Hadron spectroscopy with CMS & ATLAS

(conventional & exotic)

Snowmass EF06-HAD Topical Group meeting

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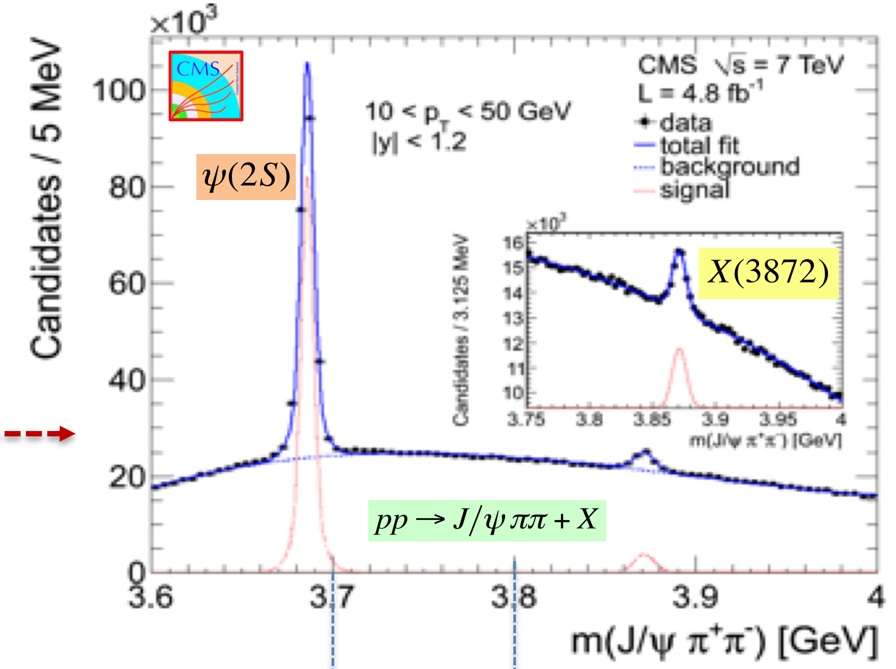
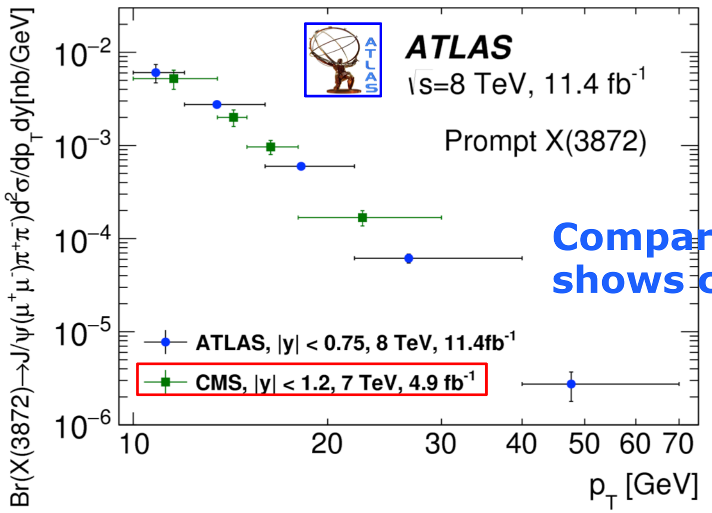
Understanding the X(3872) - I

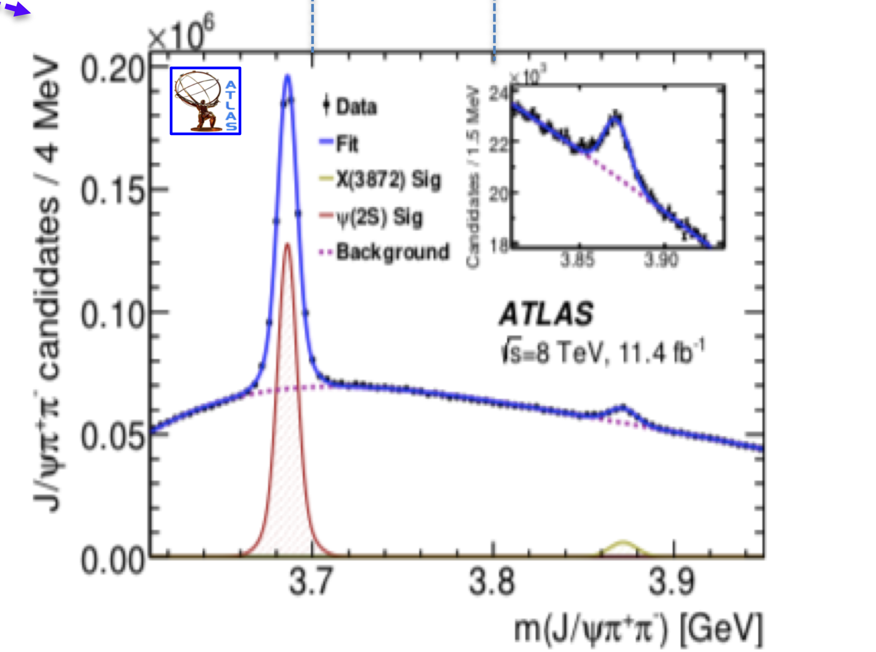
- First exotic state discovered to be discovered in 2003 by [Belle logo]
  - As soon as LHC started, quickly confirmed by [CMS logo] & [LHCb logo], **either inclusively and exclusively** (B decays) and later by [ATLAS logo].
    - [CMS logo] inclusively reconstructed the *X(3872)* in the $J/\psi\pi\pi$ final state (with $7\ TeV$ data) **JHEP 04 (2013) 154**
    - [ATLAS logo] **performed similar studies most recently (with $8\ TeV$ data)** **[JHEP 01 (2017) 117]**



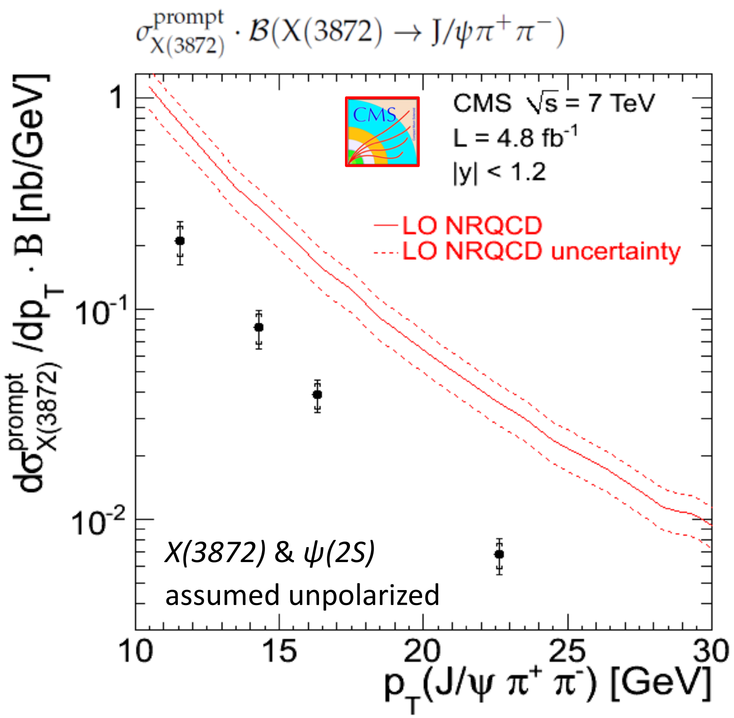
The ***prompt production xsection*** was measured as a function of p_T @ central rapidities (complementary to LHCb):

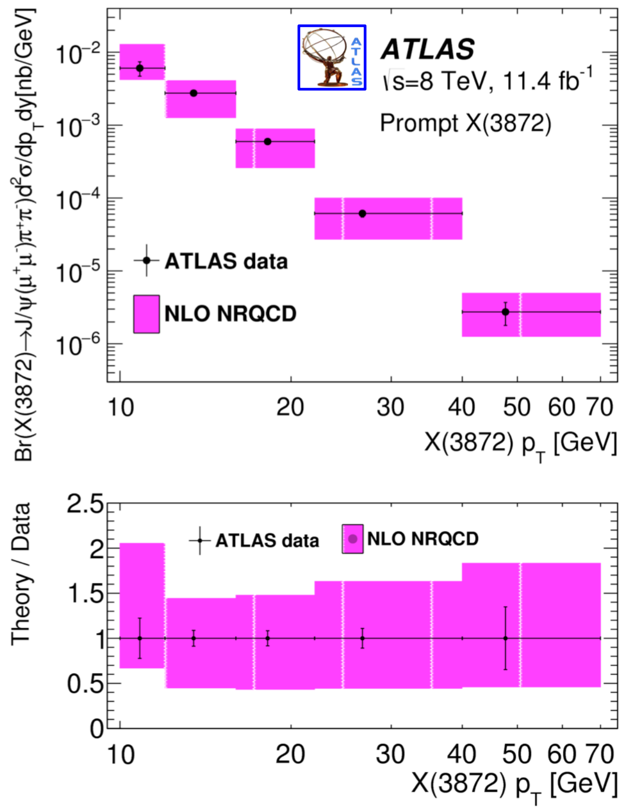


Comparison of results shows consistency



Understanding the X(3872) - II





Results are compared with a theoretical prediction based on NRQCD factorization @ LO approach by Artoisenet & Brateen (**S-wave molecular model**) **[**PhysRevD.81.114018**]** with calculations normalized using Tevatron results, modified by the authors to match CMS phase-space.

The shape is reasonably well described by the theory while the predicted cross section is overestimated by over 3σ ![the same happens with LHCb data @ low p_T]

Measurement, 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].

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

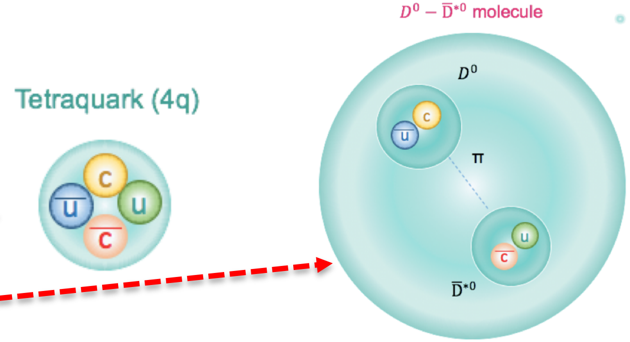
First evidence of the X(3872) in PbPb collisions - I

- **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)

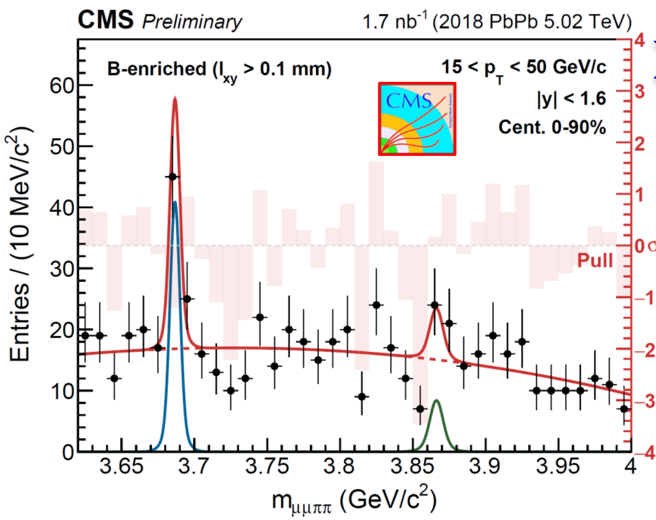
- **In relativistic HI collisions the formation of the QGP** (an extended volume of deconfined quarks & gluons)
  could enhance the production of the X(3872) state through the quark coalescence mechanism

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

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



In B-enriched data sample :

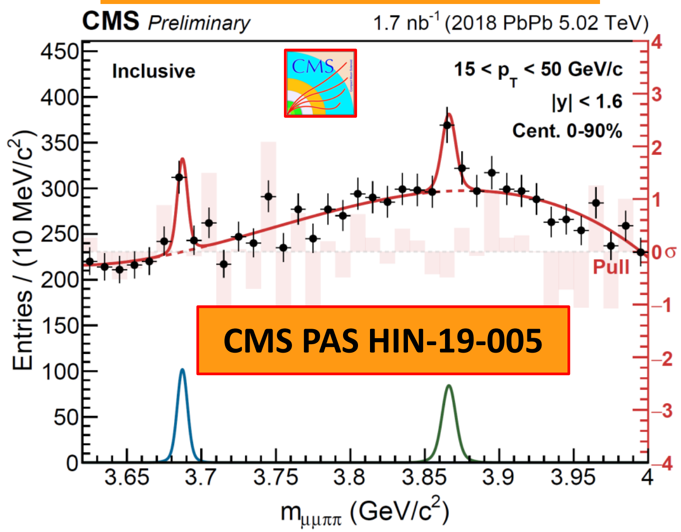


non-prompt $\psi(2S)$ is clearly visible

In inclusive data sample :

inclusive $\psi(2S)$ signal is visible

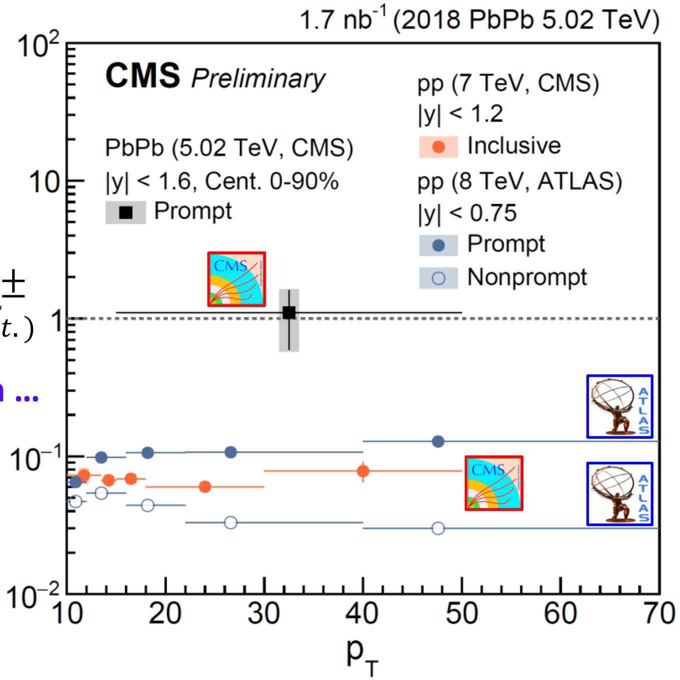
first evidence of inclusive X(3872) production in HI
[statistical significance > 3σ]



First evidence of the X(3872) in PbPb collisions - II

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

$$R = \frac{N^X_{corr}}{N^{\psi}_{corr}}$$



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

... to compare with ...

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

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

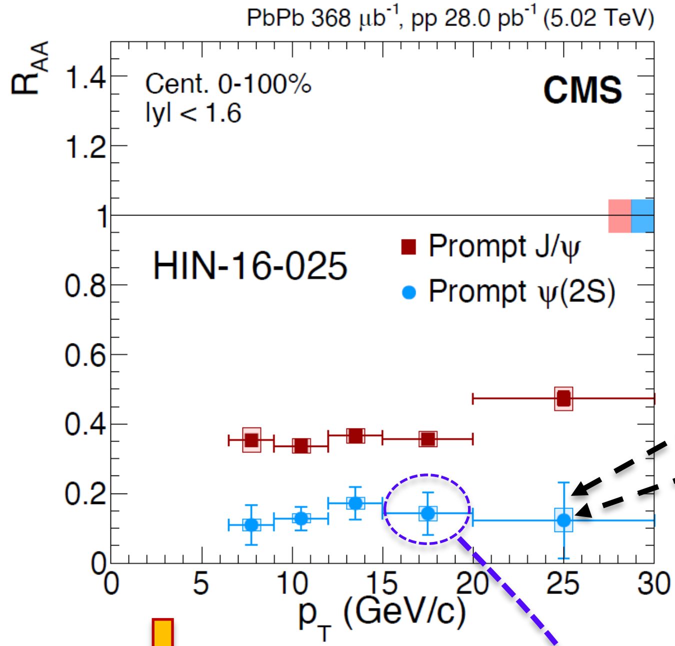
- The ratio measurement is affected by several sources of sizeable systematic uncertainty

- More statistic is needed to get a conclusive result

- 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 $\psi(2S)$:

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

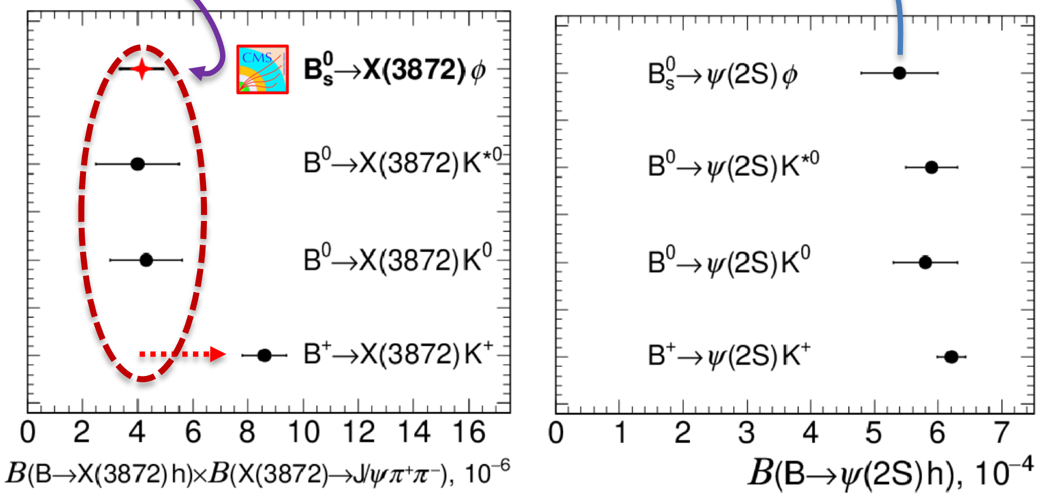
Understanding the X(3872) - III

- **First observation of the X(3872) from a B_s^0 decay:**

$$B_s^0 \to X(3872)\phi \to (J/\psi\,\pi\pi)(KK)$$

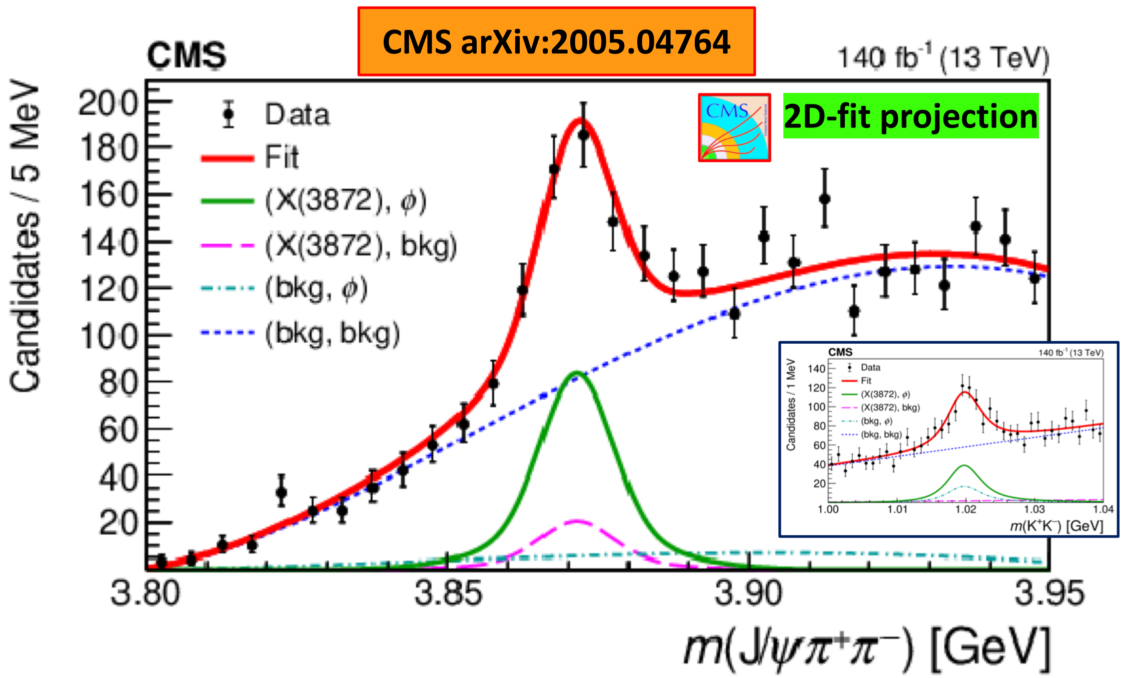
$$R \equiv \frac{\mathcal{B}(B_s^0 \to X(3872)\phi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} \equiv \frac{N(B_s^0 \to X(3872)\phi)}{N(B_s^0 \to \psi(2S)\phi)} \times \frac{\epsilon_{B_s^0 \to \psi(2S)\phi}}{\epsilon_{B_s^0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

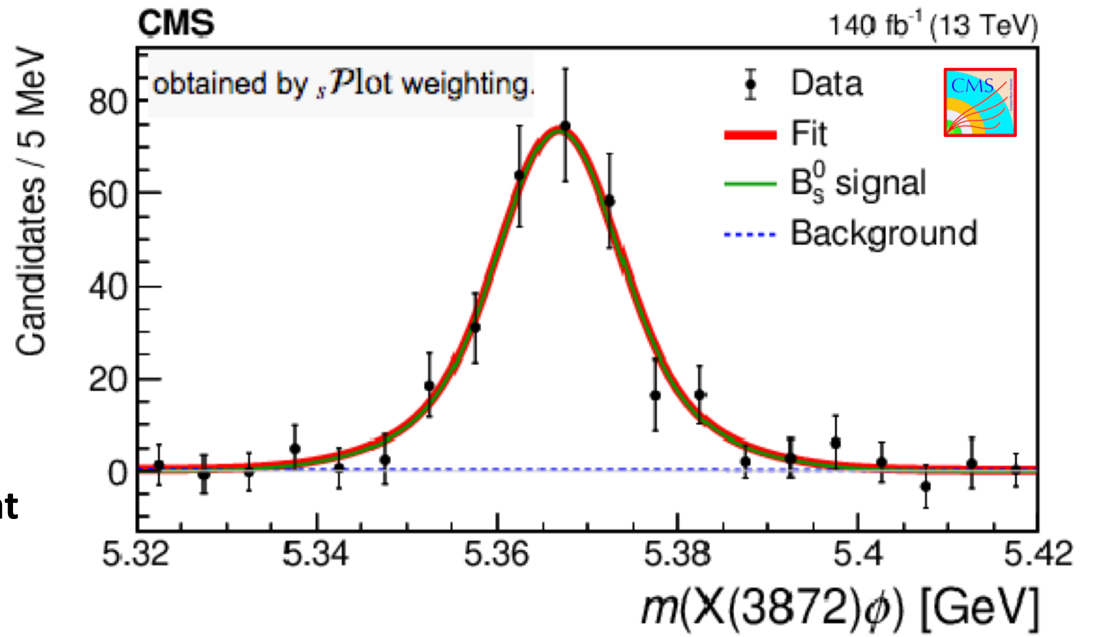
$$= (2.21 \pm 0.29\,(\text{stat}) \pm 0.17\,(\text{syst}))\%.$$



neutral VS charged meson BF hints a non-pure $c\bar{c}$ nature

- in the tetraquark scenario this is explained **by the fact that** the amplitude for the charged decay gets 2 contributions of same order instead of 1 **[Maiani *et al.* arXiv:2005.08764]**





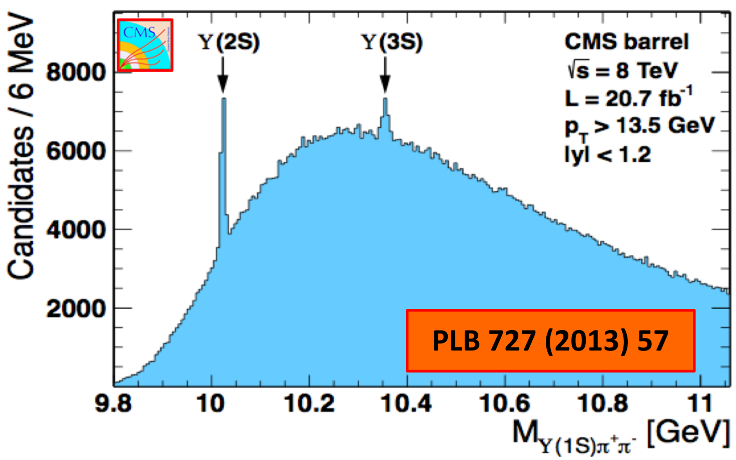
Search for X_b the bottomonium counterpart of the $X(3872)$

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

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

  search for a peak - other than known $\Upsilon(2S), \Upsilon(3S)$ - in the $\Upsilon(1S)\,\pi^+\pi^-$ spectrum within $10 \div 11 GeV$ range (*mass scan*)

  [expecting **narrow width** & possibly **sizable BF** similarly to X(3872)]



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- For each mass point (scan by 10 *MeV*-sized steps), the ratio

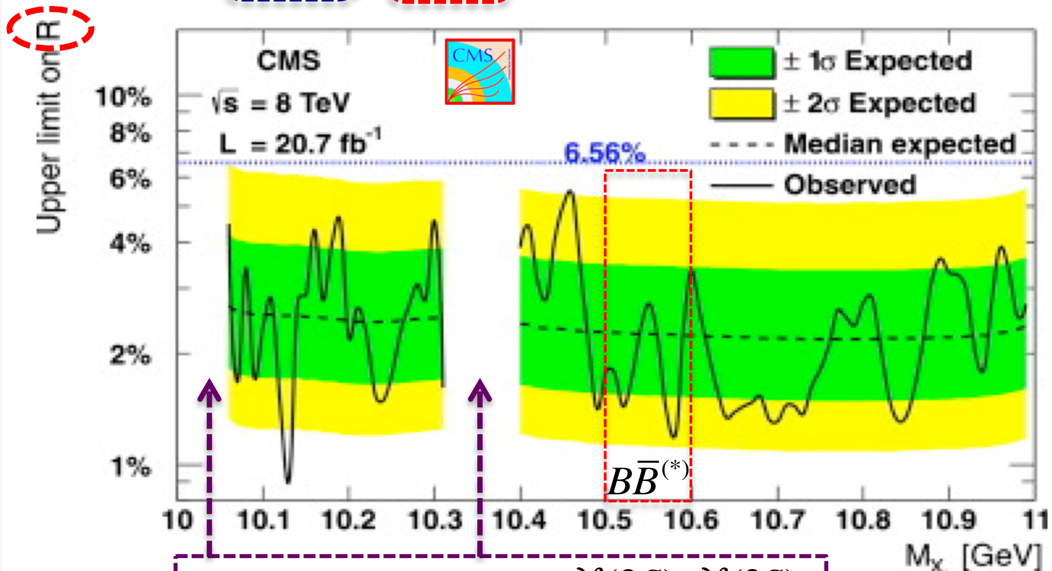
$$R \equiv \frac{\sigma(pp \to X_b)}{\sigma(pp \to \Upsilon(2S))} \cdot \frac{BF(X_b \to \Upsilon(1S)\pi^+\pi^-)}{BF(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)}$$

is evaluated as …

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

observed YIELDS

efficiency x acceptance



Exclude masses close to $\Upsilon(2S)$, $\Upsilon(3S)$

⇨ **NO significant excess observed**

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

observed UL range: 0.9% to 5.4%

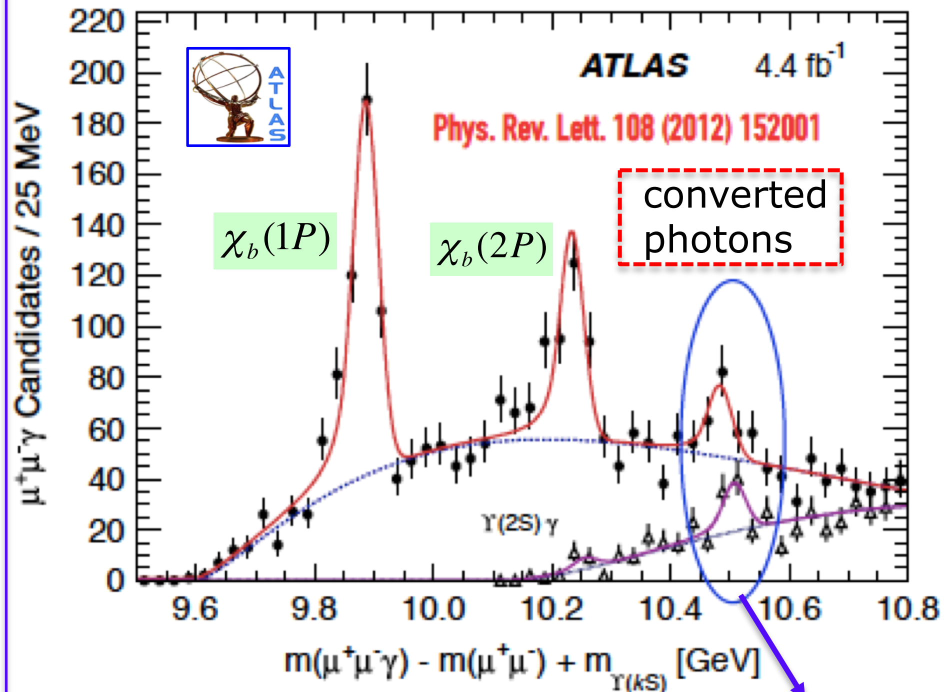
- **Similar results from : slightly more stringent limits**

PLB 740 (2015) 199

Observation of the $\chi_b(3P)$ system

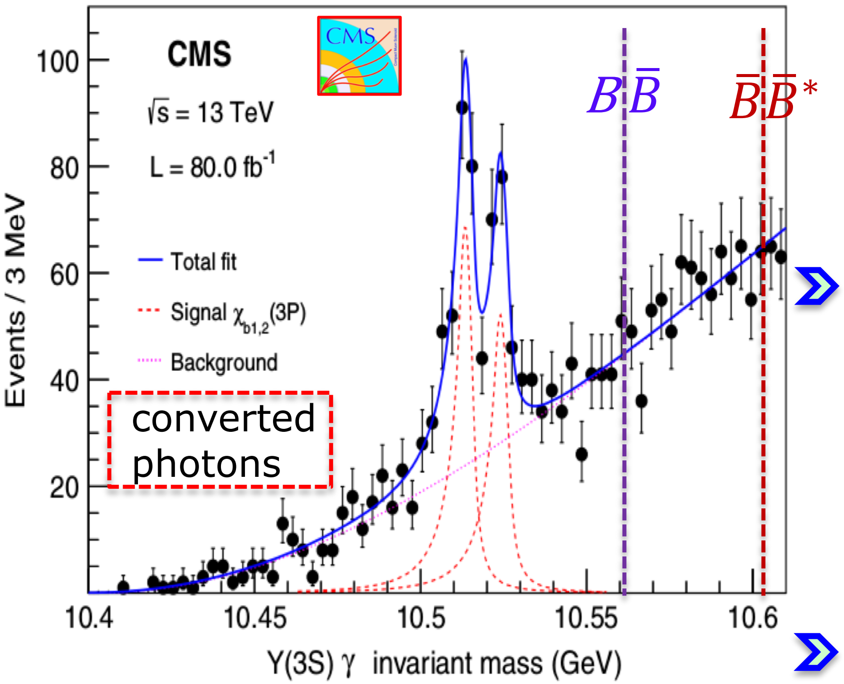
- There have been earlier measurements related to $\chi_{bJ}(3P)$ mass by ATLAS, LHCb & D0, however without being able to distinguish between the candidates of the $\chi_{bJ}(3P)$ multiplet.

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



Each peak represents an unresolved triplet

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



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

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

➡ enough precise to provide important constraint to theory models

strongly disfavours the breaking of the conventional pattern of splittings in the doublet & supports the standard hierarchy (*J=2* heavier than *J=1*)

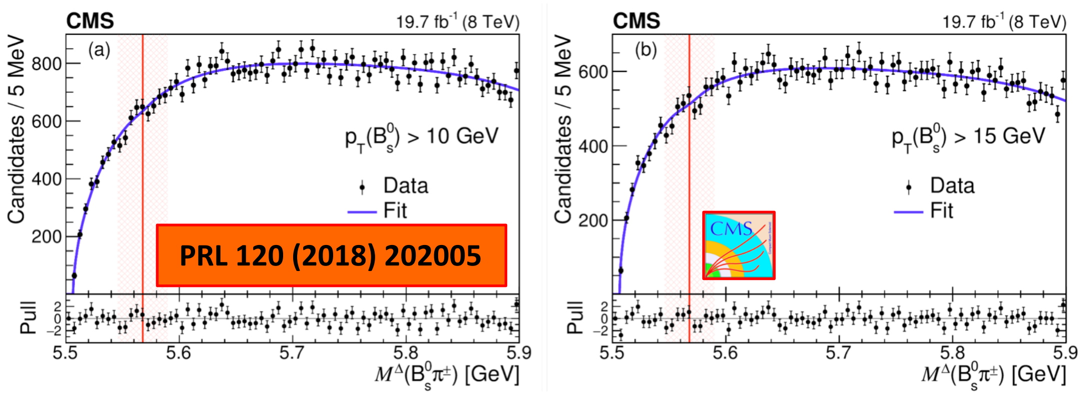
- At the current statistics no hint of the hypothetical X_b that might exist close to the $B\bar{B}^{(*)}$ threshold (decay $X_b \to \Upsilon(3S)\gamma$) [Karliner, PRD91 (2015) 014014]

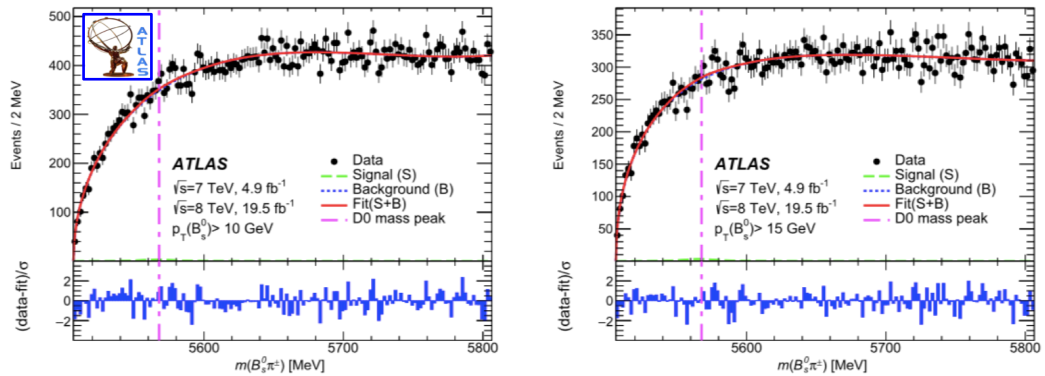
Search for the X(5568)

D0 claimed [PRL117 (2016) 022003] the **observation of a narrow structure**, called ***X(5568)*** [$\Gamma \sim 22 MeV$], **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* : $\rho_X^{D0} \cong (8.6 \pm 1.9 \pm 1.4)\%$

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

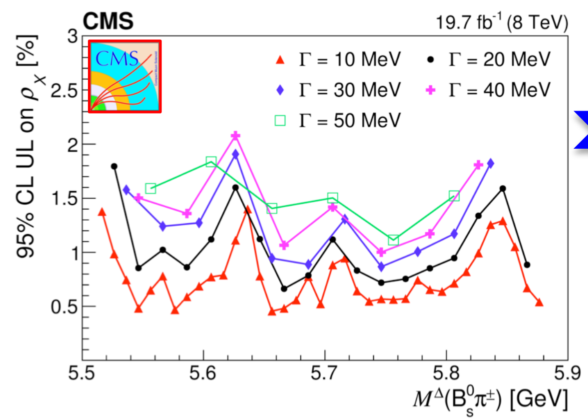




PRL 120 (2018) 202007

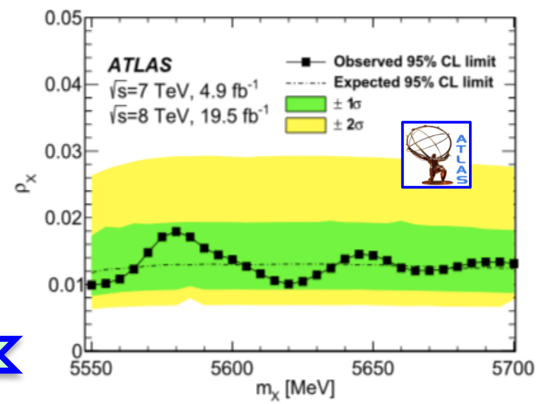
Upper limits on ρ_X, the relative production rate of $X(5568)$ & B_s^0 states, times the unknown BF of the $X(5568)^{\pm} \to B_s^0 \pi^{\pm}$ decay, computed using the *asymptotic CLs frequentist method* **:**

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



- **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

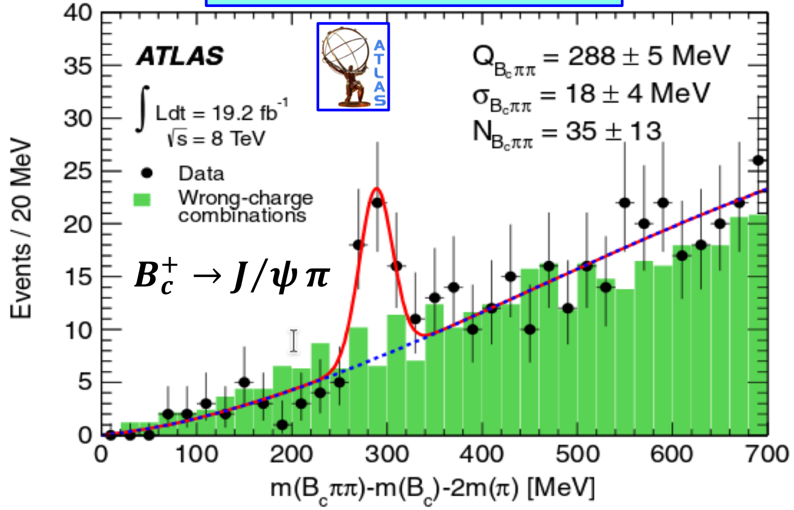


First observation of the radially excited $B_c^+(2S)$ & $B_c^{*+}(2S)$ states

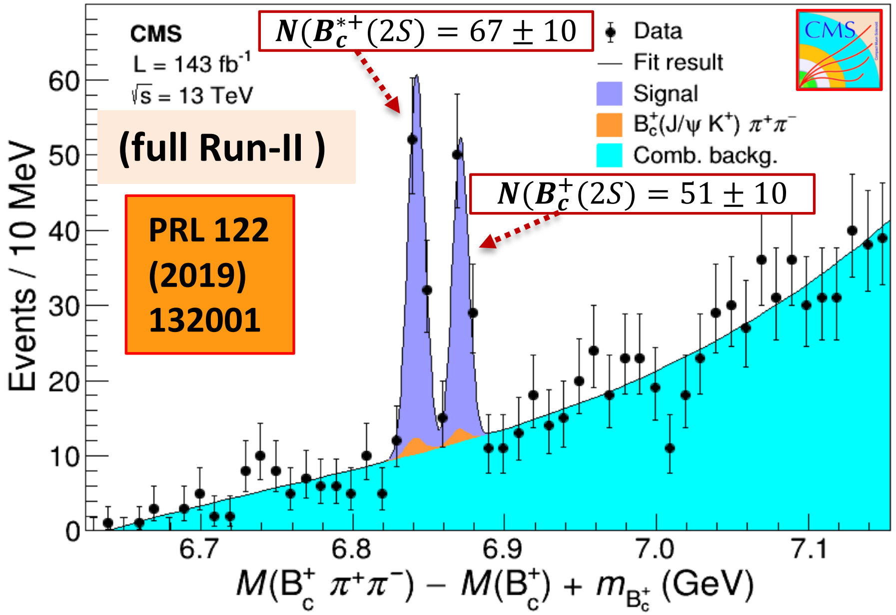
- **In the family of mesons composed of a charm quark & a bottom anti-quark,** given the different heavy quark flavors, **the only allowed transitions are through photons or pion pairs** (these mesons cannot annihilate into gluons). The first observation of a radially excited state was by ATLAS in Run-I.

Its mass consistent with predictions for $B_c^+(2S)$ with a local significance of 5.4σ. Could be the superposition of 2 closely spaced hyperfine partners (very soft photon is lost).

PRL 113 (2014) 212004



- In CMS: **Mass resolution agrees with MC expectations (~6MeV) and is much lower than ΔM thus allowing a two-peak structure to be observed**



- Local significance exceeding 6.5σ for observing two peaks rather than one. For both single peaks significance is above 5σ
- Measured two peaks' mass difference: $\Delta M = 29.1 \pm 1.5\,(stat) \pm 0.7(syst) MeV$
- The 2 peaks can be resolved since Δm is enough larger than mass resolution, in spite that the soft photon from $B_c(2S)^*$ decay is lost (too soft)
- Given that predictions indicate:

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

  … the ***$B_c(2S)^*$* peak is assumed to be the lower peak**!

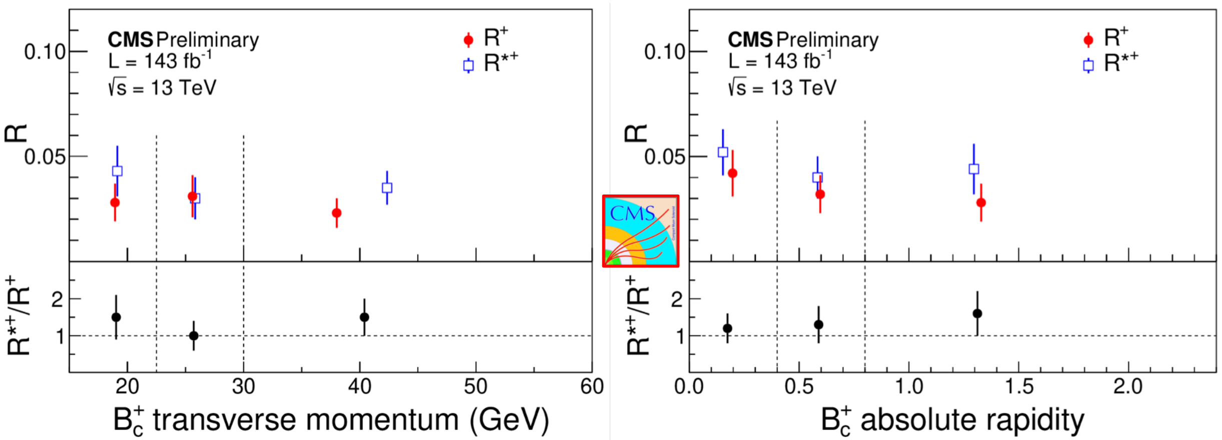
- **Later confirmed by** LHCb **[PRL 122 (2019) 232001]**

Relative cross sections of the excited $B_c^+(2S)$ & $B_c^{*+}(2S)$ states w.r.t. B_c^+

- There are **predictions (*) for relative yields of 2S-excitations decaying with a dipion emission** : **different models can bring to relevantly different predictions, thus it is important to experimentally determine the ratio of production Xsections (times BFs) of these two excited states**

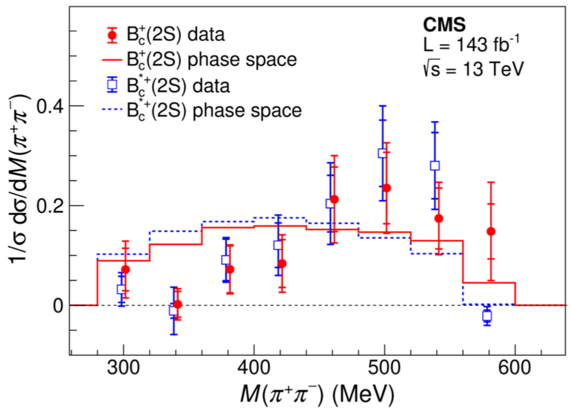
(*) E. Eichten, C. Quigg, PRD 99 (2019) 054025; A.V. Berezhnoy et al., Mod. Phys. Lett. A34 (2019) 1950331

- CMS **has recently measured the following 3 ratios of relative cross sections :** **CMS-PAS-BPH-19-001**



- $R^+ \equiv \dfrac{\sigma(B_c^+(2S))}{\sigma(B_c^+)} = 3.57 \pm 0.69\,(\text{stat}) \pm 0.32\,(\text{syst})\,\%$
- $R^{*+} \equiv \dfrac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^+)} = 4.91 \pm 0.69\,(\text{stat}) \pm 0.57\,(\text{syst})\,\%$
- $R^{*+}\,/\,R^+ \equiv \dfrac{\sigma(B_c^{*+}(2S))}{\sigma(B_c^+(2S))} = 1.39 \pm 0.35\,(\text{stat}) \pm 0.09\,(\text{syst})$

- The shape of the di-pion invariant mass is also examined :

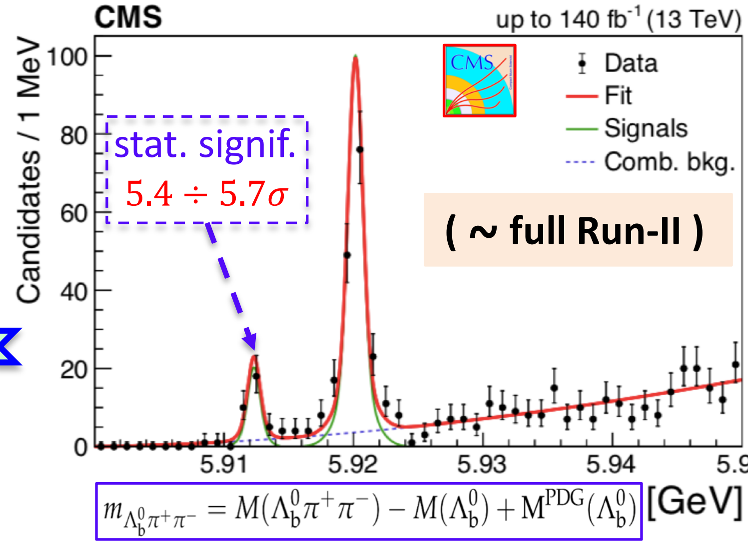


Study of excited Λ_b^0 states decaying to $\Lambda_b^0\pi^+\pi^-$

LOW-MASS REGION (near threshold)

$\Lambda_b^0 \to J/\psi\,\Lambda$
$\Lambda_b^0 \to \psi(2S)\Lambda$

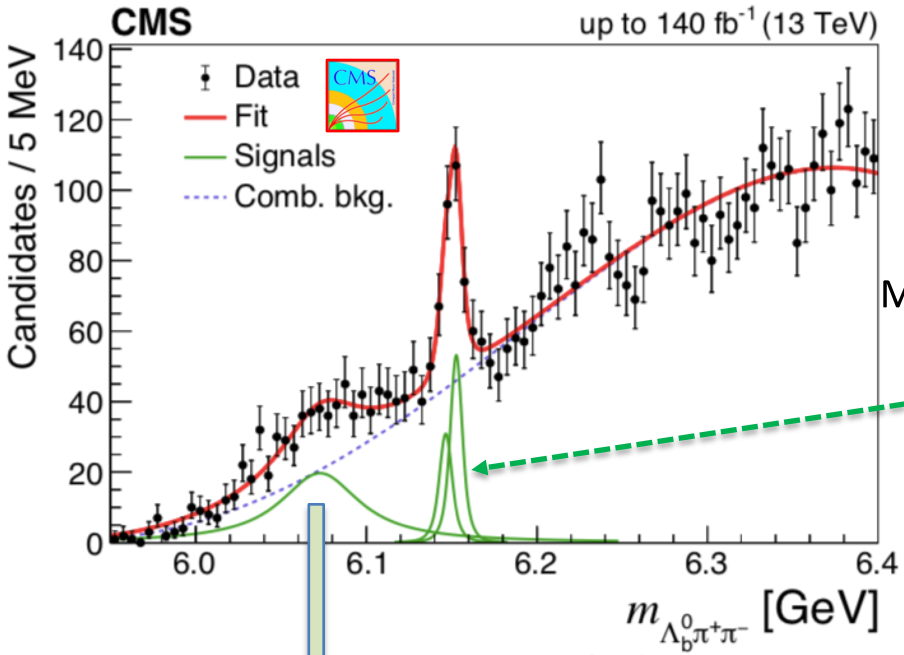
Confirmation of $\Lambda_b(5912)^0$
First confirmation of $\Lambda_b(5920)^0$



Mass measurements: consistent with LHCb/PDG & with similar precision

HIGH-MASS REGION

PLB 803 (2020) 135345



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

(very recently discovered by LHCb)

Mass measurements: in agreement with LHCb values but not as precise as

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

The amount of data is too low to try a proper interpretation of this broad structure (not present in same-sign distribution), bit later confirmed by LHCb & interpreted as further excited Λ_b^0 state

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

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

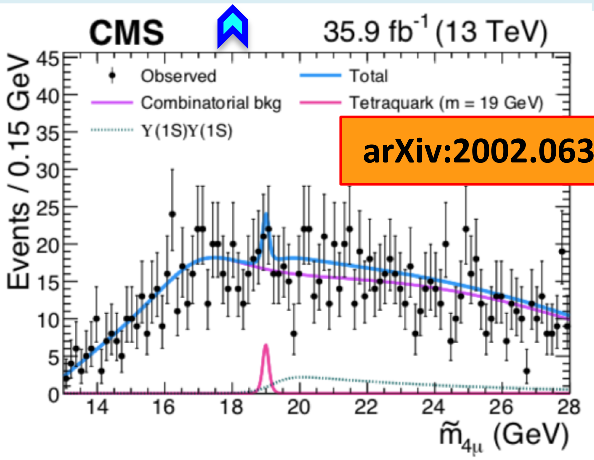
This process serves as a standard reference in a search for narrow resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ since the final state is the same and the event selection is similar.

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

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

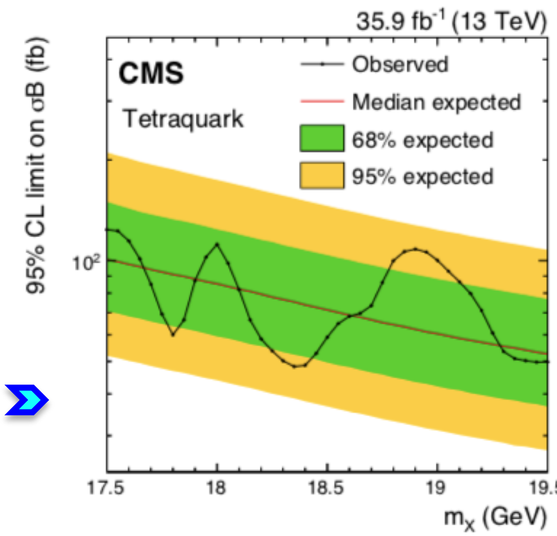
- CMS carried out a generic search for narrow resonances decaying to $\Upsilon(1S)\mu^+\mu^-$, performed in an extended mass window $16.5 \div 27\text{GeV}$, and probing a kinematical region not accessible at LHCb

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



arXiv:2002.06393

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.**).**



Searches to be performed again with full Run-II data

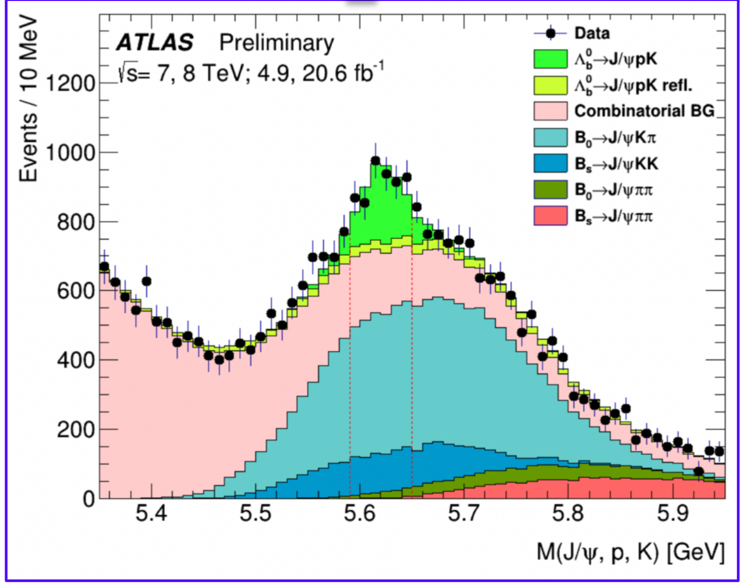
Study of $J/\psi\, p$ resonances in the $\Lambda_b^0 \to J/\psi\, pK^-$ decays

- Motivated by the LHCb observation of pentaquark states $P_c^+(uud c\bar{c})$ in the $J/\psi\, p$ final state.
  - Based on full Run-I data ATLAS reconstructs the decay $\Lambda_b^0 \to J/\psi\, pK^-$ **dominated by backgrounds.**

The pentaquark masses and widths obtained using the model with two pentaquarks are consistent with the corresponding LHCb results [5]. The fit of the model with two pentaquarks to data yields $\chi^2/N_{\rm dof} = 37.1/39$ corresponding to p-value= 55.7%. The fit with the two pentaquark signals with their masses and widths fixed to the LHCb values [5] yields $\chi^2/N_{\rm dof} = 49.0/43$ with p-value= 24.5%.

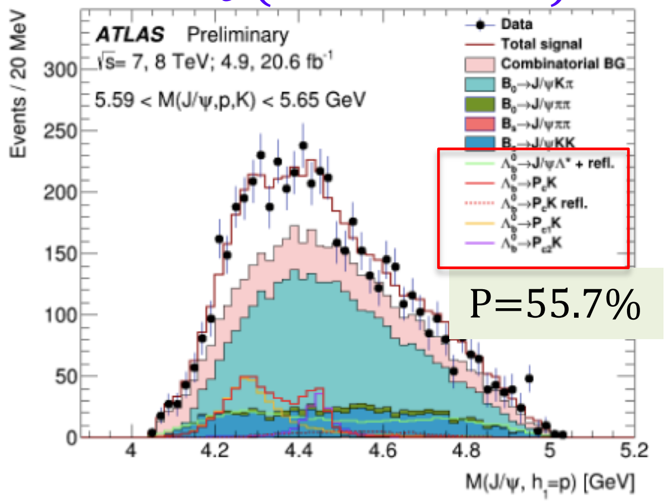
The data are also compatible with the recent LHCb observations of three narrow pentaquarks [9], although do not allow to make independent measurement of their parameters.

Although the data prefer the model with two or more pentaquark states, the model without pentaquarks is not excluded.

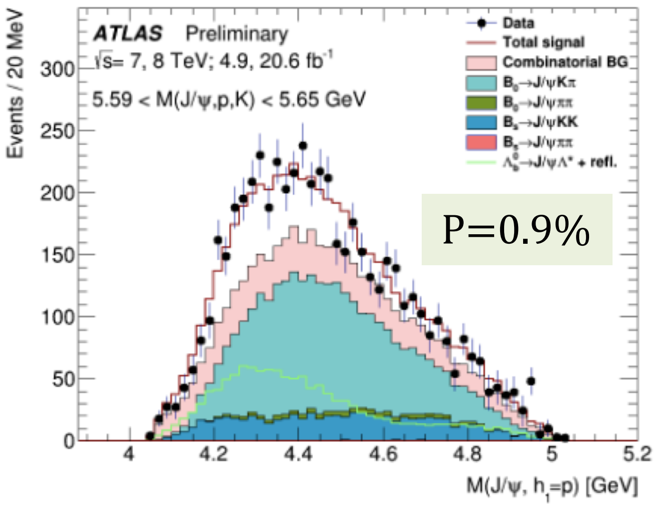


ATLAS-CONF-2019-048

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



$NO\ P_c^+$



Summary & outlook

- CMS & ATLAS are clearly engaged in performing searches & measurements in the field of conventional & exotic hadron spectroscopy

- This commitment is longstanding (since Run-I) and clearly benefits of the higher statistics collected in Run-II.
  In some cases the full Run-II data has to be (partially or fully) exploited yet.
  Many analyses has been carried out and many others are in the list.

  For instance: continue to contribute to understanding the nature of the X(3872), also exploting HI collisions, search for its bottomonium partners and its charged partners; the spectroscopy of beauty mesons with charm & strange quark; single- and (in future) doubly- heavy baryons; full heavy 4-quark systems ($b\bar{b}b\bar{b}$, $c\bar{c}b\bar{b}$, $c\bar{c}c\bar{c}$), …

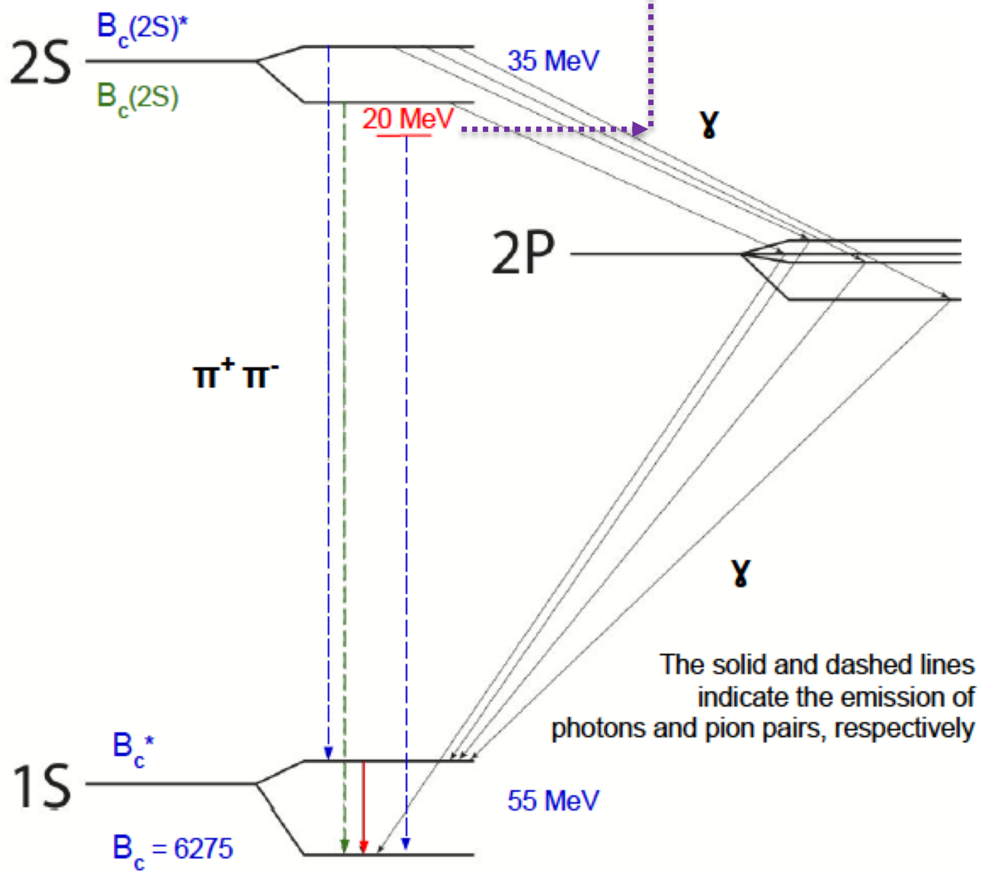
- Many kind of analyses are prohibited by overwhelming backgrounds, trigger constraints, reconstruction/identification limitations, but many others can be done successfully exploiting some excellent features of the detectors and reconstruction algorithms.

- Proper trigger strategies will be established to extend the potentialities of the two experiments to the Run-III data.

Backup & additional material

Reconstruction of the hyperfine partners

“virtual position” in the spectrum due to photon loss



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

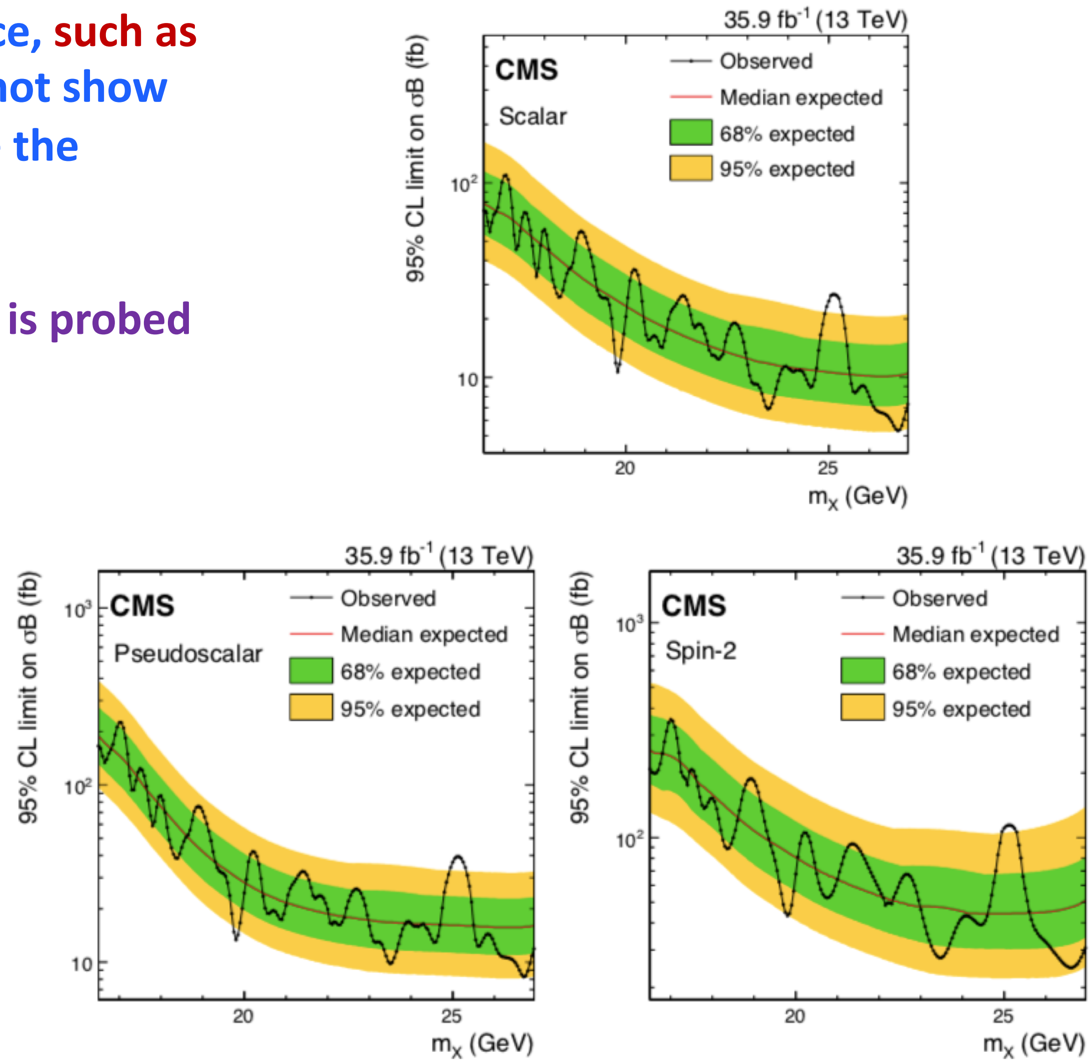
- **The results of a search for a light narrow resonance, such as a bound state beyond-the-standard model, does not show any significant narrow excess of candidates above the background expectation.**

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



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