B decays and other spectroscopy/resonance results from CMS

The 11th annual conference on Large Hadron Collider Physics
26.05.2023

Maksim Sergeev[1] and Sergey Polikarpov[1,2] on behalf of the CMS Collaboration

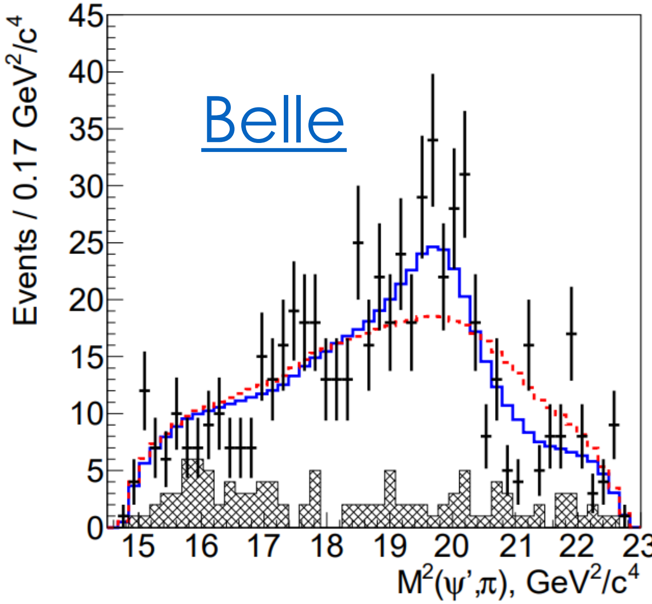
1 NRNU MEPhI, 2 LPI RAS

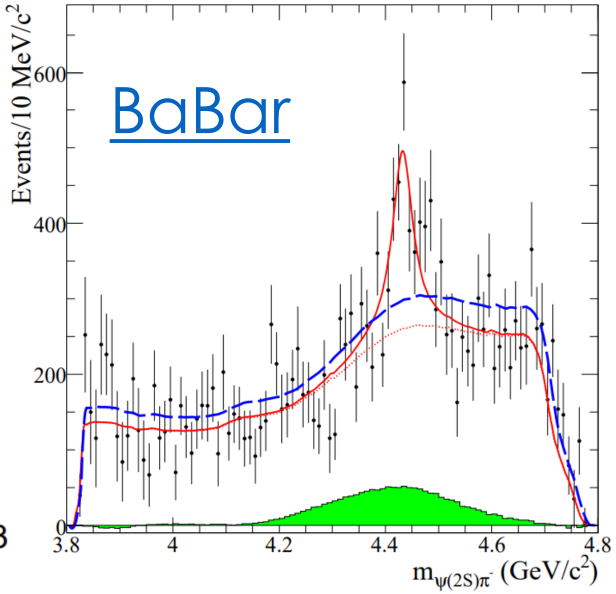
Work is supported by MEPhI program "Priority2030"

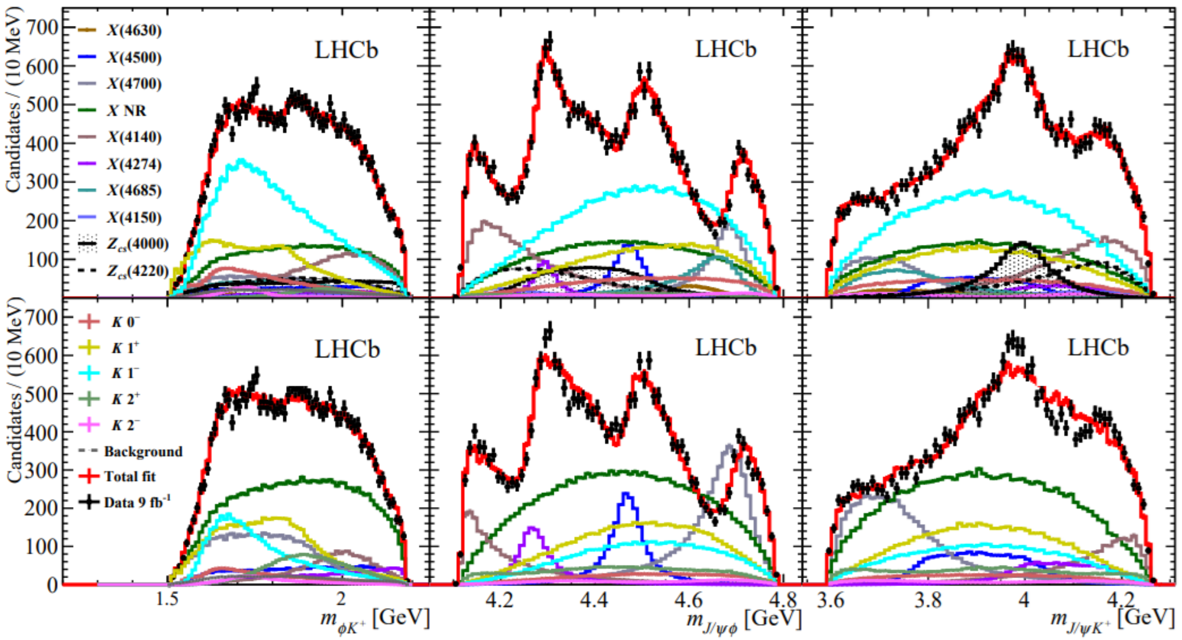
Observation of $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_S$ decays

Eur.Phys.J.C 82 (2022) 499

Motivation





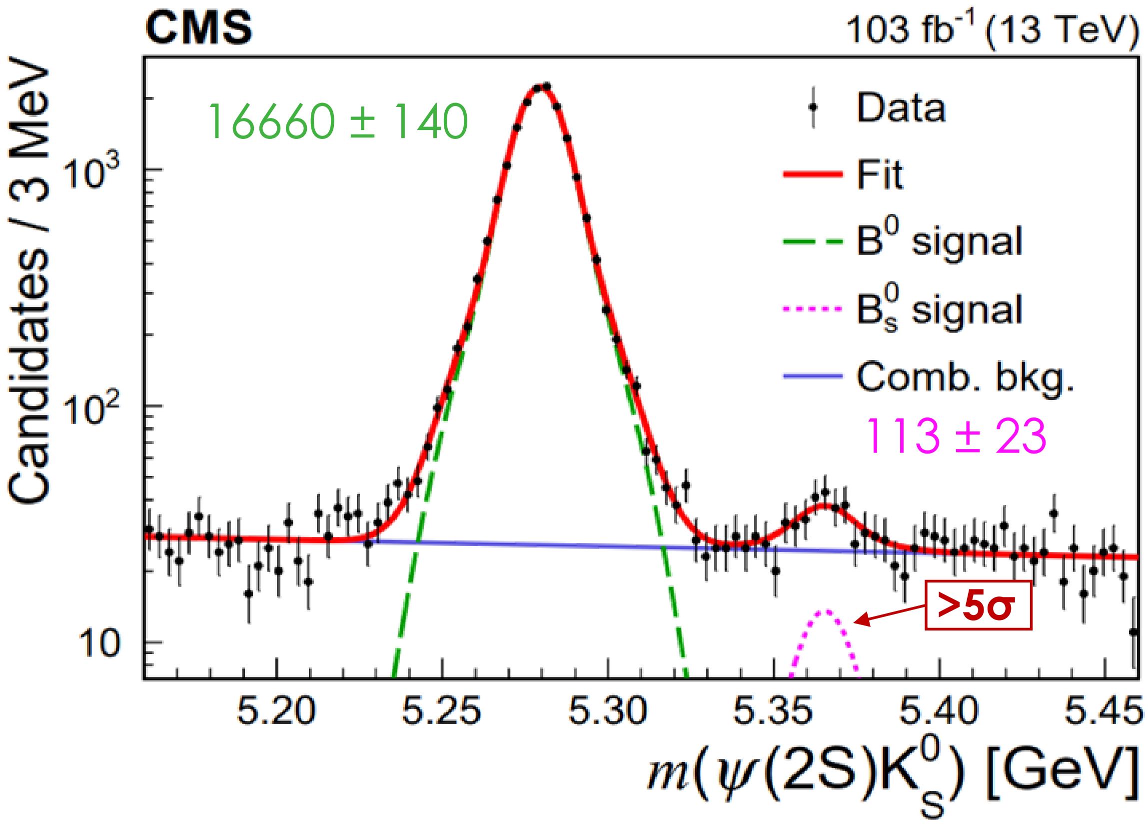


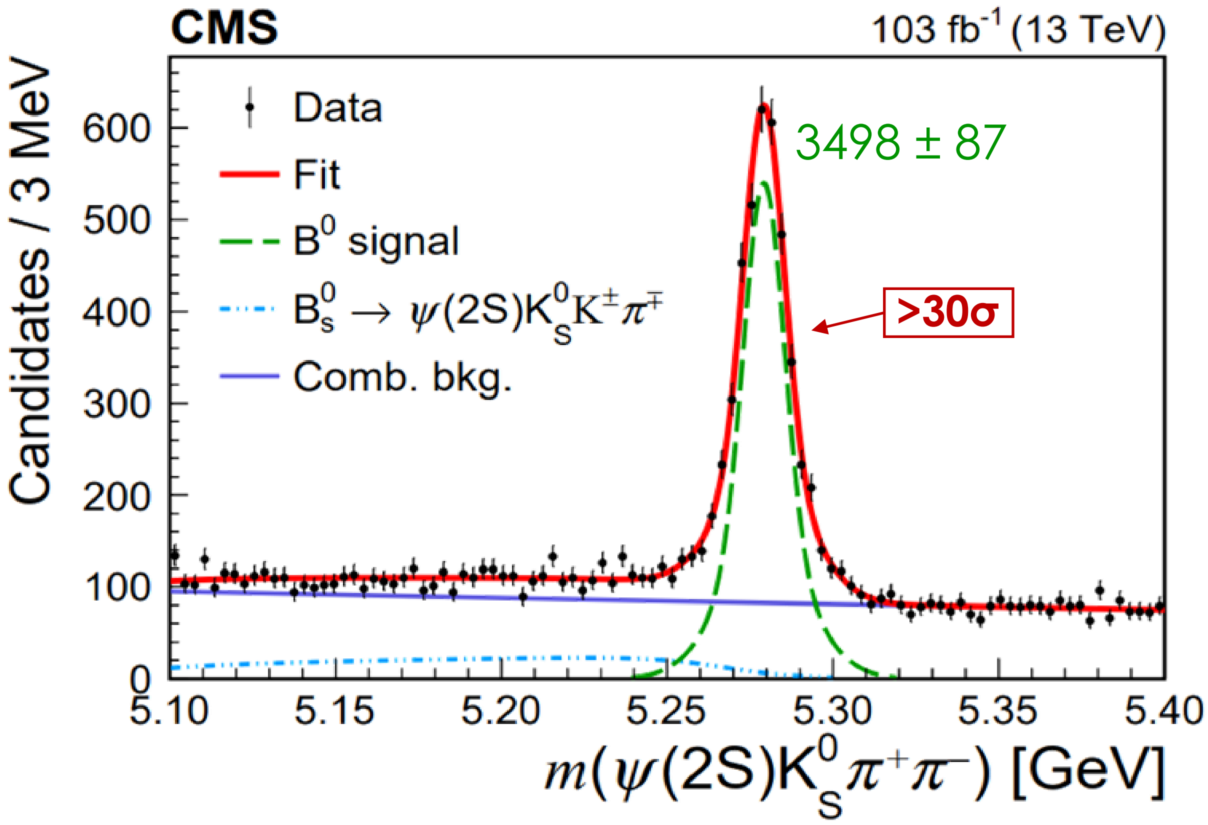
Many exotic states have been observed in the last 15 years, and the nature of most of them is still unclear

$Z_C(3900)^{\pm}$	BELLE
$Z_C(4200)^{\pm}$	BaBar
$Z_C(4430)^{\pm}$	BELLE
X(3915)	BELLE
$P(4457)^{+}$	LHCb
$Z_{CS}(4220)^{+}$	LHCb

Decays with charmonium in the final state could be a good laboratory for CP-violation measurements.

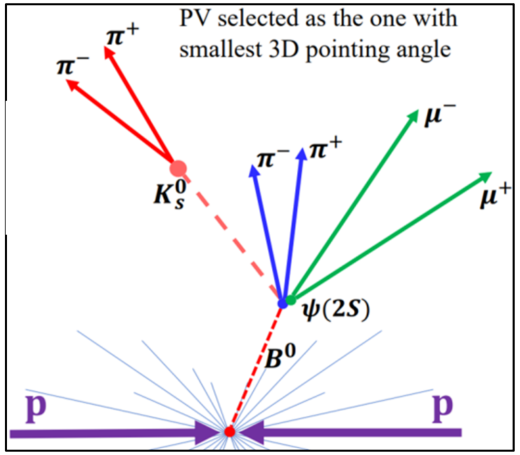
$\psi(2S)K_s^0$ and $\psi(2S)K_s^0\pi^+\pi^-$ invariant mass distributions





Double-Gaussian function for signal
Exponential for background

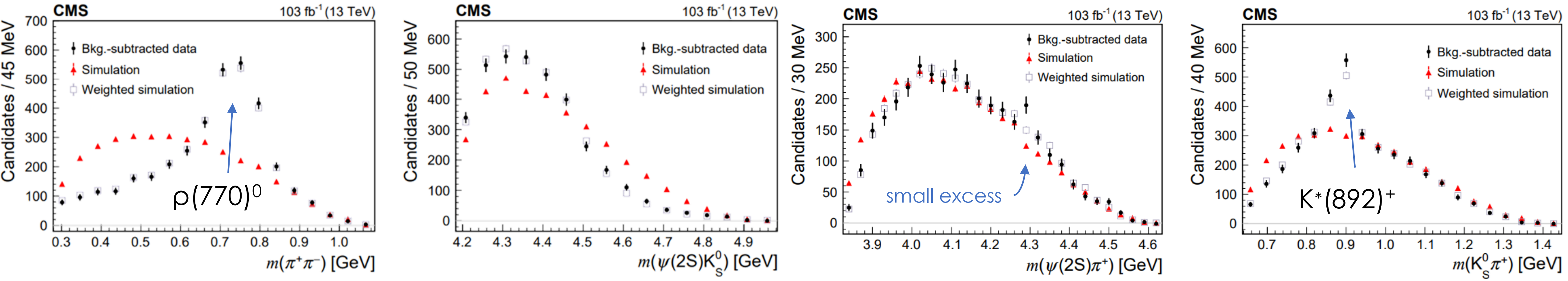
Unbinned ML fits

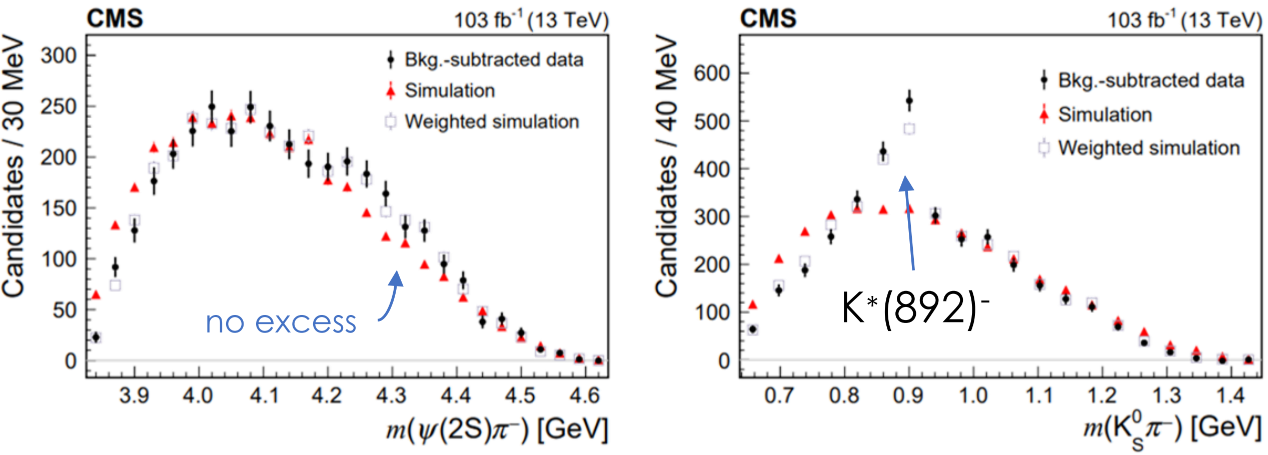


$$N(B_s^0 \to \psi(2S)K_S^0)/N(B^0 \to \psi(2S)K_S^0) = \\ = (6.8 \pm 1.4) \times 10^{-3}$$

Selection criteria are in backup

Intermediate 2body invariant mass distributions





Data: sPlot-bkg-subtracted

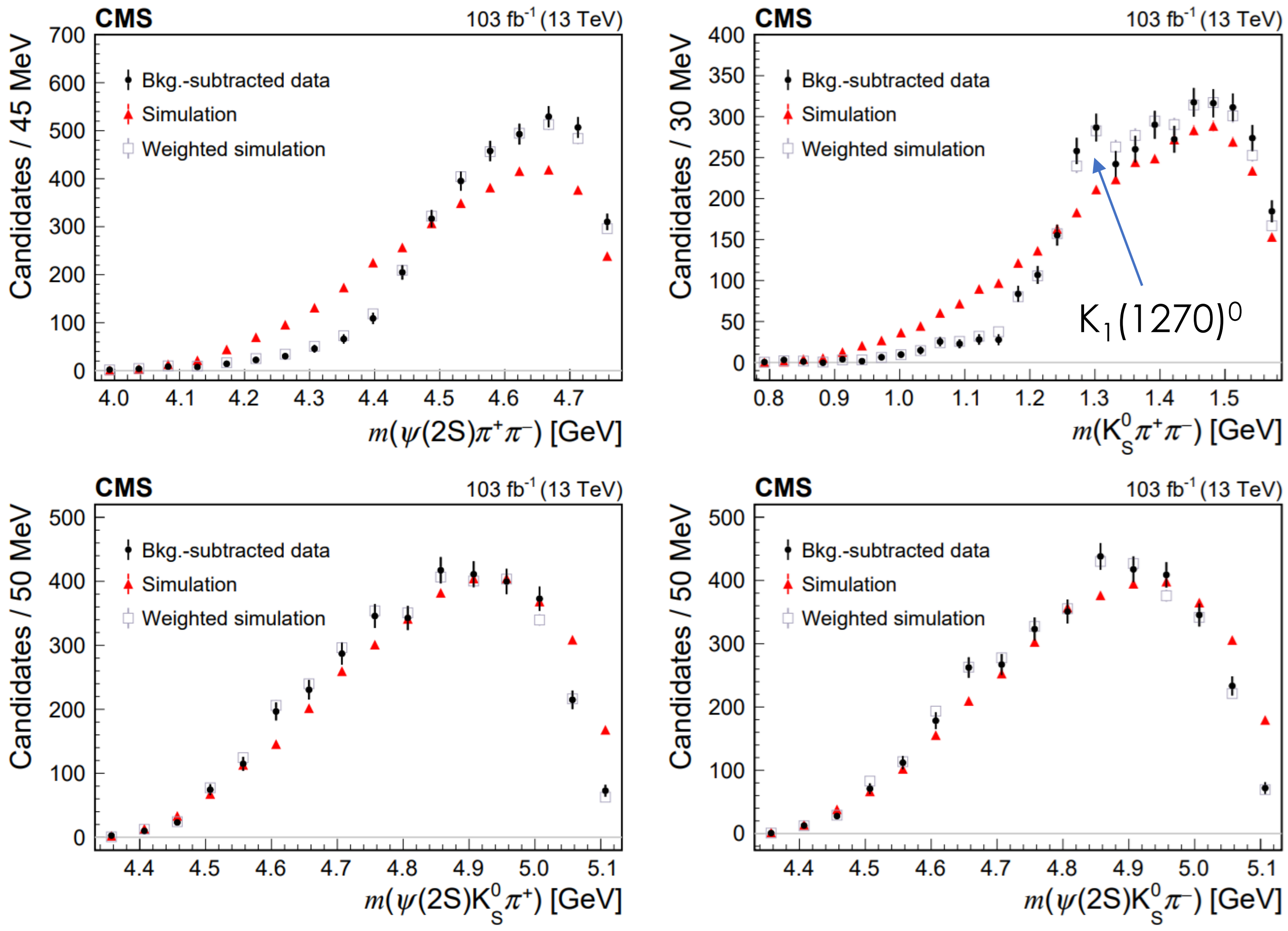
Not described well by phase-space MC

Good agreement after MC reweighting

No unexpected features, only known K* and ρ resonances

Results

Intermediate 3body invariant mass distributions



Measured branching fraction ratios:

$$R_s = \frac{\mathcal{B}(B^0_s \to \psi(2S)K^0_S)}{\mathcal{B}(B^0 \to \psi(2S)K^0_S)} =$$

$$= (3.33 \pm 0.69\,(\text{stat}) \pm 0.11\,(\text{syst}) \pm 0.34\,(f_s/f_d)) \times 10^{-2}$$

$$R_{\pi^+\pi^-} = \frac{\mathcal{B}(B^0 \to \psi(2S)K^0_S\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K^0_S)} =$$

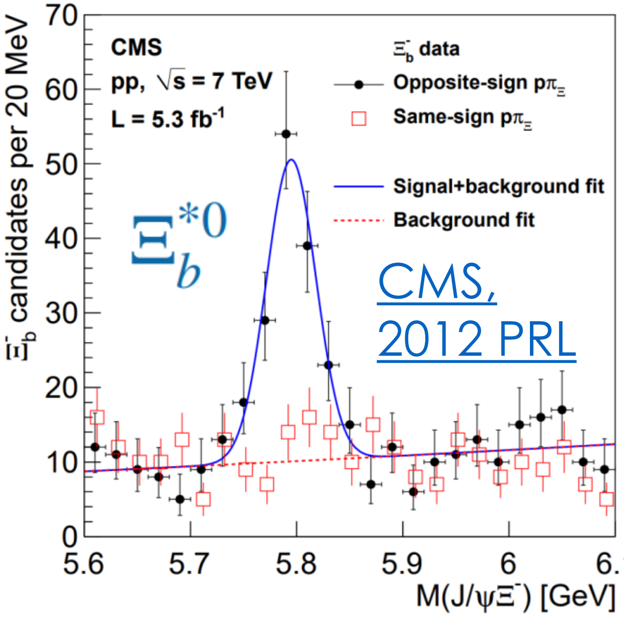
$$= 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst})$$

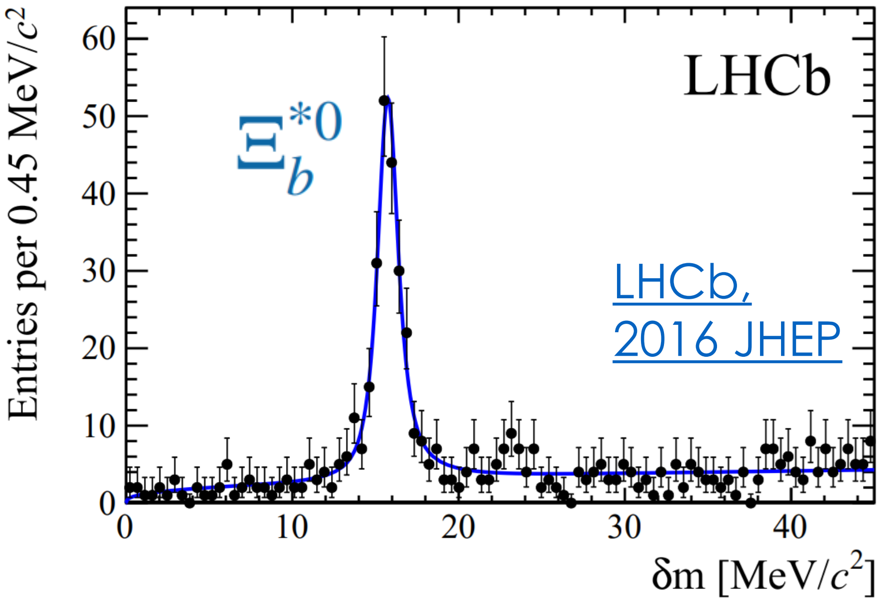
~ same order of magnitude as in decays with J/ψ instead of ψ(2S)

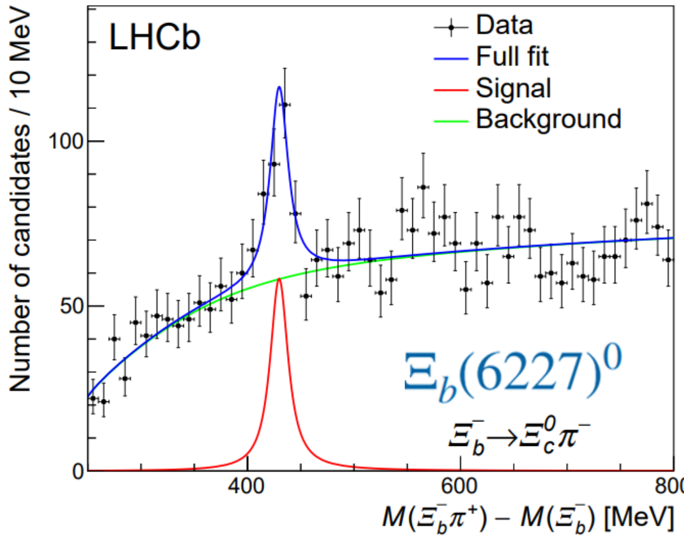
Observation of a new excited beauty strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$

Phys.Rev.Lett. 126 (2021) 25

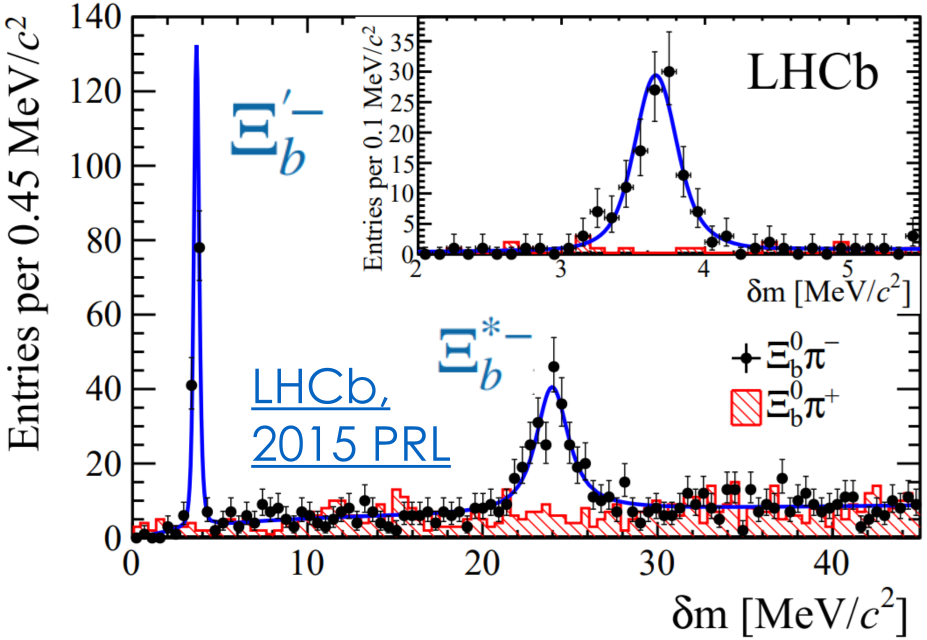
Previous results on Ξ_b resonances

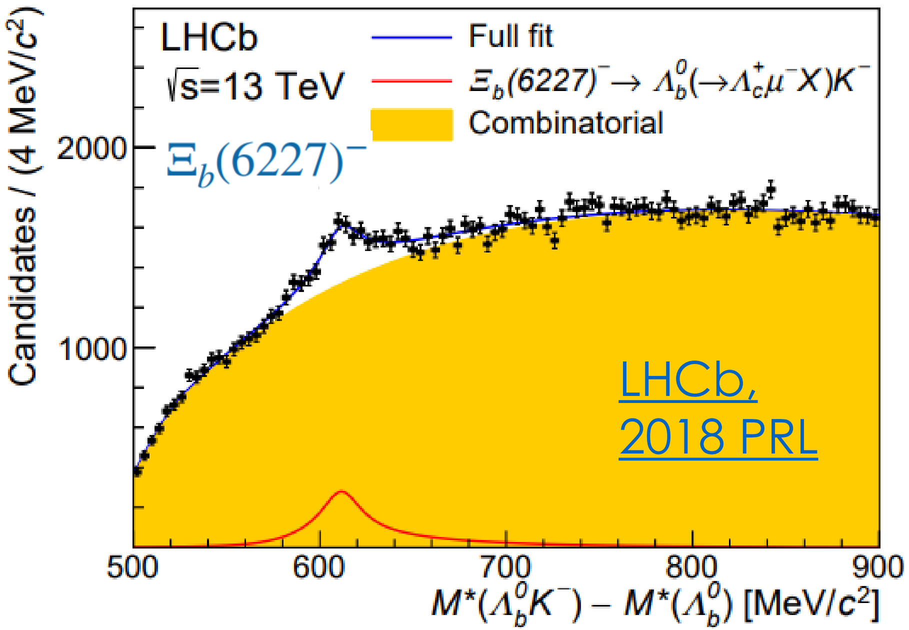




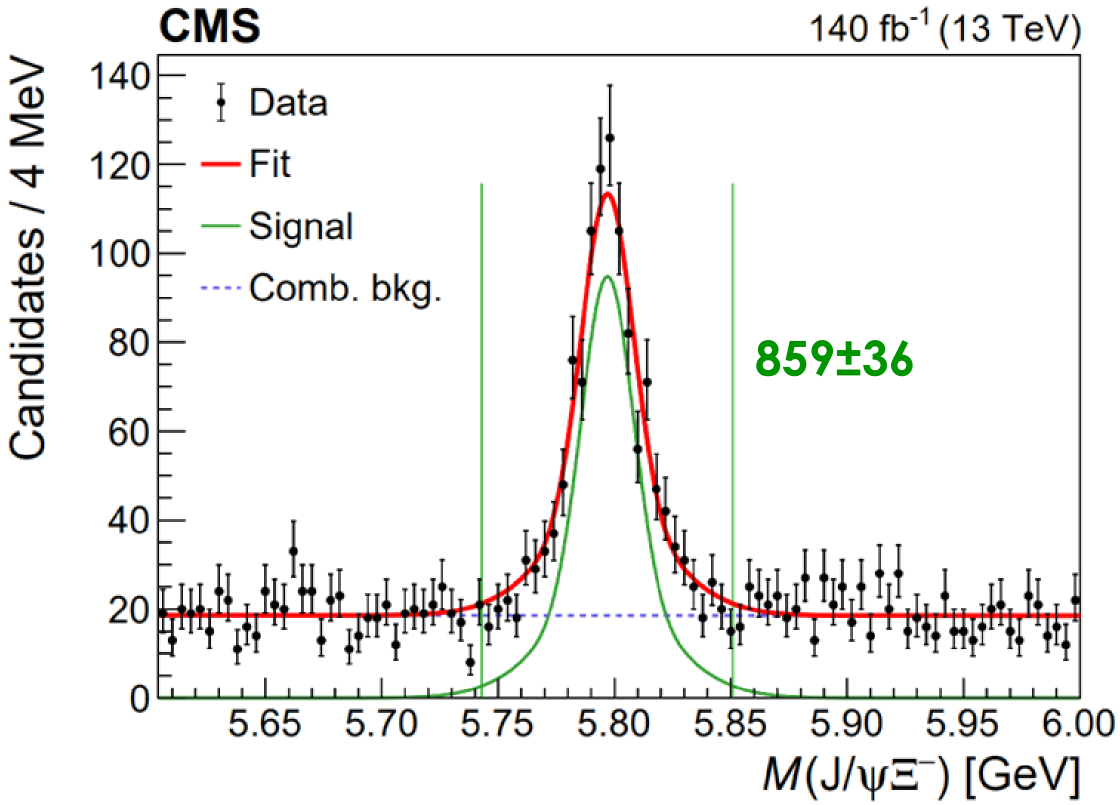


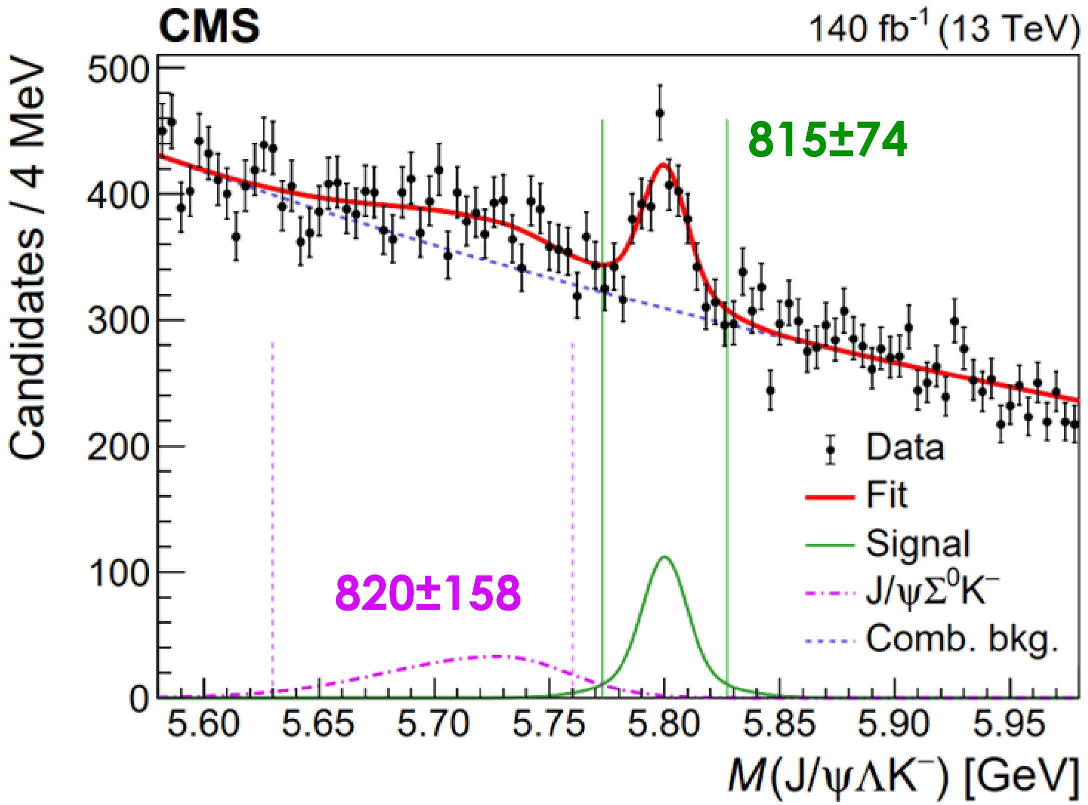
LHCb, 2020





$J/\psi\Xi^-$ and $J/\psi\Lambda K^-$ invariant mass distributions

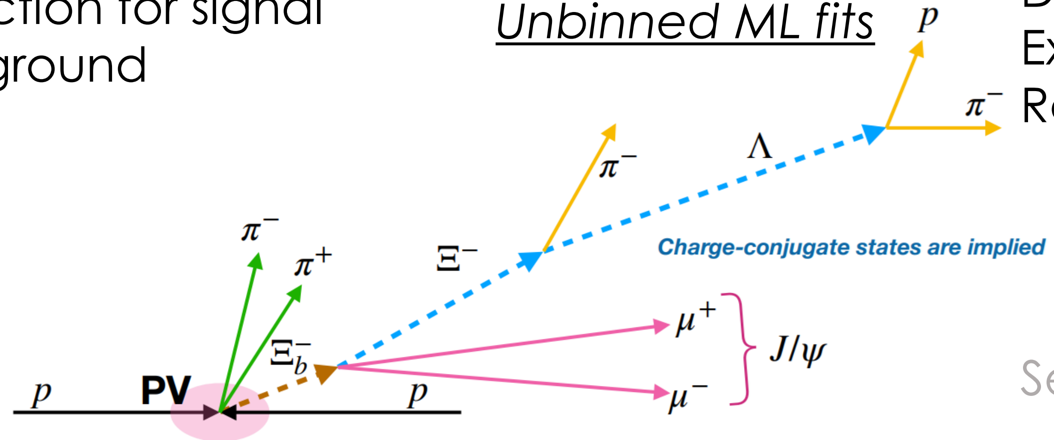




Double-Gaussian function for signal
Exponential for background

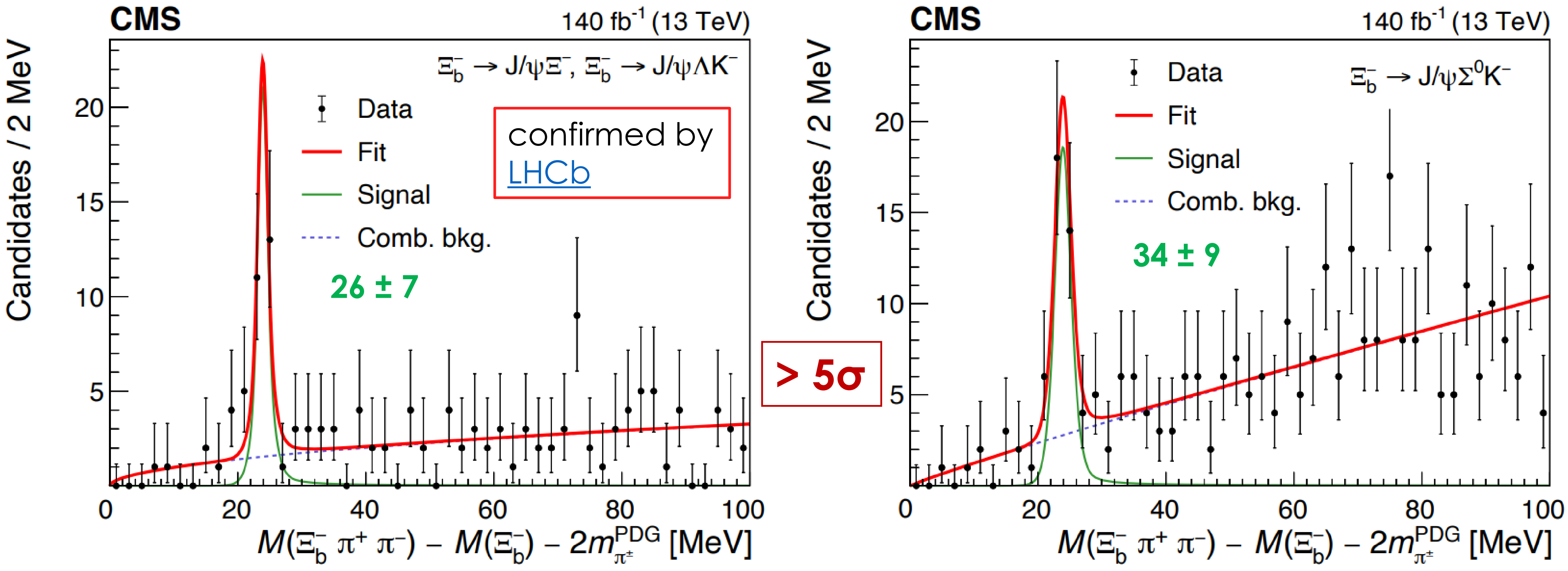
<u>*Unbinned ML fits*</u>

Double-Gaussian function for signal
Exponential for background
Reflection shape is fixed from MC



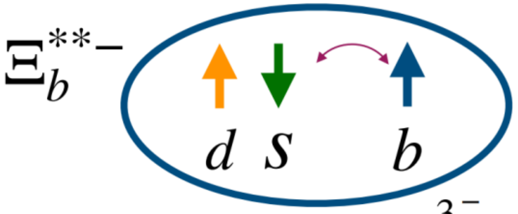
Selection criteria are in backup

Distributions of the invariant mass difference



relativistic Breit–Wigner (RBW) function for signal

$$M(\Xi_b(6100)^-) - M(\Xi_b^-) - 2\,m_{\pi^\pm}^{PDG} = $$
$$= 24.14 \pm 0.22\,(\text{stat}) \pm 0.09\,(\text{syst})\,\text{MeV}$$
$$\Gamma(\Xi_b(6100^-)) < 1.9\ MeV\ @95\,\%\ CL$$



$j_{ds} = 1$ and $J^P = \frac{3}{2}^-$

P-wave ($L = 1$)

The first observation of a J^P=3/2$^-$ beauty-strange baryon consistent with the theoretical predictions:

M = 6100-6130 MeV

Γ = 1-3 MeV

New for LHCP

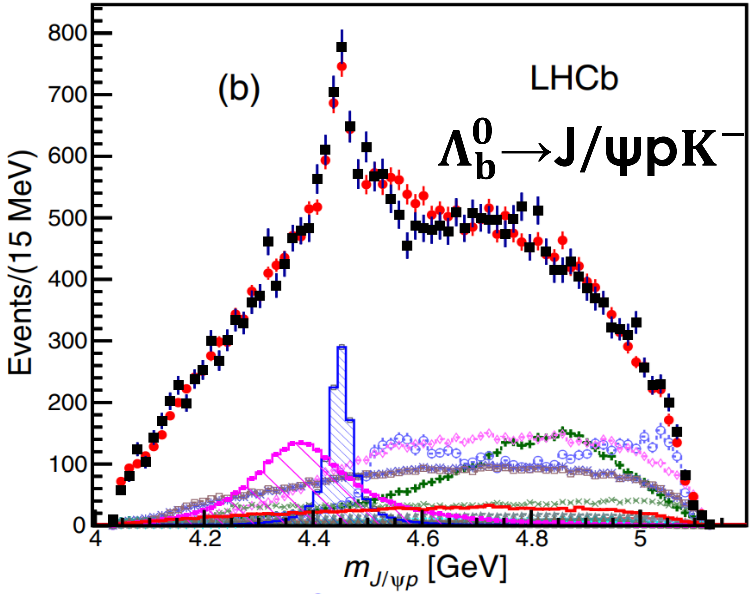
Observation of the $\Lambda_b^0 \to J/\psi\, \Xi^- K^+$ decay

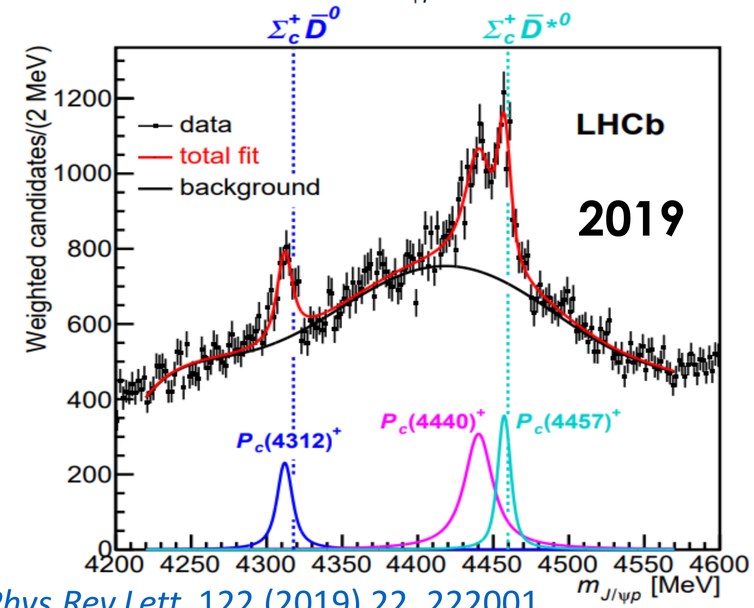
CMS-PAS-BPH-22-002

https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-22-002/index.html

LHCB 2015 [Phys.Rev.Lett. 115 (2015) 072001]

1544 citations!





[Phys.Rev.Lett. 122 (2019) 22, 222001]

Introduction

b hadron decays with charmonium and a baryon allow searching for pentaquarks in *ψ+baryon* system in the intermediate resonance structure

---

LHCb, **2015**: studied **J/ψp** mass from $\Lambda_b^0 \to J/\psi p K^-$

(full 6D angular analysis with interference between resonances)

Observed $P_c(4450)^+$ and $P_c(4380)^+$

pentaquark candidates!

Confirmed later with a model-independent analysis (**2016**)

Also seen in CS $\Lambda_b^0 \to J/\psi p \pi^-$ decay (**2016**)

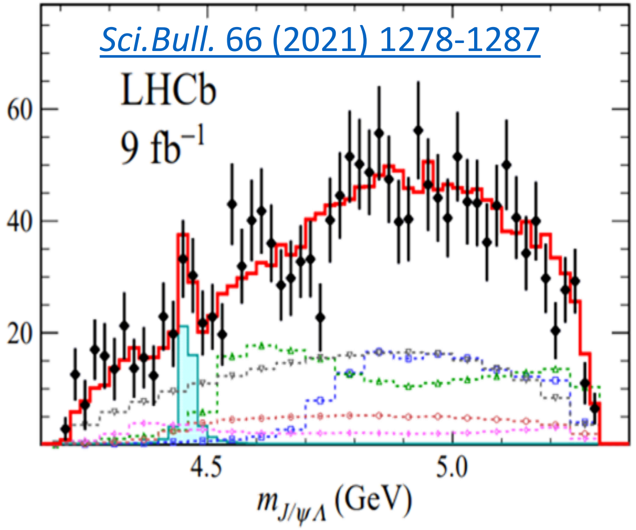
2019: adding Run-2 data, **9x** Λ_b^0 yield. From 1D fit of J/ψp mass distribution, 4450 peak is now split into two

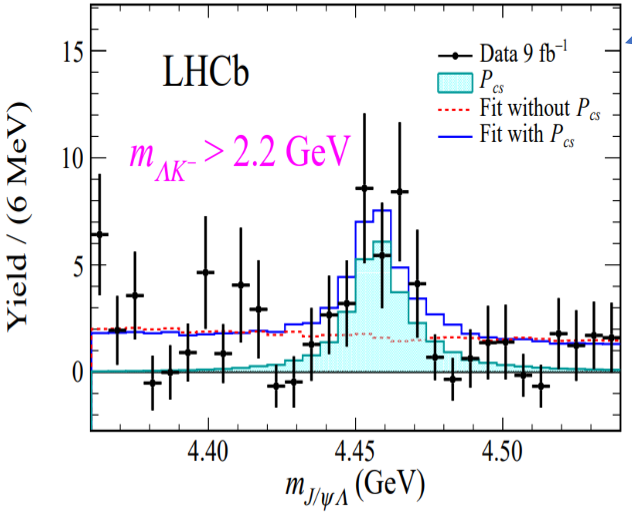
+ observe a new resonance, $P_c(4312)^+$

Introduction

LHCb 2020: $\Xi_b^- \to J/\psi \Lambda K^-$

In addition to $J/\psi p$ system, also the **$J/\psi\Lambda$** system was investigated.





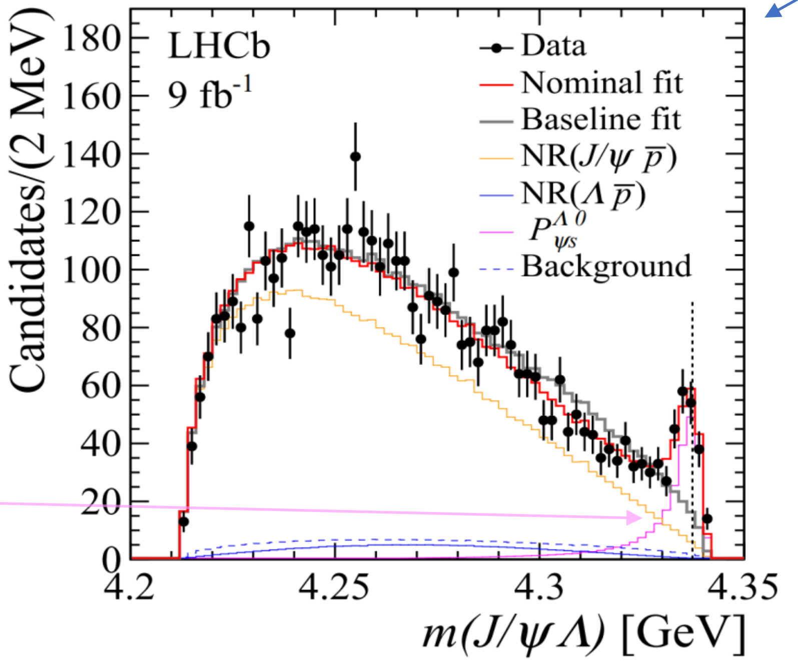
2020: 6D full angular analysis by LHCb of **$\Xi_b^- \to J/\psi\Lambda K^-$** decay revealed **evidence** for hidden-charm **strange pentaquark $P_{cs}(4459)^0$**

CMS-BPH-18-005, *JHEP 12 (2019) 100*: Based on Run-1, CMS studied the **$B^- \to J/\psi\Lambda \bar{p}^-$** decay, data is consistent with no pentaquarks in $J/\psi\Lambda$ or $J/\psi p$

arXiv:2210.10346

LHCb 2022: $B^- \to J/\psi\Lambda p^-$

$P^{\Lambda}_{\psi s}(4338)^0$



LHCb 2022: with 6D amplitude analysis of **$B^- \to J/\psi\Lambda p^-$** decay, **observe new** strange pentaquark **$P_{cs}(4338)^0 \to J/\psi\Lambda$**

no significant states decaying to $J/\psi p$

It is interesting to note that $J/\psi\Lambda$ pentaquarks are found to be *generally* ***narrower*** than $J/\psi p$ states (7-17 vs ~10-200 MeV). Even narrower pentaquarks are expected for doubly-strange hidden-charm **P_{css}**. Such states can decay into e.g. **$J/\psi\ \Xi^-$**

This motivates our search for decays having $J/\psi\Xi^-$ in the decay products, i.e. $\Lambda_b^0 \to J/\psi\Xi^- K^+$

Data and event selection

pp collisions 13 TeV, L~140 fb^{-1} (2016-2018)

Mass constraints applied on $J/\psi \to \mu^+\mu^-$, $\Lambda \to p\pi^-$ and $\Xi^- \to \Lambda\pi^-$

Λ_b^0 obtained from vertex fit of $\mu^+\mu^-\Xi^-K^+$

Normalization channel is chosen according to the similar decay topology, to reduce the systematic uncertainties associated with the track reconstruction:

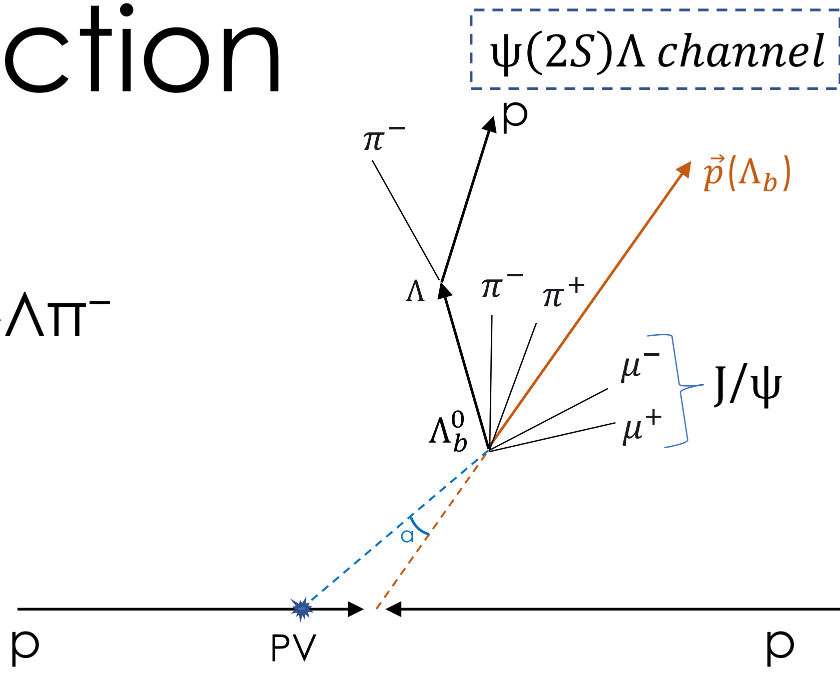
$\Lambda_b^0 \to \psi(2S)\Lambda$, with vertex fit of $\mu^+\mu^-\Lambda\pi^+\pi^+$

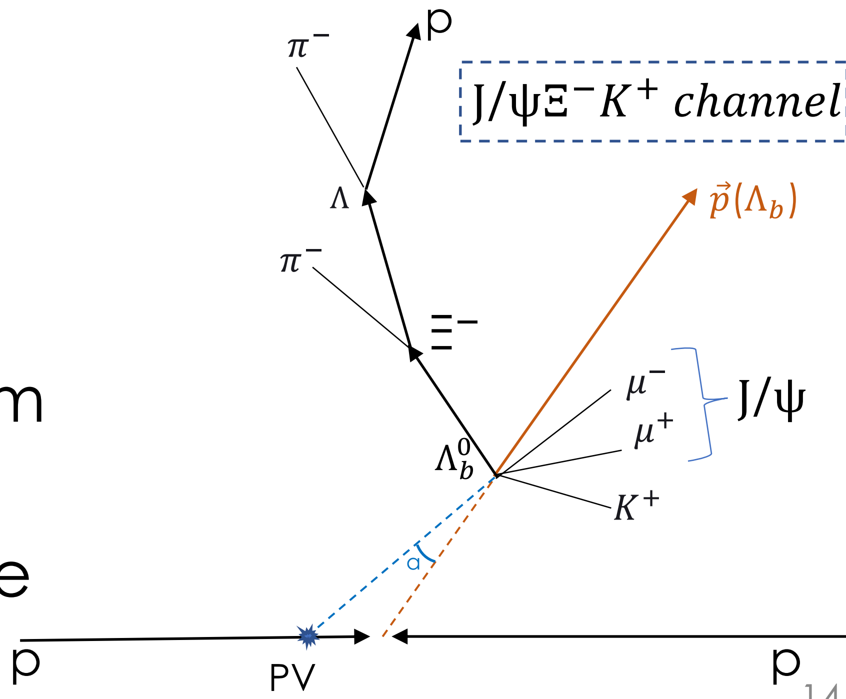
$J/\psi\pi^+\pi^-$ mass close to $M^{PDG}(\psi(2S))$

Λ_b^0 vertex should be away from PV in transverse plane

PV selected by smallest angle between Λ_b^0 momentum and the line joining PV and Λ_b^0 decay vertex

Λ_b^0 baryon momentum should be aligned with that line





Calculation of branching fraction ratio

Ratio of the signal yields in data

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} \equiv$$

$$\frac{N(\Lambda_b^0 \to J/\psi \Xi^- K^+)}{N(\Lambda_b^0 \to \psi(2S)\Lambda)} \frac{\epsilon_{\psi(2S)\Lambda}}{\epsilon_{J/\psi \Xi^- K^+}} \times \frac{\mathcal{B}(\psi(2S) \to J/\psi \pi^+ \pi^-)}{\mathcal{B}(\Xi^- \to \Lambda \pi^-)}$$

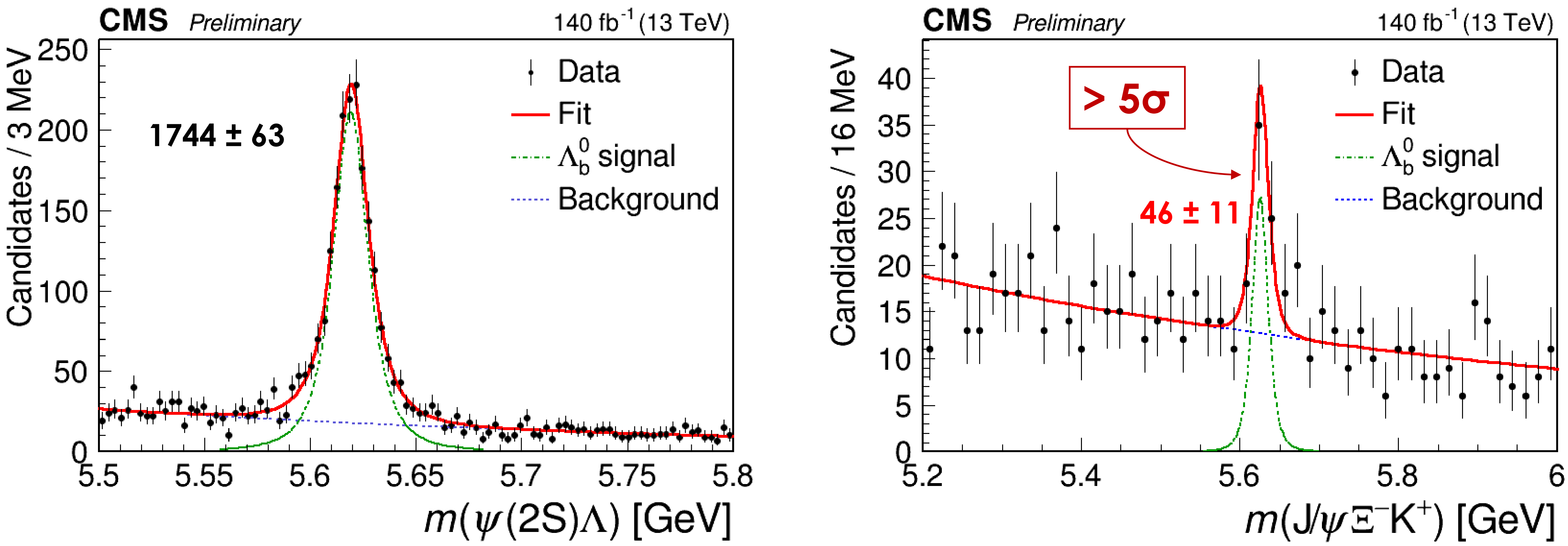
Ratio of total efficiencies from MC = 5.06±0.29

Known branching fractions from PDG

$$\mathcal{B}(\psi(2S) \to J/\psi\, \pi\, \pi) = (34.68 \pm 0.30)\%$$

$$\mathcal{B}(\Xi \to \Lambda\, \pi) = (99.887 \pm 0.035)\%$$

Invariant mass distributions



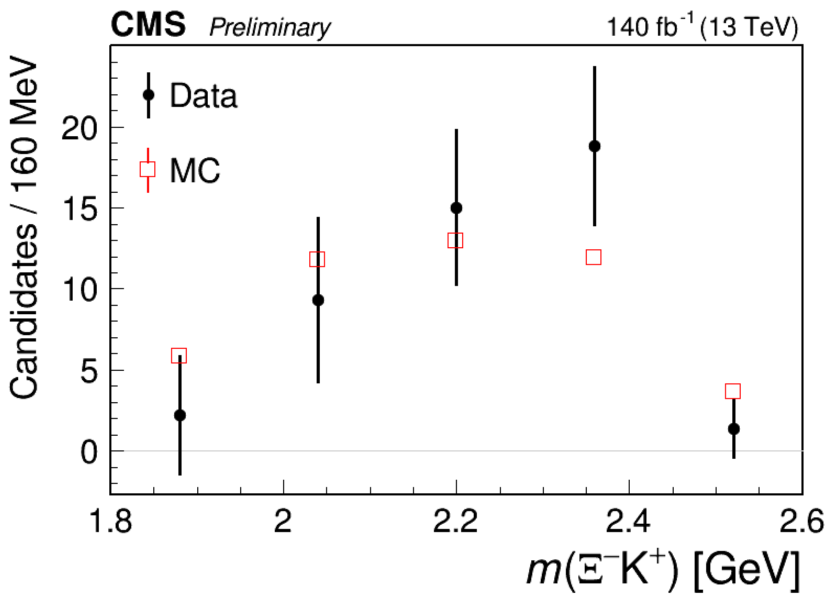
Student-T function for signal
Exponential for background

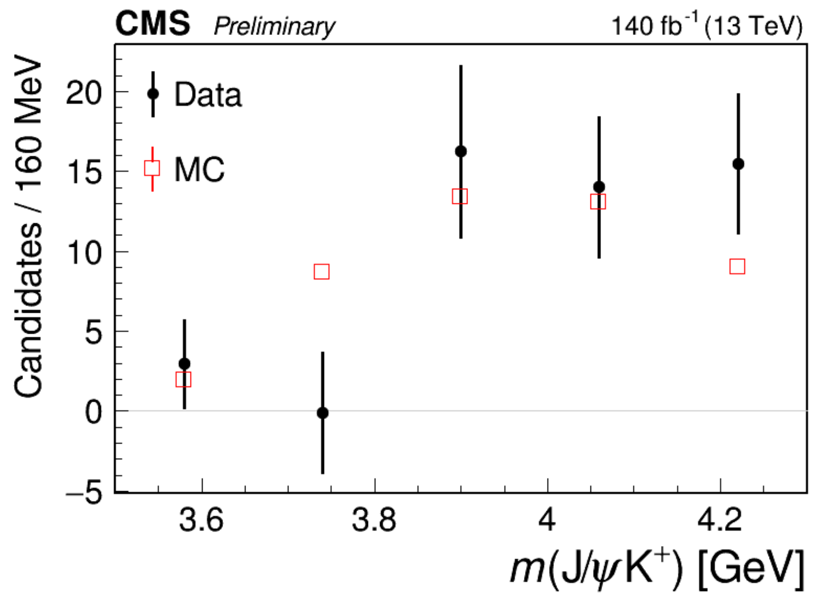
Unbinned ML fits

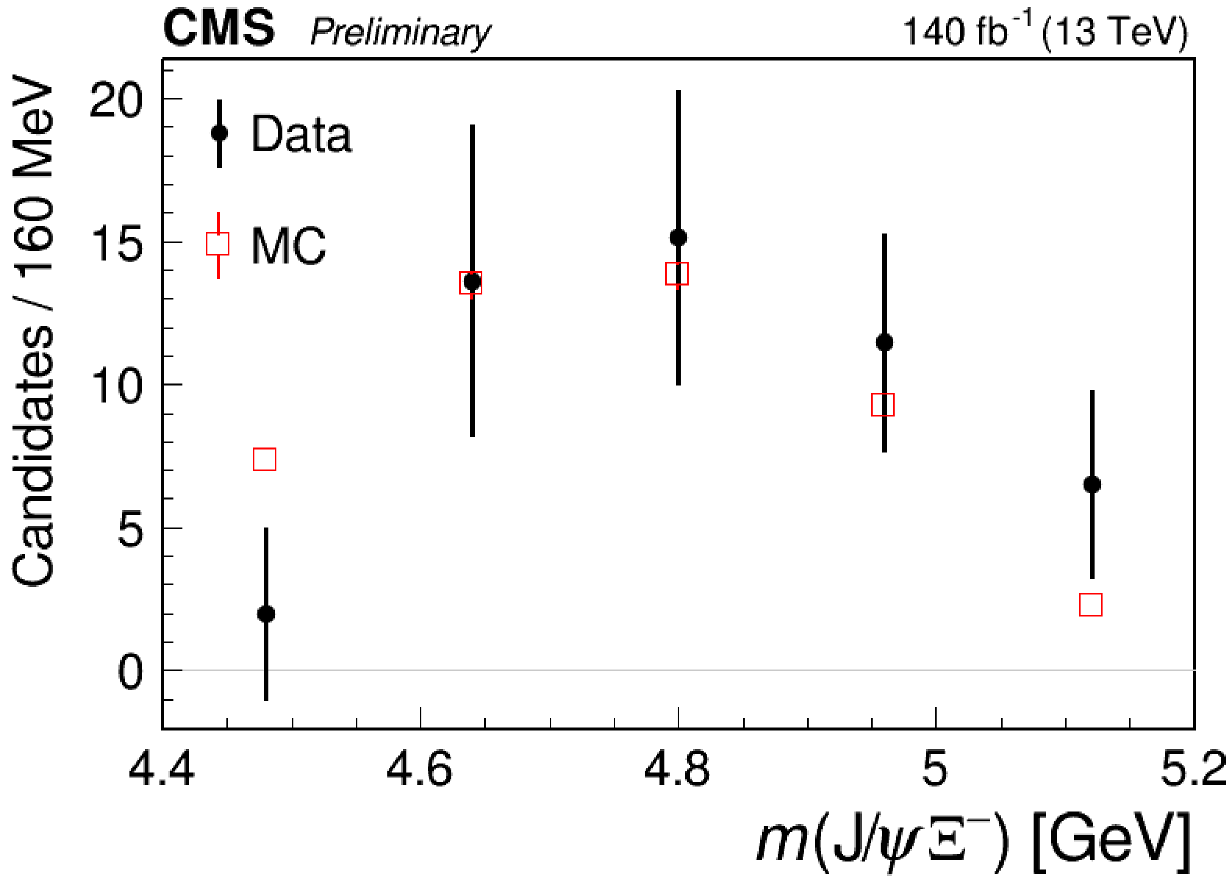
First observation!

Fit results	$m(\Lambda_b^0)$ = 5619.3 ± 0.3 MeV	*consistent with PDG*	$m(\Lambda_b^0)$ = 5625.9 ± 3.2 MeV
	σ = 8.9 ± 0.4 MeV	*consistent with MC*	σ = 10.4 ± 3.2 MeV

$J/\psi\Xi^-K^+$ Intermediate invariant mass distributions







Data: ${}_{s}$Plot-bkg-subtracted

No narrow peaks in $J/\psi\Xi^-$ *(also with narrower bins)*

Good data-MC agreement

(not unexpected with 46 signal events)

Systematic uncertainties

Source	Uncertainty (%)
Signal model	3.9
Background model	6.7
Non-$\psi(2S)$ contribution	2.5
Finite size of MC	5.6
Tracking efficiency	2.3
Alternative selection criteria	33.5
Total	35.0

Signal model, Background model: Vary the fit model, deviation in R = syst. uncertainty

Non-$\psi(2S)$ contribution: In $\Lambda_b^0 \to \Lambda J/\psi \pi^+\pi^+$ sample, evaluated vis sPlot

Tracking efficiency: Different p_T spectra between signal and norm. channels

Alternative selection criteria: Conservative estimate, based on variation of cuts near trigger/reconstruction thresholds. Accounts for correlation between the sample and its subsample

First observation of $\Lambda_b^0 \to J/\psi\Xi^-K^+$

- ***The first decay to have $J/\psi\Xi^-$ system in decay products***
- No significant narrow peaks in $J/\psi\Xi^-$ mass distribution
  - *With 46 signal events, our sensitivity is very limited*
- Measured branching fraction ratio:

CMS-PAS-BPH-22-002

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Xi^-K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = (2.54 \pm 0.78\,(\text{stat}) \pm 0.89\,(\text{syst}) \pm 0.02(\mathcal{B}))\%$$

~ same order of magnitude as $\Lambda_b^0 \to J/\psi\Lambda\varphi$ decay that has similar Feynman diagram:

Phys.Lett.B 802 (2020) 135203

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Lambda\phi)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = (8.26 \pm 0.90\,(\text{stat}) \pm 0.68\,(\text{syst}) \pm 0.11(\mathcal{B})) \times 10^{-2}$$

Summary

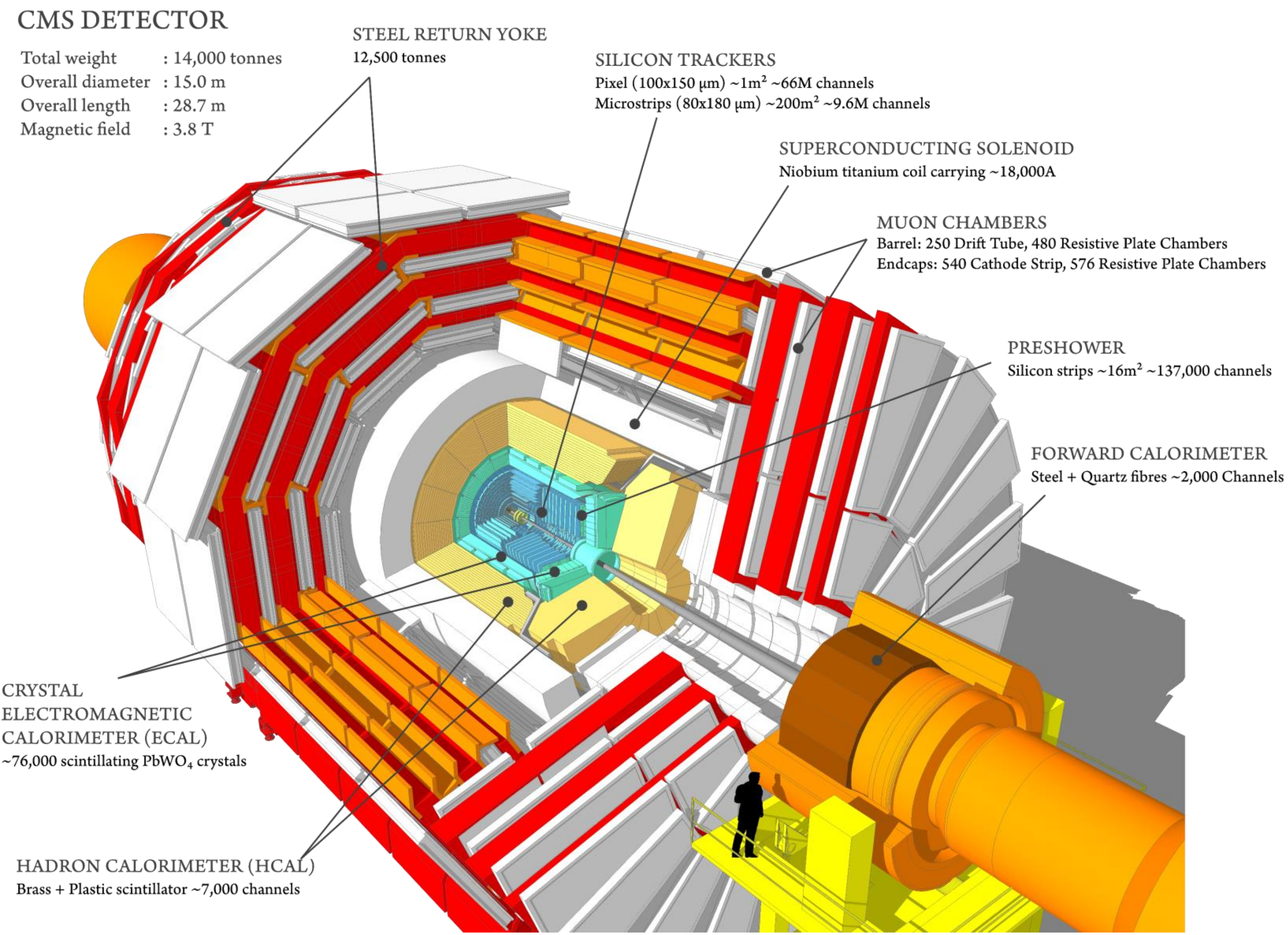
- CMS is an active experiment in flavor spectroscopy
- We **observe for the first time**:

  - $B_s^0 \rightarrow \psi(2S) K_S^0$ decay
  - $B^0 \rightarrow \psi(2S) K_S^0 \pi^+ \pi^-$ decay
  - $\Xi_b(6100)^-$ beauty-strange baryon
  - $\mathbf{\Lambda_b^0 \rightarrow J/\psi \Xi^- K^+}$ **decay [NEW RESULT]**

Thank you for attention!

BACKUP

Selection criteria for B^0 and B_s^0



pp collisions 13 TeV, L~104 fb^{-1} (2017-2018)

Trigger:

$\psi(2S) \rightarrow \mu^+\mu^-$, $p_T(\mu^+\mu^-) > 18$ GeV

$p_T(\mu^+) > 3$ GeV, $P_{vtx}(\mu\mu) > 1\%$

$K_S^0 \rightarrow \pi^+\pi^-$

$P_{vtx}(\pi^+\pi^-) > 1\%$

$m(\pi^+\pi^-)$ ±20MeV around PDG value

Distance significance $D_{xy}/\sigma > 5$

Angle between **p** and **D**: $\cos(\alpha) > 0.99$

$p_T(K_S^0) > 1$ GeV

$B \rightarrow \psi(2S)K_S^0$

$P_{vtx}(\mu^+\mu^-K_S^0) > 5\%$

Distance significance $D_{xy}/\sigma > 5$

Angle between **p** and **D**: $\cos(\beta) > 0.99$

$B \rightarrow \psi(2S)K_S^0\,\pi^+\pi^-$

$p_T(\pi^\pm) > 0.9$ GeV

$P_{vtx}(\mu^+\mu^-K_S^0\,\pi^+\pi^-) > 5\%$

Distance significance $D_{xy}/\sigma > 5$

Angle between **p** and **D**: $\cos(\beta) > 0.99$

Calculation of branching fraction ratio

[BPH-18-004]

$$R_s \equiv \frac{\mathcal{B}(B_s^0 \to \psi(2S)K_S^0)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} =$$

$$= \frac{f_d}{f_s} \frac{\epsilon(B^0 \to \psi(2S)K_S^0)}{\epsilon(B_s^0 \to \psi(2S)K_S^0)} \frac{N(B_s^0 \to \psi(2S)K_S^0)}{N(B^0 \to \psi(2S)K_S^0)}$$

Fragmentation fraction ratio

Ratio of total efficiencies from MC

Ratio of the signal yields in data

$$R_{\pi^+\pi^-} \equiv \frac{\mathcal{B}(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)}{\mathcal{B}(B^0 \to \psi(2S)K_S^0)} =$$

$$= \frac{\epsilon(B^0 \to \psi(2S)K_S^0)}{\epsilon(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)} \frac{N(B^0 \to \psi(2S)K_S^0\pi^+\pi^-)}{N(B^0 \to \psi(2S)K_S^0)}$$

Systematic uncertainties

Source	R_s	$R_{\pi^+\pi^-}$
Background model	2.5	0.8
Signal model	1.5	0.8
Shape of $B_s^0 \to \psi(2S) K_S^0 K^\mp \pi^\pm$ contribution	—	0.5
Finite size of simulation samples	1.3	1.1
Intermediate resonances	—	5.0
Tracking efficiency	—	4.2
Total	3.2	6.7

Selection criteria for $\Xi_b(6100)^-$

pp collisions 13 TeV, L~140 fb^{-1} (2016-2018)

Selection is optimized with Punzi figure of merit

Muon and J/ψ selection

- $p_T(\mu^\pm) > 3\ GeV/c$
- $|\eta(\mu^\pm)| < 2.4$
- $J/\psi_{vtxprob} > 0.01$

$|m_{\mu^+\mu^-} - m_{J/\psi}^{PDG}| < 100\ MeV$

Λ selection

- $|m_\Lambda - m_\Lambda^{PDG}| < 10\ MeV$
- $\Lambda_{vtxprob} > 0.01$
- $p_T(\Lambda) > 1\ GeV/c$
- $\cos(\Xi, \Lambda) > 0$

Ξ_b^{*0} selection

- Intermediate decay of $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$:
- $\delta m_{\Xi_b^-\pi^+} - \delta m^{\text{PDG}}_{\Xi_b^{*0}} < 5\ MeV$

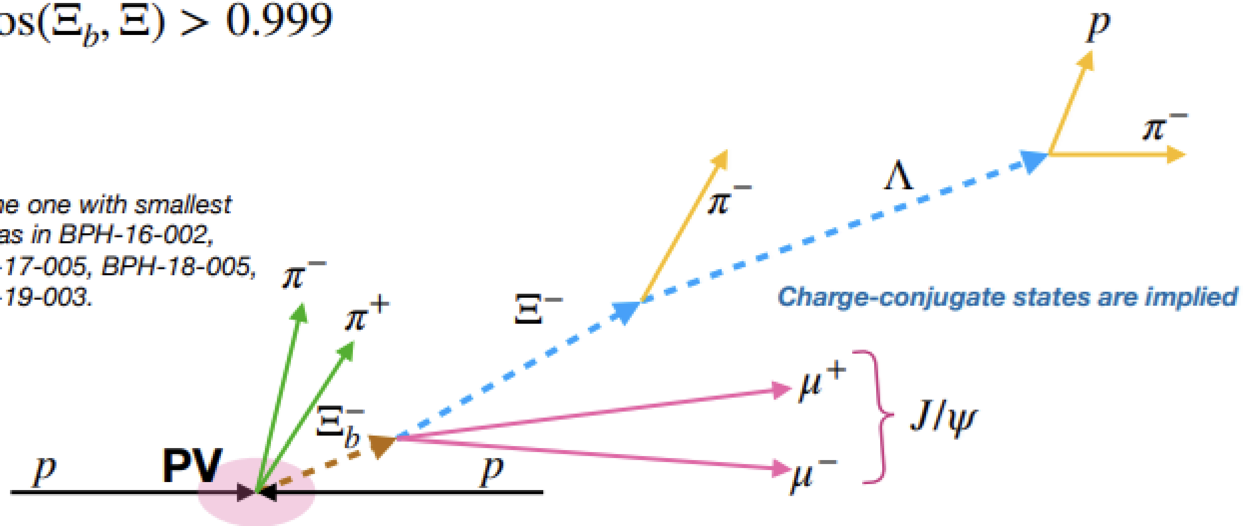
Ξ selection

- $p_T(\pi_\Xi) > 0.25\ GeV/c$
- $\Xi_{vtxprob} > 0.01$
- $p_T(\Xi) > 3\ GeV/c$
- $|m_{\Lambda\pi^-} - m_\Xi| < 9.5\ MeV$
- $d_{xy}(\pi_\Xi) > 0.9\ \sigma_{xy}(\pi_\Xi)$
- $\cos(\Xi_b, \Xi) > 0.999$

Ξ_b selection

- $|m_{J\psi\Xi^-} - m^{fit}_{\Xi_b^-}| < 54\ MeV$
- $(\Xi_b)_{vtxprob} > 0.01$
- $(\Xi_b)_{detach\ significance} > 3$
- $p_T(\Xi_b) > 10\ GeV/c$
- $\cos(PV, \Xi_b) > 0.99$

PV is selected as the one with smallest 3D pointing angle, as in BPH-16-002, BPH-16-003, BPH-17-005, BPH-18-005, BPH-19-002, BPH-19-003.



Optimization of selection criteria

[BPH-22-002]

Punzi formula is used for optimization, as it does not rely on **S** normalization

$$\boldsymbol{f} = \mathbf{S}/(\frac{463}{13} + 4\sqrt{\mathbf{B}} + 5\sqrt{25 + 8\sqrt{\mathbf{B}} + 4\mathbf{B}})$$

S is number of signal events from MC
(double-Gaussian function with common mean)

B is expected number of background events in the signal region

Extracted from data with $m_{PDG}(\Lambda_b^0)\pm 2\sigma_{eff}$ region excluded from the (bkg-only, exponential) fit.

Wrong-sign events are added to the sample to improve statistics.
CS and WS distributions are found to be consistent.

The bkg integral in the signal region is taken as **B**

Systematic uncertainties

Source	Uncertainty (%)
Signal model	3.9
Background model	6.7
Non-$\psi(2S)$ contribution	2.5
Finite size of MC	5.6
Tracking efficiency	2.3
Alternative selection criteria	33.5
Total	35.0

1) Uncertainty of efficiency ratio due to limited MC statistics
2) Signal model choice:
   - Student-T is baseline, alternatives are
     - Double-gaussian
     - Johnson PDF
3) Tracking efficiency
4) Background model choice:
   - Exp is baseline, alternatives are
     - 2nd degree polynomial
     - Modified threshold pdf $(x\text{-}x^0)^a \bullet$ exp
     - Modified threshold pdf $(x\text{-}x^0)^a \bullet Pol_1$
5) Potential non-psi(2S) contribution
6) Alternative selection criteria:
   it accounts the correlation of the statistical uncertainties