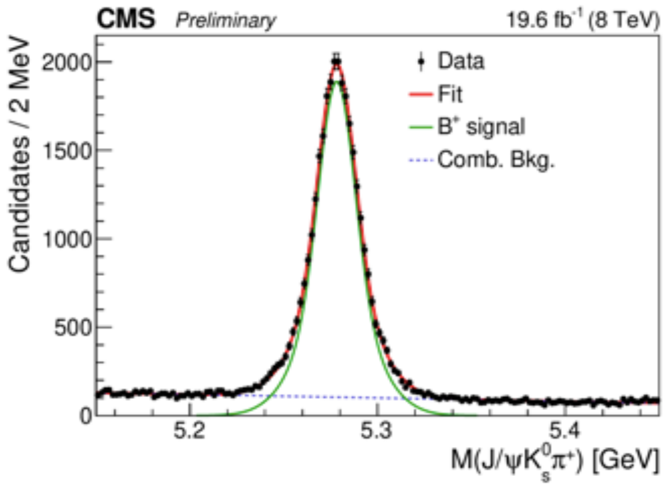
Motivation & technique of the study of the decay $B^+ \to J/\psi\,\bar{\Lambda}p$

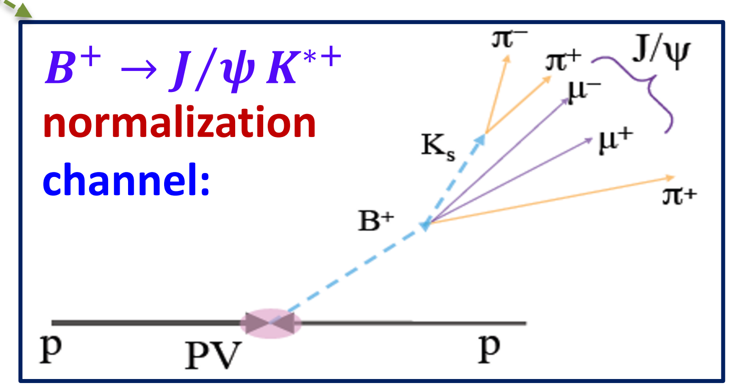
- Belle reported the observation of this decay in 2005 with low statistics [PRD 72 (2005) 051105]: it was the first observed *B* meson decay into baryons and a charmonium state.

- 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)







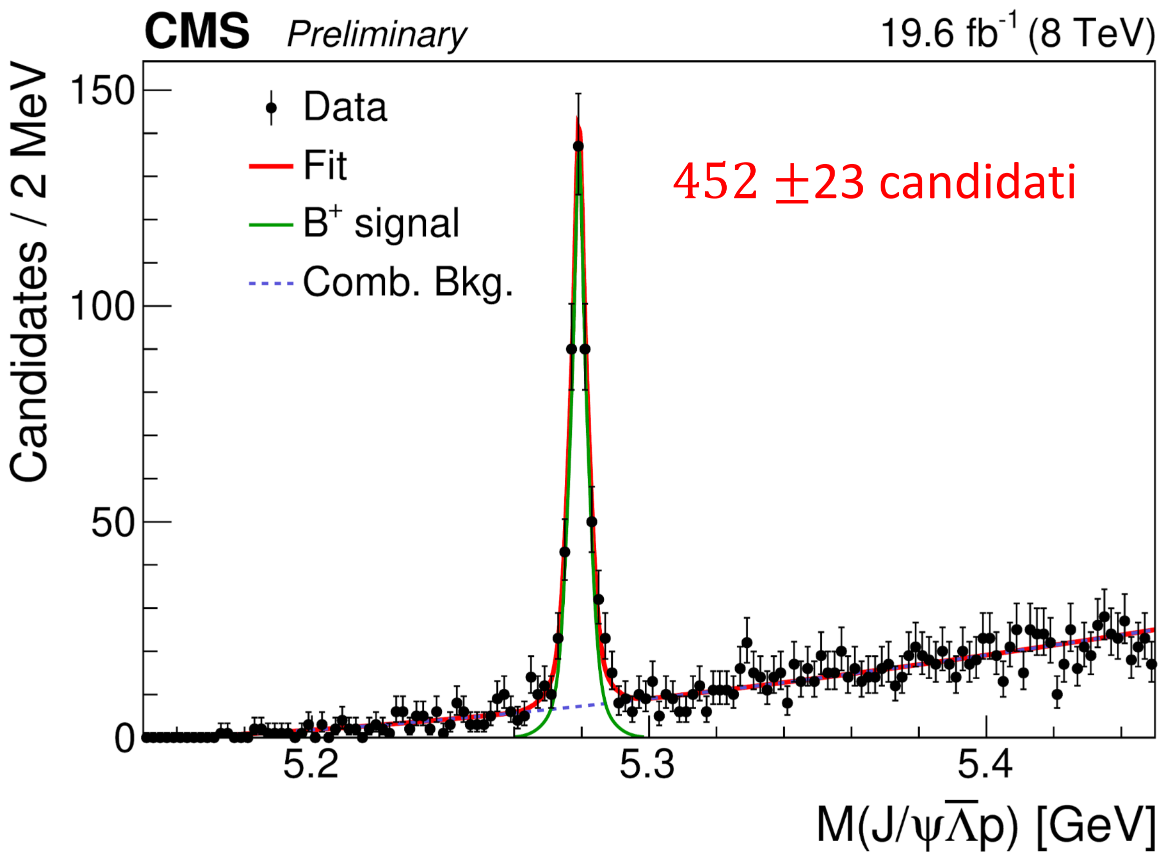
Signal extraction

- **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



- **Other details on selection criteria, efficiency calculation and systematic evaluation can be found at** http://cds.cern.ch/record/2668754

BF ratio measurement

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

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

ratio of the signal yields in data

known Branching Fractions from PDG

Ratio of total efficiencies (from MC)

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

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

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

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

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

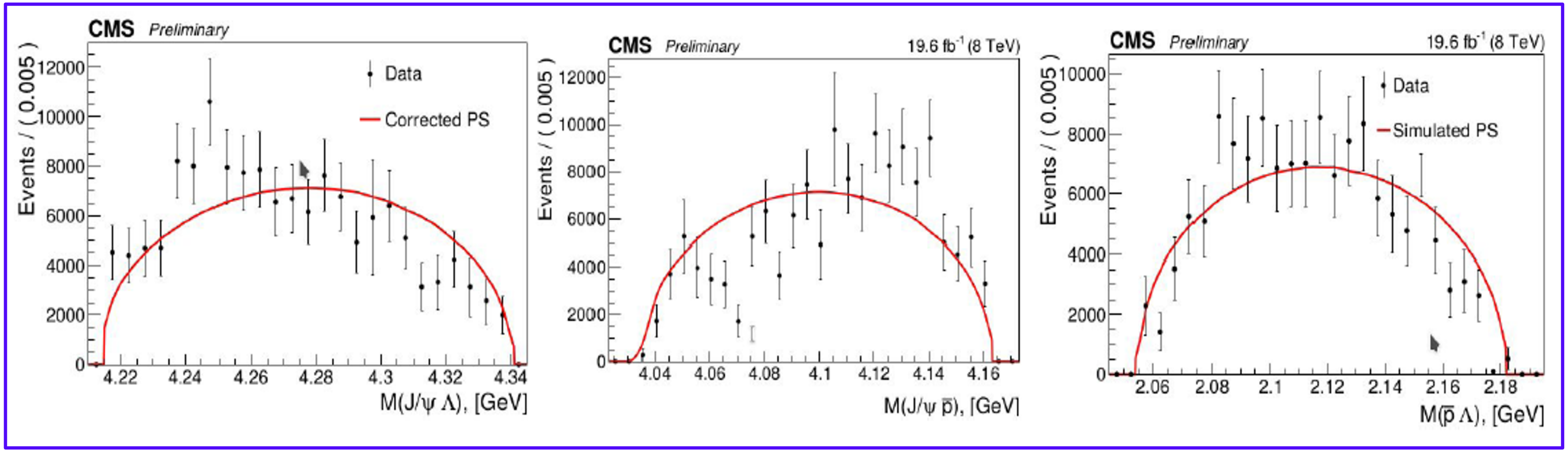
Most precise measurement to date and consistent with

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 $\mathbf{K^{*+}}$ **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.

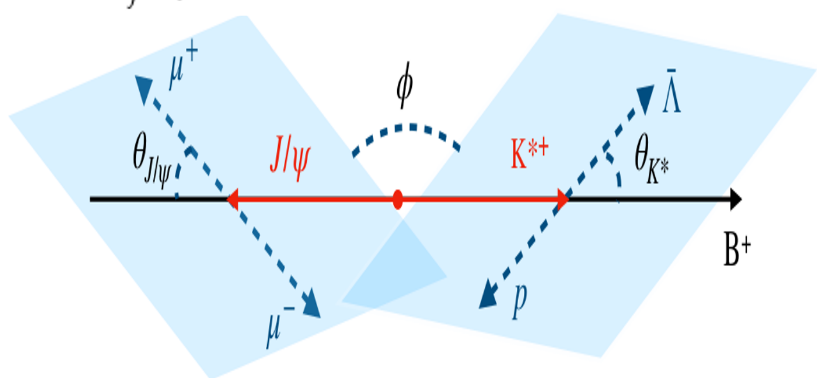
Resonance	Mass [MeV]	Natural width [MeV]	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

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:

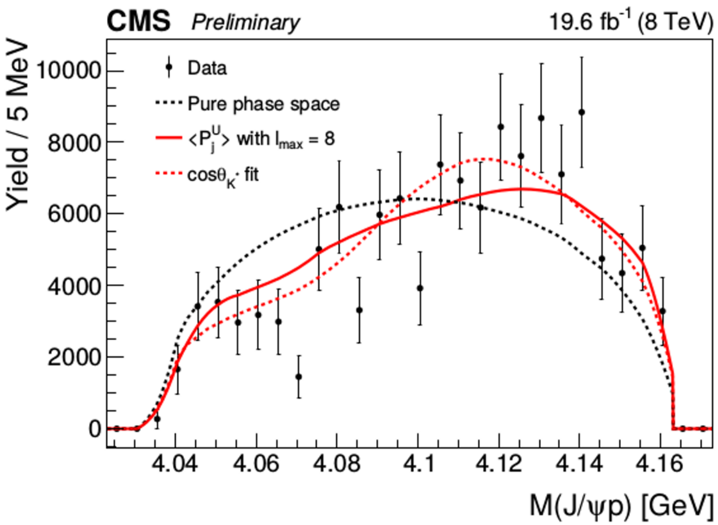
- $\ell_{MAX} =$ 2 x (spin of the highest spin resonance) can describe all resonances & interferences;
- $\cos(\vartheta_{K^*})$ is the helicity angle of the $\mathbf{K^{*+}}$ (see fig.) in the $\bar{\Lambda}p$ system rest frame.

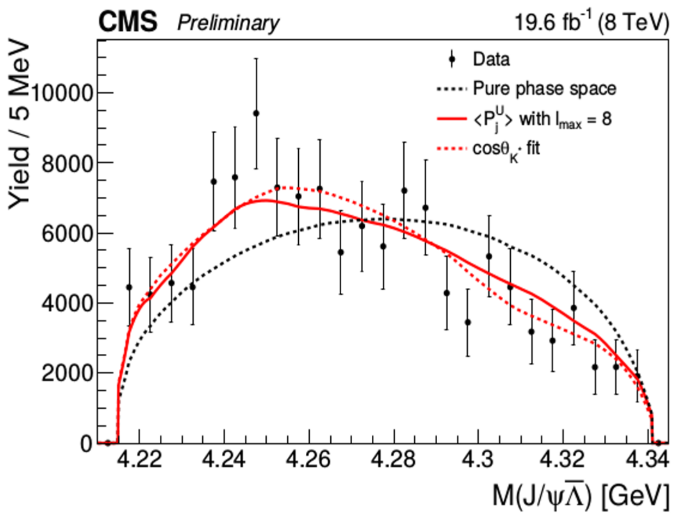


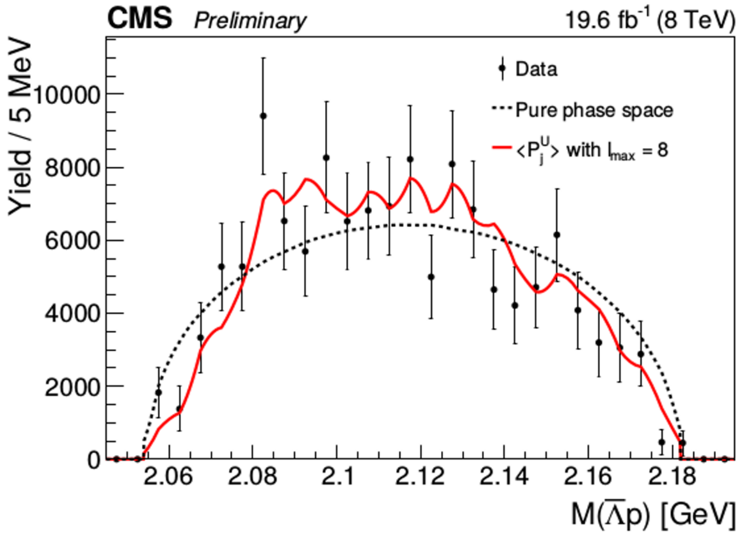
- The simulation-based reweighting according to the observed angular structure in the $\bar{\Lambda}p$ system shows that the description of the distributions of the invariant masses $m(J/\psi\,\bar{\Lambda})$ & $m(J/\psi\,p)$ is much improved after accounting for the angular and invariant mass characterizing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

  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.







Search for the tetraquark state $X(5568)$

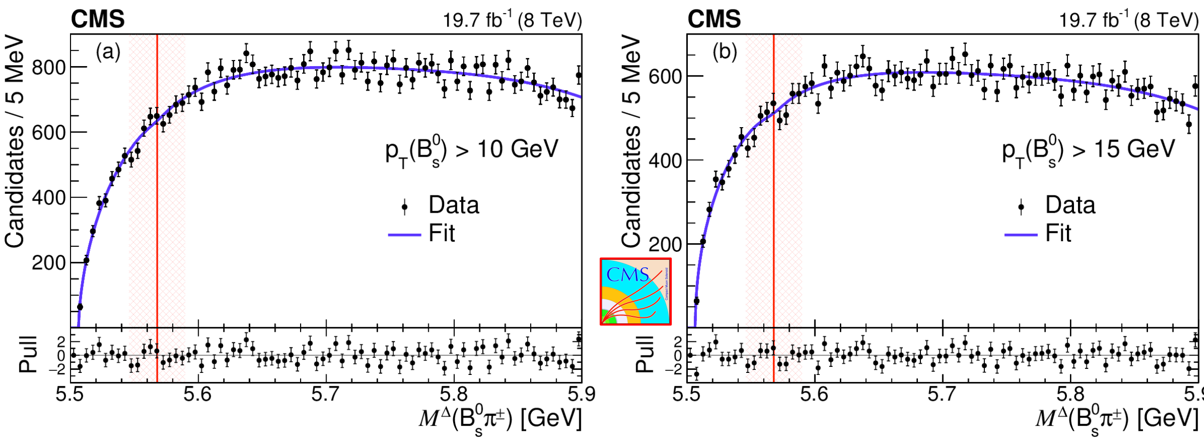
CMS — PRL 120 (2018) 202005 — $\sqrt{s} = 8TeV$ — $\mathcal{L} = 19.7fb^{-1}$ (Run-I/2012)

ATLAS — PRL 120 (2018) 202007 — $\sqrt{s} = 7 + 8TeV$ — $\mathcal{L} = 4.9 + 19.5fb^{-1}$ (full Run-I/2011-12)

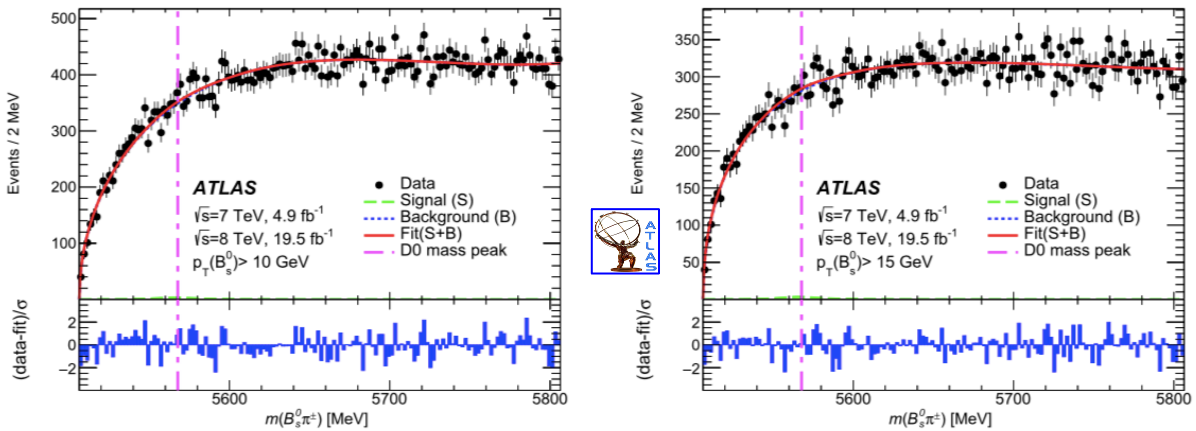
Search for the X(5568) in the $B_s^0\pi^\pm$ final state

- D0 claimed [PRL117 (2016) 022003] the **observation of a narrow structure**, called ***X(5568)*** [Γ ~ 22MeV], **inclusively produced, in the decay sequence …** $X(5568)^\pm \to B_S^0\pi^\pm,\ B_S^0 \to J/\psi\,\phi,\ J/\psi \to \mu^+\mu^-,\ \phi \to K^+K^-$
  - The X(5568) should have a 4-quark content with all quarks of different flavour (*b*, *s*, *u*, *d*)
  - Large relative production: the *fraction of* B_S^0 *from X decay* : $\rho_X^{D0} \cong (8.6 \pm 1.9 \pm 1.4)\%$ … where

$$\rho_X \equiv \frac{\sigma(pp \to X(5568)^\pm + \text{anything})\,\mathcal{B}(X(5568)^\pm \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})} = \frac{N_X}{\epsilon_{rel} N_{B_s^0}}$$



PRL 120 (2018) 202005

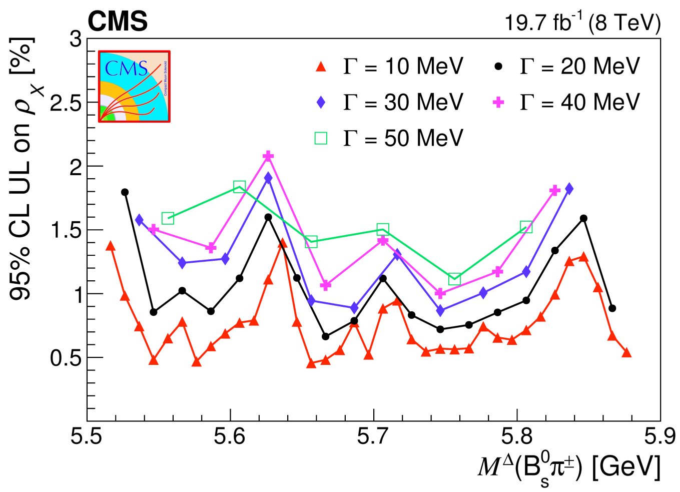


PRL 120 (2018) 202007

Search for the X(5568) in the final state $B_s^0\pi^\pm$

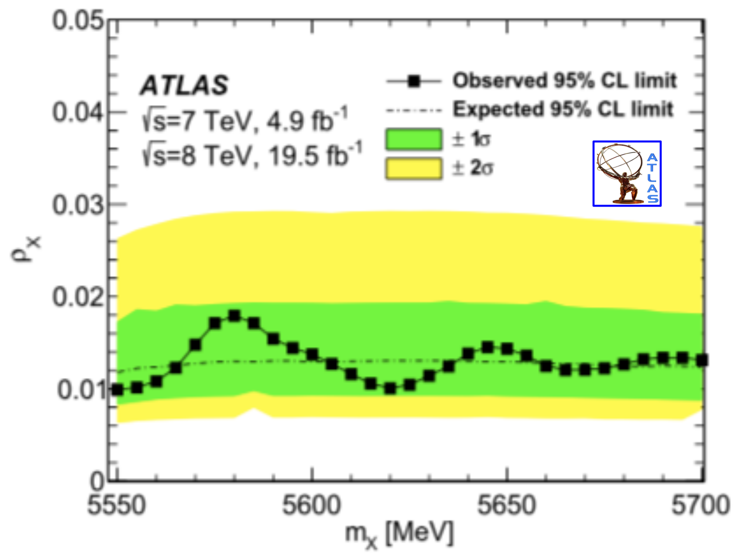
Upper limits on ρ_X, the relative production rate of X(5568) & B_s^0 states, times the unknown BF of the $X(5568)^\pm \to B_s^0\pi^\pm$ decay, computed using the *asymptotic CLs frequentist method* **:**

$$\rho_X < 1.1\ [1.0]\%\ \ @\ \ 95\%CL\ \ \text{for}\ p_T(B_s^0) > 10\ [15]GeV$$



Upper limits are also obtained for different values of natural width (Γ=10 to 50*MeV*) **& masses** [up to 5.9*GeV*-1.5Γ]

ρ_X doesn't exceed the $\pm 1\sigma$ error band from the expected limit



Backup slides

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) :

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

  Since the photon is not detected, we end up seeing

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

  Same final state as

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

  Thus, a two-peak structure in the $B_c \pi^+ \pi^-$ mass distribution, is expected, with the ***$B_c(2S)^*$*** peak at a mass **shifted by**

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

  which is predicted to be around 20 MeV.

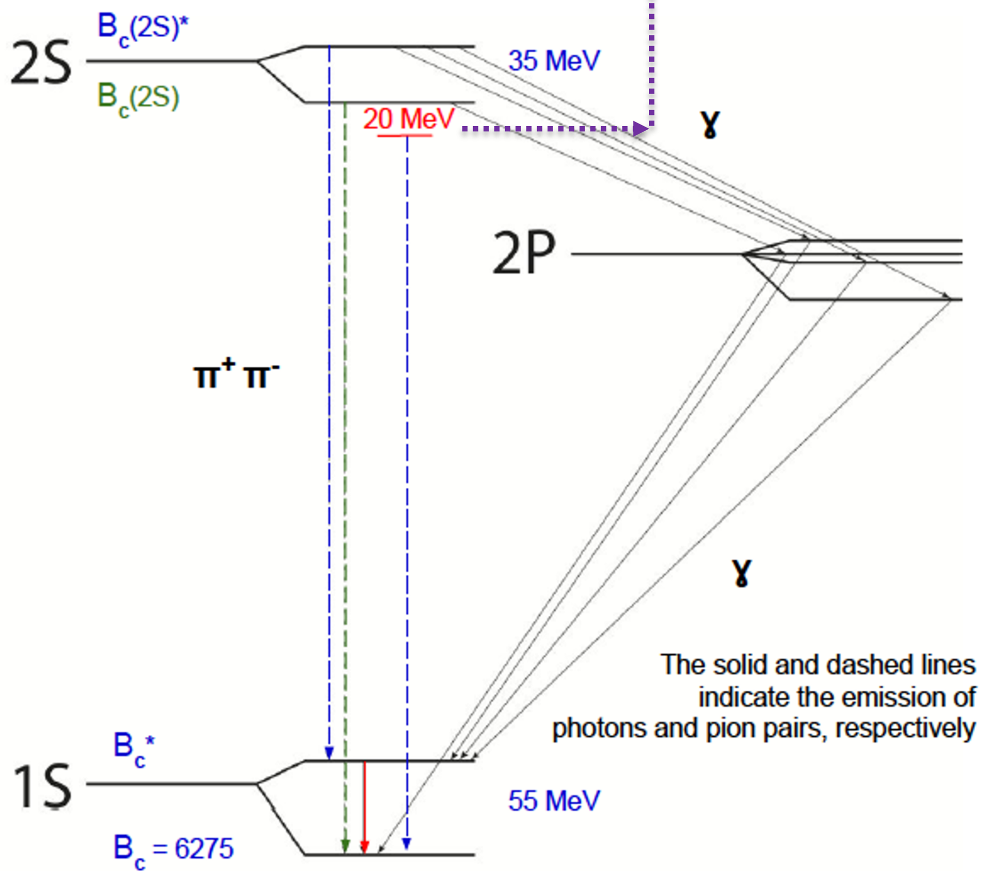
  The two-peak can be appreciated only if ΔM value is larger than experimental resolution!

  Notice that predictions indicate:

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

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

"virtual position" in the spectrum due to photon loss

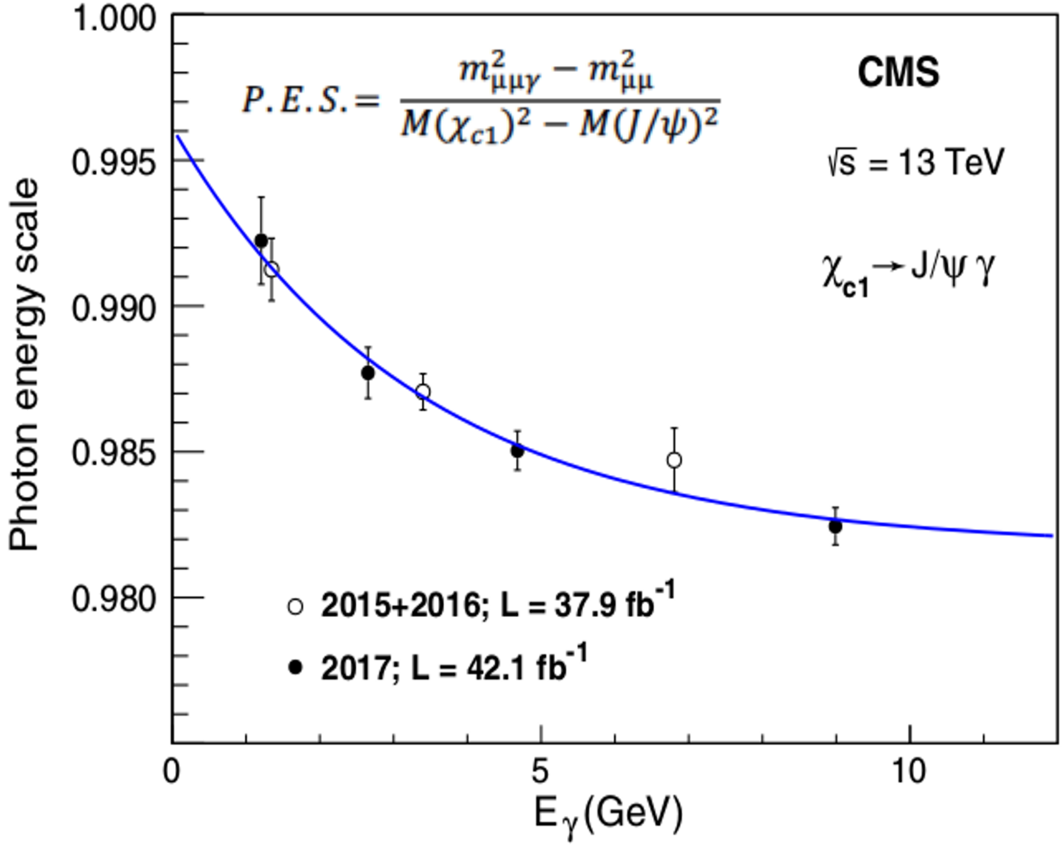


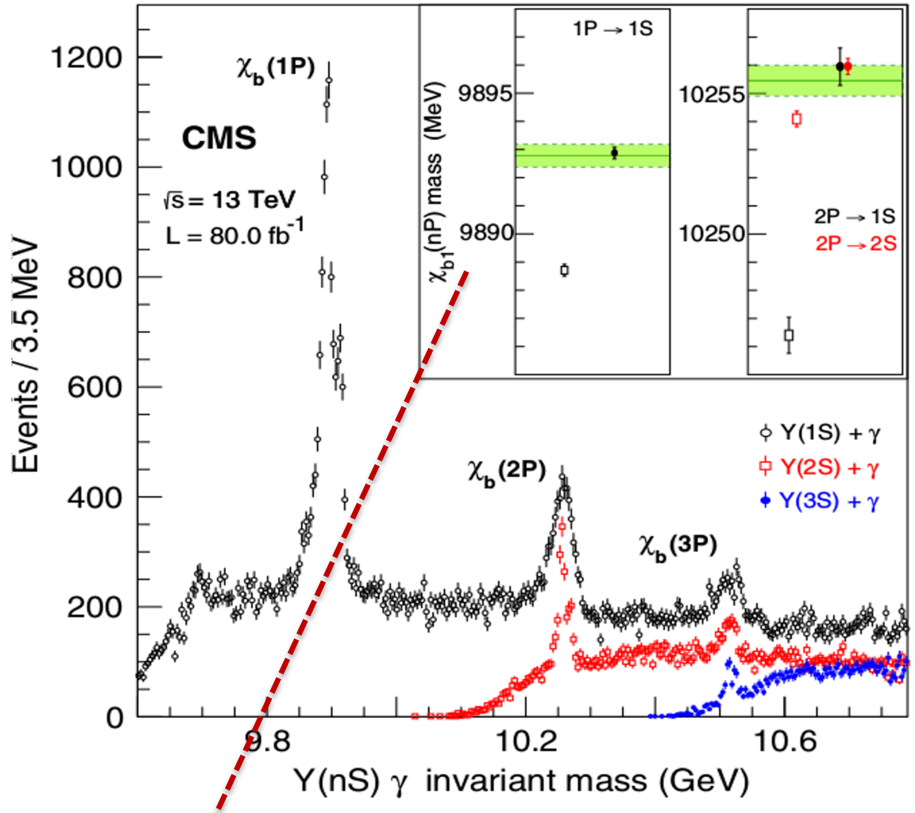
PES correction: details

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 $J/\psi\,\gamma$ events were collected in the same runs, with similar dimuon triggers, and processed in the same way as the Upsilon events





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

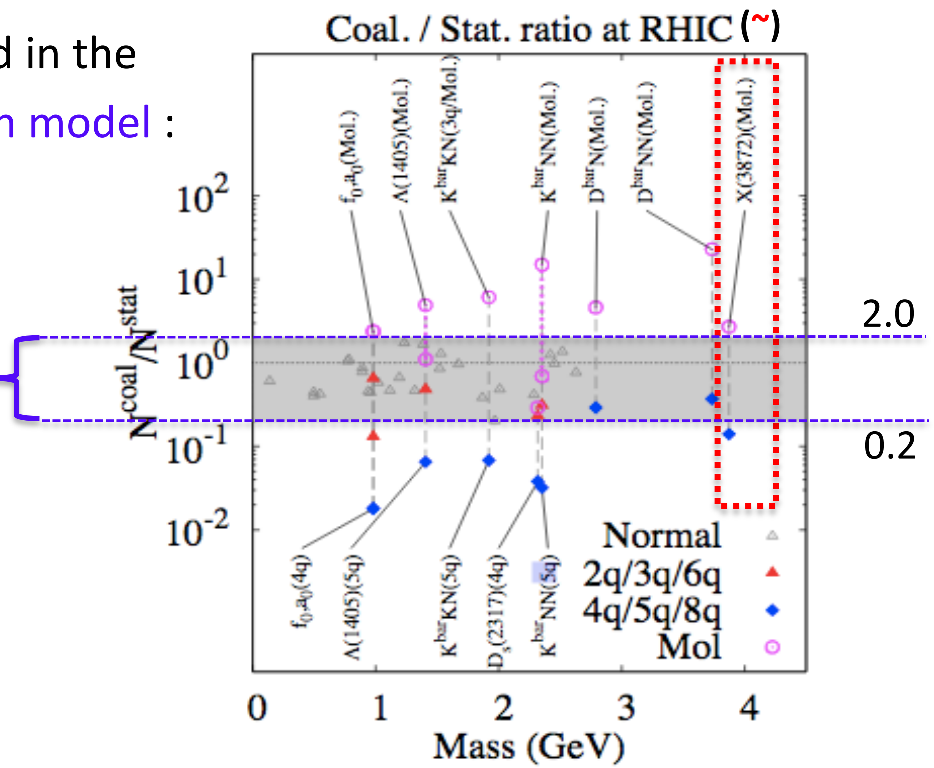
Source of uncertainty	ΔM	$M(\chi_{b1}(3P))$
Fit Model	0.05	0.05
PES correction	0.16	0.17

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

- 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: $R = \frac{N_{corr}^{X}}{N_{corr}^{\psi}}$ $\psi(2S)$
  - prompt yields are corrected for efficiency and acceptance from …
    … a PYTHIA MC embedded in HYDJET PbPb background $N_{corr}^{i} = \frac{N_{raw}^{i} \cdot f_{prompt}^{i}}{(\alpha \cdot \varepsilon_{tot})^{i}}$
  - 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 $\ell_{xy} > 0.1mm$):

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

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

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

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 $X \to J/\psi\rho^0$:**

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

  - **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:**

$$\left\{\begin{array}{l} X_b \xrightarrow{(*)} \Upsilon(1S)\omega(\to \pi^+\pi^-\pi^0), \quad \pi^0 \to 2\gamma \\ X_b \to \chi_b(1P)\pi^+\pi^-, \quad \chi_b(1P) \to \Upsilon(1S)\gamma \\ X_b \to \Upsilon(3S)\gamma \end{array}\right.$$

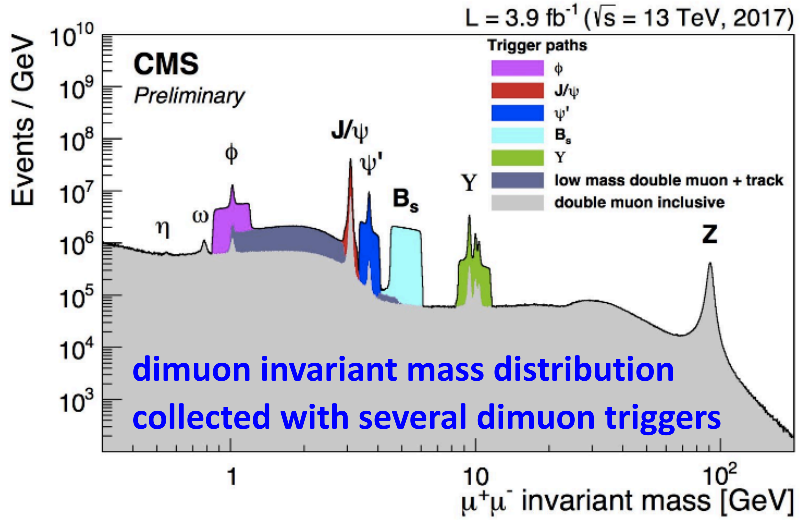
(*) No significant signal found by Belle in *Y(5S)* decays [PRL113, 142001 (2014)]

- **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 !**



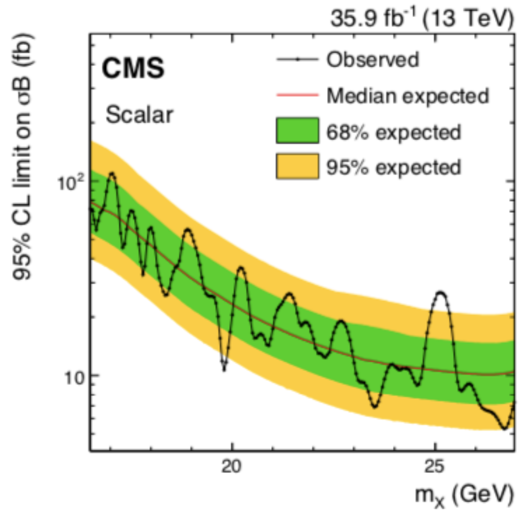
Generic search for narrow resonances in the $\Upsilon(1S)\mu^+\mu^-$ final state

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

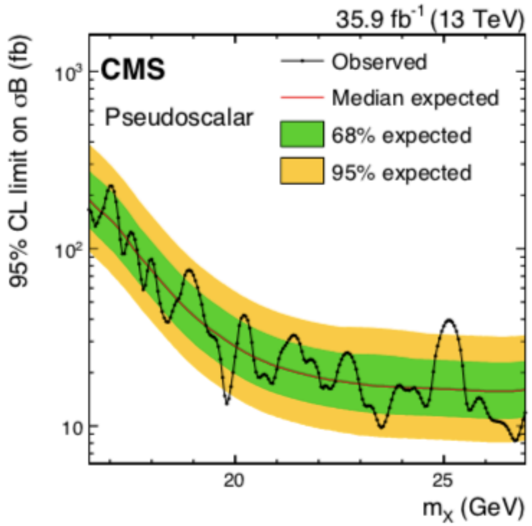
This generic search in the extended mass window is probed using the JHUGEN models.

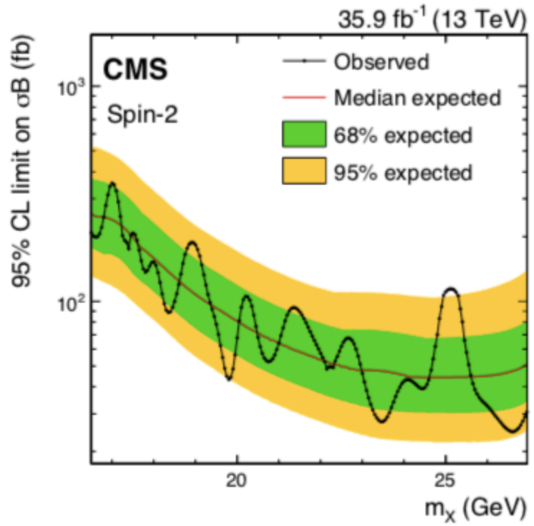
Upper limits on the product of the production Xsection of a resonance and the BF to a final state of 4 muons via an intermediate $\Upsilon(1S)$ are set @95% CL (using the modified frequentist construction CL_s in the asymptotic approx.**).**

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



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





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

Search for pentaquarks

Parameters derived from the fit for the hypothesis with 2 pentaquarks:

Parameter	Value	LHCb value [5]
$N(P_{c1})$	$400^{+130}_{-140}(\text{stat})^{+110}_{-100}(\text{syst})$	–
$N(P_{c2})$	$150^{+170}_{-100}(\text{stat})^{+50}_{-90}(\text{syst})$	–
$N(P_{c1}+P_{c2})$	$540^{+80}_{-70}(\text{stat})^{+70}_{-80}(\text{syst})$	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}(\text{stat})^{+0.2}_{-0.1}(\text{syst})$ rad	–
$m(P_{c1})$	$4282^{+33}_{-26}(\text{stat})^{+28}_{-7}(\text{syst})$ MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV

Under assumption of no interference effects

Relative fase between pentaquark amplitudes

[5] **PRL 115 (2015) 072001** ; **2** resonant structures interpreted as the $c\bar{c}uud$ states $P_c(4380)^+$ & $P_c(4450)^+$

Note : in the full Run-2 LHCb (1D) analysis [**PRL 122 (2019) 222001**] a 3rd pentaquark was observed: $P_c(4312)^+$