CMS Experiment at the LHC, CERN
Data recorded: 2017-Jul-31 02:43:27.876032 GMT
Run / Event / LS: 300156 / 28539391 / 26

Studies of Ξ_b baryons spectroscopy at CMS

Kirill Ivanov [1] on behalf of the CMS Collaboration

kirill.ivanov@cern.ch

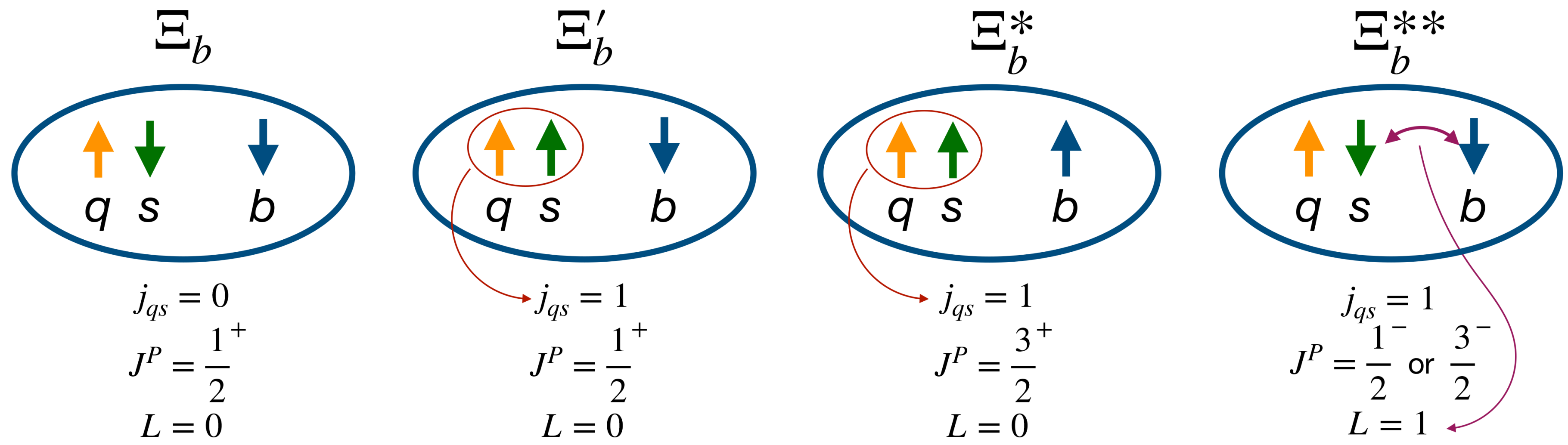
[1] Moscow Institute of Physics and Technology (MIPT)

Moscow International School of Physics 2024

1st March 2024

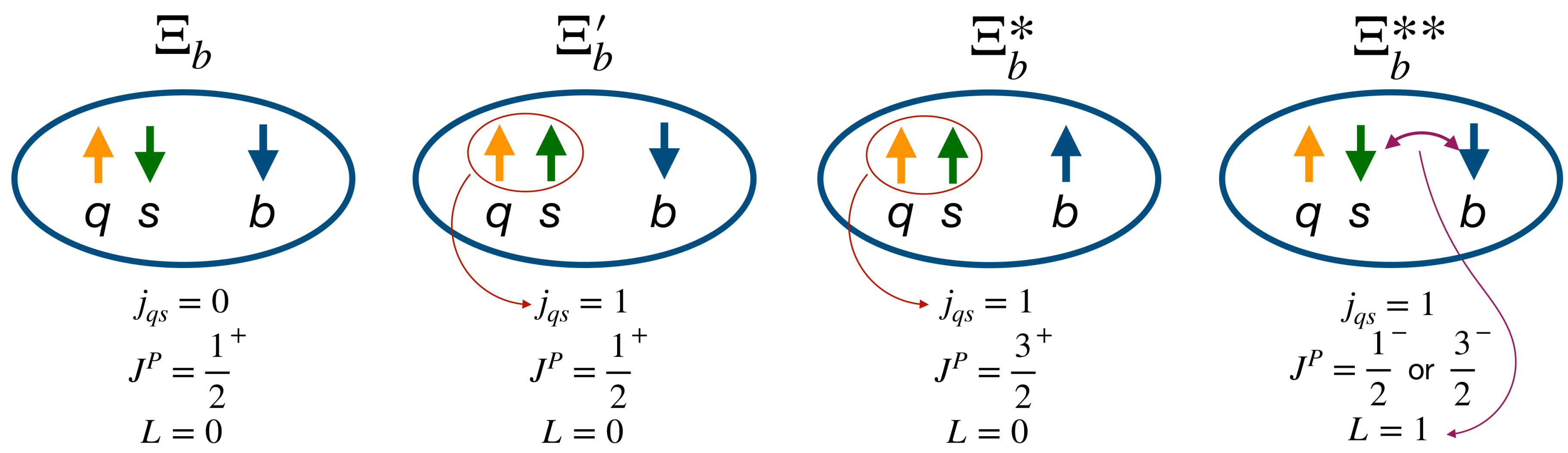
The work is supported by RSF (grant № 23-12-00083)

Ξ_b baryons spectroscopy

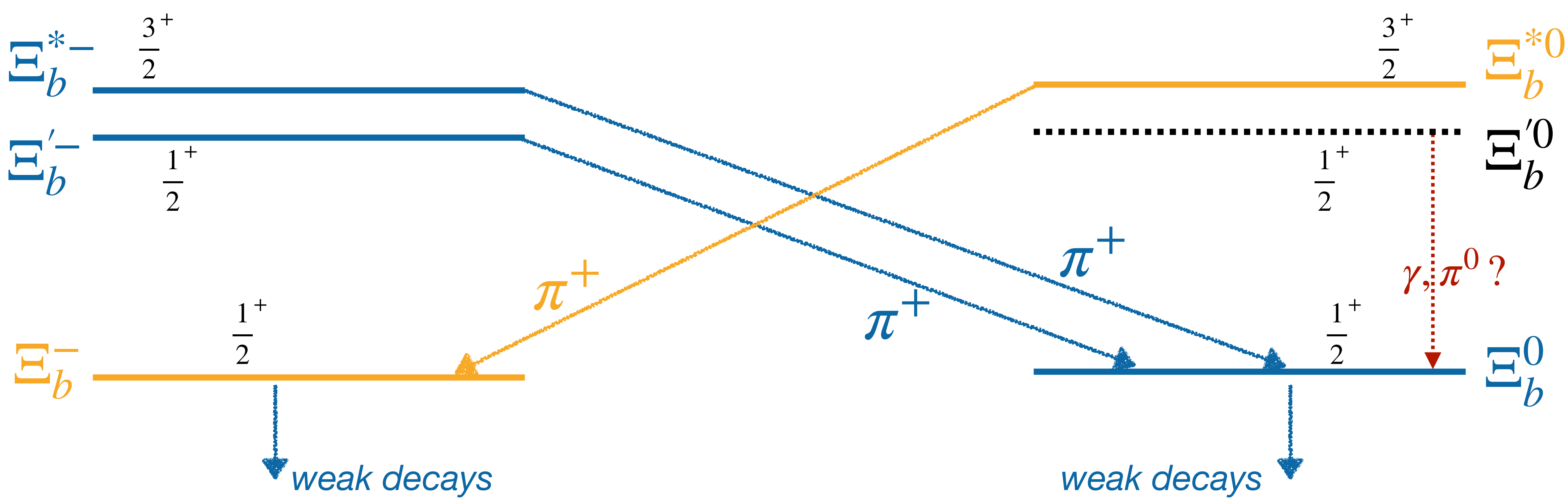


q denotes u or d quarks for Ξ_b^0 or Ξ_b^-. $L = 1$ is the orbital excitation between the light diquark qs and heavy b quark.

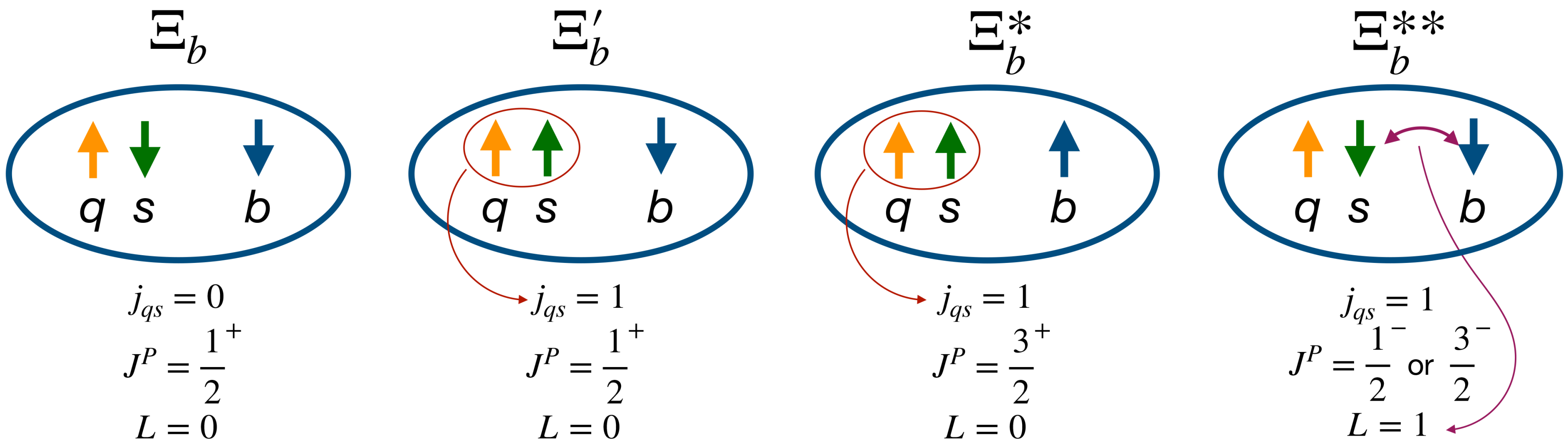
Ξ_b baryons spectroscopy



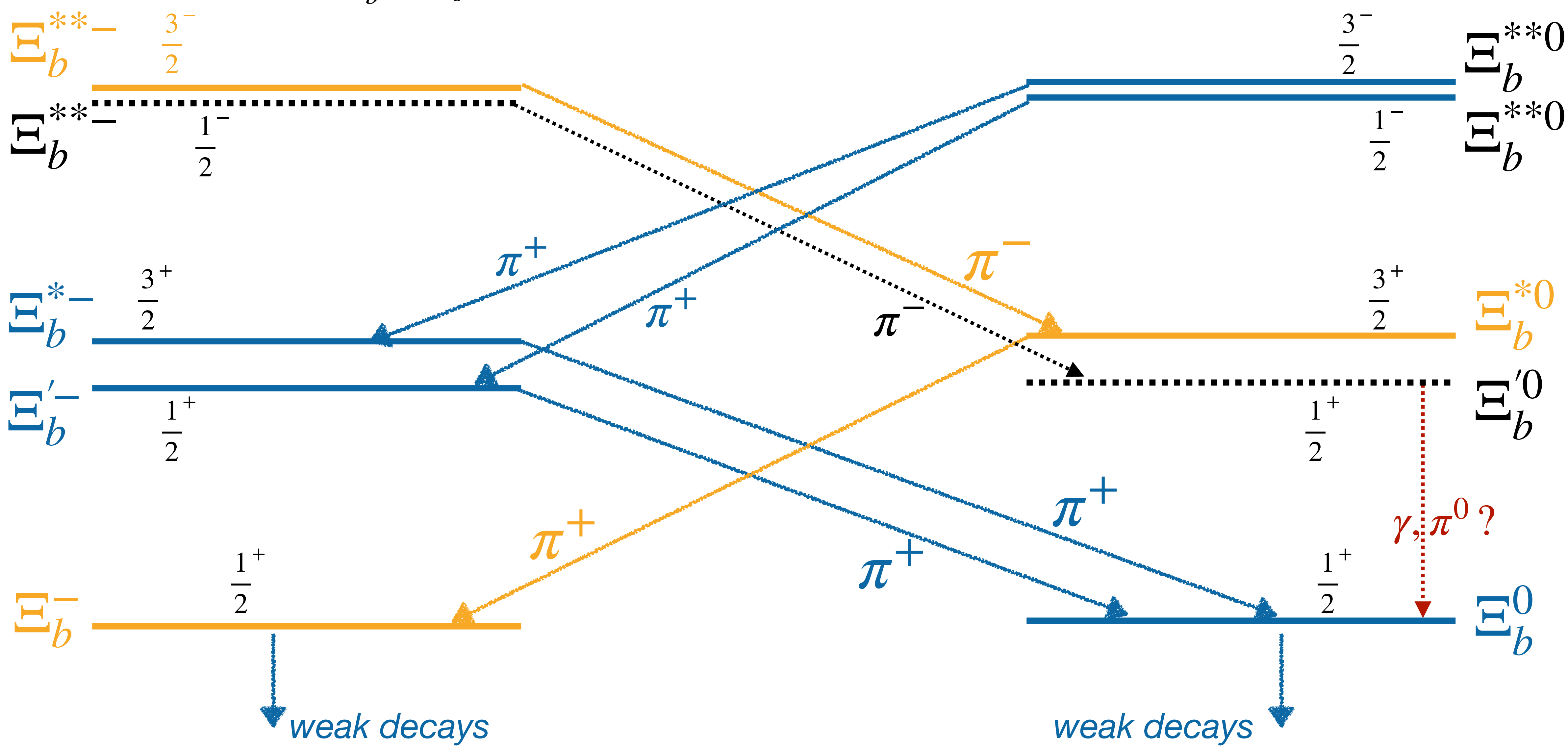
q denotes u or d quarks for Ξ_b^0 or Ξ_b^-. $L = 1$ is the orbital excitation between the light diquark qs and heavy b quark.



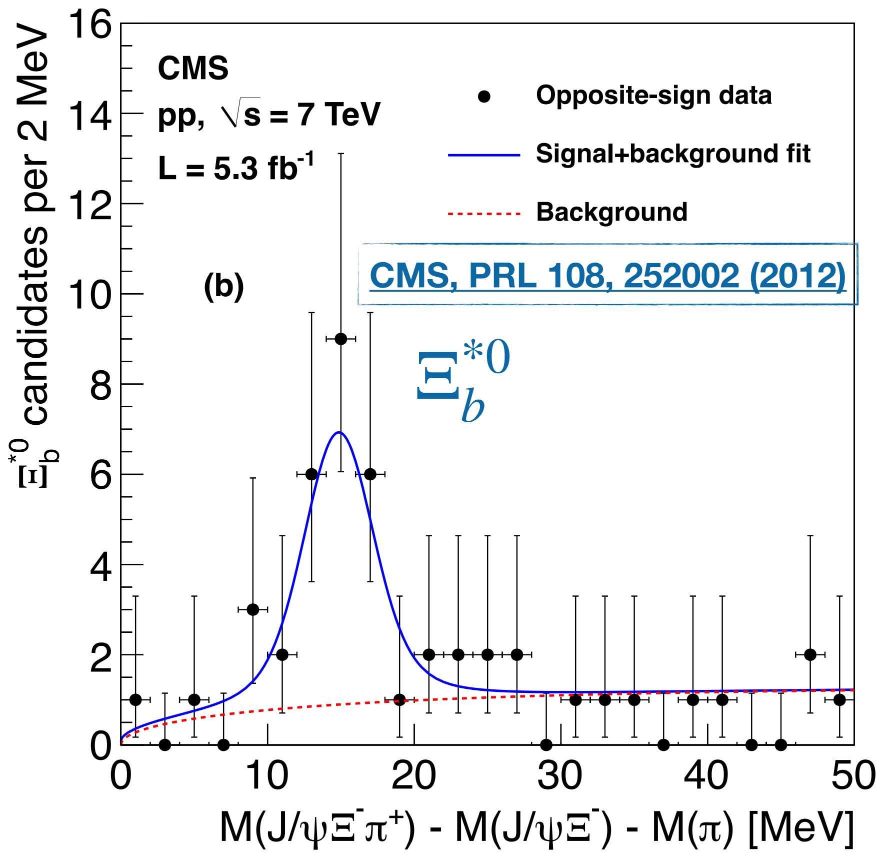
Ξ_b baryons spectroscopy



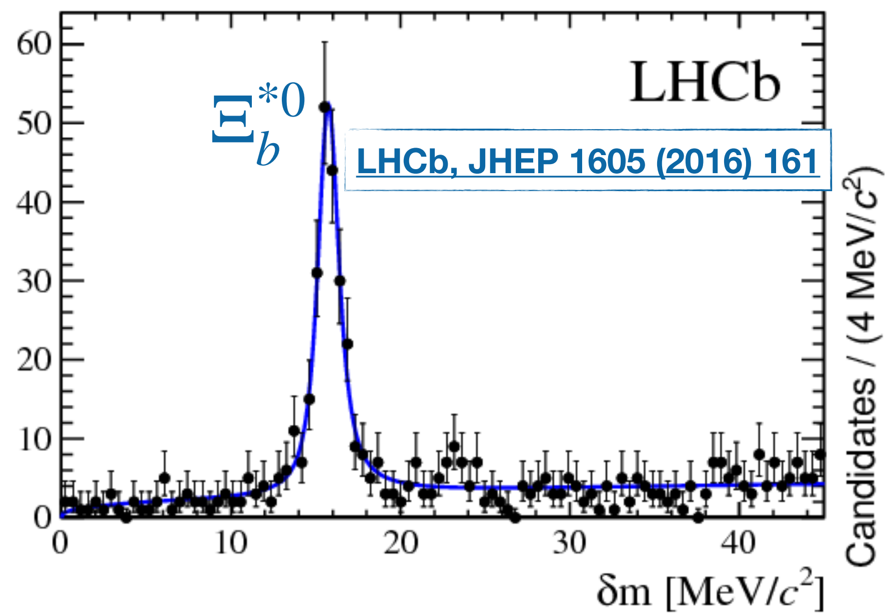
q denotes u or d quarks for Ξ_b^0 or Ξ_b^-. $L = 1$ is the orbital excitation between the light diquark qs and heavy b quark.



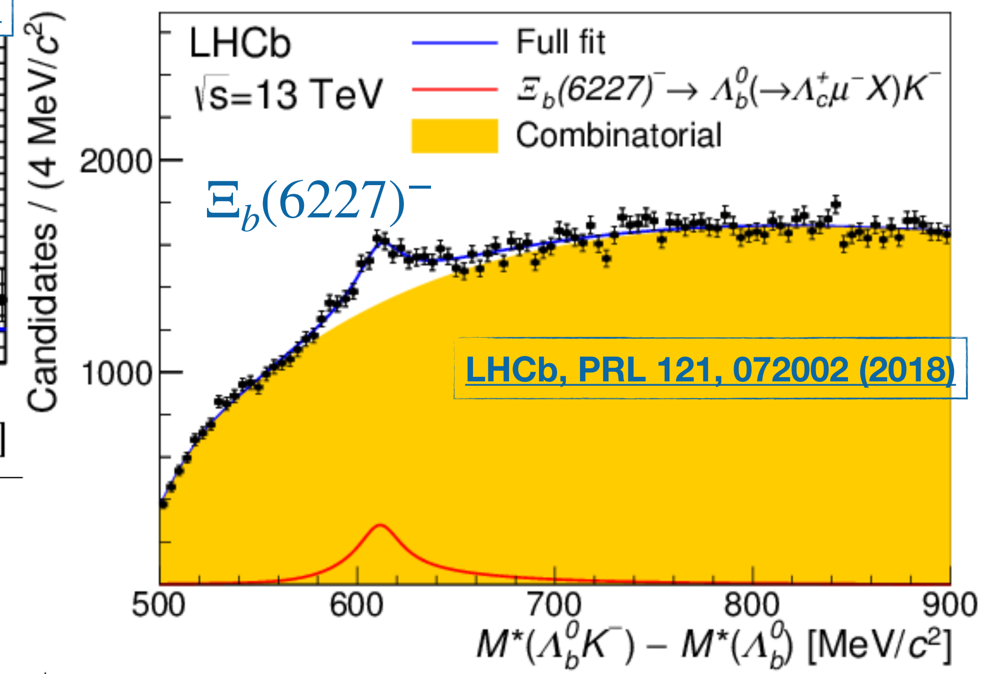
Previous results of Ξ_b resonances



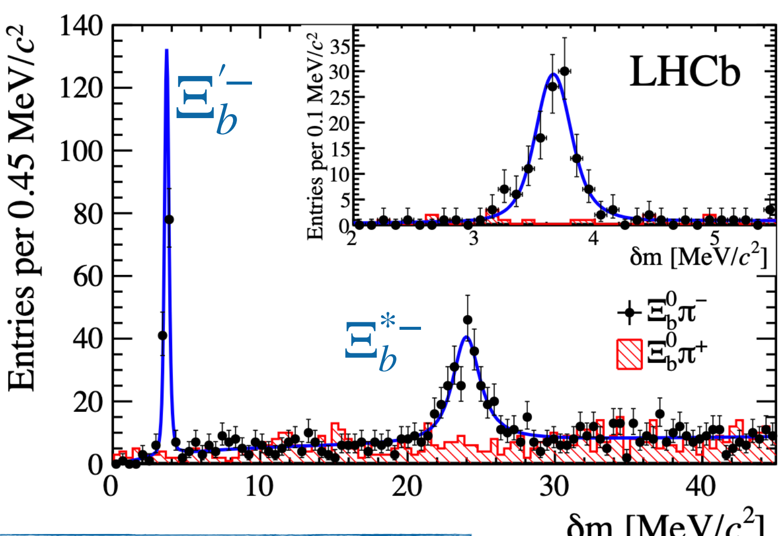
CMS, PRL 108, 252002 (2012)



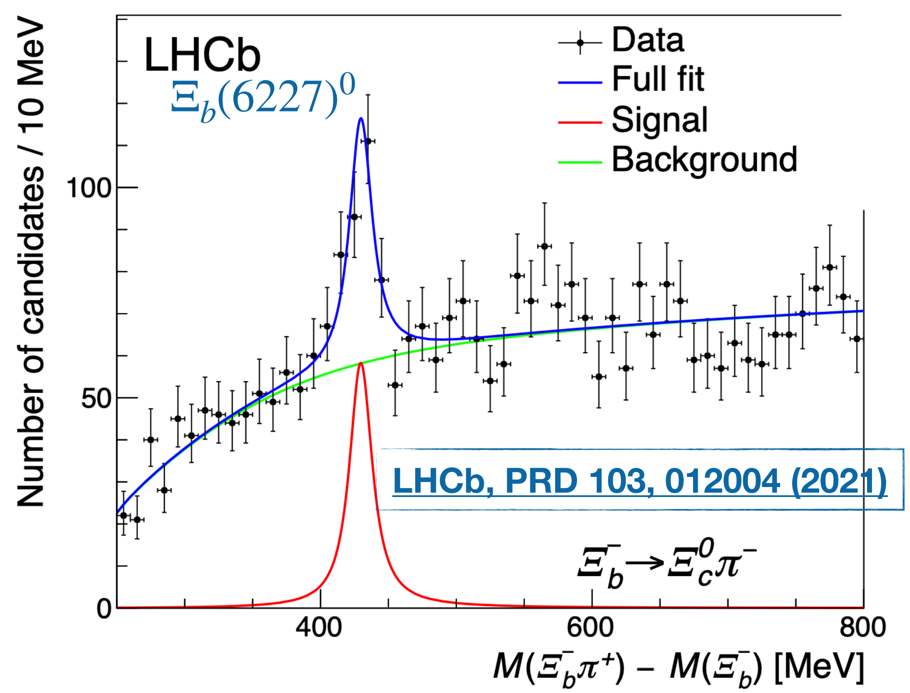
LHCb, JHEP 1605 (2016) 161



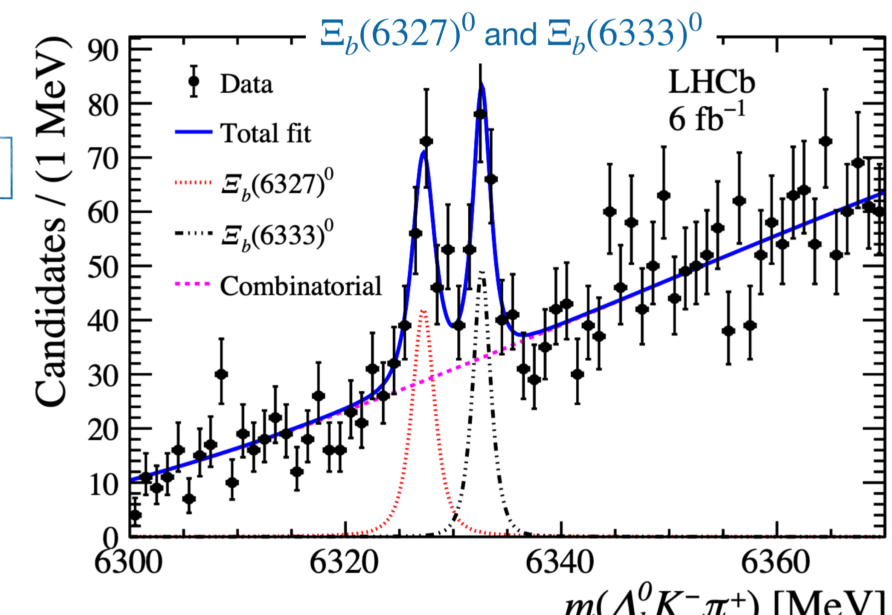
LHCb, PRL 121, 072002 (2018)



LHCb, PRL 114, 062004 (2015)



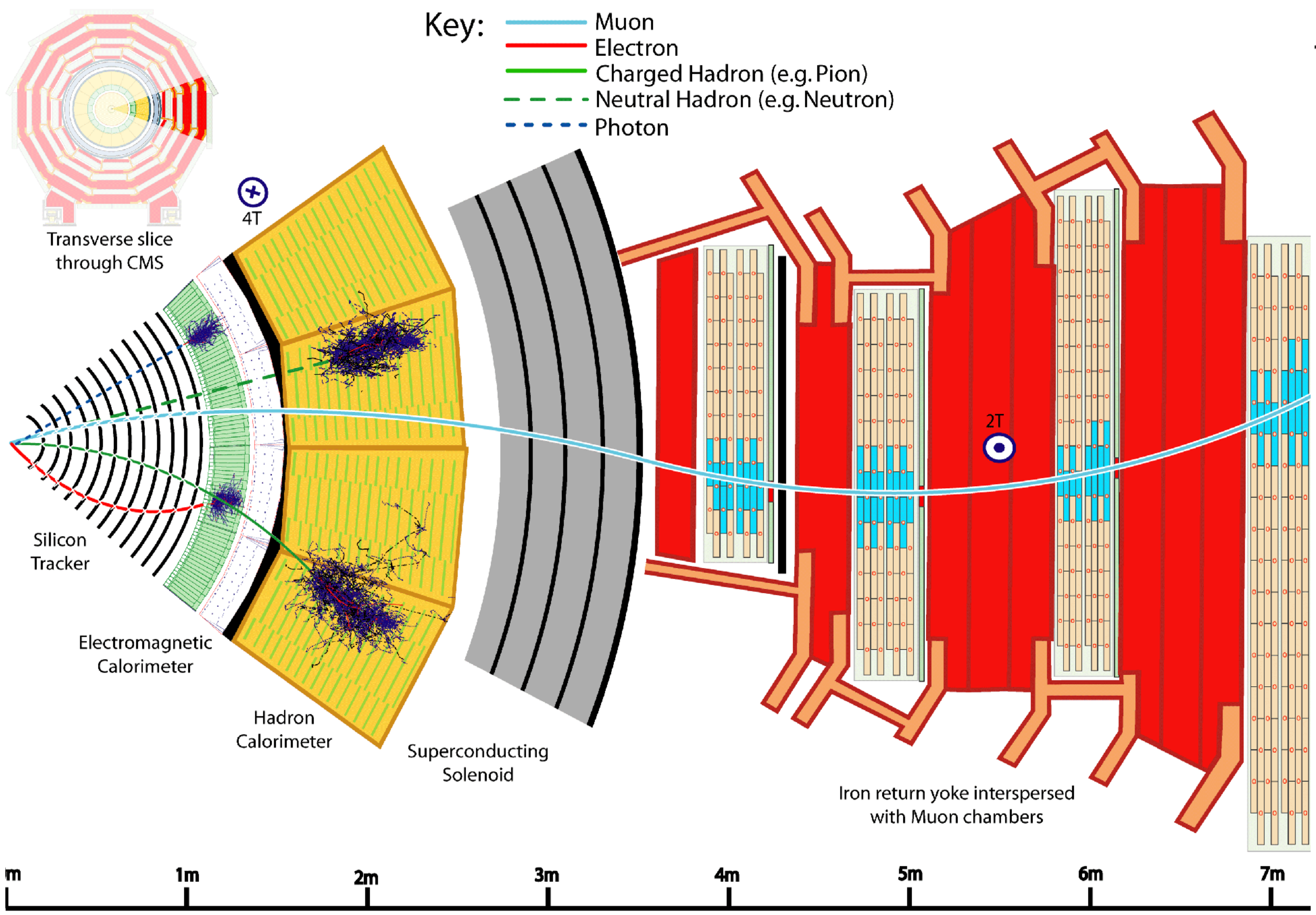
LHCb, PRD 103, 012004 (2021)

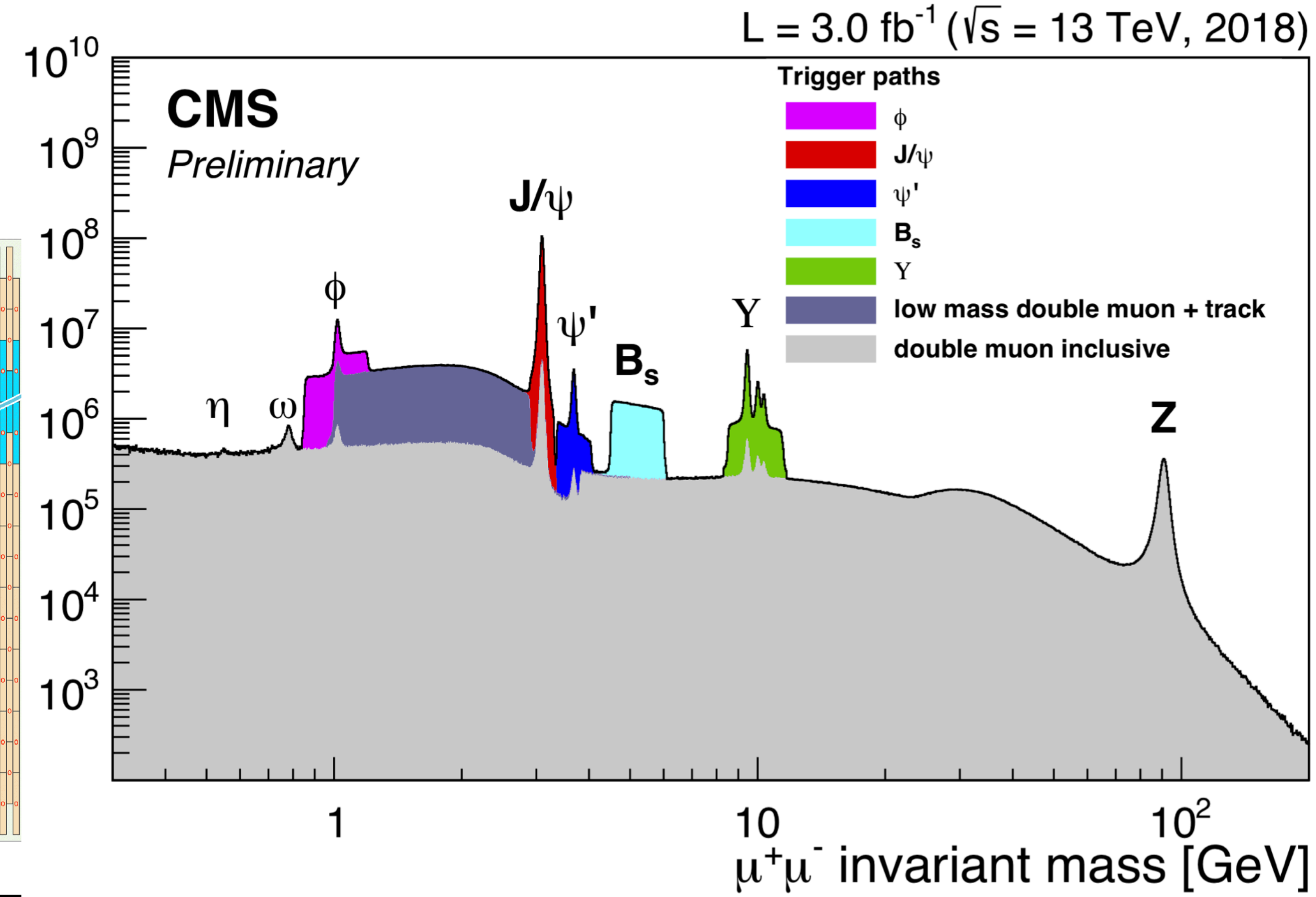


LHCb, PRL 128 16, 162001 (2022)

Cannot reconstruct Ξ_b^0 at CMS (no hadron ID, hard to work with non-charged particles)

The CMS Experiment





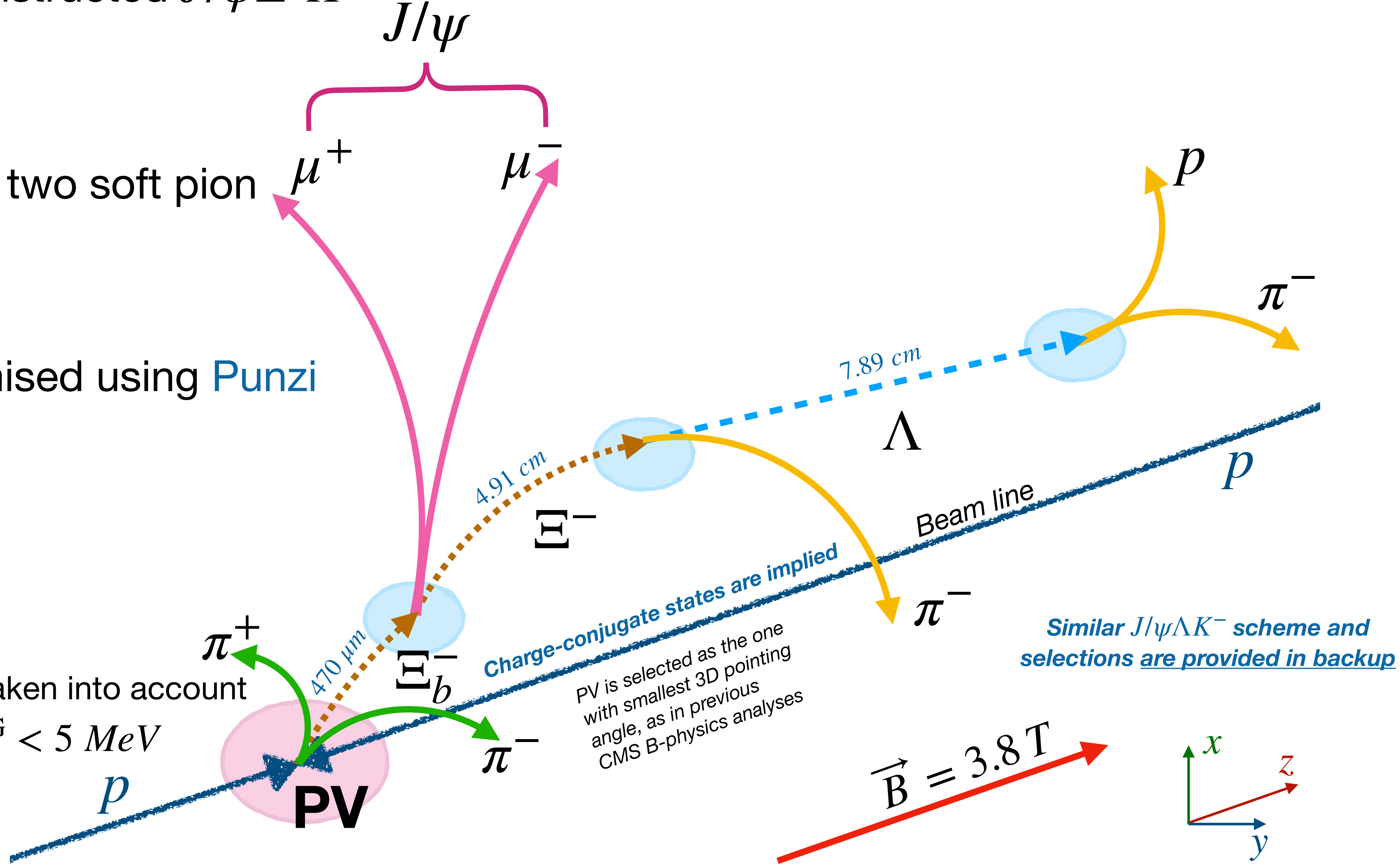
- The CMS Experiment at the LHC was designed mainly for high-p_T physics (Higgs, top-quark, SM precision measurement, New Physics searches etc)

- However, robust muon system, good p_T resolution and perfect vertex reconstruction provide promising opportunities for heavy flavour and quarkonia-related analyses

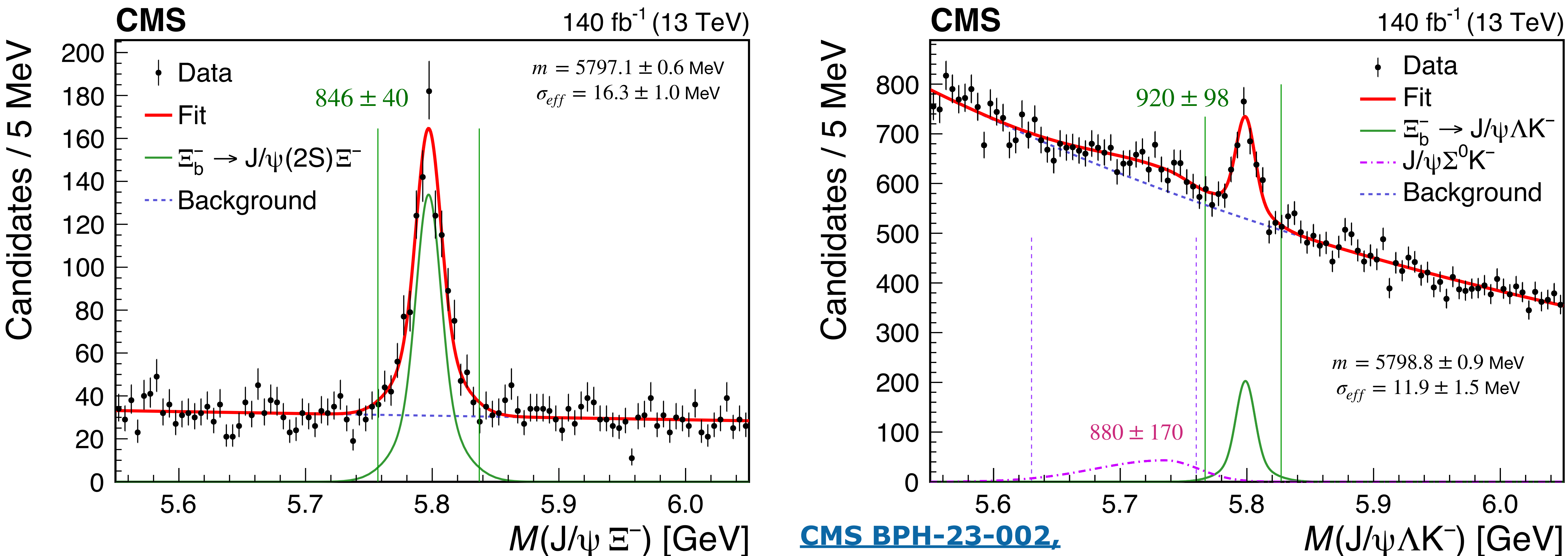
CMS Analysis Overview

- We use full Run-2 CMS data ($140\ fb^{-1}$, $\sqrt{s} = 13$ TeV) to search for a new $\Xi_b^{**-} \to \Xi_b^{*0}\pi^- \to \Xi_b^-\pi^+\pi^-$ resonance, basing on theoretical predictions and excited Ξ_c^{**} charm analogies
  Also to update the Ξ_b^{*0} parameters w.r.t. previously reported
- Ξ_b^- ground state is reconstructed via $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$ channels, where latter one also presents the partially reconstructed $J/\psi\Sigma^0 K^-$ component
- Also **search for the new decay $\Xi_b^- \to \psi(2S)\Xi^-$ is performed**
- Then Ξ_b^- is combined with two soft pion tracks from PV
- Selection criteria are optimised using Punzi Figure of Merit

Intermediate decay of $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$ taken into account w/ mass window $\Delta M(\Xi_b^-\pi^+) - \Delta m^{\mathrm{PDG}}_{\Xi_b^{*0}} < 5\ MeV$



Ξ_b^- "known" signals

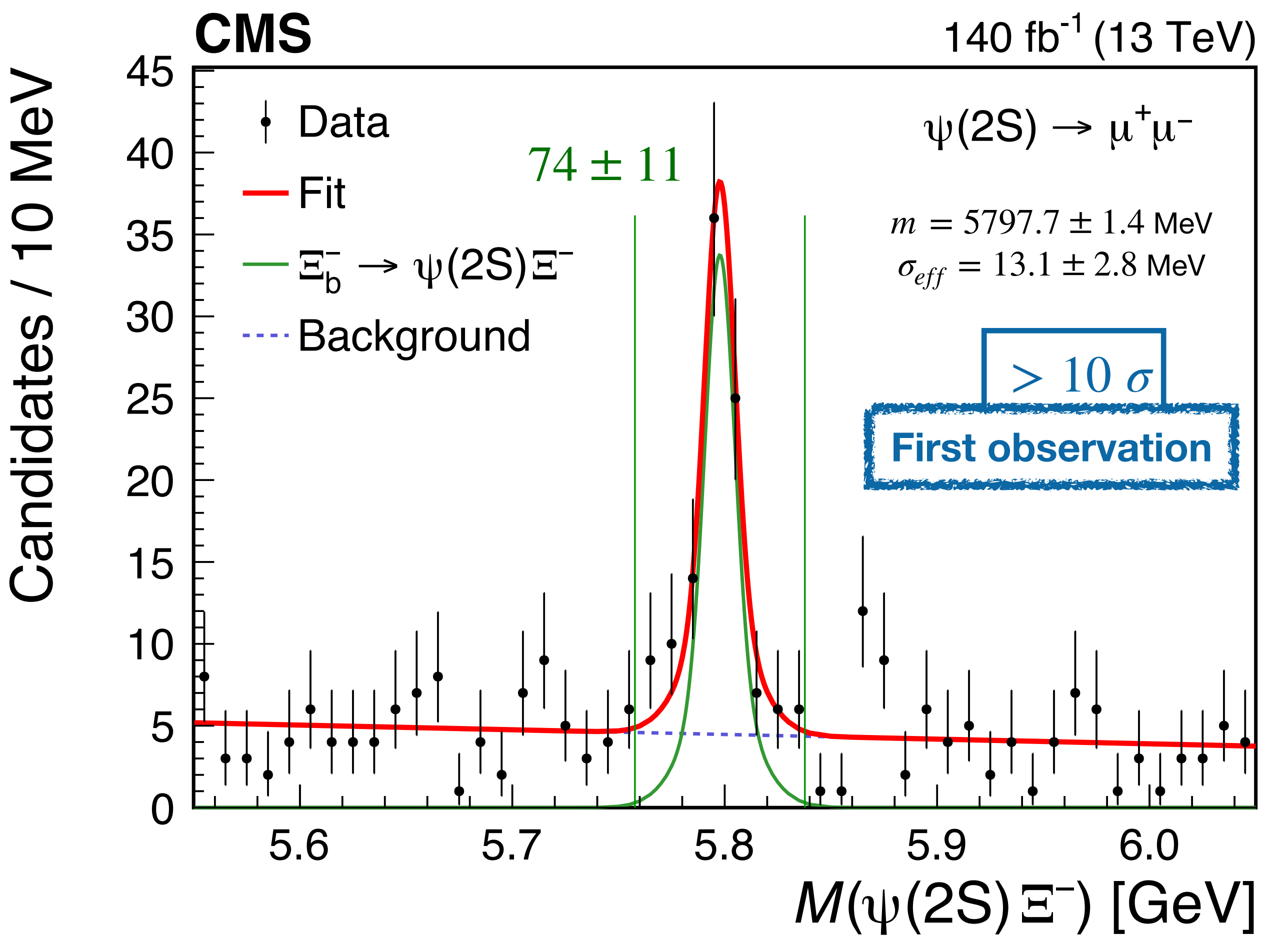


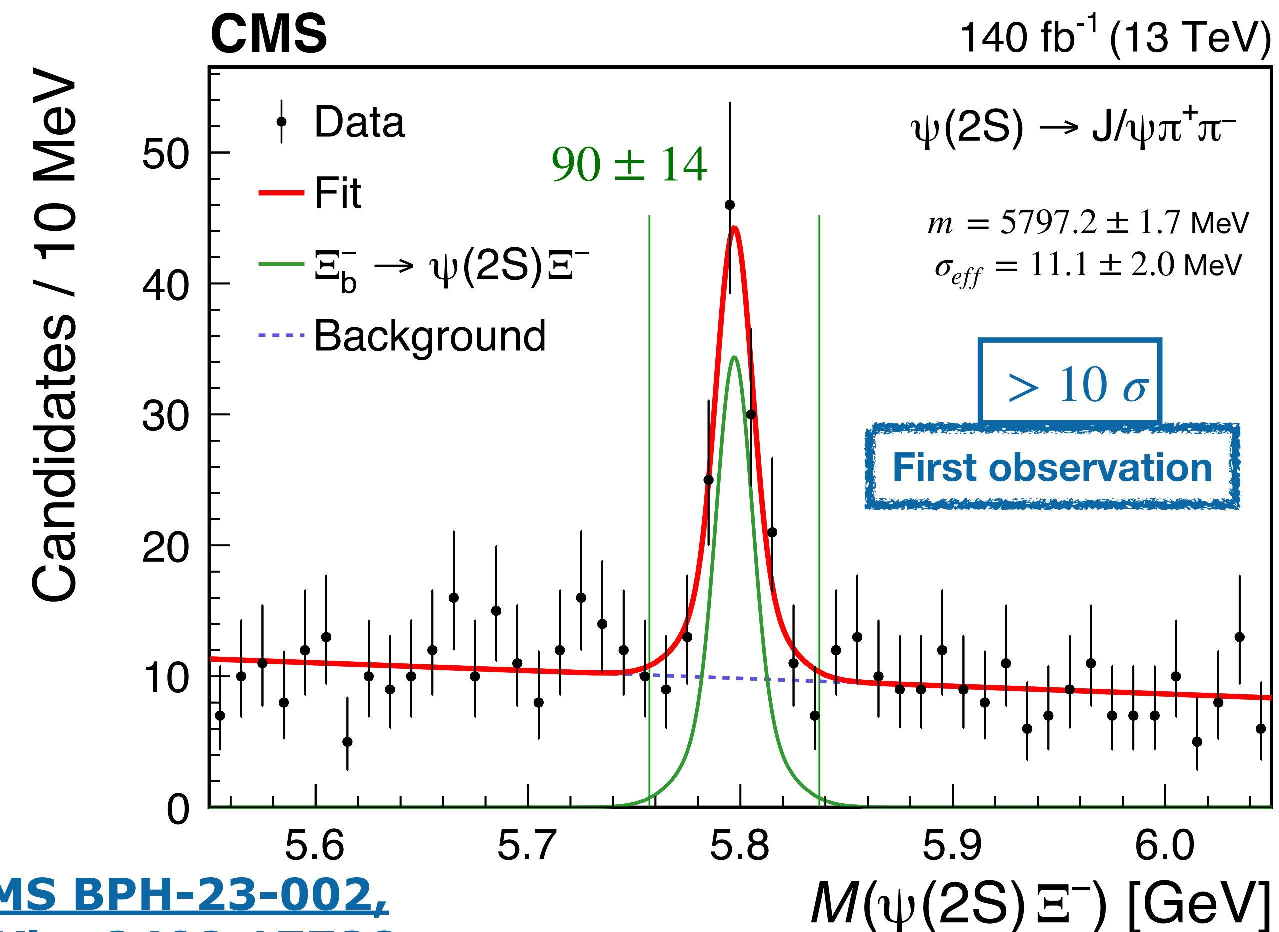
CMS BPH-23-002,
arXiv: 2402.17738

- **Signal:** double-Gaussian (MC-shape scaled to data); **Background:** linear/exponential function
  Partially reconstructed $\Xi_b^- \to J/\psi\Sigma^0 K^-$ decay: asymmetrical Gaussian (from MC)
  photon from $\Sigma^0 \to \Lambda\gamma$ is too soft to be reconstructed

- For $\Xi_b^-\pi^+$ and $\Xi_b^-\pi^+\pi^-$ studies, fully reconstructed Ξ_b^- = green lines, $\pm 54(\pm 27)$ MeV for $J/\psi\Xi^-(J/\psi\Lambda K^-)$ channels,
  partially reconstructed Ξ_b^- = purple lines, [5.63, 5.76] GeV window

Observation of $\Xi_b^- \to \psi(2S)\Xi^-$ decay





CMS BPH-23-002, arXiv: 2402.17738

- **Signal shape:** Double Gaussian, shape is fixed from MC but allowed to be scaled from data
  Background: 1st order polynomial

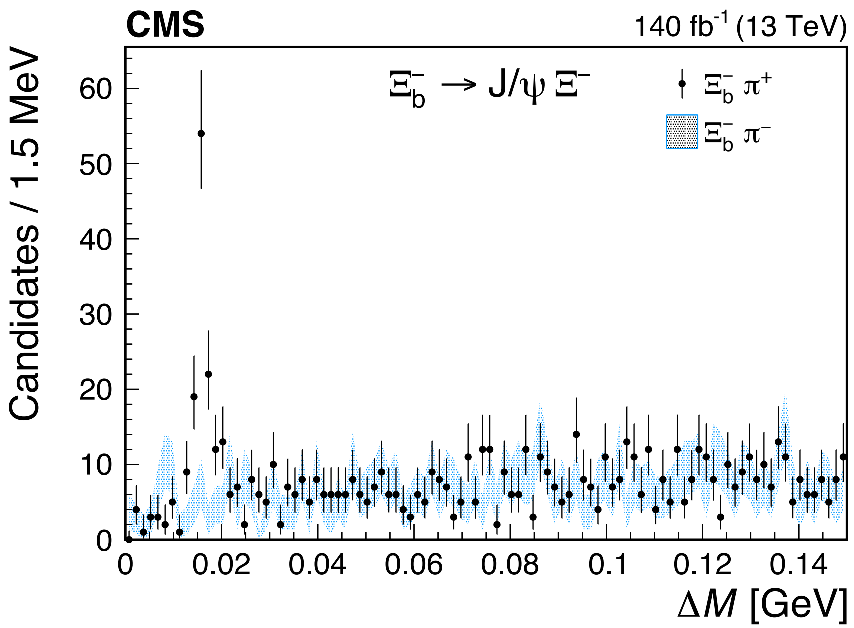
- **Local statistical significance** from likelihood ratio technique (Sig. + Bkg. versus Bkg. only hypothesis)
  Well above 5 sigma for both $\psi(2S) \to \mu^+\mu^-$ and modes $\psi(2S) \to J/\psi\pi^+\pi^-$

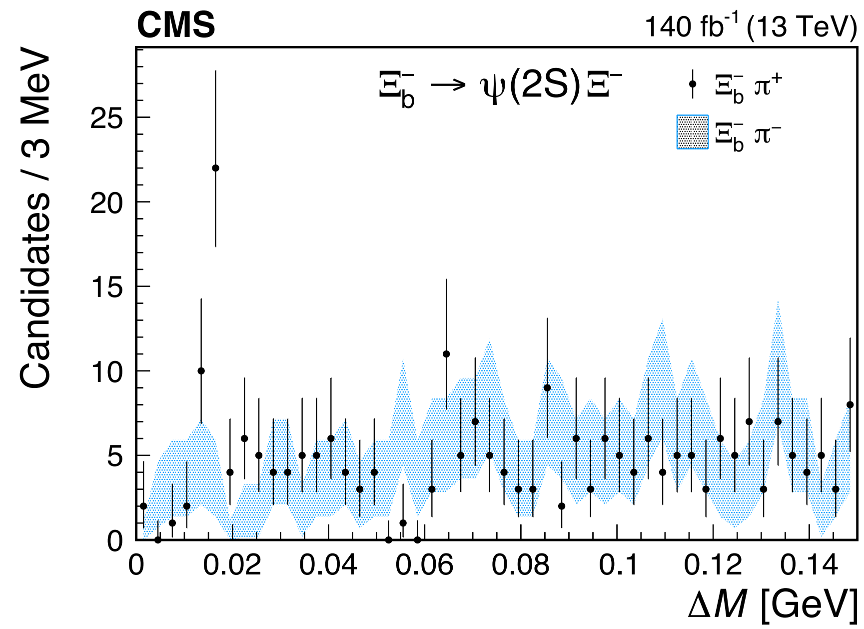
- Branching fraction of the new decay is estimated to be:

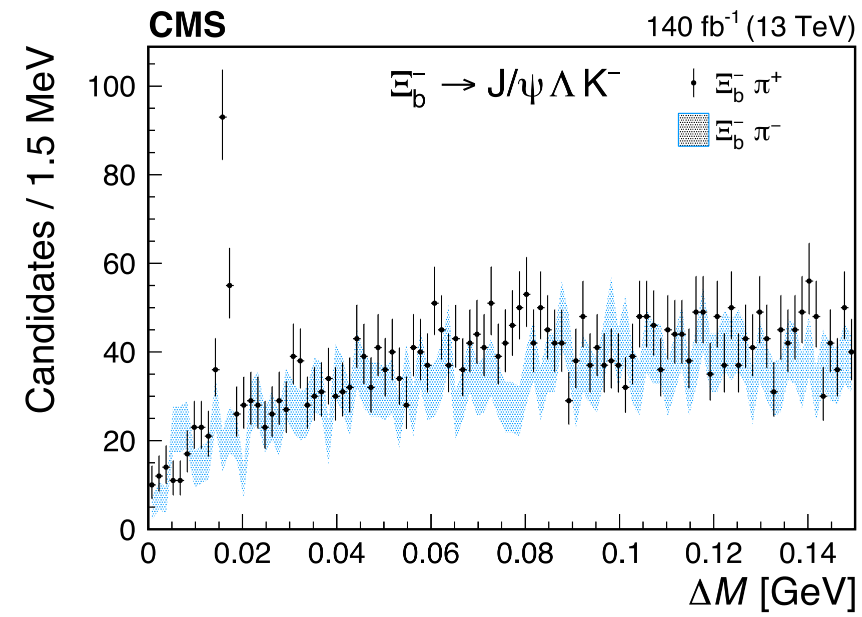
$$R = \frac{\mathscr{B}\left(\Xi_b^- \to \psi(2S)\Xi^-\right)}{\mathscr{B}\left(\Xi_b^- \to J/\psi\Xi^-\right)} = \frac{N_{\Xi_b^- \to \psi(2S)\Xi^-}}{N_{\Xi_b^- \to J/\psi\Xi^-}} \cdot \frac{\epsilon_{\Xi_b^- \to J/\psi\Xi^-}}{\epsilon_{\Xi_b^- \to \psi(2S)\Xi^-}} \cdot \frac{\mathscr{B}\left(J/\psi \to \mu^+\mu^-\right)}{\mathscr{B}\left(\psi(2S) \to \mu^+\mu^-\right)} = 0.84^{+0.21}_{-0.19} \pm 0.10 \pm 0.02$$

from data fits — from MC simulation

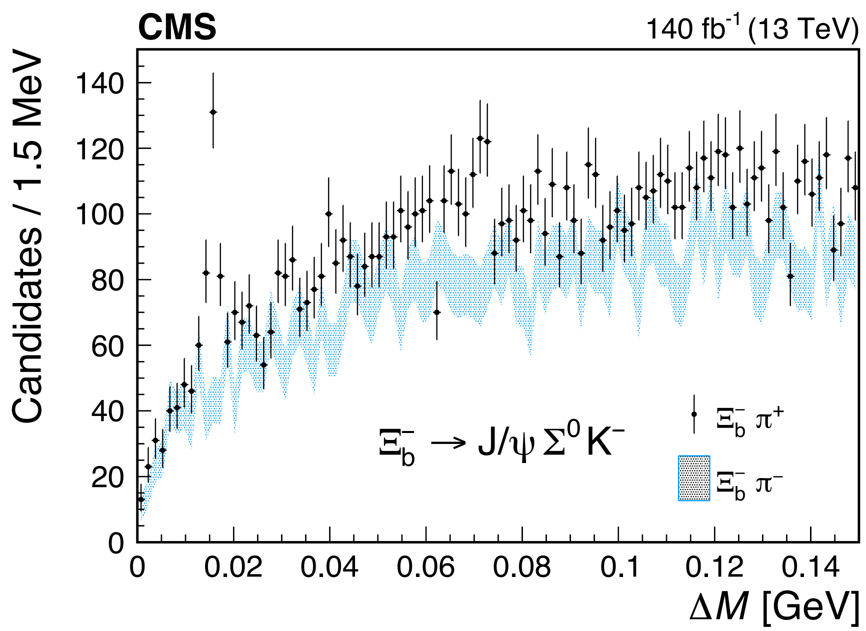
Exploration of $\Xi_b^-\pi^+$ system







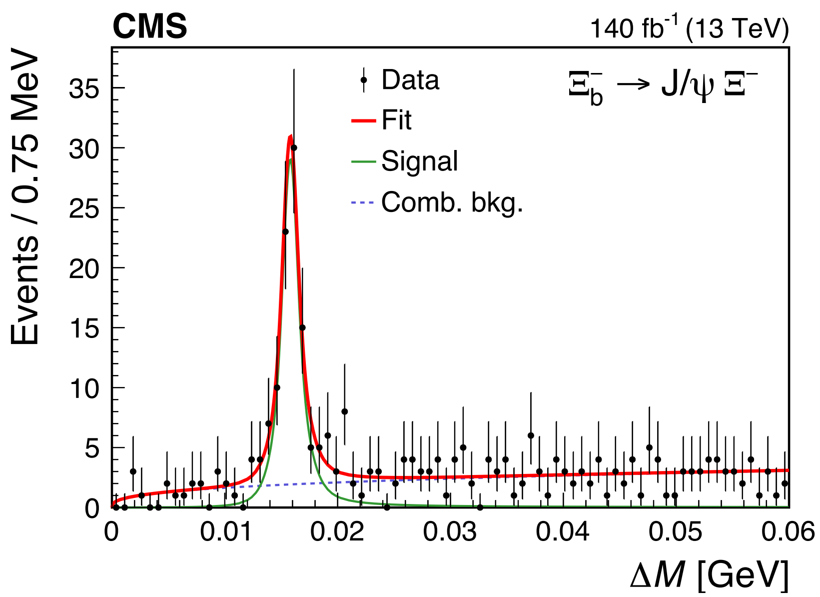
[CMS BPH-23-002](), arXiv: [2402.17738]()

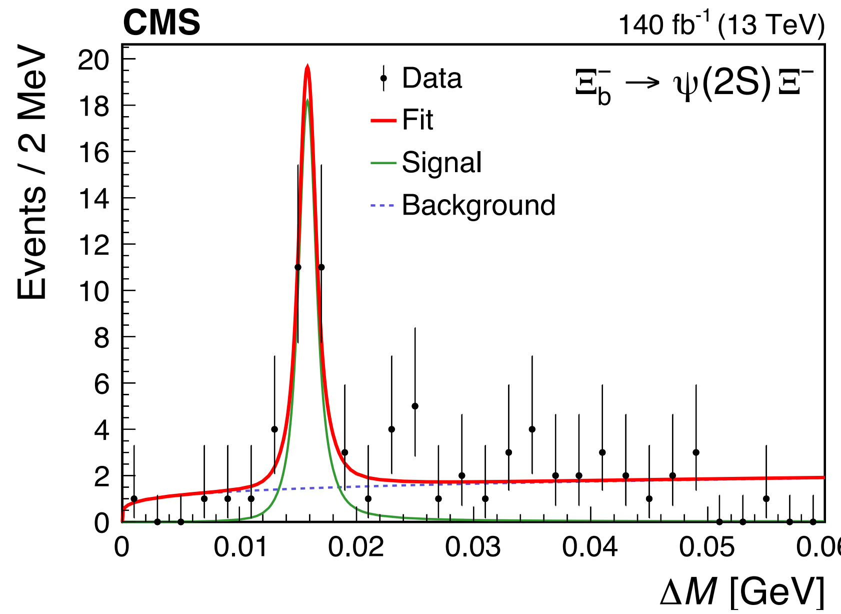


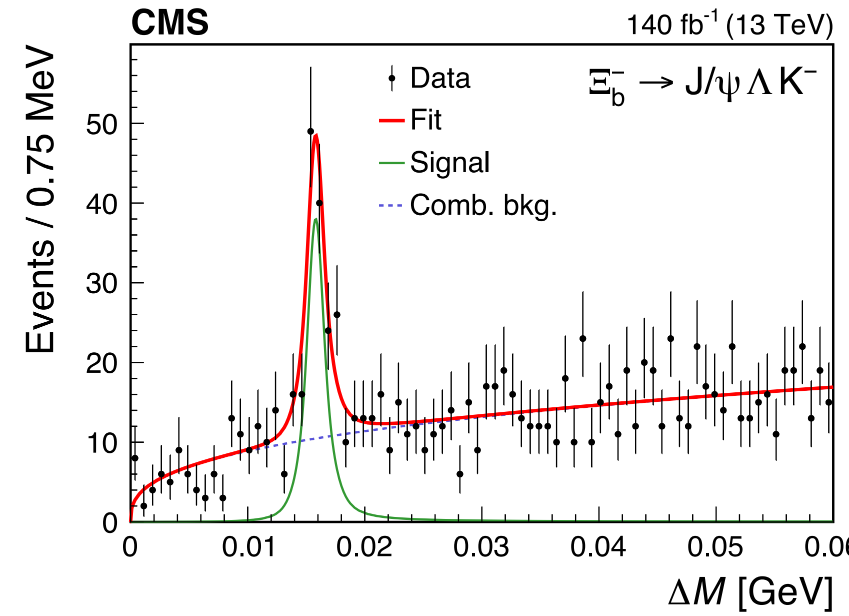
- Clear, significant peak of Ξ_b^{*0} near the kinematic threshold in $M(\Xi_b^-\pi^+)$ for all 4 channels of Ξ_b^- reconstruction
- No other structures observed in the near-threshold area *(as expected)*
- Combinatorial background is in agreement with wrong-sign *(showing us that the bkg **is** combinatorial indeed)*

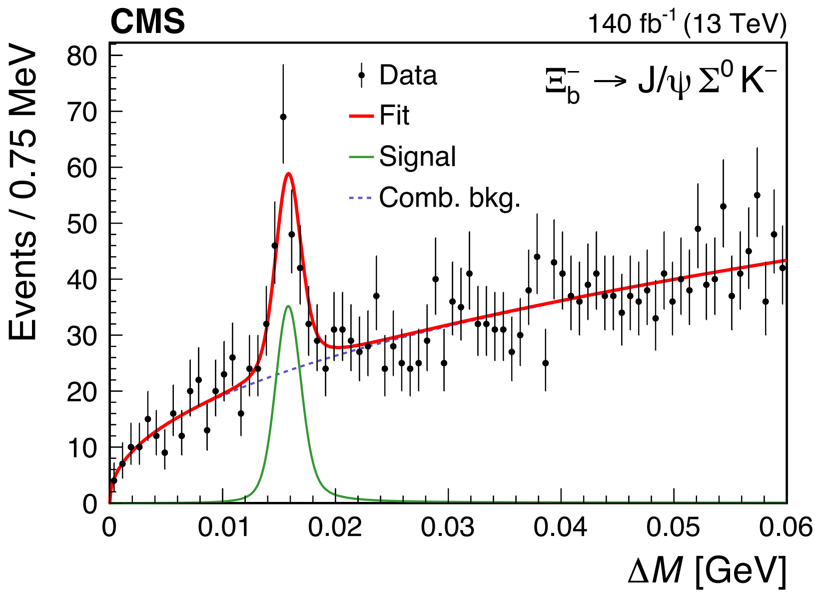
Mass difference variable $\Delta M = M(\Xi_b^-\pi^+) - M(\Xi_b^-) - m_{\pi^+}^{\text{PDG}}$ and PV refit technique ([see backup]()) are used to improve detector resolution

Fit of the $\Xi_b^{*0} \to \Xi_b^- \pi^+$ signal









CMS BPH-23-002, arXiv: 2402.17738

Decay channel	$N(\Xi_b^{*0})$
$\Xi_b^- \to J/\psi \Xi^-$	97^{+13}_{-12}
$\Xi_b^- \to \psi(2S) \Xi^-$	24^{+6}_{-5}
$\Xi_b^- \to J/\psi \Lambda K^-$	124^{+17}_{-16}
$\Xi_b^- \to J/\psi \Sigma^0 K^-$	155^{+22}_{-20}

$$\Delta M = 15.810 \pm 0.077\,(\text{stat}) \pm 0.032\,(\text{syst})\,\text{MeV}$$
$$\Gamma(\Xi_b^{*0}) = 0.87^{+0.22}_{-0.20}\,(\text{stat}) \pm 0.16\,(\text{syst})\,\text{MeV}$$

Excellent agreement with previous CMS & LHCb results!

- We perform simultaneous fit of 4 Ξ_b^- channels, using Relativistic Breit-Wigner ⊗ MC resolutions for signals; mass and Γ are shared parameters of the fit. Background is described $(\Delta M)^\alpha$ threshold function

- We also measure relative Ξ_b^{*0}/Ξ_b^- production ratio:

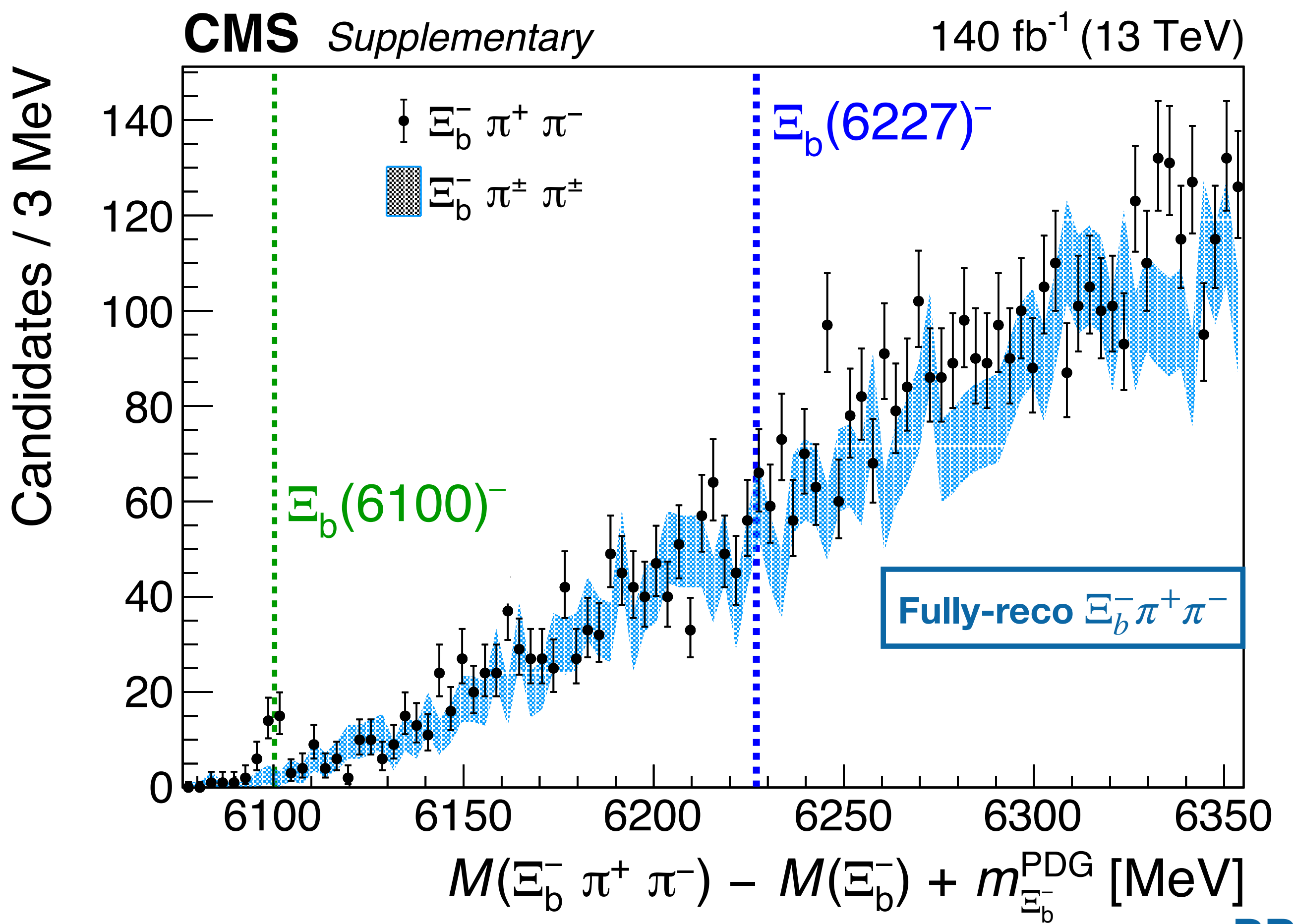
$$R_{\Xi_b^{*0}} = \frac{\sigma\left(pp \to \Xi_b^{*0} X\right) \cdot \mathcal{B}\left(\Xi_b^{*0} \to \Xi_b^- \pi^+\right)}{\sigma\left(pp \to \Xi_b^- X\right)} = \frac{N\left(\Xi_b^{*0}\right)}{N\left(\Xi_b^-\right)} \cdot \frac{\epsilon_{\Xi_b^-}}{\epsilon_{\Xi_b^{*0}}} = 0.23 \pm 0.04 \pm 0.02$$

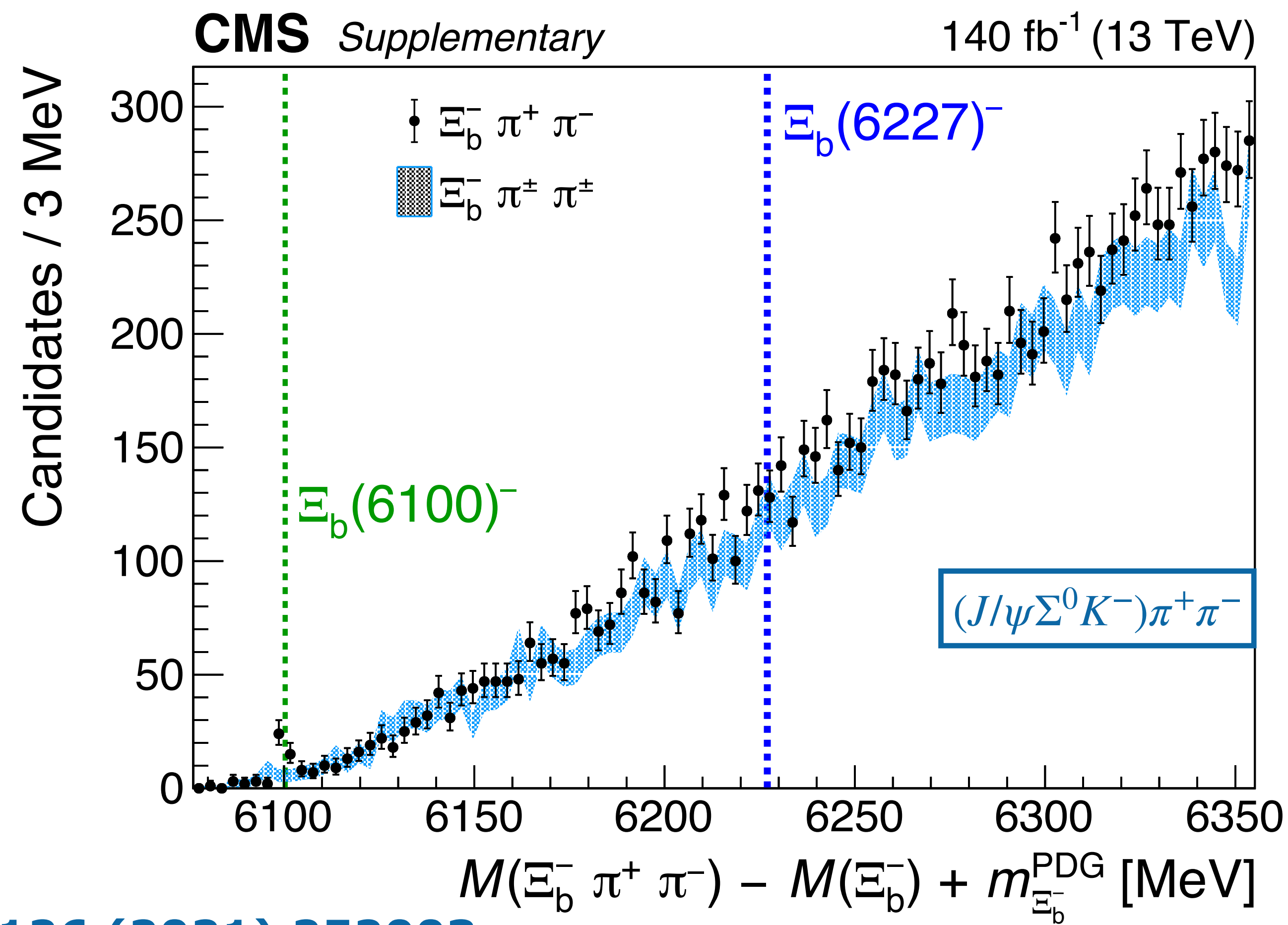
from data fits

from MC simulation

***BLUE** method is used to combine results from different channels*

Study of $\Xi_b^- \pi\pi$ invariant mass



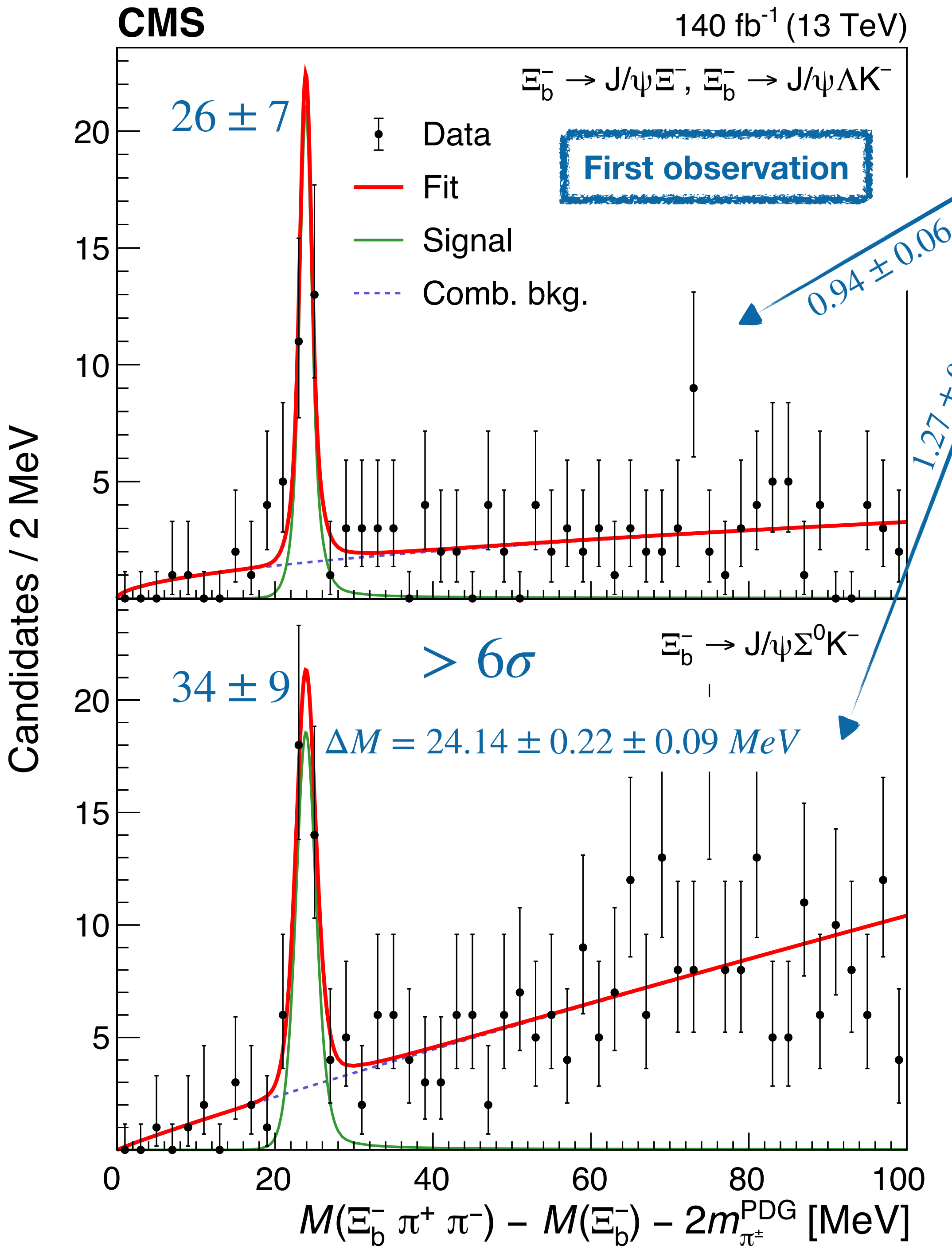


PRL 126 (2021) 252003

- Plots with no requirements of Ξ_b^{*0} in the $\Xi_b^- \pi^+$ mass, with opposite-sign (OS, circles) and same-sign (SS, band) pions.
- No other peaks except 6100 near the threshold are observed in both OS and SS distribution
- Blue vertical line — the mass where LHCb observed $\Xi_b(6227)^-$ *in the* $\Lambda_b^0 K^-$ *and* $\Xi_b^0 \pi^-$ *decay channels* (we see nothing here)

Observation of $\Xi_b(6100)^-$ baryon

[PRL 126 (2021) 252003](PRL 126 (2021) 252003)



$M(\Xi_b(6100)^-) = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6$ MeV
$\Gamma(\Xi_b(6100^-) < 1.9$ MeV @ 95 % CL

systematics are implemented in Γ calculation

- Relativistic Breit-Wigner convolved with MC resolution, background: threshold function $(x - x_0)^\alpha$. Simultaneous fit: common mass and natural width
- First observation of a new state, excited beauty strange baryon $\Xi_b(6100)^-$, expected to be the lightest orbital excitation with $J^P = 3/2^-$, beauty analogue of $\Xi_c(2815)^0$
- **Systematics studies:** include variations of fit model, fit range, possible data/MC difference

*At Moriond 2023 LHCb presented the **confirmation** of $\Xi_b(6100)^-$ state*

Conclusion and summary

- CMS Experiment is actively contributing to the heavy flavour physics, providing state-of-the-art spectroscopy results

- We report the first observation of the new $\Xi_b^- \to \psi(2S)\Xi^-$ decay and measure its branching fraction w.r.t. to the well-known $\Xi_b^- \to J\psi\Xi^-$ to be $R = 0.84^{+0.23}_{-0.22}$

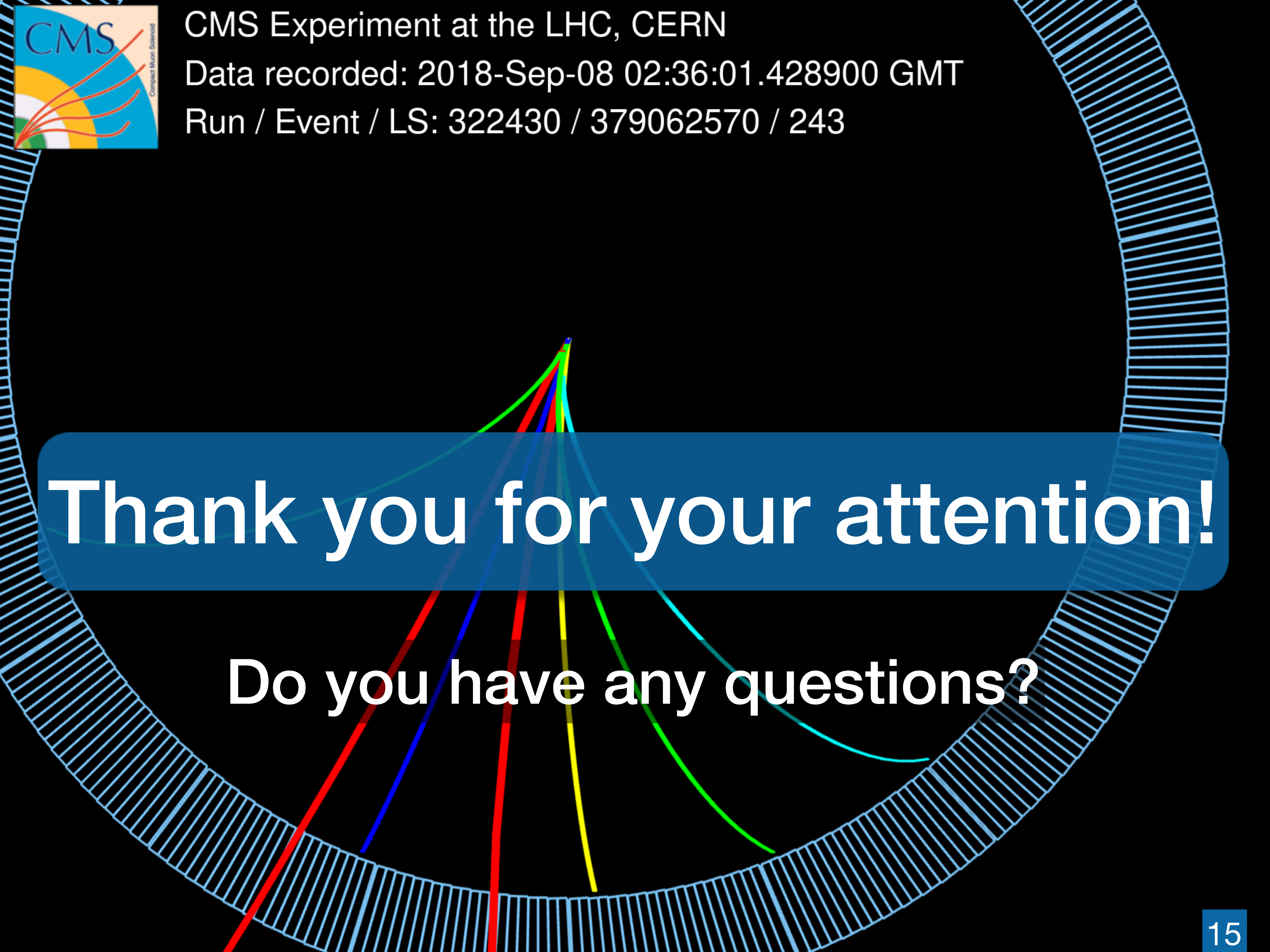
- We perform a new precise measurement of the Ξ_b^{*0} baryon mass and natural width
  We also confirm the relative Ξ_b^{*0}/Ξ_b^- production rate to be $R_{\Xi_b^{*0}} = 0.23 \pm 0.04$

- New beauty strange baryon is observed at mass 6100.3 ± 0.6 MeV in $\Xi_b^-\pi^+\pi^-$ invariant mass spectrum and natural width < 1.9 MeV @ 95% CL

  - Consistent with being the lightest orbitally excited Ξ_b^- baryon with $J^P = 3/2^-$ and orbital momentum $L = 1$ between b quark and light diquark ds

- All our Ξ_b^{*0} and $\Xi_b(6100)^-$ results are in excellent agreement with those reported by the LHCb experiment, proving CMS validity in flavour field

- Stay tuned for the new beautiful and charm results from the CMS Collaboration!



Thank you for your attention!

Do you have any questions?

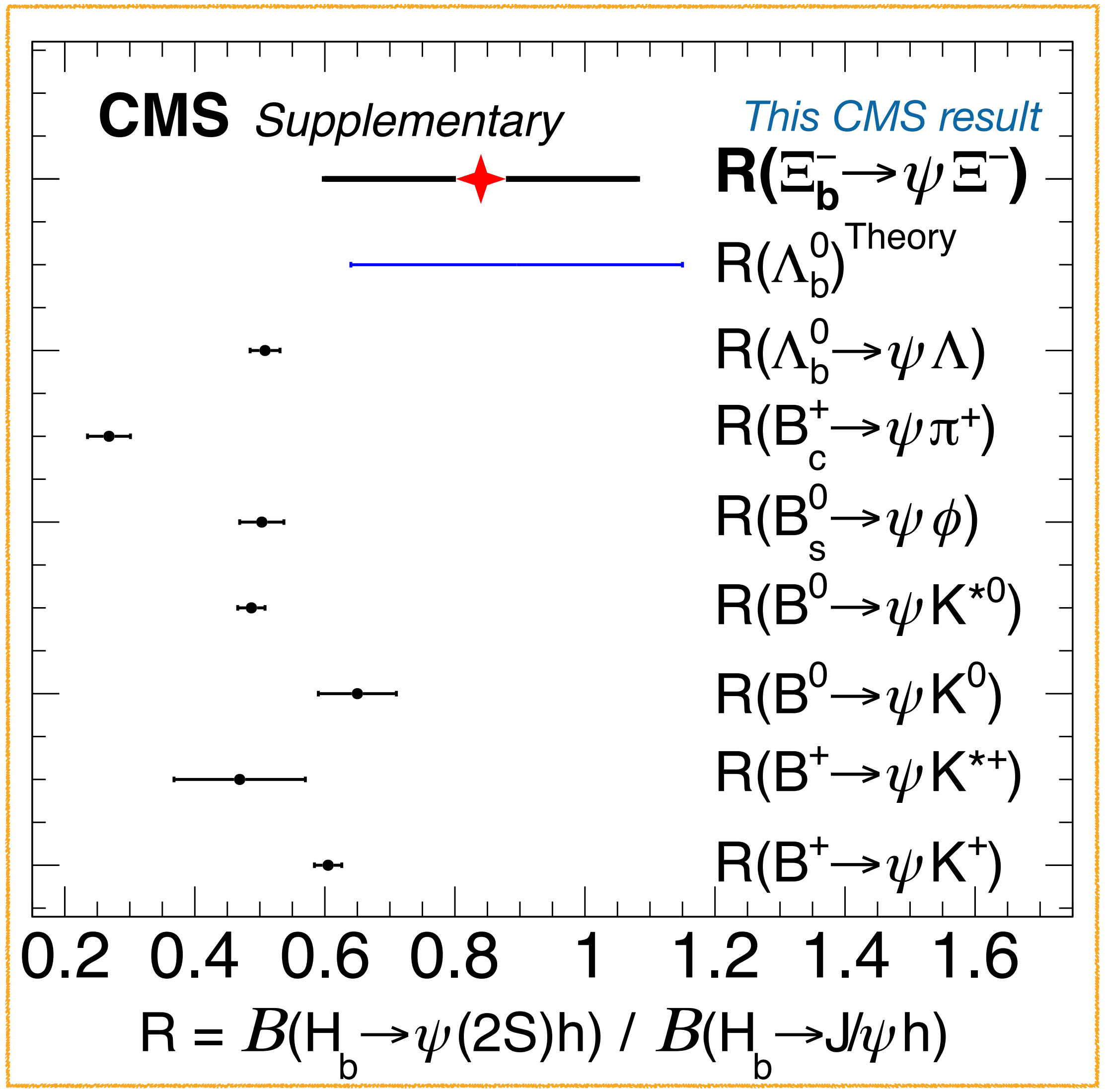
Backup slides

Branching fraction ratio discussion

- We compare our result for the measured $\mathscr{B}$ ratio with other "similar" decays: a b-hadron H_b decays to J/ψ or $\psi(2S)$ *(both referred as ψ)* plus a light hadron h

- Our $R(\Xi_b^- \to \psi\Xi^-)$ seems to be an agreement with others, but uncertainty is large

- The previously measured $R(\Lambda_b^0 \to \psi\Lambda)$ ratio is in disagreement with the theory prediction — will $R(\Xi_b^- \to \psi\Xi^-)$ repeat this "baryon deviation"?

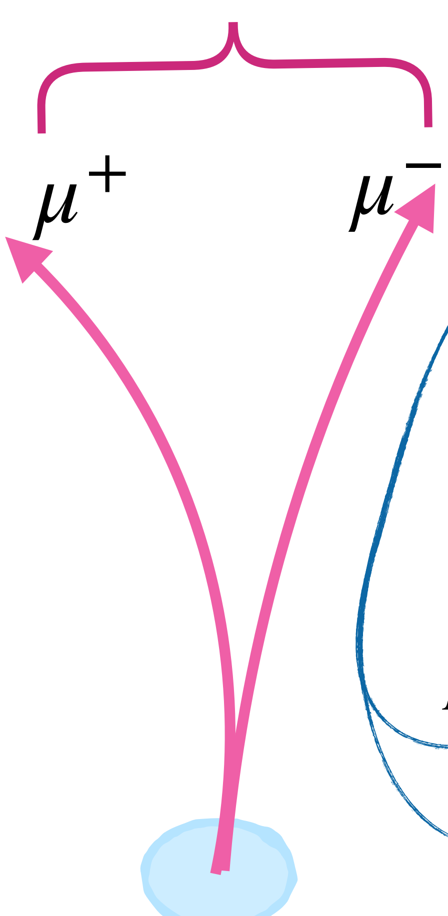


- In general we do not see any clear, "straightforward" trend for these ratios, likewise there is no great theoretical model to describe this plot

- Both new, precise measurements of such ratios and theoretical predictions are required, especially for the beauty baryon sector (Λ_b, Ξ_b, Ω_b decays…)

Trigger strategy

- While the analysis in general uses combination of all charmonia-compatible dimuon CMS HLT paths, we need to select a single dedicated HLT for $\mathscr{B}$ and production measurements
  - *to ensure robust signal yields and efficiency and cancel trigger-related systematics*
- We select the HLT suitable for the decay topology; then re-do our fits it data to estimate signal yield N we use for the ratio measurements
- Generated MC events are required to pass the selected HLT using the same reconstruction algorithm we have for data $\longrightarrow$ extract efficiency ϵ for the for the ratio measurements



$\Xi_b^- \to J/\psi \Xi^-$

$\Xi_b^- \to \psi(2S) \Xi^-$

- Inclusive dimuon triggers are used:
  - **HLT_Dimuon25_Jpsi**
  - **HLT_Dimuon18_PsiPrime**
- Require OS muons from one vertex with $J/\psi(\psi(2S))$ mass window and $p_T(\mu^+\mu^-) > 25\,(18)$ GeV

$$R = \frac{\mathscr{B}\left(\Xi_b^- \to \psi(2S)\Xi^-\right)}{\mathscr{B}\left(\Xi_b^- \to J/\psi\Xi^-\right)}$$

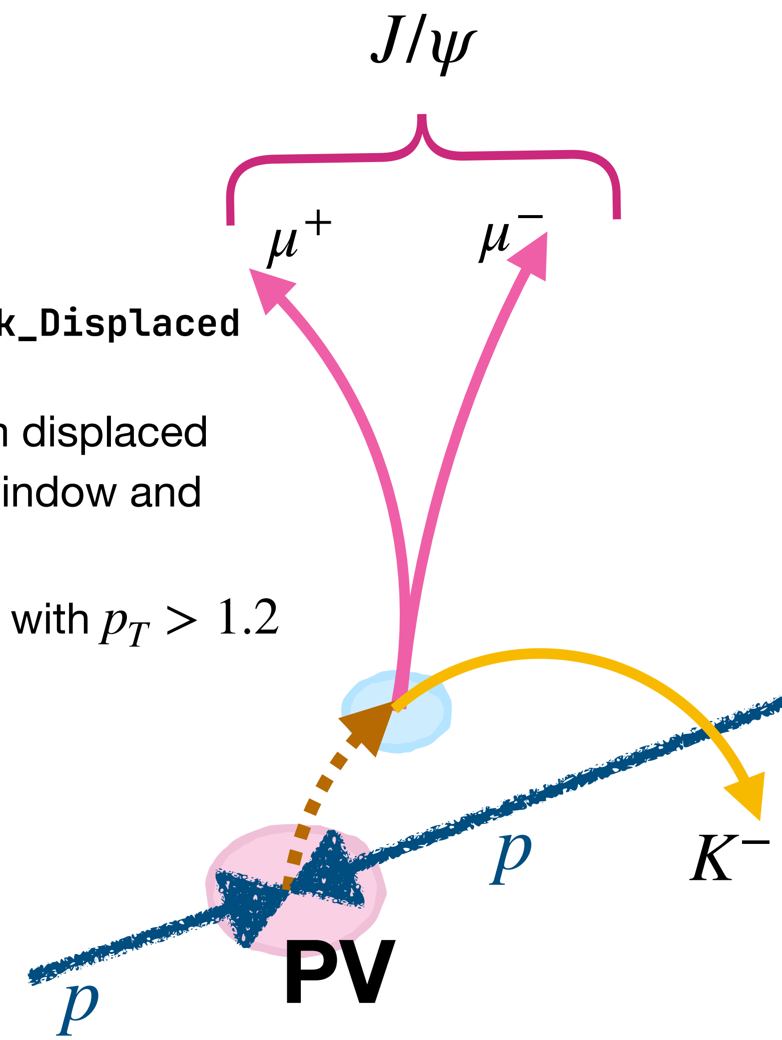
$R_{\Xi_b^{*0}}\left(J/\psi \Xi^-\right)$

HLT_Dimuon20_Jpsi and HLT_Dimuon13_PsiPrime are used for the 2016 conditions

$\Xi_b^- \to J/\psi \Lambda K^-$

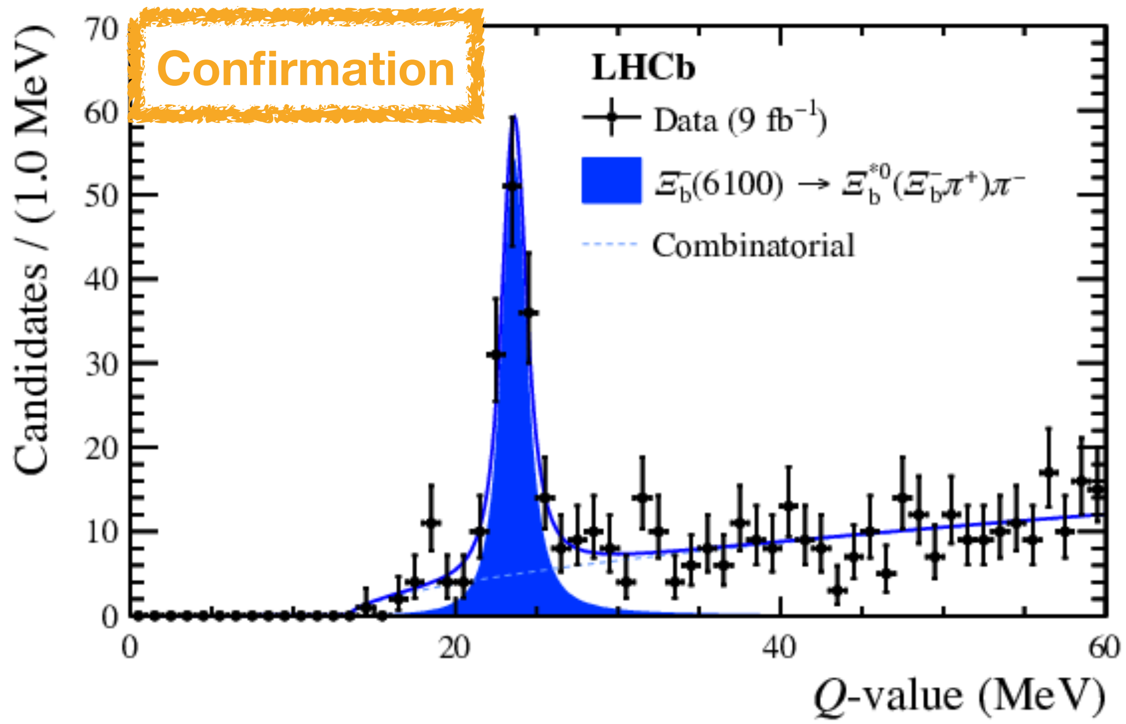
- We use dedicated HLT: **HLT_DoubleMu4_JpsiTrk_Displaced**
- Require OS muons from displaced vertex with J/ψ mass window and $p_T(\mu^\pm) > 4$ GeV and Trk from this vertex with $p_T > 1.2$ GeV and $d_{xy}/\sigma_{d_{xy}} > 2$

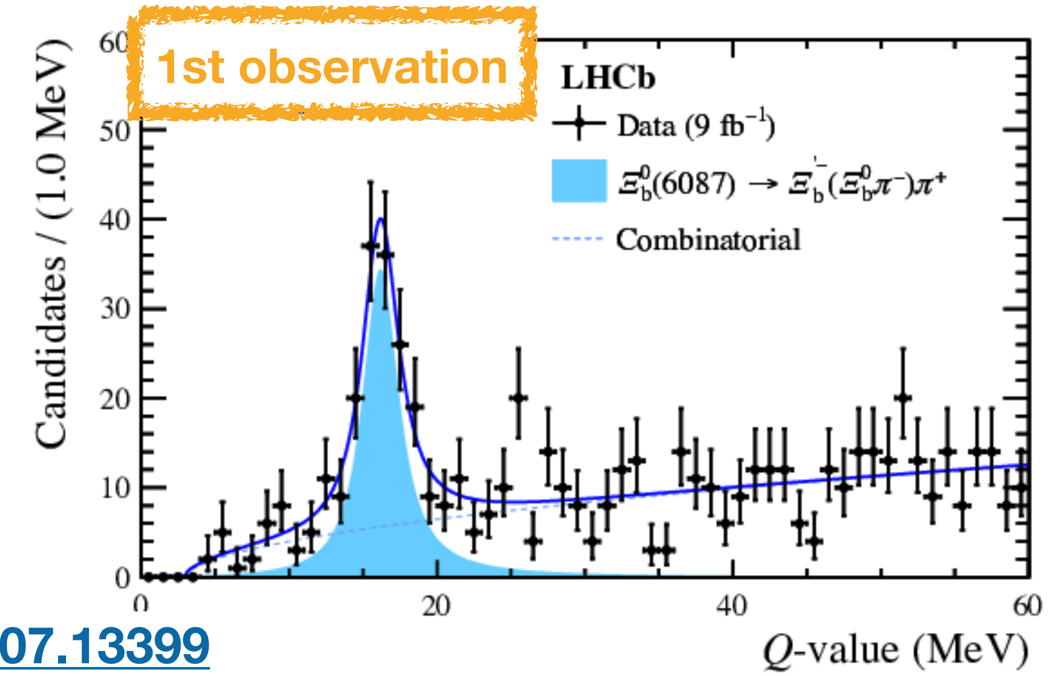
$R_{\Xi_b^{*0}}\left(J/\psi \Lambda K^-\right)$



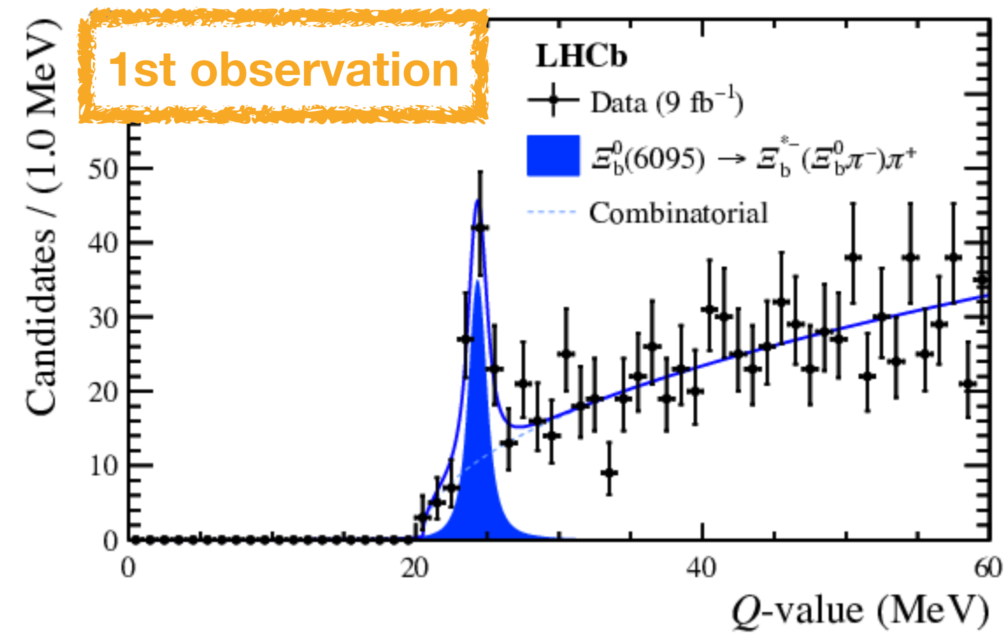
This selection is very tough — there was no good inclusive dimuon HLT @ Run-2!
New BPH Run-3 trigger Parking would significantly improve $\psi\Xi^-$ signal

Recent confirmation from LHCb





arXiv:2307.13399



- At Moriond 2023, LHCb presented updates on their $\Xi_b\pi$ and $\Xi_b\pi\pi$ results
- **Our $\Xi_b(6100)^-$ baryon is confirmed**, 2 new states with Ξ_b^0 observed and precise measurements are reported; Ξ_b^{*0} parameters are also updated
- Immense statistics of Ξ_b provided: ≈ 18 000 of Ξ_b^- v.s. ≈ 2 000 at CMS (and ≈ 30 000 of Ξ_b^0 inaccessible to us)

Ξ_b^{*0}	Q_0	$15.80 \pm 0.02 \pm 0.01$
	Γ	$0.87 \pm 0.06 \pm 0.05$
	m_0	$5952.37 \pm 0.02 \pm 0.01 \pm 0.6(\Xi_b^-)$

State	Observ.	Value (MeV)
$\Xi_b(6100)^-$	Q_0	$23.6 \pm 0.11 \pm 0.02$
	Γ	$0.94 \pm 0.30 \pm 0.08$
	m_0	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6\ (\Xi_b^-)$

Reported parameters are in excellent agreement with us!

Theoretical prediction for Ξ_b^{**-}

Table 1: Theoretical predictions for Ξ_b^{**-} mass and natural width, given in MeV.

Properties	[15]	[16]	[22]
$M(\Xi_b^{**-})$	6130	6124^{+30}_{-20}	6102
$\Gamma(\Xi_b^{**-})$	2.88	< 7.21	2.9

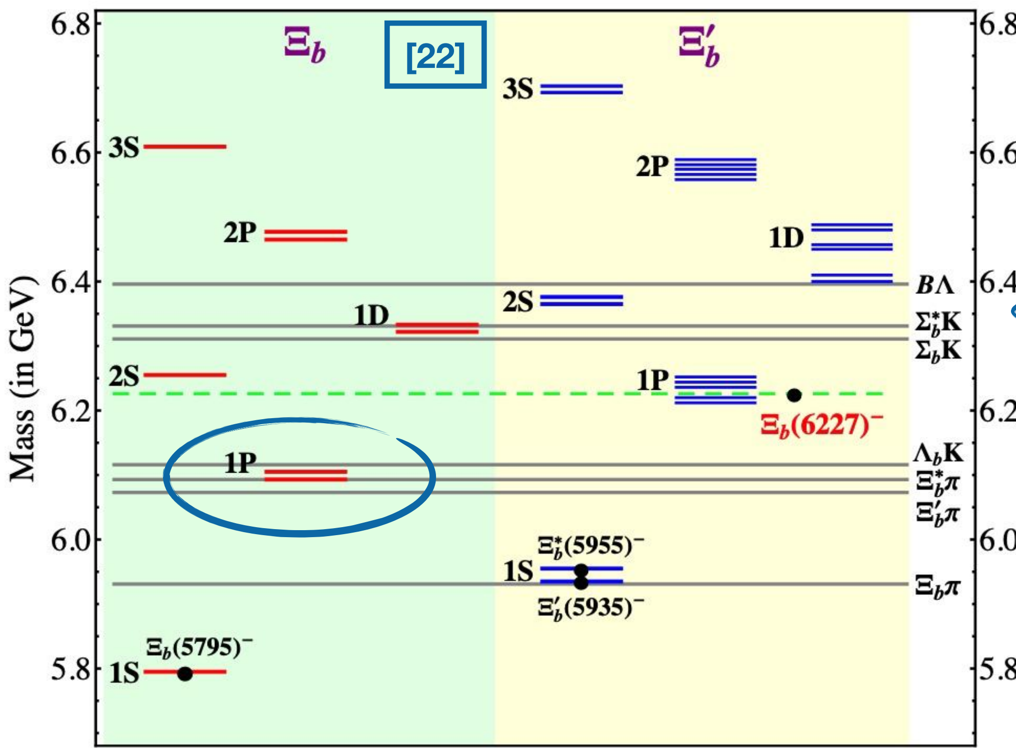


FIG. 2: The obtained masses for the bottom-strange baryons. The red solid lines (left) correspond to the predicted masses of Ξ_b states which are composed of a good diquark and a bottom quark, while the blue solid lines (right) correspond to the Ξ_b' states which contain a bad diquark. Here, we also listed the measured masses of the ground states [1] and the $\Xi_b(6227)^-$ [9], which are marked by "filled circle".

[15]

State	Ξ_b RQM [24]	Ξ_b NQM [27]
$1^2S\,\frac{1}{2}^+$	5803	5806
$1^2P_\lambda\frac{1}{2}^-$	6120	6090
$1^2P_\lambda\frac{3}{2}^-$	6130	6093

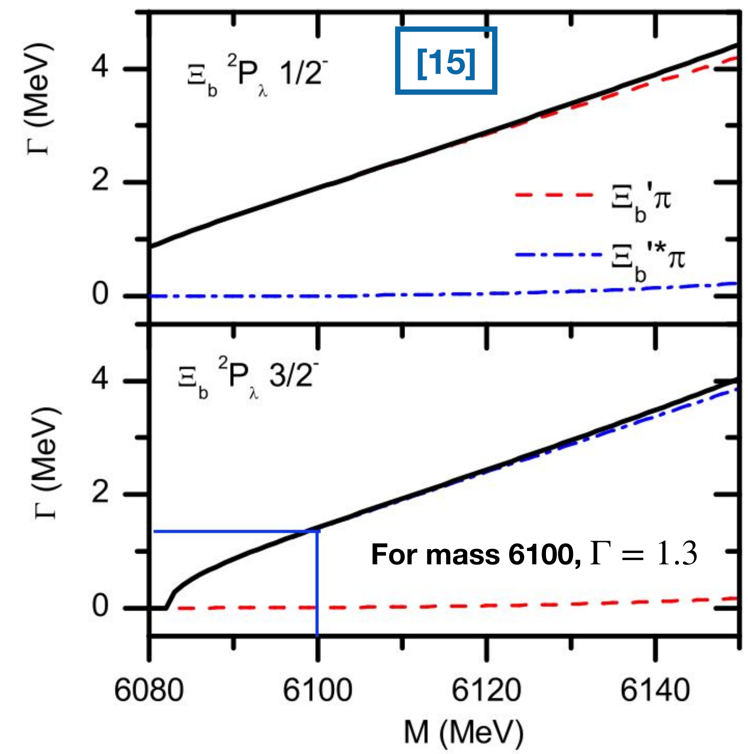


FIG. 2: Partial and total strong decay widths of the $1P$-wave Ξ_b states as functions of their mass. The solid curves stand for the total widths.

[16]

particle	our model	[30]	[36]	expt. (spin averaged)
$\Sigma_b^{(*)}$	5843^{+20}_{-37}	$5811-5835$	$\cdots$	5826.9
$\Xi_b^{\prime(*)}$	5975^{+18}_{-37}	$\cdots$	$\cdots$	5946.7
$\Omega_b^{(*)}$	6102^{+15}_{-36}	$6048-6086$	$\cdots$	6046.1 (spin-1/2)
$\Lambda_{b1}^{(*)}$	5936^{+20}_{-36}	$5980-6000$	$\cdots$	5917.33
$\Xi_{b1}^{(*)}$	6124^{+20}_{-34}	$6129-6151$	6096, 6102	$\cdots$

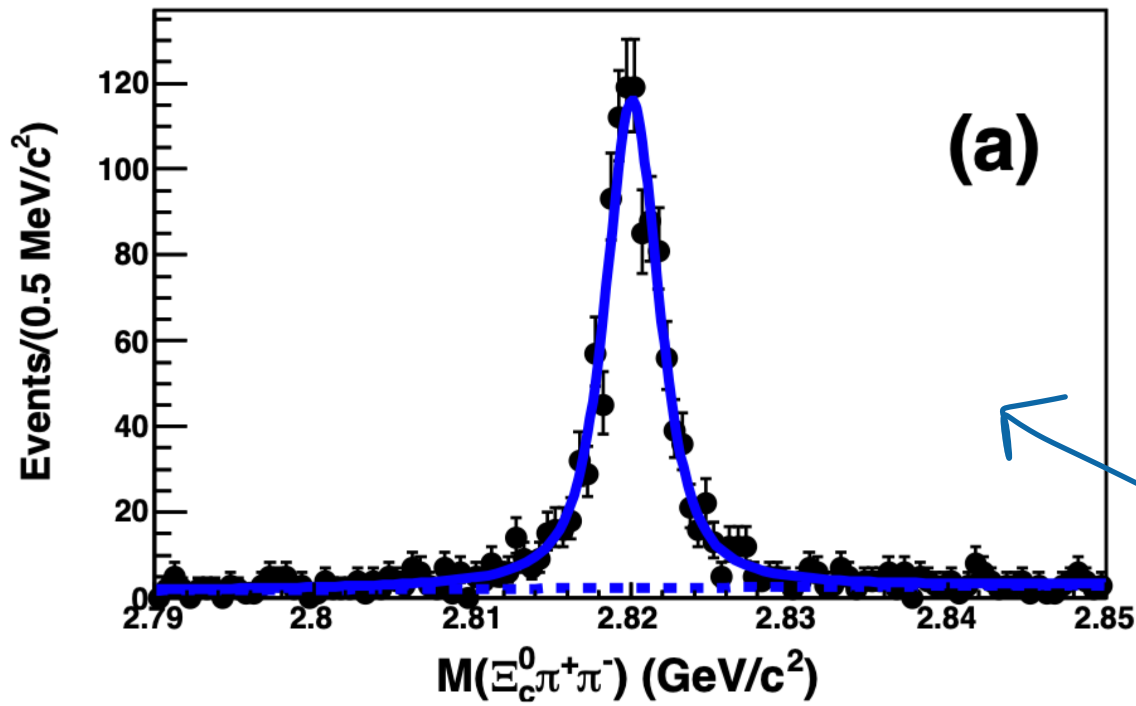
TABLE VII: Partial widths (MeV) and branching fractions for the strong decays of the $1P$-wave states in the Ξ_c and Ξ_b families.

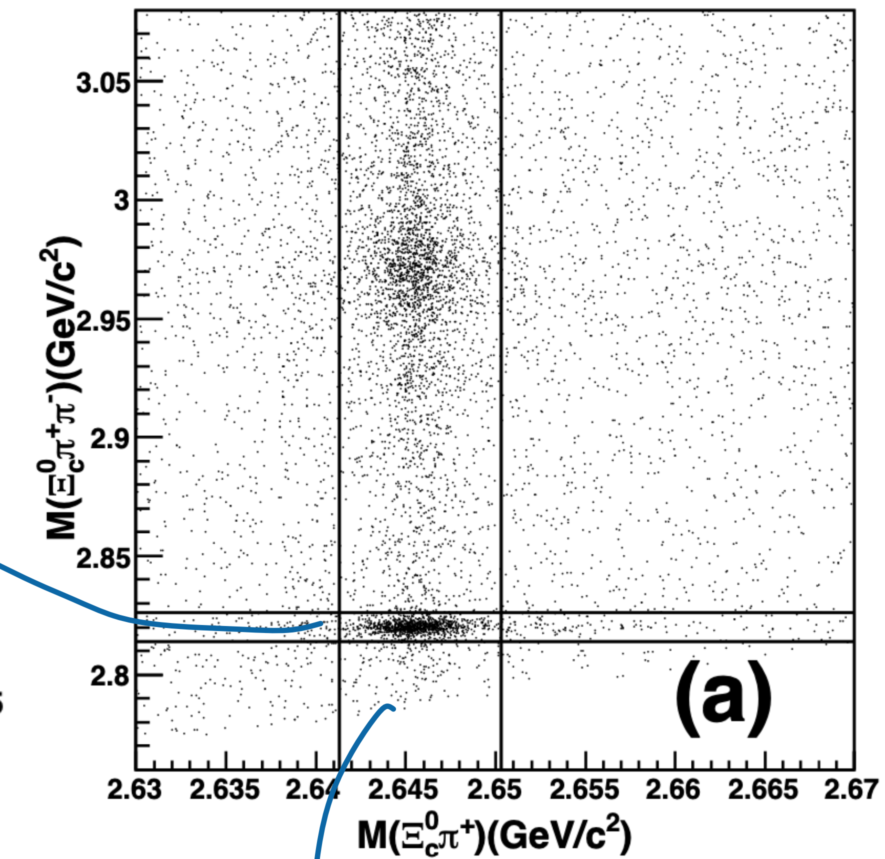
$\lvert ^{2S+1}L_\lambda\, J^P\rangle$	State	Channel	Γ_i (MeV)	$\mathcal{B}_i$	State	Channel	Γ_i (MeV)	$\mathcal{B}_i$
$\lvert ^2P_\lambda \frac{1}{2}^-\rangle$	$\Xi_c(2790)$	$\Xi_c'\pi$	3.61	100%	$\Xi_b(6120)$	$\Xi_b'\pi$	2.84	98.61%
		$\Xi_c'^*\pi$	3.9×10^{-4}	$\simeq 0.0\%$		$\Xi_b'^*\pi$	0.04	1.39%
		total	3.61			total	2.88	
$\lvert ^2P_\lambda \frac{3}{2}^-\rangle$	$\Xi_c(2815)$	$\Xi_c'\pi$	0.31	14.69%	$\Xi_b(6130)$	$\Xi_b'\pi$	0.07	2.37%
		$\Xi_c^*\pi$	1.80	85.31%		$\Xi_b'^*\pi$	2.88	97.63%
		total	2.11			total	2.95	

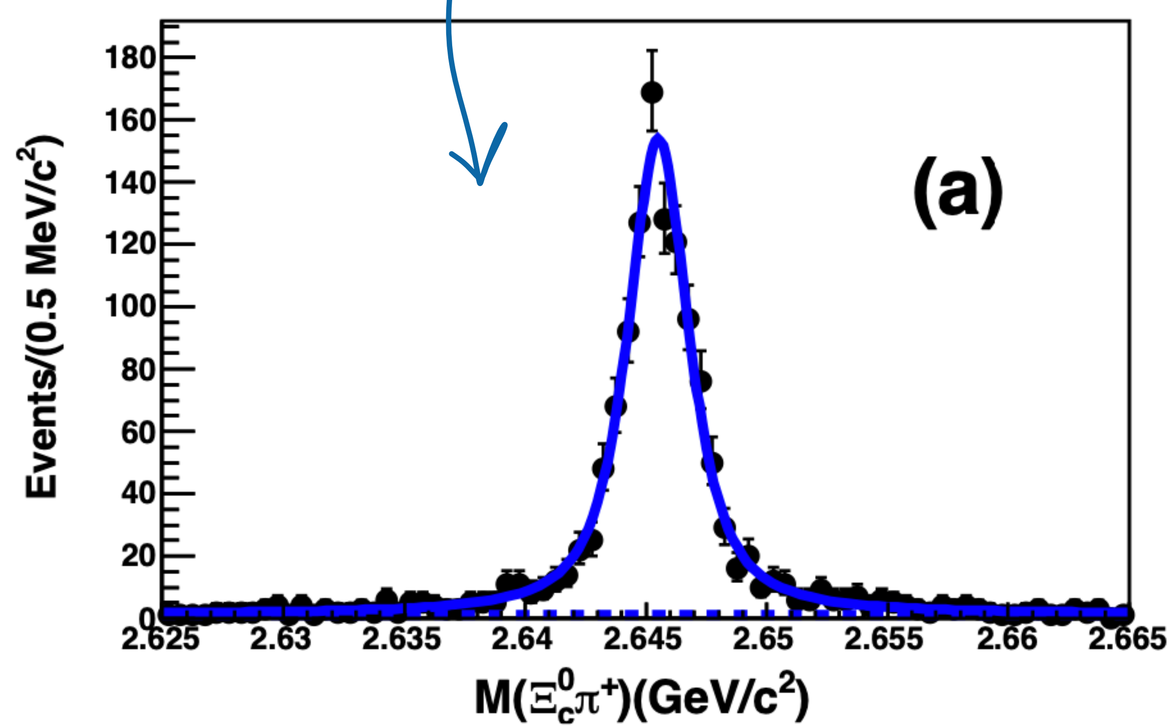
[15]

- [15] is Phys. Rev. D 96, 116016 (2017)
- [16] is Phys. Rev. D 99, 094016 (2019)
- [22] is Phys. Rev. D 98, 031502 (2018)

The $\Xi_c(2815) \to \Xi_c(2645)\pi \to \Xi_c\pi\pi$ analogy







- There are peaks in both $\Xi_c\pi$ and $\Xi_c\pi\pi$ masses
- Mass window on $\Xi_c\pi$ is used for $\Xi_c\pi\pi$ studies
- Plots from [PRD 94 (2016) 5, 052011 (Belle)]
- This analogy is a strong motivation to perform search for a peak in $\Xi_b^-\pi^+\pi^-$ mass with a window on $\Xi_b^-\pi^+$ (corresponding to a previously observed Ξ_b^{*0})

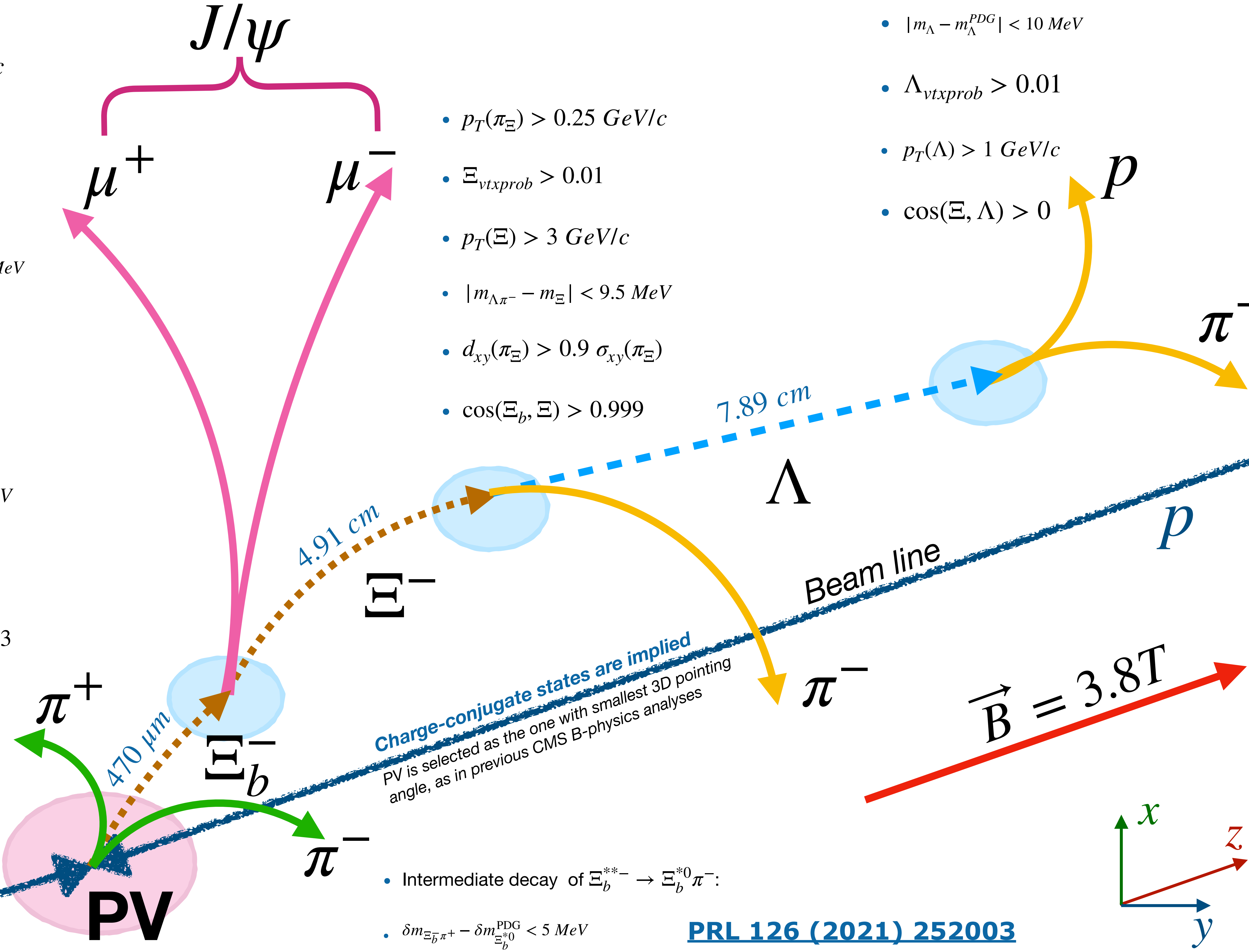
$J/\psi\Xi^-$ decay scheme

- $p_T(\mu^\pm) > 3\ GeV/c$
- $|\eta(\mu^\pm)| < 2.4$
- $J/\psi_{vtxprob} > 0.01$
- $|m_{\mu^+\mu^-} - m_{J/\psi}^{PDG}| < 100\ MeV$

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

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

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



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

PRL 126 (2021) 252003

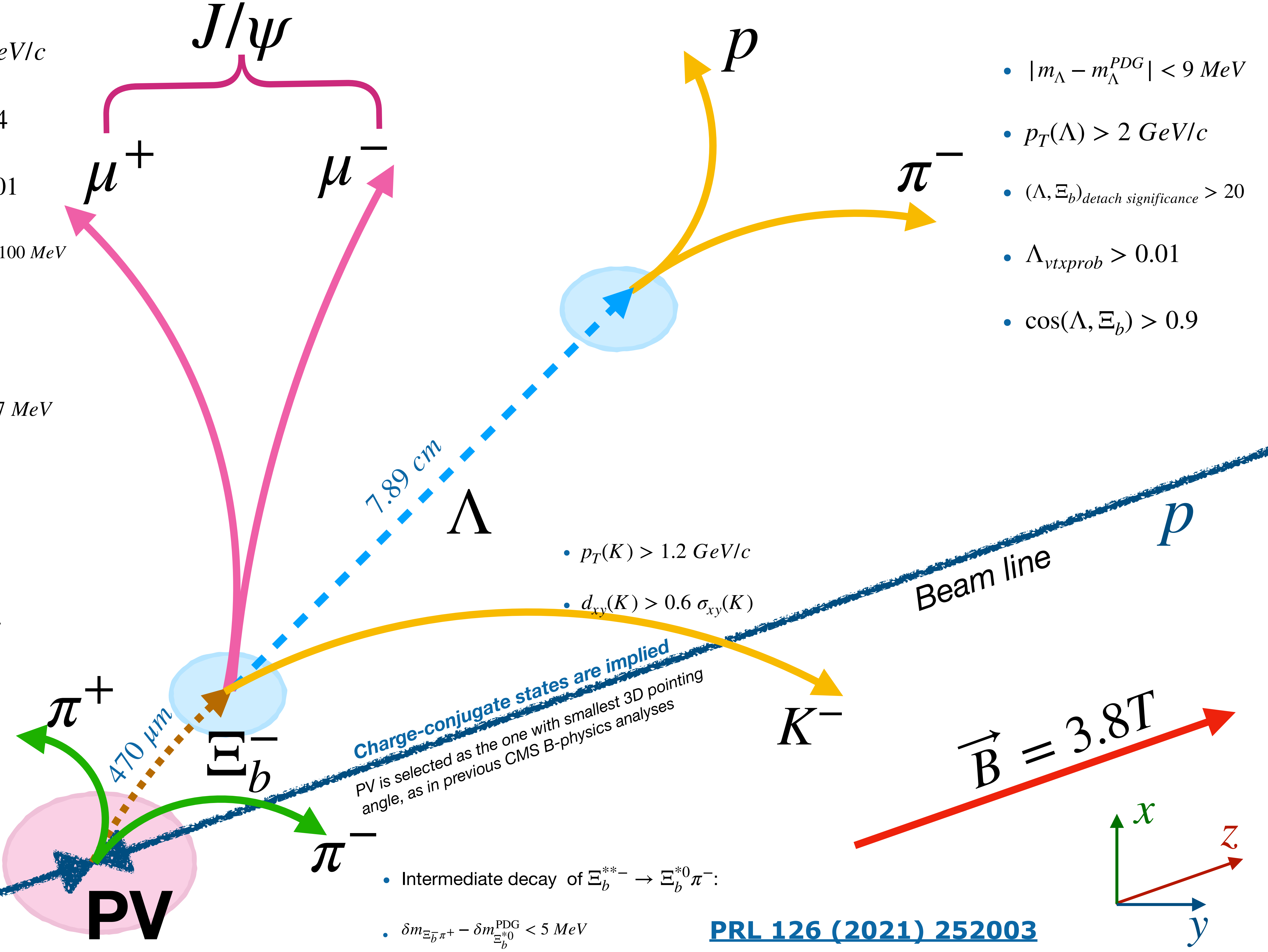
$J/\psi\Lambda K^-$ decay scheme

- $p_T(\mu^\pm) > 3\ GeV/c$
- $|\eta(\mu^\pm)| < 2.4$
- $J/\psi_{vtxprob} > 0.01$
- $|m_{\mu^+\mu^-} - m_{J/\psi}^{PDG}| < 100\ MeV$

- $|m_{J/\psi\Lambda K^-} - m_{\Xi_b^-}^{fit}| < 27\ MeV$
- $(\Xi_b)_{vtxprob} > 0.01$
- $(\Xi_b)_{detach\ significance} > 3$
- $p_T(\Xi_b) > 15\ GeV/c$
- $\cos(\Xi_b, PV) > 0.9993$

- $|m_\Lambda - m_\Lambda^{PDG}| < 9\ MeV$
- $p_T(\Lambda) > 2\ GeV/c$
- $(\Lambda, \Xi_b)_{detach\ significance} > 20$
- $\Lambda_{vtxprob} > 0.01$
- $\cos(\Lambda, \Xi_b) > 0.9$

- $p_T(K) > 1.2\ GeV/c$
- $d_{xy}(K) > 0.6\ \sigma_{xy}(K)$



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

PRL 126 (2021) 252003

Different approaches for exited B-hadrons mass calculation

- We can extract "raw" 4-momenta from prompt PV's tracks or make exited B-hadron vertex fit and extract 4-momenta from fit for signal enhancement (used in CMS $B_c^+\pi^+\pi^-$ PRL 122 (2019) 132001 analysis)

- More complicated approach for exited B-hadrons study was applied for the current $\Xi_b^-\pi^+(\pi^-)$ study (analogously to recent CMS $\Lambda_b^0\pi^+\pi^-$ PLB 803 (2020) 135345 analysis):

- We fit ALL the tracks forming the PV + B-candidate (about 20-100 tracks in each) and use 4-momenta from this vertex fit. The PV refitting procedure has improved the $\Xi_b^-\pi^+\pi^-$ mass resolution by up to 50%