Exotic quarkonium states in CMS

Leonardo Cristella (on behalf of the CMS Collaboration)

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

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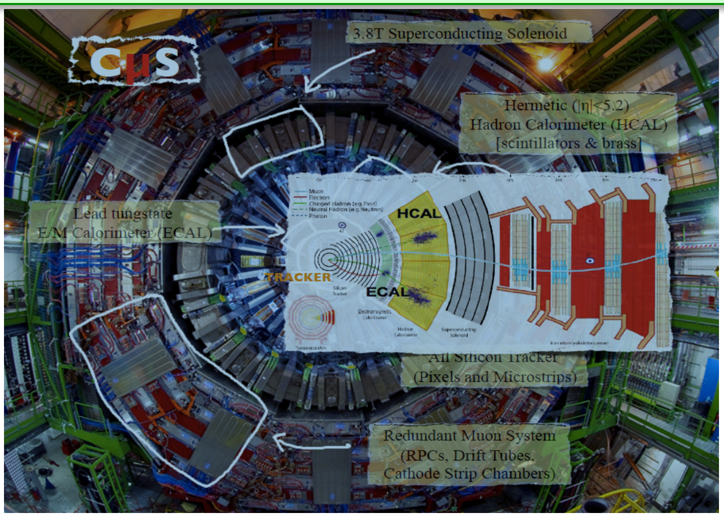
Compact Di-Muon Solenoid – μ reconstruction & triggers

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-ID: $\varepsilon(\mu \mid \pi, K, p) \leq (0.1 \div 0.2)\%$ [fake rates estimated in MC and data]

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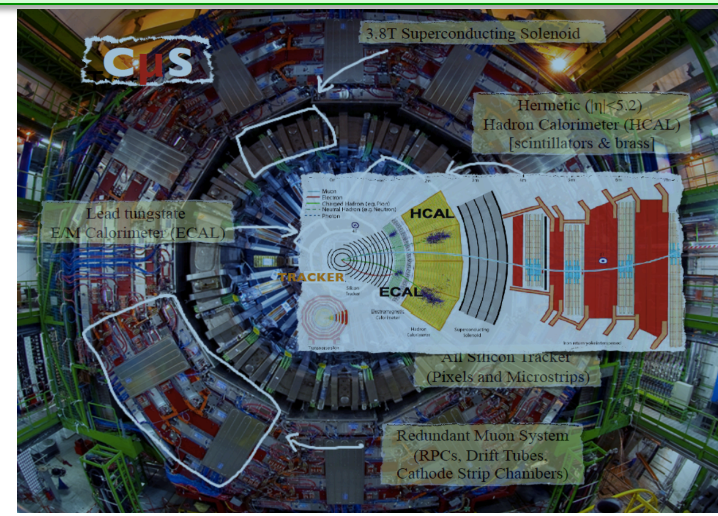

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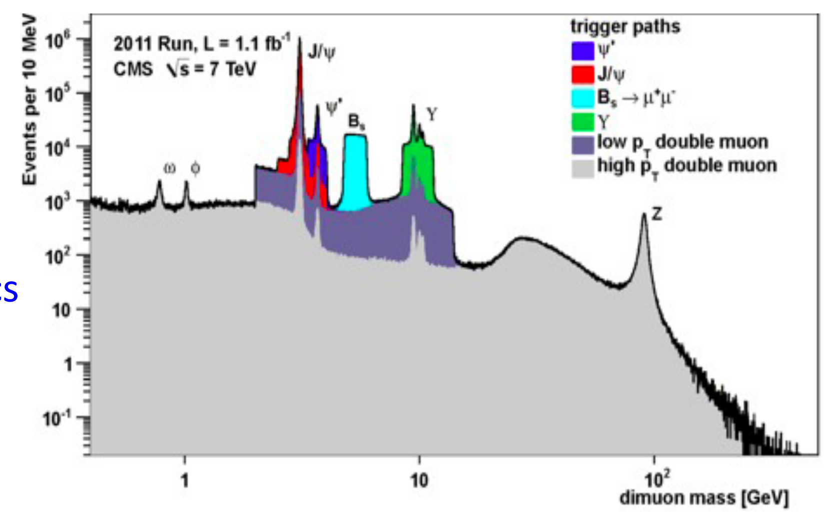
Trigger system

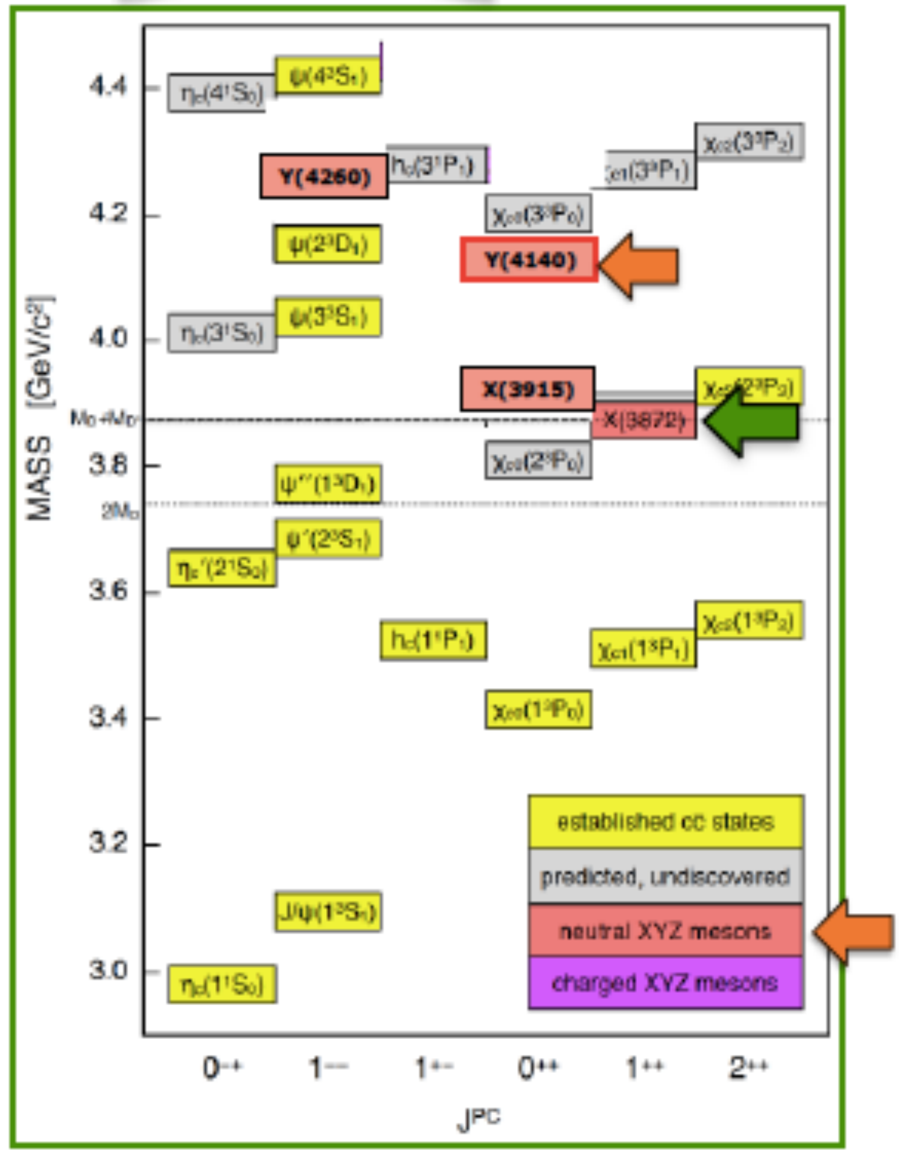
- fast HW (Muon Detector based) triggers (L1)
  SW triggers with full tracking & vtx recon. (HLT)
- rare decays/quarkonia almost 100% BKG/Signal paths
- ~10% of CMS bandwidth (~10*kHz* @L1) to flavor physics
  Data Parking in 2012: clear benefits having ~120*Hz*
  on top of the 25-30*Hz* on prompt stream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



Data samples:

- $\sqrt{s} = 7$ TeV , $\mathcal{L} = 5$ fb^{-1} (2011 run)
- $\sqrt{s} = 8$ TeV , $\mathcal{L} = 20$ fb^{-1} (2012 run)

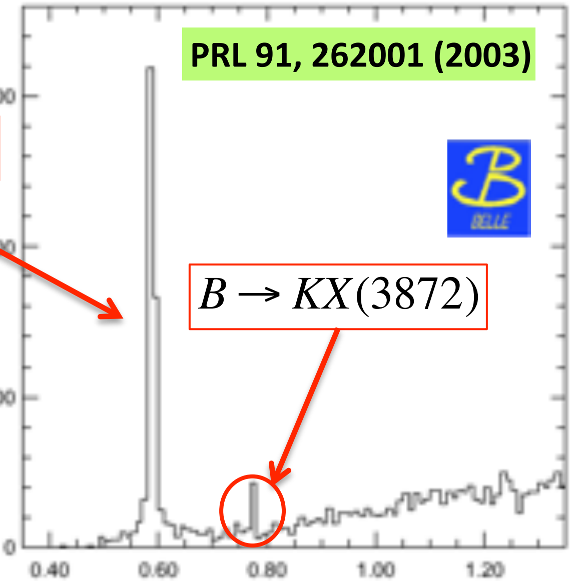
- The following "exotic" quarkonium-like states will be reviewed:
  - $X(3872)$
  - $Y(4140)$



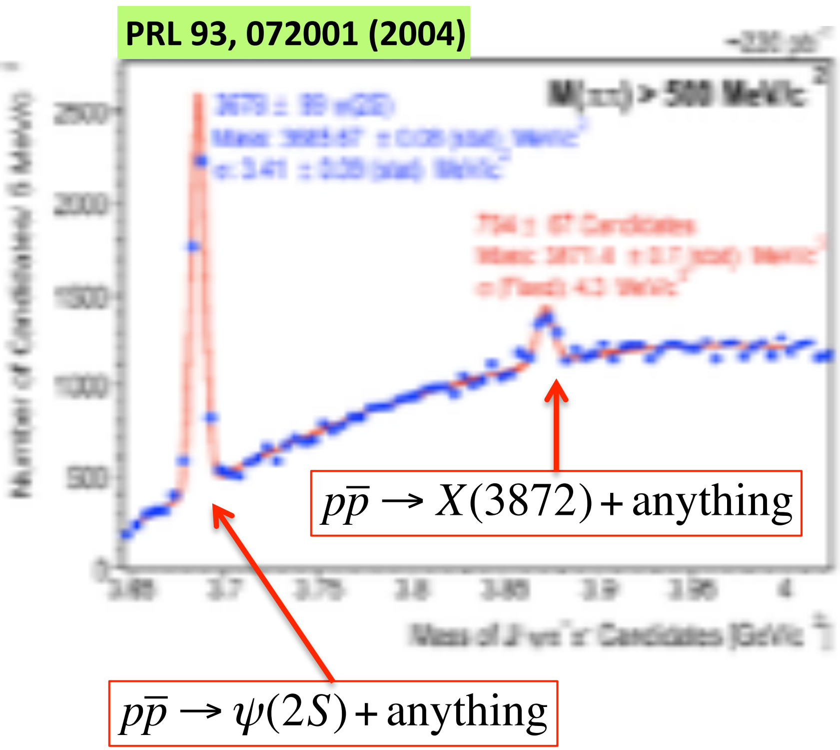
$X(3872)$ **JHEP 1304 (2013) 154**

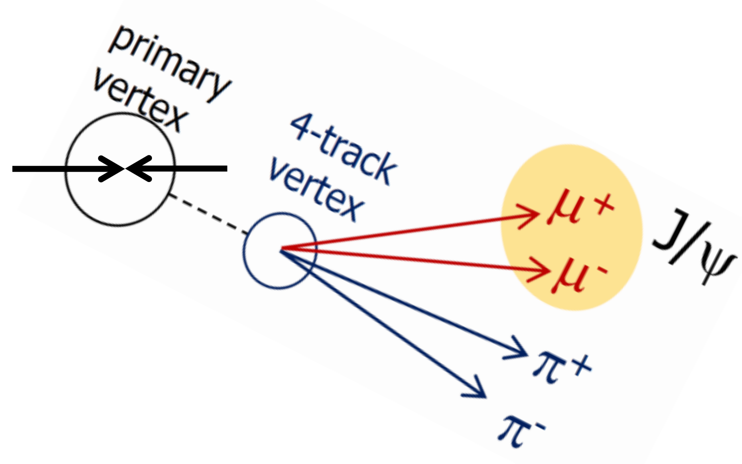
The *X(3872)* - I

- First exotic states discovered by Belle in 2003 in the decay $B \to K\,X(3872) \to K\,(J/\psi\,\pi^+\pi^-)$:



- Quickly confirmed by CDF and D0 with inclusive $p\bar{p}$ collisions:





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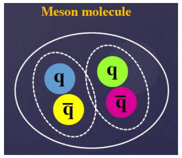
  Main hypothesis are:

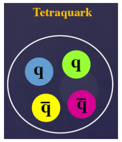


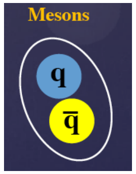
- **Loosely bound molecular state**: suggested by proximity to $D\bar{D}^{0*}$ threshold ($J^{PC} = 0^{-+}, 1^{++}$)

  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:

  X(3872) would be a large and fragile molecule with a miniscule binding energy

- **Tetraquark** ($J^{PC} = 1^{++}$)





- Conventional charmonium: assignments would be $\chi_{c1}(2^3P_1)$ or η_{c2} (1^1D_2) and quantum numbers would be respectively $J^{PC} = 1^{++}$ or 2^{-+}

  $c\bar{c} \rightarrow \rho J/\psi$ ~ ruled out by the fact that should be a pure isoscalar state; X(3872) shows an equal amount of isospin components (I=0 & I=1):

$$\frac{BF(X \rightarrow J/\psi\,\pi^+\pi^-\pi^0)}{BF(X \rightarrow J/\psi\,\pi^+\pi^-)} = 0.8 \pm 0.3$$

$\pi^+\pi^-\pi^0$ → **ω**

$\pi^+\pi^-$ → **ρ**

The *X(3872)* - II

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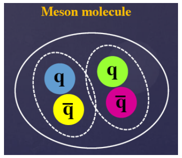

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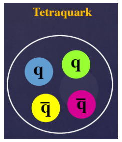

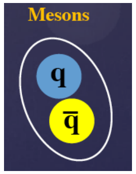

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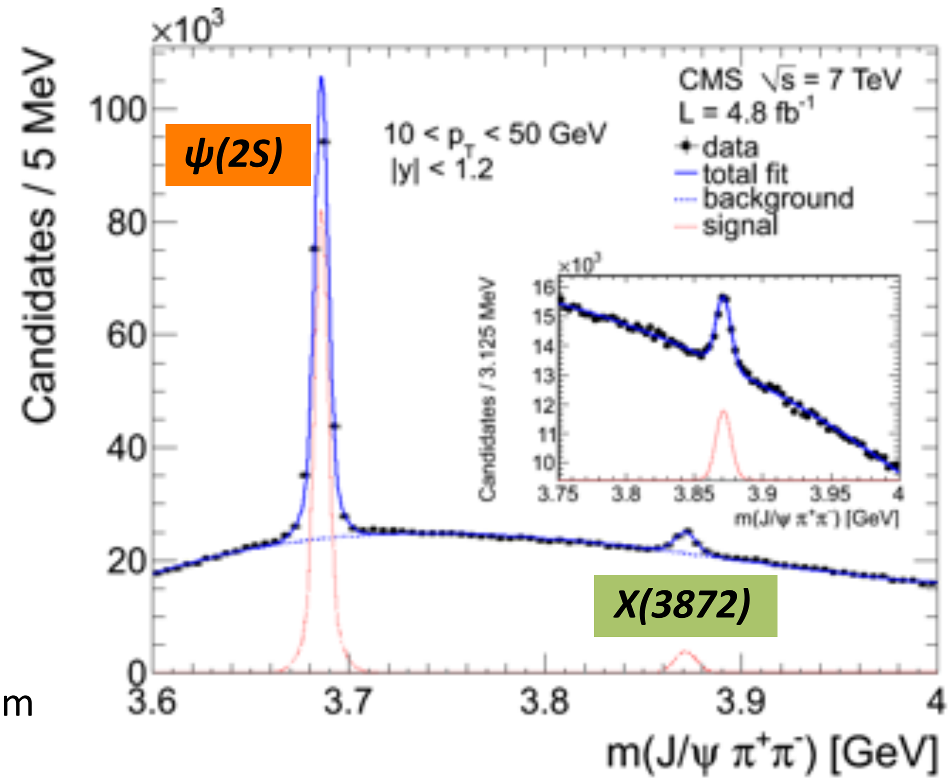
($\pi^+\pi^-\pi^0$ → **ω**; $\pi^+\pi^-$ → **ρ**)

- LHCb made a sophisticated angular analysis [**PRL 110 ('13) 222001** & **PRL 92 ('15) 011102**] of the whole decay chain $B^+ \rightarrow K^+ X(3872) \rightarrow K^+ (J/\psi\, \pi^+ \pi^-)$ dropping the assumption of lowest possible orbital angular momentum in the *X(3872)* sub-decay and unambiguously determine the quantum numbers to be $J^{PC} = 1^{++}$ under more general conditions. No hints for a large size of *X(3872)*.

- Pure molecular model is not supported by recent LHCb measurement [**NPB 886 (2014) 665**] of the radiative decay

X(3872) at CMS

- CMS can easily reconstruct the *X(3872)* in the decay channel $J/\psi(\rightarrow\mu\mu)\pi^+\pi^-$
- With $4.8 fb^{-1}$ of data at $7 TeV$ reconstructed about 12,000 *X(3872)* signal events
- CMS studied:
  - Cross section ratio w.r.t. *ψ(2S)*
  - Non-prompt component vs p_T
  - Prompt *X(3872)* cross section
  - Invariant mass distribution of the $\pi^+\pi^-$ system



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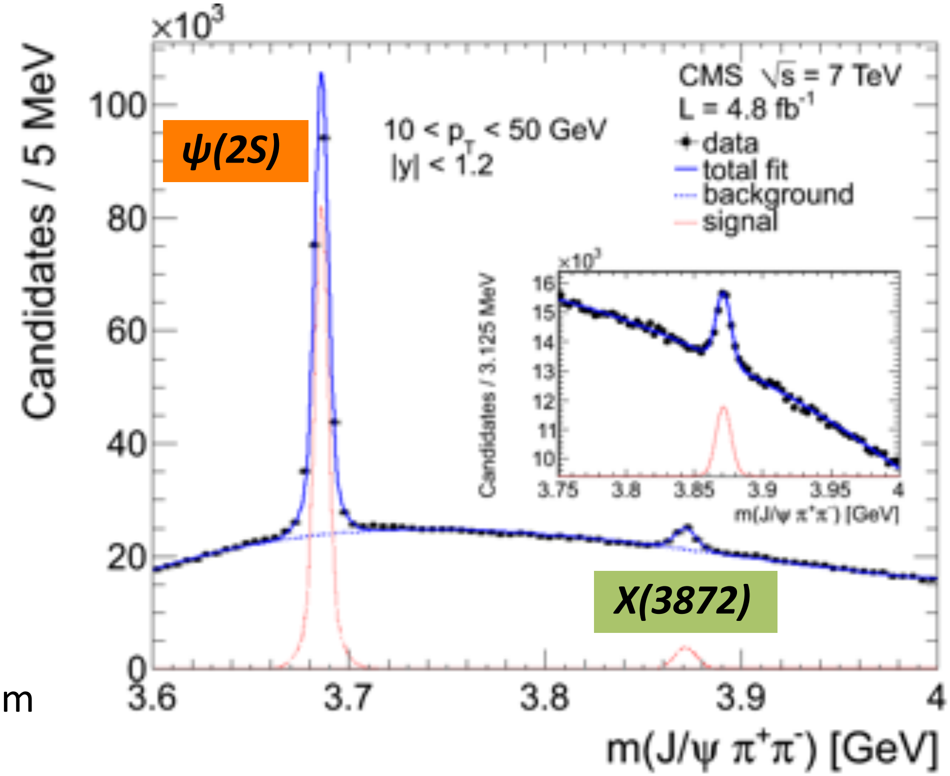
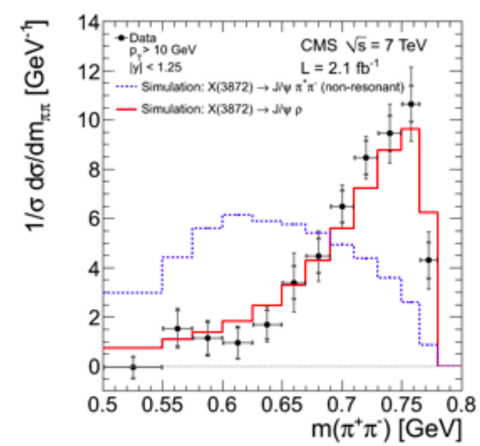


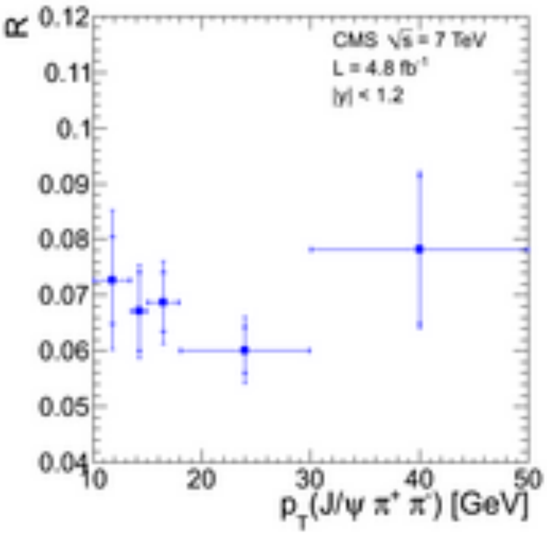
- The $\pi^+\pi^-$ invariant mass distribution from *X(3872)* decays to $J/\psi\pi^+\pi^-$ is measured in order to investigate the decay properties of the *X(3872)*
  - Studies at CDF and Belle suggest that *X(3872)* decays in J/ψ and ρ^0
  - The spectrum obtained from data is compared to simulations with and without an intermediate ρ^0 in the $J/\psi\pi^+\pi^-$ decay: the assumption of intermediate ρ^0 decay gives better agreement with data.



Cross sections ratio & non-prompt fraction

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

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



- For $10 < p_T < 50 GeV$ & |y| < 1.2:
  R = 0.0656 ± 0.0029 (stat.) ± 0.0065 (syst.)
- The ratio shows no significant dependence on the p_T of the $J/\psi\pi^+\pi^-$ system

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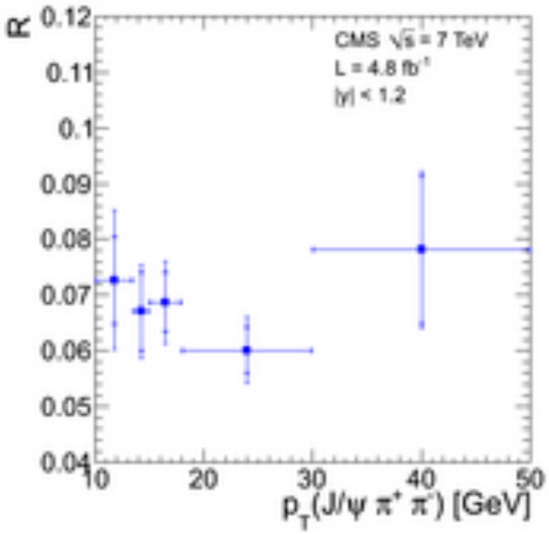

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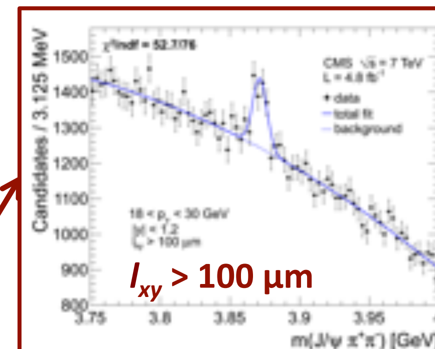
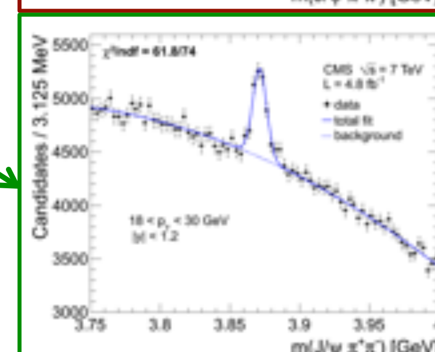
- The *X(3872)* can be produced from decays of B hadrons in a secondary vertex related to the decay length (l_{xy}) of the *B* meson
  - Events with *X(3872)* from *B* decays are selected by requiring $l_{xy} > 100 \mu m$: *non-prompt fraction* = $\frac{\text{\# of } X(3872) \text{ from } B}{\text{\# of } X(3872)}$
  - The fraction of *X(3872)* produced from decay of *B* does not show a dependence on $p_T(J/\psi\,\pi^+\pi^-)$
  - For $10 < p_T < 50 GeV$ & $|y| < 1.2$:
    X(3872) non prompt fraction = 0.263 ± 0.023 (stat.) ± 0.016 (syst.)



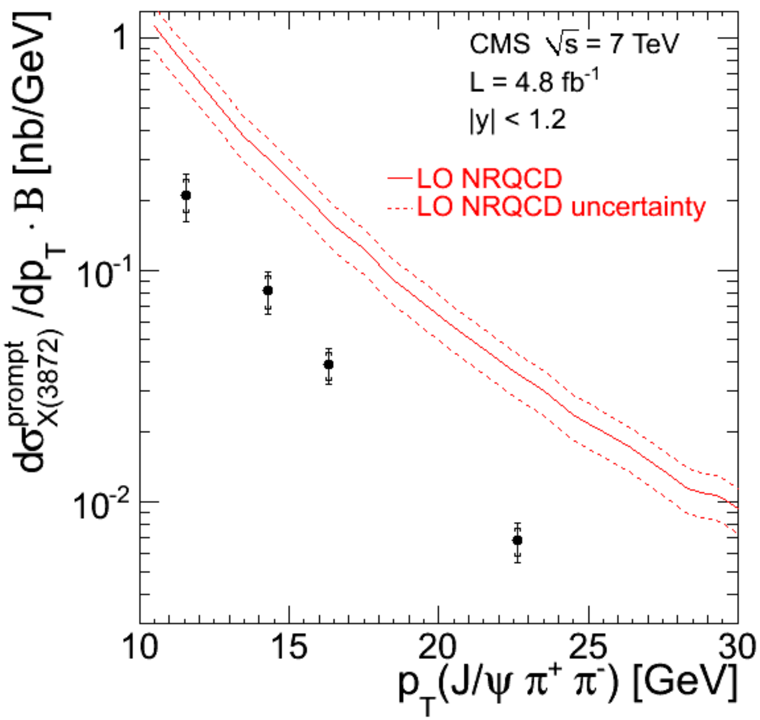


Prompt *X(3872)* production cross section & $\pi^+\pi^-$ system

- Putting together the previous measurements, the production of *X(3872)* state is measured for the first time as a function of transverse momentum as:

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

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



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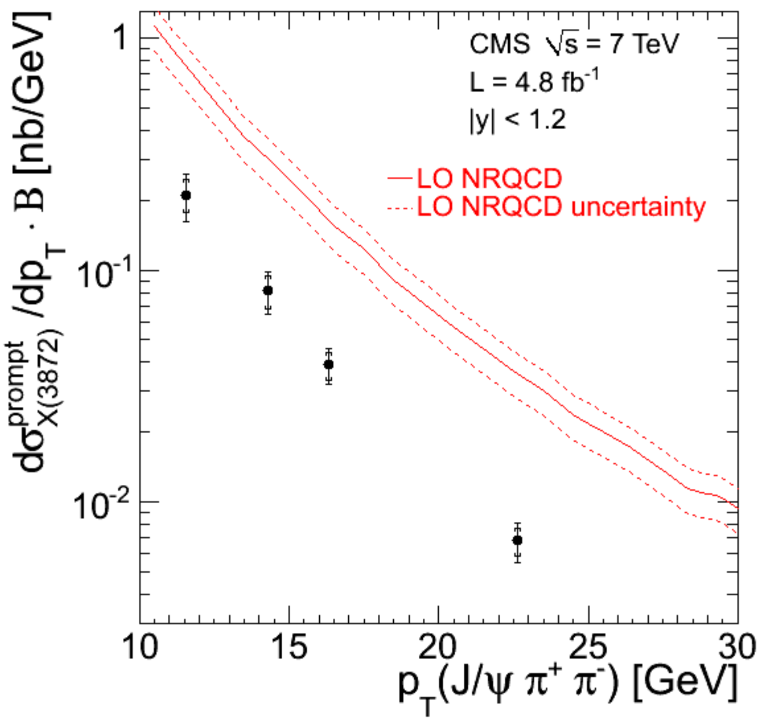

- Main systematic uncertainties are related to the measurements of *R* and prompt *ψ(2S)* cross section
- *X(3872)* and *ψ(2S)* are assumed to be unpolarized
- Results are compared with a theoretical prediction based on NRQCD factorization approach by Artoisenet & Brateen **[PhysRevD.81.114018]** with calculations normalized using Tevatron results, modified by the authors to match the phase-space of the CMS measurement
- The shape is reasonably well described by the theory while the predicted cross section is overestimated by over 3σ

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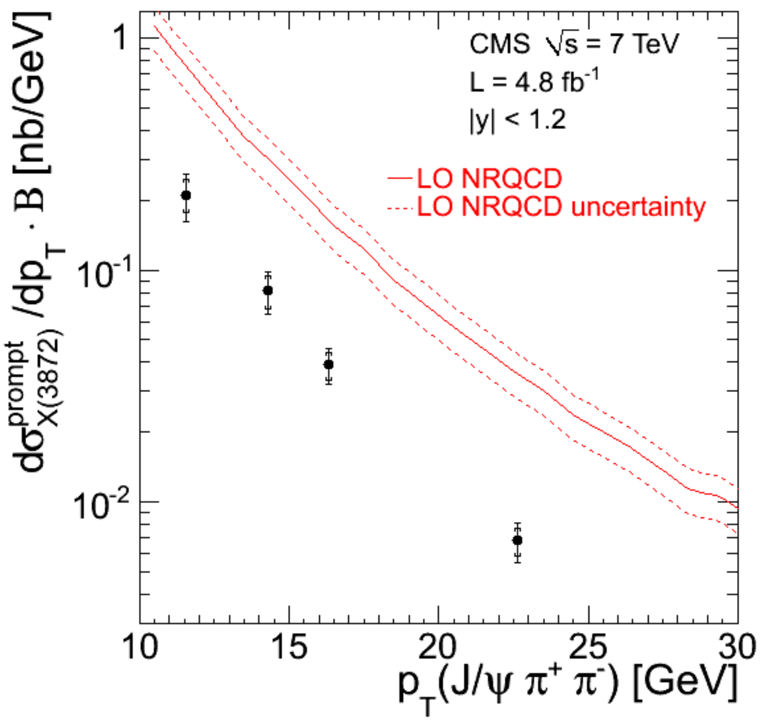

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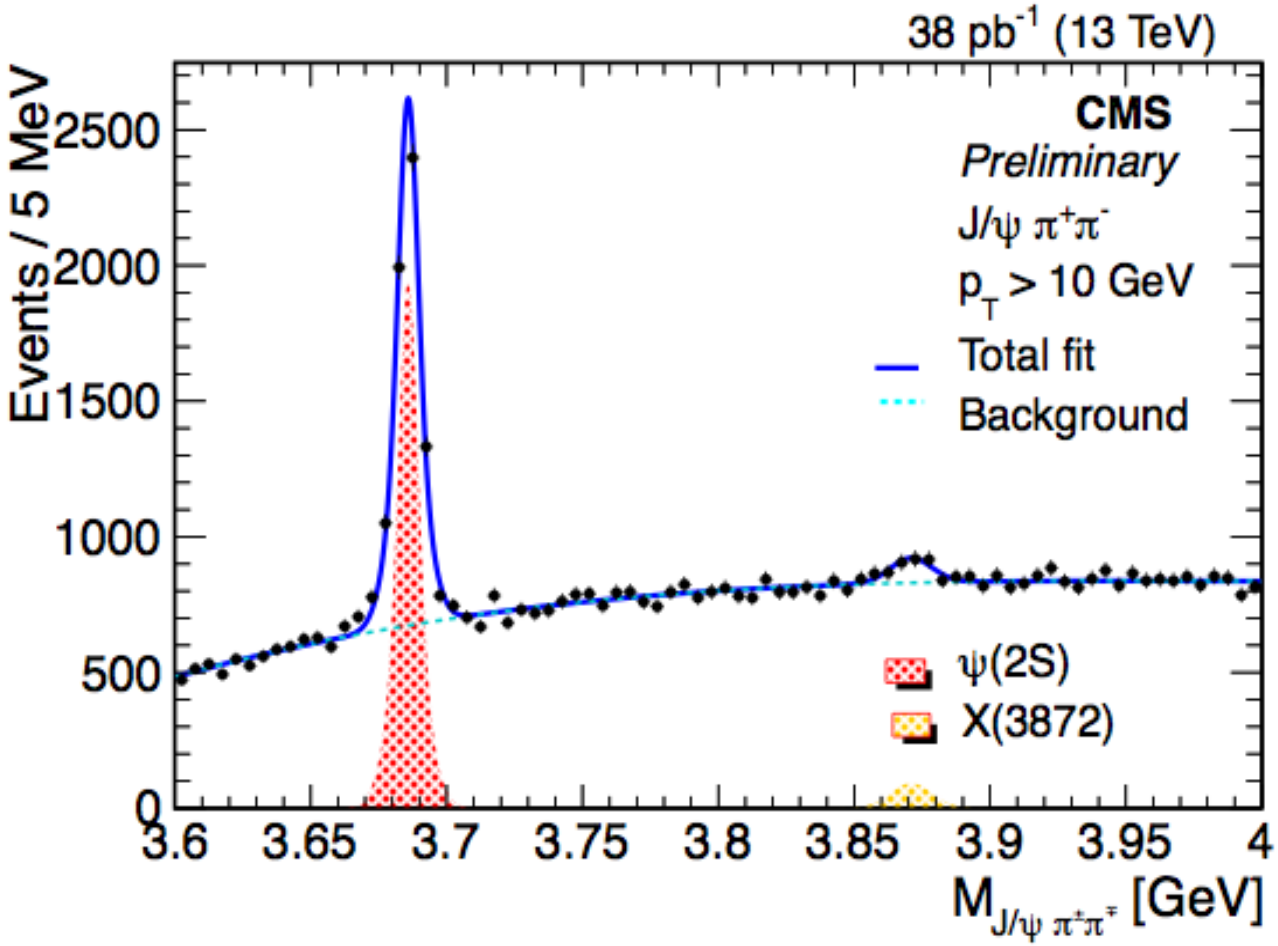
Predictions by Artoisenet & Brateen assume, within an S-wave molecular model, the relative momentum of the mesons being bound by an upper limit of 400*MeV* which is quite high for a loosely bound molecule, but they assume it is possible as a result of rescattering effects.

On the other hand, an upper limit lower of one order of magnitude would imply lower prompt production rates of few orders of magnitude **[Bignamini et al., PRL 2009, 103(16)]**

X(3872) production at Run-II

- Run-II data taking started last year at **$\sqrt{s}$ = 13*TeV*** with the first bunch of data recorded in July
- The plot shows the invariant mass of $J/\psi\ \pi^+\pi^-$ where is visible the *X(3872)* signal beyond the *ψ(2S)* one:



Search for X_b [beauty partner of the $X(3872)$]

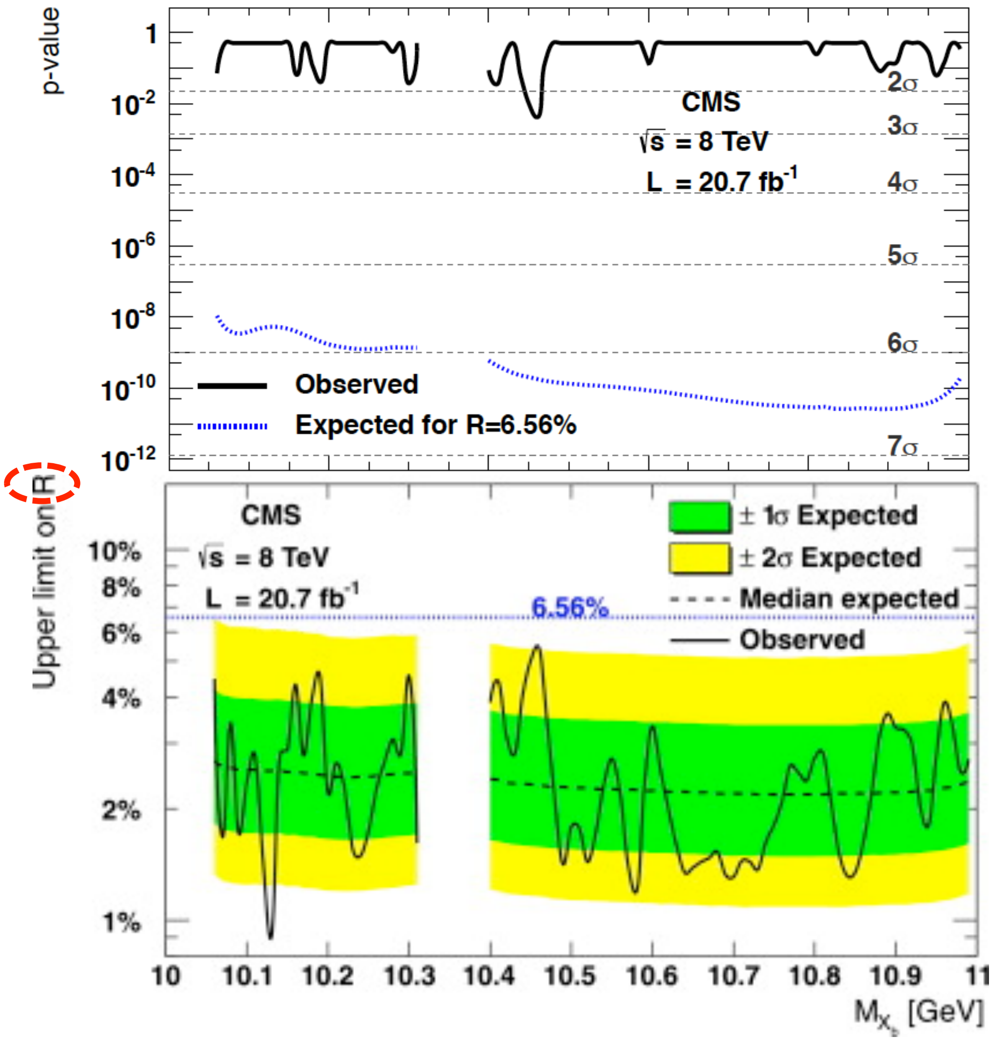
- HQ symmetry suggests an X_b analogous of X_c. Molecular model suggests to search it close to $B\bar{B}^*$ threshold (Swanson, 2004).
  - CMS looked for $X_b \to \Upsilon(1S)\,\pi^+\pi^-$ decay **seemingly analogous** to $X(3872) \to J/\psi\,\pi^+\pi^-$

    Analysis strategy: search for a peak other than known $\Upsilon(2S)$ & $\Upsilon(3S)$ in the $\Upsilon(1S)\,\pi^+\pi^-$ spectrum within 10-11*GeV*

    95% CL upper limits set on the ratio *R* of the inclusive production Xsections times BFs to $\Upsilon(1S)\,\pi^+\pi^-$ (the one for X_b is unknown):

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

Observed UL range: 0.9% to 5.4%
(similar result by ATLAS)



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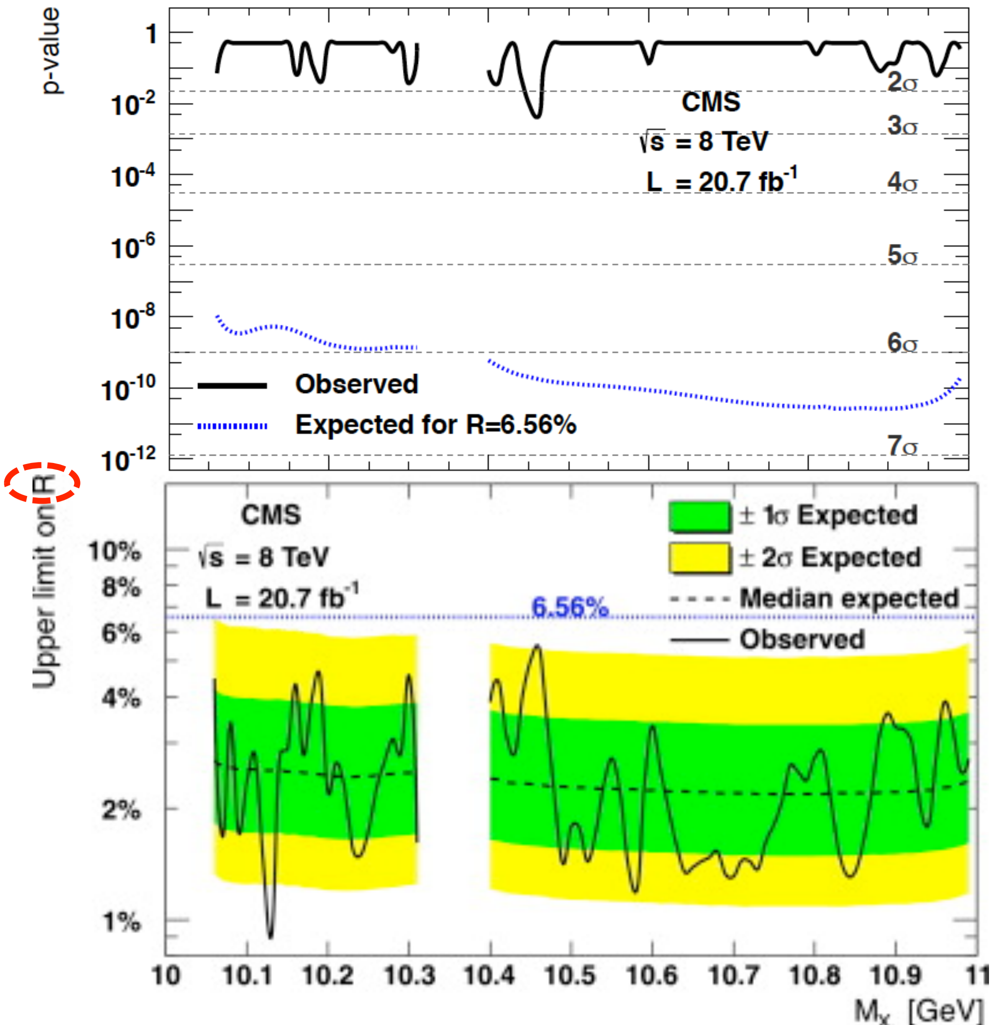
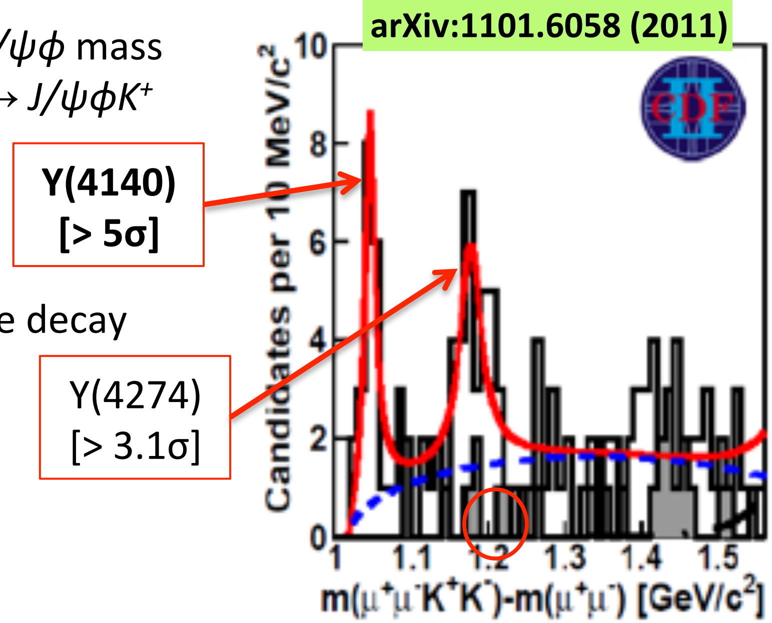


- According to Karliner & Rosner [**PRD91 (2015) 014014**], **this decay should be forbidden by G-parity conservation;** while for the *X(3872)* the isospin-conserving decay to $\omega J/\psi$ was kinematically suppressed, the same is not true for a bottomonium-like $J^{PC} = 1^{++}$ counterpart. The strategy for X_b observation should include search of $X_b \to \Upsilon(1S)\,\omega(\to\pi^+\pi^-\pi^0)$, $X_b \to \chi_{b1}(1P)\,(\to\Upsilon(1S)\gamma)\,\pi^+\pi^-$, $X_b \to \Upsilon(3S)\gamma$ (not easy: for Run-II)

$Y(4140)$ PLB 734 (2014) 261

The *Y(4140):* another long story…

- CDF (2009) reported evidence (@3.8σ) for narrow peak in $J/\psi\phi$ mass spectrum, close to the kinematical threshold, in decays $B^+ \rightarrow J/\psi\phi K^+$
- CDF (2011) presents update analysis with larger dataset, (6.0fb^{-1} vs 2.7fb^{-1}) observing the so called *Y(4140)* state:
- Belle (2009) searched and did not find this state in the same decay
- LHCb (2012) has searched for these two states reconstructing 383 ±22 $B^+ \rightarrow J/\psi\phi K^+$ candidates
  - LHCb observed no signals; this measured UL implies a 2.4σ tension with CDF



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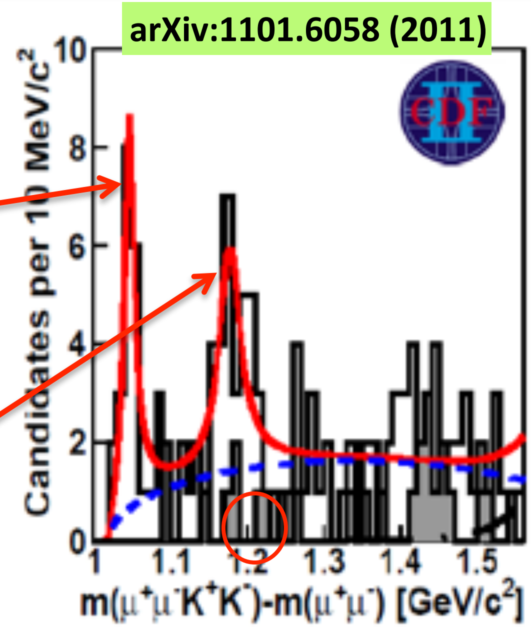

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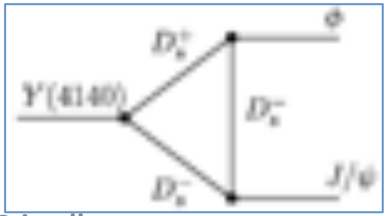
Interpretations

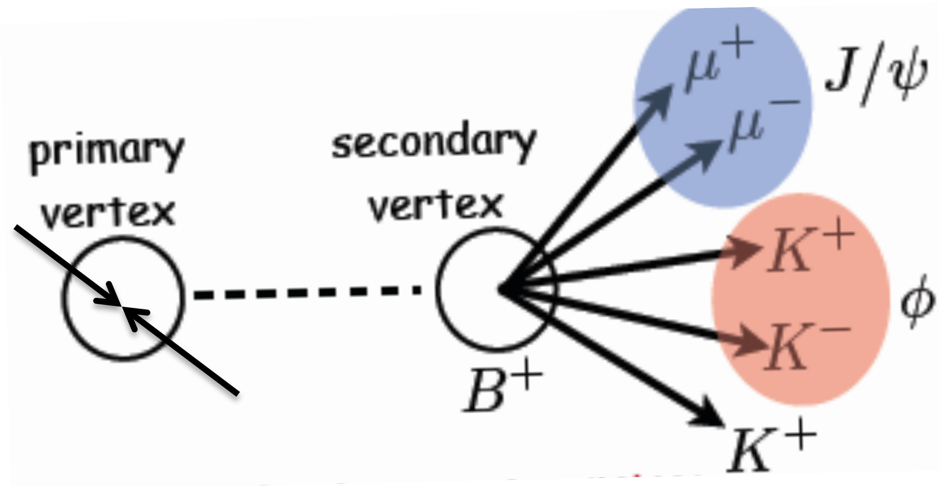
- Masses are well above 3770*MeV* open charm threshold; the conventional charmonium should decay into $D\bar{D}$, with tiny B.F. to *J/ψϕ* (OZI-suppressed)

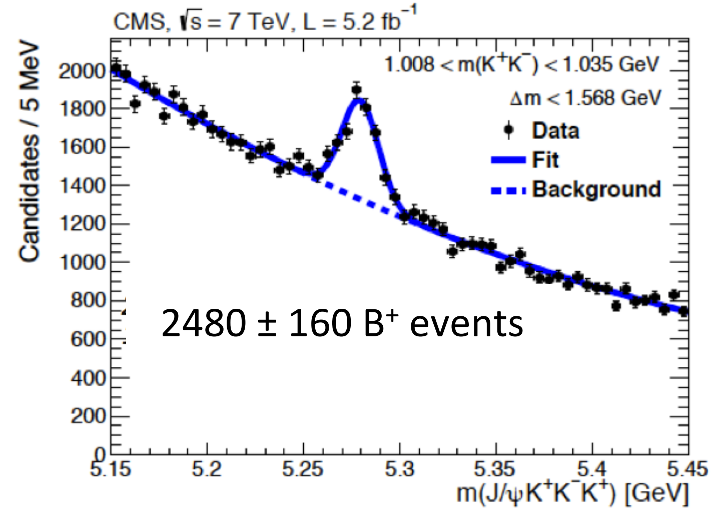
- For the Y(4140) decaying several interpretations have been proposed:
  - $D_s^*\bar{D}_s^*$ molecule, that is the molecular strange partner of the *Y(3940)*
  - $cs\bar{c}\bar{s}$ tetraquark
  - threshold kinematic effect
  - hybrid charmonium
  - weak transition with $D_s\bar{D}_s$ rescattering



CMS search for *Y(4140)*

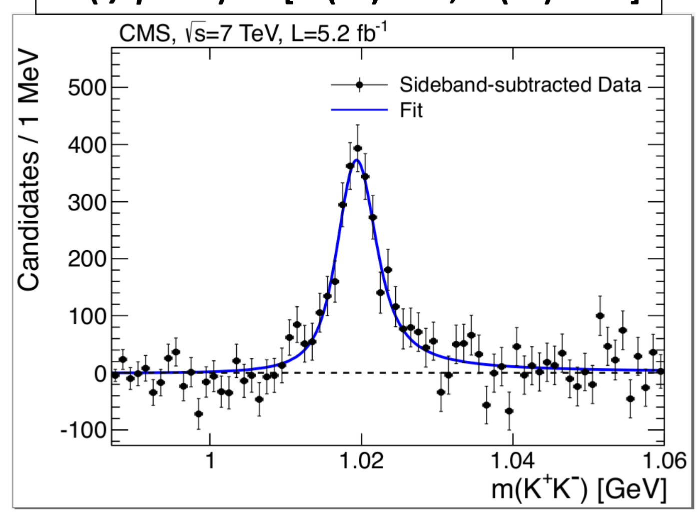
- Search performed with 5.2fb^{-1} of collision at 7TeV





- Largest B^+ sample to date
  - 20 times CDF
  - 7 times LHCb

m(*J/ψKKK*) ∈ [m(*B*$^\pm$) - 3σ, m(*B*$^\pm$) + 3σ]



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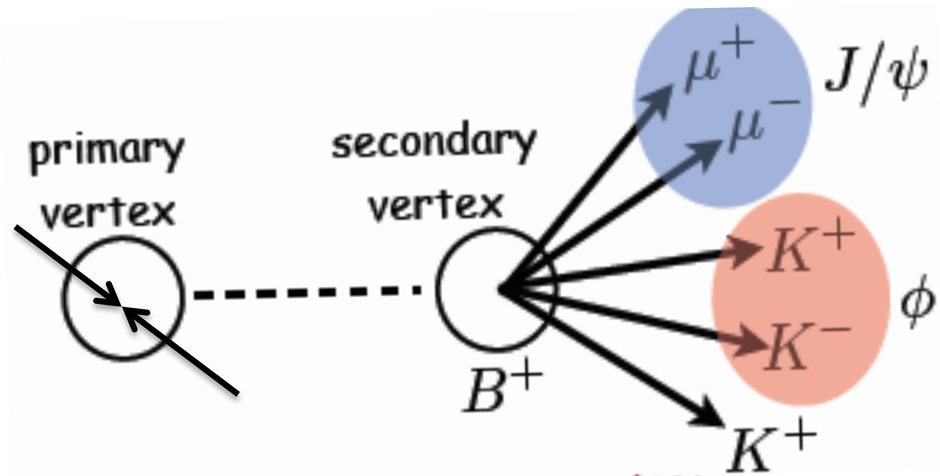

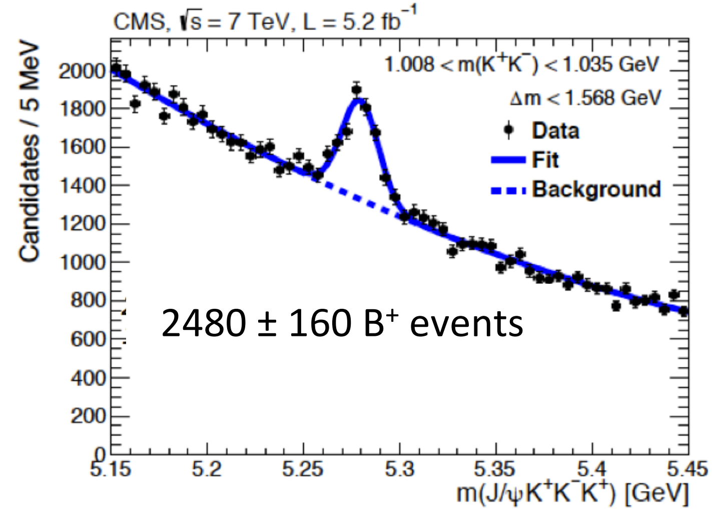

- Largest B^+ sample to date
  - 20 times CDF
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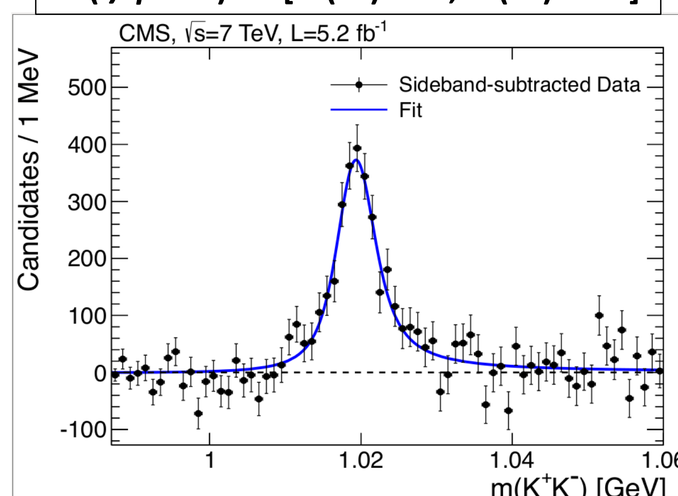
- **Signal extraction**:
  - $p_T > 1GeV$ for any kaon
  - selection on common vertex probability and angular separation between J/ψ and kaons
  - $p_T\,(J/\psi) > 7GeV$
  - transverse B^+ flight lenght significance > 3

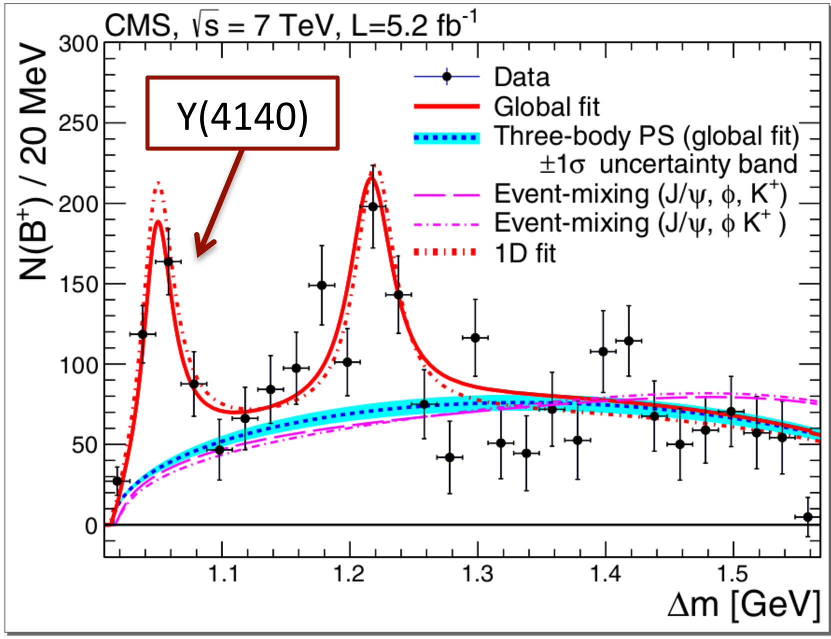
m(*J/ψKKK*) ∈ [m(*B*±) - 3σ, m(*B*±) + 3σ]



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

The $J/\psi\phi$ mass spectrum

- The $\Delta m = m(\mu^+\mu^- K^+K^-) - m(\mu^+\mu^-)$ spectrum is obtained:
  - dividing the dataset in 20*MeV* Δm bins
  - fitting every bin with:
    - Signal PDF: S-wave relativistic Breit-Wigner (BW) convoluted with mass resolution
    - 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
  - extracting the number of B^+ signal in each Δm bin by fitting the spectrum



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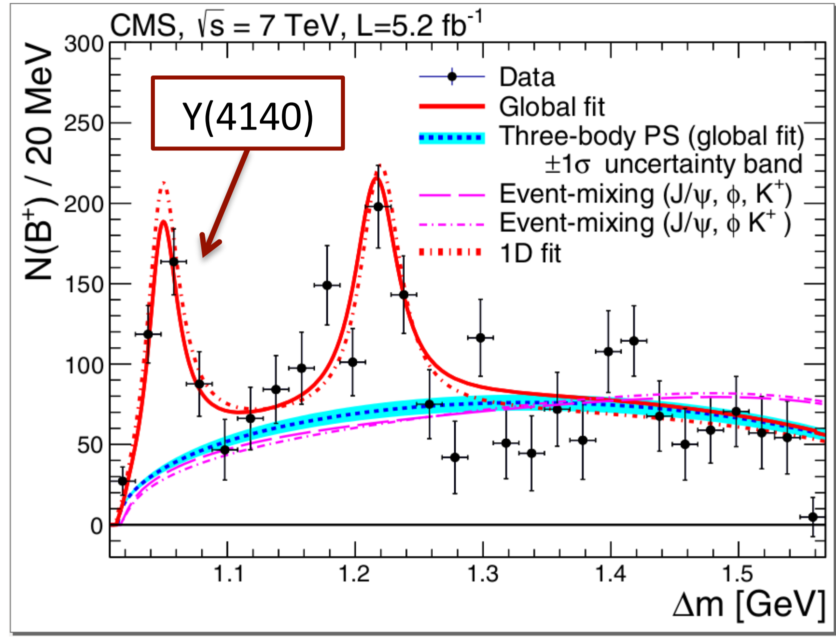


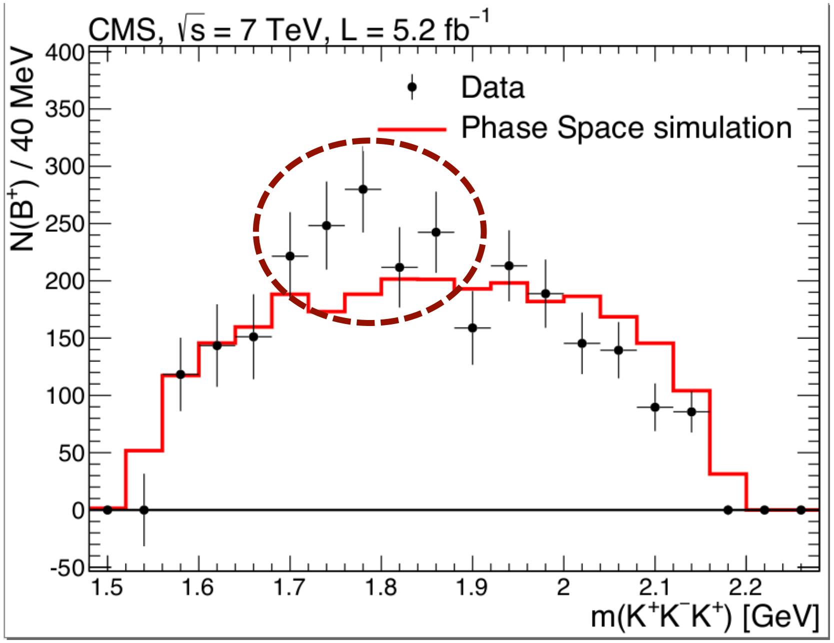
Yield	Mass [MeV]	Γ [MeV]
310 ± 70	4148.0 ± 2.4(stat) ± 6.3(syst)	28^{+15}_{-11}(stat) ± 19(syst)
418 ± 170	4313.8 ± 5.3(stat) ± 7.3(syst)	38^{+30}_{-15}(stat) ± 16(syst)

First structure is consistent with *Y(4140)* of CDF observed with a stat. significance > 5σ!
There is evidence for a second structure in the same mass spectrum

- Naïve yields' ratio estimate: $\frac{BR(Y(4140))}{BR(J/\psi\phi K^{\pm})} \approx 0.10 \pm 0.03\%$ consistent with CDF and LHCb UL

Next steps for *Y(4140)*

- Understanding the nature of both structures needs further investigation
  - The ϕK^{+} mass distribution shows an excess w.r.t. PHSP profile in the region where large resonances [$K_2(1770)$ & $K_2(1820)$] may appear; reflections studies are carried out:



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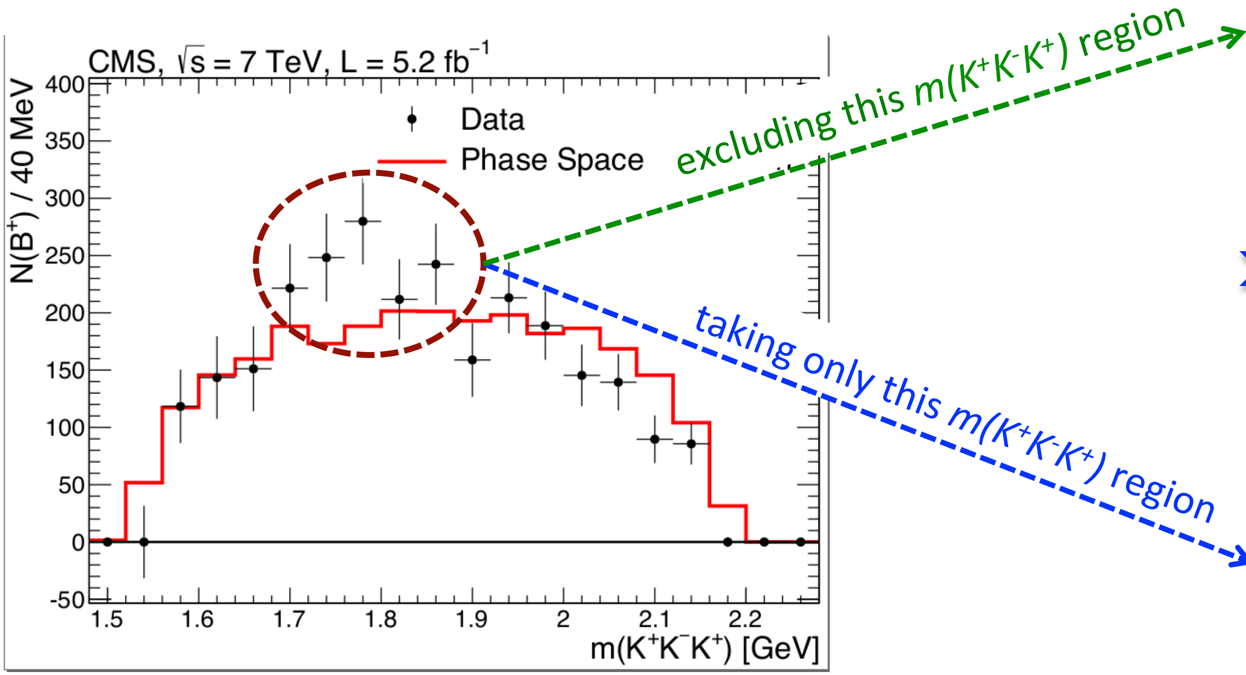
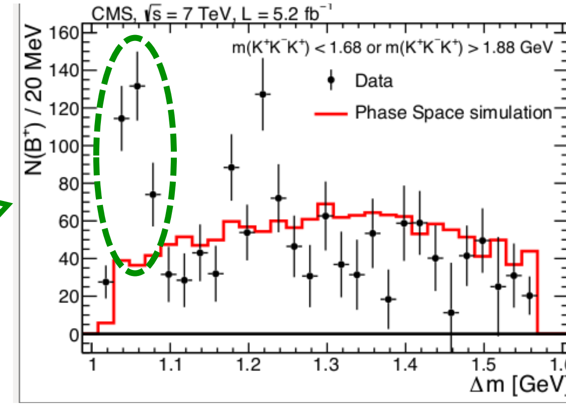
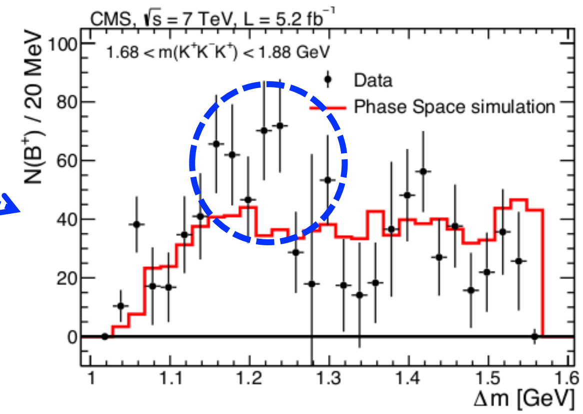




- ***Y(4140)*** **appears to be uncorrelated to ϕK^+ resonances**



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

- Understanding the nature of both structures needs further investigation & requires a full amplitude analysis (not easy task: 2 vectors in the final state!).

It is suitable for CMS adding Run-II data to extract an enough pure B^+ sample with enough statistics.

Summary & outlook

- Although designed for high-p_T physics …
  … CMS is an exceptional apparatus for dealing with flavor physics topics!

  - CMS has greatly contributed to the **study of exotic states**:
    - *X(3872)* prompt cross section
    - Search for X_b
    - *Y(4140)* confirmation

  - Their actual nature is still a challenge.
    Moreover **many final states still to be explored**!

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  - Their actual nature is still a challenge.
    Moreover **many final states still to be explored**!

- **Run-II just started**

  - CMS will record much larger integrated luminosity than LHCb,
    in an harsher environment

  - Dedicated triggers developed for the most important analyses

Backup slides / Additional material

$X(3872)$ JHEP 1304 (2013) 154

Systematic uncertainties

- Signal extraction:
  - 2 μ with $p_T > 4$GeV coming from J/ψ in the central region of the detector ($|y(\mu^+\mu^-)| < 1.25$)
  - 2 tracks with opposite charge and $p_T > 600$MeV
  - combination of these four tracks with constraint on common vertex
  - selection on common vertex probability, angular distance between J/ψ and π, Q value [m($\mu\mu\pi\pi$) - m(J/ψ_{PDG}) - m($\pi\pi$)].

- **Non-prompt fraction:**

Source	Relative uncertainty (%)
Vertex estimation	1
Background parametrization	2-3
Efficiency	3-8
Decay length resolution	4
Pileup	2
Total	**6-10**

Systematic uncertainties

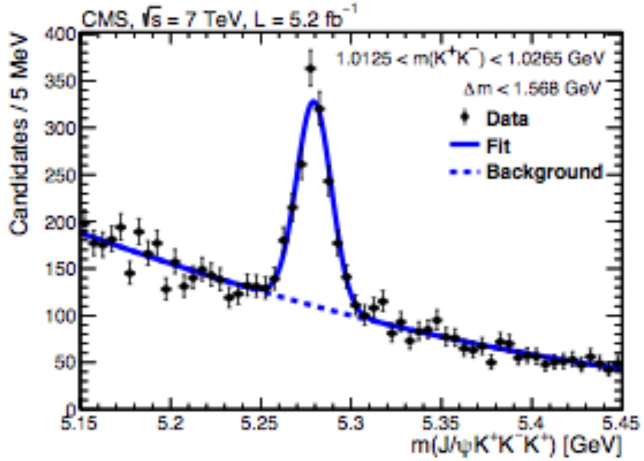
$$R \equiv \frac{\sigma\left(pp \to X(3872) + \text{anything}\right) \cdot B\left(X(3872) \to J/\psi\, \pi^+\pi^-\right)}{\sigma\left(pp \to \psi(2S) + \text{anything}\right) \cdot B\left(\psi(2S) \to J/\psi\, \pi^+\pi^-\right)} = \frac{N_{X(3872)} \cdot A_{\psi(2S)} \cdot \varepsilon_{\psi(2S)}}{N_{\psi(2S)}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

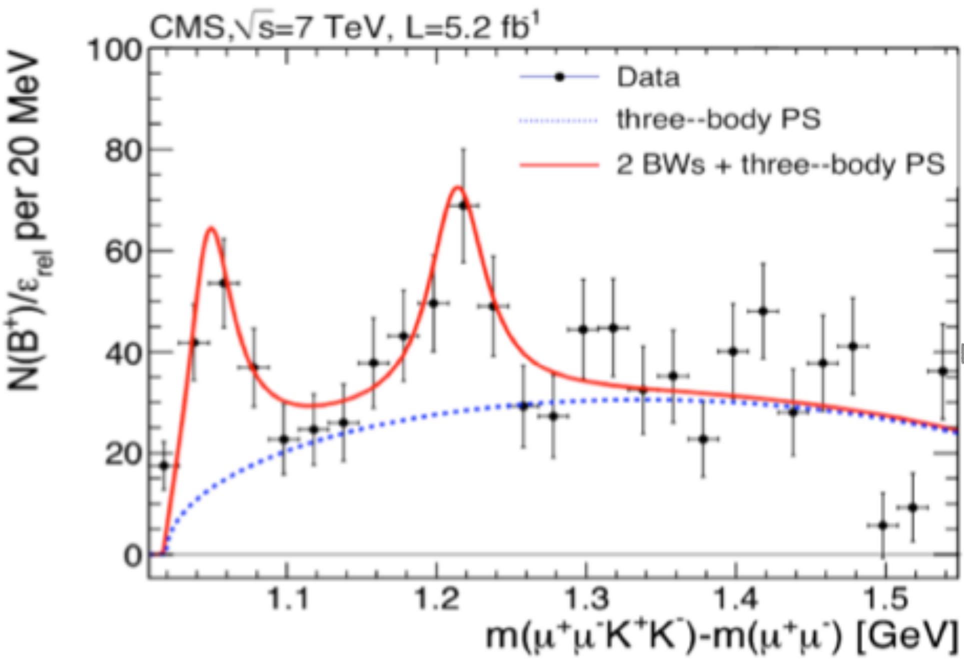
Source	Relative uncertainty (%)
Fit functions	1-2
ε ($\mu^+\mu^-$)	< 1
ε ($\pi^+\pi^-$)	1-5
Efficiency statistical precision	1-3
X(3872) p_T spectrum	1-11
ψ(2S) p_T spectrum	1–4
m($\pi^+\pi^-$) spectrum	1–2
Acceptance statistical precision	1–3
Total	**5–13**

$Y(4140)$ PLB 734 (2014) 261

Crosscheck with cleaner B^+ sample

- More stringent quality and kinematic cuts are used to produce a **cleaner sample**
  - **40% of the defaults *B* signal**
  - **10 times less background**



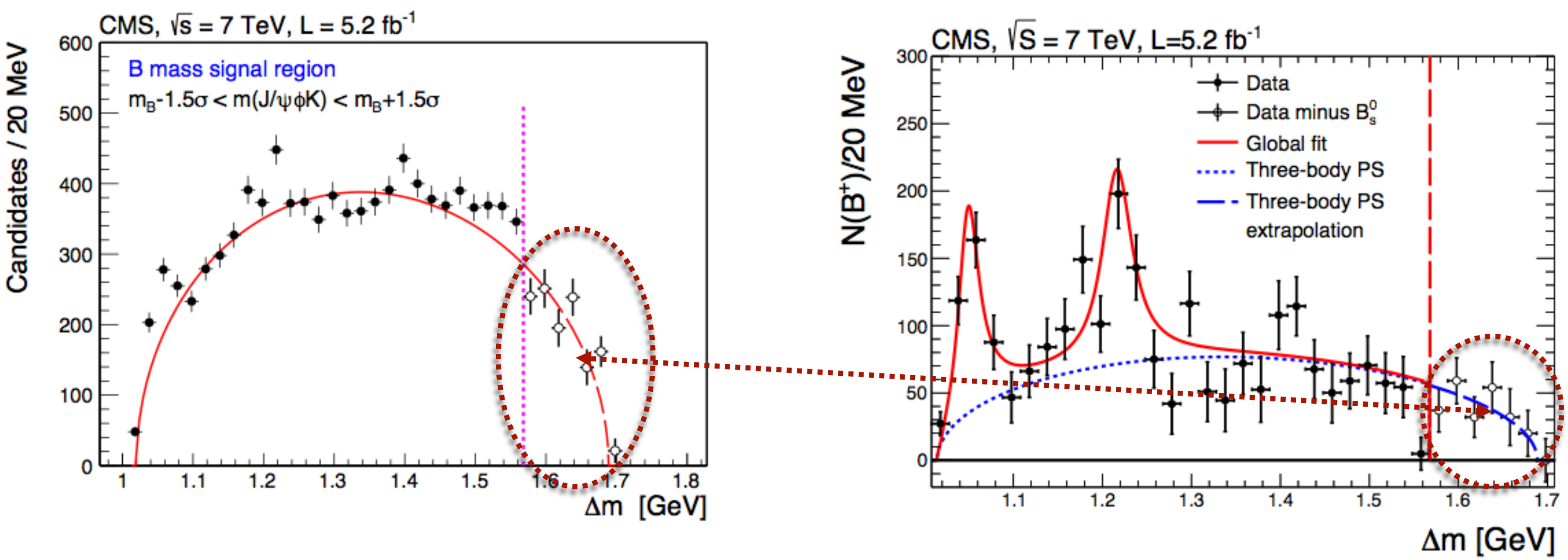


- **Found structure can be clearly seen also with this selection**

Investigation of the whole Δm region

- Check the events with *Δm* larger than 1.568*GeV* (eliminated from the analysis) to ensure that they could not cause reflections in the low-*Δm* region

- The *Δm* spectrum after subtracting B^0_s contribution but including non-*B* events within 1.5 σ of the B mass
- The extension of *Δm* spectrum after subtracting non-*B* background, to the full phase space



The events in the cutoff region are consistent with phase space.

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

Systematic uncertainties

Source	m_1 (*MeV*)	Γ_1 (*MeV*)	Γ_2 (*MeV*)	m_1 (*MeV*)
B^+ background PDF	0.8	7.4	2.6	9.9
B^+ signal PDF	0.2	3.6	2.7	0.2
Relative efficiency	4.8	6.0	0.9	10.0
Δm binning	3.7	1.5	2.7	0.2
Δm structure PDF	0.8	9.3	0.6	4.9
Δm mass resolution	0.8	6.4	0.6	4.6
Δm background shape	0.2	7.0	0.3	0.2
Selection requirements	0.8	7.8	5.5	1.8
Total	**6.3**	**19**	**7.3**	**16**