Exotic hadron spectroscopy results & perspectives in ATLAS & CMS

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(on behalf of CMS & ATLAS Collaborations)

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29th May 2018 / Exotic Hadrons & Flavor Physics / Simons Center workshop – Stony Brook (NY)

XYZ exotic hadrons

- **Since the *X(3872)* observation (2003), many (~30) unexpectedly narrow states were observed** [@ B-factories and/or at Hadron-colliders] **to decay into charmonium in spite of being above the open-charm thresholds ($D^{(*)}\bar{D}^{(*)}$), where states are expected to be large resonances rapidly decaying mainly into charmed meson pairs. They are inconsistent** (mass values, decay rates) **with $c\bar{c}$ spectrum.**
  - **Few analogue states in the bottomonium sector have been found as well**
  - **Many of them - even if established (confirmed by more than one experiment) - remain a puzzle; sometimes quantum numbers are not experimentally determined yet.**

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  Prompt (inclusive): $pp(p\bar{p}) \rightarrow (c\bar{c}) + X$

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

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Typical decay processes:

- **Hadronic transition** to a lighter $c\bar{c}$ meson through the emission of light hadrons [π, $\pi\pi$, ρ, ϕ]
  - suitable for triggering on dimuon objects (J/ψ, $\psi(2S)$, ...) but still difficult **without hadronic PID** (CMS)

- **Electromagnetic transition** to a lighter $c\bar{c}$ meson through the emission of a γ
  - challenging because of the need of converted photon (low efficiency)

Outline

Besides **LHCb** which is a dedicated experiment, **CMS & ATLAS are giving significant contributions to beauty and quarkonium sectors**, mainly using final states containing muon pairs (trigger constraints).

This is possibile thanks to :

- 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))

- ***X(3872)* production**
- $\chi_b(3P)$ **and** X_b **search**
- ***X(5568)* search**
- **(in additional material)**
  ***Y* resonances in $J/\psi\,\phi$ system**

CMS (similar for ATLAS) data samples:

$$\text{Run-I}/2011/\sqrt{s}=7TeV: L_{\text{int}} \sim 5\,fb^{-1}$$

$$\text{Run-I}/2012/\sqrt{s}=8TeV: L_{\text{int}} \sim 20\,fb^{-1}$$

$$\text{Run-II}/2015/\sqrt{s}=13TeV: L_{\text{int}} \sim 4\,fb^{-1}$$

$$\text{Run-II}/2016/\sqrt{s}=13TeV: L_{\text{int}} \sim 38\,fb^{-1}$$

$$\text{Run-II}/2017/\sqrt{s}=13TeV: L_{\text{int}} \sim 45\,fb^{-1}$$

Expected : $\text{Run-II}/2018/\sqrt{s}=13TeV: L_{\text{int}} \sim 45 \div 60\,fb^{-1}$

X(3872) production features

JHEP 04 (2013) 154

$\sqrt{s} = 7TeV$

(Run-I/2011)

JHEP 01 (2017) 117

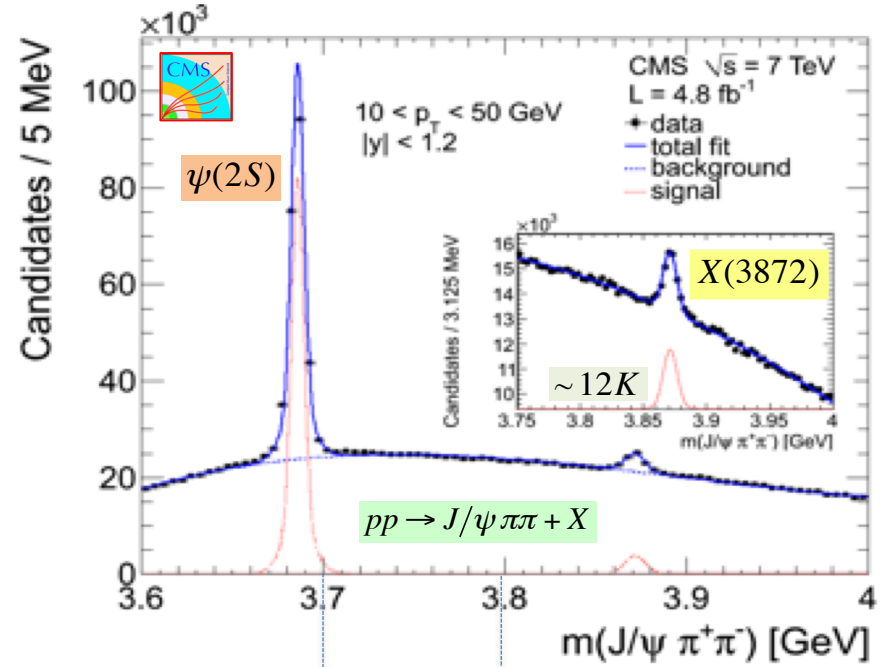
$\sqrt{s} = 8TeV$

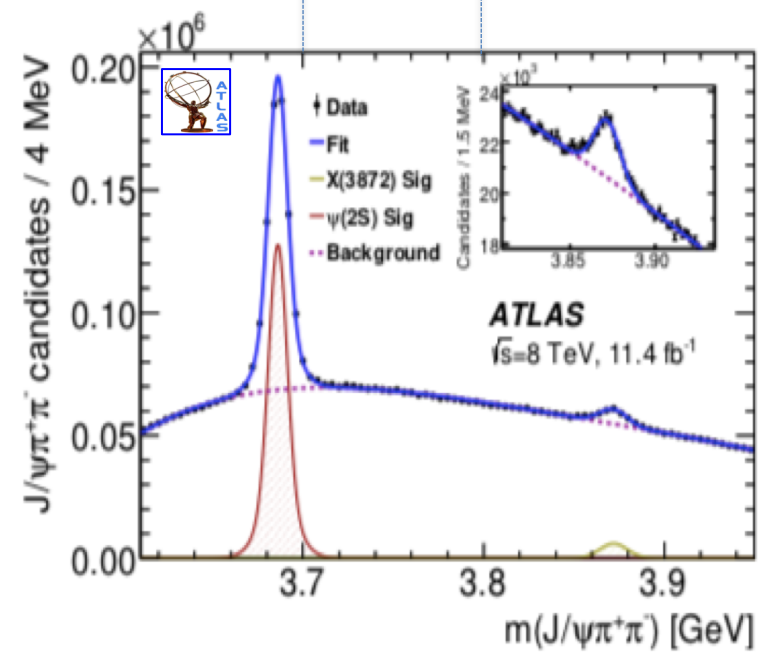
(Run-I/2012)

X(3872) @ LHC

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

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





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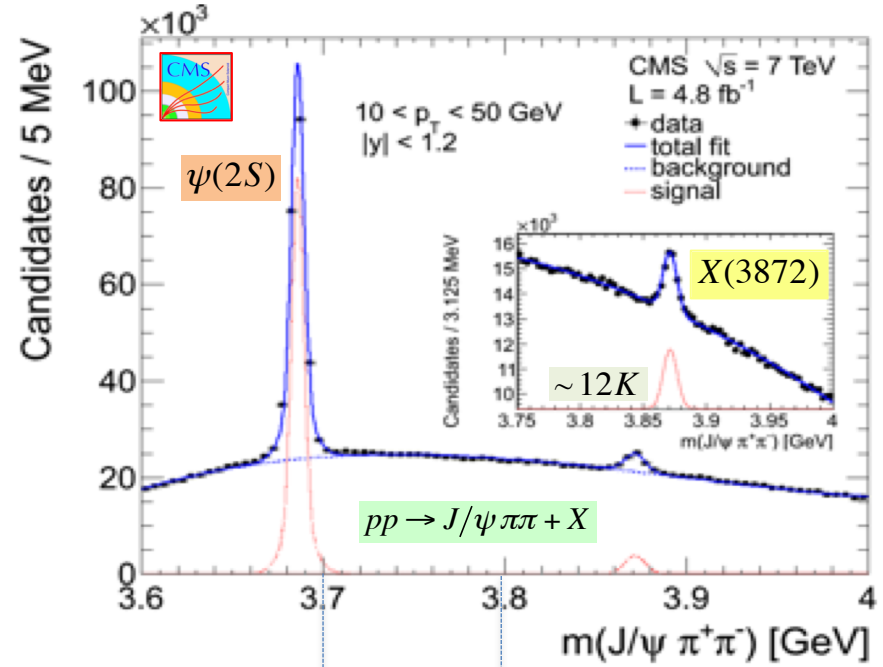
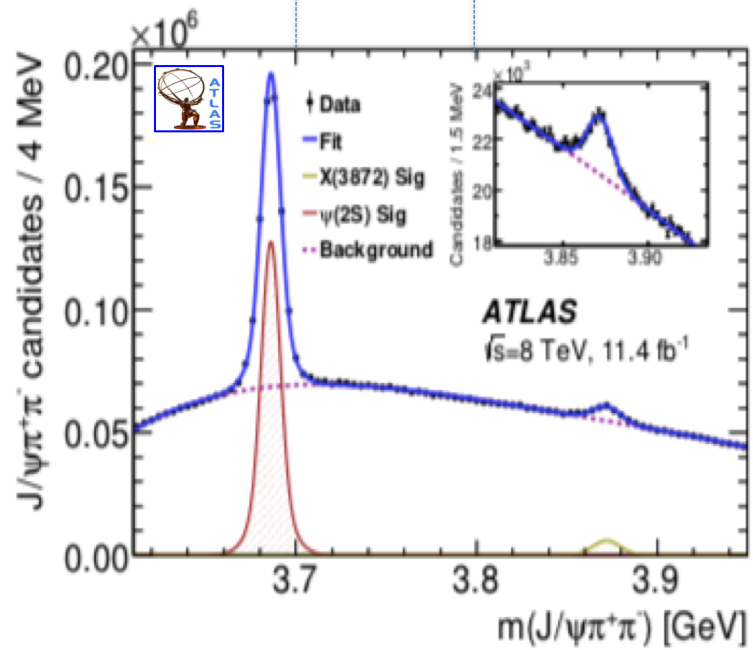
  - **CMS inclusively reconstructed the *X(3872)* in the $J/\psi \pi\pi$ final state & studied (with $7\ TeV$ data) :**
    - **Xsection ratio** w.r.t $\psi(2S)$
    - **non-prompt component** *vs* p_T
    - **prompt X(3872) prod. xsection**
    - **inv. mass distrib. of the $\pi^+\pi^-$ system**

    → next slides

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

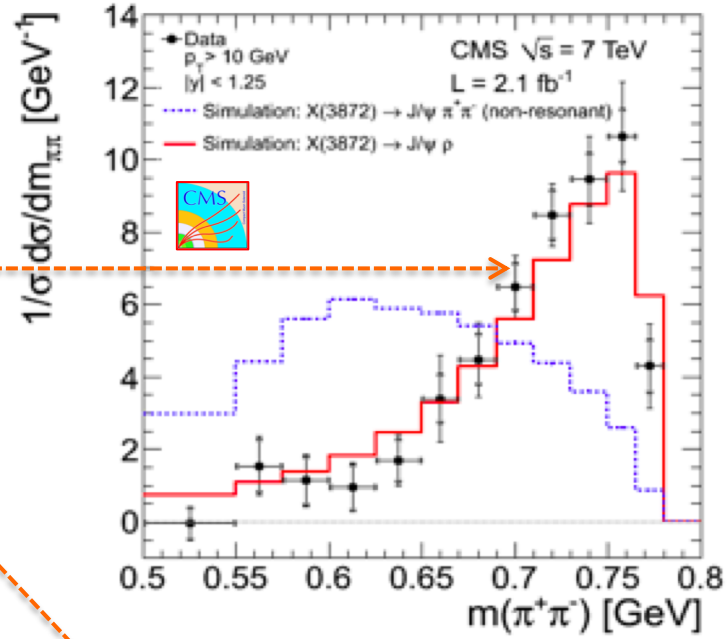




X(3872) @ CMS & ATLAS : $\pi^+\pi^-$ mass spectrum

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

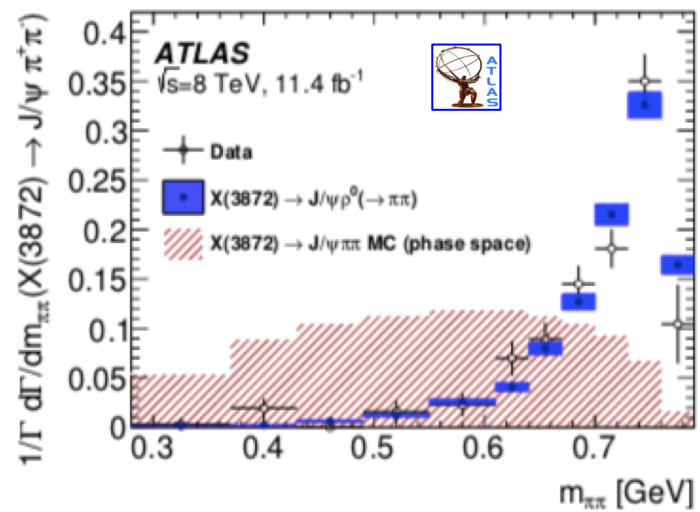
The data spectrum compared to simulations w/ & w/o an intermediate ρ^0 in the decay shows much better agreement when assuming it (as for B & D)



- 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)]

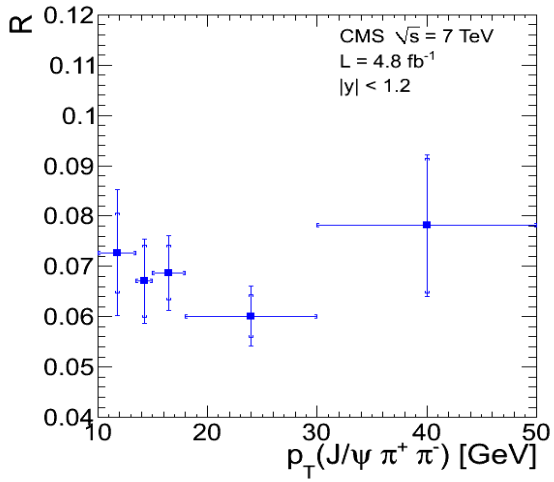
- A ratio of the cross sections has been measured to cancel out many systematic sources:

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

YIELDS from fits to data

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

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



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

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

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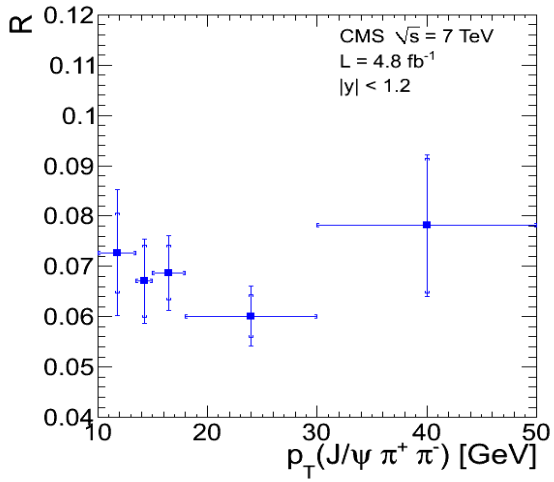

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$$R \cong 0.0656 \pm 0.0029(stat) \pm 0.0065(syst)$$

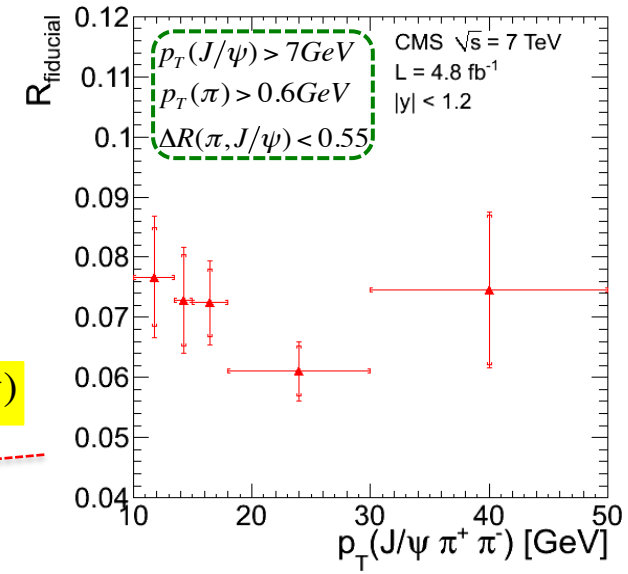
- Acceptance corrections depend on assumptions on the angular distribution of the final states (production mechanism of the X(3872) is unknown) ➡ a result without them in a fiducial region is given :

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

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

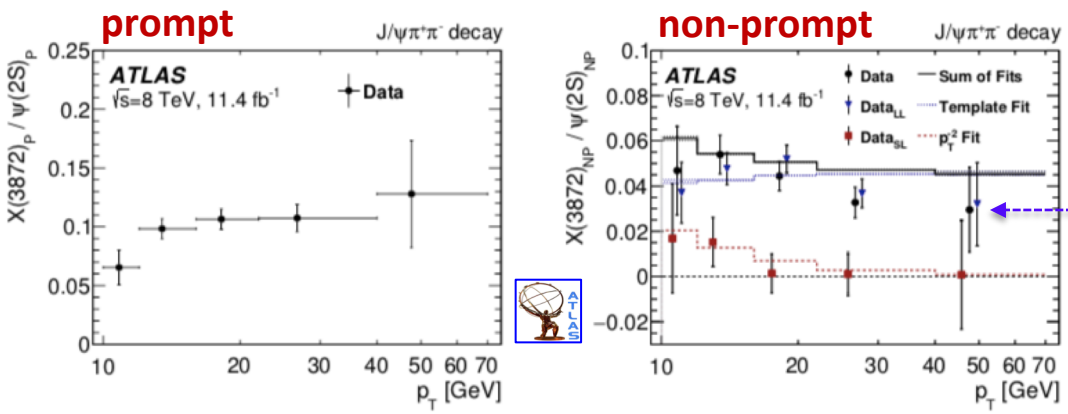
$$R_{fiducial} \cong 0.0694 \pm 0.0029(stat) \pm 0.0036(syst)$$

NO significant dependence on the p_T



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

- 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 $B^{\pm}, B^{0}, B_s^{0}$ 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. *ψ(2S)*]

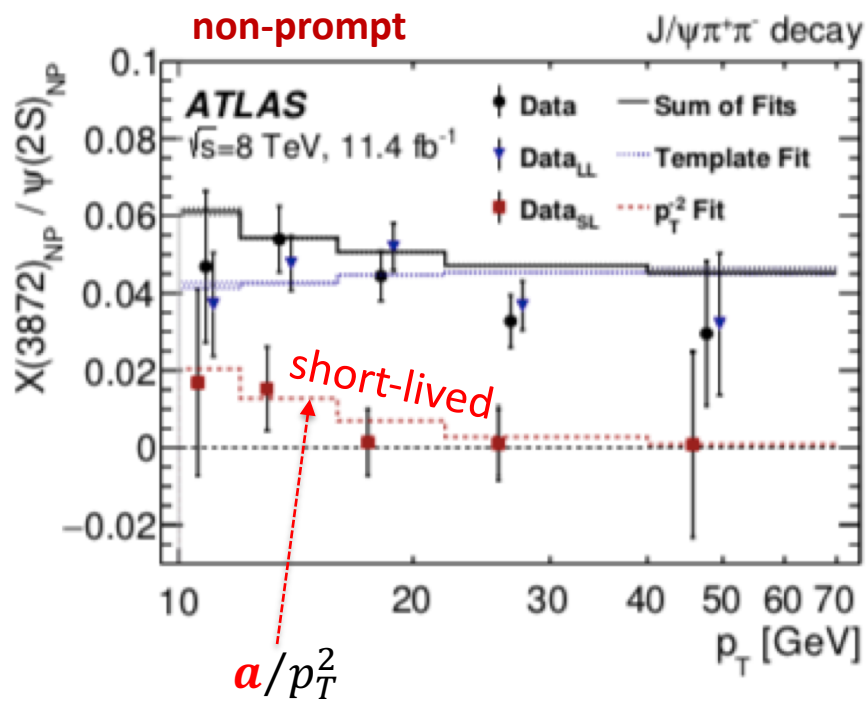
- **Production of $B_c^{\pm}$ mesons in high-energy hadronic collisions - at low p_T - is expected to be dominated by non-fragmentation processes.**

  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 $p_T > 10GeV$]



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.

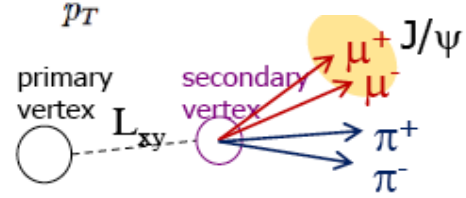
X(3872) @ CMS : non-prompt fraction

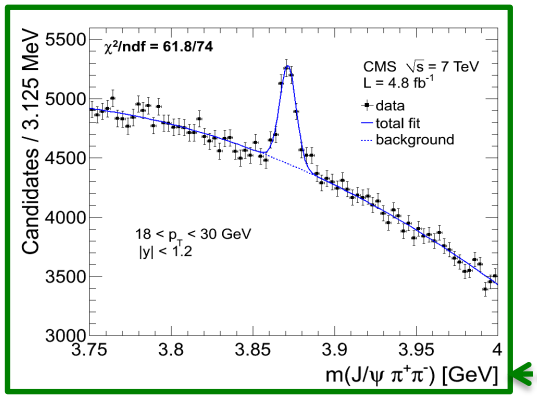
- **The *X(3872)* can be produced from B hadrons' decays into a secondary vertex : prompt & non-prompt components can be separated by <u>pseudo-proper decay length</u>**

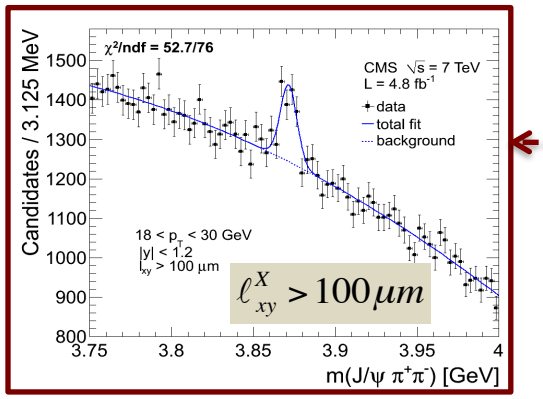
X(3872) from B decays selected requiring: $\ell_{xy}^{X} > 100\,\mu m$

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

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







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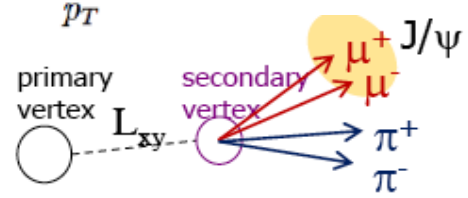
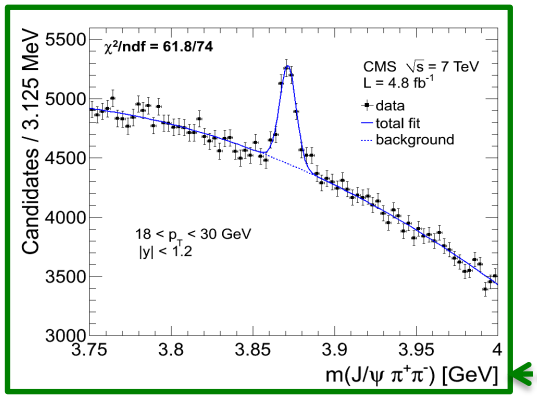
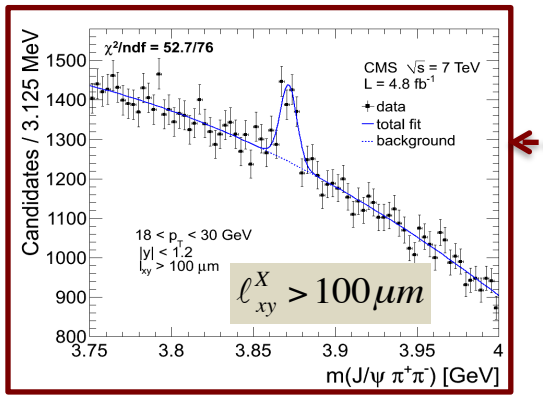


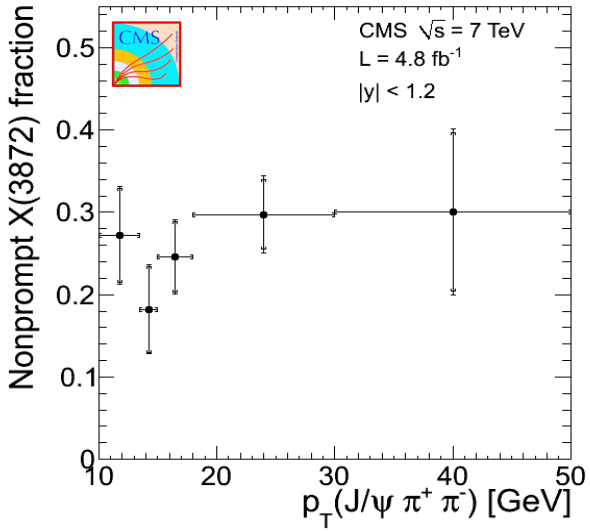




$$\textit{nonprompt fraction} = \frac{\textit{Nr. of X(3872) from B}}{\textit{Nr. of X(3872)}}$$

- **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])

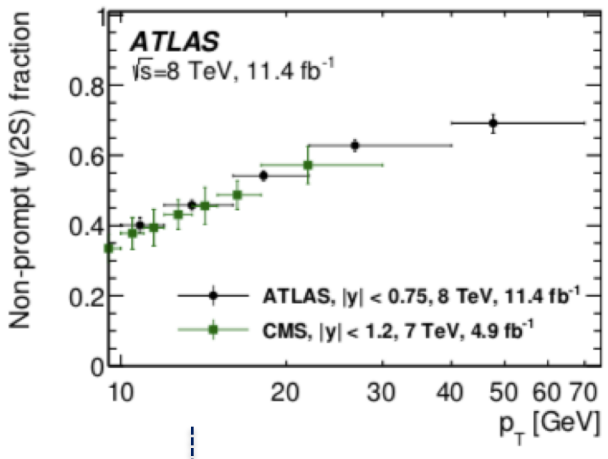


- In agreement with results by ATLAS (next slide)

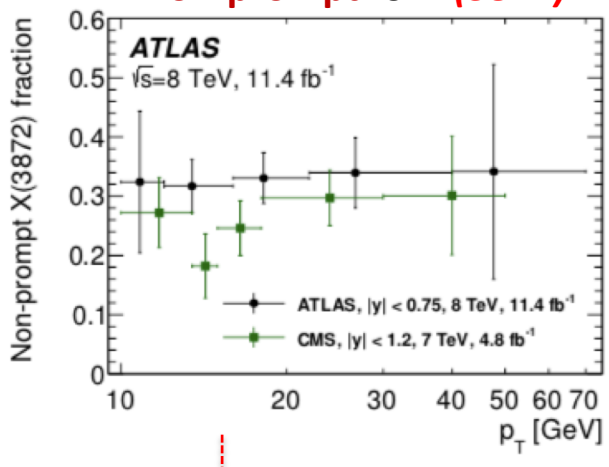
X(3872) @ : non-prompt fraction

- Indeed :

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



non-prompt for *X(3872)*

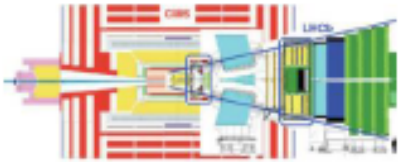


- increases with p_T
- good agreement with CMS

[**JHEP02 (2012) 011**]

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

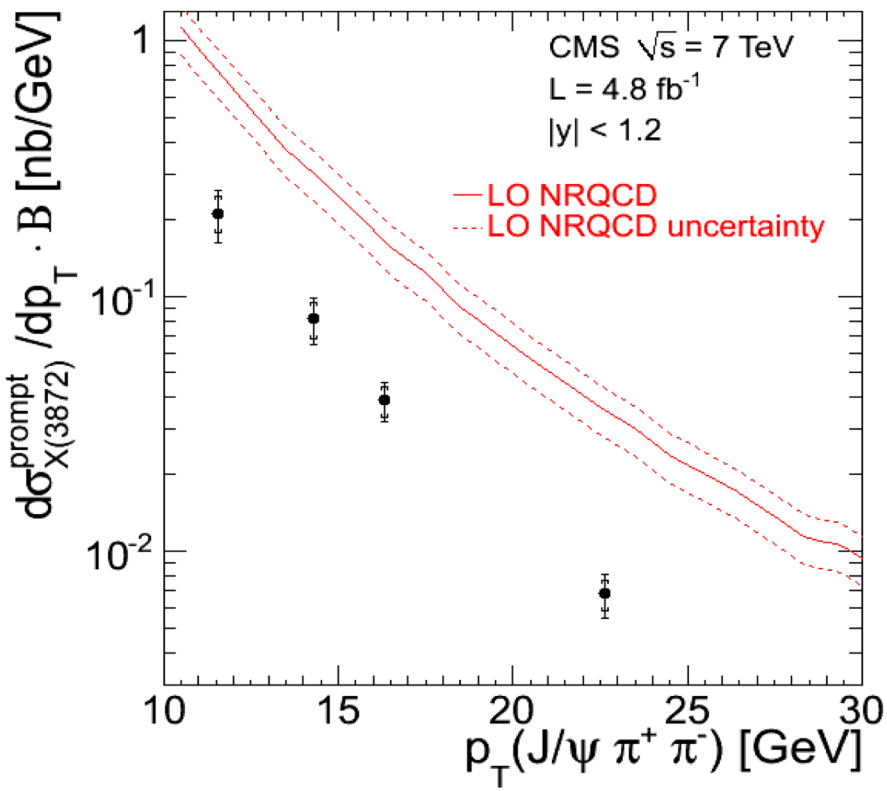
X(3872) @ CMS : prompt production cross section



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

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

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



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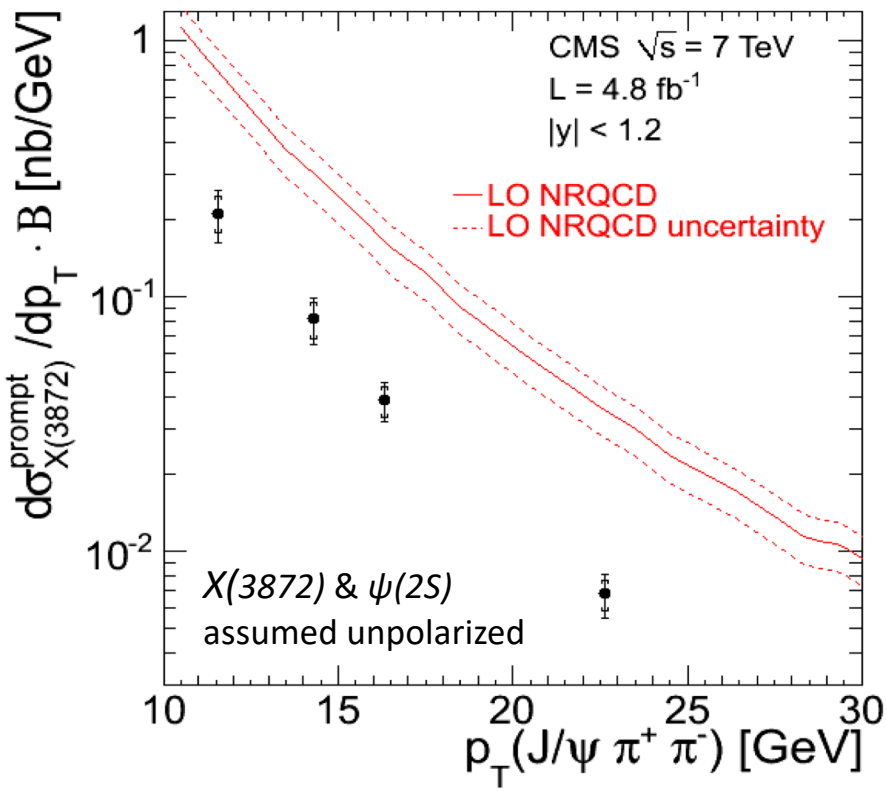

- Results are compared with a theoretical prediction based on NRQCD factorization @ LO approach by Artoisenet & Brateen [PhysRevD.81.114018] with calculations normalized using Tevatron results, modified by the authors to match CMS phase-space
- The shape is reasonably well described by the theory while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

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

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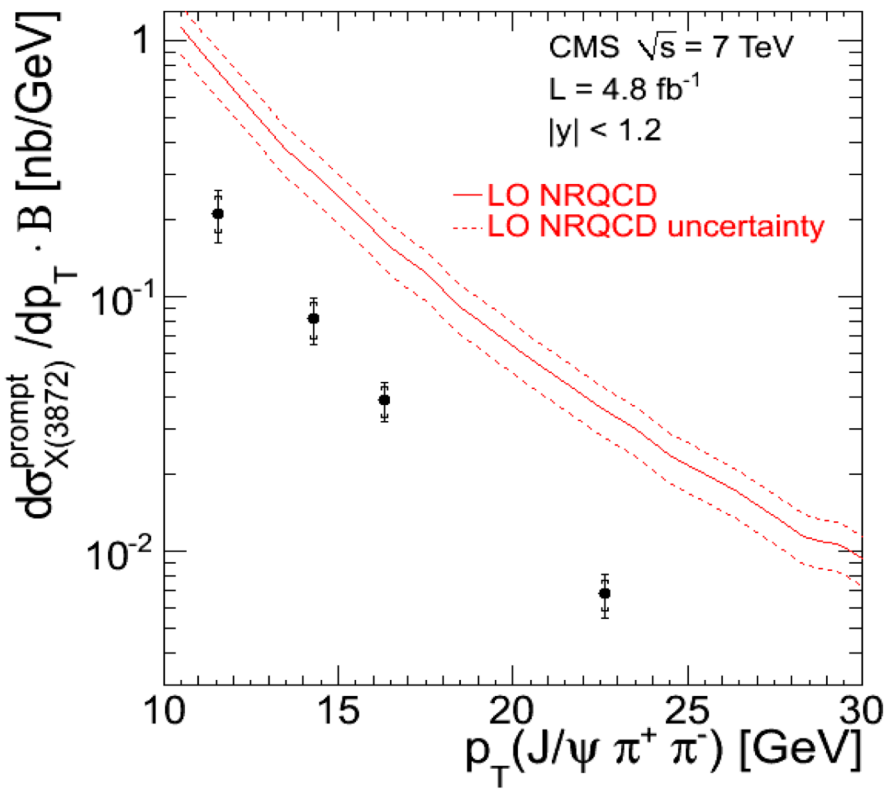


Predictions by Artoisenet & Brateen assume, within an S-wave molecular model, the relative momentum of the mesons being bound by an upper limit of 400*MeV* which is quite high for a loosely bound molecule, but they assume it is possible as a result of rescattering effects.

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

X(3872) : interpretation & prospects ? - I

- **One crucial aspect in the study of exotics is the possibility to discriminate experimentally between compact multiquark configuration ($c\bar{c}u\bar{u}$) & loosely bound hadronic molecule** (suggested for $X(3872)$ by proximity to the $D\bar{D}^{0*}$ threshold).

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

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

… that leads to a radius of ~*14 fm* (3 times as large as the deuteron) !

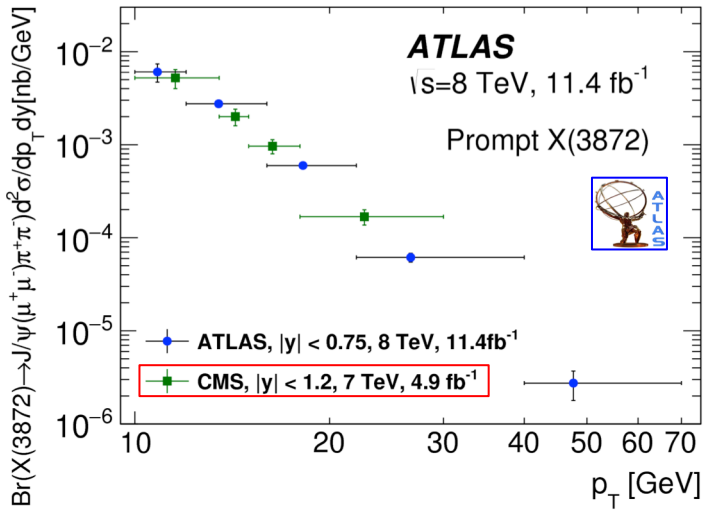
  - **The previous CMS measurement is not supporting an S-wave molecular interpretation**
  - **Pure molecular model** (Swanson *et al.*) **not supported by the LHCb measurement of the radiative** $X(3872) \to \psi(2S)\gamma$ **sub-decay in the** $B^+ \to X(3872)K^+$ **decays**
  - **Significant *L* would 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 [** [PRD 92 (2015) 011102] **]**

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

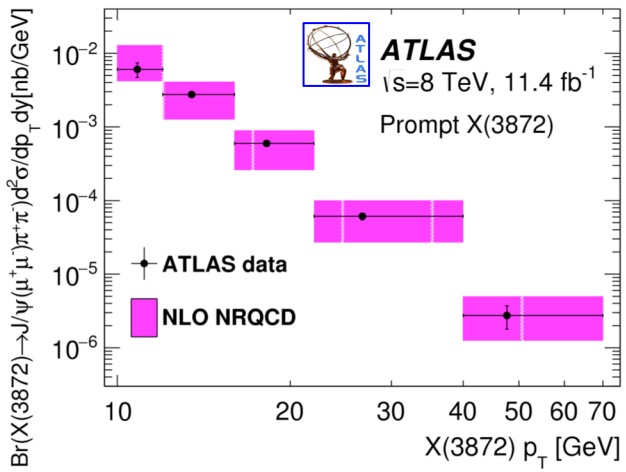
- **The recent results on** $X(3872)$ **production from ATLAS**
  have been compared with the latter model (next slide)

X(3872) : interpretation & prospects ? - I

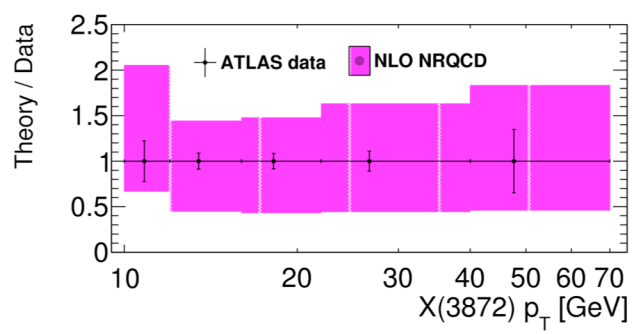
- Comparison of ATLAS with CMS results provided as paper's additional material:
  - ATLAS points positioned @ the mean p_T of the weighted signal events
  - CMS points positioned @ the mean p_T of the theoretical predictions



- **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 $J/\psi\,\rho$, $J/\psi\,\omega$.



X(3872) : interpretation & prospects ? - III

- **Prospects for new measurements at CMS & ATLAS concerning the $X(3872)$?**

  - Precision measurements using non-prompt $X(3872)$ from B decays may use displaced J/ψ triggers also for Run-II data. However it is uncertain if this could add info to the LHCb measurements.

  - Production measurements of prompt $X(3872)$ can use inclusive J/ψ triggers having much higher p_T threshold especially in Run-II and increasing along it. Uncertain how crucial would be the impact increasing the p_T range. Studying radiative decays with Run-II data might be interesting.

  - Studying radiative decays with Run-II data could be interesting
    (beware: converted photons are needed)

Search for X_b, the bottomonium partner of *X(3872)*

PLB 727 (2013) 57

$\sqrt{s} = 8TeV$ (Run-I / 2012)

PLB 740 (2015) 199

$\sqrt{s} = 8TeV$ (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 $B\bar{B}^{(*)}$ threshold ($m \cong 10.562(604) GeV$);
  [model dependent prediction for a $B\bar{B}^{(*)}$ molecule by Swanson (2004)**].**

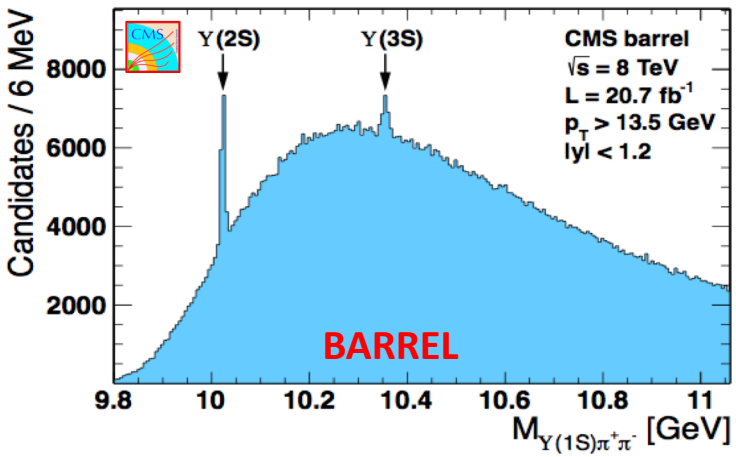
  - More recently Karliner [Acta Phys. Pol. B vol.47 (2016)] proposed **two *I=0* narrow resonances X_b** in the bottomonium system, **about 20 *MeV* below the corresponding $\bar{B}B^*$, $\bar{B}^*B^*$ thresholds.**

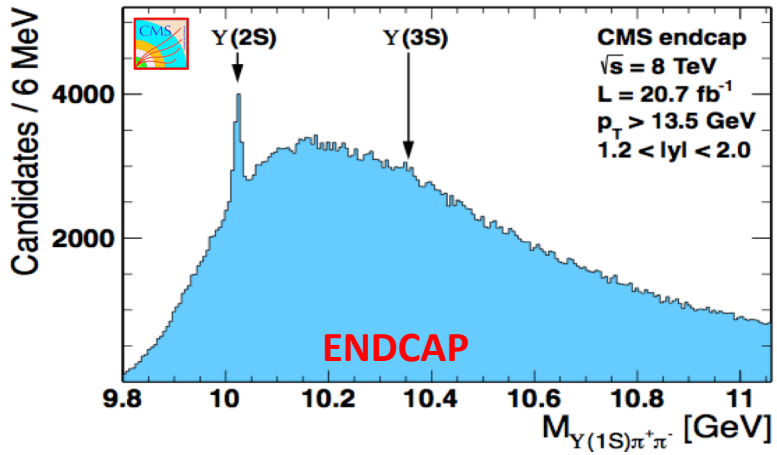
- **(&) looked for $X_b \to \Upsilon(1S)\ \pi^+\pi^-$ decay seemingly analogous to $X(3872) \to J/\psi\,\pi^+\pi^-$**

Analysis strategy : search for a peak - other than known $\Upsilon(2S), \Upsilon(3S)$ - in the $\Upsilon(1S)\ \pi^+\pi^-$ spectrum within $10 \div 11 GeV$ range [expecting **narrow width** & possibly **sizable BF** similarly to X(3872)]

Search for X_b - II

- 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 $\Upsilon(2S)$ …

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

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

Search for X_b - III

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

observed YIELDS

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

overall EFFICIENCIES estimated from SIMULATION

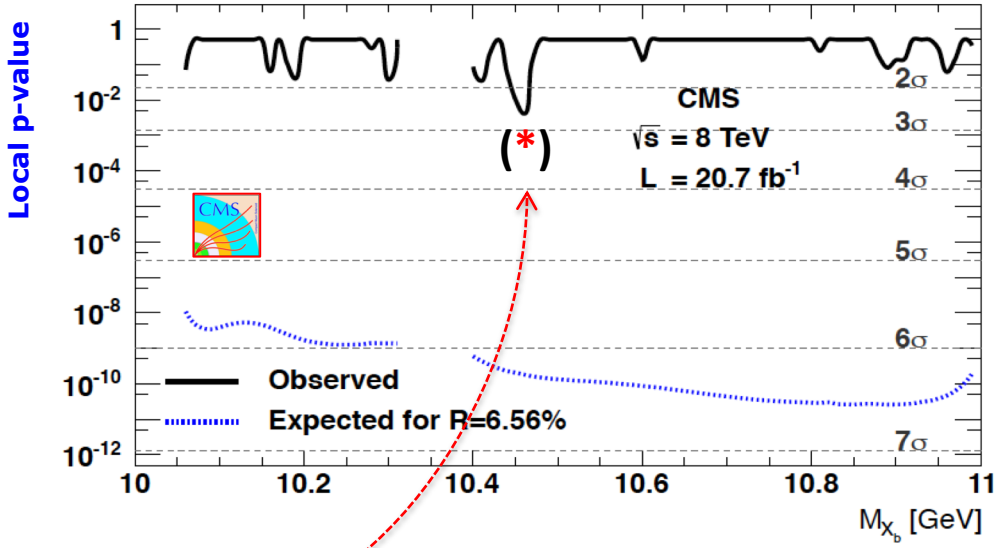
Assumptions in simulation:

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

… and a local *p-value* is calculated

(asymptotic approach & barrel/endcap combination)

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



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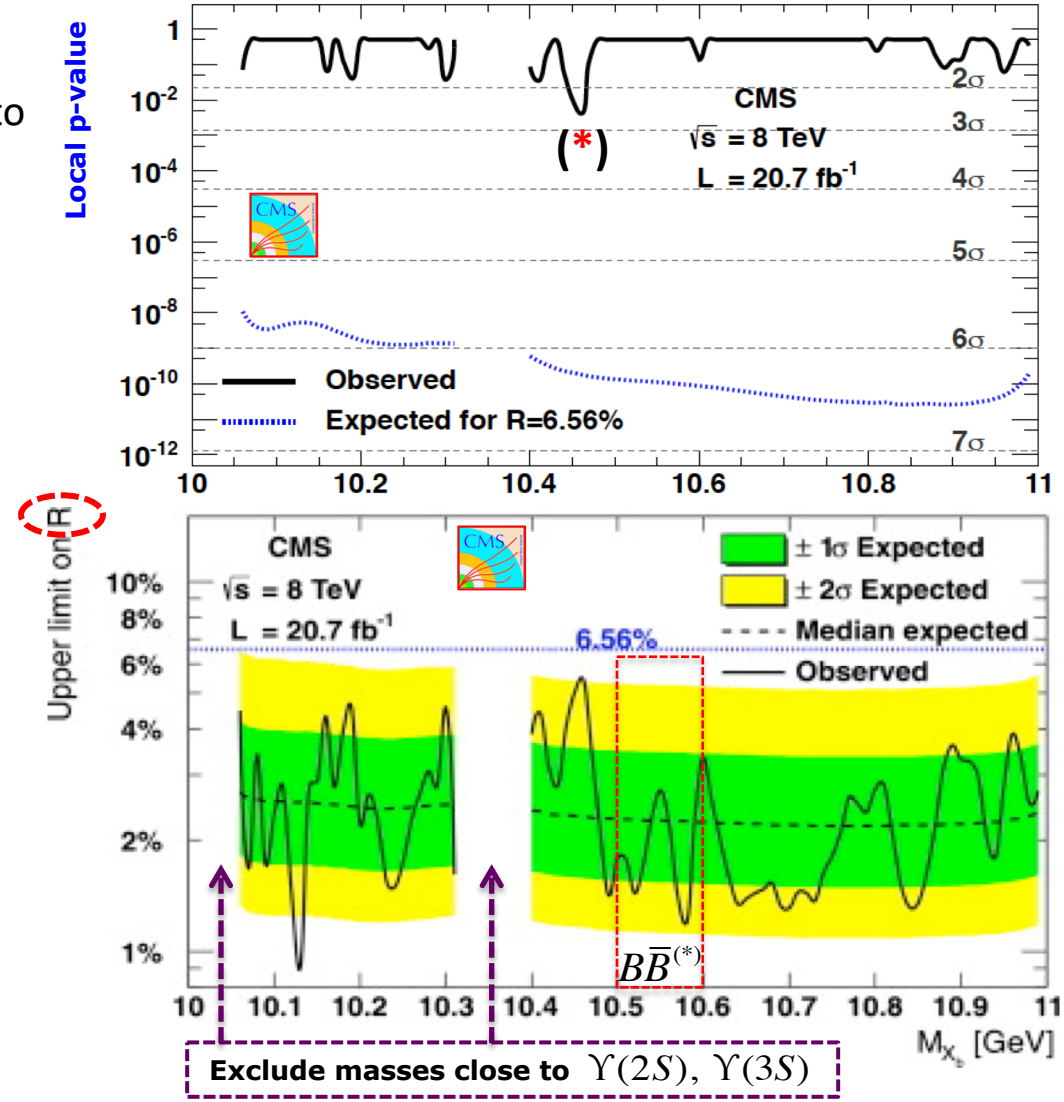

NO significant excess observed → **95% CL upper limits set on the ratio** R **:** **observed UL range: 0.9% to 5.4%**

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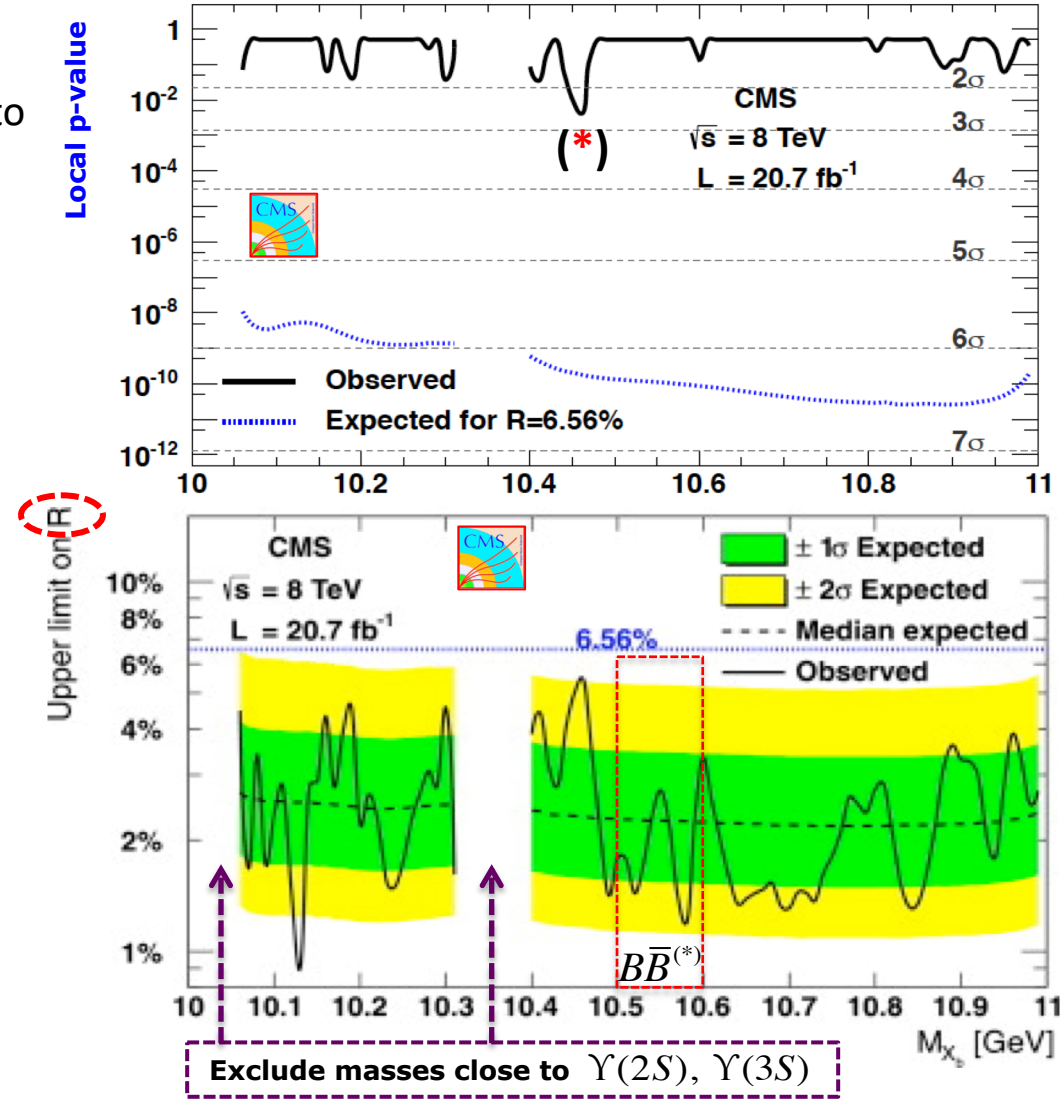
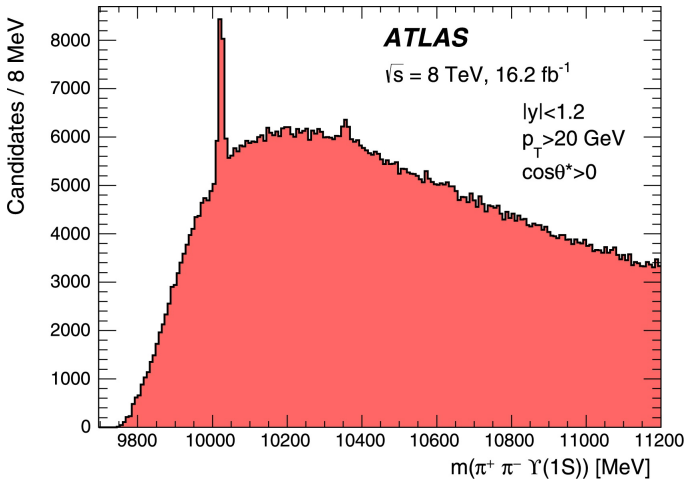


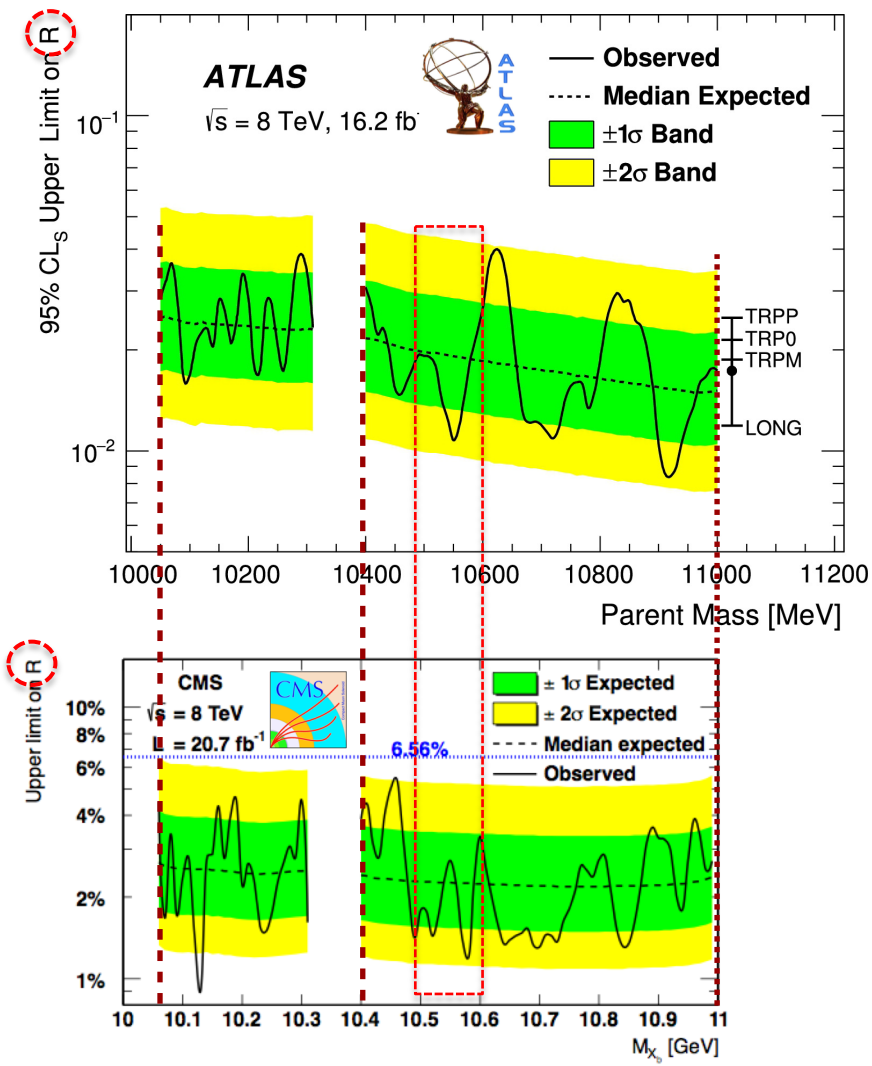
NO significant excess observed → **95% CL upper limits set on the ratio** R **:** **observed UL range: 0.9% to 5.4%**

- **Similar results from** (next slide) : **slightly more stringent limits**

Search for X_b - IV

- **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%

Search for X_b : prospects - I

- According to Karliner&Rosner [PRD91 (2015) 014014], **the analogy with $X \to J/\psi\, \pi^+\pi^-$ is misguided for this particular decay channel:** $X_b \to \Upsilon(1S)\, \pi^+\pi^-$ **should be forbidden by G-parity conservation :**

  - **For the $X(3872)$ the *I*-conserving decay $X \to J/\psi\omega$ was kinematically suppressed, thus equally likely than the *I*-violating $X \to J/\psi\rho^0$:**

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

ω^0

ρ^0

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

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

$$\begin{cases} X_b \xrightarrow{(*)} \Upsilon(1S)\omega(\to \pi^+\pi^-\pi^0) \\ X_b \to \chi_b(1P)\pi^+\pi^- \\ X_b \to \Upsilon(3S)\gamma \end{cases}$$

2γ

$\Upsilon(1S)\gamma$

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

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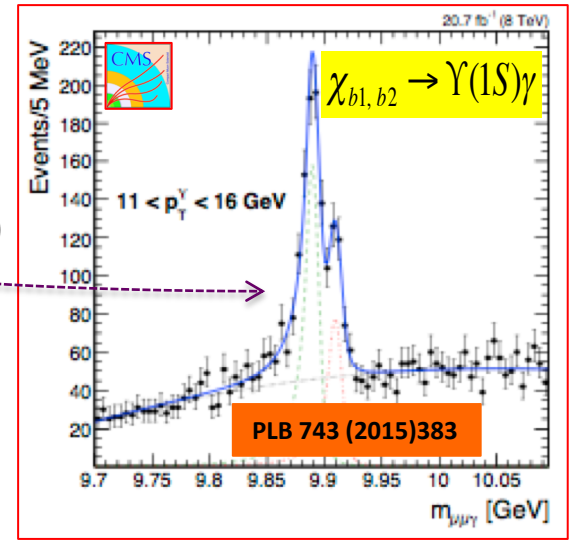
(*) No significant signal found by Belle in *Y(5S)* decays [PRL113, 142001 (2014)]

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

  Reconstruction of SOFT photons by conversions into the tracker …

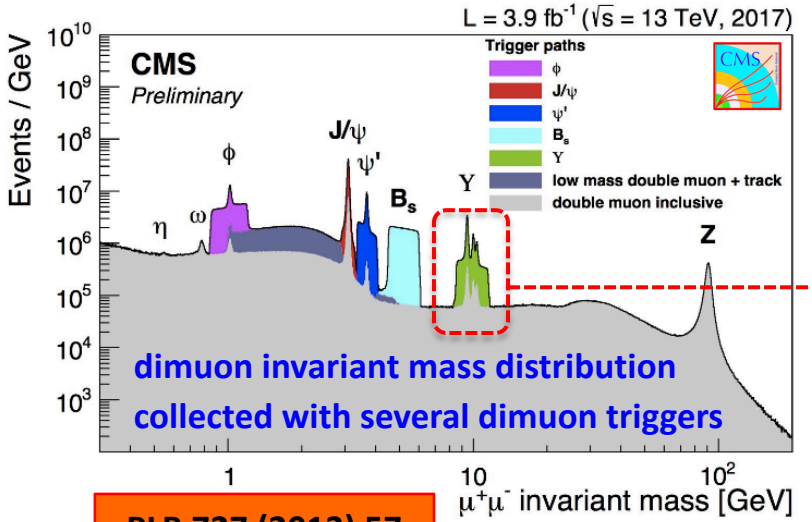
  - … provides enough mass resolution to resolve the two peaks (separated by 19*MeV*)
  - **… BUT conversion efficiency is LOW !**

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

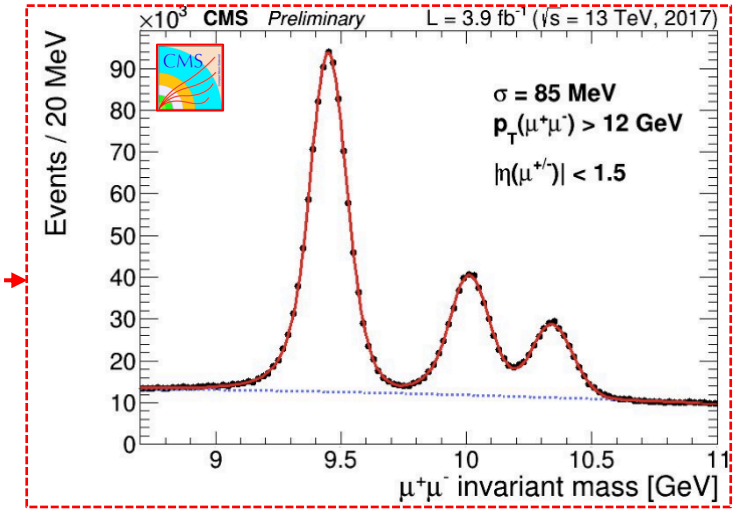


Search for X_b : prospects - II

- In Run-II data taking we have a low enough dimuon p_T-threshold (at expense of a reduced $|\eta|$ muon range)

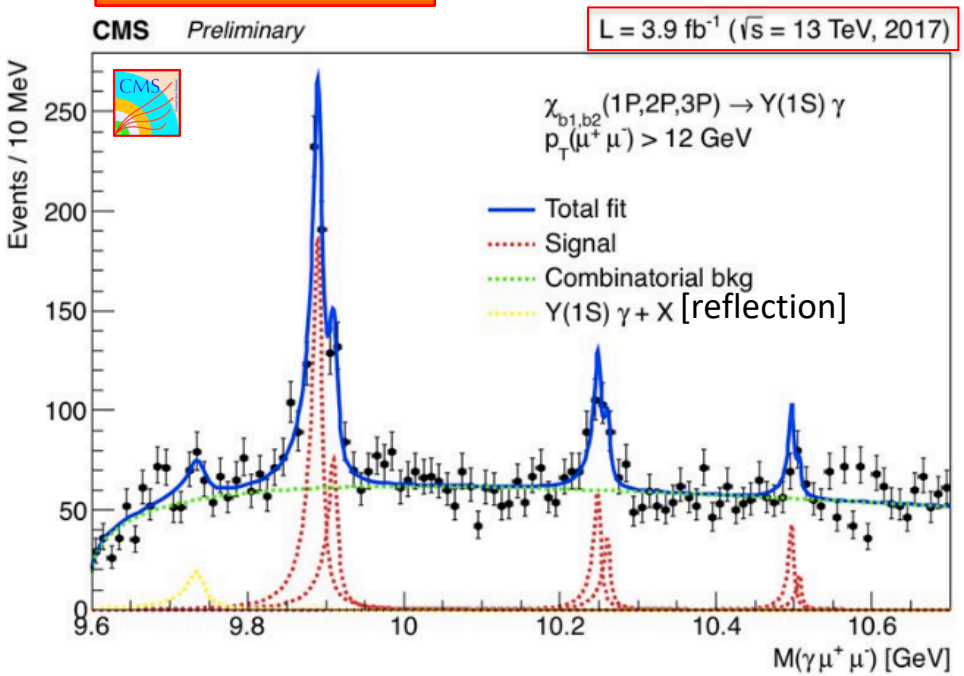


PLB 727 (2013) 57



CMS-DP- 2017-029

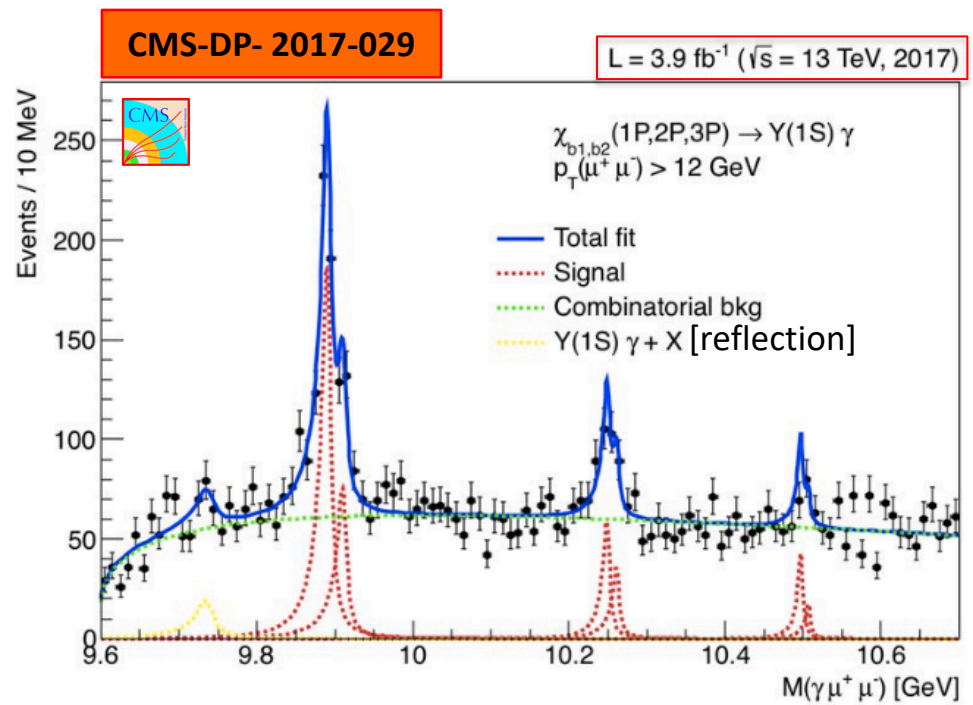
- Adding a converted photon to $\Upsilon(1S)$ ...
  [$\Upsilon(1S)\gamma$ system has vertex-fit probability >1%] :



Search for X_b : prospects - III

Interest in radiative decays to $\Upsilon(nS)\gamma \quad [n=1,2,3]$

- With the X_b far below the $B\bar{B}^{(*)}$ threshold and the I-violating decay mode $X_b \to \Upsilon(1S)\,\pi^+\pi^-$ highly suppressed, the relevance of radiative decays increases
  - According to Li & Wang [PLB733 (2014) 100], within a loosely bound hadronic molecule model, the partial widths for the $X_b \to \Upsilon(nS)\gamma$ are $\sim 1keV$ and thus the **BFs may be sizeable**, considering the fact that the total width may also be smaller than a few MeV like for the $X(3872)$.
- According to Karliner & Rosner [PRD91 (2015) 014014] the X_b **may be close** to the $\chi_{b1}(3P)$, **mixing with it and sharing decay modes** [like the $X(3872)$ might be a mixture of $\chi_{c1}(2P)$ & $D^0\bar{D}^{*0}$ molecule].



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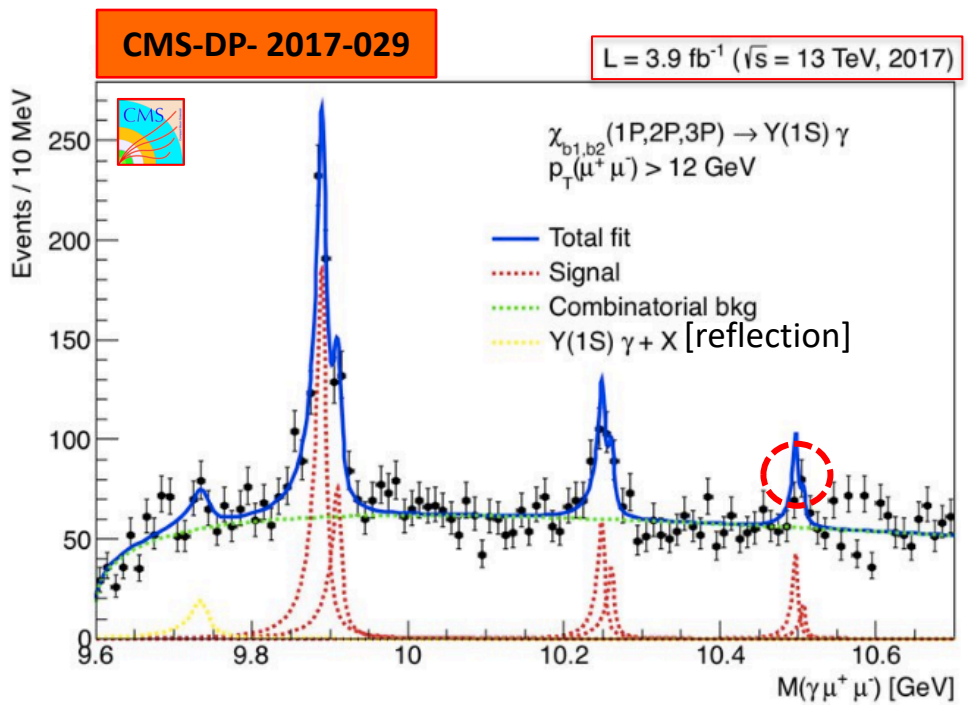
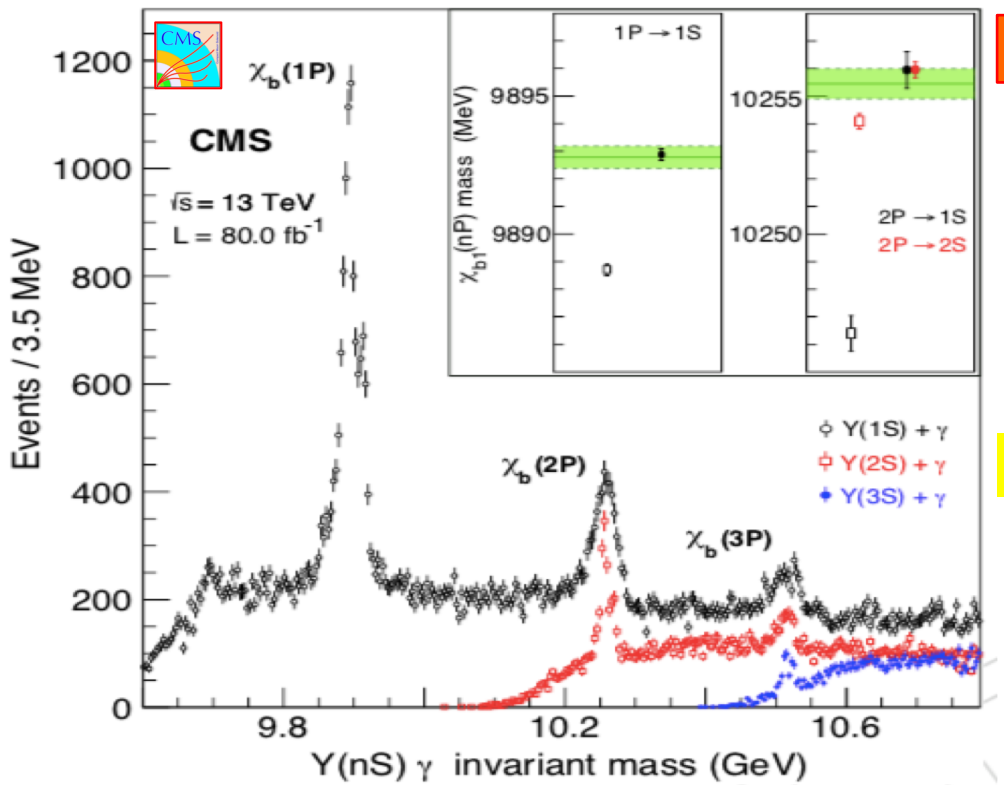
  - Thus the experiments (, ,) that reported observing $\chi_{b1}(3P) \to \Upsilon(1S,2S)\gamma$ might have actually discovered a mixture of X_b & $\chi_b(3P)$! It would be worthwhile to examine the $\Upsilon(nS)\gamma$ mass spectra for any departure from the expected lineshape.

Again… it's mandatory to use the full Run-II data!



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

- **Observed through their radiative decays to $\Upsilon(3S)\gamma$ using $\mathcal{L}\sim 80 fb^{-1}$ of 2015-2017 Run-II (*13*TeV)**
  - This is a preview. Paper has been submitted to PRL & going to appear on arXiv this afternoon
  - $\Upsilon(3S) \to \mu^+ \mu^-$
  - **Low-energy photons detected after converting to e^+e^- pairs in the silicon tracker leading to a $\chi_b(3P)$ mass resolution of *2.2*MeV.** [selection: p_T>500MeV , $|\eta| < 1.2$]
  - Photon energy scale calibrated (using $\chi_{c1} \to J/\psi\,\gamma$ decays) to allow accurate mass measurement



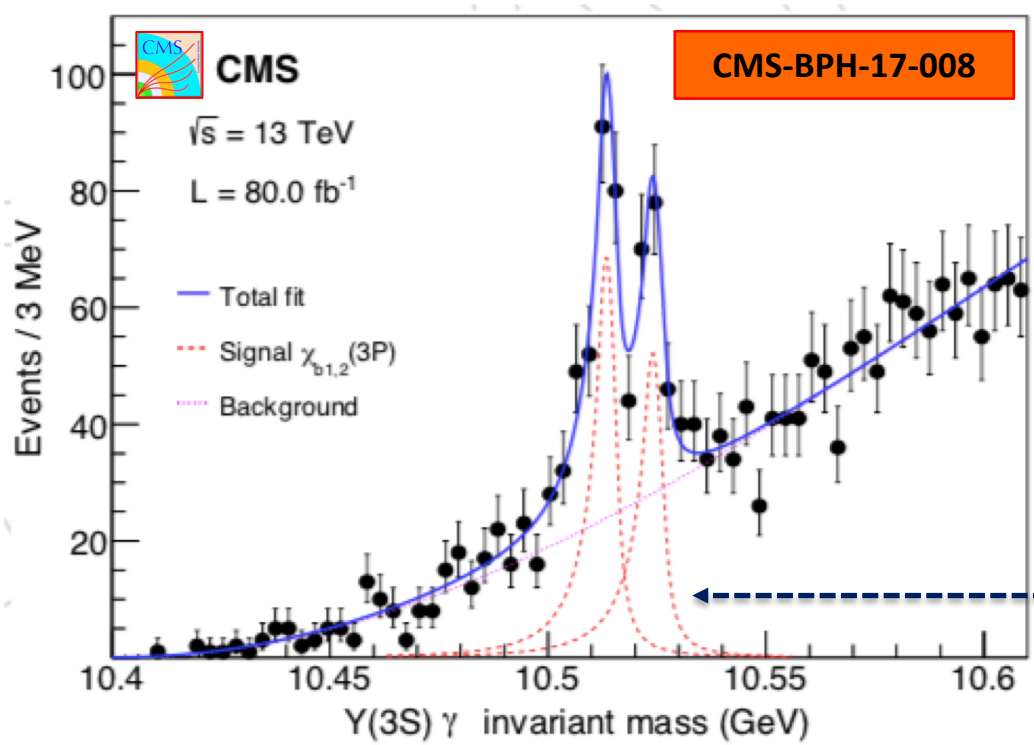
CMS-BPH-17-008

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

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

- **First time that the *J=1,2* states are well resolved** (***J=0 :*** exp. negligible radiative decay BF)

  - The two individual masses are measured and the ***Δm*** as well :



2 Double-sided Crystal Ball

$$10\,513.42 \pm 0.41\,(\text{stat}) \pm 0.18\,(\text{syst}) \text{ and } 10\,524.02 \pm 0.57\,(\text{stat}) \pm 0.18\,(\text{syst})\,\text{MeV}$$

$$\Delta M = 10.60 \pm 0.64\,(\text{stat}) \pm 0.17\,(\text{syst})\,\text{MeV}$$

→ **standard mass hierarchy**

Search for the *X(5568)*

PRL 120 (2018) 202005

$\sqrt{s} = 7TeV$

(Run-I/2011)

PRL 120 (2018) 202007

$\sqrt{s} = 7TeV$ **(Run-I/2011)**

$\sqrt{s} = 8TeV$ **(Run-I/2012)**

X(5568) : claim & issues

- **Recently D0 claimed [**PRL117 (2016) 022003**] the observation of a narrow structure, called** *X(5568)* **[** $\Gamma \sim 22MeV$ **], inclusively produced, in the decay sequence …**

$X(5568)^{\pm} \to B_S^0\pi^{\pm},\ B_S^0 \to J/\psi\phi,\ J/\psi \to \mu^+\mu^-,\ \phi \to K^+K^-$ **(meaning implicitely :** $B_S^0\pi^+,\ B_S^0\pi^-,\ \bar{B}_S^0\pi^+,\ \bar{B}_S^0\pi^-$ **)**

  - The $X(5568)$ should have a 4-quark content with all quarks of different flavour (*b*, *s*, *u*, *d*). It could be:
    - a tetraquark (tightly bound di-quark anti-diquark such as $[b\ u][\bar{d}\ \bar{s}],\ [b\ \mathrm{d}][\bar{s}\ \bar{u}],\ [s\ u][\bar{b}\ \bar{d}],\ [s\ \mathrm{d}][\bar{b}\ \bar{\mathrm{u}}]$)
    - a loosely bound $B_d^0K^{\pm}$ molecular state [disfavoured : binding energy would be ~200MeV]
  - It would have $J^P=0^+$ if produced in an S-wave or …
    $J^P=1^+$ if decay proceeds via the chain $X(5568)^{\pm} \to B_S^{*0}\pi^{\pm} \to (B_S^0\gamma)\pi^{\pm}$ (unreconstructed γ)

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- **Surprising large relative production! The *fraction of* B_S^0 *from X decay* :** $\rho_X^{D0} \cong (8.6 \pm 1.9 \pm 1.4)\%$
  - This would mean another significant source of B_S^0 mesons production !
    And - of course - it is very unlikely to imagine some sort of particular production mechanism enhanced at $p\bar{p}$ collisions and/or at lower center-of-mass energies (CDF is crucial to exclude this).
  - Many processes might contribute to the bkg (and not described by MC), such as reflections (feed-down) from higher mass states decaying into a real B_S^0 + (undetected/unassociated) tracks [$B_c^{\pm},\ B_c(2S),\ B_s^{*(*)}$]
  - Selection criteria include uncautious (potentially biasing) cut on a relevant angular variable

X(5568) search : signal extraction

- The search from LHCb reported quite soon a negative result [PRL 117 (2016) 152003].
  CMS can complement this search by probing a central kinematic region (similar to that of D0)

- Measure/constrain the relative production rate of $X(5568)$, w.r.t. B_s^0, times the unknown BF of the $X(5568)^{\pm} \to B_s^0 \pi^{\pm}$ decay :

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

X(5568) search : signal extraction

- The search from LHCb reported quite soon a negative result [PRL 117 (2016) 152003].
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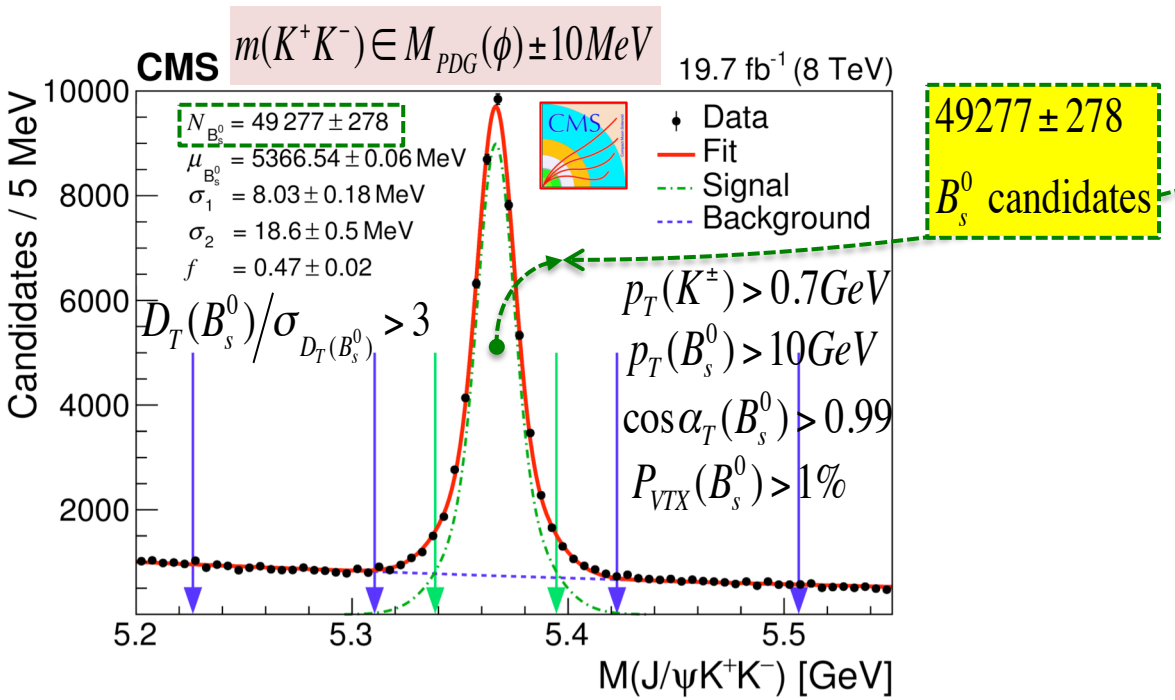

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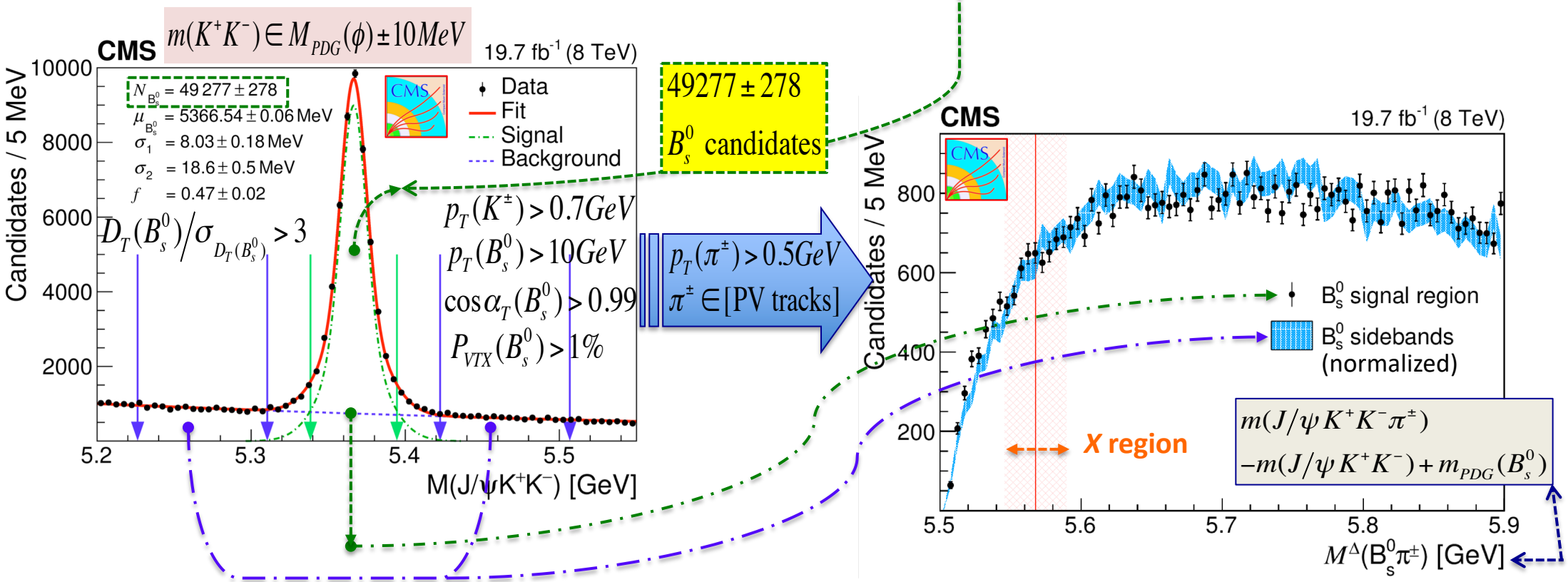

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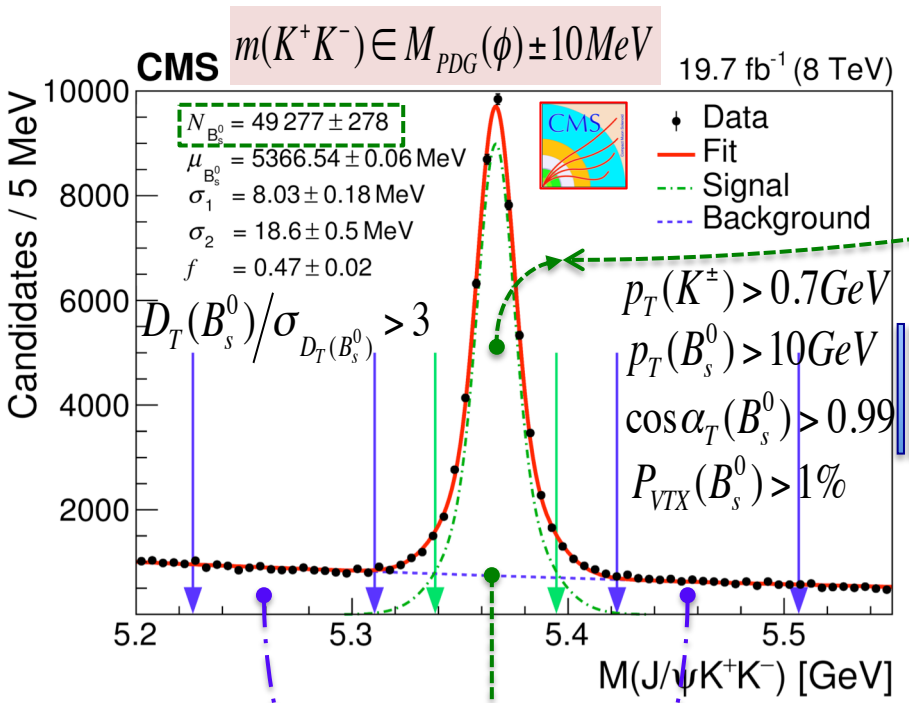
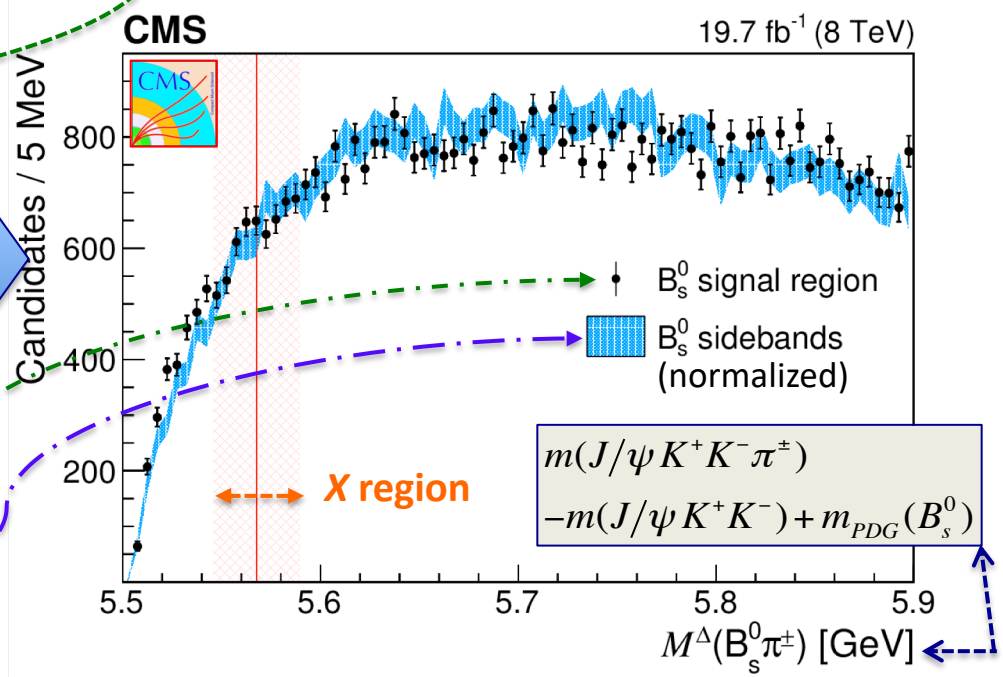
$$\varepsilon_{rel} = \frac{\varepsilon_X}{\varepsilon_{B_s^0}}$$ relative reconstruction efficiency

from fit to the $B_s^0 \pi^{\pm}$ mass spectrum (next slide)



49277 ± 278 B_s^0 candidates

$p_T(\pi^{\pm}) > 0.5 GeV$
$\pi^{\pm} \in$ [PV tracks]

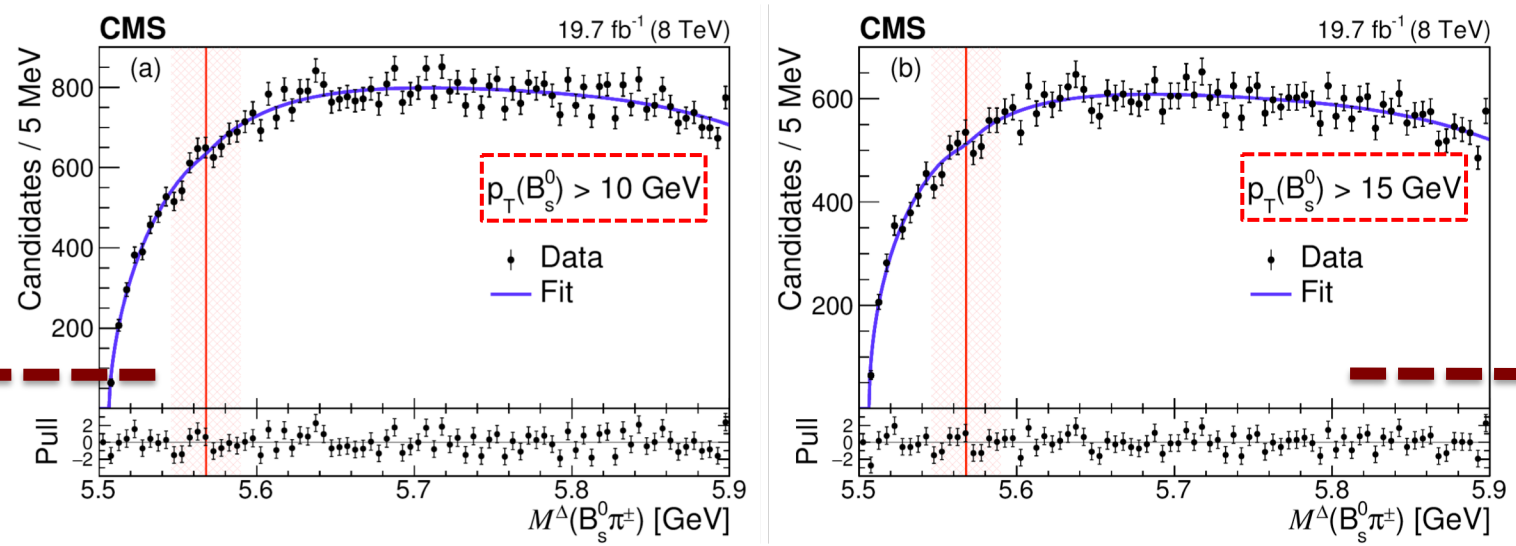


X(5568) search : spectrum fits

- Reconstruction efficiencies derived from simulation of X (spin-0, mass & widths from D0, PHSP decay) and B_s^0 signals. Systematic uncertainty on ε_{rel} due to the finiteness of MC samples.

- The model of the fit to the $M^{\Delta}(B_s^0\pi^{\pm})$ spectrum (for "baseline" selection) includes :
  - for BKG : 3rd-order polynomial shape *multiplied* by a threshold function
  - for SIGNAL : BW (D0 parameters) *convolved* with a triple-Gaussian resolution function (MC)

$N_X = -85 \pm 160$



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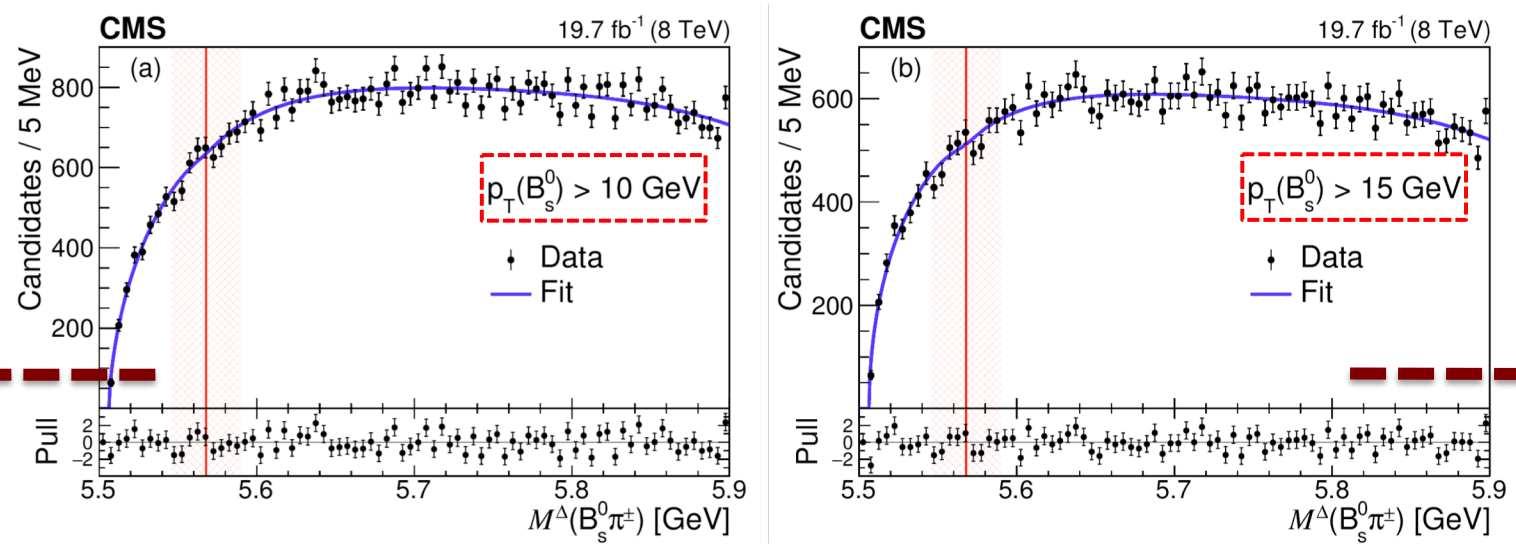

$N_X = -103 \pm 122$

- The absence of a peak is not only supported by direct comparison with the events in the B_s^0 sidebands, but also by several fits to the $M^{\Delta}(B_s^0\pi^{\pm})$ spectrum with a resonant component included, using different kinematic selection requirements (tighter than "baseline"), as well as variants of the BKG modelling, alternative fit regions and different quality criteria.

X(5568) search : upper limits by CMS

- **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* **:**

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

- Using MC of spin-1 state decaying to $B_s^{*0}\pi^{\pm}$, where the generated mass is shifted by $m(B_s^{*0}) - m(B_s^0)$, the UL were verified to differ negligibly between either the spin-1 or spin-0 assumption.

- **They are more stringent than … previous best UL by LHCb PRL117 (2016) 152003**
  … following UL by ATLAS (next slide)

- **Within a kinematic range similar to that of D0, at $p\bar{p}$ collider, no confirmation from D0 .**
  D0 [PRL 120 (2018) 202006] is able to set a not so stringent UL: $\rho_X < 6.7\%\ @\ 95\%CL$

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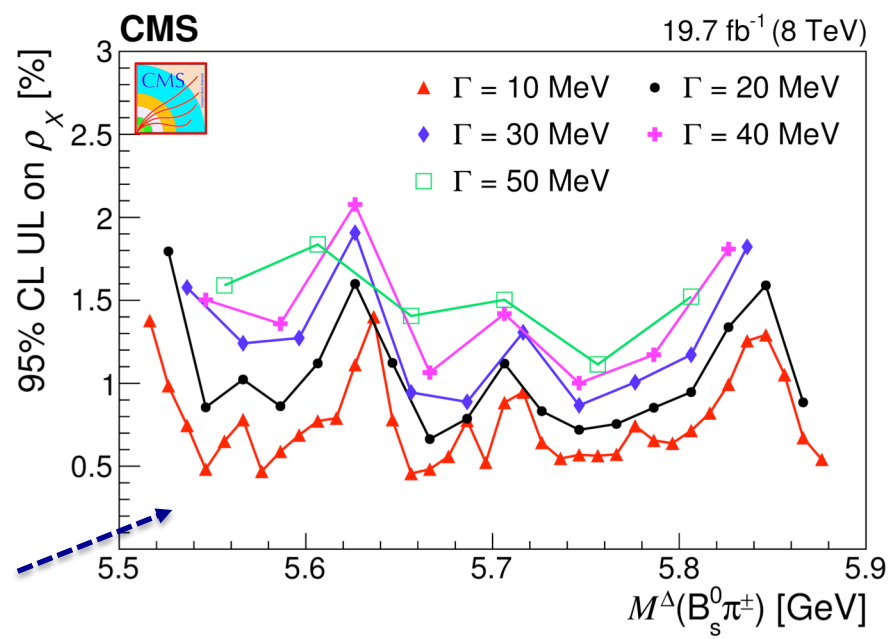
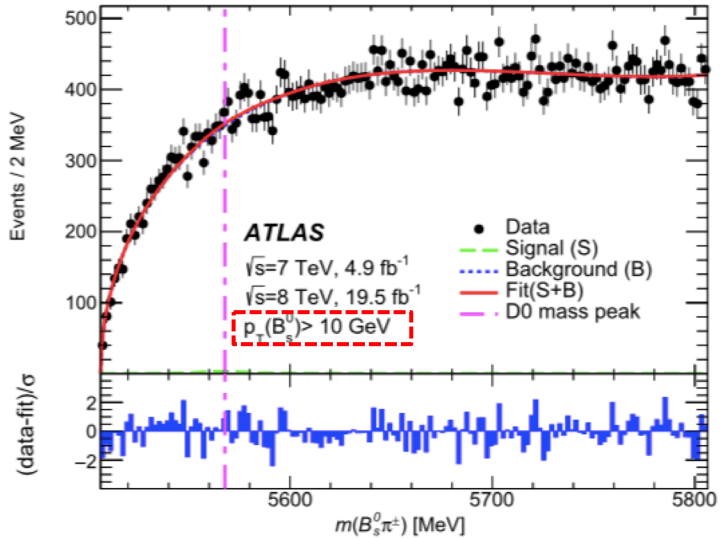
- **Upper limits are also obtained for different values of natural width** (Γ=10 to 50*MeV*) **& mass** [from $m(B_s^0) + m(\pi^{\pm}) + \Gamma$ up to 5.9*GeV*-1.5Γ] of a possible $B_s^0\pi^{\pm}$ resonance, **in order to consider an eventual exotic state with higher mass** decaying to the $B_s^0\pi^{\pm}$ final state.

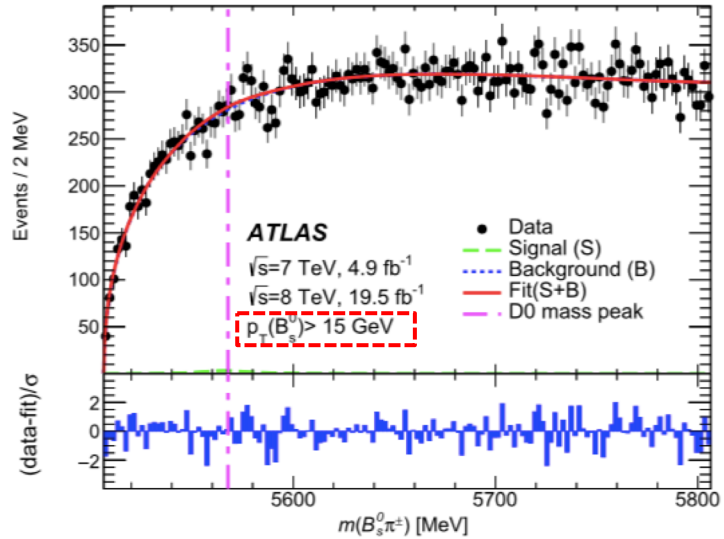


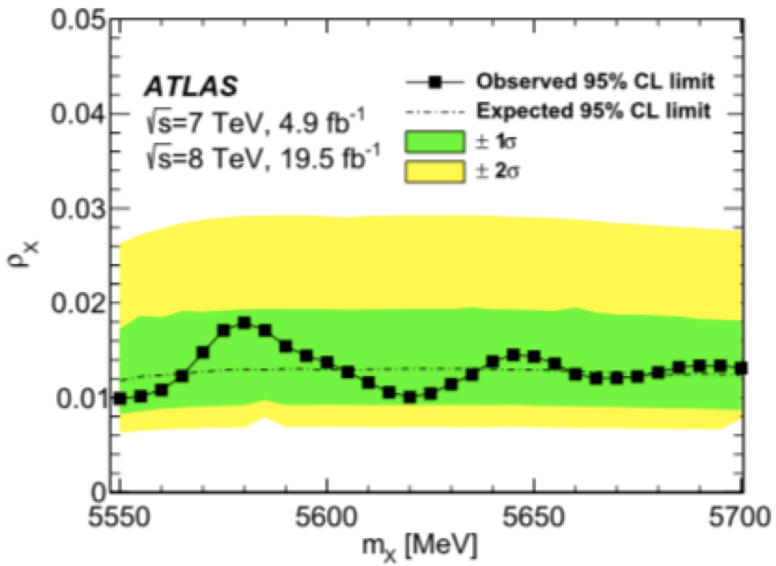
Systematic uncertainty in the relative efficiency (up to 6%) for extrapolation to high-mass values from the low-mass simulation: not accounted in the plot

X(5568) search : upper limits by ATLAS

Similar results (UL) from ATLAS :







$\rho_X < 1.5\%$ @ $95\%CL$ for $p_T > 10GeV$

Upper limits on ρ_X at 95% C.L. (black squares connected by line) at different masses of a hypothetical resonant state X decaying to $B_s^0\pi^\pm$, for events with $p_T(B_s^0) > 10$ GeV. A BW width of $21.9 \pm 6.4(\text{stat})^{+5.0}_{-2.5}(\text{syst})$ MeV is assumed, as reported by D0. The values include systematic uncertainties. The expected 95% C.L. upper limits (central black dot-dashed line) with $\pm 1\sigma$ (green) and $\pm 2\sigma$ (yellow) uncertainty bands on ρ_X are shown as a function of the assumed resonance mass.

$\rho_X \in [1.0 - 1.8]\%$ @ $95\%CL$ for $p_T > 10GeV$

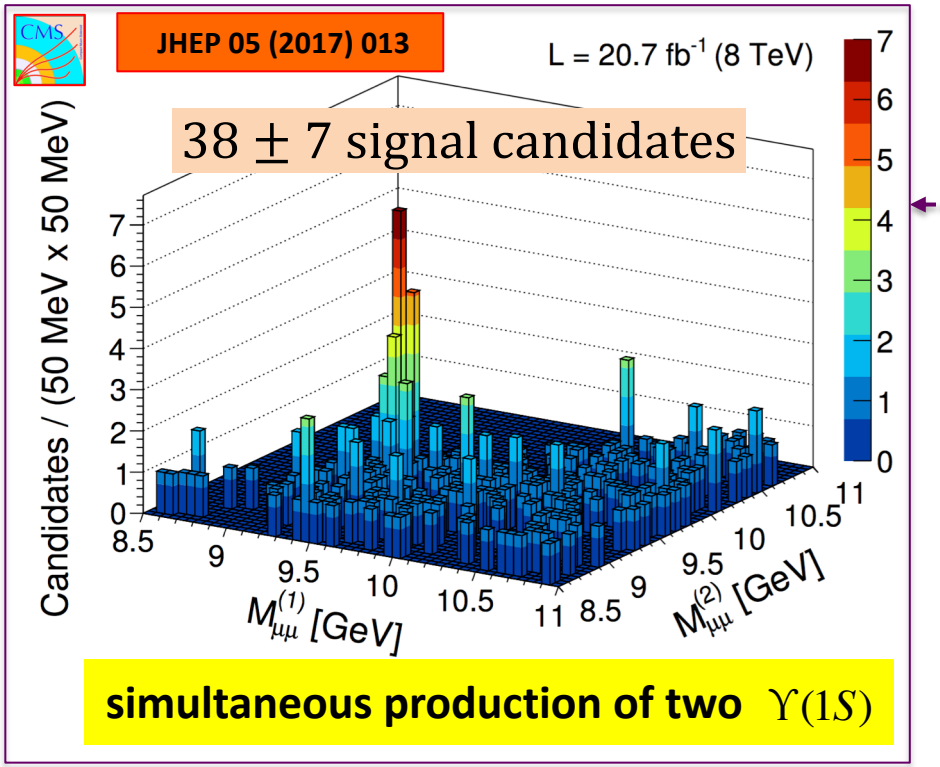
... does not exceed the $\pm 1\sigma$ error band from the expected limit

Summary & Outlook

- **LHC experiments are greatly contributing to exotic hadron spectroscopy and will continue to do it with Run-II data facing new experimental challenges.**

CMS & ATLAS try to deal with selected topics where their contribution can be important [*X(3872)*, *Y(4140)+buddies*, the search for the bottomonium partner of *X(3872)*, *X(5568)*]**.**

Example: new findings in double quarkonia frontier [recent result for *Y(1S)Y(1S)*] can be the preliminary step for **searches of heavy (tetra-)quark bound states with Run-II.**



Additional material

Peaking structures/resonances in the $J/\psi\ \phi$ mass spectrum

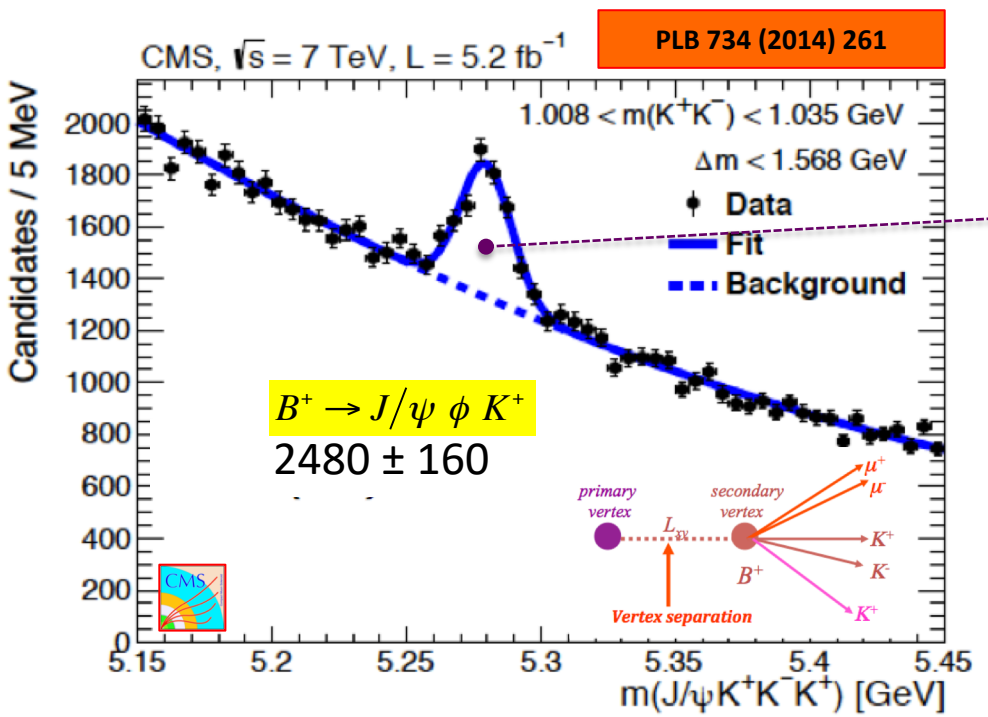
PLB 734 (2014) 261

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

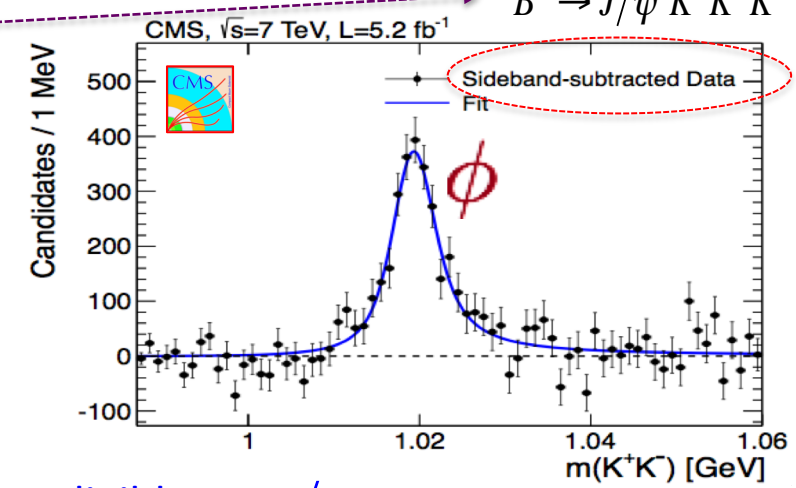
$B^+ \to J/\psi\ \phi\ K^+$ decays @ CMS

- **In 2009/2011 CDF claims [**PRL 102 (2009) 242002; arXiv:1101.6058 (2011)**] to observe two intermediate resonances decaying into $J/\psi\ \phi$ while studying $B^+ \to J/\psi\ \phi\ K^+$ decays, denoted as $Y(4140),\ Y(4274)$.**

- **In 2012 LHCb [**PRD 85 (2013) 091103R**] do not confirm them and provided an upper limit.**



$B^+ \to J/\psi\ K^+K^-K^+ \in [m(B^+) \pm 3\sigma]$



Negligible non-ϕ components

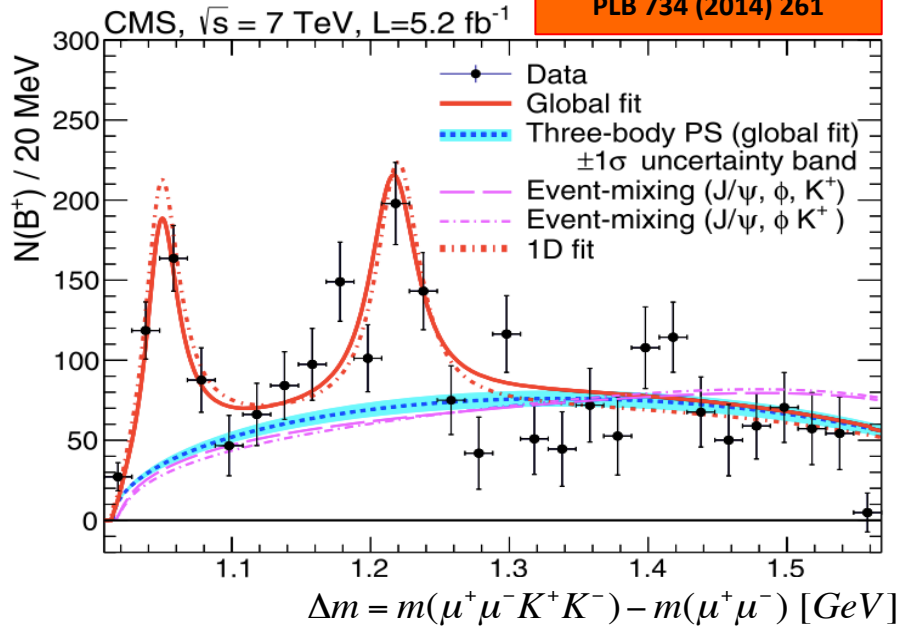
[$B^+ \to J/\psi f_0(980) K^+,\ J/\psi K^+K^-K^+$]

Peaking structures in the $J/\psi\ \phi$ mass spectrum from $B^+ \to J/\psi\ \phi\ K^+$ decays @

- **Observation of** one structure (& evidence for another) in the Δm spectrum by recostructing the $B^+ \to J/\psi\ \phi\ K^+$ decay (after background subtraction by 20*MeV*-sized bin-wise method)

- Fitting with:
  - Signal PDF: S-wave relativistic Breit-Wigner (BW) convolved with mass resolution gaussian
  - Background PDF: 3-body Phase Space Shape (PS)
  - **1-D Fit**: Binned χ^2 fit to the extracted Δm spectrum using the BW and PS shape.
  - **Global 2-D Fit**: simultaneous fit of $m(B^+)$ and Δm with implicit background subtraction

PLB 734 (2014) 261



The $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ spectrum Is considered up to 1.568 *GeV* to avoid re-flections from $B_s \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$ (but whole spectrum also investigated)

Peaking structures in the $J/\psi\ \phi$ mass spectrum from $B^+ \to J/\psi\ \phi\ K^+$ decays @ CMS

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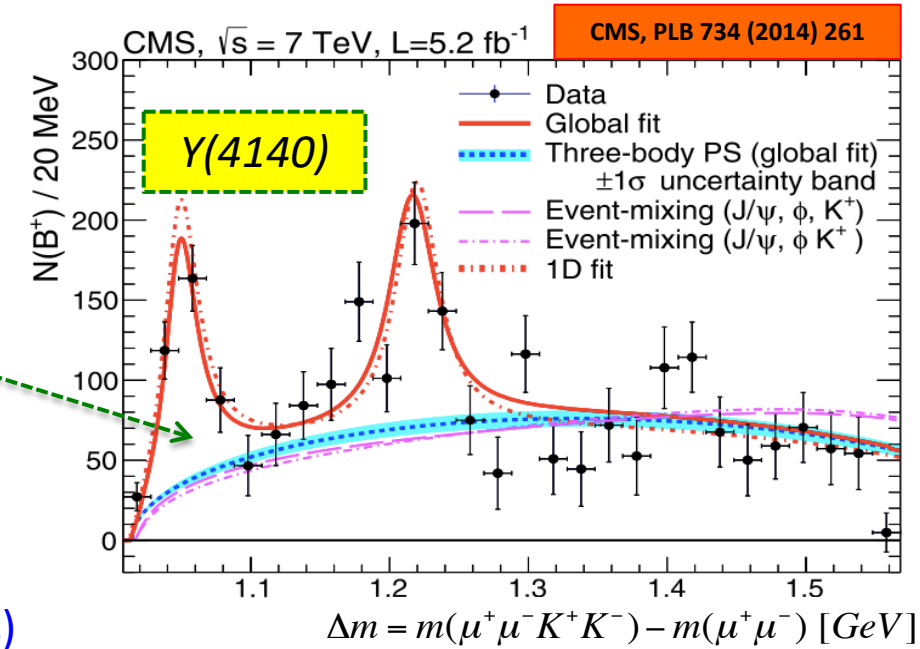

- **Peaking structure @ threshold** (yield: 310 ± 70) with:

$$m = 4148.0 \pm 2.4(\text{stat}) \pm 6.3(\text{syst}) MeV$$

$$\Gamma = 28^{+15}_{-11}(\text{stat}) \pm 19(\text{syst}) MeV$$

  - **observed** with stat. significance $>5\sigma$ (p-value by MC toys)
  - **consistent** with the charmonium-like state, possibly exotic, ***Y(4140)*** from
  - evidence from [**PRD 89 (2014) 012004**]

- Naïve yields' ratio estimate: $Y_{Y(4140)}/Y_{J/\psi\phi K} \approx 0.11 \pm 0.03\%$ consistent with & with previous **UL**

- **Evidence** of additional peak (mass-shifted w.r.t. that may be affected by possible ϕK^+resonances [see next slide]

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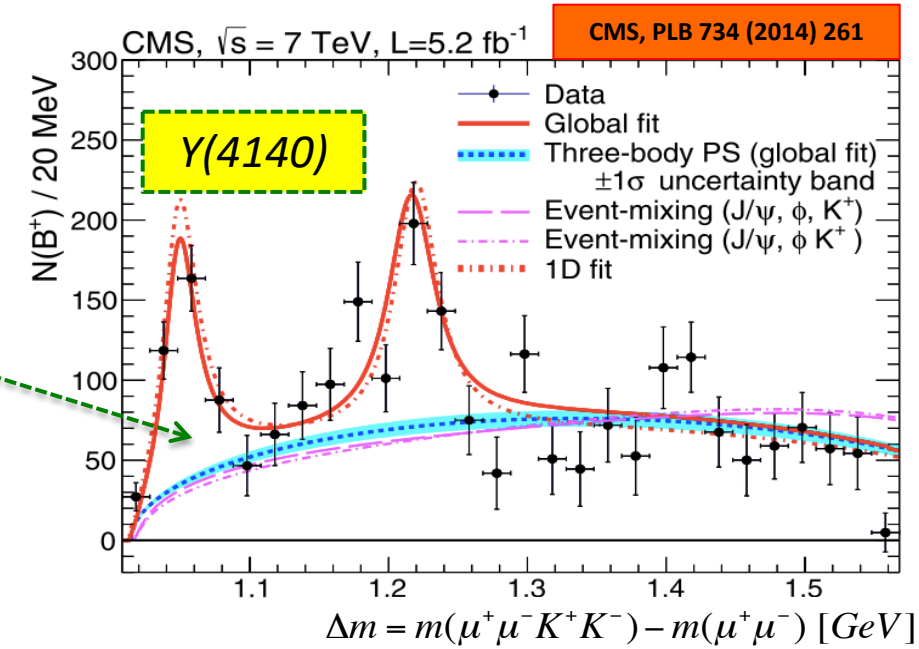

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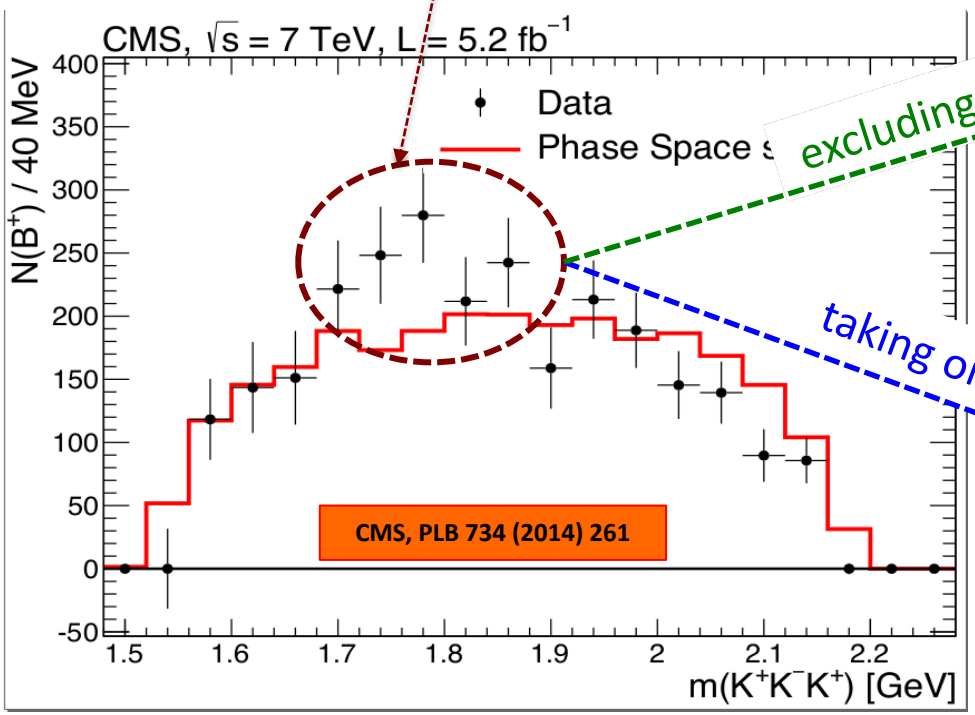
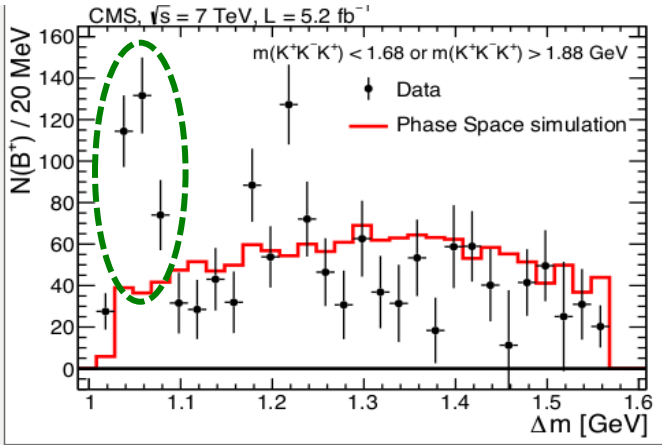
- For the *Y(4140)* decaying into $J/\psi\phi$ several **interpretations** have been proposed: $D_s^* \bar{D}_s^*$ molecule, $cs\bar{c}\,\bar{s}$ tetraquark, threshold kinematic effect, hybrid charmonium, weak transition with $D_s \bar{D}_s$ rescattering

Y(4140)@ CMS : checking reflections

- The ϕK^+ mass distrib. shows an excess w.r.t. PHSP profile in the region where large resonances [$K_2(1770)$ & $K_2(1820)$] (seen in fixed-target exps.) may appear; **reflections studies are carried out:**

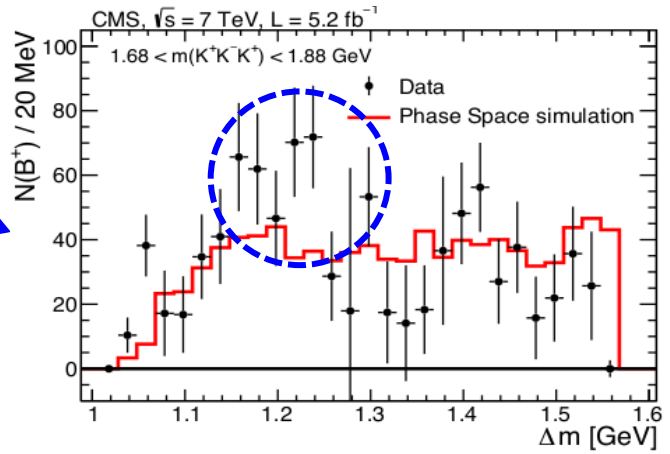


excluding this $m(K^+K^-K^+)$ region



- ***Y(4140)* appears to be uncorrelated to ϕK^+ resonances**

taking only this $m(K^+K^-K^+)$ region



- **Additional peak may be affected by them**

Understanding the nature of both structures needs further investigation & requires a full amplitude analysis (not enough statistics to get a sufficiently pure & sizable B^+ signal for an AA)

Y(4140) & "buddies" : status & prospects

- **Later (2016)** [PRL 118 (2017) 022003; PRD 95 (2017) 012002], **by performing a full amplitude analysis, observed 4 structures in the $J/\psi\ \phi$ spectrum while studying the $B^+ \to J/\psi\ \phi\ K^+$ decay, the $X(4140)$, $X(4274)$, $X(4500)$, $X(4700)$ resonances.**

  Their quantum numbers were determined to be:
  - $J^{PC} = 1^{++}$ **for** $X(4140)$, $X(4274)$
  - $J^{PC} = 0^{++}$ **for** $X(4500)$, $X(4700)$

- **observed inclusively the Y(4140) prompt production** [PRL 115 (2015) 232001]: **needs confirmation @ LHC**

  It is important in the understanding of an exotic state to know if …
  … it is promptly produced and not only seen as an intermediate state in a decay.

- **Prospects for CMS & ATLAS ?**

  - **Work with challenging amplitude analysis technique;**
    because of the high backgrounds Run-II data may be necessary.

  - **Inclusive search to confirm or not the result might be viable by exploting triggers for double charmonia.**
    Because of high background it makes sense to use full Run-2 data !

Backup slides

X(3872) : interpretation - III

A few more details concerning Meng *et al.* [PRD96 (2017) 074014] :

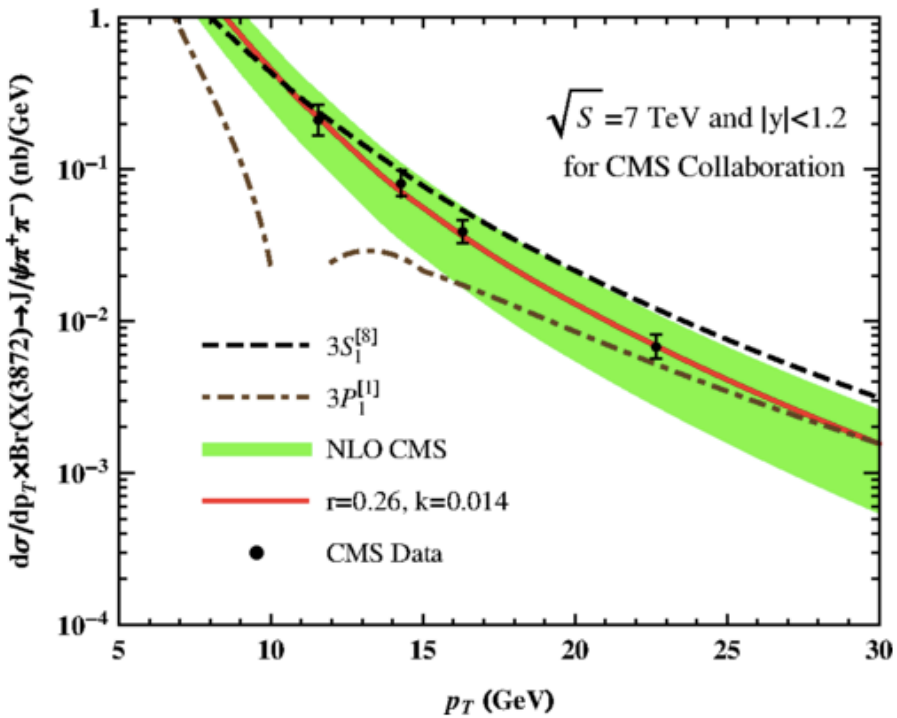
$$d\sigma(pp \to X(J/\psi\pi^+\pi^-)) = d\sigma(pp \to \chi'_{c1}) \cdot k,$$

where p is either a proton or an antiproton, and $k = Z_{c\bar{c}} \cdot Br_0$ with $Br_0 = Br(X \to J/\psi\pi^+\pi^-)$. The feed-down contributions from higher charmonia [e.g., $\psi(3S)$] are negligible for the prompt production of $X(3872)/\chi'_{c1}$, so here "prompt" is almost equal to "direct," and the cross section of χ'_{c1} in Eq. (2) can be evaluated in NRQCD factorization, which is given by

$$d\sigma(pp \to \chi'_{c1})$$
$$= \sum_n d\hat{\sigma}((c\bar{c})_n) \frac{\langle \mathcal{O}_n^{\chi'_{c1}} \rangle}{m_c^{2L_n}}$$
$$= \sum \int dx_1 dx_2 G_{i/p} G_{j/p} d\hat{\sigma}(ij \to (c\bar{c})_n) \langle \mathcal{O}_n^{\chi'_{c1}} \rangle,$$

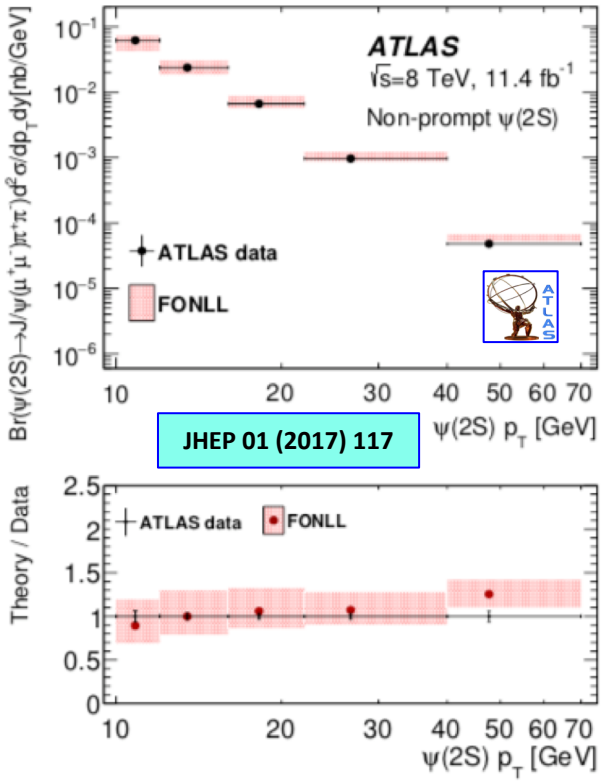
where $G_{i,j/p}$ are the parton distribution functions (PDFs) of p, and the indices i, j run over all the partonic species. The matrix element $\langle \mathcal{O}_n^{\chi'_{c1}} \rangle$ is marked by "n," which denotes the color, spin and angular momentum of the intermediate $c\bar{c}$ pair. Here we will evaluate the cross section at NLO in α_s and at LO in v (the relative velocity of $c\bar{c}$ in the rest frame of χ'_{c1}); therefore, only $n = {}^3P_1^{[1]}$ and ${}^3S_1^{[8]}$ are present here.

The outcome of the fits at CMS p_T distribution can well account for the recent ATLAS data, even at a larger range of p_T, for the CDF total xsection, and are consistent with the value of *k* constrained by the B-meson decay data.



Non-prompt X(3872) production compared with FONNL

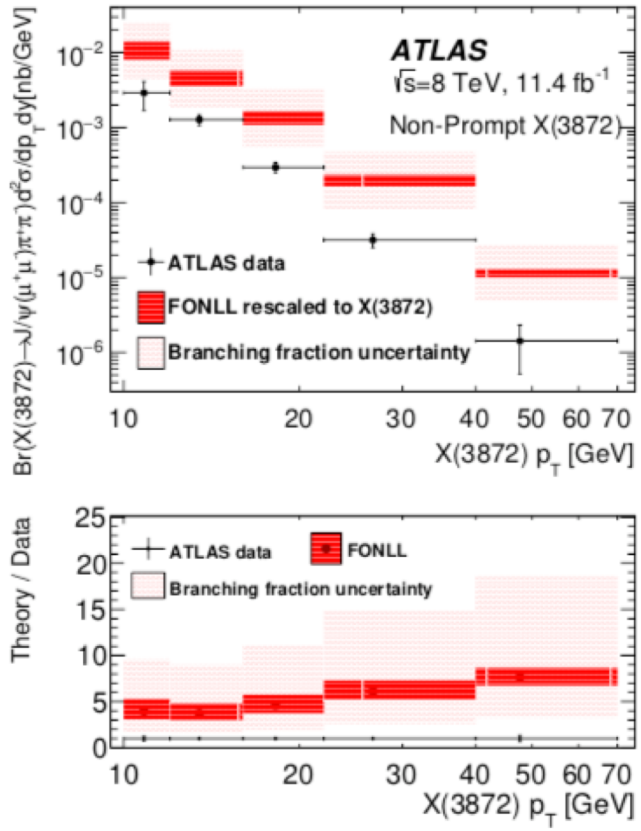
- Measured differential Xsection for non-prompt $\psi(2S)$ compared with predictions from FONLL calculations :



JHEP 01 (2017) 117

FONLL calculation describe the data well over the whole range of p_T.

Measured differential Xsection for non-prompt *X(3872)* compared with predictions from FONLL calculations :



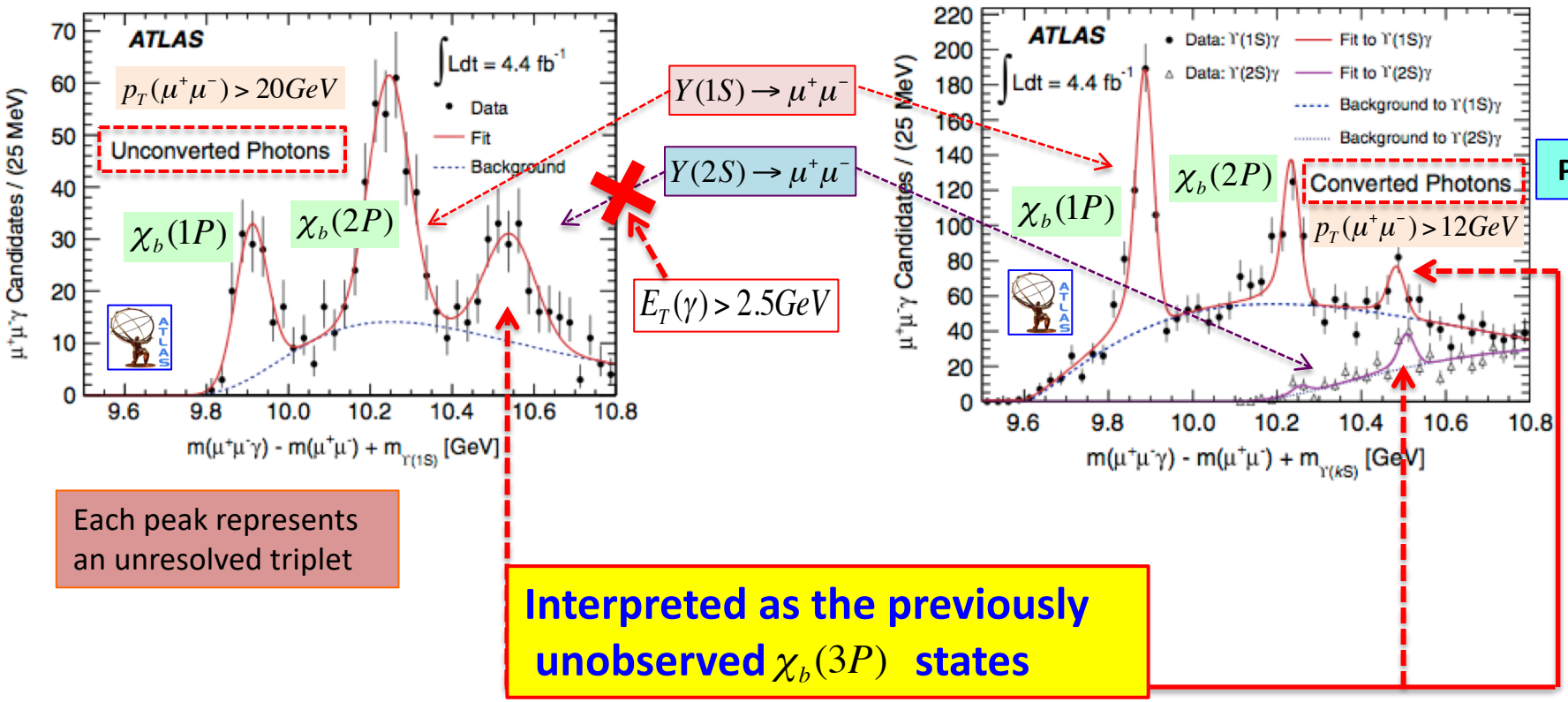
This is compared to a calculation based on the FONLL model prediction for $\psi(2S)$, re-calculated for $X(3872)$ using the kinematic template for the non-prompt $X(3872)/\psi(2S)$ ratio shown in figure 3(b) and the effective value of the product of the branching fractions $\mathcal{B}(B \to X(3872))\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (1.9 \pm 0.8) \times 10^{-4}$ estimated in ref. [11] based on the Tevatron data [33]. This calculation overestimates the data by a factor increasing with p_T from about four to about eight over the p_T range of this measurement.

Observation of $\chi_b(3P)$ system by ATLAS - I

- **has reconstructed χ_b *P-wave* quarkonium states** [each being a closely spaced triplet spin states ($\chi_{bJ},\ J=0,1,2$)] **through the radiative decays** $\chi_b(nP) \to Y(1S,2S)\gamma$

- **The χ_b cands formed associating a reco $Y \to \mu^+\mu^-$ cand with a reconstructed either unconverted or converted γ.**

Invariant mass difference $m(\mu^+\mu^-\gamma) - m(\mu^+\mu^-)$ calculated to minimize effect of $Y \to \mu^+\mu^-$ mass resolution:



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Each peak represents an unresolved triplet

Interpreted as the previously unobserved $\chi_b(3P)$ states

Observation of $\chi_b(3P)$ system by ATLAS - II

- **has reconstructed** χ_b ***P-wave* quarkonium states** [each being a closely spaced triplet spin states ($\chi_{bJ},\ J=0,1,2$)] **through the radiative decays** $\chi_b(nP) \to Y(1S,2S)\gamma$

- **Later (2014) LHCb was able to estimate the two (*J=1,2*) masses (*) and to measure for the 1st time the** $Y(3S)$ **production fraction (~40%) due to** $\chi_b(3P) \to Y(3S)\gamma$ **(first observation)**

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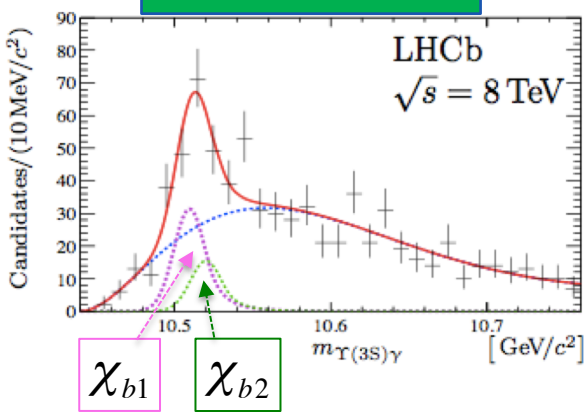
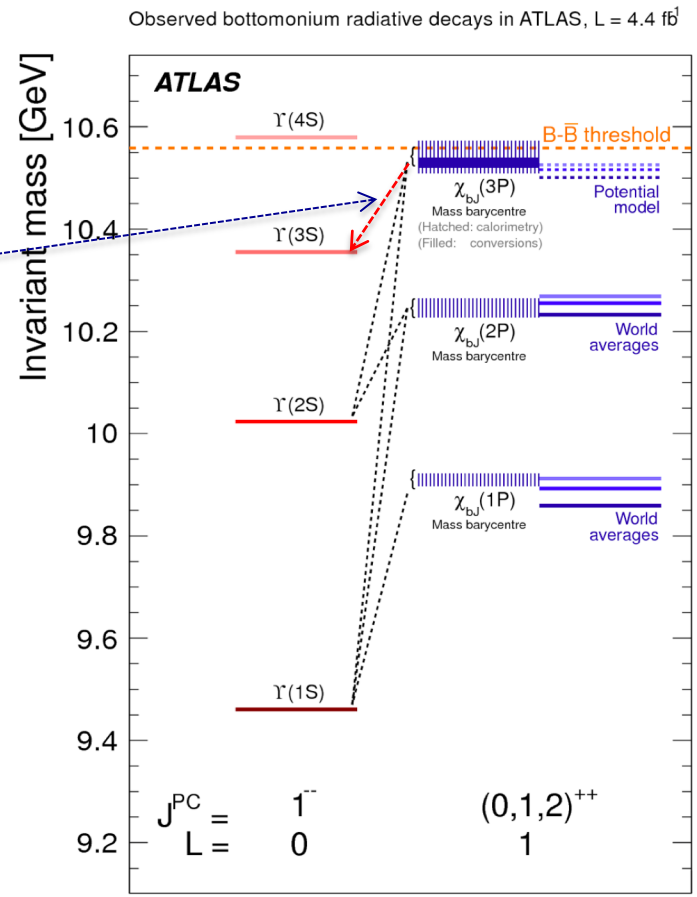




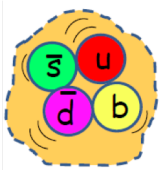
(*) **by assuming** $\Delta m \equiv 10.5\text{MeV}$ **(in agreement with our new measured value)**

X(5568) interpretation

- The *X(5568)* should have a 4-quark content with quarks of different flavours (*b, s, u, d*).

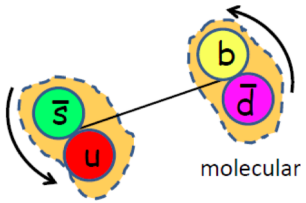
  It could be either:

  - a compact tetraquark (tightly bound di-quark anti-diquark pair such as … $[b\ u][\bar{d}\ \bar{s}]$, $[b\ \mathrm{d}][\bar{s}\ \bar{u}]$, $[s\ u][\bar{b}\ \bar{d}]$, $[s\ \mathrm{d}][\bar{b}\ \bar{\mathrm{u}}]$)



  - a loosely bound $B_d^0 K^{\pm}$ molecular state

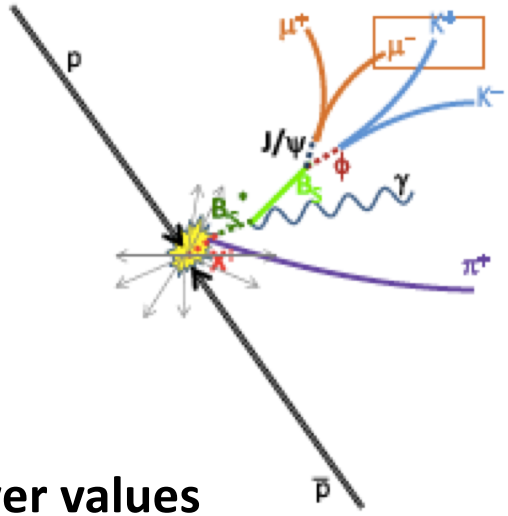
    [disfavoured: binding energy ~200*MeV*]



- If produced in an S-wave its spin-parity would be: $J^P = 0^+$

- However it cannot be excluded the following decay (with γ undetected):

$$X(5568)^{\pm} \rightarrow B_S^{0*}\pi^{\pm} \rightarrow B_S^0\ \gamma\ \pi^{\pm}$$



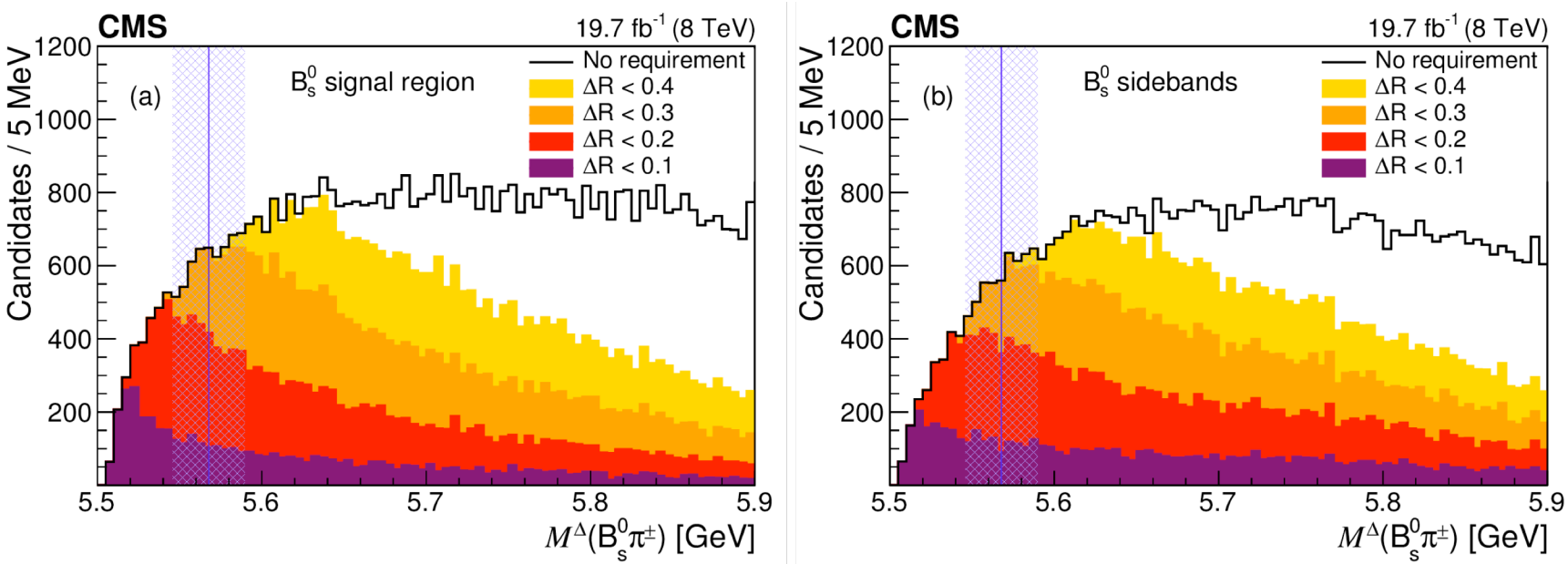
In this case :

- $J^P = 1^+$
- the mass of the new state would be shifted towards lower values

  (thus increasing the energy difference from BK threshold : molecule even more unlike!)

X(5568) search : precaution in selection

Constraints on the angle ΔR (called "cone-cuts" in jargon) between the momenta of the B_s^0 & $\pi^{\pm}$ candidates (*) are not imposed in CMS analysis, because such requirements sculpt the $B_s^0\pi^{\pm}$ invariant mass in a nontrivial way (for instance producing a peaking shape) :

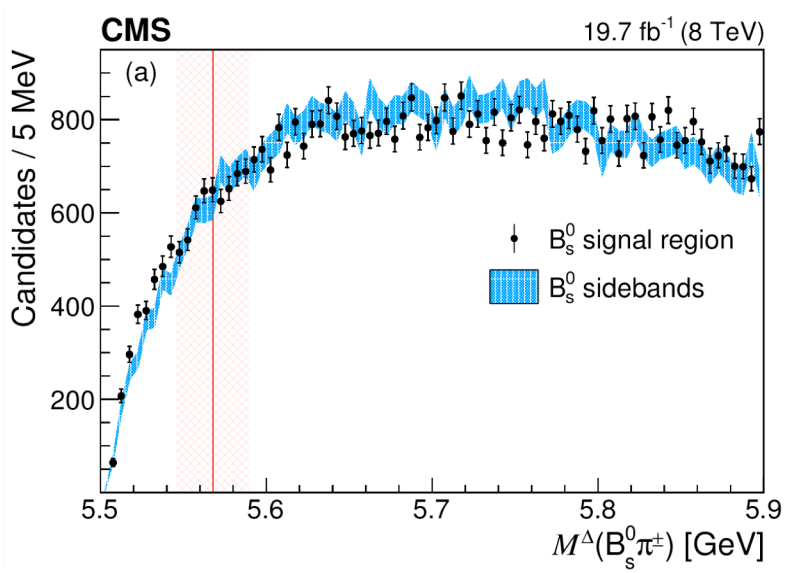


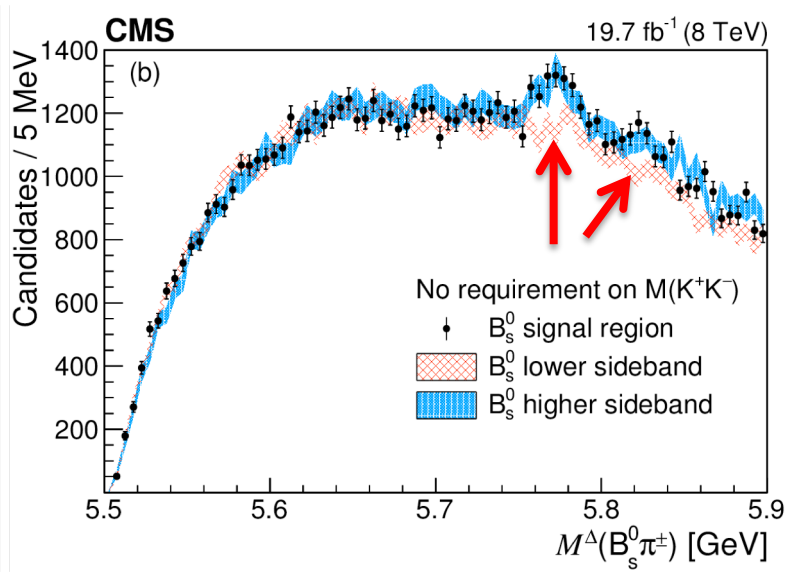
$\Delta R < 0.3$: cone-cut applied by

(*) $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

X(5568) search : selection check

To verify the reconstruction procedure the requirement $m(K^+K^-) \in M_{PDG}(\phi) \pm 10 MeV$ **is removed, thus allowing the** $B^0 \to J/\psi K\pi$ **decay to contribute to the** B_s^0 **signal & the higher sideband regions of the** $m(J/\psi K^+K^-)$ **spectrum (**as checked by simulation**) because of misreconstrution. Tighter selection criteria are imposed to reduce the BKG level.**





The two excesses in $M^{\Delta}(B_s^0\pi^{\pm})$ **for events only in the higher BKG region and** B_s^0 **signal region are consistent with contribution from the decays:** $B_1(5721)^{\pm} \to B^{*0}\pi^{\pm} \to B^0\cancel{\gamma}\,\pi^{\pm}$

$B_2^*(5747)^{\pm} \to B^{(*)0}\pi^{\pm} \to B^0(\cancel{\gamma})\,\pi^{\pm}$

… where the photon is not reconstructed while $B^0 \to J/\psi K\pi$ **is misrecontructed as** $B_s^0 \to J/\psi KK$**!**

Note that the peaks are shifted by $m(B_s^0) - m(B^{(*)0})$ w.r.t. the nominal masses of the $B_{1,2}^{(*)}$ states.

Further search in the $B_s^0\pi^\pm$ system

The extension of $M^\Delta(B_s^0\pi^\pm)$ investigated range (w.r.t. LHCb) is important, for instance, for the following reason:

PHYSICAL REVIEW D **94**, 034036 (2016)

$B_c^\pm$ decays into tetraquarks

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(Received 9 April 2016; published 23 August 2016)

The recent observation by the D0 collaboration of a narrow structure $X(5568)$ consisting of four different quark flavors $bdus$, has not been confirmed by LHCb. In the tightly bound diquark model, we estimate the lightest $bdus$, 0^+ tetraquark at a mass of about 5770 MeV, approximately 200 MeV above the reported $X(5568)$, and just 7 MeV below the $B\bar{K}$ threshold. The charged tetraquark is accompanied by $I = 1$ and $I = 0$ neutral partners almost degenerate in mass. A $bdus$, S-wave, 1^+ quartet at 5820 MeV is implied as well. In the charm sector, $cdus$, 0^+ and 1^+ tetraquarks are predicted at 2365 and 2501 MeV, about 40–50 MeV heavier than $D_{s0}(2317)$ and $D_{s1}(2460)$. The $bdus$ tetraquarks can be searched in the hadronic debris of a jet initiated by a b. However, some of them may also be produced in B_c decays, $B_c \to X_{b0} + \pi$ with the subsequent decays $X_{b0} \to B_s + \pi$, giving rise to final states such as $B_s\pi^+\pi^0$. We also emphasize the importance of B_c decays as a source of bound hidden charm tetraquarks, such as $B_c \to X(3872) + \pi$.

To be seen as resonant $B_s\pi$ states, their masses should lie below the BK threshold. A good part of the $B_s\pi$ invariant mass spectrum is excluded by the LHCb, but still there is a window of opportunity left unexplored so far.