Studies of excited heavy flavor states at CMS

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Outline

Two recent studies of excited flavor states at CMS Collaboration are reported:

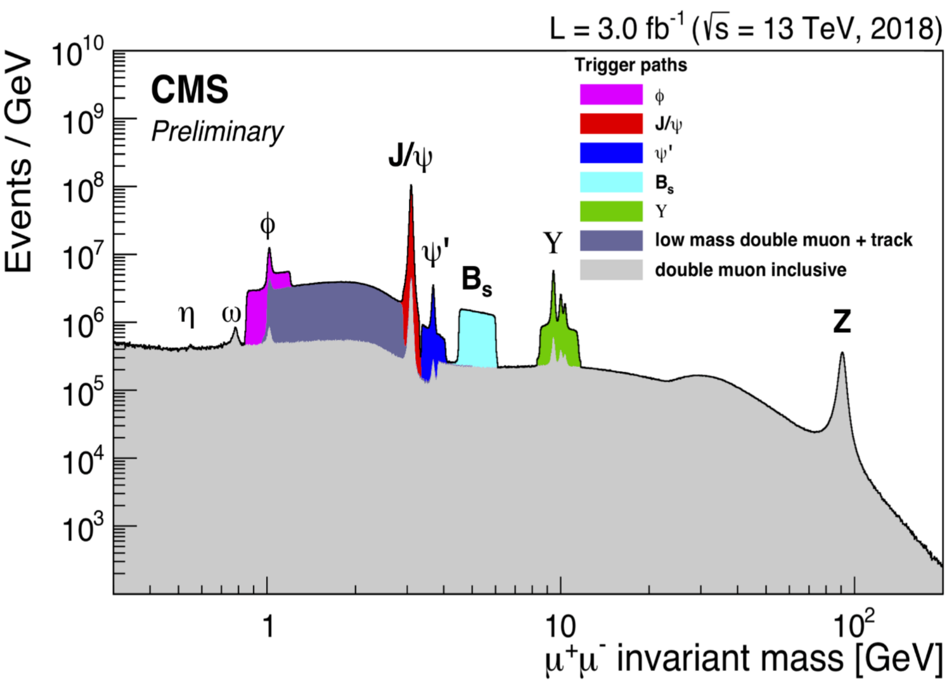
- Measurement of $\mathrm{B_c^+}(2S)$ and $\mathrm{B_c^{+*}}(2S)$ cross setion ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV

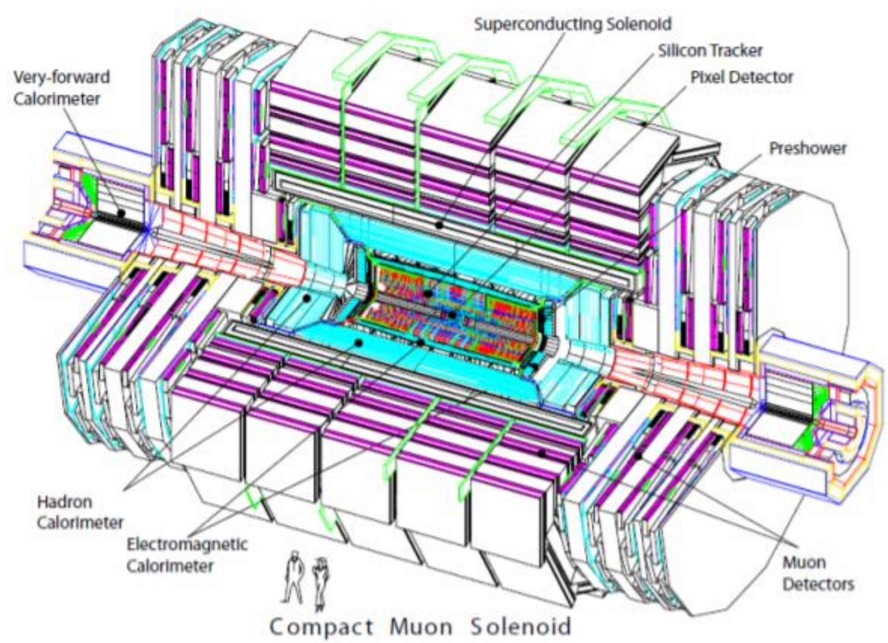
- Observation of a new excited beauty strange baryon decaying to $\Xi_\mathrm{b}^- \pi^+ \pi^-$

CMS experiment

Heavy flavor excited states studies are possible at CMS due to:

- Excellent muon system with large rapidity coverage and high-purity muon-ID
- Good resolution in $p_T \sim 1\%$ for central region of tracker
- Remarkable vertex reconstruction and impact parameter resolution down to $\approx 15\mu m$
- Efficient and very flexible set of dimuon triggers



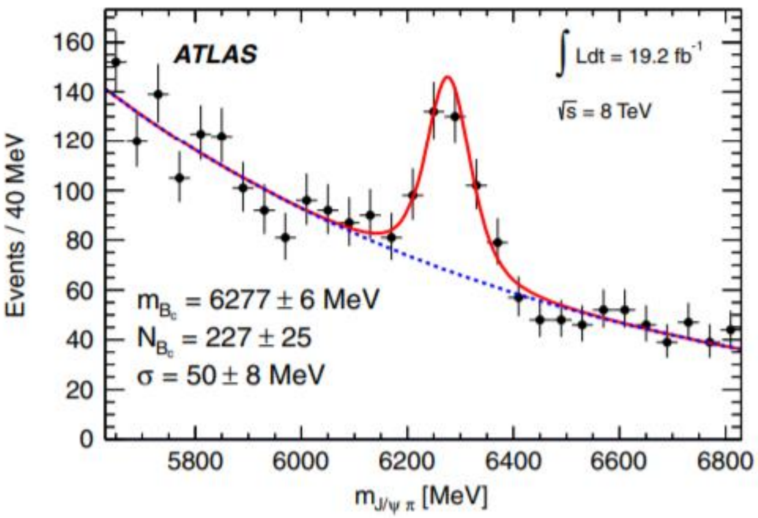


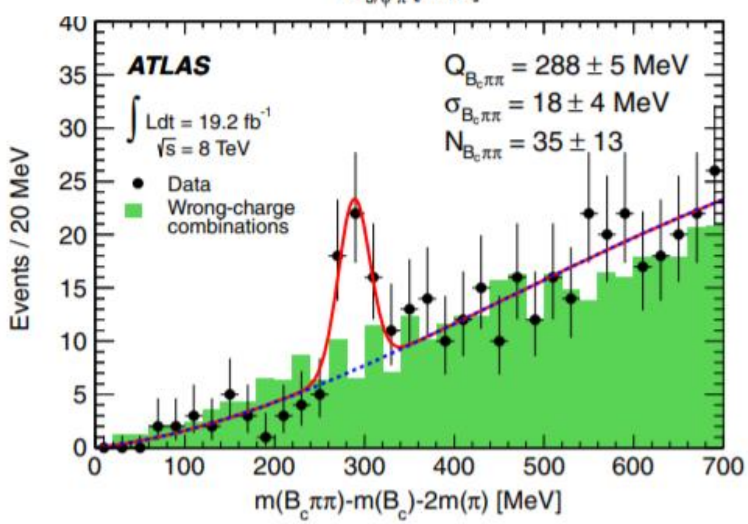
Measurement of $\mathrm{B_c^+}(2S)$ and $\mathrm{B_c^{+*}}(2S)$ cross setion ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV

[PRD 102 (2020) 092007]

Search for excited B_c^+ states

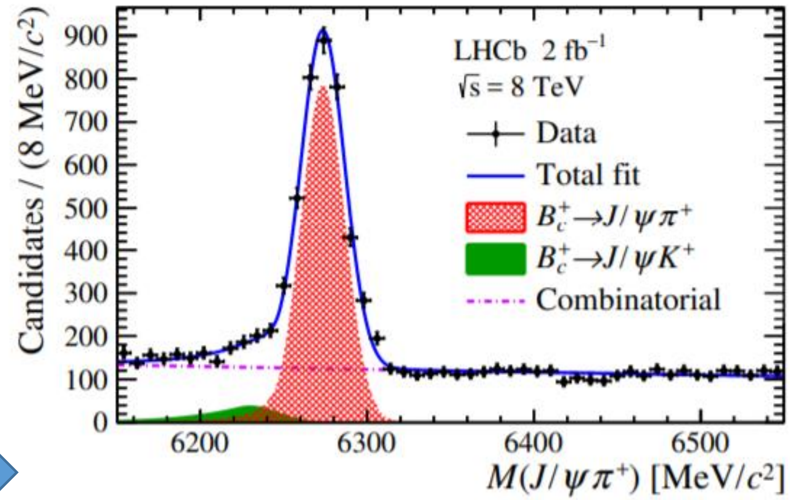
In 2014 the ATLAS Collaboration reported the observation of the new state, with mass consistient to predictions for $B_c^+(2S)$ state

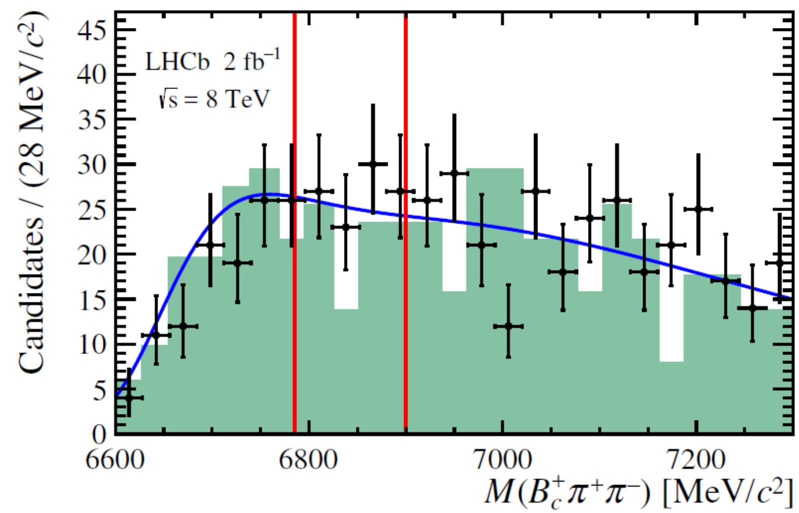




PRL 113 (2014) 212004

Then the LHCb Collaboration using 8 TeV data didn't find any significant signal in the same region





JHEP 01 (2018) 138

Theoretical predictions and motivation

- Spectrum of B_c family is predicted to be very populated, but spectroscopic observations are poor so far
- The measurement of $B_c(2S)$ masses and production cross sections will help to deeply understand the dynamics of heavy-heavy quark systems.

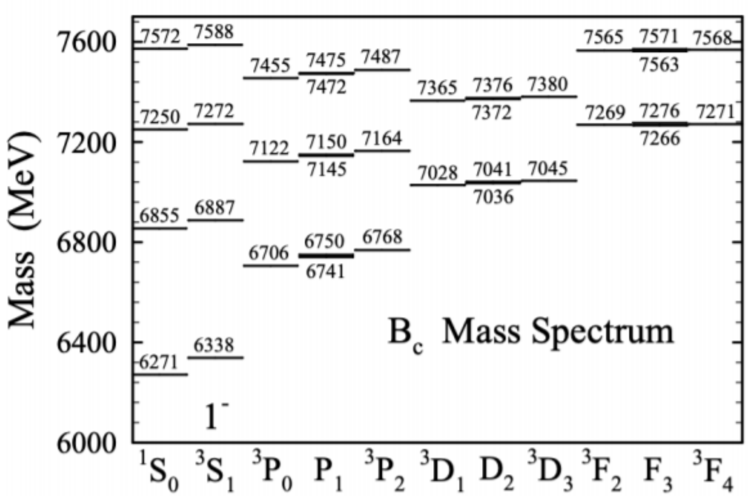
The study is based on searching for $B_c^+(2S)$ and $B_c^{+*}(2S)$ in the $B_c^+\pi^+\pi^-$ final state.

Decay modes are:

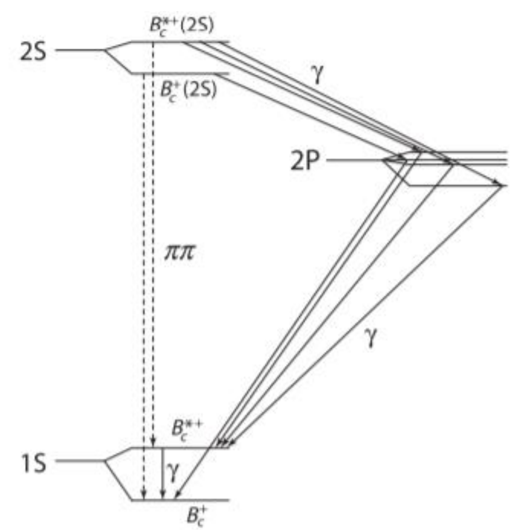
- $B_c^+(2S) \rightarrow B_c^+\pi^+\pi^-$
- $B_c^{+*}(2S) \rightarrow B_c^{+*}\pi^+\pi^-$, where $B_c^{+*} \rightarrow B_c^+\gamma$, and soft photon is lost

The theory predicts $\Delta M = [M(B_c^*) - M(B_c)] - [M(B_c^*(2S)) - M(B_c(2S))] = 20$ MeV

PRD 70 (2004) 054017



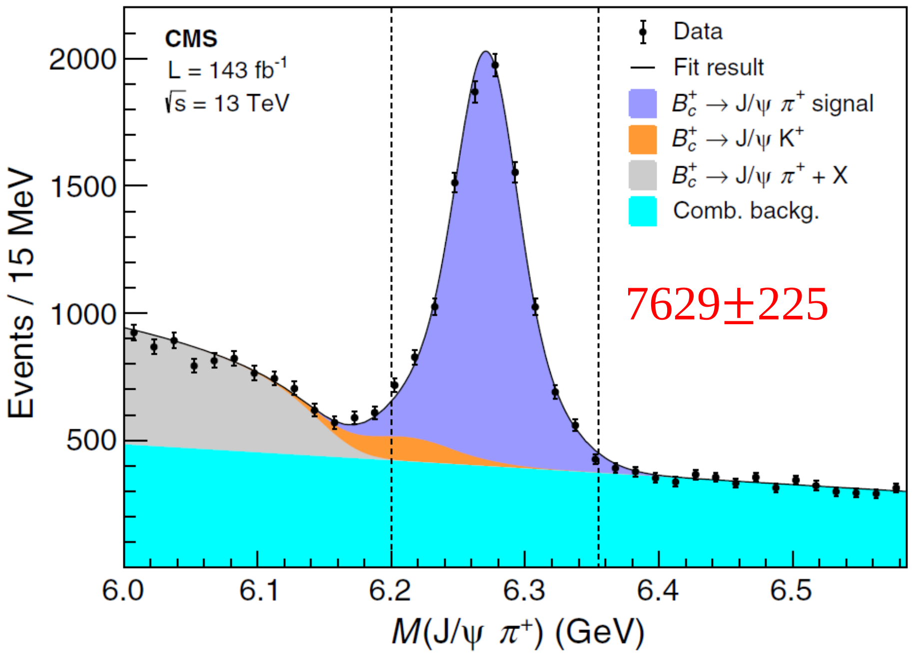
PRL 122 (2019) 132001

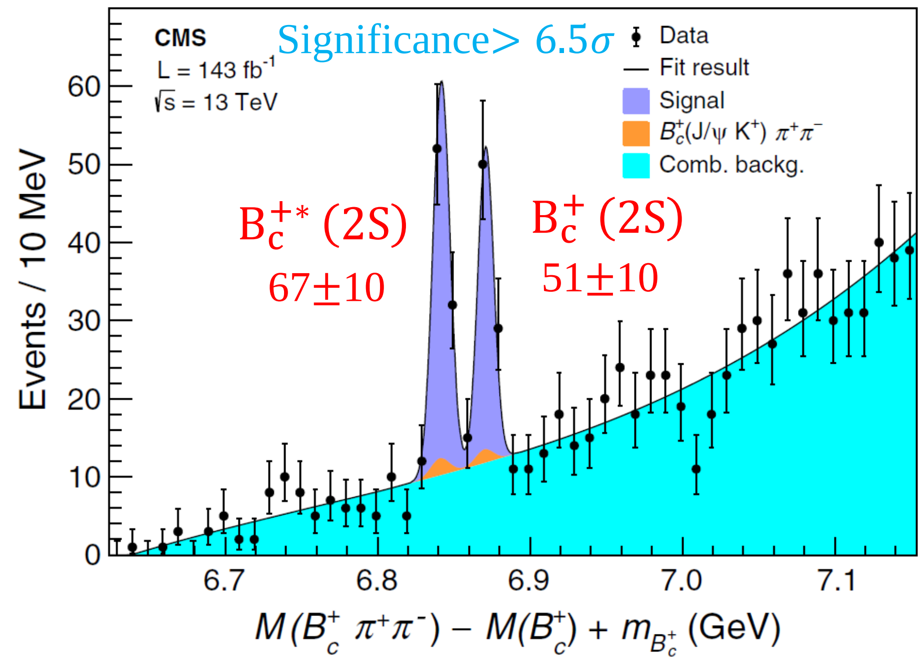


Observation of $B_c^{+(*)}(2S)$ states

Using full Run II statistics the CMS Collaboration observed two well separated $B_c^+(2S)$ and $B_c^{+*}(2S)$ states

PRL 122 (2019) 132001





- Signal: Double-Gaussian
- Comb. backg.: linear function
- Part. reco.: Argus*Gaussian

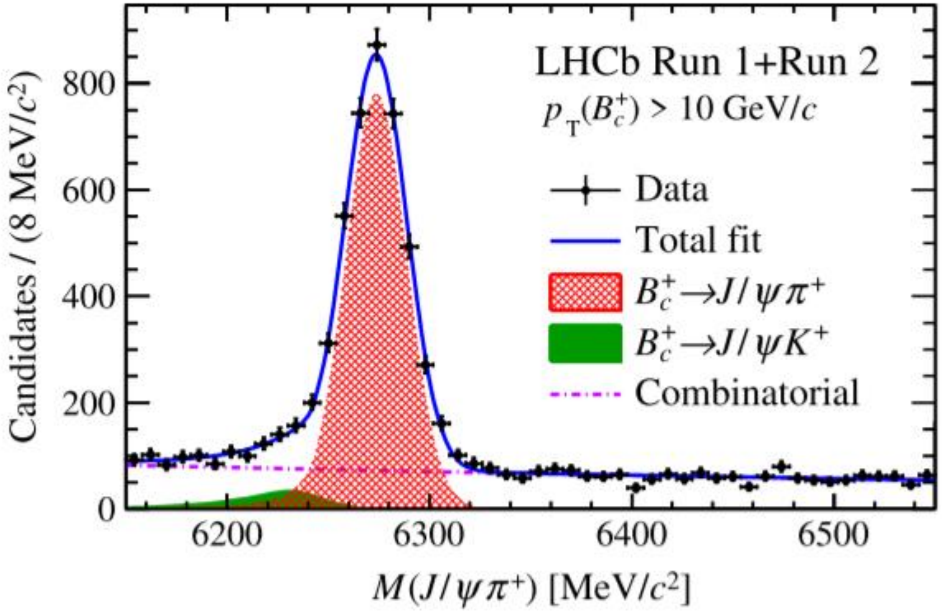
- Signals: Gaussians
- Comb. backg.: Pol3(x)

- $M\left(B_c^+(2S)\right) = 6871.0 \pm 1.2(\mathrm{stat.}) \pm 0.8(\mathrm{syst.}) \pm 0.8(B_c^+)$ MeV
- $\Delta M = 29.1 \pm 1.5(\mathrm{stat.}) \pm 0.7(\mathrm{syst.})$ MeV

Confirmation of $B_c^{+(*)}(2S)$ states by the LHCb Collaboration

In 2019 the LHCb collaboration has confirmed the two-peaks structure using Run I and Run II statistics.

PRL 122 (2019) 232001



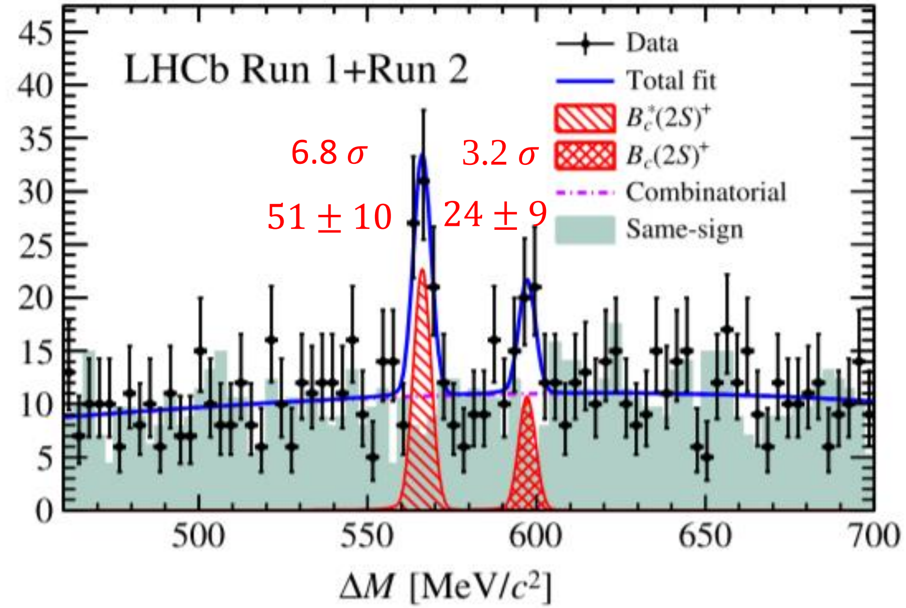


Table 1: Comparison of $B_c(2S)$ results

Collaboration	$M[B_c(2S)]$, MeV	ΔM, MeV
CMS	$6871.0 \pm 1.2 \pm 0.8 \pm 0.8$	$29.1 \pm 1.5 \pm 0.7$
LHCb	$6872.1 \pm 1.3 \pm 0.1 \pm 0.8$	$31.0 \pm 1.4 \pm 0.0$

Results of the LHCb Collaboration are in a good agreement with the CMS Collaboration

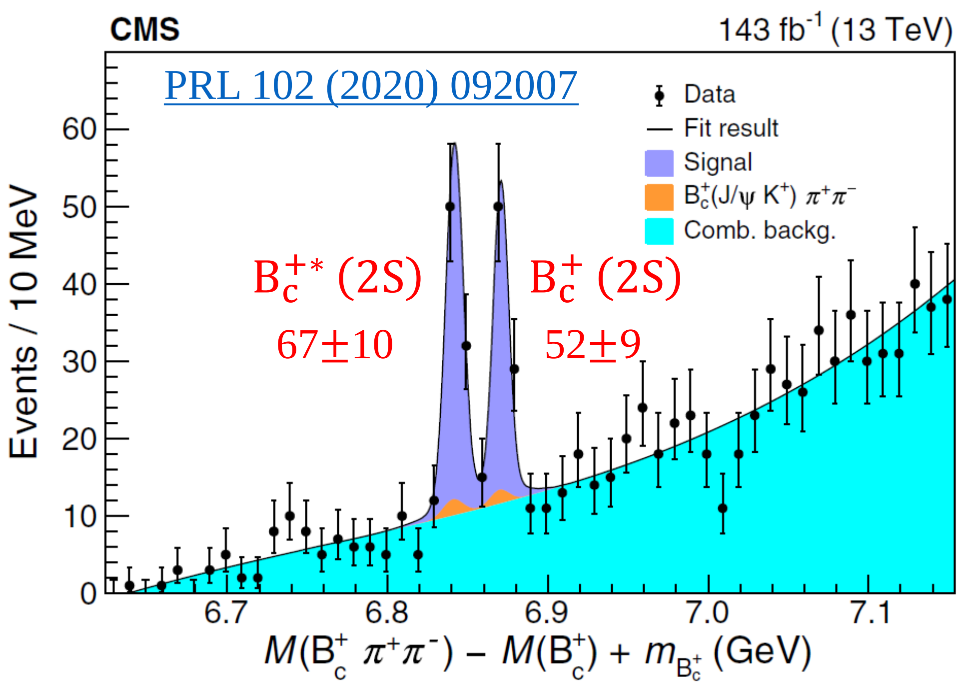
Measurement of B_c^+ (2S) and B_c^{+*} (2S) cross section ratios

The ratios of the $B_c^{+(*)}$ (2S) to B_c^+ and B_c^{+*} (2S) to B_c^+ (2S) cross sections were measured in kinematic region $p_T(B_c^+) > 15$ GeV and $|y(B_c^+)| < 2.4$

$$R^+ \equiv \frac{\sigma(B_c(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-) = \frac{N(B_c(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c(2S)^+)},$$

$$R^{*+} \equiv \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-) = \frac{N(B_c^*(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^*(2S)^+)},$$

$$R^{*+}/R^+ = \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c(2S)^+)} \frac{\mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-)}{\mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-)} = \frac{N(B_c^*(2S)^+)}{N(B_c(2S)^+)} \frac{\epsilon(B_c(2S)^+)}{\epsilon(B_c^*(2S)^+)}.$$

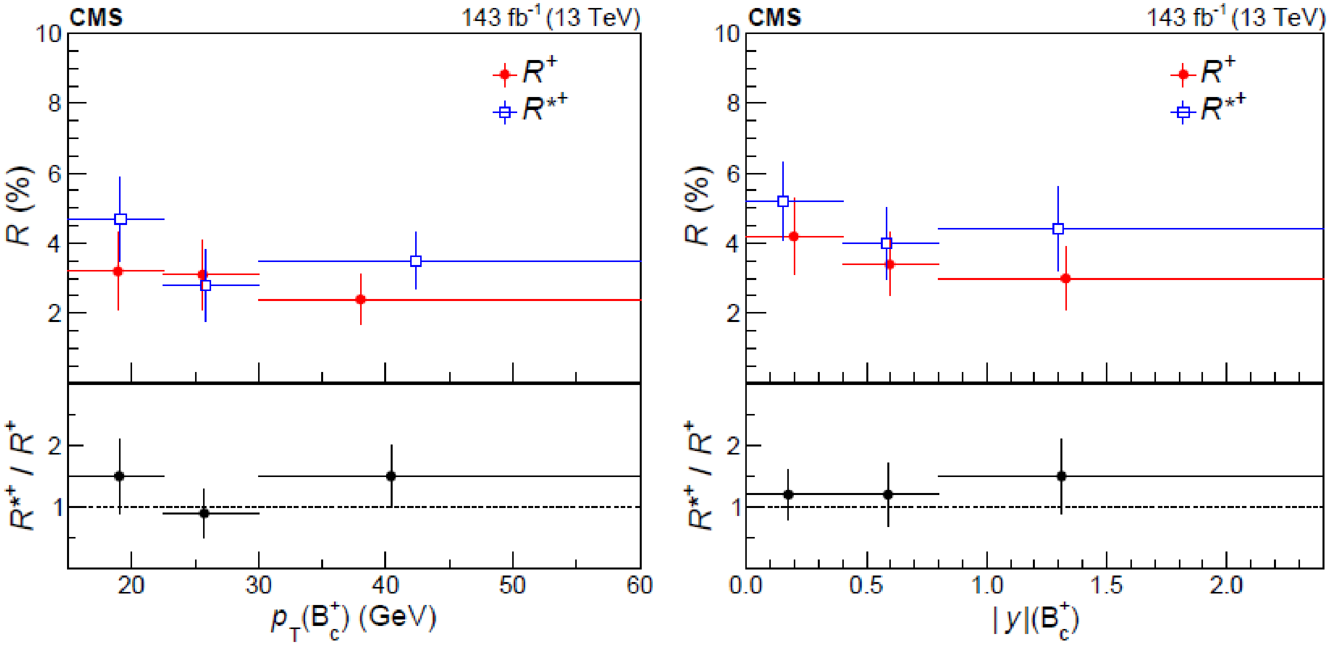


$$R^+ = (3.47 \pm 0.63\,(\text{stat}) \pm 0.33\,(\text{syst}))\%,$$
$$R^{*+} = (4.69 \pm 0.71\,(\text{stat}) \pm 0.56\,(\text{syst}))\%,$$
$$R^{*+}/R^+ = 1.35 \pm 0.32\,(\text{stat}) \pm 0.09\,(\text{syst}).$$

Systematic sources: $B_c^+\pi^+\pi^-$, $J/\psi\pi^+$ fit models, pion tracking, decay kinematics

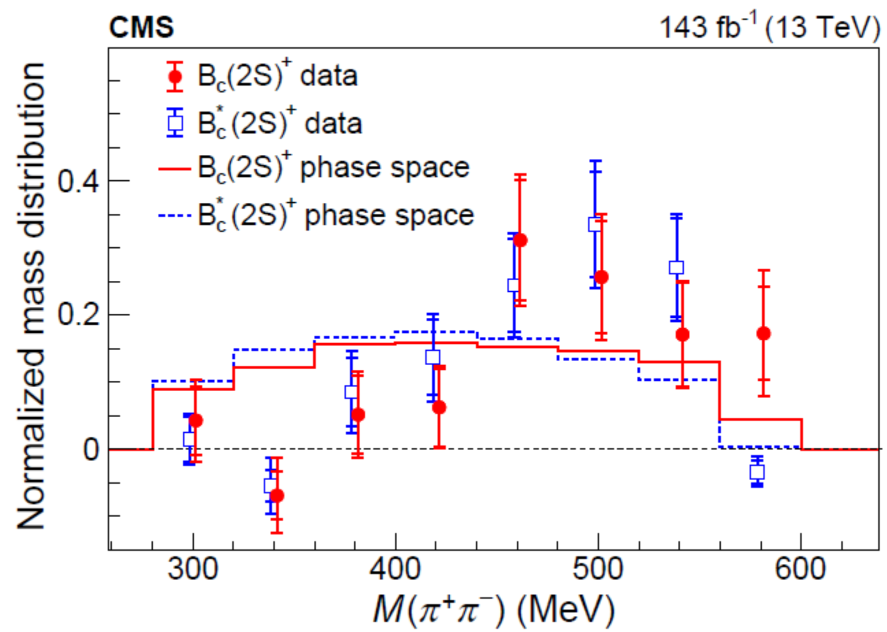
Measurement of $B_c^+(2S)$ and $B_c^{+*}(2S)$ cross section ratios

PRL 102 (2020) 092007



No significant dependences on p_T and y of B_c^+ mesons have been observed for any of these three ratios

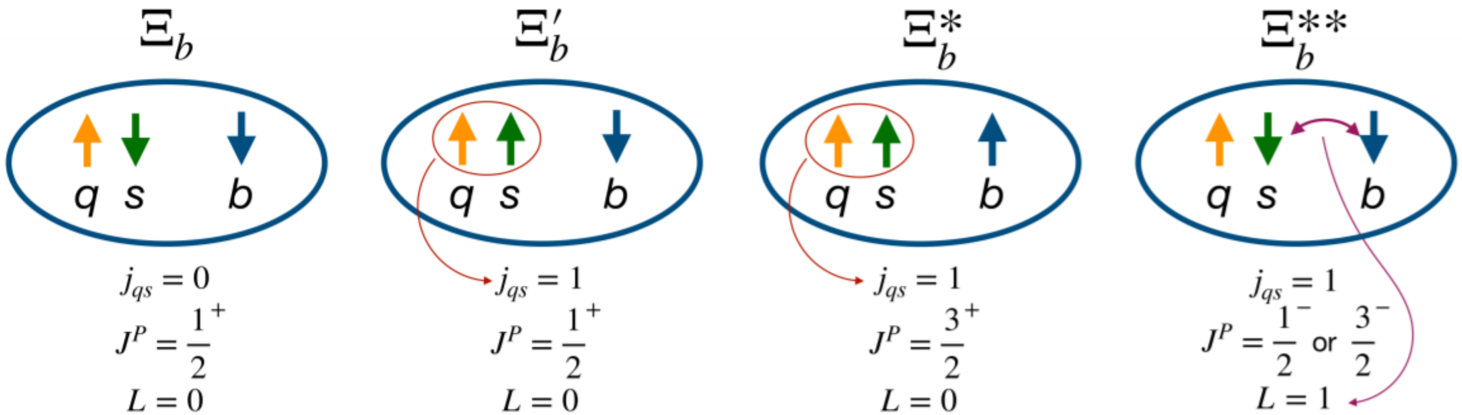
The normalized dipion invariant mass distributions for the $B_c^{+(*)}(2S) \rightarrow B_c^+\pi^+\pi^-$ decays were obtained using sPlot technique and demonstrate some discrepancy with phase space from simulations



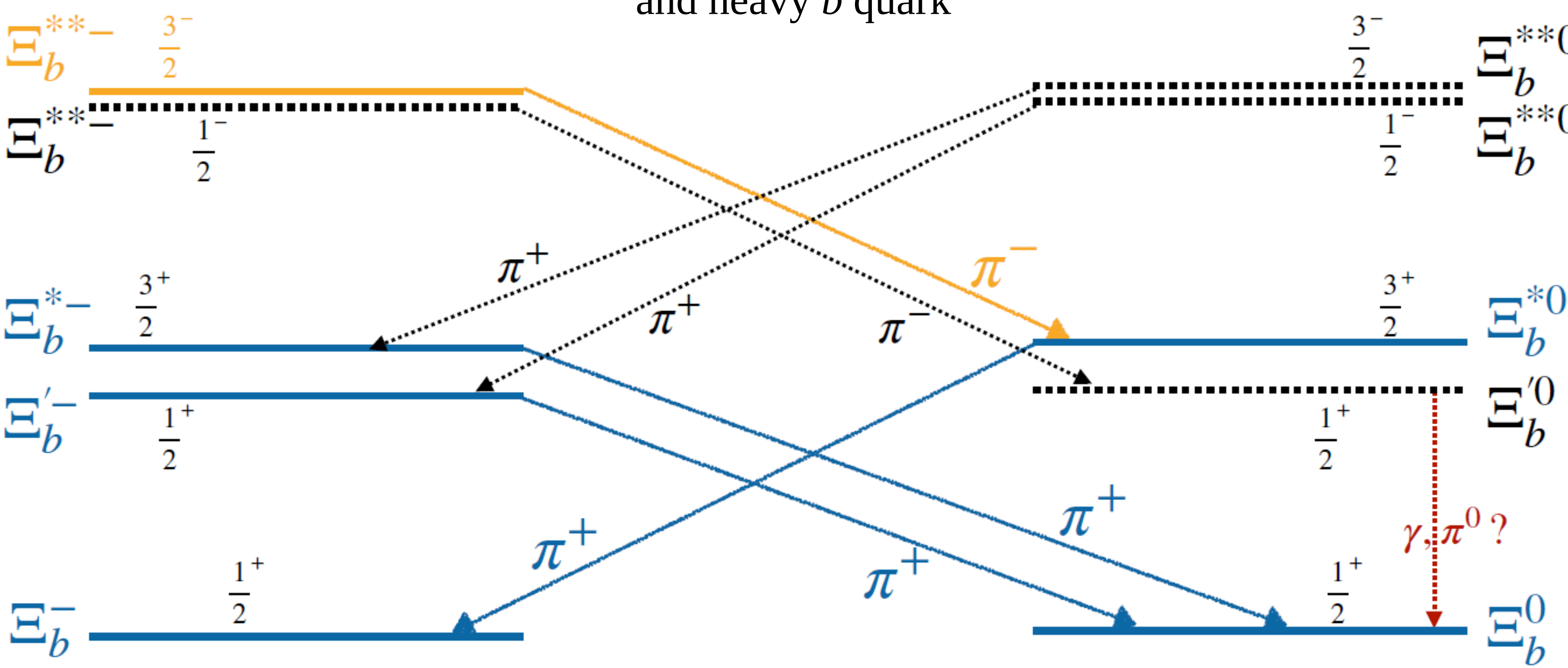
Observation of a new excited beauty strange baryon decaying to $\Xi_b^-\pi^+\pi^-$

[PRL 126 (2021) 252003]

Ξ_b baryons spectroscopy



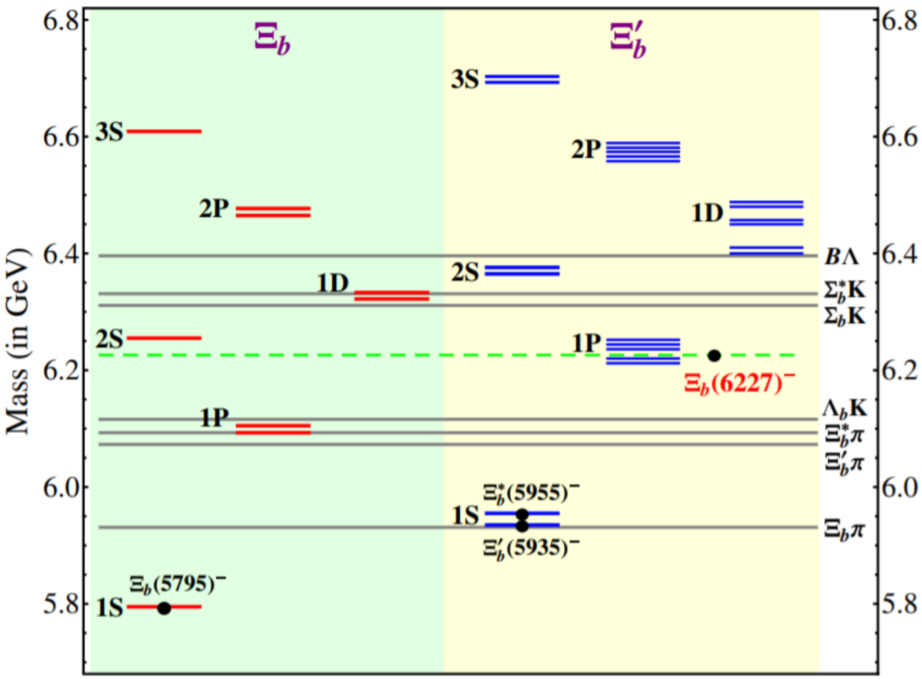
q denotes *u* or *d* quarks for Ξ_b^0 or Ξ_b^-. *L = 1* is the orbital excitation between the light diquark *qs* and heavy *b* quark



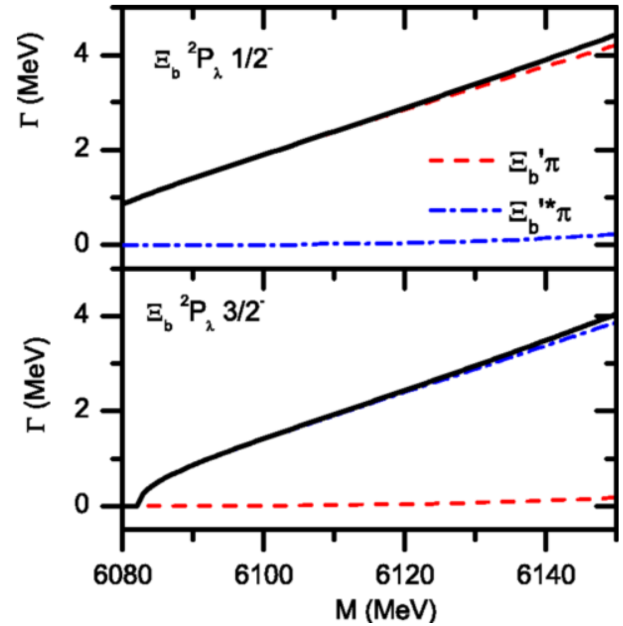
Theoretical predictions for Ξ_b^{**-}

Various theoretical models and calculations predict a spectrum of excited Ξ_b baryons. There are several predictions for orbitally excited P-wave Ξ_b^{**} states with quantum numbers $J^P = 1/2^-$ $(3/2^-)$, expected to decay to $\Xi_b'(\Xi_b^*)\pi$.

PRD 98 (2018) 031502 [2]



PRD 96 (2017) 116016 [1]



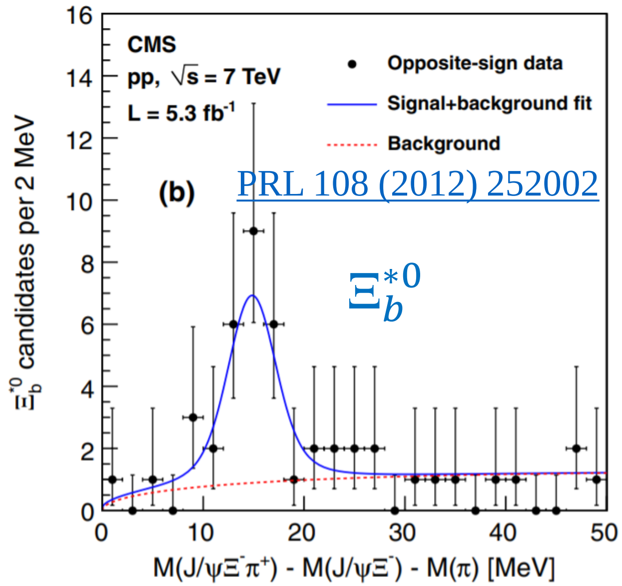
[3] is PRD 98 (2018) 031502

Table 2: Theoretical predictions for Ξ_b^{**-}

Properties	[1]	[2]	[3]
$M(\Xi_b^{**-})$ [MeV]	6130	6102	6124^{+30}_{-20}
$\Gamma(\Xi_b^{**-})$ [MeV]	2.88	2.9	<7.21

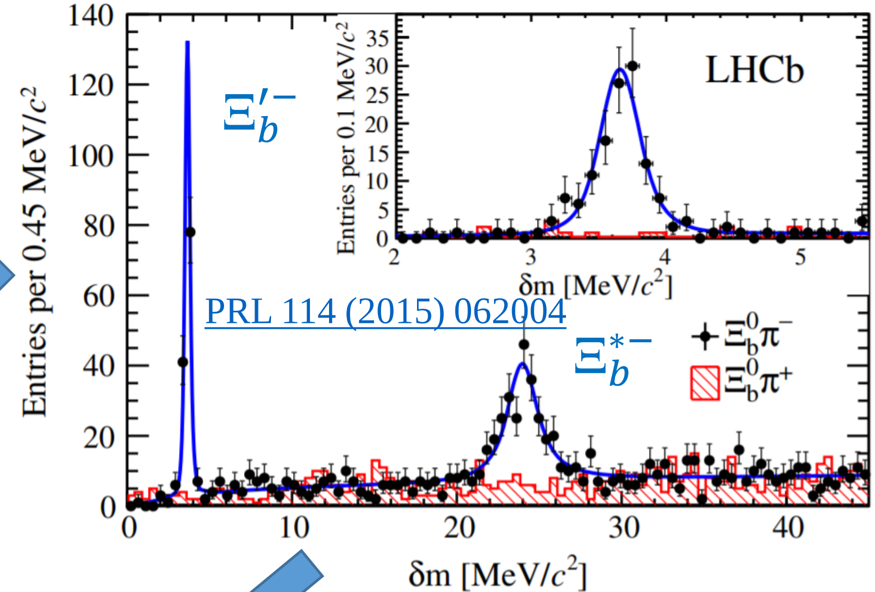
Previous experimental observations

In 2012 year the CMS Collaboration observed first excited Ξ_b^{*0} state

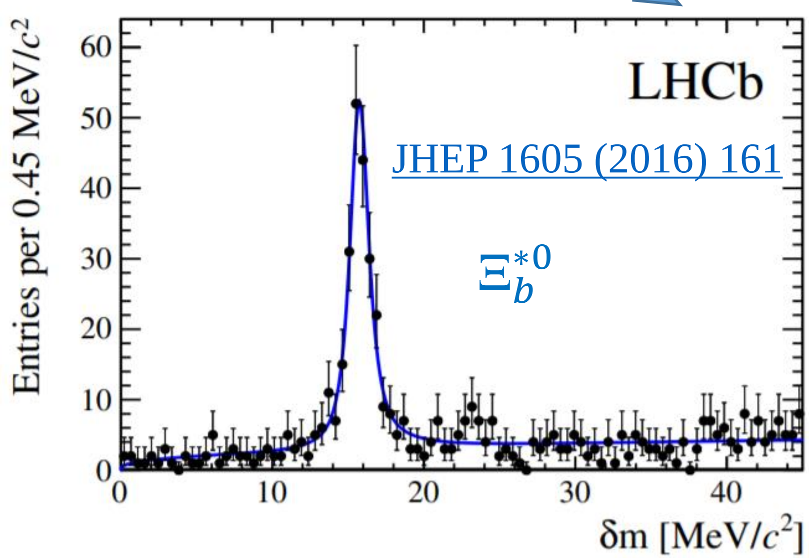


PRL 108 (2012) 252002

Later in 2015 LHCb observed two excited states: $\Xi_b^{\prime -}$ and Ξ_b^{*-}



PRL 114 (2015) 062004



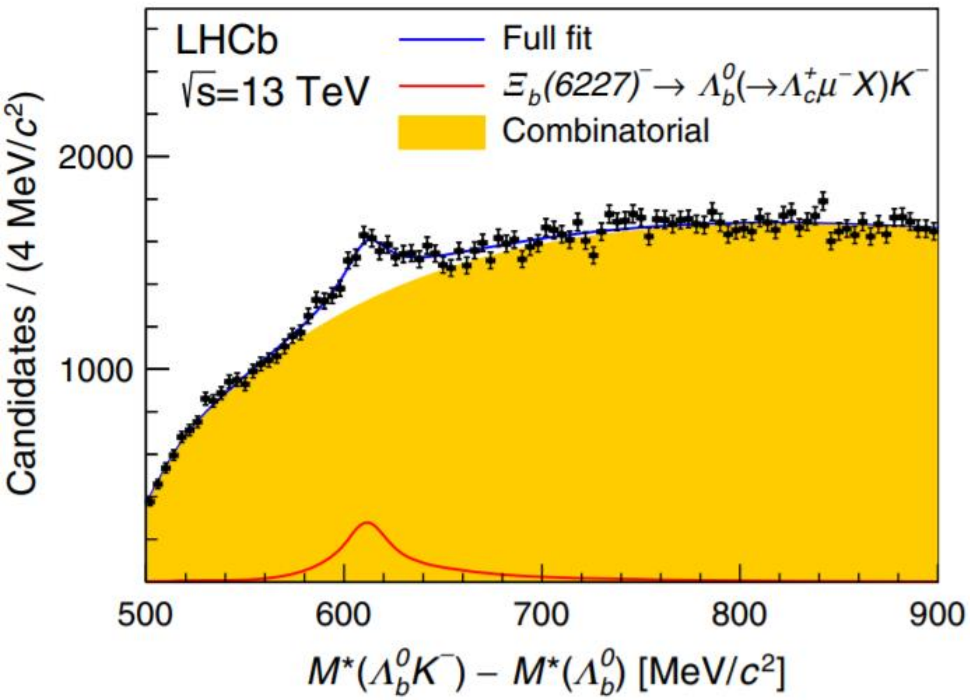
JHEP 1605 (2016) 161

In 2016 LHCb performed precision measurement of Ξ_b^{*0} properties (mass, natural width)

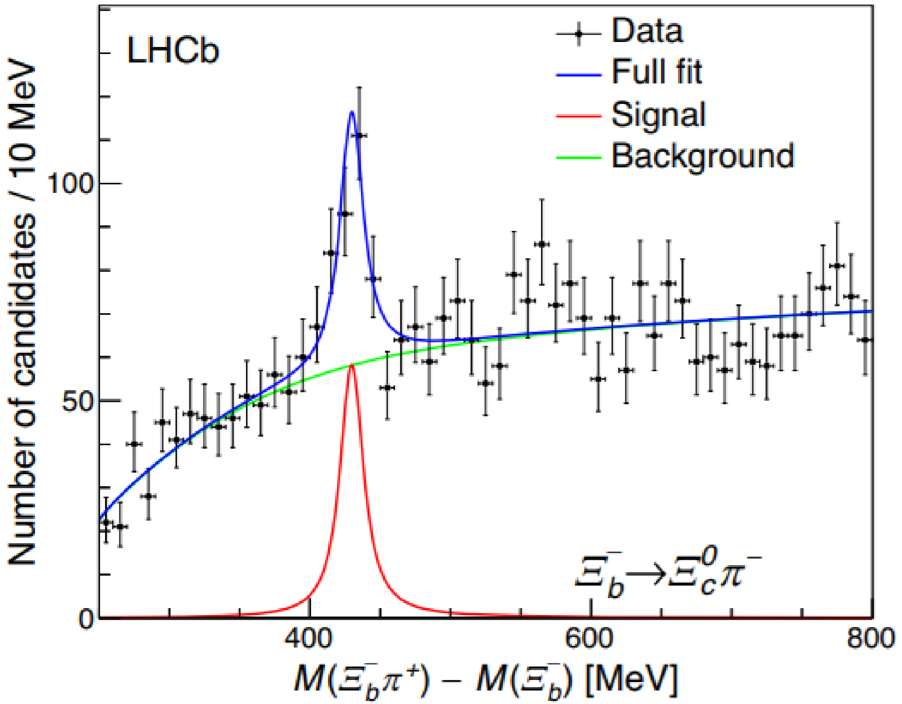
Previous experimental observations

Recently the LHCb Collaboration reported observation of a new excited $\Xi_b(6227)^-$ baryon decaying to both $\Lambda_b^0 K^-$ and $\Xi_b^0 \pi^-$ and its isospin partner $\Xi_b(6227)^0$ decaying to $\Xi_b^- \pi^+$ final state

PRL 121 (2018) 072002



PRD 103 (2021) 0120024

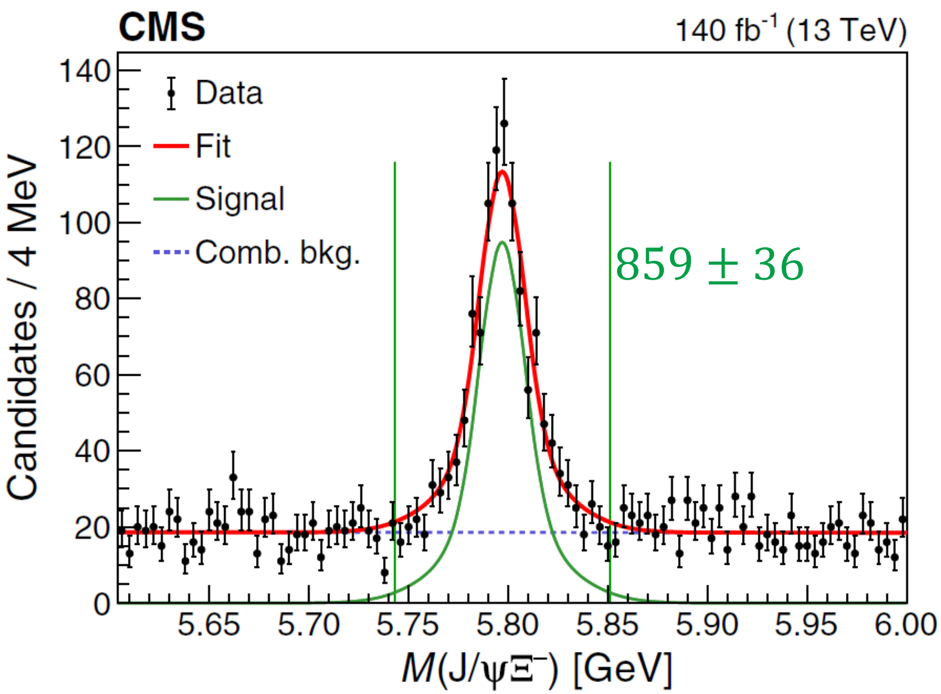


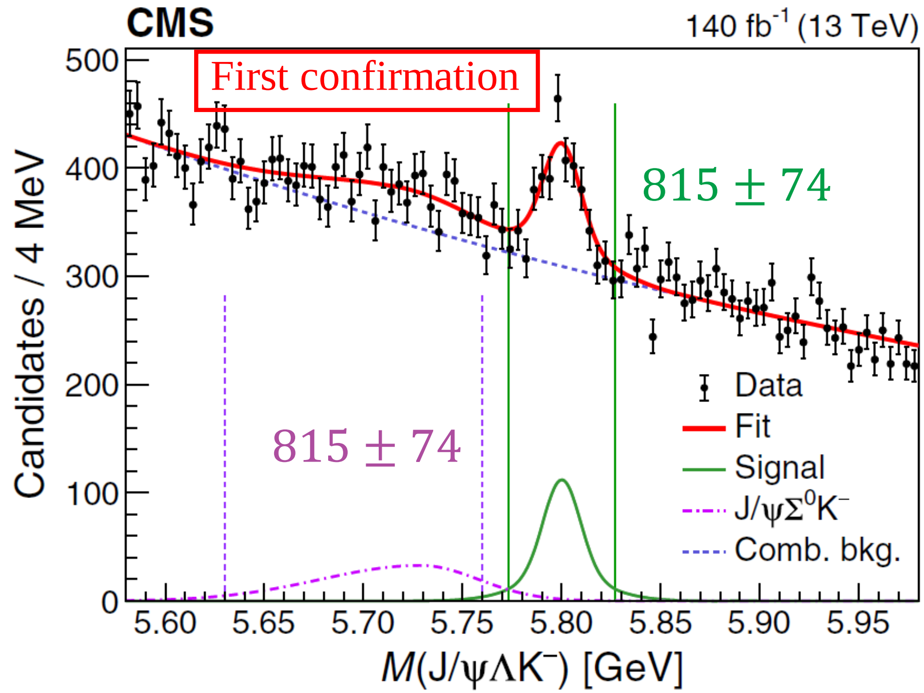
However $\Xi_b(6227)$ isodoublet does not unambiguously fit quark model predictions and analogies from charm sector, therefore its quantum numbers need further investigations

Ξ_b signals

Since CMS has no hadron ID and dedicated trigger we cannot use $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$ channel, therefore we reconstruct Ξ_b^- ground states in $J/\psi\Xi^-$ and $J/\psi\Lambda K^-$ final states

[PRL 126 (2021) 252003]





- Signal: double-Gaussian (from MC)
- Background: linear function

- Signal: double-Gaussian (from MC)
- Reflection: asymmetrical Gaussian (from MC)
- Background: exponential function

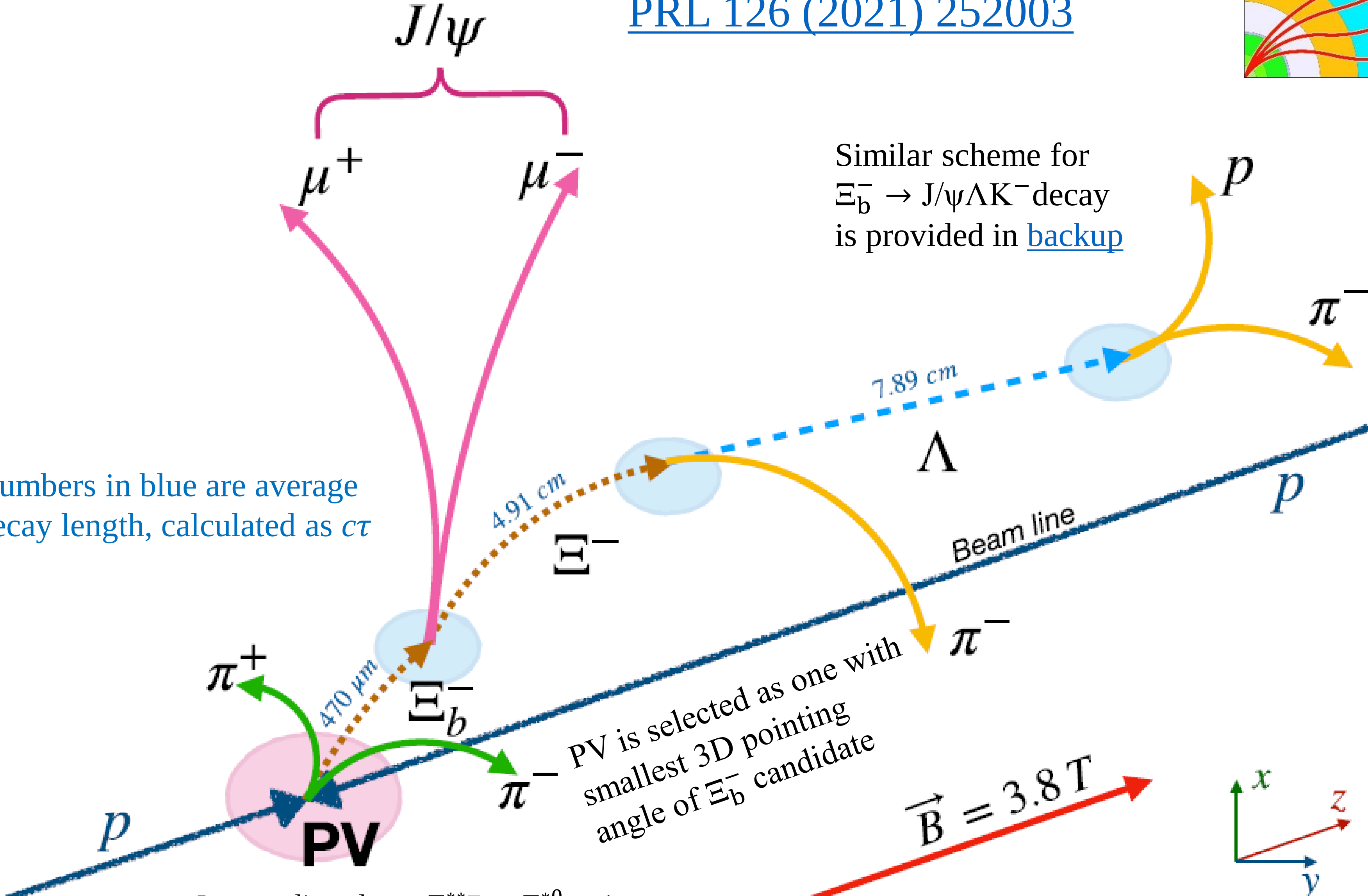
Reflection $\Xi_b^- \rightarrow J/\psi\Sigma^0 K^-$ ($\Sigma^0 \rightarrow \Lambda\gamma$, photon is not reconstructed) is also used for Ξ_b^{**-} reconstruction due to usage of mass difference variable $\Delta M = M(\Xi_b^- \pi^+ \pi^-) - M(\Xi_b^-) - 2m_{\pi^\pm}^{PDG}$

Ξ_b^{**-} decay scheme ($\Xi_b^- \to J/\psi\Xi^-$)

PRL 126 (2021) 252003

Similar scheme for $\Xi_b^- \to J/\psi\Lambda K^-$decay is provided in backup

Numbers in blue are average decay length, calculated as $c\tau$



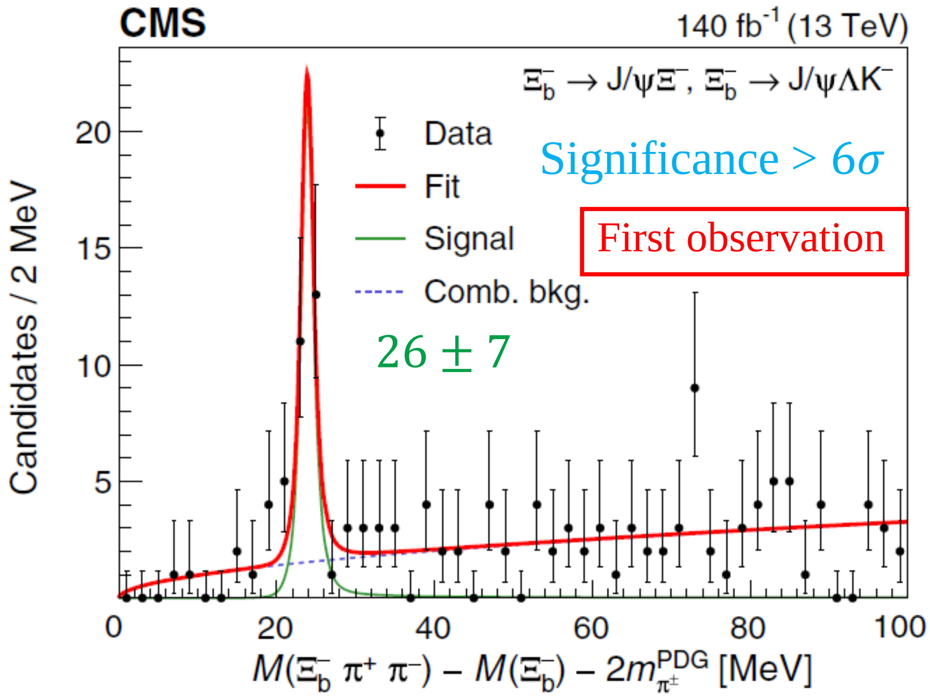
Intermediate decay $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$ is taken into account by requiring mass window $\delta m_{\Xi_b^-\pi^+} - \delta m_{\Xi_b^{*0}}^{PDG} < 5$ MeV

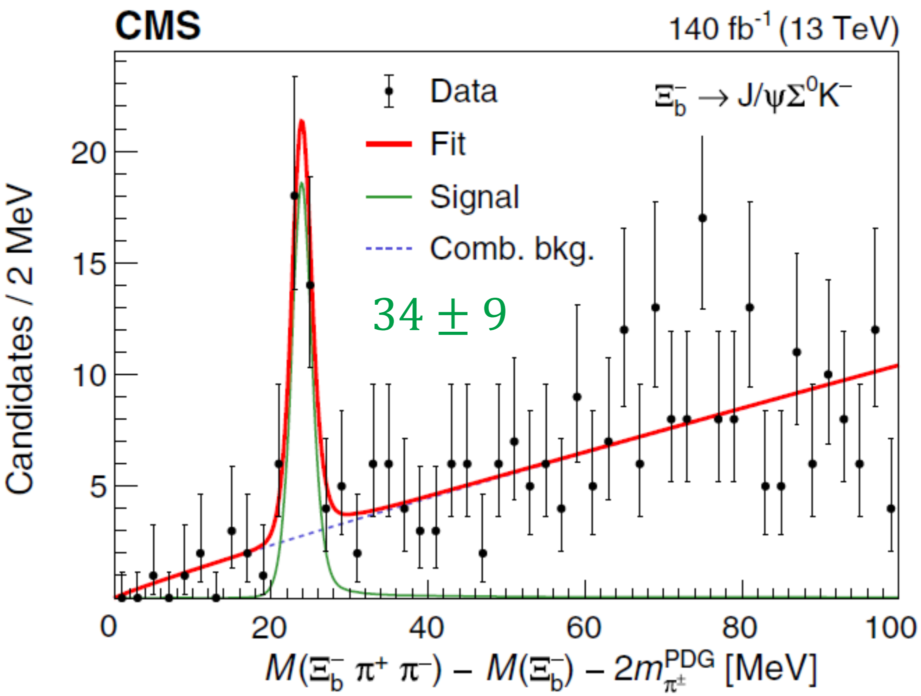
Ξ_b^{**-} signals

Using full RunII statistics the CMS Collaboration observed a clear signal of $\Xi_b(6100)^-$ in the $\Xi_b^-\pi^+\pi^-$ invariant mass spectrum near the threshold for all Ξ_b^- decay modes including partially reconstructed one

PRL 126 (2021) 252003

$$\Delta M = M(\Xi_b^-\pi^+\pi^-) - M(\Xi_b^-) - 2m_{\pi^\pm}^{PDG}$$





Simultaneous fit with common mass and natural width values

- Signal: Relativistic Breit-Wigner convolved with resolution from MC
- Background: threshold function $(x - x_0)^\alpha$

ΔM = 24.14±0.22 (stat.)±0.09 (syst.) MeV
$M[\Xi_b(6100)^-]$ = 6100.3±0.2 (stat.)±0.1 (syst.)±0.6 ($M(\Xi_b^-)$) MeV
$\Gamma[\Xi_b(6100)^-]$ < 1.9 MeV @ 95% CL

Summary

- $\mathrm{B_c^+}(2S)$ and $\mathrm{B_c^{+*}}(2S)$ cross setion ratios are measured
  - ✓ R^+, R^{*+} and R^{*+}/R^+ ratios do not demonstrate significant dependences on p_T and y of B_c^+ mesons
  - ✓ The normalized dipion invariant mass distributions for the $\mathrm{B_c^{+(*)}}(2S) \rightarrow \mathrm{B_c^+}\pi^+\pi^-$ are reported

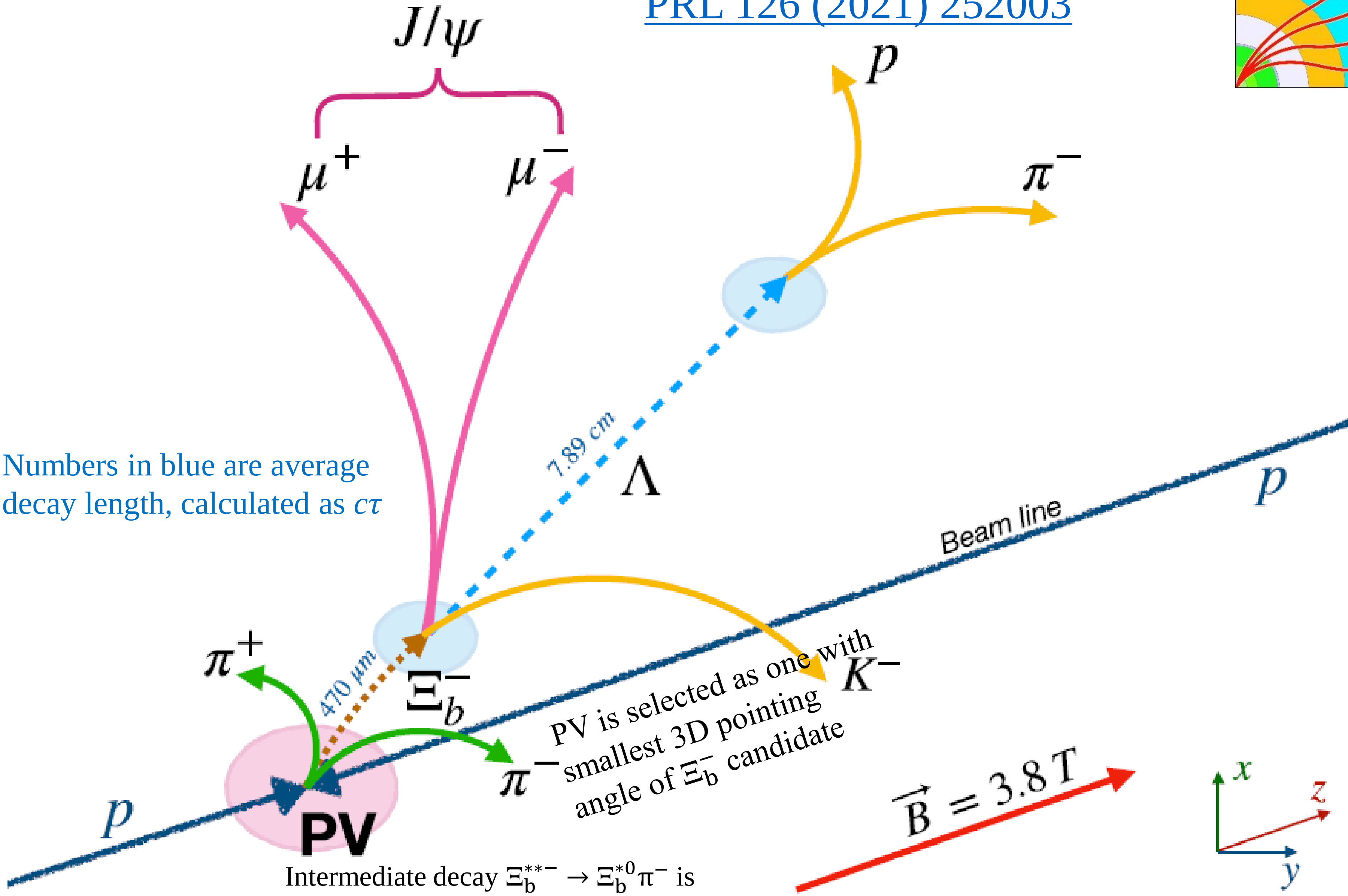
- New beauty strange $\Xi_\mathrm{b}(6100)^-$ baryon is observed in the $\Xi_\mathrm{b}^-\pi^+\pi^-$ final state for first time
  - ✓ Consistent with being the lightest orbitally excited Ξ_b^- baryon with $J^P = 3/2^-$ and orbital momentum *L* = *1* between *b* quark and light diqurark *ds*

Thank you for attention!

Backup slides

Ξ_b^{**-} decay scheme ($\Xi_b^- \to J/\psi\Lambda K^-$)

PRL 126 (2021) 252003



PV is selected as one with smallest 3D pointing angle of Ξ_b^- candidate

Numbers in blue are average decay length, calculated as $c\tau$

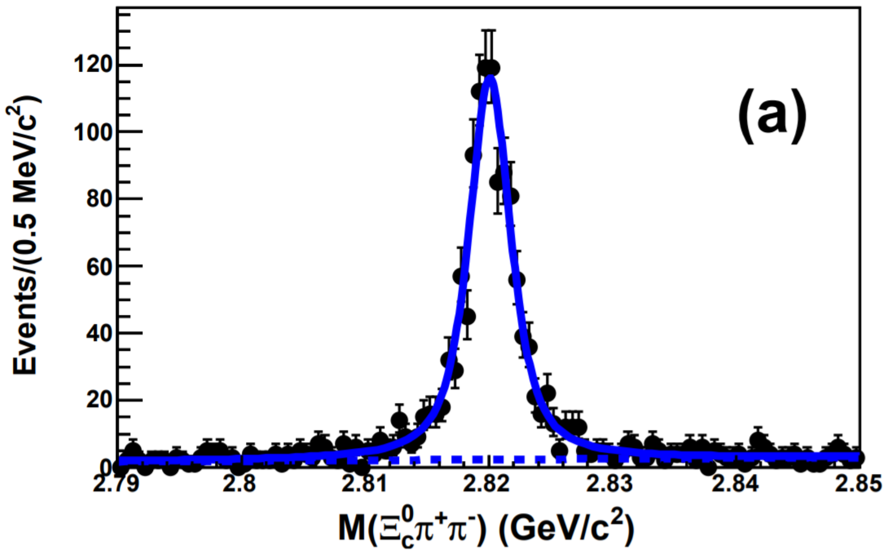
$\vec{B} = 3.8\,T$

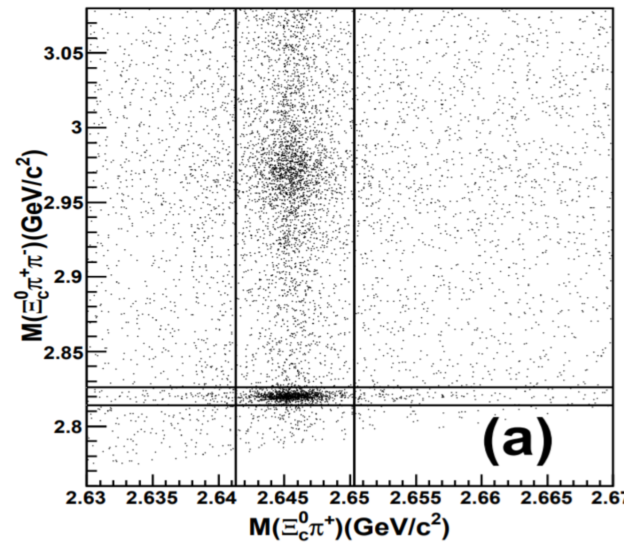
Intermediate decay $\Xi_b^{**-} \to \Xi_b^{*0}\pi^-$ is taken into account by requiring mass window $\delta m_{\Xi_b^-\pi^+} - \delta m_{\Xi_b^{*0}}^{PDG} < 5$ MeV

Charm sector analogy

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

PRD 94 (2016) 052011





- 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
- This analogy is a strong motivation to perform a 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})