



# Exotic Quarkonium states at CMS

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on behalf of the CMS Collaboration

INFN of Bari, Italy

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# Outline

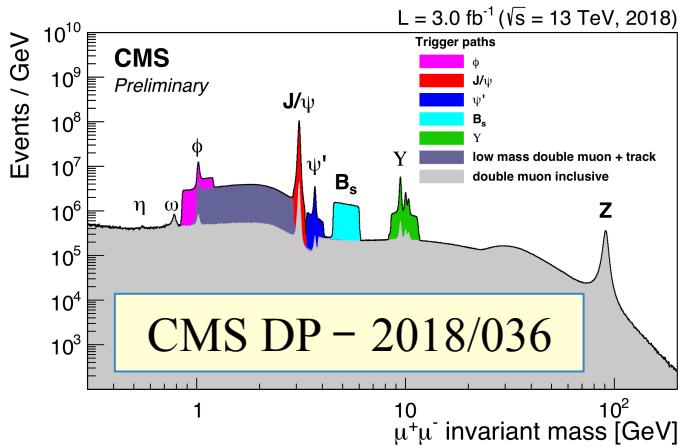
- Introduction
- Search for  $X(5568)^+ \rightarrow B_s \pi^+$
- Search for the bottomonium partner of  $X(3872)$
- Summary and Prospects

# Introduction

## Heavy flavor spectroscopy is still a developing field in HEP because of

- many observations of multi-quark states (XYZ) in the last 14 years, starting from X(3872) @Belle - it is interesting to understand more about these states
- study of hadrons consisting of two or three heavy quarks
- the need to explore higher excited states, e.g.  $B_{s/c}^{*(*)}$  spectra

## CMS is contributing in these topics thanks to



### Trigger

Very efficient hardware trigger

Highly flexible HLT:  
paths dedicated  
to specific analyses

### Tracker

Good  $p_T$  resolution  
(up to  $\Delta p_T/p_T \cong 1\%$  in the central region)

Tracking  $\epsilon > 99\%$  for muons

Good vertex reconstruction  
and impact parameter  
resolution up to  $\cong 15\mu m$

### Muon system

Redundant system with large coverage ( $|\eta| < 2.4$ )

Standalone  $\Delta p_T/p_T \cong 10\%$

High-purity muon ID  
 $\epsilon(\mu|\pi,K,p) < 0.2\%$

In this talk several highlights from Run-I & Run-II data samples will be discussed

# Hadrons: Conventional and Exotic

- Is there any quark configuration other than mesons and baryons?
- In QCD such configurations are possible
- Which of them are actually realized in nature?

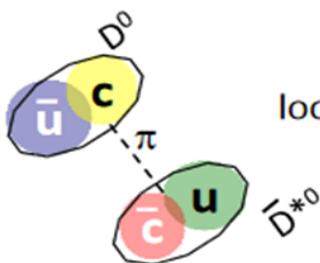
Possible “white” combinations of quarks & gluons:

## ☒ Conventional mesons & baryons



## ☒ Allowed but “exotic” combinations

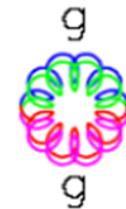
tightly bound multi-quark



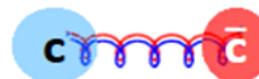
loosely bound meson-antimeson “molecule”



Color-singlet multigluon bound state (glueball)



hybrids



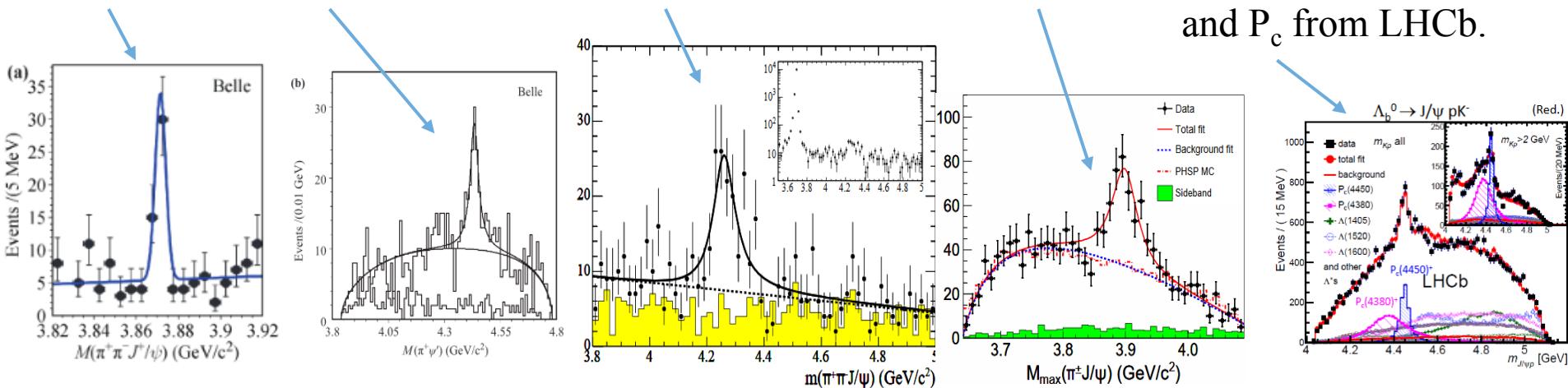
# Exotic Hadrons: experimental results and theoretical interpretation

Since 2003, thanks to the B-factories Belle and BaBar (followed by BES III and LHCb), the number of candidates for exotic hadrons is continuously growing.

These are multiquark states, some significant examples:

$X(3872)$  and  $Z(4430)^+$  from Belle,  $X(4260)$  from BaBar,  $Z(3900)^+$  from BESIII /Belle

and  $P_c$  from LHCb.



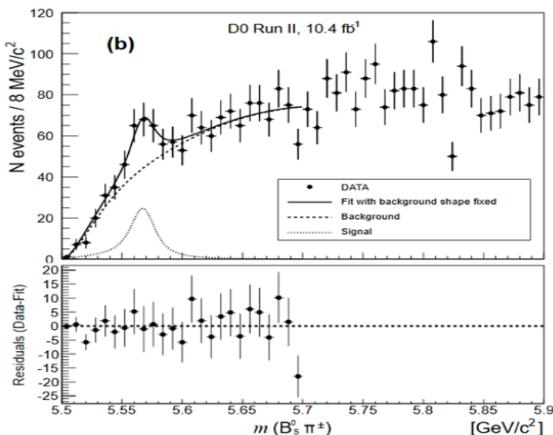
## This is a new hadron spectroscopy era

Theoretical interpretation of all these exotic states is still not clear.

→ we need more experimental information!

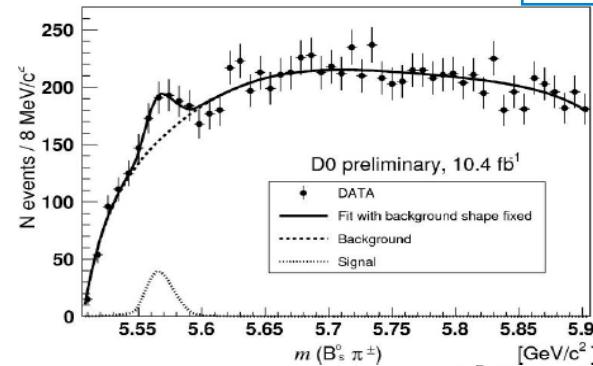
- Compact tetraquark?
- Hadronic molecule?
- Rescattering (threshold effect, cusp)?
- Hadro-charmonium?

New results are coming. For instance the claim by DØ Collaboration of an  $X(5568)^+ \rightarrow B_s \pi^+$



$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9} \text{ MeV}, \quad \rho_X^{\text{D}\bar{\text{O}}} \equiv \frac{\sigma(p\bar{p} \rightarrow X + \text{anything}) \times \mathcal{B}(X \rightarrow B_s^0 \pi)}{\sigma(p\bar{p} \rightarrow B_s^0 + \text{anything})}$$

$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5} \text{ MeV}, \quad = (8.6 \pm 1.9 \pm 1.4)\%$$



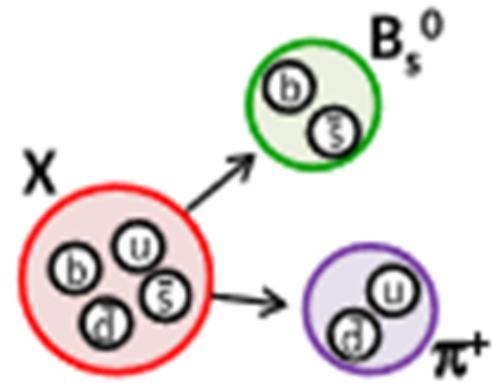
Similar results with  $B_s^0 \rightarrow D_s \mu\nu$

### Search for X(5568)<sup>+</sup> in CMS:

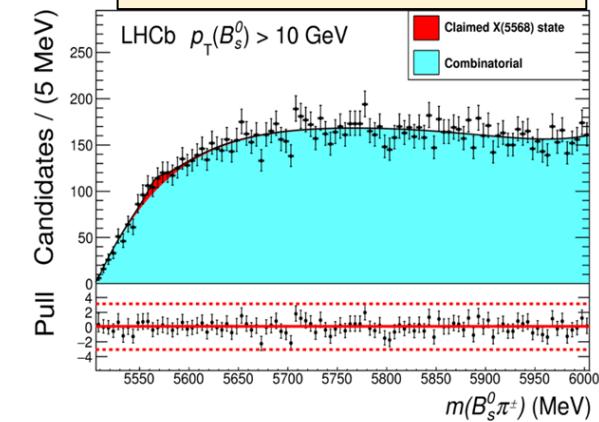
- Different  $\eta$  range w.r.t. LHCb
- b production conditions similar to DØ except for the initial state ( $pp$  vs.  $p\bar{p}$ )

# Search for $X(5568)^+ \rightarrow B_s \pi^+$

If confirmed, would be unique with 4 different flavors



PRL 117 (2016) 152003



LHCb upper limits @ 90% (95%) CL

$$\rho_X^{\text{LHCb}}(p_T(B_s^0) > 5 \text{ GeV}) < 0.011 \text{ (0.012)}$$

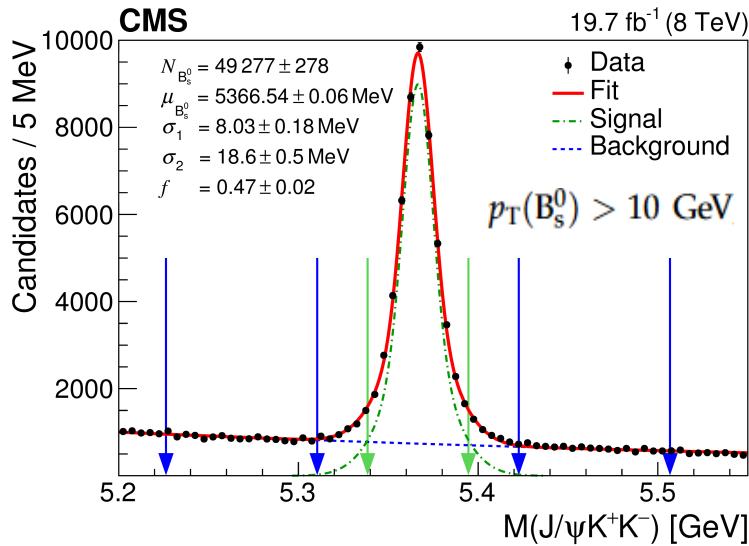
$$\rho_X^{\text{LHCb}}(p_T(B_s^0) > 10 \text{ GeV}) < 0.021 \text{ (0.024)}$$

$$\rho_X^{\text{LHCb}}(p_T(B_s^0) > 15 \text{ GeV}) < 0.018 \text{ (0.020)}$$

# Search for $X(5568)^+$ in CMS

PRL 120 (2018) 202005

$51398 \pm 283$   $B_s \rightarrow J/\psi \phi$  signal candidates



$$\sigma_{eff} = [(1-f)\sigma_1^2 + f\sigma_2^2]^{1/2} \simeq 14 \text{ MeV}$$

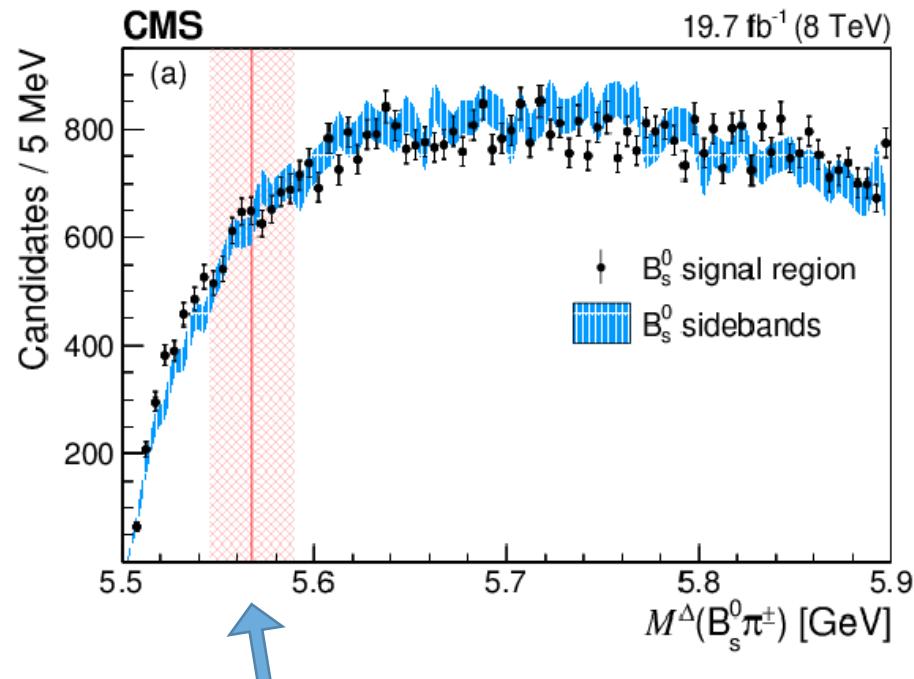
$$|M(J/\psi K^+ K^-) - m_{B_s^0}^{fit}| < 2\sigma_{eff}$$

48204  $B_s^0$  signal events (93.8%)

Comparison of  $B_s$  statistics

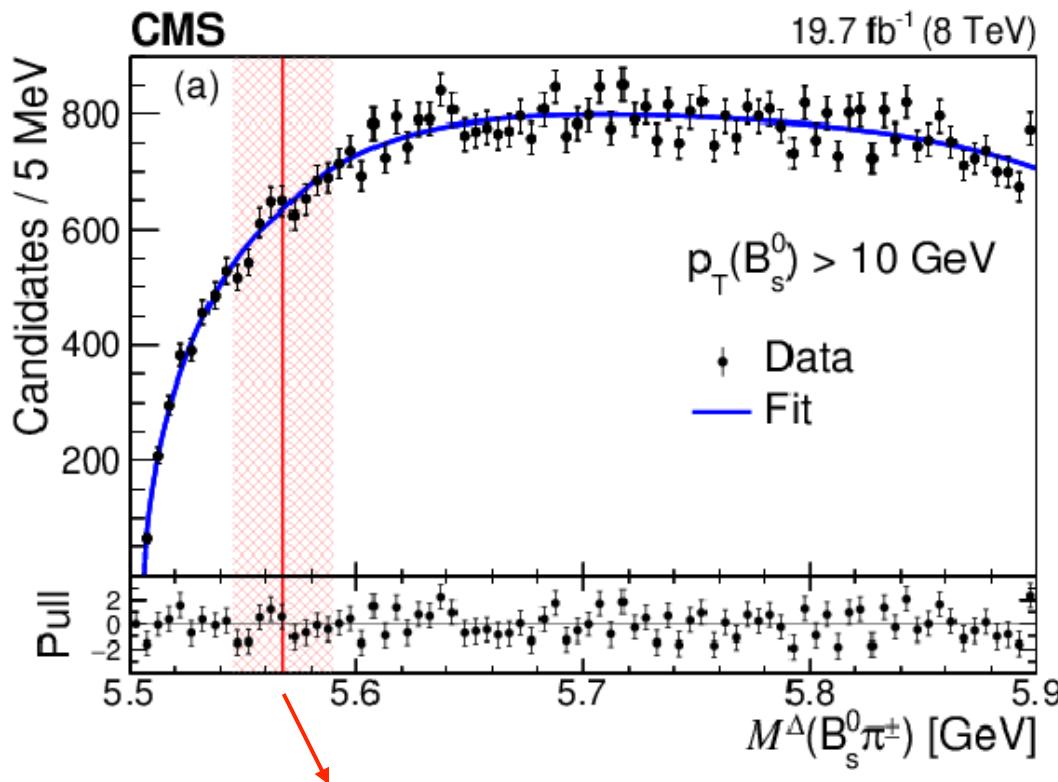
Factor 1.16 larger than LHCb reconstructed in the same  $p_T$  interval and 9.13 larger than DØ sample

Combine the  $B_s$  candidate with each  $\pi^+$  from the collection of tracks building the selected PV



No hints for the  $X(5568)^+$  signal

# Search for $X(5568)^+$ in CMS - fit results



$$N_{X(5568)} = -85 \pm 160 \text{ (stat.)}$$

Varying selection criteria,  
background parameterization,  
fit range and method of data description



in every case the obtained  $X(5568)^+$  yield is consistent with 0

PRL 120 (2018) 202005

**Fit function:**

Signal + Background

**Signal:**

S-wave Breit-Wigner with  
fixed  $m$  and  $\Gamma$  to DØ values

**Background:**

$(x - x_0)^\alpha \times \text{Pol}_n(x)$

$n = 3$  in the default fit

No hints for the  
 $X(5568)^+$  signal

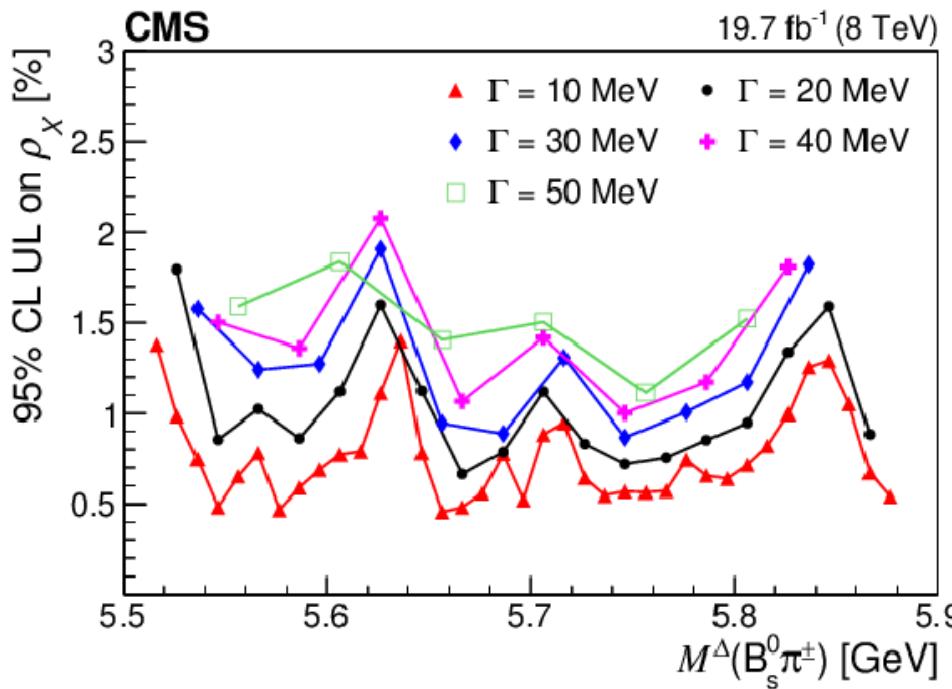
# Search for $X(5568)^+$ in CMS – upper limit

PRL 120 (2018) 202005

**Final result:** upper limit on the ratio of production cross-sections

$$\rho_X \equiv \frac{\sigma(pp \rightarrow X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \rightarrow B_s^0 \pi^\pm)}{\sigma(pp \rightarrow B_s^0 + \text{anything})} = \frac{N_{X(5568)}}{N_{B_s^0}} \frac{\epsilon_{B_s^0}}{\epsilon_{X(5568)}} < \underline{1.1\% \text{ @ 95\% CL}}$$

$p_T(B_s^0) > 10 \text{ GeV}$

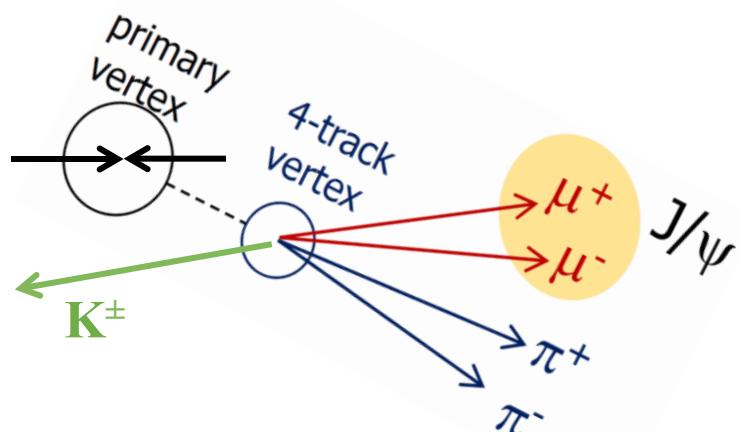
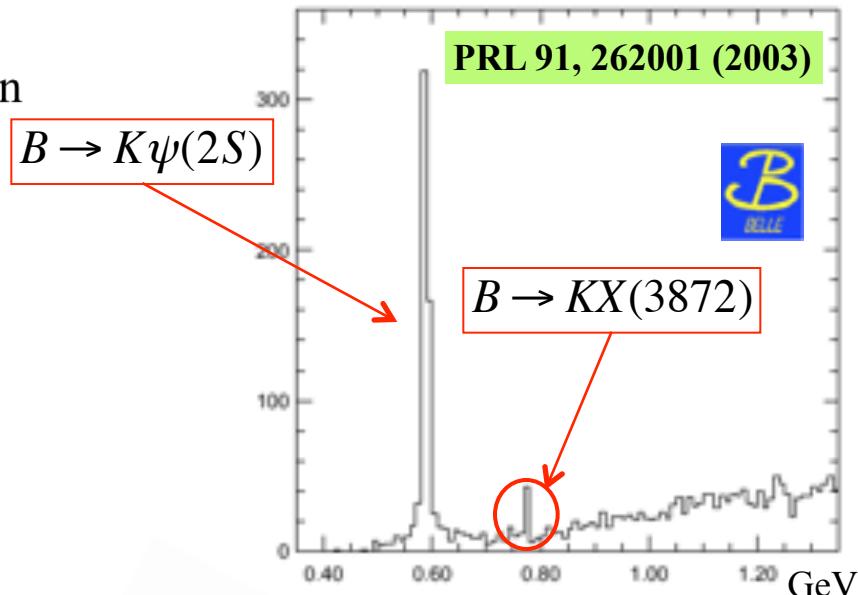
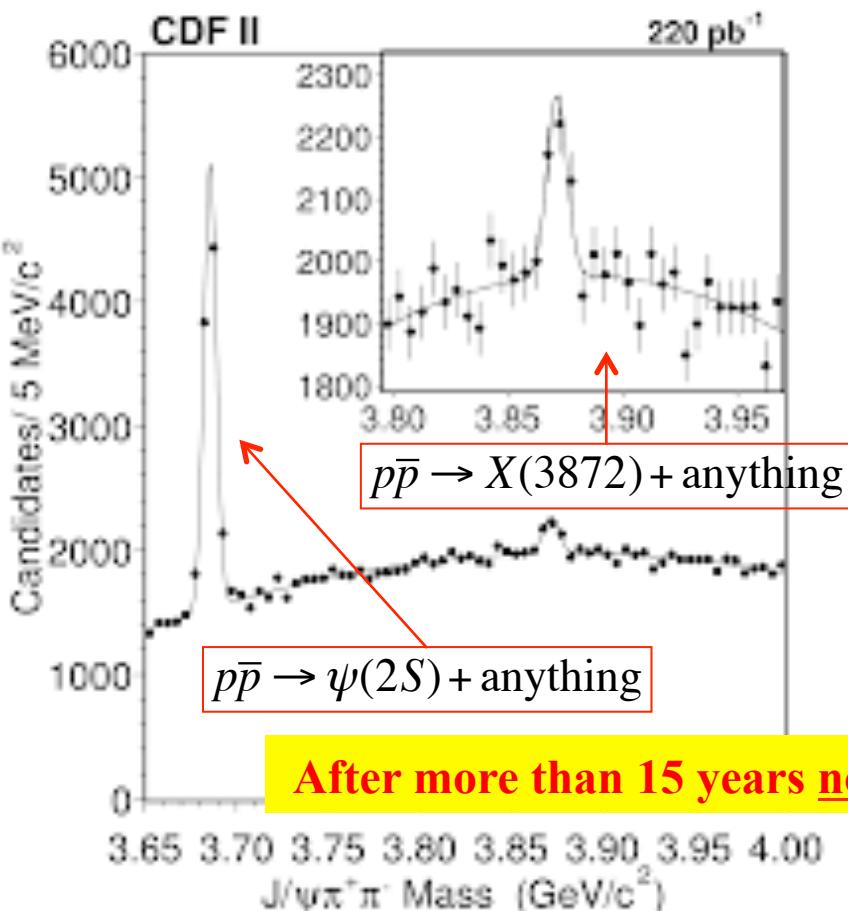


ATLAS found an UL for  $\rho_X$  from 7 and 8 TeV data sample  $< \underline{1.5\% \text{ @ 95\% CL}}$

# The X(3872) - I

- First exotic state discovered by Belle in 2003 in the decay  $B \rightarrow K X(3872) \rightarrow K (J/\psi \pi^+ \pi^-)$ :
- Quickly confirmed by CDF and DØ with inclusive  $p\bar{p}$  collisions:

PRL 93, 072001 (2004)

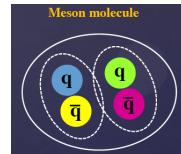


After more than 15 years no definitive answer on the nature of the  $X(3872)$

# The $X(3872)$ - II

After more than 10 years no definitive answer on the nature of the  $X(3872)$ .

Main hypotheses 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  $D\bar{D}^*$  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 minuscule binding energy

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



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

$c\bar{c} \rightarrow \rho J/\psi \sim$  ruled out because it would imply a pure isoscalar state;  $X(3872)$  shows an equal amount of isospin components ( $I=0$  &  $I=1$ ):

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



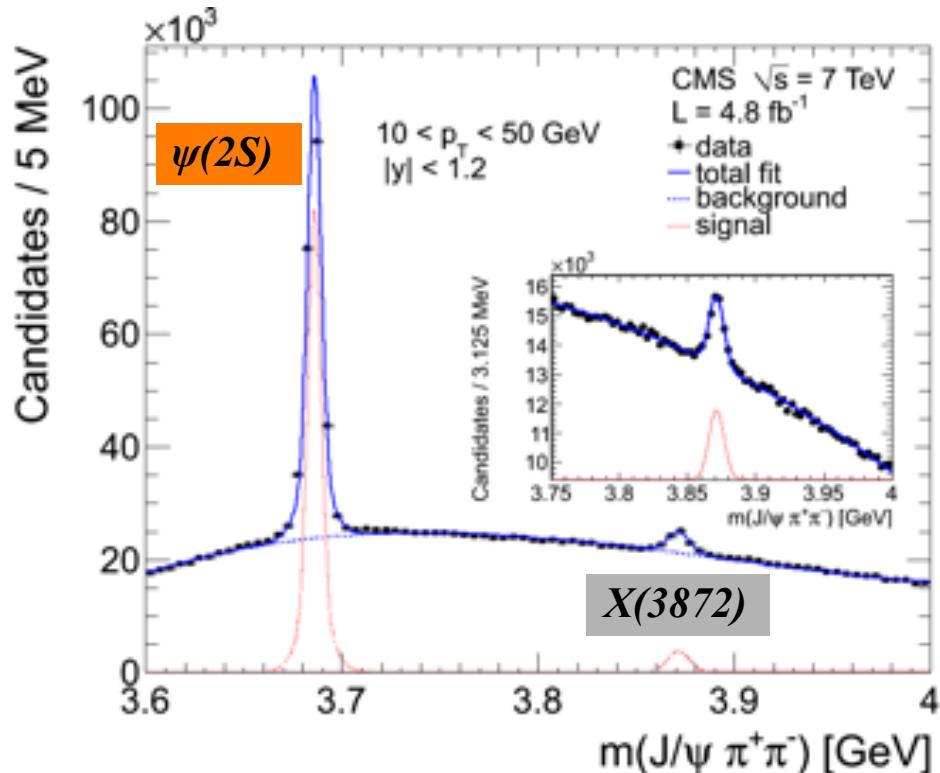
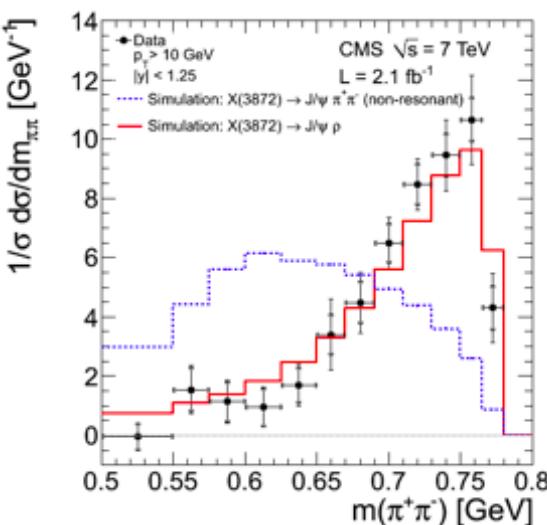
LHCb made a sophisticated angular analysis [[PRL 110 \(13\) 222001](#) & [PRL 92 \('15\) 011102](#)] of the whole decay chain  $B^+ \rightarrow K^+ X(3872) \rightarrow K^+ (J/\psi \pi^+ \pi^-)$  dropping the assumption of lowest possible orbital angular momentum in the  $X(3872)$  sub-decay and unambiguously determined 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 \('14\) 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  $4.8 \text{ fb}^{-1}$  of data at  $7 \text{ TeV}$  reconstructed about 12,000  $X(3872)$  signal events
- CMS studied:
  - Cross section ratio w.r.t.  $\psi(2S)$
  - Non-prompt component vs  $p_T$
  - Prompt  $X(3872)$  cross section
  - Invariant mass distribution of the  $\pi^+\pi^-$  system

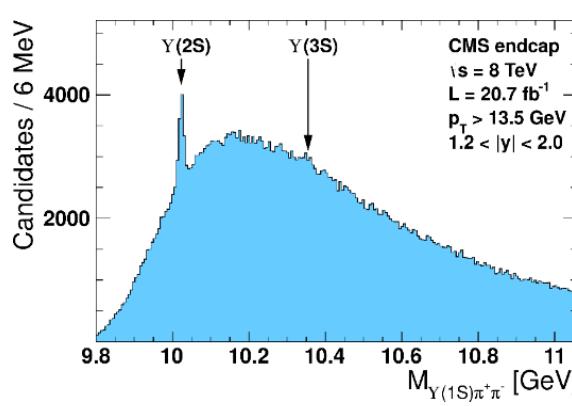
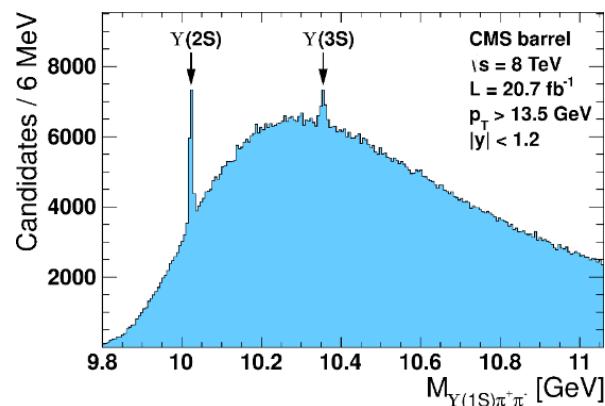
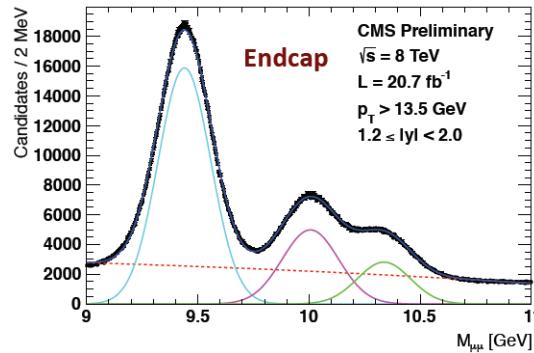
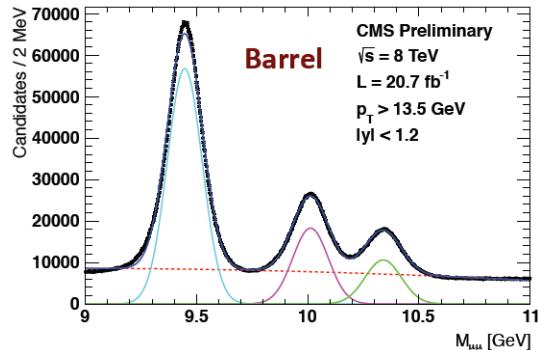


The  $\pi^+\pi^-$  invariant mass distribution from  $X(3872)$  decays to  $J/\psi\pi^+\pi^-$  is measured in order to investigate the decay properties of the  $X(3872)$ . Studies at CDF and Belle suggest that  $X(3872)$  decays in  $J/\psi$  and  $\rho^0$ . The spectrum obtained from data is compared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

# Search for exotic bottomonium states $X_b$ decaying into $\Upsilon(1S) \pi^+ \pi^-$

PLB 727 (2013) 57

- The discovery of the  $X(3872)$  has prompted the search for a bottomonium counterpart  $X_b$  decaying into  $\Upsilon(1S) \pi^+ \pi^-$ , according to HQS considerations, with mass close to the  $B\bar{B}$  or  $B\bar{B}^*$  threshold, 10.562 and 10.604 GeV.
- It is expected that this  $X_b$  would be narrow, similar to  $X(3872)$ , and has sizable BF to  $\Upsilon(1S) \pi^+ \pi^-$ .

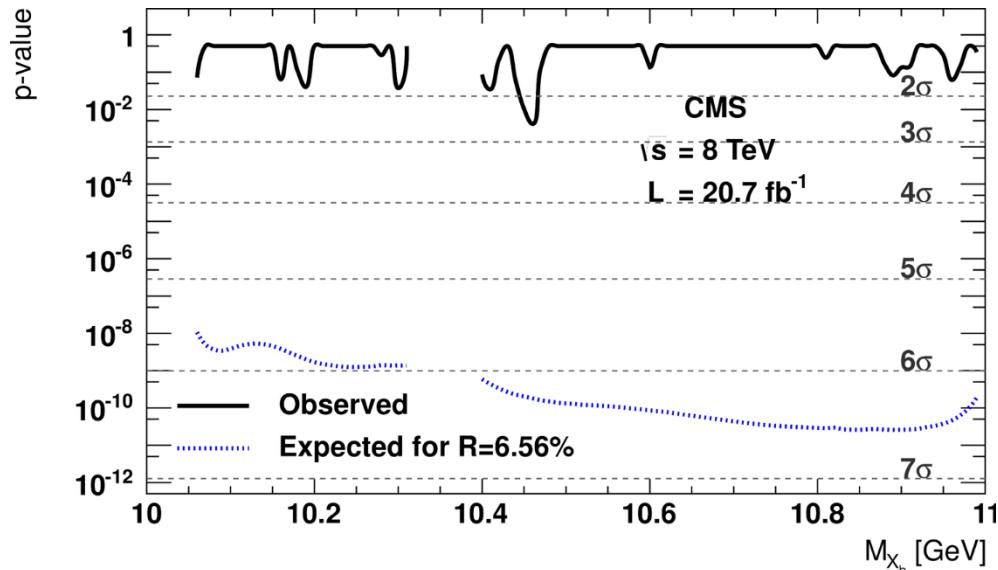


CMS has collected a large sample of  $\Upsilon(nS) \rightarrow \mu^+ \mu^-$  produced in pp collisions at  $\sqrt{s} = 8$  TeV.  
Separate barrel and endcap events to exploit better mass resolution and lower background in the barrel region.

$$p_T(\Upsilon(1S) \pi^+ \pi^-) > 13.5 \text{ GeV} \\ \& |y(\Upsilon(1S) \pi^+ \pi^-)| < 2$$

No structure found apart from  $\Upsilon(2S)$  and  $\Upsilon(3S)$

# Mass scan for $X_b \rightarrow \Upsilon(1S) \pi^+ \pi^-$

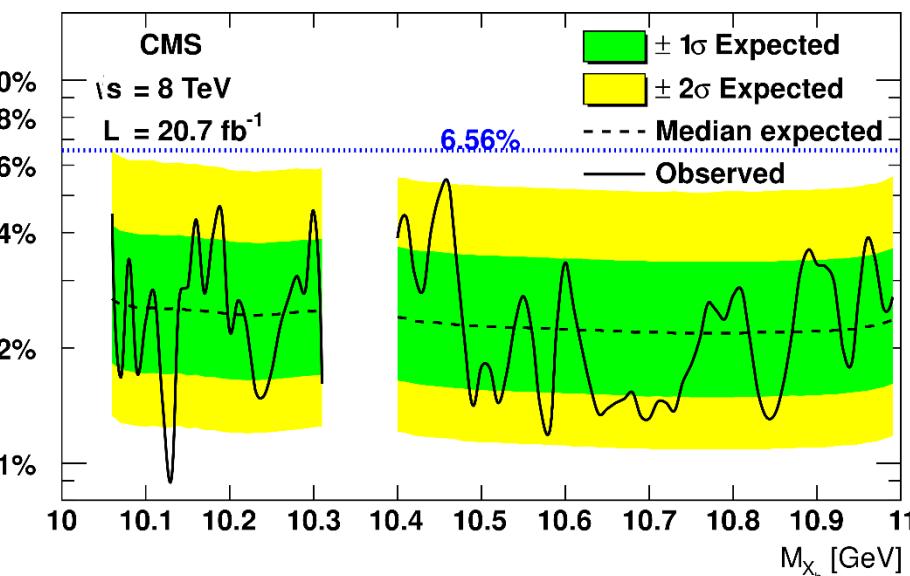


In analogy with the  $X(3872)$ , expected signal significance  $> 5\sigma$  if the ratio  $R$  of the inclusive production Xsection times BF to  $\Upsilon(2S) \rightarrow \Upsilon(1S) \pi^+ \pi^-$  is  $> 6.5\%$

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

- Local p-values calculated using asymptotic approach and combining results of fits to the barrel and endcap regions.
- Systematic uncertainties implemented as nuisance parameters.
- The smallest local p-value is 0.004 at 10.46 GeV, corresponding to a stat. signif. of  $2.6\sigma$ , which is reduced to  $0.8\sigma$  when LEE is taken into account.

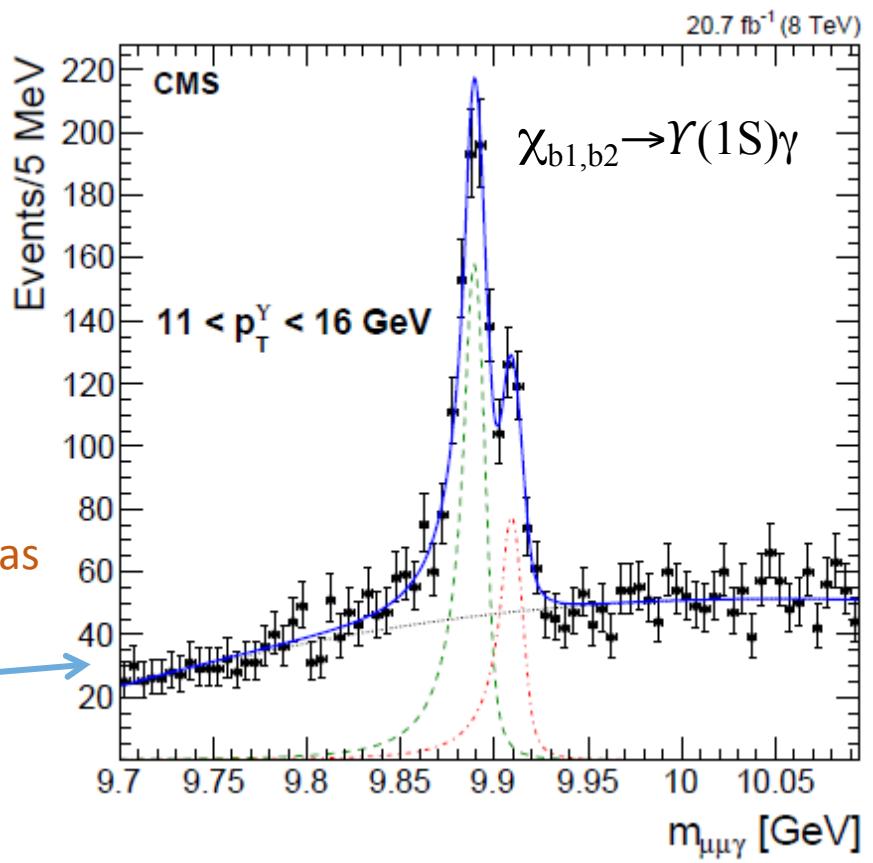
No significant excess is observed.



95% CL UL set on  $R$   
varies from 0.9% to 5.4%.  
(similar result by ATLAS  
[PLB 740 (2015) 199])

# Prospects for further $X_b$ searches

- According to Karliner&Rosner [PRD91 (2015) 014014], this search decay ( $X_b \rightarrow Y(1S) \pi^+ \pi^-$ ) should be forbidden by G-parity conservation. While for the  $X(3872)$  the isospin-conserving decay to  $J/\psi \omega$  was kinematically suppressed, the same is not true for a bottomonium-like  $J^{PC} = 1^{++}$  counterpart.
- The strategy for  $X_b$  observation should include searches for
  - $X_b \rightarrow Y(1S) \omega (\rightarrow \pi^+ \pi^- \pi^0)$
  - $X_b \rightarrow Y(3S) \gamma$
  - $X_b \rightarrow \chi_{b1}(1P) \pi^+ \pi^-$
- Tasks for CMS for Run-II.  
The possibility to work with converted  $\gamma$ 's was excellently demonstrated with the reconstruction of  $\chi_{b1,b2}(1P) \rightarrow Y(1S) \gamma$ .  
But it is not an easy task due to soft  $\gamma$ : low conversion and, therefore, reconstruction efficiency.



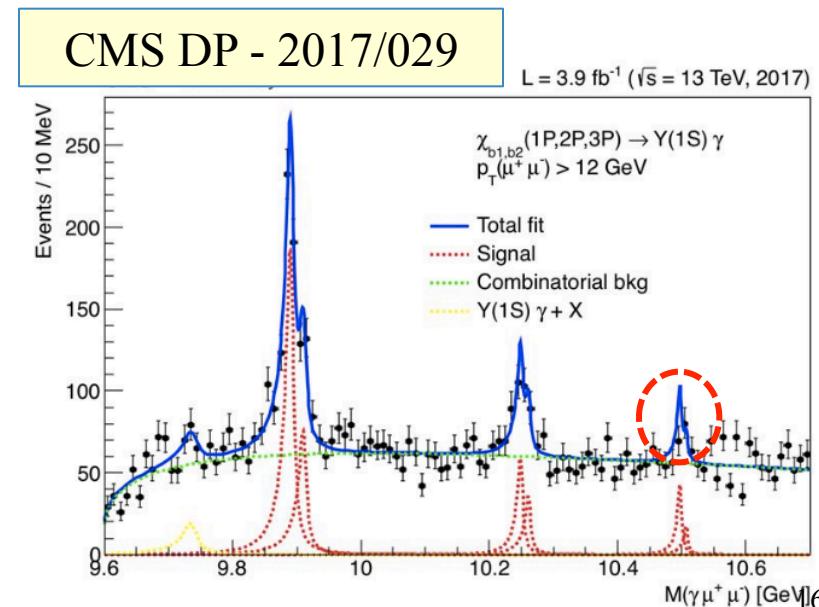
# Prospects for $X_b$ searches in radiative decays

With the  $X_b$  far below the BB<sup>(\*)</sup> threshold and the I-violating decay mode  $X_b \rightarrow Y(1S) \pi^+ \pi^-$  highly suppressed, the relevance of radiative decays increases

- According to Li & Wang [**PLB 733 (2014) 100**], within a loosely bound hadronic molecule model, the partial widths for the  $X_b \rightarrow Y(nS) \gamma$  are  $\sim 1$  keV 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  $\chi_{c1}(2P)$  &  $D^0 D^{*0}$  molecule].

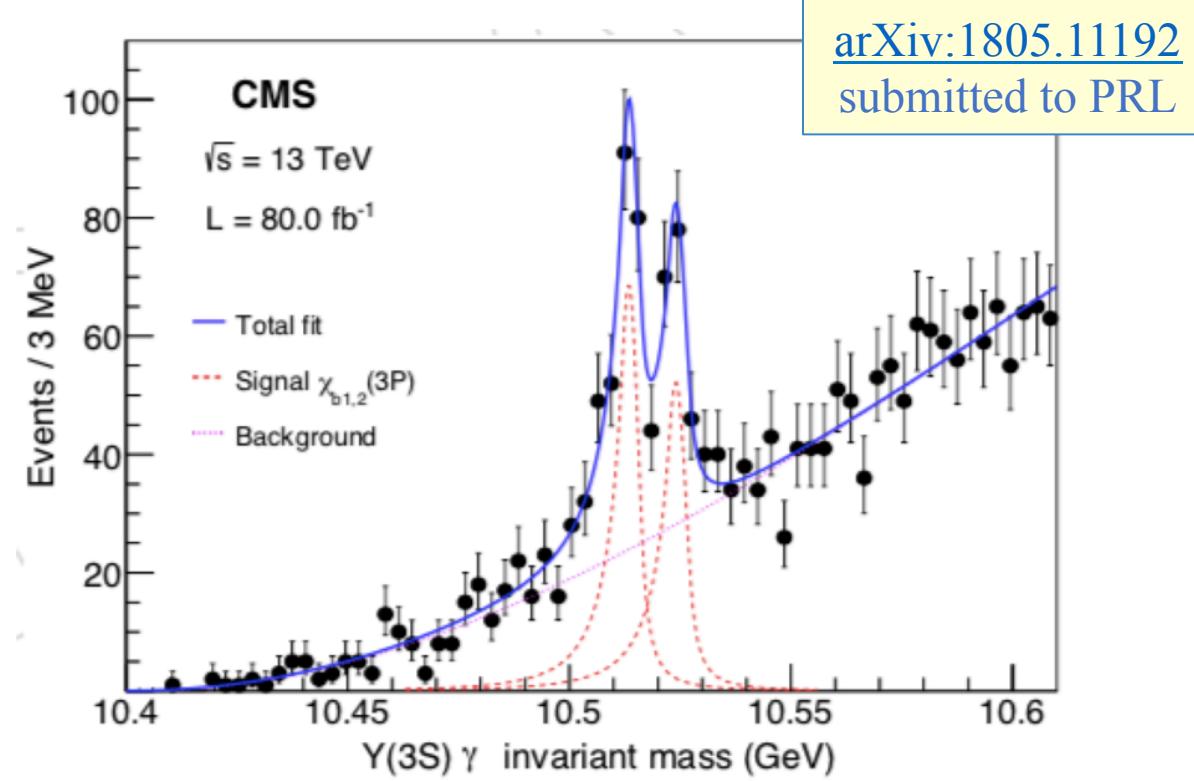
Thus the experiments that reported observing  $\chi_{b1}(3P) \rightarrow Y(1S,2S) \gamma$  **might** have actually discovered a mixture of  $X_b$  &  $\chi_b(3P)$ !

It is worthwhile to examine the full Run-II  $Y(nS) \gamma$  mass spectra for any departure from a “single BW” behaviour.



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

Observed through their radiative decays to  $Y(3S)\gamma$  using  $\mathcal{L} \sim 80 \text{ fb}^{-1}$  of 2015-2017 Run-II data  
↳ more details in Nuno Leonardo's talk



standard  
mass  
hierarchy

The two individual masses and their difference are measured:

$$m[\chi_{b1}(3P)] = 10513.42 \pm 0.41 \text{ (stat.)} \pm 0.18 \text{ (syst.) MeV}$$

$$m[\chi_{b2}(3P)] = 10524.02 \pm 0.57 \text{ (stat.)} \pm 0.18 \text{ (syst.) MeV}$$

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

# Summary and Prospects

Although designed for high- $p_T$  physics, CMS proved to be a very good apparatus for heavy flavor physics!

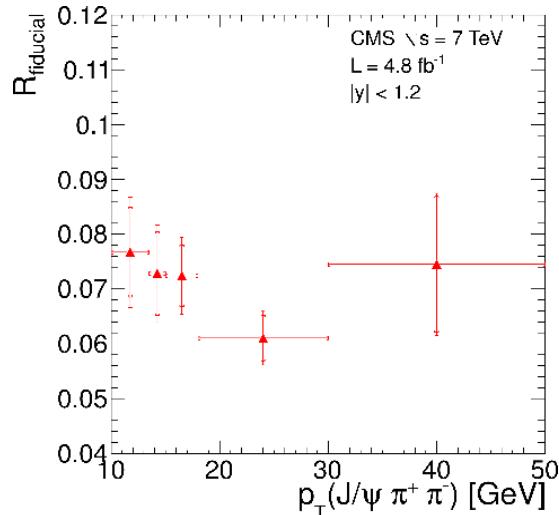
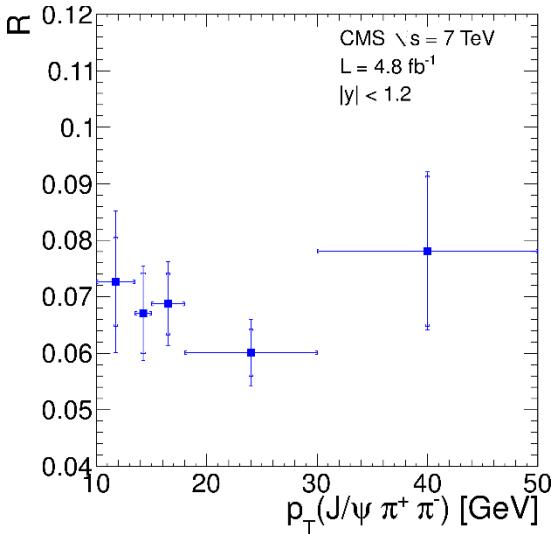
- Study of the  $B_s \pi^+$  spectrum and setting an UL on the production of X(5568)
- Measurement of X(3872) production properties in CMS
- Search for the bottomonium partner of the X(3872)

New results from CMS are foreseen soon

# Backup slides

# Study of X(3872) production properties at CMS

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



Integrated over  $10 < p_T < 50$  GeV:

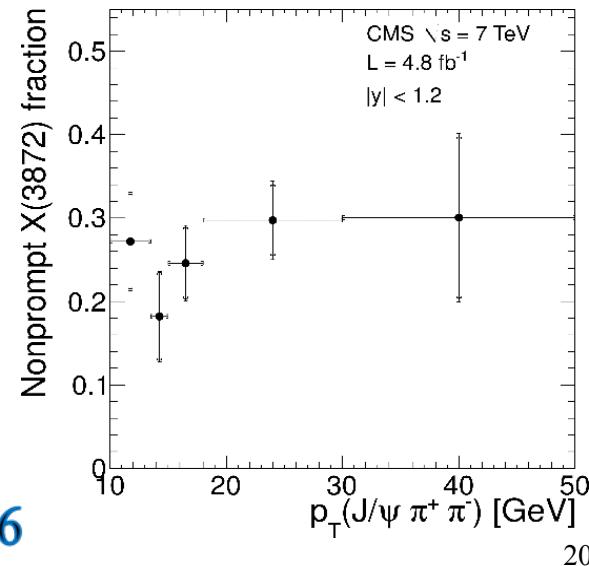
$$R = 0.0656 \pm 0.0029 \pm 0.0065 \quad R_{\text{fiducial}} = 0.0694 \pm 0.0029 \pm 0.036$$

- Non-prompt fraction also shows no dependence on  $p_T$  →
- But measurement is dominated by statistics
- For  $10 < p_T < 50$  GeV,  $|y| < 1.2$ :

Non-prompt X(3872) fraction:  $f_{\text{np}} = 0.263 \pm 0.023 \pm 0.016$

Acceptance corrections depend on assumptions on the angular distribution of the final states. So, w/o acc. corr. one can derive  $R$  in a fiducial region.

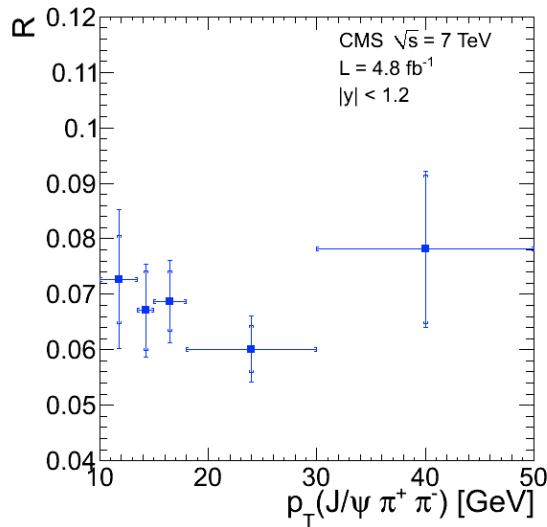
**NO SIGNIFICANT**  
dependence on the  $p_T$



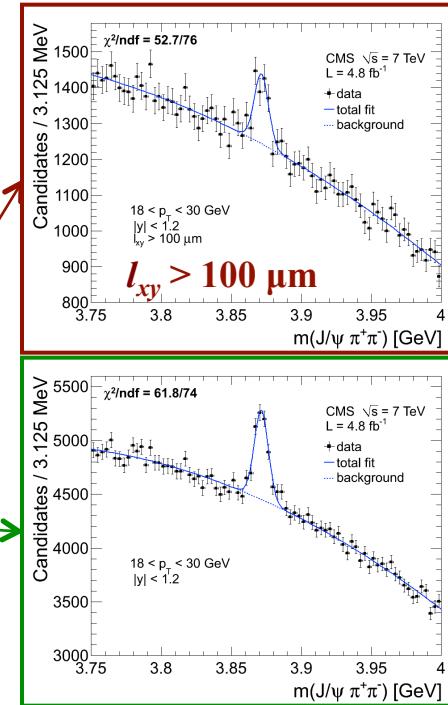
# Cross sections ratio & non-prompt fraction

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

$$R = \frac{\sigma(pp \rightarrow X(3872) + \text{anything}) \cdot B(X(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\sigma(pp \rightarrow \psi(2S) + \text{anything}) \cdot B(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} = \frac{N_{X(3872)} \cdot A_{\psi(2S)} \cdot \epsilon_{\psi(2S)}}{N_{\psi(2S)} \cdot A_{X(3872)} \cdot \epsilon_{X(3872)}}$$



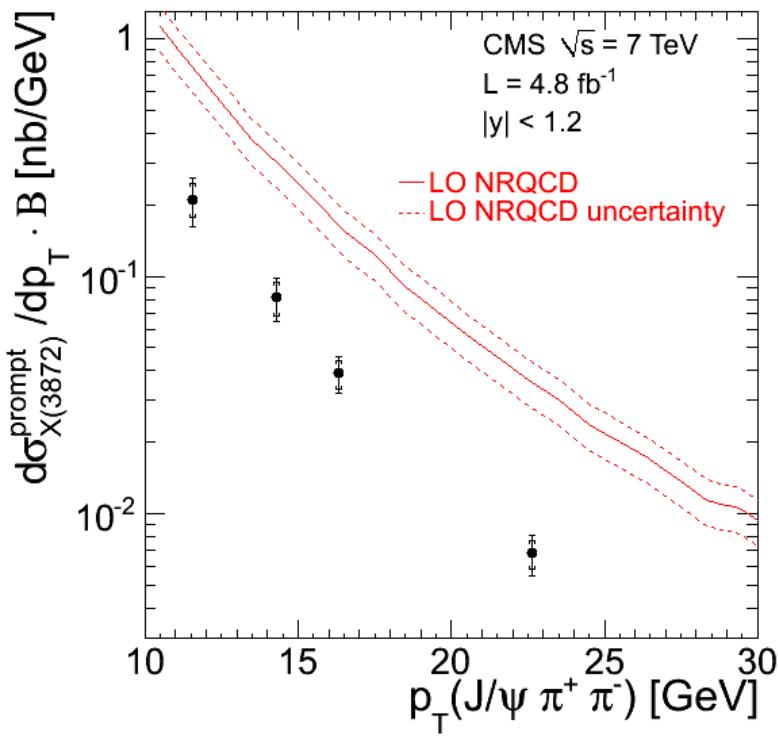
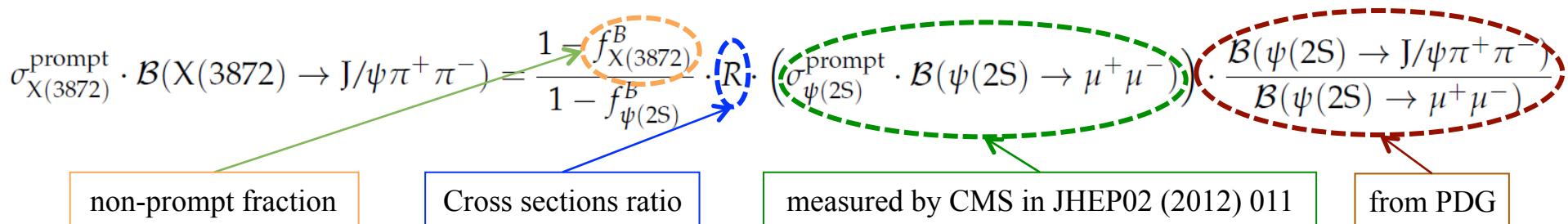
- For  $10 < p_T < 50 \text{ GeV}$  &  $|y| < 1.2$ :  
 $R = 0.0656 \pm 0.0029 \text{ (stat.)} \pm 0.0065 \text{ (syst.)}$
- The ratio shows no significant dependence on the  $p_T$  of the  $J/\psi \pi^+ \pi^-$  system



- 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  $l_{xy} > 100 \mu\text{m}$ :  $\text{non-prompt fraction} = \frac{\# \text{ of } X(3872) \text{ from } B}{\# \text{ of } X(3872)}$
- The fraction of  $X(3872)$  produced from decays of  $B$  does not show a dependence on  $p_T(J/\psi \pi^+ \pi^-)$
- For  $10 < p_T < 50 \text{ GeV}$  &  $|y| < 1.2$ :  
 $X(3872)$  non prompt fraction =  $0.263 \pm 0.023 \text{ (stat.)} \pm 0.016 \text{ (syst.)}$

# Prompt X(3872) production X 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:



- Main systematic uncertainties are related to the measurements of  $R$  and prompt  $\psi(2S)$  cross section
- $X(3872)$  and  $\psi(2S)$  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  $3\sigma$

Theoretical prediction for  $10 < p_T < 30$  GeV,  $|y| < 1.2$

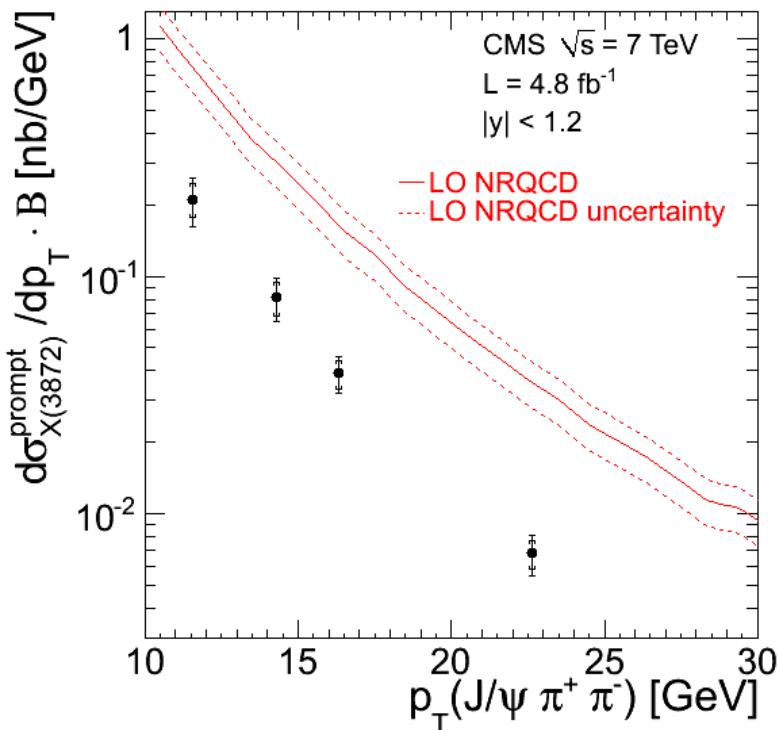
$$\sigma_{X(3872)}^{\text{prompt}} \times \mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-) \cong (4.01 \pm 0.88) \text{ nb}_{22}$$

# Prompt $X(3872)$ production X 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:

$$\sigma_{X(3872)}^{\text{prompt}} \cdot \mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-) = \frac{1}{1 - f_{\psi(2S)}^B} \cdot f_{X(3872)}^B \cdot R \cdot (\sigma_{\psi(2S)}^{\text{prompt}} \cdot \mathcal{B}(\psi(2S) \rightarrow \mu^+ \mu^-)) \cdot \frac{\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)}{\mathcal{B}(\psi(2S) \rightarrow \mu^+ \mu^-)}$$

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



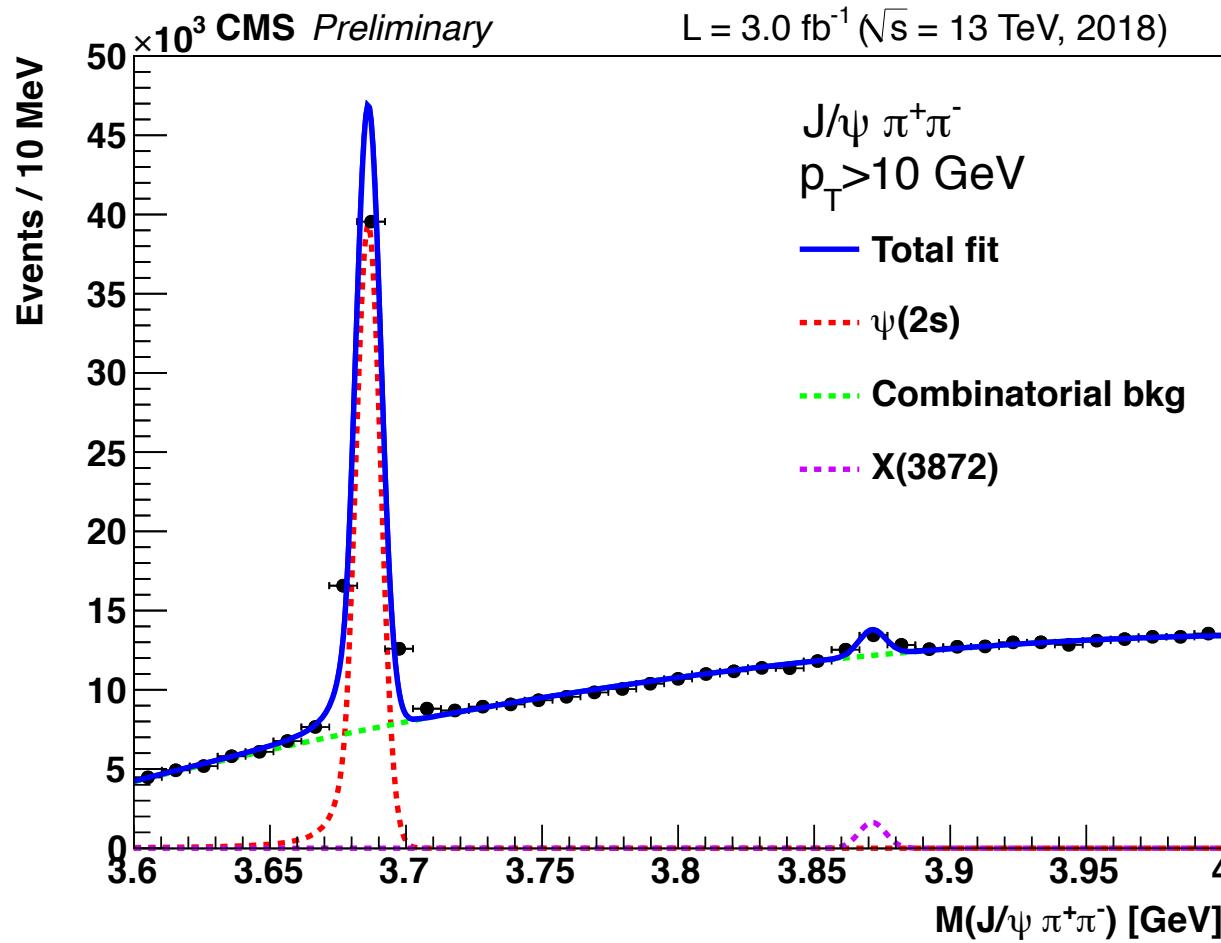
- Main systematic uncertainties are related to the measurements of  $R$  and prompt  $\psi(2S)$  cross section
- $X(3872)$  and  $\psi(2S)$  are assumed to be unpolarized

Predictions by Artoisenet & Brateen assume, within an S-wave molecular model, the relative momentum of the mesons to be 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 by one order of magnitude would imply lower prompt production rates of few orders of magnitude  
**[Bignamini et al., PRL 2009, 103(16)]**

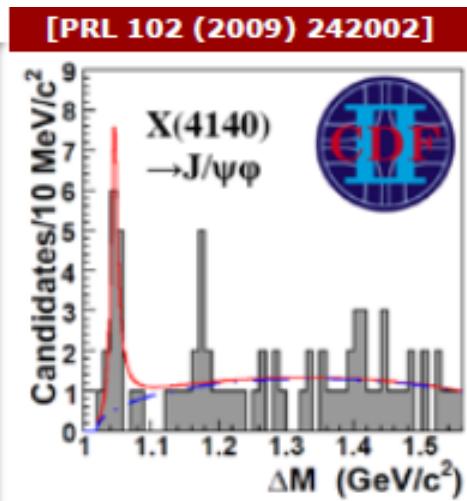
# X(3872) production at Run-II

- Run-II data taking started at  $\sqrt{s} = 13 \text{ TeV}$  with the first bunch of data recorded in July 2015
- The plot shows the invariant mass of  $J/\psi \pi^+ \pi^-$  where is visible the  $X(3872)$  signal beyond the  $\psi(2S)$  one:

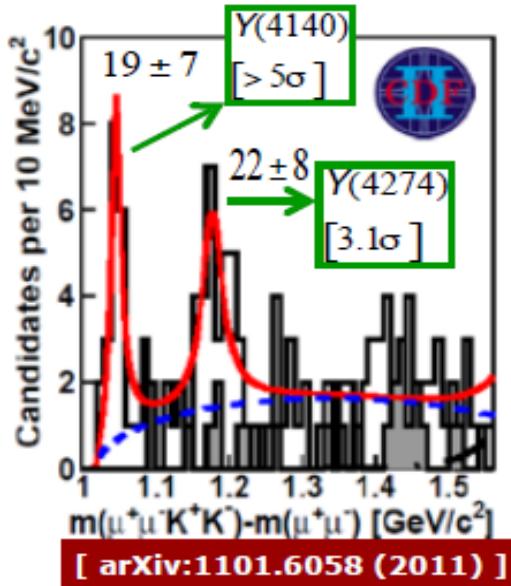


# Confirmation of $X(4140) \rightarrow J/\psi \phi$

CDF (2009) reported evidence (@ $3.8\sigma$ ) for ... narrow peak in  $J/\psi\phi$  mass spectrum, close to the kinematical threshold, in decays  $B^+ \rightarrow J/\psi \phi K^+$

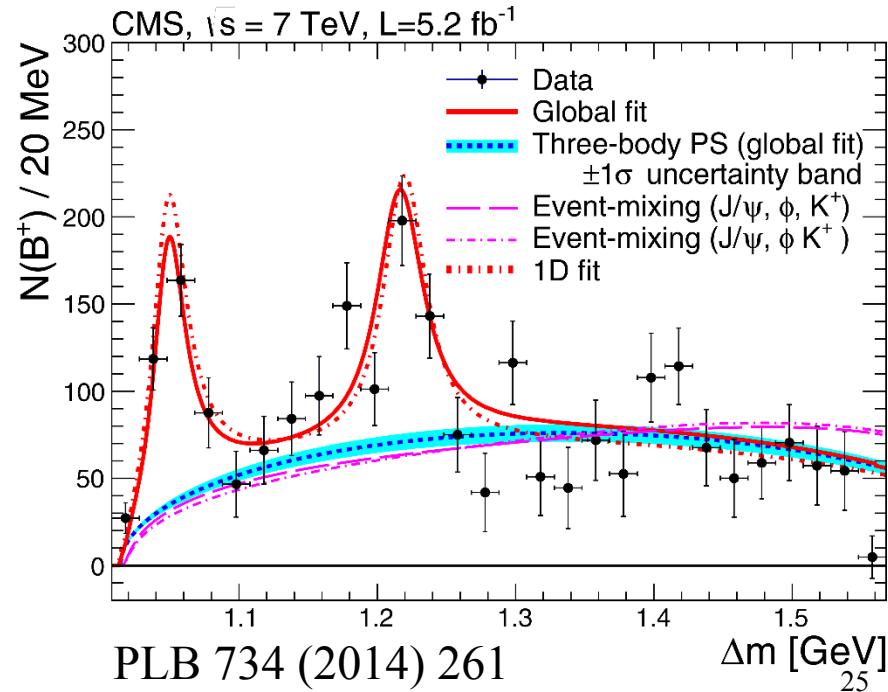


CDF (2011) presents update analysis with larger dataset, ( $6.0\text{fb}^{-1}$  vs  $2.7\text{fb}^{-1}$ ) observing



- Peaking structure at threshold and another peak in the  $\Delta m$  from  $B^+ \rightarrow J/\psi \phi K^+$  decay (after background subtraction)
- Yield:  $310 \pm 70$ ,  $M = 4148.0 \pm 2.4 \pm 6.3$  MeV,  $\Gamma = 28 +15 -11 \pm 19$  MeV, **signif.  $> 5\sigma$**
- Consistent with the  $Y(4140)$  from CDF!** (first significant confirmation)

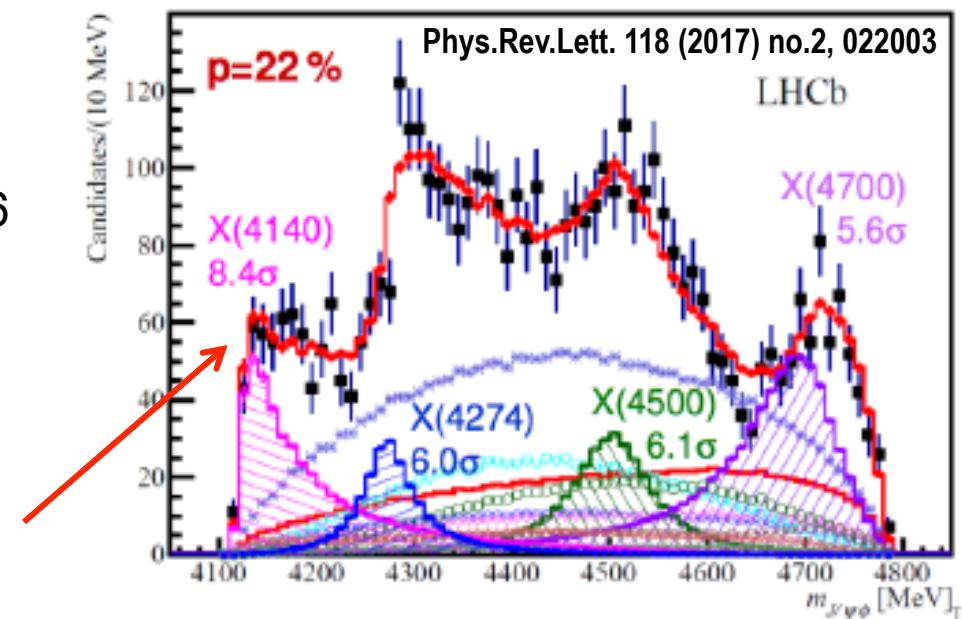
Belle and BaBar searched for and did not find that signal in the same  $B^+$  decay



# Study of the J/ $\psi$ $\phi$ system

LHCb performed two analyses:

- No signals were observed (2012) in a  $346 \pm 20$   $B^+$  sample
- The measured UL implied a  $2.4\sigma$  tension with CDF
- Four resonance-like structures were recently established in the 6D **Amplitude Analysis** using a  $4289 \pm 151$   $B^+$  sample



X(4140)	Mass [MeV]	Width [MeV]
CMS	$4148.0 \pm 2.4 \pm 6.3$	$28 +15 -11 +19$
LHCb	$4146.5 \pm 4.5 +4.6 -2.8$	$83 \pm 21 +21 -14$

X(4274)	Mass [MeV]	Width [MeV]
CMS	$4313.8 \pm 5.3 \pm 7.3$	$38 +30 -15 +16$
LHCb	$4273.3 \pm 8.3 +17.2 -3.6$	$56.2 \pm 10.9 +8.4 -11.1$

Several interpretations for the X(4140) have been proposed:  
 $D_s^{*+} D_s^{-*}$  molecule,  $c\bar{s} c\bar{s}$  tetraquark, threshold kinematic effect, hybrid charmonium,  
weak transition with  $D_s^+ D_s^-$  rescattering.

Recently, the D0 Collaboration has published the first evidence  
for the prompt production of the X(4140)

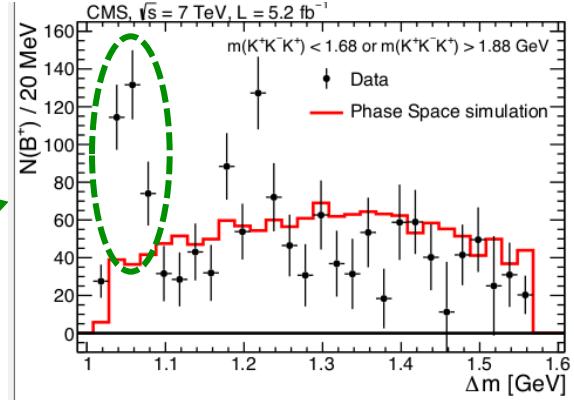
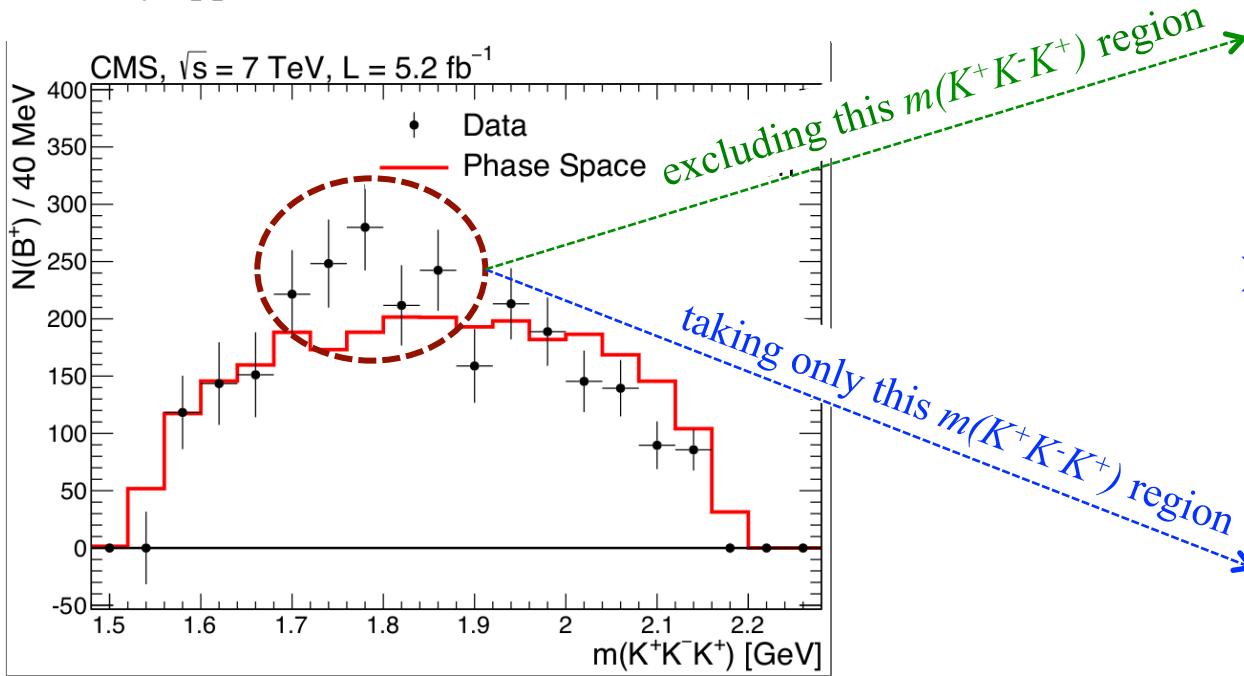
PRL 115 (2015) 232001

CMS can perform the  
same search at LHC!

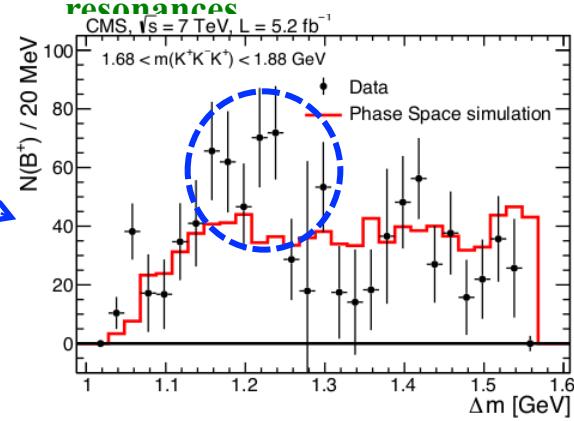
# Next steps for $\Upsilon(4140)$

➤ Understanding the nature of both structures needs further investigation

➤ The  $\phi K^+$  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:



➤  $\Upsilon(4140)$  appears to be uncorrelated to  $\phi K^+$  resonances



➤ Additional peak may be affected by them

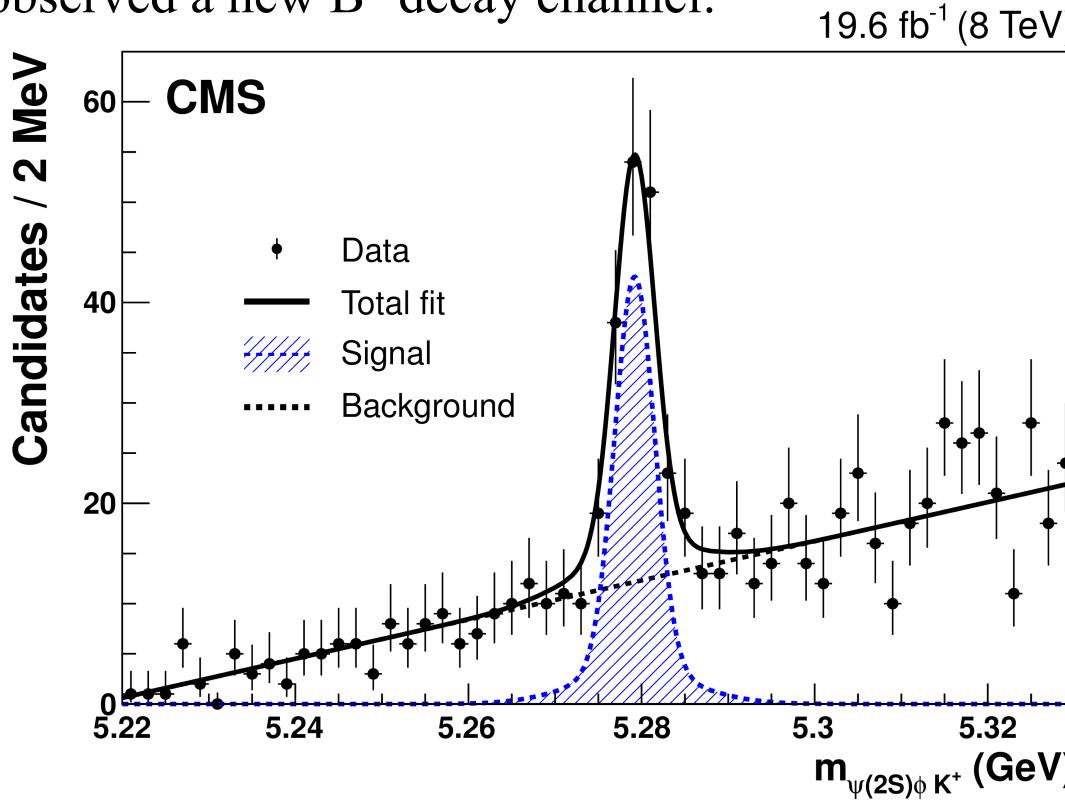
➤ Understanding the nature of both structures needs further investigation & requires a full amplitude analysis (not easy task: 2 vectors in the final state!).

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

# Observation of $B^+ \rightarrow \psi(2S) \phi K^+$ at CMS

[Phys. Lett. B 764 \(2017\) 66](#)

By reconstructing the same decay with  $\psi(2S)$  instead of  $J/\psi$   
we observed a new  $B^+$  decay channel:



The relative B.F., using the  $B^+ \rightarrow \psi(2S) K^+$  mode as normalization channel, is

$$[ 4.0 \pm 0.4 \text{ (stat.)} \pm 0.6 \text{ (syst.)} \pm 0.2 \text{ (B.F.(} B^+ \rightarrow \psi(2S) K^+ \text{))} ] \times 10^{-6}$$

This is the first step towards the exploration of  $\psi(2S) \phi$  system

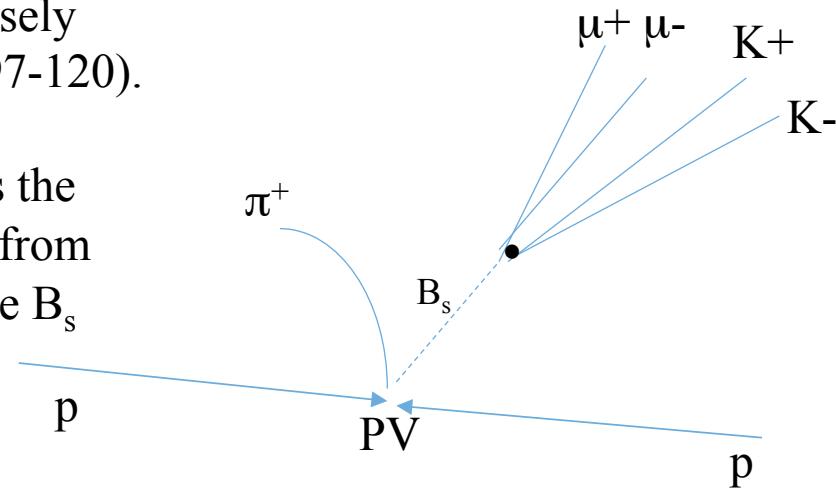
# Search for $X(5568)^+$ in CMS

## Analysis strategy:

$$B_s^0 \rightarrow J/\psi \phi \quad (J/\psi \rightarrow \mu^+ \mu^-, \phi \rightarrow K^+ K^-)$$

**HLT** - select events with mu+ mu- originating from J/psi decaying at a significant distance from the beamspot.

- 1) Reconstruct  $B_s$  by combining  $J/\psi$  and  $\phi$  and then fit 4 tracks into the common vertex  $\rightarrow$  know  $B_s$  momentum and its decay vertex (this procedure follows closely that from  $B_s$  CPV analysis in PLB 757 (2016) 97-120).
- 2) Select Primary Vertex (PV):  
from all pp collision points, the PV is chosen as the one with the smallest angle between the vector from the collision point to the  $B_s$  decay vertex and the  $B_s$  momentum.
- 3) Add charged pion from that PV and form  $B_s \pi^+$  candidate



# Search for $X(5568)^+$ in CMS

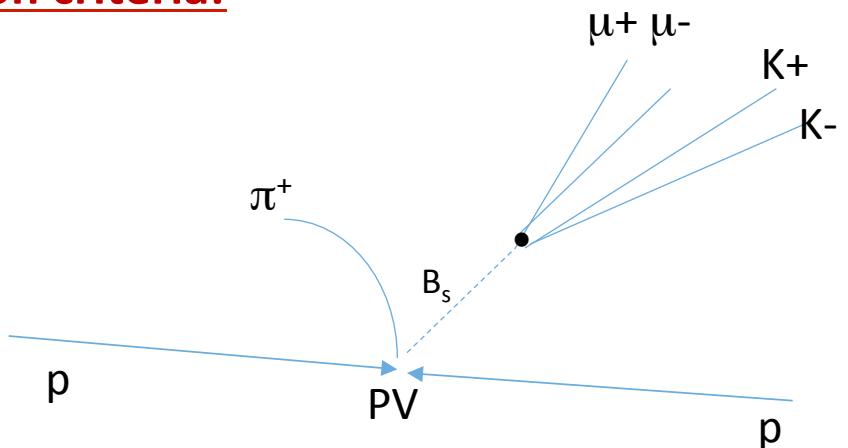
## Offline selection criteria:

- $p_T(\mu^\pm) > 4 \text{ GeV}$ ,
- $|\eta(\mu^\pm)| < 2.2$ ,
- $p_T(\mu^+\mu^-) > 7 \text{ GeV}$ ,
- dimuon vertex  $\chi^2$  fit probability  $P_{vtx}(\mu^+\mu^-) > 10\%$ ,
- distance between the beamspot and the reconstructed dimuon vertex positions in the transverse plane divided by its uncertainty  $L_{xy}(\mu^+\mu^-)/\sigma_{L_{xy}(\mu^+\mu^-)} > 3$ ,
- $\cos \alpha_T(\mu^+\mu^-) > 0.9$ , where  $\alpha_T(\mu^+\mu^-)$  is the angle between the vector from the beamspot position to the dimuon vertex in the transverse plane and the transverse dimuon momentum vector,
- dimuon invariant mass in the region  $3.04 < M(\mu^+\mu^-) < 3.15 \text{ GeV}$ .

$$p_T(K^\pm) > 0.7 \text{ GeV}, \quad p_T(B_s^0) > 10 \text{ GeV}$$

$$P_{vtx}(\mu^+\mu^-K^+K^-) > 1\%, \quad \cos \alpha_T(B_s^0) > 0.99, \quad L_{xy}(B_s)/\sigma_{L_{xy}(B_s)} > 3$$

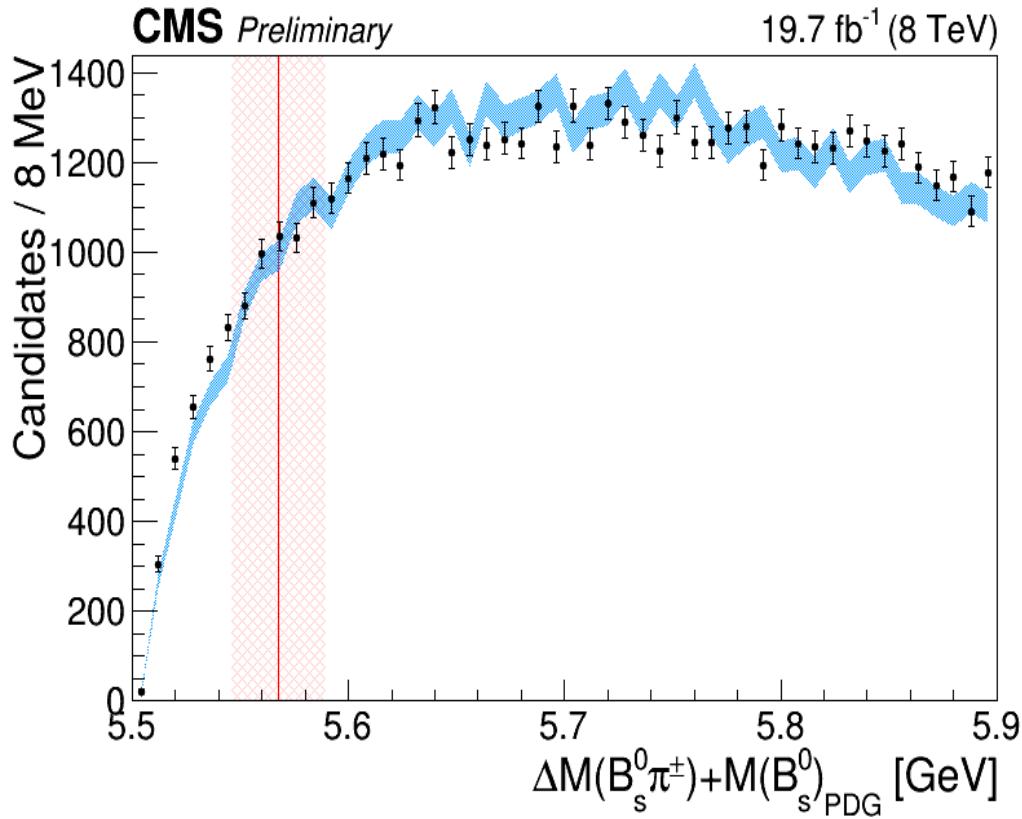
$$|M(K^+K^-) - M_{PDG}(\phi)| < 10 \text{ MeV}$$



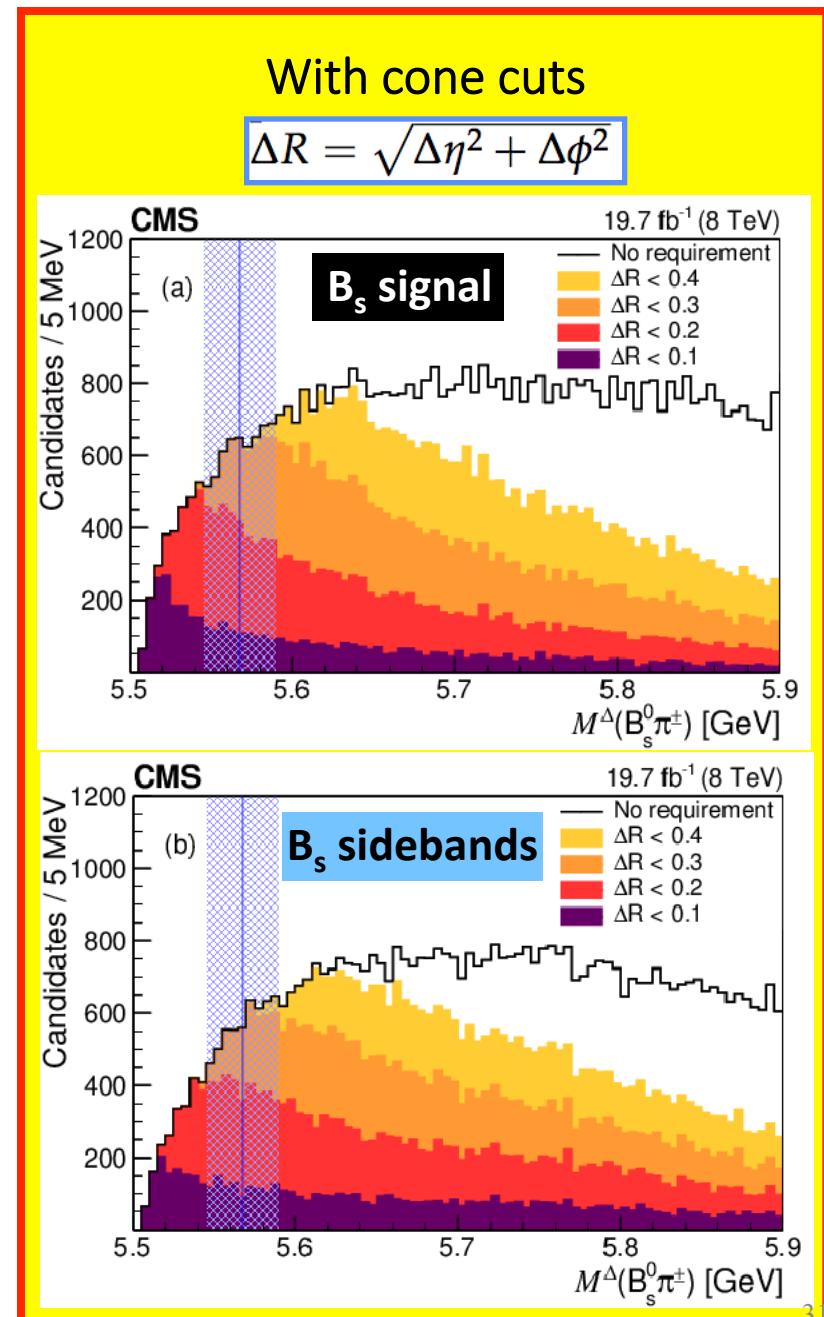
# Cone cut

PRL 120 (2018) 202005

- Combine the  $B_s^0$  candidate with each  $\pi^\pm$  from the collection of tracks building selected PV



- No significant differences observed between the distributions obtained from  $B_s$  signal and  $B_s$  sidebands



# Search for $X(5568)^+$ in CMS – systematics

PRL 120 (2018) 202005

Varying selection criteria,  
background parameterization,  
fit range and method of data description



Fits obtained:

- by varying the  $p_T$  requirements of the  $B_s^0 \pi^\pm$ ,  $B_s^0$  and  $\pi^\pm$  candidates,
  - by applying different reconstruction quality criteria,  
show no significant signal at the claimed mass.
- 
- Another cross-check is performed by removing events where more than one candidate passes the selection.
  - Furthermore, alternative background models and mass regions are used in the fit considering also the uncertainty in the BW  $m$  and  $\Gamma$  measured by DØ, resulting in negligible signal.
  - The pion tracking efficiency uncertainty (3.9%) and the uncertainty in  $\epsilon_{\text{rel}}$  due to the finite number of simulated events are also taken into account.

# Search for $X(5568)^+$ in CMS – mass range

The extension of the  $M^\Delta(B_s^0\pi^\pm)$  investigated range (w.r.t. ATLAS) is important 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  $b\bar{d}us$ , has not been confirmed by LHCb. In the tightly bound diquark model, we estimate the lightest  $b\bar{d}us$ ,  $0^+$  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  $b\bar{d}us$ ,  $S$ -wave,  $1^+$  quartet at 5820 MeV is implied as well. In the charm sector,  $c\bar{d}us$ ,  $0^+$  and  $1^+$  tetraquarks are predicted at 2365 and 2501 MeV, about 40–50 MeV heavier than  $D_{s0}(2317)$  and  $D_{s1}(2460)$ . The  $b\bar{d}us$  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,  $B_c \rightarrow X_{b0} + \pi$  with the subsequent decays  $X_{b0} \rightarrow B_s + \pi$ , 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  $B_c \rightarrow X(3872) + \pi$ .

# Double Quarkonia Production: SPS

- The measurement of **quarkonium pair production** in pp collisions provides **further insight** into the underlying mechanism of particle production. It probes specific mechanism of  $c\bar{c}c\bar{c}$  &  $b\bar{b}b\bar{b}$  systems production & transformation to **two mesons**, namely it probes the **distribution of gluons in a proton** since their production should be dominated by **gluon-gluon interactions** as well.
- According to the description by parton models of production in QCD, in a single hadron-hadron collision two partons often undergo a **single** interaction (**Single Parton Scattering: SPS**).

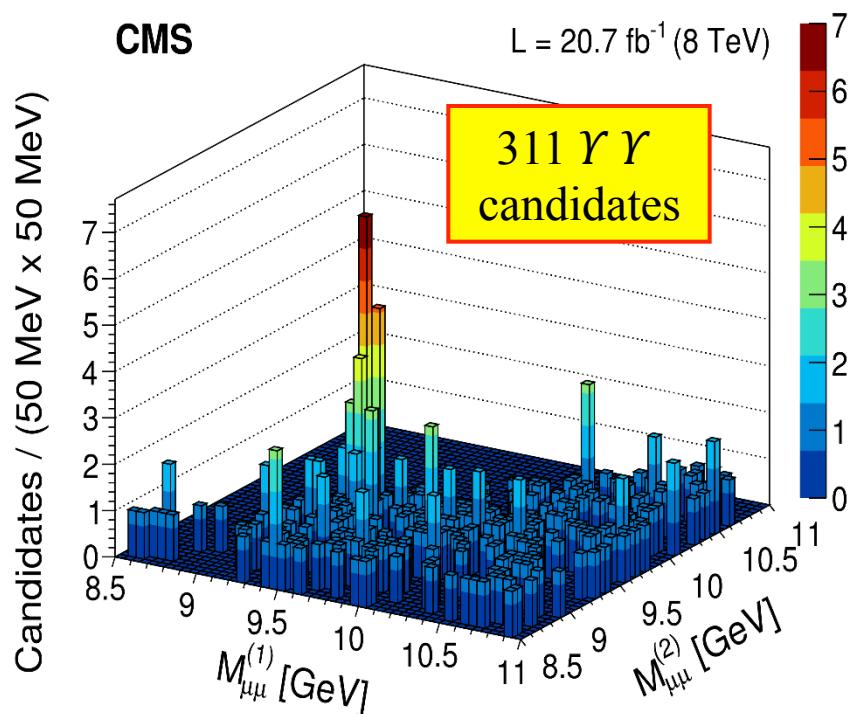
The **SPS** mechanism can be described by NRQCD.

- At the parton level the two  $J/\psi$  mesons are either produced as CS states or CO states that turn into color-singlets after emitting soft gluons. CO contributions play a greater role as  $p_T$  increases.
- Non-trivial contributions should come from NLO SPS. Models released recently begin to approach NLO (and NNLO) contributions.

# The first observation of $\Upsilon(1S)\Upsilon(1S)$ pair production

Motivation: Cross-section measurements of quarkonium pair production are essential in understanding SPS and DPS contributions and the parton structure of the proton.

Due to high parton flux and high  $\sqrt{s}$  at the LHC, DPS is expected to play a significant role in quarkonium pair production [A.V.Berezhnoy, A.K.Likhoded and A.A.Novoselov, PRD87(2013)054023; S.P.Baranov, A.M.Snigirev and N.P.Zotov, PLB705(2011)116]



**$\Upsilon(1S)$  pair production** in pp collisions at  $\sqrt{s}=8$  TeV is **observed** by CMS using a data set of  $20.7 \text{ fb}^{-1}$ , using dimuon  $\Upsilon$  decay

$p_T(\mu) > 3.5 \text{ GeV}, |\eta(\mu)| < 2.4, |\gamma(\Upsilon)| < 2.0$   
 $P_{\text{vtx}}(\Upsilon) > 0.005, P_{\text{vtx}}(4\mu) > 0.05,$

2-dimensional fit to  $\{M_{\mu\mu}^1, M_{\mu\mu}^2\}$  where  $M_{\mu\mu}^1 > M_{\mu\mu}^2$

2-dimensional fit has 5 components:

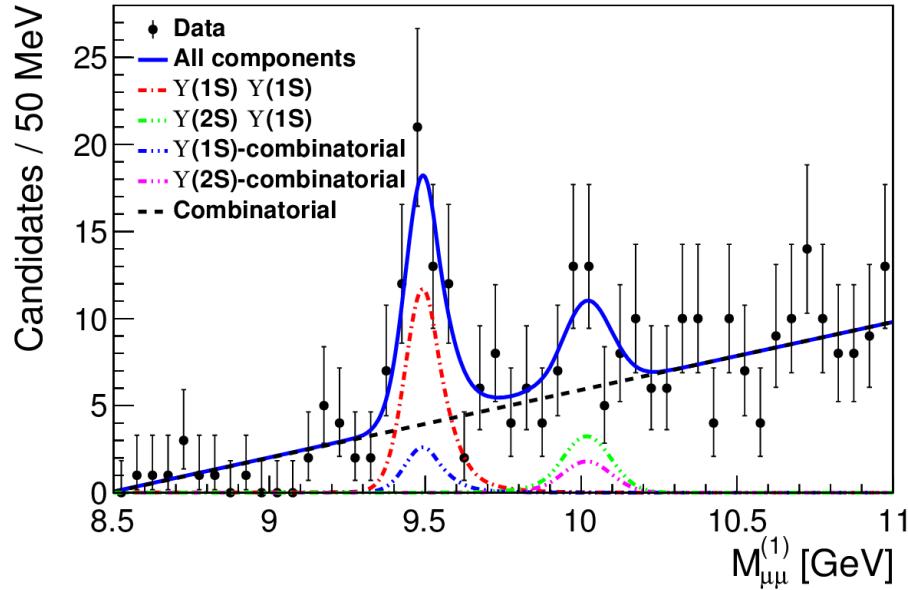
- $\Upsilon(1S)\Upsilon(1S)$  signal
- $\Upsilon(2S)\Upsilon(1S)$  signal
- $\Upsilon(1S)$ -combinatorial
- $\Upsilon(2S)$ -combinatorial
- combinatorial-combinatorial

Signals: Double Crystall-ball with fixed shape parameters  
Combinatorial: polynomial

# The first observation of $\Upsilon(1S)\Upsilon(1S)$ pair production

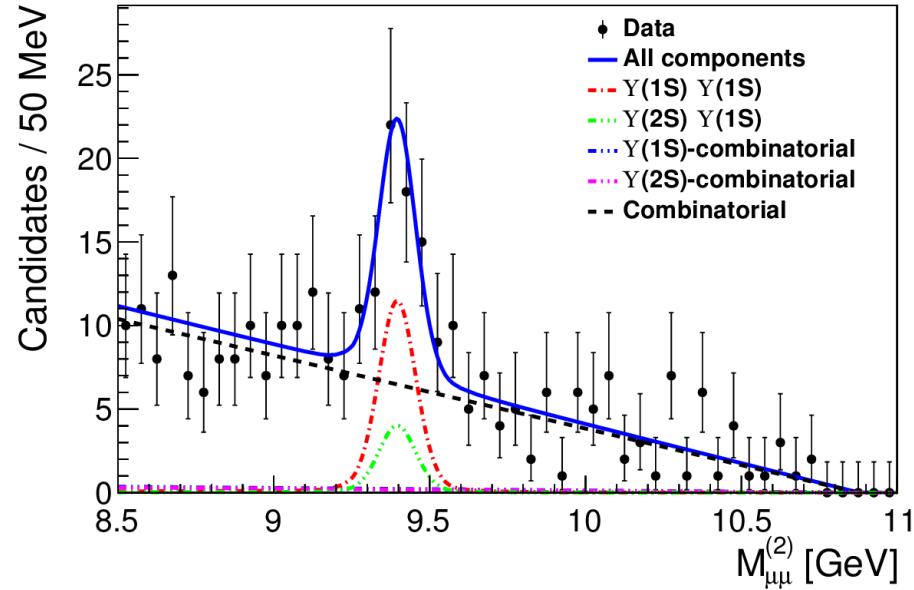
**CMS**

$L = 20.7 \text{ fb}^{-1}$  (8 TeV)



**CMS**

$L = 20.7 \text{ fb}^{-1}$  (8 TeV)



A signal yield of  $38 \pm 7$   $\Upsilon(1S)\Upsilon(1S)$  events is measured with a significance exceeding  $5\sigma$  and of  $13^{+6}_{-5}$   $\Upsilon(2S)\Upsilon(1S)$  events with a significance of  $\sim 2.6\sigma$ .

Assuming that both mesons decay isotropically:

$$\sigma_{\text{fid}}[\Upsilon(1S)\Upsilon(1S)] = 68.8 \pm 12.7 \text{ (stat.)} \pm 7.4 \text{ (syst.)} \pm 2.8 \text{ (\mathcal{B}) pb}$$

in  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$  for  $|y(\Upsilon)| < 2$

If the  $\Upsilon(1S)$  mesons are produced with different polarizations, the measured cross-section varies in the range from -38% to +36%.

# The first observation of $\Upsilon(1S)\Upsilon(1S)$ pair production

## Discussion of the result

In quarkonium pair production, the measurement of the effective cross section depends on the fraction of DPS, which is usually estimated either as a residual to the SPS prediction or as the result of a fit to the rapidity or azimuthal angle between quarkonia pairs:

$$\sigma_{\text{eff}} = \frac{[\sigma(Y)]^2}{2 f_{\text{DPS}} \sigma_{\text{fid}} [\mathcal{B}(Y(1S) \rightarrow \mu^+ \mu^-)]^2} \quad [1]$$

we use  $\sigma(Y) = 7.5 \pm 0.6 \text{ nb}$  and a value of  $f_{\text{DPS}} \approx 10\%$  [2] →  $\sigma_{\text{eff}} \approx 6.6 \text{ mb}$

In agreement with the values from heavy quarkonium measurements (2-8 mb), but is smaller than that from multi-jet studies (12-20 mb).

And it might indicate that the average transverse distance between gluons in the proton is smaller than between quarks, or between gluons and quarks.

[1] S.P. Baranov et al., PRD 87 (2013) 034035

[2] A.V. Berezhnoy, A. K. Likhoded and A.A. Novoselov, PRD 87 (2013) 054023

LHCb [JHEP 06 (2012) 141] and CMS [JHEP 09 (2014) 094] have measured total and differential cross-sections for prompt double  $J/\psi$  production in complementary regions of  $p_T$  and  $y$ .

New findings in double quarkonia frontier can be the preliminary step for searches of heavy 4-quark bound states with Run-II data (or even suppressed decays like, for instance,  $\eta_b$  into double  $J/\psi$ ).

# Double Quarkonia Production: DPS

It is also possible that multiple distinct parton interactions (MPIs) occur, the simplest case being the Double Parton Scattering (DPS): two distinct parton-parton collisions (in the same  $pp$  interaction).

- Because of the high parton flux and the high  $\sqrt{s}$  at LHC, the pair production can be potentially sensitive to DPS. This non-trivial contribution expected from DPS cannot be modeled by current NRQCD predictions: difficult to be addressed within perturbative QCD framework.
- Pair production in  $pp$  collisions via DPS is assumed to result from two independent SPSs.
- Several DPS production processes, including final states with quarkonia and with associated jets are described by an effective cross section  $\sigma_{\text{eff}}$  that characterizes the transverse area of the hard partonic interactions, expected to be independent of the final states (assuming PDFs not correlated).

It depends on the DPS fraction which is usually estimated either ...

- 1) as a residual of the SPS prediction, or ...
- 2) as the result of a fit to the rapidity or azimuthal angle difference between pairs.

Strong correlation of the two  $J/\psi$ s produced via SPS interaction should result in small values of  $\Delta y$ : large  $\Delta y$  values are possible for DPS production.

- $\sigma$  measurement of quarkonium pair production are crucial to understand SPS & DPS contributions.
- Pair production phase space @CMS nicely complements LHCb and gives access to high  $p_T$  regime.