Workshop on heavy hadron spectroscopy, 17-18 July 2017, CERN

Spectroscopy highlights and prospects from CMS

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Outline

1. Introduction
2. Search for X(5568)+ $\rightarrow$ Bs π+
3. X(4140) $\rightarrow$ J/ψ ϕ
4. Observation of B+ $\rightarrow$ ψ(2S) ϕ K+
5. Study of X(3872) production properties
6. Search for the bottomonium partner of X(3872)
7. Observation of double Y(1S) production
8. Summary and Prospects

18 July 2017

Introduction

Heavy flavor spectroscopy still is developing field in HEP because of

(1) observation of multi-quark states in recent 14 years starting from X(3872) @Belle

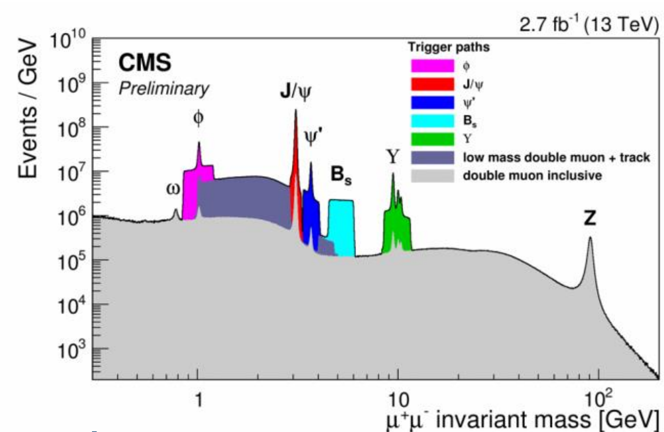
- it is interesting to understand and find more of these states -

(2) we need to explore higher excited states, e.g. B_{sJ} and B_c^{+**}

(3) study of hadrons consisting of two or three heavy quarks

congratulations to LHCb with the discovery of Ξ_{cc}^{++}

CMS is contributing in these topics



Tracker

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

Tracking efficiency >99% for muons

Good vertex reconstruction and impact parameter resolution down to $\approx 15\mu m$

Muon System

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

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

High-purity muon-ID $\varepsilon(\mu|\pi,K,p) \leq (0.1\text{-}0.2)\%$

Trigger

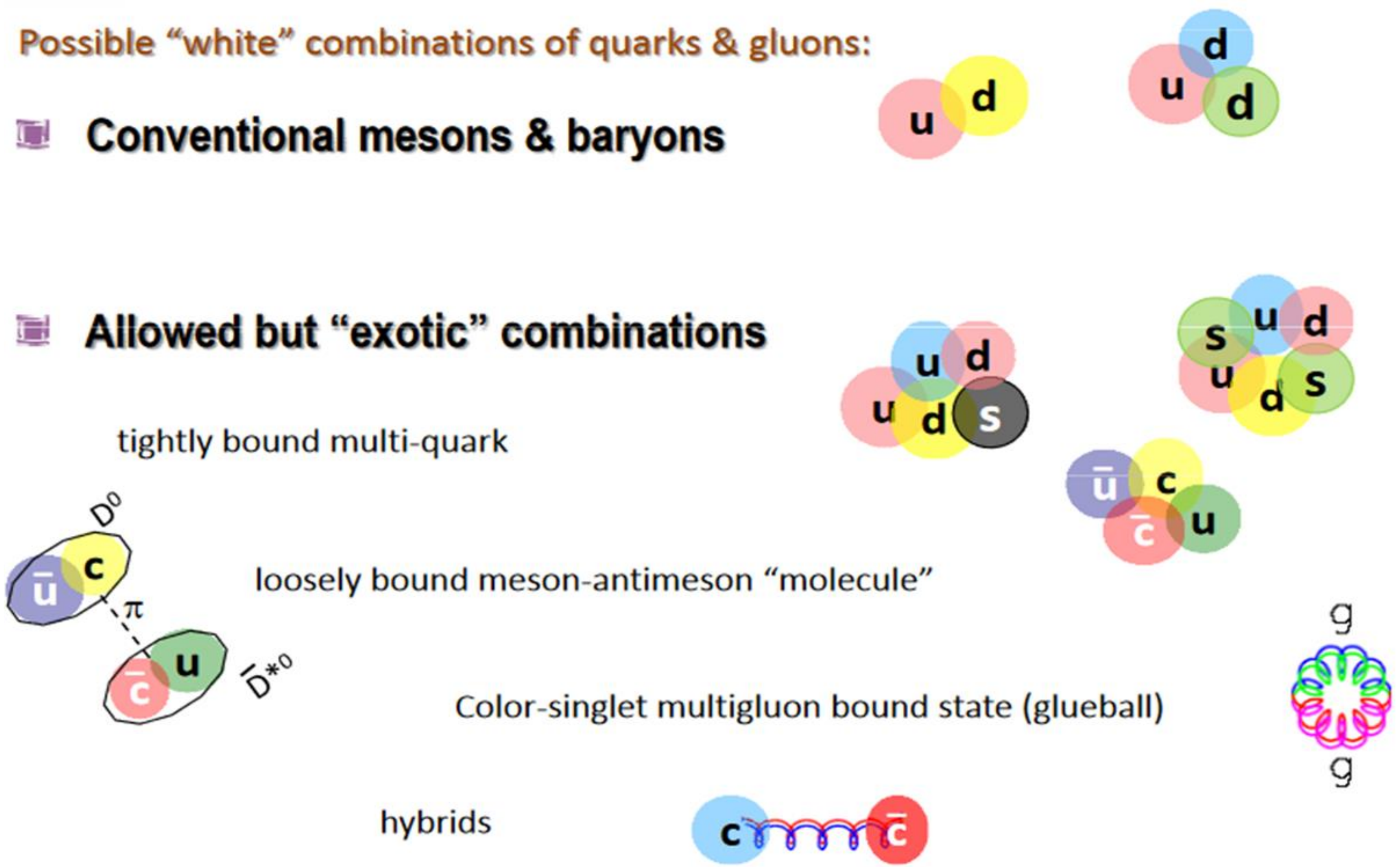
Very efficient hardware trigger

Highly flexible HLT: paths dedicated to specific analyses

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

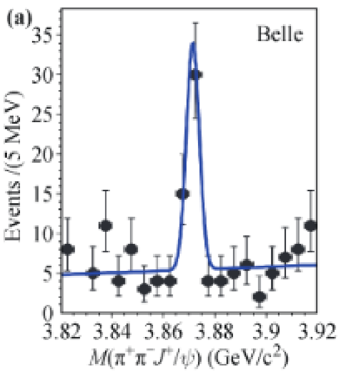
Hadrons: Conventional and Exotic

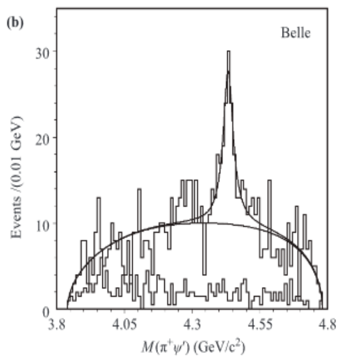
Are there any quark configurations other than mesons and baryons?
In theory such configurations are possible.
Which of them are realized in reality, in nature?

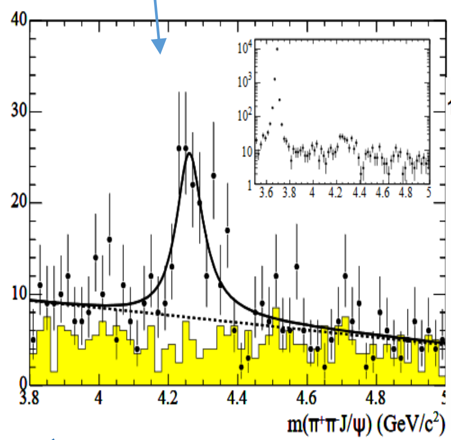


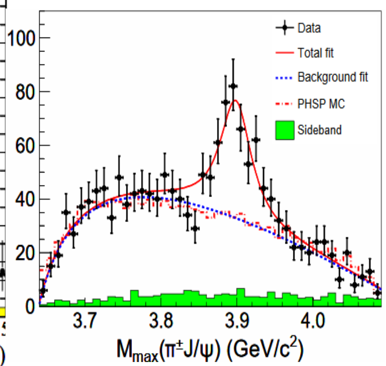
Exotic Hadrons: experimental results and theoretical interpretation

From 2003, thanks to B-factories Belle and BaBar (and then BES III and LHCb), the number of the candidates to exotic hadrons is growing continuously.
These are multiquark states. Some bright examples are
X(3872), Z(4430)+, from Belle, X(4260) from BaBar, Z(3900)+ from BESIII /Belle

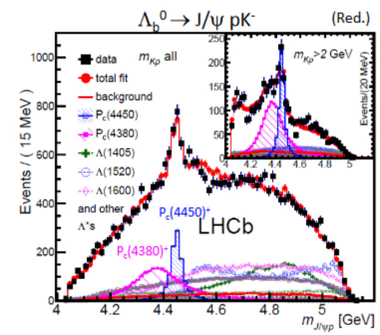








and P_c from LHCb.



This is a New Hadron Spectroscopy Era

Theoretical interpretation of all these exotic states still not clear.

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

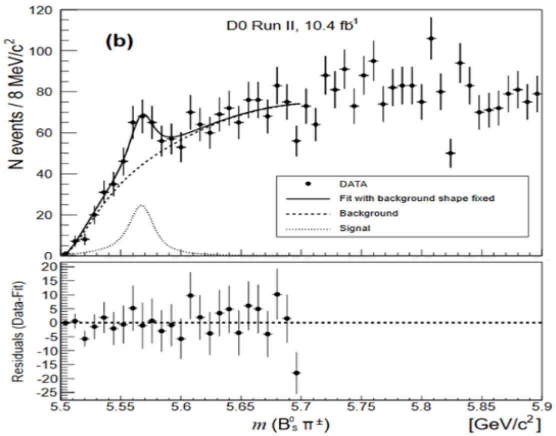
→ **We need more information !**

New results are coming. One of them is the evidence for X(5568) → Bs π^+ by D0 Collaboration.

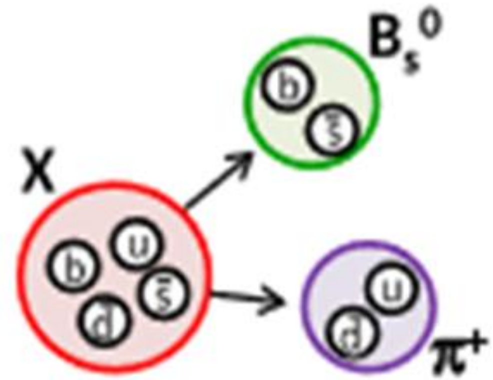
D0 Collaboration: Evidence for X(5568), new state decaying into Bs π+

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

PRL117. 022003(2016)



If confirmed, would be unique with 4 different flavours

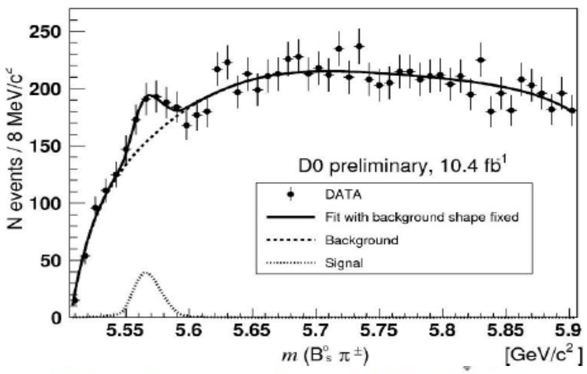


$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV},$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \mathrm{MeV},$$

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

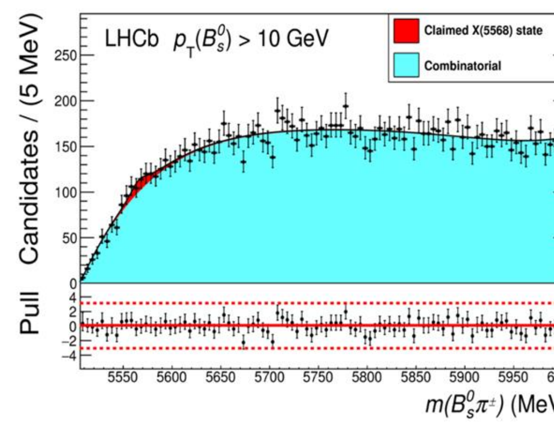
Rather big number for the prompt production of 4-quark exotic state

D0 Conf. Note 6896



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

PRL117. 152003(2016)



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

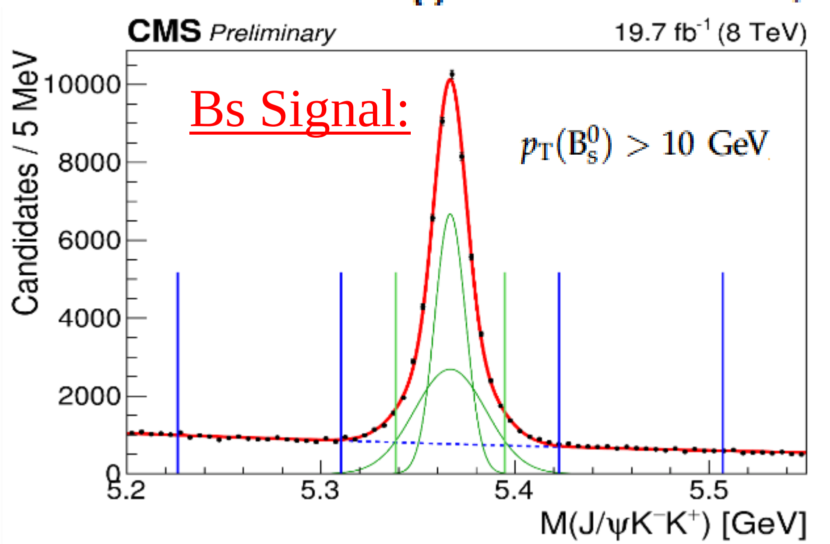
<u>Search for X(5568)+ in CMS is actual:</u>

- Different η interval with LHCb,
- Beauty hadron production conditions are similar in D0 and CMS.

Search for X(5568) in CMS

CMS-PAS-BPH-16-002

51398 ± 283 signal candidates,

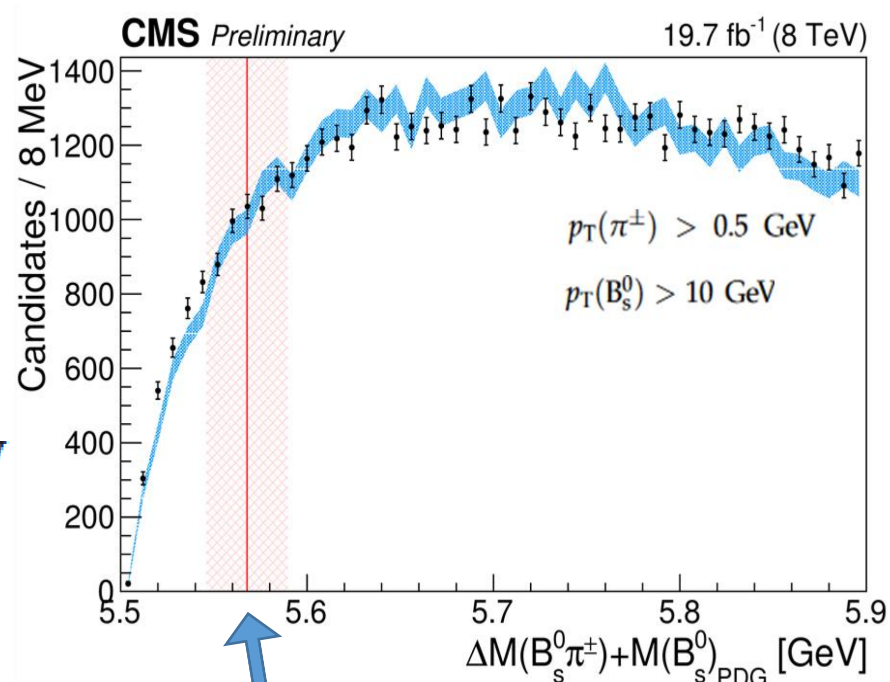


$$\sigma_{eff} = \left[(1-f)\sigma_1^2 + f\sigma_2^2\right]^{1/2} \simeq 14 \text{ MeV}$$

$$|M(J/\psi K^+K^-) - m^{fit}_{B^0_s}| < 2\sigma_{eff}$$

48204 B^0_s signal events (93.8%)

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



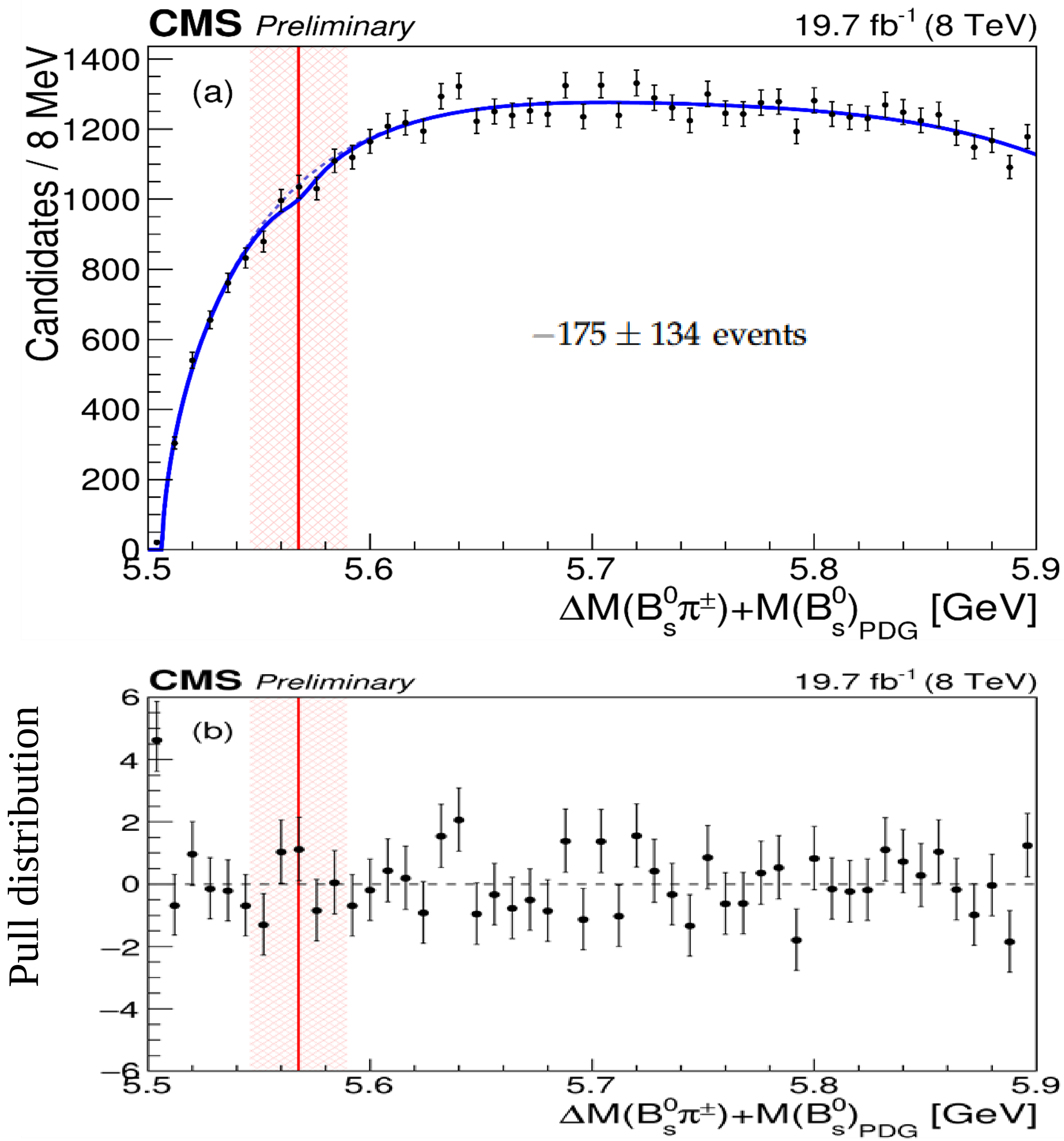
No hints for the X(5568) signal

Comparison of Bs statistics

Factor **1.16** larger than LHCb reconstructed in the same momentum interval and **9.13** larger than D0 sample.

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 D0 values

Background = $(x - \tilde{x}_0)^{\alpha} \times \mathrm{Pol}n(x)$

No hints for X(5568) signal

Search for X(5568) in CMS

CMS-PAS-BPH-16-002

Varying selection criteria,
Background parameterization,
Fit range and method of data description

In every case the obtained yield of $X(5568)$ is consistent with zero.

The most conservative upper limit obtained within these variations is 198 at 95% CL.

Preliminary Result: Upper Limit on the ration of production cross-sections

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

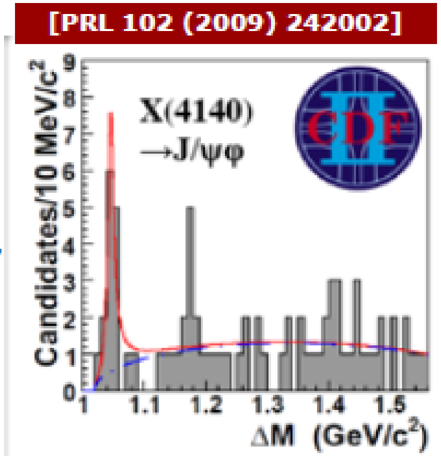
< 3.9% @95% CL

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]. (rel.eff.~10%)

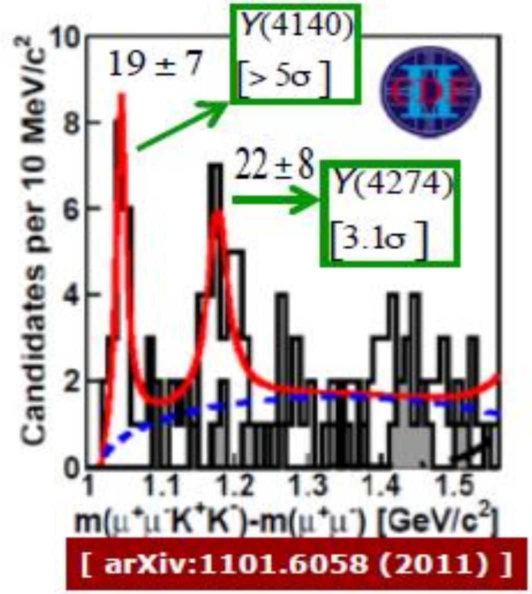
The final result on the UL of ρ_X from 8 TeV data sample will be released soon

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

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

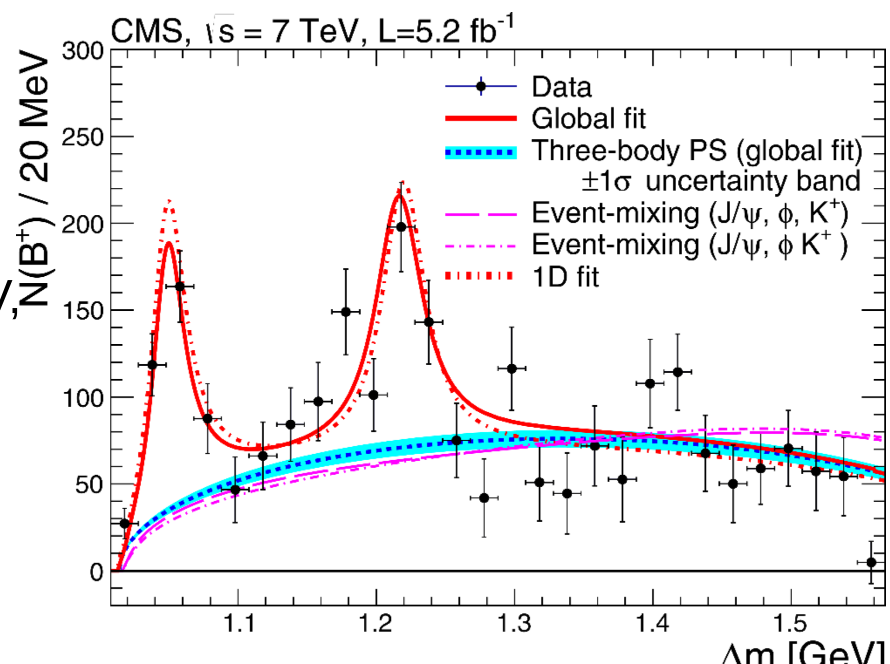


CDF (2011) presents update analysis with larger dataset,(6.0fb^{-1} vs 2.7fb^{-1})observing



- Peaking structure at the threshold and another peak in the Δm from B+ → $J/\psi\ \phi$ 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)



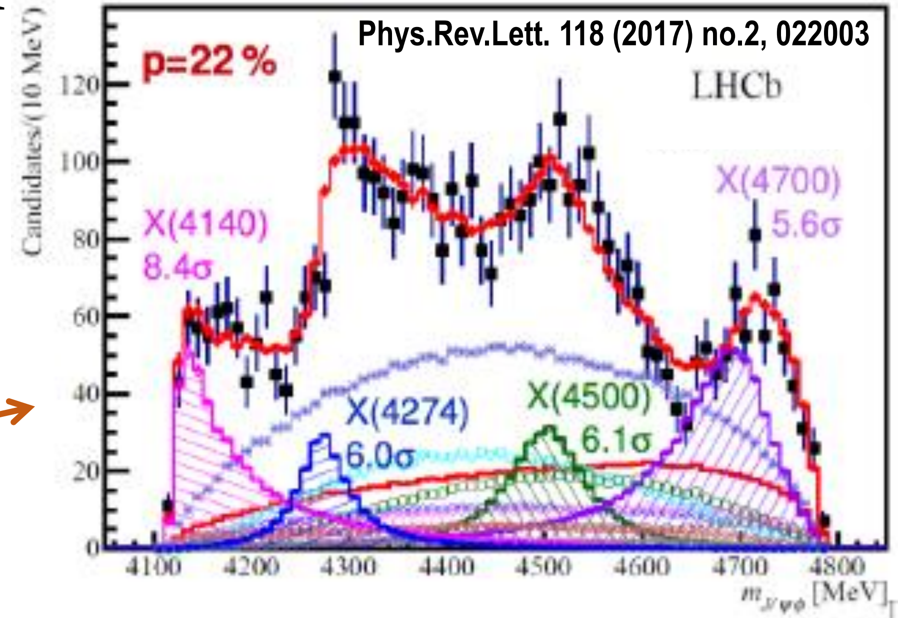
PLB 734 (2014) 261

Belle and BaBar searched for and didn't find that signal in the same B+ decay.

Study of the J/ψ ϕ system

LHCb has looked at these places:

- No signals were observed (2012) in a 346+-20 B+ sample;
- The measured UL implied a 2.4sigma tension with CDF;
- 4 resonance-like structures recently were established in the 6D AA analysis with a 4289+-151 B+ sample



Comparison of resonance parameters:

X(4140)	Yield	Mass, MeV	Width, MeV
CMS	310 ± 70	4148.0 ± 2.4 ± 6.3	38+30-15 ± 16
LHCb		4146.5±4.5+4.6-2.8	83±21+21-14

X(4274)	Yields	Mass, MeV	Width, MeV
CMS	418 ± 170	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: Ds+*Ds-* molecule, cscs tetraquark, threshold kinematic effect, hybrid charmonium, weak transition with Ds+Ds- rescattering.

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

It's interesting to perform the same search at LHC

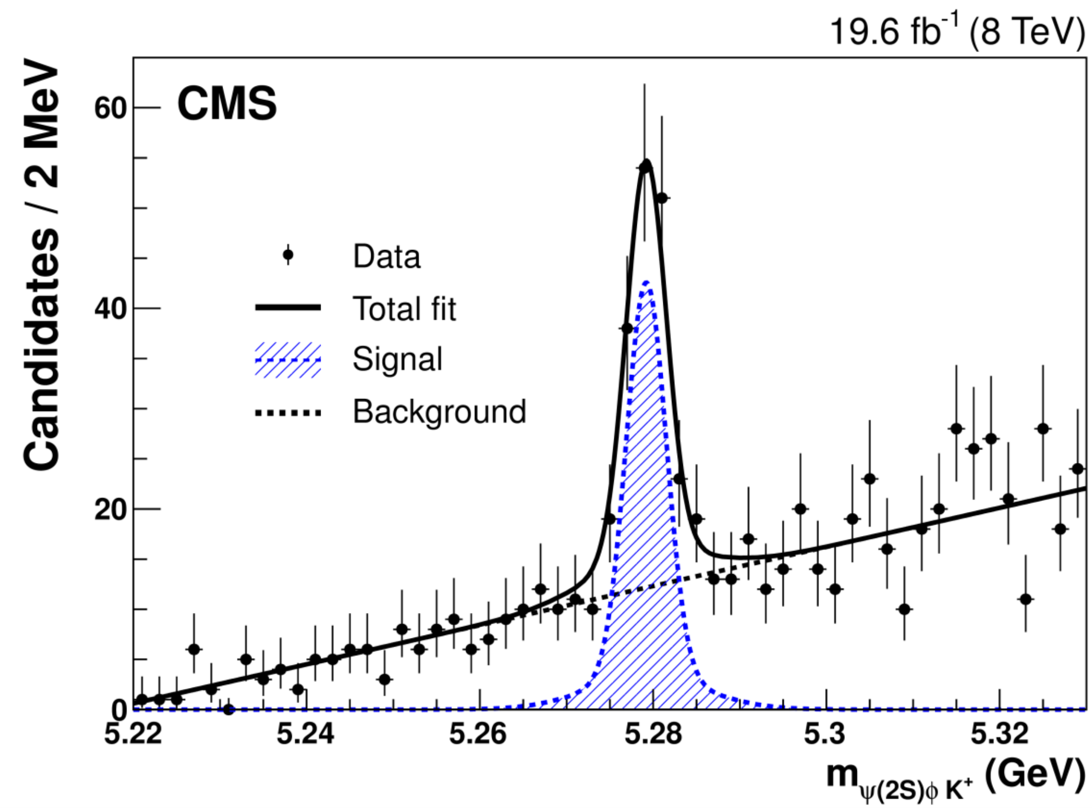
Observation of $B^+ \rightarrow \psi(2S)\, \phi\, K^+$ at CMS

[Phys. Lett. B 764 (2017) 66](https://doi.org/10.1016/j.physletb.2016.11.001)

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

The relative branching fraction, using the mode $B^+ \rightarrow \psi(2S)\, K^+$ as normalization:

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



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

Study of X(3872) at CMS

JHEP 1304(2013)154

CMS inclusively reconstructed $X(3872)\to J/\psi\pi^+\pi^-$
[of about 12k events with 4.8 fb-1 @7TeV]
and measured:

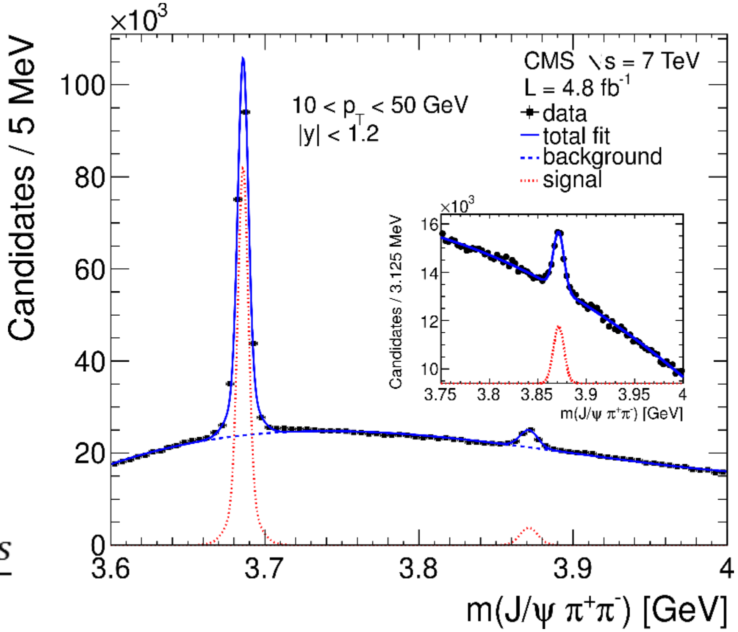
- cross-section ratio

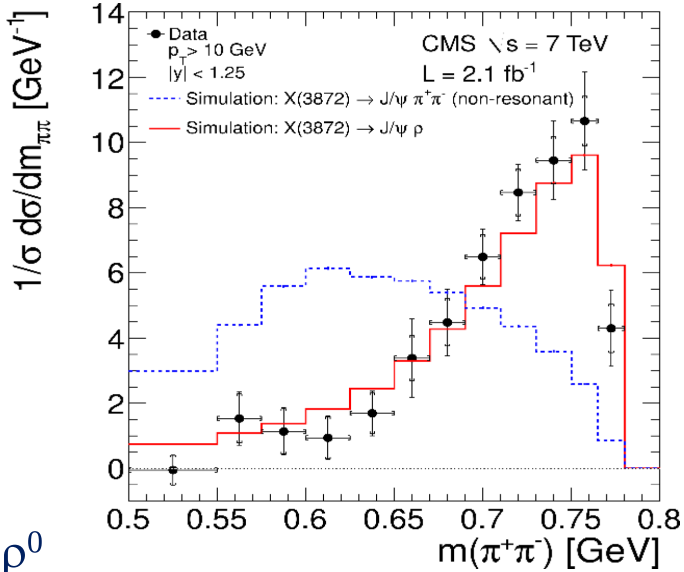
$$R \equiv \frac{\sigma\left(pp \to X(3872) + \text{anything}\right)\cdot B\left(X(3872)\to J/\psi\,\pi^+\pi^-\right)}{\sigma\left(pp \to \psi(2S) + \text{anything}\right)\cdot B\left(\psi(2S)\to J/\psi\,\pi^+\pi^-\right)}$$

- non-prompt fraction $= \dfrac{number\ of\ X(3872)\ from\ b\text{−}hadrons}{total\ inclusive\ number\ of\ X(3872)}$

- prompt cross-section of X(3872)

- invariant mass distribution of the $\pi^+\pi^-$ system →



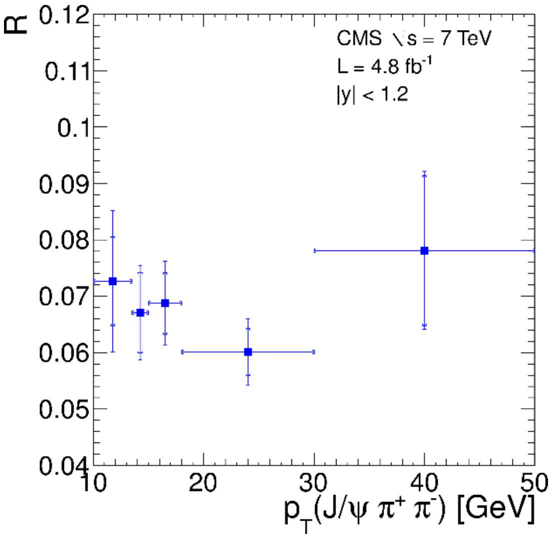


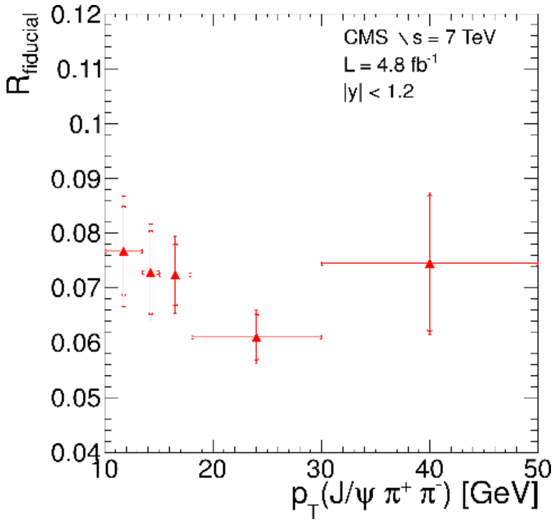
Previous studies of $m(\pi^+\pi^-)$ at Belle and CDF favor to two-body decay $X(3872) \to J/\psi\ \rho^0$.

CMS confirms that conclusion: the spectrum obtained from data is compared to simulations with and w/o an intermediate ρ^0 in the $X(3872)\to J/\psi\pi^+\pi^-$ decay. The ρ^0 hypothesis gives better agreement with data.

Study of X(3872) production properties at CMS

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





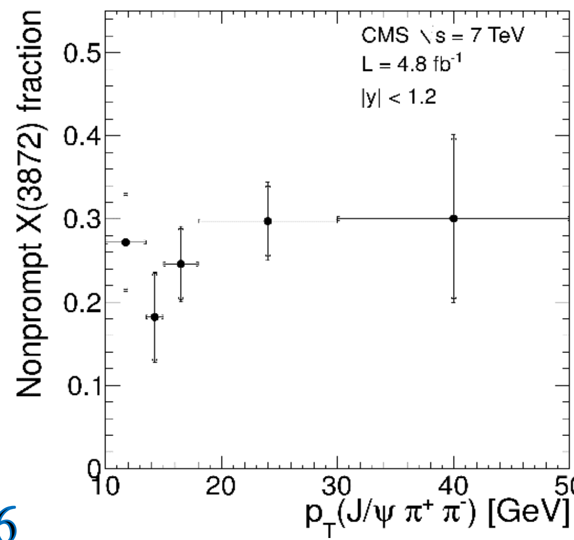
Acceptance corrections depend on assumptions on the angular distribution of the final states. So, w/o acc. corr. one can derive R in a fiducial region.

NO SIGNIFICANT dependence on the pt

Integrated over 10<pt<50 GeV:
$R = 0.0656 \pm 0.0029 \pm 0.0065$

Integrated over 10<pt<50 GeV:
$R_{fiducial} = 0.0694 \pm 0.0029 \pm 0.036$

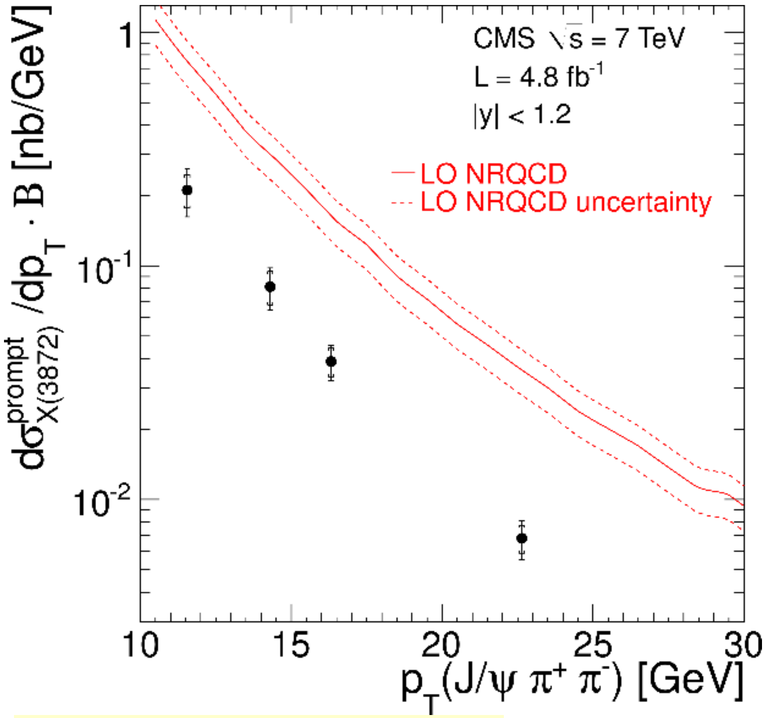
- Non-prompt fraction also shows no dependence on pt
- But measurement is dominated by statistics
- For 10<pt<50 GeV, |y|<1.2:



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

Study of X(3872) production properties at CMS

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



- Main syst. uncertainties are related to the measurement of R and prompt ψ(2S) cross-section.
- X(3872) and ψ(2S) are assumed to be unpolarized
- The results are compared with a theoretical prediction based on NRQCD factorization approach by Artoisenet and Braaten [PRD.81.114018] with calculations normalized using Tevatron results, modified by the authors to match the phase-space of the CMS measurement.

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.

The shape is reasonably well described by the theory while the predicted cross-section is overestimated by over 3σ.

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

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

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

$$\sigma^{\text{prompt}}(pp \to X(3872) + \text{anything}) \cdot \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = 1.06 \pm 0.11\,(\text{stat.}) \pm 0.15\,(\text{syst.})\ \text{nb} \quad (14)$$

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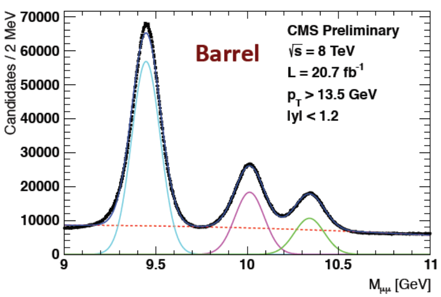
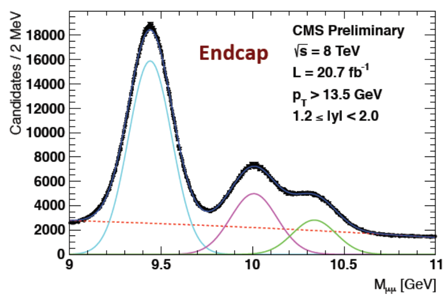
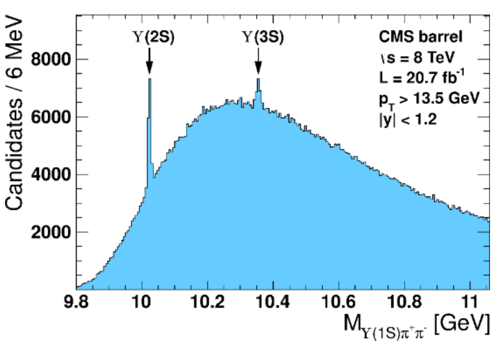
Search for exotic bottomonium states X_b decaying into Υ(1S) $\pi^+\pi^-$

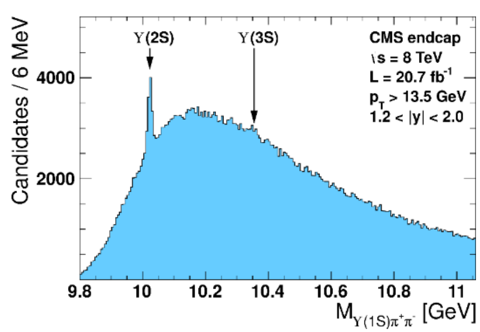
- The discovery of the X(3872) has prompted the search for a bottomonium counterpart X_b decaying into Υ(1S) $\pi^+\pi^-$ - according to HQS considerations - with mass close to the BB or BB* threshold, 10.562 and 10.604 GeV.
- It is expected that this X_b would be narrow, similar to X(3872), and has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





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





p_T(Υ(1S)$\pi^+\pi^-$) > 13.5 GeV and |y(Υ(1S)$\pi^+\pi^-$)| < 2.0

No structure found apart from Υ(2S) and Υ(3S)

Mass scan for $X_b \rightarrow Y(1S)\,\pi^+\pi^-$

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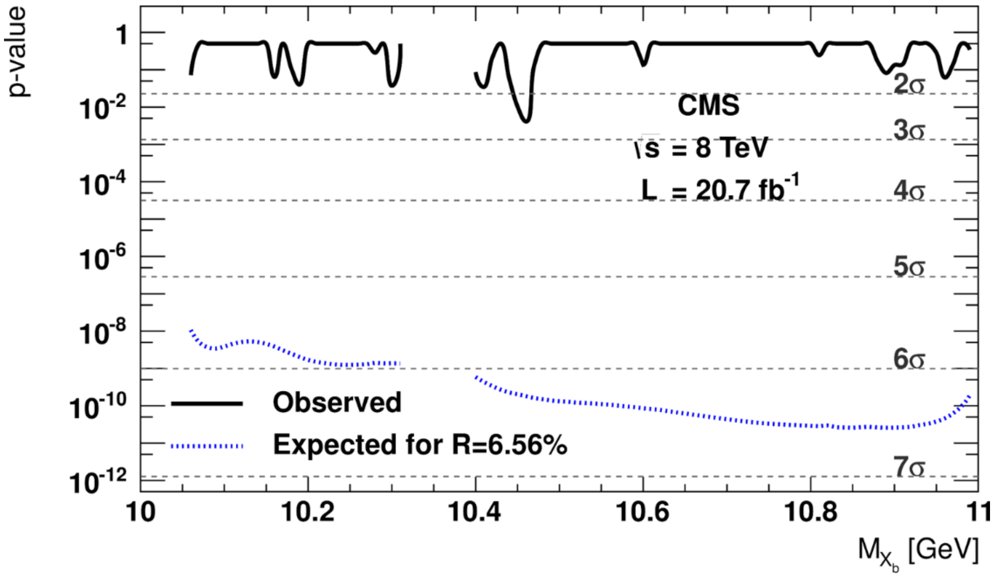
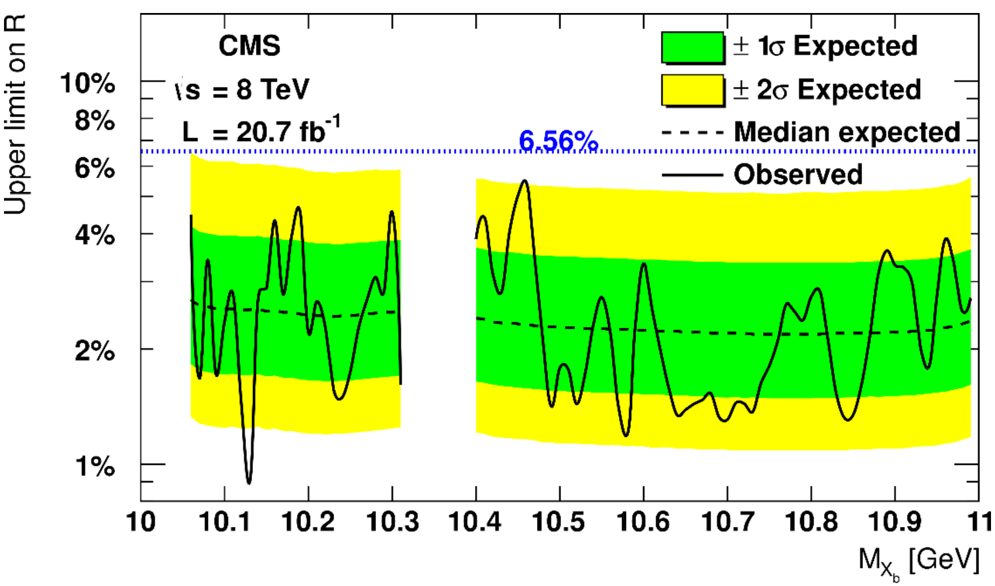




In analogy with the X(3872), expected signal significance > 5 σ if X_b(Br x cross-section)>6.5% of the corresponding product for $Y(2S) \rightarrow Y(1S)\,\pi^+\pi^-$ (R value)

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

No significant excess is observed.
95% CL UL on the
R varies from 0.9% to 5.4%.

Prospects for the further X_b searches

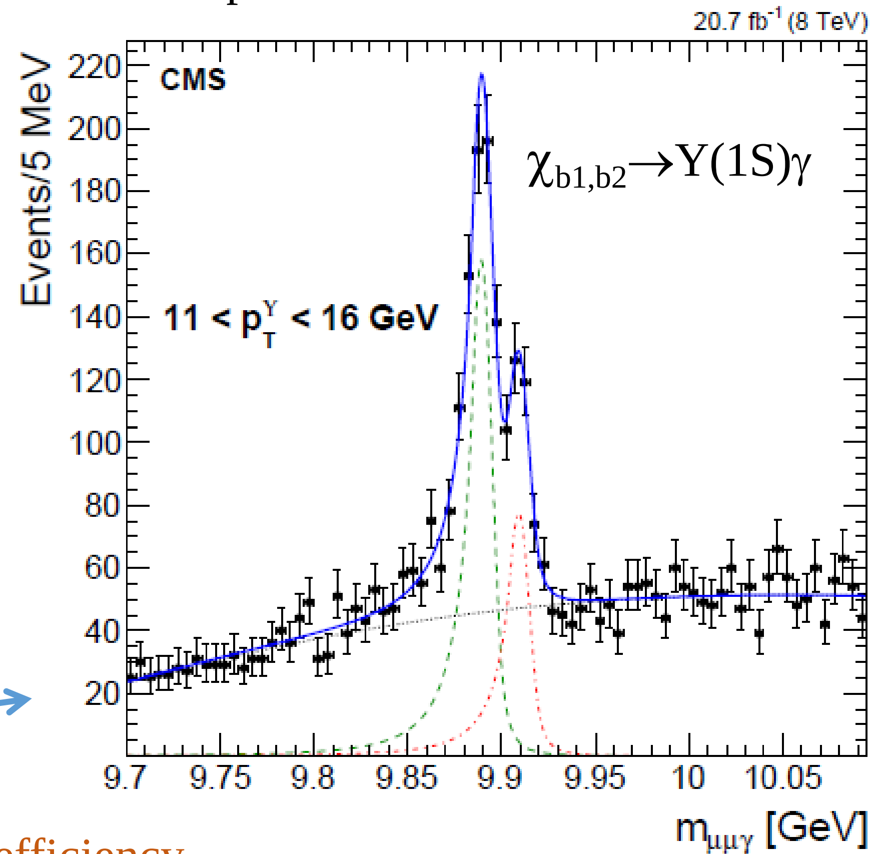
- According to Karliner&Rosner [PRD91 (2015) 014014],

this search decay ($\Upsilon(1S)\,\pi^+\pi^-$) should be forbidden by G-parity conservation.
While for the X(3872) the isospin-conserving decay to $J/\psi\omega$ was kinematically suppressed, the same is not true for a bottomonium-like $J^{PC}=1^{++}$ counterpart.

- The strategy for X_b observation should include search for

$$X_b \to \Upsilon(1S)\,\omega(\to \pi^+\pi^-\pi^0)$$
$$X_b \to \Upsilon(3S)\gamma$$
$$X_b \to \chi_{b1}(1P)\pi^+\pi^-$$

- Tasks for CMS for Run2.
  The possibility to work with converted γ's was excellently demonstrated with the reconstruction of $\chi_{b1,b2}\to\Upsilon(1S)\gamma$.
  But it is not easy task due to soft photons: low conversion and, therefore, reconstruction efficiency.



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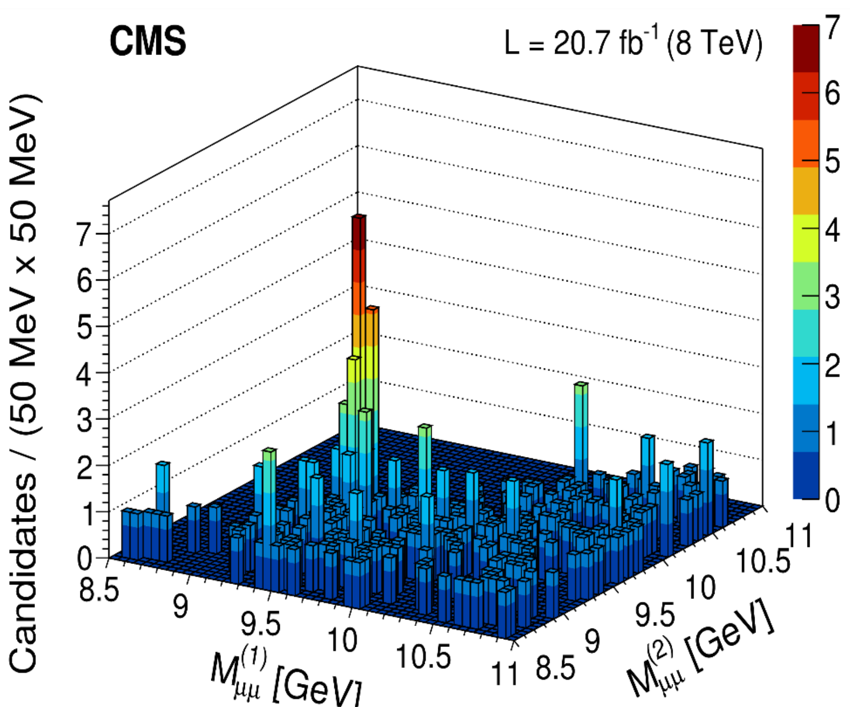
Also, Karliner&Rosner suggest that the X_b may be close in mass to the $\chi_{b1}(3P)$, mixing with it and sharing its decay.

JHEP 05(2017)13

The First Observation of Υ(1S)Υ(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]



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

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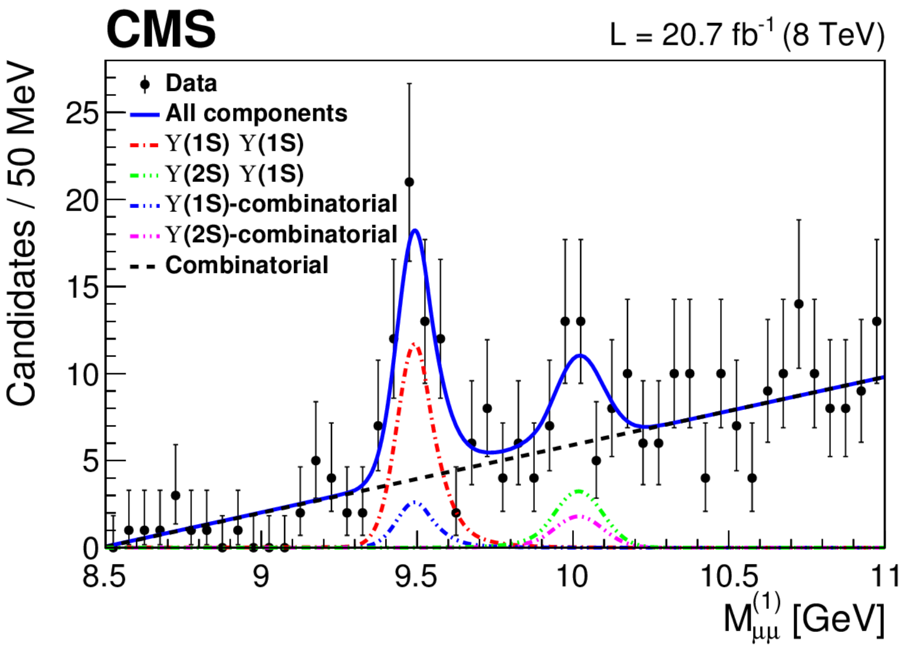
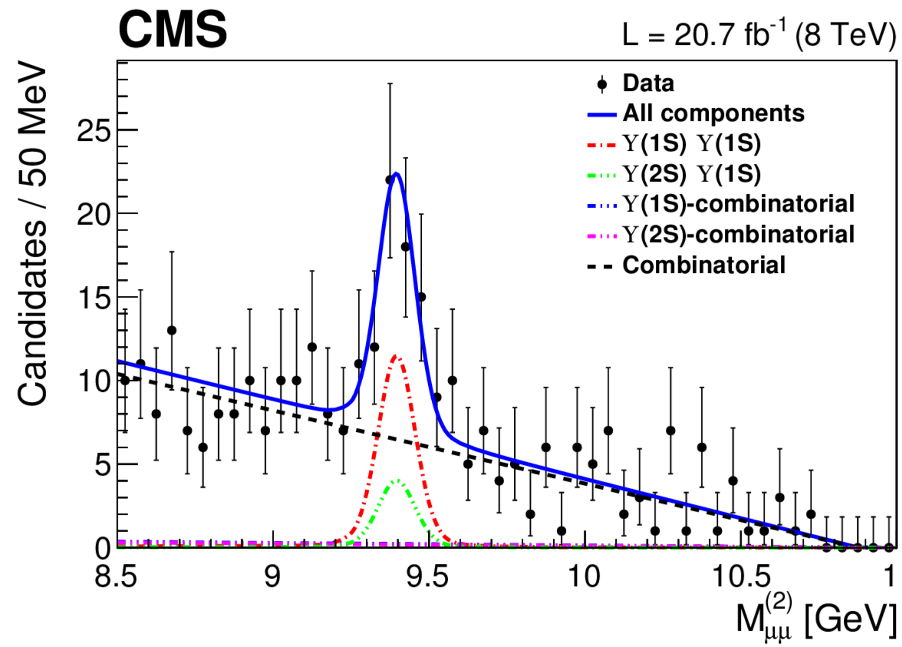
The First Observation of Υ(1S)Υ(1S) pair production





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

assuming that both mesons decay isotropically

$$\boldsymbol{\sigma(\Upsilon(1S)\Upsilon(1S)) = 68.8 \pm 12.7(\text{stat}) \pm 7.4(\text{syst}) \pm 2.8(\mathcal{B})}$$

in pp collisions at $\sqrt{s}$=8 TeV, for $|y(\Upsilon)| < 2.0$

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

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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] $\to \sigma_{\rm eff} \approx 6.6$ mb

In agreement with the values from heavy quarkonium measurements (2-8 mb), but is smaller than that from multijet 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., PRD87(2013)034035

[2] A.V.Berezhnoy, A.K.Likhoded and A.A.Novoselov, PRD87(2013)054023

LHCb (JHEP 06(2012)141) and CMS (JHEP 09(2014)094) have measured total&diff. cross-sections for prompt double J/ψ production in complementary regions of pt and y.

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

Summary and Prospects

Although designed for high-pt physics, CMS is a very good apparatus for heavy flavor physics!

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

New results from CMS are foreseen soon, one of them is the final Upper Limit on the production of X(5568) observed by the D0.

Backup slides

Search for X(5568) in CMS

CMS-PAS-BPH-16-002

Analysis Strategy:

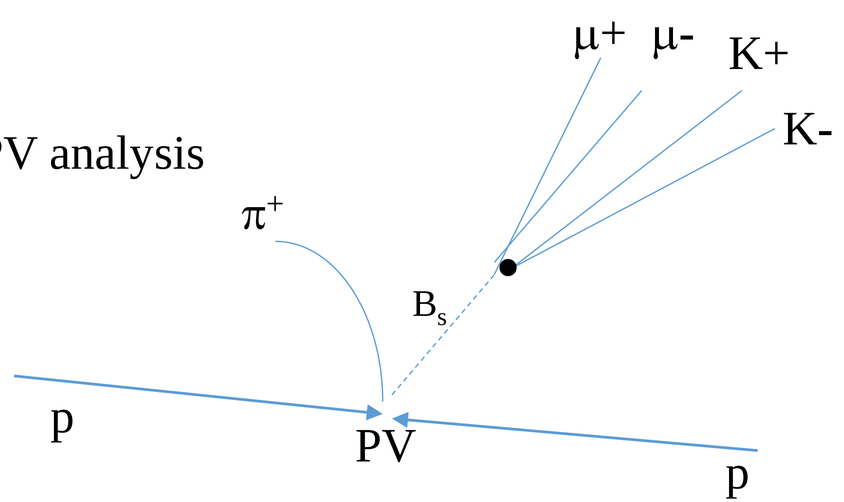
$$B_s^0 \to J/\psi\phi \; (J/\psi \to \mu^+\mu^-, \phi \to K^+K^-)$$

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

1) Reconstruct Bs by combining J/psi and phi and then fit 4t racks into the common vertex
→know Bs momentum and its decay vertex.
(This procedure follows closely that from Bs CPV analysis *Phys. Lett.* B757 (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 Bs decay vertex and the Bs momentum.

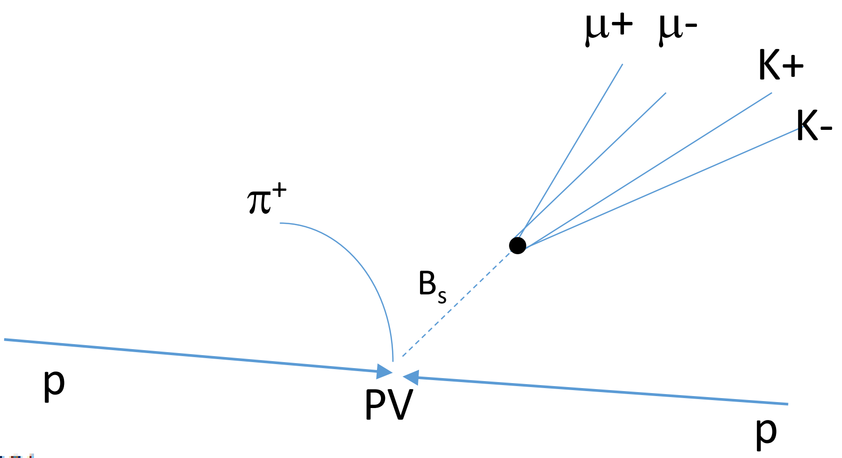
3) Add charged pion from that PV and form Bs pi+ pair



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. $p_T(B^0_s) > 10$ GeV

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

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