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Search for new exotic multiquark states at CMS

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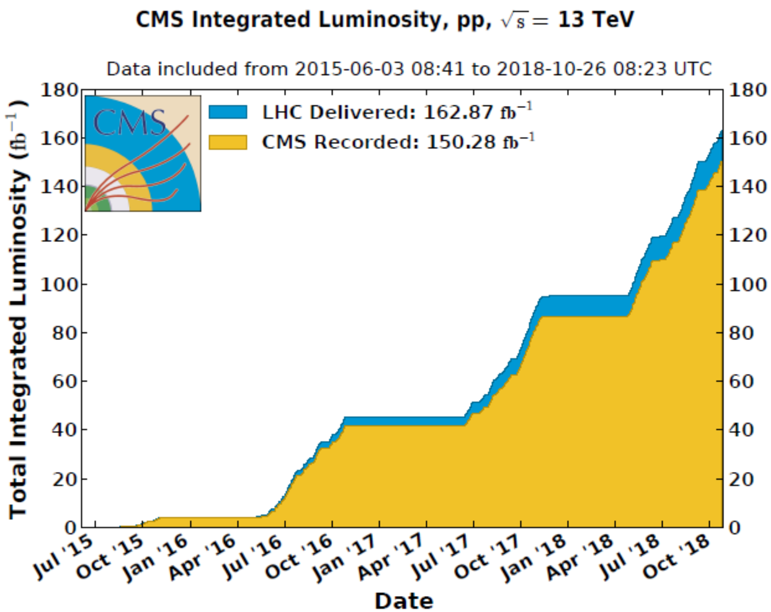
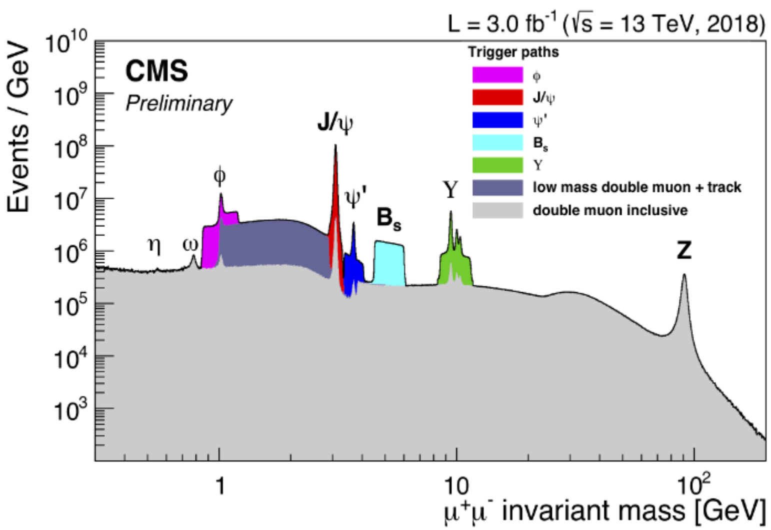
Outline

1. Introduction
2. Search for $X(5568)+ \rightarrow Bs\ \pi+$
3. Search for exotic bottomonium states decaying into $Y(1S)\ \pi+\pi-$
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. Summary and Prospects

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.

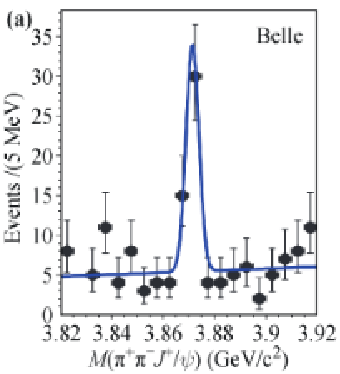
- Ingenious trigger algorithms were developed for efficient online event selection.

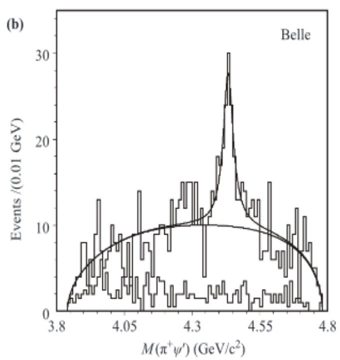
CMS is contributing intensively into the heavy flavor

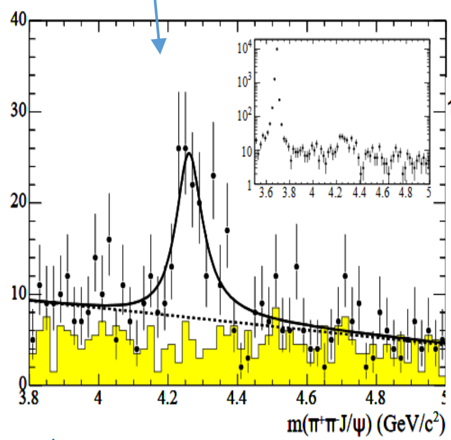
In this talk the results on a search for new multiquark states based on 13 and 8 TeV data samples will be presented

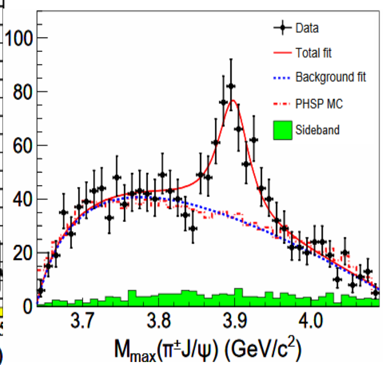
Exotic Hadrons: experimental results and theoretical interpretation

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

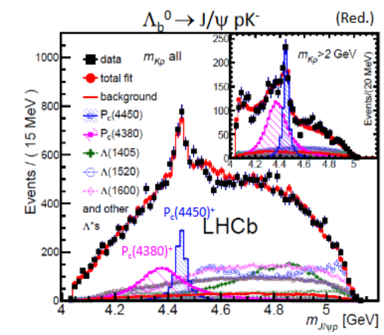








and P_c from LHCb.



This is a New Hadron Spectroscopy Era

Theoretical interpretation of all these exotic states still not clear.

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

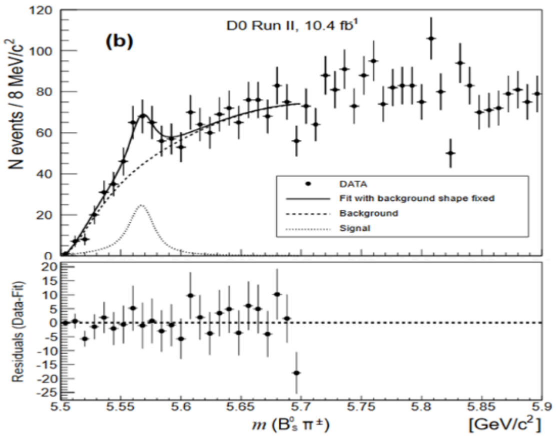
→ **WE NEED MORE INFORMATION !**

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

Search for (hidden) beauty tetraquarks

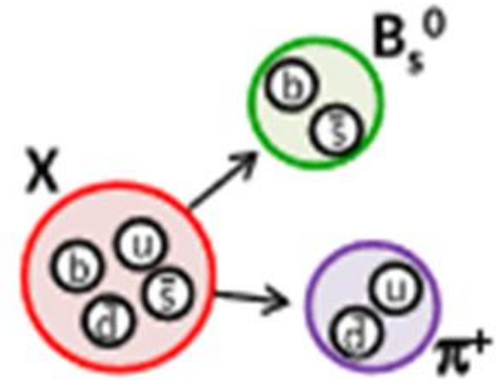
D0 Collaboration: Evidence for X(5568), new state decaying into Bs π+

PRL117. 022003(2016)



Search for X(5568)$^+$ $\rightarrow$ B$_s$ π^+

If confirmed, would be unique with 4 different flavours

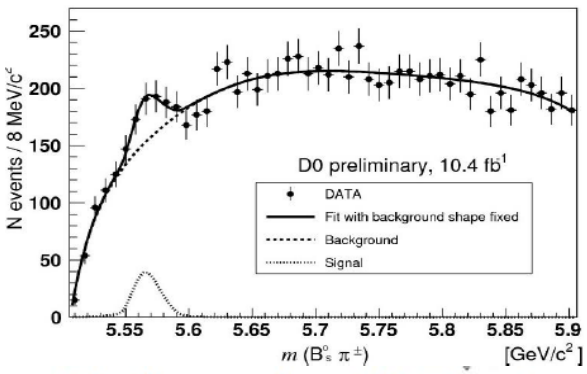


$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV},$$

$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \mathrm{MeV},$$

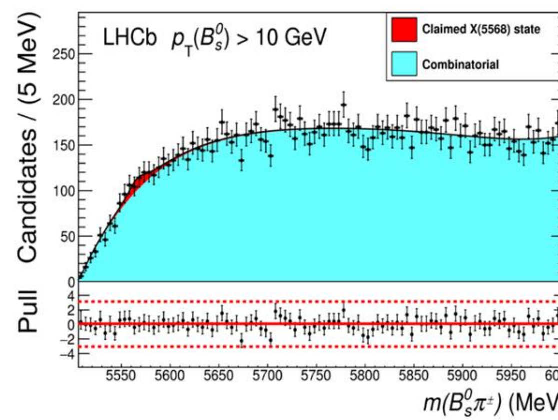
$$\rho_X^{\mathrm{D0}} \equiv \frac{\sigma(p\bar{p} \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi)}{\sigma(p\bar{p} \to B_s^0 + \text{anything})} = (8.6 \pm 1.9 \pm 1.4)\%$$

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)

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

Search for X(5568)+ in CMS is actual:

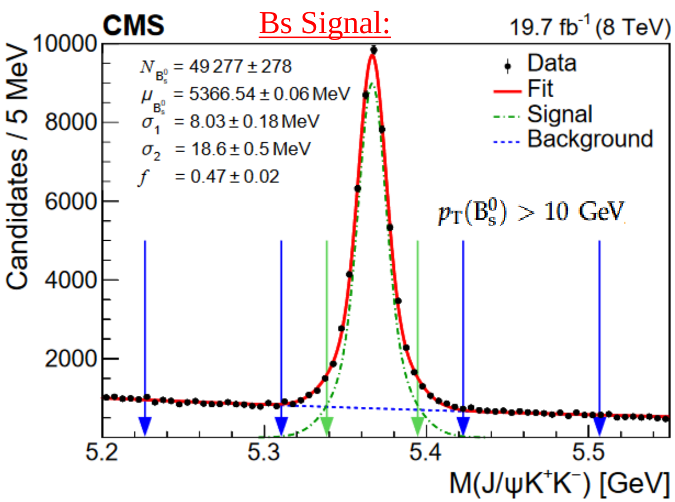
- Different η interval with LHCb,
- Beauty hadron production conditions are similar in D0 and CMS.

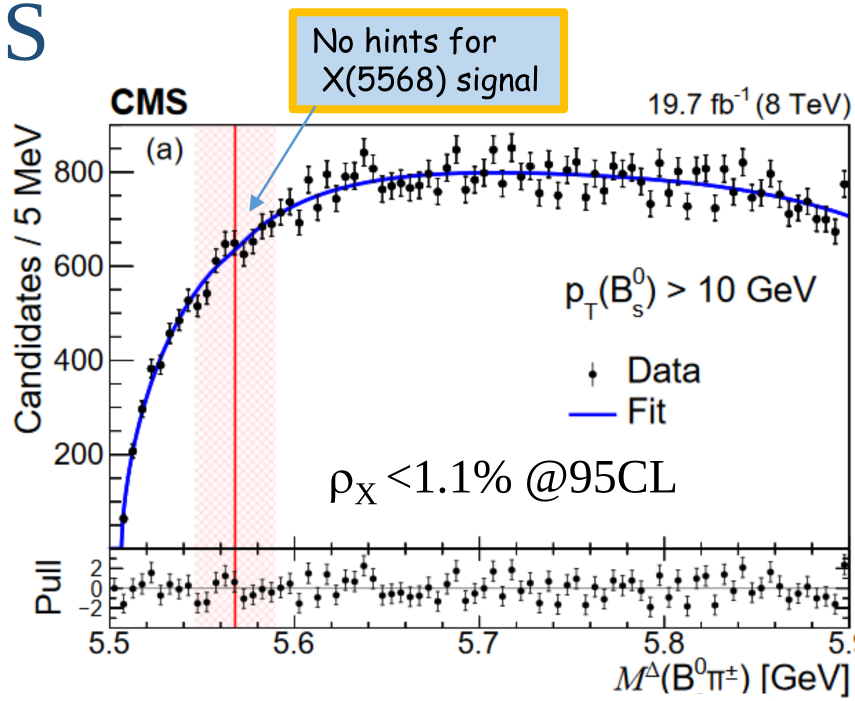
Search for X(5568) in CMS

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

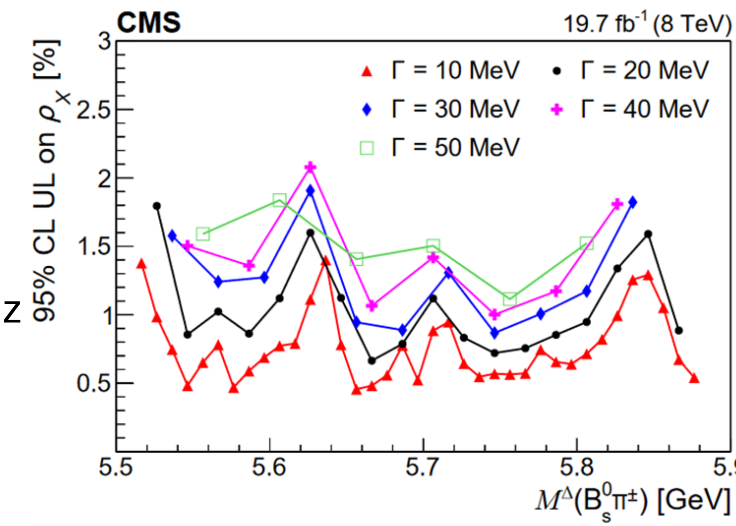
CDF: A 95% C.L. upper limit of 6.7%

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





PRL 120 (2018) 202005



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

No evidence for X(5568) at the LHC

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

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

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

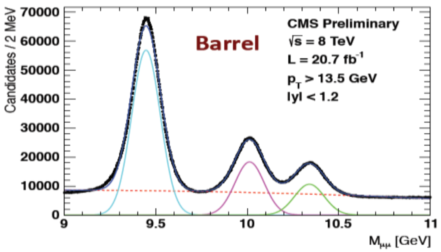
$\rho_X^{CMS} < 1.1\%$ at 95% CL for $p_T(B_s^0) > 10$ GeV

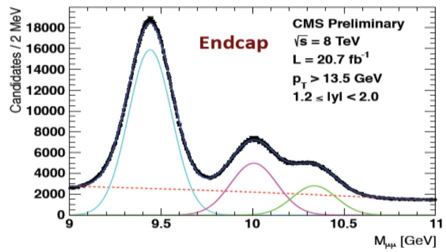
$\rho_X^{CMS} < 1.0\%$ at 95% CL for $p_T(B_s^0) > 15$ GeV

PLB 727 (2013) 57

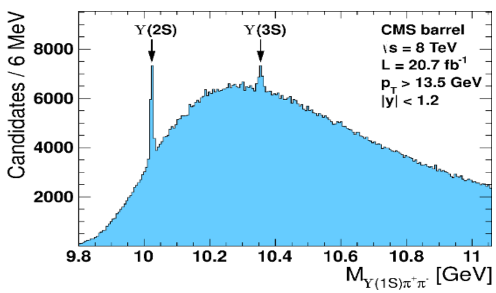
Search for exotic bottomonium states X_b decaying into $\Upsilon(1S)\ \pi+\pi-$

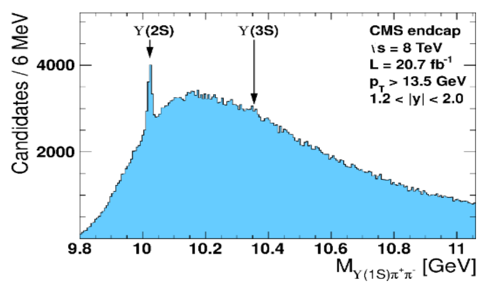
- The discovery of the X(3872) has prompted the search for a bottomonium counterpart $X_b \rightarrow \Upsilon(1S)\ \pi+\pi-$ - according to HQS considerations - with mass close to the BB or BB* threshold, 10.562 and 10.604 GeV.
- It is expected that this X_b would be narrow, similar to X(3872), and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





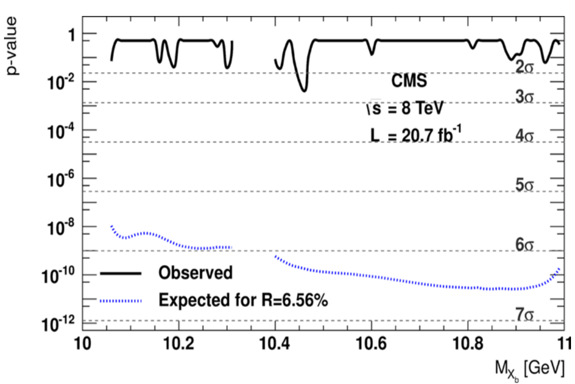
CMS has collected a large sample of $\Upsilon(nS)\rightarrow\mu+\mu-$ produced in pp collisions at 8TeV.
Separate barrel and endcap events to exploit better mass resolution and lower background in the barrel region.

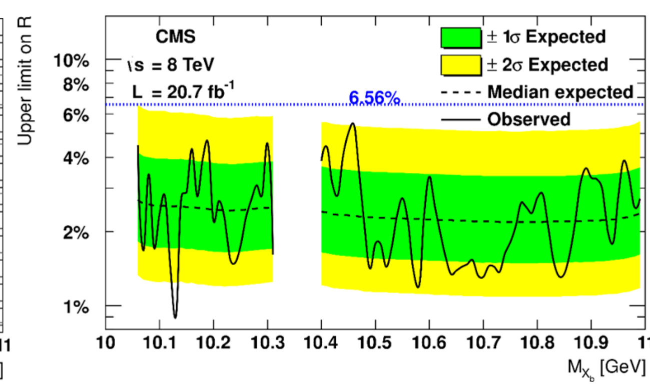




$p_T(\Upsilon(1S)\pi^+\pi^-) > 13.5$ GeV and $|y(\Upsilon(1S)\pi^+\pi^-)| < 2.0$

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





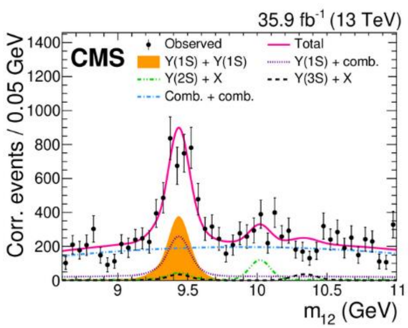
In analogy with the X(3872), expected signal significance > 5 σ if X_b(Br x cross-section)>6.5% of the corresponding product for $\Upsilon(2S) \rightarrow \Upsilon(1S)\ \pi^+\pi^-$ (R value)

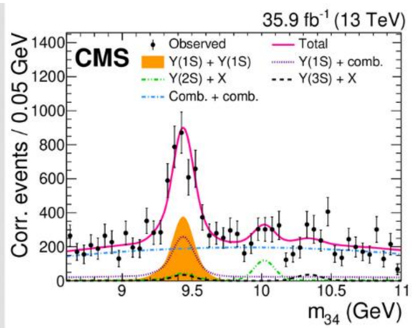
Measurement of the Υ(1S) pair production cross section and search for resonances decaying to Υ(1S)μ+μ− in proton-proton collisions at s√= 13 TeV

arXiv:2002.06393, submitted to PLB

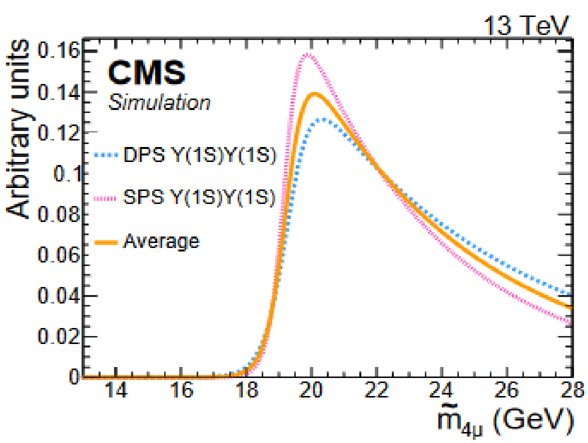
NEW

- 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

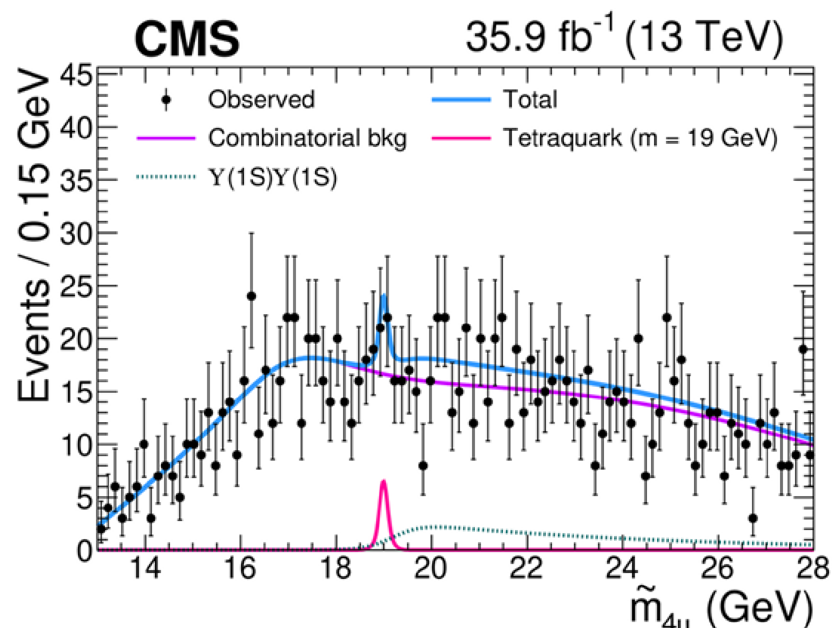




The two projections and the results of the 2D fit to the muon pair invariant masses.



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

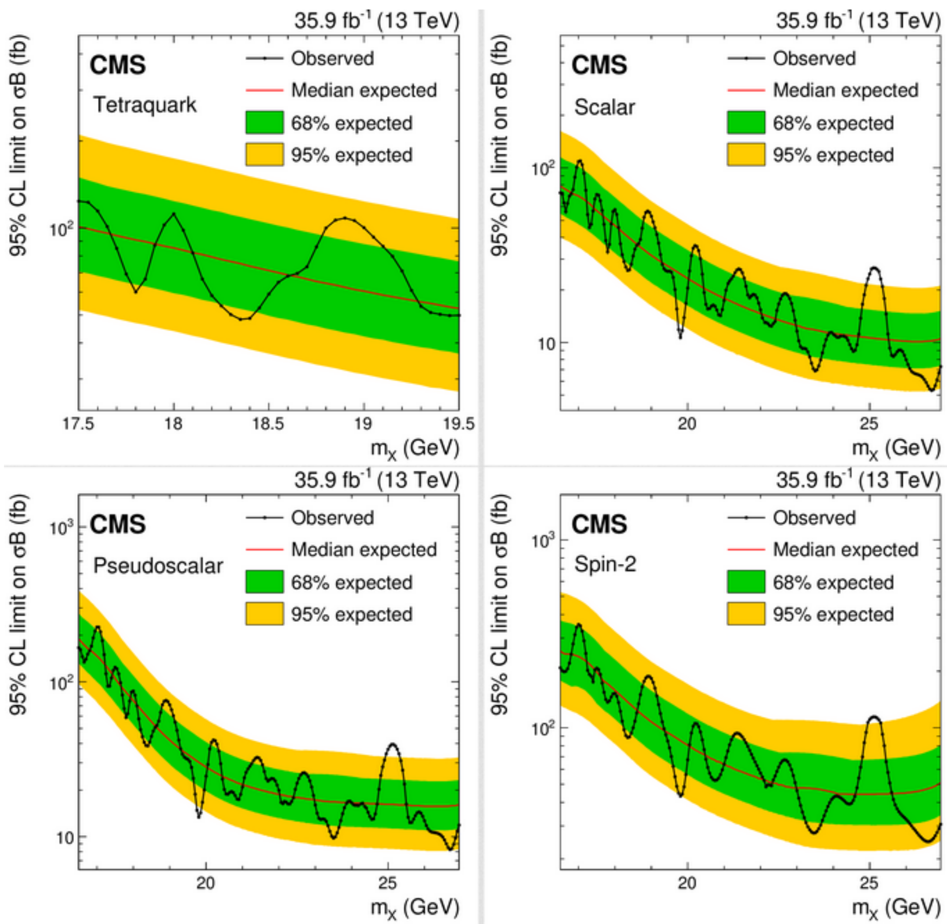


Measurement of the $\Upsilon(1S)$ pair production cross section and search for resonances decaying to $\Upsilon(1S)\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 13$ TeV

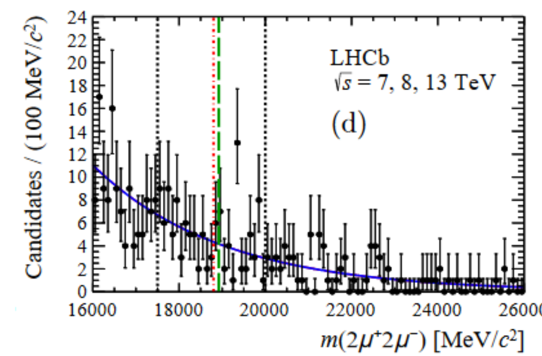
arXiv:2002.06393, submitted to PLB

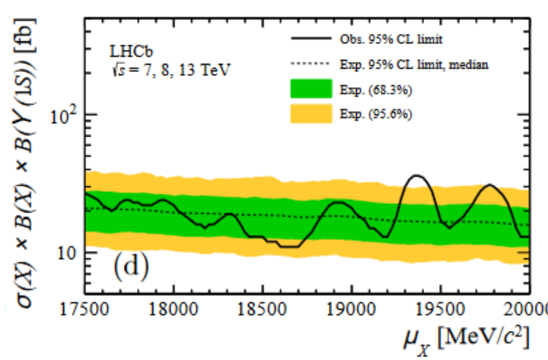
NEW

UL's at 95% CL on the σxBr



LHCb results

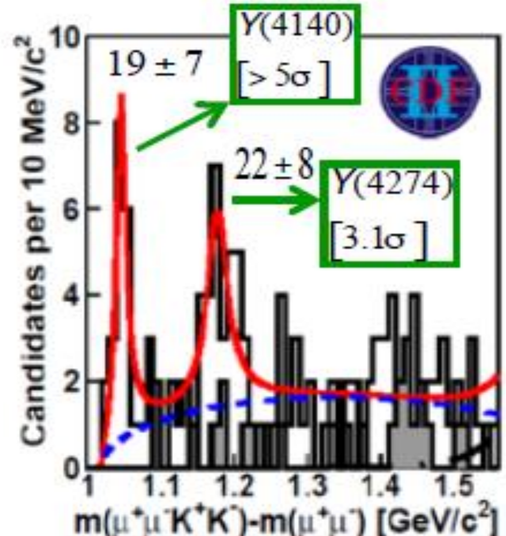




Search for hidden charm tetraquarks and pentaquarks

Confirmation of X(4140) → J/ψ ϕ

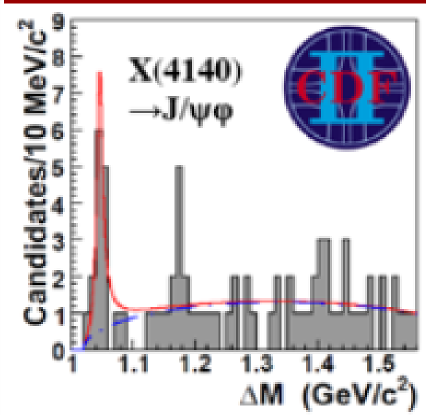
CDF (2011) presents update analysis with larger dataset,(6.0fb^{-1} vs 2.7fb^{-1})observing



[arXiv:1101.6058 (2011)]

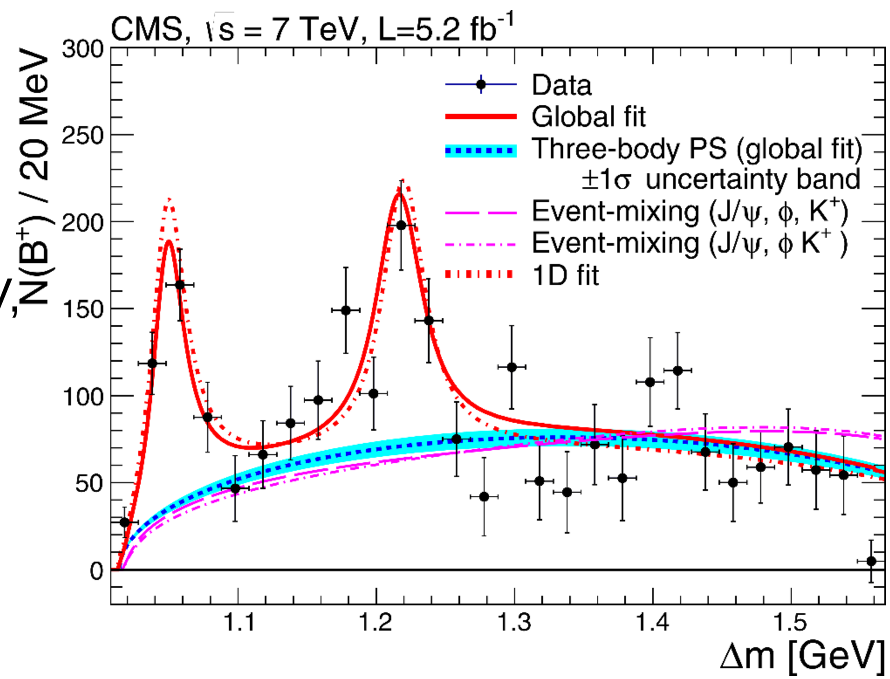
CDF (2009) reported evidence (@3.8σ) for ... narrow peak in $J/\psi\varphi$ mass spectrum, close to the kinematical threshold, in decays $B^{+} \to J/\psi\ \phi\ K^{+}$

[PRL 102 (2009) 242002]



- Peaking structure at the threshold and another peak in the 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)



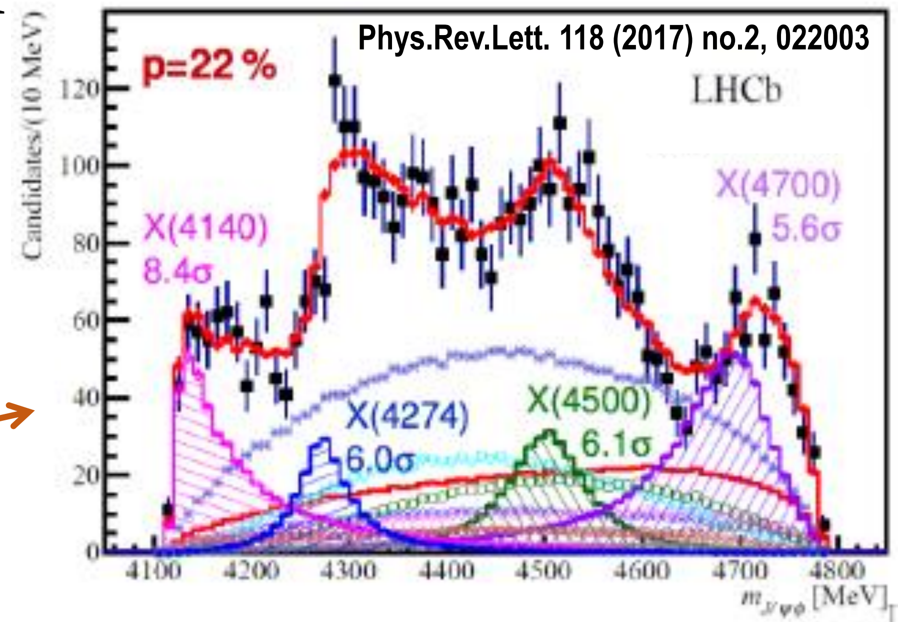
PLB 734 (2014) 261

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

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

JHEP 12 (2019) 100

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

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

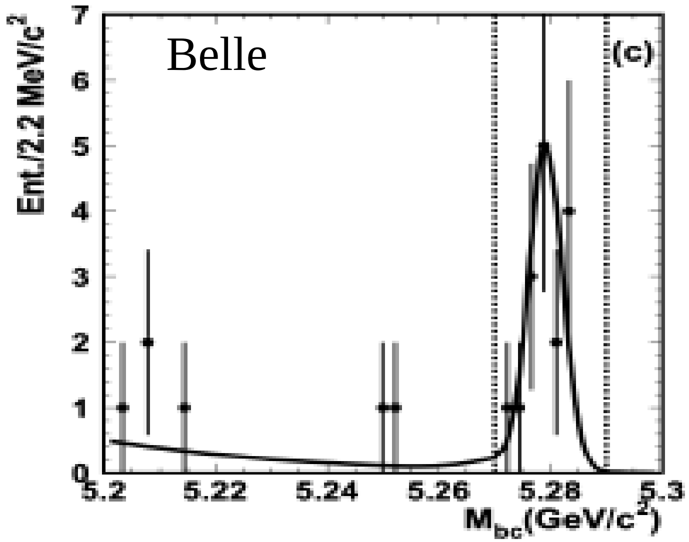
The existence of a molecular baryon decaying to $J/\psi\ \Lambda$ has been predicted

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 $\mathscr{B}(B^+ \rightarrow J/\psi\bar{\Lambda}p)$

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 $B^+ \to J/\psi\,\bar{\Lambda}\,p$

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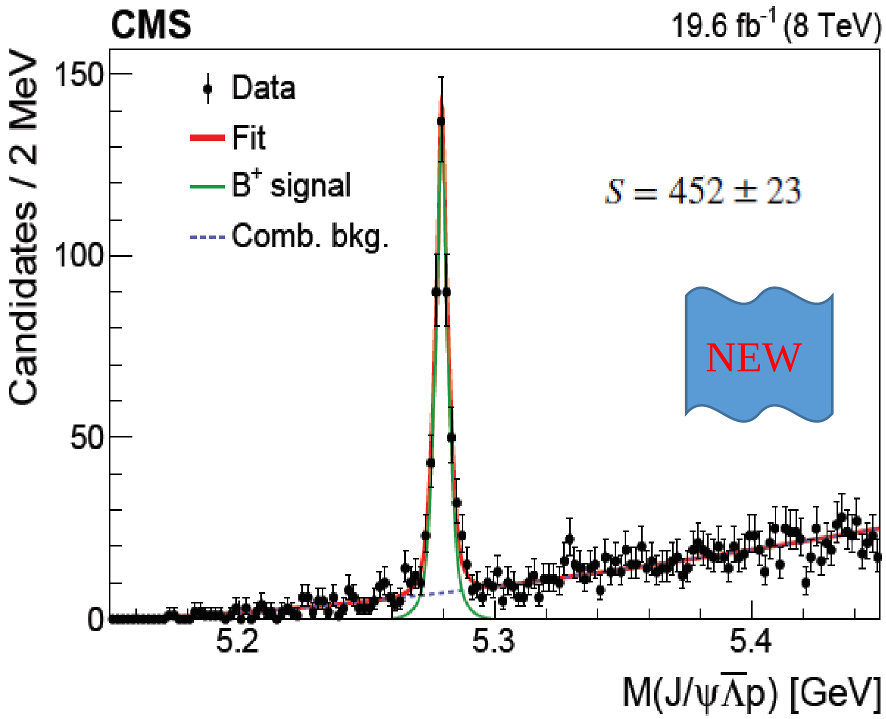
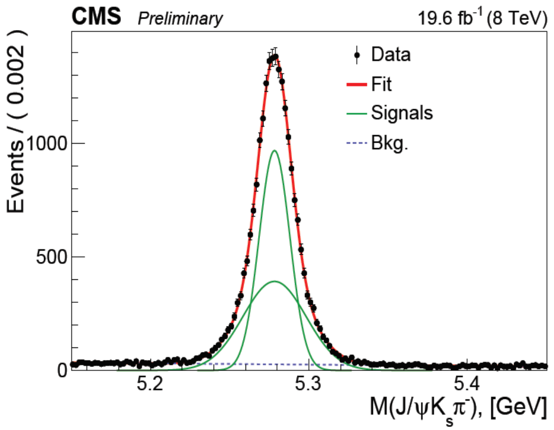
This study is based on 2012 8 TeV data (19.6 fb^{-1})



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



$$\frac{\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = (1.054 \pm 0.057(stat.) \pm 0.028(syst.) \pm 0.011(br.)) \times 10^{-2},$$

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

$$\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p) = (15.07 \pm 0.81(stat.) \pm 0.40(syst.) \pm 0.86(br.)) \times 10^{-6}$$

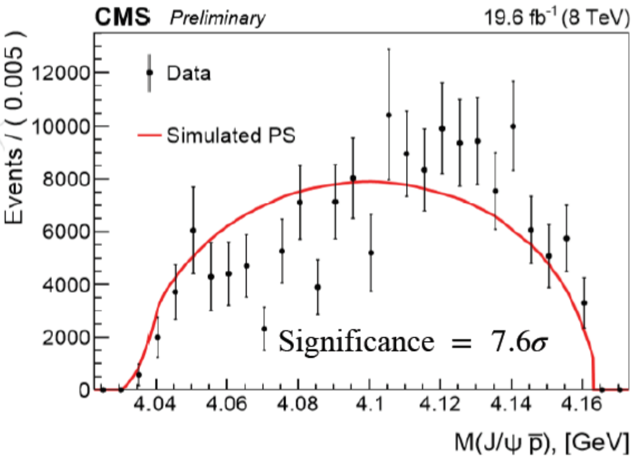
PDG mean value of $\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p) = (11.8 \pm 3.1) \times 10^{-6}$

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

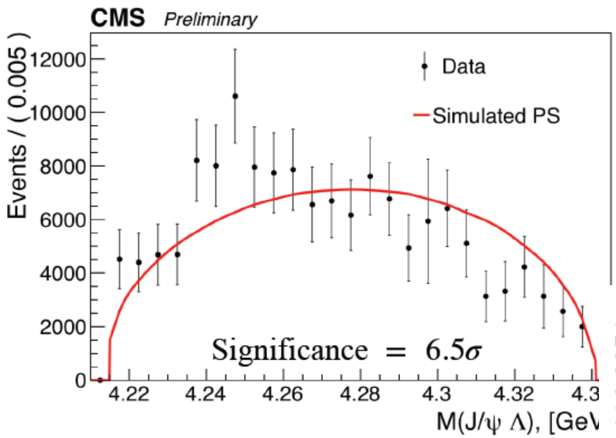
CMS: Study of $B^+ \to J/\psi\,\overline{\Lambda}\,p$

JHEP 12 (2019) 100

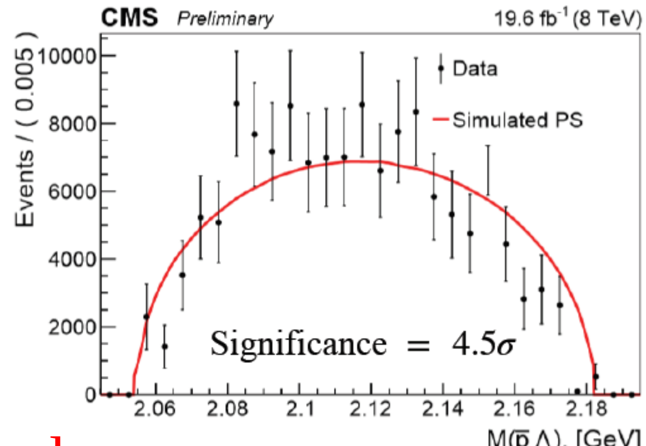
Comparison of phase space MC with efficiency corrected data



The significance of incompatibility with the phase space hypothesis is > 5.5σ for J/ψ Λ , > 6σ 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

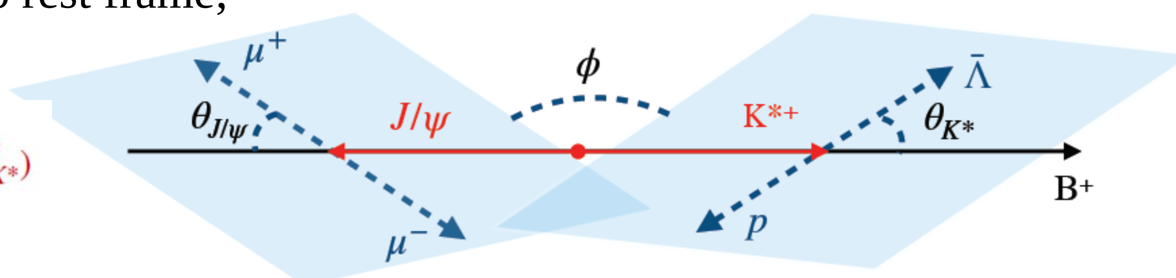
Model-independent approach: method of moments

- 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(θ_{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 θ_{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 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

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

NEW

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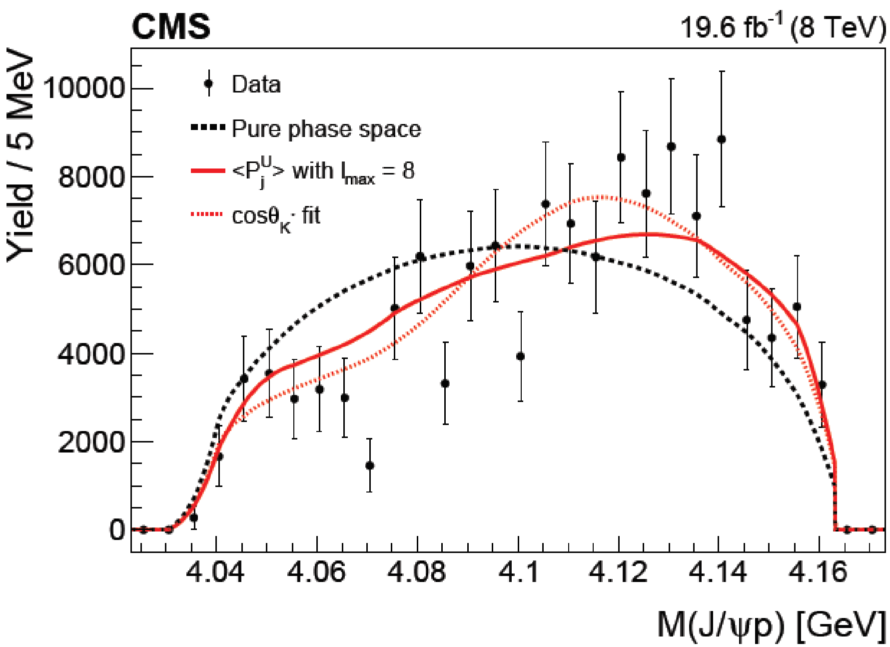
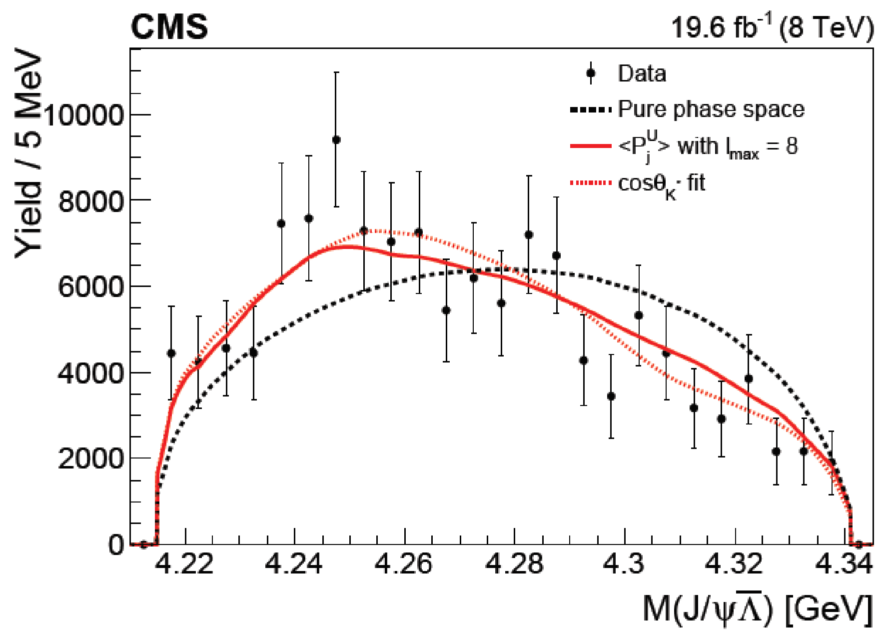
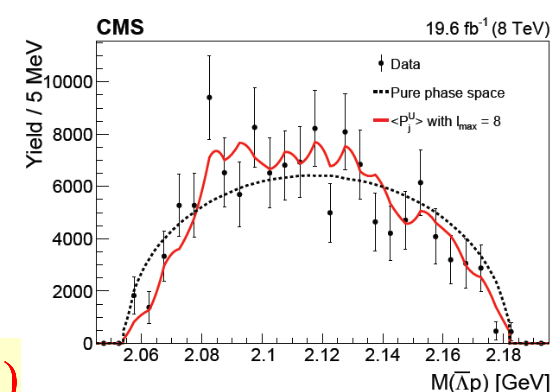
Simulation reweighting according to the observed structure in Λp





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



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

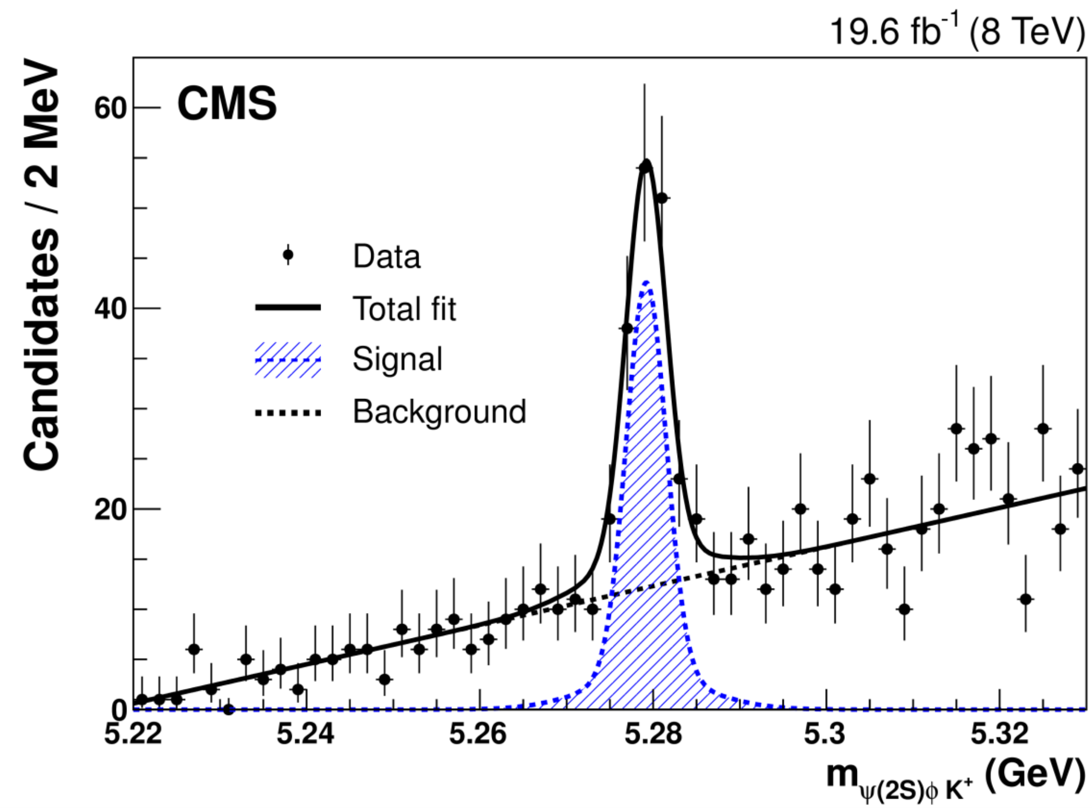
Observation of $B^+ \rightarrow \psi(2S)\,\phi\,K^+$

Phys. Lett. B 764 (2017) 66

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:

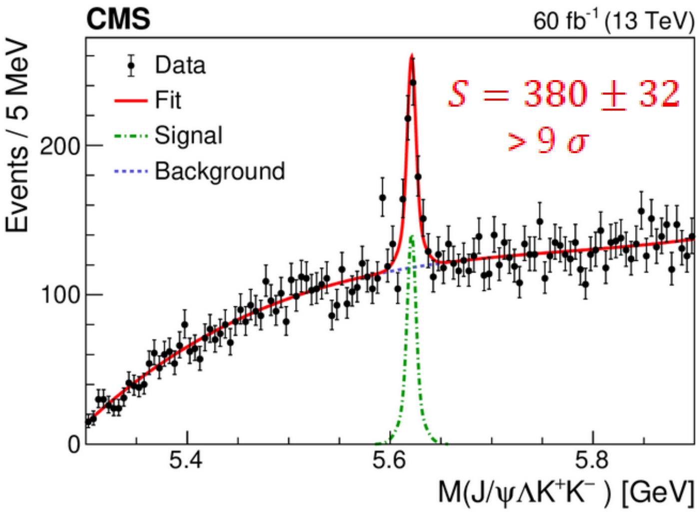
$$[\,4.0 \pm 0.4\,(\text{stat}) \pm 0.6\,(\text{syst}) \pm 0.2\,(\text{BF}(B^+ \rightarrow \psi(2S)\,K^+))\,] \times 10^{-6}$$

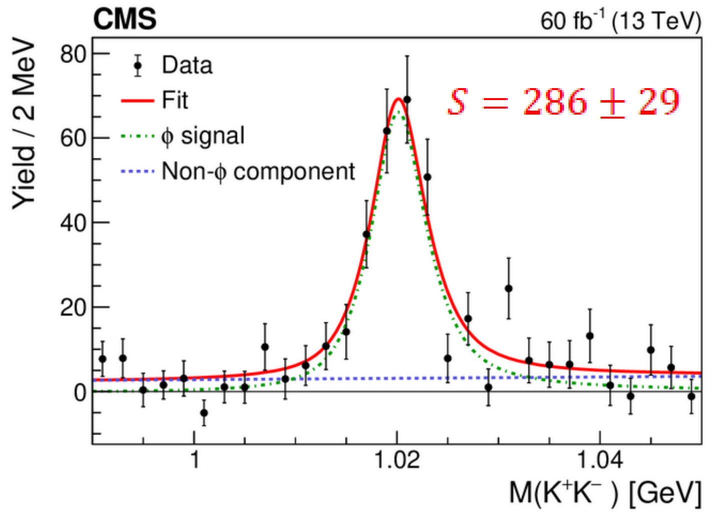


This is the first step towards the exploration of $\psi(2S)\,\phi$ system.

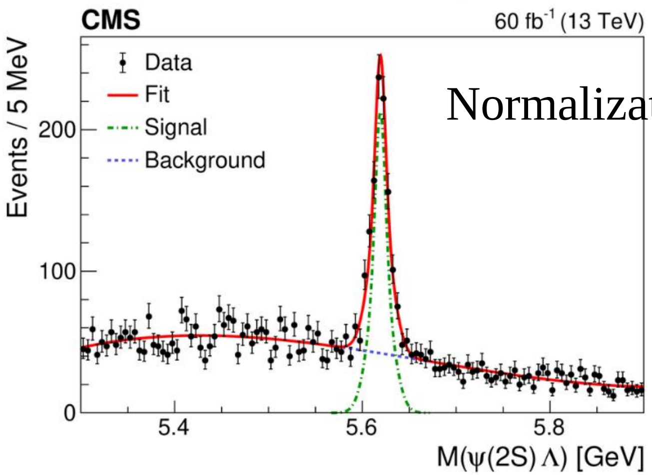
Observation of $\Lambda_b \rightarrow J/\psi\ \Lambda\ \phi$

Phys. Lett. B 802 (2020) 135203





NEW



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

Summary

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

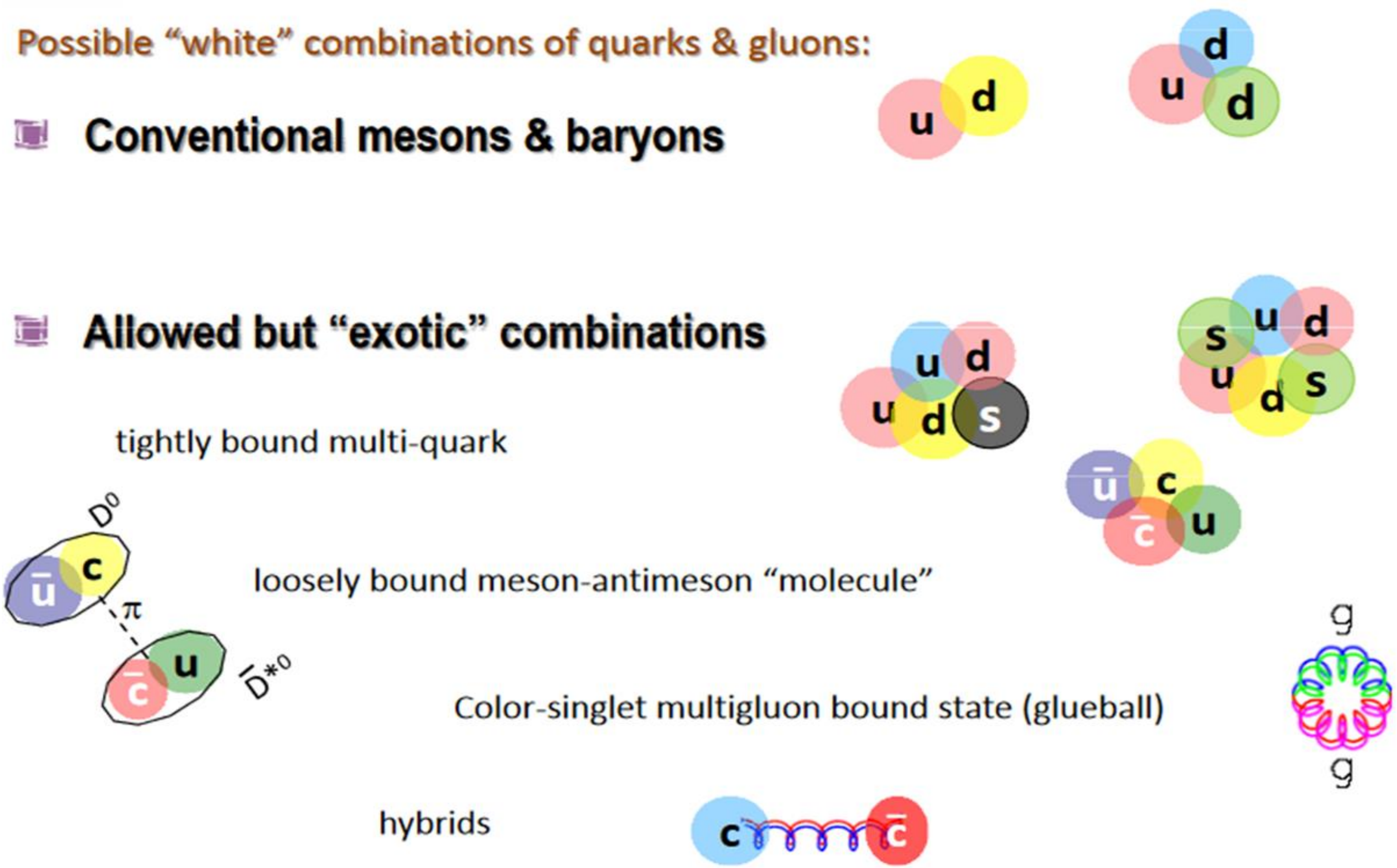
- Study of $B_s \pi^+$ spectrum and
  setting an UL on the production of X(5568)
- Search for the bottomonium partner of the X(3872)
  in $Y(1S)\pi^+\pi^-$ channel
- Search for resonances decaying to $Y(1S)\mu+\mu-$
- Study of $B^+ \rightarrow J/\psi \, \Lambda \, p$
- First significant confirmation of the X(4140) → $J/\psi \, \phi$ at LHC,
  observation of $B+ \rightarrow \psi(2S) \, \phi \, K+$ and Λ_b → $J/\psi \, \Lambda \, \phi$

New results from CMS are expected soon.

Backup slides

Hadrons: Conventional and Exotic

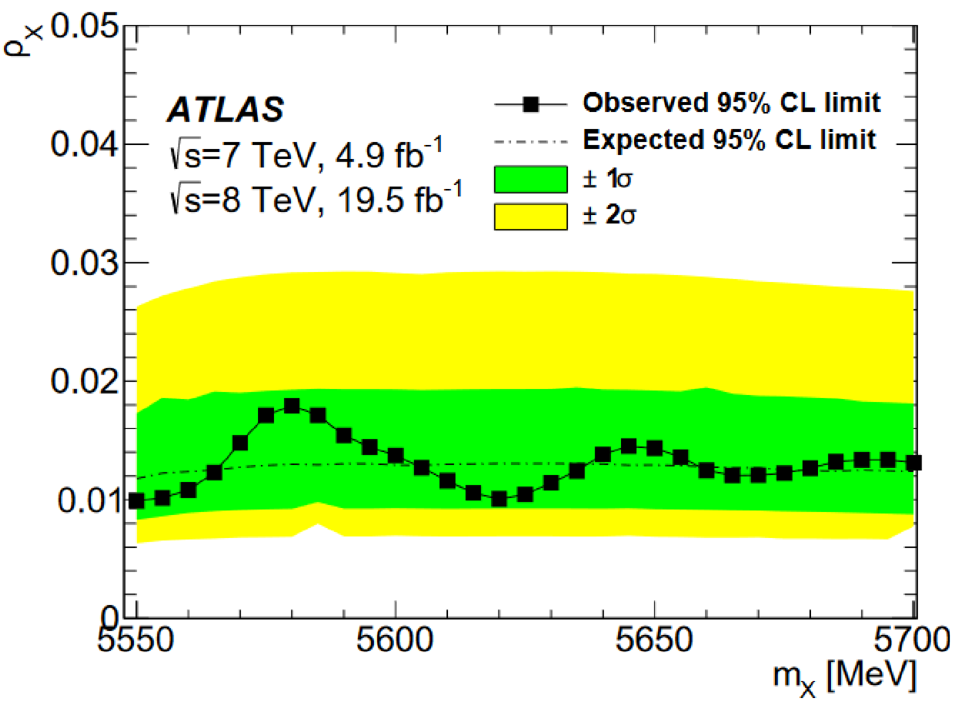
Are there any quark configurations other than mesons and baryons?
In theory such configurations are possible.
Which of them are realized in reality, in nature?

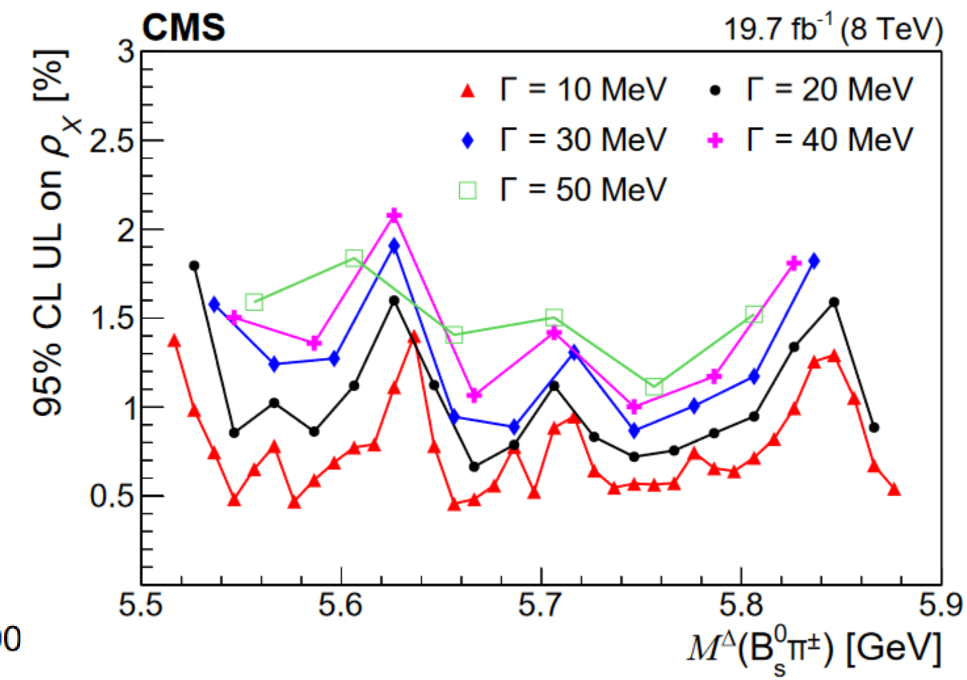


Search for X(5568) in ATLAS and CMS: **results**

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

No evidence of X(5568) at the LHC





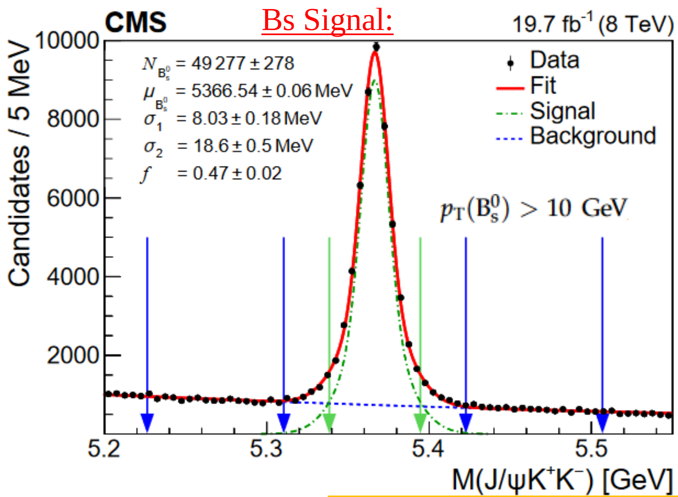
$\rho_X^{\mathrm{ATLAS}} < 0.015$ at 95% CL for $p_{\mathrm{T}}(\mathrm{B_s^0}) > 10$ GeV

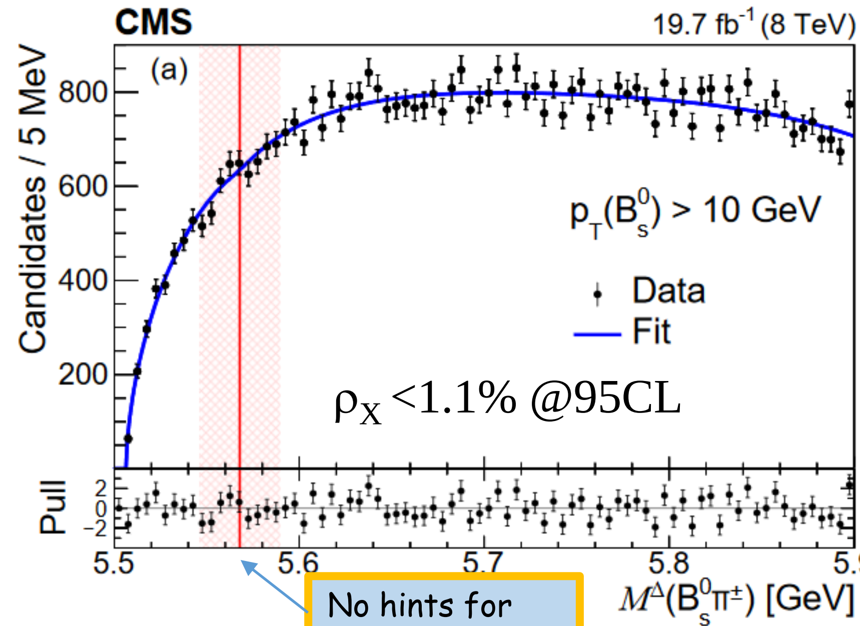
$\rho_X^{\mathrm{ATLAS}} < 0.016$ at 95% CL for $p_{\mathrm{T}}(\mathrm{B_s^0}) > 15$ GeV

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

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

Search for X(5568) in ATLAS and CMS



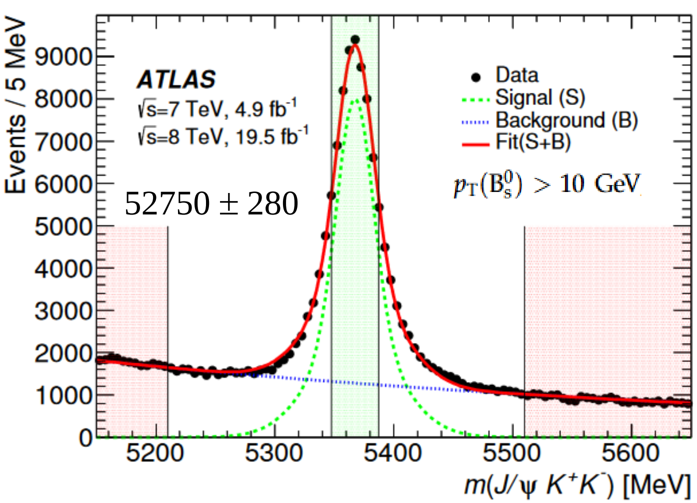


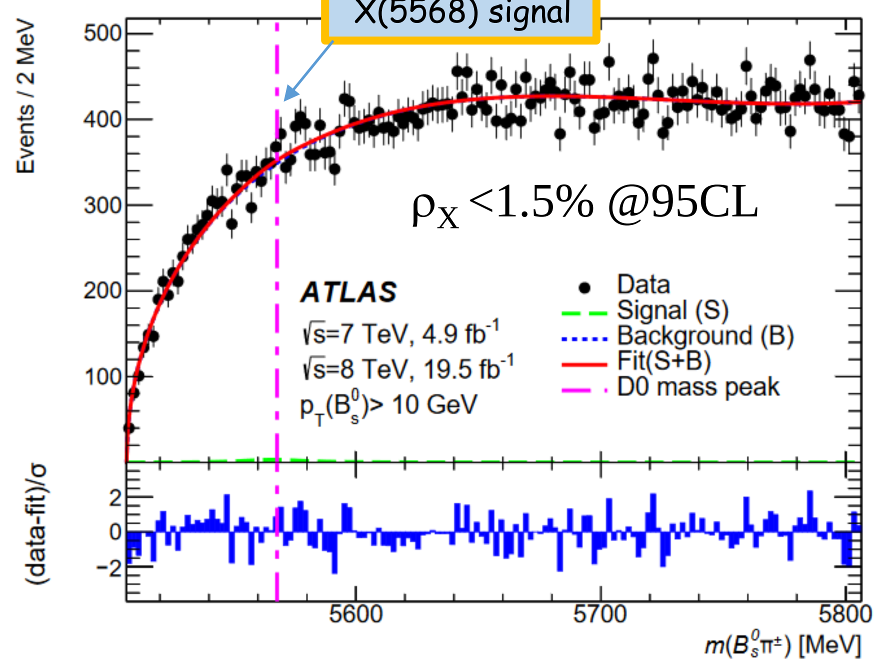
PRL 120 (2018) 202005

Comparison of Bs statistics

Factor **1.16** larger in CMS and **1.24** in ATLAS than LHCb reconstructed in the same momentum interval and for both ATLAS and CMS more than **9** larger than D0 sample.

No hints for X(5568) signal

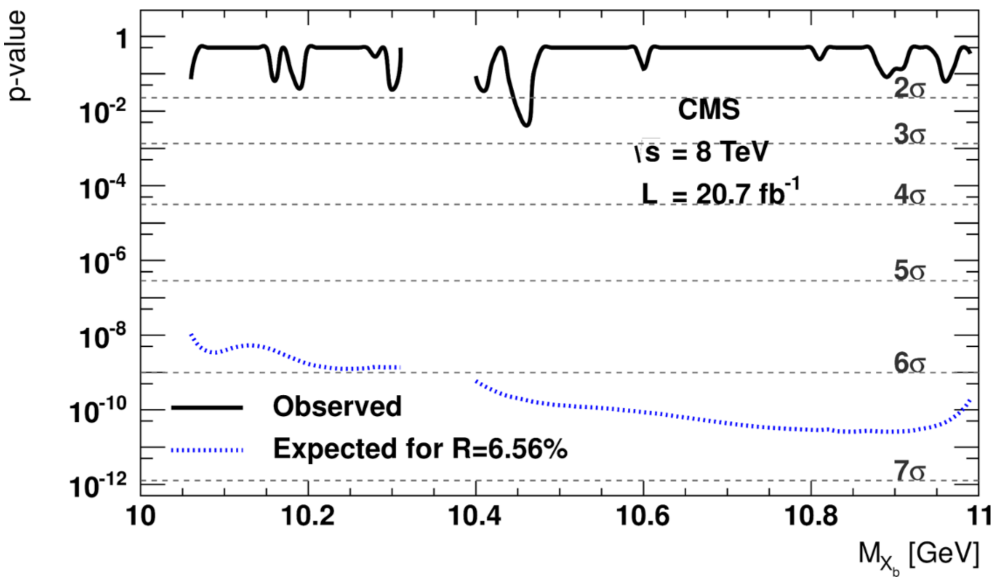


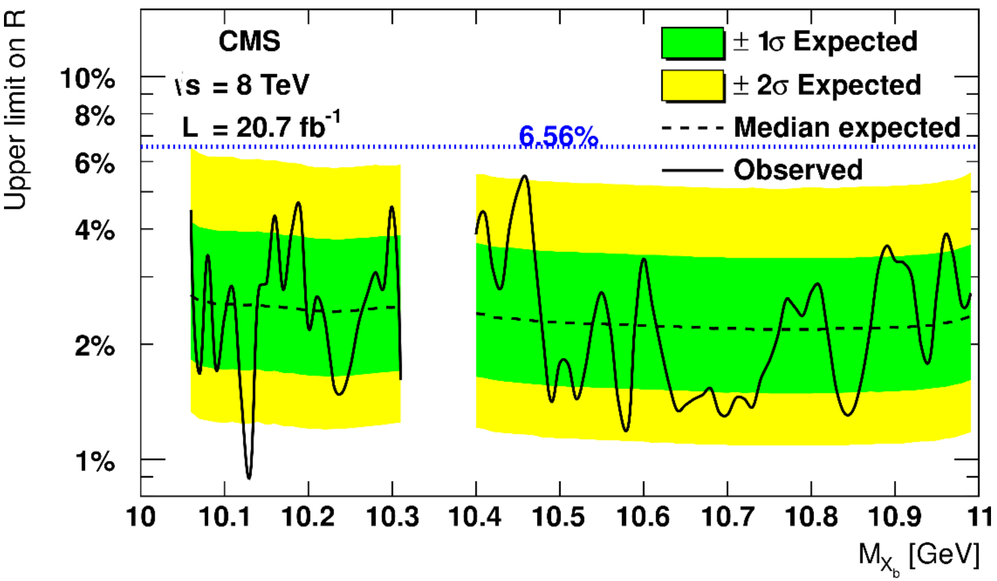


PRL 120 (2018) 202007

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

PLB 727 (2013) 57





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

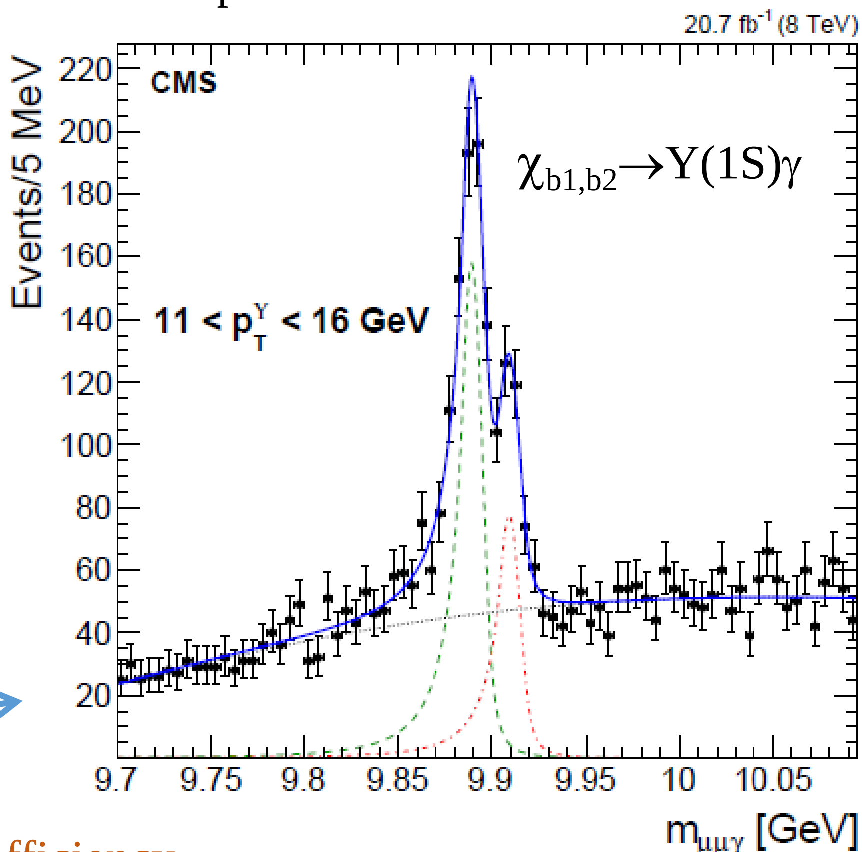
$$X_b \to \Upsilon(1S)\ \omega(\to \pi^+\pi^-\pi^0)$$

$$X_b \to \Upsilon(3S)\gamma$$

$$X_b \to \chi_{b1}(1P)\pi^+\pi^-$$

- 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.



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.