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

CMS results on heavy flavour spectroscopy and production

Kirill Ivanov [1] on behalf of the CMS Collaboration

kirill.ivanov@cern.ch

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

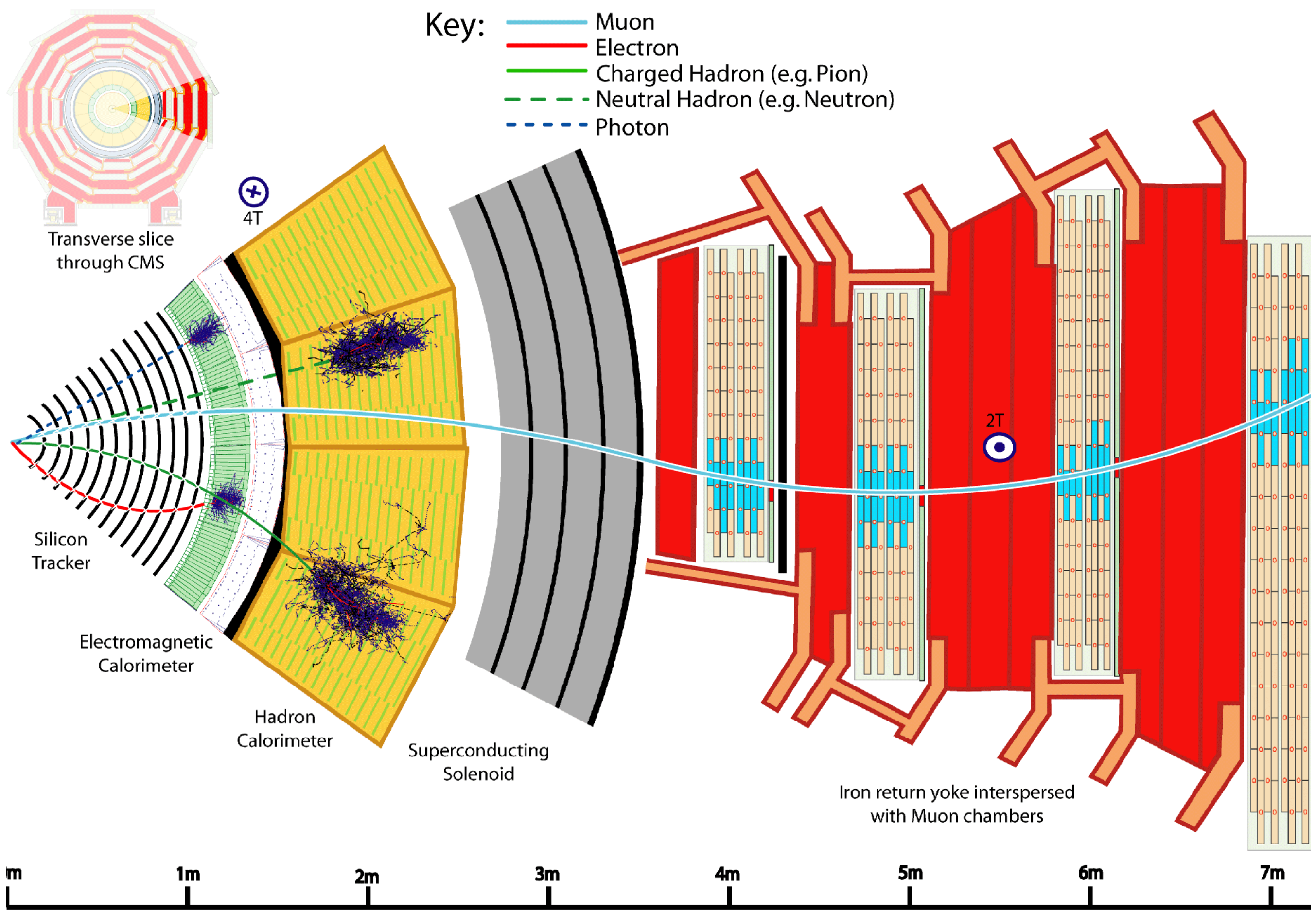
XXI Lomonosov Conference

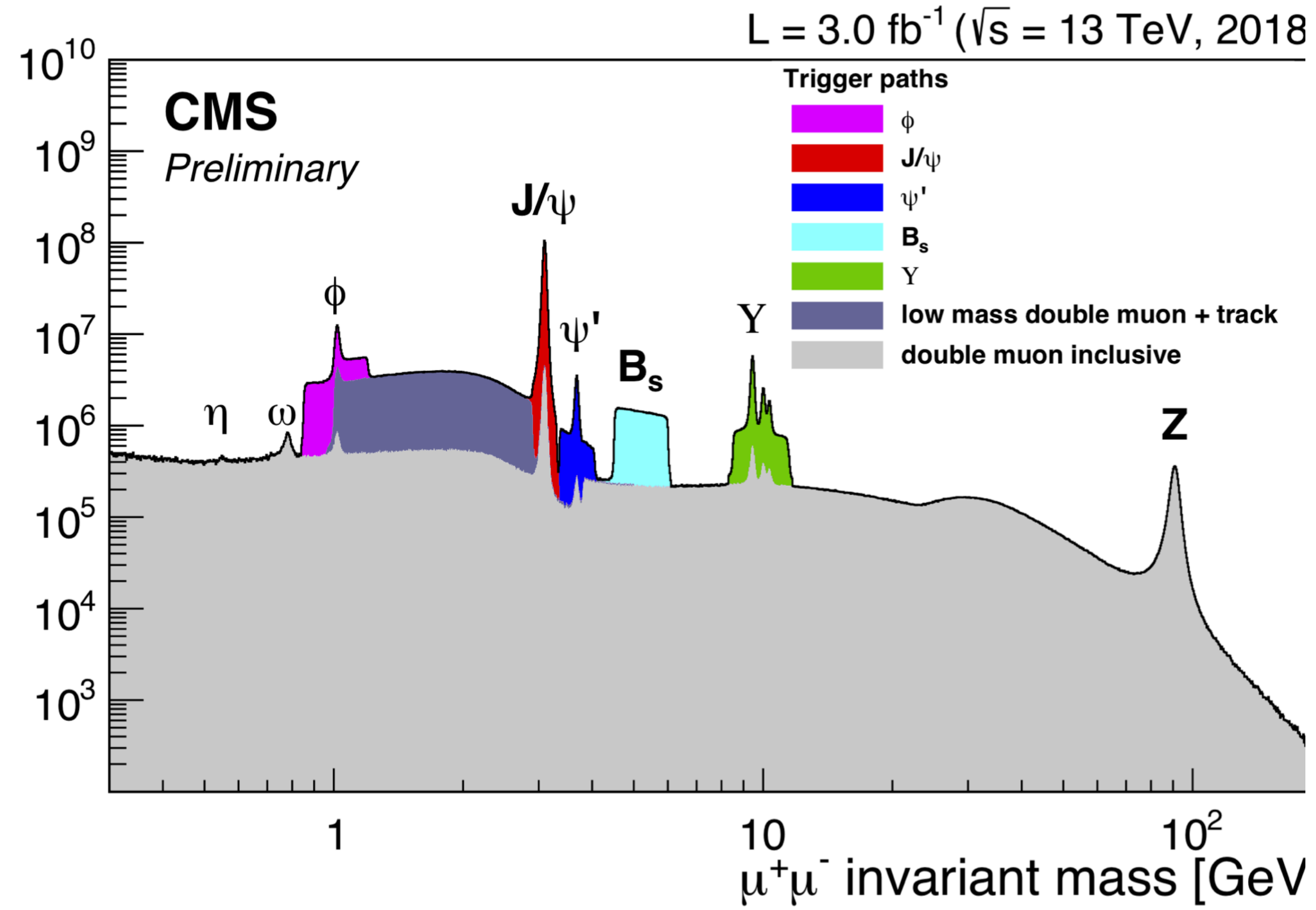
28th August 2023

Introduction and overview

- The CMS Experiment
- Measurement of the dependence of the hadron production fraction ratio f_s/f_u on B meson kinematic variables in proton-proton collisions at $\sqrt{s}$ = 13 TeV
- Observation of a new excited beauty strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$
- Conclusion and summary

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

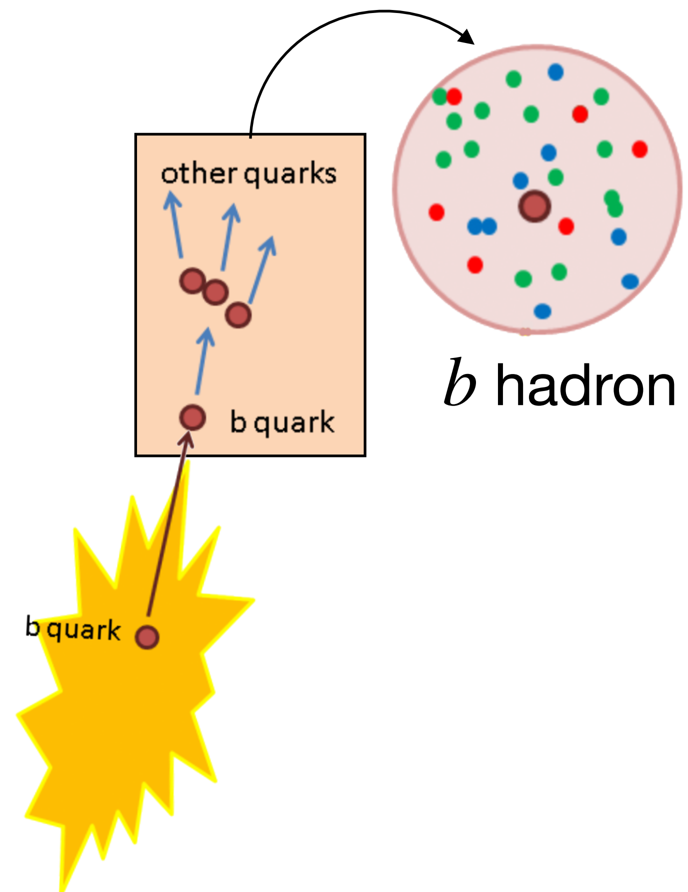
Measurement of the dependence of the hadron production fraction ratio f_s/f_u on B meson kinematic variables in proton-proton collisions at $\sqrt{s}$ = 13 TeV

CMS-BPH-21-001, arXiv:2212.02309,

accepted by Phys. Rev. Lett.

Production (fragmentation) fractions

- When b quark is produced in colliders, it forms one of b hadrons: a $B_{(s)}$ meson or a b baryon (hadronization process)



- The probability of hadronization into a specific hadron is defined by production (or fragmentation) fractions (in sum to be unity):

$f_u \rightarrow B^+$ $\quad f_d \rightarrow B^0$ $\quad f_s \rightarrow B_s^0$ $\quad f_{baryon} \rightarrow$ b-baryon $\quad f_{other} \rightarrow$ other (exited) b-hadrons

- Their ratios are very widely-used for the branching fractions measurements, especially f_s/f_d — thank to b-factories *(such as Belle and BaBar)* B^+/B^0 decays are measured very well from $e^+e^- \rightarrow \Upsilon(4S)$ (given equal production $f_u = f_d$ from isospin symmetry)

- Thus B_s^0 branching can be measured w.r.t. to a one with B^+ or B^0, however f_s/f_d term enter such a ratio, often resulting to be a leading uncertainty due to low precision

High precision is essential for robust $B_s^0 \rightarrow \mu^+\mu^-$ measurement

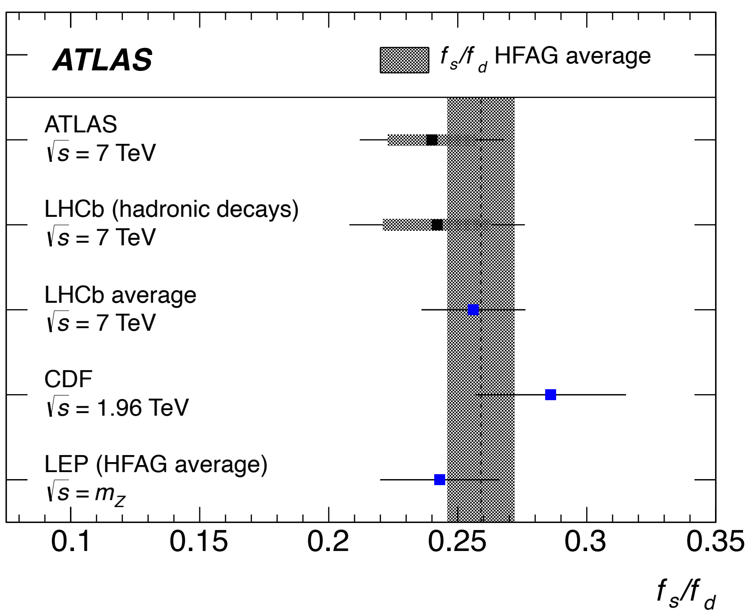
LHCb, Phys.Rev.D 87 (2013) 7, 072004

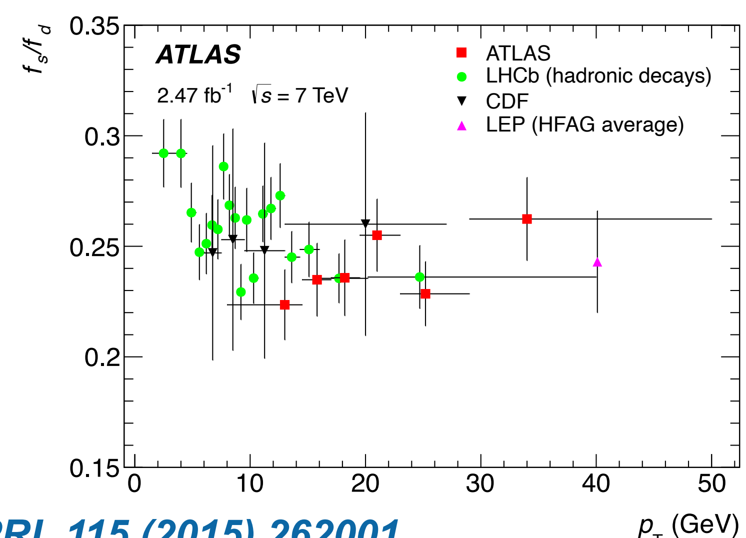
$$\mathscr{B}\left(B_s^0 \rightarrow J/\psi\phi\right) = (10.50 \pm 0.13 \pm 0.64 \pm 0.82) \times 10^{-4}$$

Previous results of f_s/f_d studies

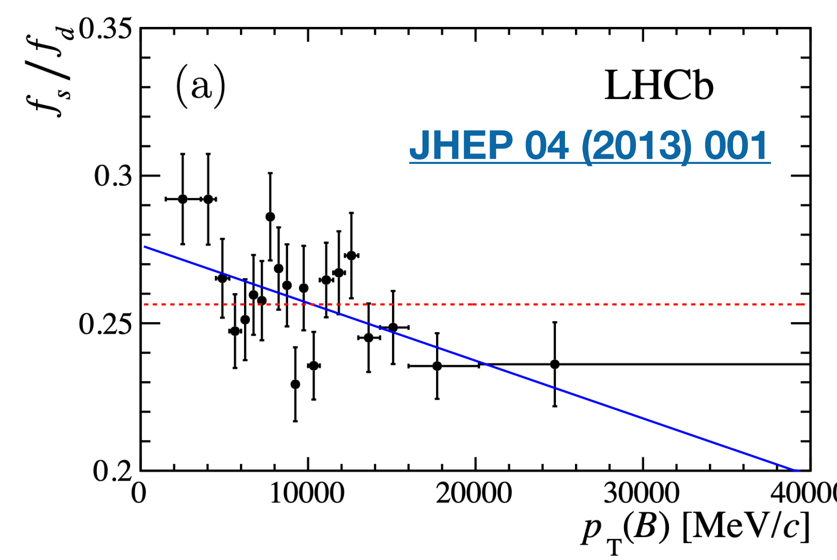
- Hard to predict these values and their ratios from QCD theory — experimental input is needed!

- However, they are expected to be universal and fundamental properties w/o any conditions dependence (*unless the opposite is observed*)

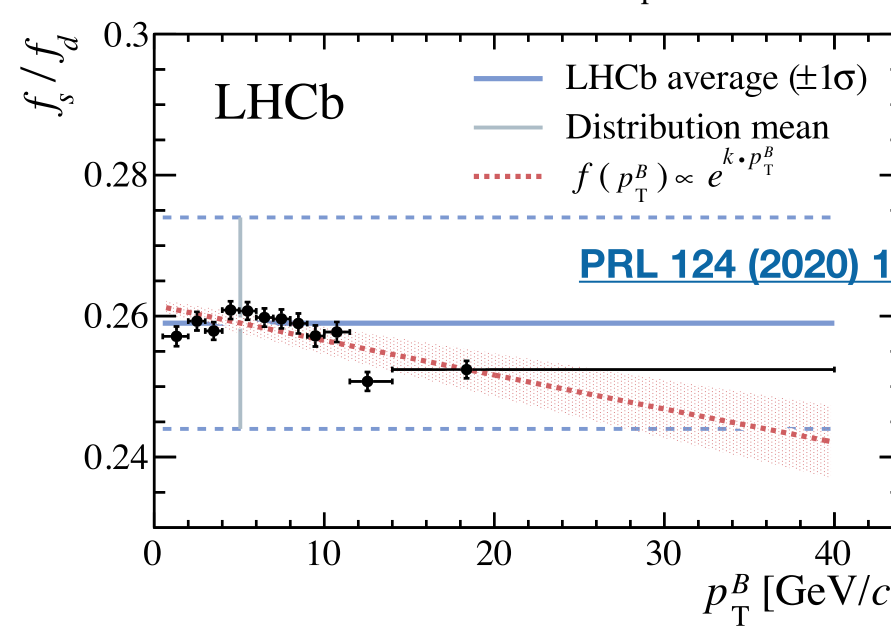




PRL 115 (2015) 262001



JHEP 04 (2013) 001



PRL 124 (2020) 12, 122002

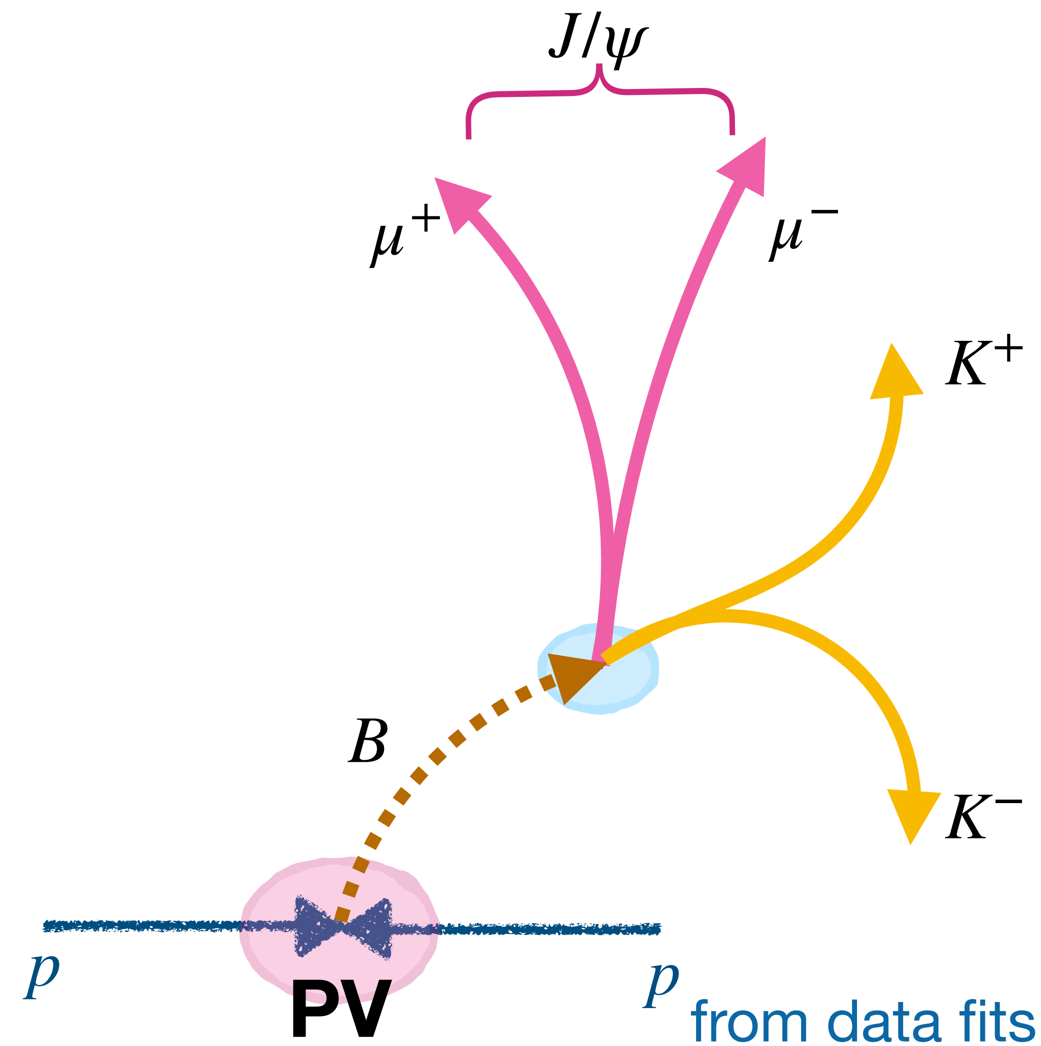
- Recently LHCb observed f_s/f_d dependence from B meson p_T (6σ significance)
  No η dependence has been found

- In agreement with their earlier result; ATLAS 7 TeV result does not have precision to confirm a p_T trend $\longrightarrow$ new studies are required

CMS Analysis Overview

- In this paper we perform relative f_s, f_u and f_d measurements in kinematic region of $p_T > 12$ GeV and $|y| < 2.4$, using CMS 2018 data ($\sqrt{s} = 13$ TeV, $61.6\ fb^{-1}$)

- The following decays are reconstructed:
  $B^+ \to J/\psi K^+$
  $B^0 \to J/\psi K^{*0}$, $K^{*0} \to K^+\pi^-$
  $B_s^0 \to J/\psi\phi$, $\phi \to K^+K^-$



- Events are selected using trigger, requiring a dimuon J/ψ vertex, displaced from PV, with a track compatible to be produced in this vertex

- B meson candidate obtain from kinematic vertex fit of 2 muons and 1 or 2 tracks with dimuon mass constrained to PDG J/ψ

- We measure the following value: $R_s = \frac{f_s}{f_u} \frac{\mathcal{B}\left(\mathrm{B_s^0} \to \mathrm{J}/\psi\phi\right)\mathcal{B}\left(\phi \to \mathrm{K^+K^-}\right)}{\mathcal{B}\left(\mathrm{B^+} \to \mathrm{J}/\psi\mathrm{K^+}\right)} = \frac{N_{B_s^0}}{N_{B^+}} \frac{\epsilon_{B^+}}{\epsilon_{B_s^0}}$

  from data fits ($\frac{N_{B_s^0}}{N_{B^+}}$); from MC simulation ($\frac{\epsilon_{B^+}}{\epsilon_{B_s^0}}$)

  (f_s/f_u ratio is multiplied by B_s^0 branching fr. which is strongly correlated with f_s)

- Similar measurement is performed for R_d (or f_d/f_u, which we can report directly)

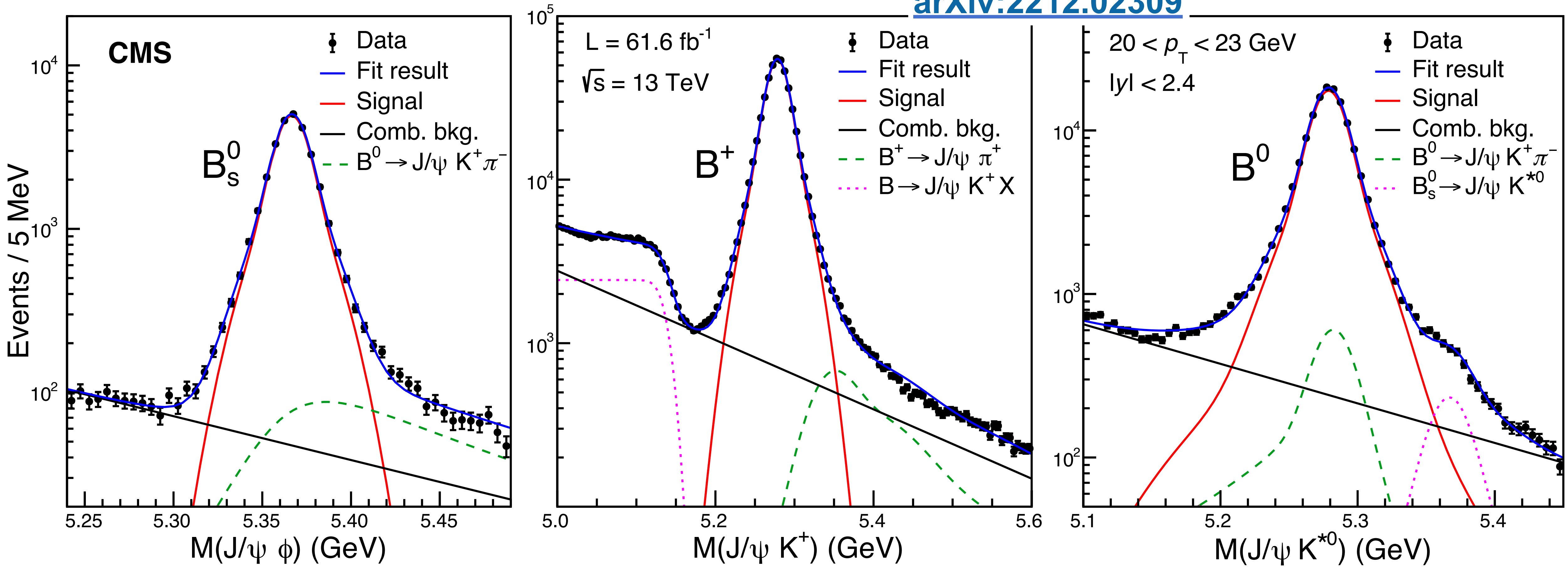
B mesons signals

- Data sample is split into 12 p_T bins or 7 $|y|$ bins, fit is performed in each bin to extract the signal yields

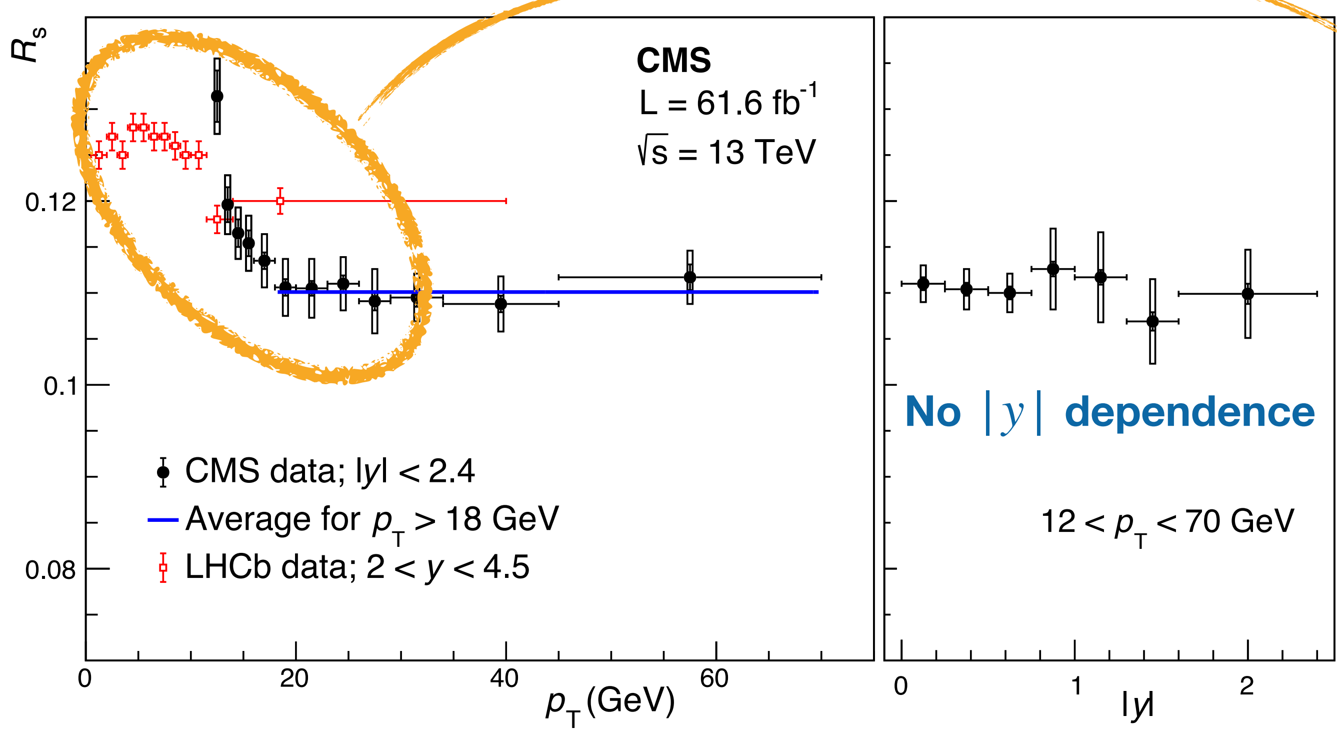
- Fit is constructed as double Gaussian w/ common mean for signal and exponential for the background

- Reflections from $B^0 \to J/\psi K^+\pi^-$, $B^+ \to J/\psi\pi^+$, K-π swap present due to lack of hadron ID; their shapes obtained from simulation
  Partially-reconstructed $B \to J/\psi K^+ X$ described with error function
  Cabibbo-suppressed $B_s^0 \to J/\psi K^{*0}$ also presents; described with shape similar to B^0

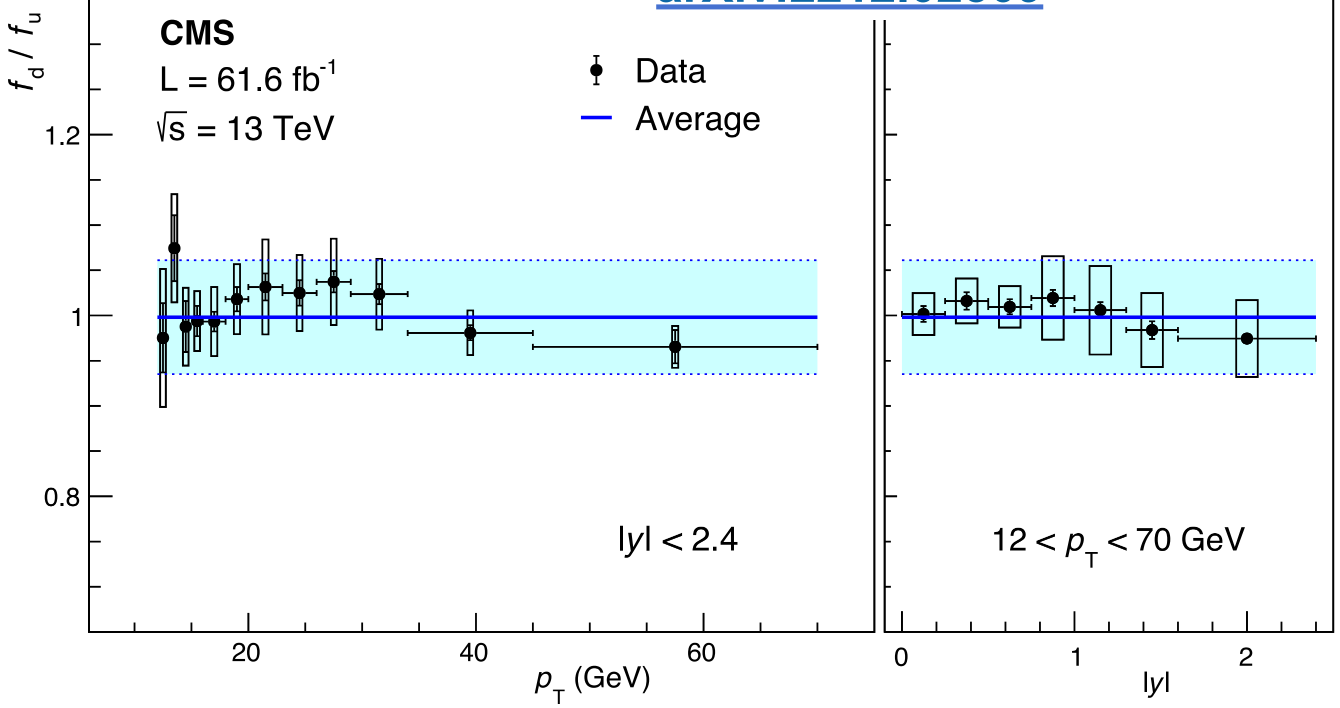
arXiv:2212.02309



CMS results for f_s/f_u and f_d/f_u



arXiv:2212.02309



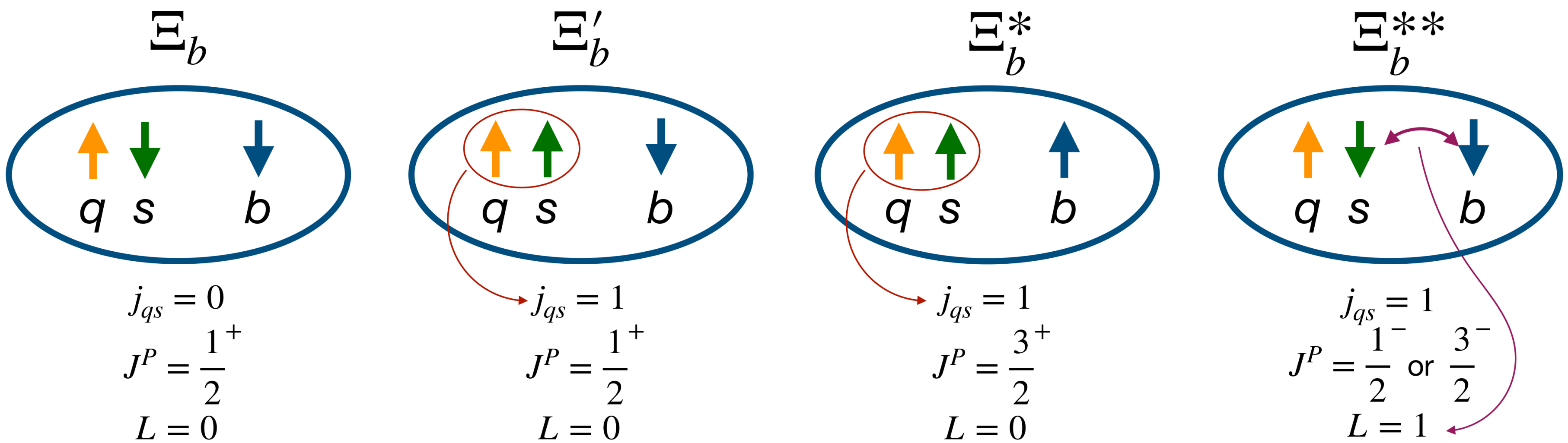
Splitting B mesons signals into 12 p_T bins or 7 $|y|$ bins, we extract the needed yields

- Clear p_T dependence is observed for f_s/f_u at low-p_T, confirming LHCb trend!
- However, starting from $p_T \gtrsim 18$ GeV f_s/f_u seems to be flat from p_T
  Average $R_s = 0.1102 \pm 0.0027$
- This result provides crucial input to our f_s/f_u understanding and improves $B_s^0 \to \mu^+\mu^-$ measurements
- On the other hand, f_d/f_u ratio is very consistent with unity w/o any dependence
  Average $f_d/f_u = 0.998 \pm 0.063$
- First direct measurement of isospin invariance in B meson production at hadron colliders!

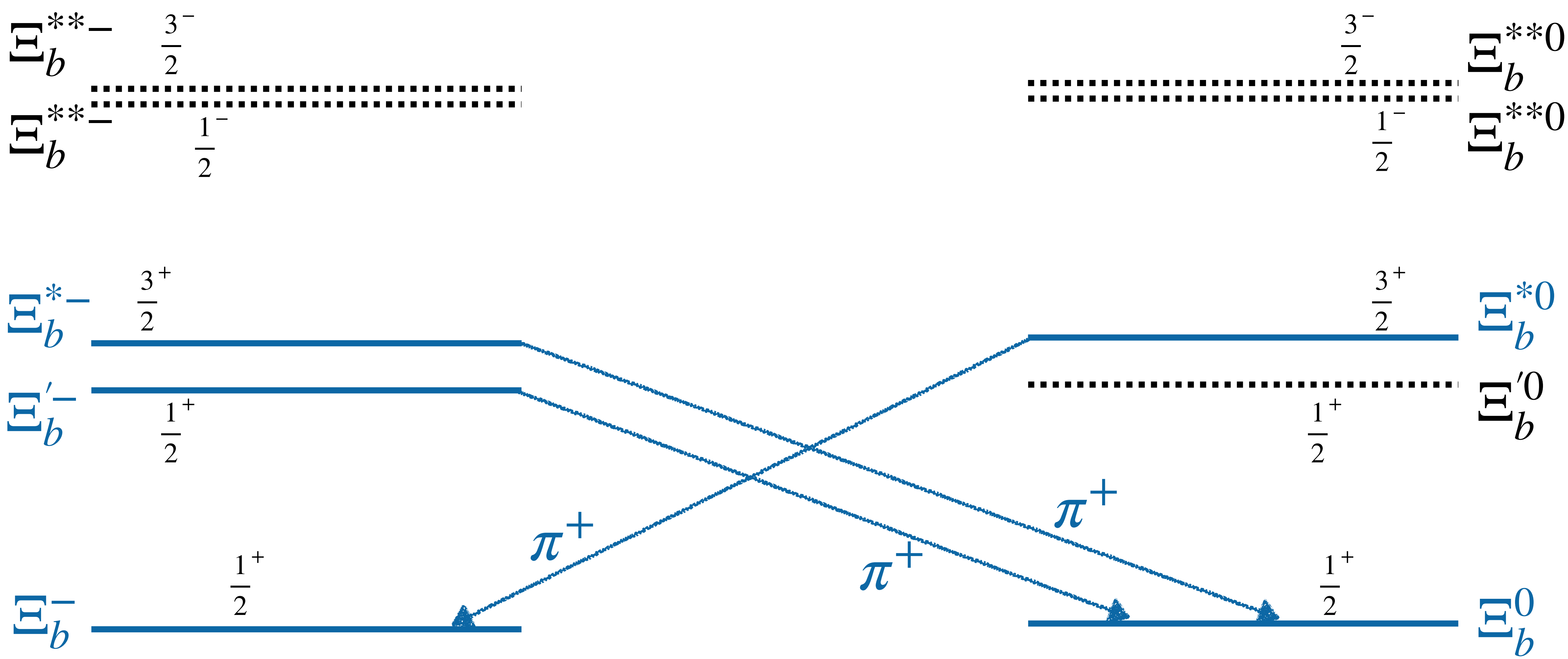
Observation of a new excited beauty strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$

CMS-BPH-20-004, Phys. Rev. Lett. 126 (2021) 252003

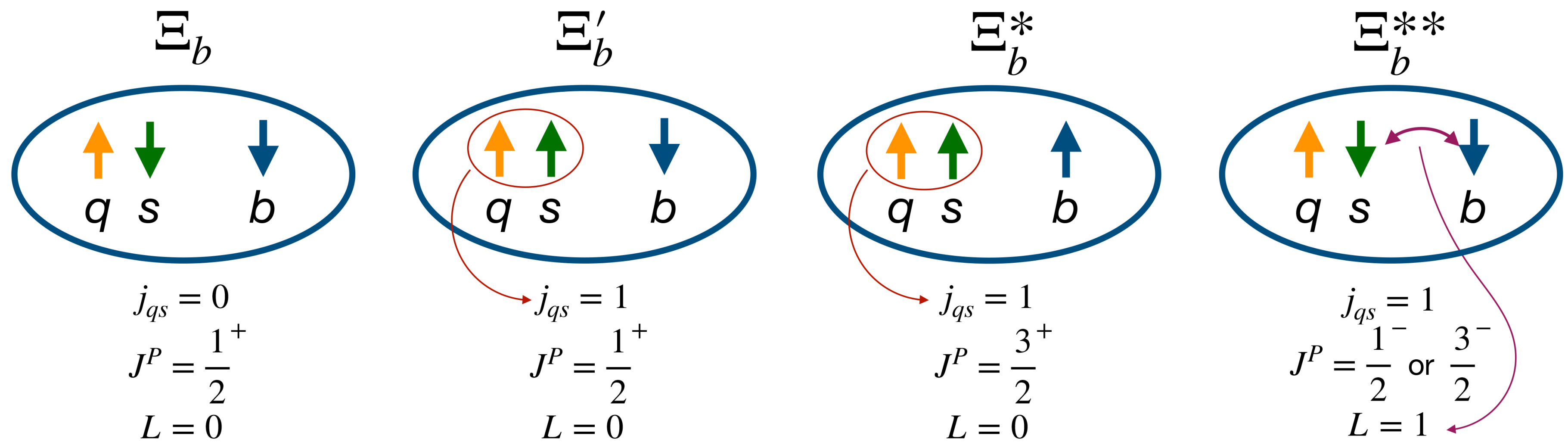
Ξ_b baryons spectroscopy



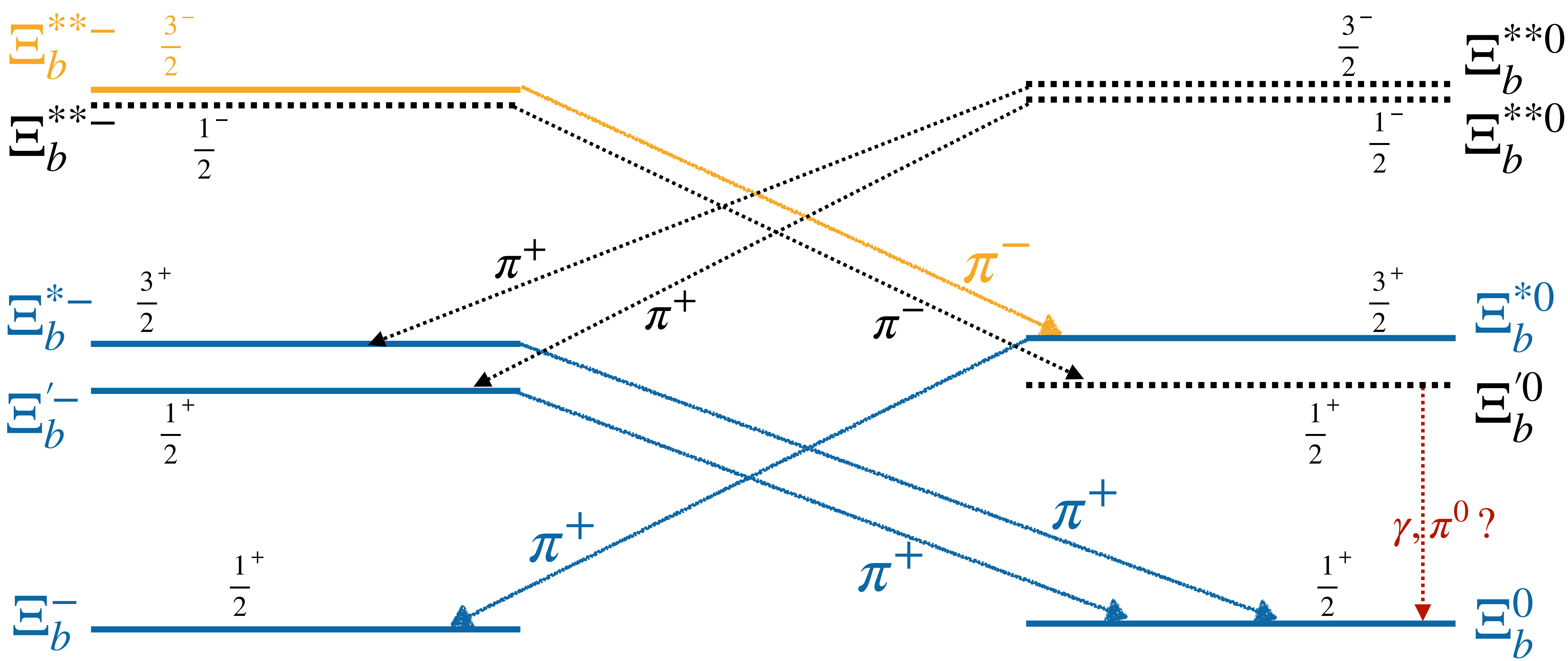
q denotes u or d quarks for Ξ_b^0 or Ξ_b^-. $L = 1$ is the orbital excitation between the light diquark qs and heavy b quark.



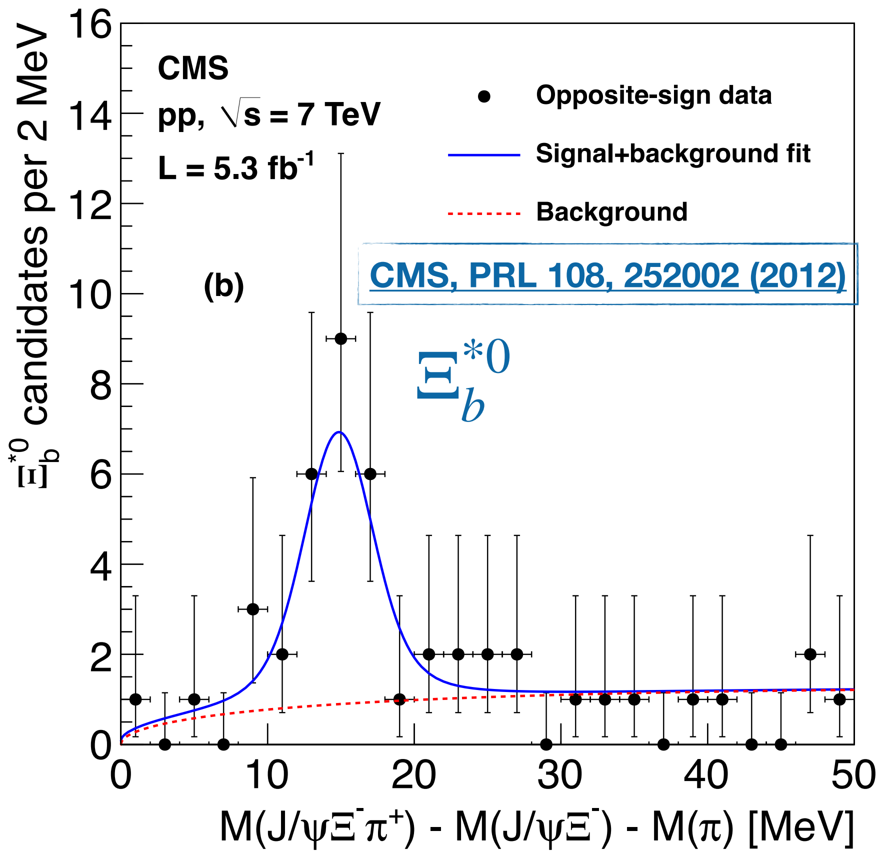
Ξ_b baryons spectroscopy



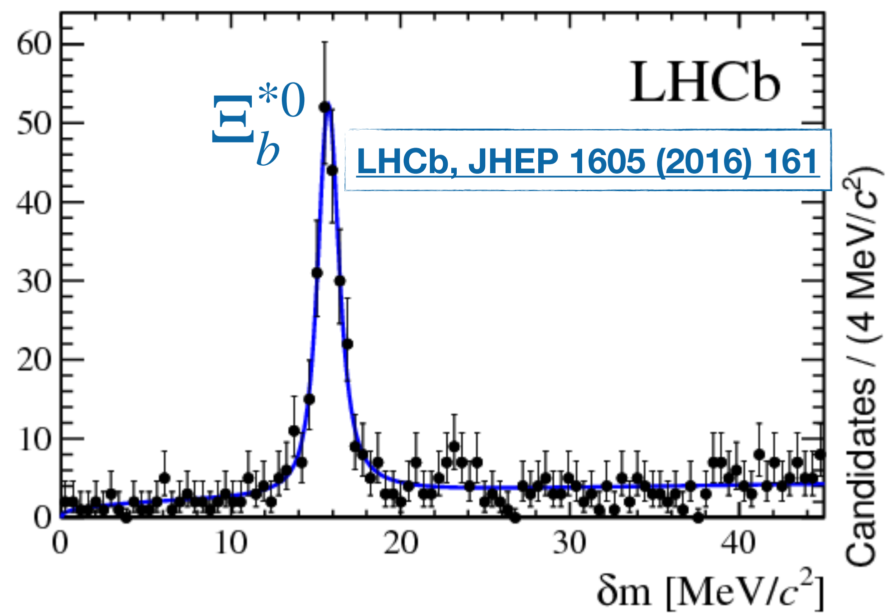
q denotes u or d quarks for Ξ_b^0 or Ξ_b^-. $L = 1$ is the orbital excitation between the light diquark qs and heavy b quark.



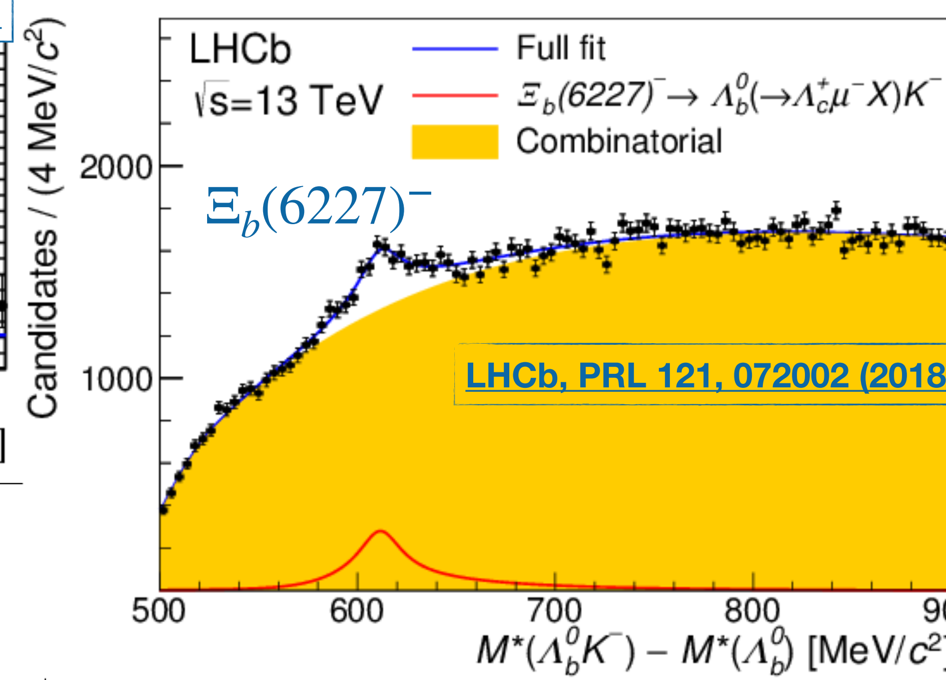
Previous results of Ξ_b resonances



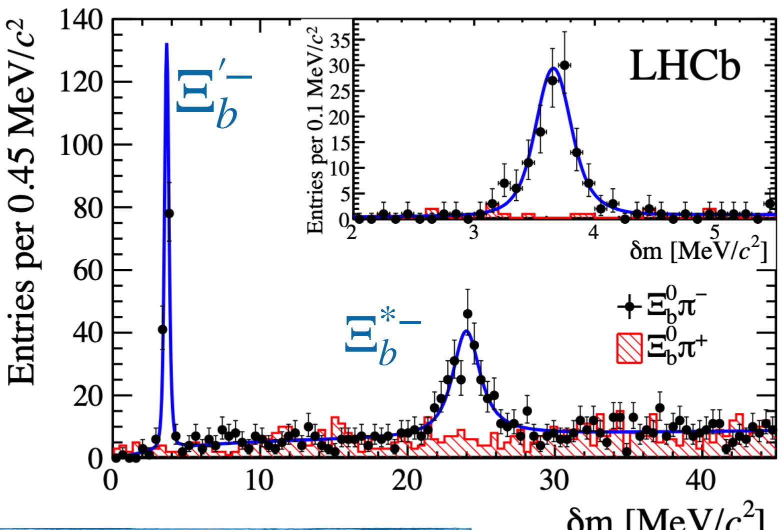
CMS, PRL 108, 252002 (2012)



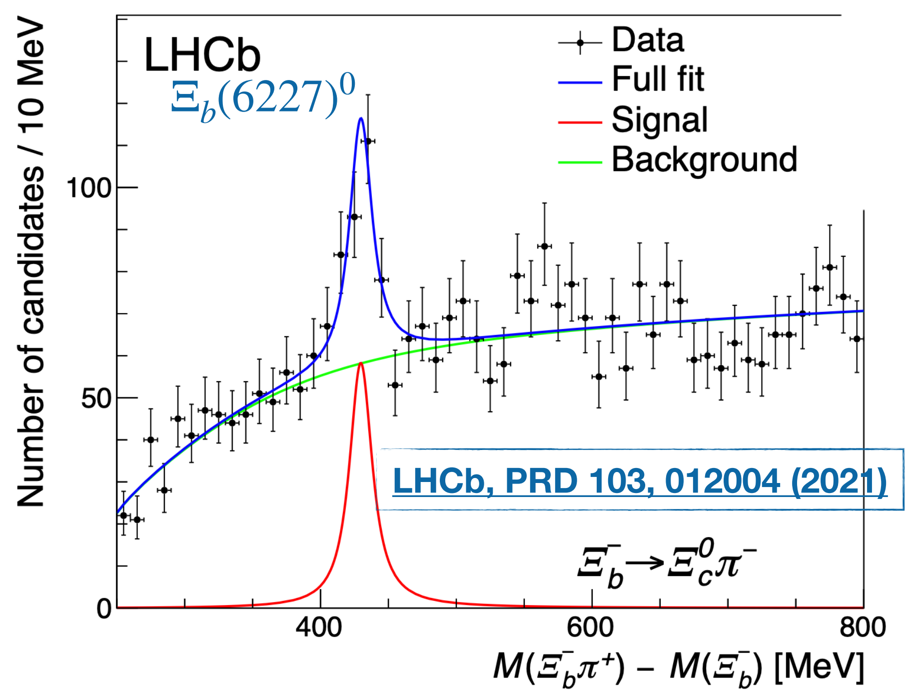
LHCb, JHEP 1605 (2016) 161



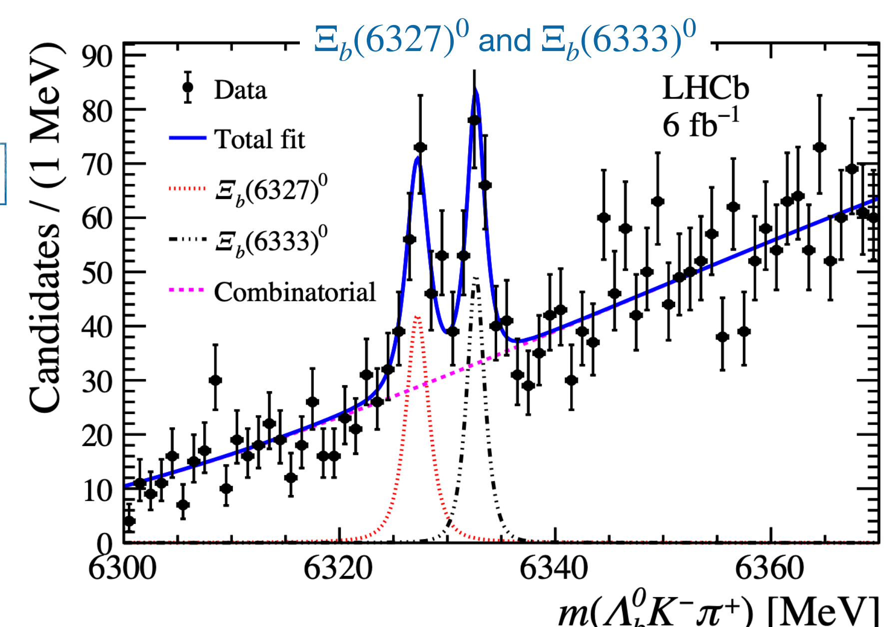
LHCb, PRL 121, 072002 (2018)



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)

CMS Analysis Overview

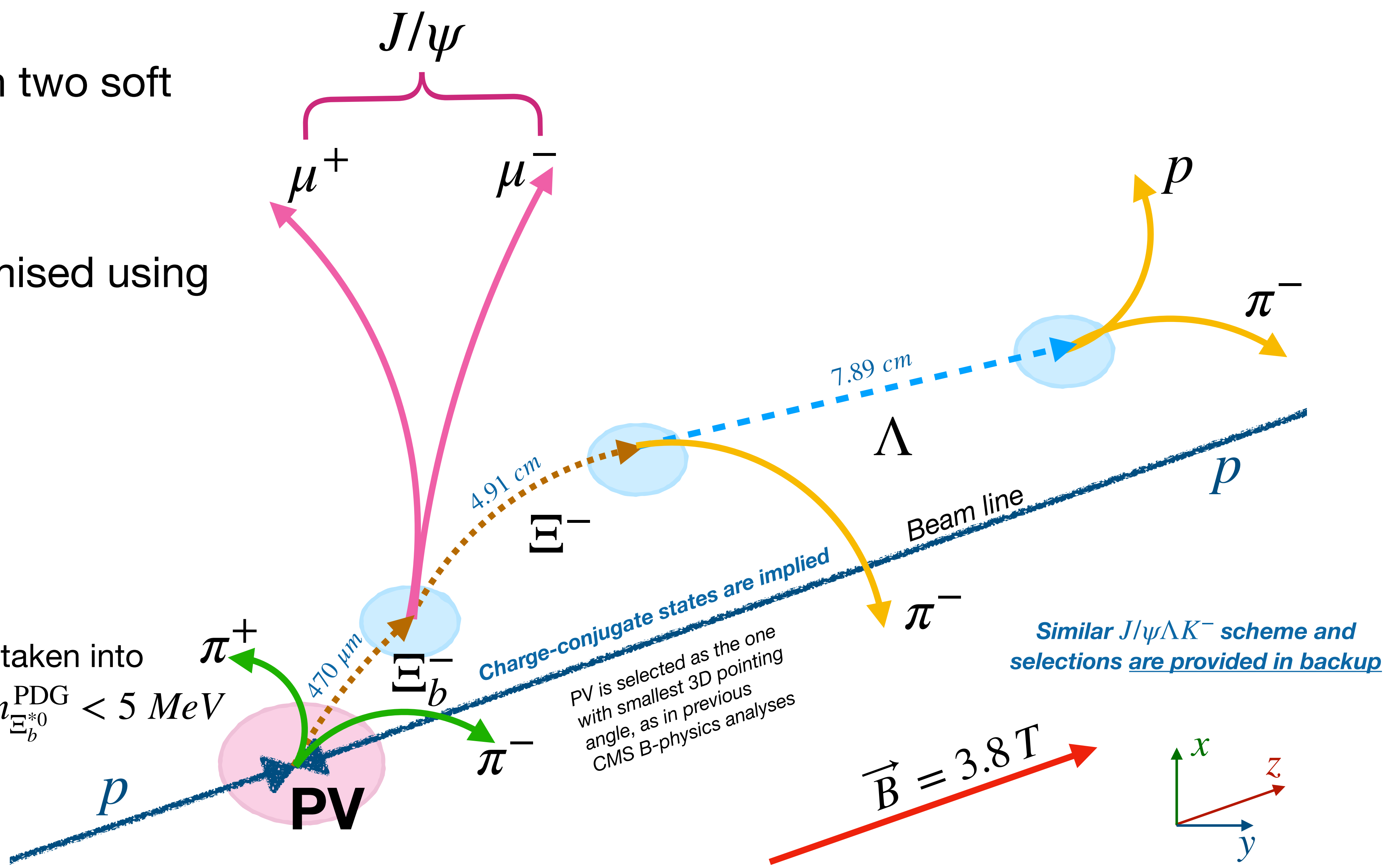
- Use full Run-2 CMS data ($140\, fb^{-1}$, $\sqrt{s} = 13$ TeV) to search for a new $\Xi_b^{**-} \to \Xi_b^{*0}\pi^- \to \Xi_b^-\pi^+\pi^-$ resonance, basing on theoretical predictions and excited Ξ_c^{**} charm analogies

- 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

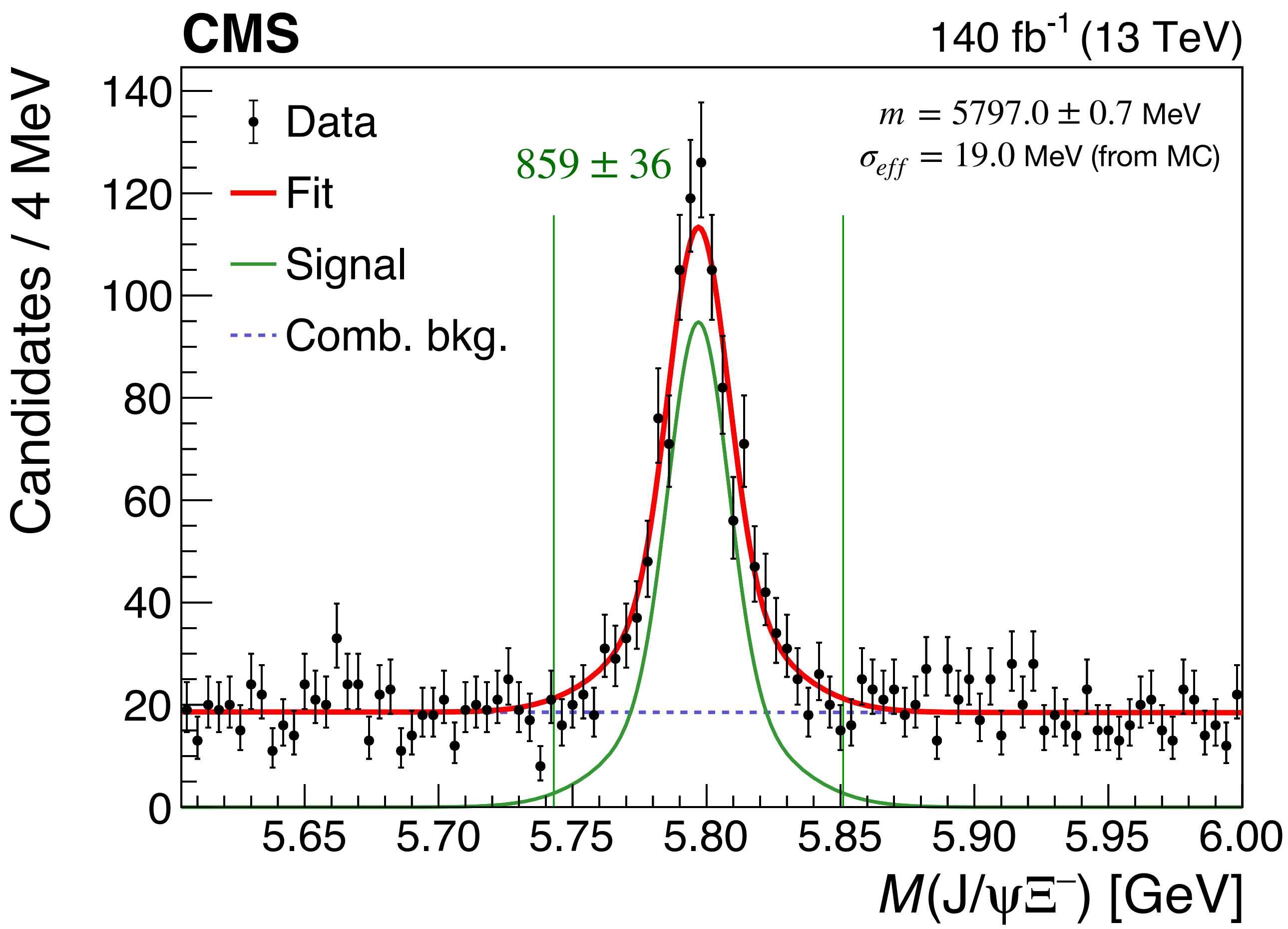
- Then Ξ_b^- is combined with two soft pion tracks from PV

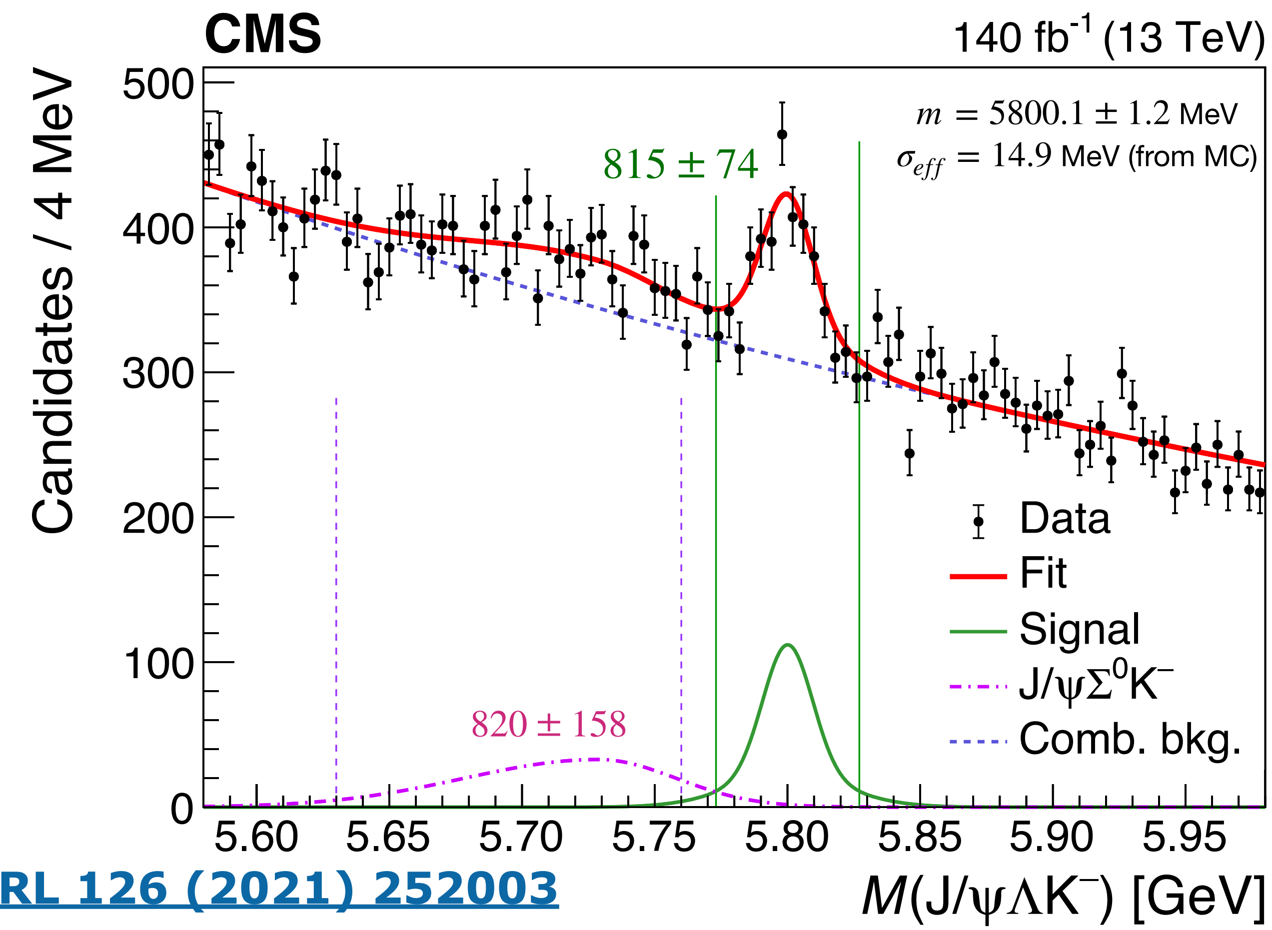
- Selection criteria are optimised using Punzi Figure of Merit

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



Ξ_b^- signals



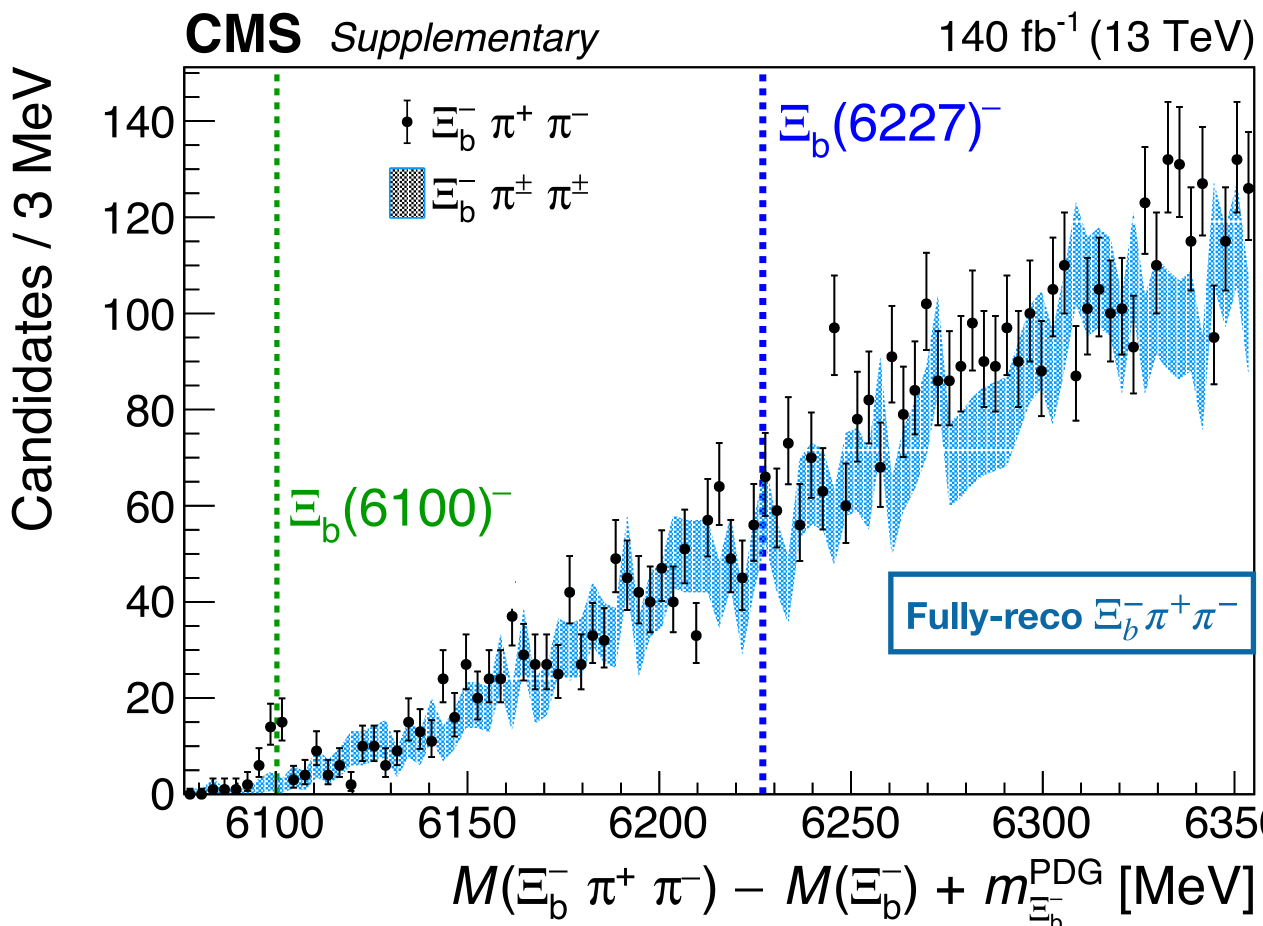


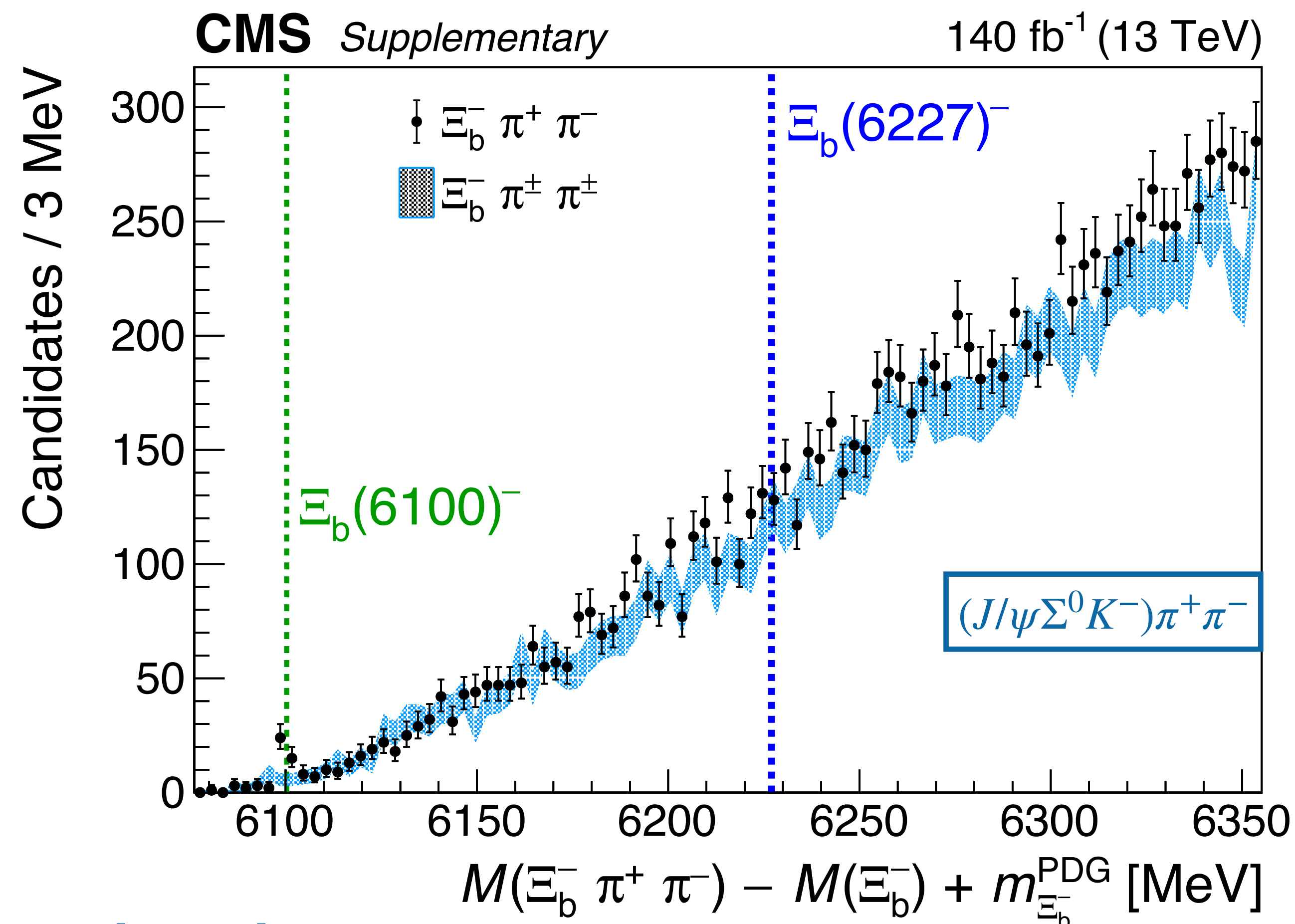
PRL 126 (2021) 252003

- **Signal:** double-Gaussian (from MC); **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 $\Xi_b^-\pi^+\pi^-$ 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

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



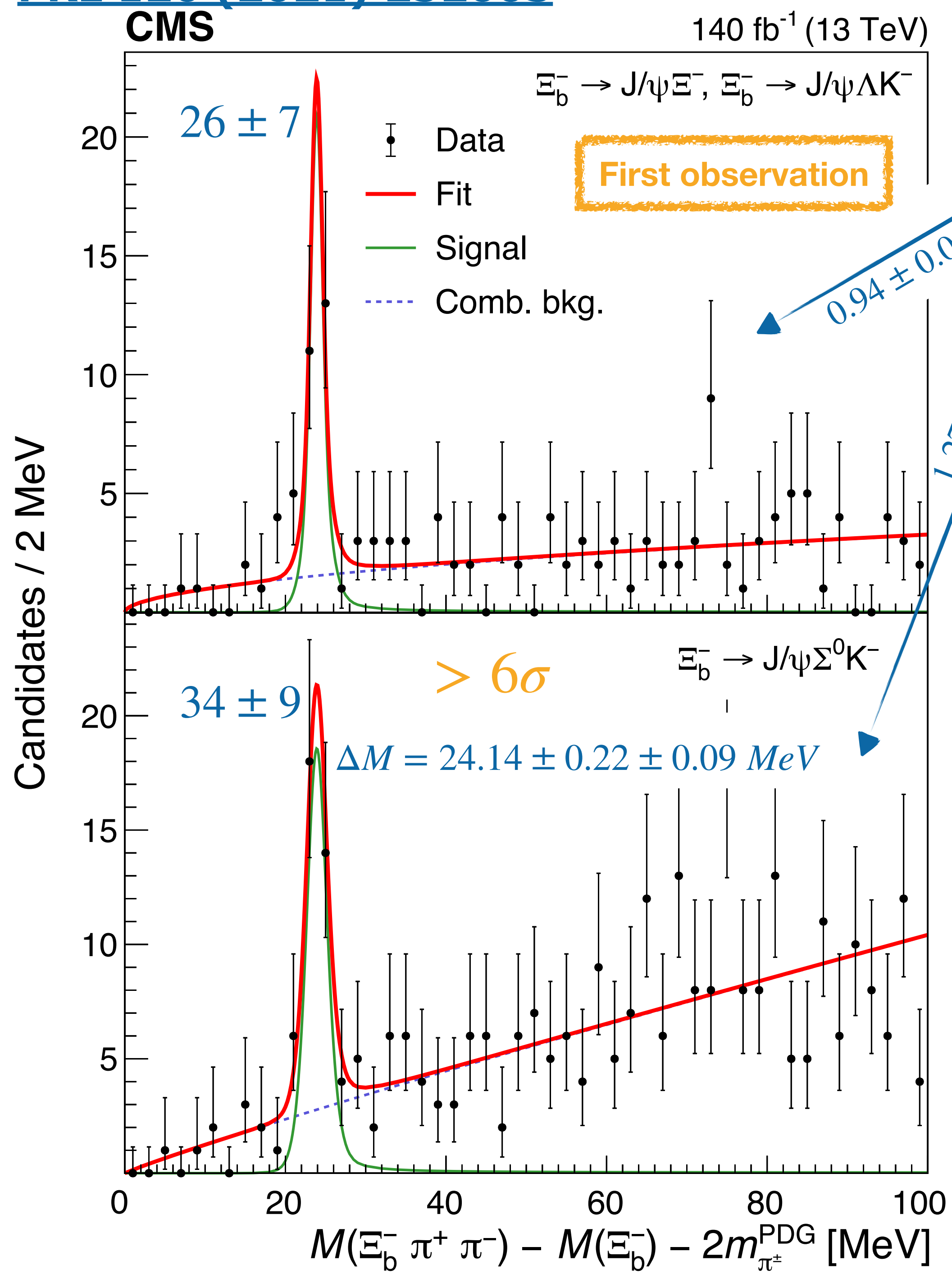


PRL 126 (2021) 252003

- 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 $\Xi_b(6100)^-$

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

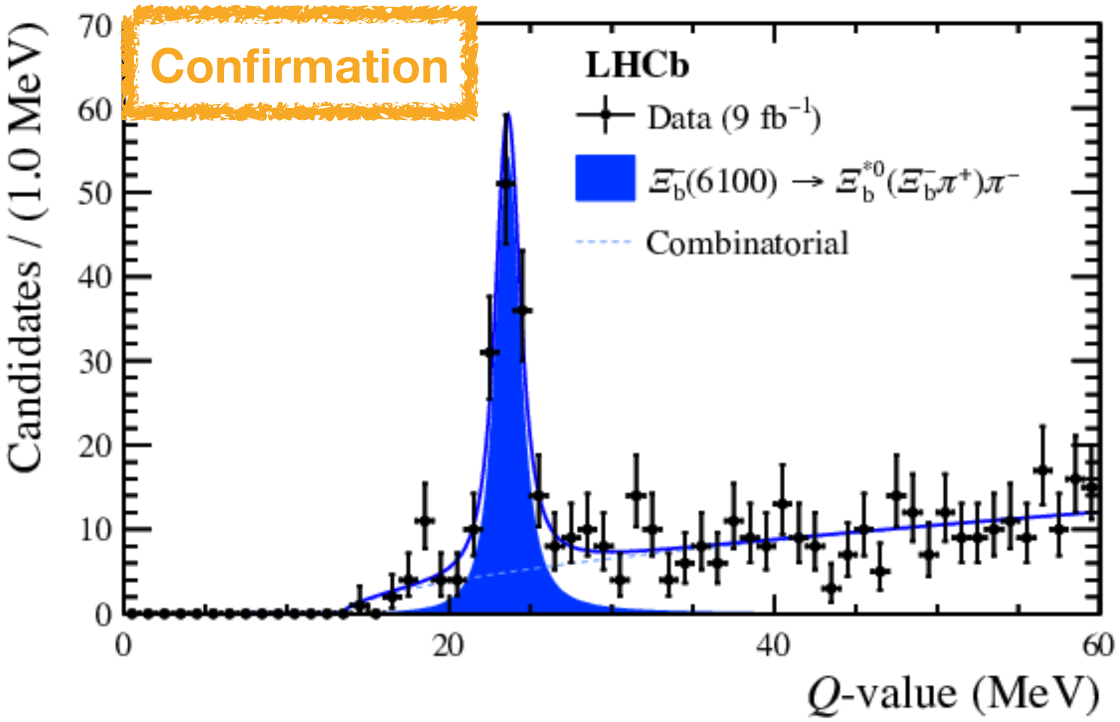
- Relativistic Breit-Wigner convolved with MC resolution,
  background: threshold function $(x - x_0)^\alpha$.
  Simultaneous fit: common mass and natural width

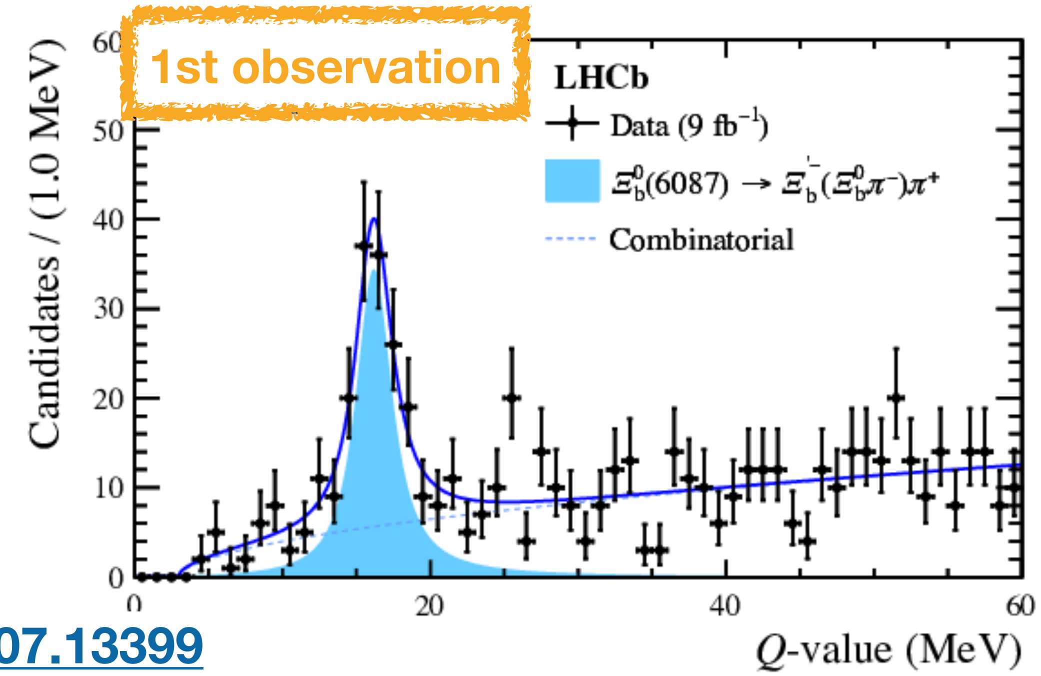
- First observation of a new state, excited beauty strange baryon $\Xi_b(6100)^-$, expected to be the lightest orbital excitation with $J^P = 3/2^-$, beauty analogue of $\Xi_c(2815)^0$

- **Systematics studies:** include variations of fit model, fit range, possible data/MC difference

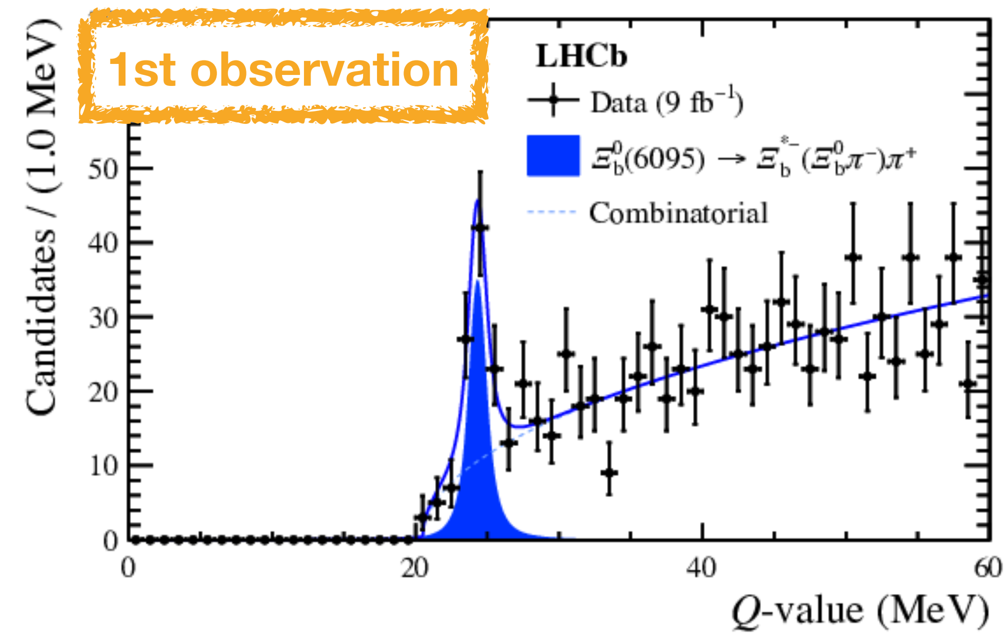
Mass difference variable $\Delta M = M(\Xi_b^-\pi^+\pi^-) - M(\Xi_b^-) - 2m_{\pi^\pm}^{PDG}$ and PV refit technique (see backup) are used to improve detector resolution

Recent confirmation from LHCb





arXiv:2307.13399



- Very recently 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 reported
- 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)

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!

Conclusion and summary

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

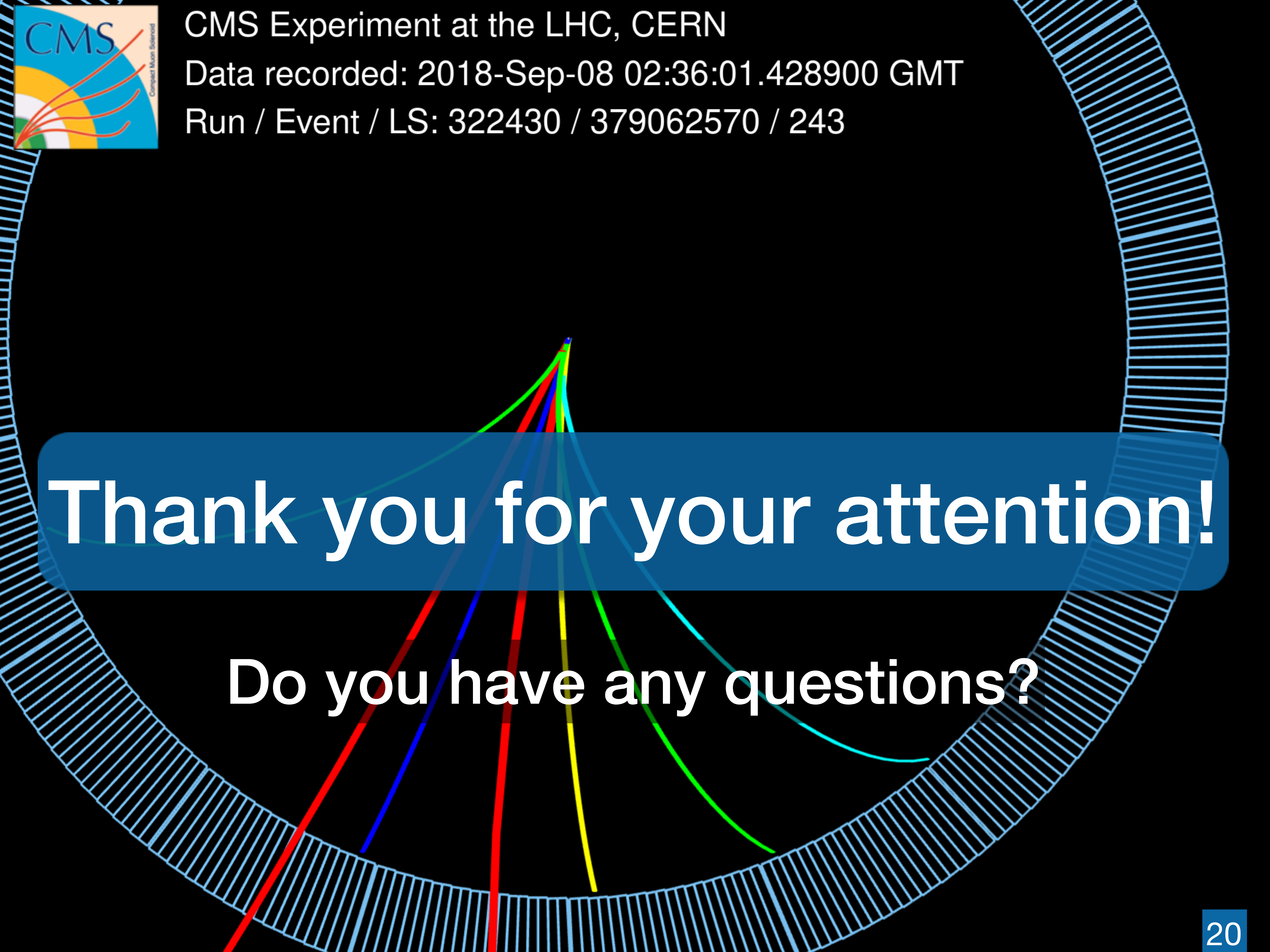
- We report precise measurement of f_s/f_d ratio in the central rapidity region, confirming LHCb' p_T-depending trend for low-p_T

  - f_d/f_u ratio is also measured (consistent with unity), providing first direct measurement of isospin invariance in B meson production at hadron colliders

- 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

- 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

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

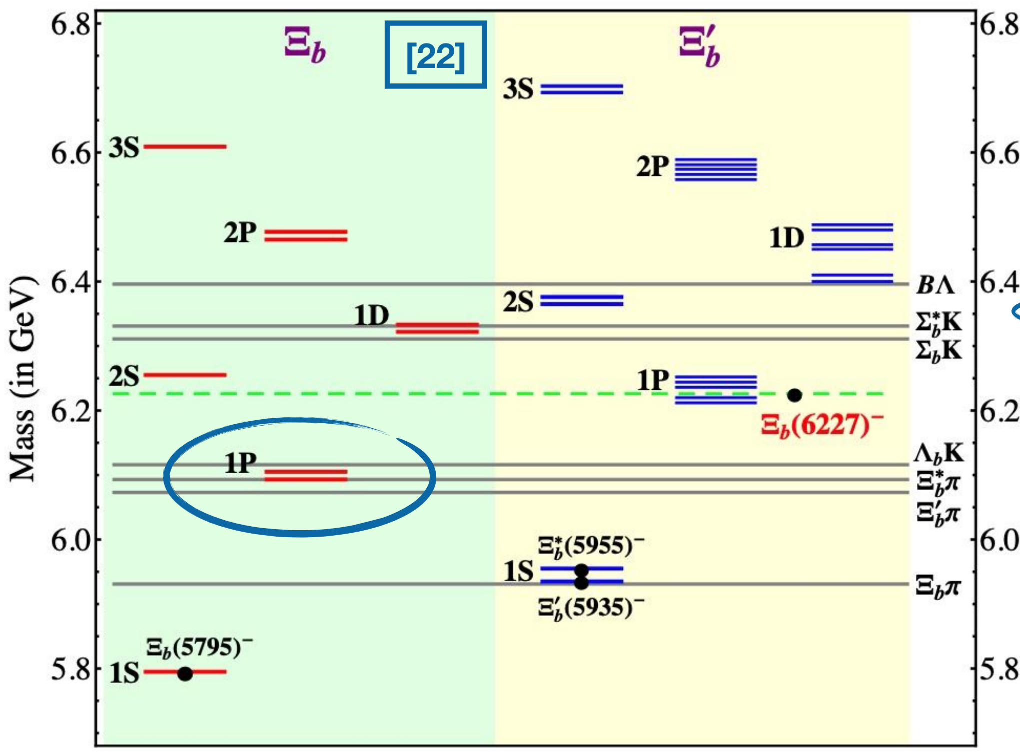


FIG. 2: The obtained masses for the bottom-strange baryons. The red solid lines (left) correspond to the predicted masses of Ξ_b states which are composed of a good diquark and a bottom quark, while the blue solid lines (right) correspond to the Ξ_b' states which contain a bad diquark. Here, we also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

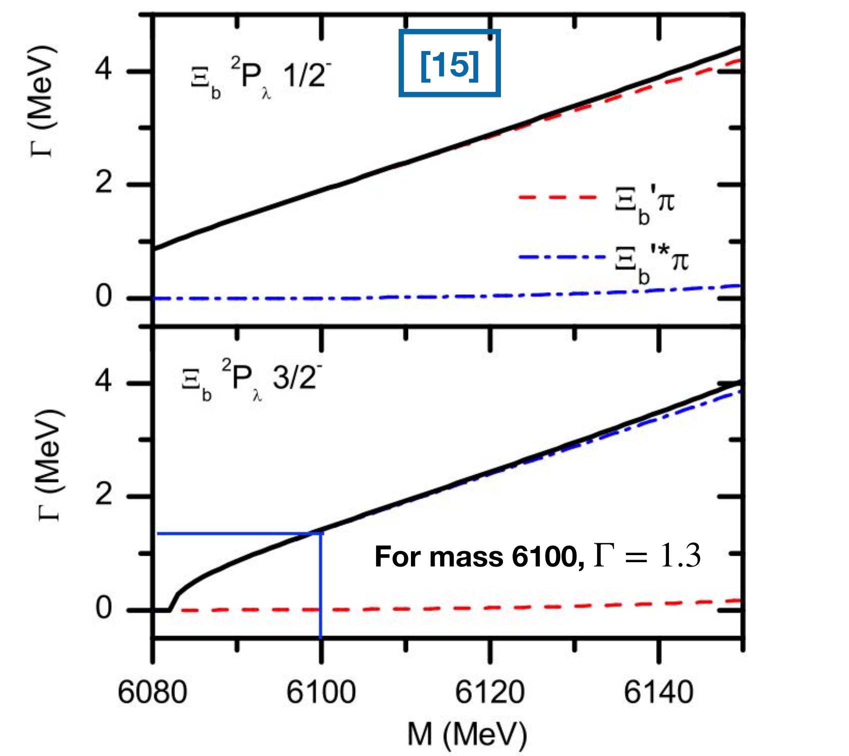


FIG. 2: Partial and total strong decay widths of the $1P$-wave Ξ_b states as functions of their mass. The solid curves stand for the total widths.

[16]

particle	our model	[30]	[36]	expt. (spin averaged)
$\Sigma_b^{(*)}$	5843^{+20}_{-37}	5811 – 5835	⋯	5826.9
$\Xi_b^{\prime(*)}$	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	⋯

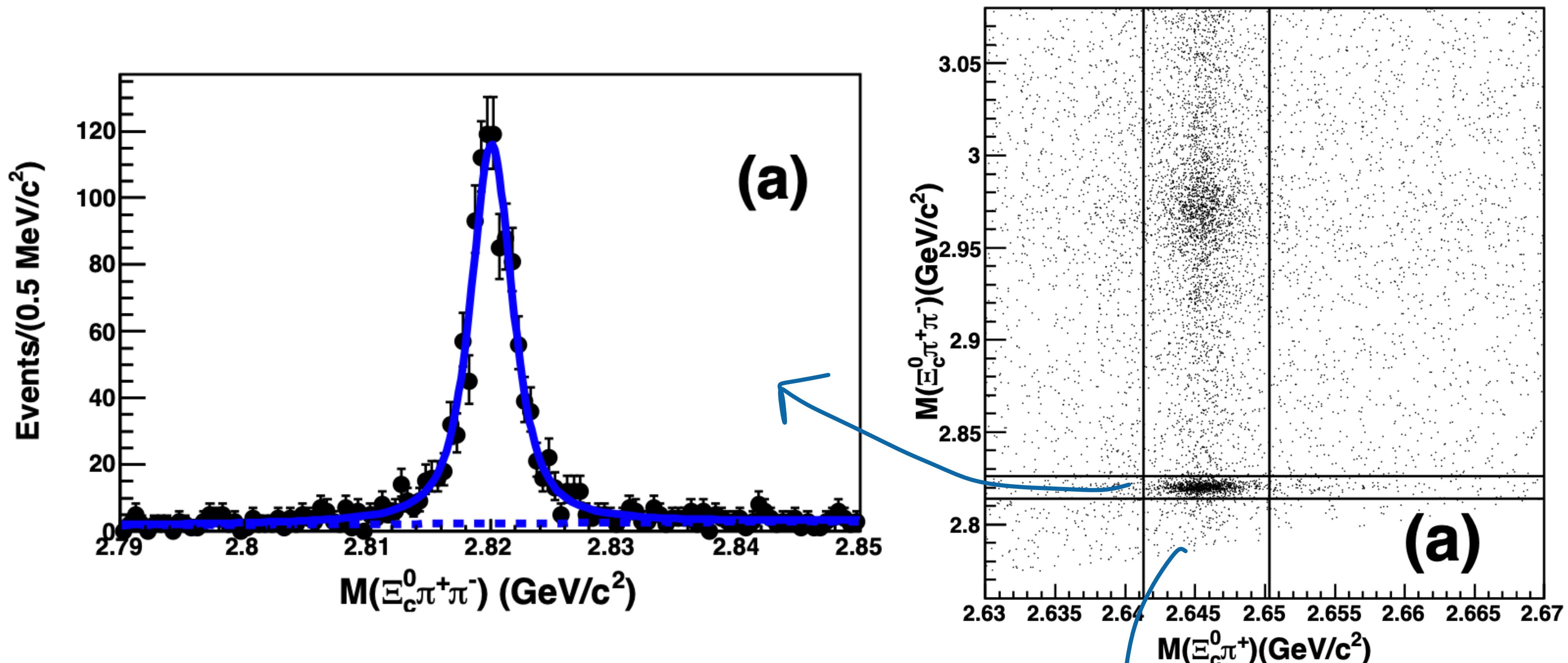
TABLE VII: Partial widths (MeV) and branching fractions for the strong decays of the $1P$-wave states in the Ξ_c and Ξ_b families.

$\lvert ^{2S+1}L_\lambda J^P\rangle$	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	

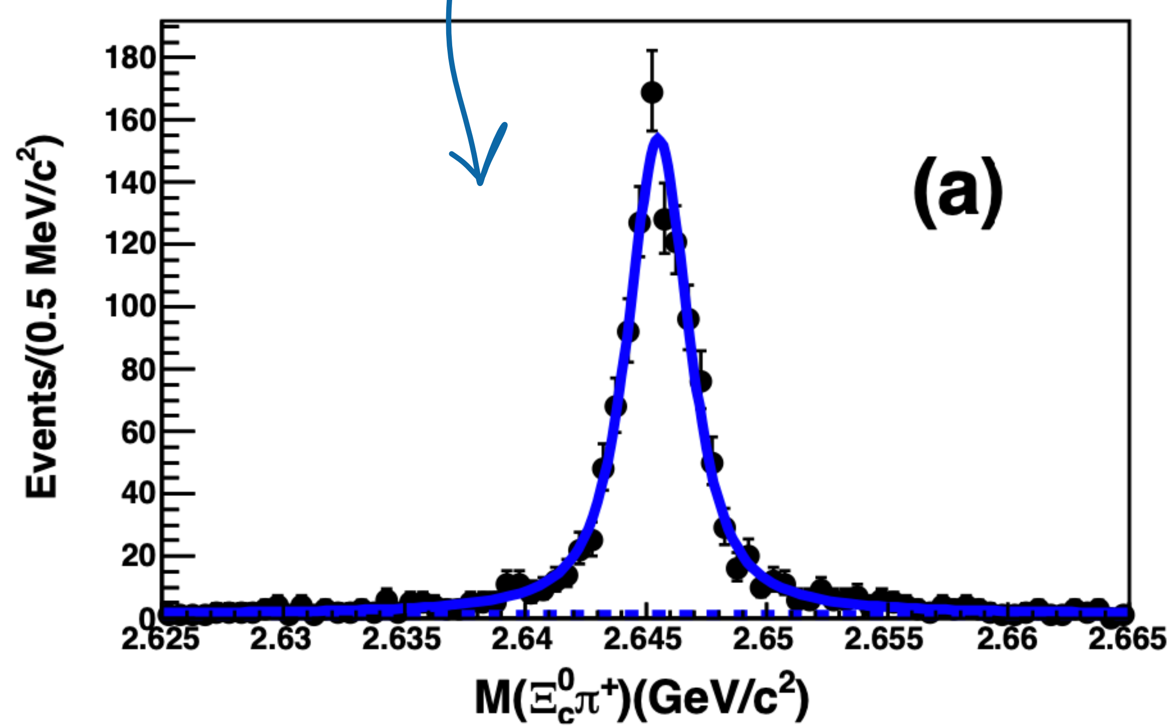
[15]

- [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})



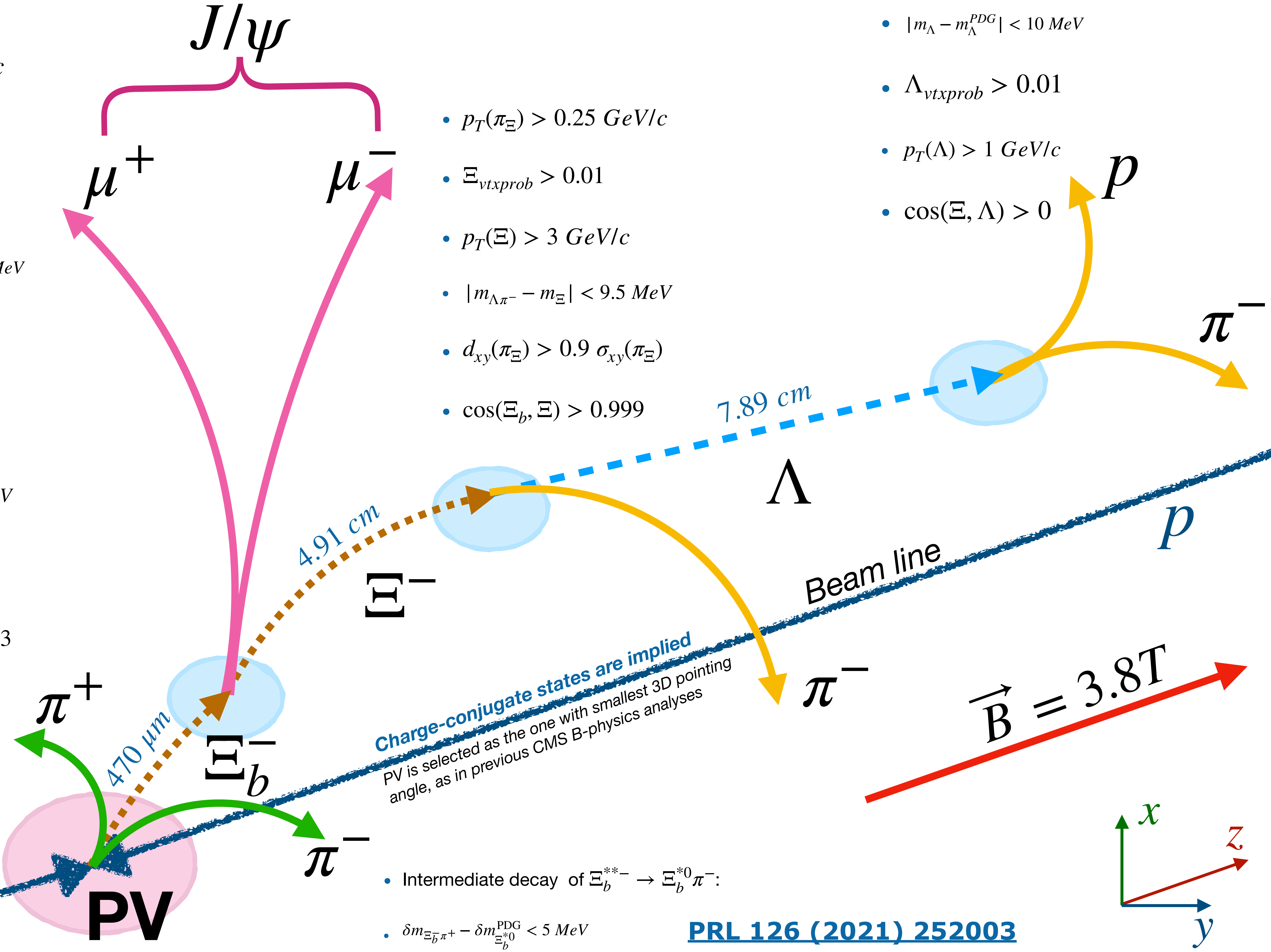
$J/\psi\Xi^-$ decay scheme

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

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

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

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



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

PRL 126 (2021) 252003

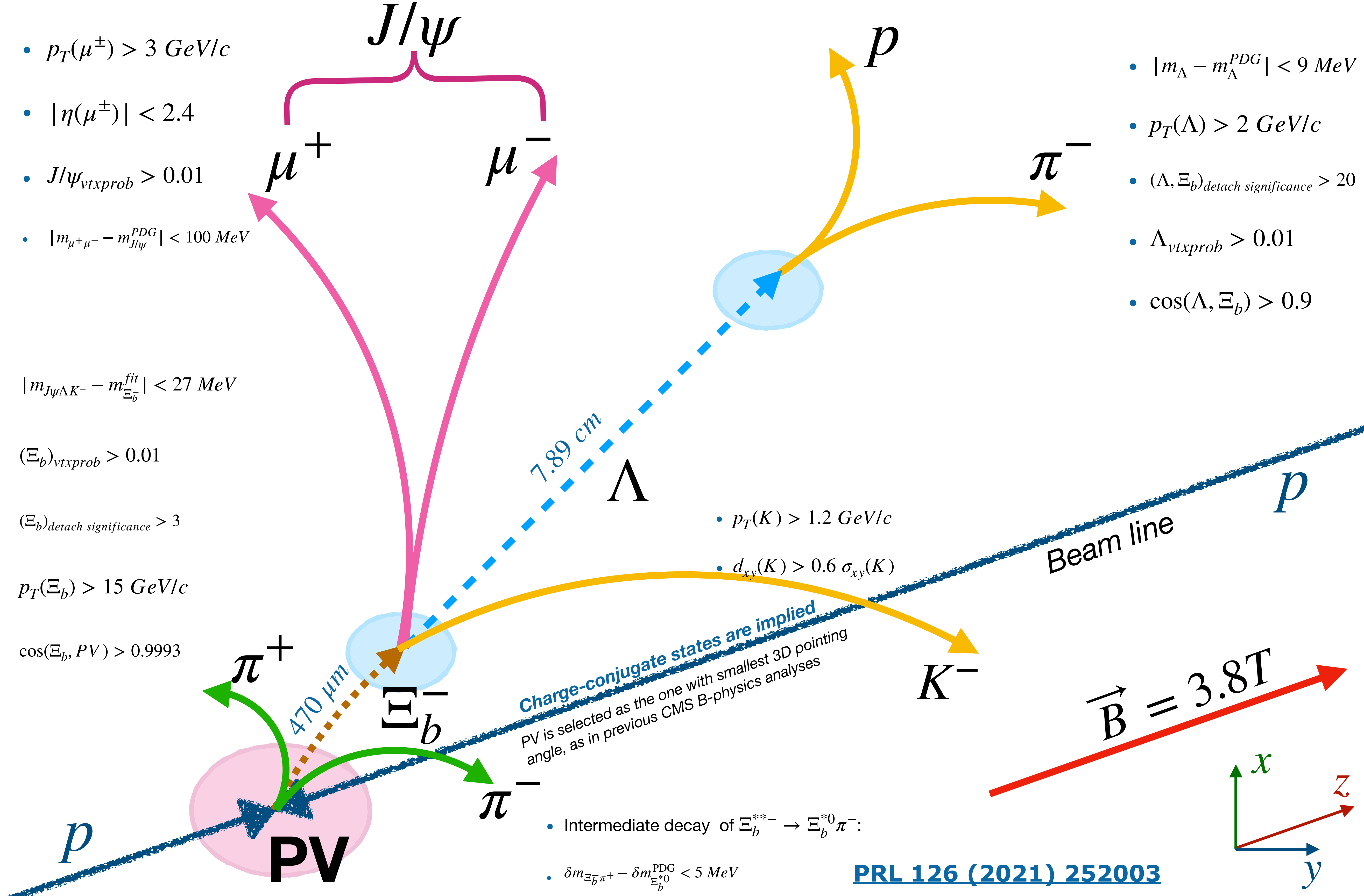
$J/\psi\Lambda K^-$ decay scheme

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

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

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

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



- 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%