CMS Status Report on Hadron Spectroscopy

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Outline

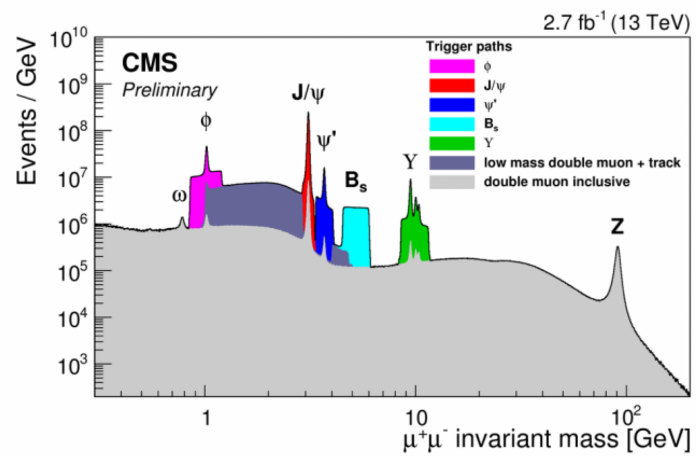
- Introduction
- Search for $X(5568)^+ \to B_s\,\pi^+$
- $Y(4140) \to J/\psi\,\phi$
- Observation of $B^+ \to \psi(2S)\,\phi\,K^+$
- Study of X(3872) production properties
- Search for the bottomonium partner of X(3872)
- Observation of double $\Upsilon(1S)$ production
- Summary and Prospects

Introduction

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

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

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 $\varepsilon > 99\%$ for muons

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

Muon system

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

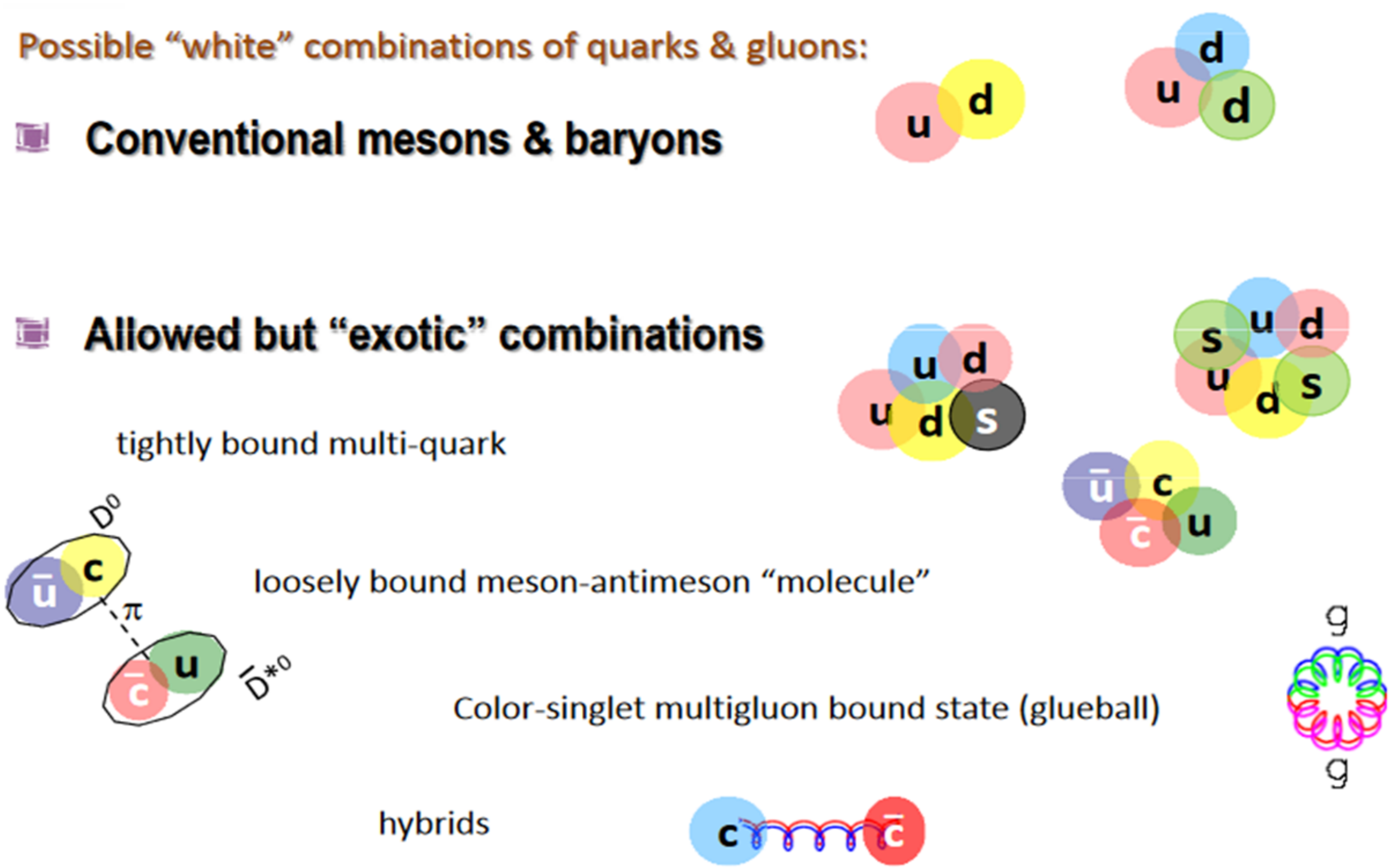
Standalone $\Delta p_T/p_T \cong 10\%$

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

In this talk several highlights from 7 and 8 TeV data samples will be discussed

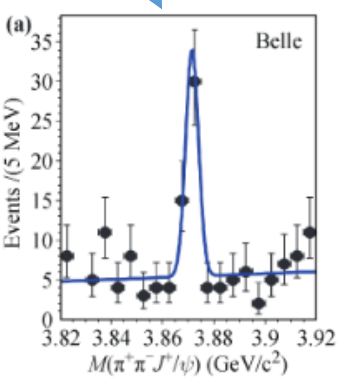
Hadrons: Conventional and Exotic

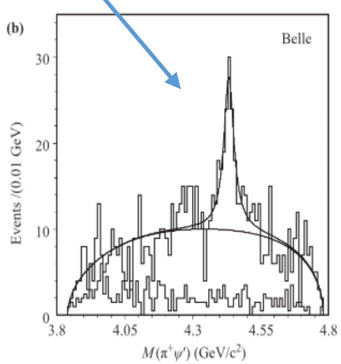
- Is there any quark configuration other than mesons and baryons?
- In theory such configurations are possible
- Which of them are actually realized in nature?

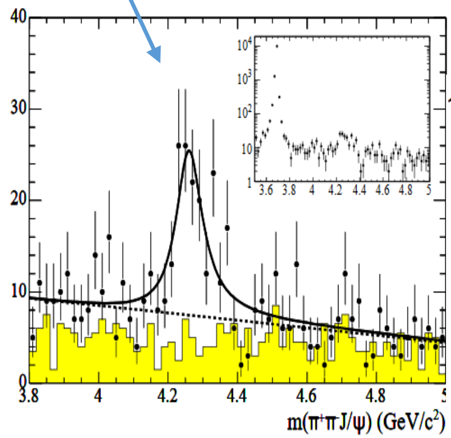


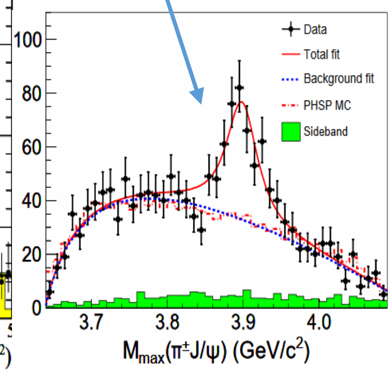
Exotic Hadrons: experimental results and theoretical interpretation

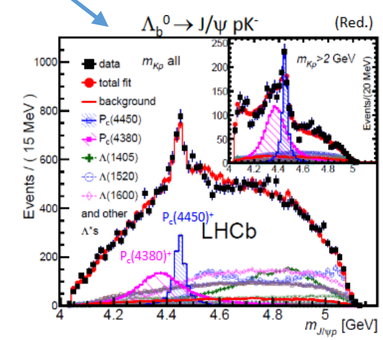
Since 2003, thanks to the B-factories Belle and BaBar (followed by BES III and LHCb), the number of candidates for exotic hadrons is continuously growing.
These are multiquark states, some bright examples:
X(3872) and $Z(4430)^+$ from Belle, X(4260) from BaBar, $Z(3900)^+$ from BESIII /Belle and P_c from LHCb.











This is a new hadron spectroscopy era

Theoretical interpretation of all these exotic states is still not clear.
$\rightarrow$ we need more information!

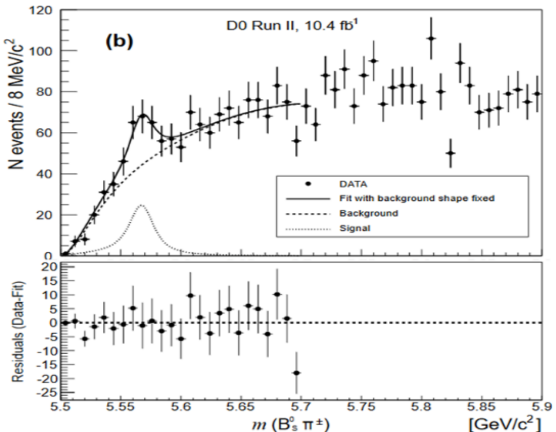
- Hadrocharmonium?
- Molecule?
- Rescattering (threshold effect, cusp)?
- Tetraquark?

New results are coming. One of them is the evidence for $X(5568)^+ \rightarrow B_s\, \pi^+$ by DØ Collaboration.

Search for X(5568)$^+$ → $B_s\,\pi^+$

DØ Collaboration: Evidence for X(5568): new state decaying into $B_s\,\pi^+$

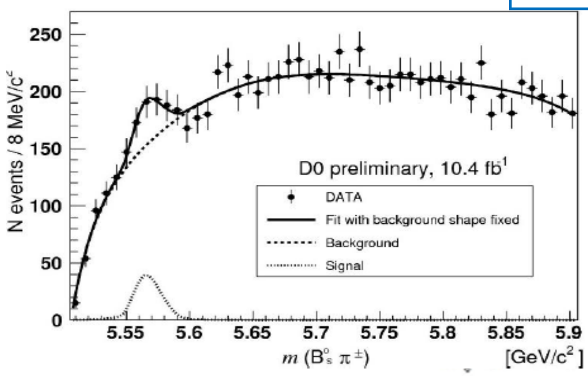
PRL117. 022003(2016)



$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \text{MeV},$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \text{MeV},$$

$$\rho_X^{D0} \equiv \frac{\sigma(p\bar{p} \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi)}{\sigma(p\bar{p} \to B_s^0 + \text{anything})} = (8.6 \pm 1.9 \pm 1.4)\%$$

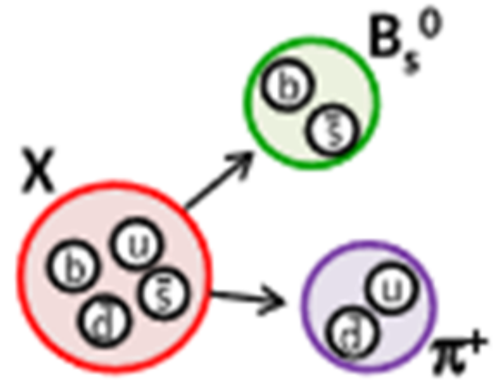
DØ Conf. Note 6896

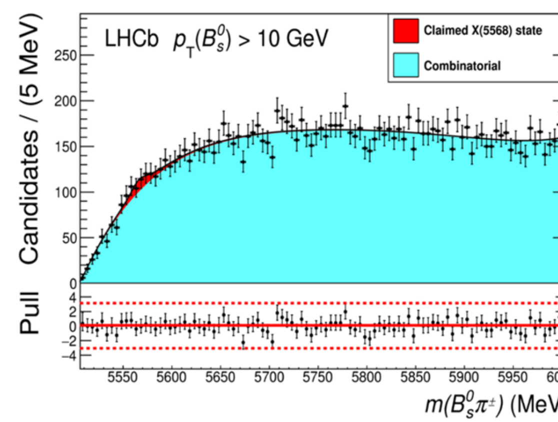


Similar results with $B_s^0 \to D_s \mu\nu$

Rather big number for the prompt production of 4-quark exotic state

If confirmed, would be unique with 4 different flavors





PRL117. 152003(2016)

$$\rho_X^{\text{LHCb}}(p_T(B_s^0) > 5\,\text{GeV}) < 0.011\ (0.012)$$
$$\rho_X^{\text{LHCb}}(p_T(B_s^0) > 10\,\text{GeV}) < 0.021\ (0.024)$$
$$\rho_X^{\text{LHCb}}(p_T(B_s^0) > 15\,\text{GeV}) < 0.018\ (0.020)$$

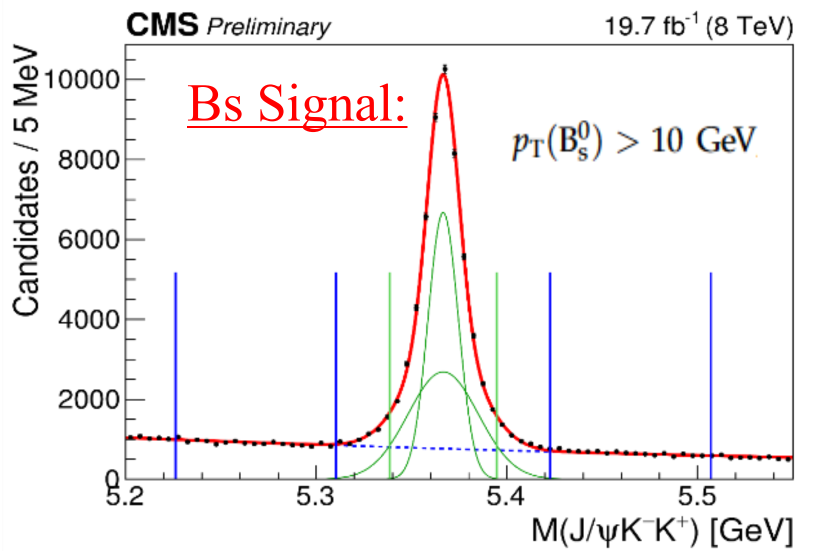
Search for X(5568)$^+$ in CMS:

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

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

CMS-PAS-BPH-16-002

51398 ± 283 signal candidates,

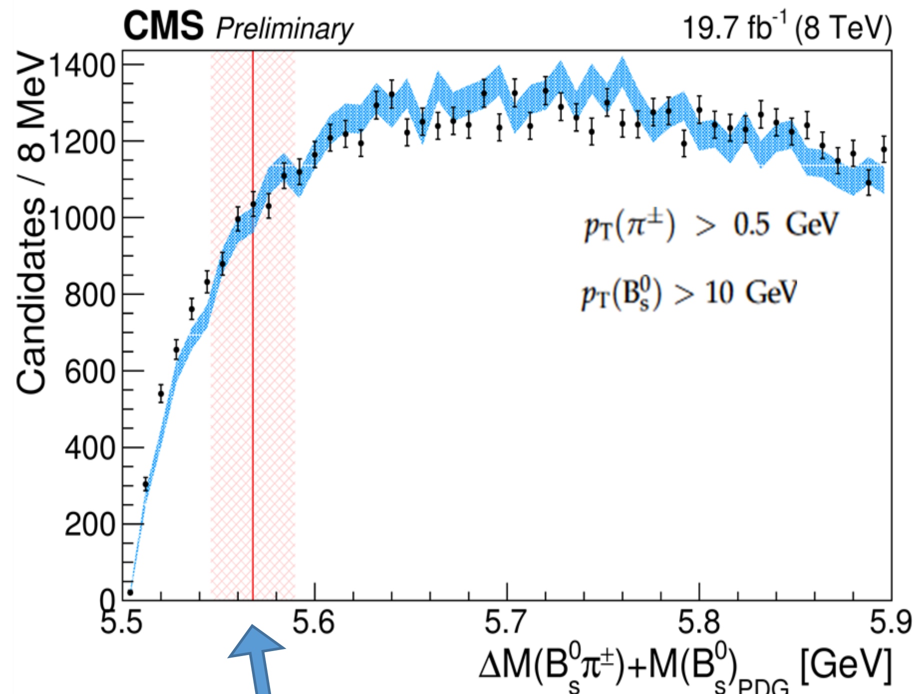


$$\sigma_{eff} = \left[(1-f)\sigma_1^2 + f\sigma_2^2\right]^{1/2} \simeq 14 \text{ MeV}$$

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

48204 B_s^0 signal events (93.8%)

Combine the B_s candidate with each π^+ from the collection of tracks building the selected PV



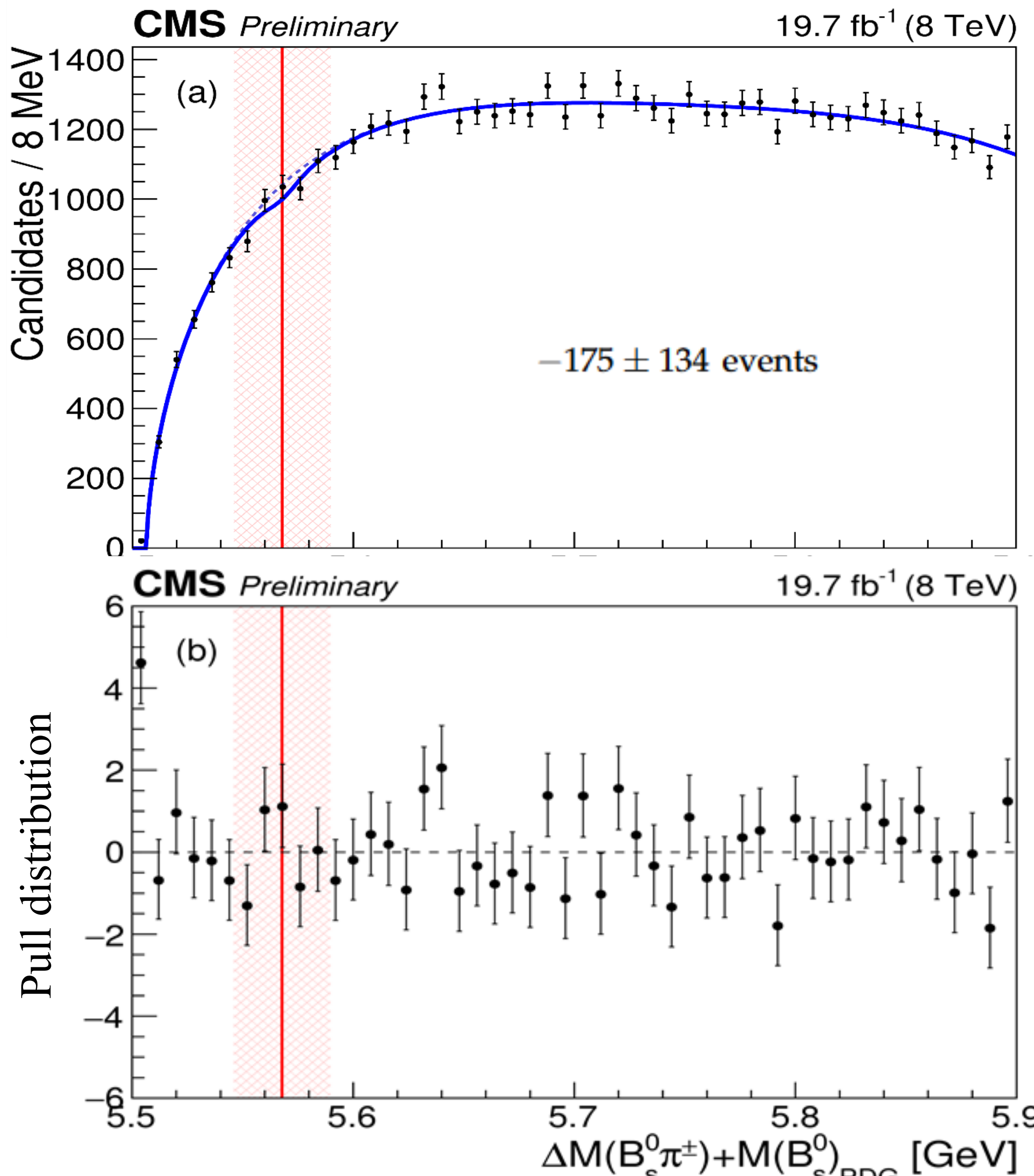
Comparison of B_s statistics

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

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

LHCb: Phys. Rev. Lett. 117 (2016) 152003
DØ: Phys. Rev. Lett. 117 (2016) 022003

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



CMS-PAS-BPH-16-002

Fit function:
Signal + Background

Signal:
S-wave Breit-Wigner with fixed m and Γ to DØ values

Background:

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

No hints for the X(5568)+ signal

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

CMS-PAS-BPH-16-002

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

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

The most conservative upper limit is 198 @ 95% CL

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

$$\rho_X \equiv \frac{\sigma(pp \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to B_s^0 \pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})} = \frac{N_{X(5568)}}{N_{B_s^0}} \frac{\epsilon_{B_s^0}}{\epsilon_{X(5568)}} < 3.9\% \text{ @ } 95\% \text{ CL}$$

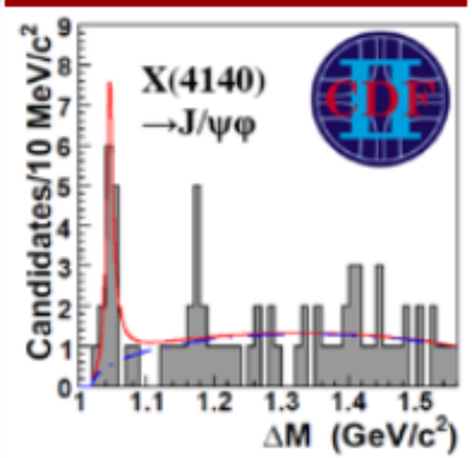
$B_s^0 \to J/\psi\phi$ ($X(5568) \to B_s^0\pi^\pm$) **(rel. eff. ~10%).** The most conservative estimation of the efficiency ratio, determined from preliminary simulations, leads to an upper limit of $\rho_X < 3.9\%$ at 95% CL, which can be compared against the DØ measurement of $(8.6 \pm 1.9 \pm 1.4)\%$ [1].

The final result on the UL of ρ_X from 8 TeV data sample will be released soon

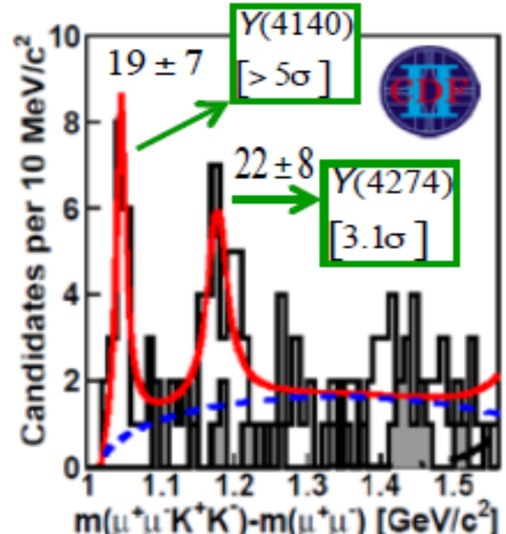
Confirmation of X(4140) $\rightarrow J/\psi\ \phi$

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

[PRL 102 (2009) 242002]

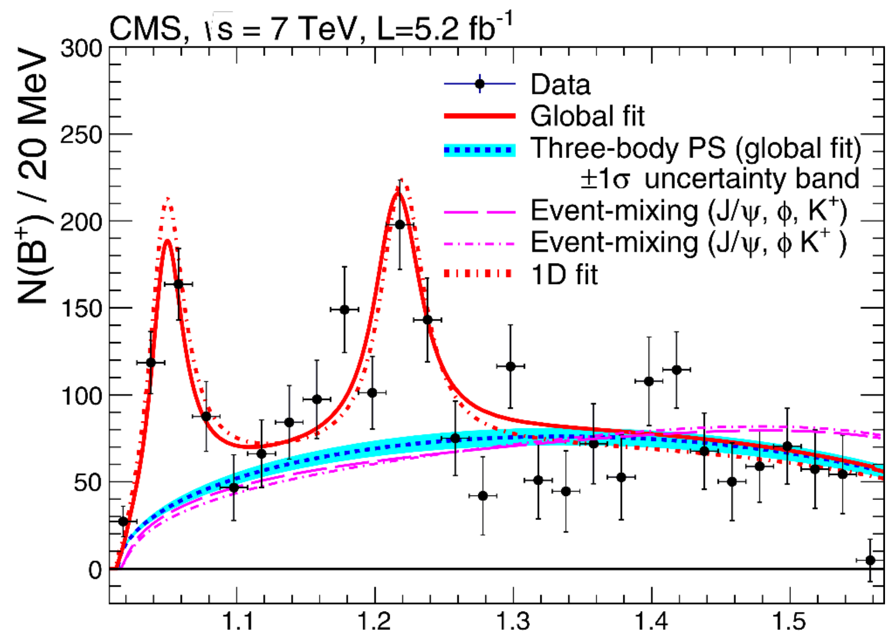


CDF (2011) presents update analysis with larger dataset,(6.0fb^{-1} vs 2.7fb^{-1})observing



[arXiv:1101.6058 (2011)]

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



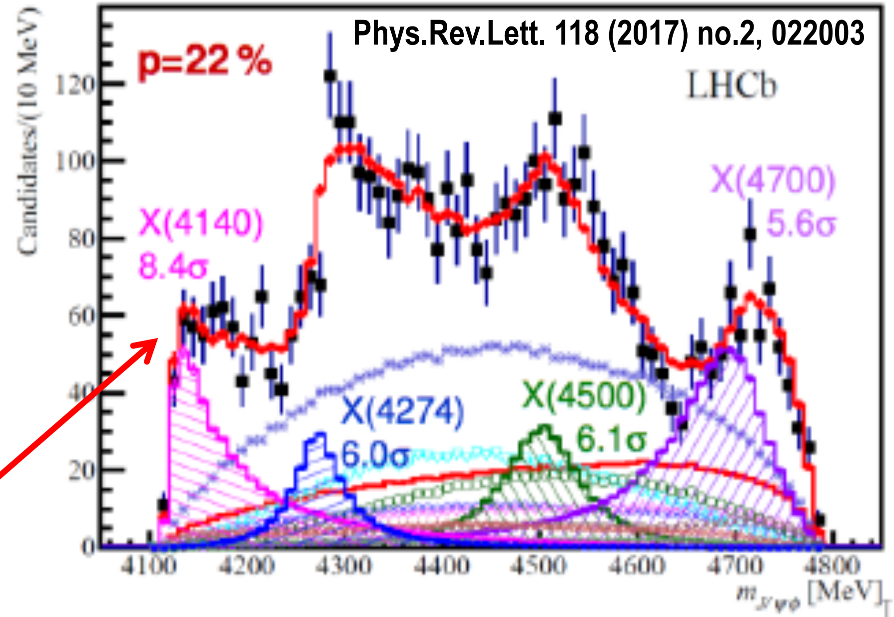
PLB 734 (2014) 261

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

Study of the J/ψ ϕ system

LHCb performed two analyses:

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



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

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

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

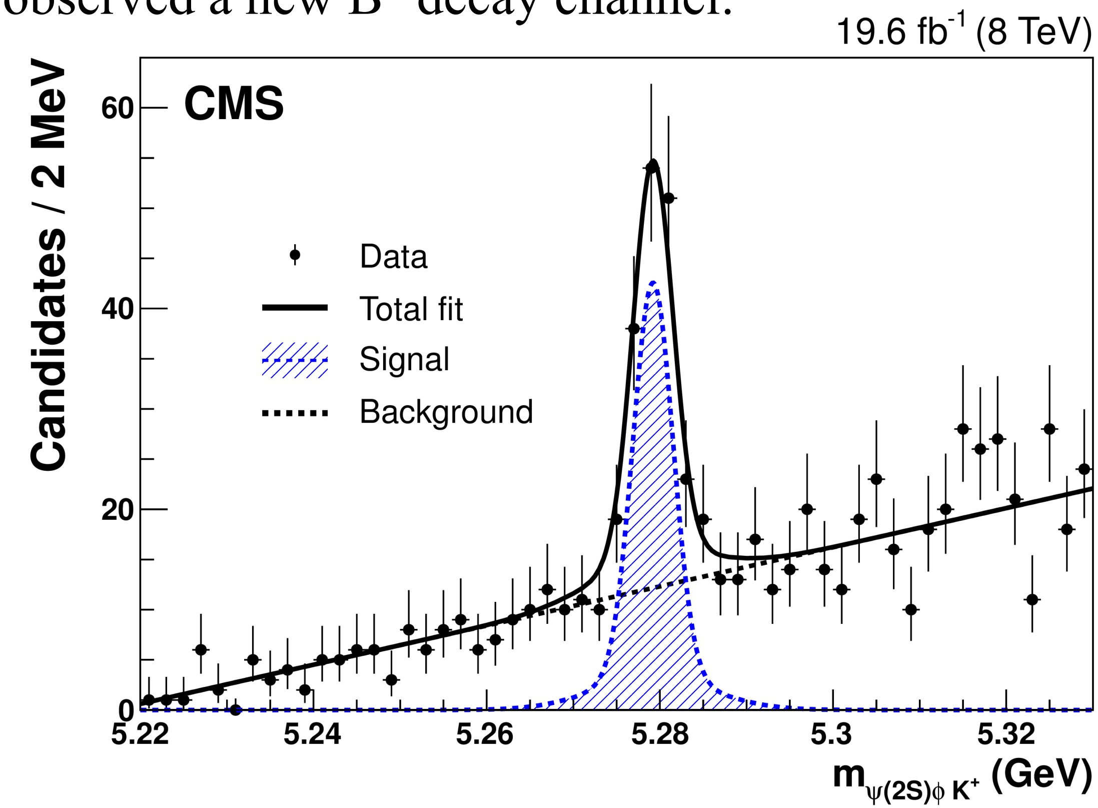
Recently, the D0 Collaboration has published the first evidence for the prompt production of the X(4140) PRL 115 (2015) 232001

CMS can perform the same search at LHC!

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

Phys. Lett. B 764 (2017) 66

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



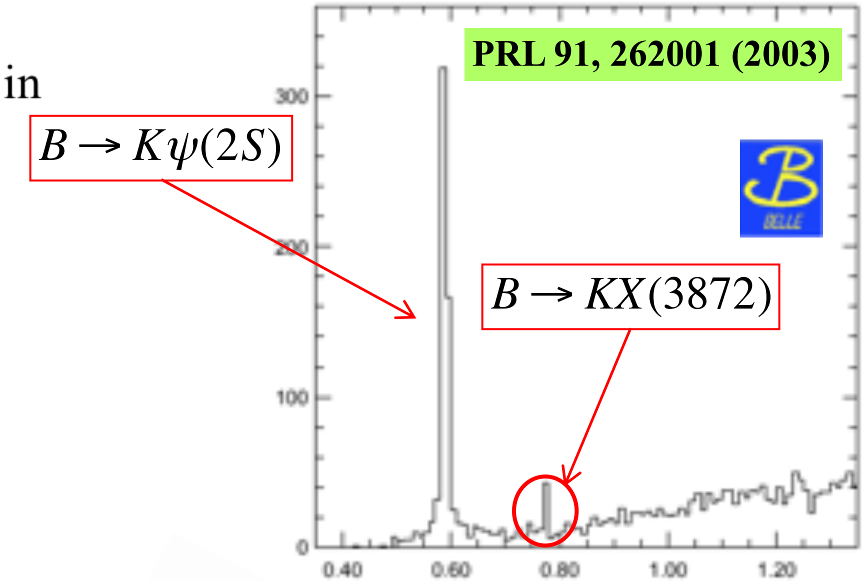
The relative B.F., using the $B^+ \to \psi(2S)\,K^+$ mode as normalization channel, is

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

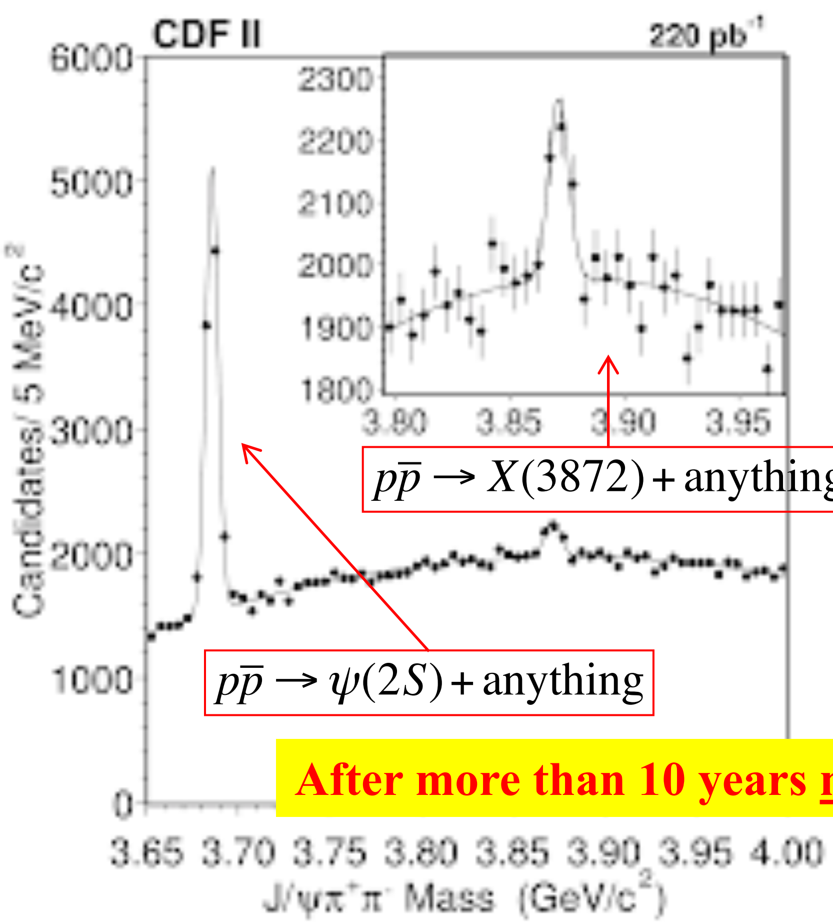
This is the first step towards the exploration of ψ(2S) ϕ system

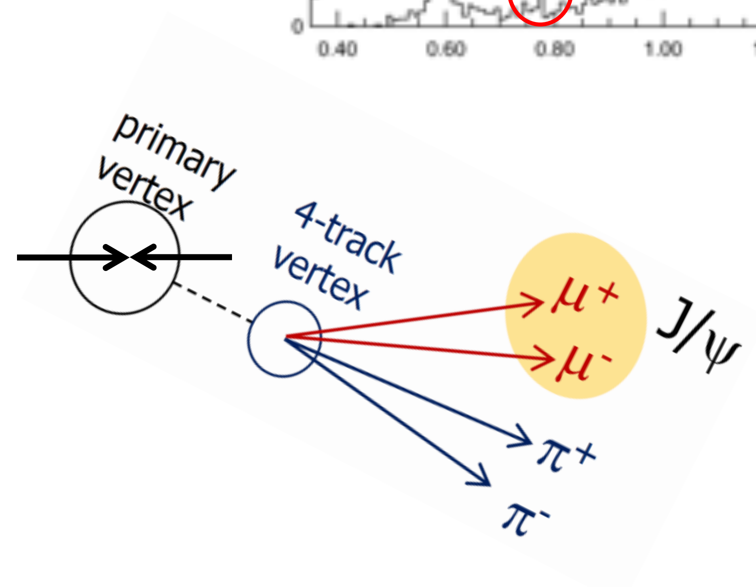
The X(3872) - I

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



PRL 93, 072001 (2004)

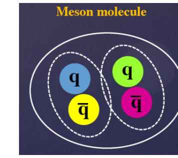




After more than 10 years <u>no definitive answer</u> on the nature of the *X(3872)*

The X(3872) - II

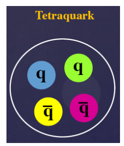
After more than 10 years no definitive answer on the nature of the *X(3872)*.



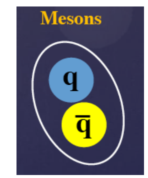
Main hypotheses are:

- **Loosely bound molecular state**: suggested by proximity to $D\overline{D}^{0*}$ 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 $\eta_{c2}(1^1D_2)$ and quantum numbers would be respectively $J^{PC} = 1^{++}$ or 2^{-+}.
  $c\bar{c} \to \rho\, J/\psi$ ~ ruled out because it would imply a pure isoscalar state; X(3872) shows an equal amount of isospin components (I=0 & I=1):



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

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

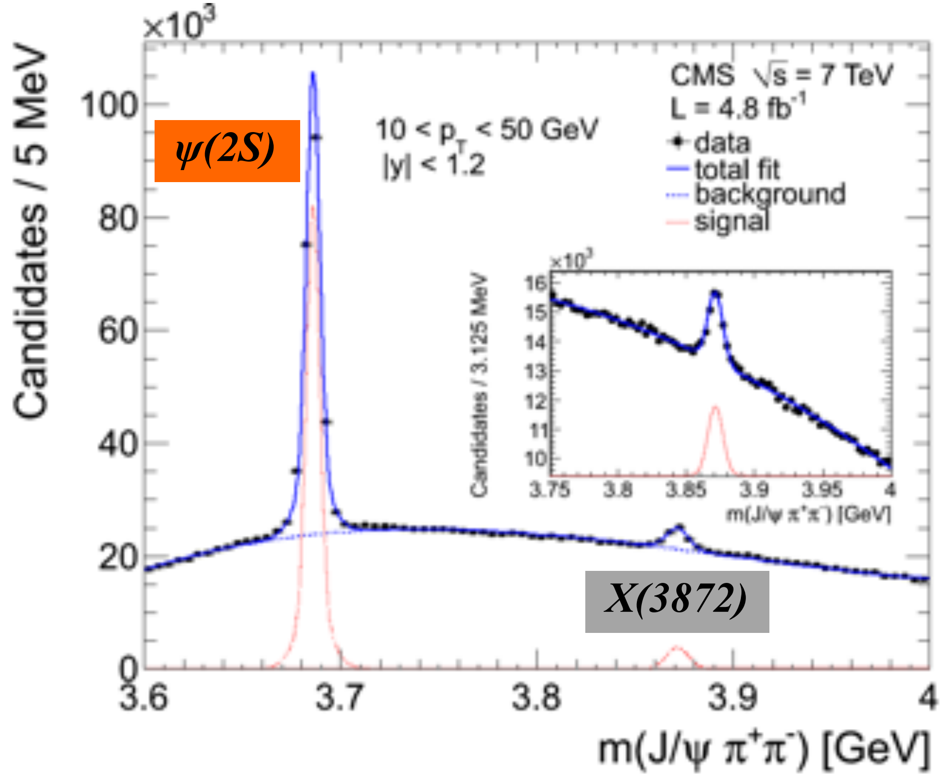
LHCb made a sophisticated angular analysis [**PRL 110 ('13) 222001** & **PRL 92 ('15) 011102**] of the whole decay chain $B^+ \to K^+ X(3872) \to K^+ (J/\psi\, \pi^+ \pi^-)$ dropping the assumption of lowest possible orbital angular momentum in the *X(3872)* sub-decay and unambiguously determined the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

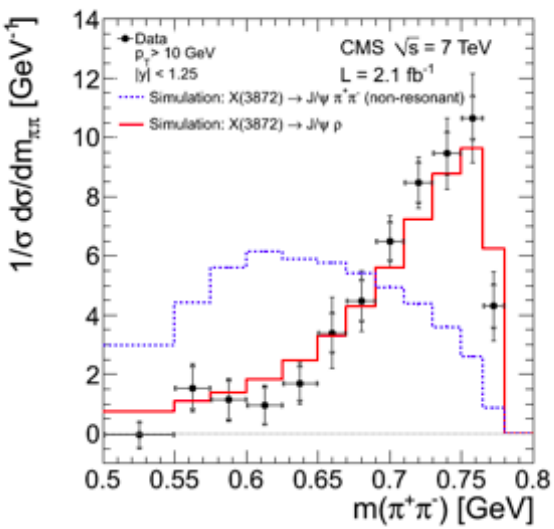
Pure molecular model is not supported by recent LHCb measurement [**NPB 886 ('14) 665**] of the radiative decay.

JHEP 1304 (2013) 154

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. $\psi(2S)$
  - Non-prompt component vs p_T
  - Prompt *X(3872)* cross section
  - Invariant mass distribution of the $\pi^+\pi^-$ system





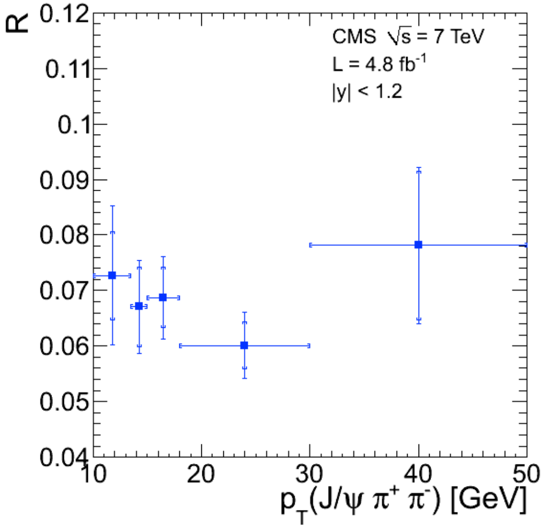
The $\pi^+\pi^-$ invariant mass distribution from *X(3872)* decays to $J/\psi\pi^+\pi^-$ is measured in order to investigate the decay properties of the *X(3872)*. Studies at CDF and Belle suggest that *X(3872)* decays in J/ψ and ρ^0

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.

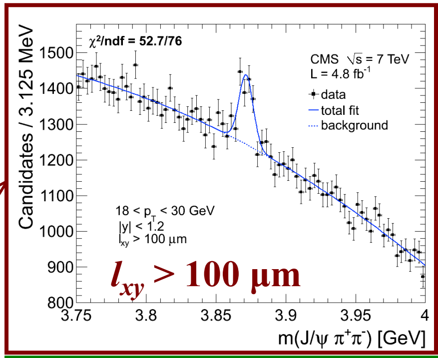
Cross sections ratio & non-prompt fraction

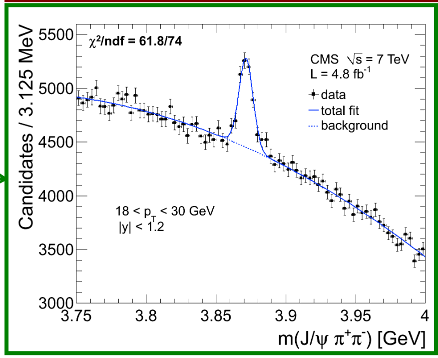
A ratio of the cross sections have been measured to cancel out many systematic sources:

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



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





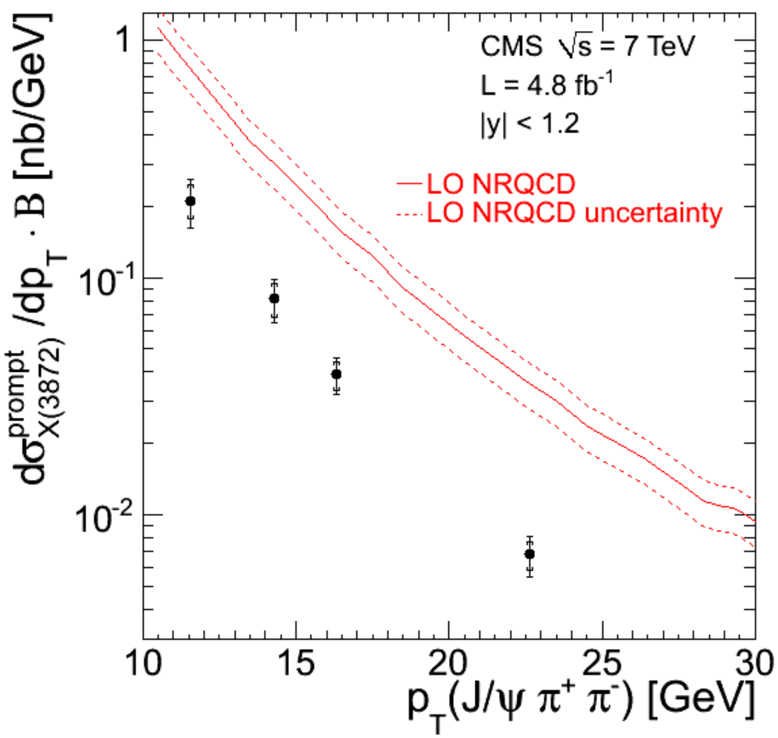
- The *X(3872)* can be produced from decays of *B* hadrons in a secondary vertex related to the decay length (l_{xy}) of the *B* meson
  - Events with *X(3872)* from *B* decays are selected by requiring $l_{xy} > 100\ \mu m$: *non-prompt fraction* = $\frac{\#\text{ of } X(3872) \text{ from } B}{\#\text{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

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

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



- 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

Theoretical prediction for 10 < pT < 30 GeV, |y| <1.2

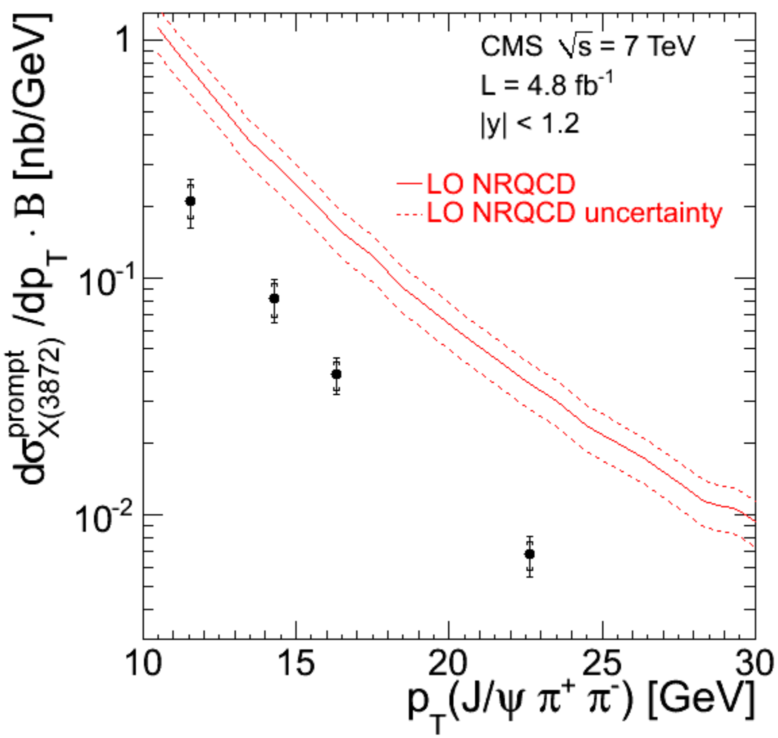
$$\sigma^{prompt}_{X(3872)} \times B\left(X(3872) \to J/\psi\ \pi^+\pi^-\right) \cong (4.01 \pm 0.88) nb$$

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:

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

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



- 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

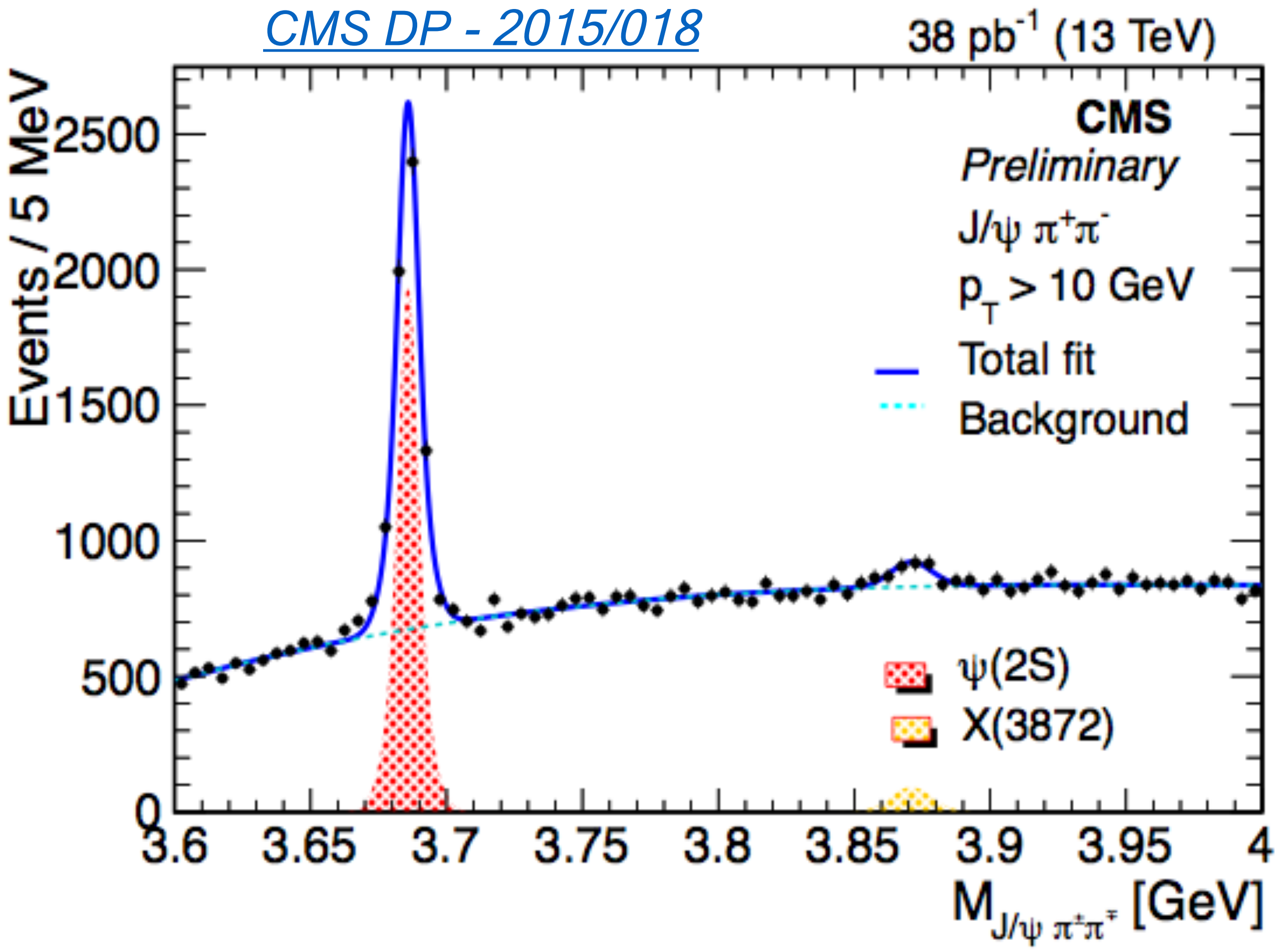
Predictions by Artoisenet & Brateen assume, within an S-wave molecular model, the relative momentum of the mesons to be bound by an upper limit of 400 *MeV* which is quite high for a loosely bound molecule, but they assume it is possible as a result of rescattering effects.

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 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:

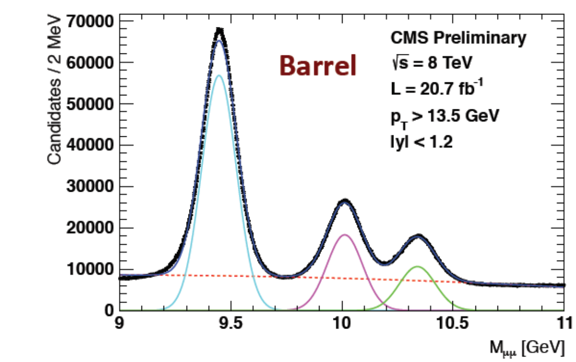
CMS DP - 2015/018

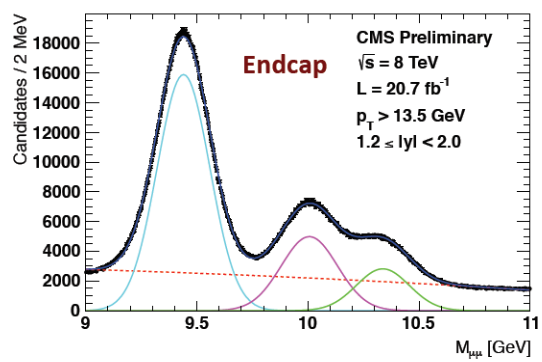


Search for exotic bottomonium states X_b decaying into $\Upsilon(1S)\ \pi^+\pi^-$

PLB 727 (2013) 57

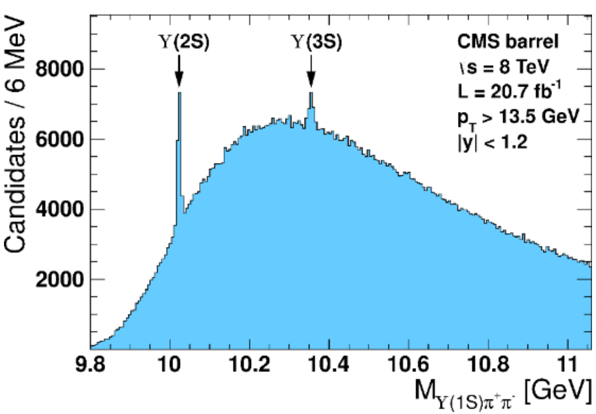
- The discovery of the X(3872) has prompted the search for a bottomonium counterpart X_b decaying into $\Upsilon(1S)\ \pi^+\pi^-$, according to HQS considerations, with mass close to the $B\overline{B}$ or $B\overline{B}^*$ threshold, 10.562 and 10.604 GeV.
- It is expected that this X_b would be narrow,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

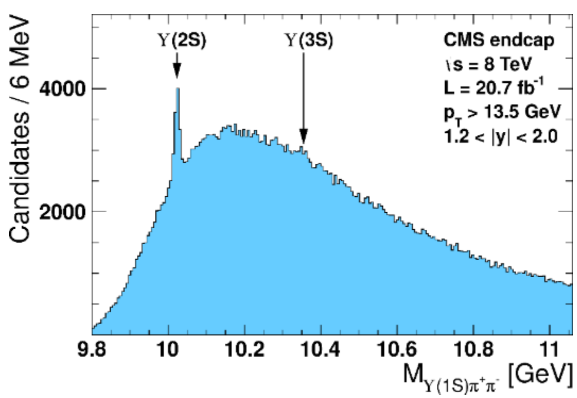




CMS has collected a large sample of $\Upsilon(nS) \to \mu^+\mu^-$ produced in pp collisions at $\sqrt{s} = 8$ TeV.

Separate barrel and endcap events to exploit better mass resolution and lower background in the barrel region.



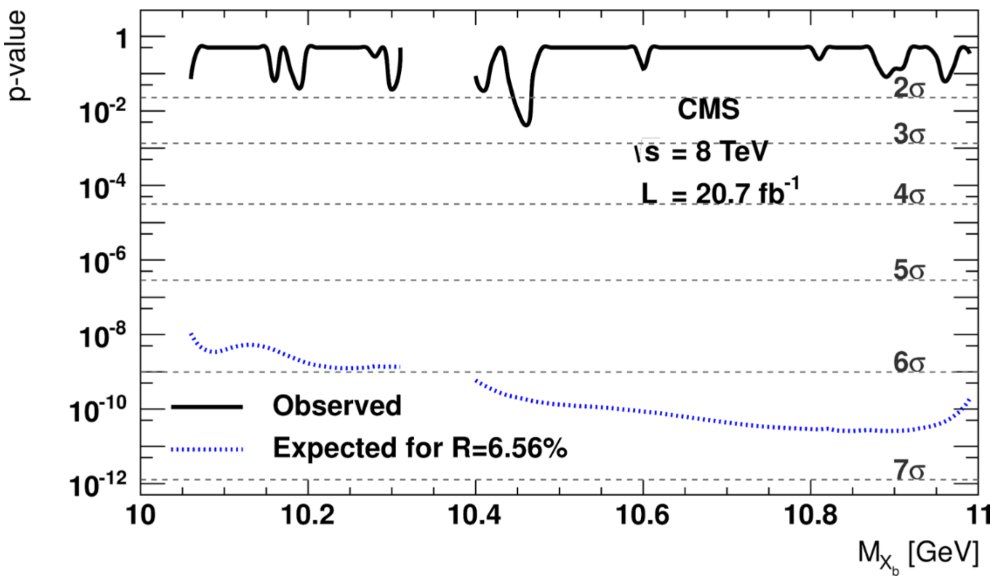


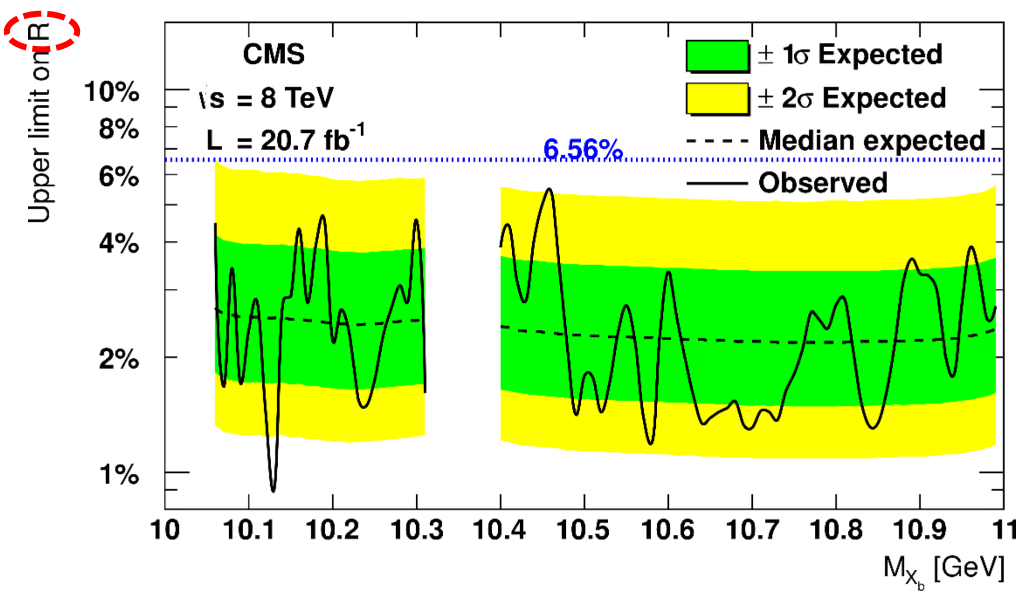
$p_T(\Upsilon(1S)\ \pi^+\pi^-) > 13.5$ GeV & $|y(\Upsilon(1S)\ \pi^+\pi^-)| < 2$

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

Mass scan for $X_b \to \Upsilon(1S)\,\pi^+\pi^-$

PLB 727 (2013) 57





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

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

- 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 2.6σ, which is reduced to 0.8σ when LEE is taken into account.

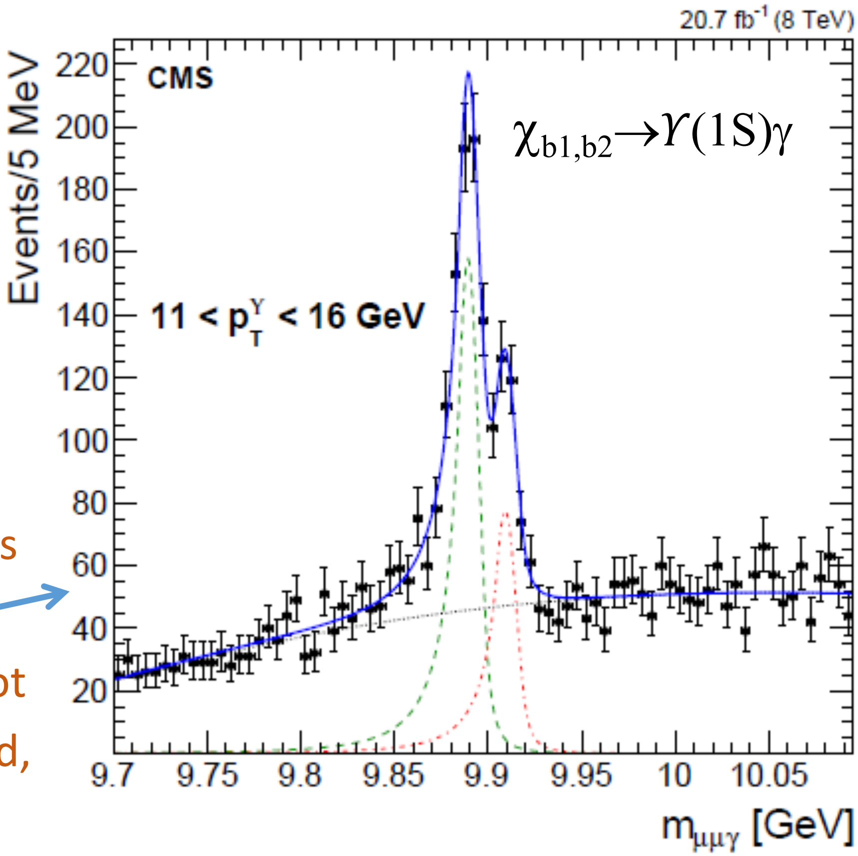
No significant excess is observed.
95% CL UL set on R
varies from 0.9% to 5.4%.
(similar result by ATLAS)

Prospects for further X_b searches

- According to Karliner&Rosner [**PRD91 (2015) 014014**], this search decay ($X_b \longrightarrow \Upsilon(1S)\,\pi^+\pi^-$) should be forbidden by G-parity conservation. While for the X(3872) the isospin-conserving decay to $J/\psi\omega$ was cinematically suppressed, the same is not true for a bottomonium-like $J^{PC}=1^{++}$ counterpart.

- The strategy for X_b observation should include searches for
  - $X_b \longrightarrow \Upsilon(1S)\,\omega\,(\longrightarrow \pi^+\pi^-\pi^0)$
  - $X_b \longrightarrow \Upsilon(3S)\,\gamma$
  - $X_b \longrightarrow \chi_{b1}(1P)\,\pi^+\pi^-$

- Tasks for CMS for Run-II.
  The possibility to work with converted γ's was excellently demonstrated with the reconstruction of $\chi_{b1,b2} \longrightarrow \Upsilon(1S)\gamma$. But it is not an easy task due to soft γ: low conversion and, therefore, reconstruction efficiency.



PLB 743(2015) 383

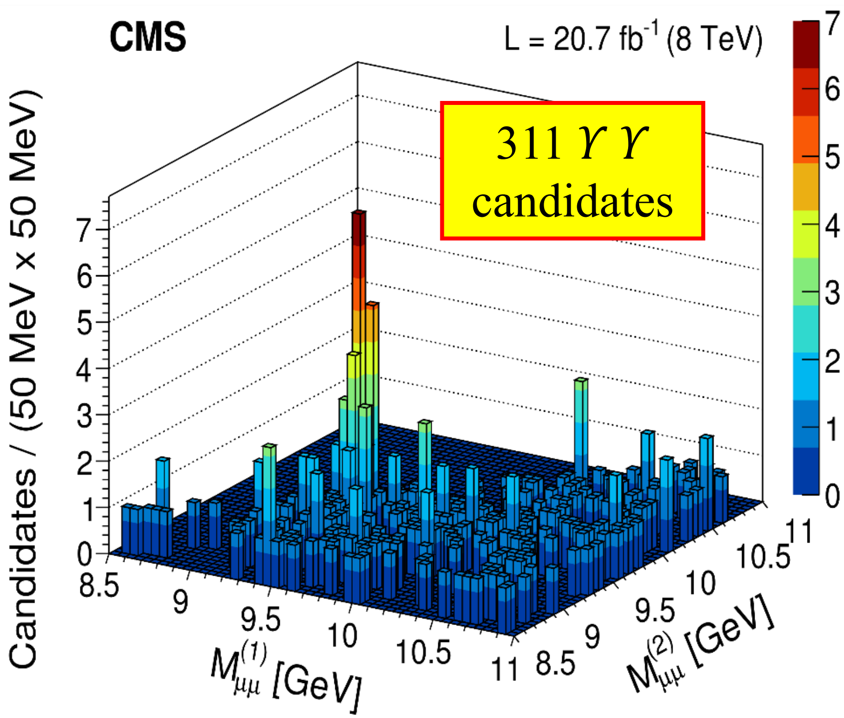
Also, Karliner&Rosner suggest that the X_b may be close in mass to the $\chi_{b1}(3P)$, mixing with it and sharing its decay.

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

JHEP 05 (2017) 13

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]



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

$p_T(\mu) > 3.5$ GeV, $|\eta(\mu)| < 2.4$, $|y(\Upsilon)| < 2.0$

$P_{vtx}(\Upsilon) > 0.005$, $P_{vtx}(4\mu) > 0.05$,

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

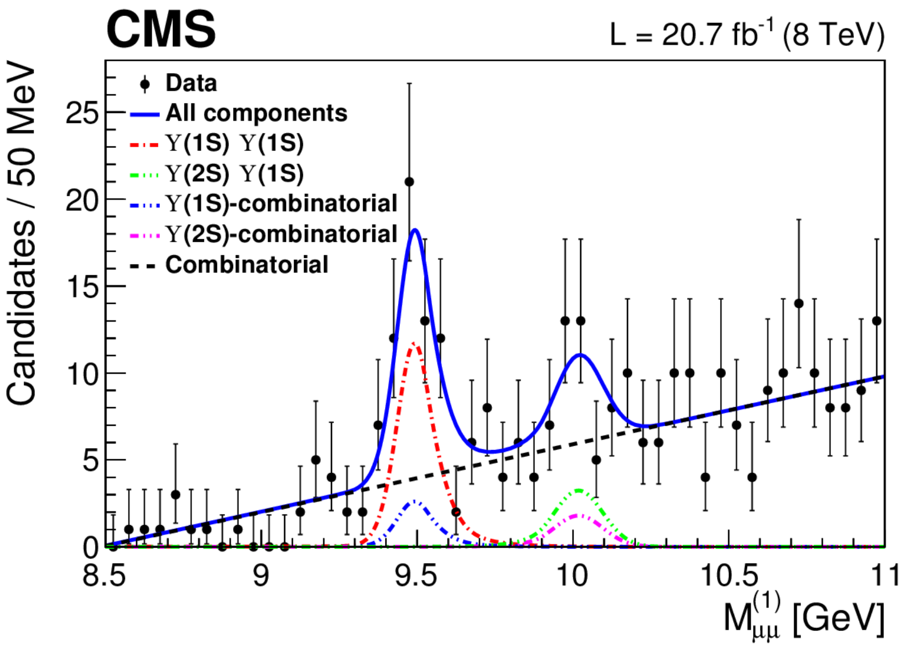
2-dimensional fit has 5 components:

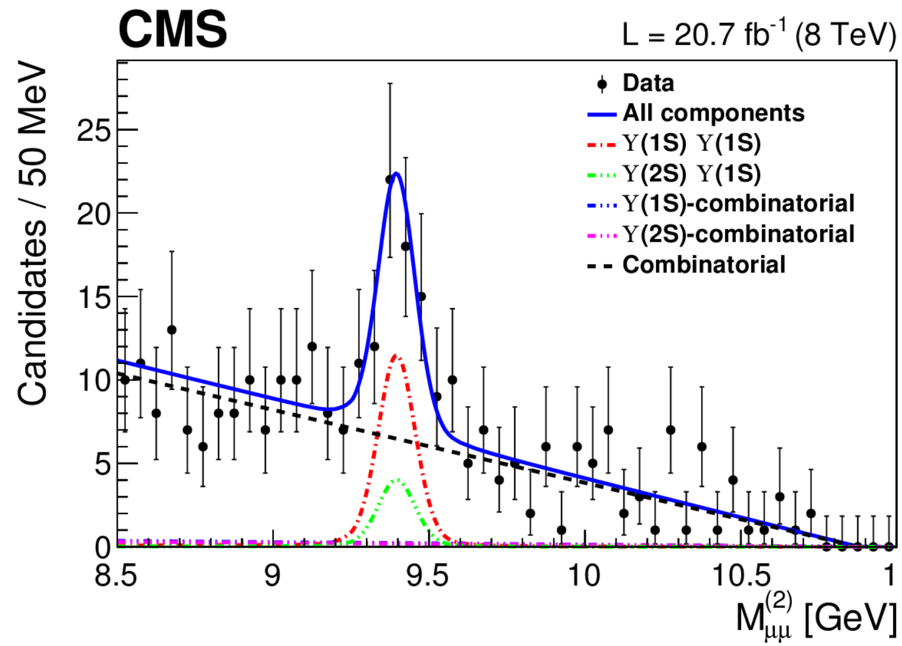
- ϒ(1S)ϒ(1S) signal
- ϒ(2S)ϒ(1S) signal
- ϒ(1S)–combinatorial
- ϒ(2S)–combinatorial
- combinatorial–combinatorial

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

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

JHEP 05 (2017) 13





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

Assuming that both mesons decay isotropically:

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

in *pp* collisions at $\sqrt{s}$ = 8 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

JHEP 05 (2017) 13

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:

$$\sigma_{\rm eff} = \frac{[\sigma(\Upsilon)]^2}{2\, f_{\rm DPS}\, \sigma_{\rm fid}\, [\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)]^2} \quad [1]$$

we use $\sigma(\Upsilon) = 7.5 \pm 0.6\,\text{nb}$ and a value of $f_{\rm DPS} \approx 10\%$ [2] $\rightarrow \sigma_{\rm eff} \approx 6.6$ 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/ψ 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, η_b into double J/ψ).

Summary and Prospects

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

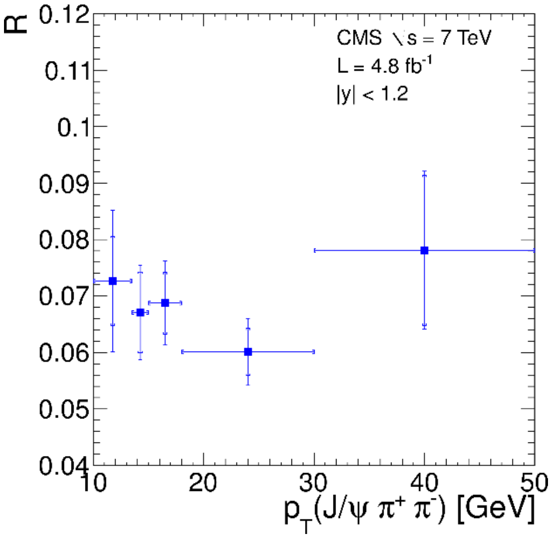
- Study of the $B_s\ \pi^+$ spectrum and setting an UL on the production of X(5568)
- First significant confirmation of the X(4140) $\longrightarrow$ J/ψ ϕ at LHC
- Observation of $B^+ \rightarrow \psi(2S)\ \phi\ K^+$
- Measurement of X(3872) production properties in CMS
- Search for the bottomonium partner of the X(3872) in $\Upsilon(1S)\pi^+\pi^-$ channel
- First observation of $\Upsilon(1S)\Upsilon(1S)$ pair production at LHC

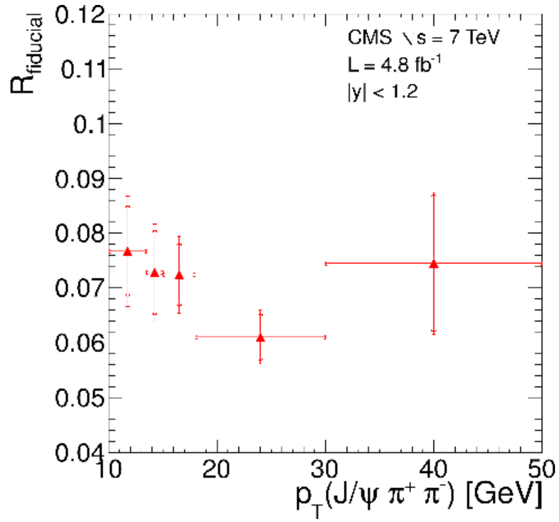
New results from CMS are foreseen soon, one of them is the final Upper Limit on the production of the X(5568) observed by DØ.

Backup slides

Study of X(3872) production properties at CMS

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





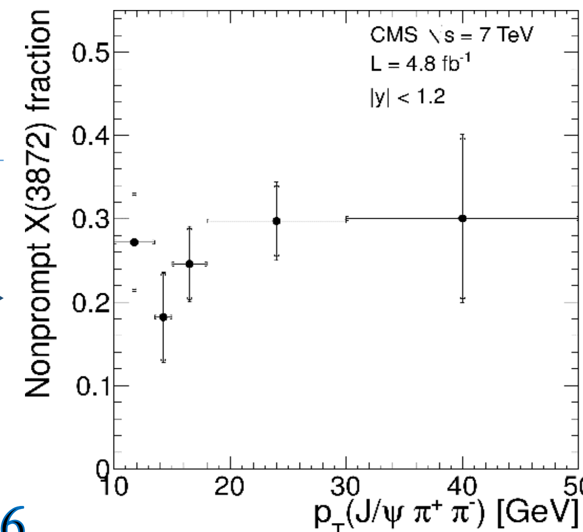
Acceptance corrections depend on assumptions on the angular distribution of the final states. So, w/o acc. corr. one can derive R in a fiducial region.

NO SIGNIFICANT dependence on the p_T

Integrated over $10 < p_T < 50$ GeV:

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

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

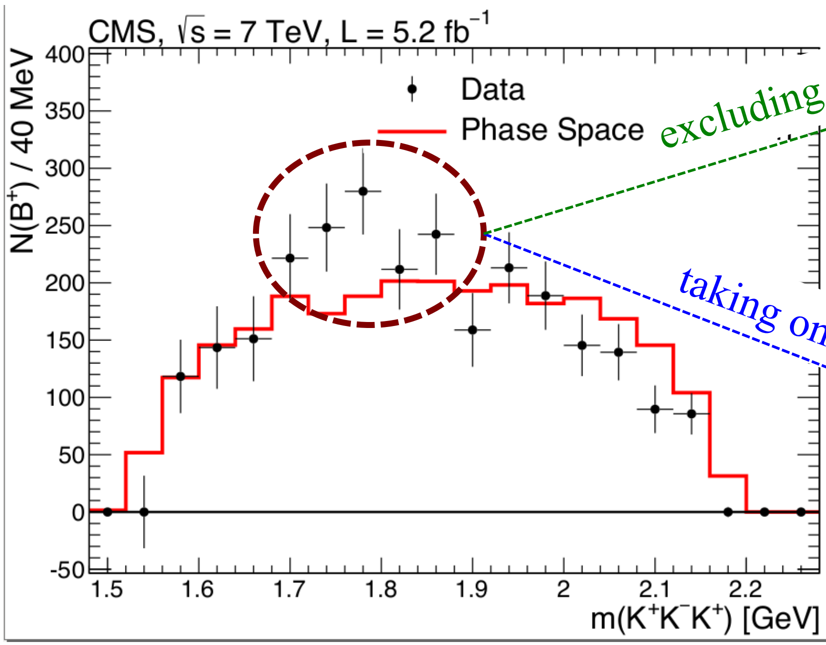


Non-prompt X(3872) fraction: $f_{np} = 0.263 \pm 0.023 \pm 0.016$

Next steps for Y(4140)

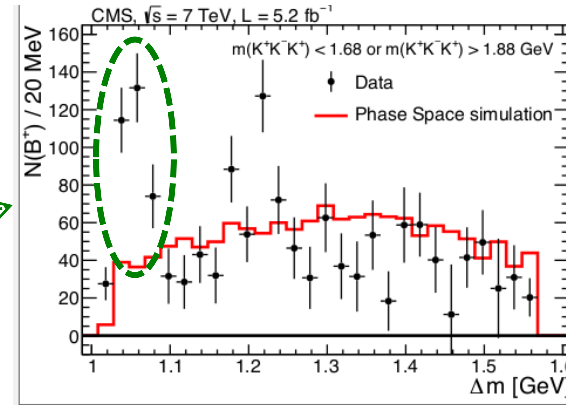
- Understanding the nature of both structures needs further investigation

  - 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:

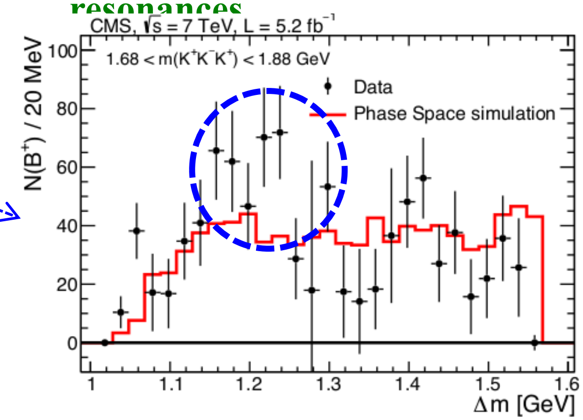


excluding this $m(K^+K^-K^+)$ region

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 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.

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

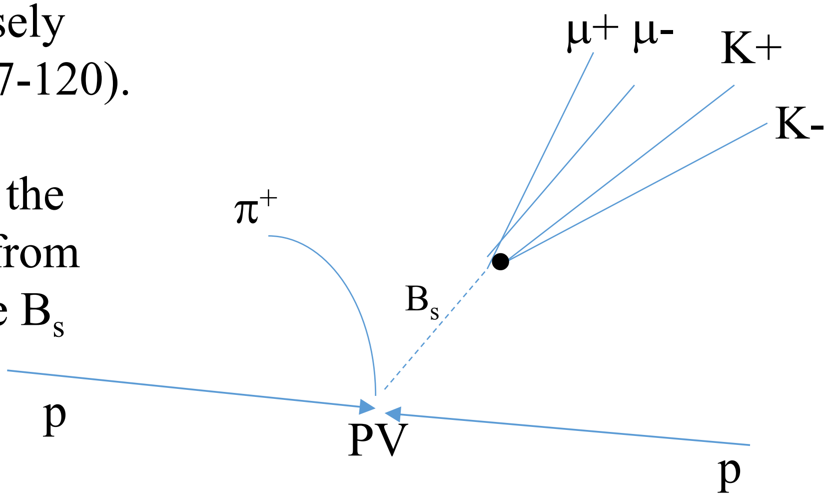
CMS-PAS-BPH-16-002

Analysis strategy:

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

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

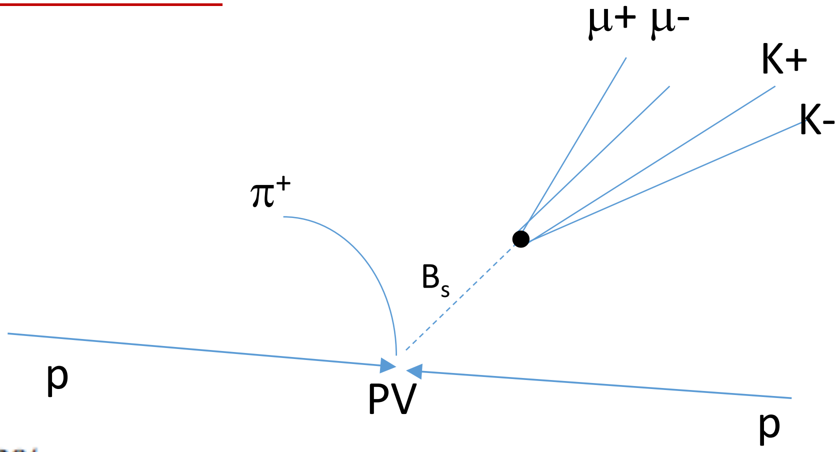
1) Reconstruct B_s by combining J/ψ and ϕ and then fit 4 tracks into the common vertex $\longrightarrow$ know B_s momentum and its decay vertex (this procedure follows closely that from B_s CPV analysis in PLB 757 (2016) 97-120).
2) Select Primary Vertex (PV):
   from all pp collision points, the PV 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

CMS-PAS-BPH-16-002

Offline selection criteria:



- $p_T(\mu^\pm) > 4$ GeV,
- $|\eta(\mu^\pm)| < 2.2$,
- $p_T(\mu^+\mu^-) > 7$ GeV,
- dimuon vertex χ^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 $3.04 < M(\mu^+\mu^-) < 3.15$ GeV.

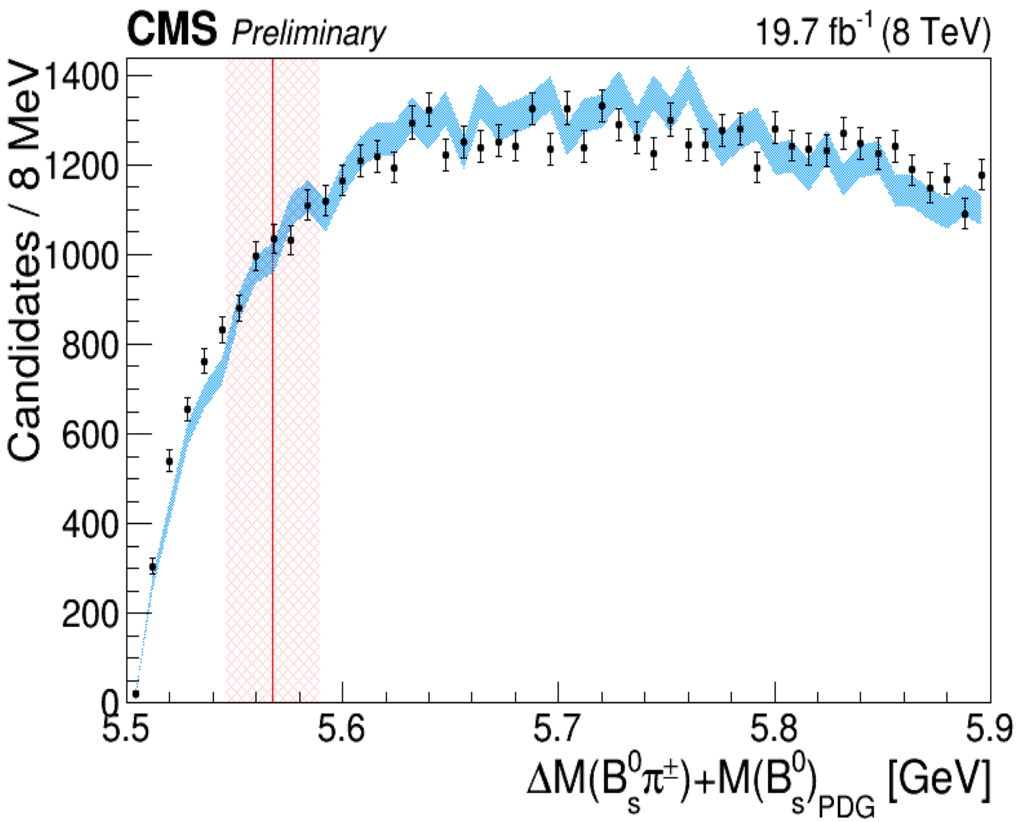
$p_T(K^\pm) > 0.7$ GeV. $p_T(B_s^0) > 10$ GeV

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

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

Cone cut

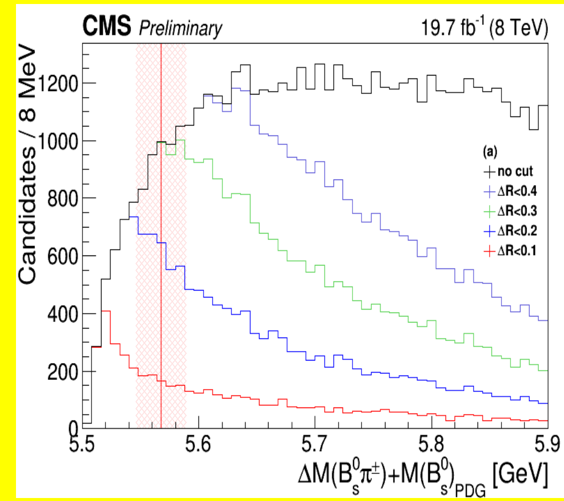
- Combine the B^0_s candidate with each π^+ from the collection of tracks building selected PV

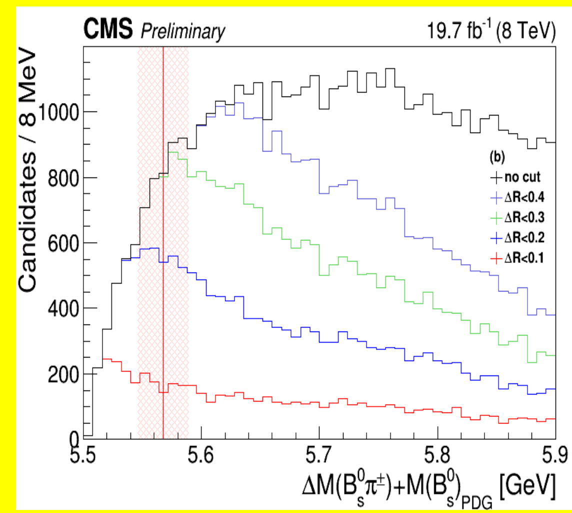


- No significant differences observed between the distributions obtained from B_s signal and B_s sidebands

With cone cuts

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





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

CMS-PAS-BPH-16-002

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

↓

Fits obtained by varying the p_T requirements of the $B^0{}_s\pi^{\pm}$, $B^0{}_s$ and $\pi^{\pm}$ candidates, and also 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, resulting in negligible signal.

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/ψ 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.

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 √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 $\boldsymbol{\sigma_{eff}}$ 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/ψs produced via SPS interaction should result in small values of Δy: large Δy values are possible for DPS production.

σ 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.