Pentaquark Candidates at LHCb

Liming Zhang, Tsinghua University

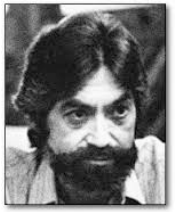
On behalf of the LHCb Collaboration

22 August, 2017

Exotic Hadrons at ICNFP2017

Quark model

In the beginning of quark model, multiquark objects were predicted - now called exotic



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

...

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig
CERN--Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\overline{A}AAAA$, $\overline{AA}AAAA$, etc., where $\overline{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\overline{A}A$, $\overline{AA}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\overline{A}A$ and AAA, that is, "deuces and treys".

$qqqq\bar{q}$ baryons later called “pentaquarks”;
$qq\bar{q}\bar{q}$ meson called “tetraquarks”

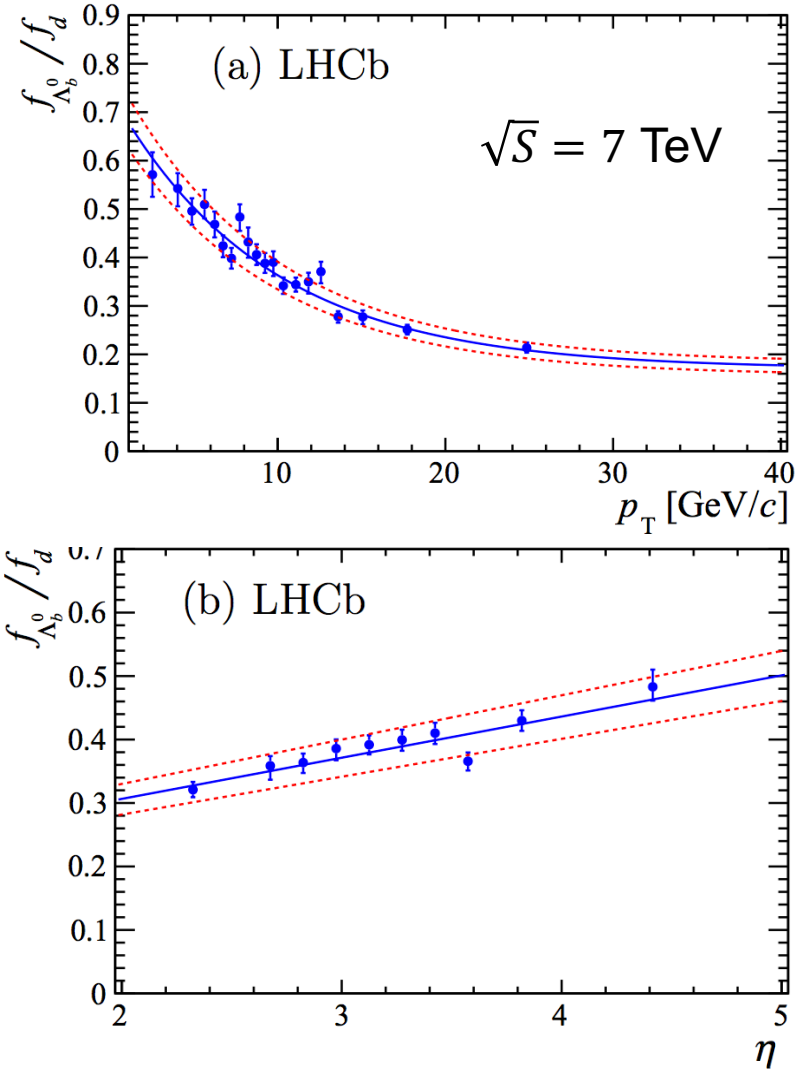
Why pentaquarks?

- Interest in pentaquarks arises from the fact that they would be new type of particles beyond the simple quark-model picture. Could teach us a lot about QCD.
- There is no reason they should not exist
  - Predicted by Gell-Mann (64), Zweig (64), others later in context of specific QCD models: Jaffe (76), Högaasen & Sorba (78), Strottman (79), Lipkin (87)
- These would be short-lived ~10^{-23} s "resonances" whose presence is detected by mass peaks & angular distributions showing the presence of unique J^P quantum numbers

$P_c(4380)^+, P_c(4450)^+ \rightarrow J/\psi p$ in $\Lambda_b^0 \rightarrow J/\psi p K^-$

Full amplitude fit and
model-independent approach

$f_{\Lambda_b^0}/f_d$



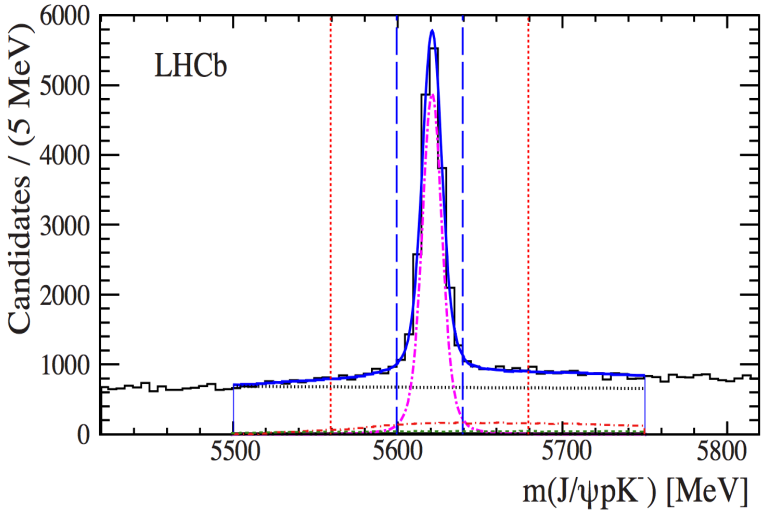
- Determine the p_T and η dependence of $f_{\Lambda_b^0}/f_d$

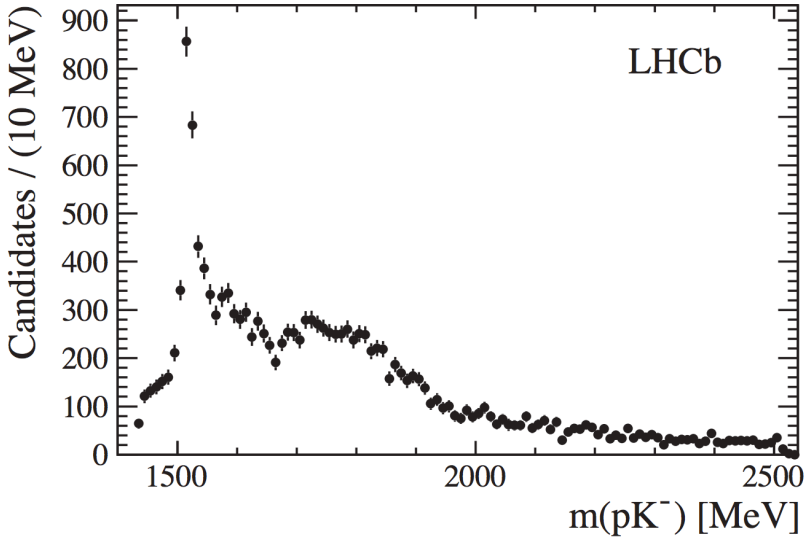
[LHCb, JHEP 08(2014) 143, arXiv:1405.6842]

- Clear increase of Λ_b^0 at low p_T and large η

- The LHCb is a Λ_b^0 factory: 4:2:1 ≈ B^0:Λ_b^0:B_s in LHCb acceptance

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





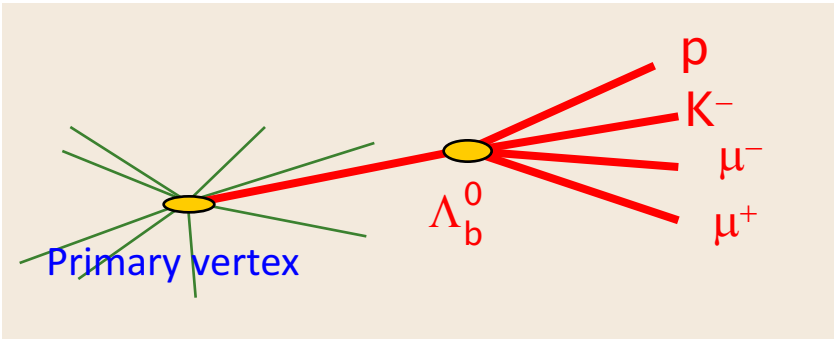
- First observation of the decay with 2011 data
- Unexpected large yield, interesting structure in pK mass
- Used to measure Λ_b^0 lifetime

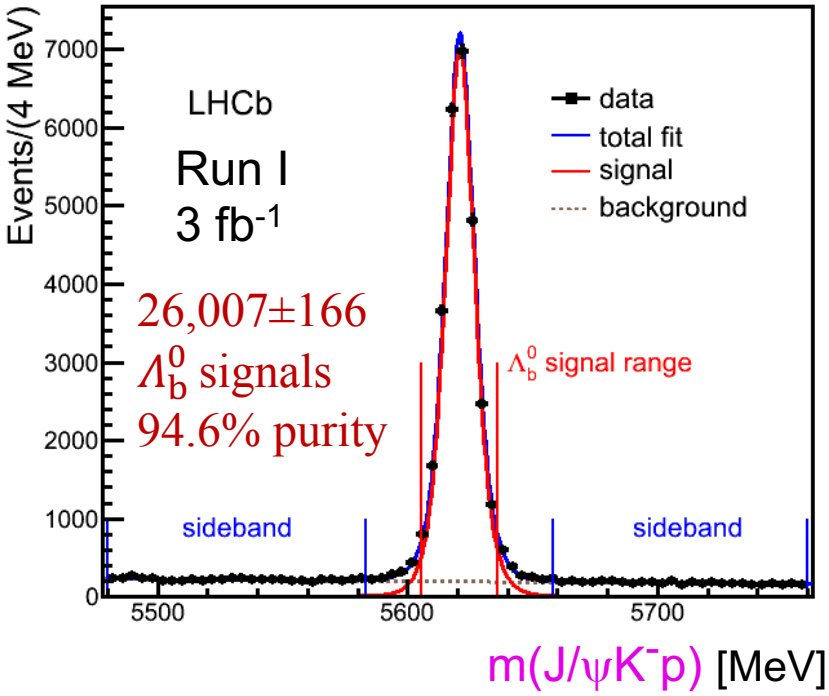
[LHCb, PRL 111 (2013) 102003, arXiv:1307.2476]

Update with 2011+2012 data
[LHCb, PLB 734 (2014) 122, arXiv:1402.6242]

Data and selection

- 2011+2012 3 fb^{-1}
- Reoptimized selection
- $\bar{B}_s^0 \to J/\psi K^- K^+$ & $\bar{B}^0 \to J/\psi K^- \pi^+$ misID backgrounds are vetoed
- Neural network based selection
- Large and clean Λ_b^0 signals





[PRL 115, 072001 (2015)]

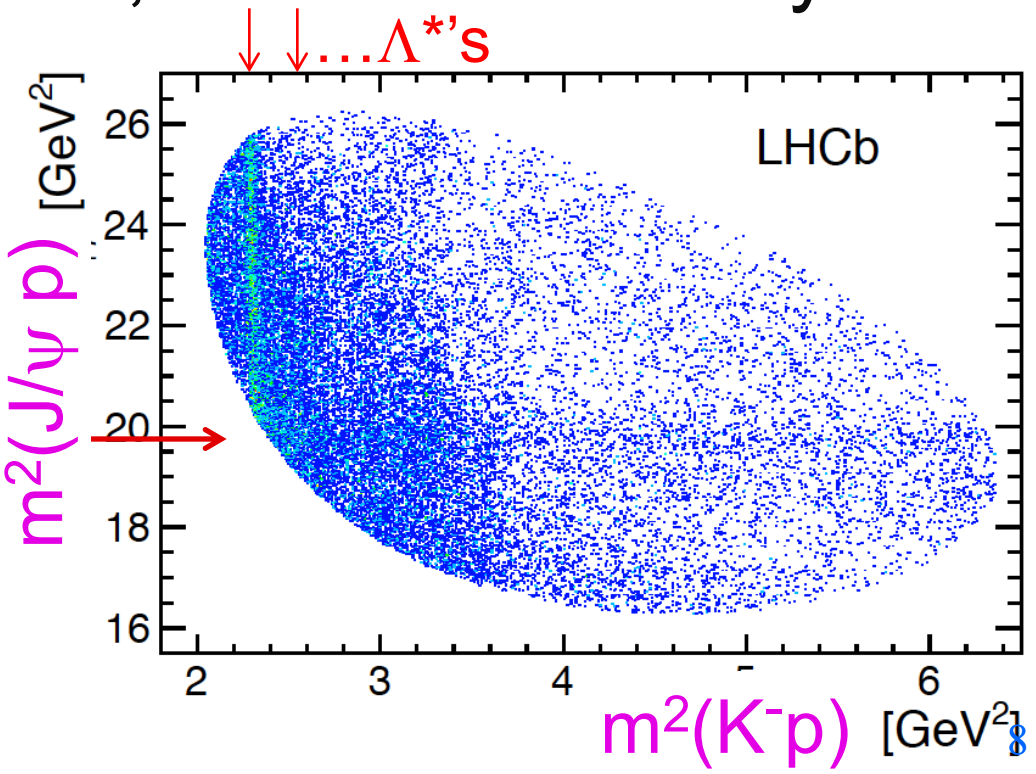
"Dalitz-plot" distribution

- Dalitz-plot generally used for studying 3-body decays
- 3-body decays are often dominated by resonance processes, can be viewed by the distribution

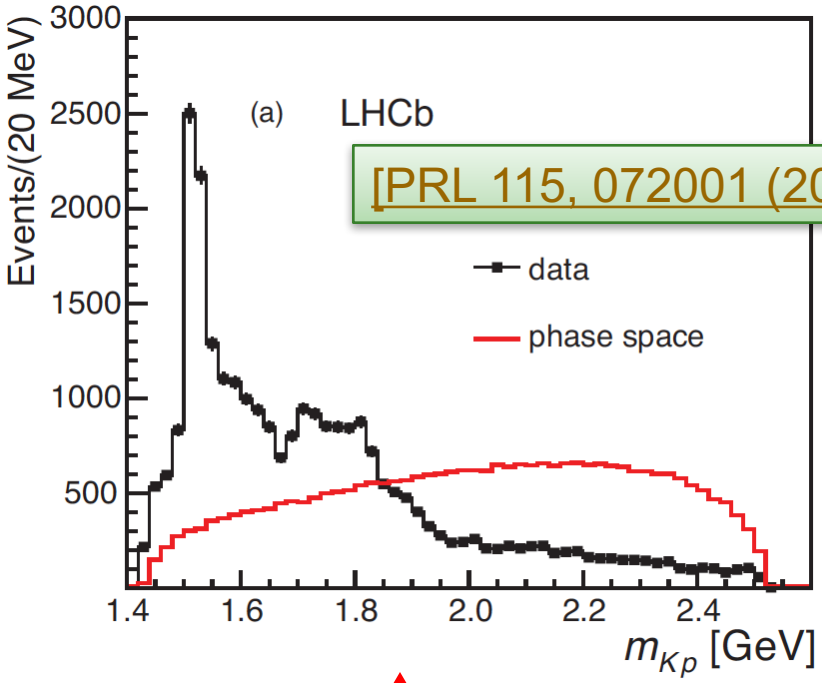
Make a Dalitz plot.

Showed an unusual feature

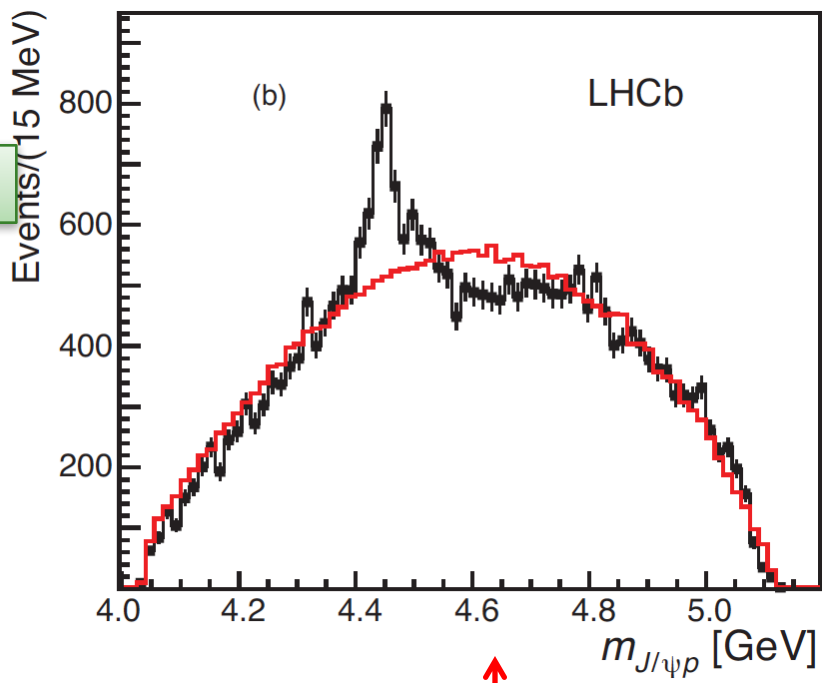
[PRL 115, 072001 (2015)]

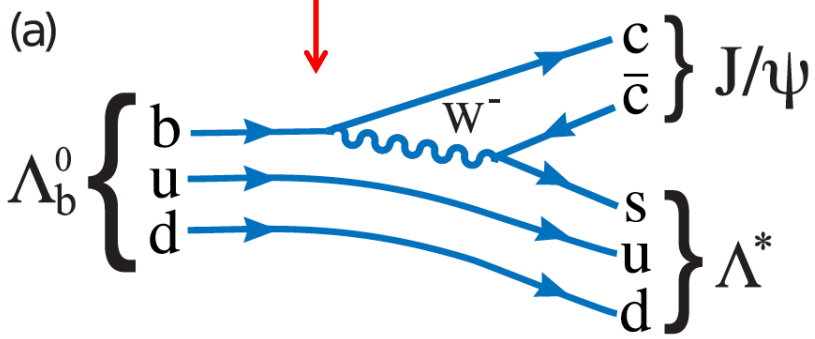


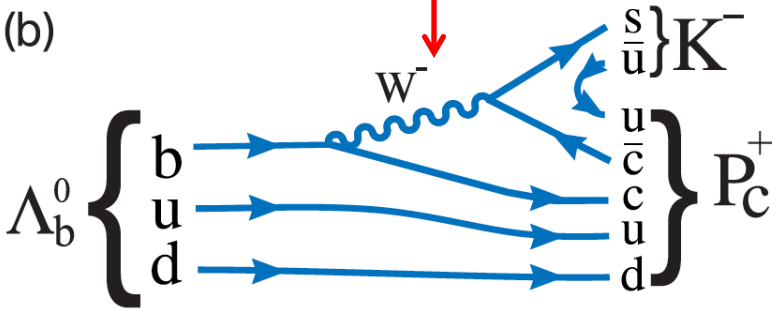
Projections



[PRL 115, 072001 (2015)]



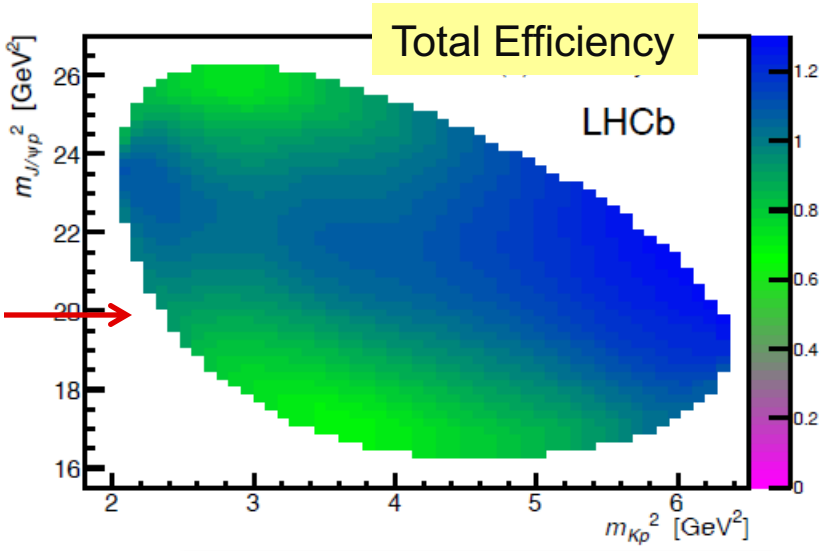




Does a 4 quark + $\bar{q}$ state exist?

Is the peak "an artifact"?

- Many checks done: this is not be the case:
  - MisID background of B^0 and B_s are vetoed
  - Ξ_b decays checked
  - Efficiency doesn't make narrow peak
  - No peaking sideband bkg
  - Clones & ghost tracks eliminated



[PRL 115, 072001 (2015)]

- Can interference between Λ^* resonances generate a peak in the $J/\psi p$ mass spectrum?
  - A full amplitude analysis is performed using all known Λ^* resonances

Amplitude analysis

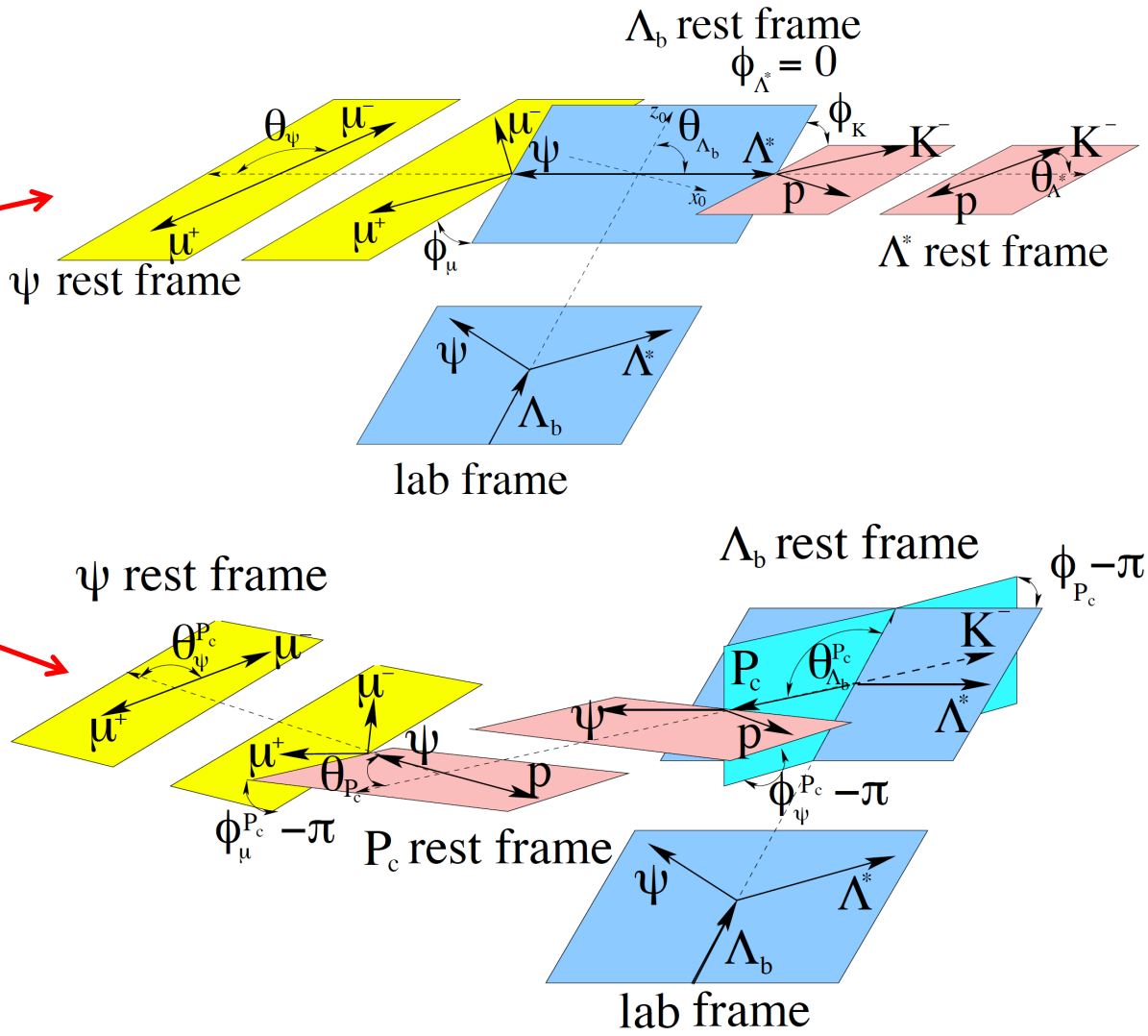
- Two interfering channels:

$\Lambda_b^0 \to J/\psi\Lambda^*$,
$\Lambda^* \to pK^-$

&

$\Lambda_b^0 \to P_c^+ K^-$,
$P_c^+ \to J/\psi p$

- Use m(K^-p) & 5 decay $\angle$'s as fit observables



Amplitude Analysis

- The matrix element for the Λ^* decay is:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^* \mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp})\, D^1_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

- And for the P_c:

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^* \mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\; D^1_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

- $\mathcal{H}$ are complex helicity couplings to describe decay dynamics, determined from the fit

Amplitude Analysis

- The matrix element for the Λ^* decay is:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^* \mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp})\, D^1_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

- And for the P_c:

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^* \mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\; D^1_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

- $R(m)$ are resonance parametrizations, generally are described by Breit-Wigner, Flatté amplitude

Amplitude Analysis

- The matrix element for the Λ^* decay is:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^* \mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp}) D^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

- And for the P_c:

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^* \mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p}) D^{1}_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

- Wigner D-matrix arguments are Euler angles corresponding to the fitted angles

Amplitude Analysis

- The matrix element for the Λ^* decay is:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^* \mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_n(m_{Kp})\, D^1_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*$$

- And for the P_c:

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^* \mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\; D^1_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

- Add together coherently to model their interfering

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu} \right|^2$$

Rotation angles to align helicity axes of μ & p between two decay chains

Models: extended & reduced

- Consider all Λ^* states & all allowed L values

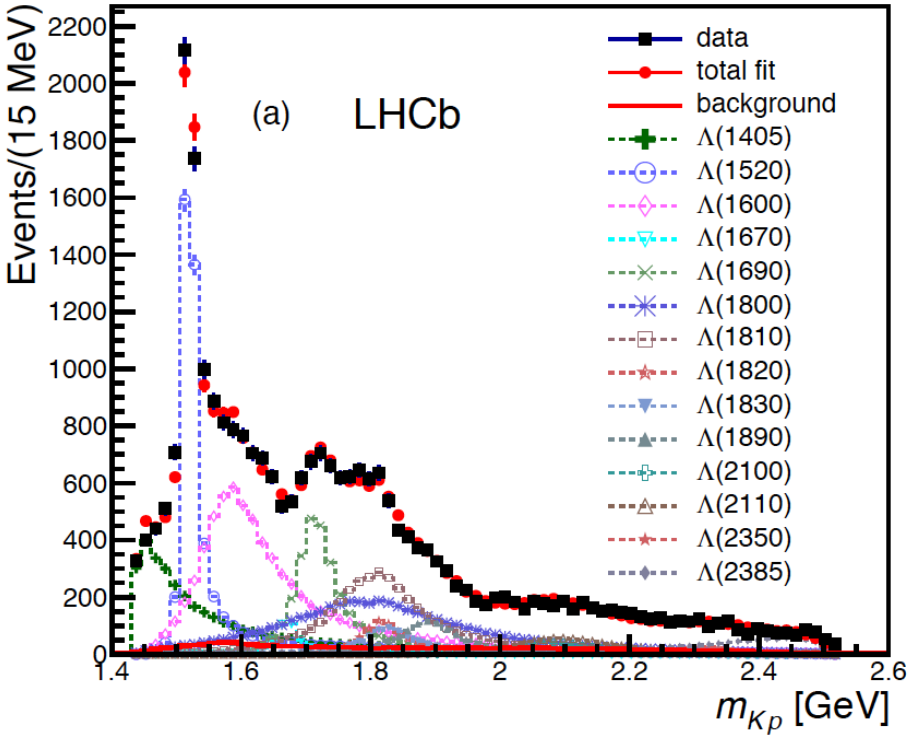
Flatté BW ↓

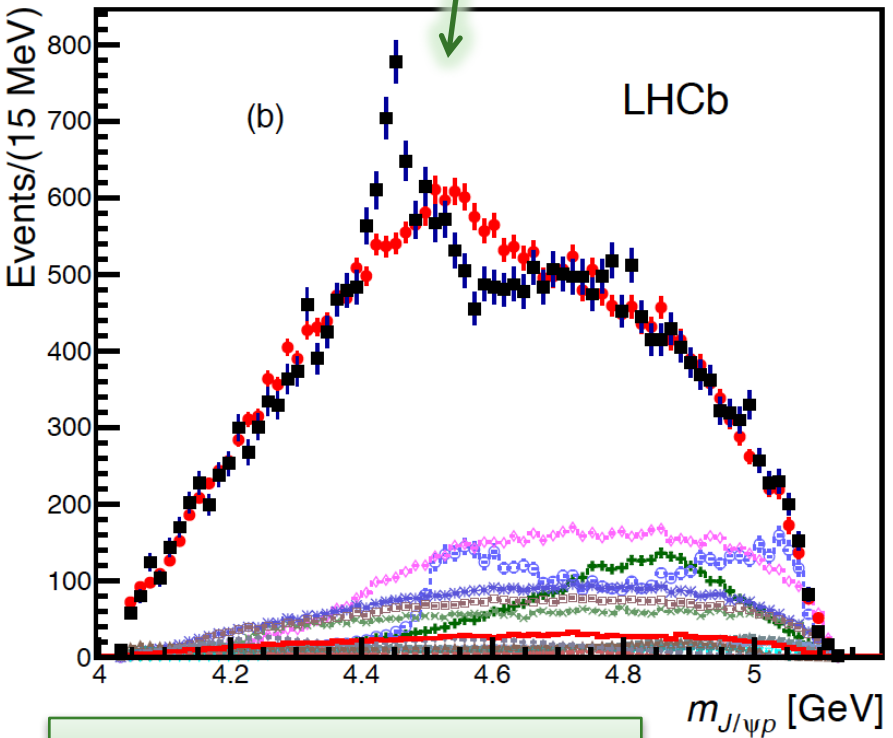
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	–	6
$\Lambda(2585)$	?	≈2585	200	–	6
				# parameters 64	146

[PRL 115, 072001 (2015)]

Results without P_c states

- Use extended model, so all possible known Λ^* amplitudes. m_{Kp} looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant, extra Λ^*, all Σ^* (isospin violating process) don't help

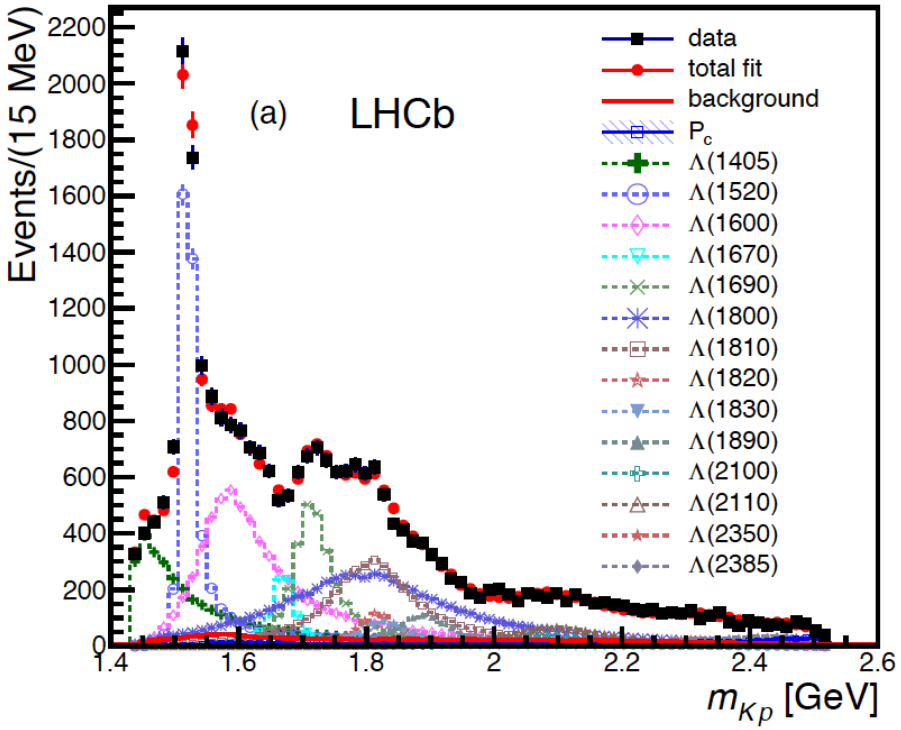


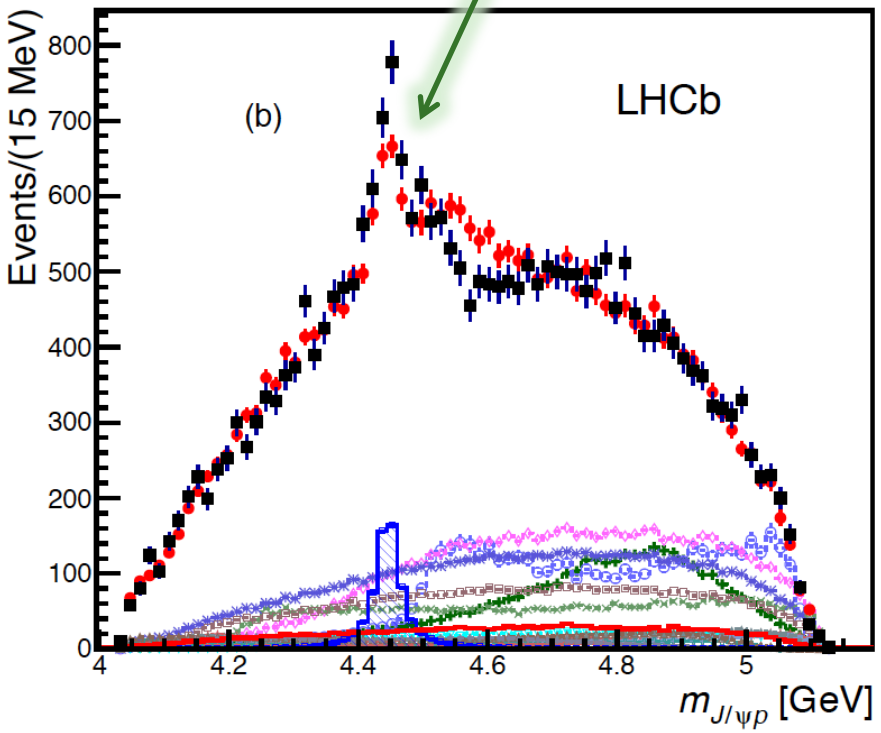


[PRL 115, 072001 (2015)]

Extended model with 1 P_c

- Try all J^P up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit

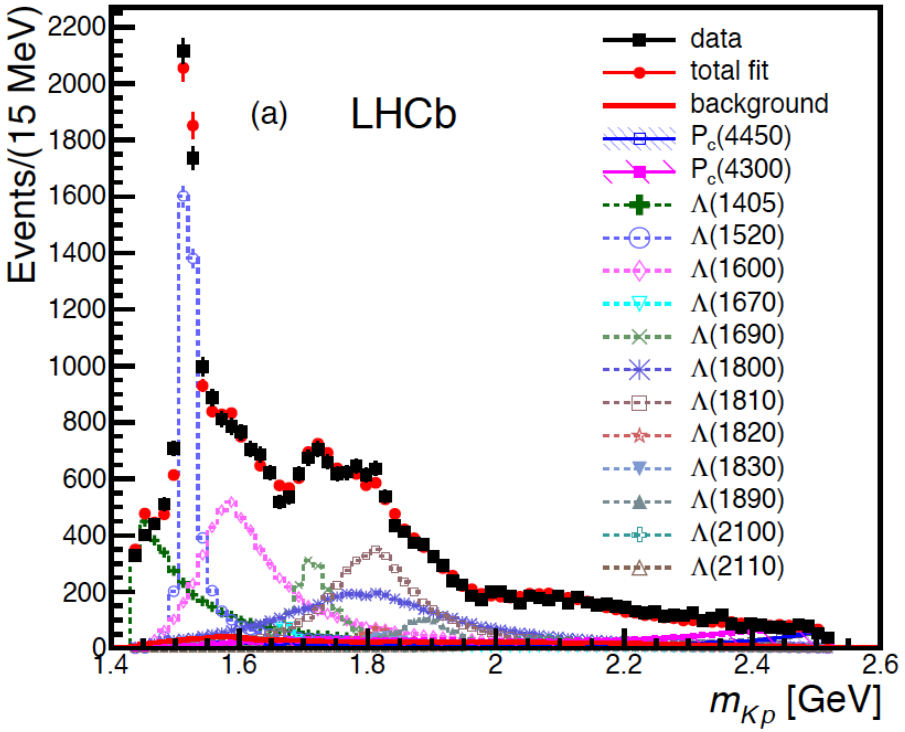


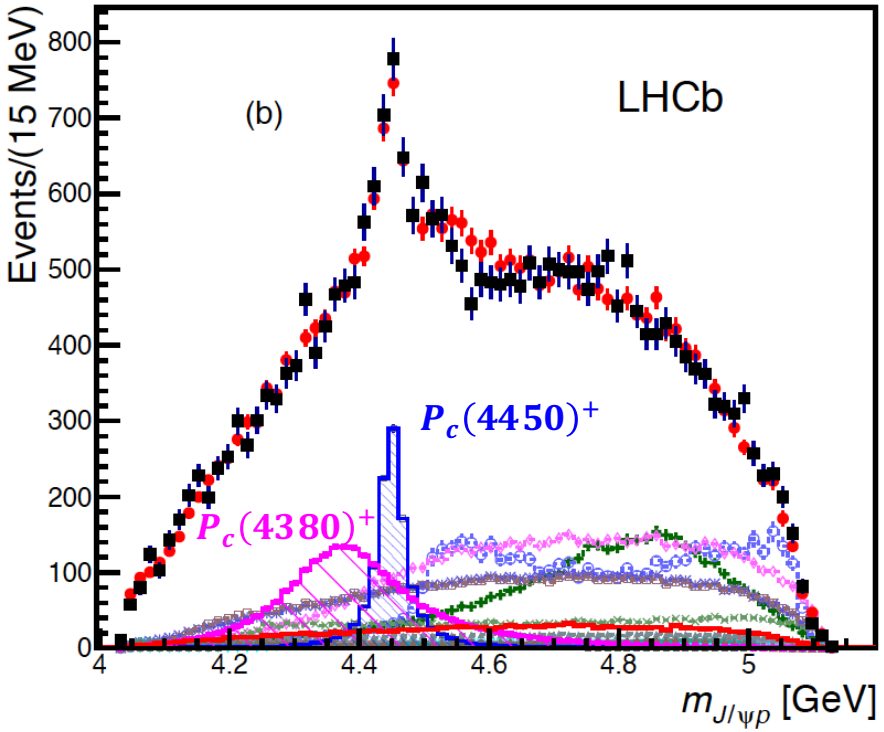


[PRL 115, 072001 (2015)]

Reduced model with 2 P_c's

- Best fit has J^P=(3/2$^-$, 5/2$^+$), also (3/2$^+$, 5/2$^-$) & (5/2$^+$, 3/2$^-$) are preferred

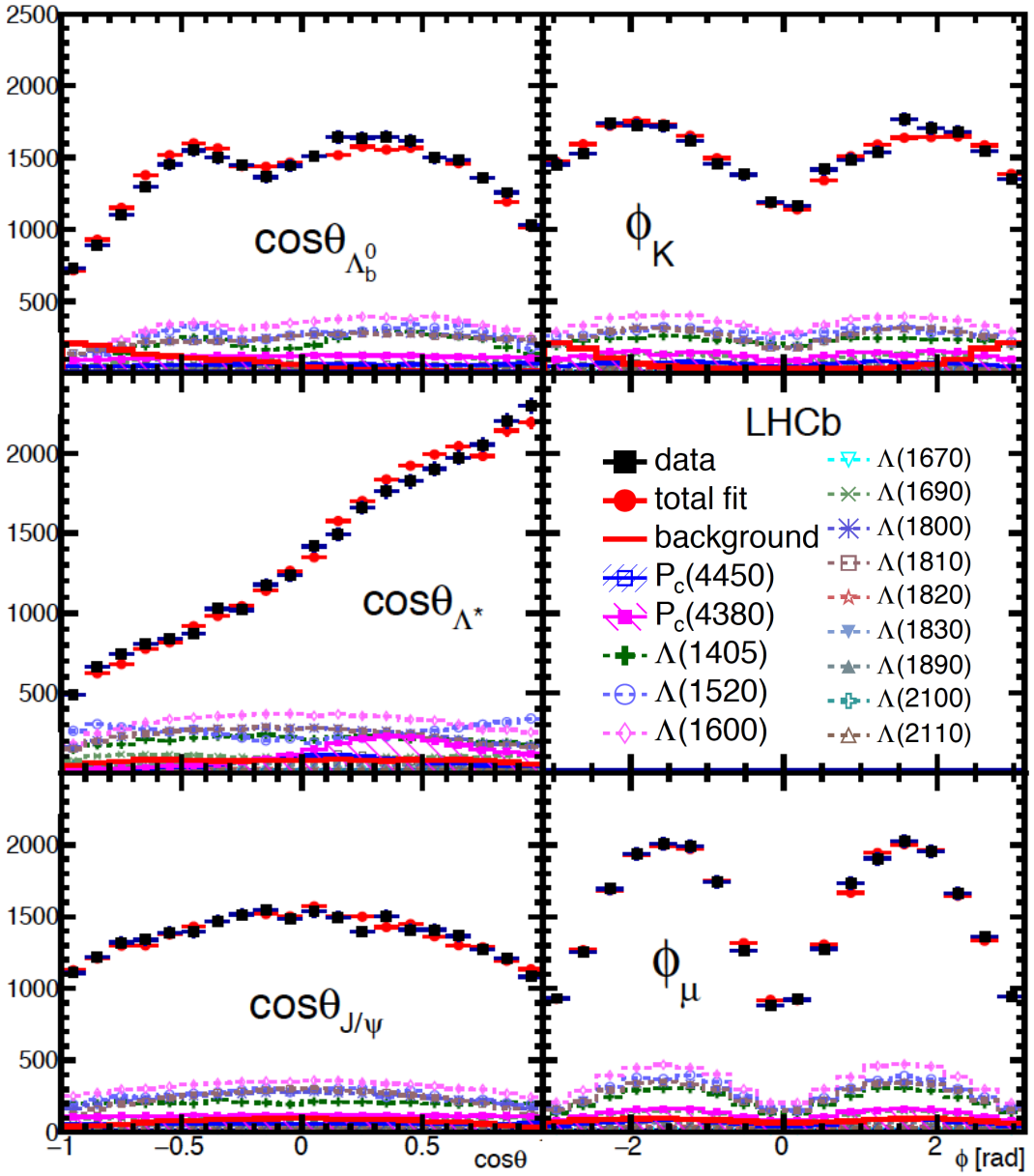




[PRL 115, 072001 (2015)]

Angular distributions

Good fits in the angular variables



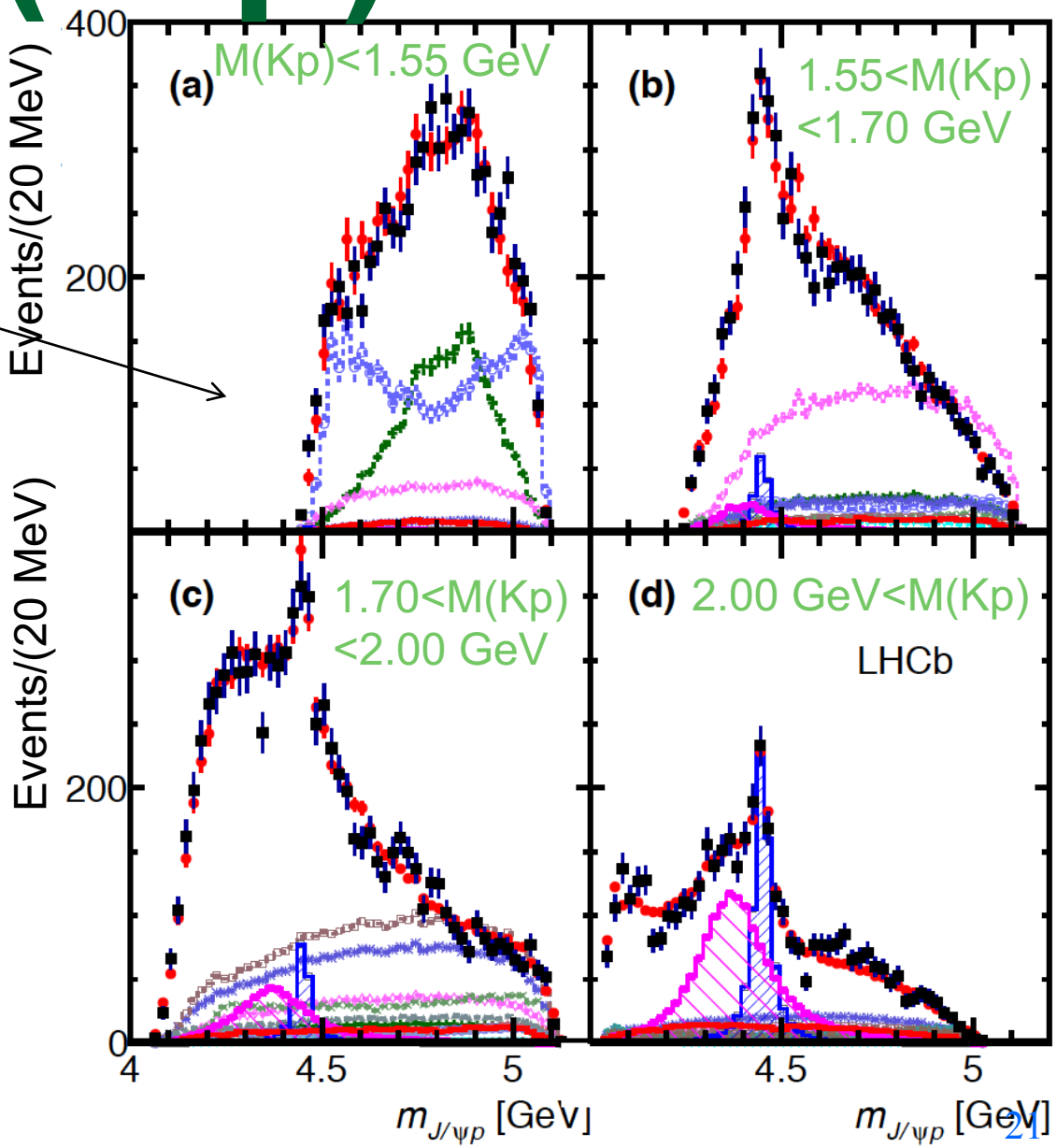
[PRL 115, 072001 (2015)]

In m(K⁻p) slices

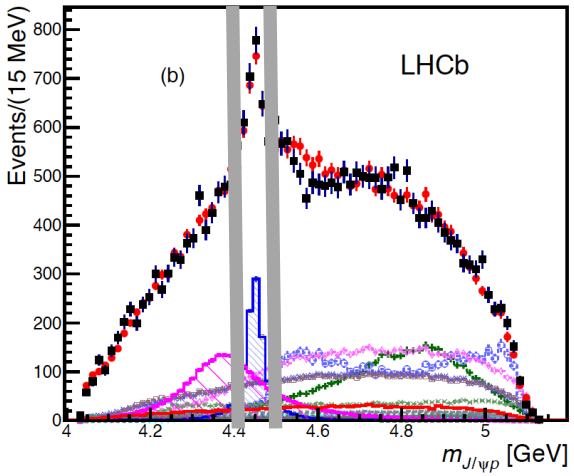
P_c's not appear in first interval as they outside of the Dalitz plot boundary

[PRL 115, 072001 (2015)]

- data
- total fit
- background
- $P_c(4450)$
- $P_c(4380)$
- $\Lambda(1405)$
- $\Lambda(1520)$
- $\Lambda(1600)$
- $\Lambda(1670)$
- $\Lambda(1690)$
- $\Lambda(1800)$
- $\Lambda(1810)$
- $\Lambda(1820)$
- $\Lambda(1830)$
- $\Lambda(1890)$
- $\Lambda(2100)$
- $\Lambda(2110)$

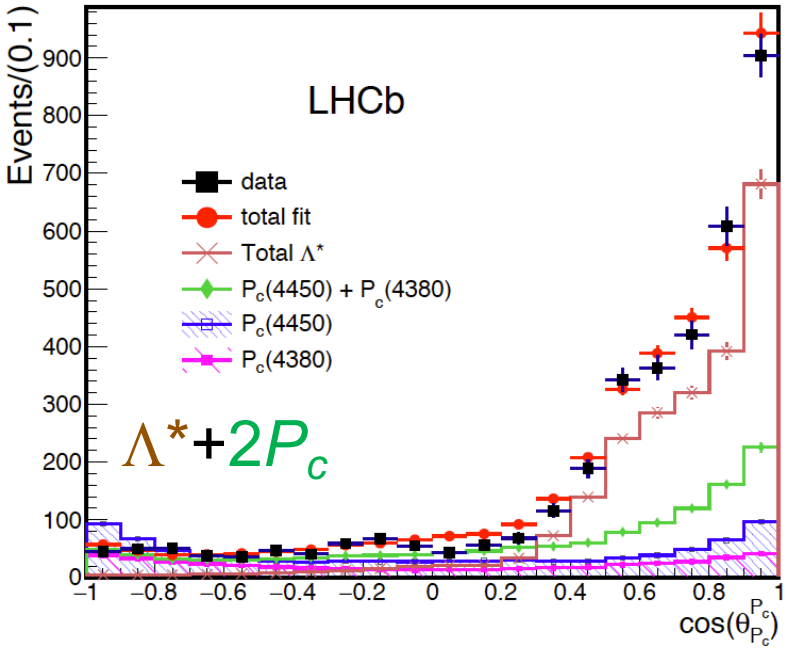


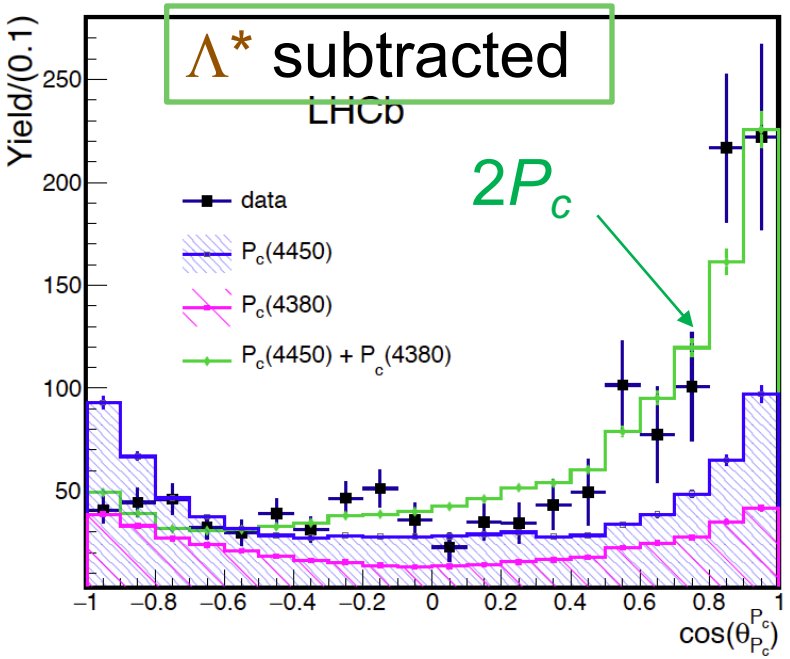
$P_c^{\pm}$ decay angle distribution



- Events in $m_0 \pm \Gamma$ of $P_c(4450)$
- Asymmetric distribution from $2P_c$ is evident
- 2 P_c overlap and interfere

CERN-THESIS-2016-086

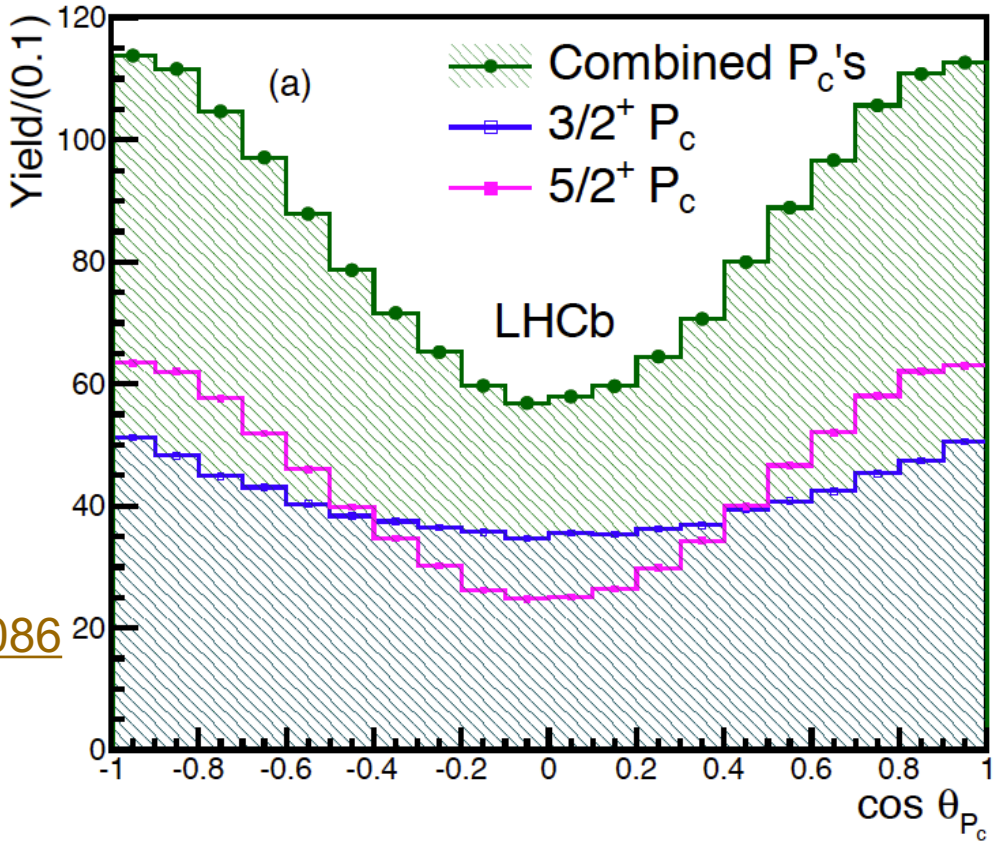




Data demands 2 states

- 1 P_c (parity conservation in strong decays) generates forward-backward symmetric distribution
- **Same parity** states also generates **symmetric** distribution

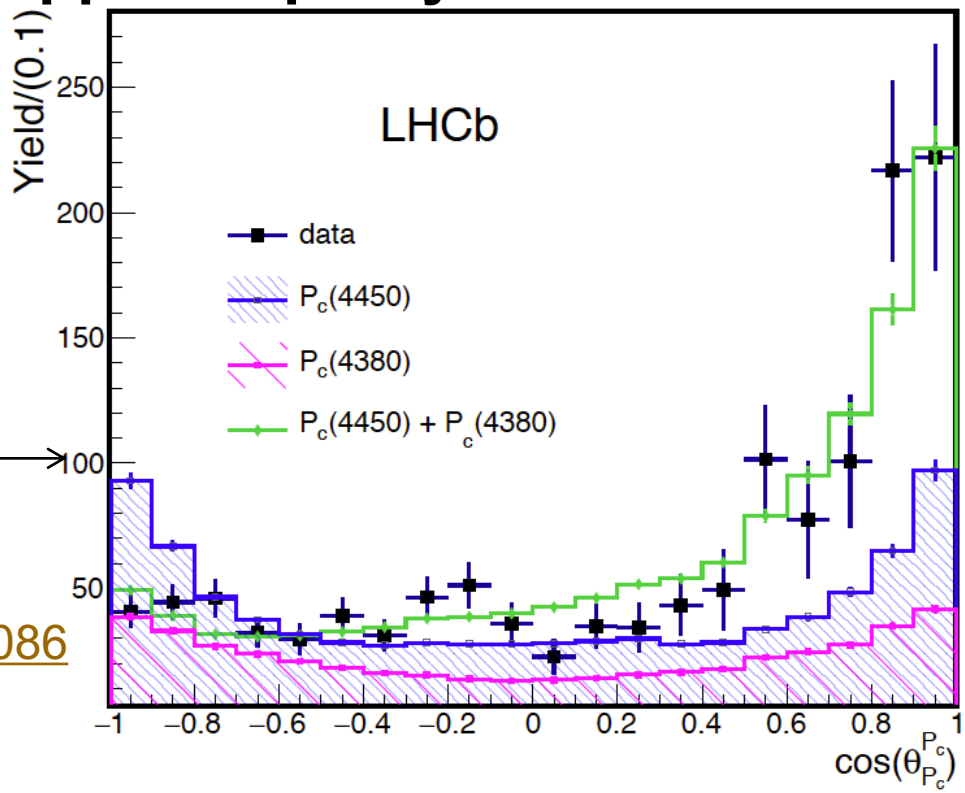
Cannot explain the data



CERN-THESIS-2016-086

J^P determination

- **opposite parity** states needed to explain the angle distribution
- Angular information determines: **one P_c is 3/2 and another is 5/2 with opposite parity**



negative interference, high m_{Kp}

positive interference, low m_{Kp}

CERN-THESIS-2016-086

Systematic uncertainties

Source [PRL 115, 072001 (2015)]	M_0 (MeV) low	M_0 (MeV) high	Γ_0 (MeV) low	Γ_0 (MeV) high	Fit fractions (%) low	Fit fractions (%) high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	0.01
Nonresonant	3	0.3	34	2	2.35	0.13	3.28	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	1.2	34	10	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L^{P_c}_{\Lambda_b^0}$ $\Lambda_b^0 \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi p$	4	0.4	31	7	0.63	0.37		
$L^{\Lambda_n^*}_{\Lambda_b^0}$ $\Lambda_b^0 \to J/\psi \Lambda^*$	11	0.3	20	2	0.81	0.53	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

For Run-II, we are working on improved Λ^* model from coupled-channels

Fit results

- Best fit has J^P=(3/2$^-$, 5/2$^+$), also (3/2$^+$, 5/2$^-$) & (5/2$^+$, 3/2$^-$) are preferred for low and high P_c^+

Resonance	Mass (MeV)	Width (MeV)	Significance	Fit fraction(%)
$P_c(4380)^{\pm}$	4380 ± 8 ± 29	205±18±86	$9\,\sigma$	8.4 ± 0.7 ± 4.2
$P_c(4450)^{\pm}$	4449.8 ± 1.7 ± 2.5	39±5±19	$12\,\sigma$	4.1 ± 0.5 ± 1.1
$\Lambda(1405)$				15 ± 1 ± 6
$\Lambda(1520)$	[PRL 115, 072001 (2015)]			19 ± 1 ± 4

For $P_c(4380)^+$, Chin. Phys. C40 (2016) 011001

$$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.38})\times 10^{-5}$$

For $P_c(4450)^+$,

$$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18})\times 10^{-5}$$

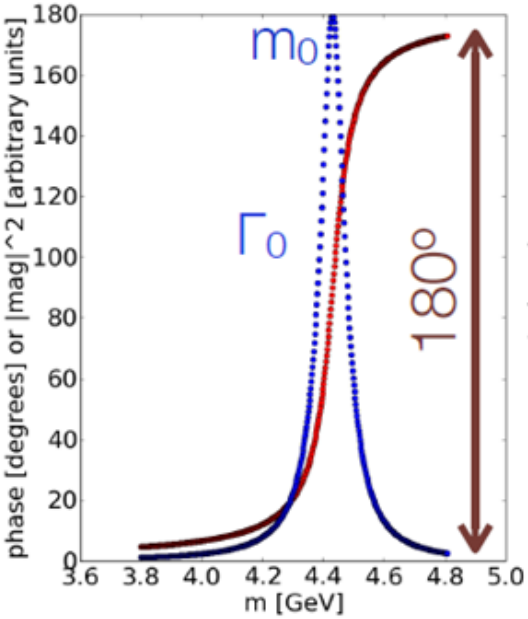
Ref: $\mathcal{B}(B^0 \to Z_c(4430)^- K^+, Z_c^- \to \psi' \pi^-) = (3.4 \pm 0.5^{+0.9}_{-1.9} \pm 0.2)\times 10^{-5}$

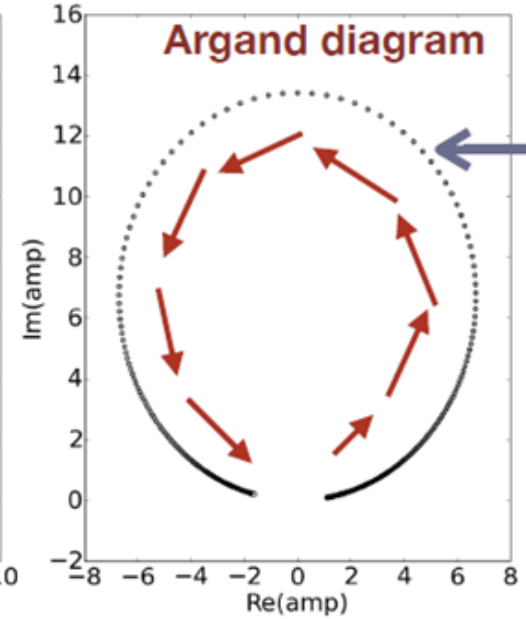
Breit-Wigner amplitude

- Often a relativistic Breit-Wigner amplitude is used to model resonance
- Function has Re & Im parts

$$BW(m|M_0,\Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0\Gamma(m)}$$

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{M_0}{m} B'_L(q,q_0,d)^2$$

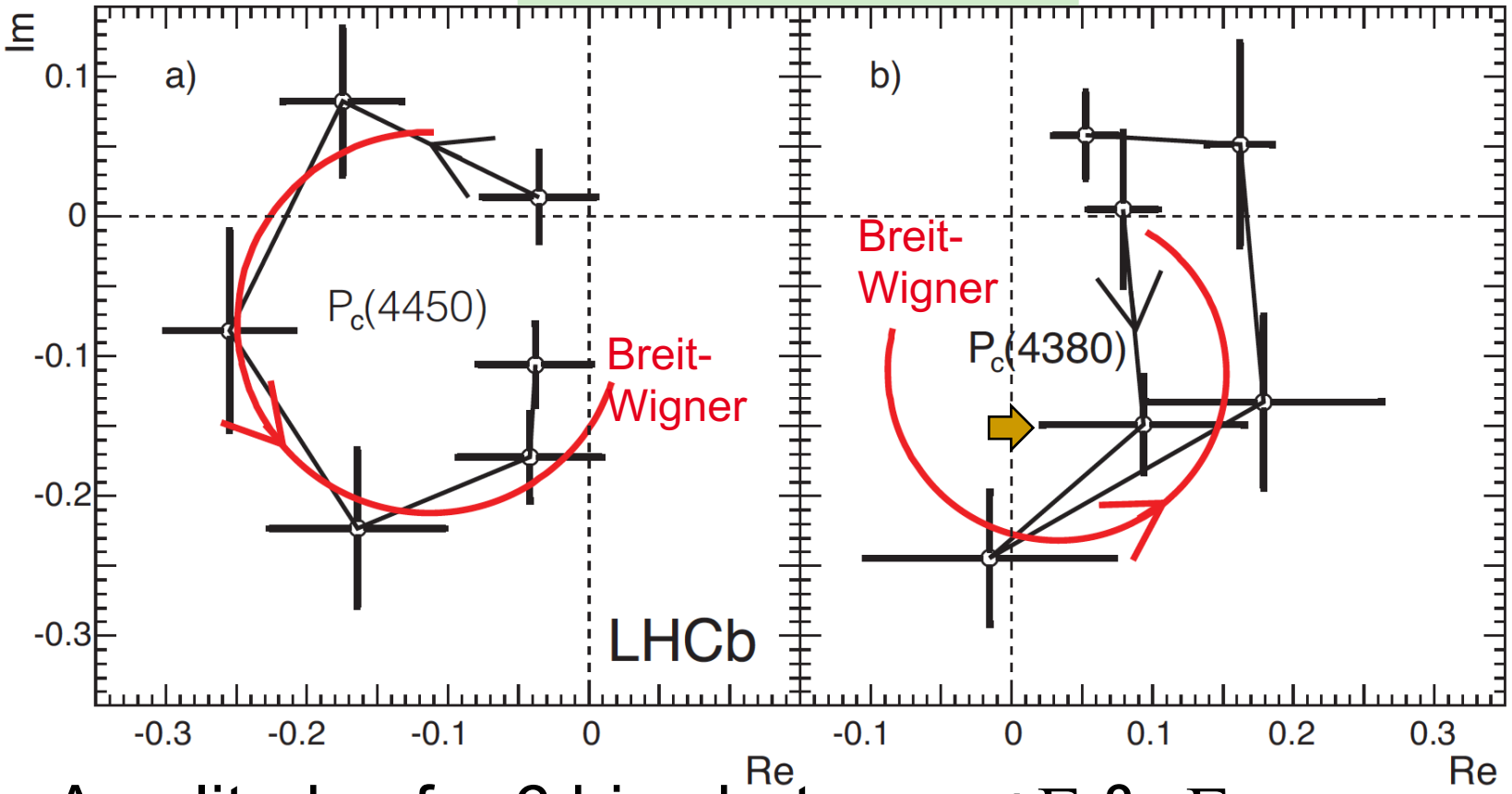




- Circular trajectory in complex plane is characteristic of resonance
- Circle can be rotated by arbitrary phase
- Phase change of 180° across the pole

Argand diagrams

[PRL 115, 072001 (2015)]



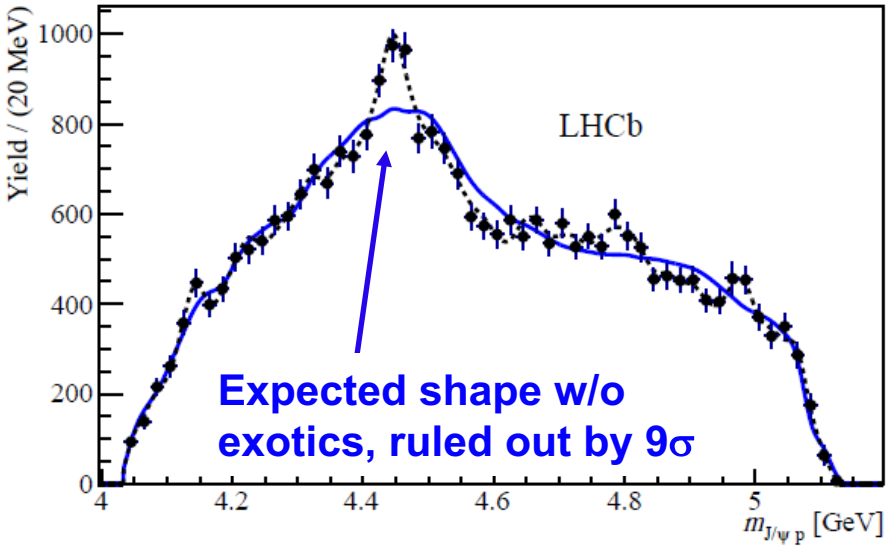
- Amplitudes for 6 bins between $+\Gamma$ & $-\Gamma$
- Left: too good, Right: one point 2σ away from expectation

Model-independent confirmation

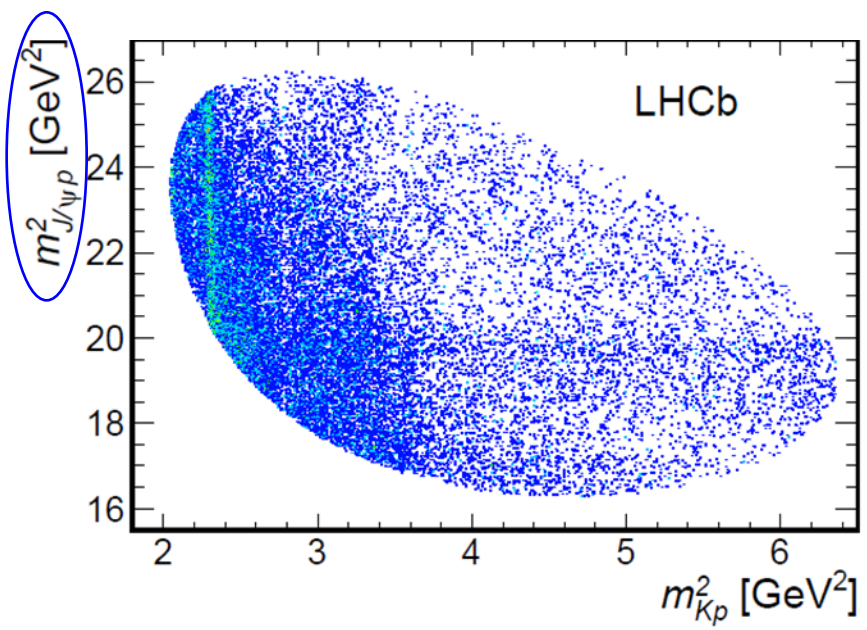
- Model-independent analysis is complimentary to the amplitude fit

Model-independent	Amplitude fit
No Λ^* model needed	Λ^* model needed
Can **only** tell if exotics present	Can tell the **property** of the exotics

PRL 117, 082002 (2016)

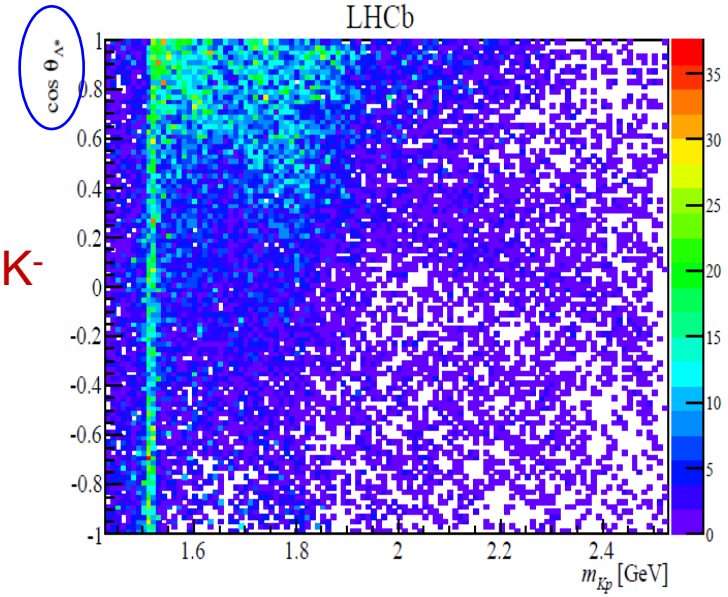


Rectangular Dalitz plane



PRL 115, 072001 (2015)

$\Lambda_b^0 \rightarrow J/\psi p K^-$

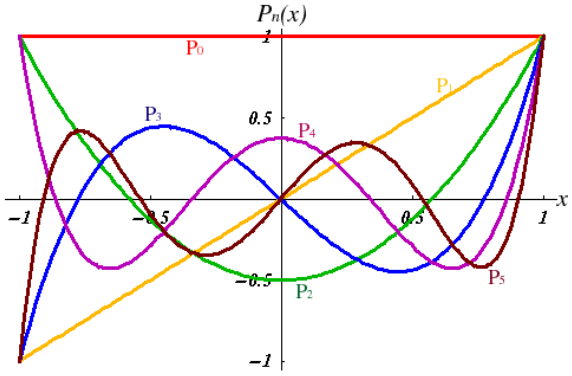


PRL 117, 082002 (2016)

Legendre moments

$$\frac{dN}{d\cos\theta} = \sum_{l=0}^{l_{max}} \left\langle P_l^U \right\rangle P_l(\cos\theta)$$

$$\left\langle P_l^U \right\rangle = \int_{-1}^{+1} \frac{dN}{d\cos\theta} P_l(\cos\theta) d\cos\theta \propto \sum_{i=1}^{n_{events}} \frac{1}{\varepsilon_i} P_l(\cos\theta_i)$$



Λ^* can contribute only to low-order moments

Λ^*-only hypothesis called H_0

$$l_{max} = 2J_{max}$$

J_{max} is the highest spin of Λ^* resonance possible

Reflections of exotic hadrons can contribute to low **and high** order moments:

- Detecting non-zero moments above $2J_{max}$ signals presence of exotics

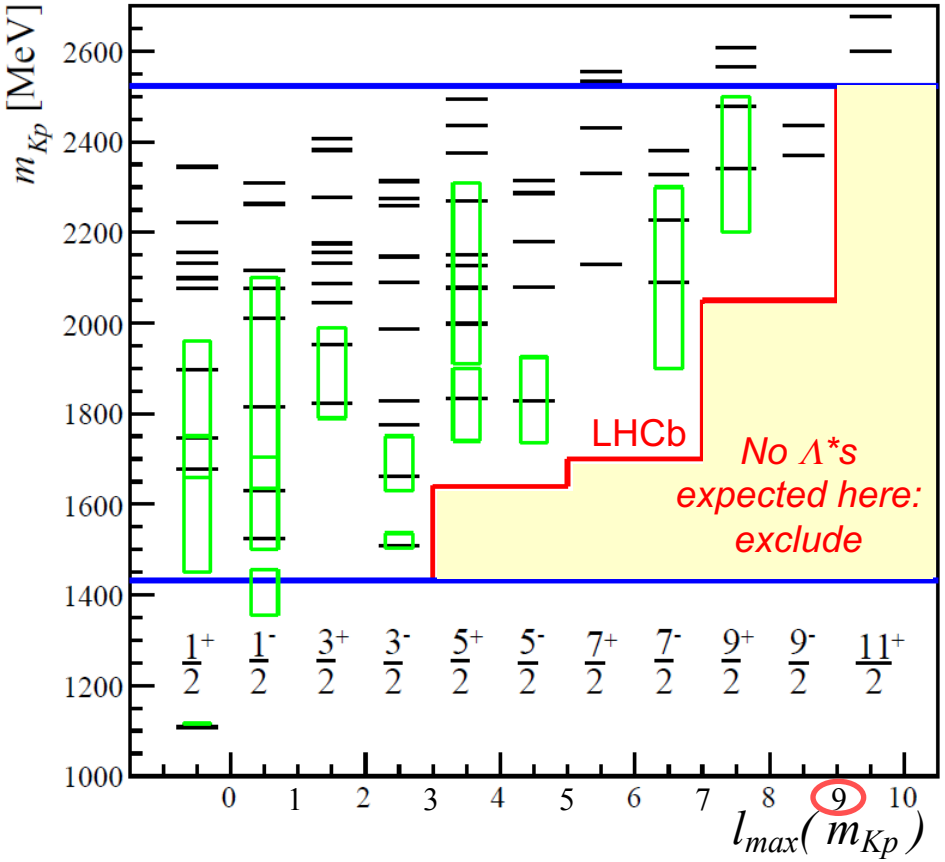
Moments coefficients as function of m_{Kp}

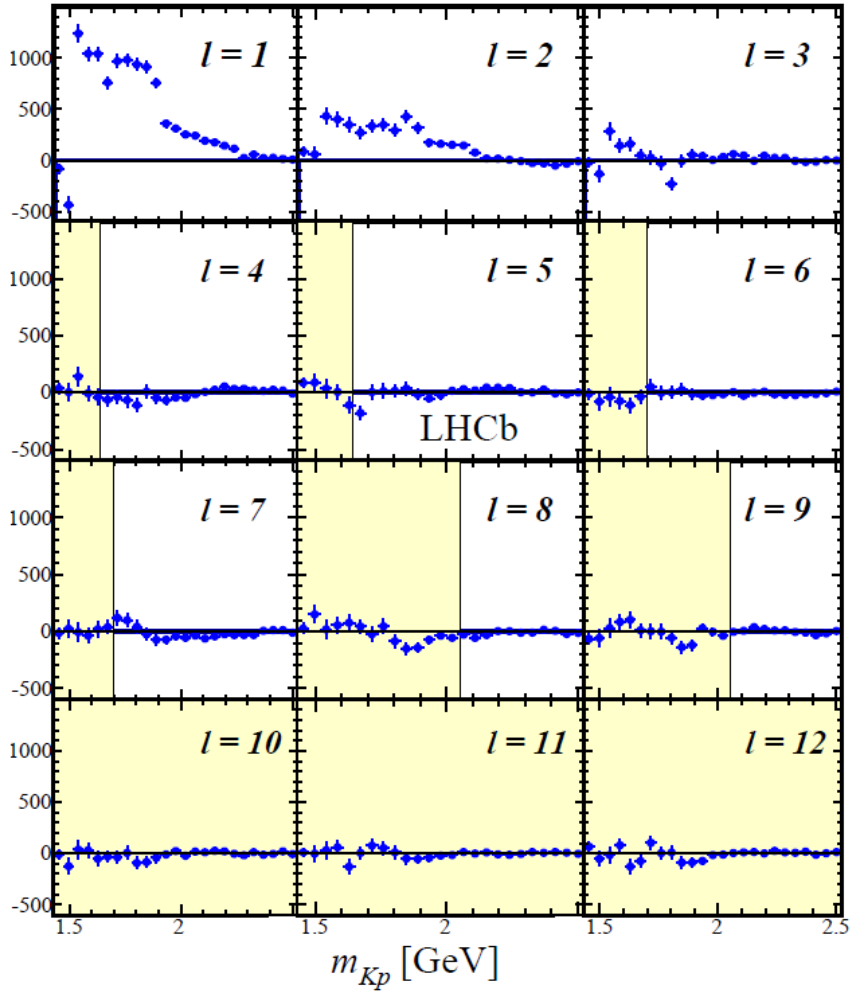
From **know Λ^* resonances**, **quark model predictions** as a guide

Much fewer known states than predicted!

Known Λ^* states: boxes $M_0 \pm \Gamma_0$

Λ^* mass predictions by Loring-Metsch-Petry EPJ, A10, 447 (2001)





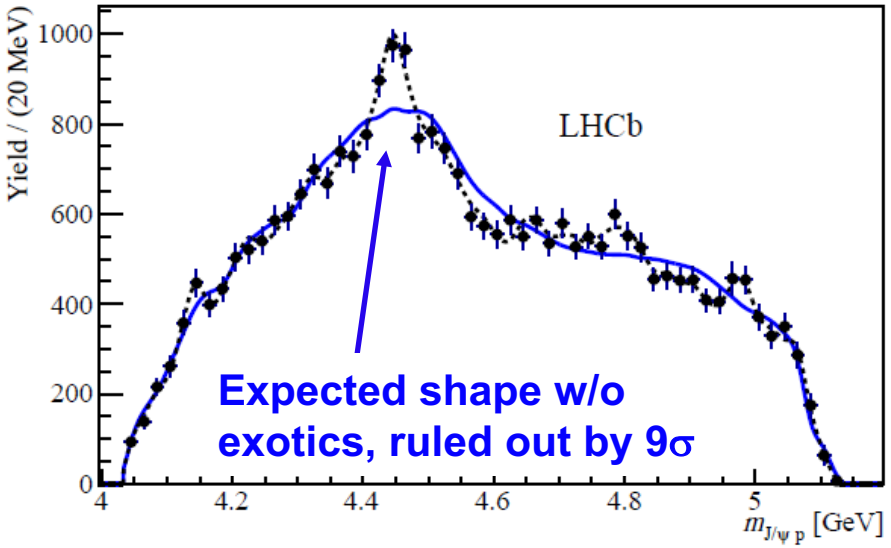
PRL 117, 082002 (2016)

Model-independent confirmation

- Model-independent analysis is complimentary to the amplitude fit

Model-independent	Amplitude fit
No Λ^* model needed	Λ^* model needed
Can **only** tell if exotics present	Can tell the **property** of the exotics

PRL 117, 082002 (2016)



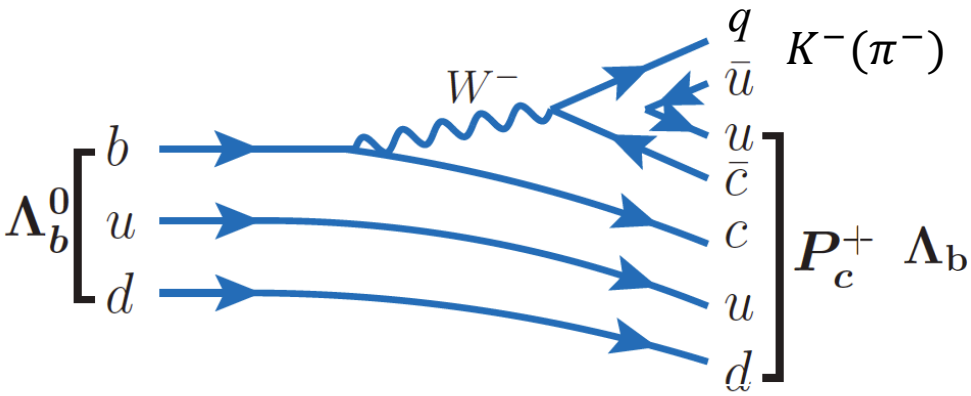
Cabibbo suppressed decays

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

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

- Find the same P_c^+ in other channels is helpful to understand P_c^+ production mechanism and internal structure
- Two P_c^+ production mechanisms predicted:

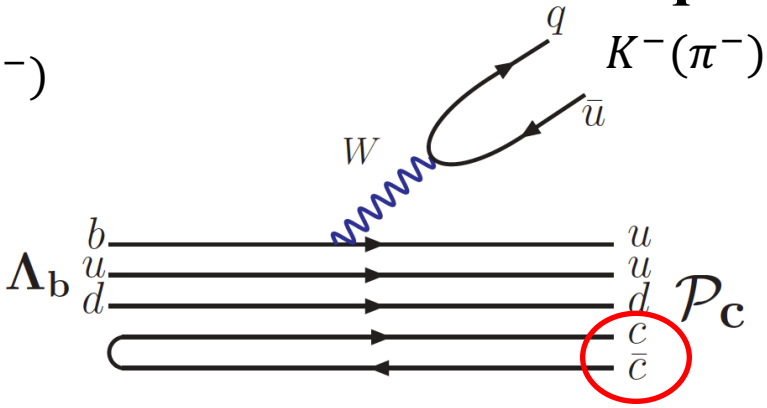
$b \to c$



$$R_{\pi/K} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} = 0.07 \sim 0.08$$

[Cheng, PRD 92, 096009 (2015)]

$b \to u$ & $c\bar{c}$ from sea quarks



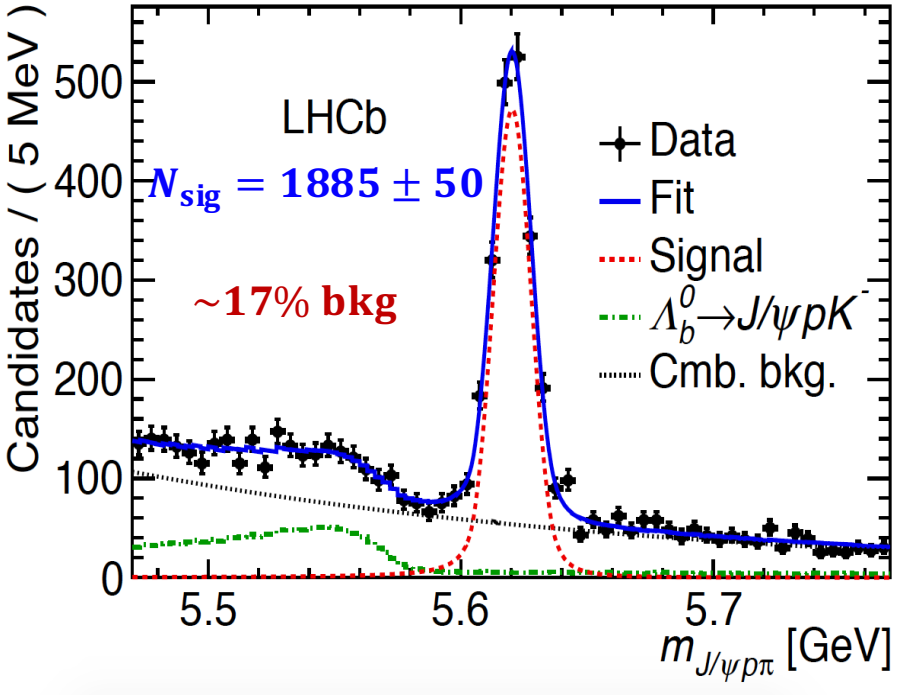
$$R_{\pi/K} = 0.58 \pm 0.05$$

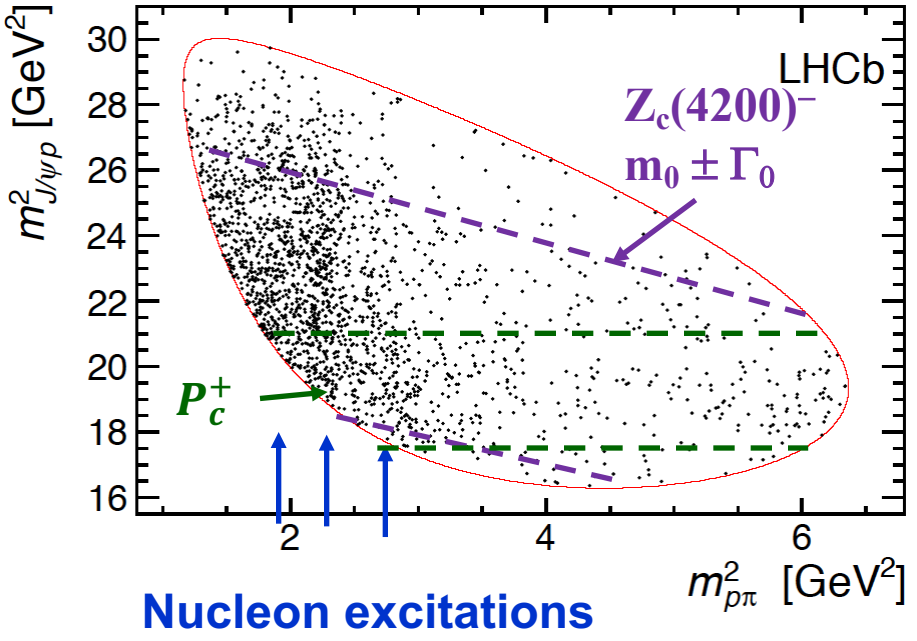
[Hsiao, PLB 751, 572 (2015)]

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

- $\mathcal{B}$ is ~8% of the favored $\Lambda_b^0 \to J/\psi p K^-$ decays
- But more complex because of possible $Z_c^- \to J/\psi \pi^-$

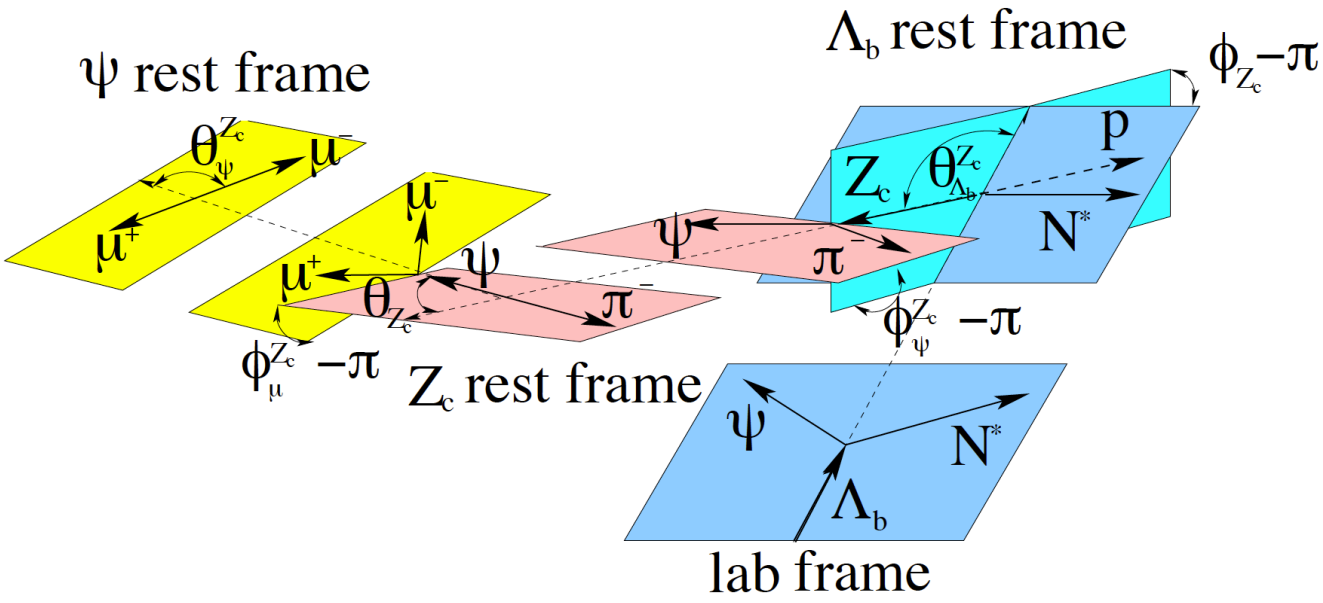
PRL 117, 082003 (2016)





Nucleon excitations

Amplitude Analysis



$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}=\pm\frac{1}{2}} \sum_{\lambda_p=\pm\frac{1}{2}} \sum_{\Delta\lambda_\mu=\pm 1} \left| \mathcal{M}^{N^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu} \right.$$

$$\left. + e^{i\,\Delta\lambda_\mu \alpha_\mu^{Z_c}} \sum_{\lambda_p^{Z_c}} e^{i\lambda_p^{Z_c}\alpha_p^{Z_c}} d^{\frac{1}{2}}_{\lambda_p^{Z_c},\lambda_p}(\theta_p^{Z_c})\, \mathcal{M}^{Z_c}_{\lambda_{\Lambda_b^0},\lambda_p^{Z_c},\Delta\lambda_\mu} \right|^2 .$$

Additional Z_c^- decay chain

N^* resonance models

PRL 117, 082003 (2016)

Flatté

State	J^P	Mass (MeV)	Width (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	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	100	-	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	-	3
$N(1900)$	$3/2^+$	1900	200	-	3
$N(2190)$	$7/2^-$	2190	500	-	3
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106

← *LS* couplings

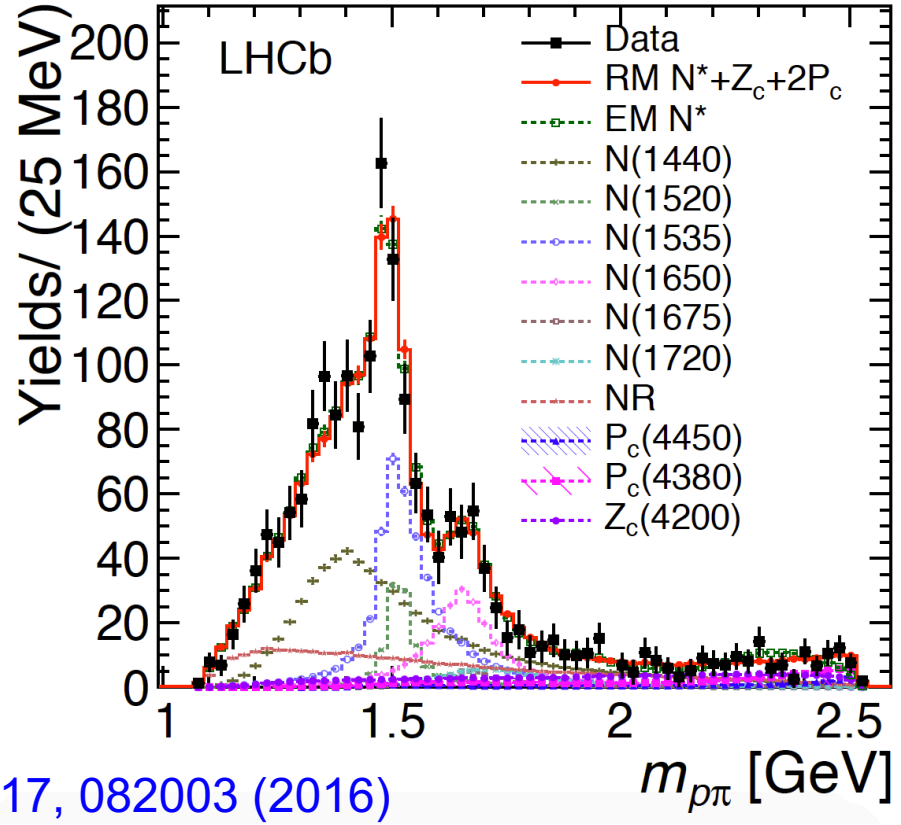
allow for reduction of the number of free parameters by excluding high *L* values

} BES-III

Reduce Model for central value, Extended model for significance and syst.

Amplitude model

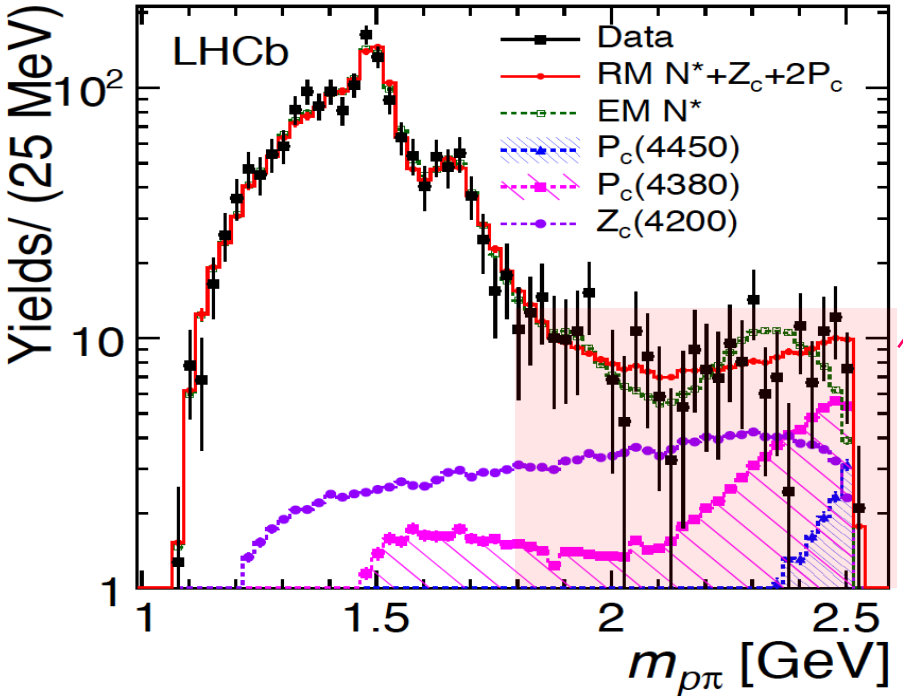
- Almost as many free parameters as in $\Lambda_b^0 \to J/\psi p K^-$
- Fixed m_0 and Γ_0 for the N* and exotic states
- $Z_c(4200)$: 10 free parameters
- Each P_c: 4 free parameters + 6 fixed to that from $\Lambda_b^0 \to J/\psi p K^-$

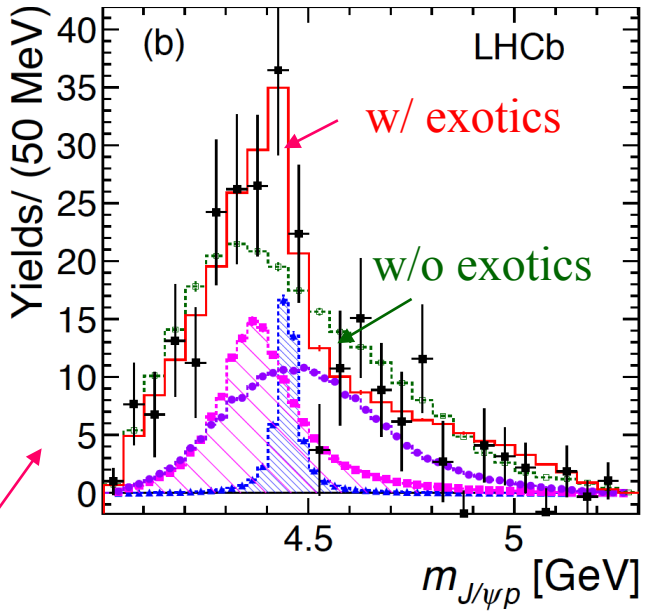


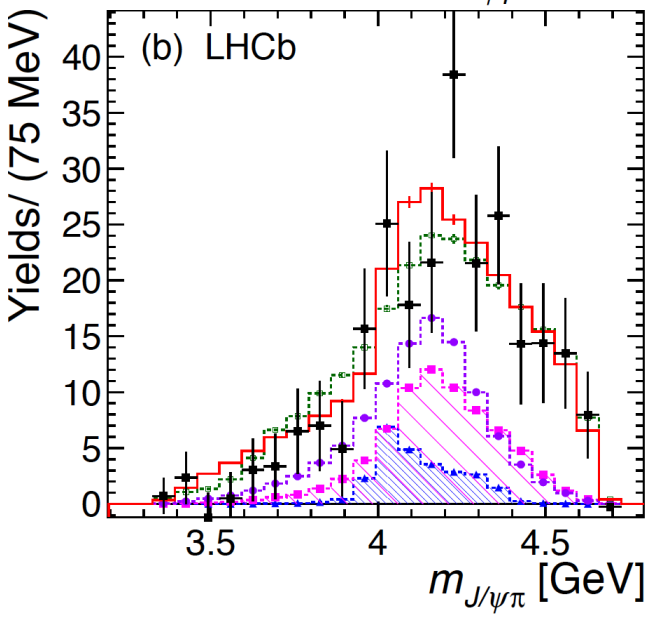
PRL 117, 082003 (2016)

Full amplitude fits

- Significance of the two P_c^+ and $Z_c(4200)^-$ together is 3.1σ.
- **Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p\pi^-$!**







PRL 117, 082003 (2016)

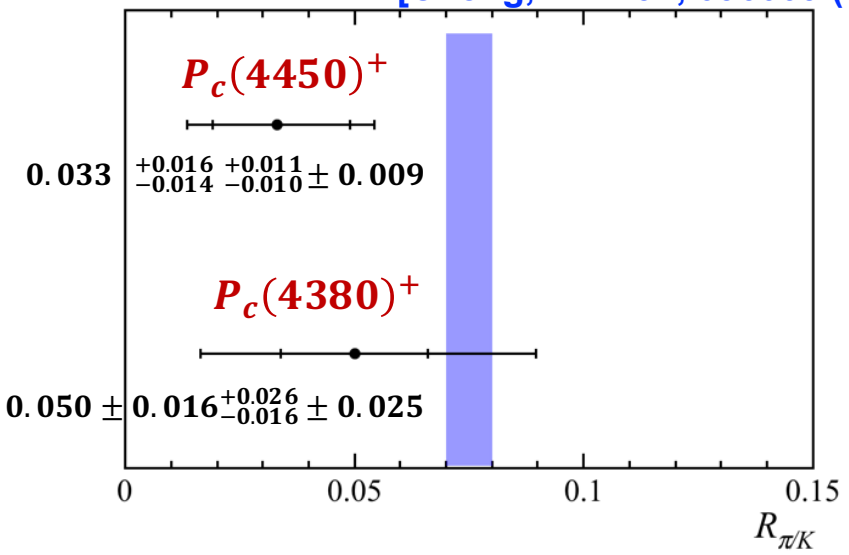
Further results

- If assume production of $Z_c(4200)^-$ is negligible, significance of two P_c^+ is 3.3σ
- **Overall, P_c^+ productions are consistent between the two Λ_b^0 decays**

PRL 117, 082003 (2016)

State	Fit fraction (%)
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.6}_{-1.6}$
$P_c(4450)^+$	$1.6\ ^{+0.8\ +0.6}_{-0.6\ -0.5}$

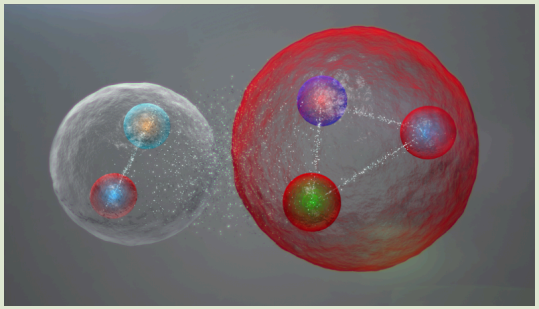
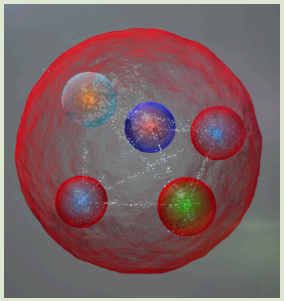
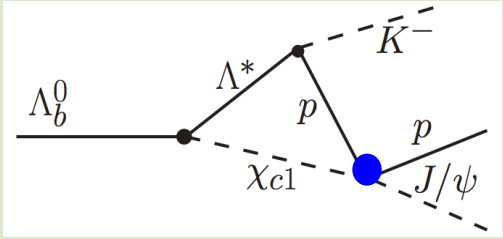
Prediction
0.07~0.08
[Cheng, PRD 92, 096009 (2015)]



✘ Another prediction $R_{\pi/K} = 0.58 \pm 0.05$ is ruled out ($b \to u$ & $c\bar{c}$ from sea quarks)
[Hsiao, PLB 751, 572 (2015)]

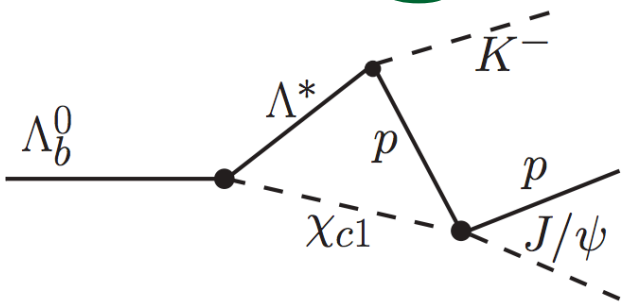
What's a pentaquark

Some explanations

Hadronic molecules	Tightly-bounded states	Kinematic effects
		 $\chi_{c1}p \rightarrow J/\psi p$
Close to two heavy hadron thresholds	Predicted more than 10 J^P states	Predicted no decay of $P_c(4450)^+ \rightarrow \chi_{c1}p$
Karliner&Rosner, PRL 115 (2015) 122001	Maiani et al, PLB 749 (2015) 289	Guo et al, PRD 92 (2015) 071502

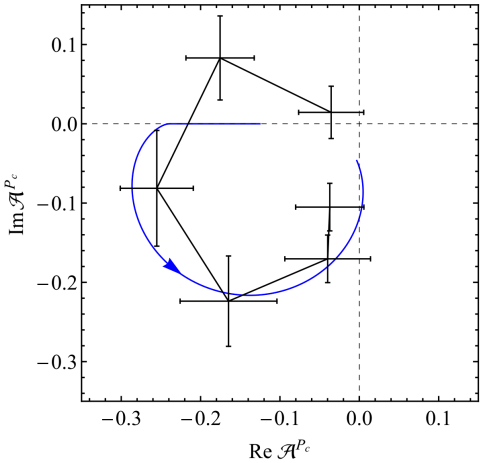
Rescattering

- As m(χ_{c1}p)=m(P_c(4450)), P_c(4450) is explained as χ_{c1}p→J/ψp



- Can explain phase motion

- Hard to predict the size of the rescattering amplitude



- Experimental test: Could be killed if seeing P_c(4450) → χ_{c1}p from Λ_b→χ_{c1}pK$^-$

[PRD 92 (2015) 071502; PRD 94 (2016) 074039]

Other channels

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

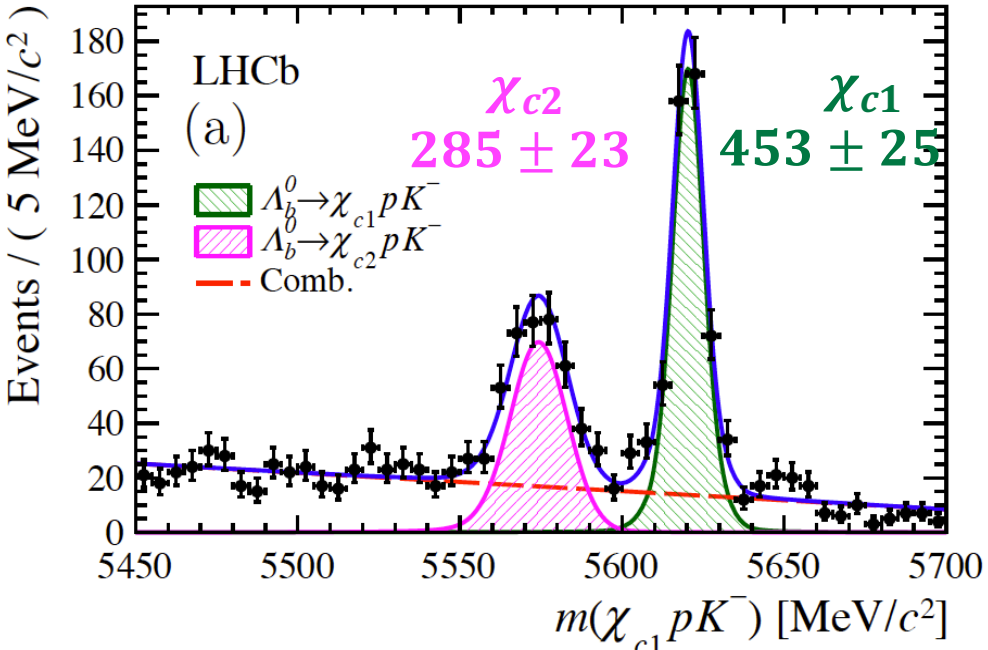
- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \chi_{c1} p\, K^-$ decays
  $\Rightarrow$Test hypothesis of kinematic rescattering effect
- $\chi_{c2} p$ can be used for higher mass and higher J P_c searches

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

$\mathcal{B}(\chi_{cJ})$

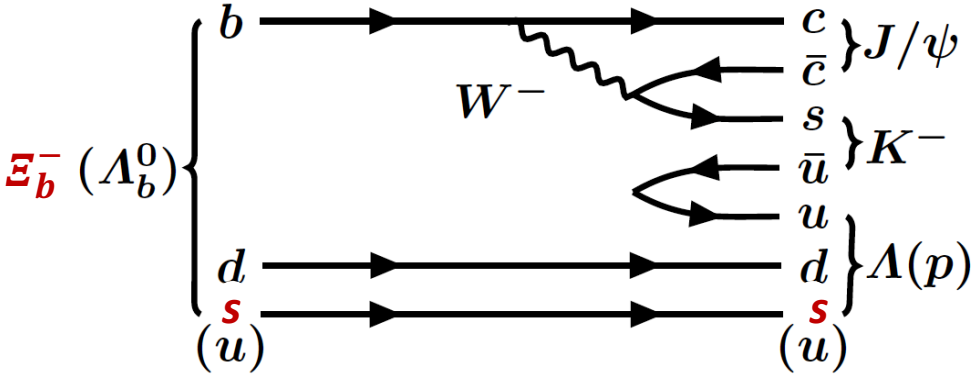
PRL 119, 062001 (2017)

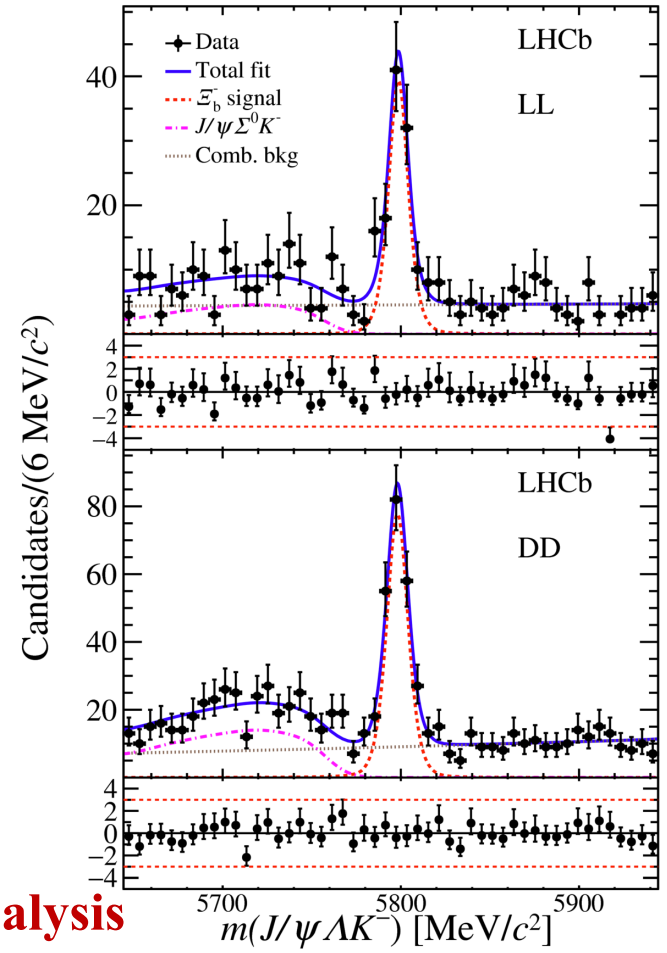


Next step: full amplitude analysis with more data

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

- Strange pentaquark ($udsc\bar{c}$) predicted in
  [PRL 105, 232001 (2010)]
- Can be searched for in the Ξ_b^- decay
  [PRC 93, 065203 (2016)]





$N_{sig} = 308 \pm 21\ (21\sigma)$ PLB 772 (2017) 265-273

Expect ~1500 signals after 2018 for amplitude analysis

Other P_c channels

- LHCb ongoing activities
  - Hadronic: $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-$
  - J=1/2 P_c^+ in $\Lambda_b^0 \to \eta_c p K^-$
  - Direct production: background is high in low p_T, other LHC experiment can do it in high p_T?
  - Generic pentaquarks: $[\bar{b}qqqq]$ and $[\bar{c}qqqq]$

Yields: at least 1/10 smaller than ideal mode $J/\psi p$

- From non-hadron collider experiment:
  - Photon production: $\gamma p \to J/\psi p$ could be done at JLab
  - $e^+e^-(\Upsilon) \to J/\psi p\bar{p}$

Conclusions

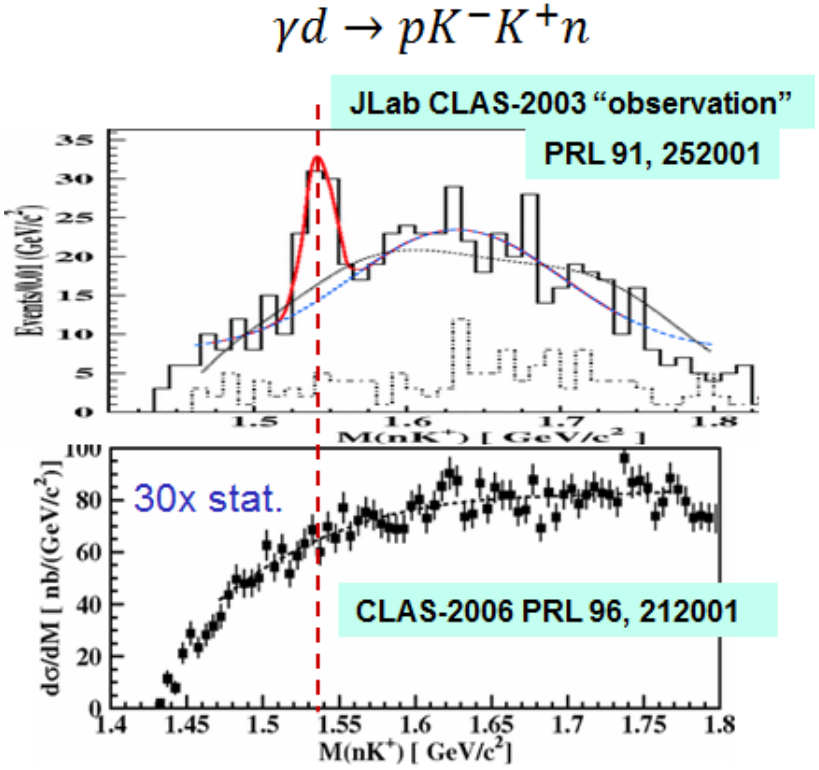
- LHCb has found two resonances decaying into $J/\psi p$ with pentaquark content of $uudc\bar{c}$. PRL 115, 072001 (2015) PRL 117, 082002 (2016)
- They are confirmed by a model-independent way
- They have spin 3/2 & 5/2 & opposite Parity
- P_c^+ productions are consistent between the two Λ_b^0 decays PRL 117, 082003 (2016)
- Determination of their internal binding will require more study

- We are updating results with Run-II data and improved modelling
- Also more channels, stay tuned

Thanks for your attention

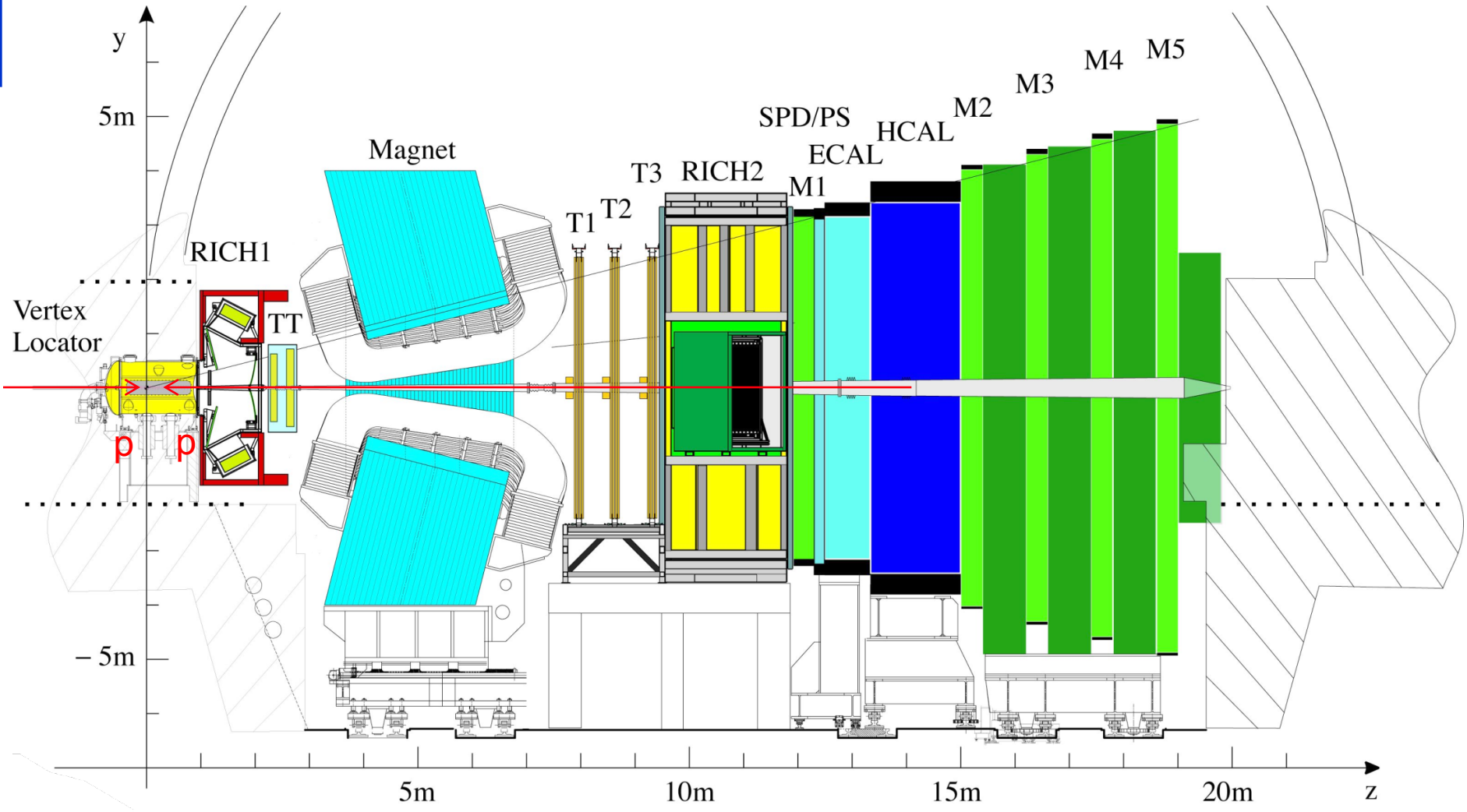
Past claimed pentaquark

- No convincing states 50 years after Gell-mann paper proposing $qqqq\bar{q}$ states
- Prediction: Θ^+ ($uudd\bar{s}$) could exist with m ≈1530 MeV
- In 2003,10 experiments reported evidences of narrow peaks of K^0p or K^+n, all >4 σ
- High statistics repeats from JLab showed the original claims were fluctuation
- It was merely a case of "bump hunting"



See summary by [K. H. Hicks, Eur. Phys. J. H37 (2012) 1]

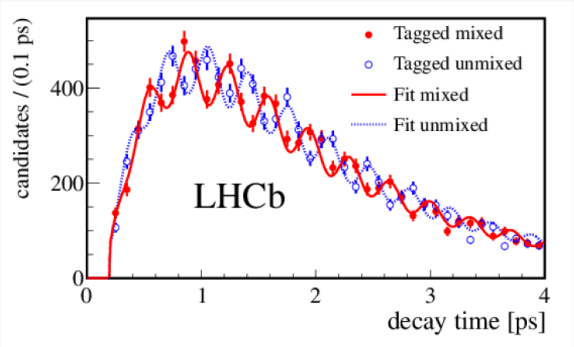
LHCb Detector



Detector performance

Vertexing

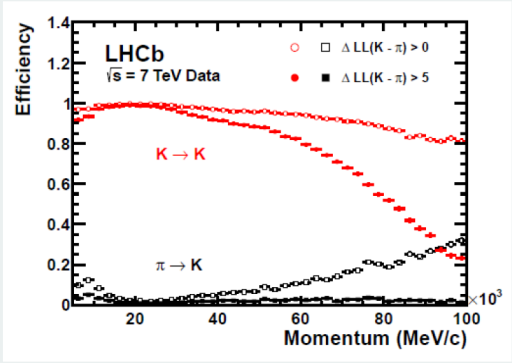
B_s^0 oscillations with $B_s^0 \to D_s\pi$



[New J. Phys. 15 (2013) 053021]

PID

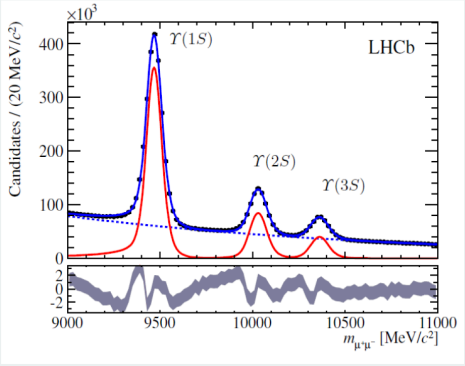
K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

Tracking

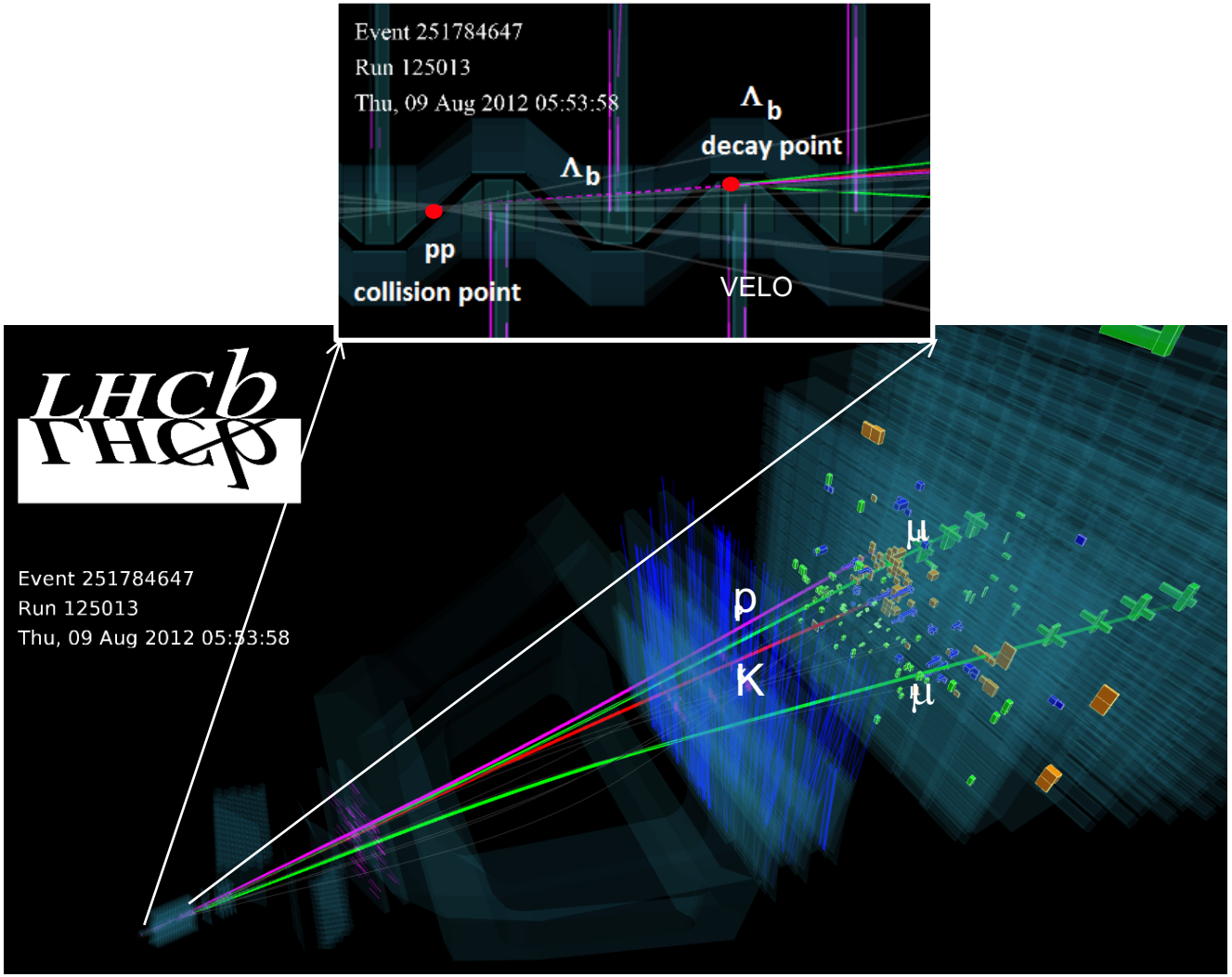
$\mu^+\mu^-$ mass spectrum



[PRL 111 (2013) 101805]

Impact parameter:	$\sigma_{IP} = 20\ \mu\text{m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ \text{GeV}/c)$
Mass :	$\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $\text{m}_{J/\psi}$)
RICH $K - \pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
Muon ID:	$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

A $\Lambda_b^0 \to J/\psi p K^-$ candidate

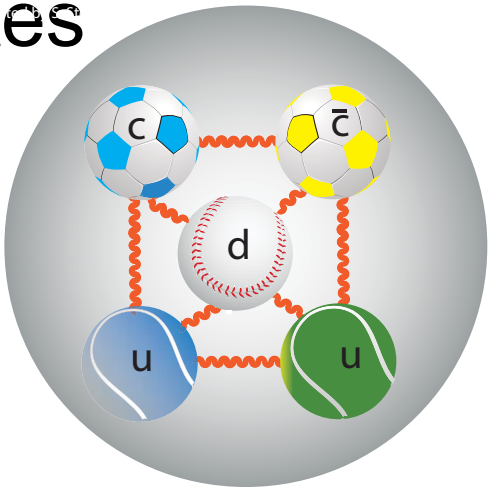


Cross-checks

- Many done, some listed here:
- Signal found using different selections by others
- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data shows consistency: 2011/2012, magnet up/down, $\overline{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
- Selection varied
  - BDTG>0.5 instead of 0.9 (default)
  - B^0 and B_s misID background modeled in the fit instead of veto

Pentaquark models

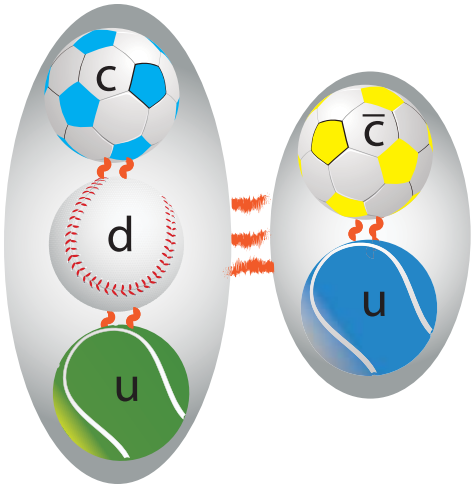
- All models must explain J^P of two states not just one. They also should predict properties of other states: masses, widths, J^P.



- Many models: Lets start with **tightly bound quarks** ala′ Jaffe
  - Two colored diquarks plus the anti-quark, L.Maiani, et. al, [arXiv:1507.04980]
  - Colored diquark + colored triquark, R. Lebed [arXiv:1507.05867]

Molecular models

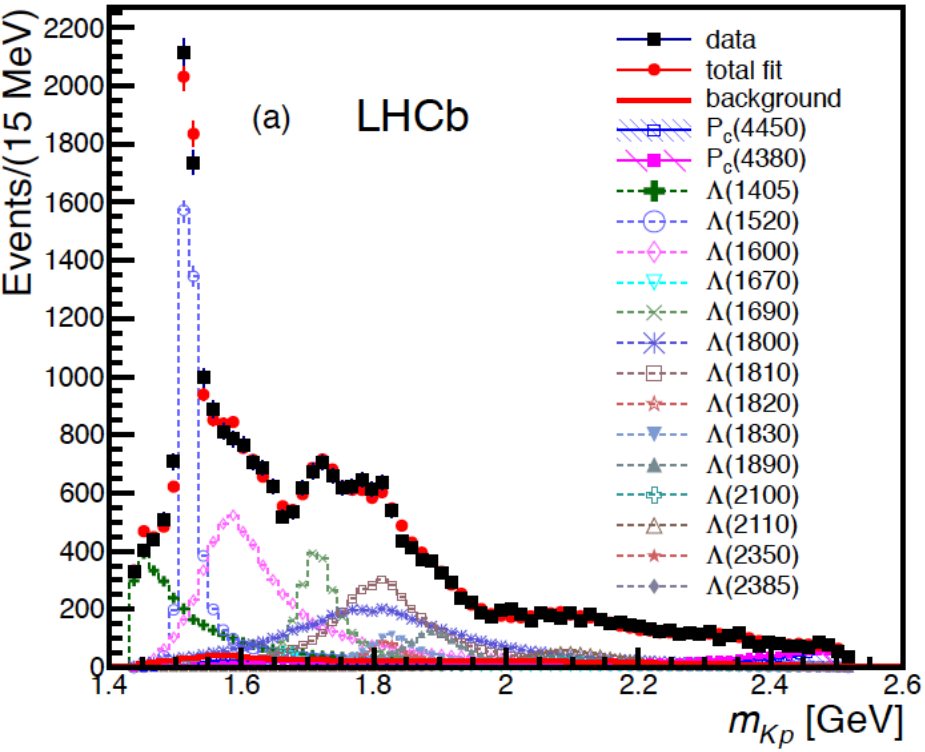
- Molecular models, generally with meson exchange for binding
- Inspired by proximity of baryon-meson mass sums to P_c masses

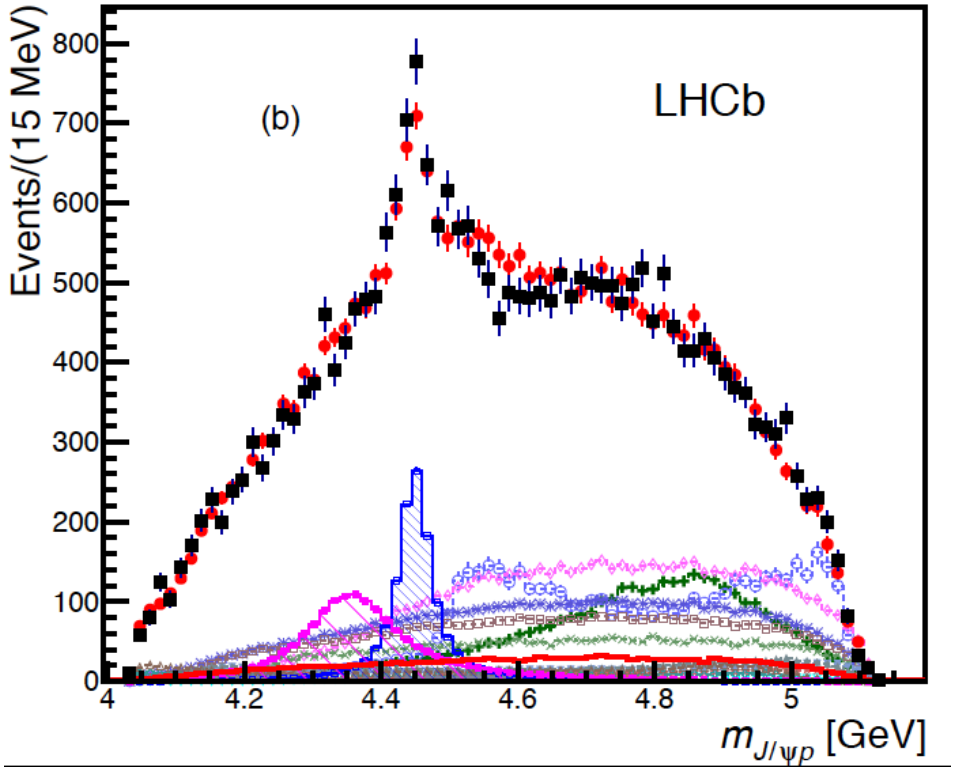


		$P_c(4450)$			$P_c(4380)$	
composition→	$\chi_{c1}p$	$\Sigma_c\bar{D}^*$	$\Lambda_c^*\bar{D}$	$J/\psi N^*$	$\Sigma_c^*\bar{D}$	$J/\psi N^*$
Possible decay modes						
$J/\psi N$	✓	✓	✓	✓	✓	✓
$\eta_c N$	×	×	✓	×	×	×
$J/\psi\Delta$	×	✓	×	×	✓	×
$\eta_c\Delta$	×	✓	×	×	✓	×
$\Lambda_c\bar{D}$	✓	[×]	[✓]	×	[×]	×
$\Lambda_c\bar{D}^*$	✓	✓	[✓]	✓	✓	✓
$\Sigma_c\bar{D}$	✓	[×]	✓	×	[×]	×
$\Sigma_c^*\bar{D}$	✓	✓	[×]	✓		
$J/\psi N\pi$	×	✓	×	✓	✓	✓
$\Lambda_c\bar{D}\pi$	×	×	×	×	✓	×
$\Lambda_c\bar{D}^*\pi$	×	✓	×	×		
$\Sigma_c^+\bar{D}^0\pi^0$	×	✓	✓	×		

[Burns arXiv:1509.02460]

Extended model with 2 P_c's





Amplitude formalism V

- They are summed as:

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0}, \lambda_p, \Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c}, \lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0}, \lambda_p^{P_c}, \Delta\lambda_\mu} \right|^2$$

- α_μ & θ_p are rotation angles needed to align the final state helicity axes of the μ & p, as the initial helicity frames are different for the two decay chains
- Helicity couplings $\mathcal{H} \Rightarrow$ LS amplitudes *B* via:

$$\mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C} = \sum_L \sum_S \sqrt{\tfrac{2L+1}{2J_A+1}} B_{L,S} \left(\begin{array}{cc|c} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B - \lambda_C \end{array} \right) \times \left(\begin{array}{cc|c} L & S & J_A \\ 0 & \lambda_B - \lambda_C & \lambda_B - \lambda_C \end{array} \right)$$

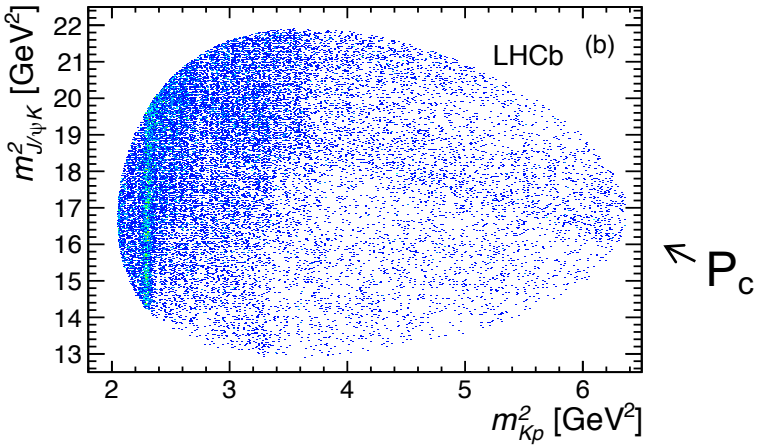
- Convenient way to enforce parity conservation in the strong decays via: P_A

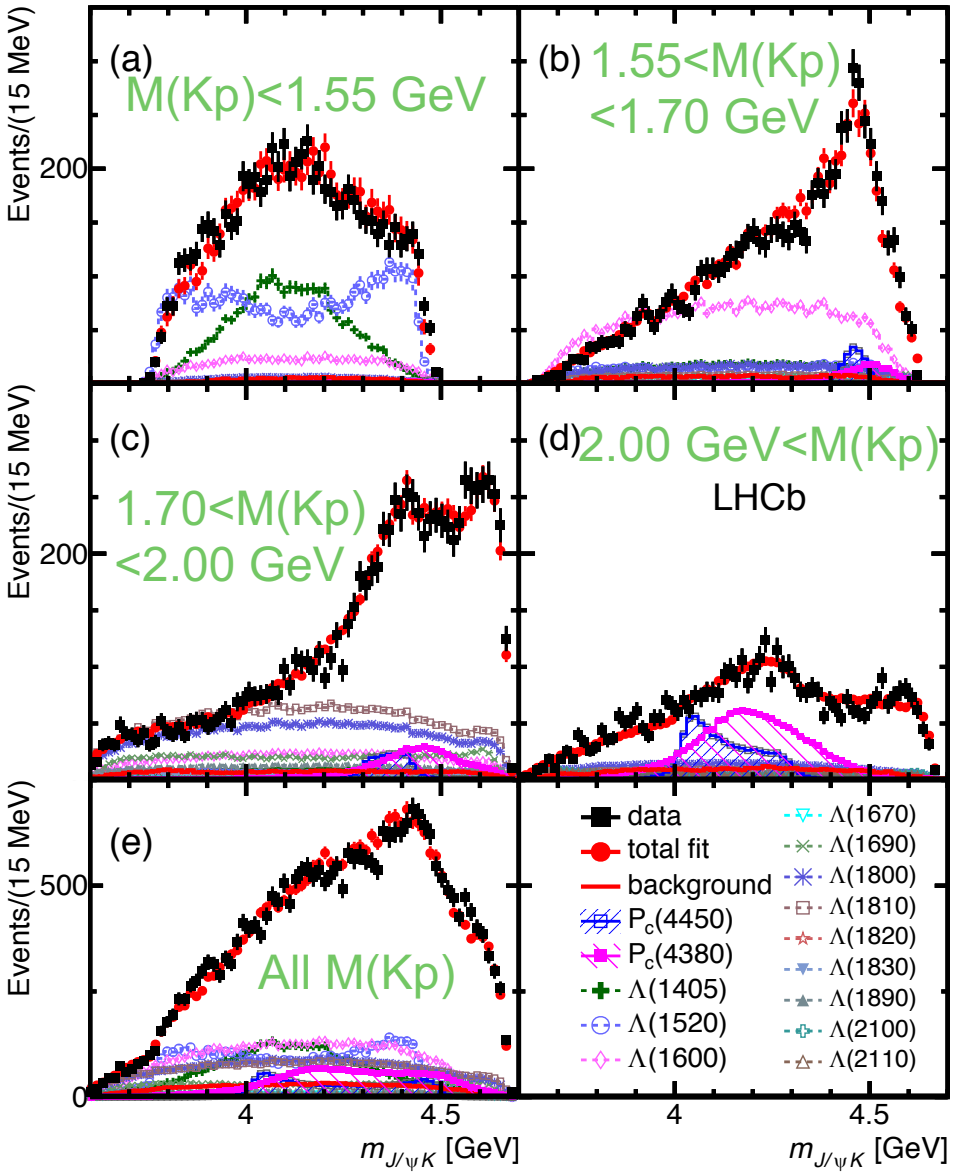
LHCb goals

- Find or establish limits on physics beyond the standard model using CP violating & rare beauty & charm decays
- Rare: $B_{(s)} \to \mu^+\mu^-$, $B^0 \to K^*\mu^+\mu^-$, $B^- \to Ke^+e^-/K\mu^+\mu^-$
- CP violation: determine $\angle$'s: γ, β, ϕ_s
  - γ measured with $B^- \to D^0 K^-$ decays
  - ϕ_s measured with $B_s \to J/\psi\phi$ & $J/\psi\pi^+\pi^-$ decays
  - All $B \to J/\psi\, \pi^+\pi^-$ & $J/\psi K^+K^-$ studied
  - In study of $B^0 \to J/\psi K^+K^-$ [arXiv:1308.5916], $\Lambda_b \to J/\psi K^- p$ was suggested as a potential background

m(J/ψ K-)

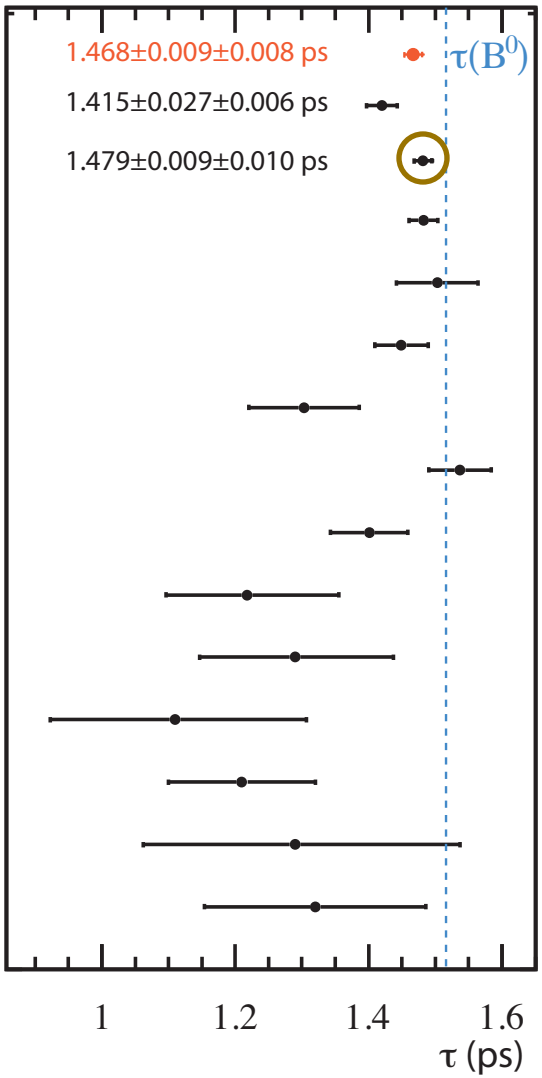
- Our fit explains m(J/ψ K-)





Significances

- To include systematic uncertainty, the extended model fits are used
- Fit improves greatly, for 1 P_c $\Delta(-2\ln\mathcal{L})=14.7^2$, adding the 2nd P_c improves by 11.6^2, for adding both together $\Delta(-2\ln\mathcal{L})=18.7^2$
- Toy MCs are used to obtain significances based on $\Delta(-2\ln\mathcal{L})$
- Significances:
  - 1st P_c $(4450)^+$: 12σ
  - 2st P_c $(4380)^+$: $9\ \sigma$
  - Total : 15σ

Measurement of Λ_b^0/B^0 lifetime

- Long history of a puzzling discrepancy between Λ_b^0 and B^0 lifetime
- Heavy Quark Expansion (HQE) predicts similar lifetime
- With our precision measurements, this story now ends