XYZ Workshop, 12-15 April 2021

# CMS results and prospects on XYZ states

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## Outline

1. Introduction
2. Search for X(5568)+ $\rightarrow$ Bs $\pi$+
3. Search for exotic bottomonium states decaying into $\Upsilon$(1S) $\pi$+$\pi$-
4. Search for resonances decaying to $\Upsilon$(1S) $\mu$+$\mu$-
5. Study of B+ $\rightarrow$ J/$\psi$ $\Lambda$ p
6. Confirmation of X(4140) $\rightarrow$ J/$\psi$ $\phi$ and observation of B+ $\rightarrow$ $\psi$(2S) $\phi$ K+ and $\Lambda_b \rightarrow$ J/$\psi$ $\Lambda$ $\phi$
7. Observation of Bs$\rightarrow$X(3872) $\phi$
8. Evidence for X(3872) in PbPb
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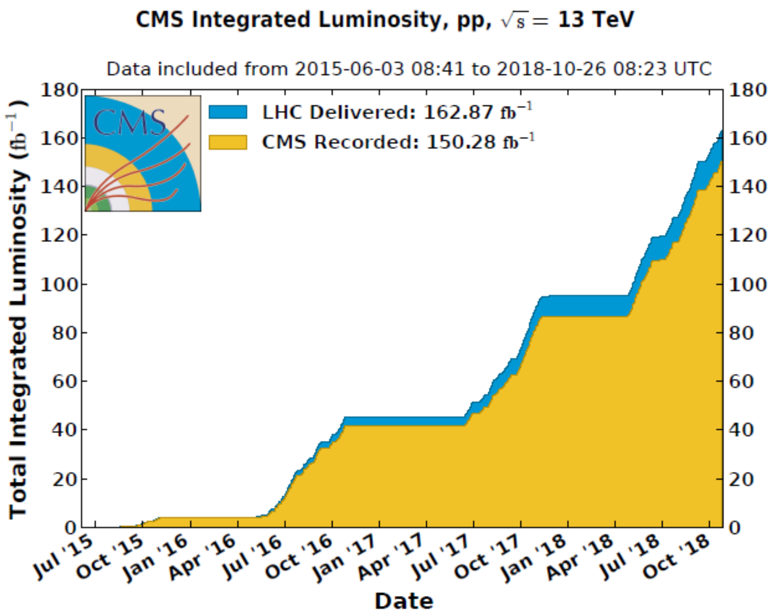
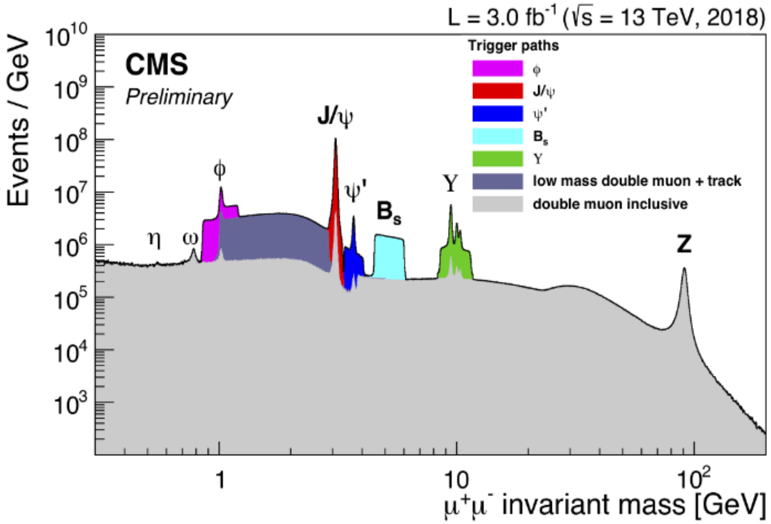
# Introduction



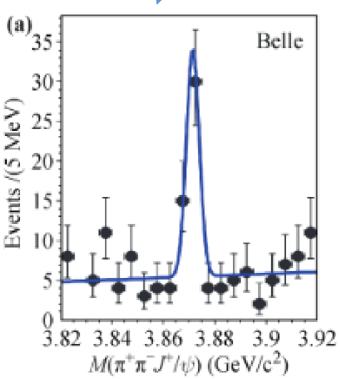

- 160 $fb^{-1}$ has been delivered by the LHC in Run 2 (2015-2018) at $\sqrt{s}$=13 TeV.
- Very efficient data collection by CMS with improved track momentum resolution → recorded over 140 $fb^{-1}$ of physics-quality data.
- Ingenious trigger algorithms were developed for efficient online event selection.

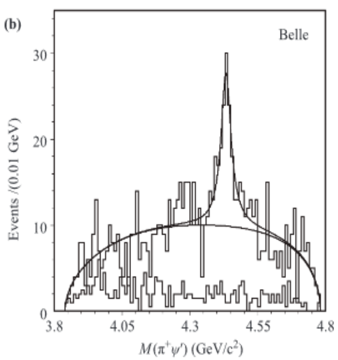
CMS is contributing intensively to heavy flavor physics

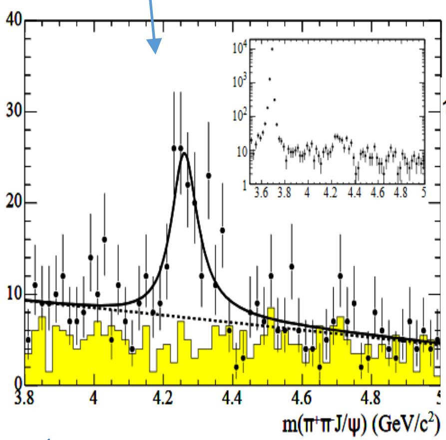
In this talk the results on a search for new multiquark states based on 13 and 8 TeV data samples will be presented

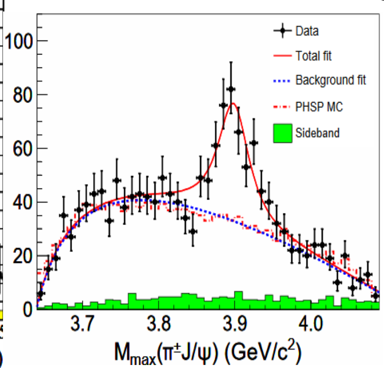
# Exotic Hadrons: experimental results and theoretical interpretation

From 2003, thanks to B-factories Belle and BaBar (and then BES III and LHCb), the number of exotic hadrons candidates 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

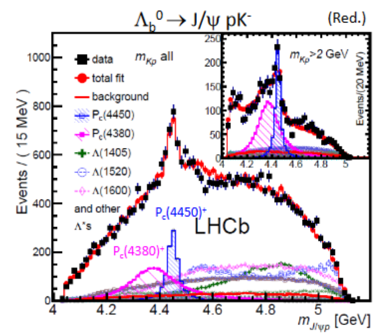



and $P_c$ from LHCb.




**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 !**

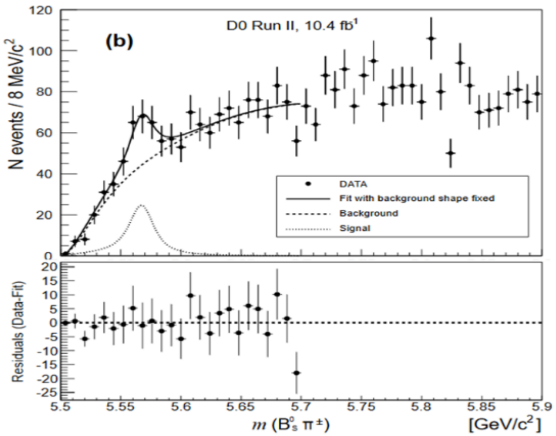
New results are coming. First of them to discuss is the evidence for X(5568) → Bs $\pi^+$ by D0 Collaboration and search for this state in CMS.

# Search for beauty tetraquarks

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

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

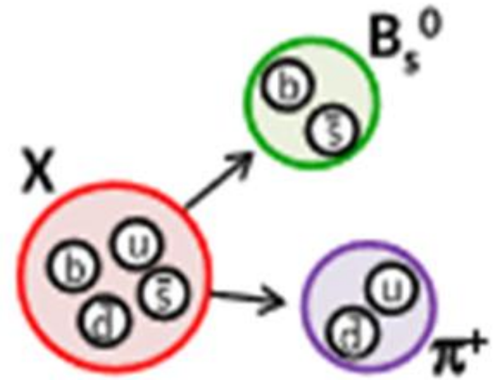
PRL117. 022003(2016)



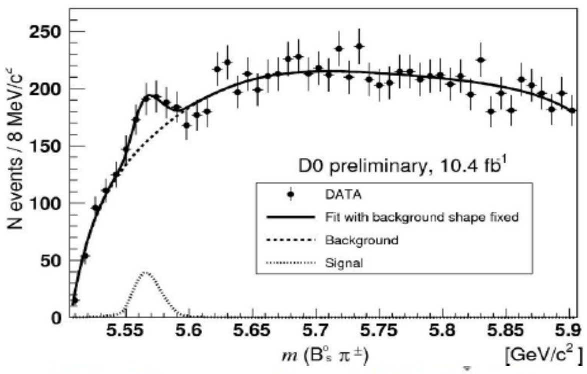

$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \text{MeV},$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \text{MeV},$$

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

If confirmed, would be unique with 4 different flavours

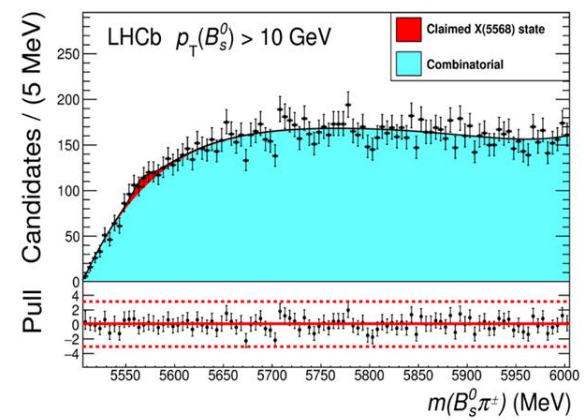



D0 Conf. Note 6896




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

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




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 is actual:

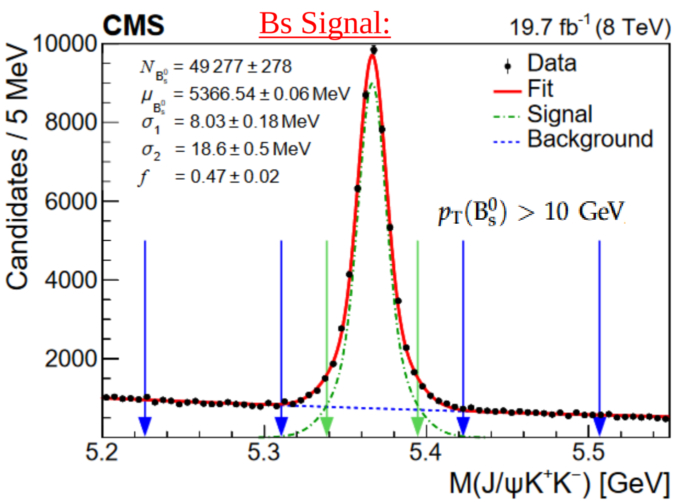
- Different η interval with LHCb,
- Beauty hadron production conditions are similar in D0 and CMS.

# Search for X(5568) in CMS

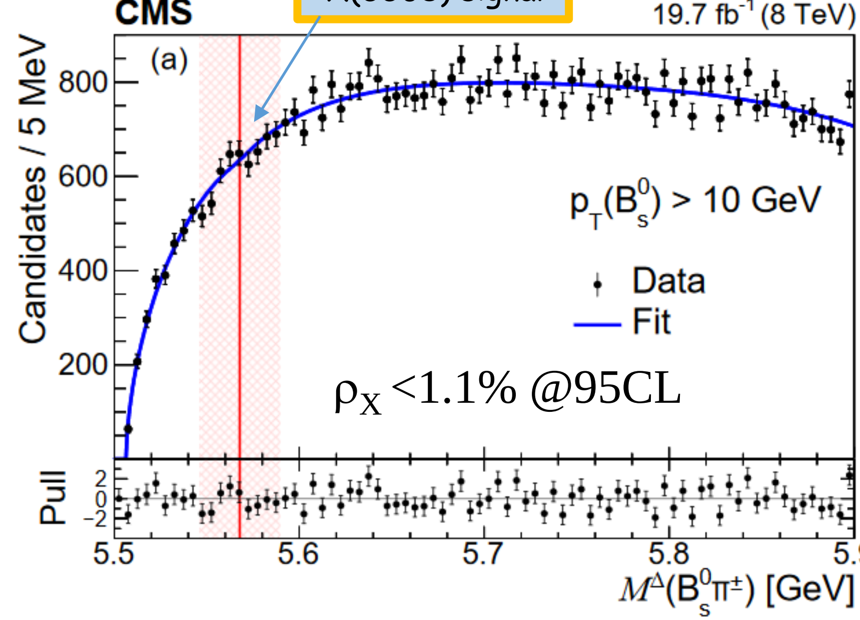
$$\rho_X^{D0} \equiv \frac{\sigma(p\bar{p} \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi)}{\sigma(p\bar{p} \to B_s^0 + \text{anything})} = (8.6 \pm 1.9 \pm 1.4)\%$$

CDF: A 95% C.L. upper limit of 6.7%

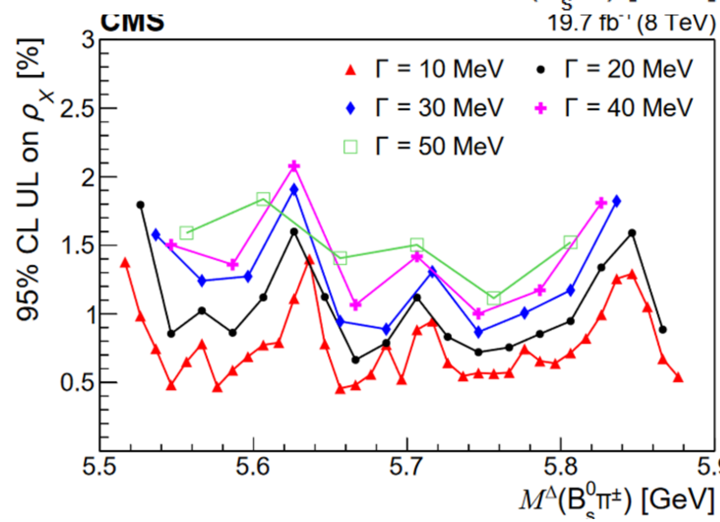
Phys.Rev.Lett. 120 (2018) no.20, 202006




No hints for X(5568) signal




PRL 120 (2018) 202005




By varying selection criteria, background parameterization, fit range and method of data description, the yield for X(5568) remains consistent with 0.

**No evidence for X(5568) at the LHC**

$\rho_X^{\text{ATLAS}} < 0.015$ at 95% CL for $p_T(B_s^0) > 10$ GeV

$\rho_X^{\text{ATLAS}} < 0.016$ at 95% CL for $p_T(B_s^0) > 15$ GeV

Phys.Rev.Lett. 120 (2018) no.20, 202007

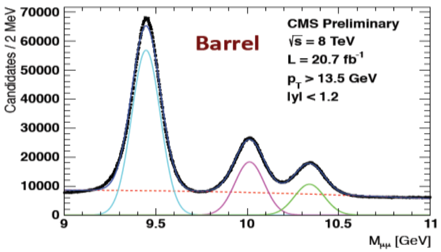
$\rho_X^{\text{CMS}} < 1.1\%$ at 95% CL for $p_T(B_s^0) > 10$ GeV

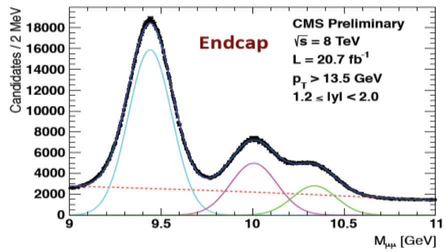
$\rho_X^{\text{CMS}} < 1.0\%$ at 95% CL for $p_T(B_s^0) > 15$ GeV

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

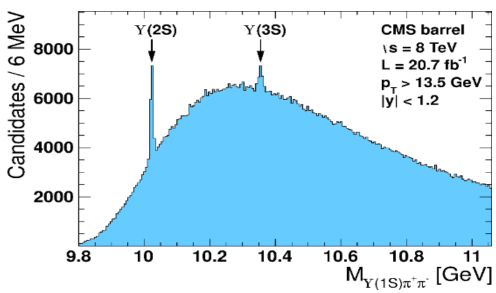
PLB 727 (2013) 57

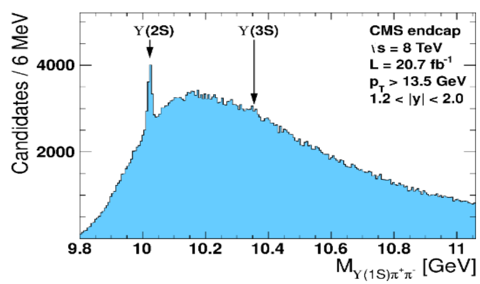
- The discovery of the X(3872) has prompted the search for a bottomonium counterpart $X_b \rightarrow \Upsilon(1S)\ \pi^+\pi^-$ - according to HQS considerations - with mass close to the BB or BB* threshold, 10.562 and 10.604 GeV.
- It is expected that this $X_b$ would be narrow, similar to X(3872),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



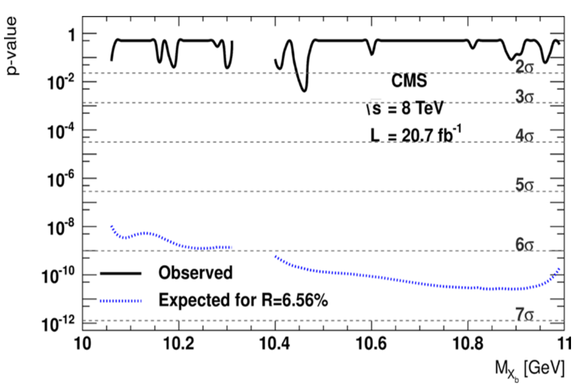

CMS has collected a large sample of $\Upsilon(nS)\rightarrow\mu^+\mu^-$ produced in pp collisions at 8TeV.
Separate barrel and endcap events to exploit better mass resolution and lower background in the barrel region.

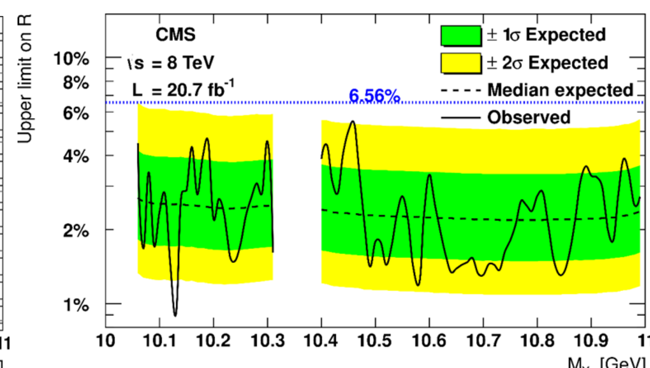



$p_T(\Upsilon(1S)\pi^+\pi^-) > 13.5$ GeV and $|y(\Upsilon(1S)\pi^+\pi^-)| < 2.0$

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



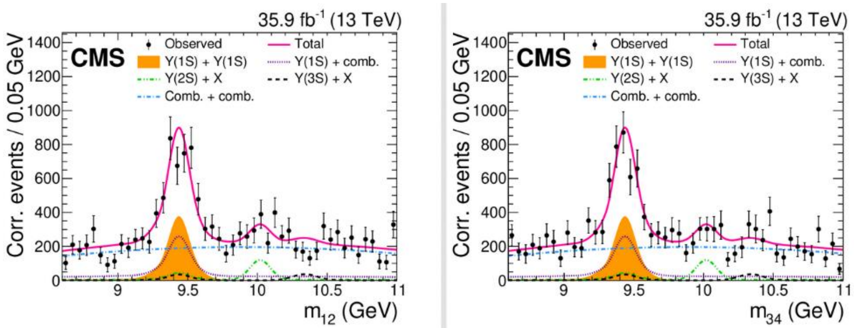




In analogy with the X(3872), expected signal significance > 5 σ if $X_b$(Br x cross-section)>6.5% of the corresponding product for $\Upsilon(2S) \rightarrow \Upsilon(1S)\ \pi^+\pi^-$ (R value)

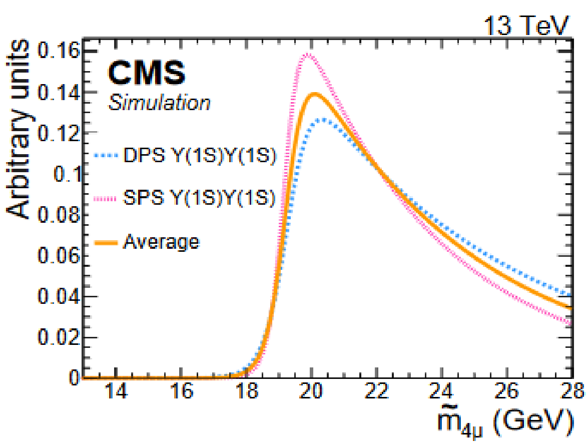
# Measurement of the Υ(1S) pair production cross section and search for resonances decaying to Υ(1S)μ+μ− in proton-proton collisions at s√= 13 TeV

PLB 808 (2020) 135578

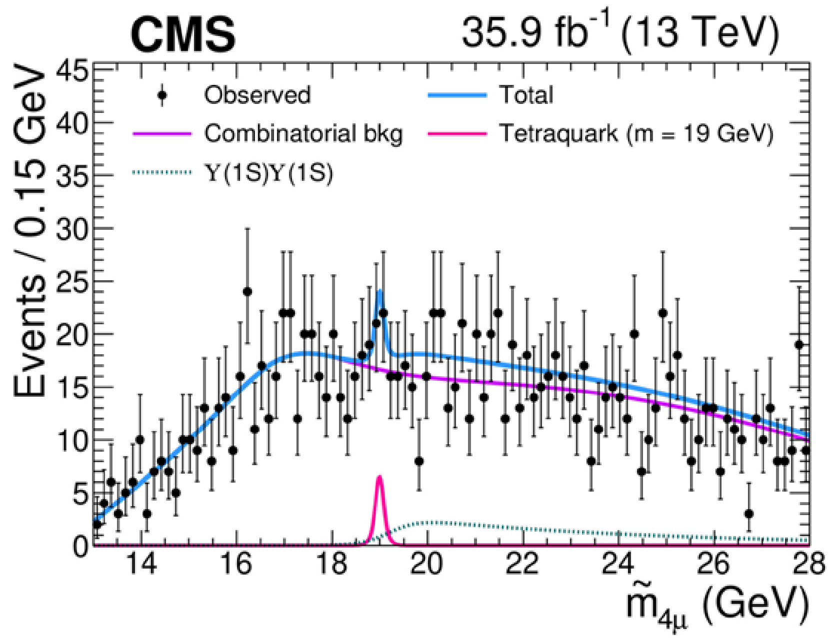
- Tetraquarks composed of 2 b quarks and 2 b anti-quarks could decay to a Υ(1S) + 2 leptons that possibly come from a Υ(1S) off-shell decay.
- Even with a small production cross section, it could result in a prominent signature at the LHC




The two projections and the results of the 2D fit to the muon pair invariant masses.



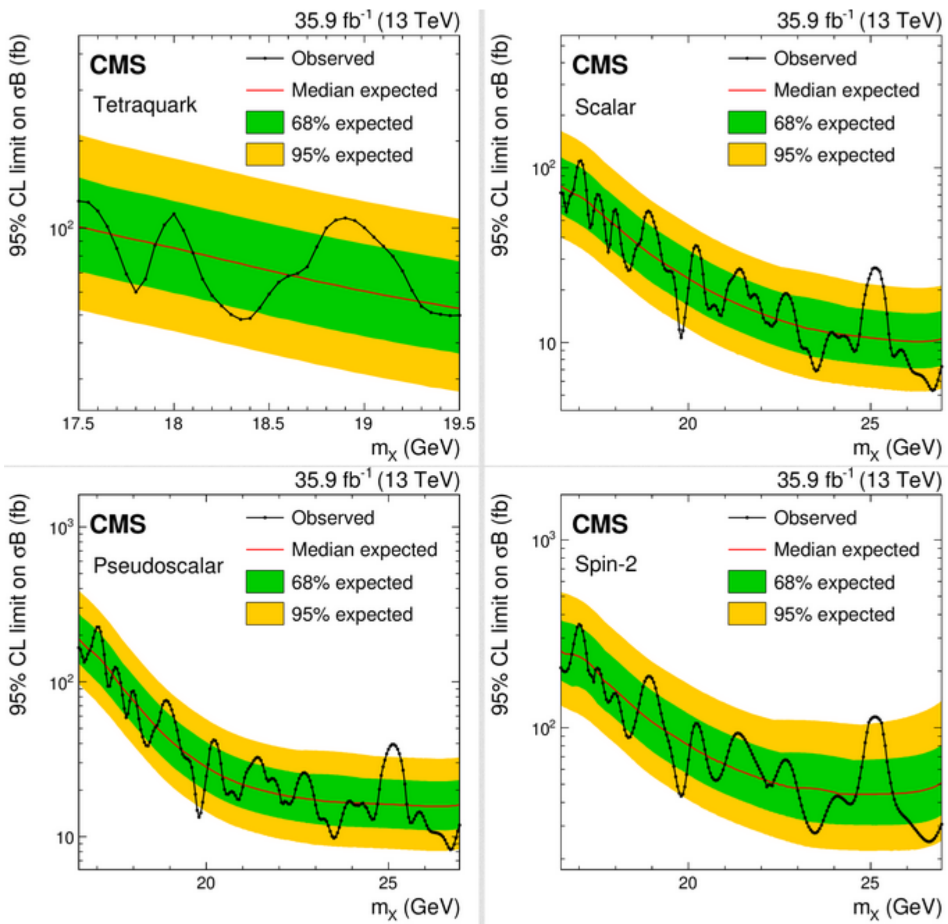

Distributions of $\tilde{m}_{4\mu}$ for simulated Υ(1S)Υ(1S) events.



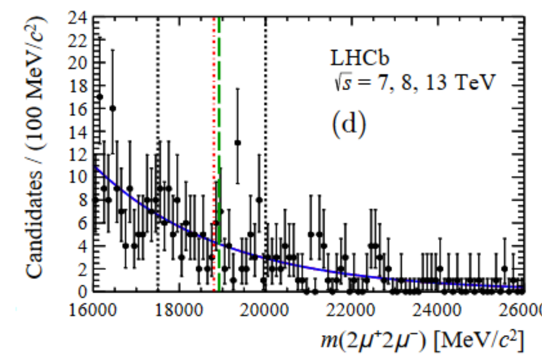
# Measurement of the Y(1S) pair production cross section and search for resonances decaying to Y(1S)μ+μ− in proton-proton collisions at s√= 13 TeV

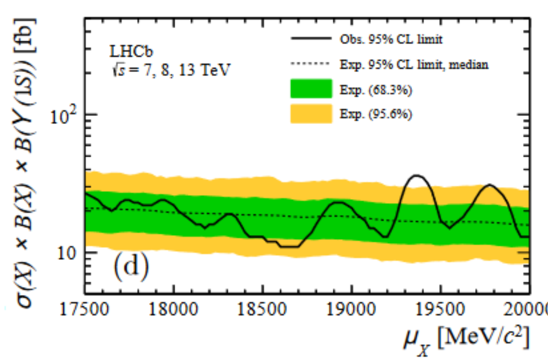
PLB 808 (2020) 135578

UL's at 95% CL on the σxBr




LHCb results



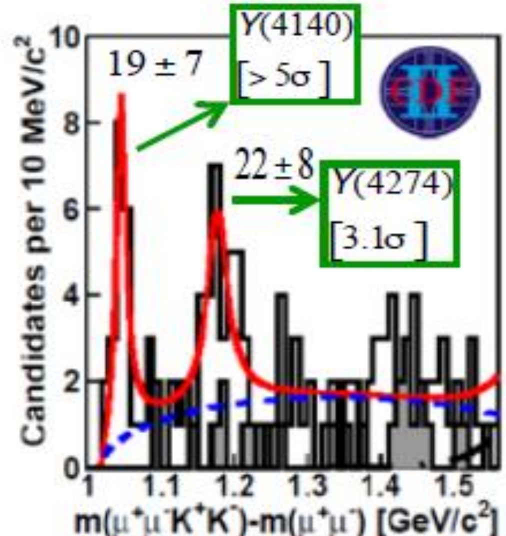



# Search for charm tetraquarks
# and pentaquarks

*and Perspectives*

# Confirmation of X(4140) → J/ψ ϕ

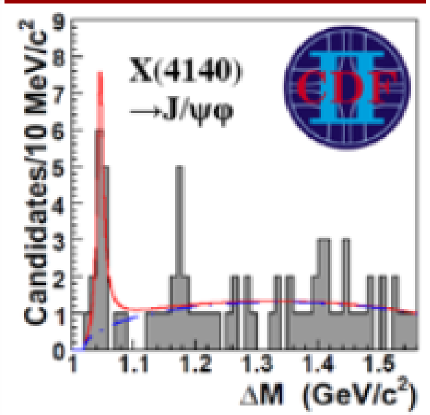
CDF (2011) presents update analysis with larger dataset,(6.0$fb^{-1}$ vs 2.7$fb^{-1}$ )observing




[ arXiv:1101.6058 (2011) ]

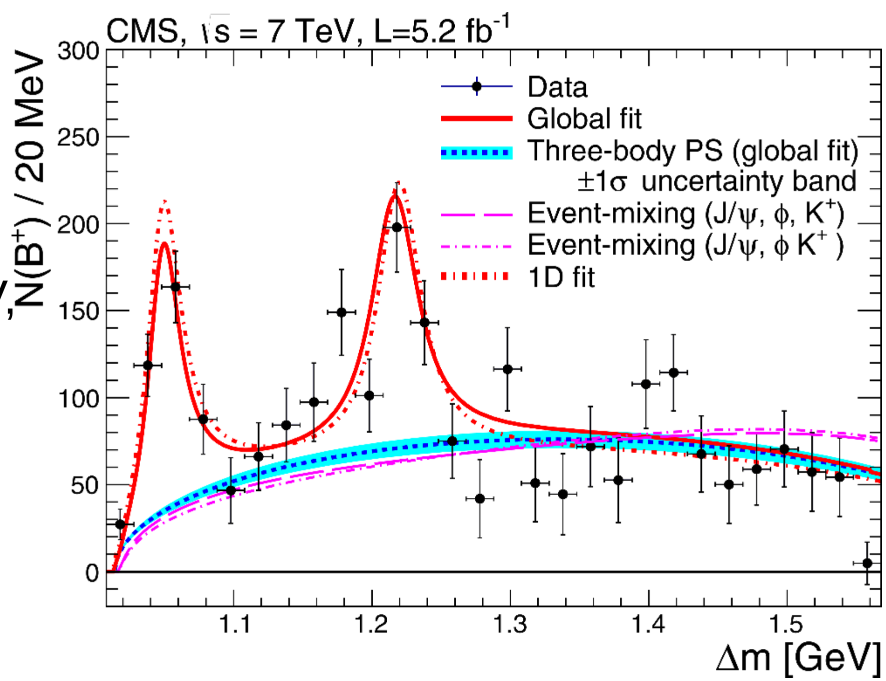
CDF (2009) reported evidence (@3.8σ ) for …
narrow peak in $J/\psi\varphi$ mass spectrum, close to the kinematical threshold, in decays
$B^{+} \to J/\psi\ \phi\ K^{+}$

[PRL 102 (2009) 242002]




- Peaking structure at the threshold and another peak in Δm from B+ → J/ψ ϕ 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.

# CMS: Study of $B^+ \to J/\psi\, \bar{\Lambda}\, p$

JHEP 12 (2019) 100

**Motivation and experimental situation**

## $M(J/\psi\bar{\Lambda})$ and $M(J/\psi p)$ study

The study is motivated by the recent observation of $P^+_c$ states by LHCb collaboration in $J/\psi p$ system. This decay provides a possibility to study both $J/\psi\Lambda$ and $J/\psi p$ systems.

New states are expected near threshold in The extended chromomagnetic model.

C. W. Xiao, J. Nieves, and E. Oset, "Prediction of hidden charm strange molecular baryon states with heavy quark spin symmetry", Phys. Lett. B799 (2019) 135051

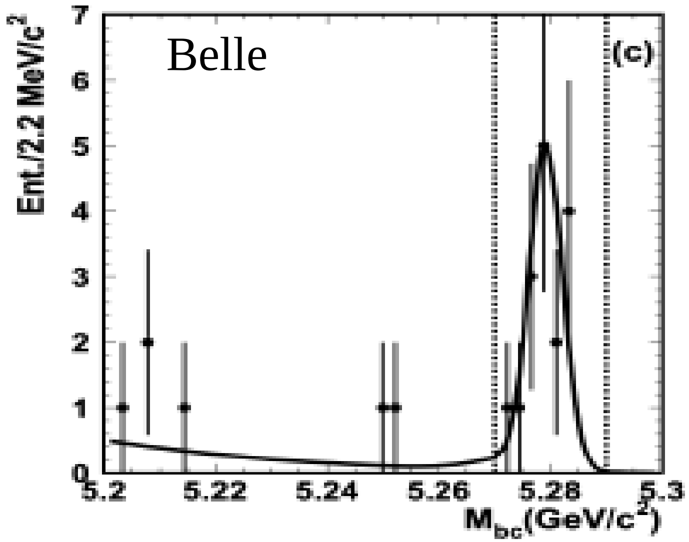
The existence of a molecular baryon decaying to $J/\psi\ \Lambda$ has been predicted

X.-Z. Weng, X.-L. Chen, W.-Z. Deng, and S.-L. Zhu, "Hidden-charm pentaquarks and Pc states",Phys. Rev. D 100 (2019) 016014

## Measurement of the $\mathscr{B}(B^+ \to J/\psi\bar{\Lambda}p)$

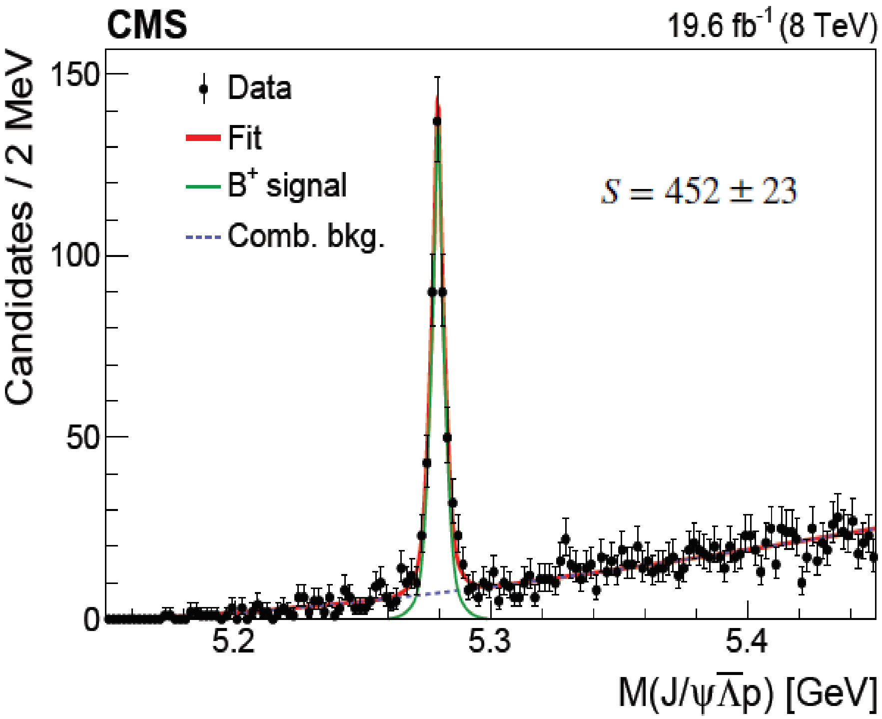
The only available measurement at the moment performed by Belle in 2005 with a large uncertainty Phys.Rev. D72:051105, 2005

Br.fr.= $(11.6 \pm 2.8\ ^{+1.8}_{-2.3}) \times 10^{-6}$

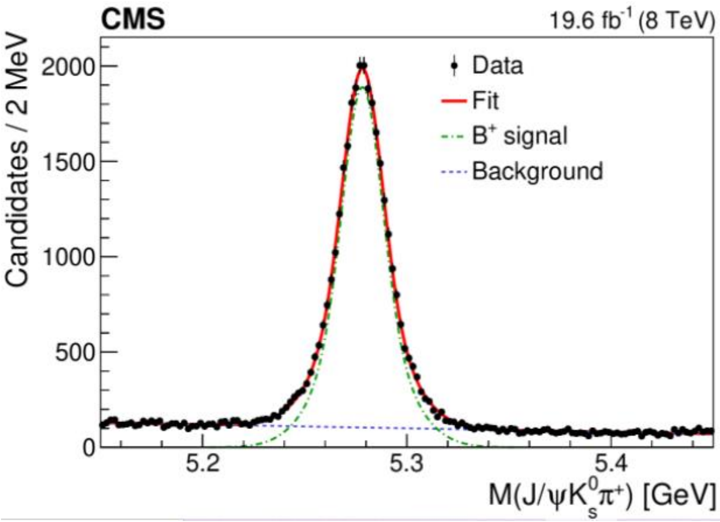


# CMS: Study of $B^+ \to J/\psi \, \overline{\Lambda} \, p$

This study is based on 2012 8 TeV data (19.6 $fb^{-1}$)




The B+ → J/ψ K*+ → J/ψ (K0s π+) was chosen as a normalization channel since it has the same decay topology




$$\frac{\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = (1.054 \pm 0.057(stat.) \pm 0.035(syst.) \pm 0.011(br.)) \times 10^{-2},$$

and using $\mathcal{B}(B^- \to J/\psi K^{*-}) = (1.43 \pm 0.08) \times 10^{-2}$

$$\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p) = (\ 15.1 \pm 0.8\ (stat.) \pm 0.5\ (syst.) \pm 0.9\ (br.)\ ) \times 10^{-6}$$

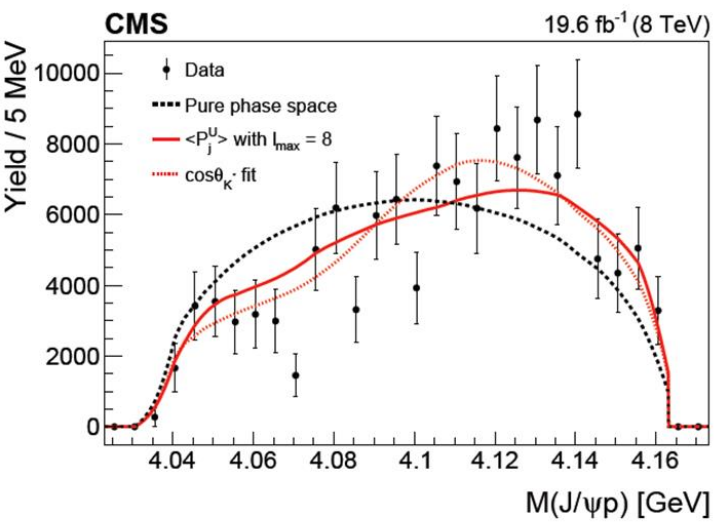
PDG mean value of $\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p) = (11.8 \pm 3.1) \times 10^{-6}$

The latest Belle measurement $\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p) = (11.7 \pm 2.8^{+1.8}_{-2.3}) \times 10^{-6}$

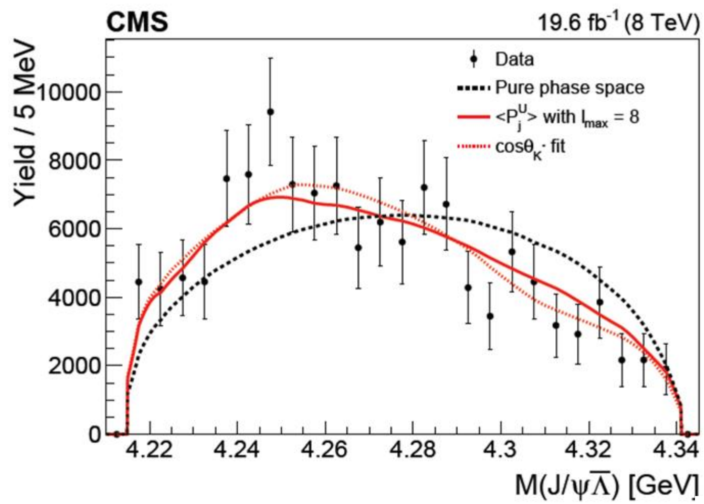
# CMS: Study of $B^+ \to J/\psi \bar{\Lambda} p$

JHEP 12 (2019) 100

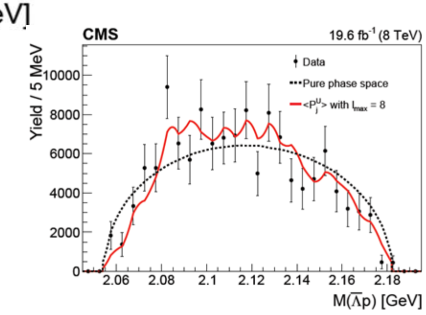
## Comparison of phase space MC with efficiency corrected data




The significance of incompatibility with the phase space hypothesis is > 5.5σ for J/ψ Λ , > 6.1σ for J/ψ p and > 3.4σ for Λ p mass spectra, including systematics.




The significance of data incompatibility with data is calculated using likelihood ratio method




Before assuming new resonances, one should exclude another non-exotic scenarios

# CMS: Study of $B^+ \to J/\psi\,\bar{\Lambda}\,p$

JHEP 12 (2019) 100

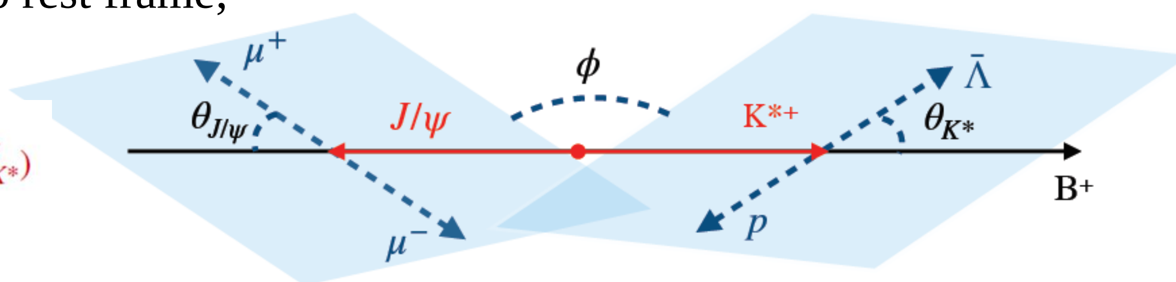
## Model-independent approach: method of moments

- Introduced by BaBar [PRD 79 (2009) 112001] and then used by
LHCb [PRD 92 (2015) 112009, PRL 117 (2016) 082002];
- There are 3 known K* resonances that can decay to Λp, so these K*'s can contribute to the 2-body invariant mass distributions;
- In each M(Λ p) bin, the cos($\theta_{K*}$) distribution can be expressed as an expansion in terms of Legendre polinomials:

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{j=0}^{l_{\max}} \langle P_j^U \rangle P_j(\cos\theta_{K^*})$$

where $\theta_{K*}$ is the helicity angle defined as the angle between Λ momentum and B+ momentum in the Λp rest frame;

$$w^i = 1 + \sum_{j=1}^{l_{max}} < P_j^N > P_j(cos\theta^i_{K*})$$



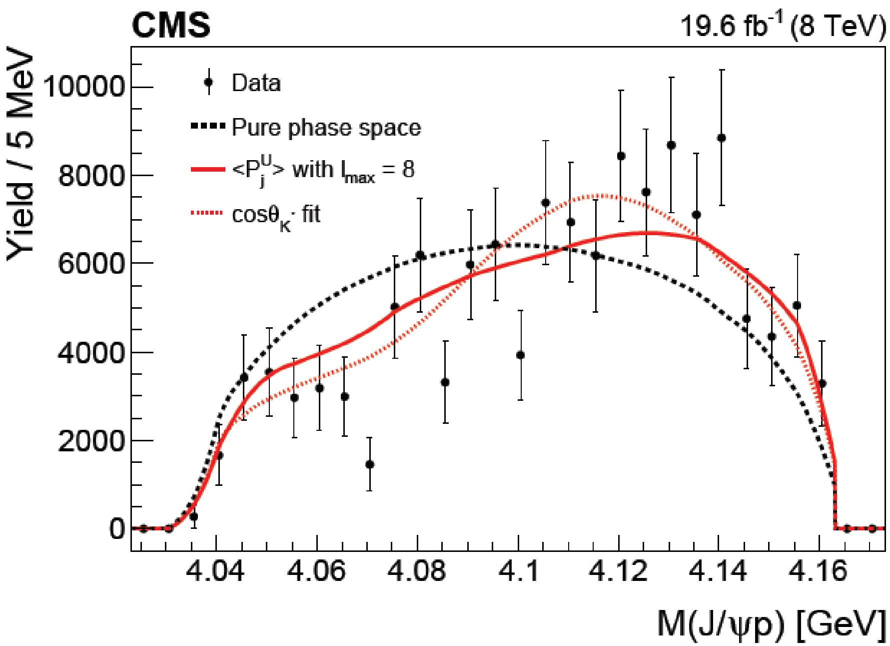

- For $l_{max}$ = 2xJ, where J is the total spin of the highest-spin K*, one can take into account all these K* → Λp.
- From table $l_{max}$ = 2x4=8.

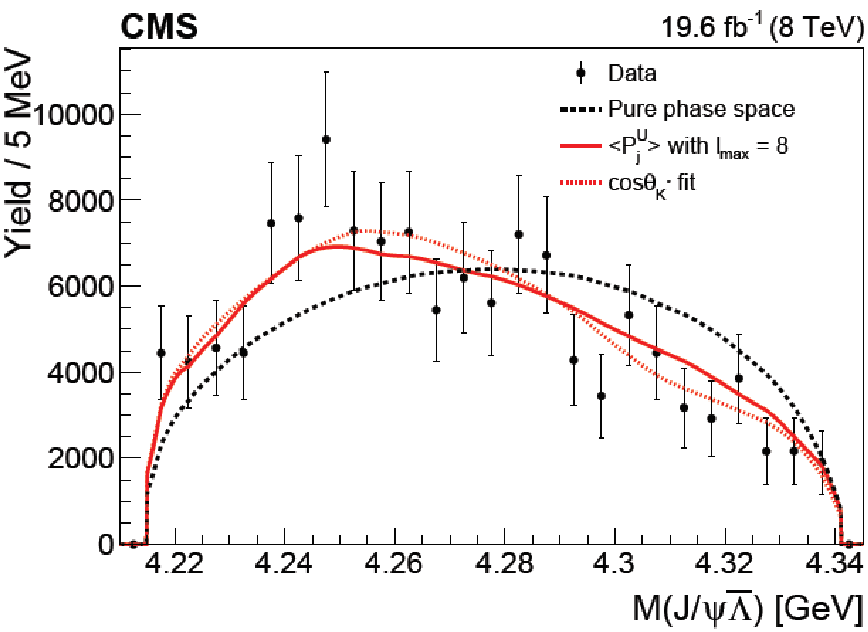
| Resonance | Mass, MeV | Natural width, MeV | $J^P$ |
|---|---|---|---|
| $K_4^*(2045)^+$ | $2045 \pm 9$ | $198 \pm 30$ | $4^+$ |
| $K_2^*(2250)^+$ | $2247 \pm 17$ | $180 \pm 30$ | $2^-$ |
| $K_3^*(2320)^+$ | $2324 \pm 24$ | $150 \pm 30$ | $3^+$ |

# CMS: Study of $B^+ \to J/\psi \overline{\Lambda} p$

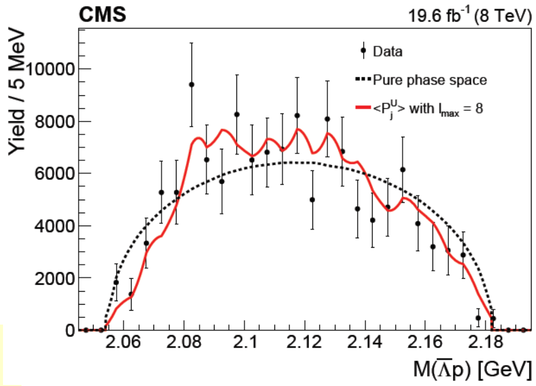
JHEP 12 (2019) 100

Simulation reweighting according to the observed structure in $\Lambda p$




A model-independent approach that accounts for the contribution from known K*'s with spins up to 4 in the $\Lambda p$ system improves the agreement with data significantly!




Compatibility with data (incompatibility < 2.8 $\sigma$ including syst.) eliminating the need for exotic resonances in this 3-body decay

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

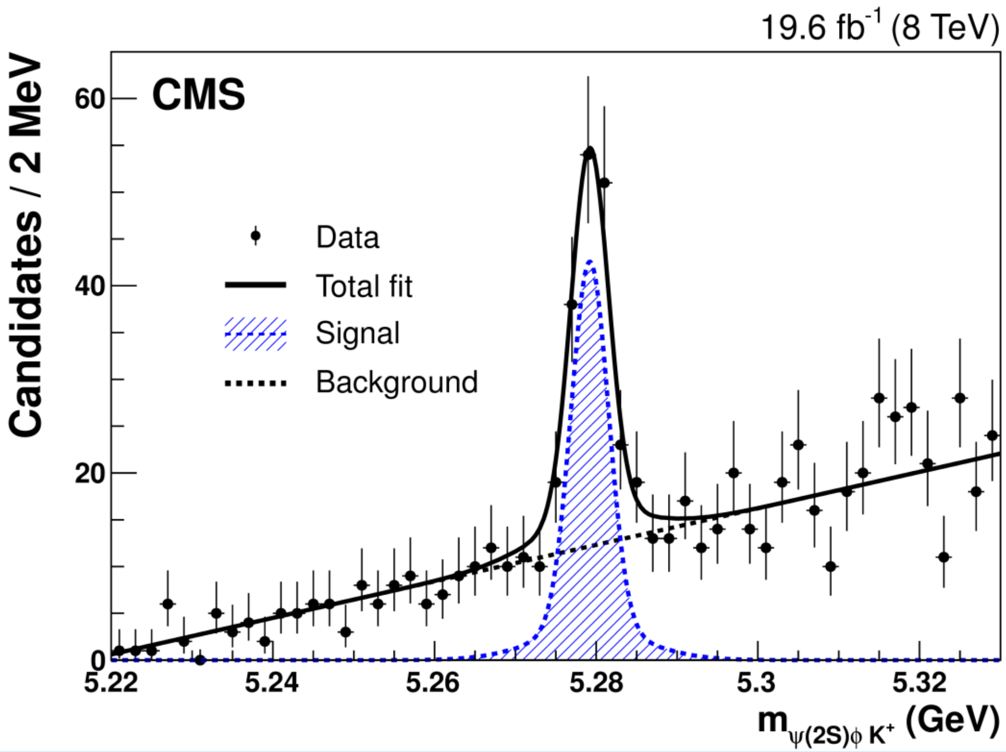
*Phys. Lett. B 764 (2017) 66*

Similar to famous B+ → J/ψ ϕ K+

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

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

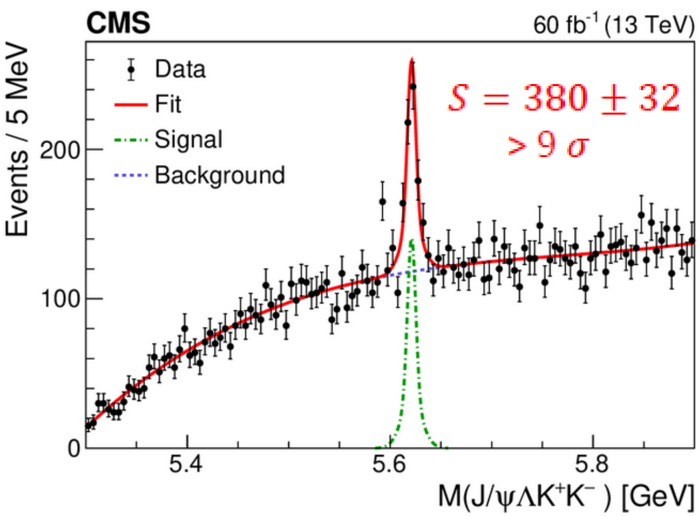
$$[\,4.0 \pm 0.4\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst}) \pm 0.2\,(\mathrm{BF}(B^+ \rightarrow \psi(2S)\,K^+))\,] \times 10^{-6}$$

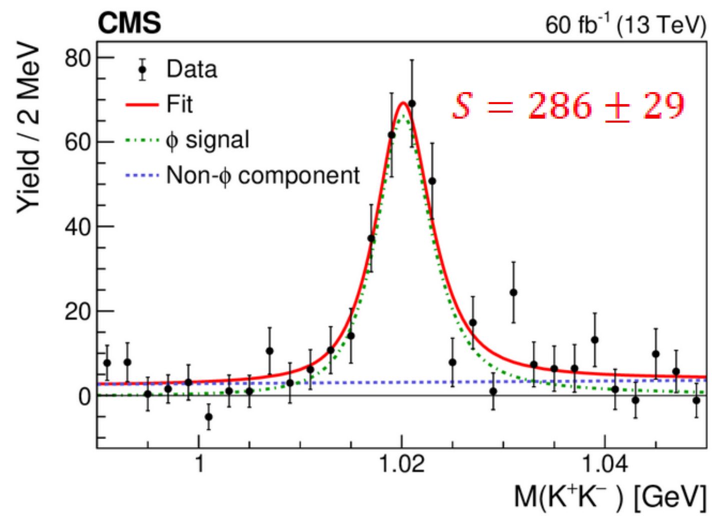


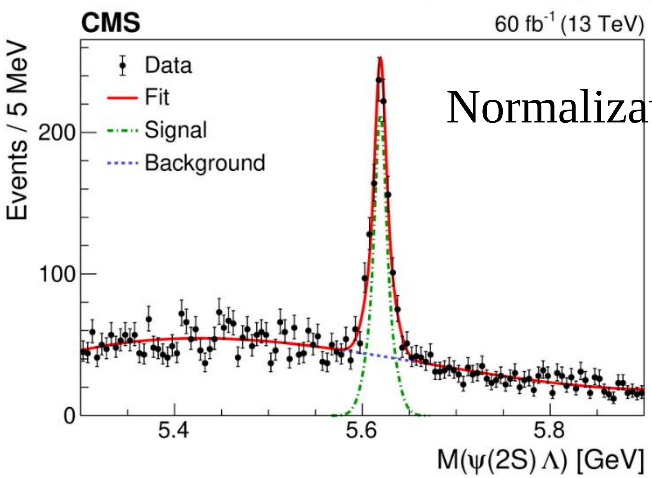

This is the first step towards the exploration of $\psi(2S)\,\phi$ system.

# Observation of $\Lambda_b \rightarrow J/\psi\ \Lambda\ \phi$

*Phys. Lett. B 802 (2020) 135203*




Normalization mode

The study is based on 2018 13 TeV data (60 $fb^{-1}$)

$$\frac{B(\Lambda_b^0 \rightarrow J/\psi\Lambda\varphi)}{B(\Lambda_b^0 \rightarrow \psi(2s)\Lambda)} = (8.26\ \pm 0.90\ (\text{stat.}) \pm 0.68(\text{syst.}) \pm 0.11(\text{br.}))\%$$

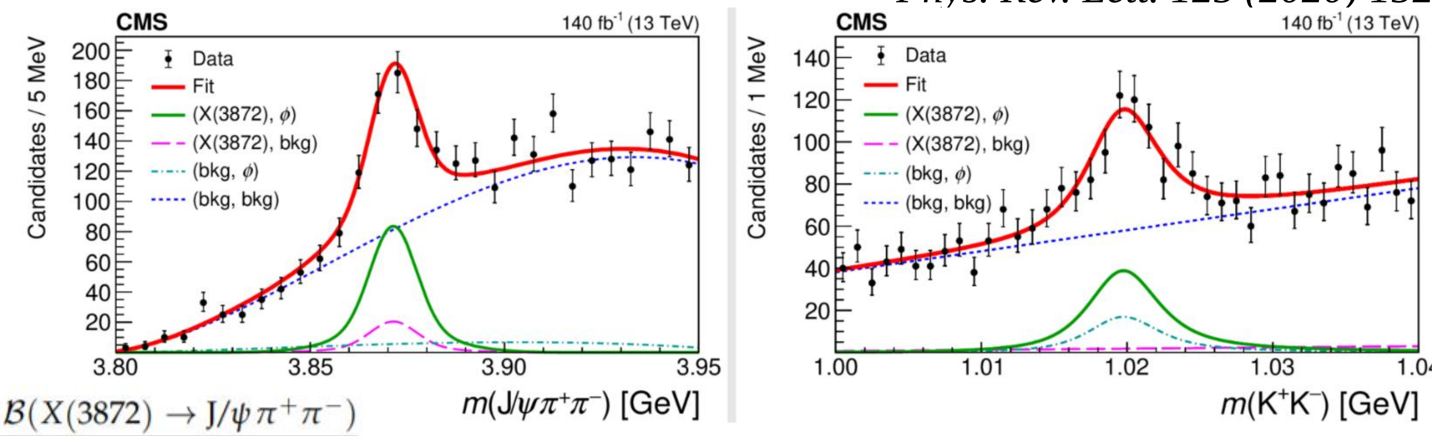
This new decay provides an opportunity to further explore the $J/\psi\ \phi$ **and** $J/\psi\ \Lambda$ systems

# New Results on

# X(3872) production properties

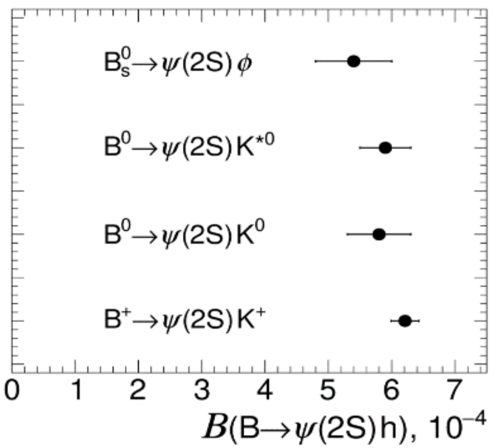
# Observation of $B_s^0 \to X(3872)\,\phi$

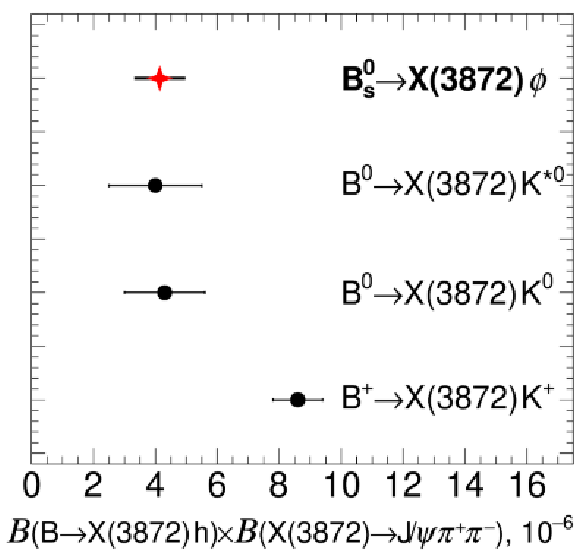
*Phys. Rev. Lett. 125 (2020) 152001*




$$R \equiv \frac{\mathcal{B}(B_s^0 \to X(3872)\phi)\,\mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi)\,\mathcal{B}(\psi(2S) \to J/\psi\,\pi^+\pi^-)}$$

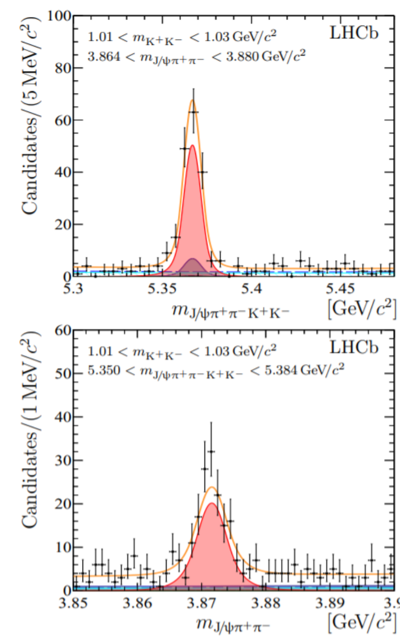
$$R = (2.21 \pm 0.29\,(\text{stat}) \pm 0.17\,(\text{syst}))\%$$




**X(3872)**
*formation in B decays is different from **psi(2S)** !*

JHEP 02 (2021) 024




$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2} \quad (20)$$

# Evidence for X(3872) production in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

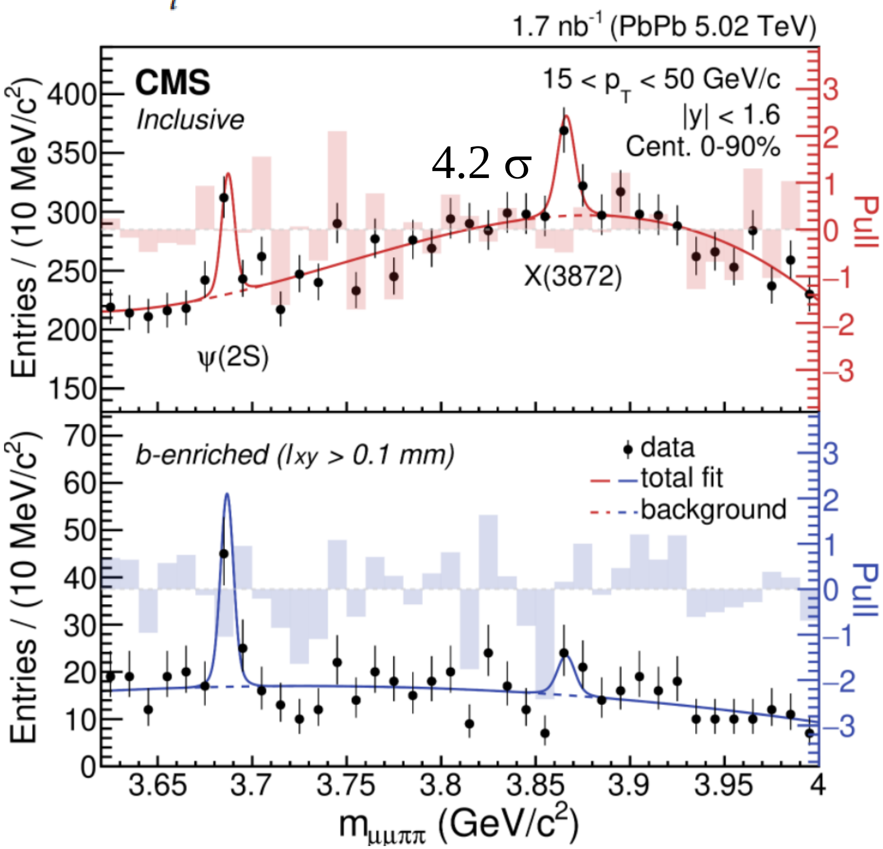
arXiv:2102.13048

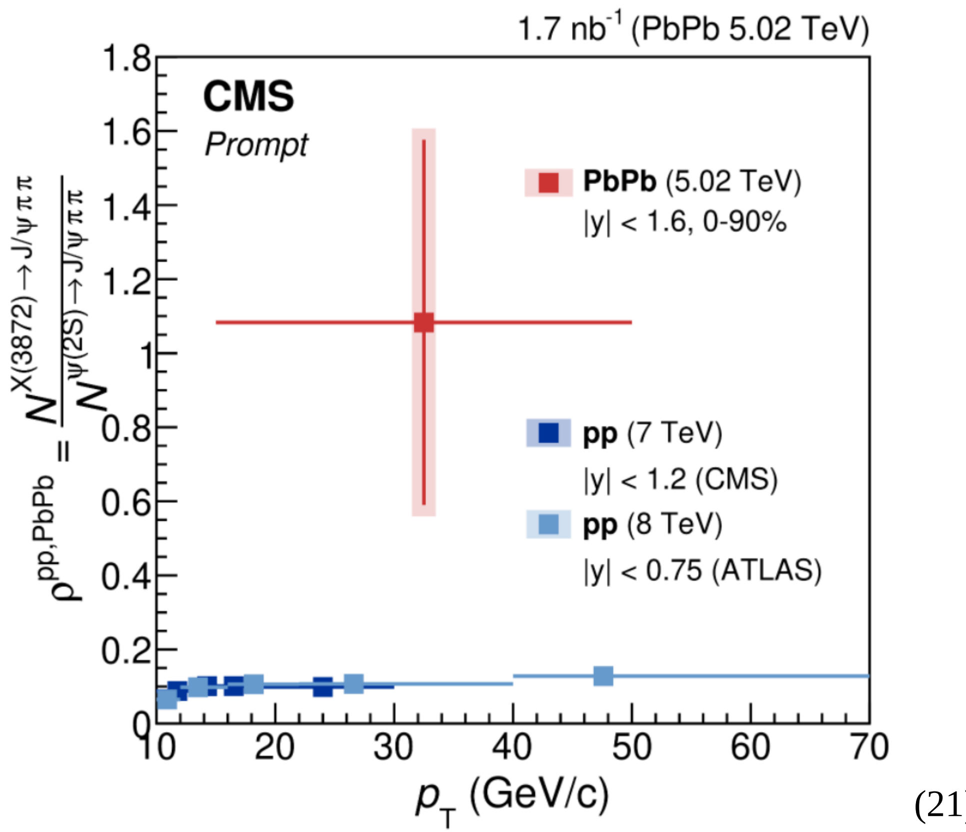
The production and survival of X(3872) in QGP is expected to depend upon X's internal structure

$$\rho^{i} = \frac{N_i^{X(3872)\to J/\psi\,\pi\pi}}{N_i^{\psi(2S)\to J/\psi\,\pi\pi}} \qquad \rho^{\mathrm{PbPb}} = \rho^{\mathrm{pp}}\frac{R_{\mathrm{AA}}^{X(3872)}}{R_{\mathrm{AA}}^{\psi(2S)}}$$

$$\rho^{\mathrm{PbPb}} = 1.08 \pm 0.49\,(\mathrm{stat}) \pm 0.52\,(\mathrm{syst})$$

$$R_{\mathrm{AA}}^{\psi(2S)} = 0.142 \pm 0.061\,(\mathrm{stat}) \pm 0.020\,(\mathrm{syst})$$



# Summary

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)
- Search for the bottomonium partner of the X(3872)
  in $Y(1S)\pi^+\pi^-$ channel
- Search for resonances decaying to Y(1S)μ+μ−
- Study of $B^+ \to J/\psi\ \Lambda\ p$
- First significant confirmation of the X(4140) → $J/\psi\ \phi$ at LHC,

observation of B+ $\to \psi(2S)\ \phi$ K+ and $\Lambda_b$ → $J/\psi\ \Lambda\ \phi$

- First observation of Bs $\to$ X(3872) $\phi$
- First evidence for X(3872) production in heavy ion collisions

New results from CMS are expected soon.

# Backup slides