



***b*-baryon decays and the search for exotic hadrons at LHCb**

Xuesong Liu

Tsinghua University

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Outline

- ① Introduction
- ② Studies of $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ decays
- ③ Observation of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decays
- ④ Summary and future perspective

Multi-quark states in quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

8182/TH. 401

17 January 1964

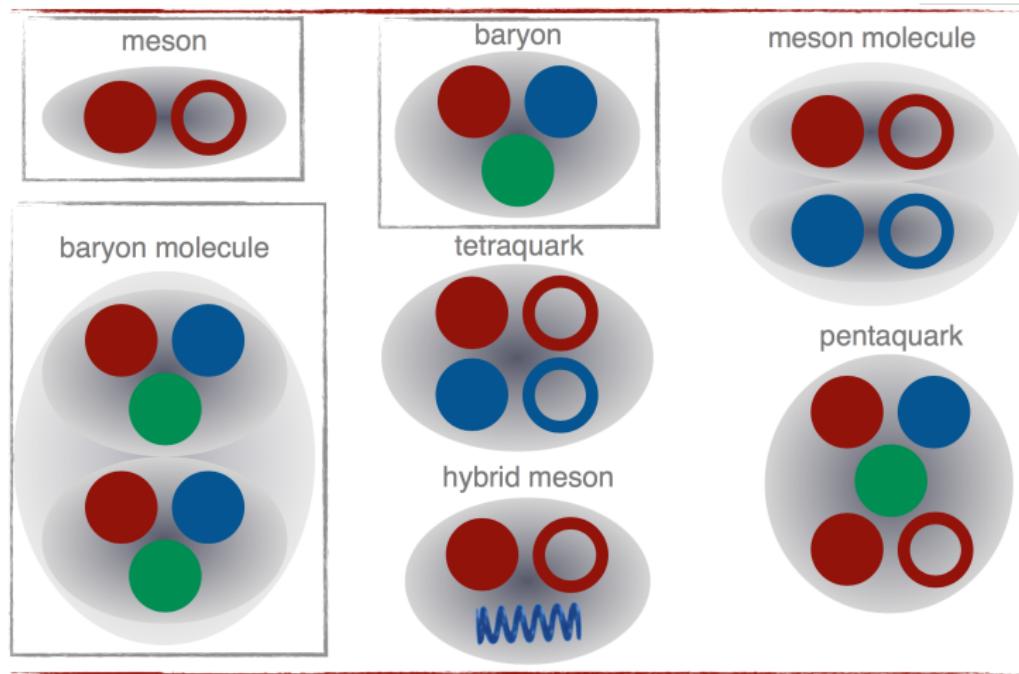
G. Zweig *)

CERN - Geneva

- Both papers mentioned explicitly the possibility for penta-quark states: $qqqq\bar{q}$
- Later in context of specific QCD models:
Jafee (76), Hogaasen & Sorba (78),
Strottman (79)



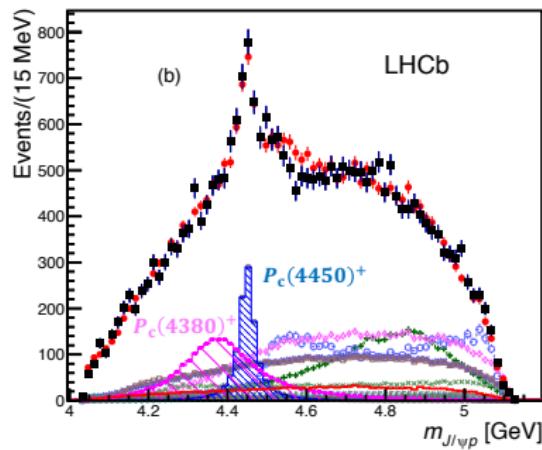
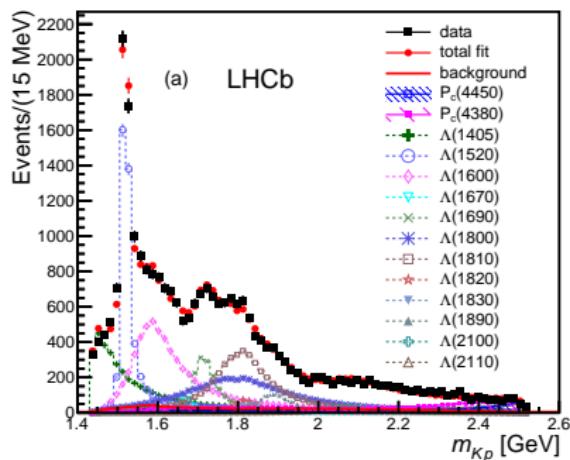
Pentaquark



- No obvious reasons for their non-existence
- Fertilize our understanding of QCD
- No convinced experimental evidence for light pentaquark

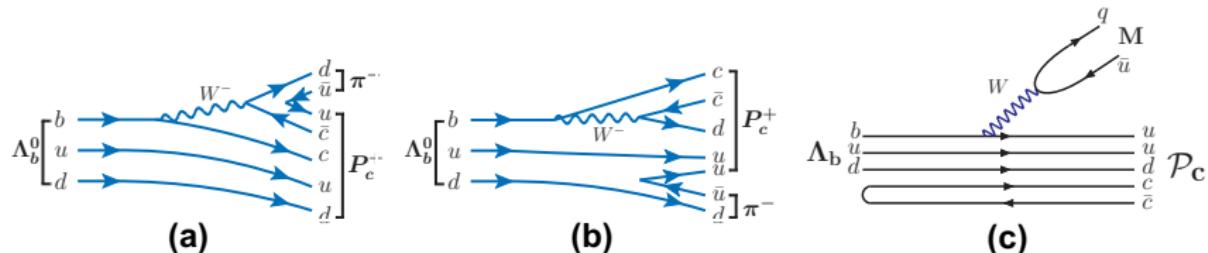
Pentaquark states in $\Lambda_b^0 \rightarrow J/\psi p K^-$ [PRL115(2015)072001]

- 2015: Two pentaquarks discovered by LHCb!!!
- A six-dimensional amplitude fit was done. 9σ and 12σ significances for two P_c states.



- However, J^P have three possibilities $(3/2^-, 5/2^+)$, $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ which need further check.

Search for exotics in $\Lambda_b^0 \rightarrow J/\psi p\pi^-$



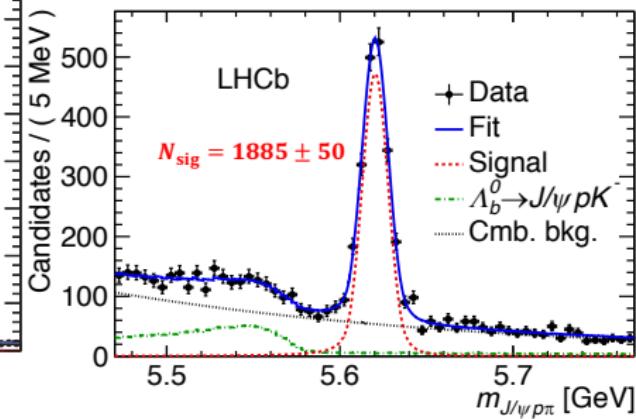
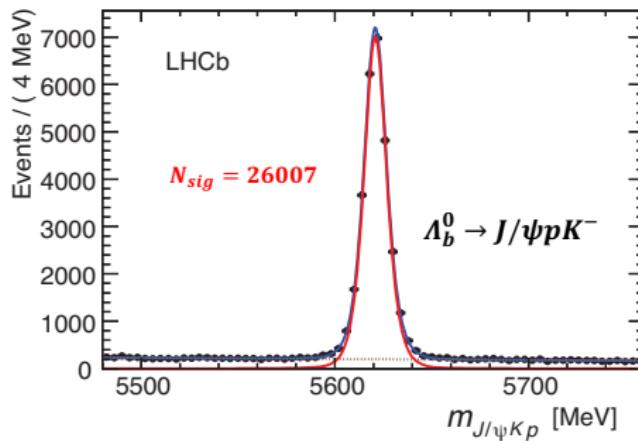
- Observing the same P_c states in a different decay mode could indicate they are really resonances and not some kinematical effects [PRD 93,094001(2016)]
- Cabibbo-suppressed Λ_b^0 decays to baryonic exotic resonances are predicted to have

$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \rightarrow K^- P_c^+)}$$

- $R \approx 0.07 - 0.08$ Fig(a)(b) [PRD 92,096009(2015)]
- $R = 0.58 \pm 0.05$ Fig(c) [PLB 572-575,751(2015)]

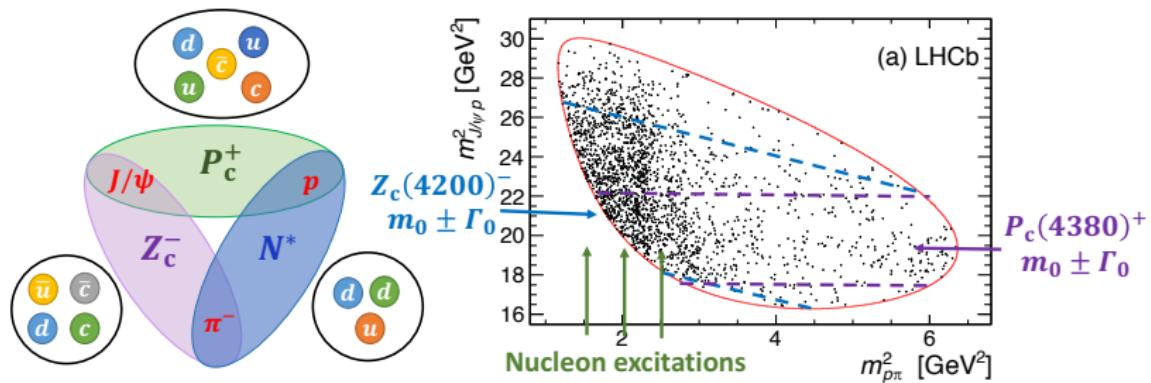
Studies of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ decays [PRL117, 082003(2016)]

- Analysis: six-dimensional amplitude fit(invariant masses, helicity and decay planes angles)

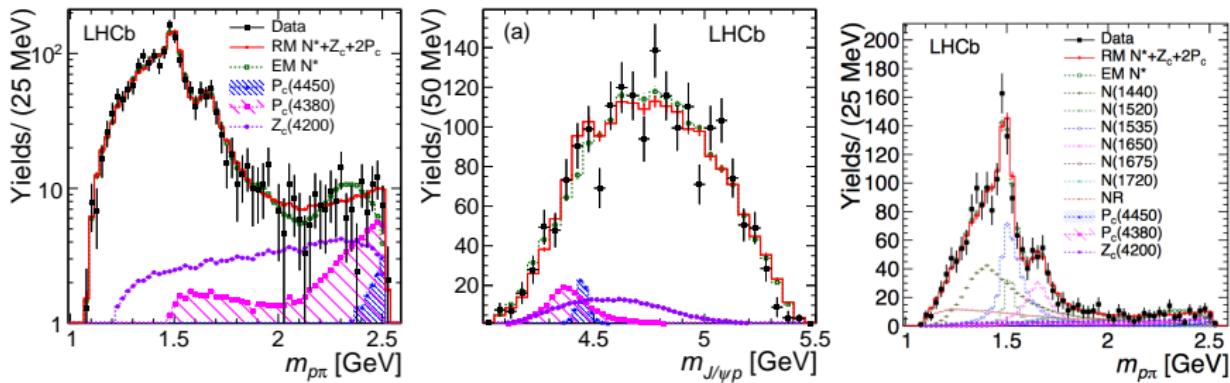


Possible exotic contribution in $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

- More complex due to possible Z_c^- states
- Exotic hadron contributions examined are:
 $P_c(4380)^+, P_c(4450)^+ \rightarrow J/\psi p$ and $Z_c(4200)^- \rightarrow J/\psi \pi^-$
- $Z_c(4200)^- : m_0 = 4196^{+35}_{-32} \text{ MeV}, \Gamma_0 = 370^{+99}_{-149} \text{ MeV}$
 $J^P = 1^+$ by Belle(6.2σ) in $B^0 \rightarrow J/\psi \pi^- K^+$ decays

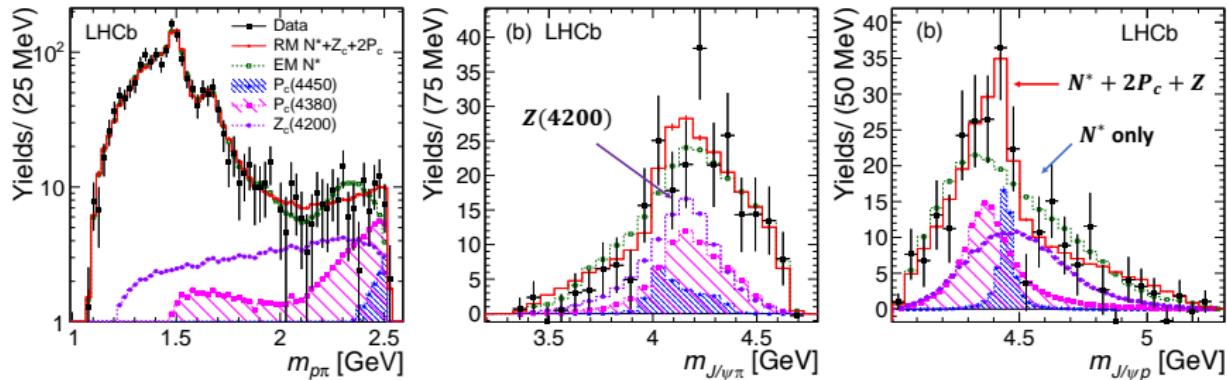


Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$



- No obvious structure in $m(J/\psi p)$.
- Breit-Wigners for all resonances. Flatte for $N(1535)$ to account for the threshold of $n\eta$ channel.
- Check consistency with the two P_c states from $\Lambda_b^0 \rightarrow J/\psi p K^-$

Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$



- Introduce exotic states can significantly improve N^* fit quality.
- Significance of two P_c is 3.3σ , if assume production of $Z_c(4200)^-$ is negligible. No independent confirmation of P_c^+ states.
- Significance of both type of exotics taken together is 3.9σ , with syst. considered is 3.1σ

Amplitude analysis of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

- 15 established N^* states
- Reduced(RM): central values
- Extended(EM): syst. +signif.

State	J^P	M_0 (MeV)	Γ_0 (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	0	3
$N(1700)$	$3/2^-$	1700	150	0	3
$N(1710)$	$1/2^+$	1710	100	0	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	0	3
$N(1900)$	$3/2^+$	1900	200	0	3
$N(2190)$	$7/2^-$	2190	500	0	3
$N(2220)$	$9/2^+$	2250	400	0	0
$N(2250)$	$9/2^-$	2275	500	0	0
$N(2600)$	$11/2^-$	2600	650	0	0
$N(2300)$	$1/2^+$	2300	340	0	3
$N(2570)$	$5/2^-$	2570	250	0	3
Free parameters			40	106	

- Without the high-mass and low spin $N^*(N(2300), N(2570))$, the exotic states have more than 5σ
- Better understanding conventional resonances is important for exotic searches.

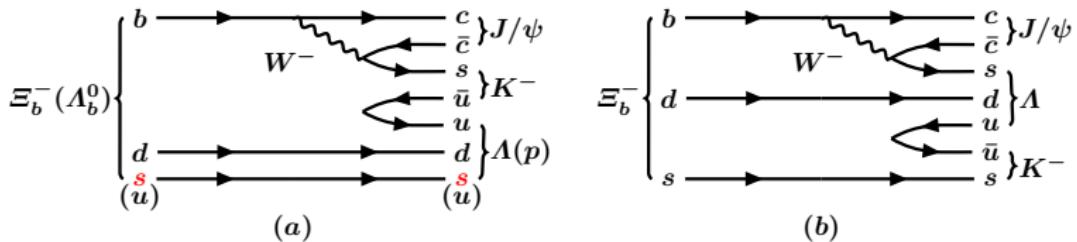
Futher results of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$

State	Fit fraction(%)	$\mathcal{B}(\Lambda_b^0 \rightarrow \pi^- P_c^+)/\mathcal{B}(\Lambda_b^0 \rightarrow K^- P_c^+)$
$Z_c(4200^-)$	$7.7 \pm 2.8^{+3.4}_{-4.0}$	---
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.6}_{-1.6}$	$0.050 \pm 0.016^{+0.026}_{-0.016} \pm 0.025$
$P_c(4450)^+$	$1.6^{+0.8+0.6}_{-0.6-0.5}$	$0.033^{+0.016+0.011}_{-0.014-0.010} \pm 0.009$

- $R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \rightarrow K^- P_c^+)}$ tests P_c^+ production mechanism
 - $R \approx 0.07 - 0.08$ ✓
 - $R = 0.58 \pm 0.05$ ✗
- Overall outlook: $J/\psi p\pi$ data is **consistent** with P_c 's seen in $J/\psi pK$

Search for $\Xi_b^- \rightarrow J/\psi \Lambda K^-$

- $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decays is similar to that of $\Lambda_b^0 \rightarrow J/\psi p K^-$



- A strange hidden-charm pentaquark state, decaying into $J/\psi \Lambda$ can be searched through $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decays.
[PRL 105,232001(2010)][PRC 93,065203(2016)]

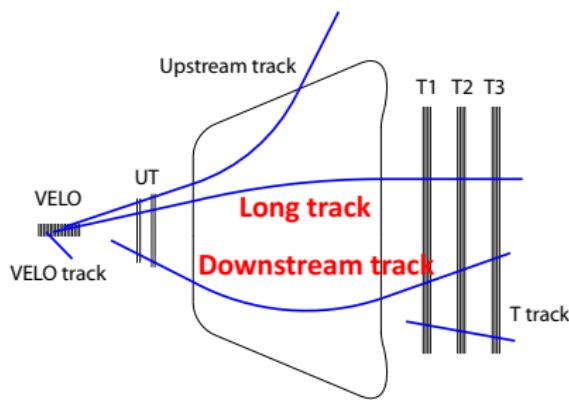
Analysis strategy for $\Xi_b^- \rightarrow J/\psi \Lambda K^-$

- Using 3 fb^{-1} full Run-I data
- Measure the branching fraction related to $\Lambda_b^0 \rightarrow J/\psi \Lambda$

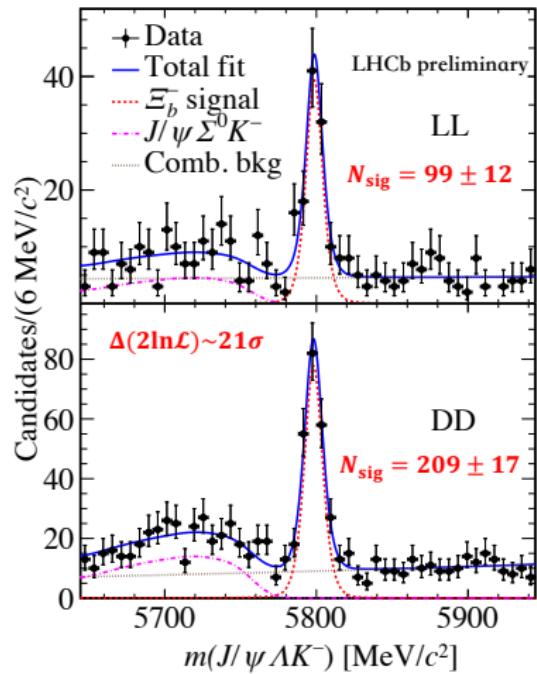
$$R = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \times \frac{\mathcal{B}(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = \frac{N(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{N(\Lambda_b^0 \rightarrow J/\psi \Lambda)} \times \frac{\epsilon_{\Lambda_b^0}^{tot}}{\epsilon_{\Xi_b^-}^{tot}}$$

- $f_{\Xi_b^-}/f_{\Lambda_b^0}$ is the ratio of fragmentation fractions
- Fiducial range: $p_T < 25 \text{ GeV}$, $2.0 < y < 4.5$ on b -baryons
- BDTG is used to further discriminate between signal and combinatorial background
- Efficiencies estimated with simulation and data

Signal yield of the two modes



Two types of tracks used to reconstruct Λ .



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

- Results

$$R_{\Xi_b^-/\Lambda_b^0} \equiv \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \times \frac{\mathcal{B}(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29(\text{stat.}) \pm 0.14(\text{syst.})) \times 10^{-2}$$

$$\delta M \equiv M(\Xi_b^-) - M(\Lambda_b^0) = 177.08 \pm 0.47 \pm 0.16 \text{ MeV}/c^2$$

- A simultaneous fit is performed to the four samples, and the fit gives an identical results for the ratio $R_{\Xi_b^-/\Lambda_b^0}$.
- Consistent with the LHCb measurement using open-charm decays: $\delta M = 178.36 \pm 0.46 \pm 0.16 \text{ MeV}/c^2$.
[PRL 113,242002(2014)]

Most precise!!!

Conclusions

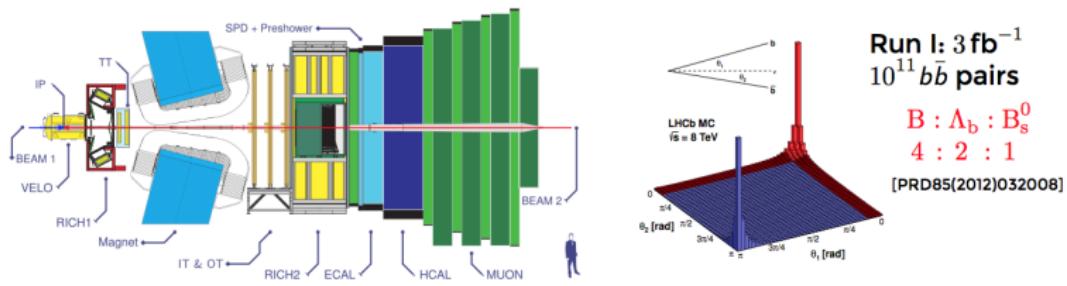
- $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ analysis supports the pentaquark states observed in the amplitude analysis in $\Lambda_b^0 \rightarrow J/\psi pK^-$ decays
- $\Xi_b^- \rightarrow J/\psi \Lambda K^-$ decay is first observed, the δM between Λ_b^0 and Ξ_b^- is measured. Full amplitude analysis will perform after LHC Run-II !
- Several analysis processing are digging the structure and physics nature of pentaquarks in LHCb
 - $\Lambda_b \rightarrow J/\psi p\pi K_s^0$
 - $\Lambda_b \rightarrow \chi_{c1}(1P) pK$
 - $\Lambda_b \rightarrow \Lambda_c^+ \bar{D}^0 K$
 - ...
- Looking forward to RunII to obtain further exciting results!

Thanks and stay tuned!

Back up

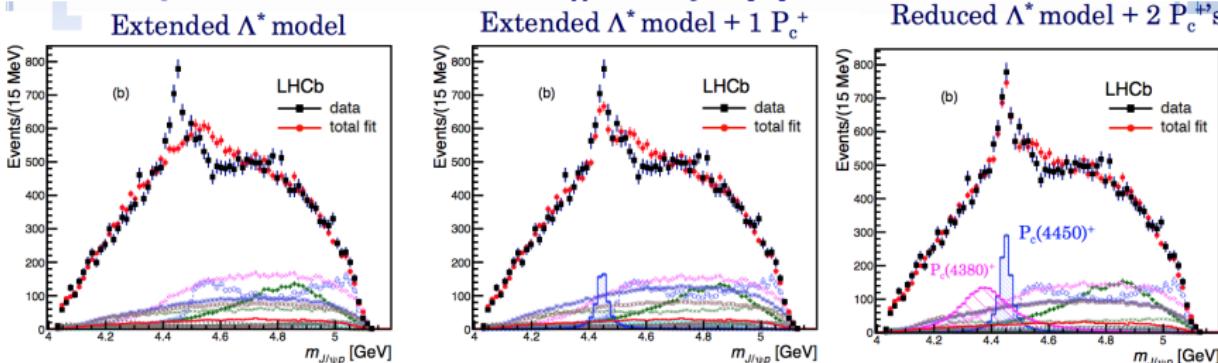
The LHCb Experiment [IJMP A30(2015)1530022]

- LHCb is single-arm ($2 < \eta < 5$) spectrometer at the LHC
 - CP violation measurements, rare decays,
heavy flavour decays as source for exotic hadrons
 - Exploit the correlated production of $b\bar{b}$ pairs in LHC environment



- Clean B-hadron samples through excellent vertex resolution: $\mathcal{O}(\infty \nabla) \preceq m(\text{VELO})$
- Flavor tagging, final state discrimination needs excellent particle ID (RICH)
- Highly efficient trigger: di-muons, displaced vertices (topological B-hadron), ..

Pentaquark states in $\Lambda_h^0 \rightarrow J/\psi p K^-$ [PRL115(2015)072001]

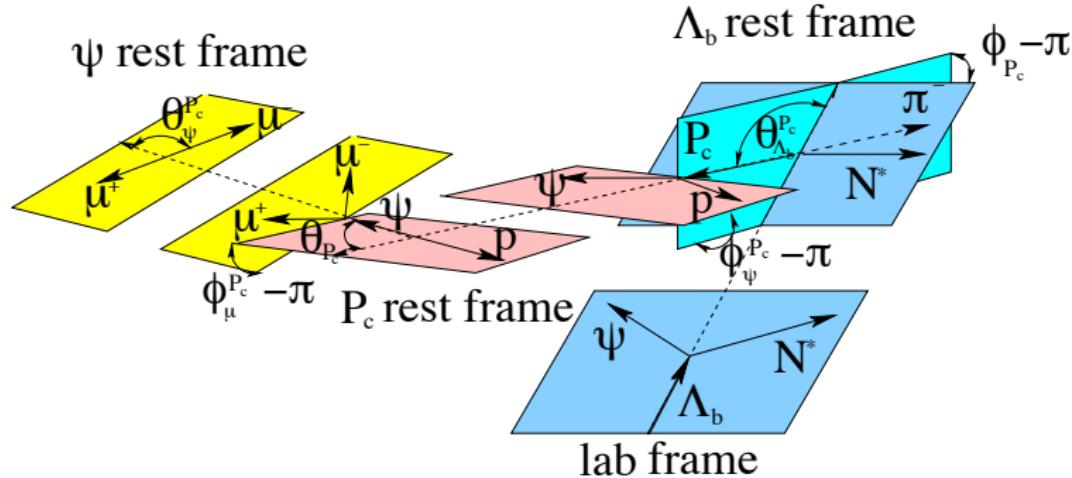


State	Mass(MeV)	Width(MeV)	Fit fraction(%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$

- Obtain good fits with reduced $\Lambda^* + 2$ Pentaquarks model.
- Best fits has $J^P = (3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ are preferred.
- Interference of two states of opposite parity required by forward-backward asymmetry in P_c helicity angle

Some details of $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ analysis

- Six-dimensional amplitude fit: resonance invariant mass, three helicities angles, and two differences between decay planes
- Lorentz transformations relates the two helicity representantions



- Resonances described by Breit-Wigner
- Angular distribution calculated using helicity formalism.