Exotic hadron spectroscopy results & perspectives in CMS

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(on behalf of CMS Collaboration)

UNIVERSITÀ DEGLI STUDI
DI BARI "ALDO MORO" &
I.N.F.N. SEZIONE DI BARI

13^{th} March 2018 / Bound States in strongly coupled systems – Arcetri (Italy)

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**
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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**
- X_b **search**
- Y **resonances in** $J/\psi\,\phi$ **system**
- ***X(5568)*** **search**

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

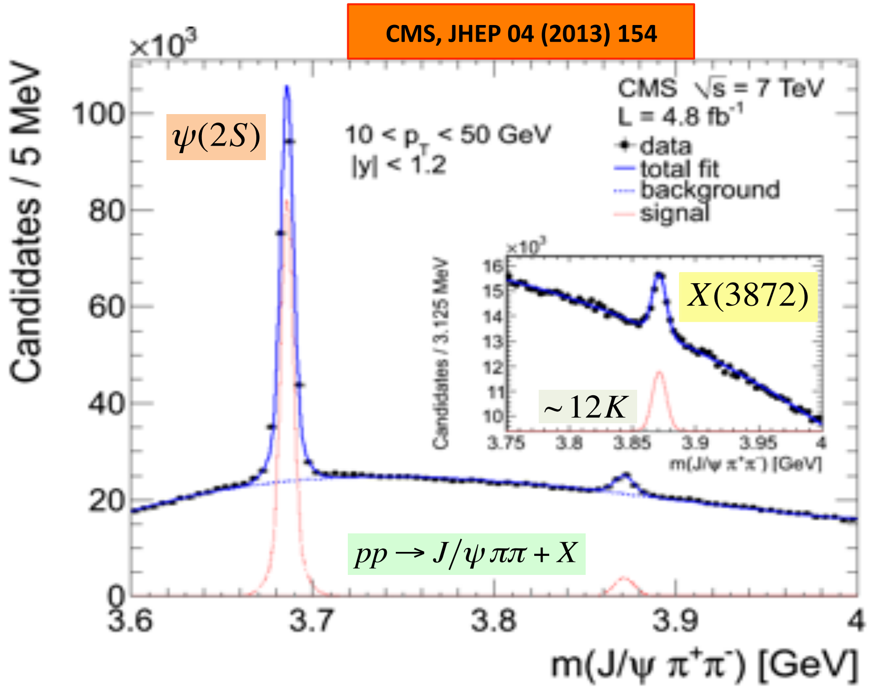
JHEP 04 (2013) 154

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

X(3872) @ LHC

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

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



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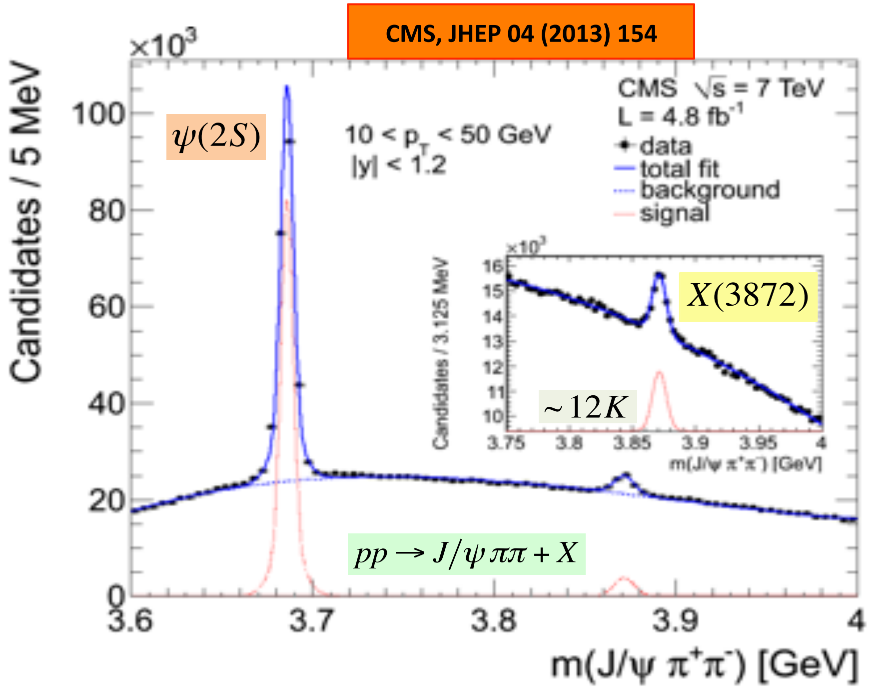
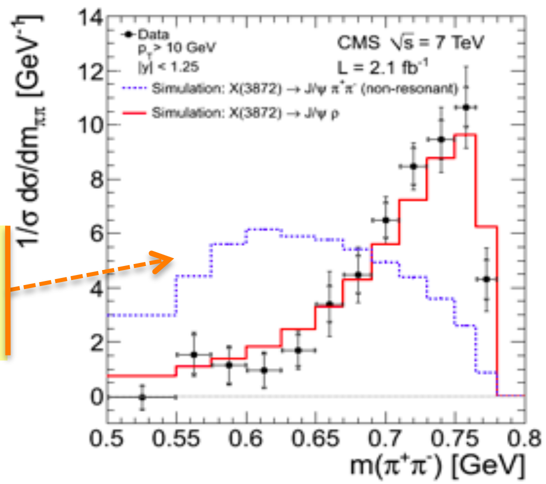
  - [CMS] **inclusively reconstructed the *X(3872)* in the** $J/\psi \pi\pi$ **final state & studied (with** $7 TeV$ **data) :**
    - **Xsection ratio** w.r.t $\psi(2S)$
    - **non-prompt component** *vs* p_T
    - **prompt X(3872) prod. xsection**

    → next slides

    - **inv. mass distrib. 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])





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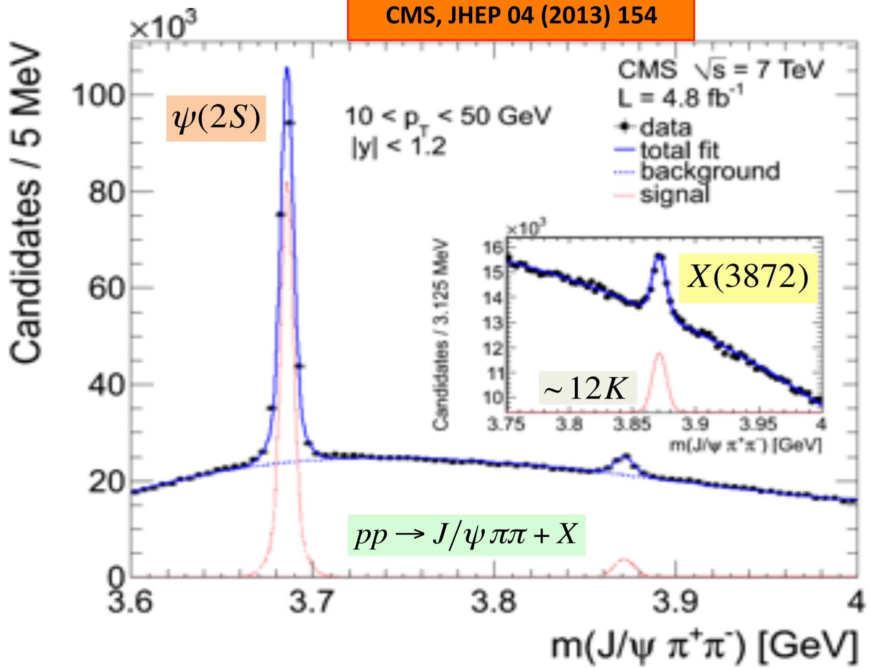
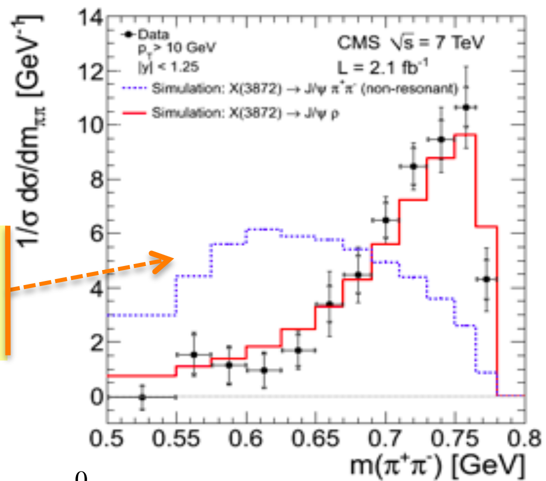
CMS, JHEP 04 (2013) 154





- [LHCb] **performed 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, thus unambiguously determining the quantum numbers:** $J_X^{PC} = 1^{++}$

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

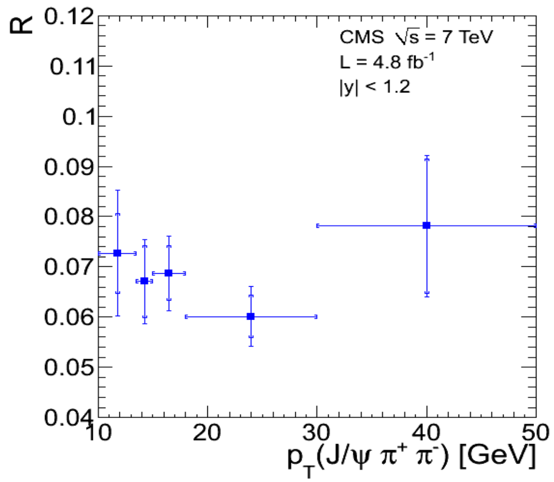
X(3872) @ CMS : Xsection x BF ratio [w.r.t. $\psi(2S)$]

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

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

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) & $\psi(2S)$ unpolarized and $J_X^{PC} = 1^{++}$

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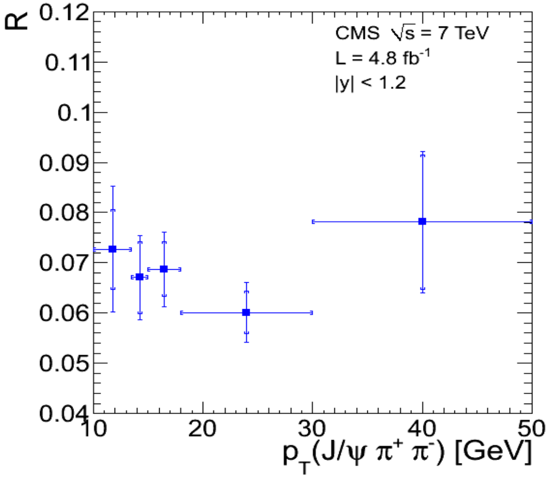

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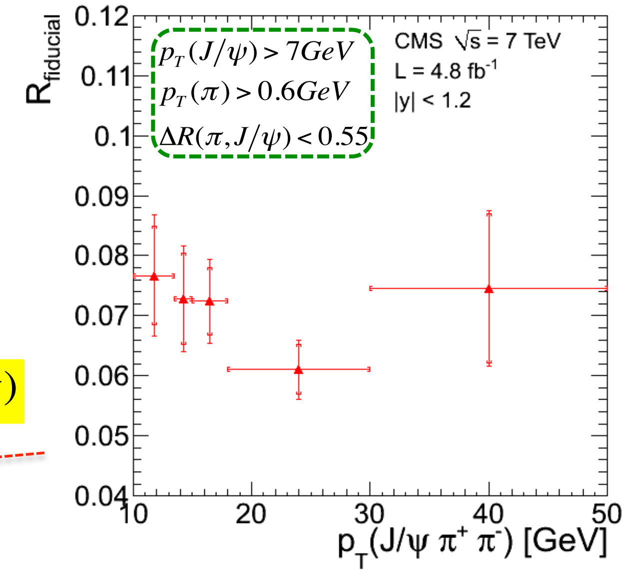
- Acceptance corrections depend on assumptions on the angular distribution of the final states (production mechanism of the X(3872) is unknown) ➡ a result without them in a fiducial region is given :

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

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

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

NO significant dependence on the p_T

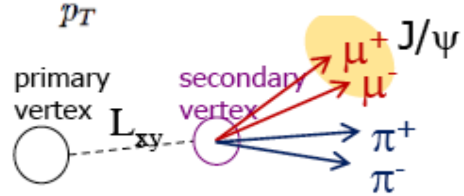


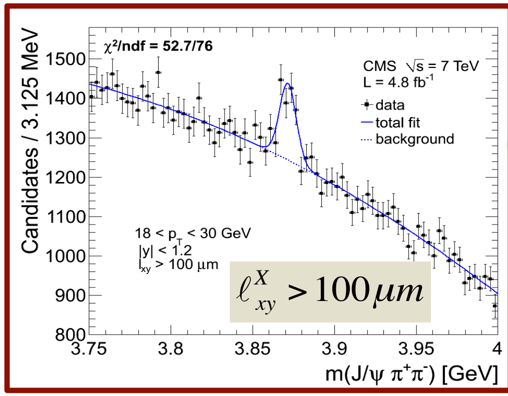
- The *X(3872)* can be produced from B hadrons' decays into a secondary vertex :
  prompt & non-prompt components can be separated by pseudo-proper decay length

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

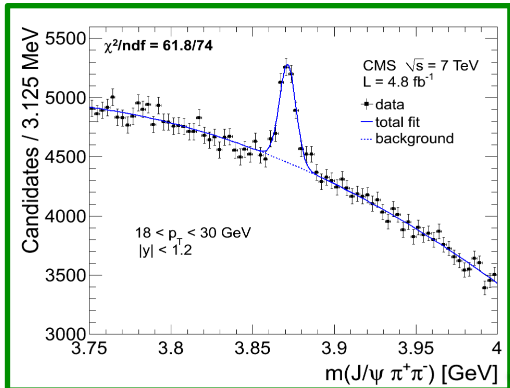
… for which prompt-fraction is negligible (<0.1%) [MC]

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





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



X(3872) @ CMS : non-prompt fraction

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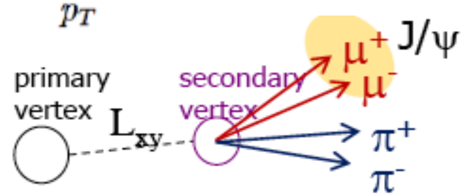

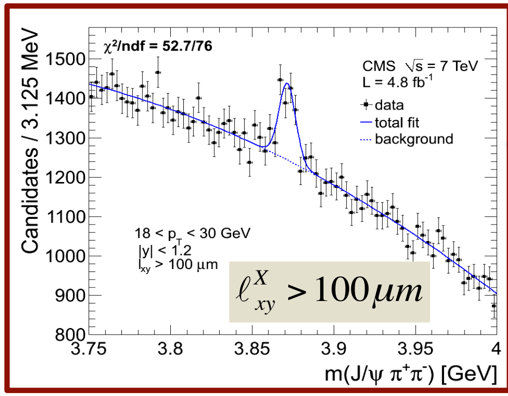

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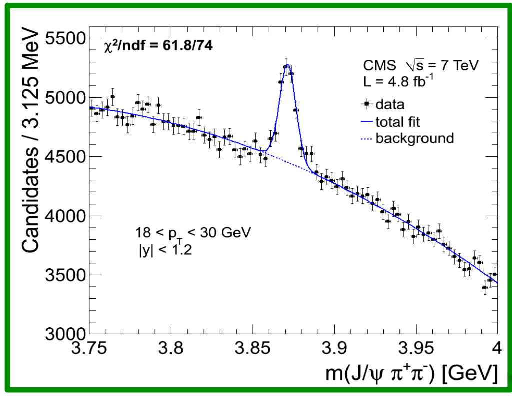
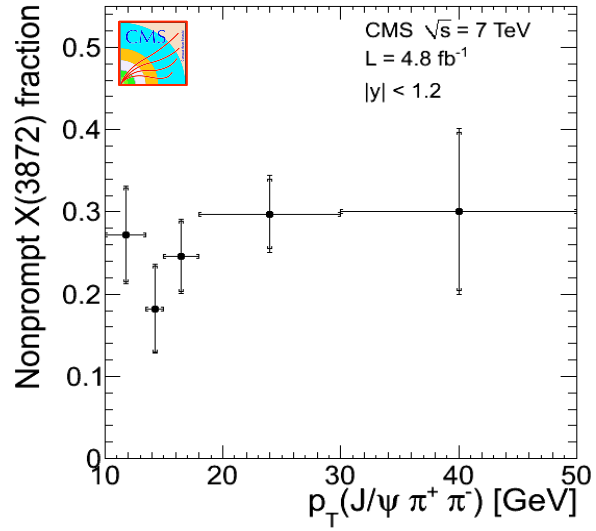


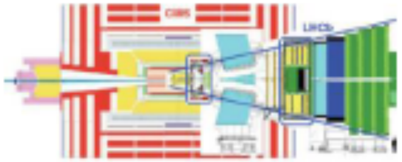
- **non-prompt fraction : NO dependence on p_T**
- integrating over $10 < p_T < 50 GeV$(for $|y| < 1.2$): $f_{NP} \cong 0.263 \pm 0.023 \pm 0.016$

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



- In agreement with recent results by ATLAS [JHEP 01 (2017) 117]

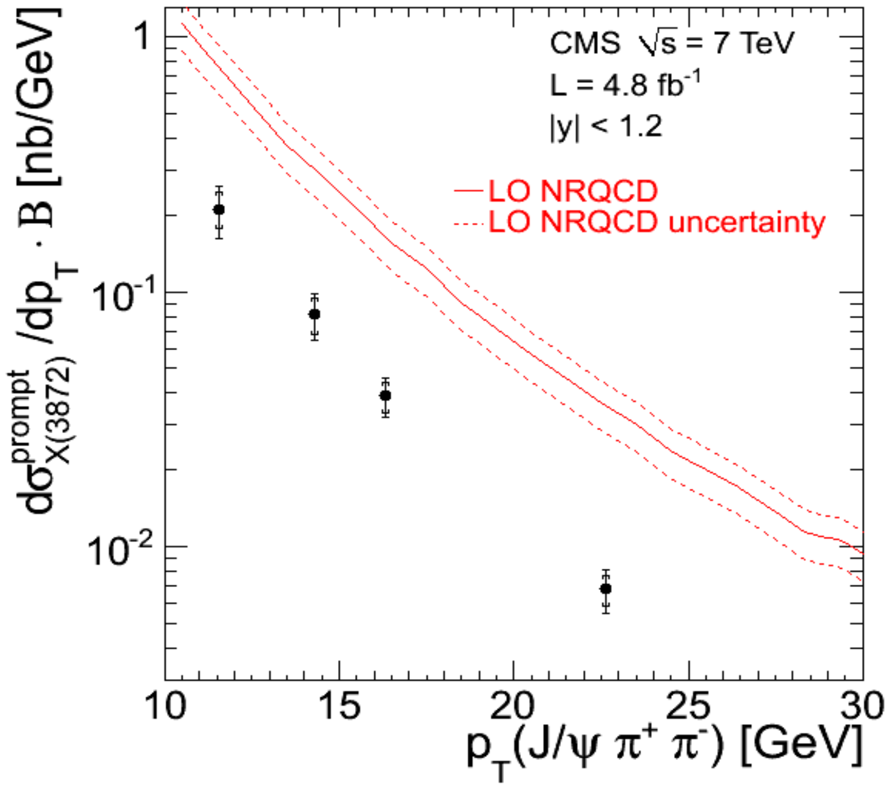
X(3872) @ CMS : prompt production cross section



- 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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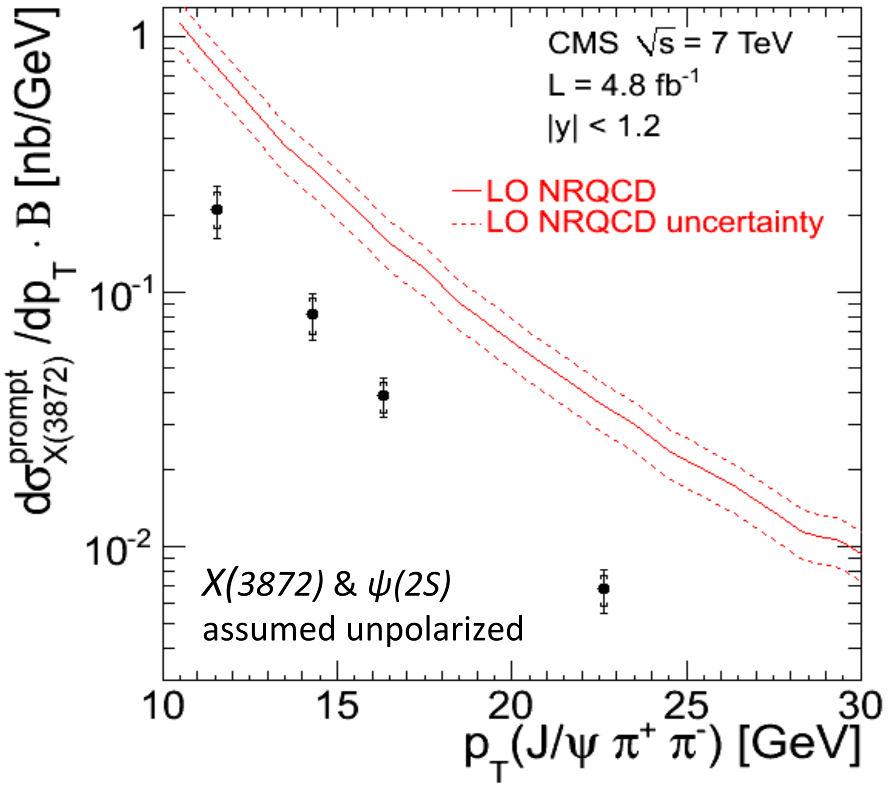

- Results are compared with a theoretical prediction based on NRQCD factorization @ LO approach by Artoisenet & Brateen [PhysRevD.81.114018] with calculations normalized using Tevatron results, modified by the authors to match CMS phase-space
- The shape is reasonably well described by the theory while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

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

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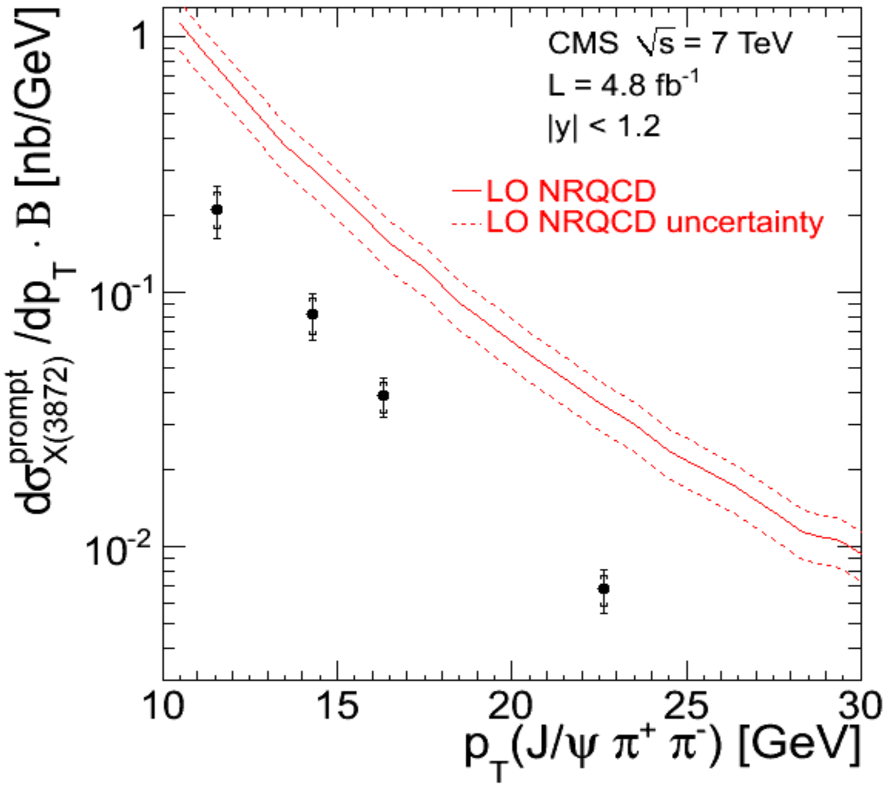

Predictions by Artoisenet & Brateen assume, within an S-wave molecular model, the relative momentum of the mesons being bound by an upper limit of 400*MeV* which is quite high for a loosely bound molecule, but they assume it is possible as a result of rescattering effects.

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*)**
    … 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**

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

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Recent results on $X(3872)$ production from ATLAS [JHEP 01 (2017) 117] have been compared with the latter model (next slide)

Comparison 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

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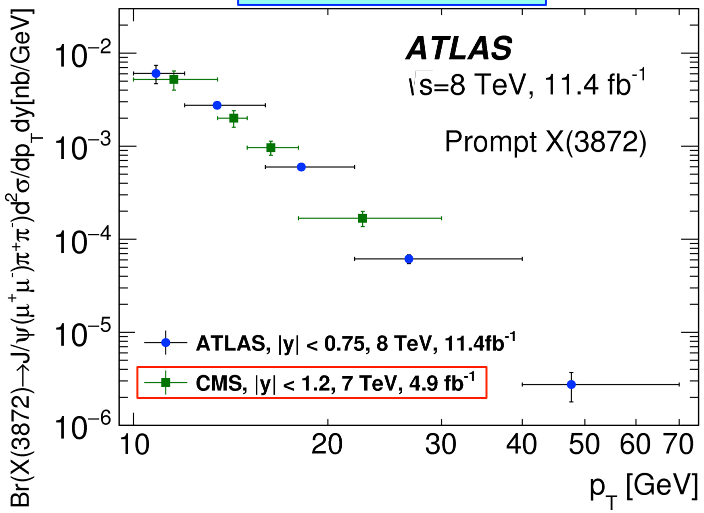
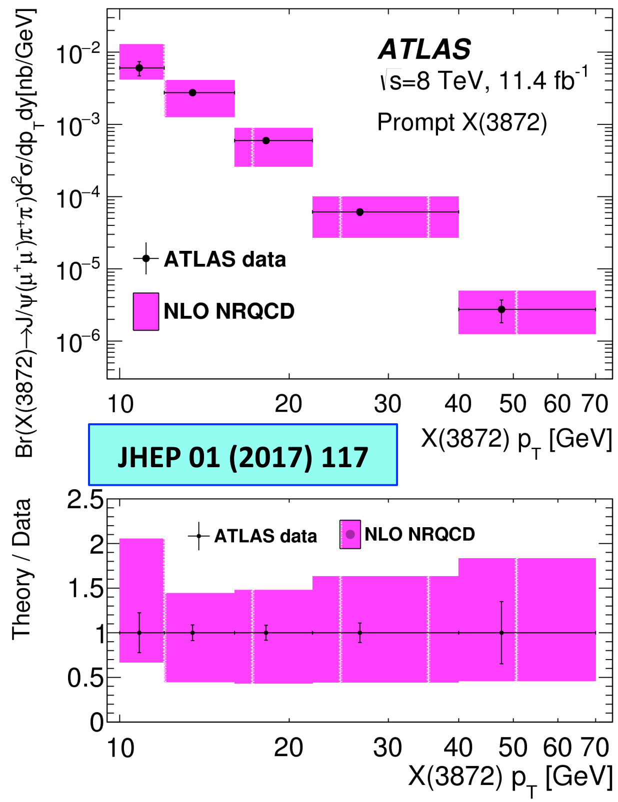


- **Measured prompt production xsection (times BFs), as a function of p_T, is compared to NLO NRQCD predictions assuming the $X(3872)$ modelled as a mixture of $\chi_{c1}(2P)$ & a $\bar{D}^0 D^{*0}$ molecular state** by Meng *et al.* [PRD96 (2017) 074014].

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



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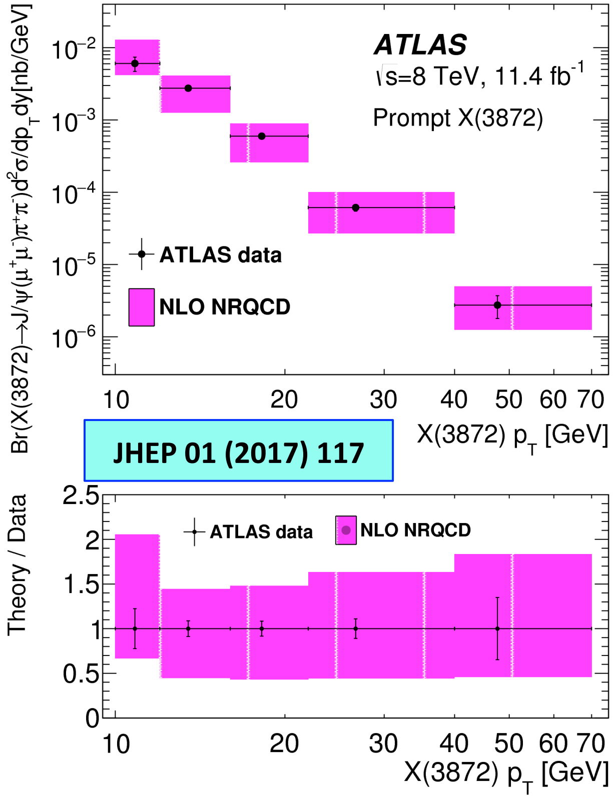

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- **Prospects for new measurements at CMS concerning the** $X(3872)$ **?**
  - Precision measurements using non-prompt $X(3872)$ from B decays may use displaced J/ψ triggers also for Run-II data. However it is uncertain if this could add info to the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

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

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

- **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.**

- 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 $\Upsilon(2S), \Upsilon(3S)$ - in the $\Upsilon(1S)\,\pi^+\pi^-$ spectrum within $10 \div 11 GeV$ range [expecting **narrow width** & possibly **sizable BF** similarly to X(3872)]

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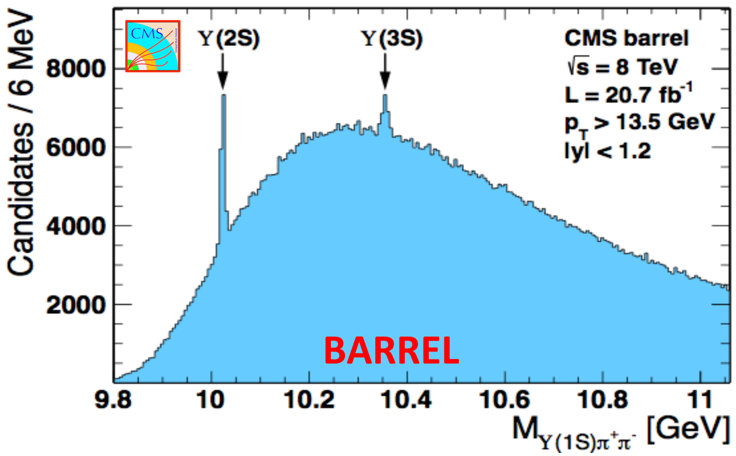
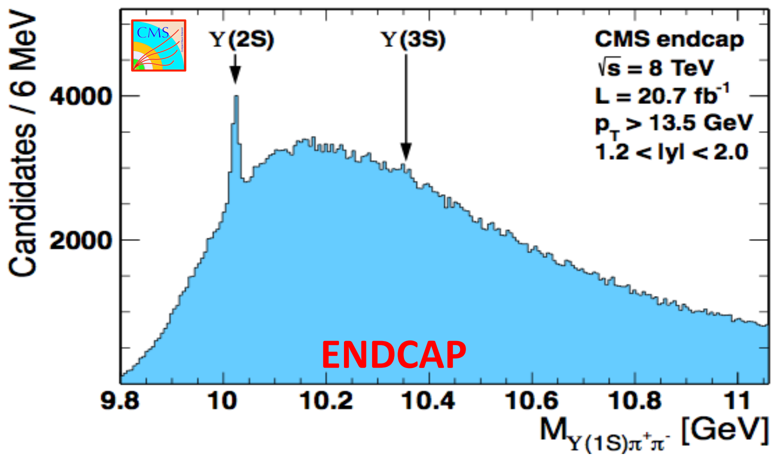




- **For each mass point of a mass scan (by 10 *MeV*-sized steps), the mass spectrum is fitted** (gaussian signal with width fixed to values from the simulation & 3rd order polynomial bkg) **and** R **is evaluated as ...**

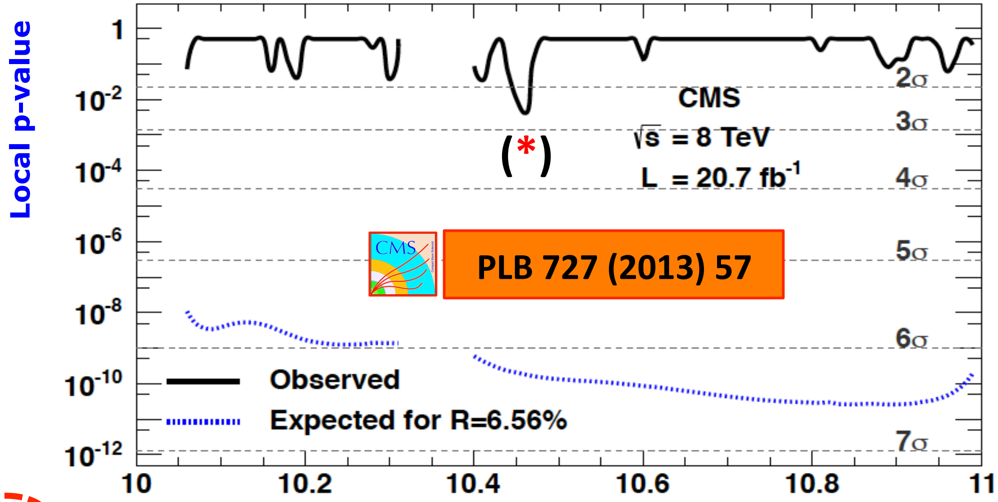
observed YIELDS

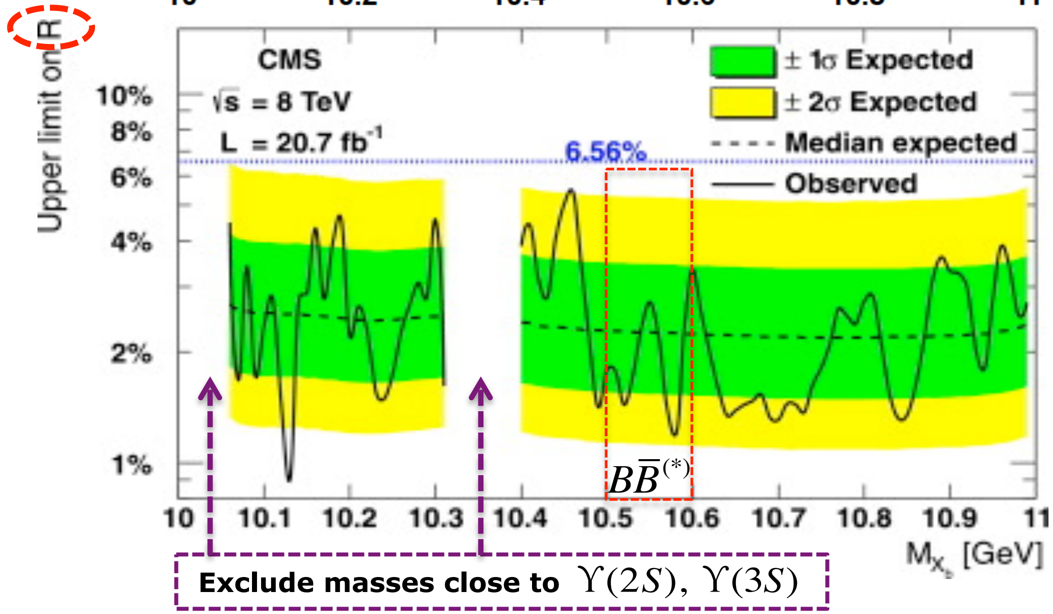
$$R = \frac{N^{obs}_{X_b}}{N^{obs}_{\Upsilon(2S)}} \cdot \frac{\varepsilon_{\Upsilon(2S)}}{\varepsilon_{X_b}}$$

overall EFFICIENCIES estimated from SIMULATION

Assumptions in simulation:

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





... and a local *p-value* is calculated
(asymptotic approach & barrel/endcap combination)
[(*) : smallest *p-value* = 0.004 $\Rightarrow 2.8\sigma \xrightarrow{LEE} 0.8\sigma$ **]**

NO significant eccess observed ⇒ **95% CL upper limits set on the ratio** R **:**

observed UL range: 0.9% to 5.4%

- **Similar results from** ATLAS **JHEP 740 (2015) 199**

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

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

($\pi^+\pi^-\pi^0$: ω^0; $\pi^+\pi^-$: 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:**

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

$$X_b \to \chi_b(1P)\pi^+\pi^- \quad (\chi_b(1P) \to \Upsilon(1S)\gamma)$$

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

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

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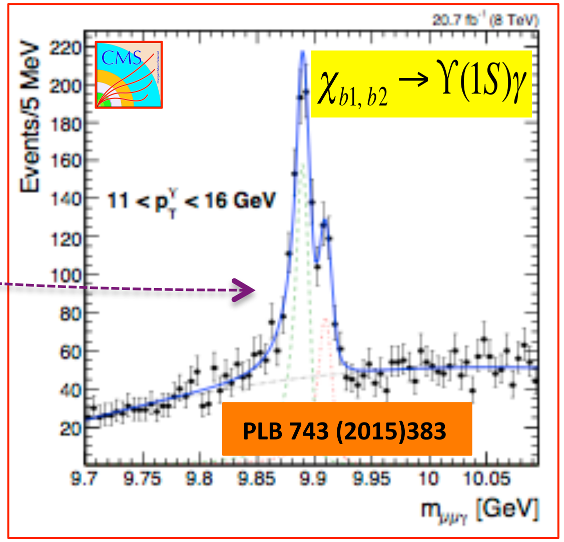
- **NOT easy task for CMS & ATLAS :**

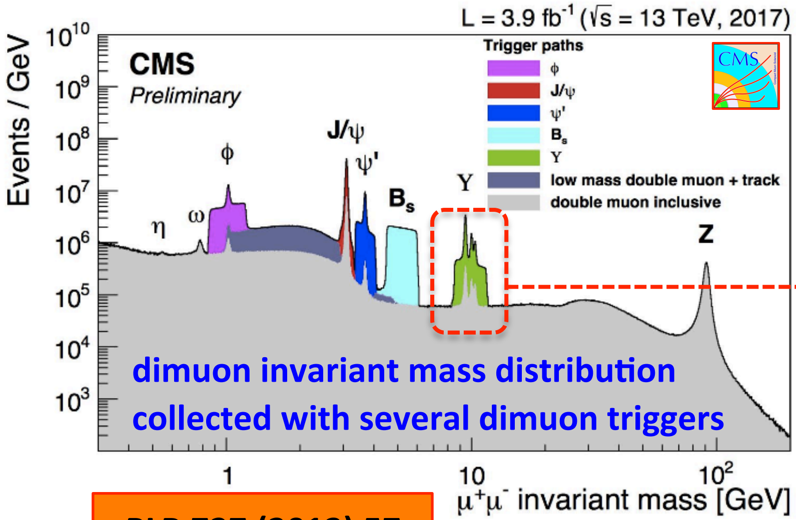
  Reconstruction of SOFT photons by conversions into the tracker …
  - … provides enough mass resolution to resolve the two peaks (separated by 19*MeV*)
  - **… BUT conversion efficiency is LOW !**



- **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)



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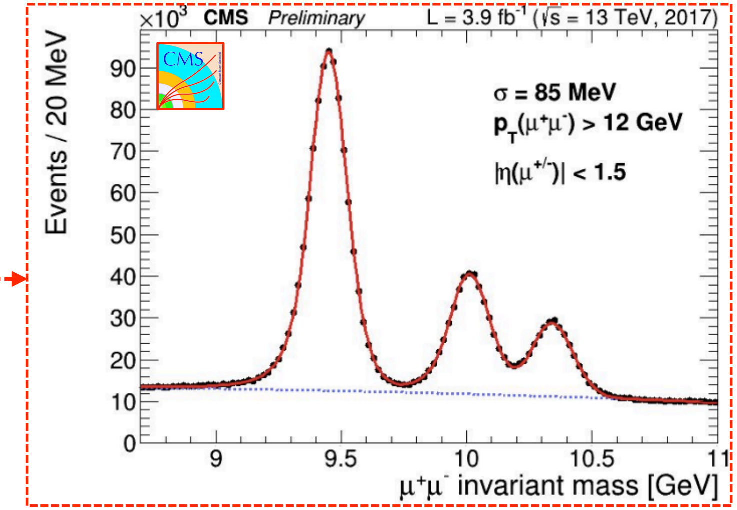
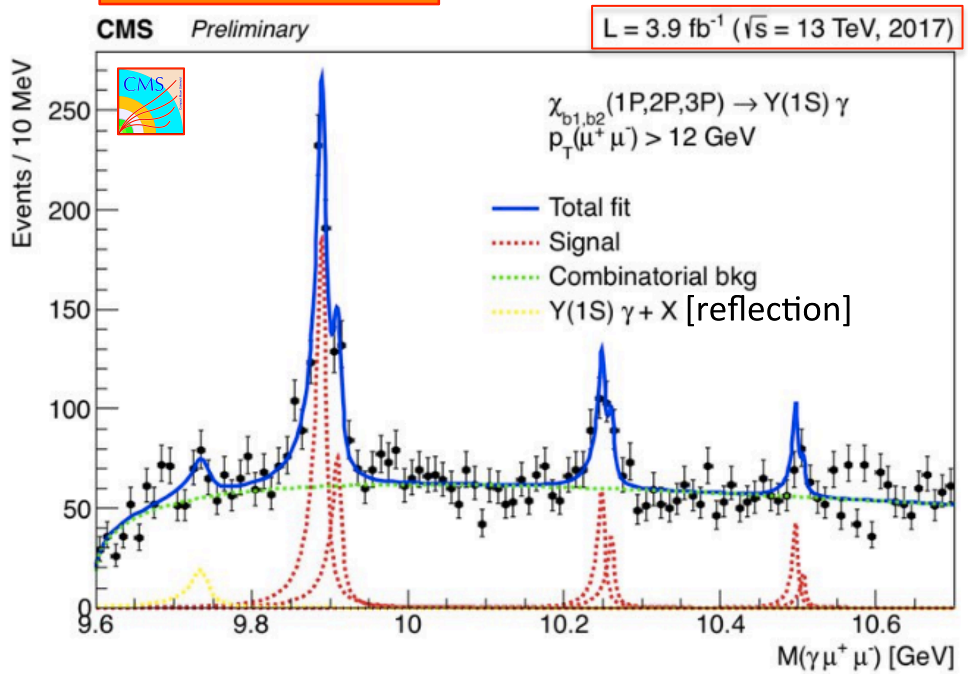


CMS-DP- 2017-029

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



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

- 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 $X(3872)$.

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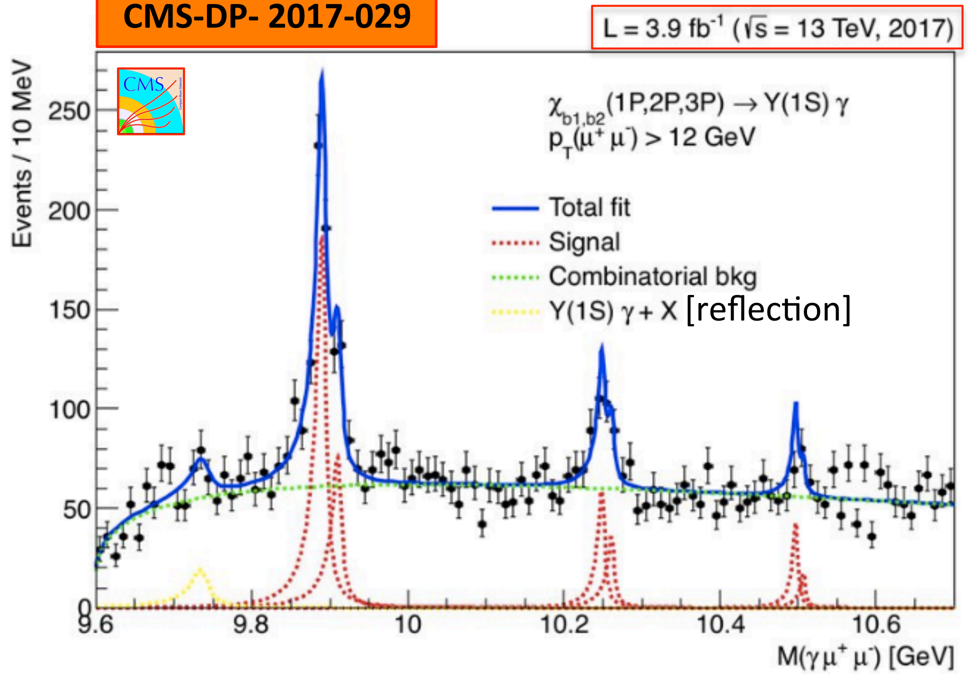
CMS-DP- 2017-029



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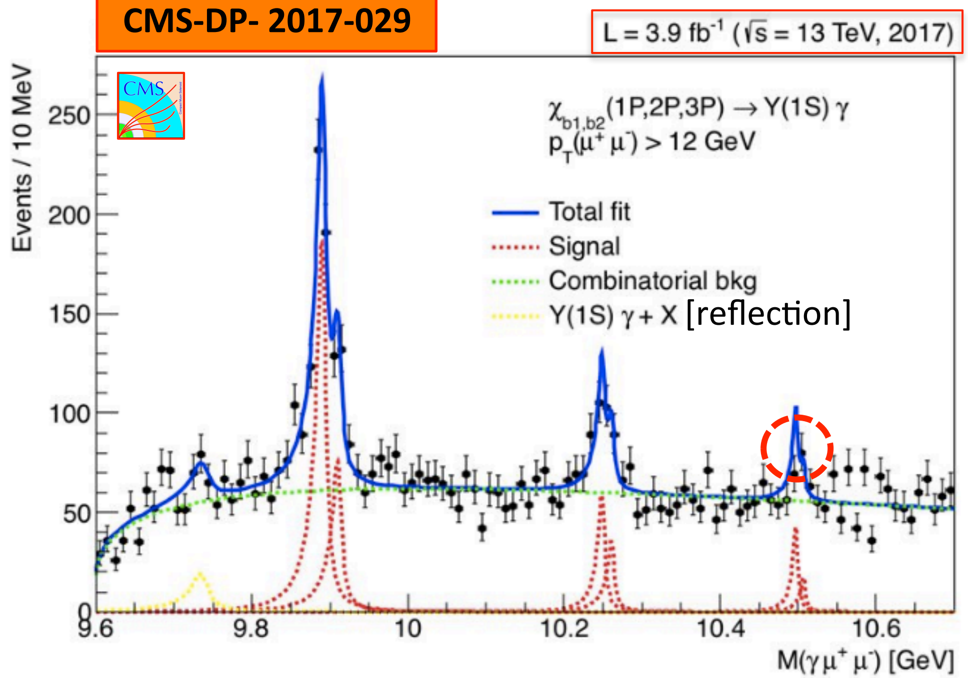
  - Thus the experiments (ATLAS, D0, LHCb) that reported observing $\chi_{b1}(3P) \to \Upsilon(1S,2S)\gamma$ might have actually discovered a mixture of X_b & $\chi_b(3P)$! It would be worthwhile to examine the $\Upsilon(nS)\gamma$ mass spectra for any departure from a "single BW" behaviour.

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

CMS-DP- 2017-029



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

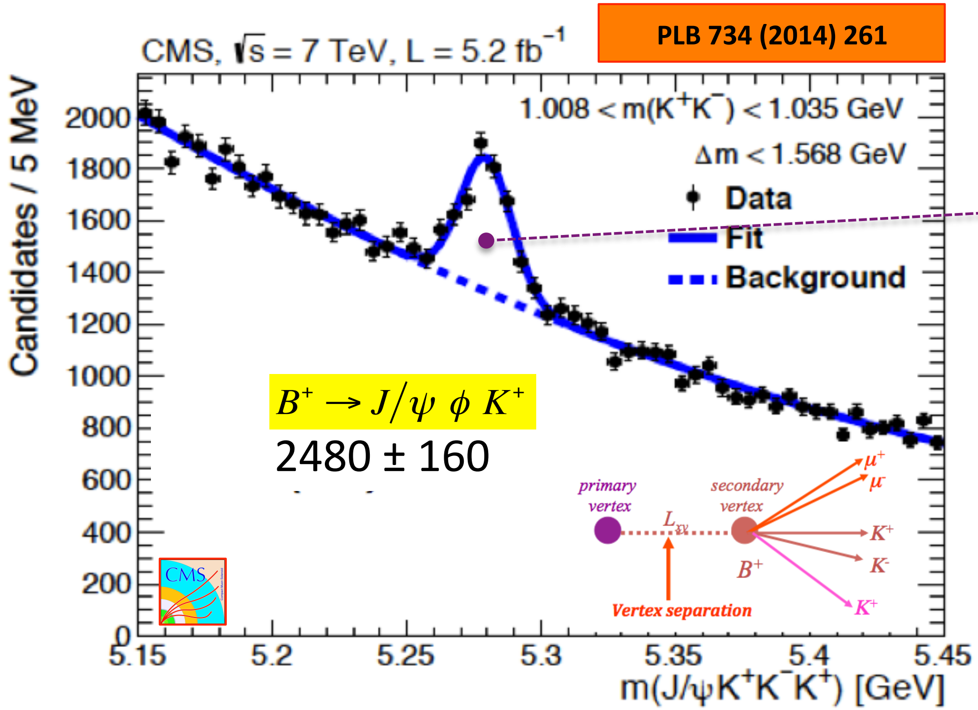
PLB 734 (2014) 261

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

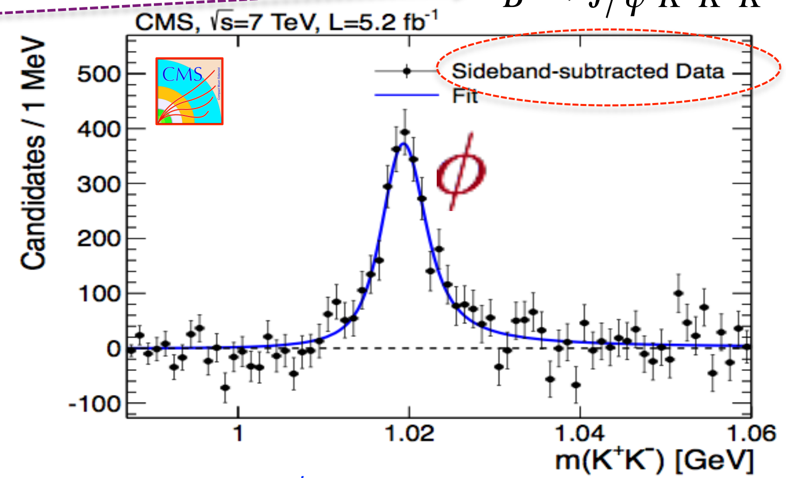
- **In 2009/2011 CDF claims [**PRL 102 (2009) 242002; arXiv:1101.6058 (2011)**] to observe two intermediate resonances decaying into $J/\psi\ \phi$ while studying $B^+ \to J/\psi\ \phi\ K^+$ decays, denoted as $Y(4140)$, $Y(4274)$.**

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

PLB 734 (2014) 261



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



Negligible non-ϕ components

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

- **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)

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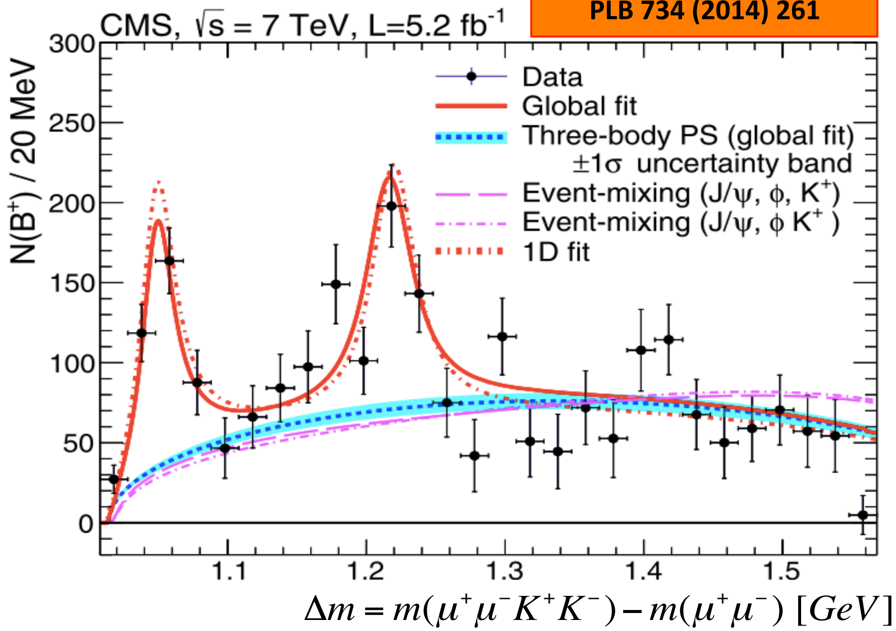
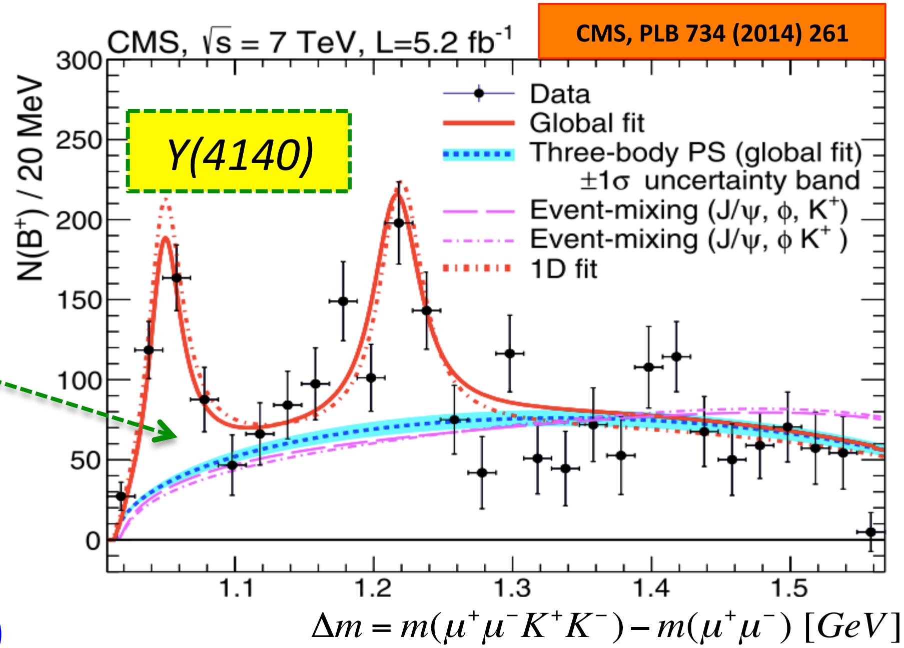


- Fitting with:
  - Signal PDF: S-wave relativistic Breit-Wigner (BW) convolved with mass resolution gaussian
  - Background PDF: 3-body Phase Space Shape (PS)
  - **1-D Fit**: Binned χ^2 fit to the extracted Δm spectrum using the BW and PS shape.
  - **Global 2-D Fit**: simultaneous fit of $m(B^+)$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

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 @

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



  - **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 CDF
    - evidence from D0 [**PRD 89 (2014) 012004**]

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

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

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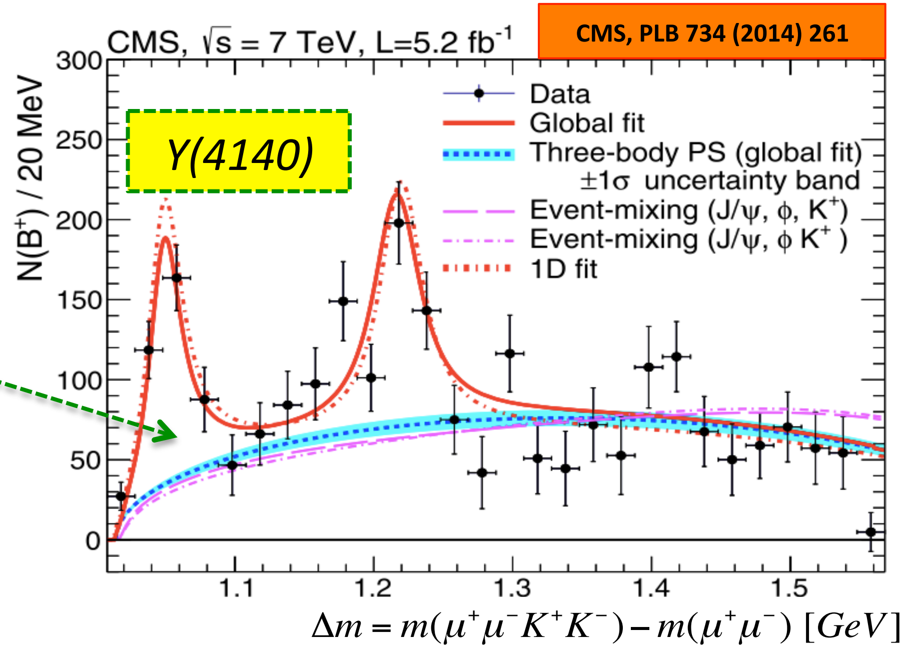

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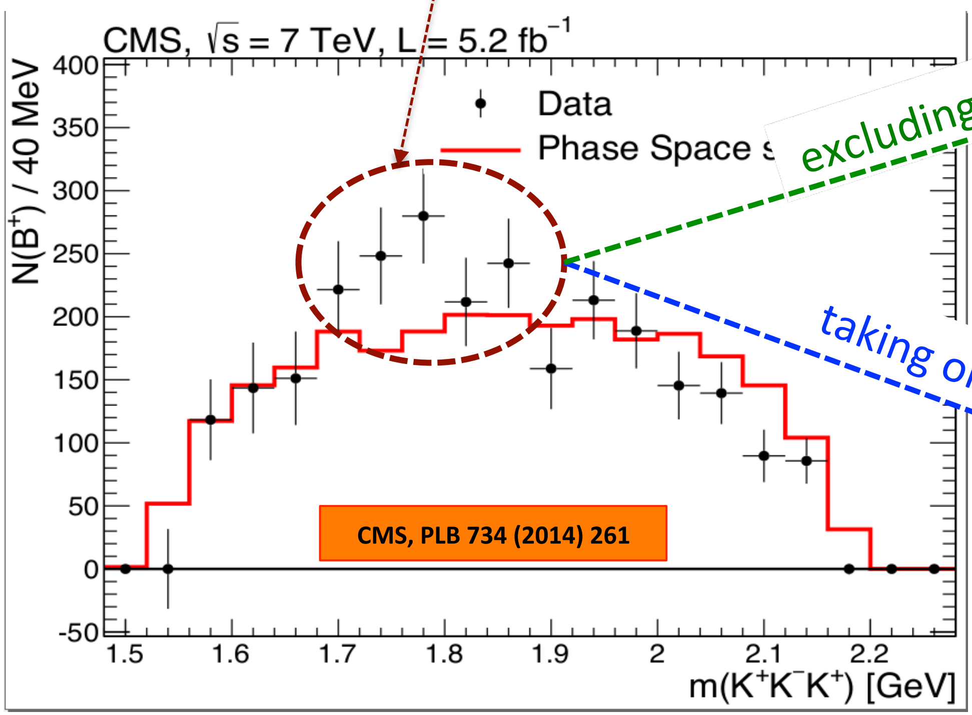
- For the *Y(4140)* decaying into $J/\psi\phi$ several **interpretations** have been proposed: $D_s^* \bar{D}_s^*$ molecule, $cs\bar{c}\bar{s}$ tetraquark, threshold kinematic effect, hybrid charmonium, weak transition with $D_s \bar{D}_s$ rescattering

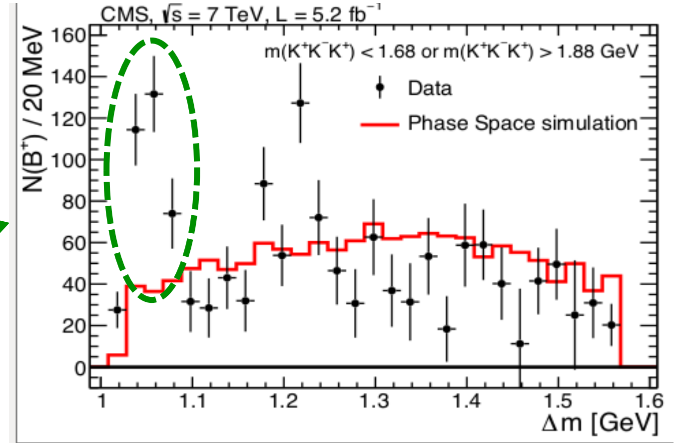
Y(4140)@CMS : checking reflections

- 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:**

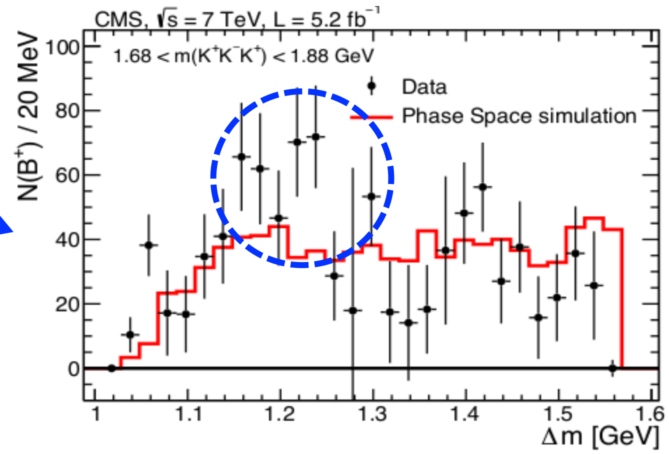


excluding this $m(K^+K^-K^+)$ region

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



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



- **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**)**

- **Later (2016) LHCb [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** $X(4500)$, $X(4700)$

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

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- **Prospects for CMS ?**

  - **Started working with challenging amplitude analysis technique; however going to apply first to an easier B decay. Because of the high BKG Run-II data may be necessary.**

  - **Inclusive search to confirm or not the D0 result might be viable by exploting triggers for double charmonia. Because of high background it makes sense to use full Run-2 data !**

Search for the *X(5568)*

arXiv:1712.06144 - Submitted to PRL

$\sqrt{s} = 8TeV$ (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 $B_d^0 K^{\pm}$ 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 :

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

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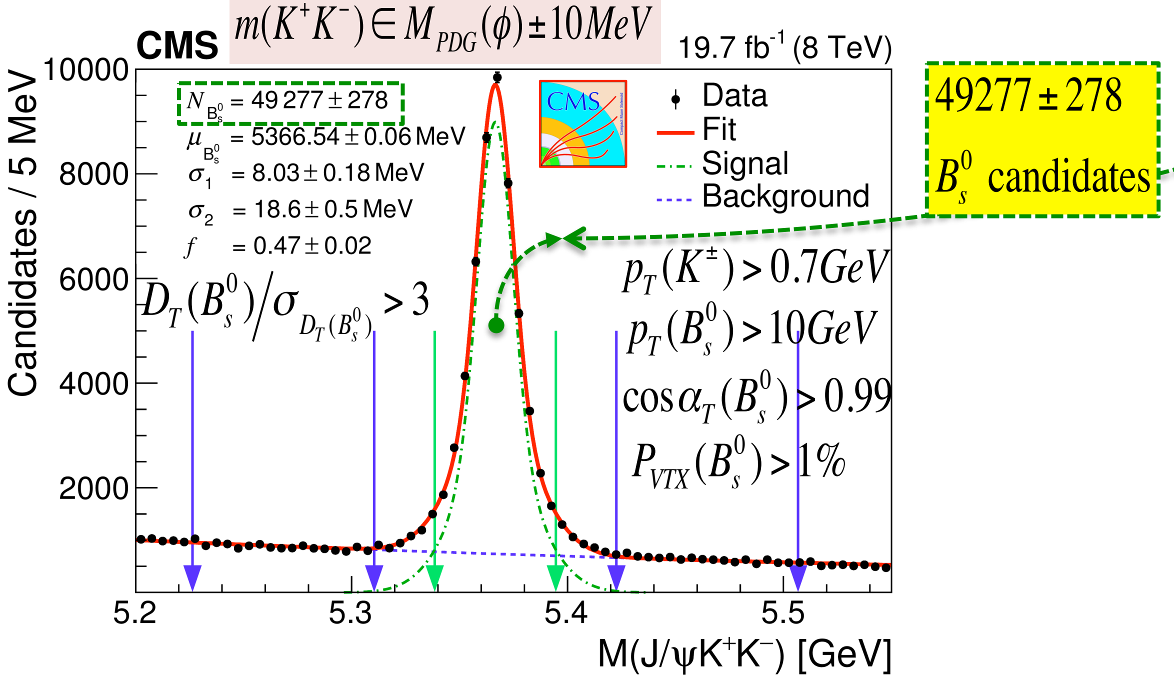
$m(K^+K^-) \in M_{PDG}(\phi) \pm 10 MeV$



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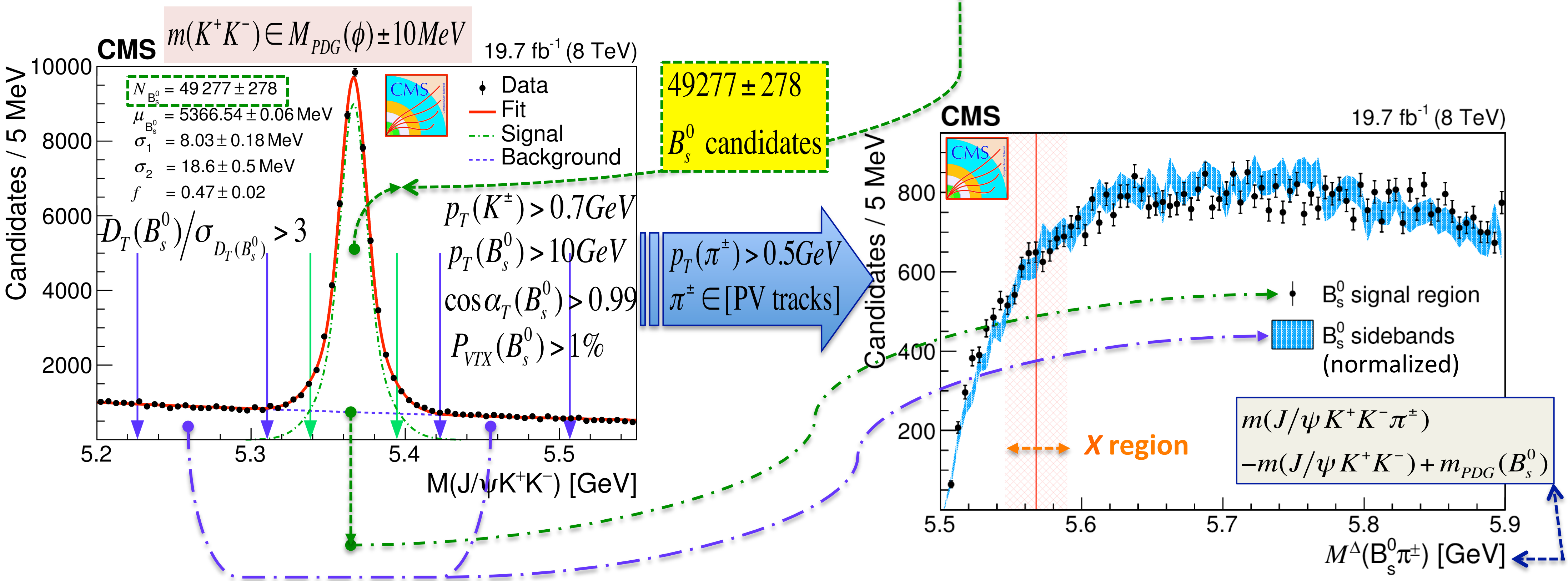

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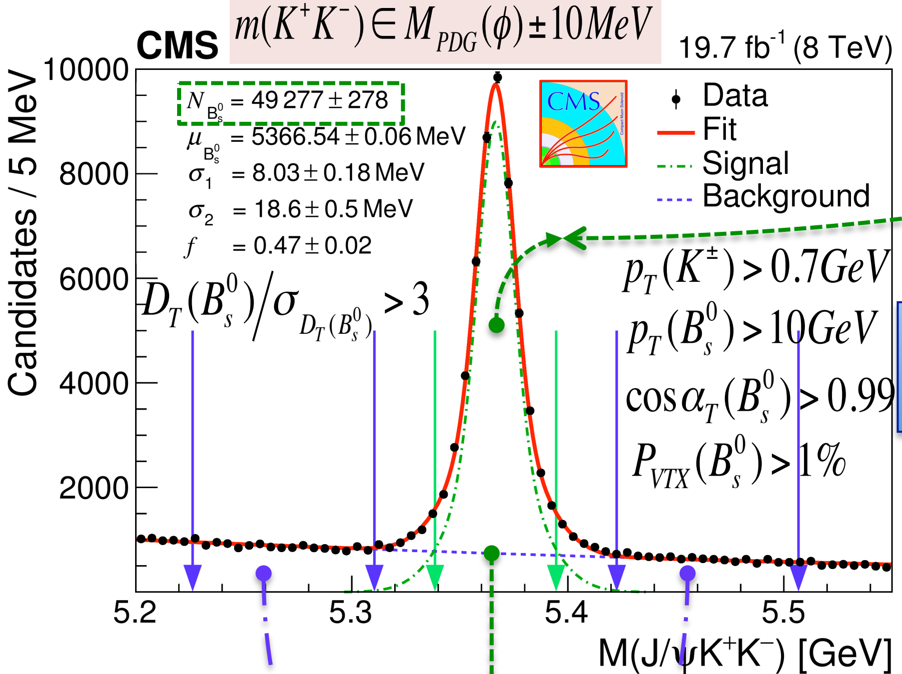
$$\varepsilon_{rel} = \frac{\varepsilon_X}{\varepsilon_{B_s^0}}$$ **relative reconstruction efficiency**

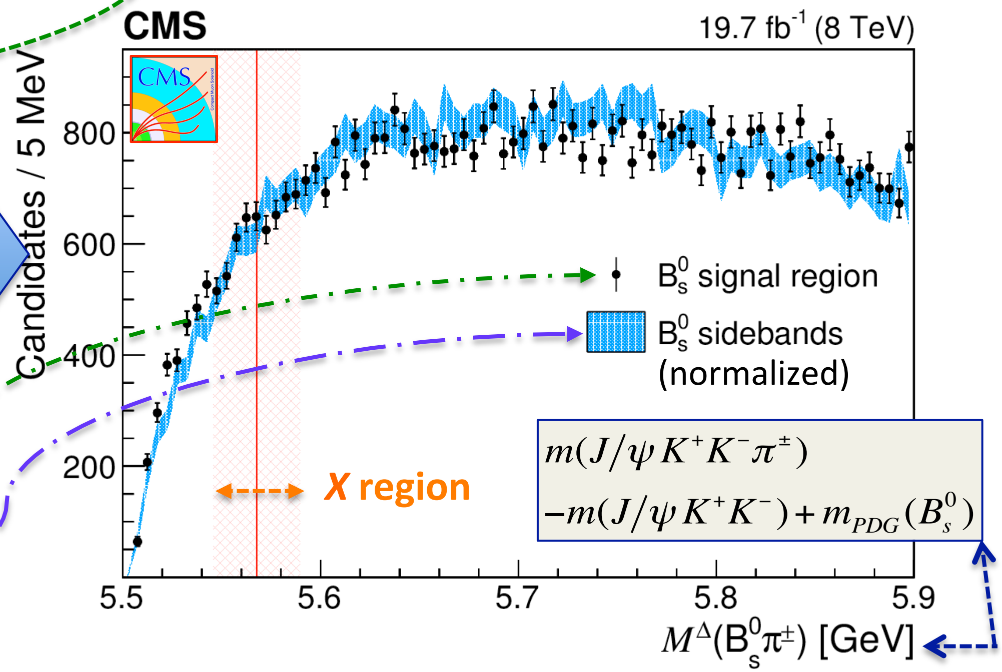
from fit to the $B_s^0 \pi^{\pm}$ mass spectrum (next slide)

$m(K^+K^-) \in M_{PDG}(\phi) \pm 10 MeV$



49277 ± 278 B_s^0 candidates

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

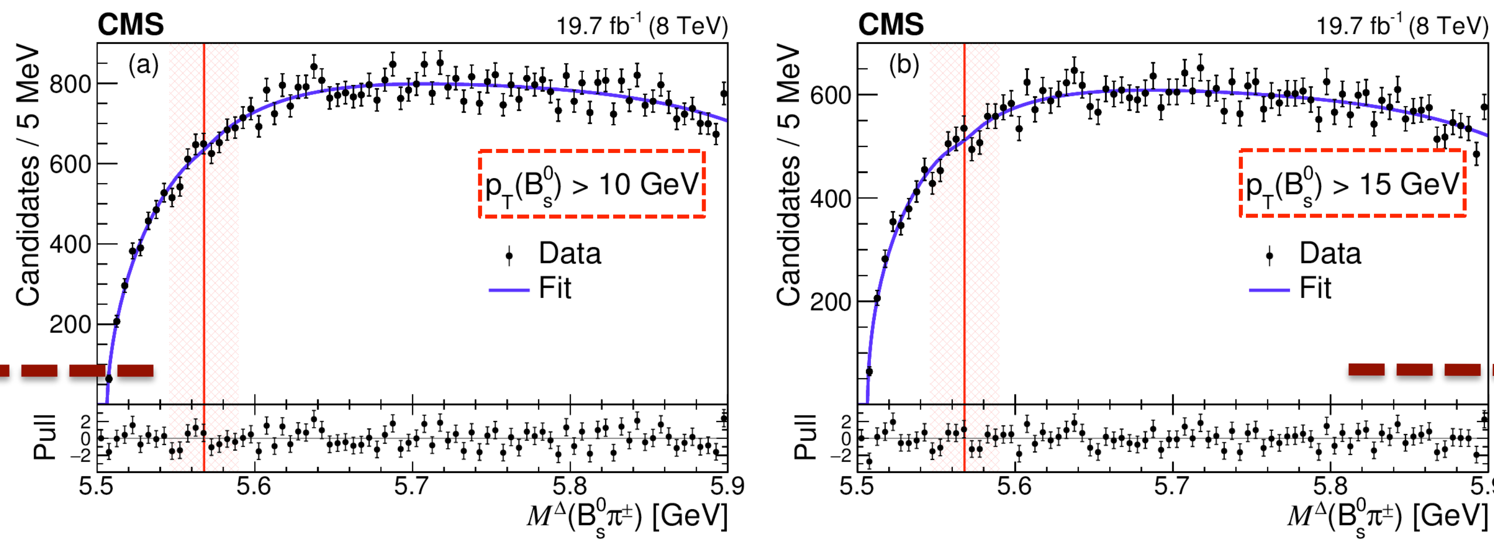


X(5568) search : spectrum fits

- Reconstruction efficiencies derived from simulation of X (spin-0, mass & widths from DØ, 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 (DØ parameters) *convolved* with a triple-Gaussian resolution function (MC)

$N_X = -85 \pm 160$



$N_X = -103 \pm 122$

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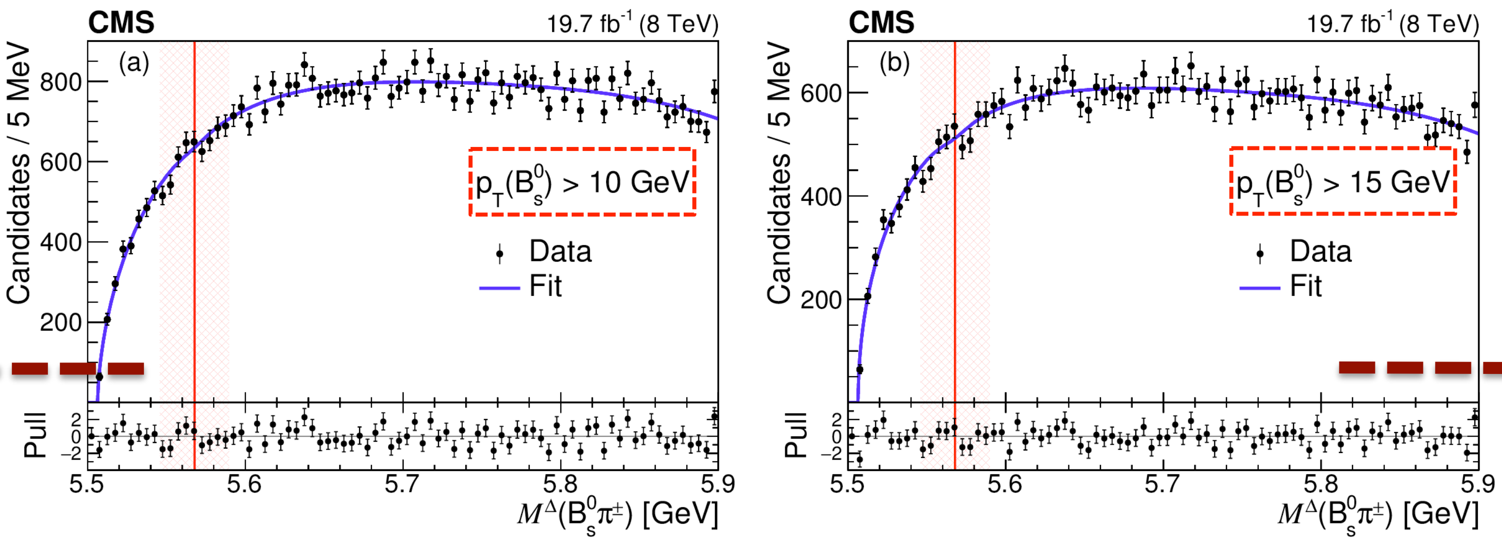

$N_X = -103 \pm 122$

- 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

- **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 **arXiv:1802.01840**

- **Within a kinematic range similar to that of** D0**, at $p\bar{p}$ collider, no confirmation from** CDF **.**
  CDF **[arXiv:1712.09620] is able to set a not so stringent UL:** $\rho_X < 6.7\%\ @\ 95\%CL$

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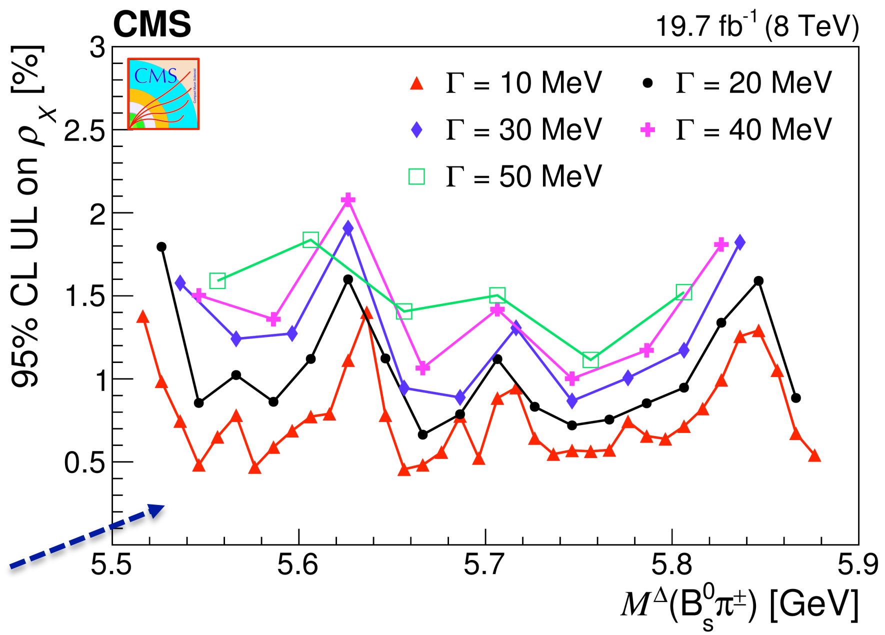
Upper limits are also obtained for different values of natural width (Γ=10 to 50*MeV*) **& mass** [from $m(B_s^0) + m(\pi^\pm) + \Gamma$ up to 5.9*GeV*-1.5Γ] of a possible $B_s^0\pi^\pm$ resonance, **in order to consider an eventual exotic state with higher mass** decaying to the $B_s^0\pi^\pm$ final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

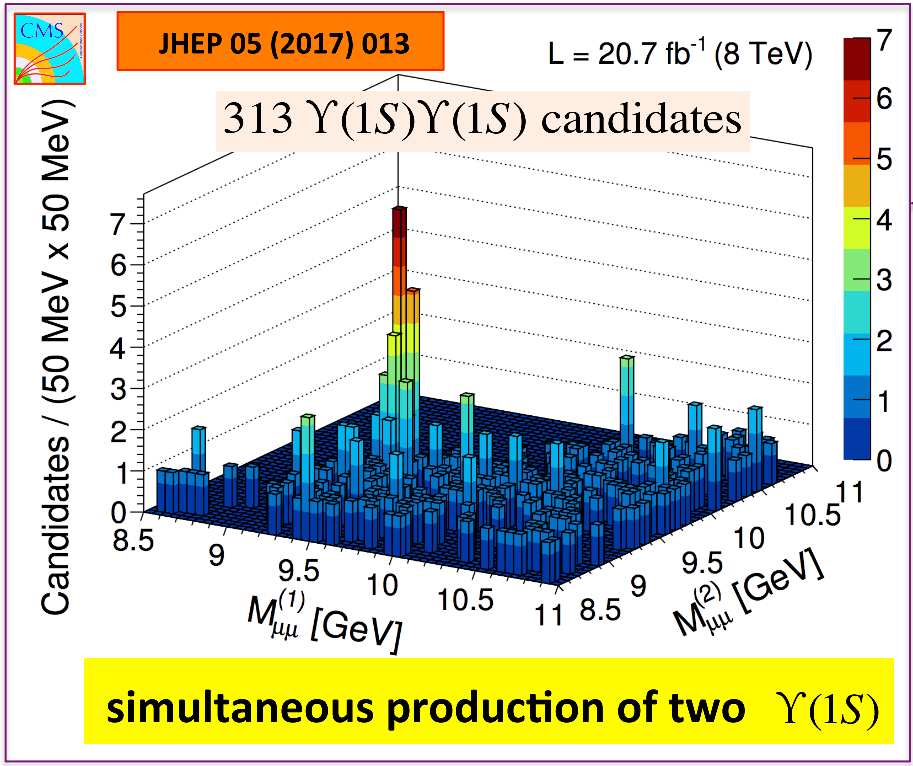


Summary & Outlook

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

CMS tries to deal with selected topics where its 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 *Υ(1S)Υ(1S)*] can be the preliminary step for **searches of heavy (tetra-)quark bound states with Run-II.**

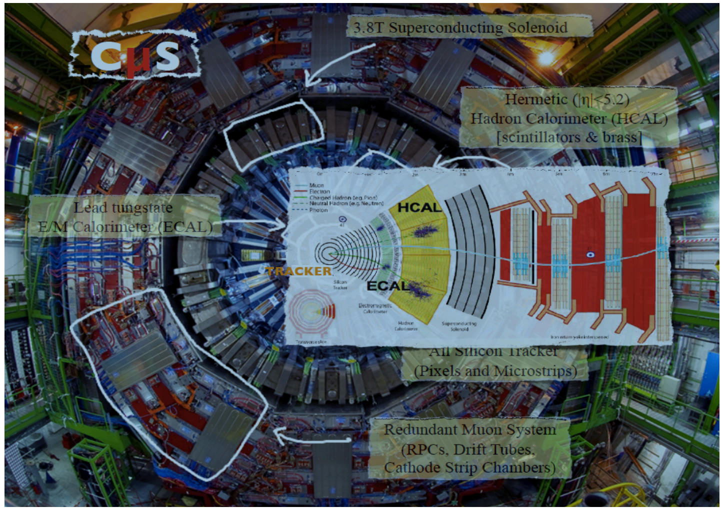


Backup slides / Additional material

Compact Di-Muon Solenoid – μ reconstruction

Tracking system

- Good p_T resolution (down to $\Delta p_T/p_T \approx 1\%$ in barrel)
- Tracking efficiency >99% for central muons
- Good vertex reconstruction &
  impact parameter resolution down to $\approx 15\mu m$



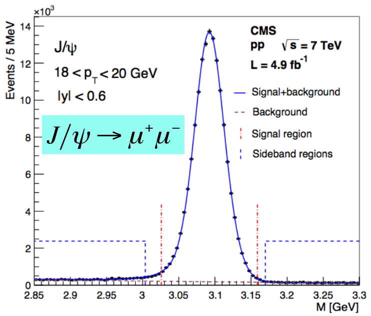
Muon system

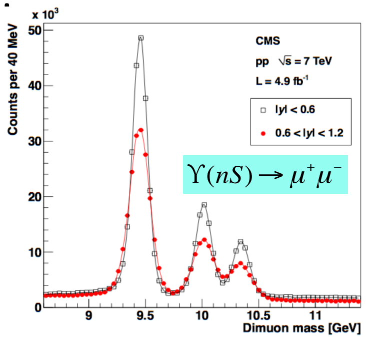
- Muon candidates by matching muon segments and a silicon track in a large rapidity coverage ($|\eta| < 2.4$)
- Good dimuon mass resolution (depending on $|y|$): $\Delta M/M \approx 0.6 \div 1.5\%$ (⇨ $J/\psi :\approx (20 \div 70) MeV$)
- Excellent (high-purity) muon identification : $\varepsilon(\mu | \pi) \leq (0.05 \div 0.13)\%$, $\varepsilon(\mu | K) \leq (0.08 \div 0.22)\%$, $\varepsilon(\mu | p) \leq (0.04 \div 0.15)\%$
  [fake rates estimated in MC and data (K_s, D^*, Λ)]

Di-muons provide a clean signature & are easier to be reconstructed and triggered on !

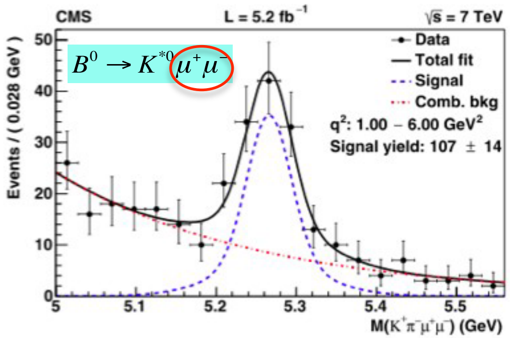
All shown results here involve dimuons …

… with definite invariant mass





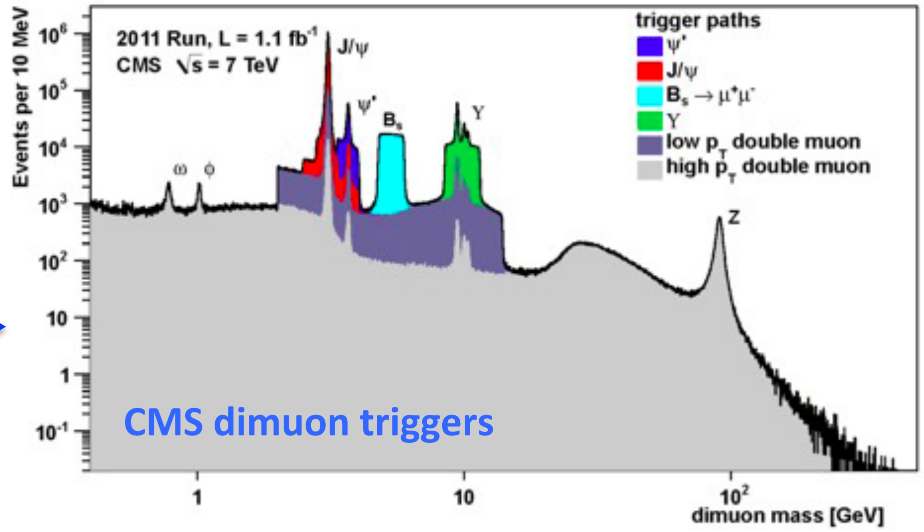
… or not



Compact Di-Muon Solenoid - triggers

Trigger system

Flexible triggers are essential to collect data @ increasing luminosity (and pile-up).
Flavour physics analyses rely on displaced (or inclusive) quarkonium (J/ψ, ψ', $\Upsilon(nS)$), $B_{(s)}$ & non-resonant dimuon triggers: ----------------->



- fast HW (Muon Detector based) triggers (L1)
- SW triggers with full tracking & vtx recon. (HLT)
- specific triggers developed for various analyses
- ~10% of CMS bandwidth (~10*kHz* @L1) given to flavour physics
- different features & needs: rare decays/quarkonia almost 100% BKG/Signal paths
- Data Parking in 2012 : clear benefits having ~120*Hz* (@HLT) on top of the 25-30*Hz* on prompt stream

Data samples:

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

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

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

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

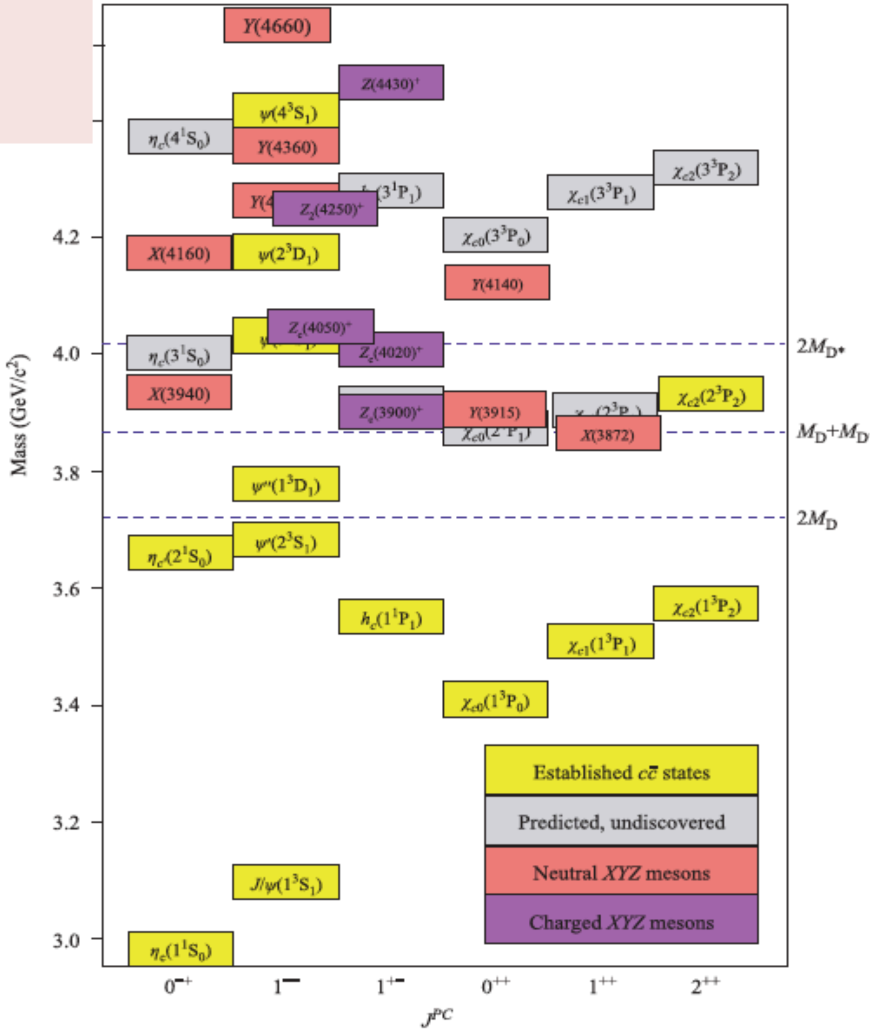
$\text{Run-II}/2016/\sqrt{s}=13TeV : L_{\text{int}} \sim 45\,fb^{-1}$

Trigger strategy for Run-II being defined in view of higher luminosities and pile-up:

Constant work-in-progress (to stay within 100Hz of bandwidth @ $L_{int}=2\ 10^{34} cm^{-2}s^{-1}$) is crucial for the capability of carrying out flavour physics in Run-II !

The possibility of Data Parking (delayed reconstruction) is under discussion for 2018 as CMS did in 2012.

- After the *X(3872)* observation (2003), many (~30) unexpected states observed either @ B-factories and/or at Hadron-colliders.



Among them:

- 3 states of equal mass that differ for quantum numbers: *X(3940),Y(3940), Z(3940)*
- 2 states with C-parity = +1 : *Y(4140)* and *X(4350)*
- a family of vector states (*Y* states with $J^{PC}=1^{--}$): *Y(4260), Y(4350), Y(4660)/Y(4630)*
- a set of charged states: *Z(4430)⁺*, $Z_1(4050)^+$, $Z_2(4250)^+$, … and recently *Z(3900)⁺*

- Few of these states were subsequently adopted into the exististing $c\bar{c}$ scheme, some others remained in a limbo (not confirmed by other experiments), …

…but many of them, even if experimentally established, still remain a puzzle (for many of them … quantum numbers are not experimentally determined yet).

- Analogue states in the bottomonium sector have been found. “Beauty partner” searched for [see backup for *X(3872)* partner]

Exotic charmonium-like – II

To explain their nature ... alternative models have been introduced:

(i) *conventional quarkonium*, which consists of a color-singlet heavy quark-antiquark pair: $(Q\bar{Q})_1$,

(ii) *quarkonium hybrid meson*, which consists of a color-octet $Q\bar{Q}$ pair to which a gluonic excitation is bound: $(Q\bar{Q})_8 + g$,

(iii) *compact tetraquark* [8], which consists of a $Q\bar{Q}$ pair and a light quark q and antiquark $\bar{q}$ bound by interquark potentials into a color singlet: $(Q\bar{Q}q\bar{q})_1$,

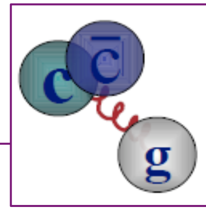
(iv) *meson molecule* [9], which consists of color-singlet $Q\bar{q}$ and $\bar{Q}q$ mesons bound by hadronic interactions: $(Q\bar{q})_1 + (\bar{Q}q)_1$,

(v) *diquarkonium* [10], which consists of a color-antitriplet Qq diquark and a color-triplet $\bar{Q}\,\bar{q}$ diquark bound by the QCD color force: $(Qq)_{\bar{3}} + (\bar{Q}\,\bar{q})_3$,

(vi) *hadroquarkonium* [11], which consists of a color-singlet $Q\bar{Q}$ pair to which a color-singlet light-quark pair is bound by residual QCD forces: $(Q\bar{Q})_1 + (q\bar{q})_1$. An essentially equivalent model is a quarkonium and a light meson bound by hadronic interactions.

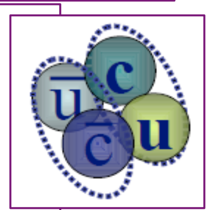
(vii) *quarkonium adjoint meson* [12], which consists of a color-octet $Q\bar{Q}$ pair to which a light quark-antiquark pair is bound: $(Q\bar{Q})_8 + (q\bar{q})_8$.

from Brateen et al., PRD 90 (2014) 014044

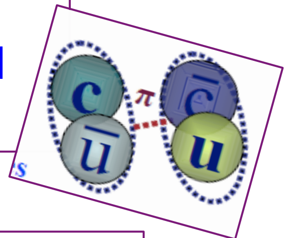


Hybrids :
bound states of quarks and gluons
(i.e. charmonium + excited gluons)

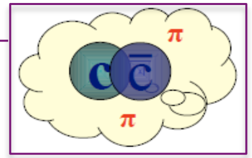
Tetraquarks :
bound states made of a diquark-antidiquark pair (charged and doubly charged states foreseen)



Hadron molecules :
weakly bound states formed by 2 (or more) hadrons



Hadro-charmonium :
binding a compact charmonium state inside an excited state of light hadronic matter (QCD analog of the Van der Waals force)



Non-resonant kinematic effect (in proximity to thresholds) - CUSP

Decay processes & experimental strategy

Decay processes

- An hadronic transition to a lighter $c\bar{c}$ meson through the emission of light hadrons, such as a single vector meson (ϕ or ω), a single π or a $\pi\pi$ pair.
  - suitable for triggering on dimuon objects (J/ψ , $\psi(2S)$, …)
- An 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)
- Hadronic decay into a pair of charmed mesons ($D\bar{D}$, …) , or a pair of charmed baryons ($\Lambda_c^+\Lambda_c^-$)
  - more suitable for LHCb

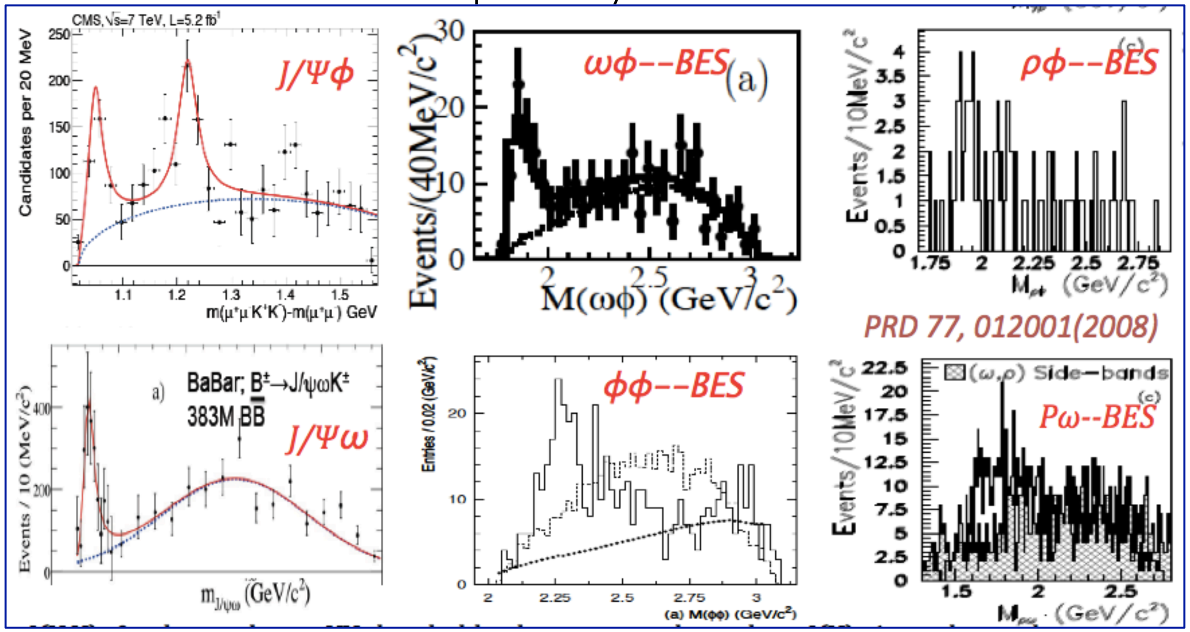
To identify the exotics:
- measure J^{PC} that is forbidden for charmonium
- observe a narrow width above thresholds (in 3-body decays of beauty mesons/baryons)
- observe $c\bar{c}$-like states with charged and/or strangeness (Z states, *Y(4140)*, *X(5568)*, …)
- look for prompt production through inclusive searches

To further explore them:
- reconstruct as many decay modes as possible (radiative, …) for these states
- measure BF ratios
- observe resonance character through a circular trajectory in complex plane (Argand diagram)
  (180° phase change across poles of the S-matrix;
  beware: kinematical effects correspond to "Landau" singularities of the S-matrix but are not poles)

Vector-vector threshold enhacements & beyond

- Maybe worthy to note that the Y(4140) state is the most recent of a series of vector-vector threshold enhancements from OZI suppressed strong processes:

Compilation by K.Yi



Possibility to similar behaviour in pairs of heavy quarkonia?

- So far we have discussed how many states have a minimal quark content of 4 quark, and regardless the way they are organized and interacting [compact system or molecular system?] they can be considered 4-valence quarks bound systems (2 heavy + 2 light): X(3872) , Z(4430) , Y(4140)

  $c\bar{c}u\bar{u}$ $c\bar{c}u\bar{d}$ $c\bar{c}s\bar{s}$

  Nothing prevents from thinking about *4-heavy-quark systems*;
  e.g. $c\bar{c}c\bar{c}$ [Berezhnoy *et al.*, PRD84 (2011) 094023]

X(3872) interpretation - I

Main hypothesis are :

Tetraquark ($J_X^{PC} = 1^{++}$)

Diquark–diantiquark

[proposed pattern by Maiani et al., PRD89 (2014) 114010**]**

$Z_c(3900)^0$ is the neutral partner of X(3872);
$Z_c(3900)^+$ is its charged partner;
$Z(4430)^+$ is its first radial excitation.

Conventional charmonium: assignments would be $\chi_{c1}(2^3P_1)$ or ~~$\eta_{c2}(1^1D_2)$~~ with *J^{PC}* = 1^{++} or ~~2^{-+}~~

Unlikely: $c\bar{c} \to \rho J/\psi$ **violates isospin**; it should be a pure isoscalar & instead $\frac{B(X \to J/\psi\, \pi^+\pi^-\pi^0)}{B(X \to J/\psi\, \pi^+\pi^-)} = 1.0 \pm 0.4 \pm 0.3$

Loosely bound molecular state: suggested by proximity to $D\bar{D}^{0*}$ threshold (*J^{PC}* = ~~0^{-+}~~, 1^{++})

D^0–$\bar{D}^{*0}$ "molecule"

The **size** of the *X(3872)* as a ***DD* molecule*** is determined by its scattering length which in turn depends, by quantum mechanical considerations, upon the binding energy:

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

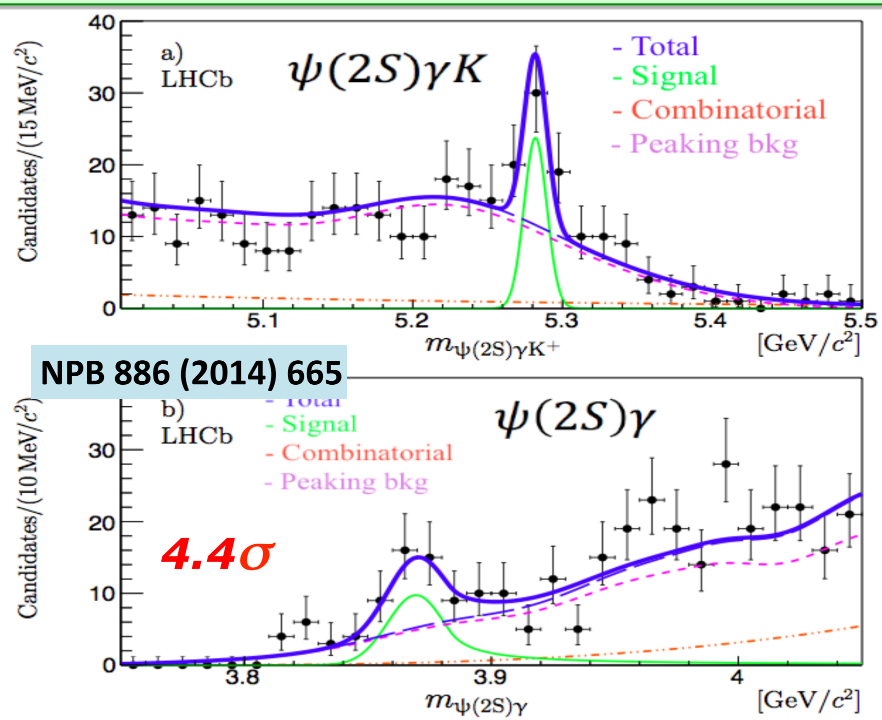
***X(3872)* would be a large and fragile molecule with a miniscule binding energy (~100 *KeV*)**
… that leads to a radius of ~*14 fm* (3 times as large as the deuteron) !

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

X(3872) interpretation - II

- **Pure molecular model (Swanson *et al.*) not supported by the recent LHCb measurement of the radiative sub-decay $X(3872) \to \psi(2S)\gamma$ in the $B^+ \to X(3872)K^+$ decays ...**

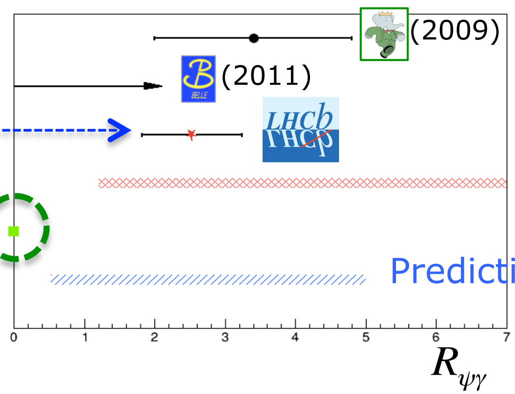
[Peaking Bkg? From : missing or random γ in B decays]



NPB 886 (2014) 665

... because of the following BF ratio:

$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\,\gamma)} = 2.46 \pm 0.64 \pm 0.29$$



Barnes et al.(2005), Li et al.(2009)

Prediction for pure $c\bar{c}$ state

Prediction for pure $\bar{D}^0 D^{*0}$ molecule

[Swanson, PLB 588 (2004) 189, Dong et al.(2011)]

Prediction for admixture of $c\bar{c}$ + $\bar{D}^0 D^{*0}$

Eichten et al.(2006), Badalin et al.(2012)

- **Alternatively to the tetraquark option ($c\bar{c}\ u\bar{u}$), the *X(3872)* may have a significative $\chi_{c1}(2^3P_{1^{++}})$ component [see** Karliner&Rosner, PRD91 (2015) 014014**]:**

$$\bar{D}^0 D^{*0} + c\bar{c}\left[\chi_{c1}\left(2^3P_1\right)\right]$$

(mixed wave-functions)

$X(3872)$: interpretation - III

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

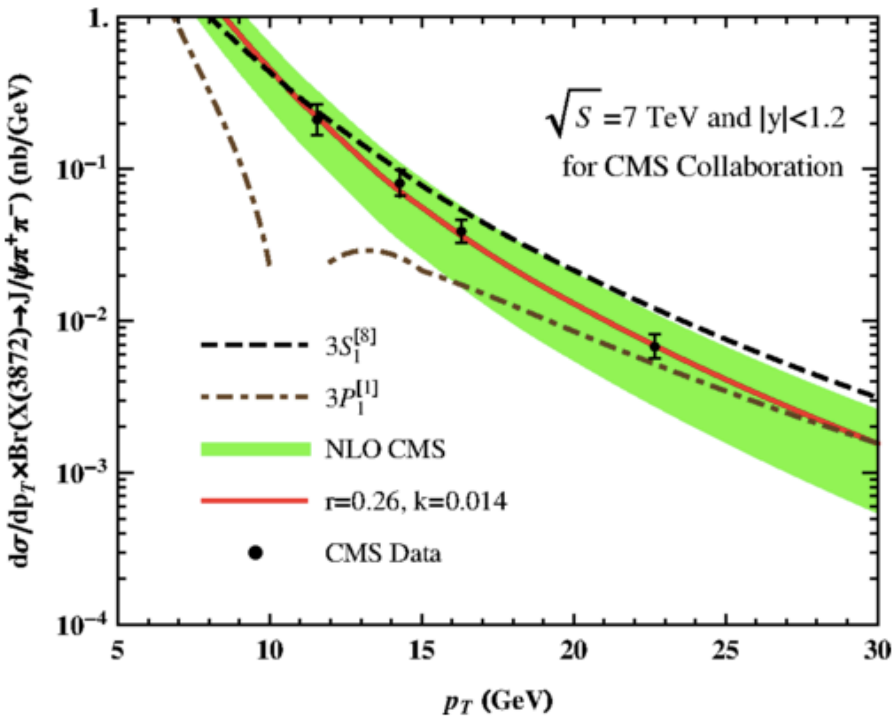
$$d\sigma(pp \to X(J/\psi\pi^+\pi^-)) = d\sigma(pp \to \chi'_{c1}) \cdot k,$$

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

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

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.

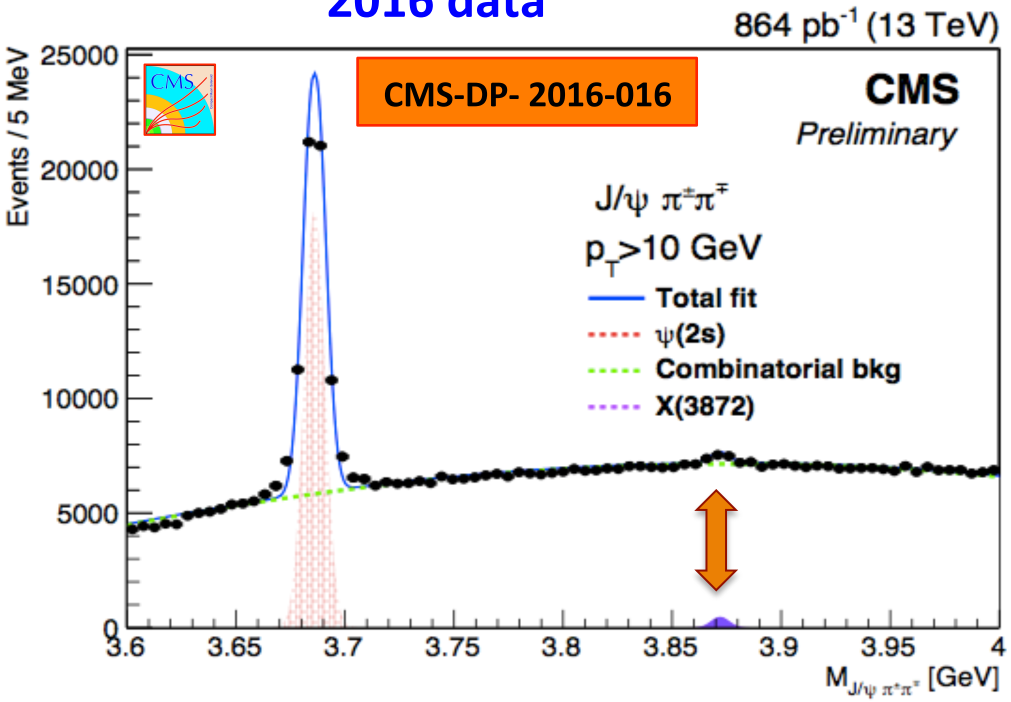
The outcome of the fits at CMS p_T distribution can well account for the recent ATLAS data, even at a larger range of p_T, for the CDF total xsection, and are consistent with the value of k constrained by the B-meson decay data.



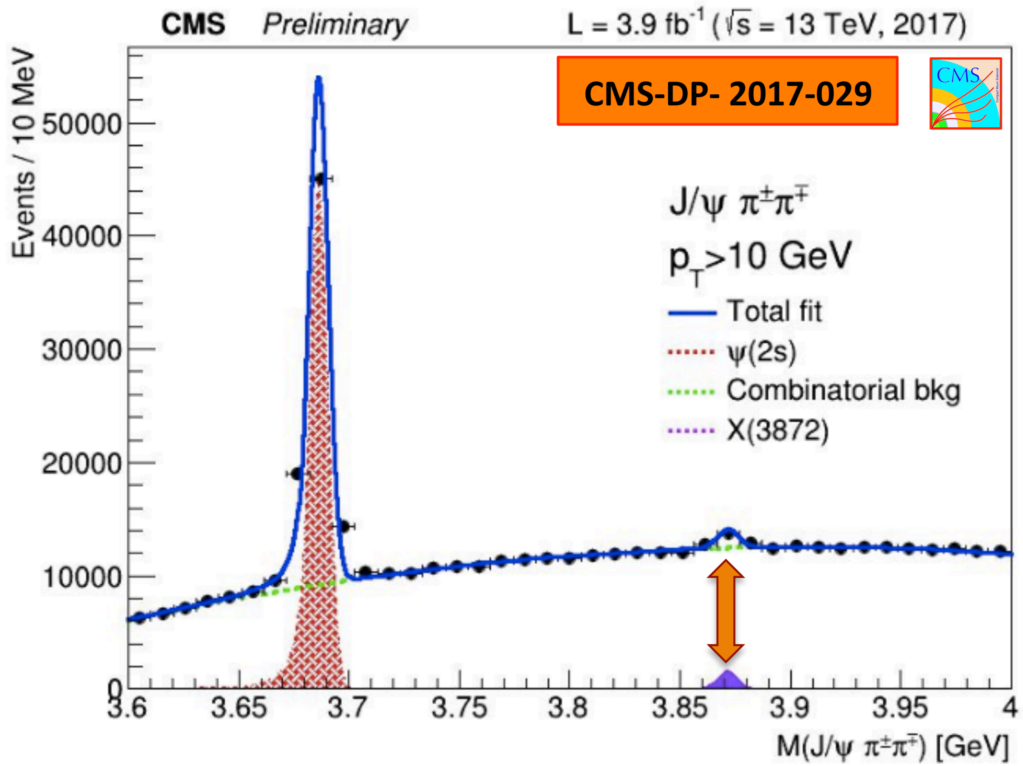
X(3872) in Run-II data

- Transverse momentum threshold is still low enough **only** for events triggered with a **displaced** J/ψ :

2016 data

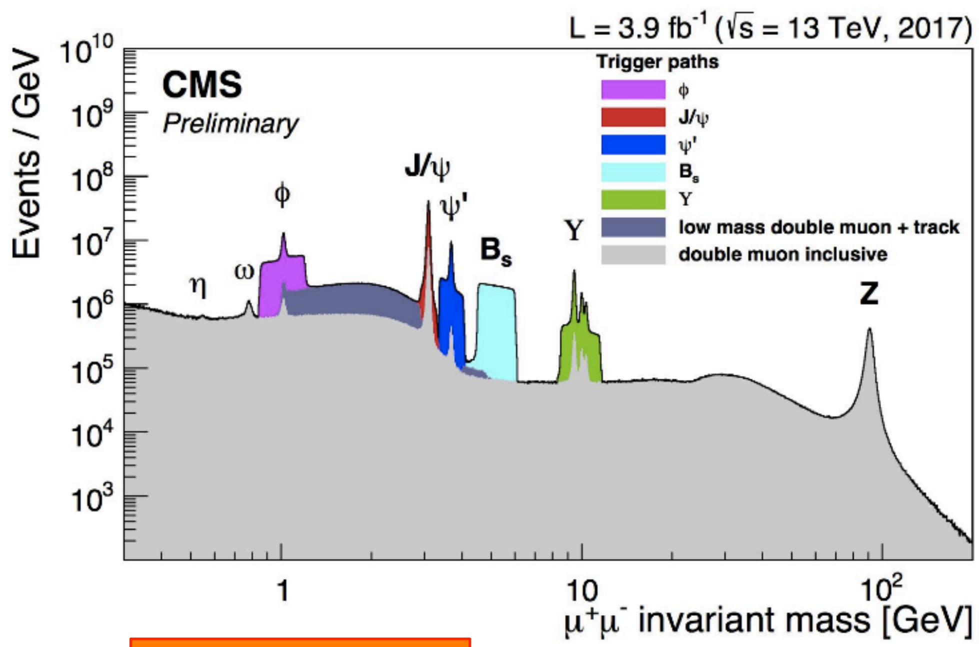


2017 data



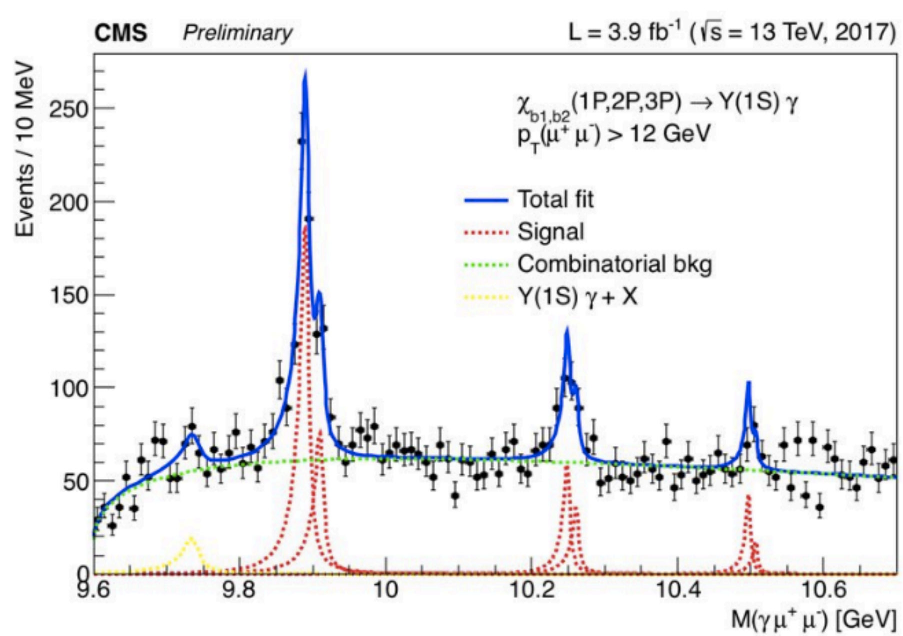
Dimuon invariant mass spectrum

- Dimuon mass distribution collected with various dimuon triggers.
- The light gray continuous distribution represents events collected with inclusive dimuon triggers with high p_T thresholds.
- The dark gray band is collected by a trigger with low-mass non-resonant dimuon plus a track.
- The other colored spectra are acquired using specialized triggers which require a pair of muons with opposite charge, a vertex-fit probability > 0.5%, and specific dimuon invariant mass and p_T regions:
  - Magenta: dimuon mass within [0.85, 1.2] GeV, dimuon p_T > 14 GeV, dimuon |y| < 1.25
  - Red: dimuon mass within [2.9, 3.3] GeV, dimuon p_T > 25 GeV; or dimuon mass within [2.9, 3.3] GeV, dimuon p_T > 20 GeV, dimuon |y| < 1.25
  - Blue: dimuon mass within [3.35, 4.05] GeV, dimuon p_T > 18 GeV; or dimuon mass within [3.35, 4.05] GeV, dimuon p_T > 10 GeV, dimuon |y| < 1.25
  - Cyan: dimuon mass within [4.5, 6] GeV, the leading muon p_T > 4 GeV and the sub-leading muon p_T > 3 GeV
  - Green: dimuon mass within [8.5, 11.5] GeV, dimuon p_T > 12 GeV, single muons $|\eta|$ < 1.5



CMS-DP- 2017-029

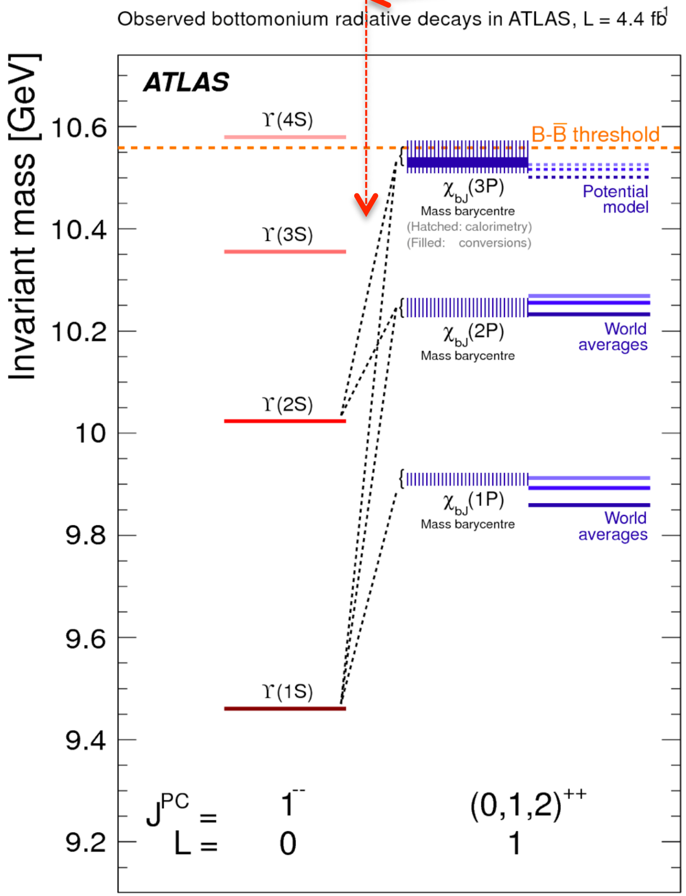
- Trigger conditions: opposite-sign muon pair with invariant mass in range 8.5-11.5 GeV, p_T > 12 GeV, single muons $|\eta|$ < 1.5 and vertex-fit probability > 0.5%
- The Υ has p_T > 12 GeV
- The γ is a converted photon
- The distance between the Υ and the γ vertices along the beam direction is < 1 mm
- The $\Upsilon\gamma$ system has a vertex-fit probability > 1%
- Fit method: unbinned extended maximum likelihood
  - Signal: double side Crystal Ball for each peak with common n, α
    - $m(\chi_{b2})$ - $m(\chi_{b1})$ fixed to previous CMS results
    - first peak corresponds to the misreconstructed decay $\chi_b(2P) \to \gamma\, \Upsilon(2S)$ ($\to \Upsilon(1S)\pi^+\pi^-$)
  - Background: exponential times power law



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

- ATLAS **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** $\chi_b(nP)\rightarrow Y(1S,2S)\gamma$

-



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

from electromagnetic clusters
(good efficiency but …
…worse momentum & direction resolution):

selected energy deposits
- not matched to any track
- pointing at the dimuon vtx

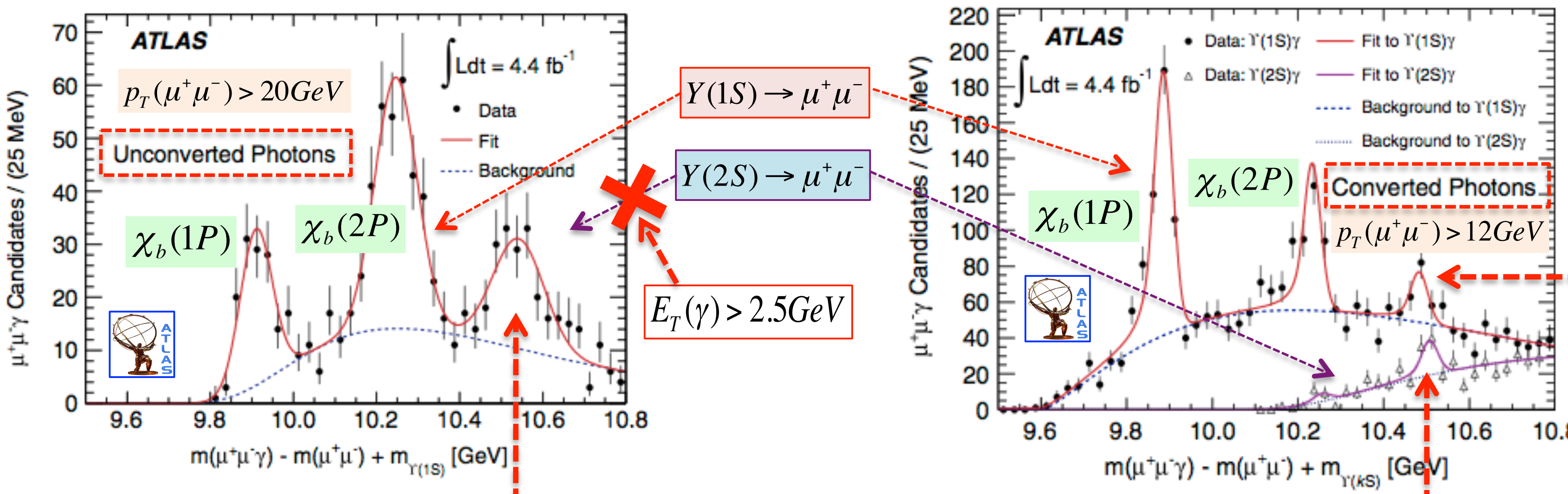
from e^+e^- conversions
(better resolution but …
… much lower efficiency):

selected pairs of oppositely charged tracks
- with common vtx
- consistent with the electron hypothesis

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

- **has reconstructed χ_b *P-wave* quarkonium states** [each being a closely spaced triplet spin states (χ_{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:



Each peak represents an unresolved triplet

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

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

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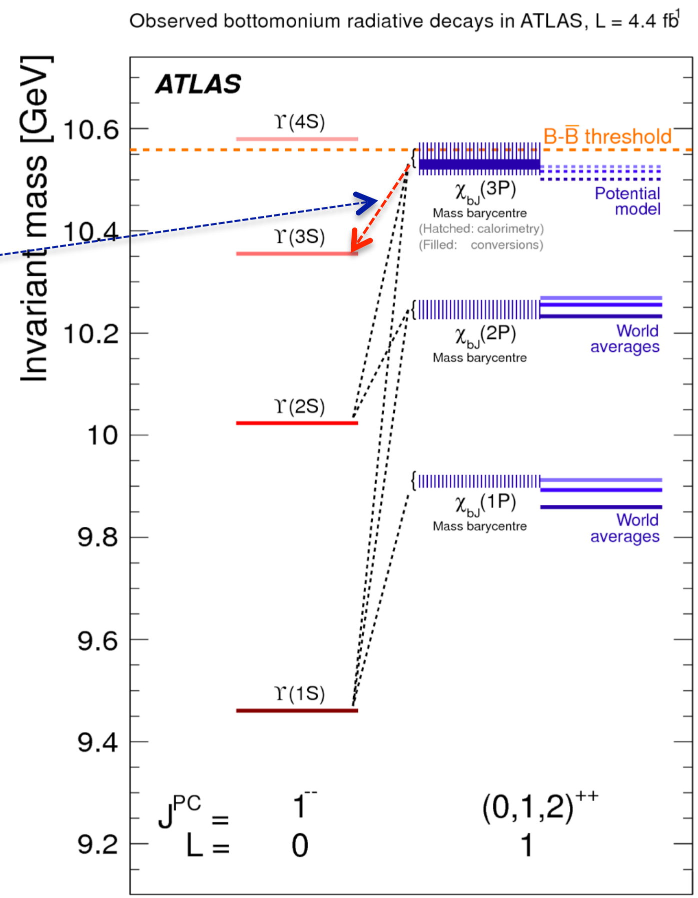

- **Later (2014) LHCb was able to estimate more precisely $m_{\chi_{b1}(3P)}$ and to measure for the 1st time the $Y(3S)$ production fraction (~40%) due to $\chi_b(3P) \rightarrow Y(3S)\gamma$.**

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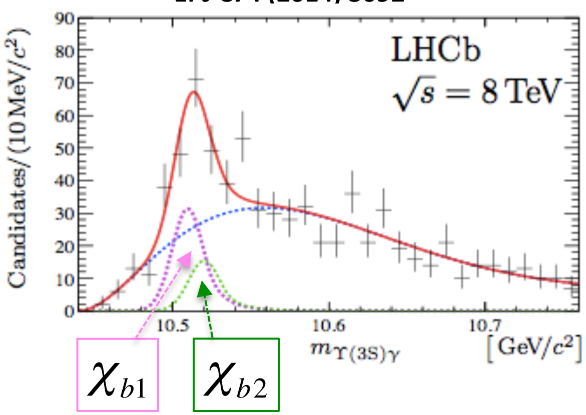
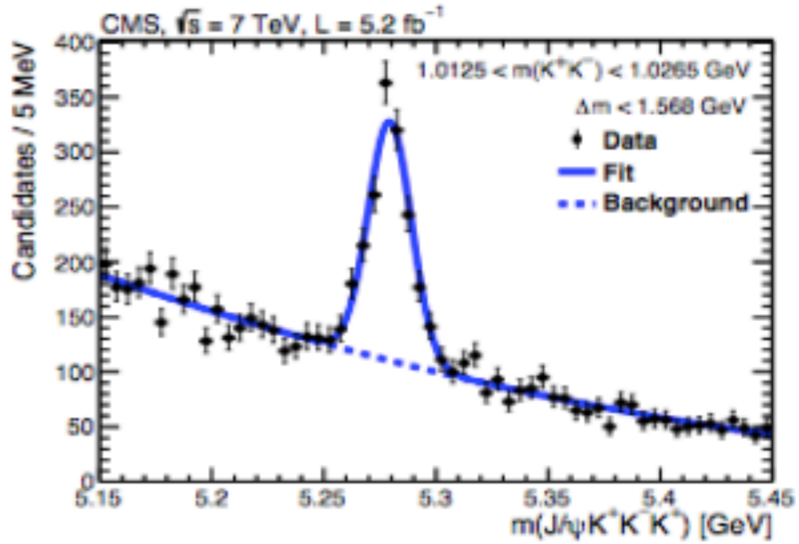


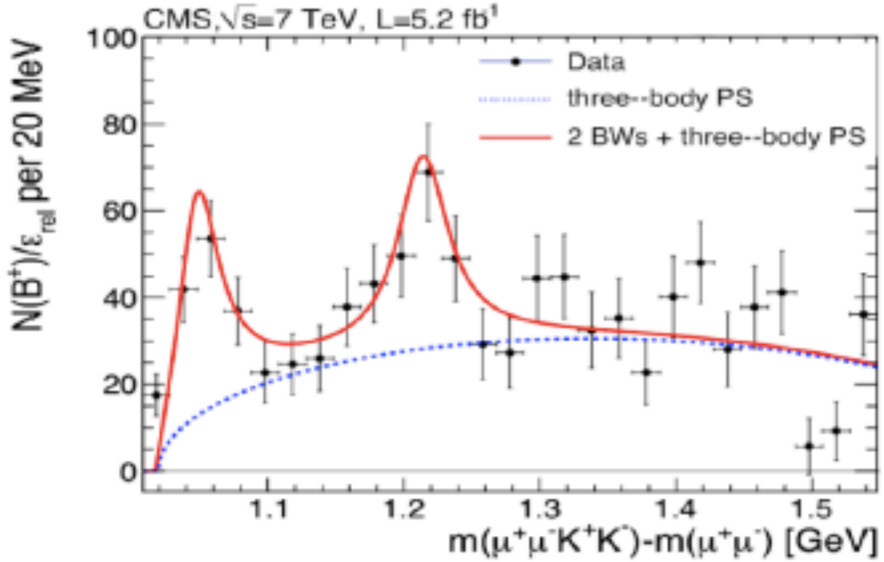
Cross-check for peaking structures ($B^+ \to J/\psi\ \phi\ K^+$)

- More stringent quality and kinematical cuts are used to produce a cleaner sample :

Additional requirements:

- kaon $p_T > 1.5$ GeV
- B^+ vertex CL > 10%
- B^+ vertex detachment: >7X from beamspot
- m(K+K-) within 7 MeV of ϕ mass



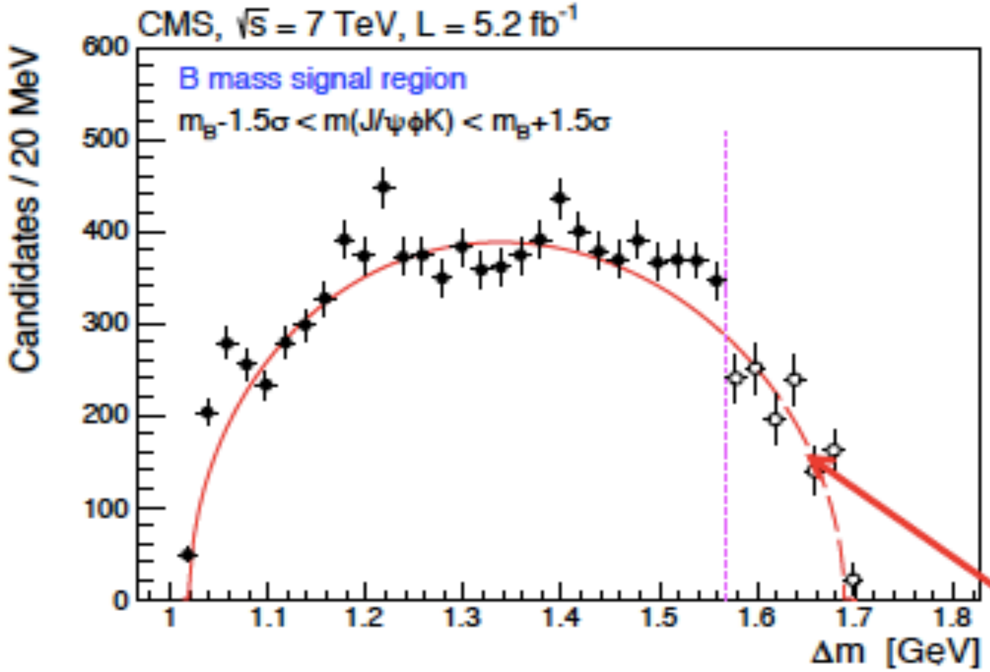


Solid structures appear in clean B sample.

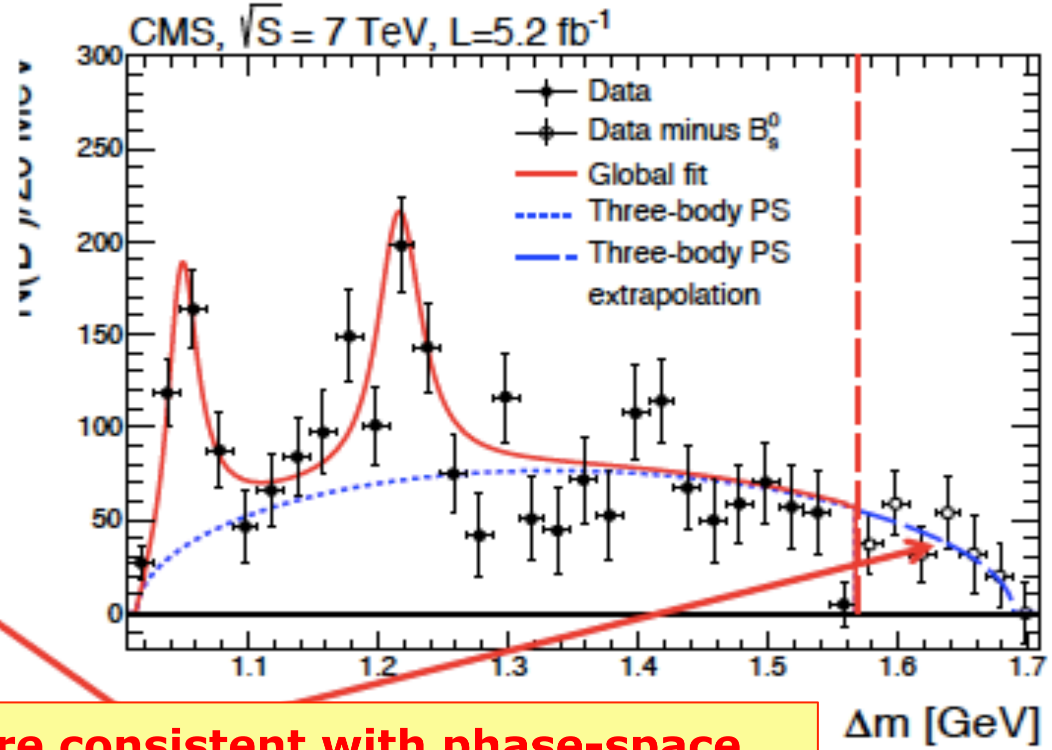
40% of default B signal, 10X less non-B background

Further investigation in the whole Δm region ($B^+ \to J/\psi\ \phi\ K^+$)

The Δm spectrum after subtracting B^0_s contribution but including non-B evens, within 1.5σ *(σ = 9.3MeV) of the B mass.*



The extension of the Δm spectrum, after subtracting non-B background, to the full phase space.

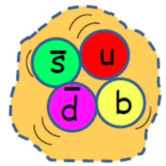


Candidates in the region previously cut-off are consistent with phase-space

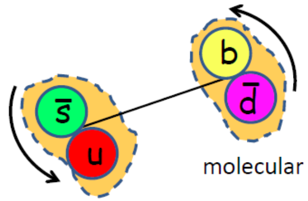
The absence of strong activity in the high- Δ m region reinforces our conclusion that the near-threshold narrow structure is not due to a reflection of other resonances.

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 … $[b\ u][\bar{d}\ \bar{s}]$, $[b\ \mathrm{d}][\bar{s}\ \bar{u}]$, $[s\ u][\bar{b}\ \bar{d}]$, $[s\ \mathrm{d}][\bar{b}\ \bar{\mathrm{u}}]$)



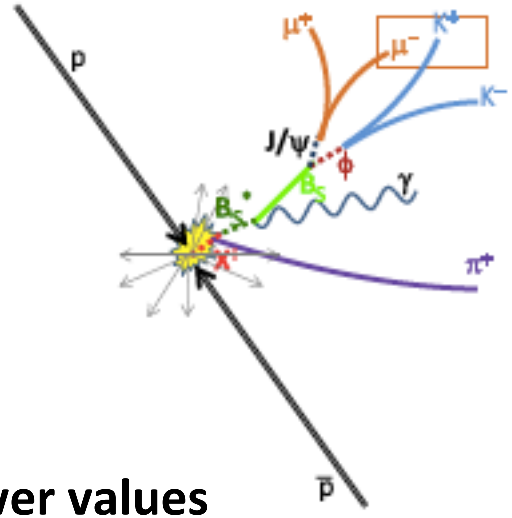
  - a loosely bound $B_d^0 K^{\pm}$ molecular state
    [disfavoured: binding energy ~200*MeV*]



- 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):

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

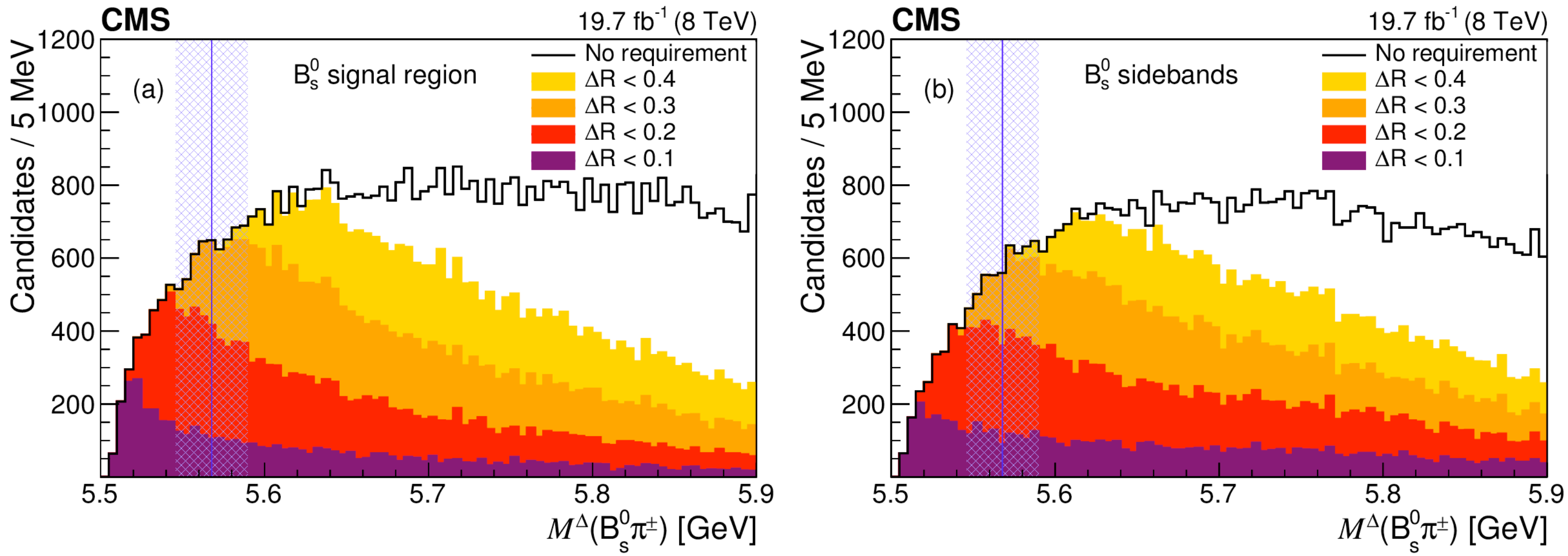


In this case :

- $J^P = 1^+$
- 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

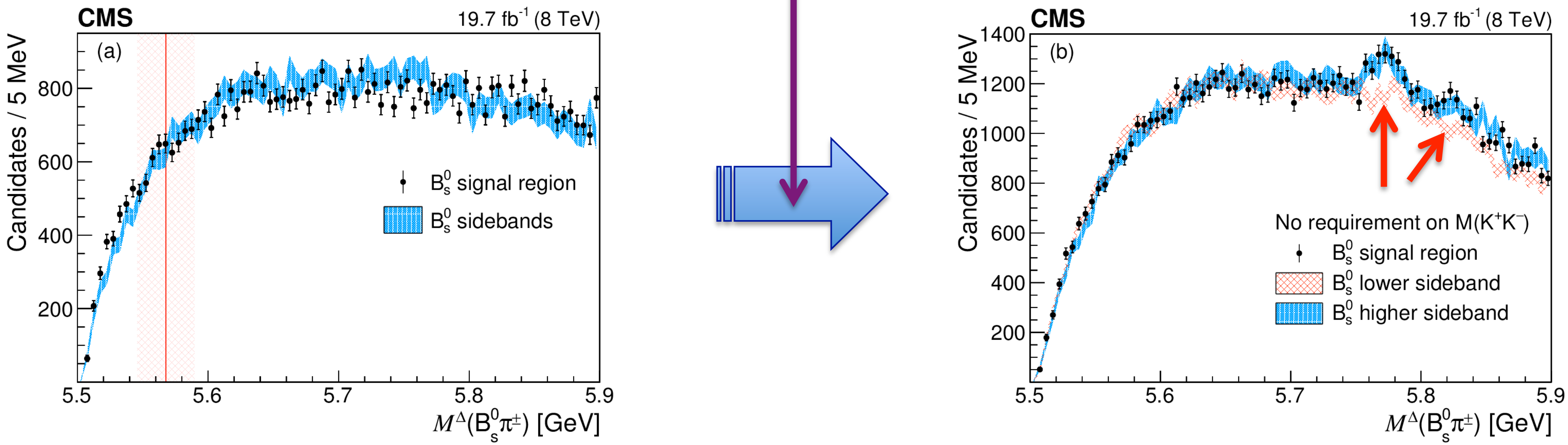
Constraints on the angle ΔR (called "cone-cuts" in jargon) between the momenta of the B_s^0 & $\pi^{\pm}$ candidates (*) are not imposed in CMS analysis, because such requirements sculpt the $B_s^0\pi^{\pm}$ invariant mass in a nontrivial way (for instance producing a peaking shape) :



$\Delta R < 0.3$: cone-cut applied by D0

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

To verify the reconstruction procedure the requirement $m(K^+K^-) \in M_{PDG}(\phi) \pm 10MeV$ 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: $B_1(5721)^{\pm} \to B^{*0}\pi^{\pm} \to B^0 \not\gamma\, \pi^{\pm}$

$B_2^*(5747)^{\pm} \to B^{(*)0}\pi^{\pm} \to B^0 (\not\gamma)\, \pi^{\pm}$

… 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:

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$B_c^\pm$ decays into tetraquarks

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[4]*CERN, Theory Division, Geneva 23, Switzerland*
(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.

Double Quarkonia - I

- New findings in this frontier will potentially have beneficial effects on other measurements.

Among them … not only rare Higgs decay to pair of quarkonia …

… but also searches for heavy (tetra-)quark bound states.

Indeed it is possible to immagine *4-quark valence bound systems* with 4 heavy quarks (e.g. or $c\bar{c}c\bar{c}$ or $c\bar{c}b\bar{b}$ or $b\bar{b}b\bar{b}$ [Berezhnoy *et al.*, PRD86 (2012) 034017] **) above the relative vector quarkonia pair thresholds, in analogy with other vector-vector systems such as $J/\psi\,\rho$ and $J/\psi\,\omega$ [*X(3872)* and *Y(3940)/X(3915)* with $c\bar{c}u\bar{u}$ / $c\bar{c}d\bar{d}$ content] or $J/\psi\,\phi$ [*Y(4140)* (+ others ?) with $c\bar{c}s\bar{s}$ content].**

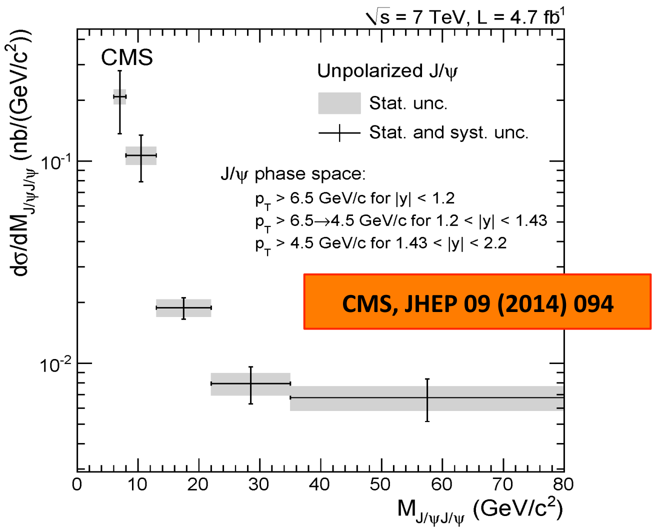
Double Quarkonia - I

- New findings in this frontier will potentially have beneficial effects on other measurements.

Among them … not only rare Higgs decay to pair of quarkonia …

… but also searches for heavy (tetra-)quark bound states.

- [JHEP 06 (2012) 141] **and** [JHEP 09 (2014) 094] **have measured total & diff. xsections for prompt double J/ψ production in complementary regions of transverse momentum and rapidity:**



When considering the $M_{J/\psi J/\psi}$ around the η_b mass region the yield in the η_b 3σ-signal window $[(9.16 \div 9.64) GeV/c^2]$ is $\cong 15 \pm 4$, perfectly agreeing with the expectations derived from the sideband regions.

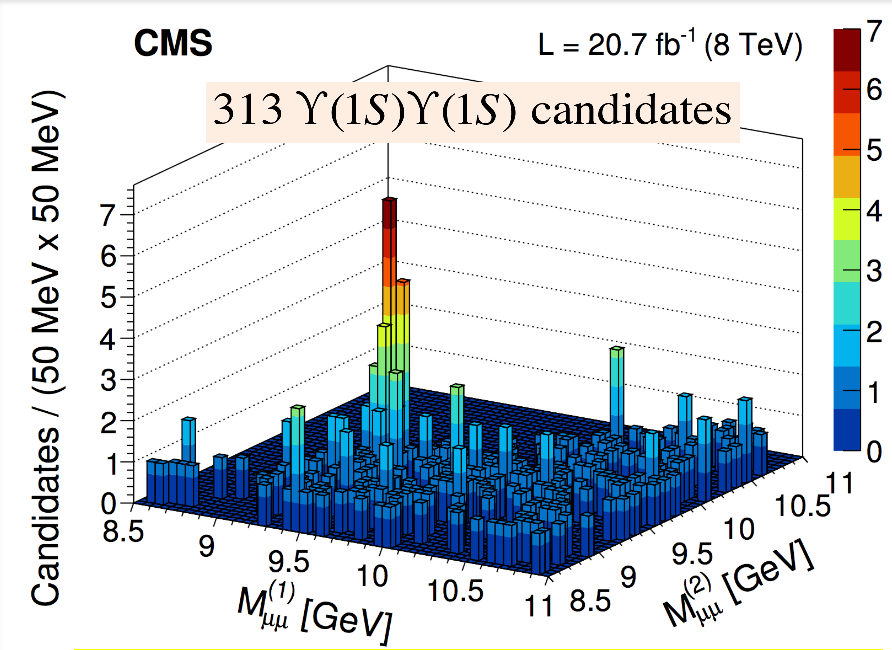
- **No evidence found for the η_b resonance ($\eta_b \to J/\psi J/\psi$) [suggested in analogy to $\eta_c \to \phi\phi$] that is expected to be rather suppressed [but FSI may enhance short-distance *Br~10^{-8}*]. No evidence for any other signal (exotic 4quark or CP-odd Higgs boson of NMSSM) as well.**

- **To be redone with 8TeV Run-I data and Run-II data.**

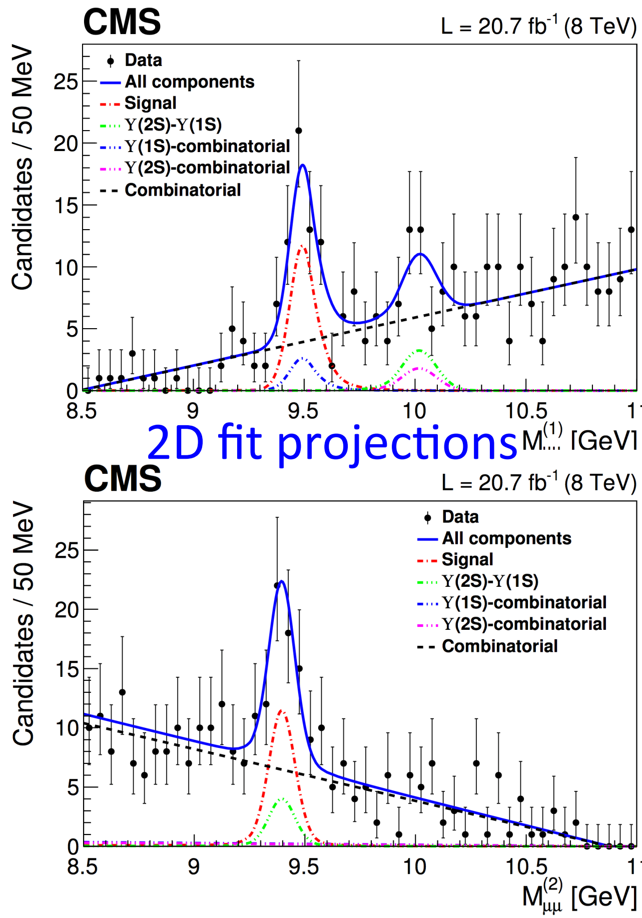
Double Quarkonia - II

[JHEP 05 (2017) 013] **observed for the first time the simultaneous production of two** $\Upsilon(1S)$ **mesons & measured the total xsection for the** $\Upsilon(1S)$ **pair production** (assumed unpolarized).

JHEP 05 (2017) 013



simultaneous production of two $\Upsilon(1S)$



- **This analysis will be extended with Run-II data (diff. xsection with higher statistics; try pairs with havier S-wave bottomonia).**
- **Search for signals in double** $\Upsilon(1S)$ **invariant mass to be explored with Run-II data.**