Recent CMS results on rare heavy flavour decays

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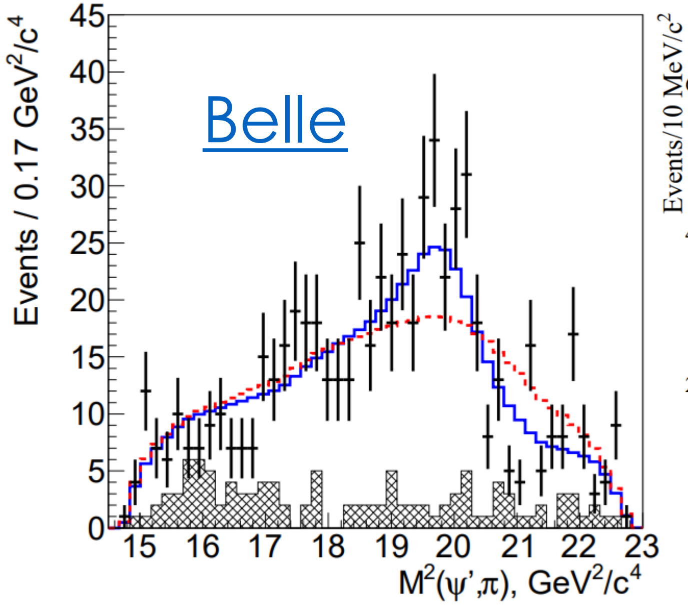
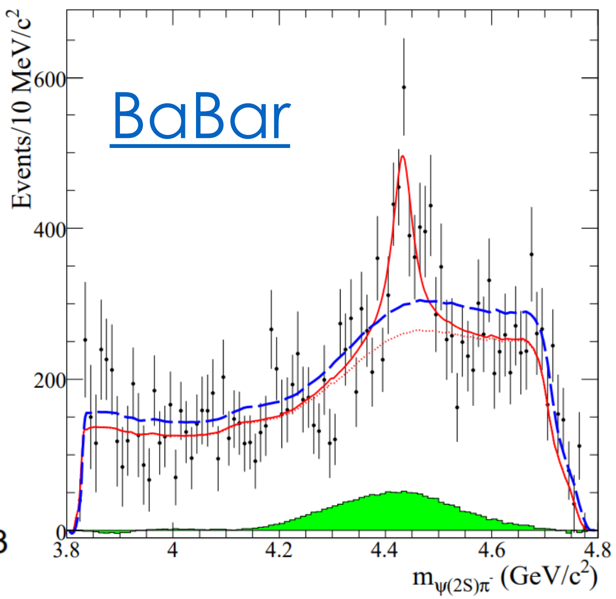
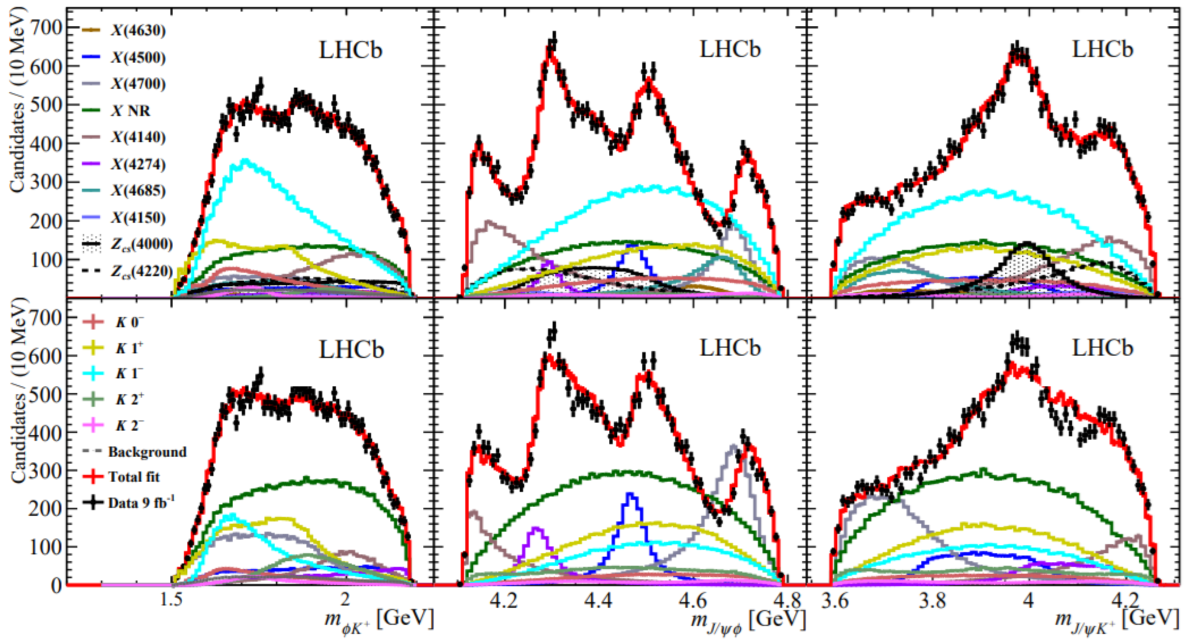
Observation of $B^0 \to \psi(2S)K^0_S\pi^+\pi^-$ and $B^0_s \to \psi(2S)K^0_S$ decays

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

Motivation





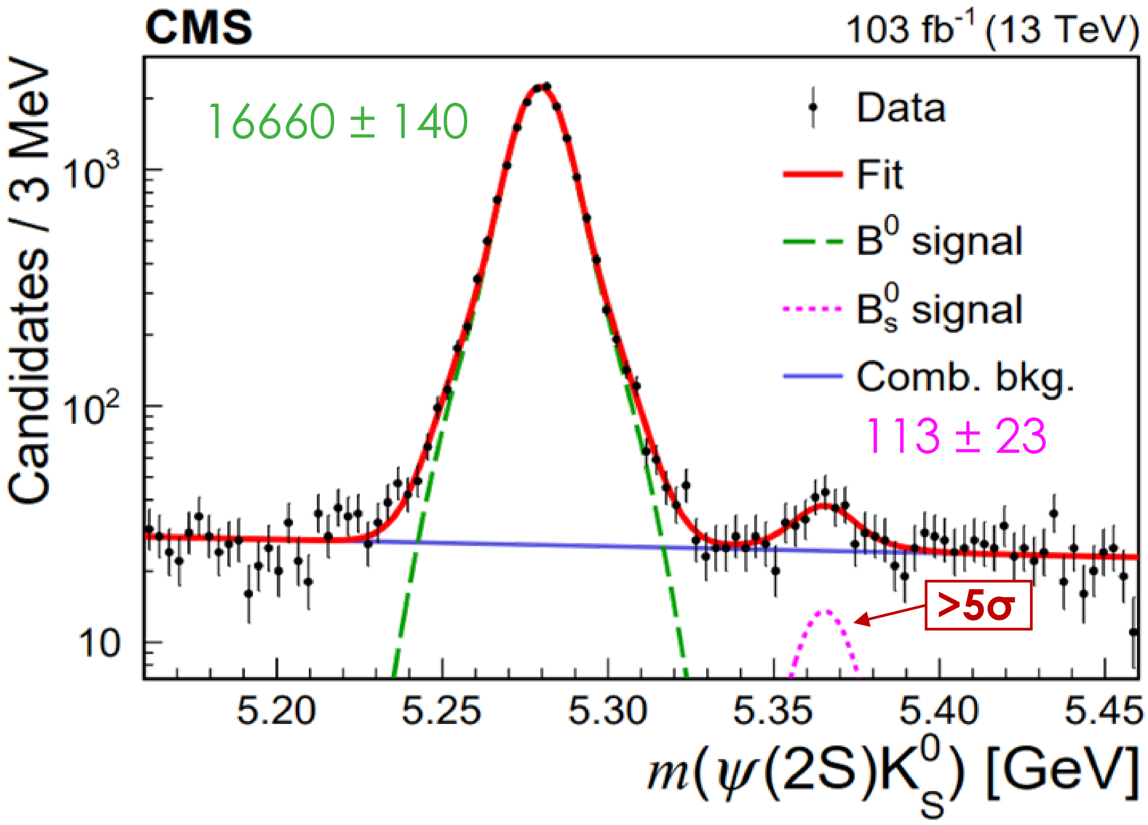


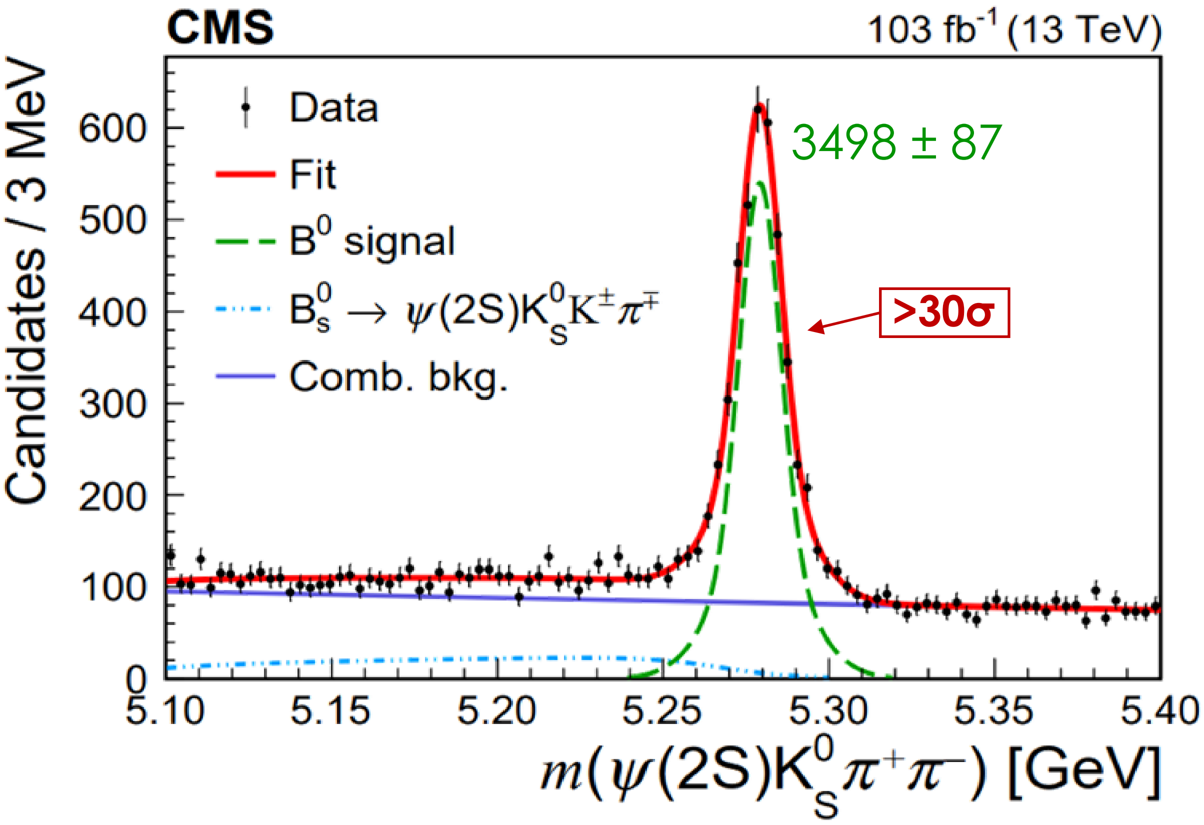
Many exotic states have been observed in the last 15 years, and the nature of most of them is still unclear

$Z_C(3900)^{\pm}$	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

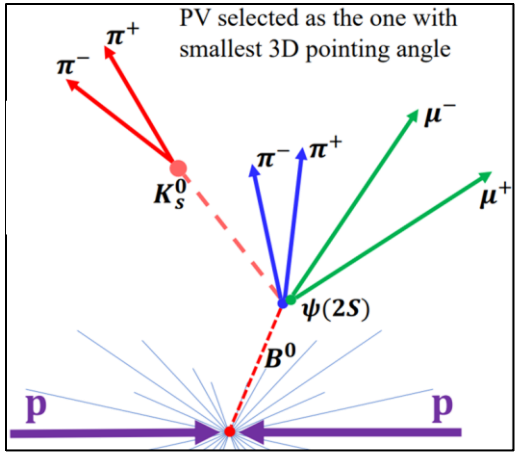




Double-Gaussian function for signal
Exponential for background

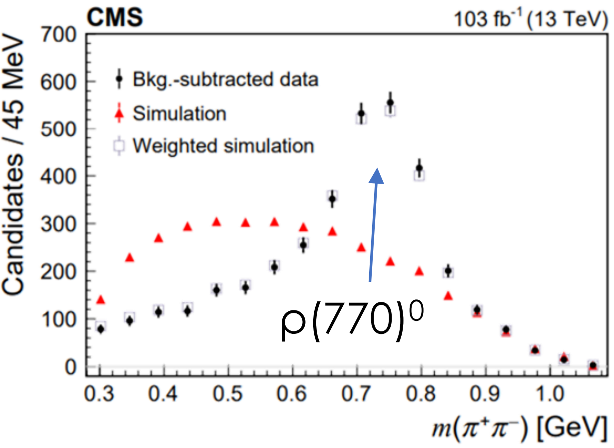
Unbinned ML fits

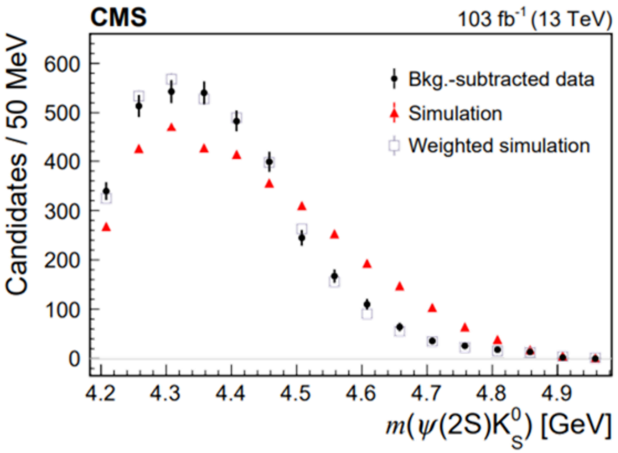
$$N(B_s^0 \to \psi(2S)K_S^0)/N(B^0 \to \psi(2S)K_S^0) = \\ = (6.8 \pm 1.4) \times 10^{-3}$$

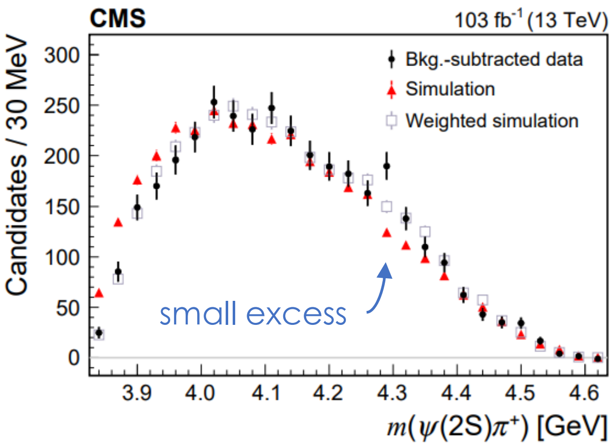


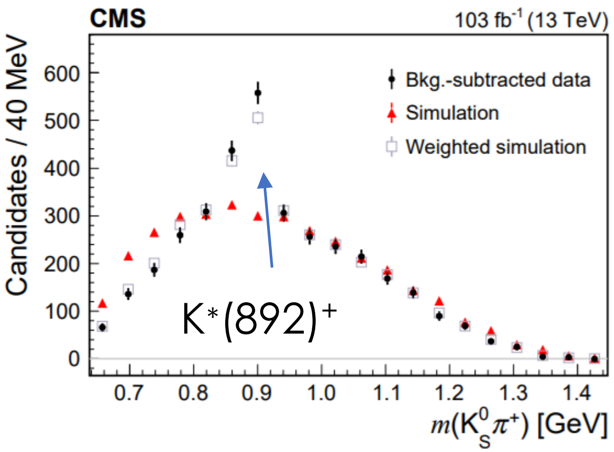
Selection criteria are in backup

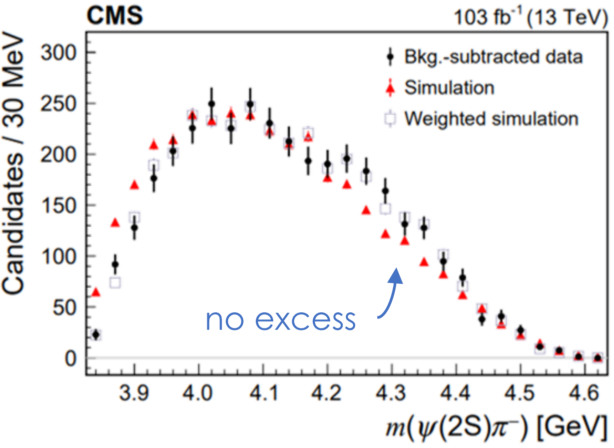
Intermediate 2body invariant mass distributions

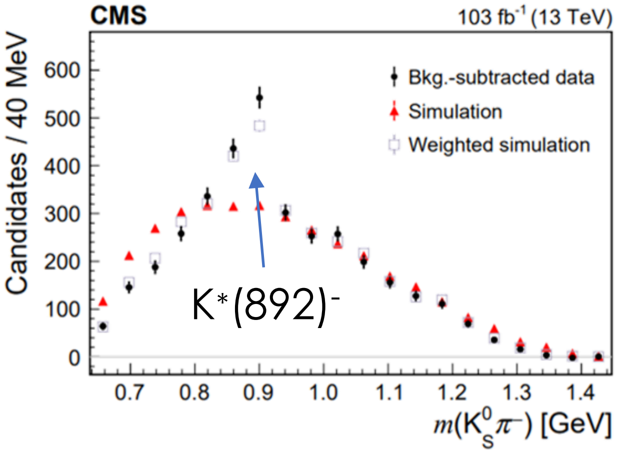












Data: $_s$Plot-bkg-subtracted

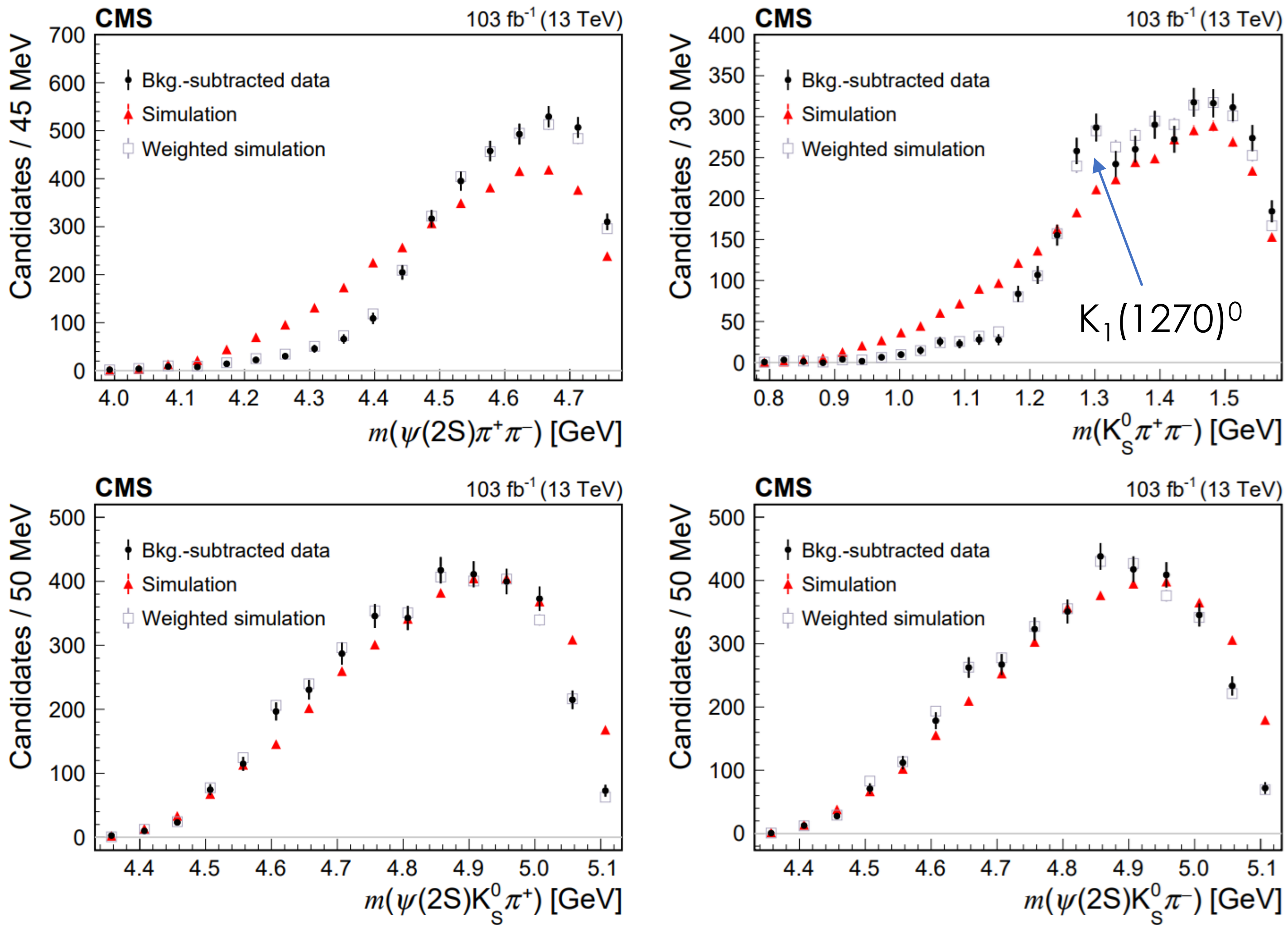
Not described well by phase-space MC

Good agreement after MC reweighting

No unexpected features, only known K* and ρ resonances

Results

Intermediate 3body invariant mass distributions



Measured branching fraction ratios:

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

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

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

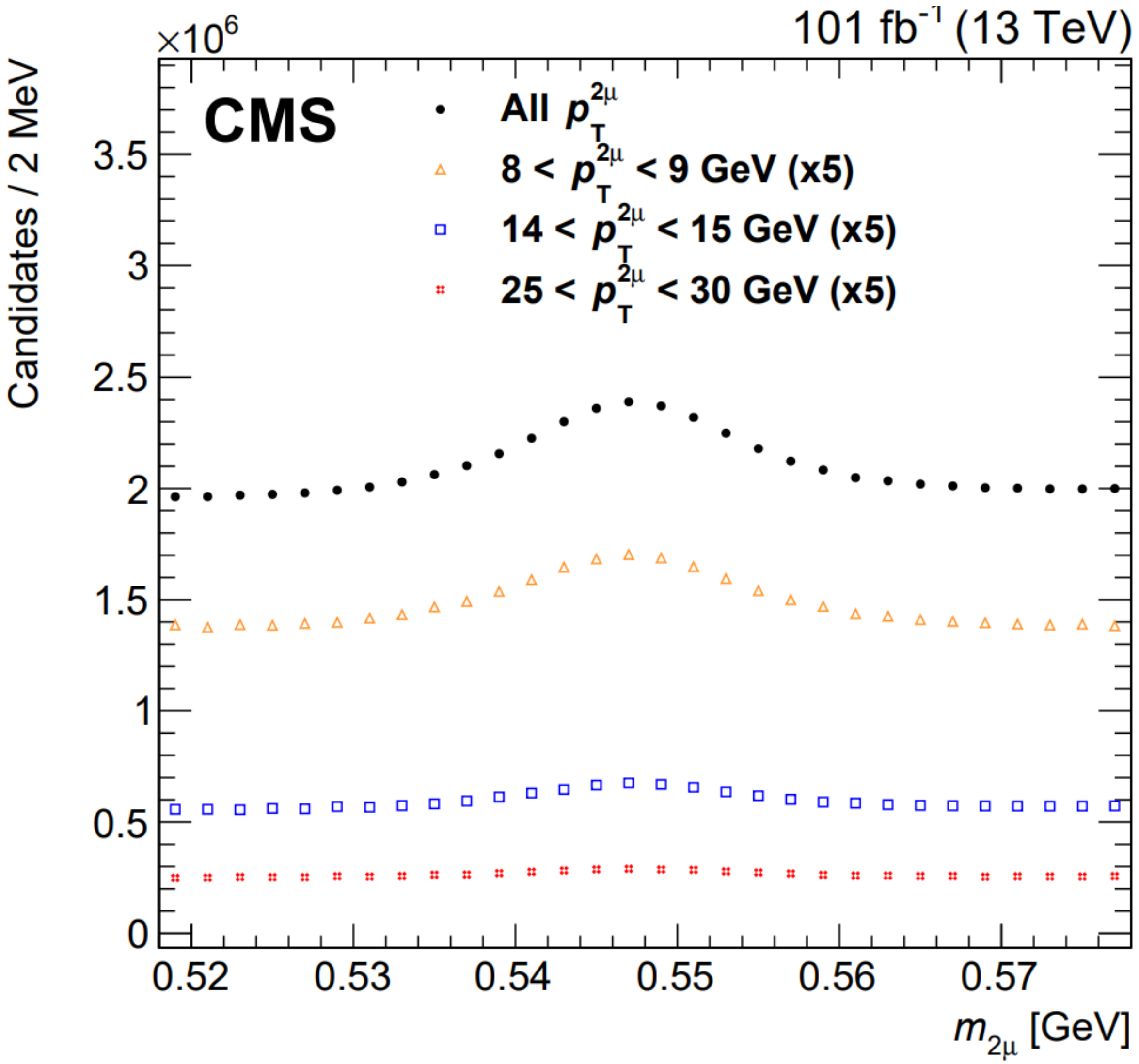
$$= 0.480 \pm 0.013\,(\text{stat}) \pm 0.032\,(\text{syst})$$

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

Observation of the rare decay of the η meson to four muons

arXiv:2305.04904

$\eta \to \mu^+\mu^-$ in scouting data

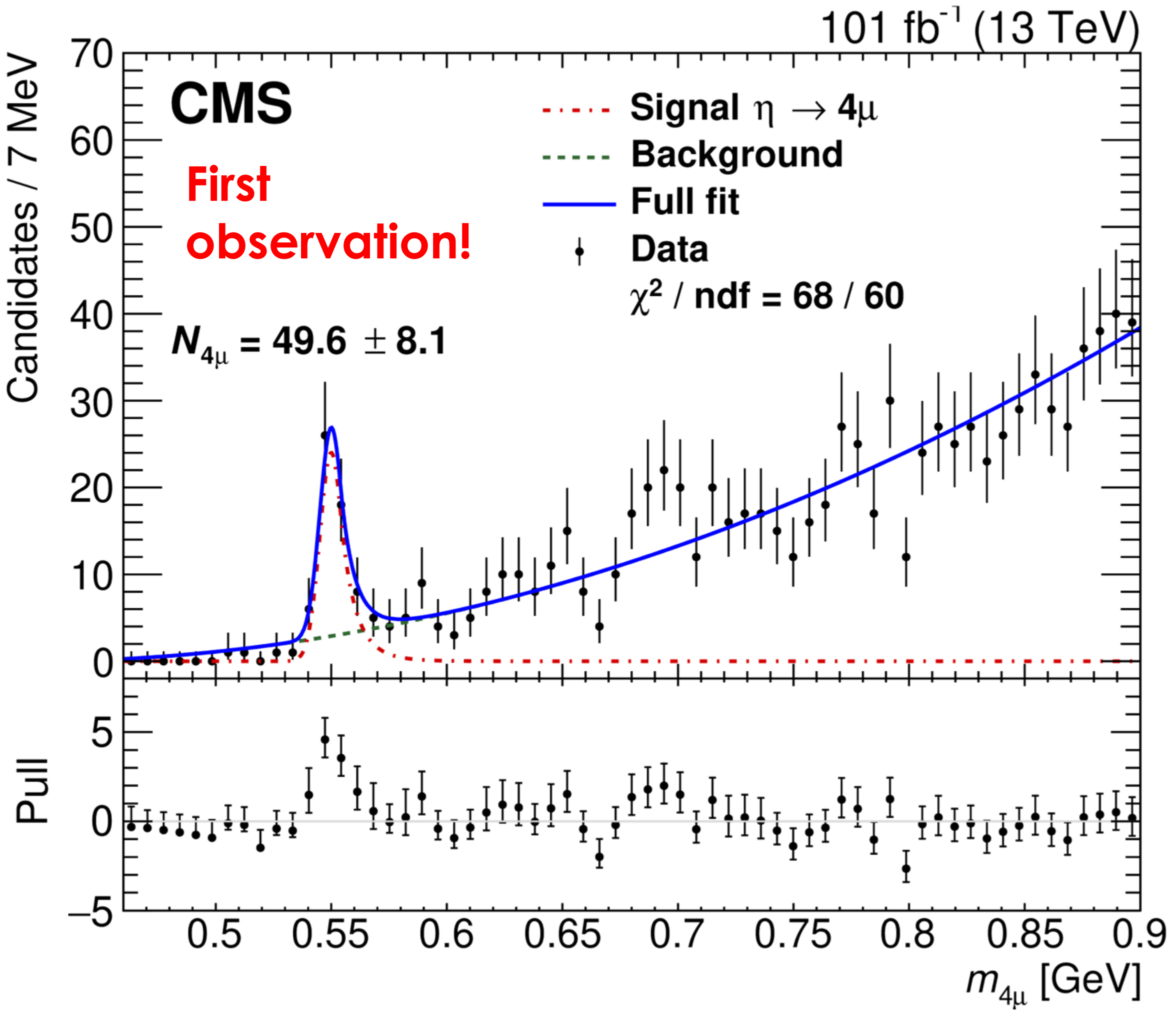


- Around **4.5 x 10⁶** signal $\eta \to \mu^+\mu^-$ events in the scouting data!
- $B(\eta \to \mu+\mu-) \sim 6 \times 10^{-6}$!

→ ~**10¹²η** produced in "CMS acceptance"
(even more after correcting for efficiency)

$\eta \to \mu^+\mu^-$signal is used to calibrate η meson production vs. p_T and y in MC

$\eta \to \mu^+\mu^-\mu^+\mu^-$ observation



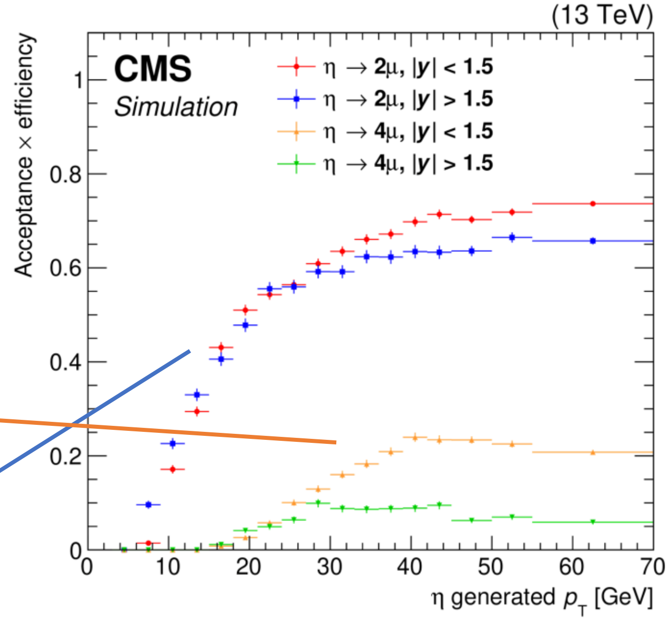
- A clear narrow peak of ~50 events, near the kinematic threshold
- Fit with Crystall-Ball+ threshold

$(m_{4\mu} - 4m_\mu)^\beta$

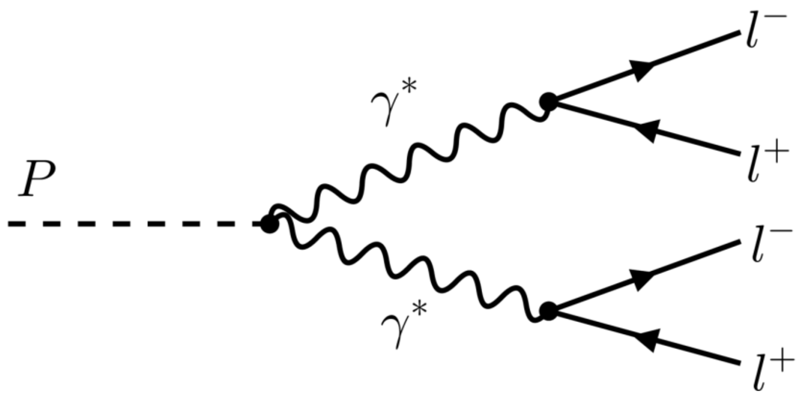
- **Significance > 5σ**
- Several misreconstructed decays were shown to not be able to produce such a peak

B measured relative to $\eta \to \mu^+\mu^-$ using **A×ε** ratio $^{4\mu}/_{2\mu}$ map vs. p_T and y:

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = \frac{N_{4\mu}}{\sum_{i,j} N_{2\mu}^{i,j} \frac{A_{4\mu}^{i,j}}{A_{2\mu}^{i,j}}}$$



$\eta \to \mu^+\mu^-\mu^+\mu^-$



Fully-leptonic decays of pseudoscalar mesons η and η':

- Allow precision tests of the SM
- Impact the knowledge of hadronic correction $(g\text{-}2)_\mu$

So far, the following modes have been observed:

$\eta \to \mu^+\mu^-$ (SERPUKHOV-134, 1980), $\eta \to e^+e^-e^+e^-$ (KLOE-2, 2011), $\eta' \to e^+e^-e^+e^-$ (BESIII, 2022)

We present the first observation of $\eta \to \mu^+\mu^-\mu^+\mu^-$, and measurements

$$\frac{\mathcal{B}_{4\mu}}{\mathcal{B}_{2\mu}} = (0.86 \pm 0.14\,(\text{stat}) \pm 0.12\,(\text{syst})) \times 10^{-3}$$

$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \ \pm 0.7\,(\mathcal{B}_{2\mu})) \times 10^{-9}$$

In agreement with SM prediction: $3.98 \pm 0.15 \cdot 10^{-9}$ *[Chin.Phys.C42 (2018) 2, 023109]*

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

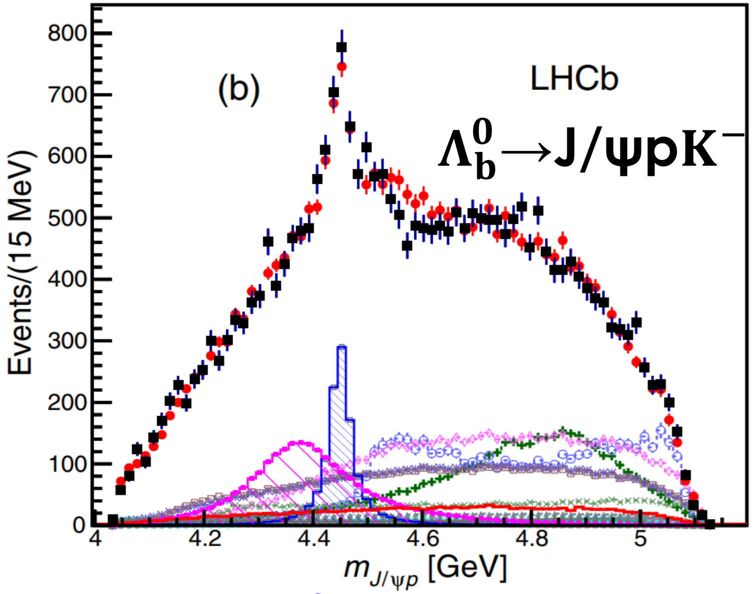
CMS-PAS-BPH-22-002

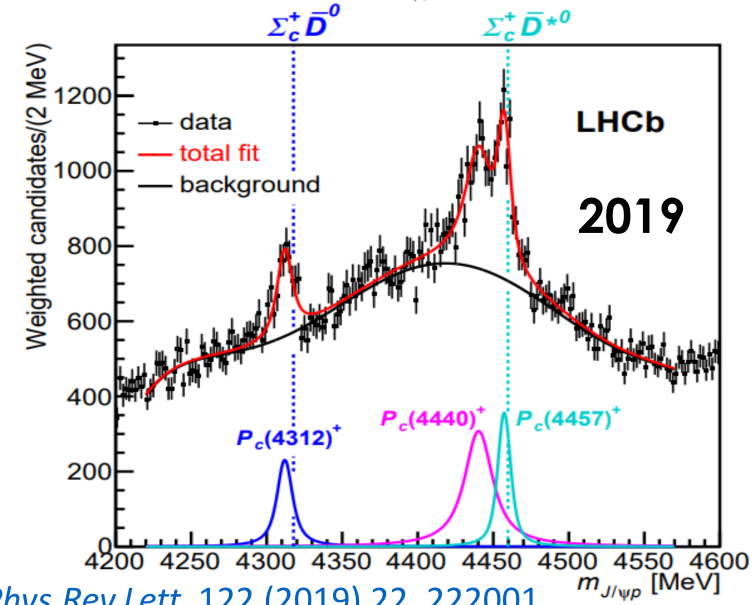
https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/BPH-22-002/index.html

Introduction

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

1544 citations!





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

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

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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**)

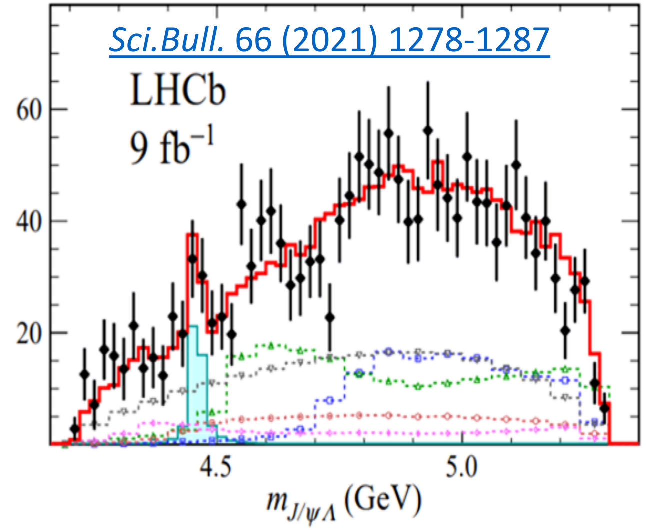
2019: adding Run-2 data, **9x** Λ_b^0 yield. From 1D fit of J/ψp mass distribution, 4450 peak is now split into two

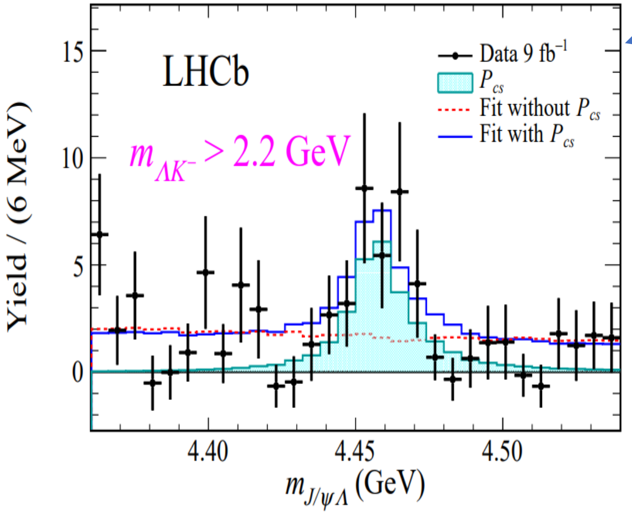
+ observe a new resonance, $P_c(4312)^+$

Introduction

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

In addition to J/ψp system, also the **J/ψΛ** system was investigated.





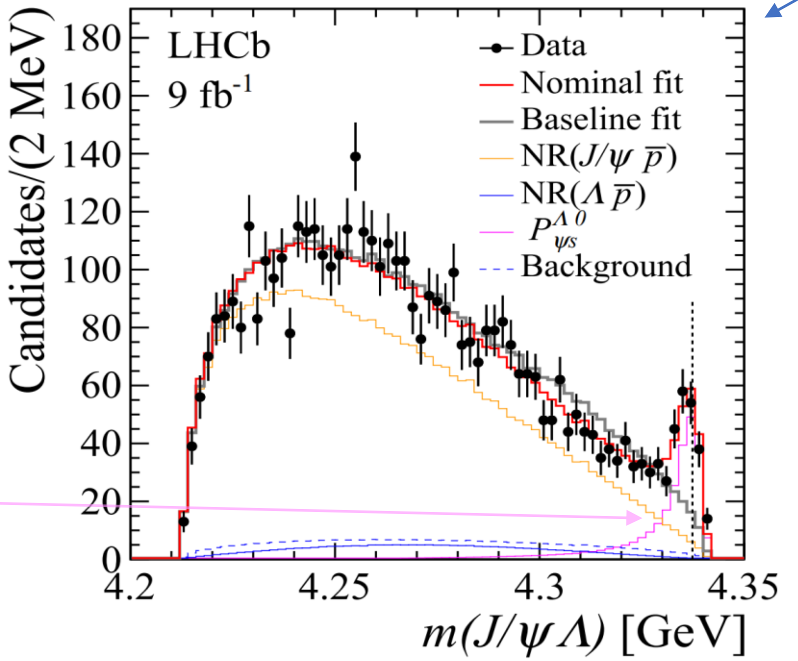
2020: 6D full angular analysis by LHCb of $\Xi_b^- \to J/\psi \Lambda K^-$ decay revealed **evidence** for hidden-charm **strange pentaquark $P_{cs}(4459)^0$**

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/ψΛ or J/ψp

arXiv:2210.10346

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

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



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

no significant states decaying to J/ψp

It is interesting to note that J/ψΛ pentaquarks are found to be *generally* ***narrower*** than J/ψp 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:

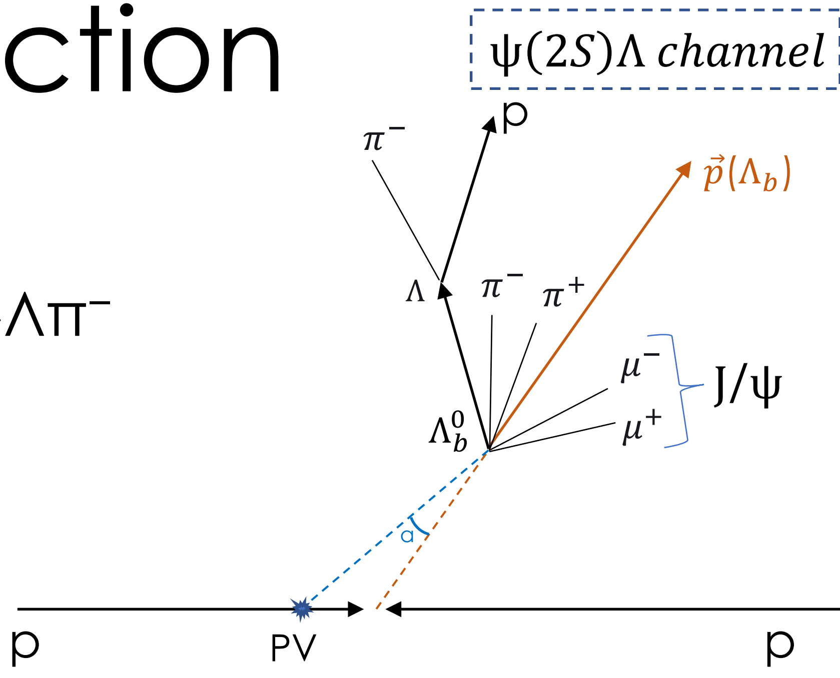
$\Lambda_b^0 \to \psi(2S)\Lambda$, with vertex fit of $\mu^+\mu^-\Lambda\pi^+\pi^+$

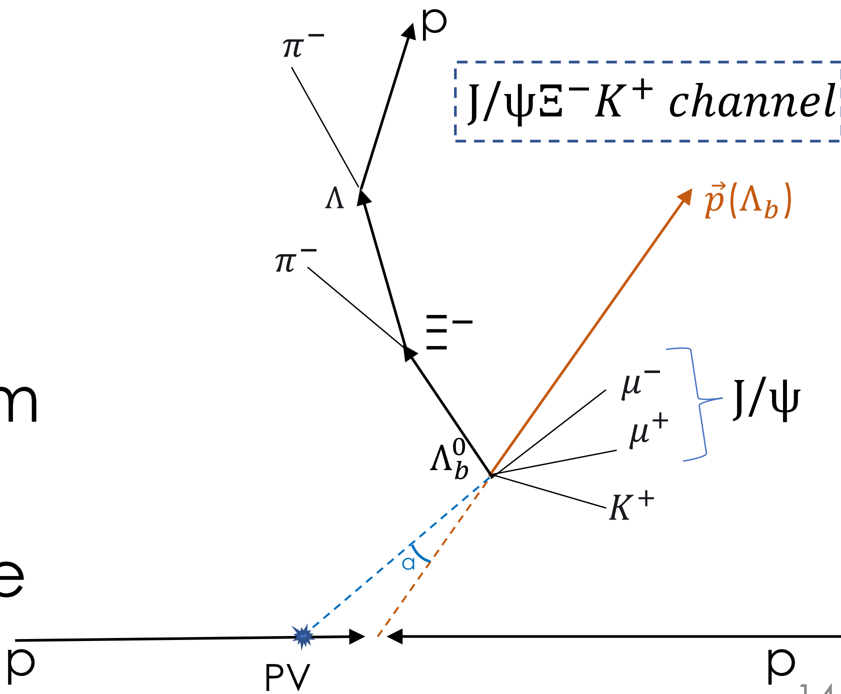
$J/\psi\pi^+\pi^-$ mass close to $M^{PDG}(\psi(2S))$

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

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

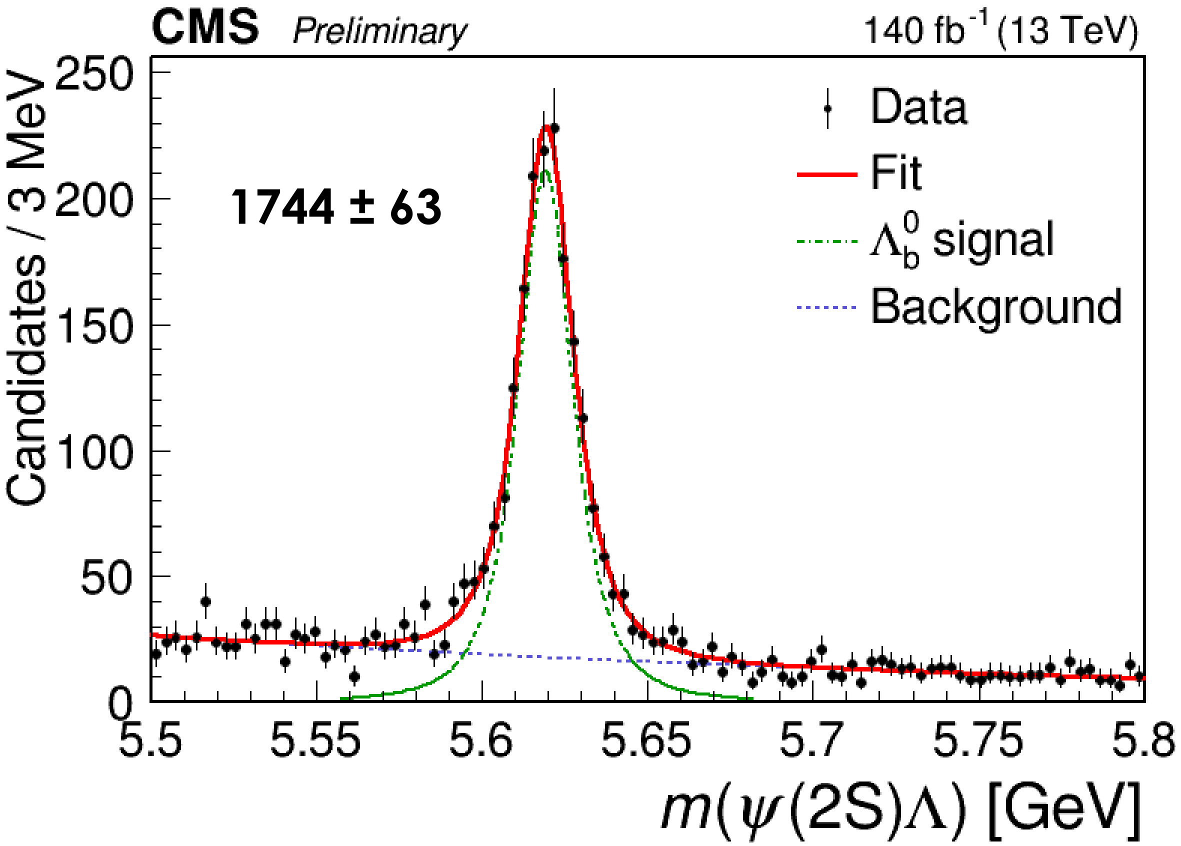
Ratio of total efficiencies from MC = 5.06±0.29

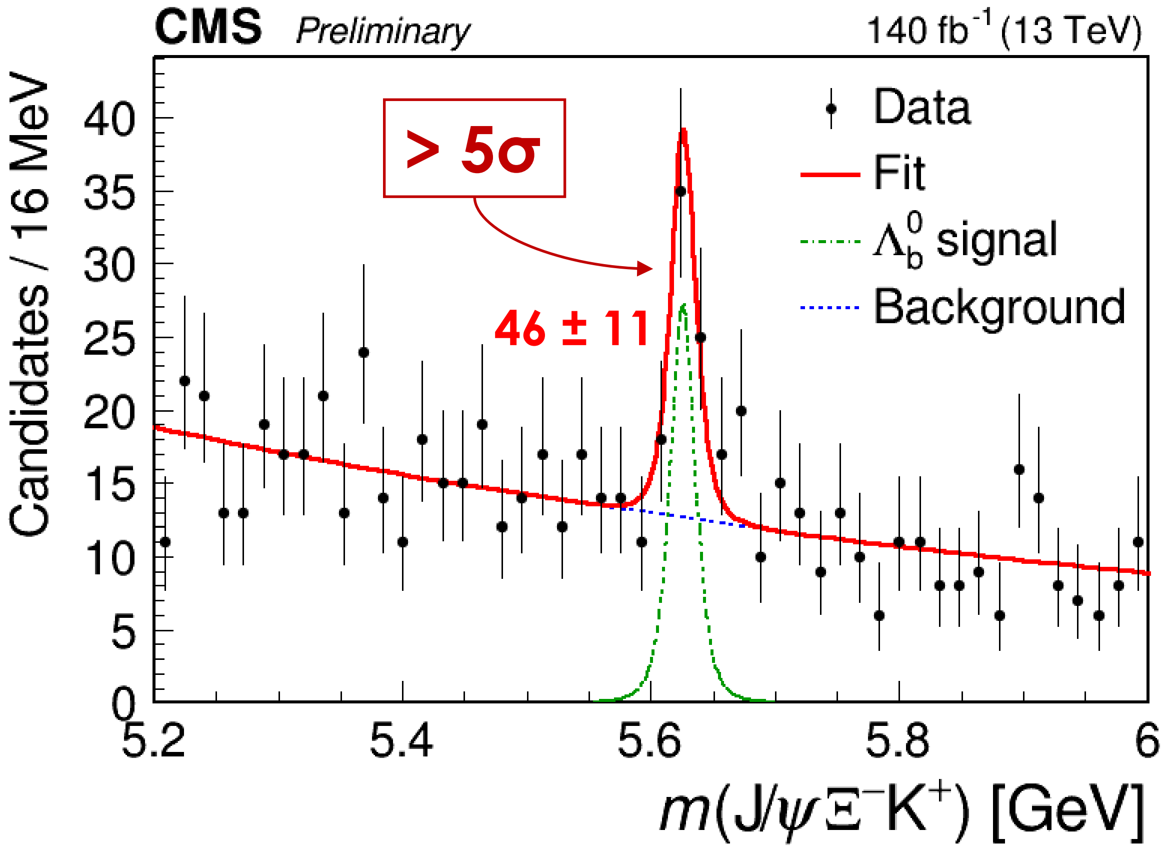
Known branching fractions from PDG

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

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

Invariant mass distributions





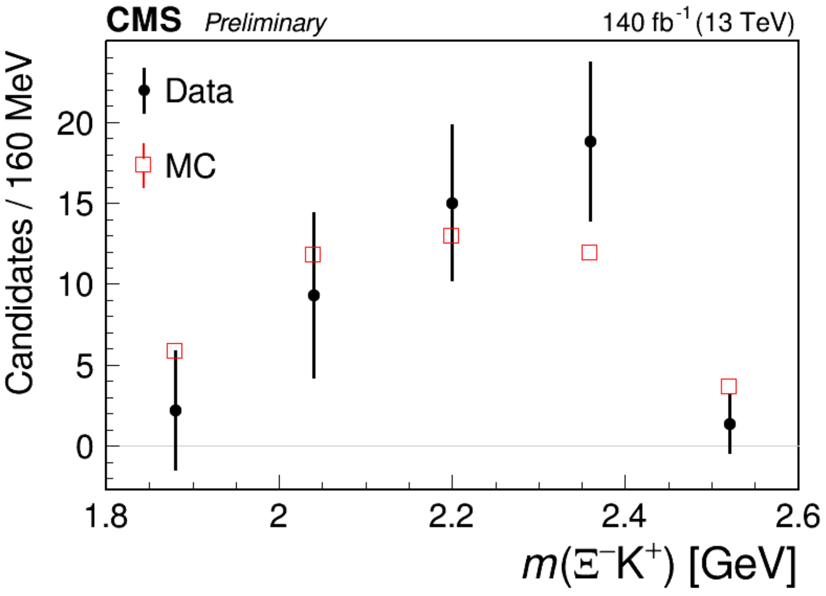
Student-T function for signal
Exponential for background

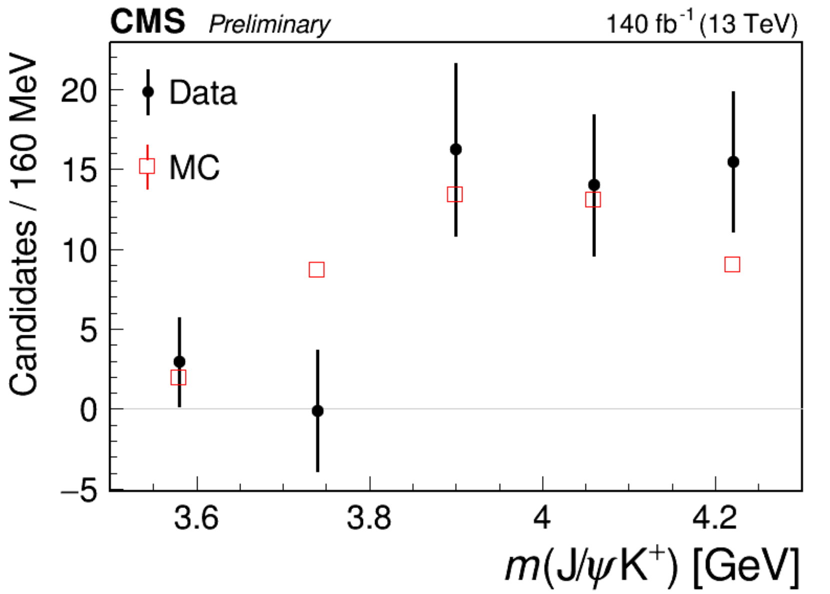
Unbinned ML fits

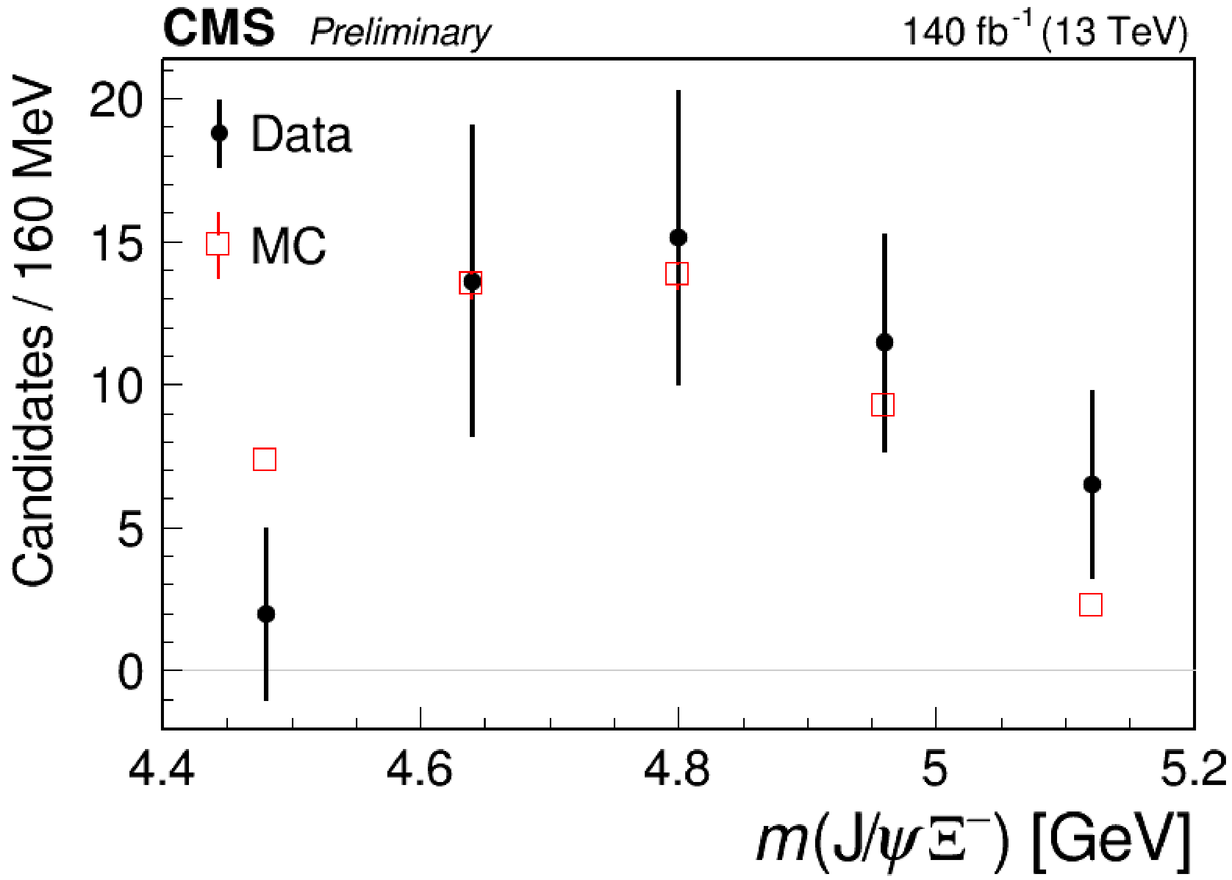
First observation!

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/ψΞ⁻K⁺ Intermediate invariant mass distributions







Data: sPlot-bkg-subtracted

No narrow peaks in J/ψΞ⁻ *(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

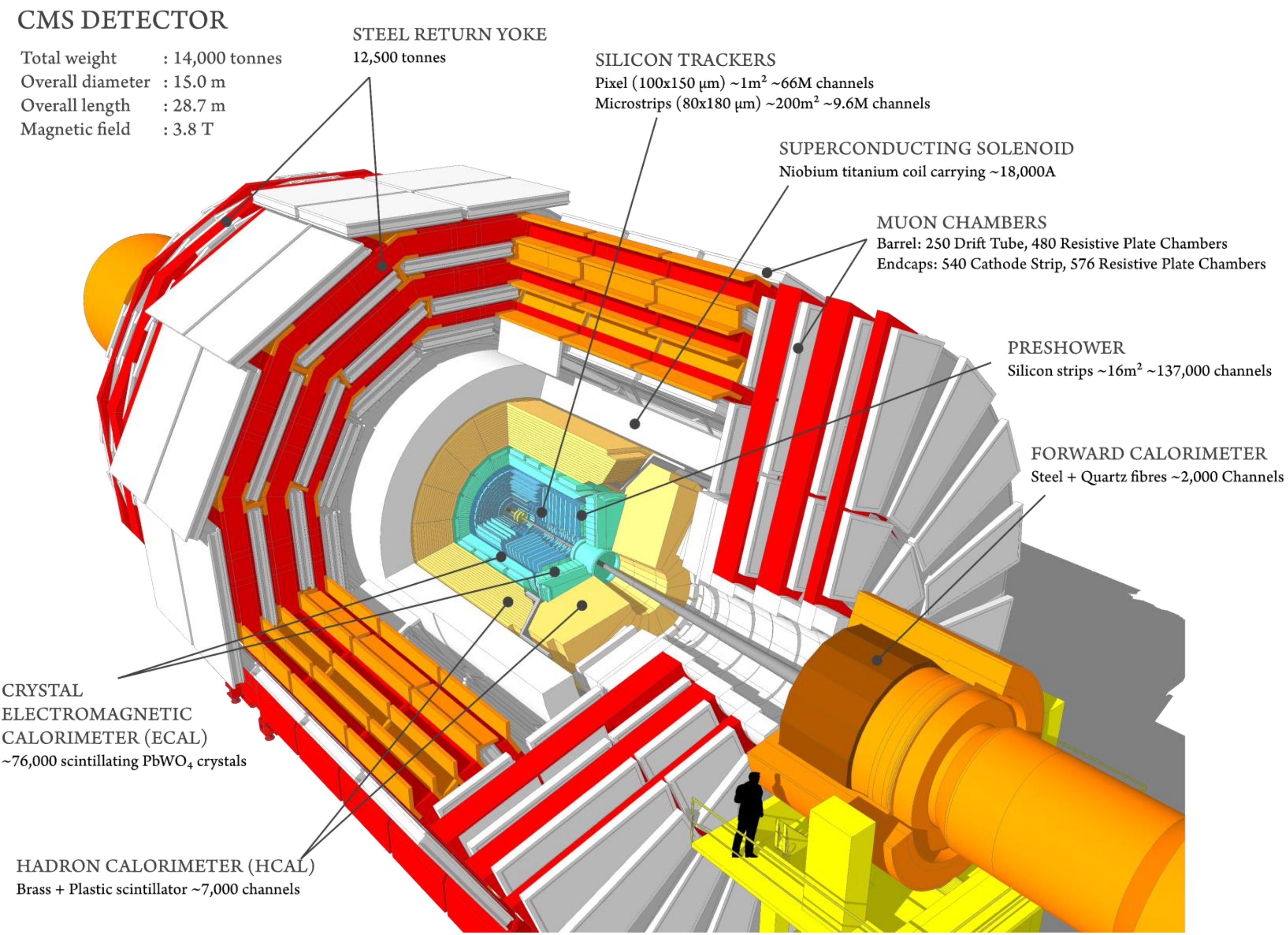
- CMS is an active experiment in flavor spectroscopy
- We **observe for the first time**:

  - $B_s^0 \rightarrow \psi(2S) K_s^0$ decay
  - $B^0 \rightarrow \psi(2S) K_s^0 \pi^+ \pi^-$ decay
  - $\eta \rightarrow \mu^+ \mu^- \mu^+ \mu^-$
  - $\mathbf{\Lambda_b^0 \rightarrow J/\psi \Xi^- K^+}$ **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:

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

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

$\mathbf{K_S^0 \to \pi^+\pi^-}$

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

$\mathbf{B \to \psi(2S) K_S^0}$

- $P_{vtx}(\mu^+\mu^- K_S^0) > 5\%$
- Distance significance $D_{xy}/\sigma > 5$
- Angle between **p** and **D**: $\cos(\beta) > 0.99$

$\mathbf{B \to \psi(2S) K_S^0 \pi^+\pi^-}$

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

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 $(x-x^0)^a$ • exp
     - Modified threshold pdf $(x-x^0)^a$ • Pol_1
5) Potential non-psi(2S) contribution
6) Alternative selection criteria:
   it accounts the correlation of the statistical uncertainties