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Recent Results on Heavy Flavor from CMS

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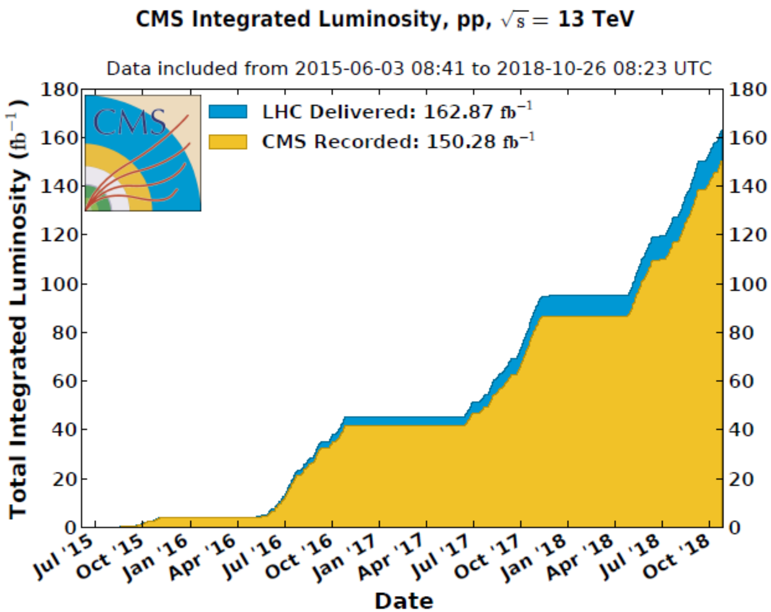
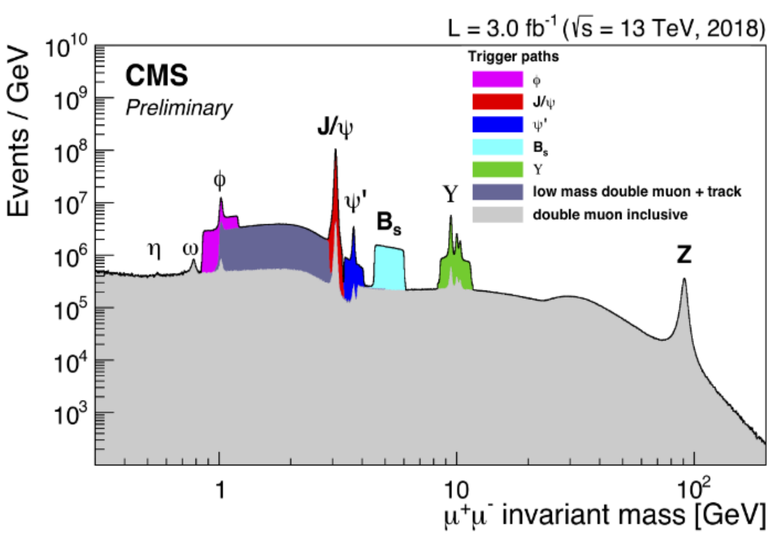
Outline:

1. Introduction
2. Selected highlights on heavy flavor from Heavy Ion collisions
3. Recent results on heavy flavor from pp collisions:
   - 3.1) Observation of two resolved states $\chi_{b1,2}(3P)$
   - 3.2) Study of $B_{s2}^*(5840)^0 \to B^+K^-$ and observation of $B_{s2}^*(5840)^0 \to B^0 K^0_s$
   - 3.3) Observation of two excited B_c^+ states and measurement of $B_c(2S)^+$ mass
   - 3.4) Study of $B^+ \to J/\psi\ \Lambda\ p$
   - 3.5) Search for charge-lepton flavor violating $\tau \to 3\mu$
4. Summary

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 selected recent highlights from 13 and 8 TeV data samples will be discussed

Highlights on heavy flavor from Heavy Ion collisions

CMS: Production of Λ_c^+ in pp and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

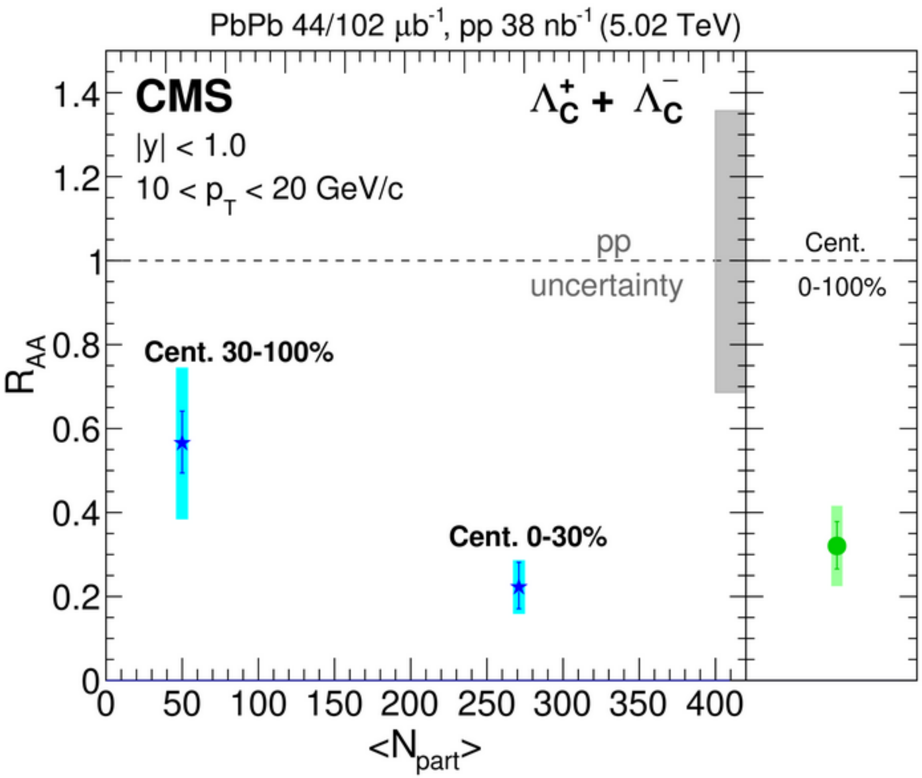
CMS PAS HIN-18-009

More details in Rui Xiao's talk

- Different mechanisms dominate the interaction between heavy quarks and the medium.
- In relativistic HI collisions, in addition to the fragmentation process in pp, hadron production can also occur via coalescence.
- The coalescence contribution to the baryons production is expected to be more significant than for mesons because of their large number of constituent quarks.

check it in experiment! (Λ_c^+ / D^0)

And also test the predictions for R_{AA} (Λ_c^+) !

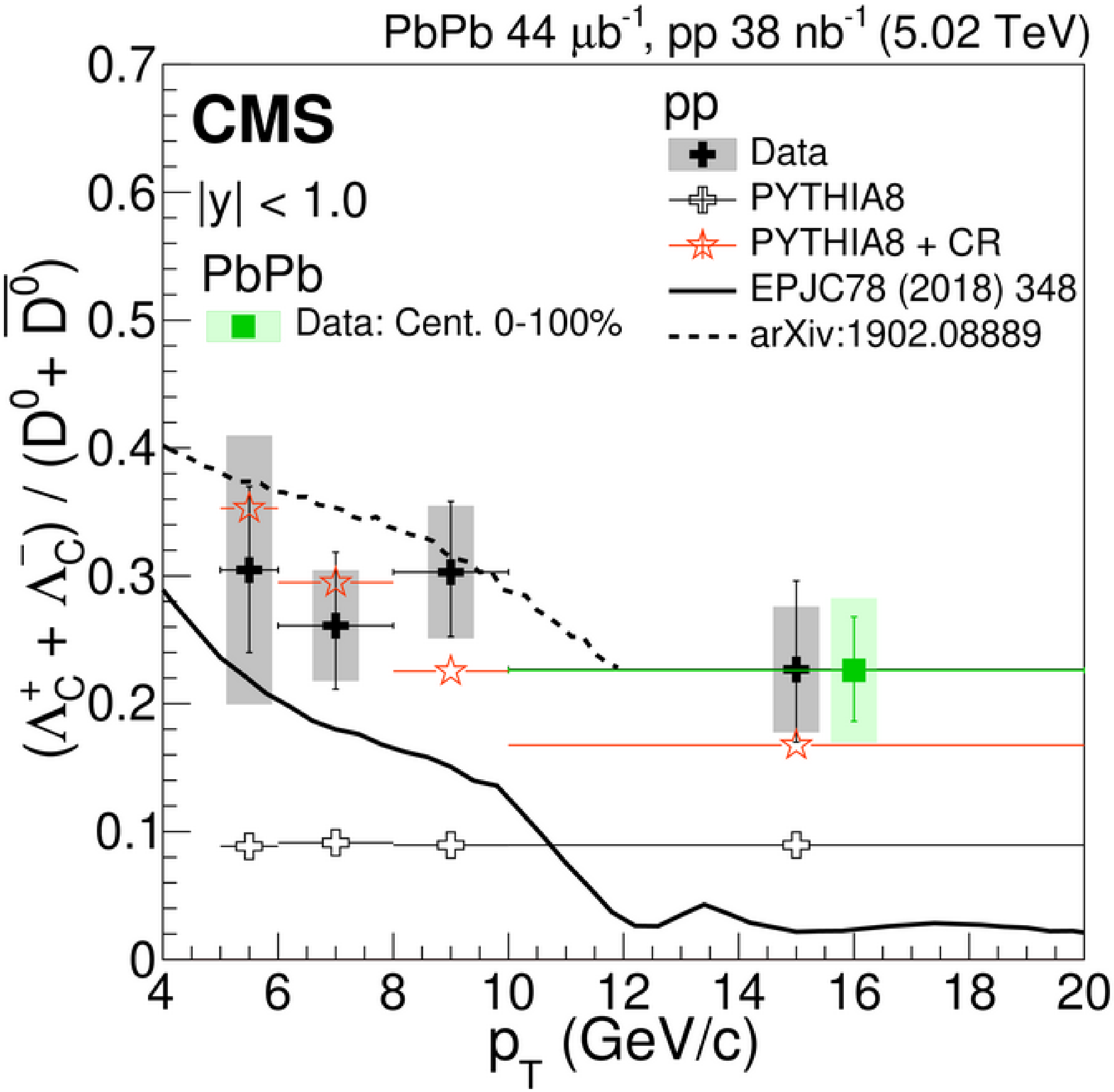


There is an indication that production of Λ_c^+ is suppressed in PbPb for pt>10 GeV

Moreover, the suppression is higher in more central PbPb collisions (~3.2σ)

CMS: Production of Λ_c^+ in pp and PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

CMS PAS HIN-18-009



More details and more comparisons with the predictions – in Rui Xiao's talk

PbPb ~ pp result in 10-20 GeV/c, suggests no significant contribution from coalescence in PbPb for p_T > 10

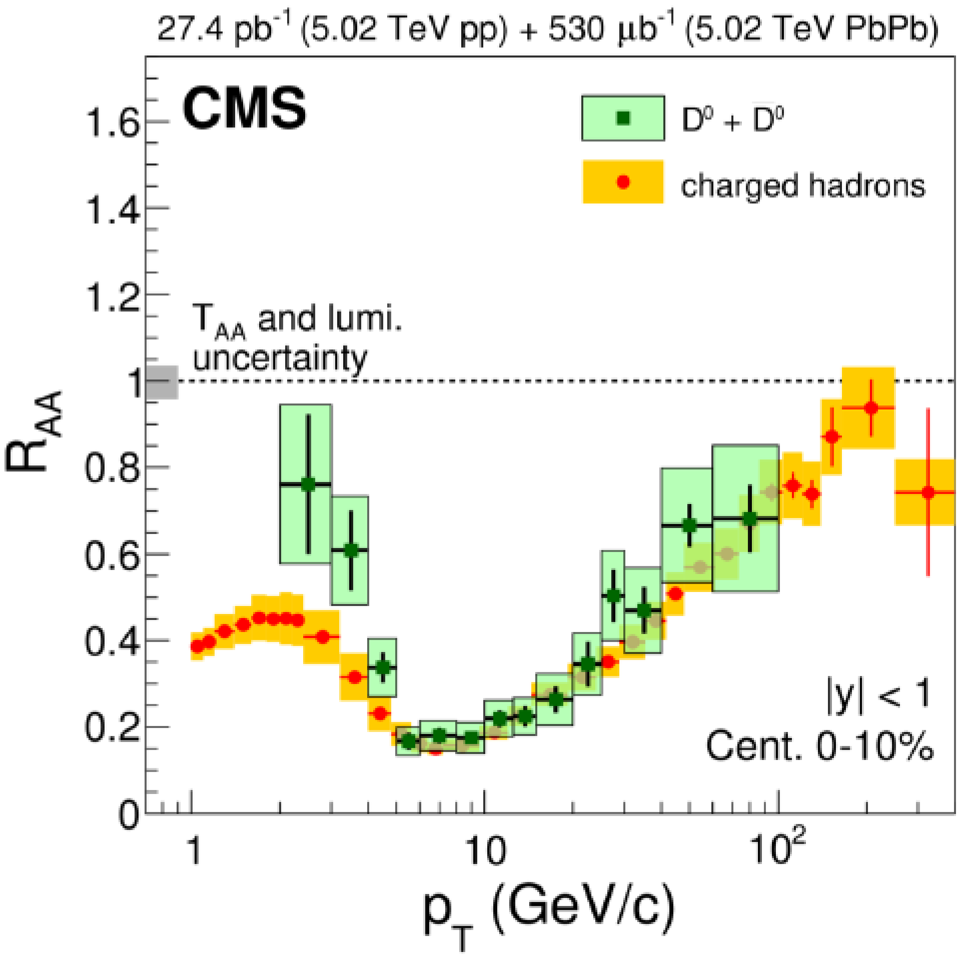
PYTHIA8 + color reconnection describes data.

JHEP 08 (2015) 003

More precise update with 2018 data!

CMS: Nuclear modification factor for D^0 in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

More details in
Cheng Chieh Peng's talk



D^0 R_{AA} at 5.02 TeV PbPb

- Strong suppression of D^0 R_{AA}
- $R_{AA}(D^0) \sim R_{AA}(h^{\pm})$ at high p_T
- $R_{AA}(D^0) > R_{AA}(h^{\pm})$ at low p_T

Charm quarks loose significant fraction of energy in QGP medium

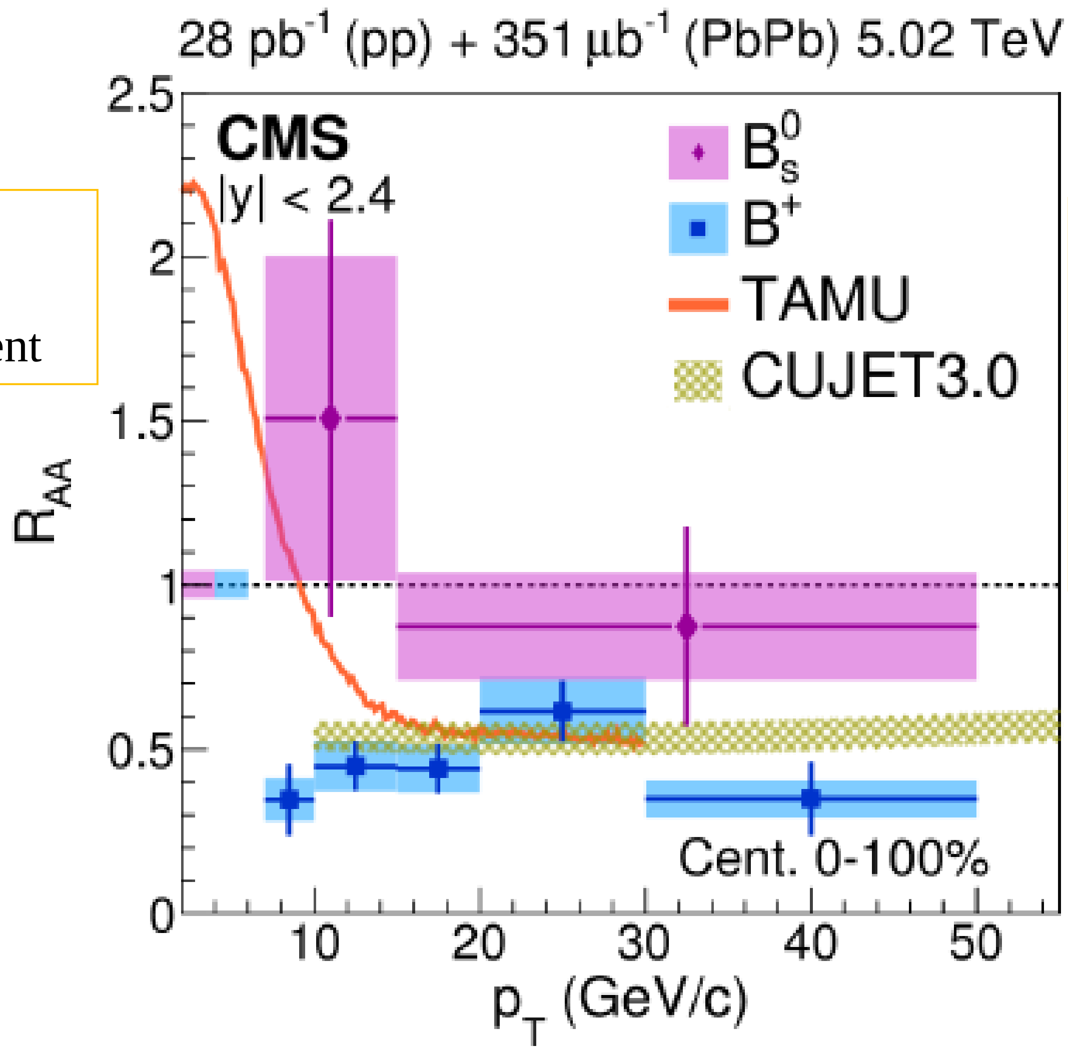
Phys.Lett. B 782, 474 (2018)

CMS: R_{AA} for B^+ and B_s^0 in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

More details in
Fuqiang Wang's talk

- Indication of less Bs suppression.
- With 2018 heavy ions data there will be more precise measurement

B^+ R_{AA} ~0.3—0.6 with
no evidence for any trend,
within uncertainties.
compatible with theory within
errors for pt 10-50 GeV

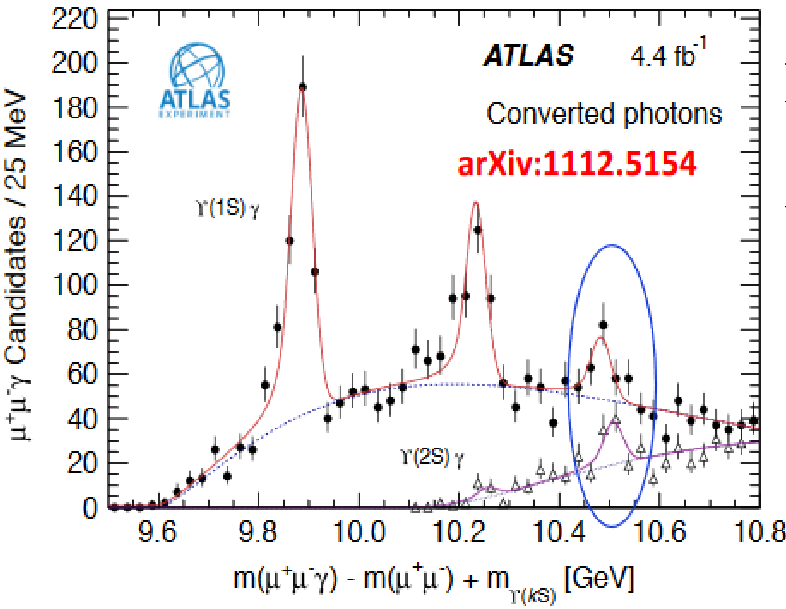


arXiv:1810.03022

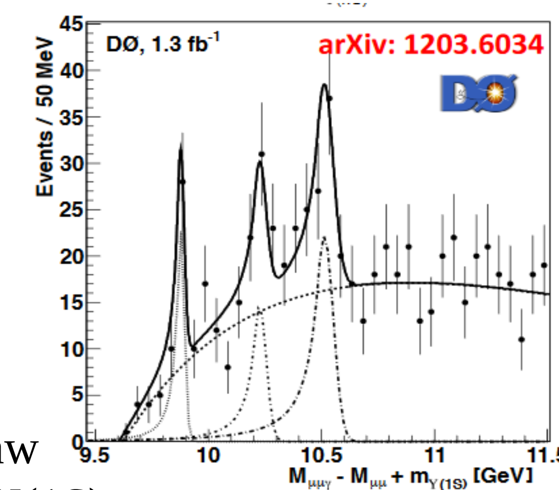
Highlights on heavy flavor from pp collisions

CMS: Observation of two resolved states $\chi_{b1,2}(3P)$

The history of the topic:

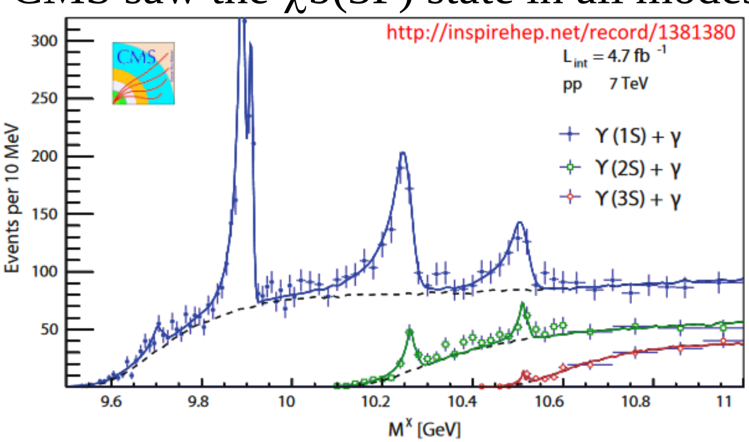


ATLAS observed the χb(3P) state as a new Structure in Υ(1S) γ and Υ(2S) γ decays.

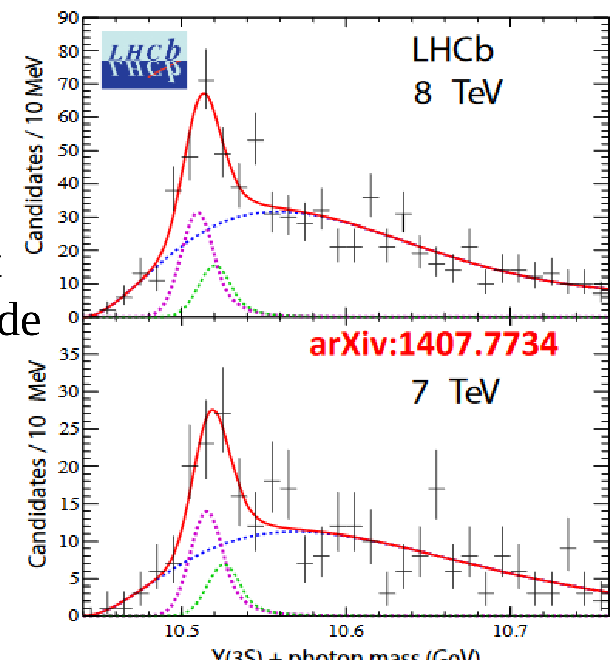


The D0 saw χb(3P)→Υ(1S)γ

CMS saw the χb(3P) state in all modes



LHCb confirmed it
In a new decay mode
Υ(3S) γ



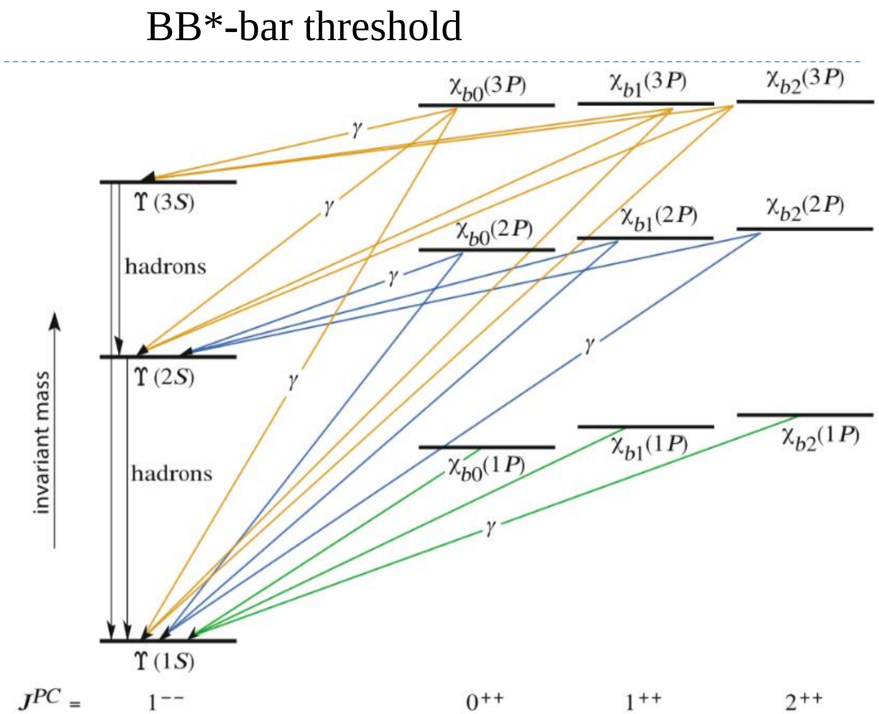
CMS: Observation of two resolved states $\chi_{b1,2}(3P)$

<u>Motivation:</u>

PRL 121 (2018) 092002

∗ The (bb-bar) family plays a special role in understanding how the strong force binds quarks.

Particularly stringent tests of current theories of quarkonium production can be achieved by examining the individual spin states of the quarkonium multiplets.

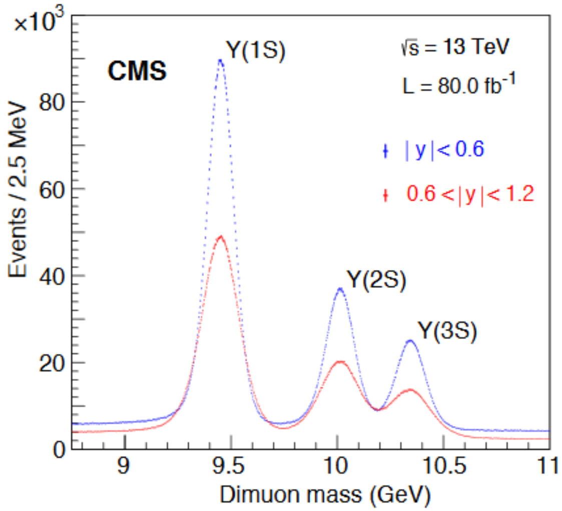


Picture from : V. Knünz, Measurement of Quarkonium Polarization to Probe QCD - *DOI 10.1007/978-3-319-49935-2_2*

• Measurements of the masses of the $\chi_{bJ}(3P)$ triplet states probe details of the bb-bar interaction and test theoretical treatments of the influence of open-beauty states on the bottomonium spectrum.

• The observation of a doublet structure in the 10.5 GeV peak should confirm the nature of the state and clarify the existence or absence of effects induced by the nearby open-beauty threshold.

CMS: Observation of two resolved states $\chi_{b1,2}(3P)$



PRL 121 (2018) 092002

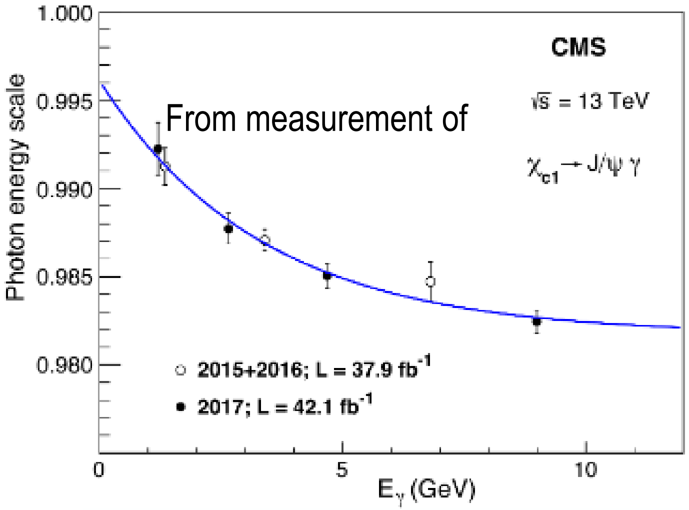
← Upsilon(1,2,3S) sample

- Analyzing the full LHC Run 2 dataset (**13 TeV, 80 fb^{-1}**), CMS has **observed for the first time** the split in the **χ_{b1} (3P) - χ_{b2} (3P) doublet** and measured the masses of the two states

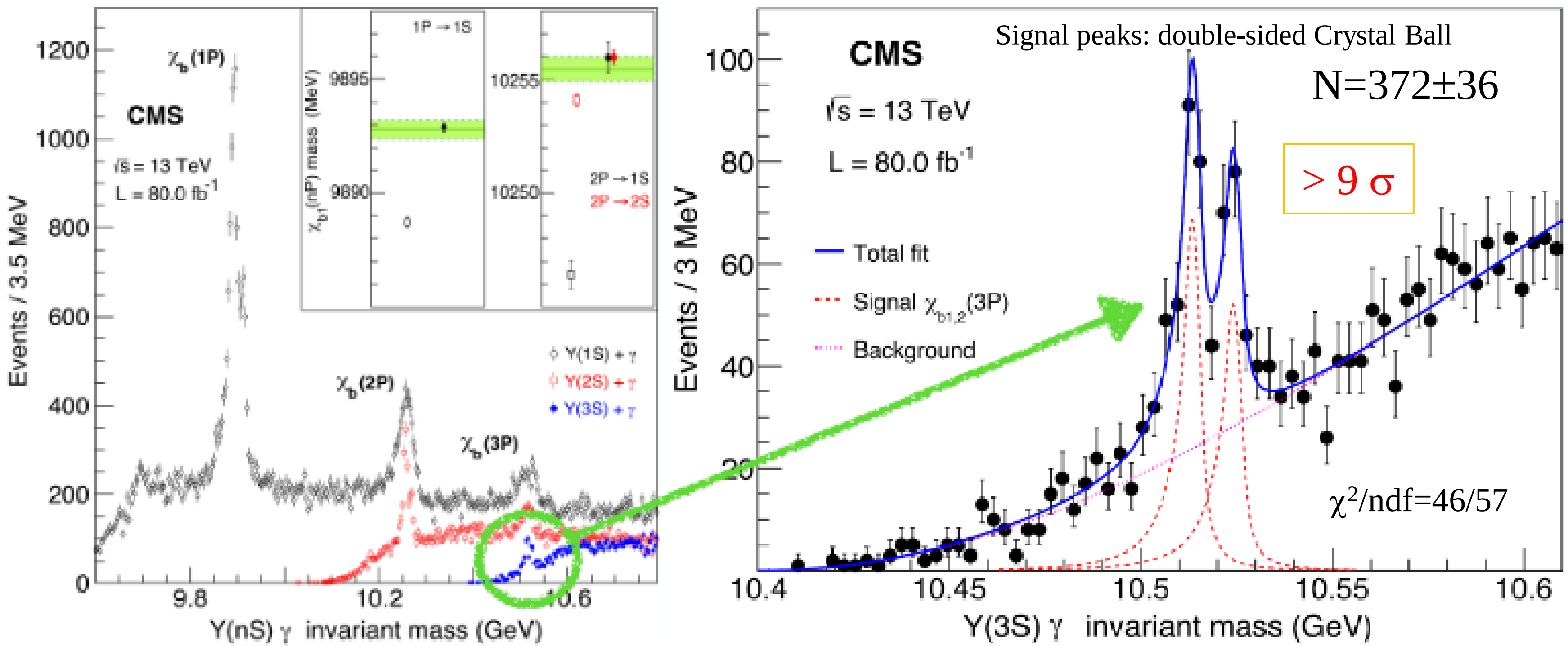
- **χ_b (3P)** is reconstructed in **Υ(3S) + γ** mode. The low energy **γ** is detected through **$\gamma \to e^+e^-$** conversion inside the silicon tracker

- Photon energy scale is calibrated using high yield **$\chi_{c1} \to J/\psi + \gamma$** samples for high accuracy mass measurements

- Tested with **χ_b (1P, 2P)** states



CMS: Observation of two resolved states $\chi_{b1,2}(3P)$



PRL 121 (2018) 092002

M_1 = 10513.42 ± 0.41(stat) ± 0.18(syst) MeV

M_2 = 10524.02 ± 0.57(stat) ± 0.18(syst) MeV

ΔM = 10.6 ± 0.64(stat) ± 0.17(syst) MeV

This result strongly disfavours the breaking of the conventional pattern of splittings and supports the standard mass hierarchy.

J=1,2 states well resolved for the first time

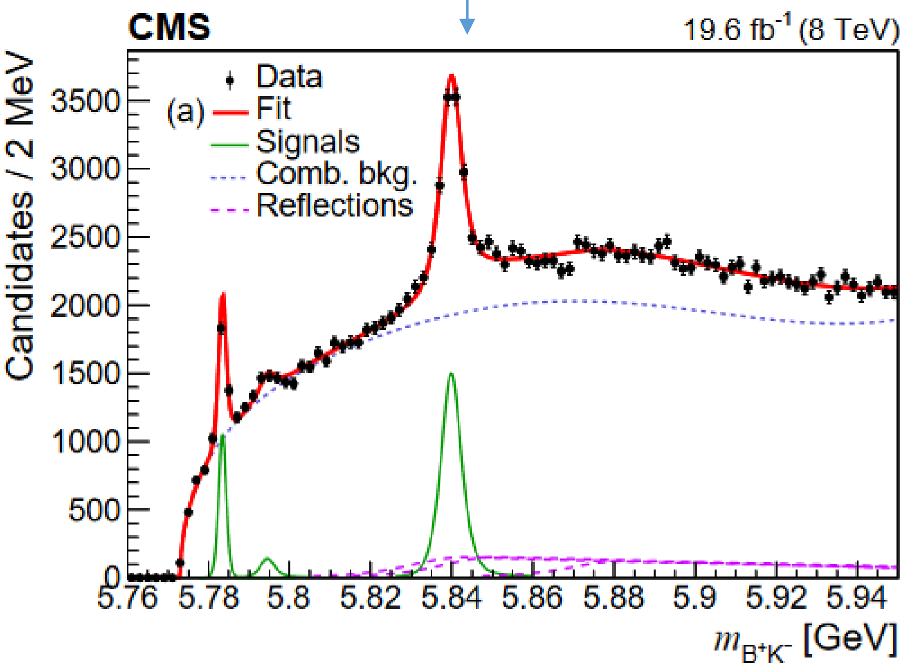
Significantly constrains theoretical predictions, which give mass splits in the range [-2, 18] GeV

This measurement fills a gap in the spin-dependent bottomonium spectrum below the open-beauty threshold and should significantly contribute to an improved understanding of the non-perturbative spin-orbit interactions affecting quarkonium spectroscopy.

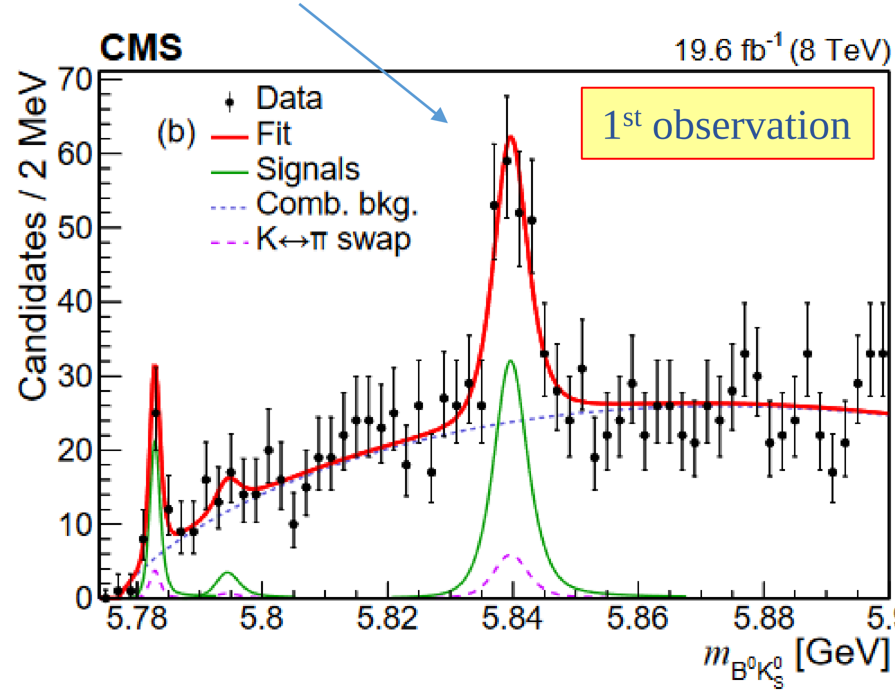
CMS: Studies of $B_{s2}^*(5840)^0$ and $B_{s1}(5830)^0$ decaying into B^+K^- and observation of $B_{s2}^*(5840)^0 \rightarrow B^0 K_s^0$

EPJC (2018) 78:939

$B_{s2}^*(5840)^0 \rightarrow B^+ K^-$



$B_{s2}^*(5840)^0 \rightarrow B^0 K_s^0$



Masses, ΔM and ratios of σ∗Br measured.
Results are in agreement with existing measurements by CDF and LHCb

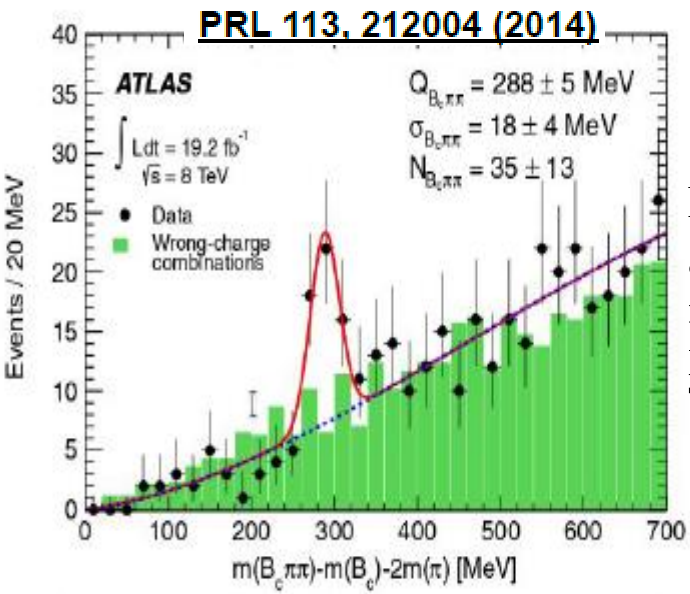
LHCb 2013: doi:10.1103/PhysRevLett.110.151803
CDF 2014: doi:10.1103/PhysRevD.90.012013

First observation of the decay $B_{s2}^* \rightarrow B^0 K_s^0$

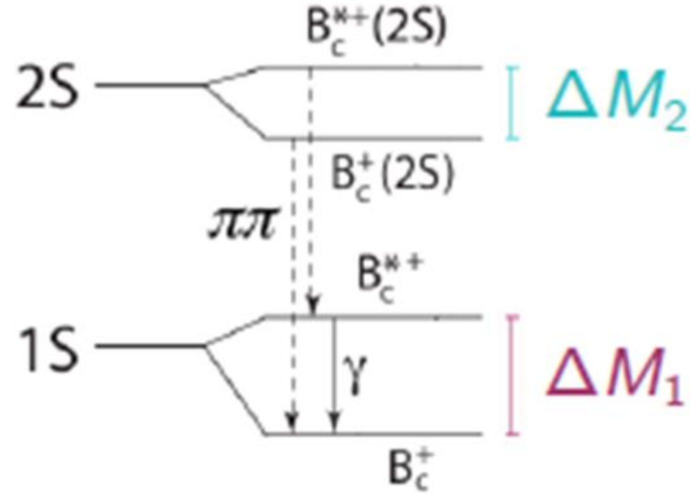
First evidence of the decay $B_{s1} \rightarrow B^{*0} K_s^0$

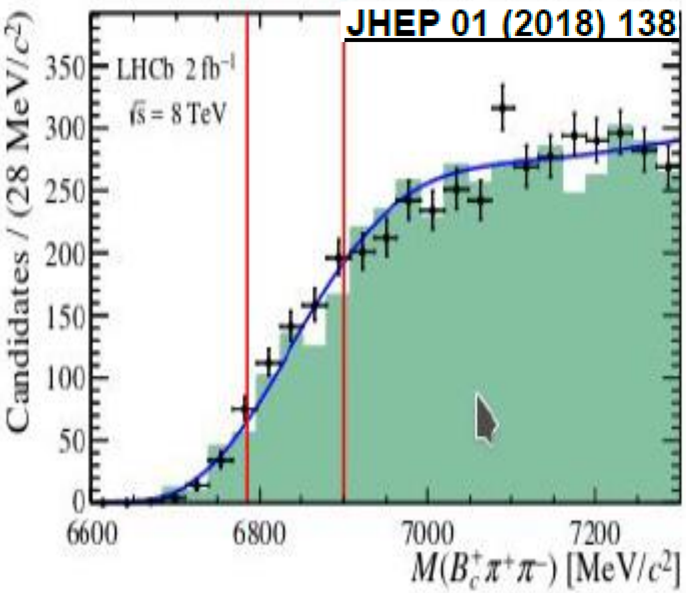
Excited B_c^+ states

The spectrum of B_c (bc) states will help to understand in a greater depth the dynamics of heavy-heavy quark systems



ATLAS reported the observation (5.4σ) of a new state with mass consistent with predictions for the Bc(2S)+. They used Run I data.





LHCb with 3325+-73 Bc+ (8 TeV data): "no significant signal is found"

[$M(B_c(1S)^*)$ - $M(B_c(1S))$] > [$M(B_c(2S)^*)$ - $M(B_c(2S))$]

$B_c(2S)^* \rightarrow B_c^* \pi^+ \pi^-$ followed by $B_c^* \rightarrow B_c \gamma_{lost}$

$B_c(2S) \rightarrow B_c \pi^+ \pi^-$

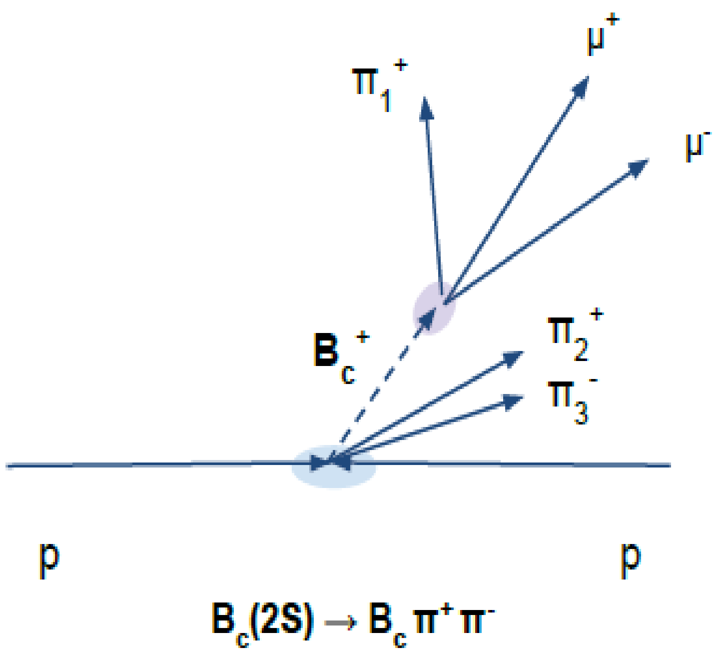
Two-peak structure with the $B_c(2S)^*$ peak at a mass shifted by

ΔM = [$M(B_c^*)$ - $M(B_c)$] - [$M(B_c(2S)^*)$ - $M(B_c(2S))$]

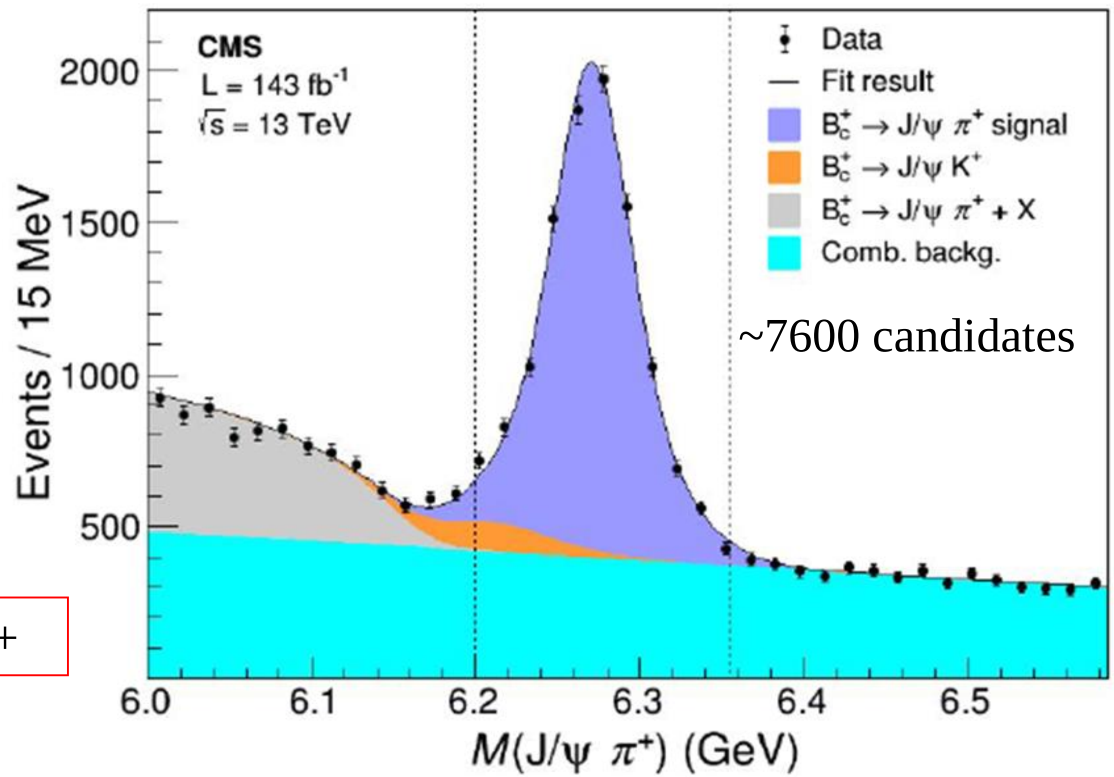
Theory predicts ~20 MeV

CMS: Selection of excited B_c^+ candidates

[Phys.Rev.Lett. 122 (2019) 132001]



Reconstructed ground state Bc+



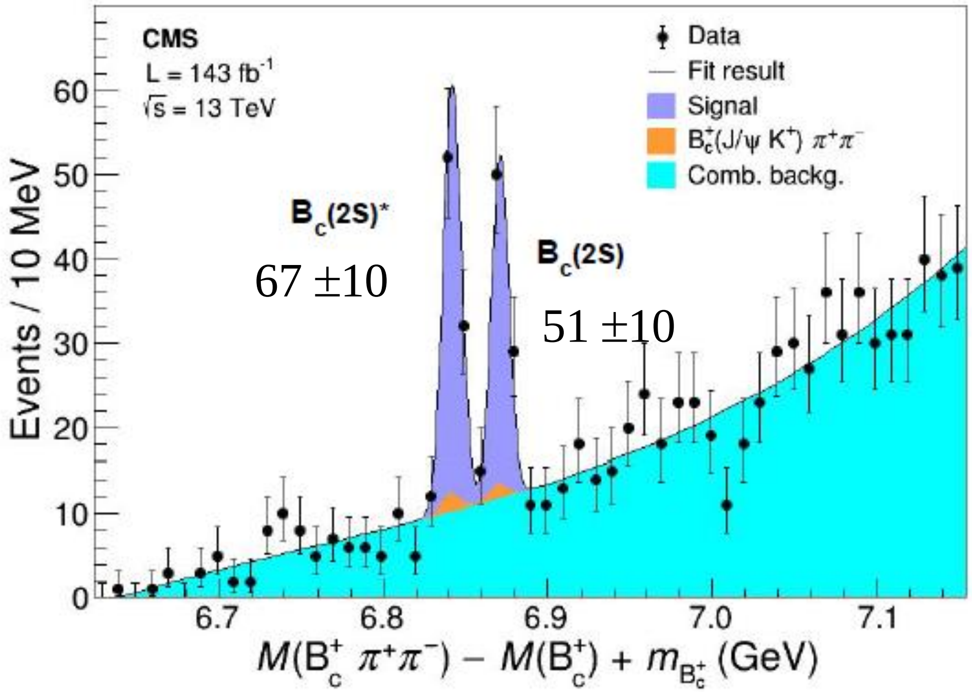
~7600 candidates

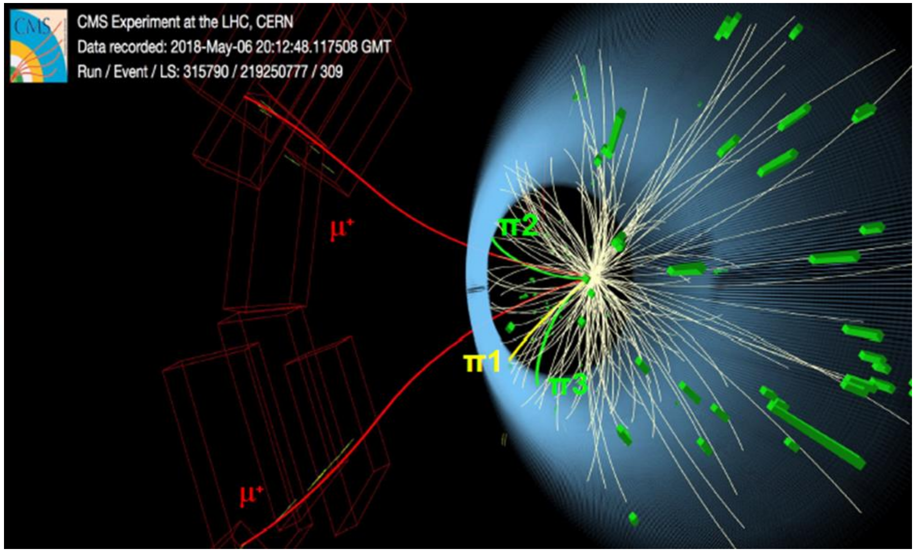
Full Run II data analysis, Bc+ → J/ψ π+

Selection:
Pt(pi1 –from Bc) >3.5 GeV;
Bc meson momentum (pt>15 GeV) should point to the PV in xy;
Pi2 (pt>0.8) and pi3 (pt>0.6) are tracks from PV which are combined with Bc+;
keep only one Bc+ pi2 pi3 combination with highest pt.

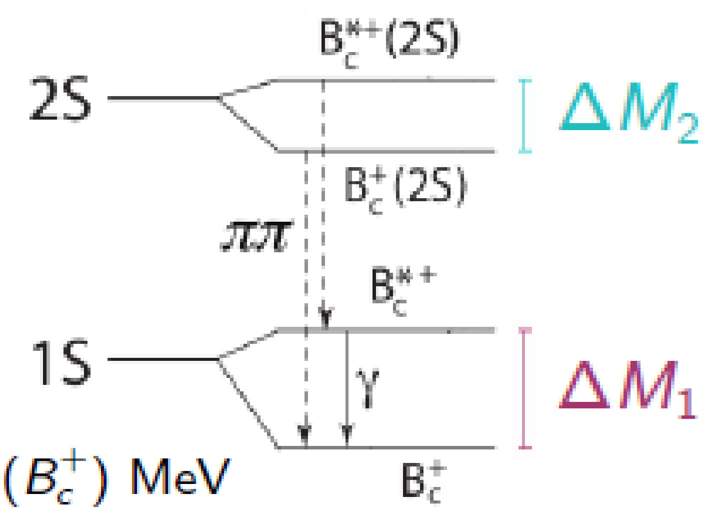
CMS: Observation of two excited B_c^+ states and measurement of $B_c(2S)^+$ mass

[Phys.Rev.Lett. 122 (2019) 132001]





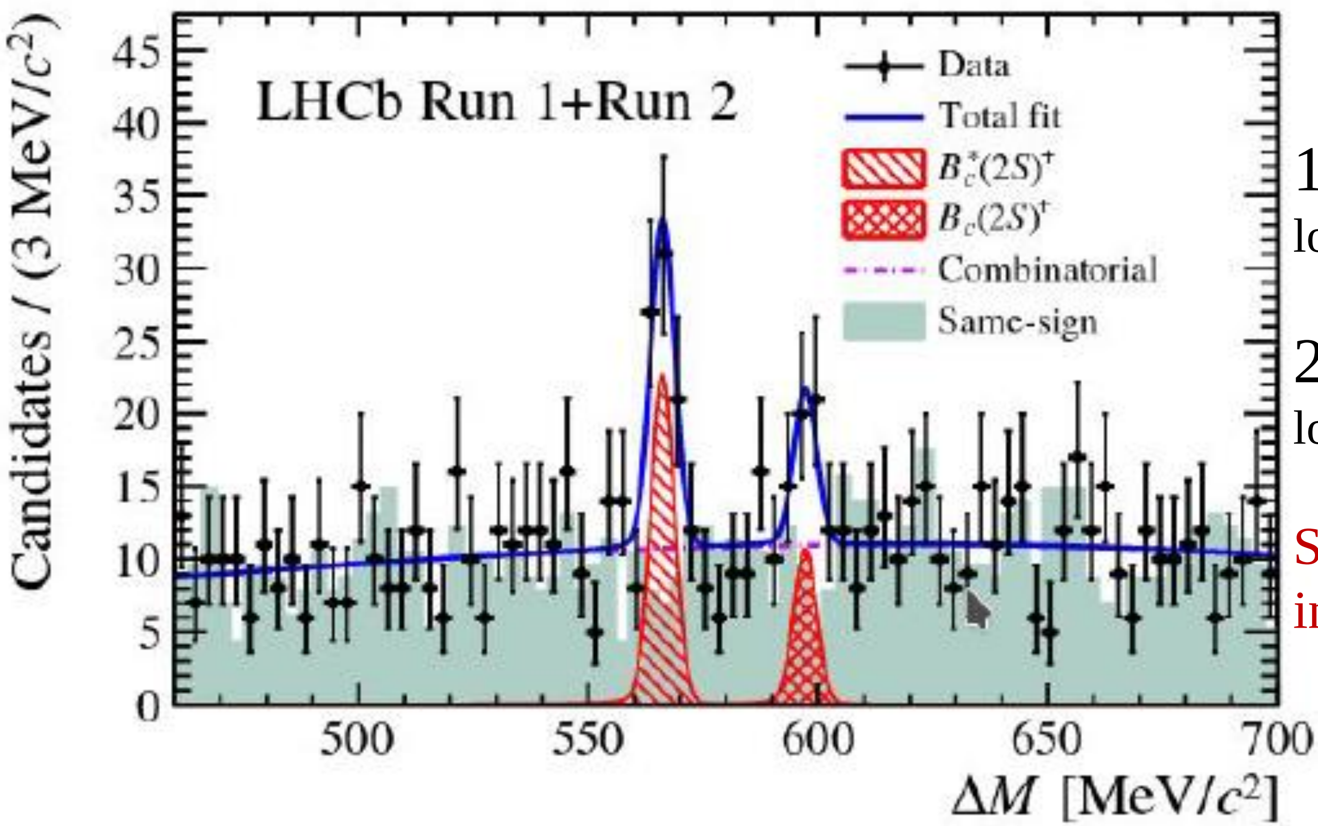
Mass resolution from MC ~ 6 MeV



Two-peak structure observed, well resolved:
$\Delta M = \Delta M1 - \Delta M2 = 29.1 \pm 1.5 \pm 0.7$ MeV,
each with > 5 σ significance

Mass of Bc+(2S): $6871.0 \pm 1.2(\text{stat}) \pm 0.8(\text{syst}) \pm 0.8(B_c^+)$ MeV

LHCb has confirmed the two-peaks structure



arXiv: 1904.00081,
submitted to PRL

1^{st} peak:
local signif.=6.8σ, N=51±10

2^{nd} peak:
local signif.=3.2σ, N=24±9

Smaller yields
in comparison with CMS.

The mass of Bc(2S)+ and ΔM are in agreement with CMS
and statistical errors are similar:

	$M(B_c(2S)^+)$, MeV	ΔM, MeV
CMS	$6871.0 \pm 1.2 \pm 0.8 \pm 0.8$	$29.1 \pm 1.5 \pm 0.7$
LHCb	$6872.1 \pm 1.3 \pm 0.1 \pm 0.8$	$31.0 \pm 1.4 \pm 0.0$

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

CMS-PAS-BPH-18-005

Motivation and experimental situation

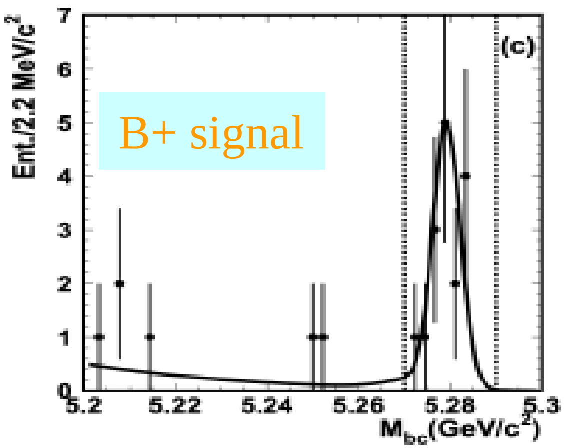
$M(J/\psi\bar{\Lambda})$ and $M(J/\psi p)$ study

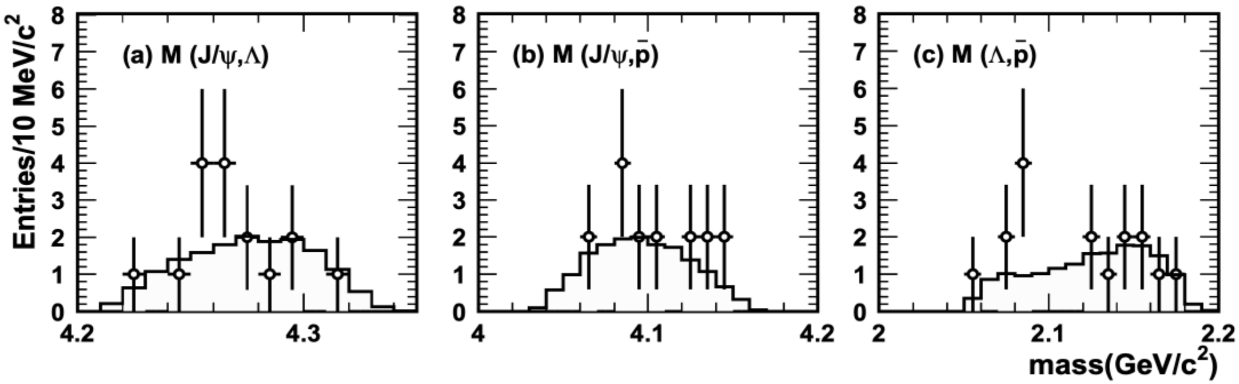
The study is motivated by the recent observation of P^+_c states by LHCb collaboration in $J/\psi p$ system. This decay provides a possibility to study both $J/\psi\Lambda$ and $J/\psi p$ systems.

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





Only 16 events in the signal region

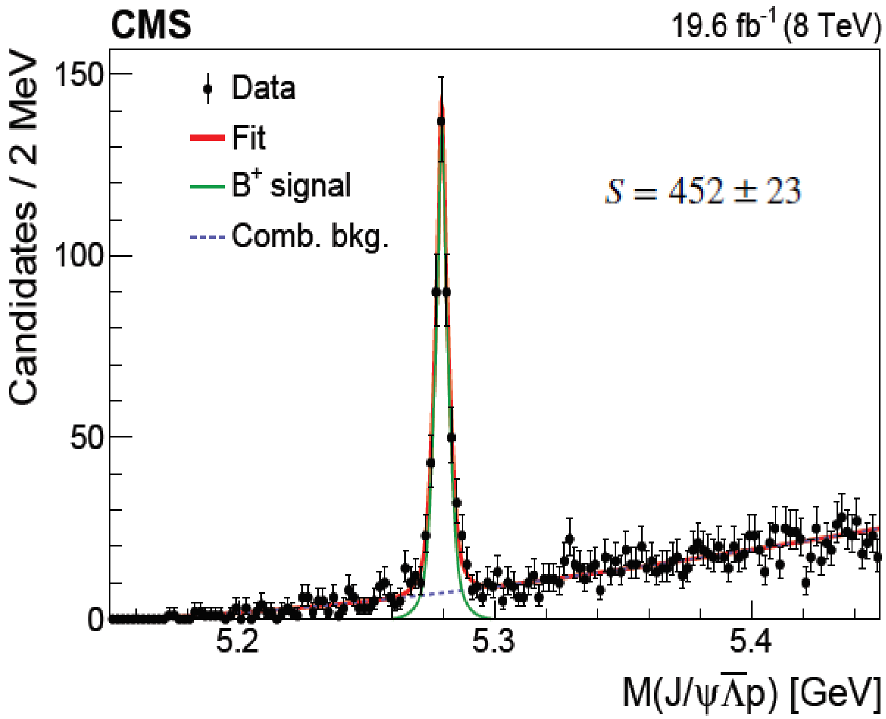
Br.fr.= $(11.6 \pm 2.8\ ^{+1.8}_{-2.3}) \times 10^{-6}$

Also, LHCb Collaboration recently observed $B_c^+ \to J/\psi\, pp\pi$,[1] $B_s^0 \to J/\psi\, pp$ and $B^0 \to J/\psi\, pp$ [2] but no studies of $J/\psi\, p$ masses have been reported.

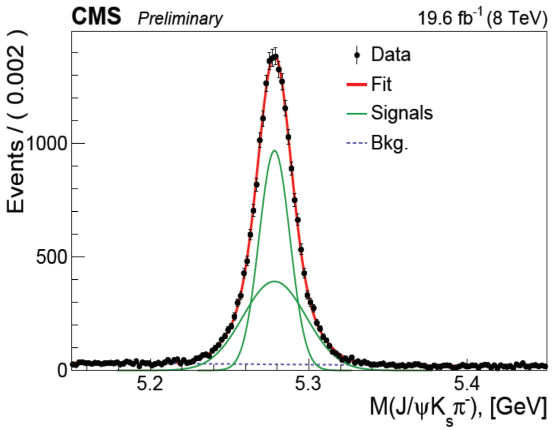
[1] PRL 113 (2014) 153003 ; [2] PRL 122 (2019) 191804.

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

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

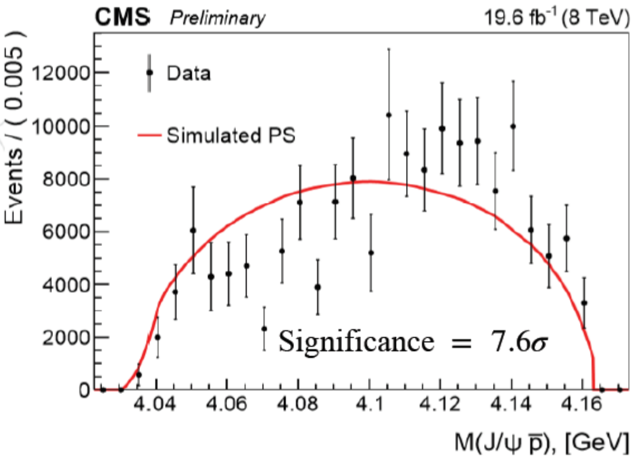
PDG mean value of $\mathcal{B}(B^+ \to J/\psi\bar{\Lambda}p) = (11.8 \pm 3.1) \times 10^{-6}$

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

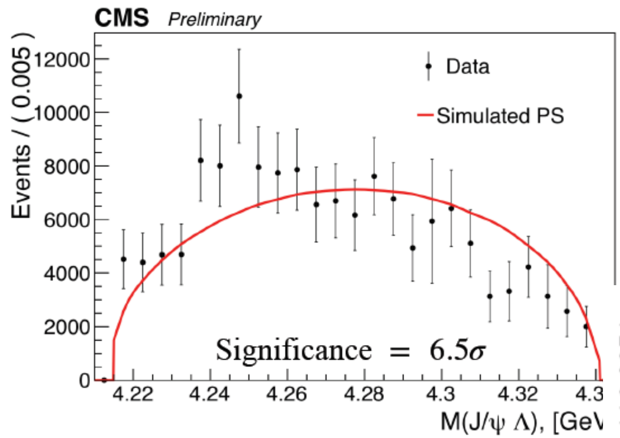
CMS-PAS-BPH-18-005

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

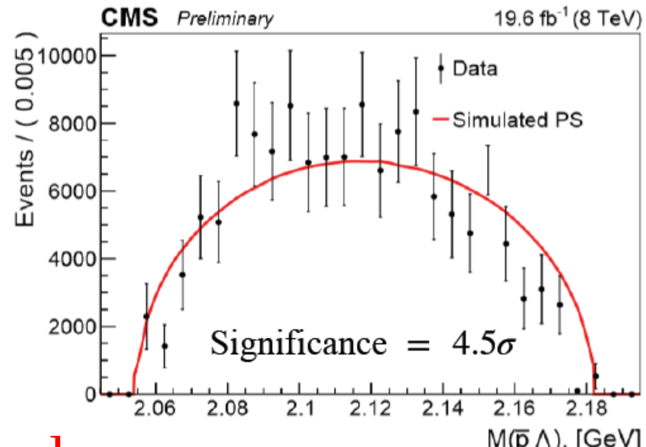
Comparison of phase space MC with efficiency corrected data



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

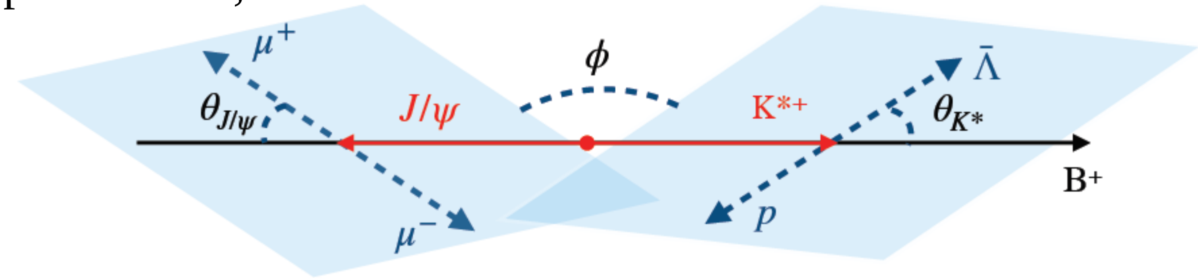
CMS: Study of $B^+ \to J/\psi\,\bar{\Lambda}\,p$

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 θ_{K^*} is the helicity angle defined as the angle between Λ momentum and B+ momentum in the Λp rest frame;

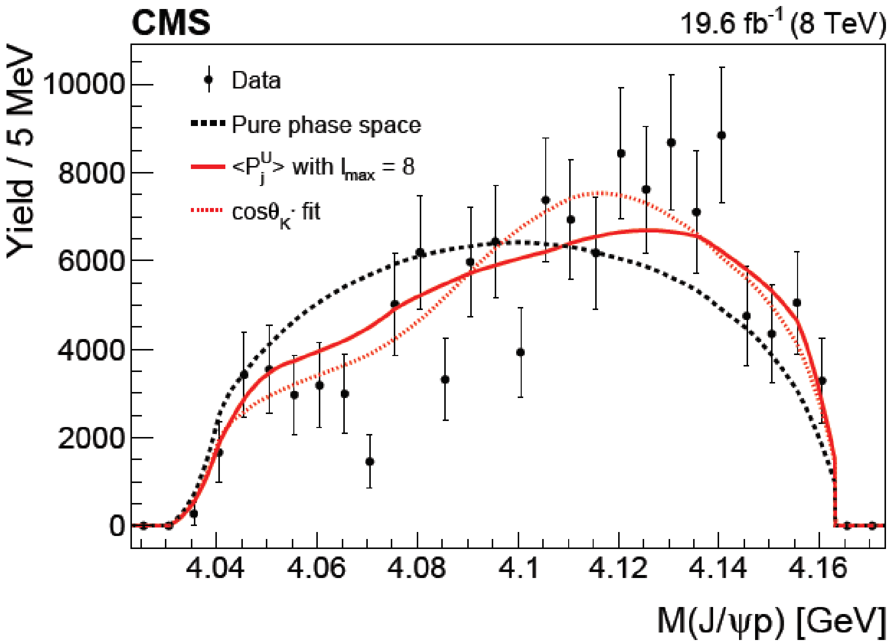


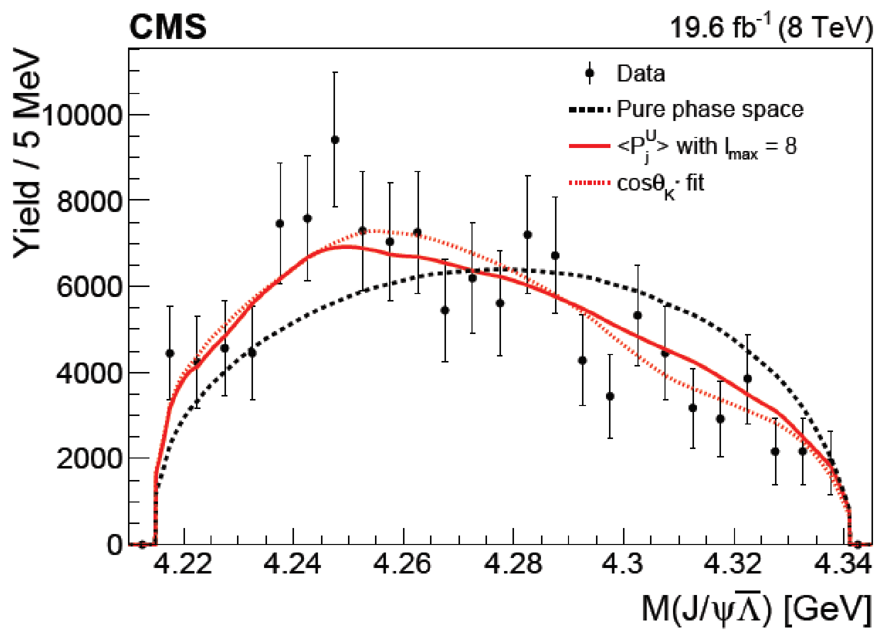
- For l_{max} = 2xJ, where J is the total spin of the highest-spin K*, one can take into account all these K* → Λp.
- From table l_{max} = 2x4=8.

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^+

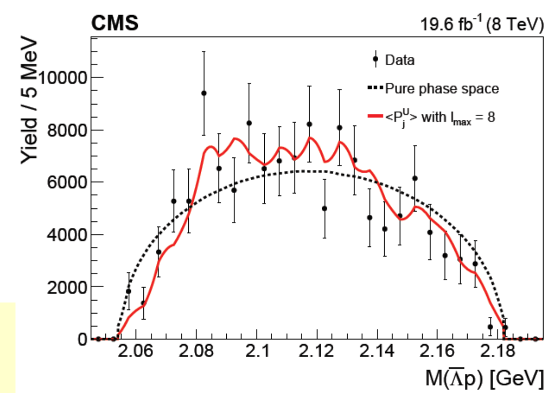
CMS: Study of $B^+ \to J/\psi\,\bar{\Lambda}\,p$

Simulation reweighting according to the observed structure in Λp





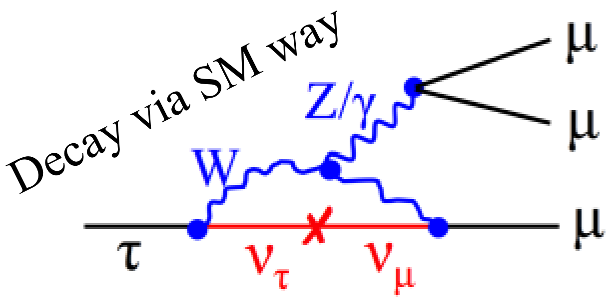
A model-independent approach that accounts for the contribution from known K*'s with spins up to 4 in the Λp system improves the agreement with data significantly!



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

CMS: Search for charge-lepton flavor violating $\tau \to 3\mu$

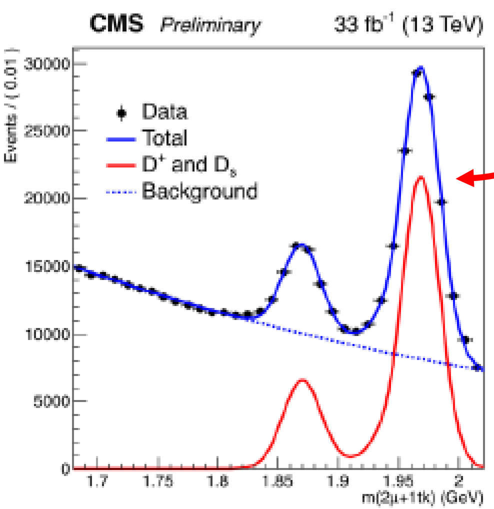
- Many New-Physics models predict Br.fr. enhancement
- Previous searches were performed by
  Belle[1], BaBar[2], LHCb[3], ATLAS[4]



[1]Phys. Lett. B687 (2010) 139143
[2]Phys. Rev. D81 (2010) 111101
[3]JHEP 02 (2015) 121
[4]Eur. Phys. J. C (2016) 76:232

- Most stringent limit by Belle[1]: Br.fr < 2.1 10^{-8} @90%CL

- **New** CMS analysis: search for $\tau \to 3\mu$ in a sample of τ's produced in D and B decays using data collected in 2016 (33 fb^{-1})

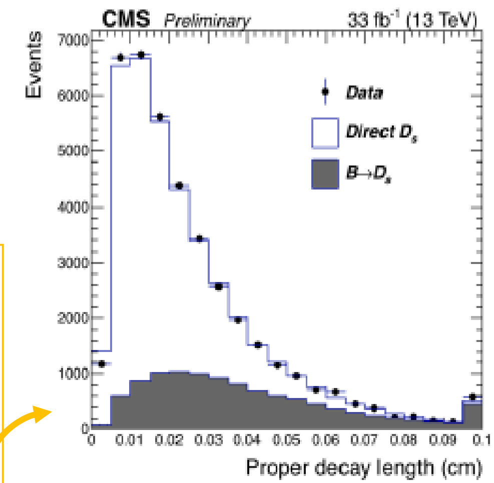


Normalization channel
$D_s^+ \to \phi\pi^+ \to (\mu^+\mu^-)\pi^+$

Fraction of Ds+ from B decays

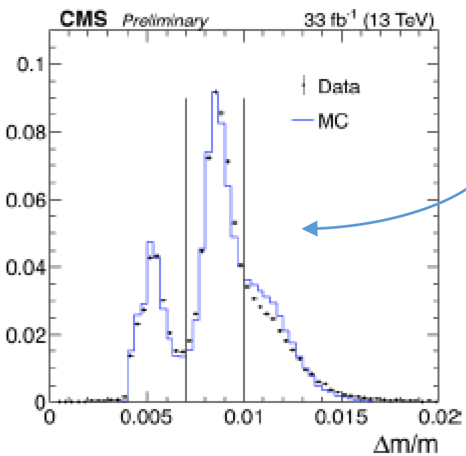
$$f = \frac{\sigma(pp \to B)\mathcal{B}(B \to D_s + ...)}{\sigma(pp \to D_s)}$$

is extracted from a template fit to the proper decay length



CMS: Search for $\tau \rightarrow 3\mu$

CMS-PAS-BPH-17-004



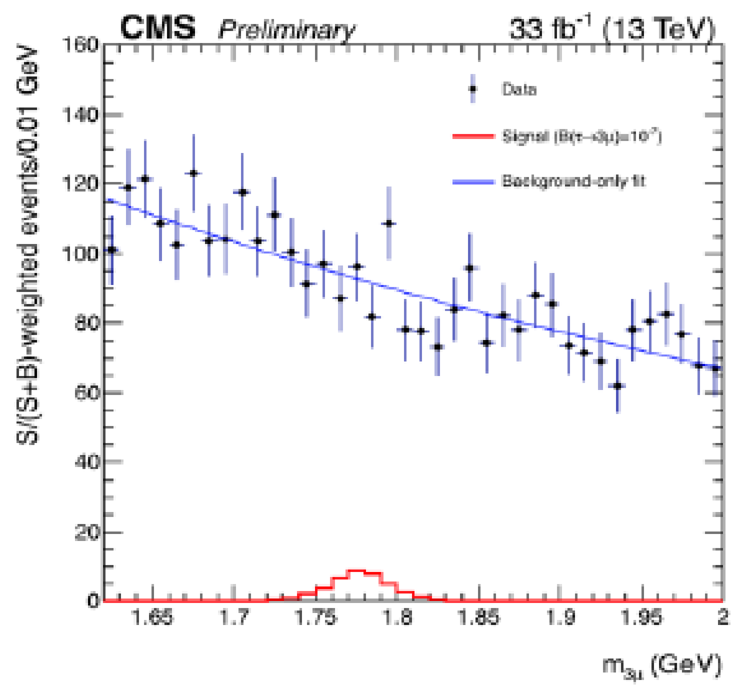
- 3 categories by mass resolution due to different muon rapidity;

- then train BDT discriminator using vertex and muon qualities; output for each resolution category divided into 3 categories (1 is rejected)

- ML fit performed simultaneously on the 6 categories

Weighted combination

No excess is observed in the signal region



Extracted UL @ 90% CL:
$Br(\tau \rightarrow 3\mu) < 8.8 \times 10^{-8}$

Although designed for high-pt physics, CMS is good experiment for heavy flavor physics for both pp and PbPb collisions!

Summary

- New results on Heavy Flavor form HI collisions:
  - measurement of Λc pt spectrum, R_{AA} and Λc/D^0
  - measurement of D^0 suppression
  - measurement of B+ and Bs^0 R_{AA}
- First observation of two resolved states $\chi_{b1,2}(3P)$:
  measurement of their masses and mass difference.
- Study of $B_{s2}^*(5840)^0 \rightarrow B^+K^-$ and observation of $B_{s2}^*(5840)^0 \rightarrow B^0 K^0_s$:
  measurement of many mass values and ratios of production Xsection;
  many of them for the first time.
- Observation of two excited Bc+ states and measurement of Bc(2S)+ mass:
  first observation of two distinct states Bc(2S)+ and Bc(2S)*+.
- Study of $B+ \rightarrow J/\psi\ \Lambda\ p$:
  the accuracy in measured Br.fr. is the best to date;
  the study of 2-body inv.mass distributions resulted in conclusion
  that no new resonances are needed.
- Search for charged lepton flavor violating decay $\tau \rightarrow 3\mu$
  no excess observed, UL set: Br.fr. $< 8.8\times10^{-8}$ @90% CL.

Backup slides