Studies of pentaquarks at LHCb

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CLHCP 2017, Dec 22nd 2017 @Nanjing, China

Outline

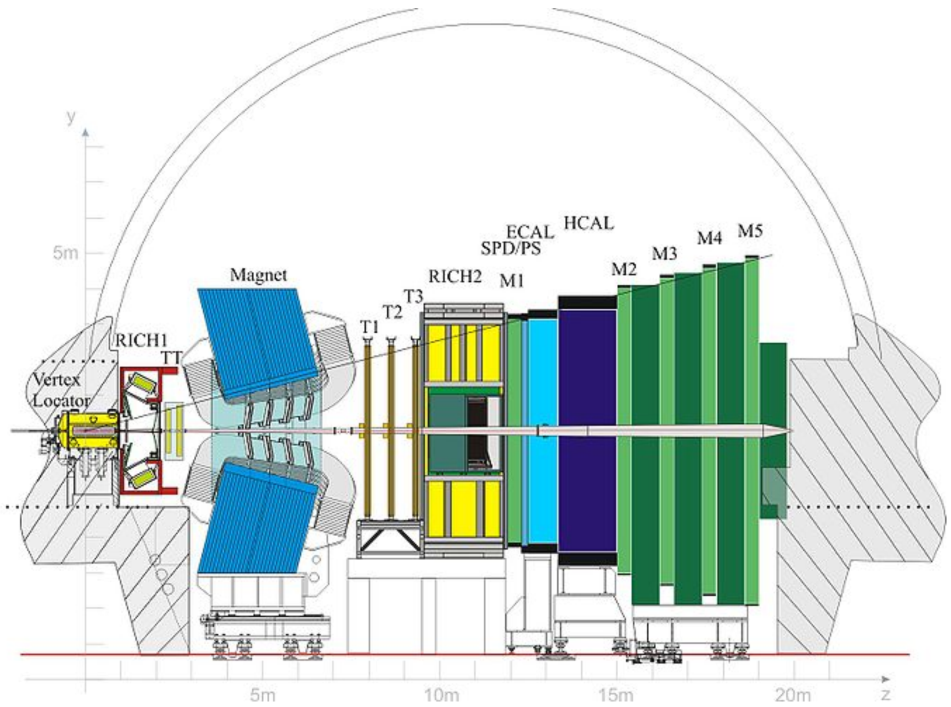
- The LHCb experiment
- Studies about pentaquarks from LHCb
  - Discovery of pentaquarks in Λ_b^0 decays
  - First observation of $\Lambda_b^0 \to \chi_{c\{1,2\}} p K^-$ decays
  - First observation of $\Xi_b^- \to J/\psi \Lambda K^-$ decays
- Summary

The LHCb experiment

- The LHC is a beauty and charm factory
  - In LHCb acceptance, $\sigma_{b\bar{b}} \sim 70(140)$ μb at $\sqrt{s} = 7(13)$ TeV

PRL. 118, 052002 (2017)

- The LHCb detector
  - Single-arm forward spectrometer, $2 < \eta < 5$
  - Designed for the study of heavy flavor physics



High-precision vertexing and tracking

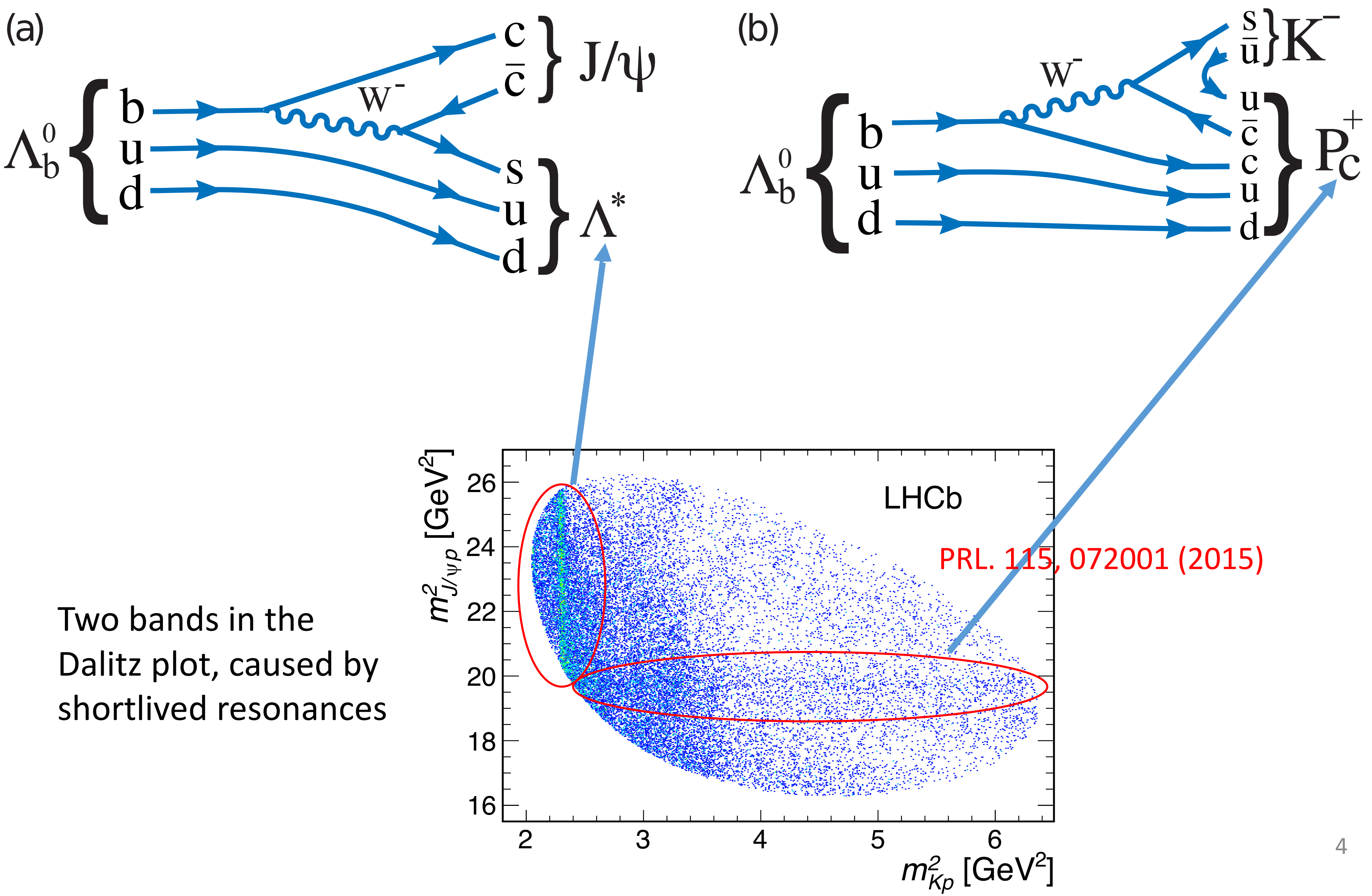
Excellent particle identification

Versatile trigger system

Int. J. Mod. Phys. A 30, 1530022 (2015)

JINST 3 (2008) S08005

Resonance in $\Lambda_b^0 \to J/\psi p K^-$ decays



PRL. 115, 072001 (2015)

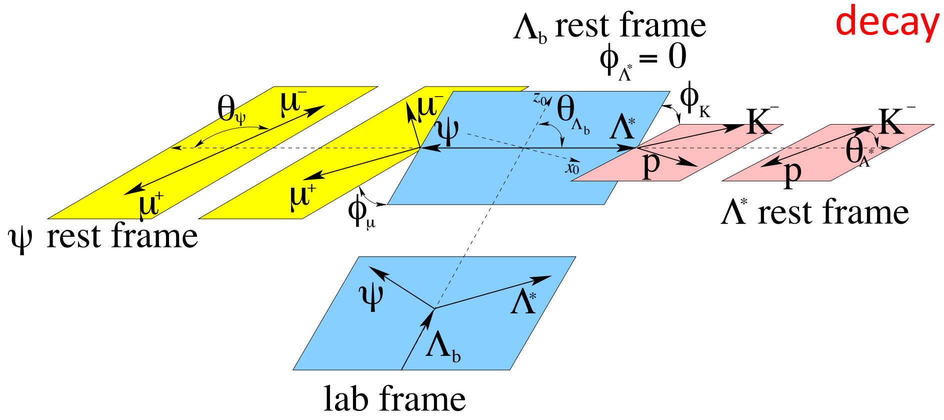
Two bands in the Dalitz plot, caused by shortlived resonances

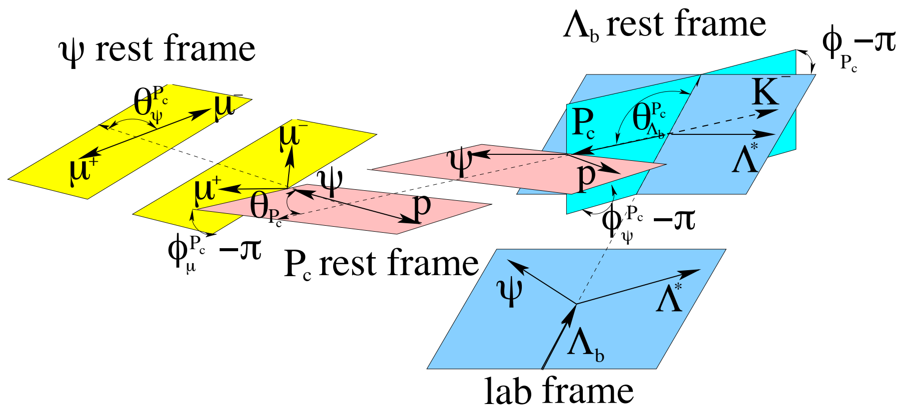
$\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

- Λ^* decay chain:
  - $\Lambda_b^0 \to J/\psi(\to \mu^+\mu^-)\Lambda^*(\to pK)$
- 5 angles and 1 mass
  - $\theta_{\Lambda_b^0}, \theta_K, \phi_K, \theta_\psi, \phi_\psi, m_{pK}$

- P_c^+ decay chain:
  - $\Lambda_b^0 \to P_c^+(\to J/\psi(\to \mu^+\mu^-)p)K$
- 6 angles and 1 mass
  - $\theta_{\Lambda_b^0}^{P_c}, \phi_{P_c}, \phi_\psi^{P_c}, \theta_{P_c}, \phi_\mu^{P_c}, \theta_\psi^{P_c}, \phi_\psi, m_{J/\psi p}$

Not independent to variables in Λ^* decay chain





- Fit the angular distributions. Each node contributes to a helicity coupling and angular structures
  - No float parameters in angular structure
  - Helicity couplings are float in fit

$\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

- Partial wave resonance function

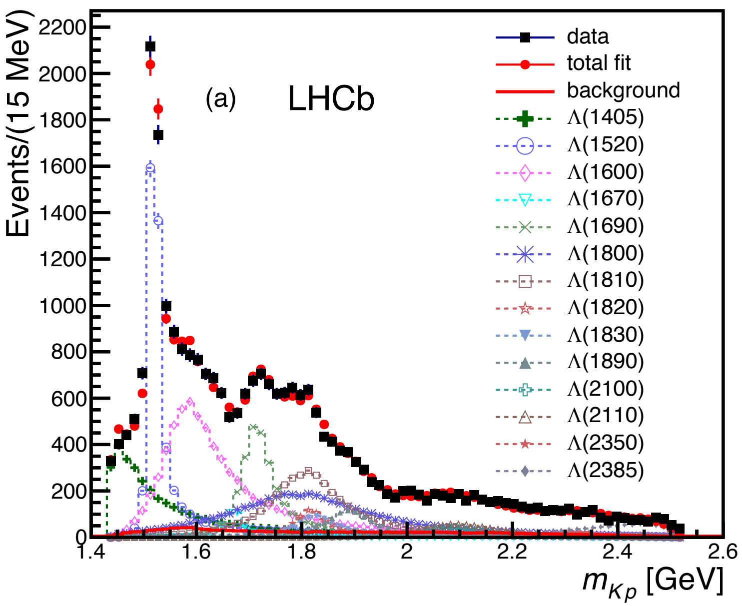
$$R_X(m) = \boxed{B'_{L^X_{\Lambda_b^0}}(p, p_0, d)} \left(\frac{p}{M_{\Lambda_b^0}}\right)^{L^X_{\Lambda_b^0}} \boxed{\mathrm{BW}(m|M_{0X}, \Gamma_{0X})} \boxed{B'_{L_X}(q, q_0, d)} \left(\frac{q}{M_{0X}}\right)^{L_X}$$

Blatt-Weisskopf — Relativistic Breit-Wigner — Blatt-Weisskopf

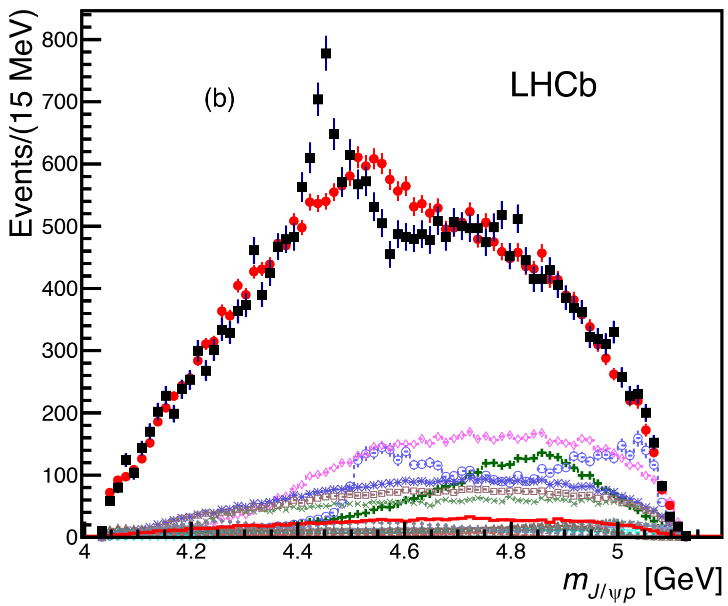
- The fit projection including only Λ^* states

PRL. 115, 072001 (2015)

acceptable



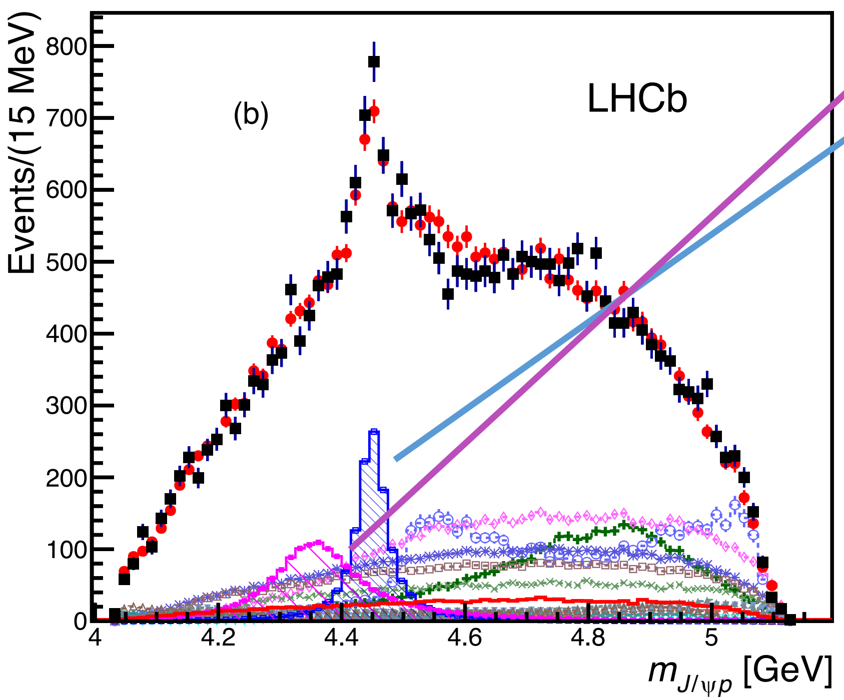
Not satisfactory



$\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

- Two P_c^+ states are required to get acceptable fits
  - 6D amplitude analysis allows to measure the resonance parameters

PRL. 115, 072001 (2015)



State	Mass(MeV/c^2)	Width(MeV/c^2)	J^P
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$\frac{3}{2}^-$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$\frac{5}{2}^+$

- The best solution of spin-parity is $(\frac{3}{2}^-, \frac{5}{2}^+)$, while $(\frac{3}{2}^+, \frac{5}{2}^-)$ and $(\frac{5}{2}^-, \frac{3}{2}^+)$ are not excluded
- The existence of these two particles is confirmed in another model-independent analysis

PRL. 117, 082002 (2016)

Branching fraction of $\Lambda_b^0 \to P_c^+(J/\psi p)K^-$

Chinese Physics C 40 (2016) 011001

- Absolute branching fraction of $\Lambda_b^0 \to J/\psi p K^-$ measured

$$R_{\Lambda_b^0/\bar{B}^0} = \frac{\sigma(\Lambda_b^0)B(\Lambda_b^0 \to J/\psi p K^-)}{\sigma(\bar{B}^0)B(\bar{B}^0 \to J/\psi K^{*0})}$$

From data

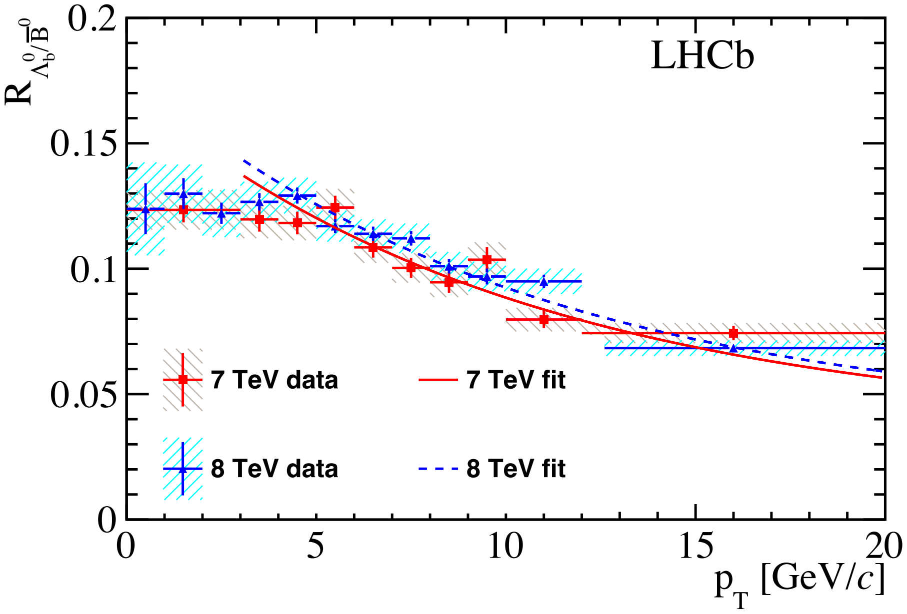
Result from Belle

PLB538 (2002) 11

Previous LHCb results

PRD 85, 032008 (2012)

JHEP 08(2014)143



Fraction of P_c^+ from the $\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

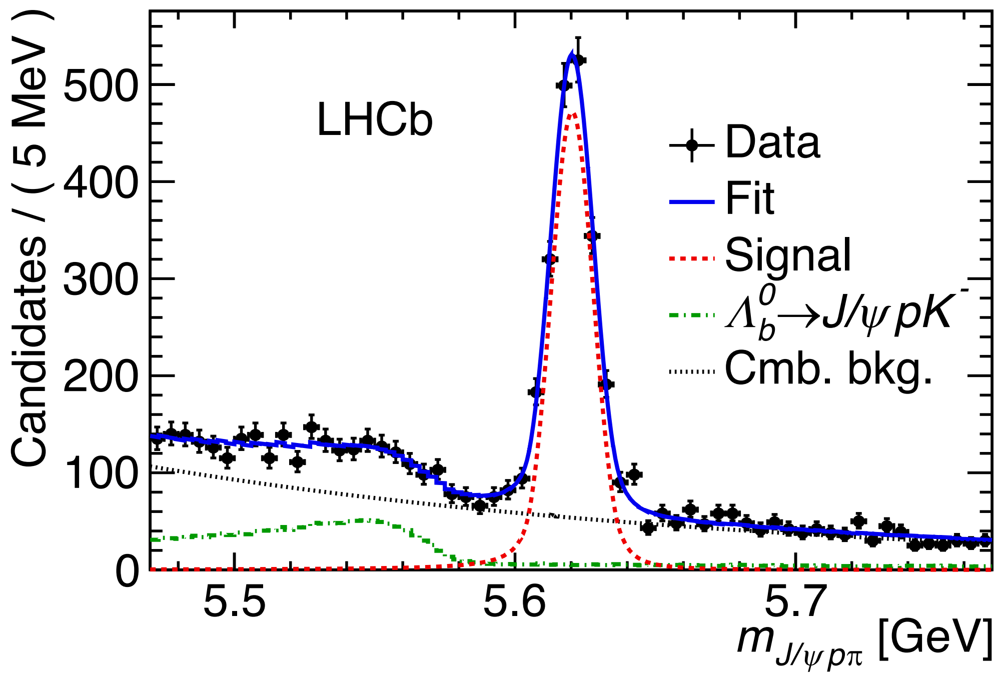
$$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = f(P_c^+)\mathcal{B}(\Lambda_b^0 \to J/\psi\, pK^-)$$

$$= \begin{cases} (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.38}) \times 10^{-5} & \text{for} \quad P_c(4380)^+, \\ (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18}) \times 10^{-5} & \text{for} \quad P_c(4450)^+, \end{cases}$$

$\Lambda_b^0 \to J/\psi p \pi^-$ amplitude analysis

- One way to examine the existence of P_c^+ resonance states: search them in other decay channels
- $\frac{B(\Lambda_b^0 \to J/\psi p \pi^-)}{B(\Lambda_b^0 \to J/\psi p K^-)} \sim 0.08$ due to Cabibbo suppression effect

PRL. 117, 082003 (2016)

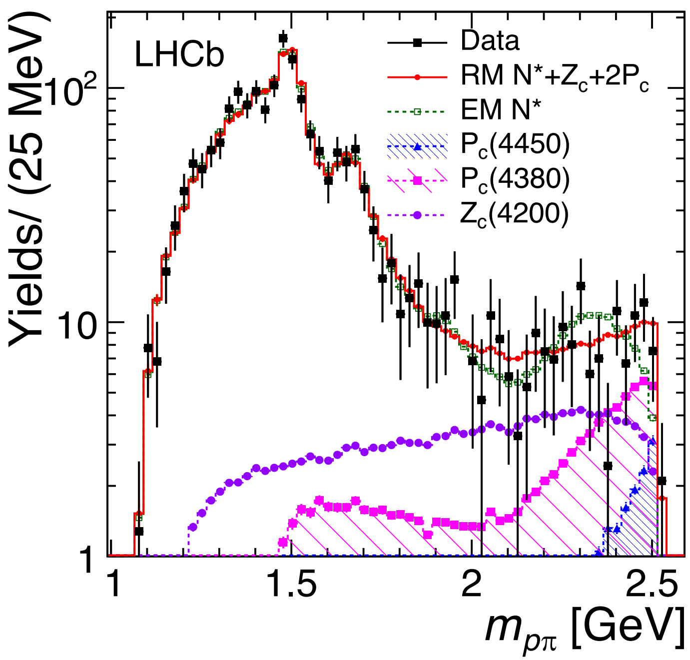


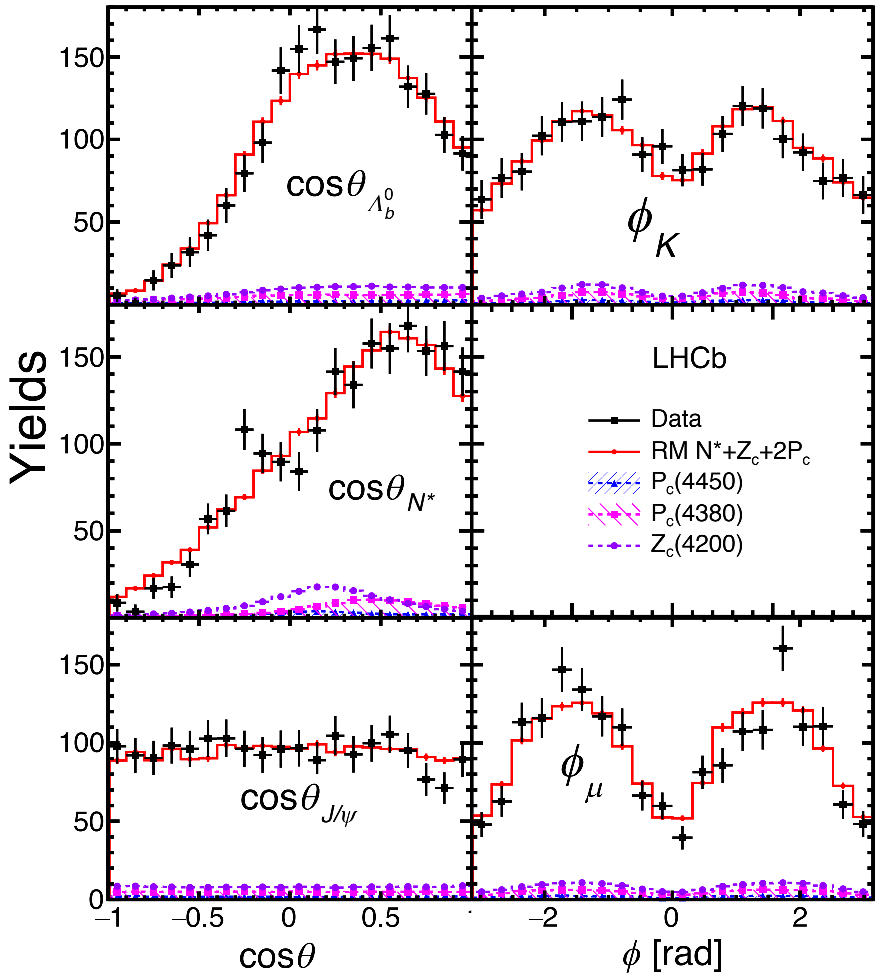
- Obtained 1885 ± 50 $\Lambda_b^0 \to J/\psi p \pi^-$ candidates with run-I data. Use them to examine the exotic hadron contribution from the $P_c^+ \to J/\psi p$ states.
- The amplitude model includes several $N^* \to p\pi^-$ resonances.

$\Lambda_b^0 \to J/\psi p\pi^-$ amplitude analysis

- If $P_c(4380)^+, P_c(4450)^+$ and $Z_c(4200)^-$ are included in fit model, the total significance for them is 3.1σ

PRL. 117, 082003 (2016)

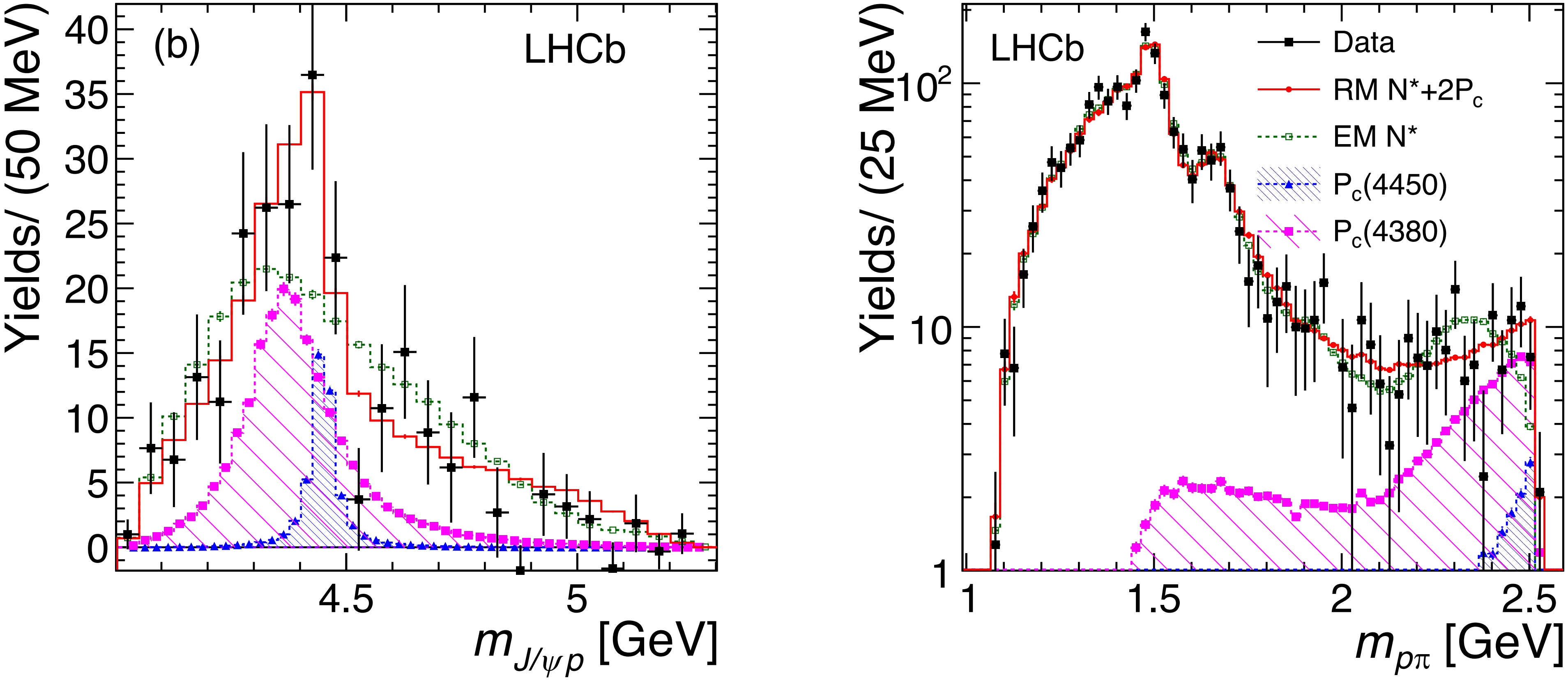




- The rate is consistent with the results of $\Lambda_b^0 \to J/\psi p K^-$ decays, taking into account the Cabibbo suppression.

$\Lambda_b^0 \to J/\psi p \pi^-$ amplitude analysis

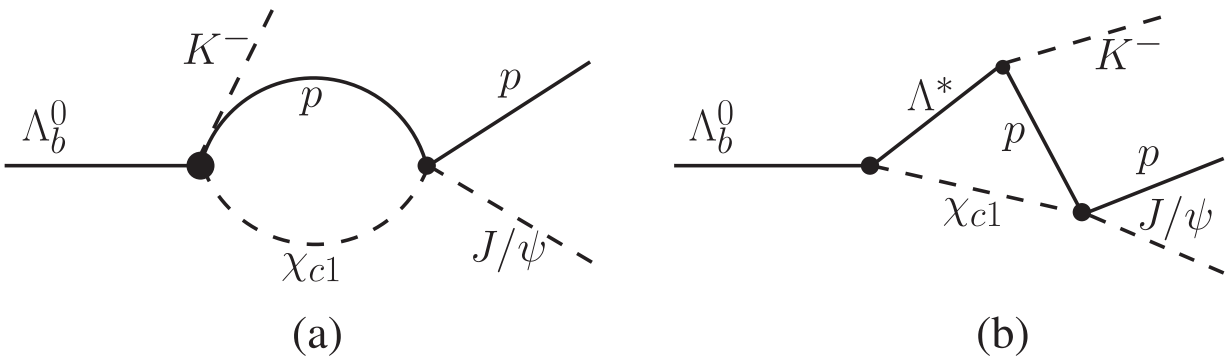
- If assume the contribution of $Z_c(4200)^-$ is negligible, the model with two P_c^+ resonance yields a significance of 3.3σ PRL. 117, 082003 (2016)



Observation of $\Lambda_b^0 \to \chi_{c\{1,2\}} p K^-$

- The $P_c(4450)^+$ mass is just above the $[\chi_{c1} p]$ threshold.
  - $m_{P_c(4450)^+} - m_{\chi_{c1}} - m_p \sim$ 0.9 MeV
- Real resonance or kinematic re-scattering?

PRD 92, 071502 (2015)

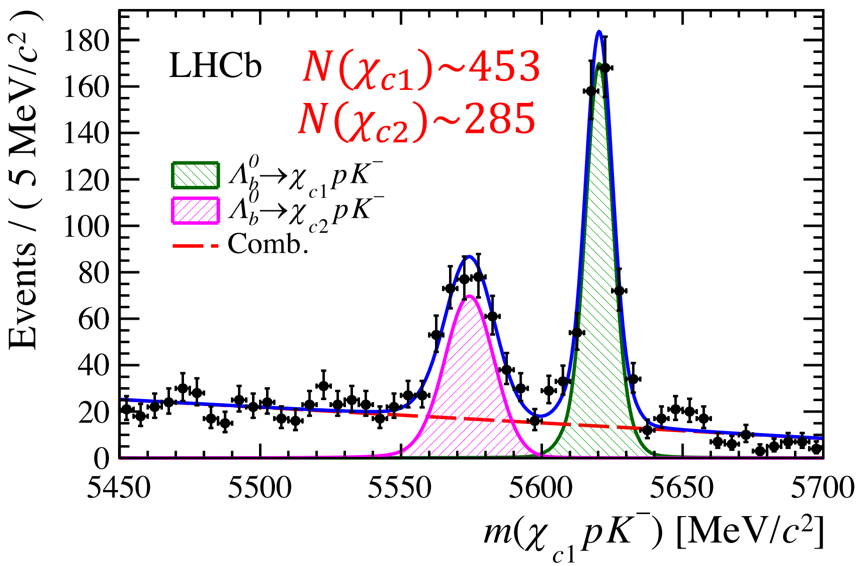


- Kinematic re-scattering would not lead to $P_c(4450)^+$ peaking in $[\chi_{c1} p]$ invariant mass
- The initial stage: observe these decays $\Lambda_b^0 \to \chi_{c\{1,2\}} p K^-$

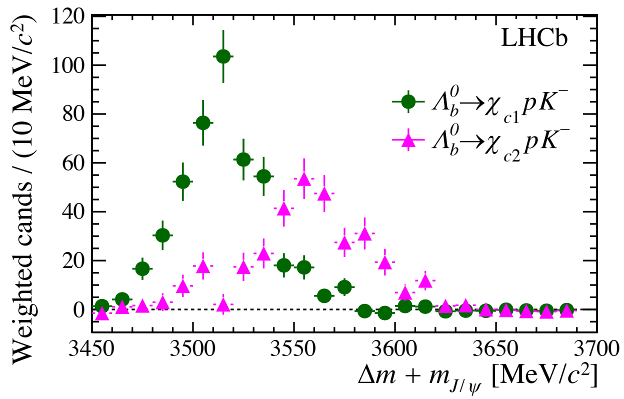
Observation of $\Lambda_b^0 \to \chi_{c\{1,2\}} p K^-$

- First observation with LHCb Run-I data. $\Lambda_b^0 \to J/\psi p K^-$ as control mode to measure the branching fractions
- Reconstruct $\chi_{c\{1,2\}}$ with $J/\psi\gamma,\ J/\psi$ with $\mu^+\mu^-$
- Gradient-boosted Decision Tree to subtract background
- Λ_b^0 mass fit with J/ψ and χ_{c1} mass constrained:
  - Mass peak of $\chi_{c2} p K^-$ is shifted (wrong mass hypothesis).

PRL. 119, 062001 (2017)



Background subtracted χ_{cJ} mass distribution, with no χ_{c1} mass-constraint



Observation of $\Lambda_b^0 \to \chi_{c\{1,2\}} p K^-$

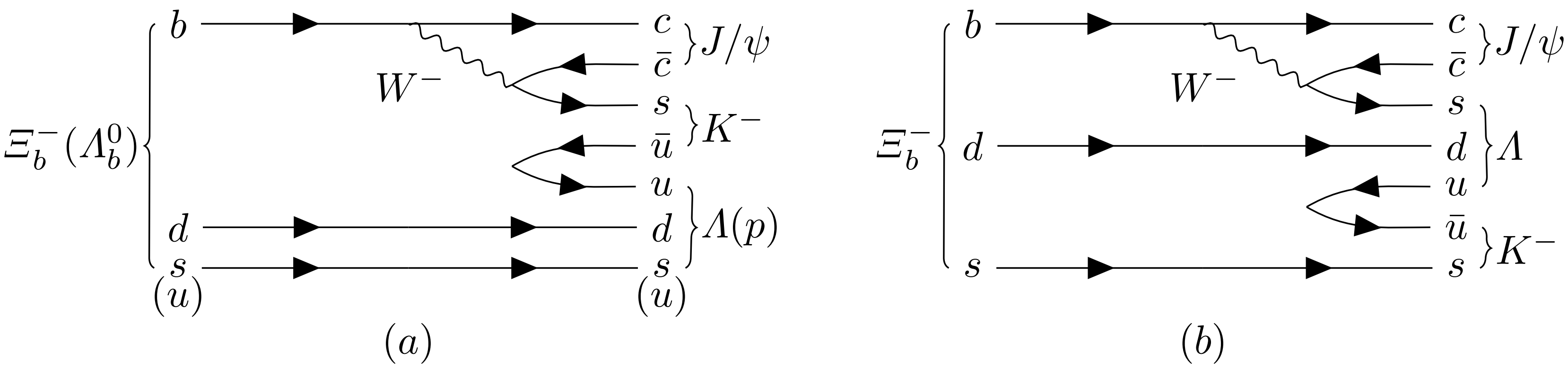
PRL. 119, 062001 (2017)

- Measure the branching fraction:
  - $\frac{B(\Lambda_b^0 \to \chi_{c1} p K^-)}{B(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.021, \frac{B(\Lambda_b^0 \to \chi_{c2} p K^-)}{B(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.026$
- Some unexpected difference with B^0 decays:
  - $\frac{B(\Lambda_b^0 \to \chi_{c2} p K^-)}{B(\Lambda_b^0 \to \chi_{c1} p K^-)} = 1.02 \pm 0.11, \frac{B(B^0 \to \chi_{c2} K^*)}{B(B^0 \to \chi_{c1} K^*)} = 0.17 \pm 0.05$
- Obtain 453 ± 25 χ_{c1} candidates. Need more data for the $m(\chi_{c1} p)$ investigation
- Number of χ_{c1} candidates with Run-I and Run-II data is expected to be 4 times compared to the Run-I data

PLB 772 (2017) 265-273

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

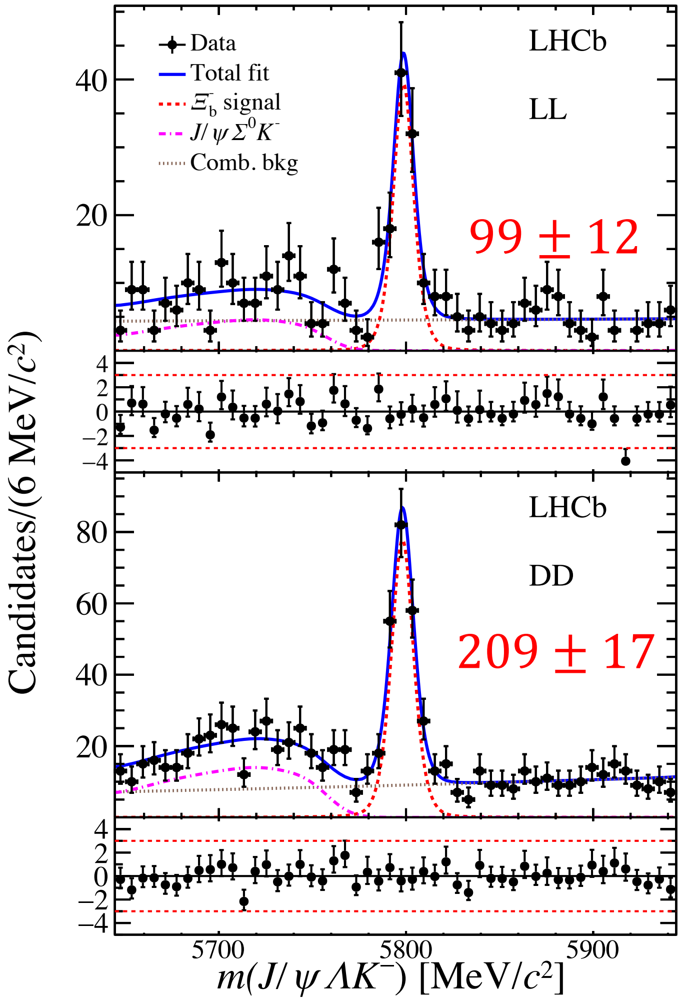
- Open strangeness pentaquark P_{cs} predicted in the $J/\psi\Lambda$ structure (m~4650 MeV, Γ~10 MeV)[PhysRevC.93.065203]
- Should be seen in $\Xi_b^- \to J/\psi \Lambda K^-$: similar topology as $\Lambda_b^0 \to J/\psi p K$, with a u-quark replaced by an s-quark



- First observation of this decay with entire Run-I data

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

- Use $\Lambda_b^0 \to J/\psi\Lambda$ as control channel.
- Reconstruct J/ψ with $\mu^+\mu^-$, reconstruct Λ with $p\pi^-$



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- Separate analyses for Λ that decays inside (LL) or outside (DD) the Vertex Detector
- Gradient-boosted Decision Tree for event selection
- $\frac{f_{\Xi_b}}{f_{\Lambda_b^0}} \frac{B(\Xi_b^- \to J/\psi\Lambda K^-)}{B(\Lambda_b^0 \to J/\psi\Lambda)} = 0.0419 \pm 0.0029 \pm 0.0014$
  - $f_{\{\Xi_b, \Lambda_b^0\}}$ are the $b \to \{\Xi_b, \Lambda_b^0\}$ fragmentation functions.
- An amplitude analysis is expected with Run-I and Run-II data

Summary

- LHCb is a huge factory of heavy quark baryons
- Discovery of two pentaquark states in $\Lambda_b^0 \to J/\psi p K^-$ decays
- Search for P_c^+ resonances in other decay channels
  - Analysis in $\Lambda_b^0 \to J/\psi p \pi^-$ decays shows consistent results
  - First observation of $\Lambda_b^0 \to \chi_{c\{1,2\}} p K^-$ decays
    - Amplitude analysis is under way for possible $\chi_{c1} p$ structure
- Search for new kind of pentaquarks
  - First observation of $\Xi_b^- \to J/\psi \Lambda K^-$ decays
    - Search for open strangeness pentaquark P_{cs} expected

Thank you for your attention!