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

Moscow International School of Physics 2024
Young Scientist Forum

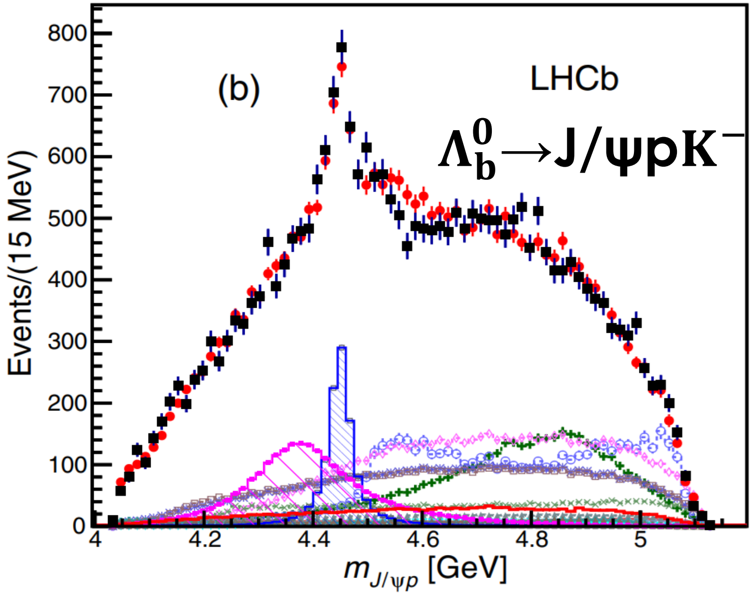
Maksim Sergeev[1,2]
Sergey Polikarpov[1,2]

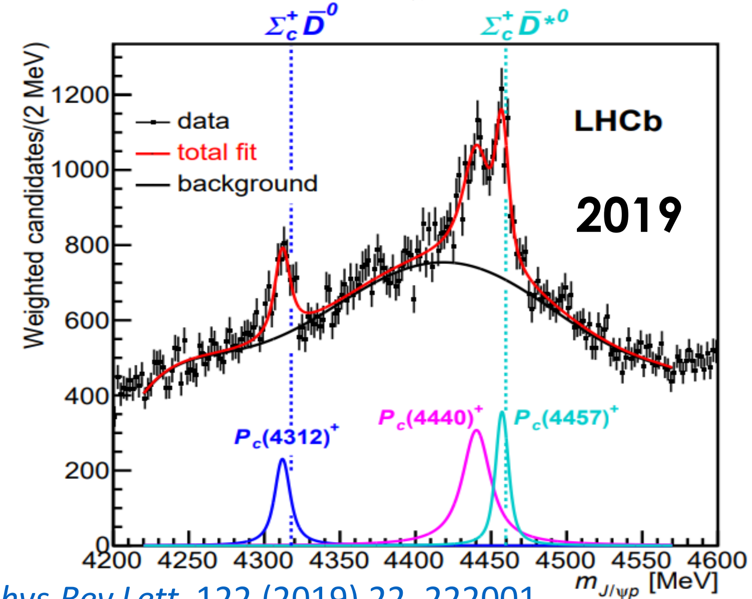
1 NRNU MEPhI, 2 LPI RAS

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

---

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;

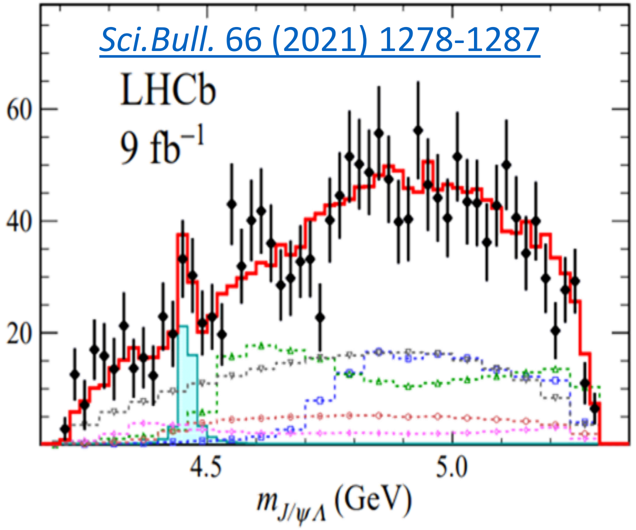
+ observe a new resonance, $P_c(4312)^+$

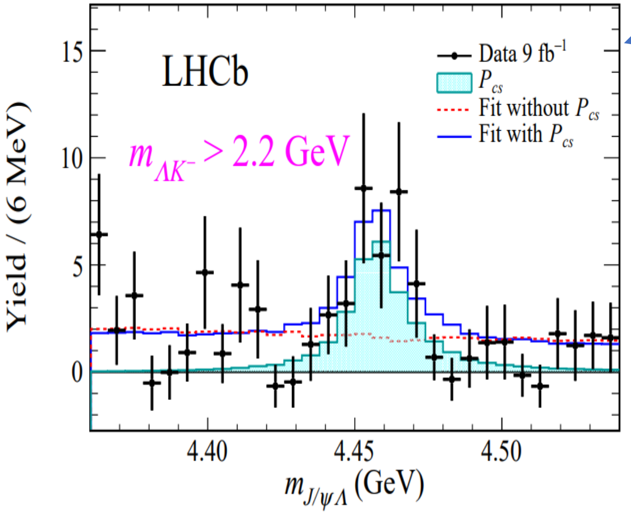
"Too much data" for a full 6D angular resonance analysis to converge!

Introduction

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

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


Sci.Bull. 66 (2021) 1278-1287



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

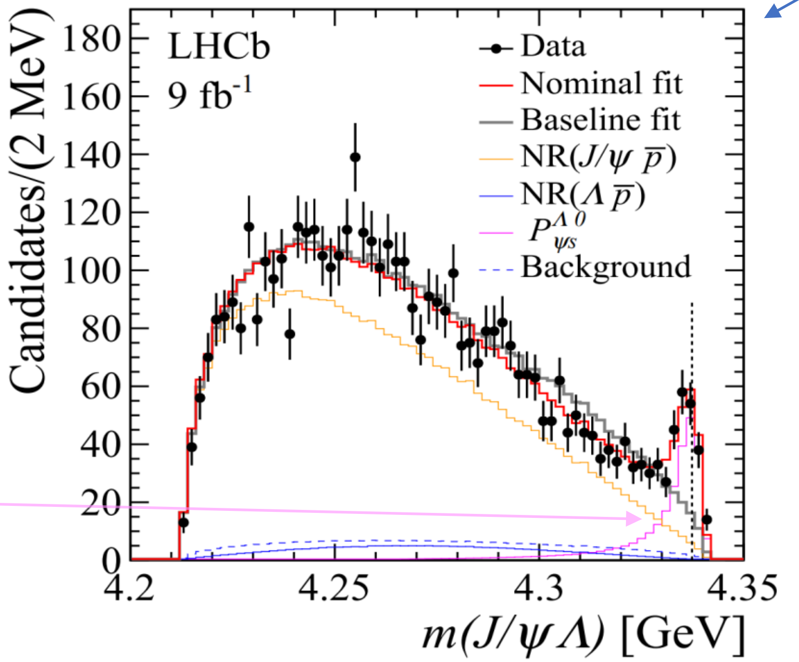
LHCb 2022: with 6D amplitude analysis of **$B^- \to J/\psi \Lambda \bar{p}$** decay, **observe new** strange pentaquark **$P_{cs}(4338)^0 \to J/\psi\Lambda$**

no significant states decaying to J/ψp

arXiv:2210.10346

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

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



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

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

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

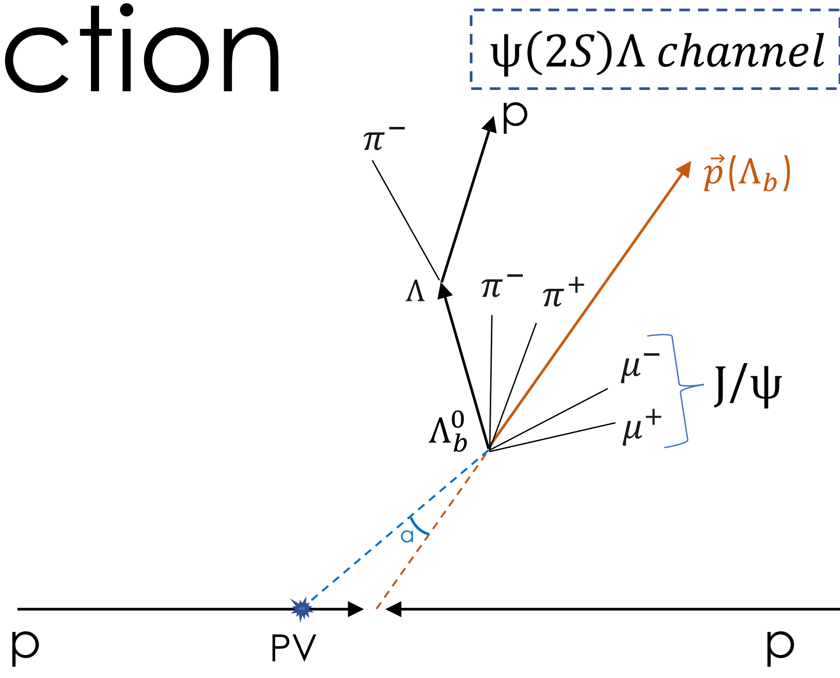
Normalization channel is chosen according to the similar decay topology, to reduce the systematic uncertainties associated with the track reconstruction:

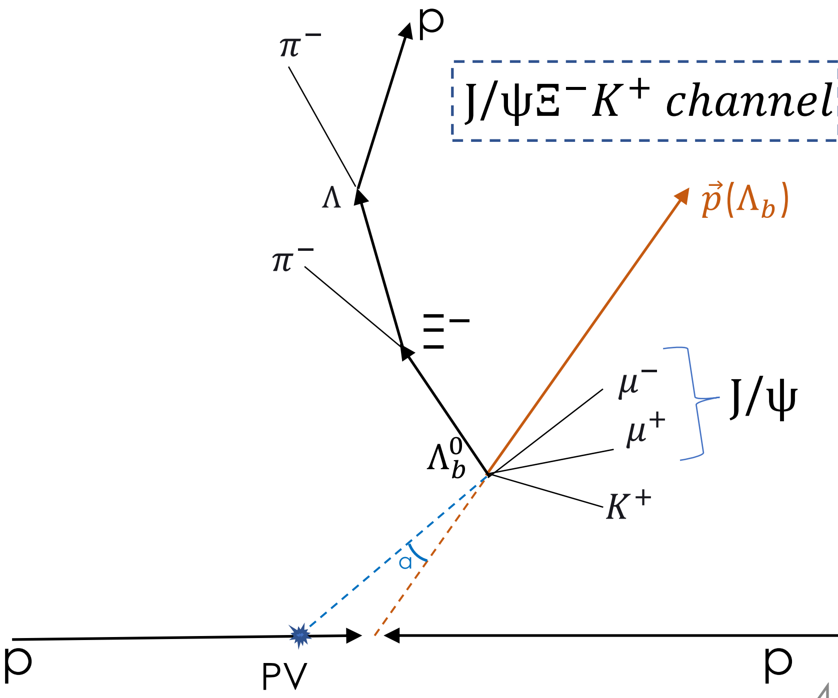
$\Lambda_b^0 \rightarrow \psi(2S)\Lambda$, with vertex fit of $\mu^+\mu^-\Lambda\pi^+\pi^+$, and a requirement on $J/\psi\pi^+\pi^-$ mass to be close to $M^{PDG}(\psi(2S))$

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


$\psi(2S)\Lambda$ *channel*


$J/\psi\Xi^-K^+$ *channel*

Optimization of selection criteria

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

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

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**

Variables

Mass windows:

$$m(\Lambda),\ m(\Xi^-)$$

Distance significance between vertices

$$L_{xy}/\sigma_{L_{xy}}(\Xi^-, \Lambda_b^0)\ ,\quad L_{xy}/\sigma_{L_{xy}}(\Lambda, \Xi^-)\ ,\quad L_{xy}/\sigma_{L_{xy}}(\Lambda_b^0, \mathrm{PV})$$

Angle between particle momentum and the line passing joining its birth vertex and decay vertex

$$\cos(\overrightarrow{L_{xy}}, \overrightarrow{p_T})\ (\Xi^-, \Lambda_b),\quad \cos(\overrightarrow{L_{xy}}, \overrightarrow{p_T})\ (\Lambda, \Xi^-)\ ,$$
$$\cos(\overrightarrow{L_{xy}}, \overrightarrow{p_T})\ (\Lambda_b, \mathrm{PV})$$

Transverse momentum

$$p_T(\Lambda_b^0),\ p_T(\mathrm{J}/\psi), p_T(\Xi^-), p_T(\Lambda), p_T(\mathrm{K}^+),\ p_T(\pi^-)$$

Vertex fit probabilities

$$P_{vtx}(\Lambda_b^0) \qquad P_{vtx}(\Xi^-) \qquad P_{vtx}(\Lambda)$$

Track impact parameter w.r.t. PV

$$\mathrm{IPS}(\pi),\ \mathrm{IPS}(\mathrm{K}^+)$$

Calculation of branching fraction ratio

Ratio of the signal yields in data

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

Ratio of total efficiencies from MC

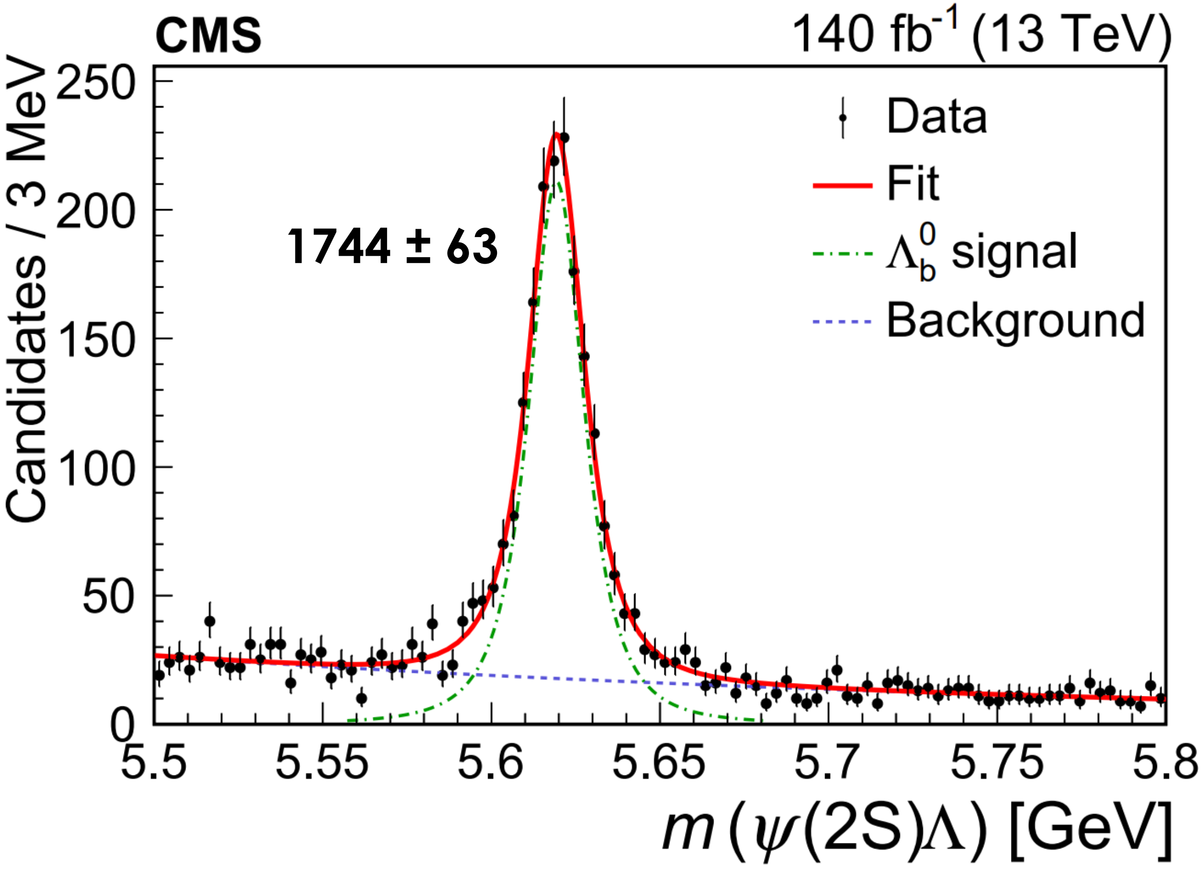
Known branching fractions from PDG

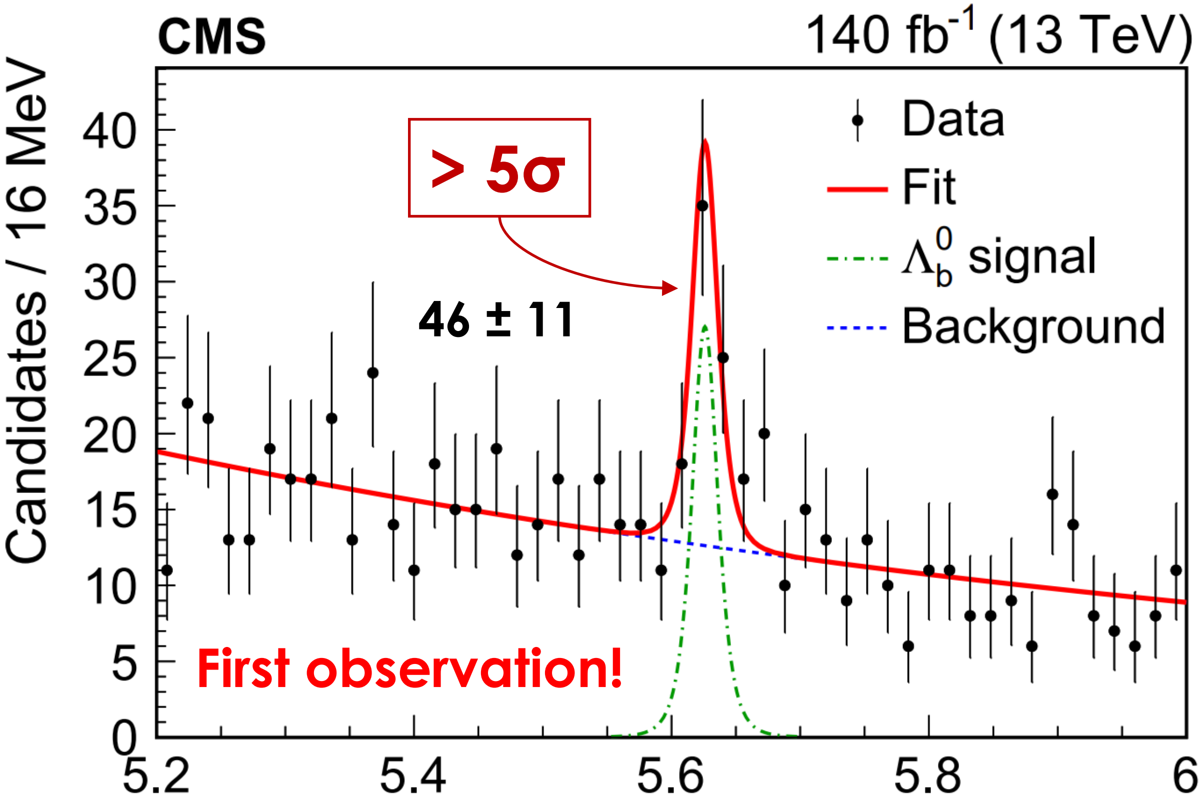
$$\boxed{\begin{aligned}\mathcal{B}(\psi(2S) \to J/\psi\,\pi\,\pi) &= (34.68 \pm 0.30)\% \\ \mathcal{B}(\Xi \to \Lambda\,\pi) &= (99.887 \pm 0.035)\%\end{aligned}}$$

$$\boxed{\frac{\epsilon_{\psi(2S)\Lambda}}{\epsilon_{J/\psi \Xi^- K^+}} = \frac{4.00 \pm 0.10}{0.79 \pm 0.04} = 5.06 \pm 0.29}$$

Invariant mass distributions

arXiv:2401.16303



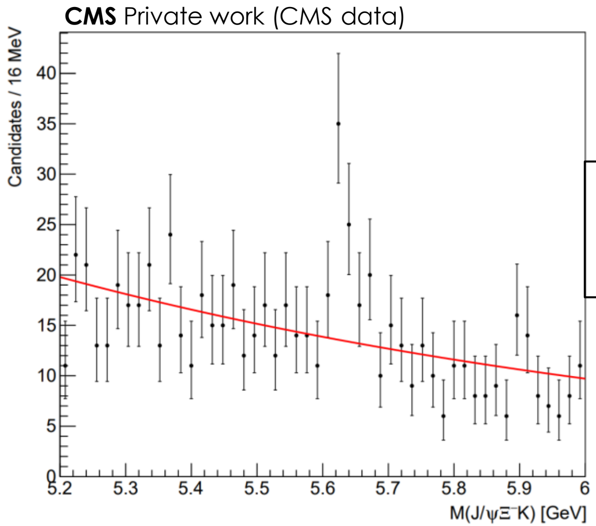


> 5σ

First observation!

Unbinned ML fits

Student-T function for signal
Exponential for background



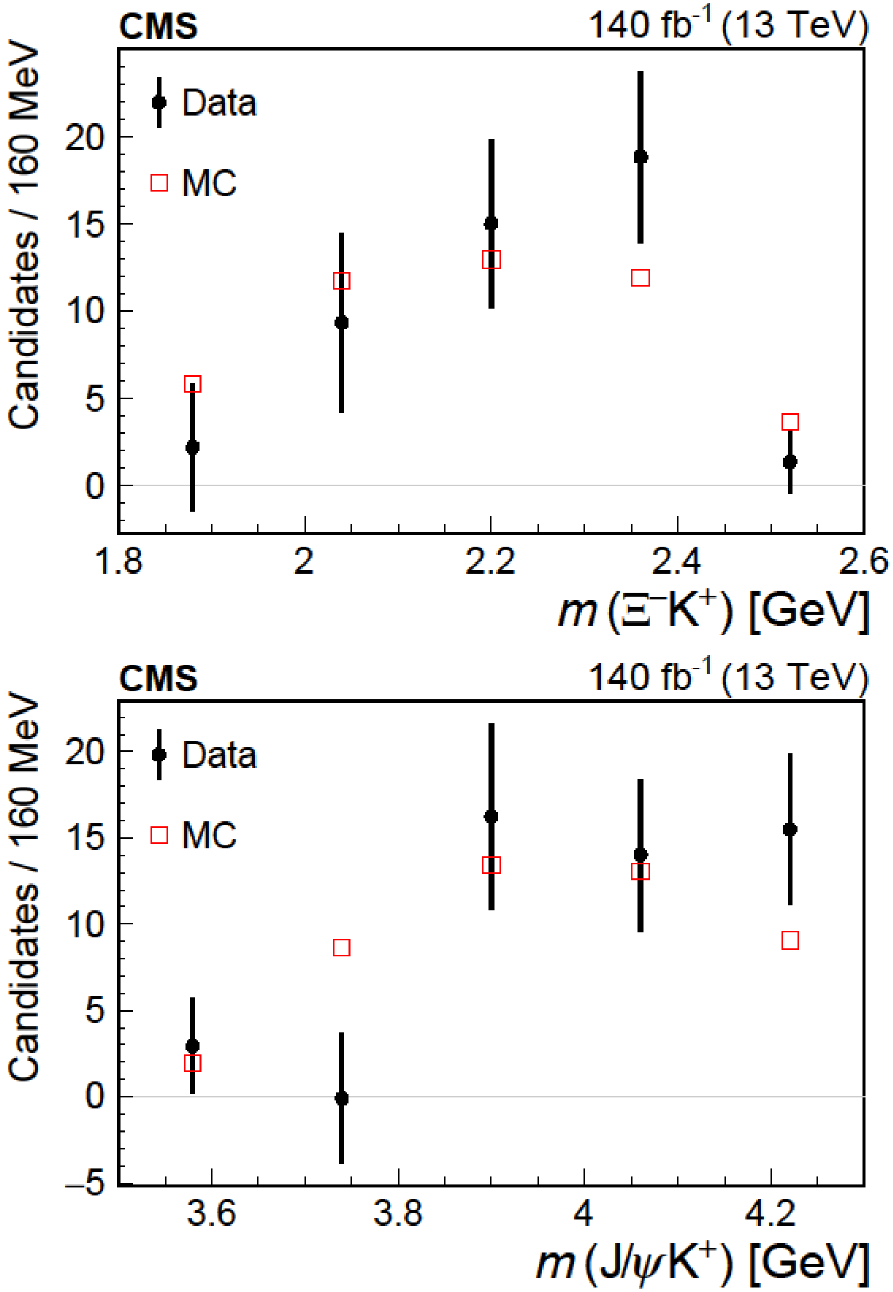
Hypothesis without signal

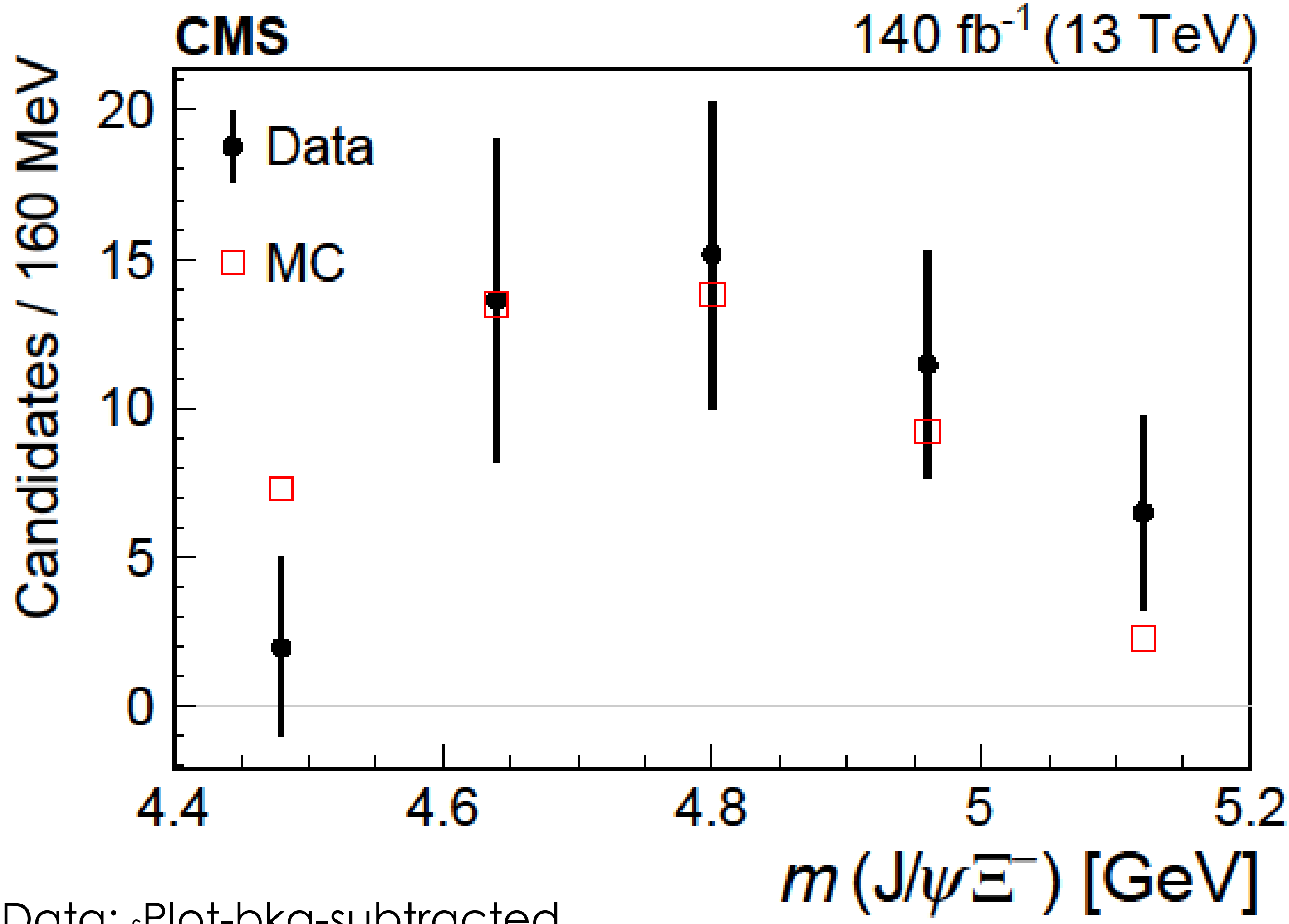
Fit results

$m(\Lambda_b^0)$ = 5619.3 ± 0.3 MeV — *consistent with PDG*
σ = 8.9 ± 0.4 MeV — *consistent with MC*

$m(\Lambda_b^0)$ = 5625.9 ± 3.2 MeV
σ = 10.4 ± 3.2 MeV

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





Data: sPlot-bkg-subtracted

No narrow peaks in $J/\psi\Xi^-$; good data-MC agreement

(not unexpected with 46 signal events)

arXiv:2401.16303

Systematic uncertainties

Source	Uncertainty (%)
Tracking efficiency	2.3
$p_{\mathrm{T}}(\Lambda_{\mathrm{b}}^{0})$ spectrum	4.7
Signal model	3.9
Background model	6.7
Non-$\psi(2S)$ contribution	2.5
Limited size of MC samples	5.6
Selection efficiency	14.3
Total	18.2

Different p_T spectra

Vary the fit model, deviation in R = syst. unc.

Potentially poorly modeled regions of phase space

Total uncertainty is calculated as sum in quadrature of individual sources.

Summary

- First observation of $\Lambda_b^0 \to J/\psi\Xi^- K^+$
  - ***The first decay to have $J/\psi\Xi^-$ system in products***
- No significant narrow peaks in $J/\psi\Xi^-$ mass distribution
  - *With 46 signal events, our sensitivity is very limited*
- Measured branching fraction ratio:

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to J/\psi\Xi^- K^+)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S)\Lambda)} = [3.38 \pm 1.02\,(\text{stat}) \pm 0.61\,(\text{syst}) \pm 0.03\,(\mathcal{B})]\%$$

arXiv:2401.16303

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

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

The end.

BACKUP

The CMS detector

The central element of the CMS is a **superconducting solenoid** with an internal diameter of 6 m, providing a magnetic field of 3.8 T. Inside the solenoid are **silicon pixel** and **strip detectors**, **electromagnetic** and **scintillation calorimeters**.

Muons are measured using the following detectors: **drift tubes, cathode strip chambers with resistive plates**.

Triggers have 2 levels of information dropout:

- **first-level trigger (L1)** is a hardware system of triggers that decreases frequency of events to record from 40 MHz to 100 kHz
- **high-level trigger (HLT)** uses rapid algorithms of event partial reconstruction with decreasing the frequency to 1 kHz

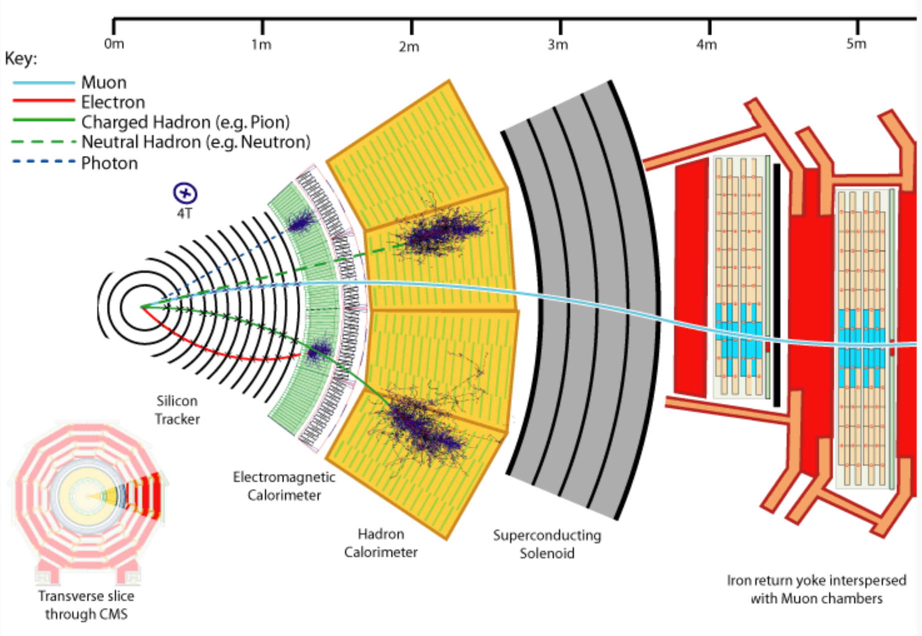
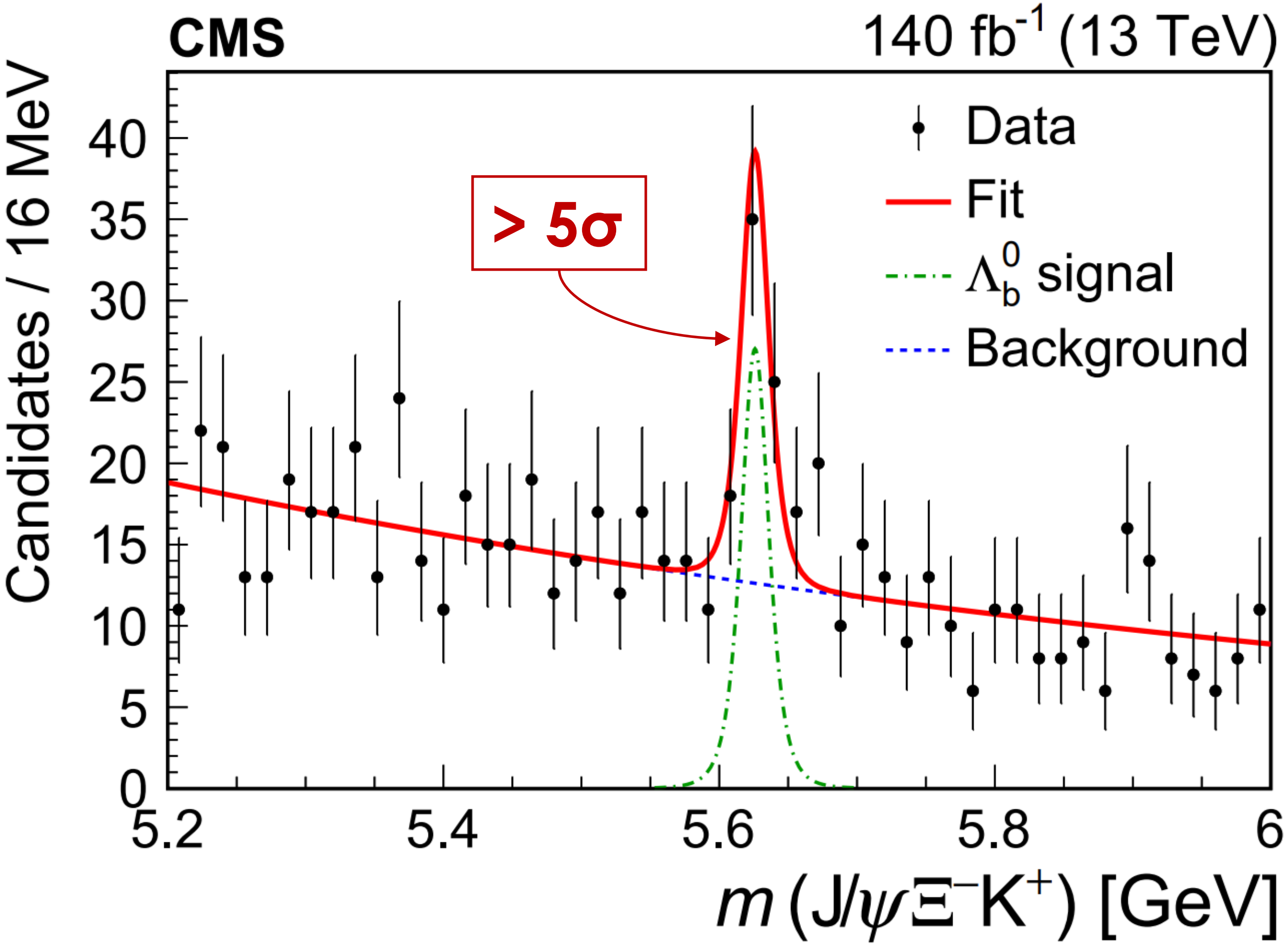
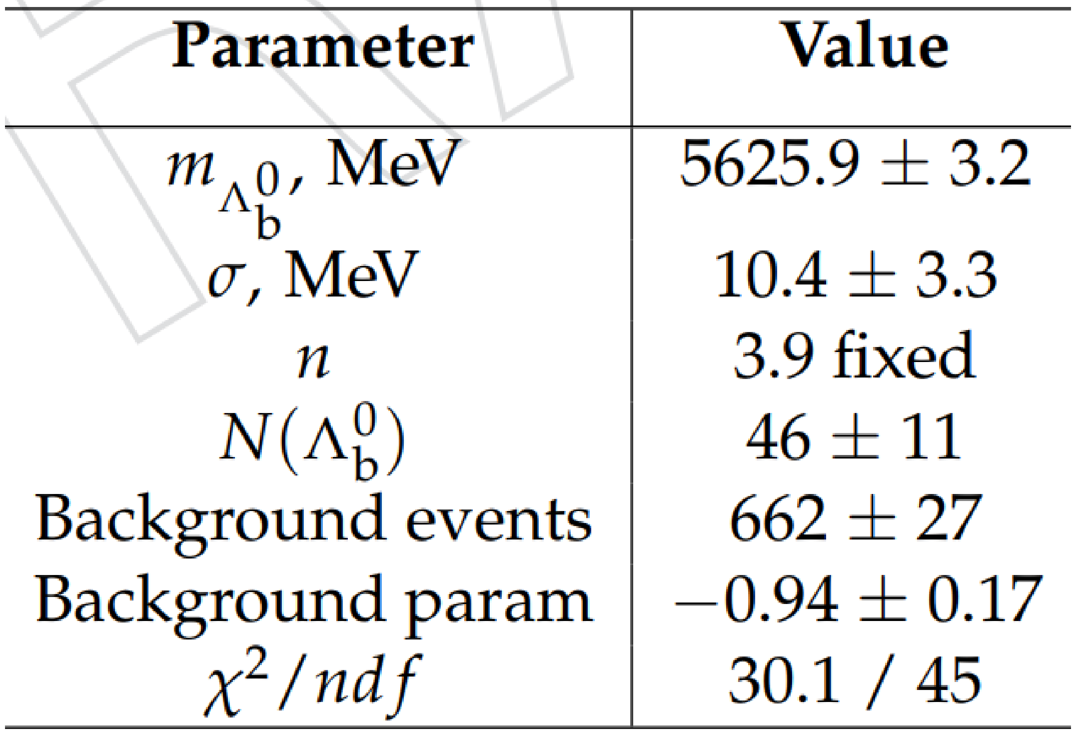


Figure 2: CMS scheme

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



Fit results:



Parameter	Value
$m_{\Lambda_b^0}$, MeV	5625.9 ± 3.2
σ, MeV	10.4 ± 3.3
n	3.9 fixed
$N(\Lambda_b^0)$	46 ± 11
Background events	662 ± 27
Background param	-0.94 ± 0.17
χ^2/ndf	30.1 / 45

Student-T function for signal
Exponential for background

arXiv:2401.16303

Optimization of selection criteria

Punzi formula is used for optimization, with SC recommendation
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**

Optimization of selection criteria for $\mathrm{J}/\psi\Xi^-\mathrm{K}^+$

- ✓ Series of scans over variables performed to find optimal cut values to maximize the expected significance of the signal
- ✓ In each scan, the cut value when ***f*** takes the largest value is recorded and used in the following scans
- ✓ When iteration shows the same result (cut values) as the previous one, the optimization is complete
- ✓ Selection criteria for normalization channel are chosen similar (as close as possible) to those found for the signal channel

Variables

Mass windows: m(Λ), m(Ξ^-)

Distance significance between vertices

$$L_{xy}/\sigma_{L_{xy}}(\Xi^-,\Lambda_b^0)\ ,\quad L_{xy}/\sigma_{L_{xy}}(\Lambda,\Xi^-)\ ,\quad L_{xy}/\sigma_{L_{xy}}(\Lambda_b^0,\mathrm{PV})$$

Angle between particle momentum and the line passing joining its birth vertex and decay vertex

$$\cos(\overrightarrow{L_{xy}},\overrightarrow{p_T})\ (\Xi^-,\Lambda_b),\quad \cos(\overrightarrow{L_{xy}},\overrightarrow{p_T})\ (\Lambda,\Xi^-)\ ,$$
$$\cos(\overrightarrow{L_{xy}},\overrightarrow{p_T})\ (\Lambda_b,\mathrm{PV})$$

Transverse momentum

$$p_T(\Lambda_b^0),\ p_T(\mathrm{J}/\psi),\ p_T(\Xi^-),\ p_T(\Lambda),\ p_T(\mathrm{K}^+),\ p_T(\pi^-)$$

Vertex fit probabilities

$$P_{vtx}(\Lambda_b^0)\qquad P_{vtx}(\Xi^-)\qquad P_{vtx}(\Lambda)$$

Track impact parameter w.r.t. PV

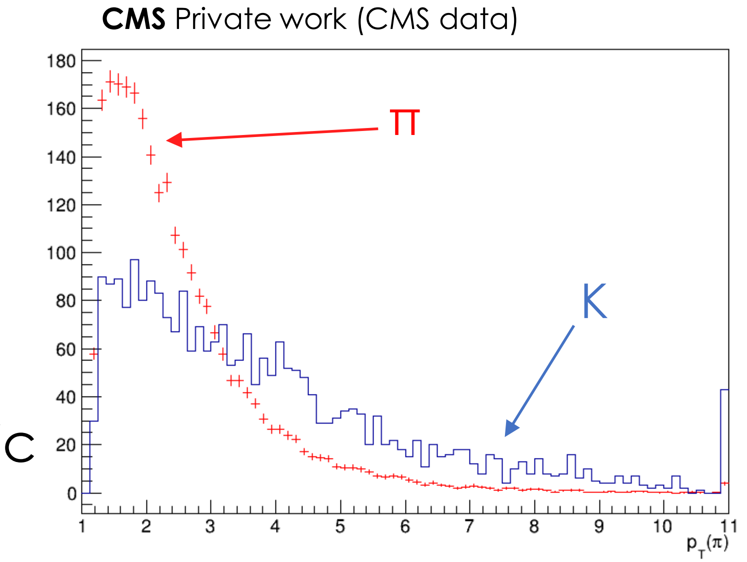
$$\mathrm{IPS}(\pi),\ \mathrm{IPS}(\mathrm{K}^+)$$

Systematic uncertainties

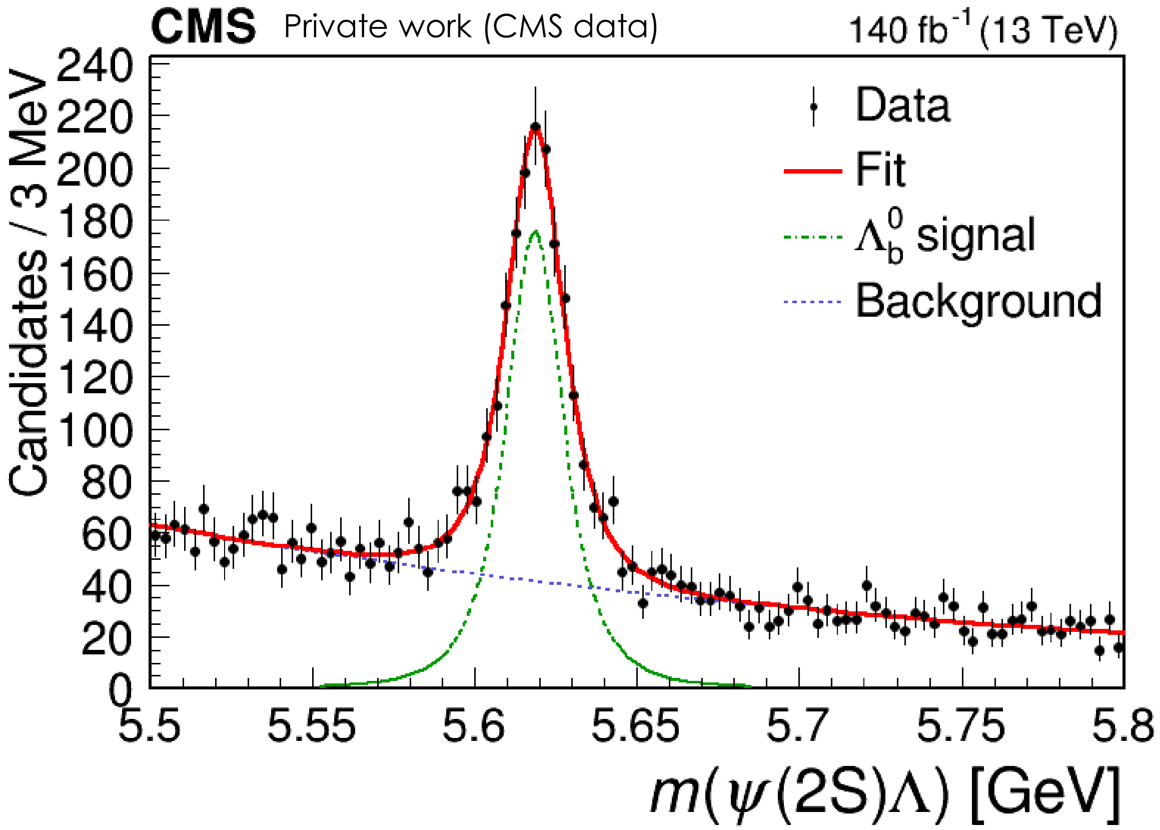
1) Uncertainty of efficiency ratio due to limited MC statistics
2) Signal model choice: try several alternative models, take the largest variation in R as systematics
    - Student-T is baseline, alternatives are
        - Double-gaussian
        - Johnson PDF

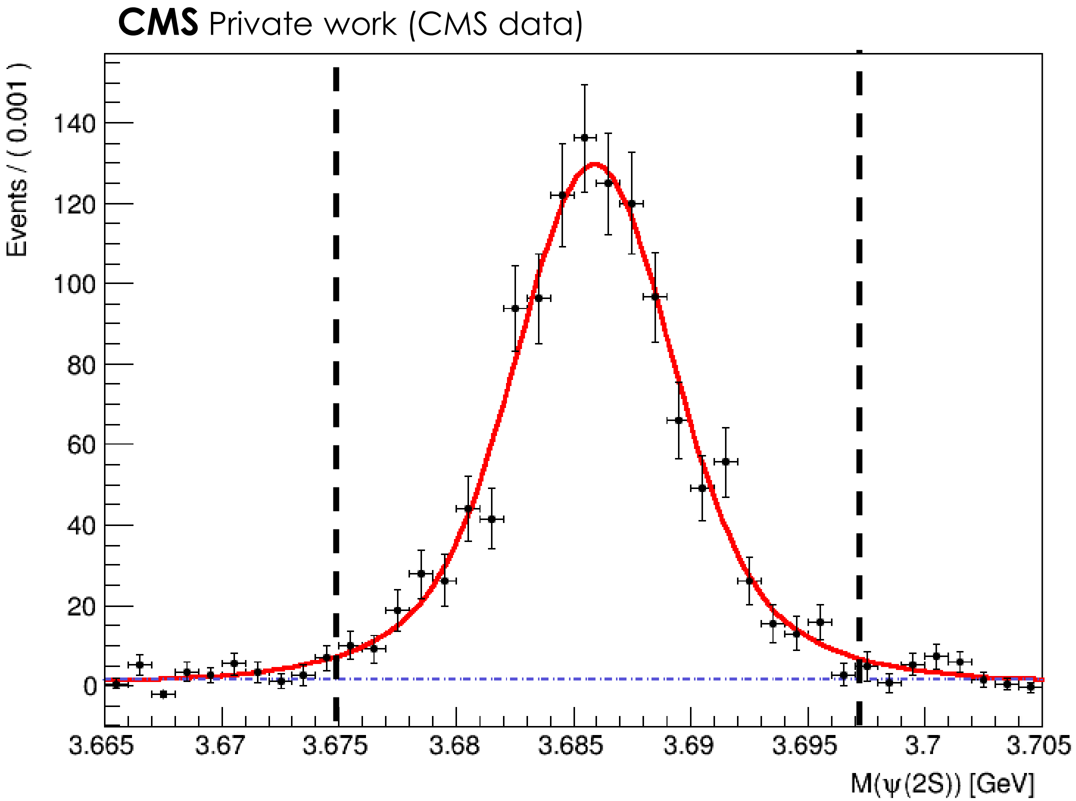
3) Background model choice: several alternative models → largest variation in R
    - Exp is baseline, alternatives are
        - 2nd degree polynomial
        - Modified threshold pdf $(x-x^0)^a \bullet \exp$
        - Modified threshold pdf $(x-x^0)^a \bullet \mathrm{Pol}_1$

4) Tracking efficiency:
    the pT spectra of the harder of the two tracks
    are found to differ significantly between signal and norm.
    channels → **conservatively** taking 2.3% as additional systematic
    as if there were different number of tracks in 2 channels



Systematic uncertainties - Potential non-psi(2S) contribution





To estimate background under ψ(2S) we use *sPlot* method to subtract the background under Λ_b^0. The m(J/ψππ) range was expanded to 5σ around mPDG(ψ(2S)). Integral of bckg function in baseline region [|m(J/ψππ) − mPDG(ψ(2S))|< 11.1 MeV] is *30±18*

Thus, the additional systematic uncertainty is 30/1179 = **2.5%**
1179 - the signal yield for R measurement cuts

Systematic uncertainties - Selection efficiency

Variable	10% drop (20% drop)	$\mathcal{R}$, %	$\mathcal{R}_{uncor}$, %	$\sqrt{d^2-(\delta d)^2}/3.38\%$
$p_{\mathrm{T}}(\mu)$	4.45 GeV	3.50 ± 1.12	3.50 ± 0.53	–
$p_{\mathrm{T}}(\mu)$	(4.8 GeV)	3.03 ± 1.06	3.03 ± 0.42	–
$p_{\mathrm{T}}(\mathrm{J}/\psi)$	10.5 GeV	3.44 ± 1.14	3.44 ± 0.32	–
$p_{\mathrm{T}}(\mathrm{J}/\psi)$	(12.0 GeV)	2.68 ± 1.14	2.68 ± 0.52	14.3%
$P_{vtx}(\mathrm{J}/\psi)$	19%	3.25 ± 1.07	3.25 ± 0.41	–
$P_{vtx}(\mathrm{J}/\psi)$	(30%)	3.35 ± 1.14	3.35 ± 0.56	–
$IPS(\mathrm{K}^+\_\Lambda_{\mathrm{b}}^0)$	2.8	3.30 ± 1.04	3.30 ± 0.11	–
$IPS(\mathrm{K}^+\_\Lambda_{\mathrm{b}}^0)$	(3.45)	3.84 ± 1.20	3.84 ± 0.67	–
$p_{\mathrm{T}}(\pi_{\Xi}^-)$	0.55 GeV	3.60 ± 1.13	3.60 ± 0.45	–
$p_{\mathrm{T}}(\pi_{\Xi}^-)$	(0.67 GeV)	3.23 ± 1.15	3.23 ± 0.43	–
$cos(\overrightarrow{L_{xy}}, \overrightarrow{p_{\mathrm{T}}})(\mathrm{J}/\psi\_PV)$	0.9975	3.40 ± 1.07	3.40 ± 0.59	–
$cos(\overrightarrow{L_{xy}}, \overrightarrow{p_{\mathrm{T}}})(\mathrm{J}/\psi\_PV)$	(0.9985)	3.77 ± 1.27	3.77 ± 0.50	–
$L_{xy}/\sigma_{L_{xy}}(\mathrm{J}/\psi\_PV)$	11.5	2.95 ± 1.03	2.95 ± 0.45	–
$L_{xy}/\sigma_{L_{xy}}(\mathrm{J}/\psi\_PV)$	(16.0)	2.90 ± 1.10	2.90 ± 0.53	–
Baseline		3.38 ± 1.02	3.38	

Change in R:

$$d = 2.68 - 3.38 = 0.70\%$$

↓

Its uncertainty:

$$\delta d = 0.52\%$$

↓

Square root difference between them:

$$\sqrt{d^2-(\delta d)^2} = 0.47\%$$

↓

Additional systematic uncertainty :

$$0.47/3.38 = 14.3\%$$

We strengthen the cut and evaluate the uncertainty in the phase space where the signal events are located. We vary the each cut individually, strengthening the requirement until the efficiency is at 80% with respect to the nominal value and at 90% as a cross-check.