CMS Experiment at the LHC, CERN
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Spectroscopy of beauty strange baryons at CMS

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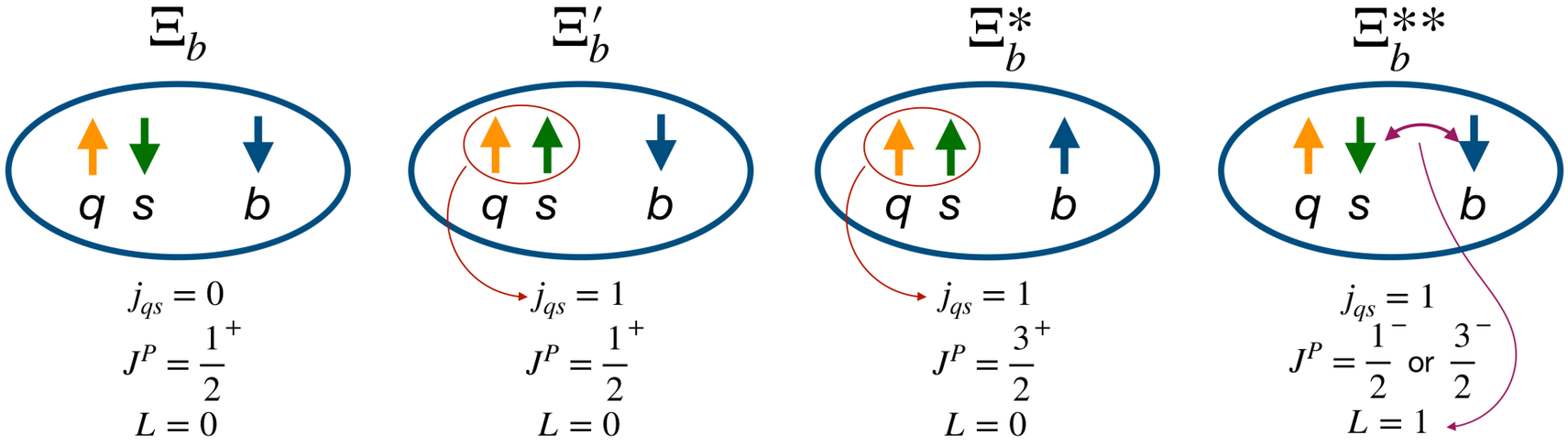
7th International Conference
on Particle Physics and Astrophysics

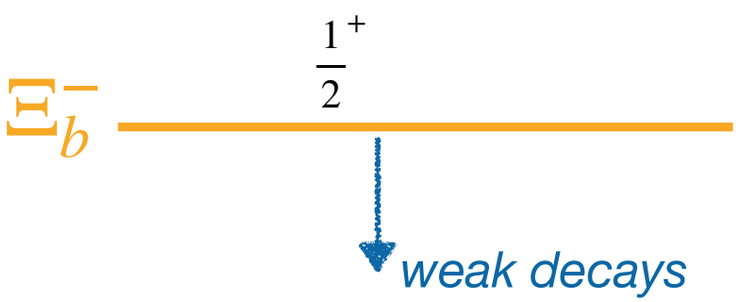
24th October 2024

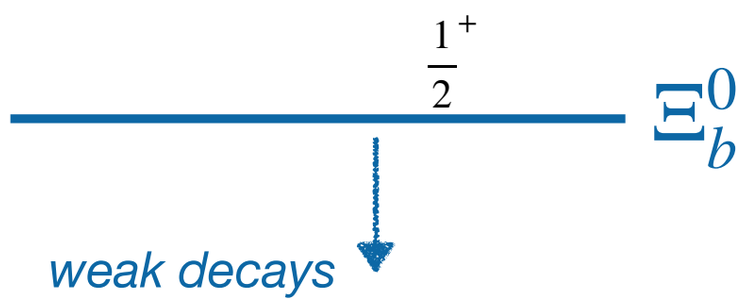
The work is supported by RSF (grant № 23-12-00083)

Ξ_b baryons spectroscopy

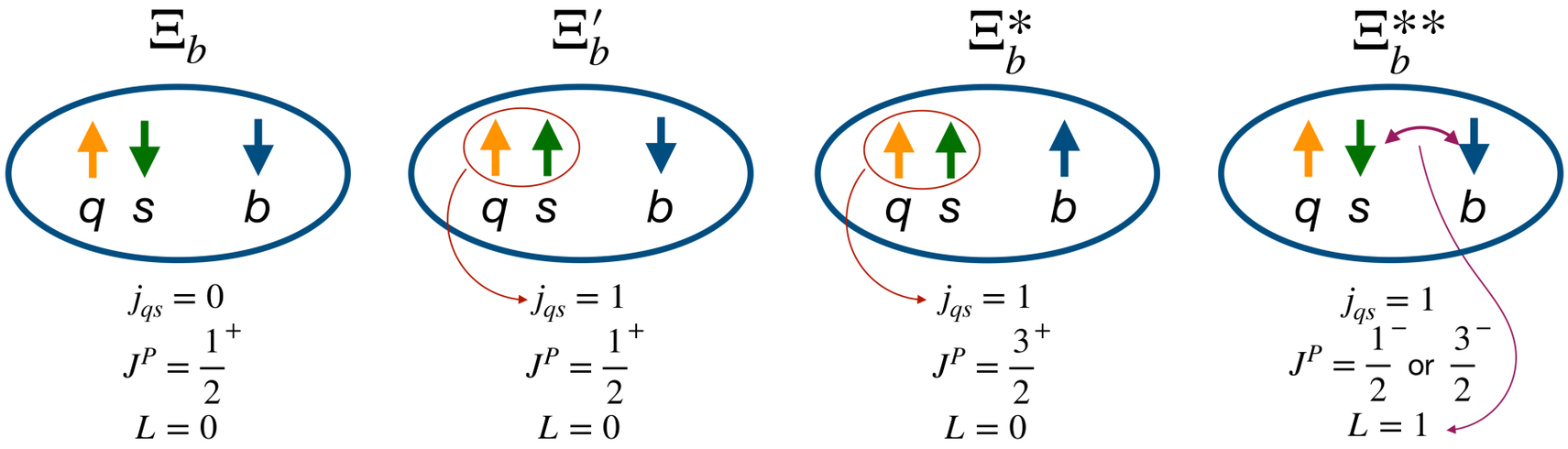


q denotes u or d quarks for Ξ_b^0 or Ξ_b^-. $L = 1$ is the orbital excitation between the light diquark qs and heavy b quark.





Ξ_b baryons spectroscopy



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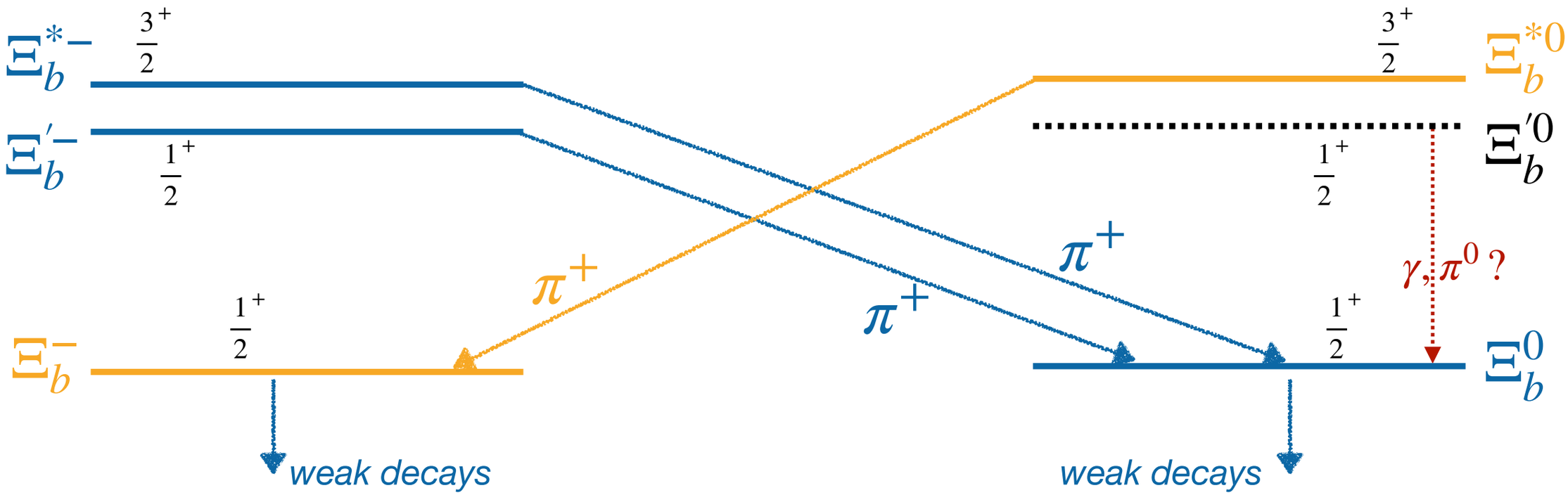
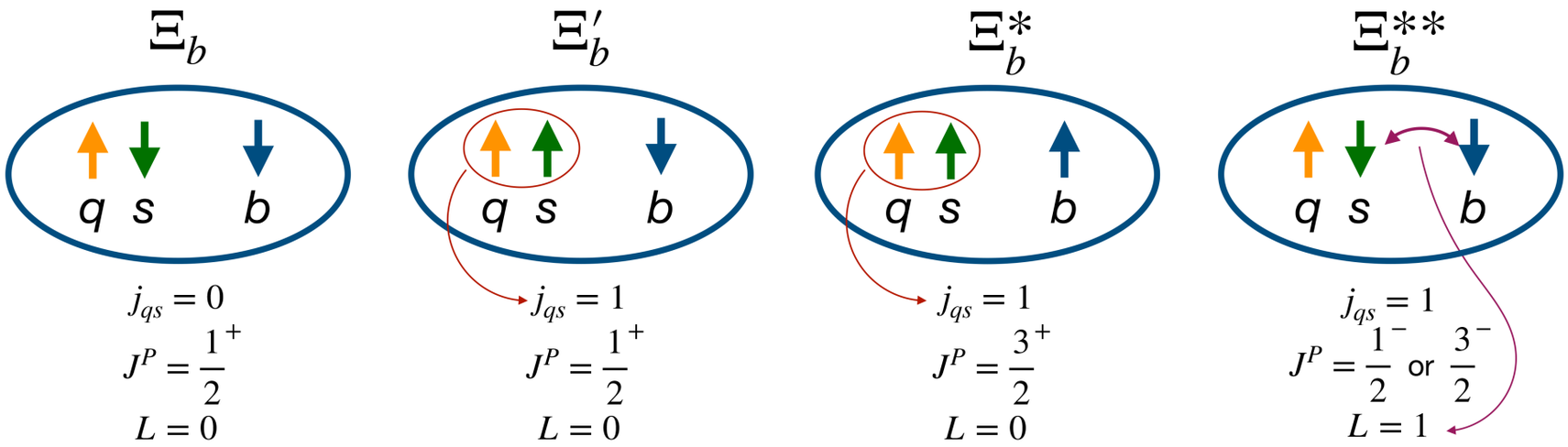


Ξ_b baryons spectroscopy



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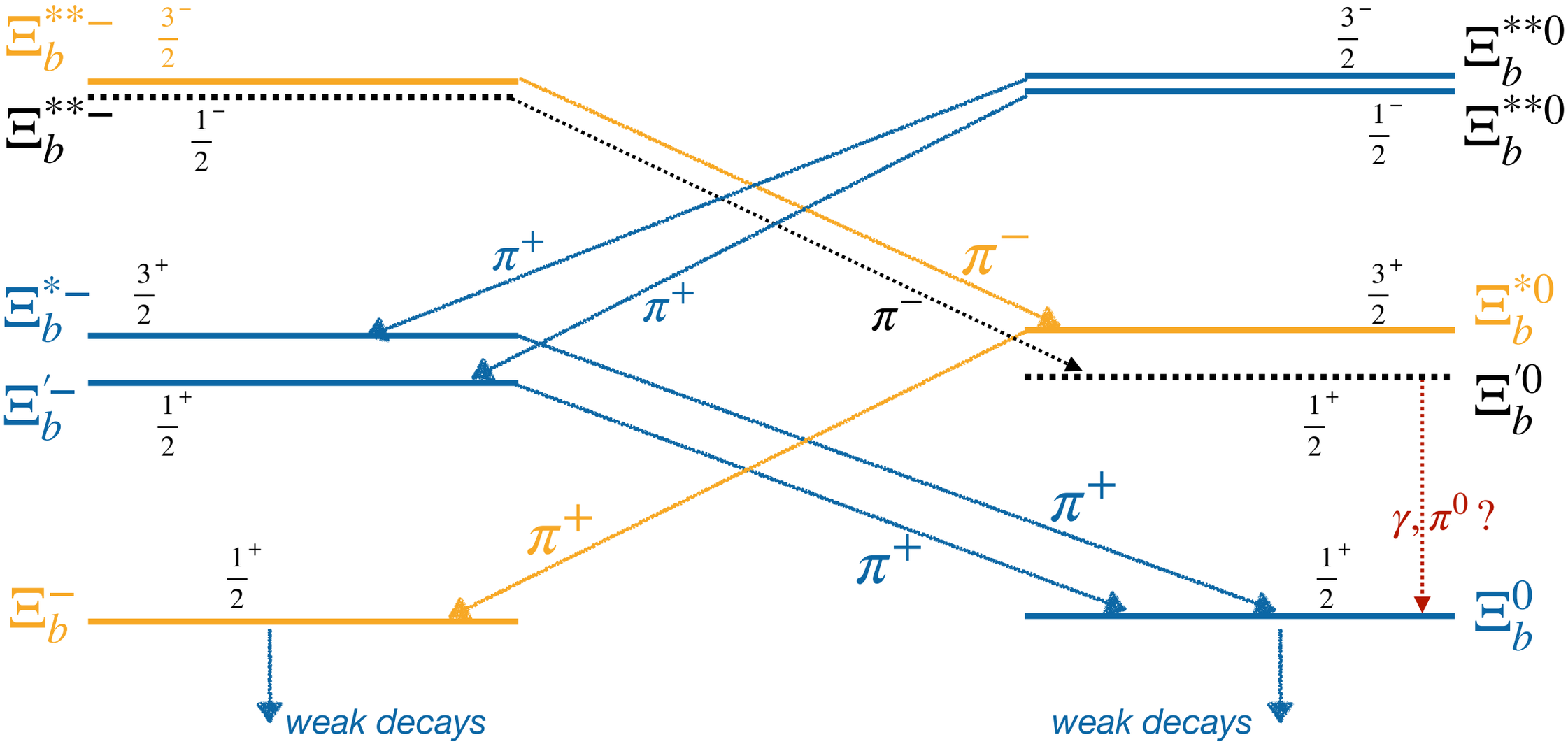
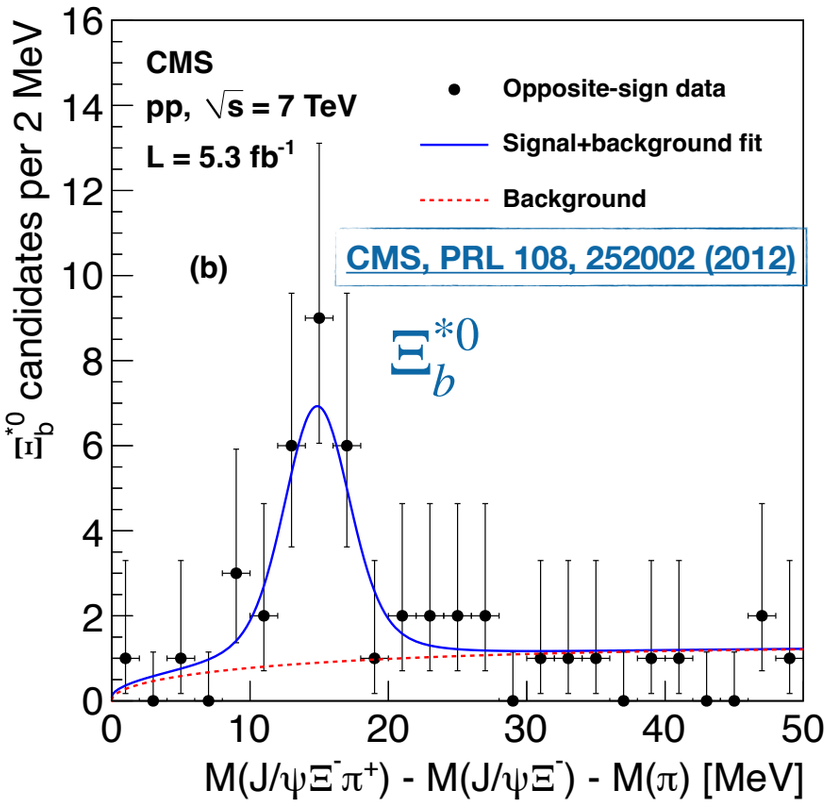
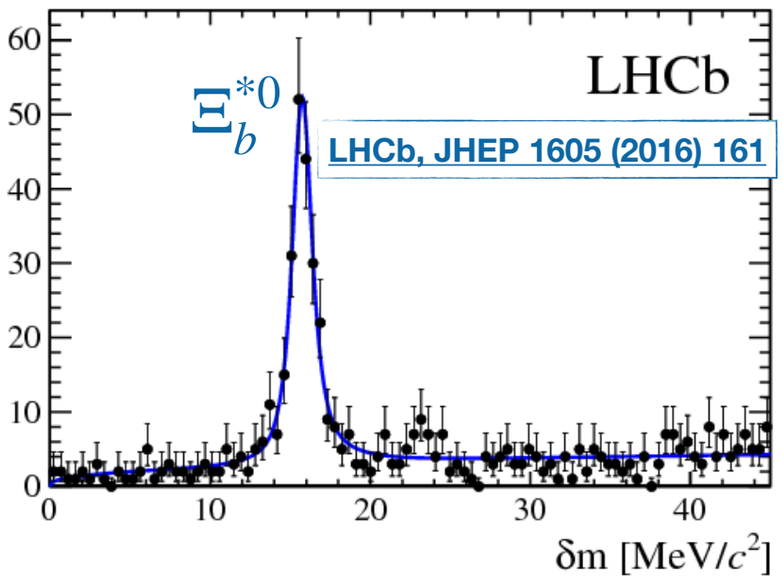
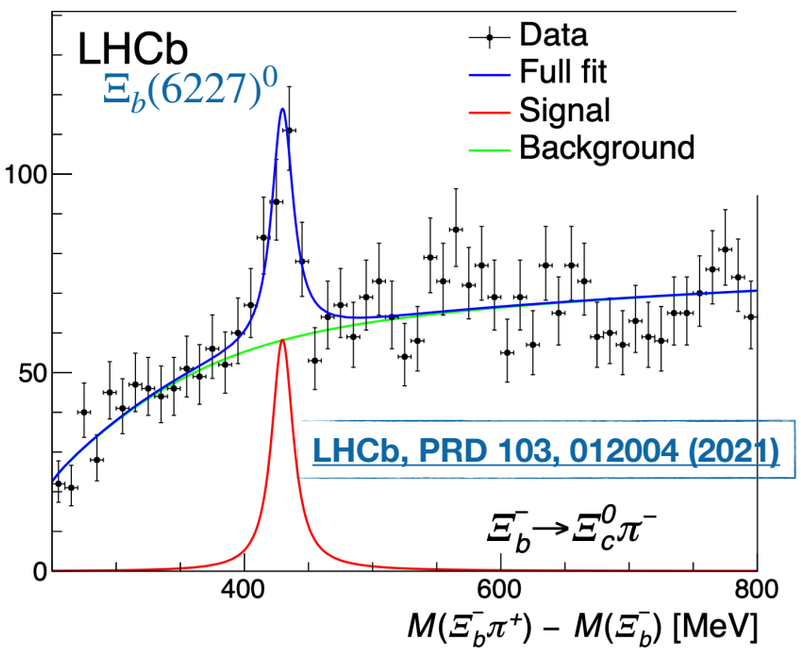
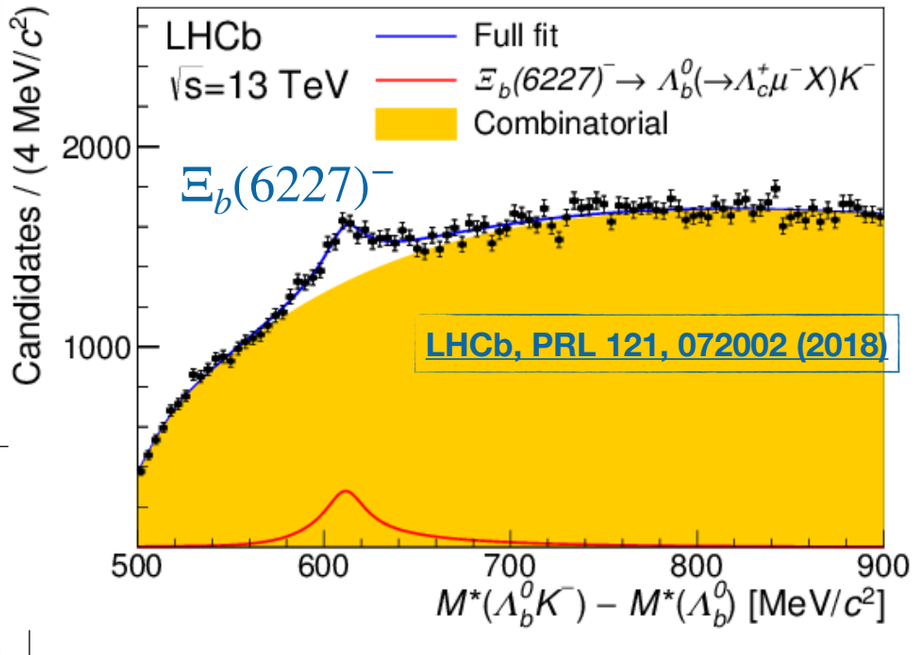


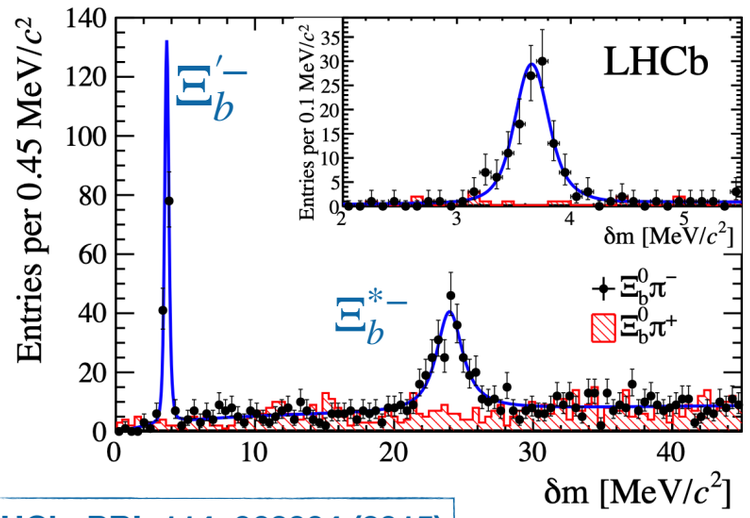
Previous results of Ξ_b resonances



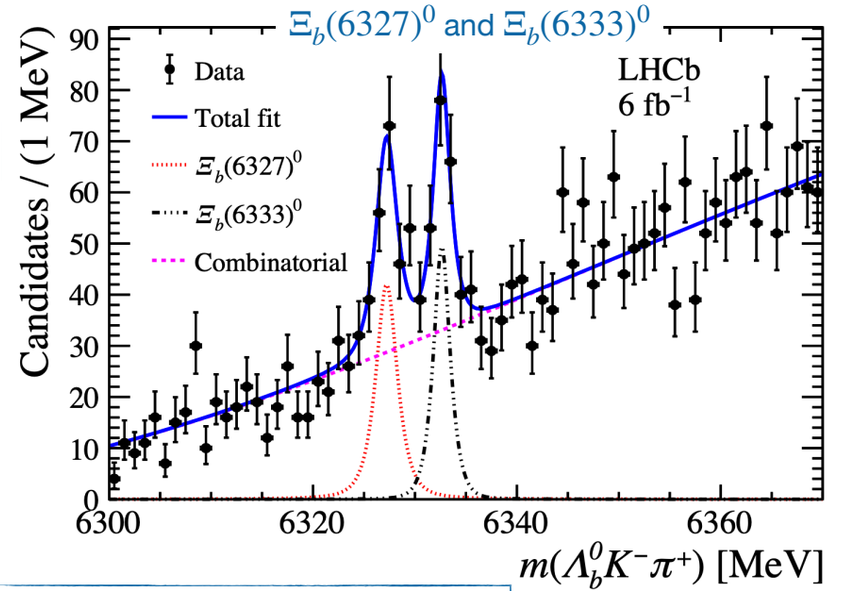








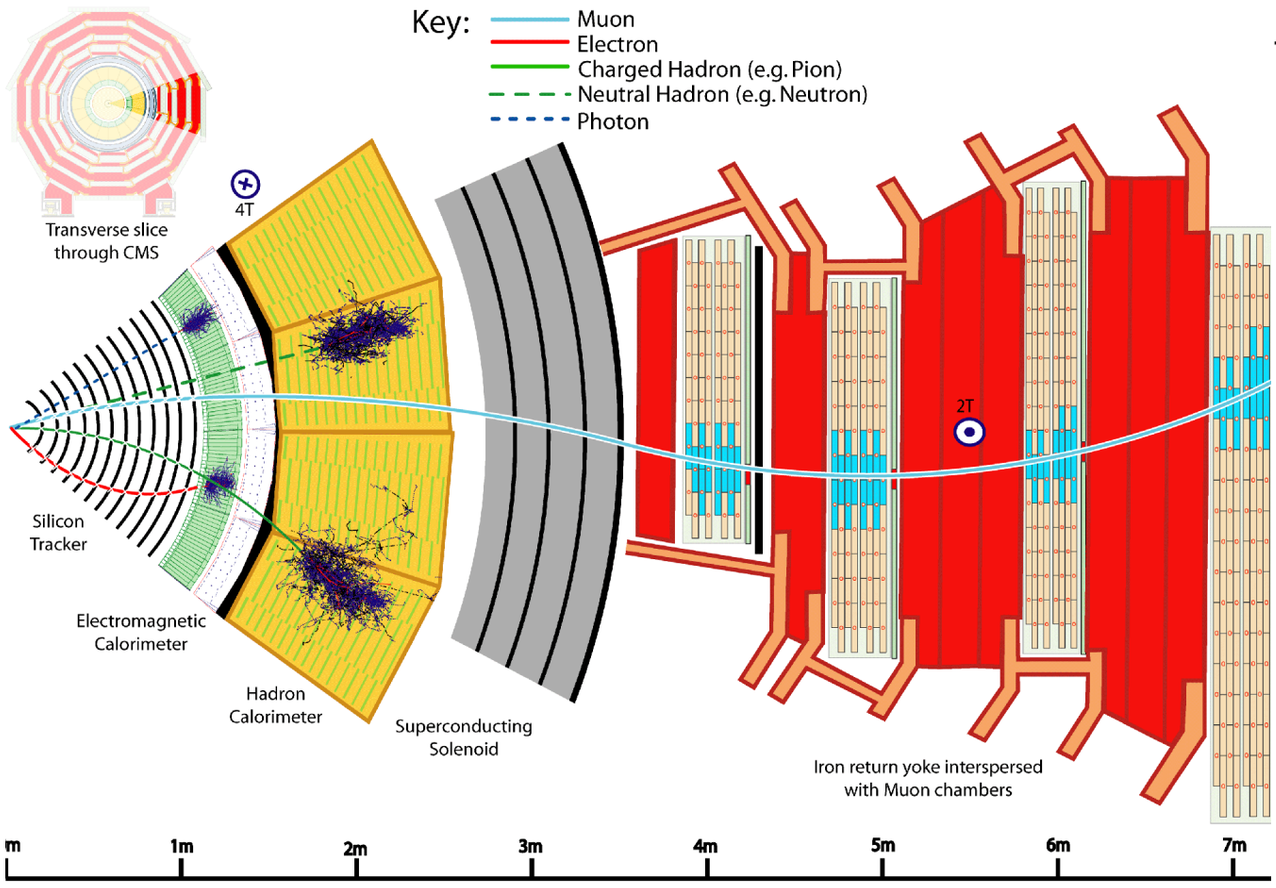
LHCb, PRL 114, 062004 (2015)

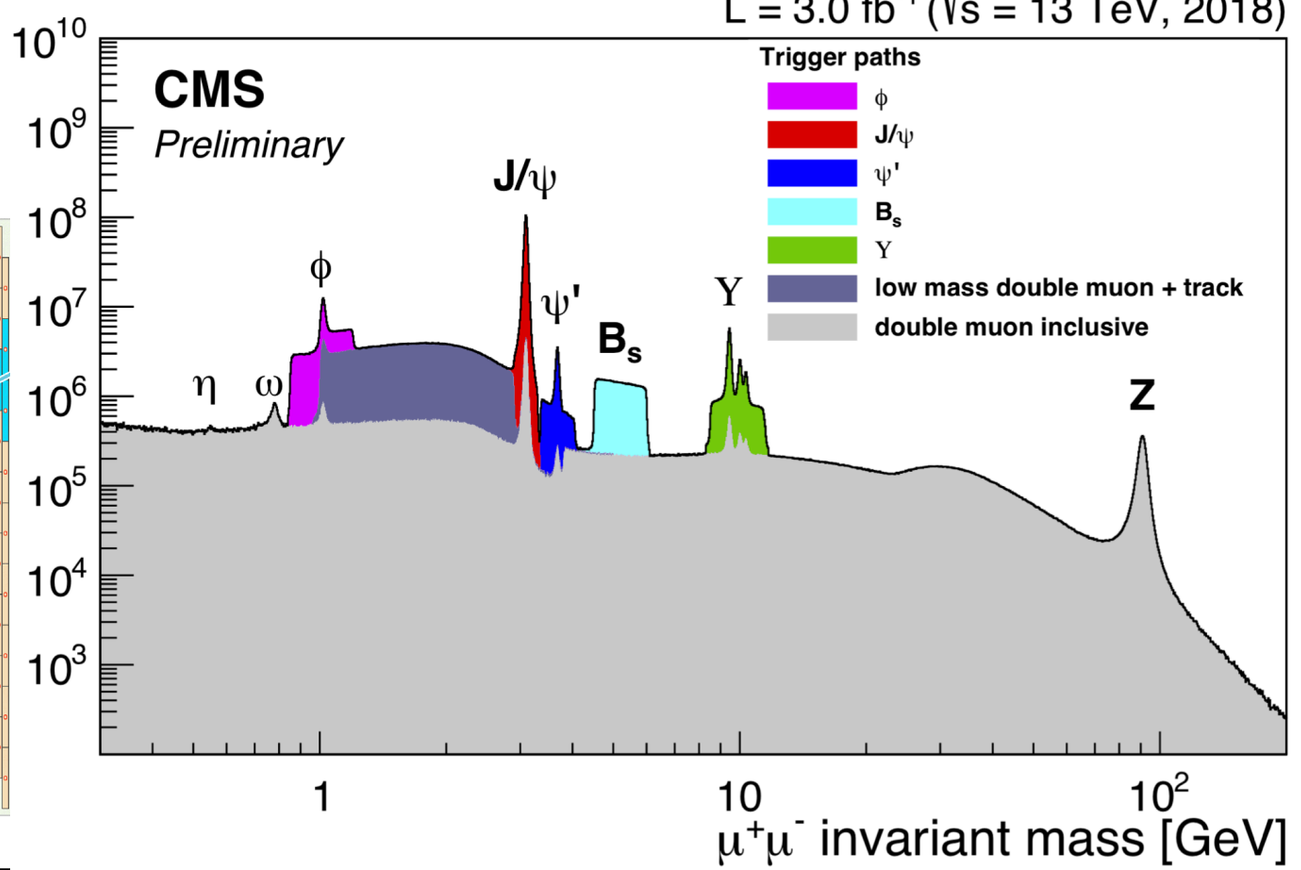


LHCb, PRL 128 16, 162001 (2022)

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

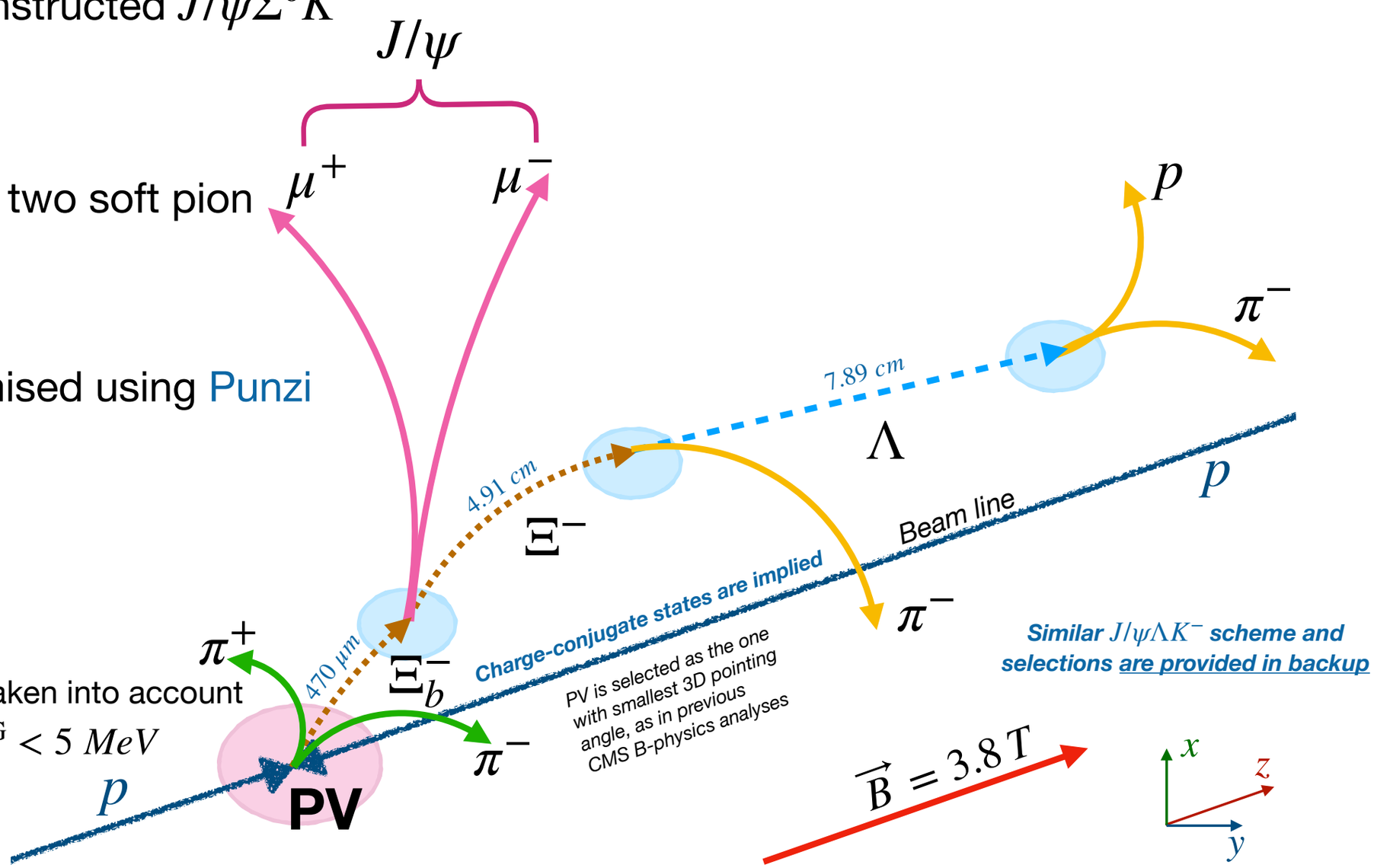
- We use full Run-2 CMS data ($140\ fb^{-1}$, $\sqrt{s} = 13$ TeV) to search for a new $\Xi_b^{**-} \to \Xi_b^{*0}\pi^- \to \Xi_b^-\pi^+\pi^-$ resonance, basing on theoretical predictions and excited Ξ_c^{**} charm analogies
  Also to update the Ξ_b^{*0} parameters w.r.t. previously reported

- 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**

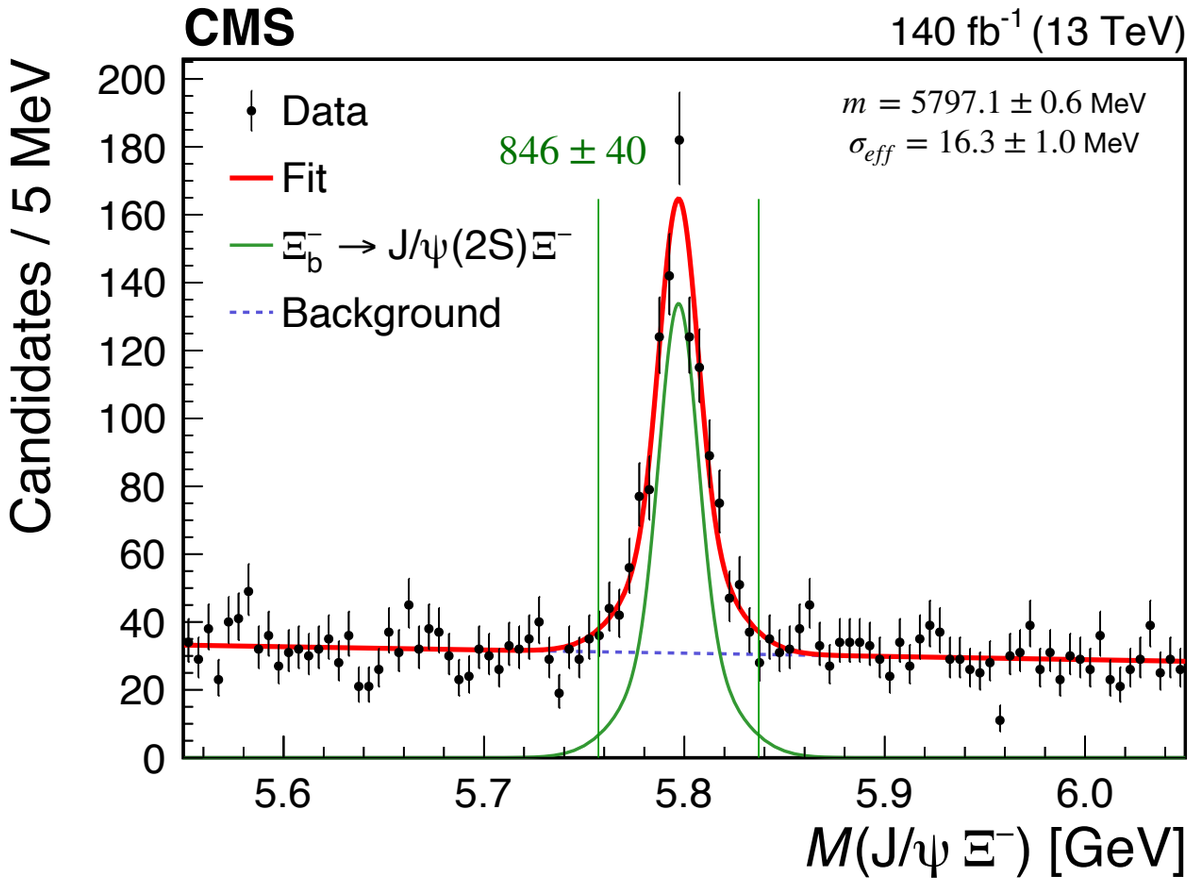
- Then Ξ_b^- is combined with two soft pion tracks from PV

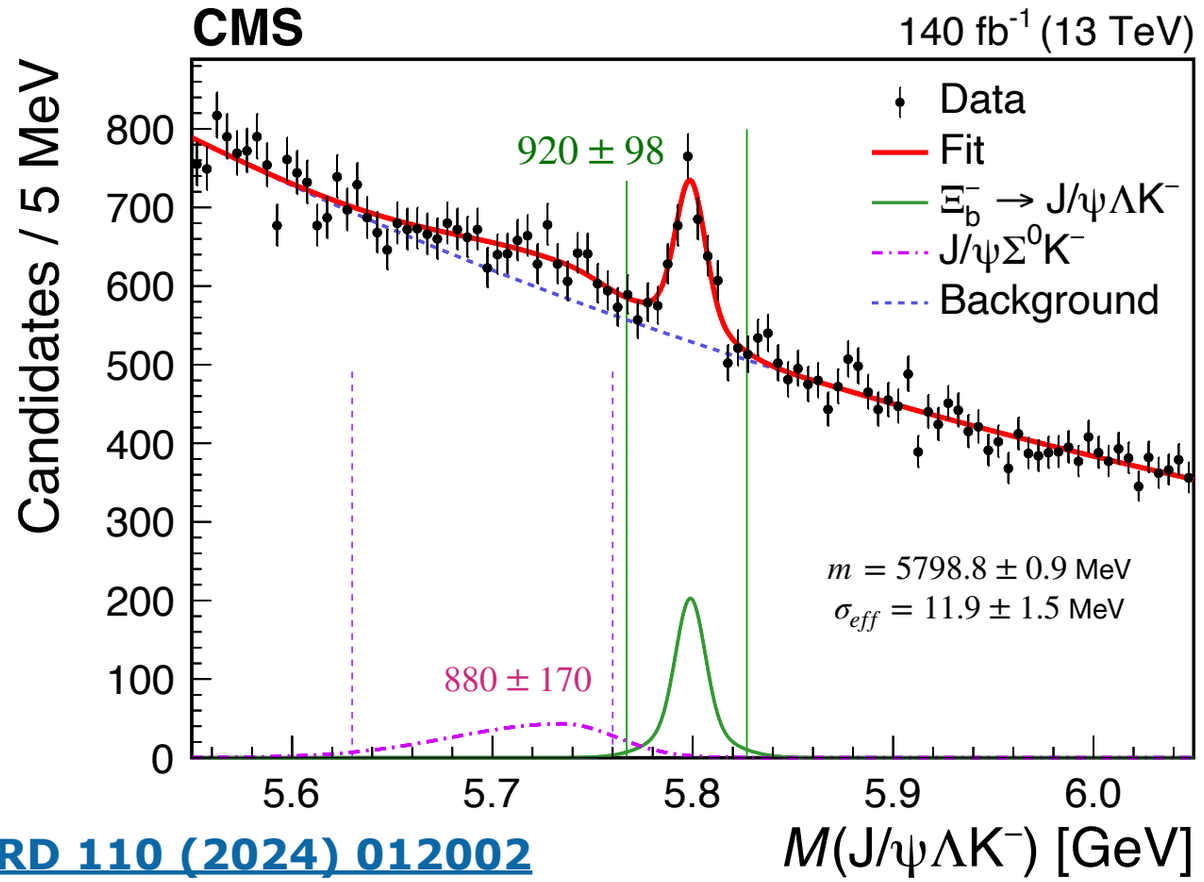
- Selection criteria are optimised using Punzi Figure of Merit



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



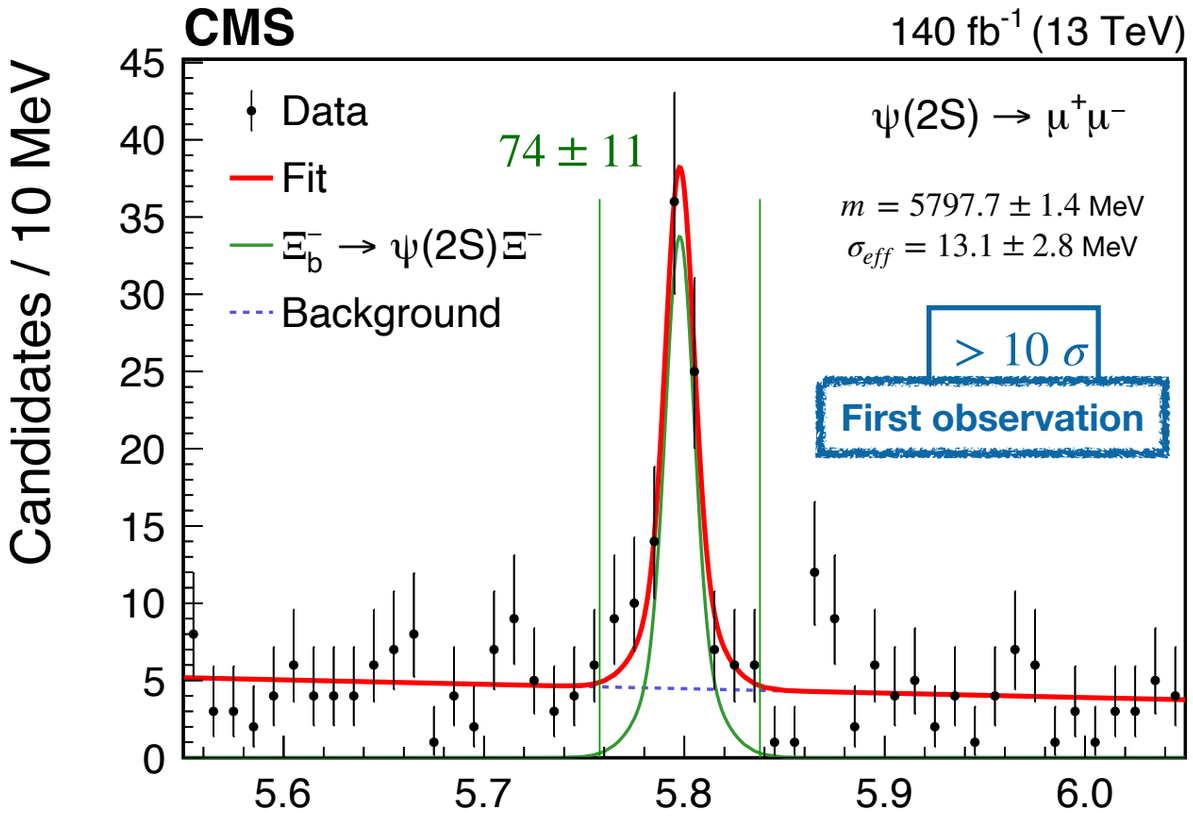


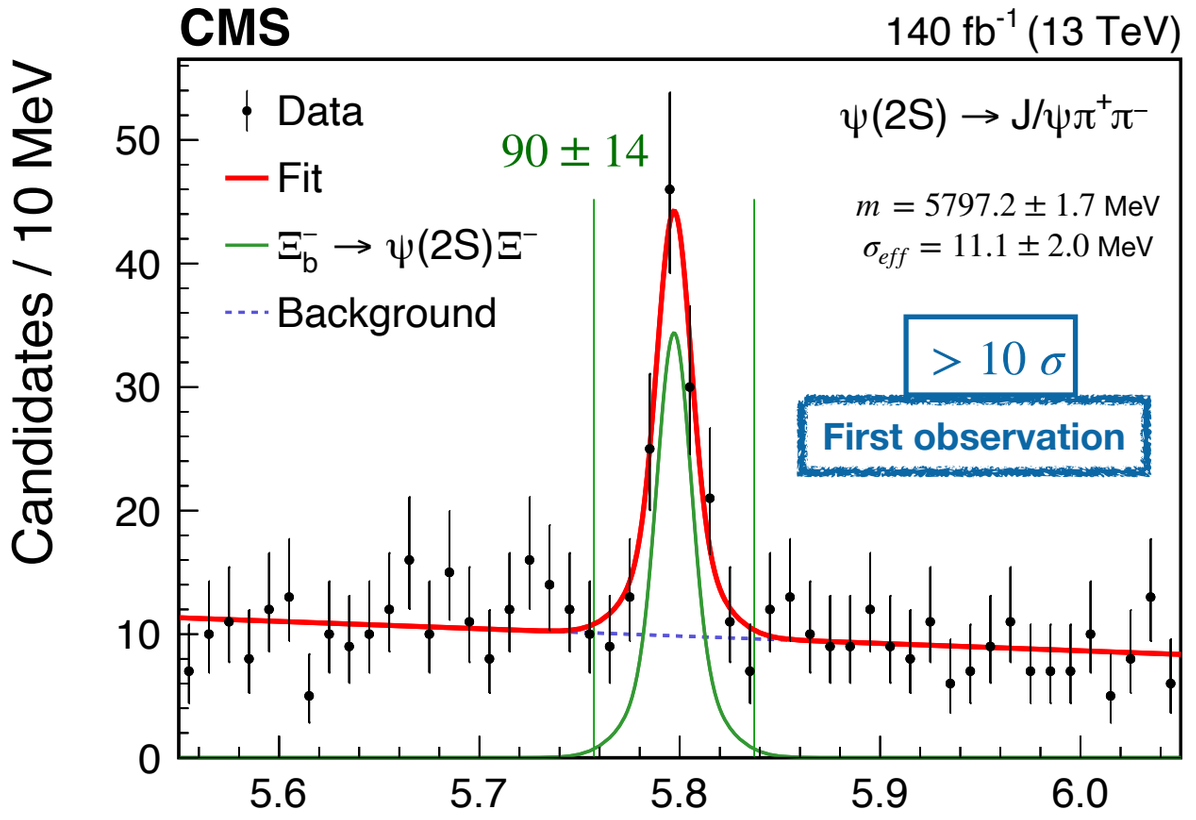
PRD 110 (2024) 012002

- **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





PRD 110 (2024) 012002

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

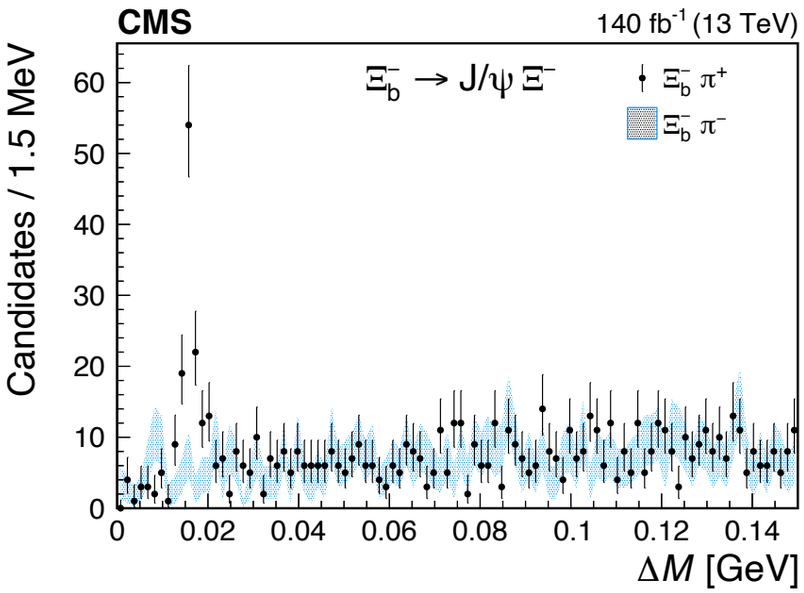
- **Local statistical significance** from likelihood ratio technique (Sig. + Bkg. versus Bkg. only hypothesis)
  Well above 5 sigma for both $\psi(2S) \to \mu^+\mu^-$ and modes $\psi(2S) \to J/\psi\pi^+\pi^-$

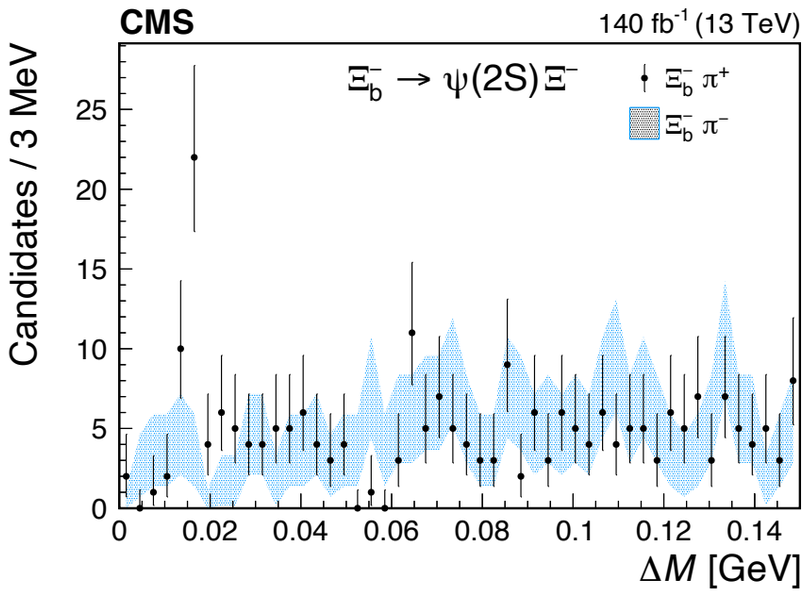
- Branching fraction of the new decay is estimated to be:

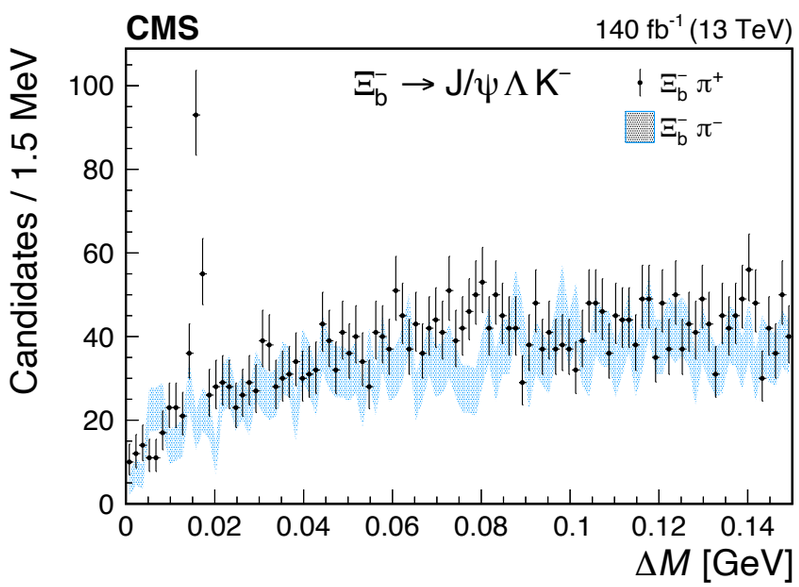
$$R = \frac{\mathcal{B}\left(\Xi_b^- \to \psi(2S)\Xi^-\right)}{\mathcal{B}\left(\Xi_b^- \to J/\psi\Xi^-\right)} = \frac{N_{\Xi_b^- \to \psi(2S)\Xi^-}}{N_{\Xi_b^- \to J/\psi\Xi^-}} \cdot \frac{\epsilon_{\Xi_b^- \to J/\psi\Xi^-}}{\epsilon_{\Xi_b^- \to \psi(2S)\Xi^-}} \cdot \frac{\mathcal{B}\left(J/\psi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

from data fits — from MC simulation

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







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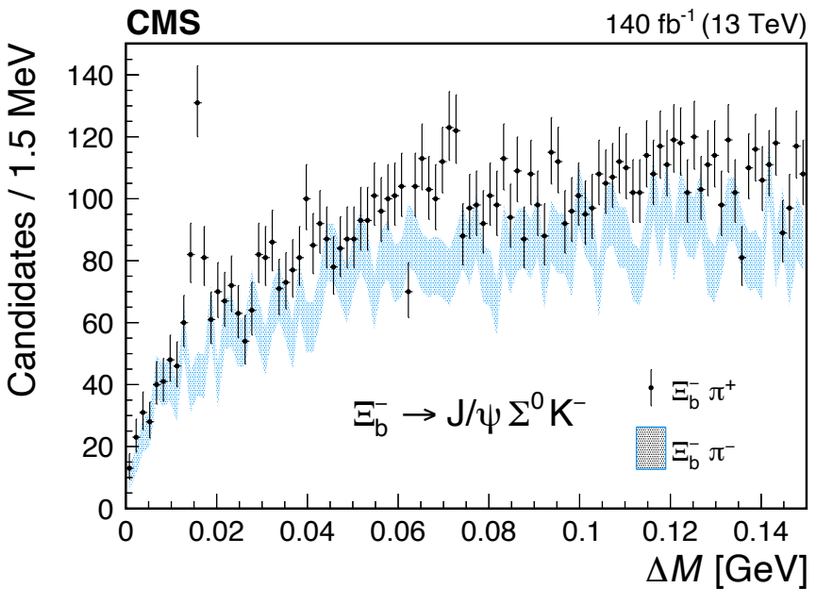
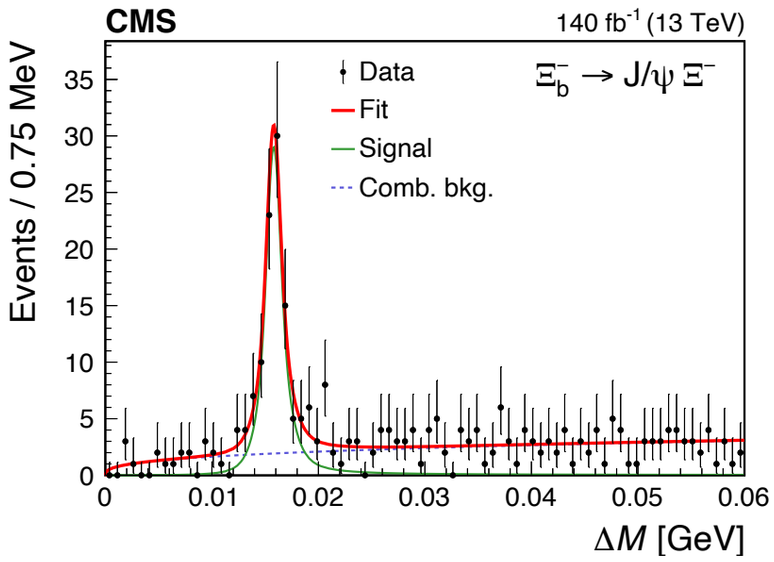
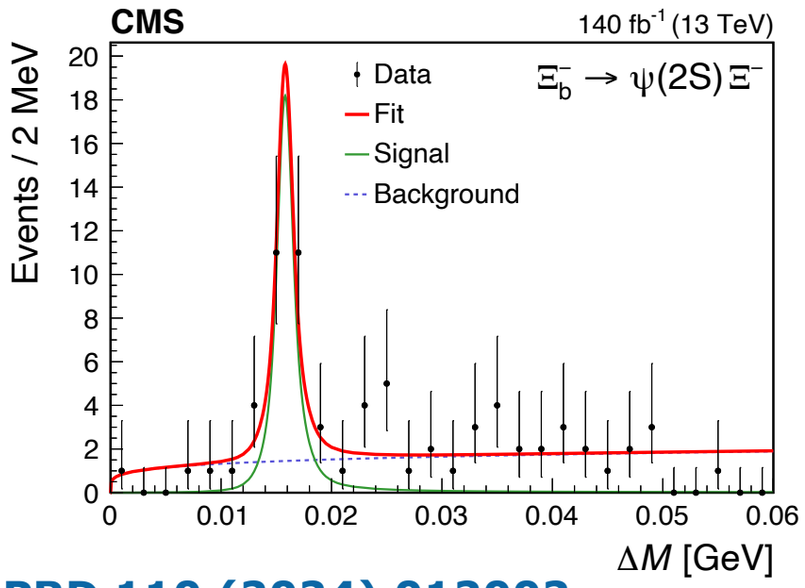


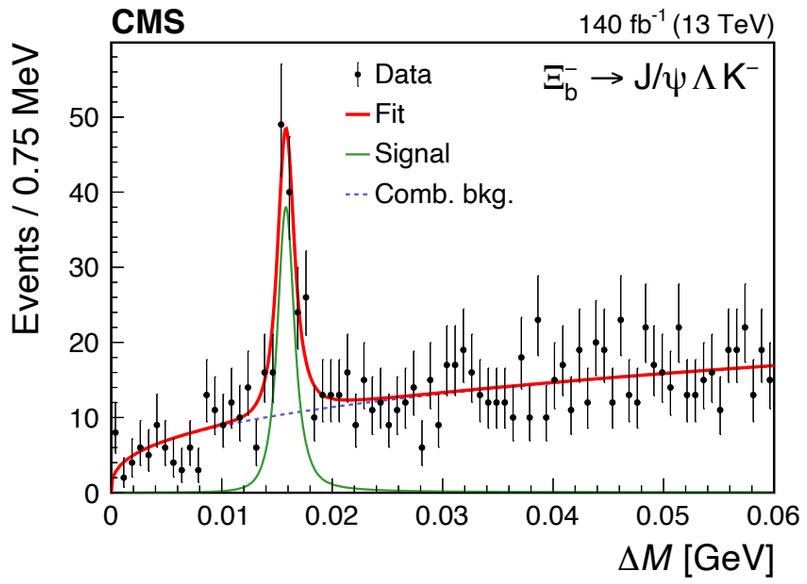
Mass difference variable $\Delta M = M(\Xi_b^- \pi^+) - M(\Xi_b^-) - m_{\pi^+}^{\mathrm{PDG}}$ and PV refit technique (see backup) are used to improve detector resolution

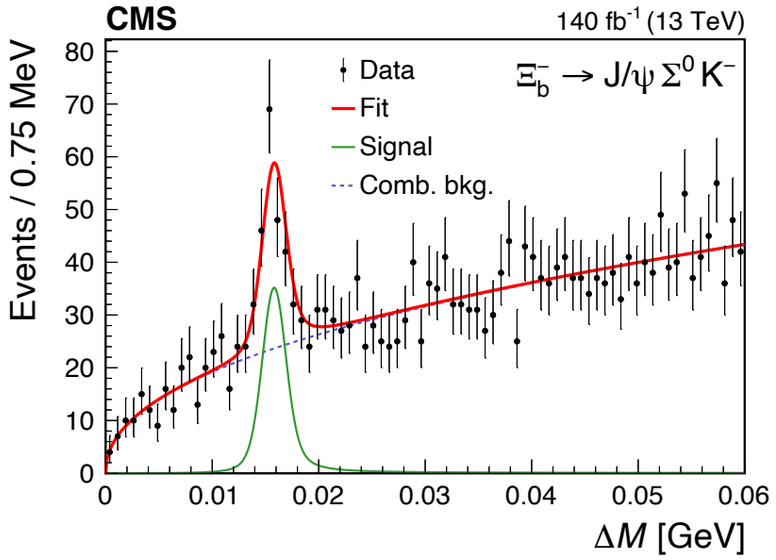
- Clear, significant peak of Ξ_b^{*0} near the kinematic threshold in $M(\Xi_b^- \pi^+)$ for all 4 channels of Ξ_b^- reconstruction
- No other structures observed in the near-threshold area *(as expected)*
- Combinatorial background is in agreement with wrong-sign *(showing us that the bkg **is** combinatorial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

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









PRD 110 (2024) 012002

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}

$$\Delta M = 15.810 \pm 0.077\,(\text{stat}) \pm 0.052\,(\text{syst})\ \text{MeV}$$
$$\Gamma(\Xi_b^{*0}) = 0.87^{+0.22}_{-0.20}\,(\text{stat}) \pm 0.16\,(\text{syst})\ \text{MeV}$$

Excellent agreement with previous CMS & LHCb results!

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

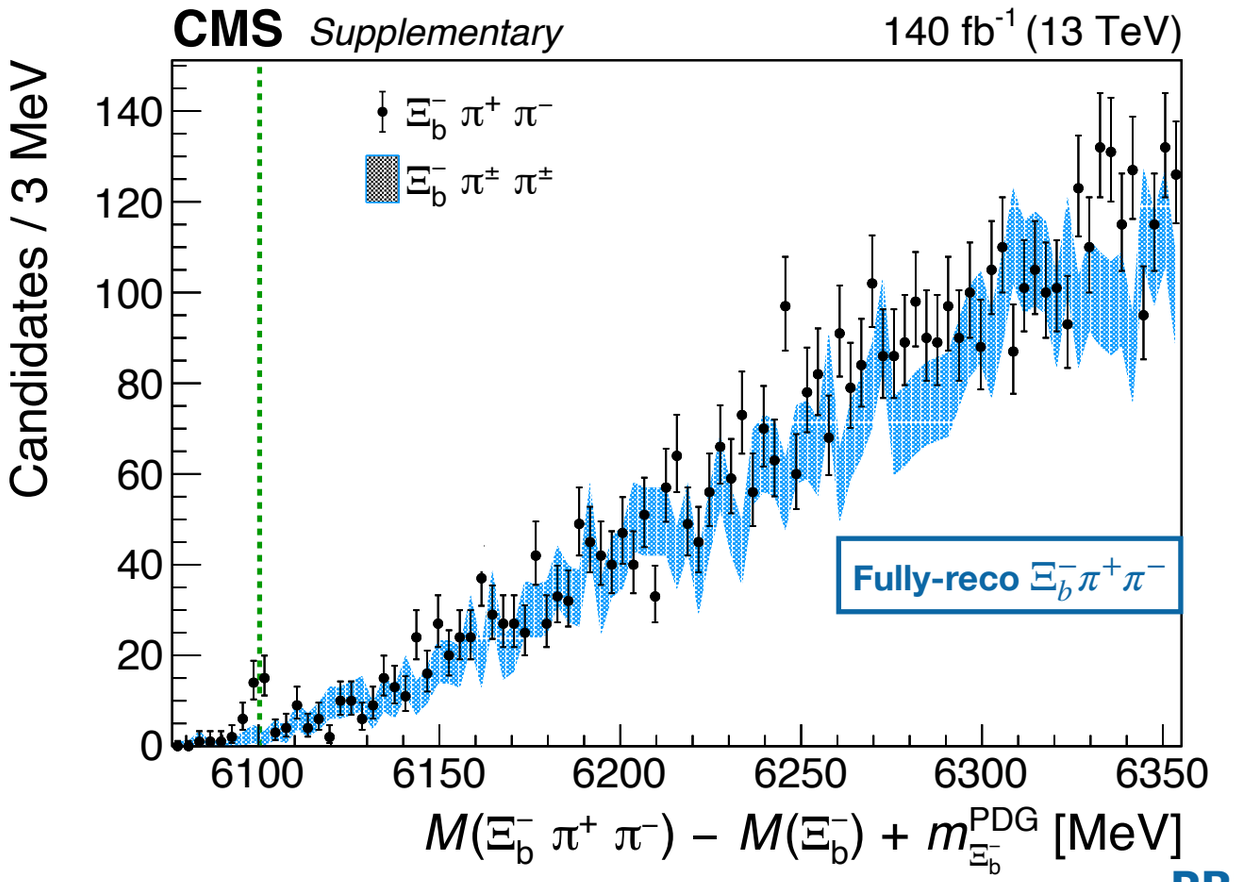
- We also measure relative Ξ_b^{*0}/Ξ_b^- production ratio:

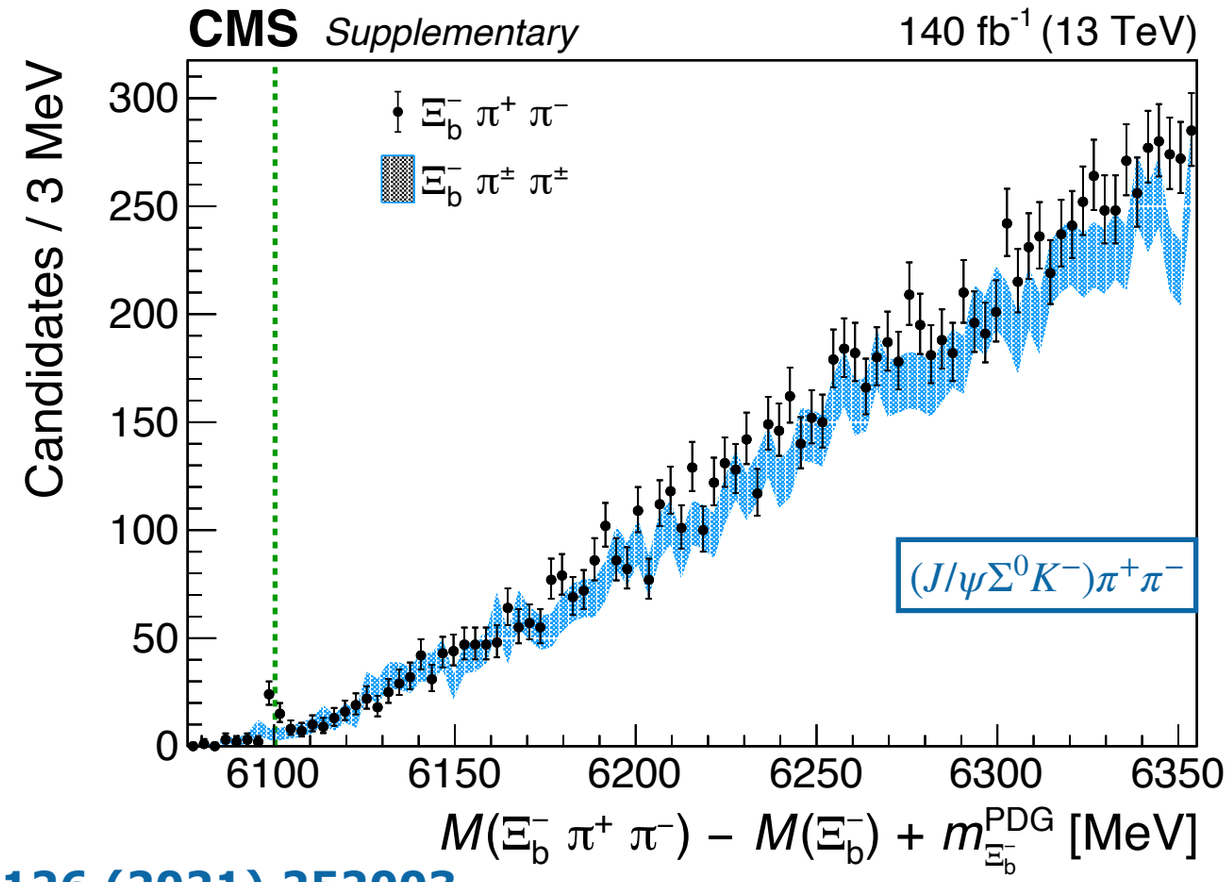
$$R_{\Xi_b^{*0}} = \frac{\sigma\left(pp \to \Xi_b^{*0} X\right) \cdot \mathcal{B}\left(\Xi_b^{*0} \to \Xi_b^- \pi^+\right)}{\sigma\left(pp \to \Xi_b^- X\right)} = \frac{N\left(\Xi_b^{*0}\right)}{N\left(\Xi_b^-\right)} \cdot \frac{\epsilon_{\Xi_b^-}}{\epsilon_{\Xi_b^{*0}}} = 0.23 \pm 0.02 \pm 0.02$$

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

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

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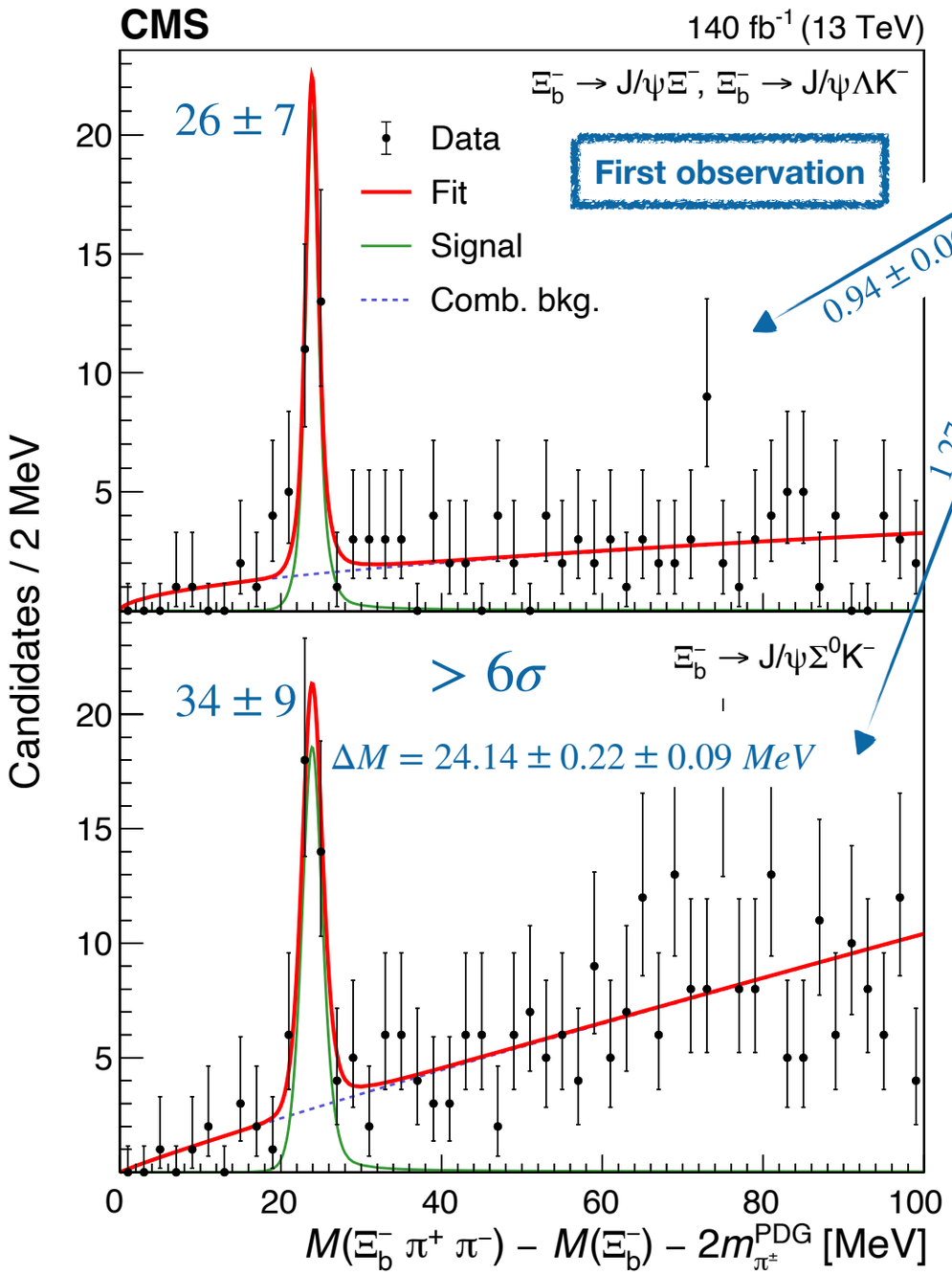


$M(\Xi_b(6100)^-) = 6100.3 \pm 0.2 \pm 0.1 \pm 0.6\ MeV$

$\Gamma(\Xi_b(6100^-) < 1.9\ MeV\ @95\ \%\ CL$

systematics are included 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 $R_{\Xi_b^{*0}} = 0.23 \pm 0.03$

- 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 charming results from the CMS Collaboration!

CMS Experiment at the LHC, CERN

Data recorded: 2018-Sep-08 02:36:01.428900 GMT

Run / Event / LS: 322430 / 379062570 / 243

Thank you for your attention!

Do you have any questions?

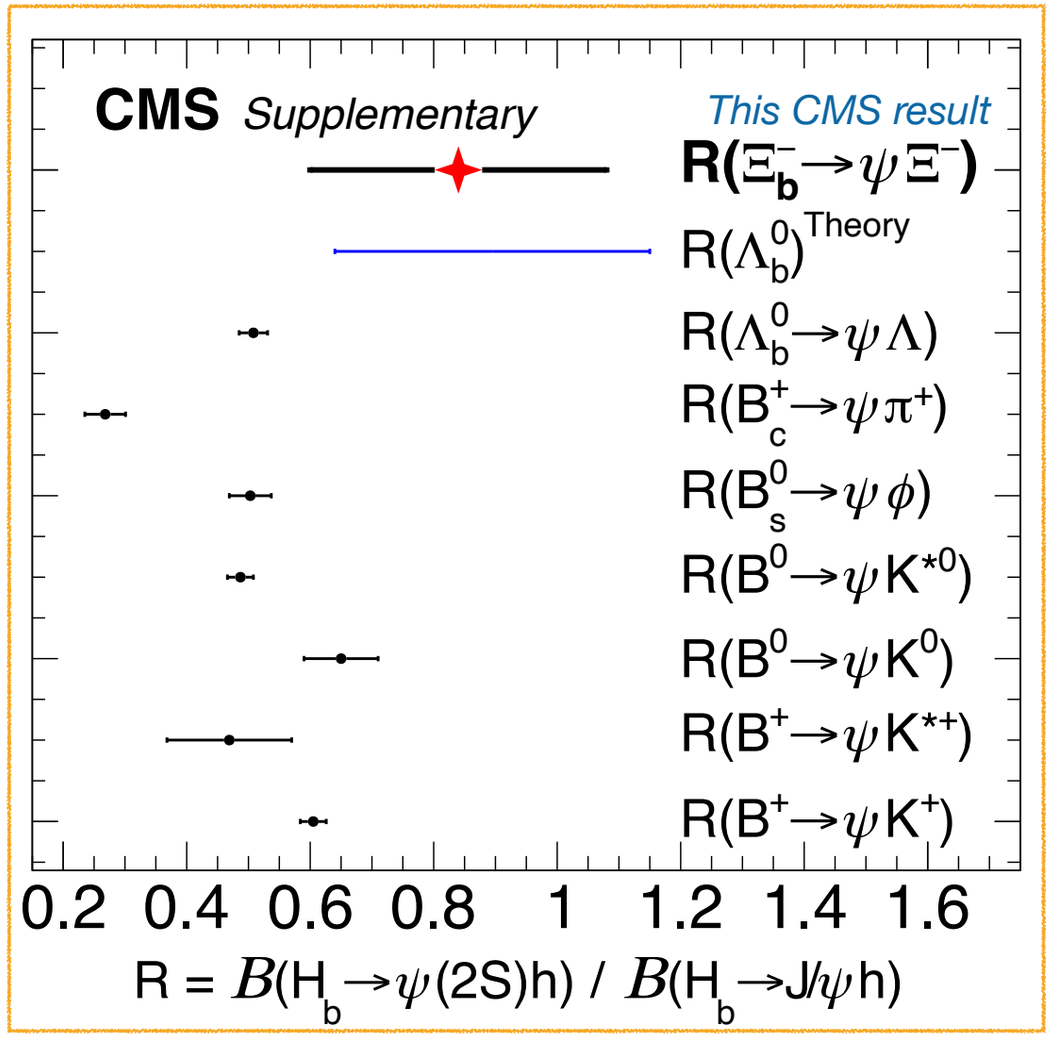
Backup slides

Branching fraction ratio discussion

- We compare our result for the measured $\mathcal{B}$ 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

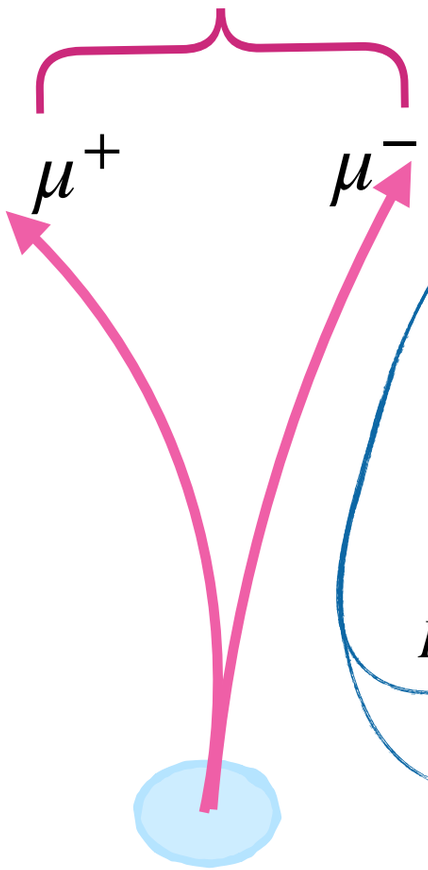
- Both new, precise measurements of such ratios and theoretical predictions are required, especially for the beauty baryon sector (Λ_b, Ξ_b, Ω_b decays…)

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 ⟶ extract efficiency ϵ for the for the ratio measurements

J/ψ **or** $\psi(2S)$



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

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

- 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

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

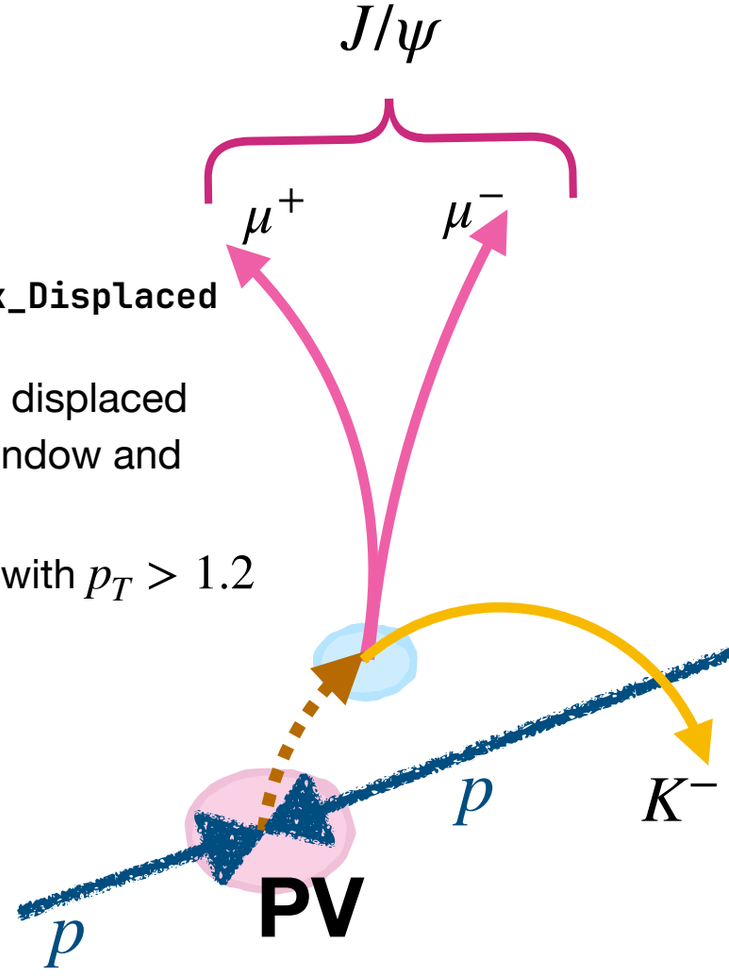
$R_{\Xi_b^{*0}}\left(J/\psi\Xi^-\right)$

`HLT_Dimuon20_Jpsi` and `HLT_Dimuon13_PsiPrime` are used for the 2016 conditions

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

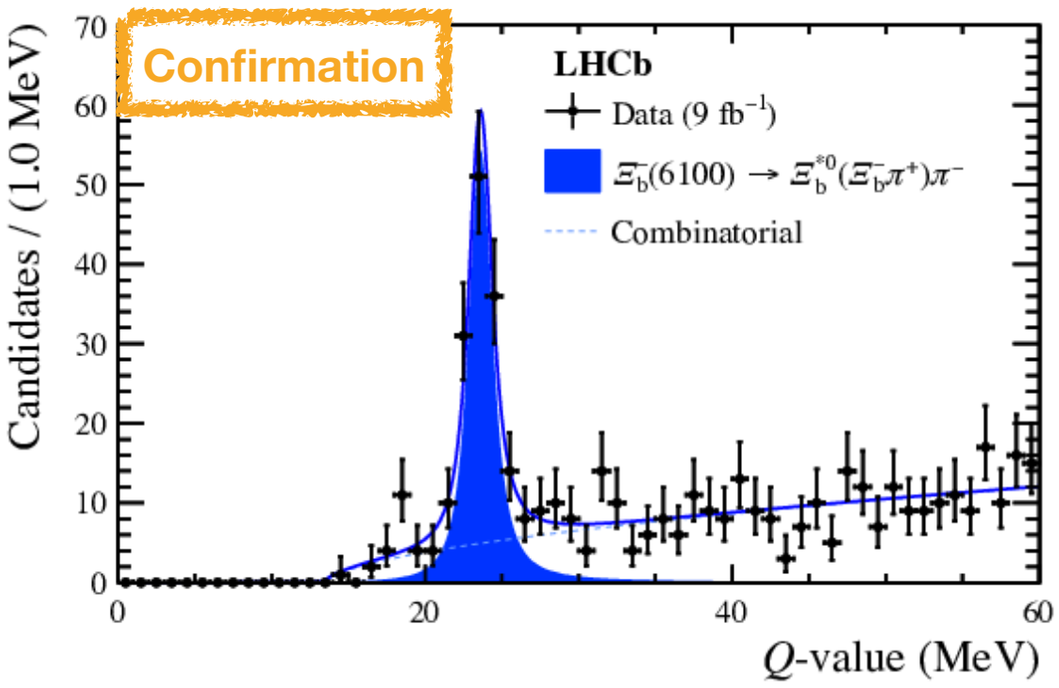
- We use dedicated HLT: **`HLT_DoubleMu4_JpsiTrk_Displaced`**
- Require OS muons from displaced vertex with J/ψ mass window and $p_T(\mu^\pm) > 4$ GeV and Trk from this vertex with $p_T > 1.2$ GeV and $d_{xy}/\sigma_{d_{xy}} > 2$

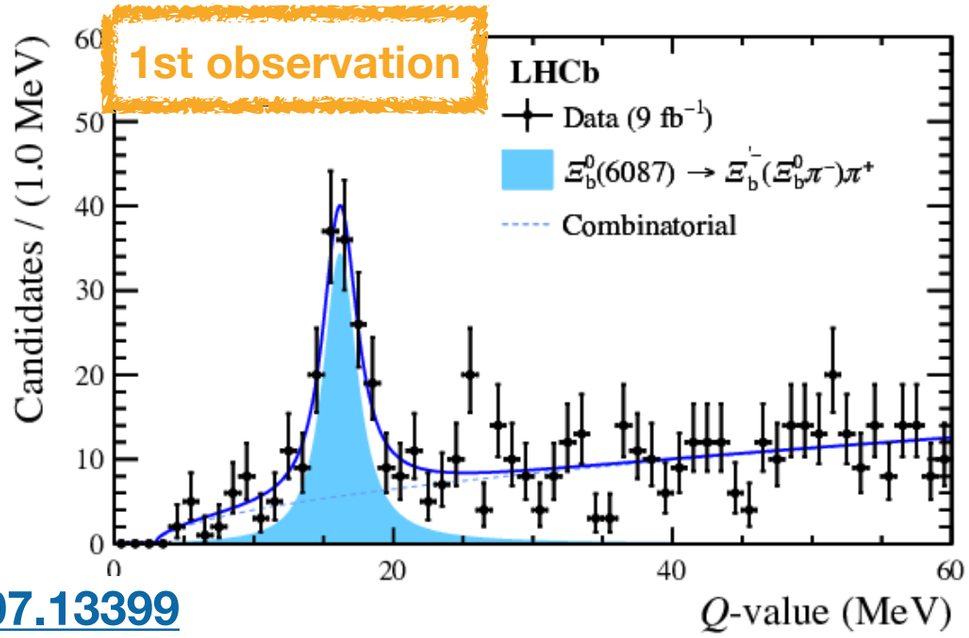
$R_{\Xi_b^{*0}}\left(J/\psi\Lambda K^-\right)$



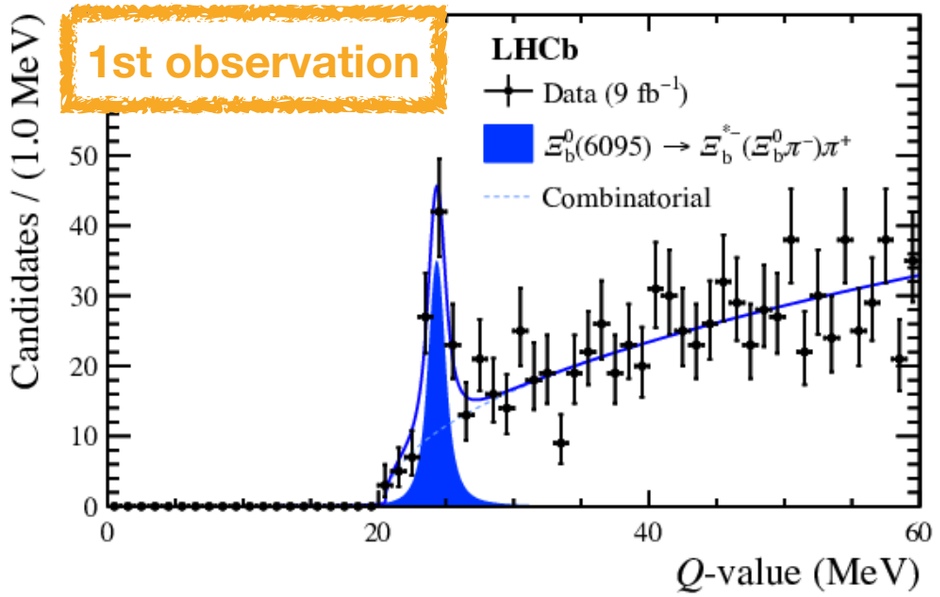
This selection is very tough — there was no good inclusive dimuon HLT @ Run-2!
New BPH Run-3 trigger Parking would significantly improve $\psi\Xi^-$ signal

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

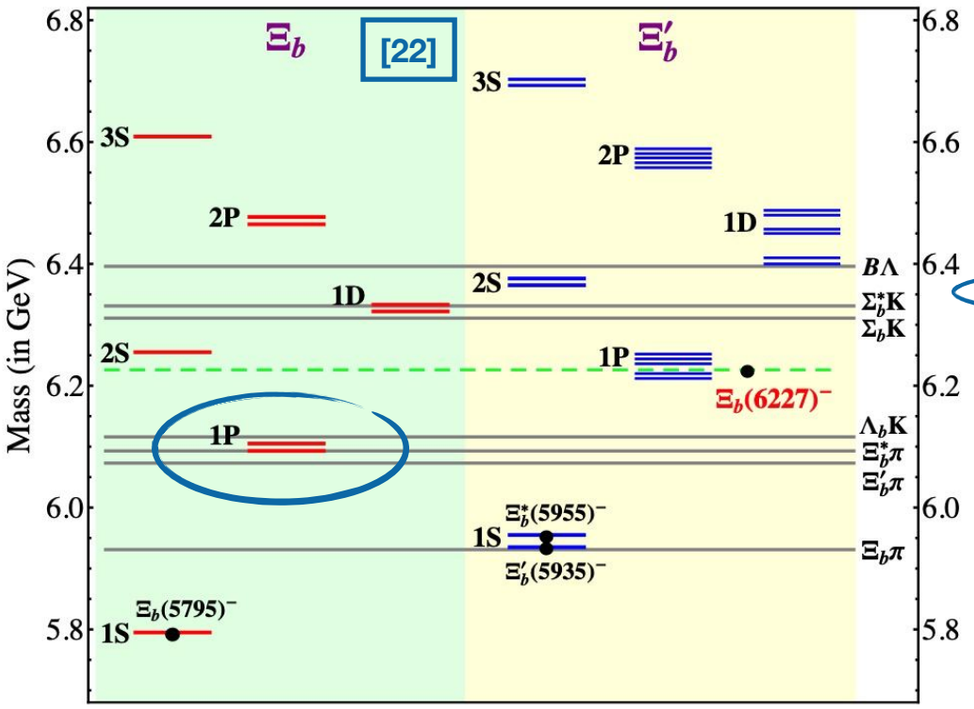


FIG. 2: The obtained masses for the bottom-strange baryons. The red solid lines (left) correspond to the predicted masses of Ξ_b states which are composed of a good diquark and a bottom quark, while the blue solid lines (right) correspond to the Ξ_b' states which contain a bad diquark. Here, we also 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]	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

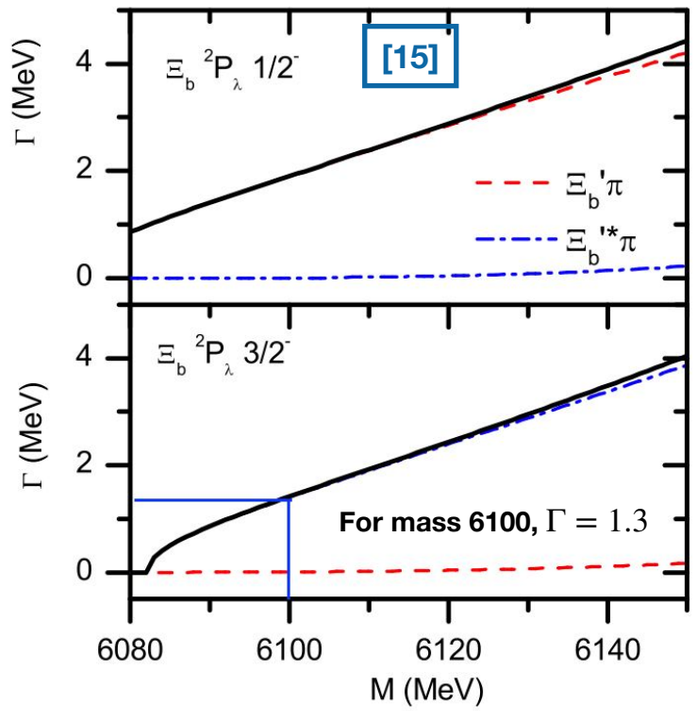


FIG. 2: Partial and total strong decay widths of the $1P$-wave Ξ_b states as functions of their mass. The solid curves stand for the total widths.

[16]

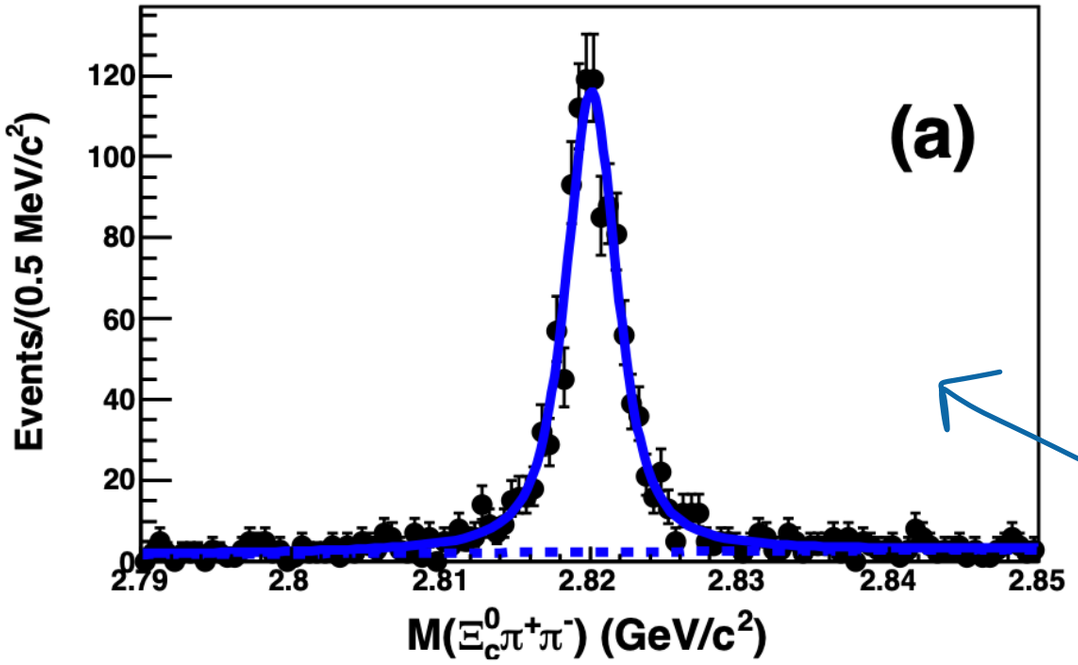
particle	our model	[30]	[36]	expt. (spin averaged)
$\Sigma_b^{(*)}$	5843^{+20}_{-37}	$5811-5835$	...	5826.9
$\Xi_b'^{(*)}$	5975^{+18}_{-37}	...	...	5946.7
$\Omega_b^{(*)}$	6102^{+15}_{-36}	$6048-6086$	...	6046.1 (spin-1/2)
$\Lambda_{b1}^{(*)}$	5936^{+20}_{-36}	$5980-6000$	...	5917.33
$\Xi_{b1}^{(*)}$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

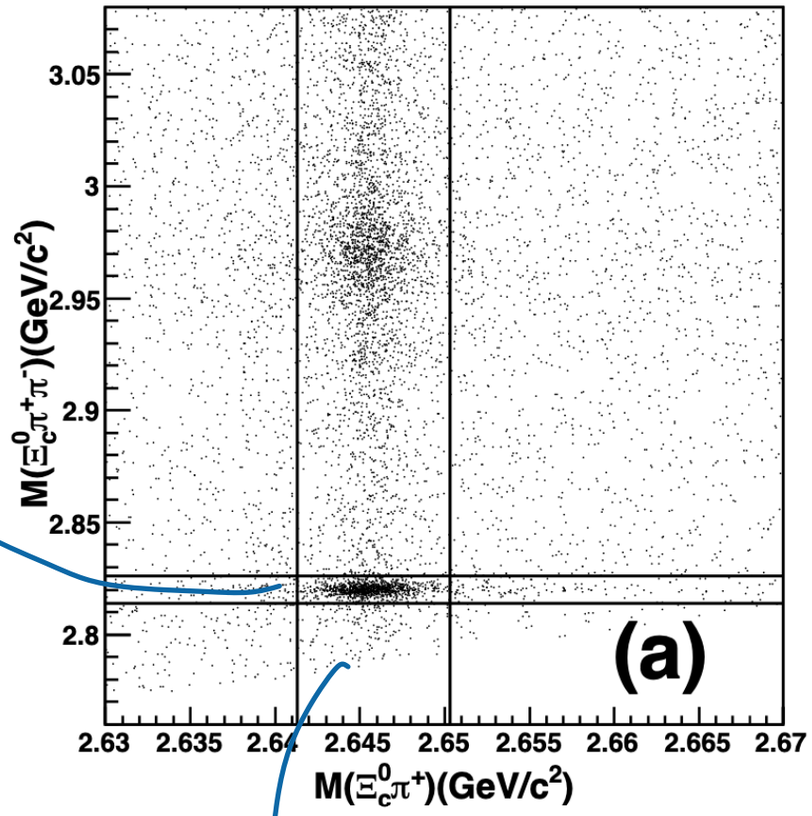
TABLE VII: Partial widths (MeV) and branching fractions for the strong decays of the $1P$-wave states in the Ξ_c and Ξ_b families.

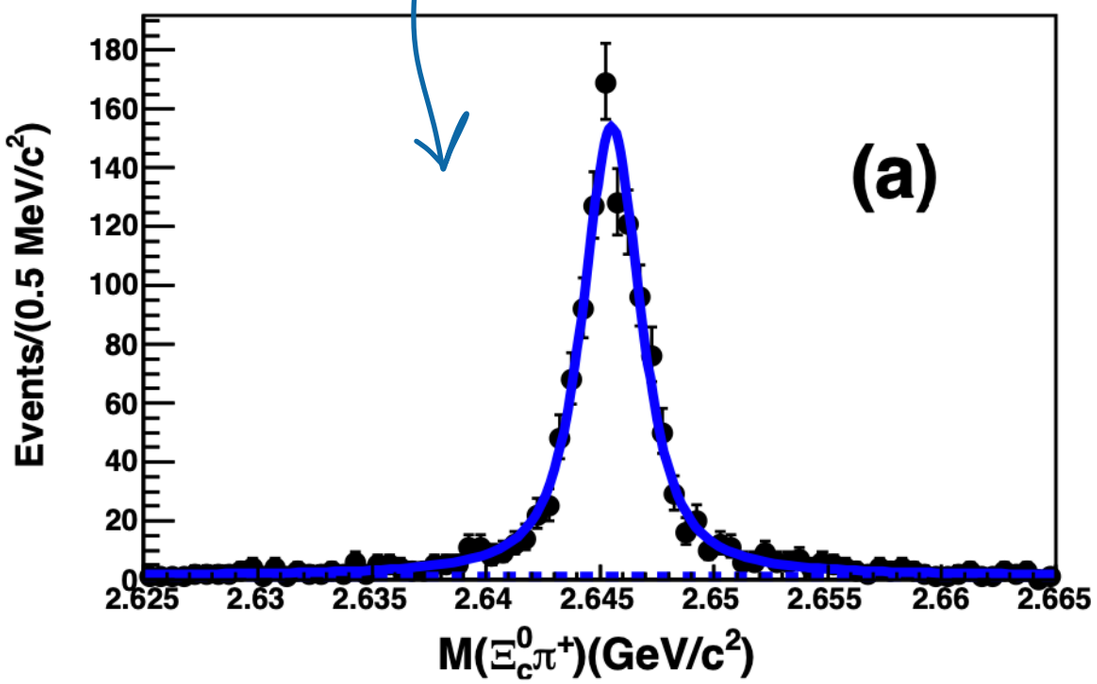
$\|^{2S+1}L_\lambda\ J^P\rangle$	State	Channel	Γ_i (MeV)	$\mathcal{B}_i$	State	Channel	Γ_i (MeV)	$\mathcal{B}_i$
$\|^2P_\lambda\frac{1}{2}^-\rangle$	$\Xi_c(2790)$	$\Xi_c'\pi$	3.61	100%	$\Xi_b(6120)$	$\Xi_b'\pi$	2.84	98.61%
		$\Xi_c'^*\pi$	3.9×10^{-4}	$\simeq 0.0\%$		$\Xi_b'^*\pi$	0.04	1.39%
		total	3.61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

- [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})

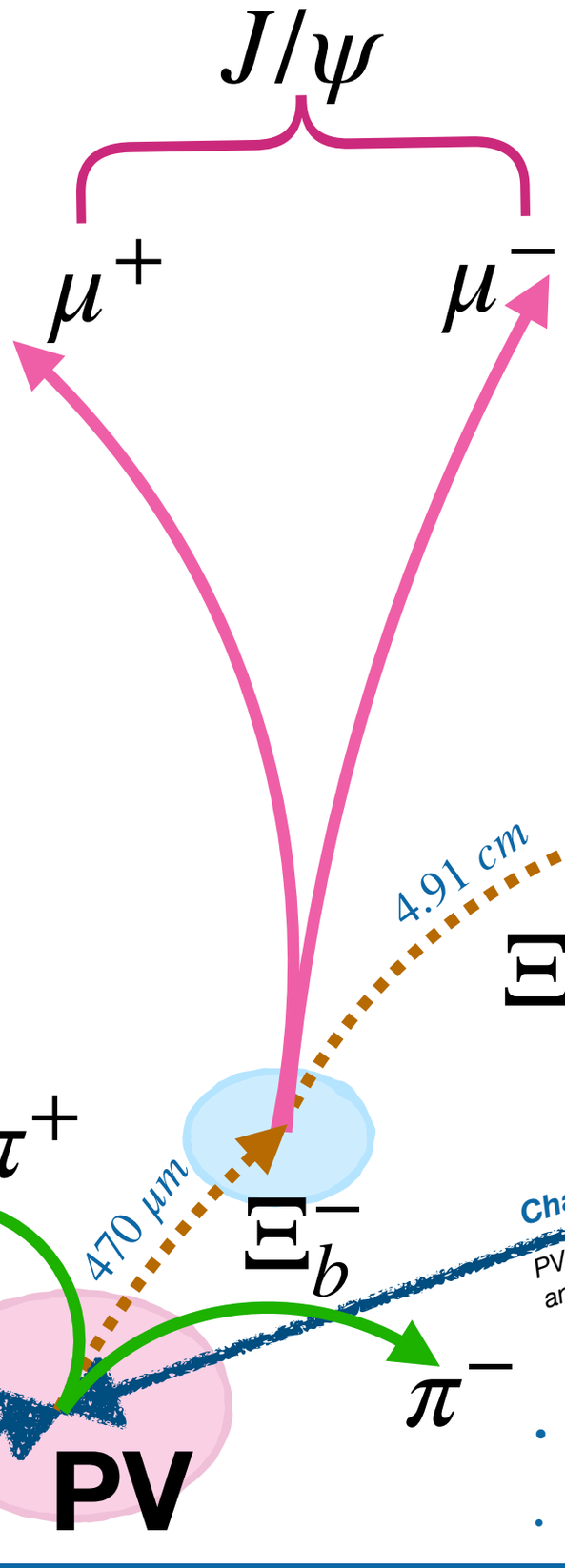
$J/\psi\Xi^-$ decay scheme

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

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

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

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



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

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

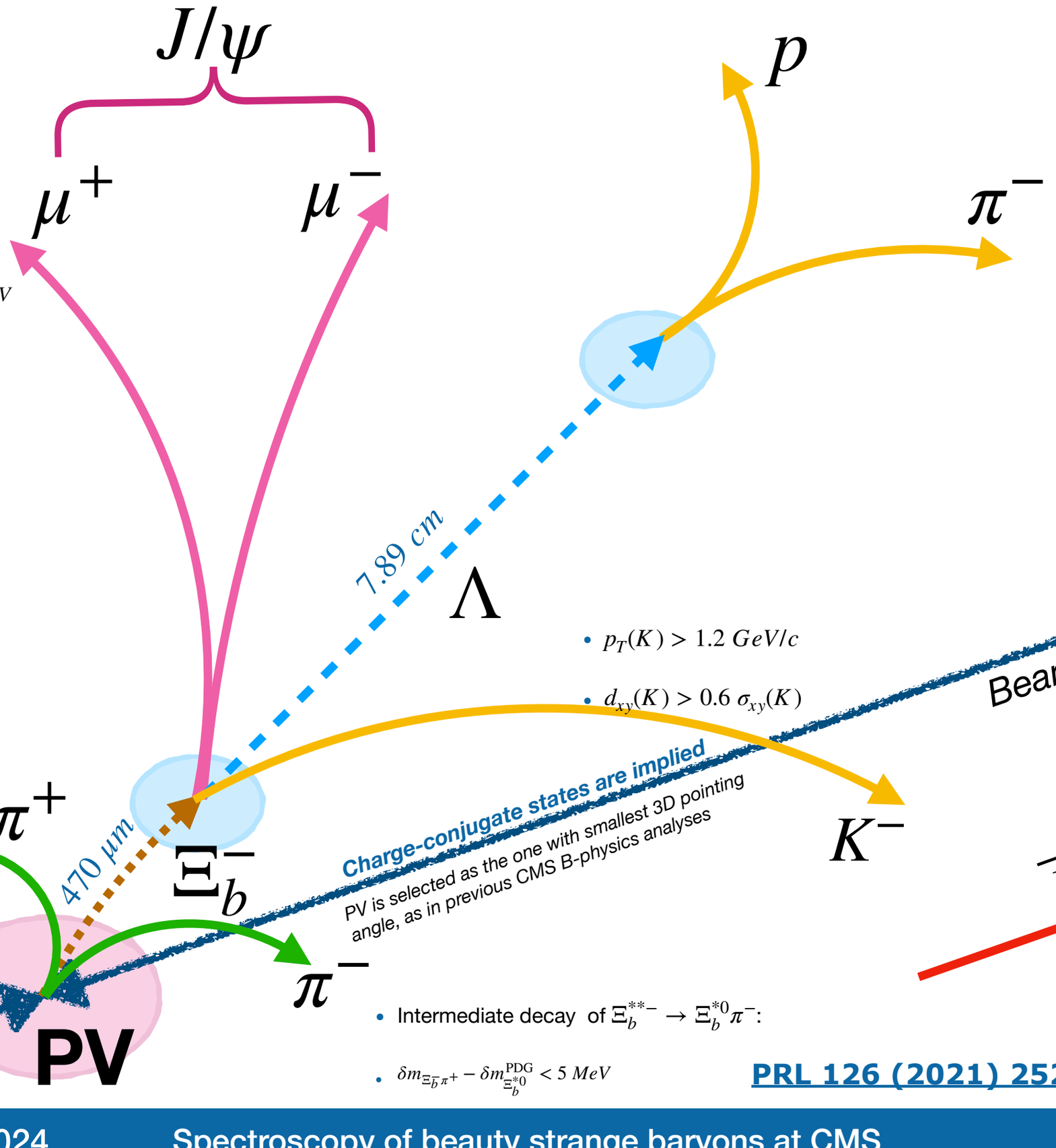
- $p_T(\mu^\pm) > 3\ GeV/c$
- $|\eta(\mu^\pm)| < 2.4$
- $J/\psi_{vtxprob} > 0.01$
- $|m_{\mu^+\mu^-} - m^{PDG}_{J/\psi}| < 100\ MeV$

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

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

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

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



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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 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%