Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b \to J/\psi\, p K^-$ decays

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On behalf of the LHCb Collaboration

Tetra- and Penta-quarks conceived at the birth of Quark Model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

...

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, $\overline{A}\overline{A}$AAAAAA, etc., where $\overline{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\overline{A}$A, $\overline{A}\overline{A}$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".

- Searches for such states made out of the light quarks (u,d,s) are ~50 years old, but no undisputed experimental evidence have been found for them

Two waves of past pentaquark claims (with $\bar{s}$)

e.g. PDG 1976

Baryons

Z^*'s, $Z_0(1780)$, $Z_0(1865)$, $Z_1(1900)^-$

S=1 I=0 EXOTIC STATES (Z_0)

$Z_0(1780)$ 95 Z*0(1780, JP=1/2+) I=0 P_{01}

SEE THE MINI-REVIEW PRECEDING THIS LISTING.

WILSON 72 AND GIACOMELLI 74 FIND SOME SOLUTIONS
WITH RESONANT-LIKE BEHAVIOR IN THE PO1 PARTIAL WAVE.
THE EFFECT SEEN IN THE I=0 TOTAL CROSS SECTIONS,
IF A RESONANCE, MUST HAVE SPIN=1/2, BECAUSE THE
INELASTIC CROSS SECTION IS VERY SMALL AND THE TOTAL
CROSS SECTION IS ABOUT 4*PI/K**2.

95 Z*0(1780) MASS (MEV)

		1780.0	10.0		COOL	70 CNTR +	K+P, D TOTAL	1/71
M	D			SEEN	DOWELL	70 CNTR	K+P,D TOTAL	7/70
M	D			SEE ALSO DISCUSSION OF LYNCH 70				7/70
M	W	(1800.)			WILSON	72 PWA	K+N PO1 WAVE	3/72
M	W	ESTIMATE OF PARAMETERS FROM BW + QUADRATIC BACKGROUND FIT TO PO1.						3/72
M	1	(1750.)			CARROLL	73 CNTR	KN I=0 TCS,FIT 1	9/73
M	1	(1825.)			CARROLL	73 CNTR	KN I=0 TCS,FIT 2	9/73
M	1	FIT 1=FIT OF SINGLE L=1 BW+BACKGROUND TO I=0 TCS FROM .4-1.1 GEV/C						9/73
M	1	FIT 2=FIT OF L=1 AND L=2 BWS TO SAME DATA,SEE Z0(1865) FOR L=2 PART						9/73
M	(1740.)				GIACOMEL	74 PWA	.38-1.51 GEV/C	10/74*

Last mention of baryonic Z*'s PDG 1992

Z BARYONS ($S = +1$)

NOTE ON THE $S = +1$ BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and has also been reviewed by Kelly[2] and by Oades.[3] New partial-wave analyses[4,5] appeared in 1984 and 1985, and both claimed that the P_{13} and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 20 years. The standards of proof must simply be more severe here than in a channel in which many resonances are already known to exist. The skepticism about baryons not made of three quarks, and the lack of any experimental activity in this area, make it likely that another 20 years will pass before the issue is decided. Nothing new at all has been published in this area since our 1986 edition,[6] and we simply refer to that for listings of the $Z_0(1780)P_{01}$, $Z_0(1865)D_{03}$, $Z_1(1725)P_{11}$, $Z_1(2150)$, and $Z_1(2500)$.

Last mention of 2nd pentaquark wave: PDG 2006

Found/debunked by looking for "bumps" in mass spectra

$\Theta(1540)^+$ $I(J^P) = 0(?^?)$ Status: *

OMITTED FROM SUMMARY TABLE

PENTAQUARK UPDATE

Written February 2006

In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997 paper [1], considering only u, d, and s quarks, Diakonov et

. . .

To summarize, with the exception described in the previous paragraph, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the Θ^+; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the Θ^+; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the Θ^+, in particular, do not exist, appears compelling.

"XYZ" States

- Several charmonium and bottomonium-like states have been observed by several different experiments.

- These states do not fit into the conventional quark model and are candidates for tetraquarks.

- Example: The Z(4430) is a $c\bar{c}d\bar{u}$ candidate first seen by Belle in 2007 and confirmed in 2014 by LHCb.
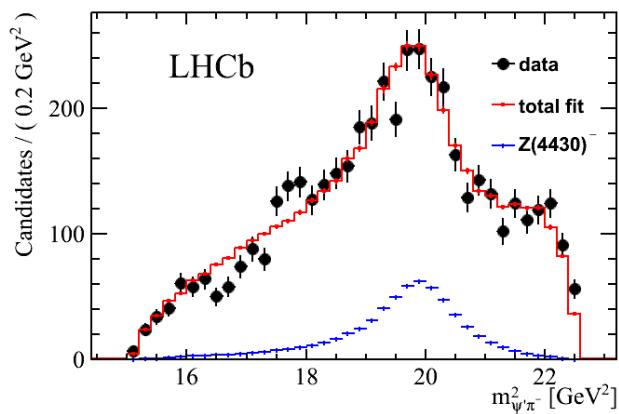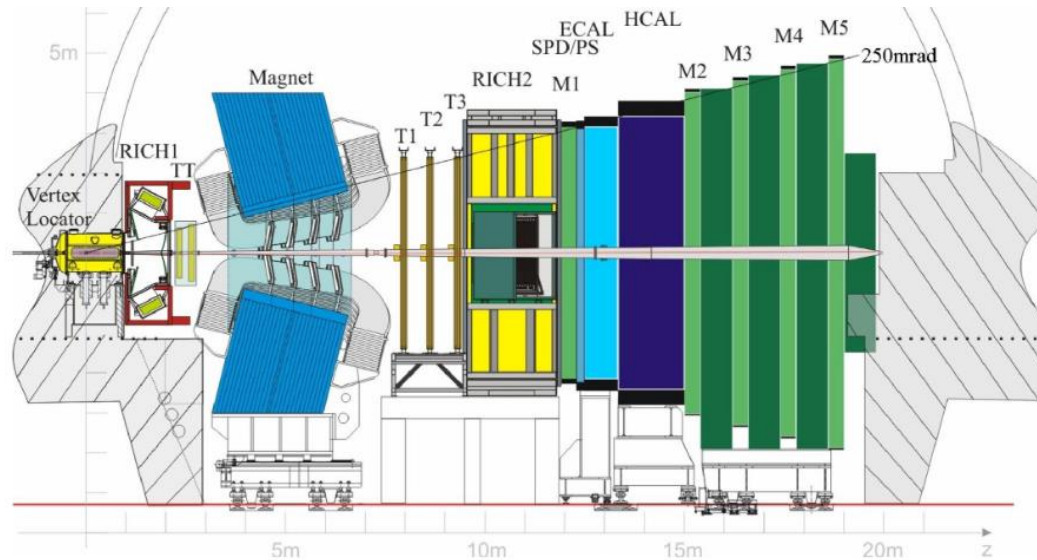

PRL 112, 222002 (2014)
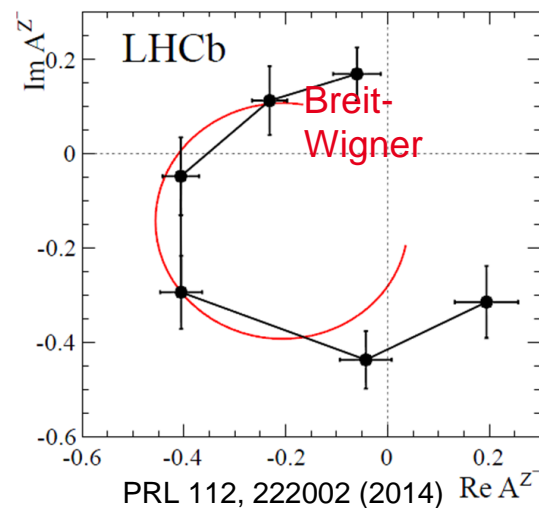
PRL 112, 222002 (2014)

- Despite the history of pentaquarks, the discovery of strong tetraquark candidates makes their existence appear more plausible!
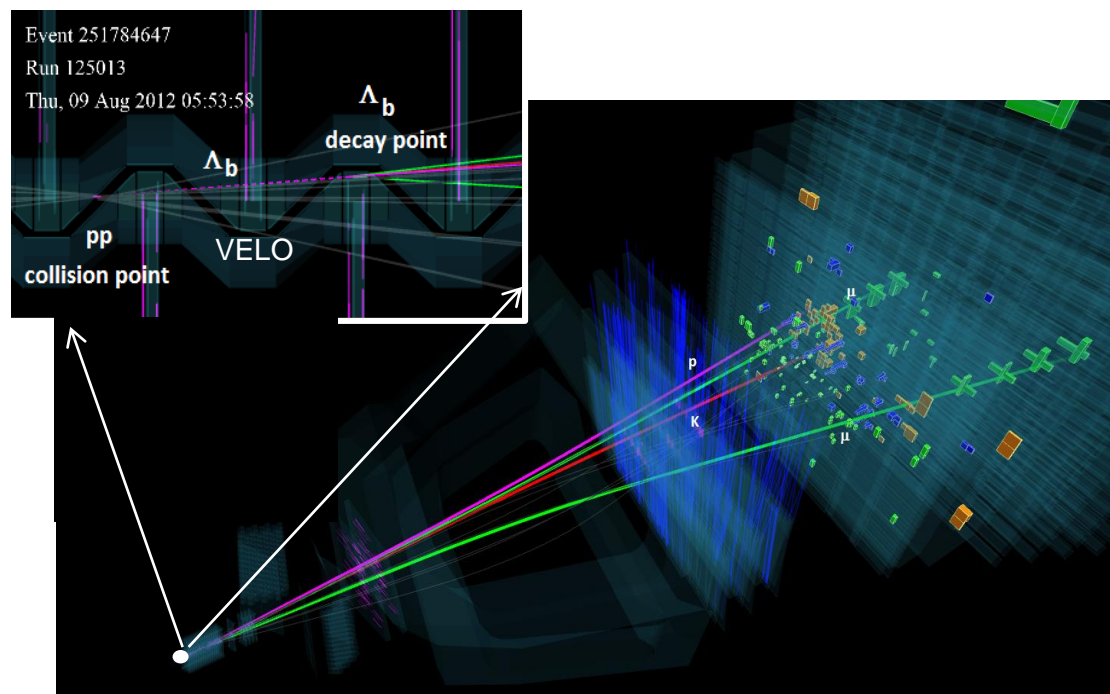
The LHCb detector
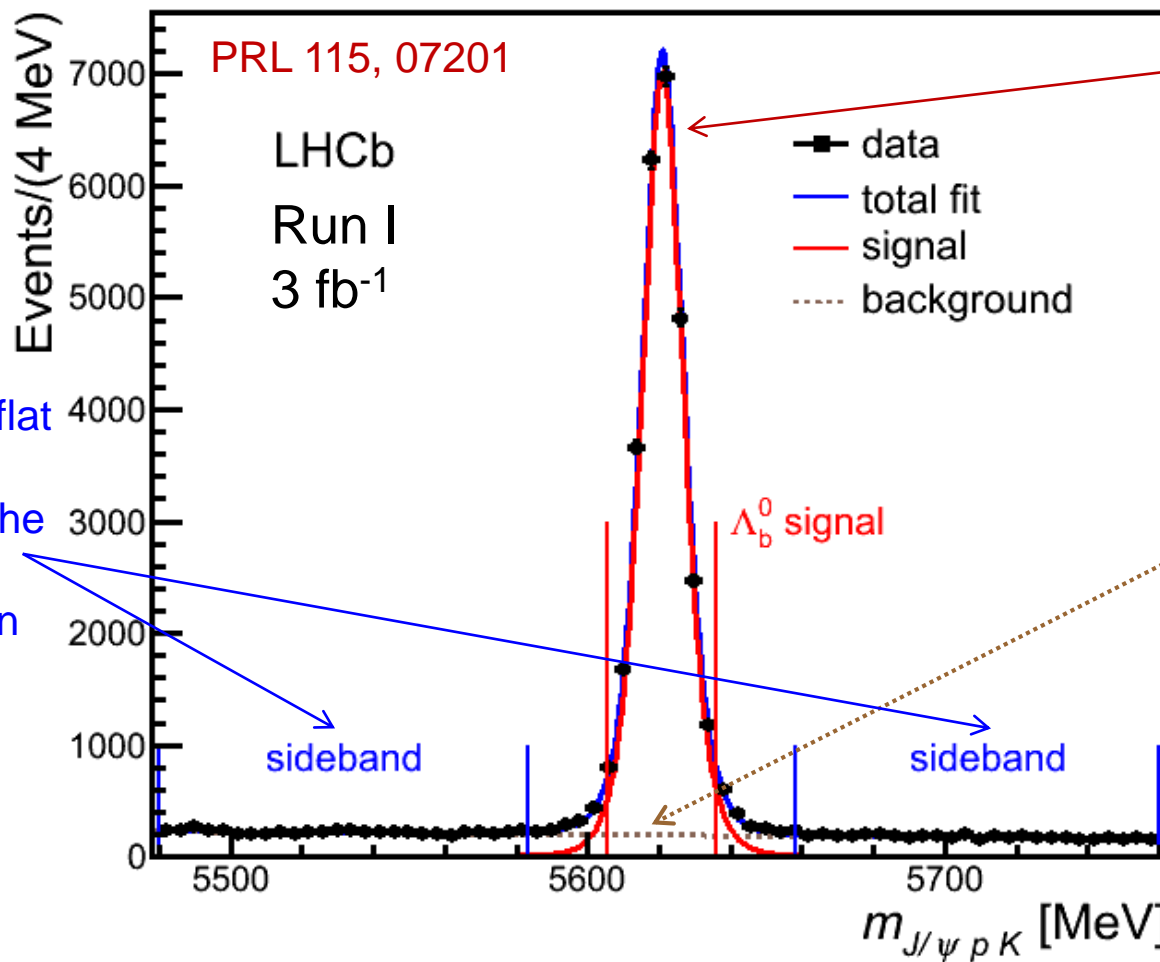

Int. J. Mod. Phys. A 30 (2015) 1530022

- Forward arm spectrometer designed for precision CP violation measurements and decays of bottom and charm hadrons.
- Rapidity coverage $2.0 < y < 4.5$
- Excellent particle identification:
  - Muons: $\varepsilon \sim 97\%$ for $1 - 3\% \, \pi \to \mu$ misidentification
  - Kaons: $\varepsilon \sim 95\%$ for $5\% \, \pi \to K$ misidentification
- Very good vertex resolution: $\sigma = 20\mu m$ impact parameter resolution
- Momentum resolution $\Delta p/p = 0.5\%$ at 20GeV to 0.8% at 100 GeV

$\Lambda_b^0 \to$ J/ψ p K$^-$ Selection

- The data sample consists of the full LHCb Run 1 data set of 3fb^{-1}

- Candidates have a $(\mu^+\mu^-)Kp$ vertex, with the $(\mu^+\mu^-)$ pair consistent with a J/ψ

Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58

Λ_b decay point

Λ_b

pp collision point

VELO

- Standard selection to ensure good track and vertex quality, as well as cuts on particle identification, p_T cuts, and separation from the primary vertex.

- Reflections from B^0 and B_s are vetoed.

- Final background suppression is done with a multivariate analyzer (boosted decision tree).

# $\Lambda_b^0 \rightarrow J/\psi\, p\, K^-$ At LHCb

PRL 115, 07201

LHCb

Run I
3 fb^{-1}

26,007±166
Λ_b^0 candidates

- data
- total fit
- signal
- background

The sideband distributions are flat $\rightarrow$ no major reflections from the other b-hadrons after the selection

The background is only 5.4% in the signal region!

Λ_b^0 signal

sideband

sideband

- The decay first observed by LHCb and used to measure Λ_b^0 lifetime PRL 111, 102003 (2013)

An unexpected structure in $m_{J/\psi\, p}$

LHCb

$P_c^+ \rightarrow J/\psi\, p$?
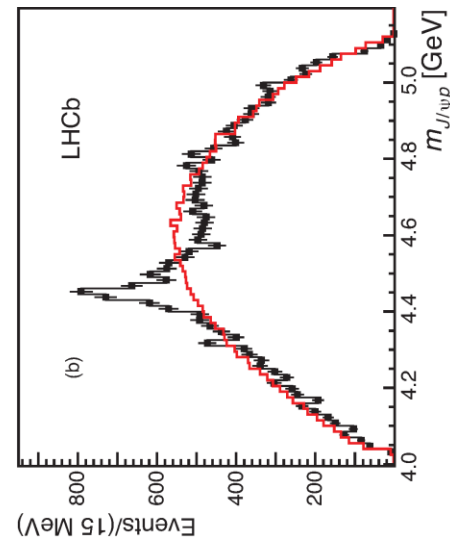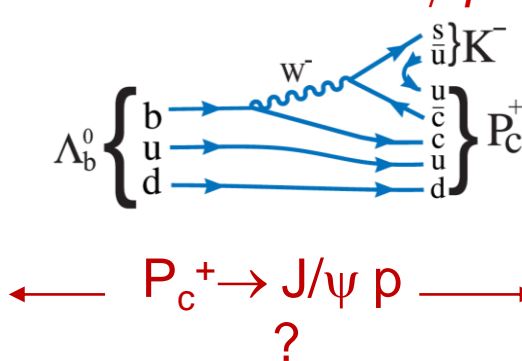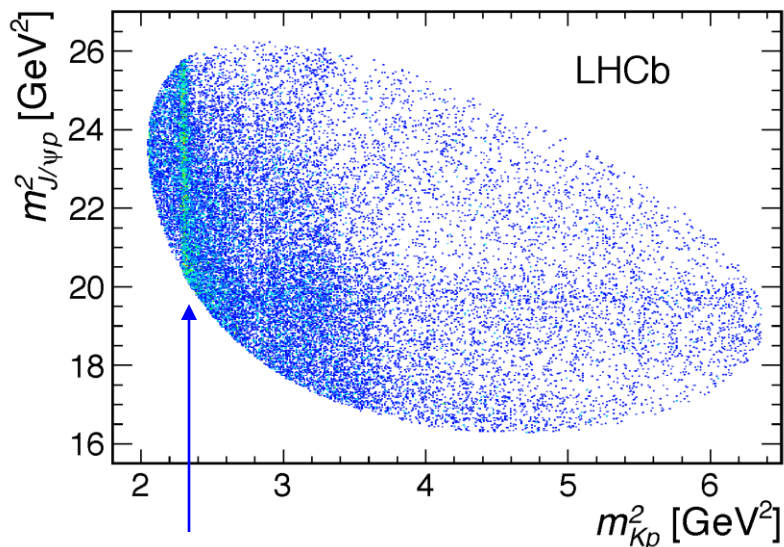
$\Lambda(1520)$ and other Λ^*'s $\rightarrow$ p K$^-$
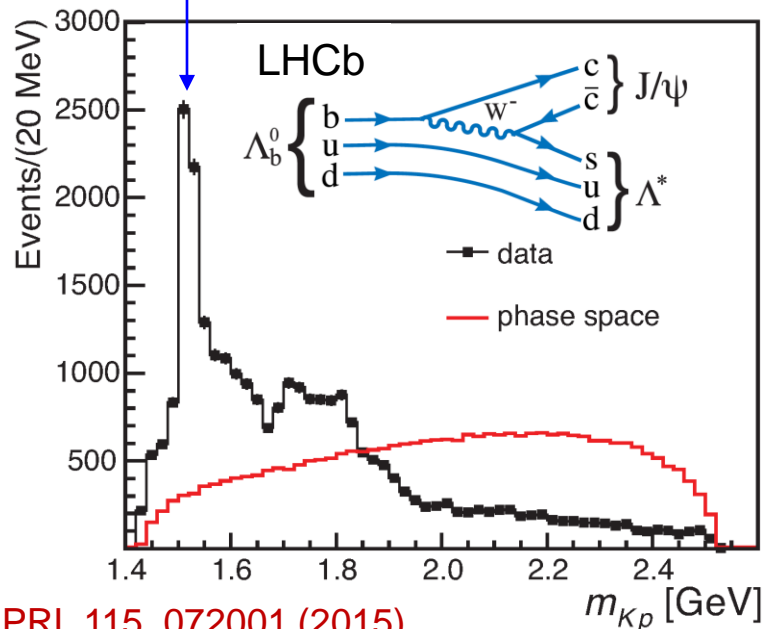
Unexpected narrow peak in $m_{J/\psi\, p}$!

PRL 115, 072001 (2015)

Necessary Checks

- Many checks done to
  ensure it is not an "artifact"
  of selection:

  - Efficiency across Dalitz
    plane is smooth,
    wouldn't create peaking
    structures.

  - The same P_c^+ structure found using very different selections
    by different LHCb teams

  - Split data shows consistency: 2011/2012, magnet up/down,
    $\Lambda_b/\overline{\Lambda}_b$, $\Lambda_b(p_T$ low$)/\Lambda_b(p_T$ high$)$

  - Exclude Ξ_b or other high mass decays as a possible source

  - Veto $B_s \to J/\psi K^- K^+$ & $B^0 \to J/\psi K^- \pi^+$ decays

  - Suppress fake tracks: the peak is not an experimental
    artifact.
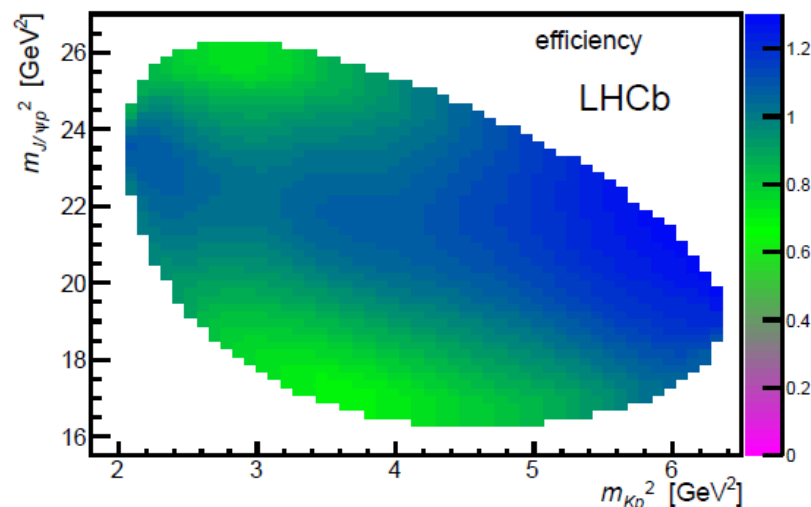
Amplitude Analysis of $\Lambda_b^0 \rightarrow J/\psi p K^-$, $J/\psi \rightarrow \mu^+\mu^-$

- Could it be a reflection of interfering $\Lambda^{*\prime}$s $\rightarrow$ p K$^-$?
  - Full amplitude analysis absolutely necessary!
- Analyze all dimensions of the decay kinematics for $\Lambda_b^0 \rightarrow J/\psi p K^-$, $J/\psi \rightarrow \mu^+\mu^-$:
  - to maximize sensitivity to the decay dynamics
  - to avoid biases due to averaging over some dimensions in presence of non-uniform detector efficiency
- Our PDF used in the fit is:

6D $\vec{\omega}$ - Fitted parameters (helicity couplings,M_0,Γ_0)

$$\mathcal{P}_{\text{sig}}(m_{Kp}, \Omega | \vec{\omega}) = \frac{1}{I(\vec{\omega})} |\mathcal{M}(m_{Kp}, \Omega | \vec{\omega})|^2 \, \Phi(m_{Kp}) \epsilon(m_{Kp}, \Omega)$$

$\mathcal{M}(m_{Kp}, \Omega | \vec{\omega})$ Matrix element describing decay

$\Phi(m_{Kp})$ Phase space factor

$\epsilon(m_{Kp}, \Omega)$ Selection efficiency

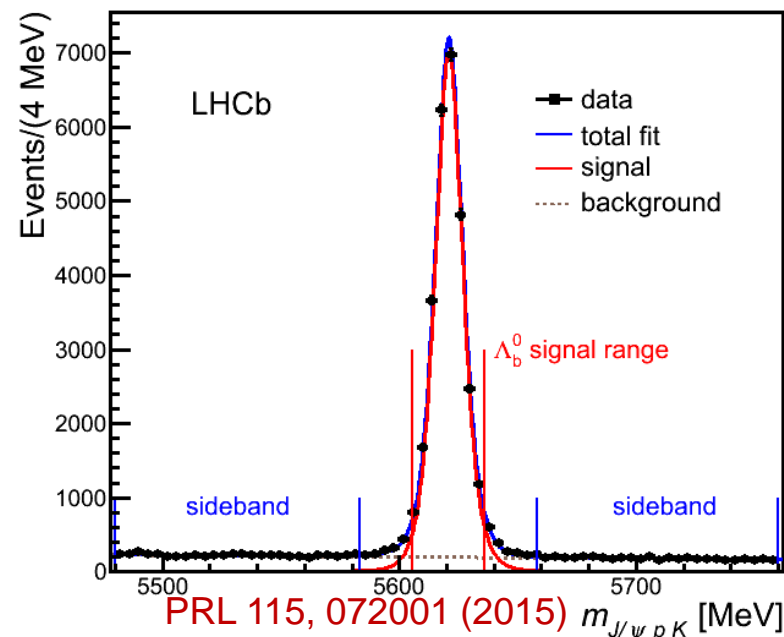$I(\vec{\omega})$ Normalization integral

Background modeling

The remaining background can be handled in two ways. In the fit we minimize:

$$-2\ln\mathcal{L}(\vec{\omega}) = -2s_W \sum_i W_i \ln \mathcal{P}(m_{Kpi}, \Omega_i|\vec{\omega})$$

$$s_W \equiv \sum_i W_i / \sum_i W_i^2$$

"sFit"

LHCb

data
total fit
signal
background

Λ_b^0 signal range

sideband   sideband

PRL 115, 072001 (2015) $m_{J/\psi pK}$ [MeV]

Events/(4 MeV)

- W_i are sWeights (arXiv:0402083v3) based on the fit to $m_{J/\psi pK}$ distribution

- Negative weights correspond to background events, and are used to subtract the background in the likelihood.

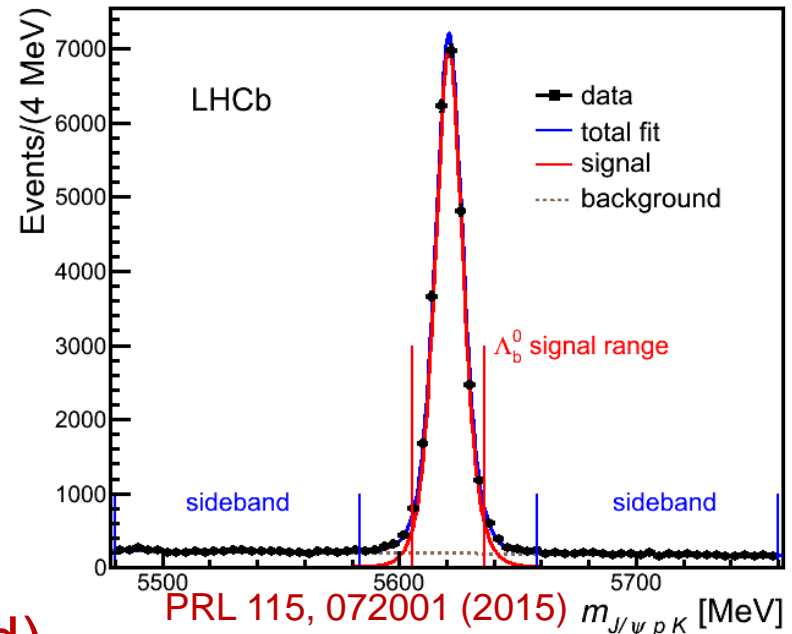- The data in the extended $m_{J/\psi pK}$ range including the sidebands is passed to the amplitude fit

Background modeling

The remaining background can be handled in two ways. In the fit we minimize:

$$-2\ln\mathcal{L}(\vec{\omega}) = -2s_W \sum_i W_i \ln\mathcal{P}(m_{Kpi}, \Omega_i|\vec{\omega})$$

$$s_W \equiv \sum_i W_i / \sum_i W_i^2$$

PRL 115, 072001 (2015)

"cFit" (default method)

- $W_i = 1$; no event weights. Sideband data used to construct 6D model of the background which is added to the signal PDF:

$$\mathcal{P}(m_{Kp}, \Omega|\vec{\omega}) = (1-\beta)\,\mathcal{P}_{\text{sig}}(m_{Kp}, \Omega|\vec{\omega}) + \beta\,\mathcal{P}_{\text{bkg}}(m_{Kp}, \Omega)$$

  $\beta = 5.4\%$ background fraction

- Data only in the Λ_b^0 signal range passed to the amplitude fit.

- Fitters using cFit and sFit were coded completely independently and used to cross-check each other.

Helicity Formalism

- The matrix element for these decays is written using the helicity formalism.

- Each sequential decay $A \to BC$ of a spin J_A resonance adds a term:

Wigner D-matrix

$$\mathcal{H}_{\lambda_B, \lambda_C}^{A \to BC} \; D_{\lambda_A, \lambda_B - \lambda_C}^{J_A}(\phi_B, \theta_A, 0)^* R_A(m_{BC})$$
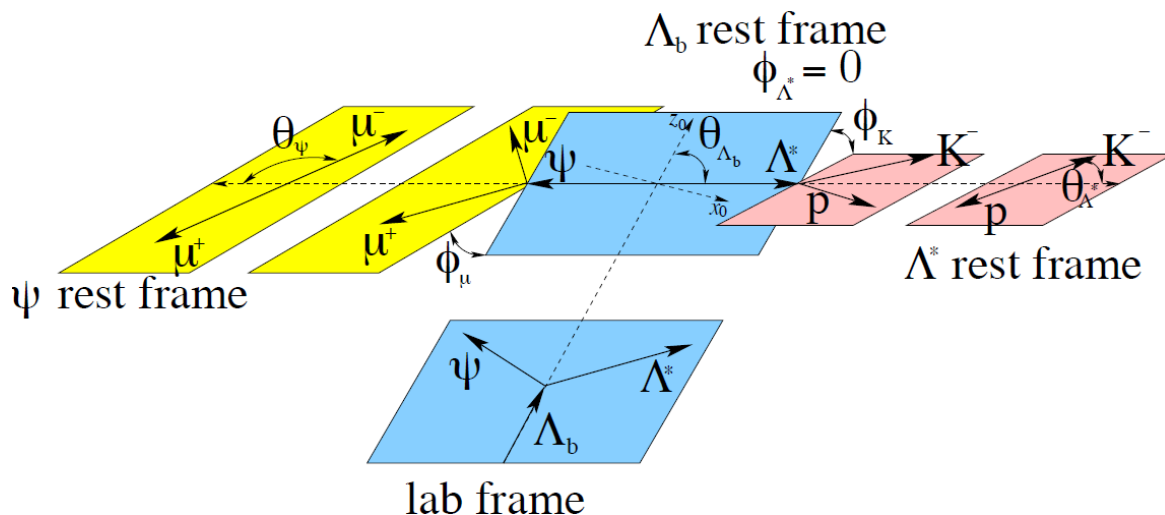
Helicity coupling to final-state helicities λ_B, λ_C

Rest frame of A

Helicity frame of A

- $R_A(m_{BC})$ is the resonance parametrization used if A has a non-negligible natural width.

- The three arguments of Wigner's D-matrix are Euler angles describing the rotation from helicity frame of A to helicity frame of B

Λ^* Matrix Element

Λ_b rest frame
$\phi_{\Lambda^*} = 0$

ψ rest frame

Λ^* rest frame

lab frame
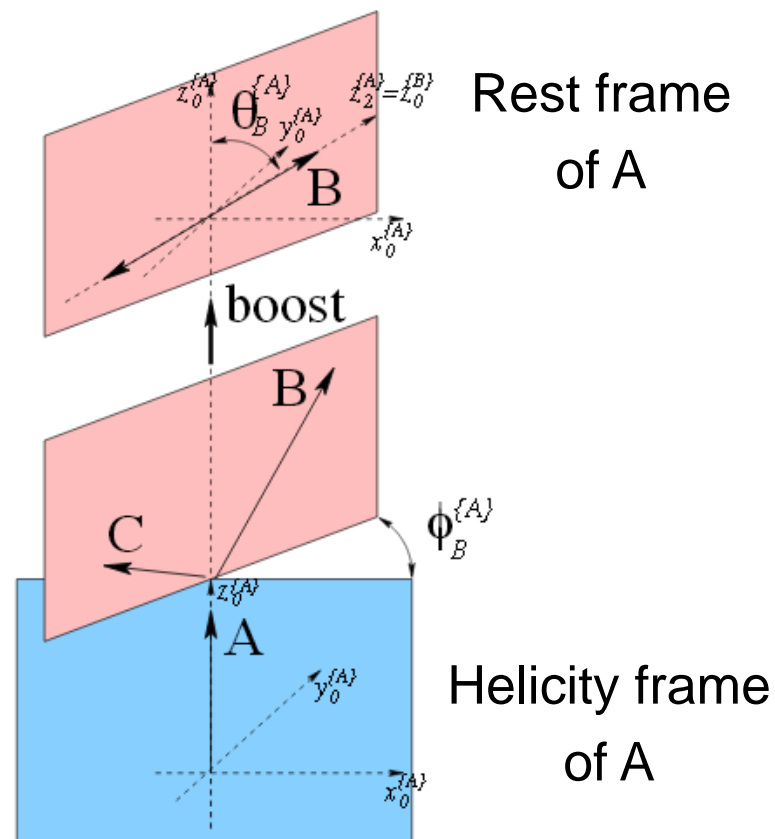
Completely describes the decay
$\Lambda_b \to \Lambda^* J/\psi$ with $\Lambda^* \to Kp$ and $J/\psi \to \mu\mu$

4-6 independent **complex** helicity couplings per Λ_n^* resonance

6 independent data variables:
1 mass, 5 angles

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

$$\mathcal{H}^{\Lambda_n^* \to Kp}_{\lambda_p, 0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*}, \lambda_p}(\phi_K, \theta_{\Lambda^*}, 0)^* R_n(m_{Kp}) D^1_{\lambda_\psi, \Delta\lambda_\mu}(\phi_\mu, \theta_\psi, 0)^*$$

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

Blatt-Weisskopf functions

$$\mathrm{BW}(m | M_{0X}, \Gamma_{0X}) = \frac{1}{M_{0X}^2 - m^2 - i M_{0X} \Gamma(m)}$$

Breit-Wigner

Λ^* resonance model

- Large number of possibly contributing resonances, each contributing 4-6 complex amplitudes.

- $\Sigma^* \to pK^-$ contributions would have $\Delta I = 1$ and are excluded, based off expectation that they're suppressed in analogy with $\Delta I = 1/2$ rule in kaon decays.

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

Λ^* resonance model

- We use two models in our fits to study the dependence on Λ^* model.

- "Extended model" includes all states, all possible amplitudes

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

Total fit parameters: 146

Λ^* resonance model

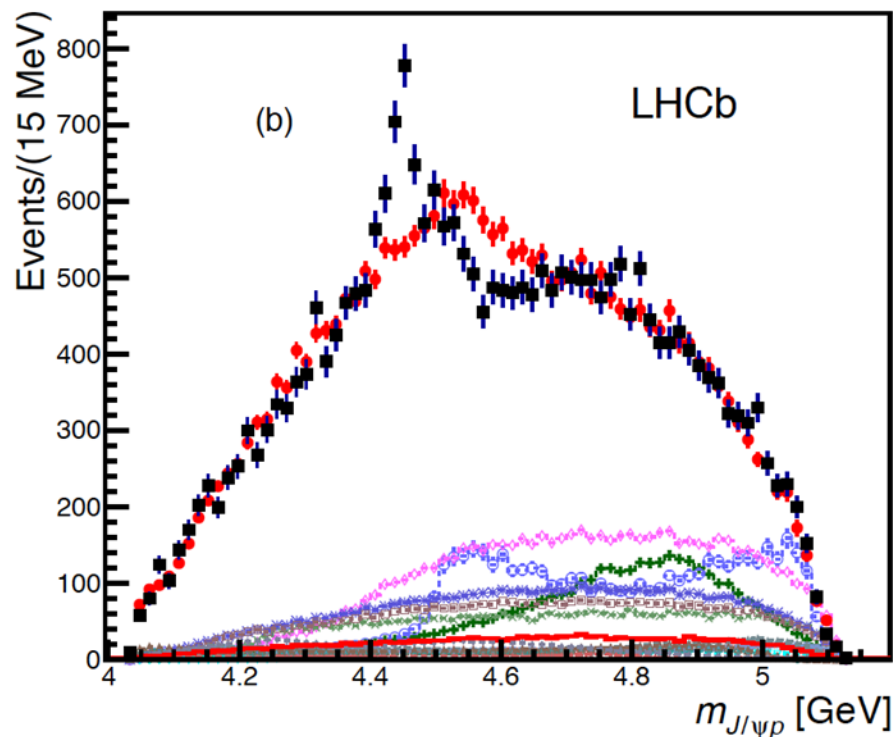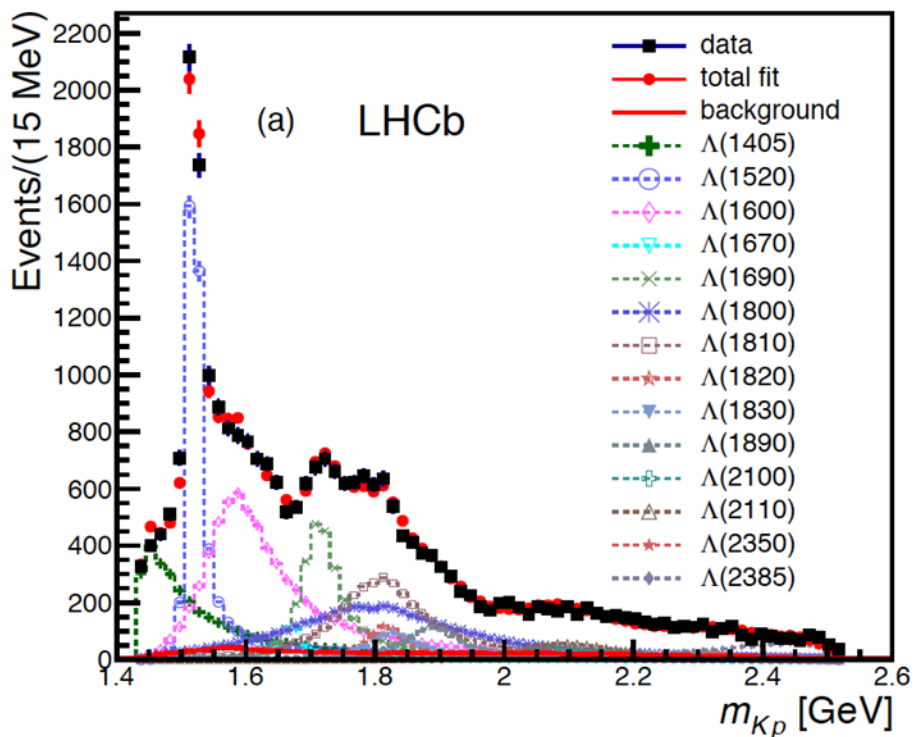- Helicity couplings are rewritten in terms of LS couplings:

$$\mathcal{H}^{A \to BC}_{\lambda_B, \lambda_C} = \sum_L \sum_S \sqrt{\tfrac{2L+1}{2J_A+1}} B_{L,S} \begin{pmatrix} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B - \lambda_C \end{pmatrix} \times \begin{pmatrix} L & S & J_A \\ 0 & \lambda_B - \lambda_C & \lambda_B - \lambda_C \end{pmatrix}$$

- Reduced model excludes high-mass, high-spin states and also places limitations on L amplitudes

| 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	0	6
$\Lambda(2585)$	$5/2^-$?	≈ 2585	200	0	6

Total fit parameters: 64   146

So is it just a reflection?

- Can interfering Λ^* resonances reproduce the peaking structure seen in $m_{J/\psi p}$?

- We use the extended model to answer this, with the philosophy being that we should throw everything we can at it before introducing pentaquark states.

Fit with $\Lambda^* \to pK^-$ contributions only

(a) LHCb — Events/(15 MeV) vs m_{Kp} [GeV]

legend: data, total fit, background, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$, $\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Lambda(2100)$, $\Lambda(2110)$, $\Lambda(2350)$, $\Lambda(2385)$

(b) LHCb — Events/(15 MeV) vs $m_{J/\psi p}$ [GeV]

- m_{Kp} looks fine, but $m_{J/\psi p}$ looks terrible
- Addition of non-resonant terms, Σ^*'s or extra Λ^*'s doesn't help.
- There is no ability to describe the peaking structure with conventional resonances!

P_c^+ Matrix Element

ψ rest frame

Λ_b rest frame

P_c rest frame

lab frame
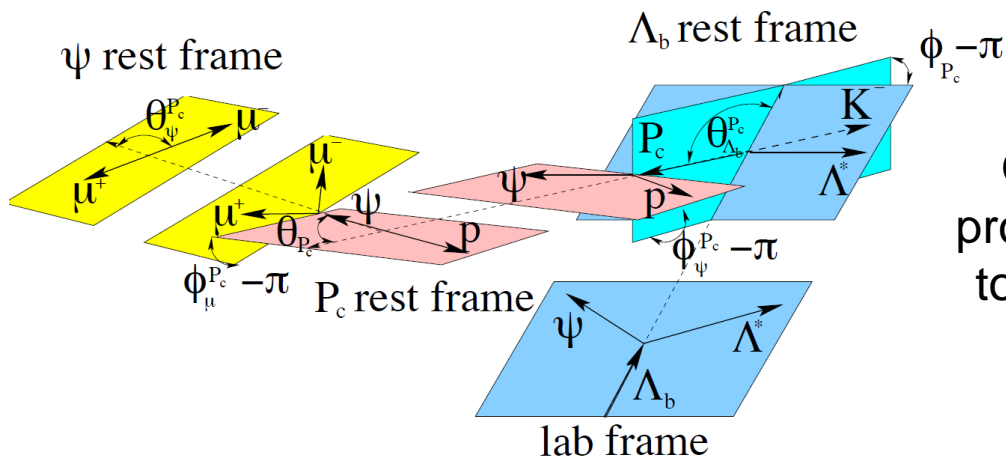
Completely describes the decay
$\Lambda_b \to P_c K$ with $P_c \to J/\psi\, p$ and $J/\psi \to \mu\mu$

One more angle than in Λ^* decay: P_c^+ production angles must be defined relative to the Λ_b reference frame established for $\Lambda_b \to J/\psi\Lambda^*$ decay

1 mass ($m_{J/\psi p}$), 6 angles
all derivable from the Λ^* decay variables

3-4 independent **complex** helicity couplings per P_{cj}^+ resonance depending on its J^P

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\, \lambda_p^{P_c},\, \Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0 \to P_{cj} K}_{\lambda_{P_c},\, 0}\, D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\, \lambda_{P_c}}\!\left(\phi_{P_c}, \theta_{\Lambda_b^0}^{P_c}, 0\right)^*$$

$$\mathcal{H}^{P_{cj} \to \psi p}_{\lambda_\psi^{P_c},\, \lambda_p^{P_c}}\, D^{J_{P_{cj}}}_{\lambda_{P_c},\, \lambda_\psi^{P_c} - \lambda_p^{P_c}}\!\left(\phi_\psi, \theta_{P_c}, 0\right)^* R_{P_{cj}}\!\left(m_{\psi p}\right)\, D^1_{\lambda_\psi^{P_c},\, \Delta\lambda_\mu^{P_c}}\!\left(\phi_\mu^{P_c}, \theta_\psi^{P_c}, 0\right)^*$$

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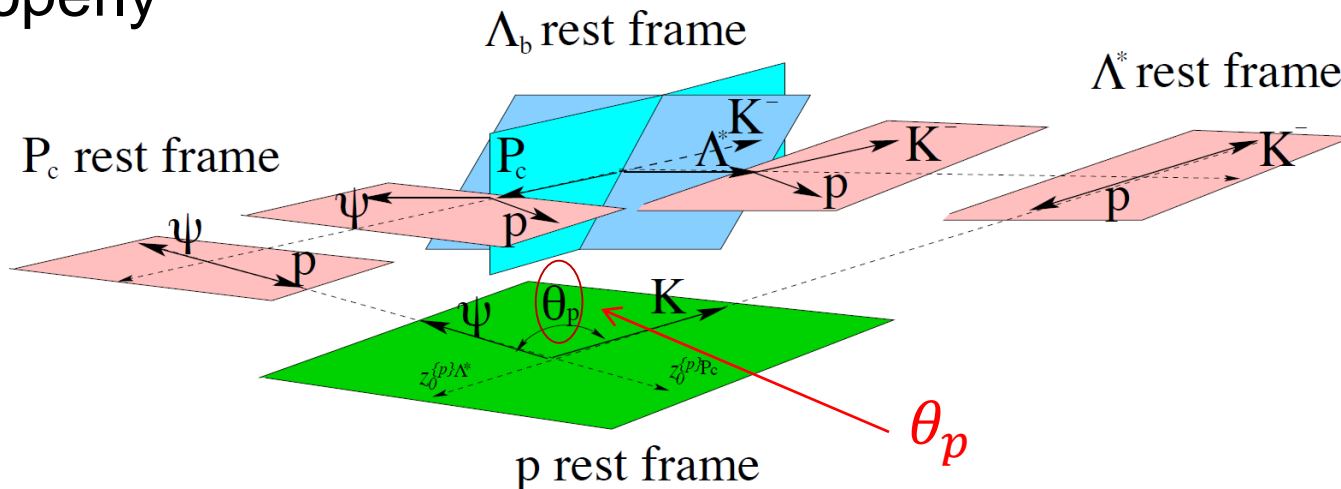
Breit-Wigner

$$\mathrm{BW}(m \mid M_{0X}, \Gamma_{0X}) = \frac{1}{{M_{0X}}^2 - m^2 - i M_{0X}\Gamma(m)}$$

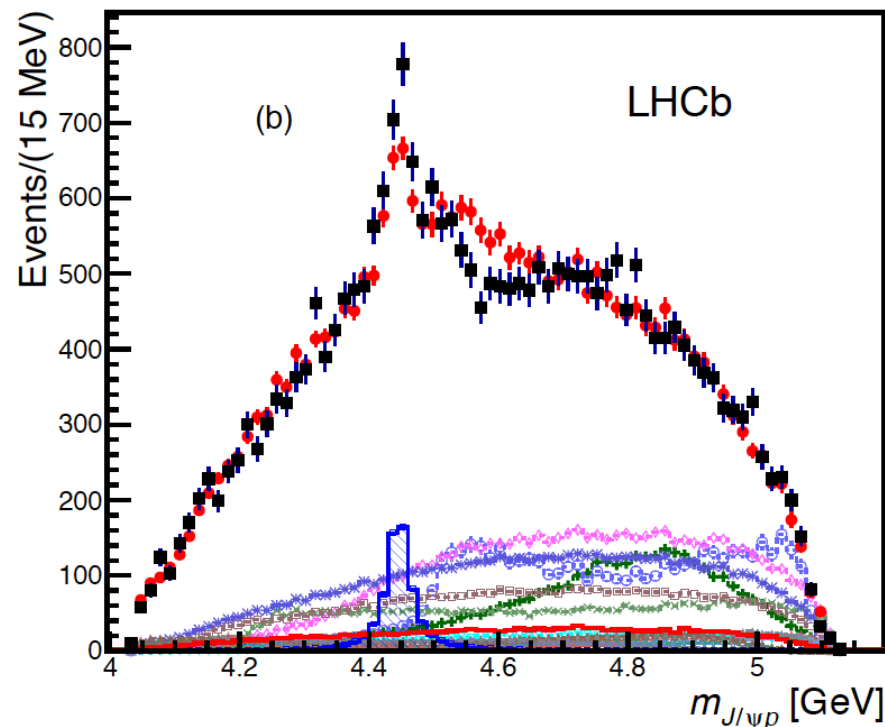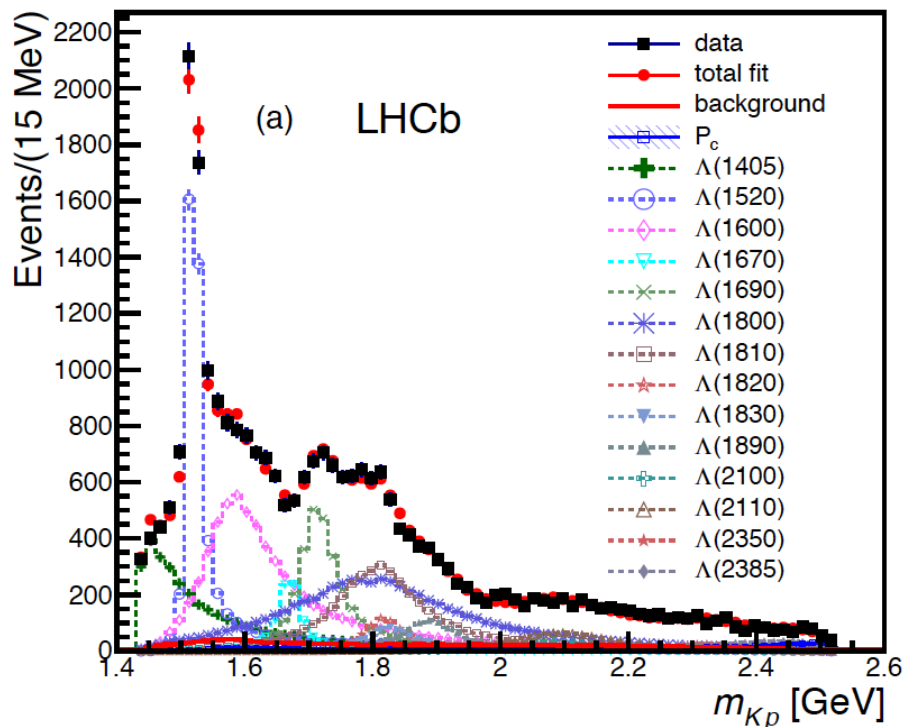Blatt-Weisskopf functions

Λ^* Plus P_c^+ Matrix Element

- To add the two matrix elements together we need two additional angles to align the muon and proton helicity frames between the Λ^* and P_c decay chains.

    – This is necessary to describe Λ^* plus P_c^+ interferences properly

- With θ_p, α_μ the full matrix element is written as

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

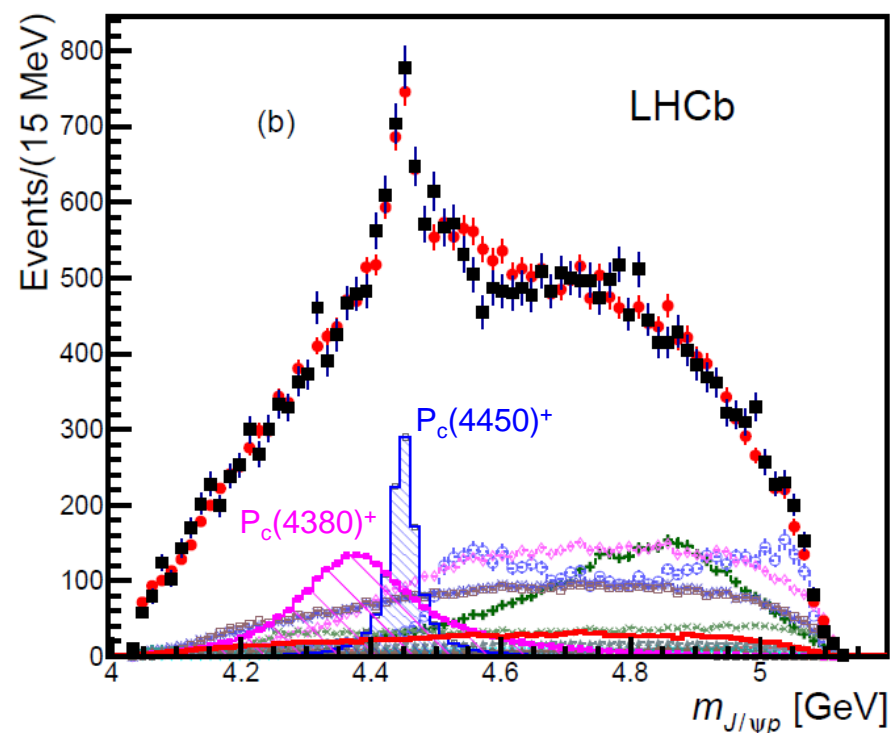# Fit with Λ^*'s and one $P_c^+ \rightarrow J/\psi p$ state

(extended Λ^* model)

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

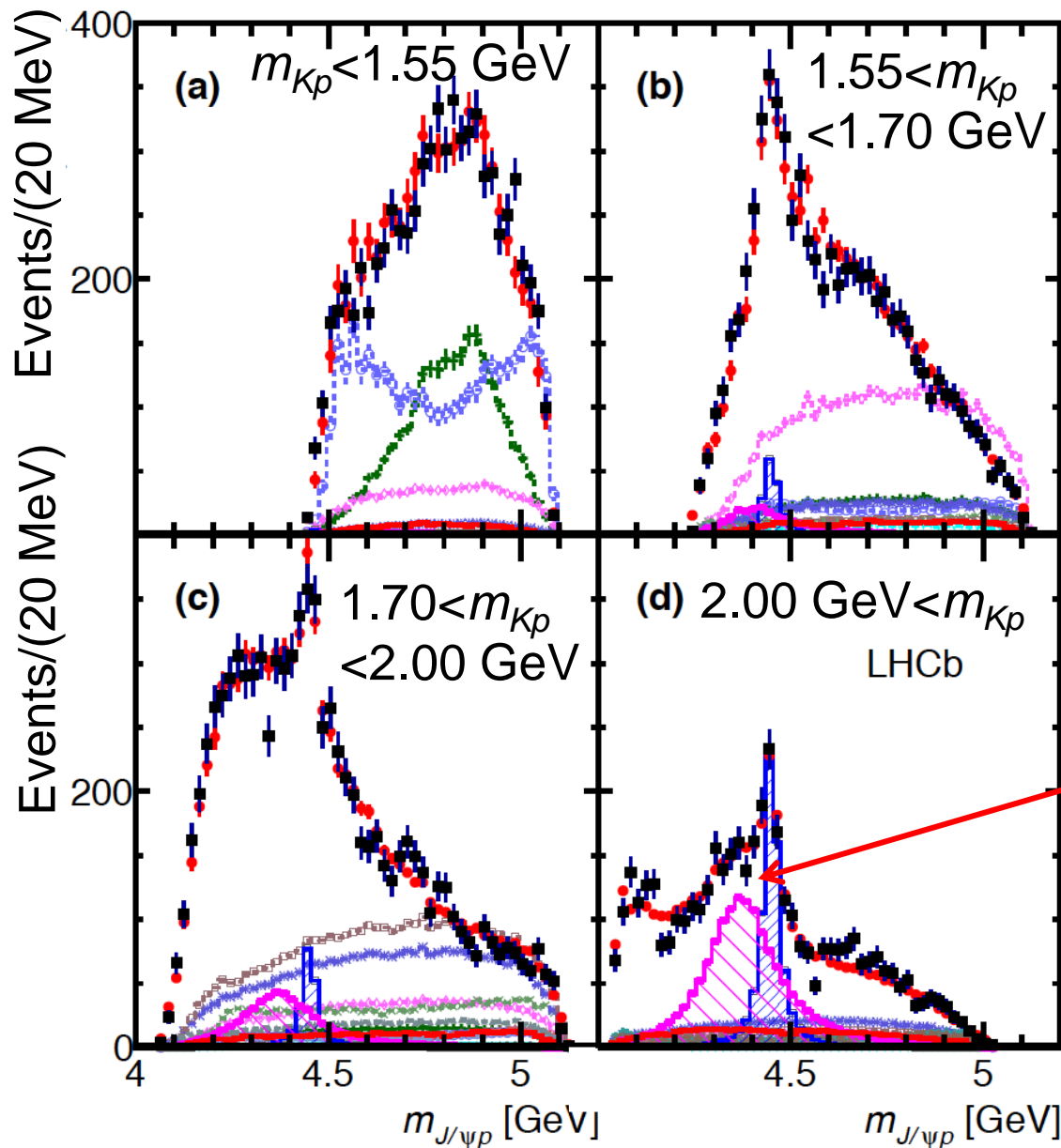# Fit with Λ^{*}'s and two $P_c^+ \rightarrow J/\psi p$ states
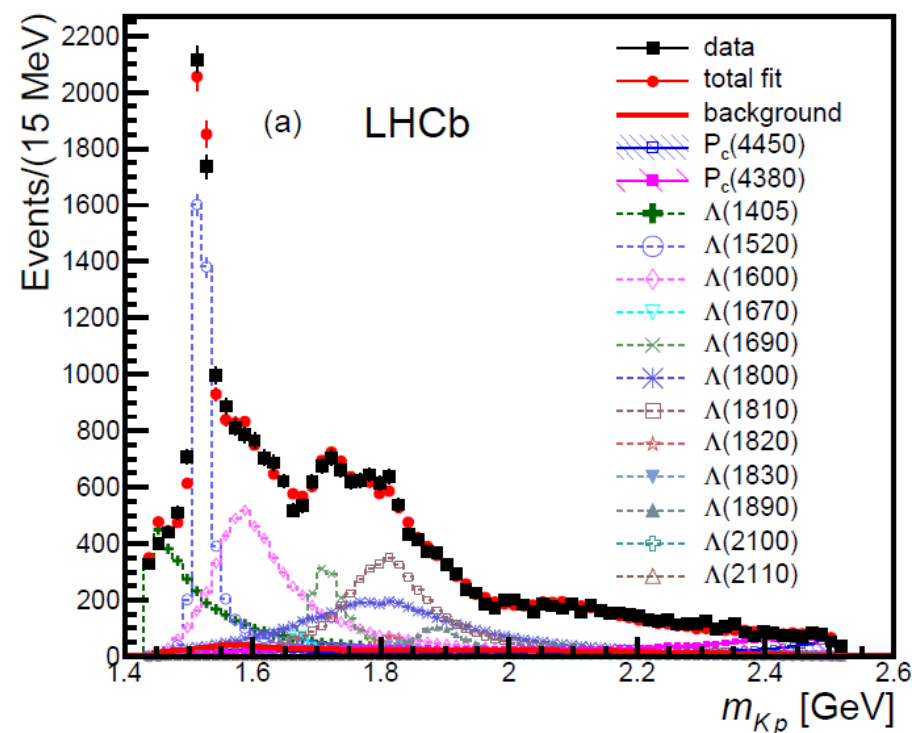
(reduced Λ^* model)

- With two P_c resonances we are able to describe the peaking structure!

- Obtain good fits even with the reduced Λ^* model

- Best fit has $J^P(P_c(4380), P_c(4450))=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ are preferred

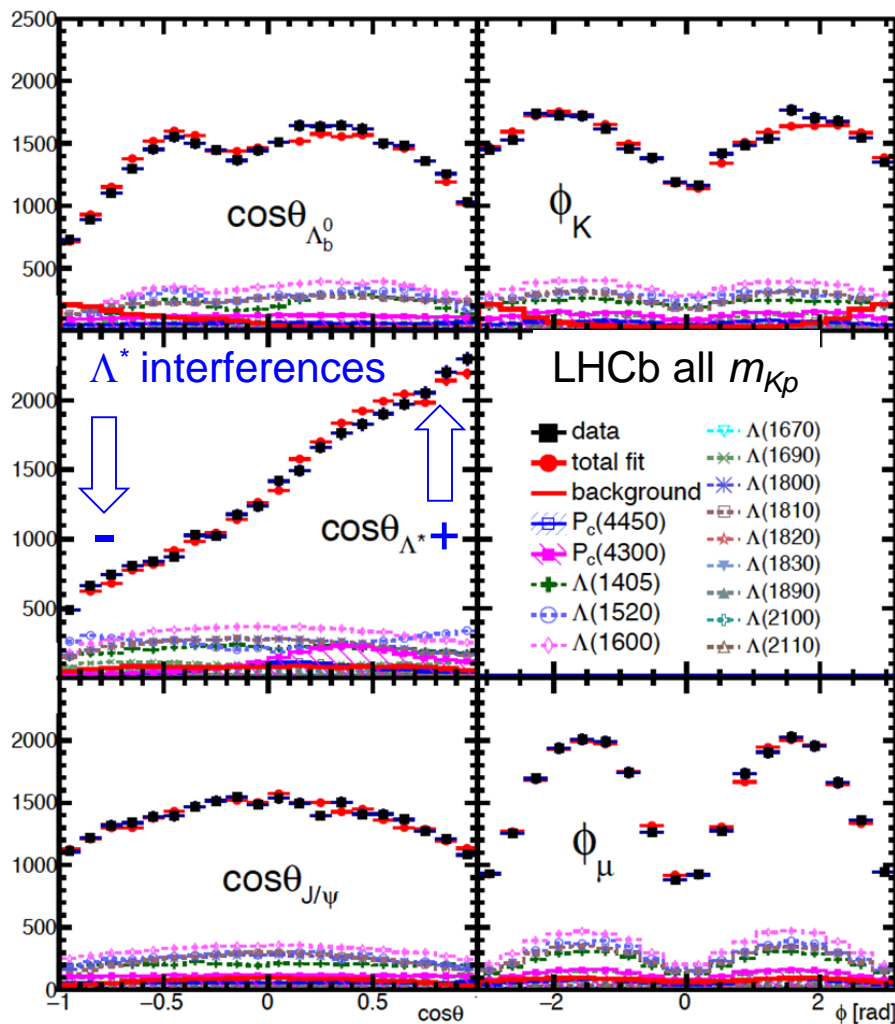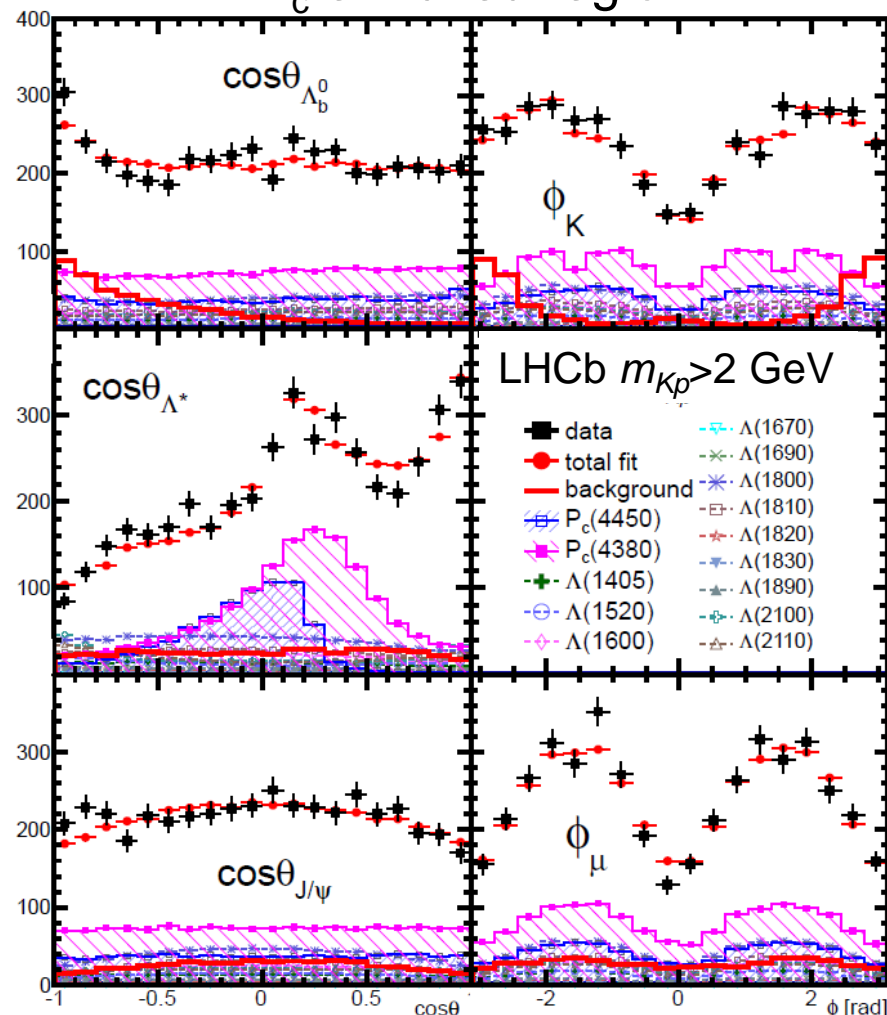# Fit with Λ^*'s and two $P_c^+ \to J/\psi p$ states

- Need for the 2nd broad P_c^+ state becomes visually apparent in the region where the $\Lambda^* \to pK^-$ background is the smallest
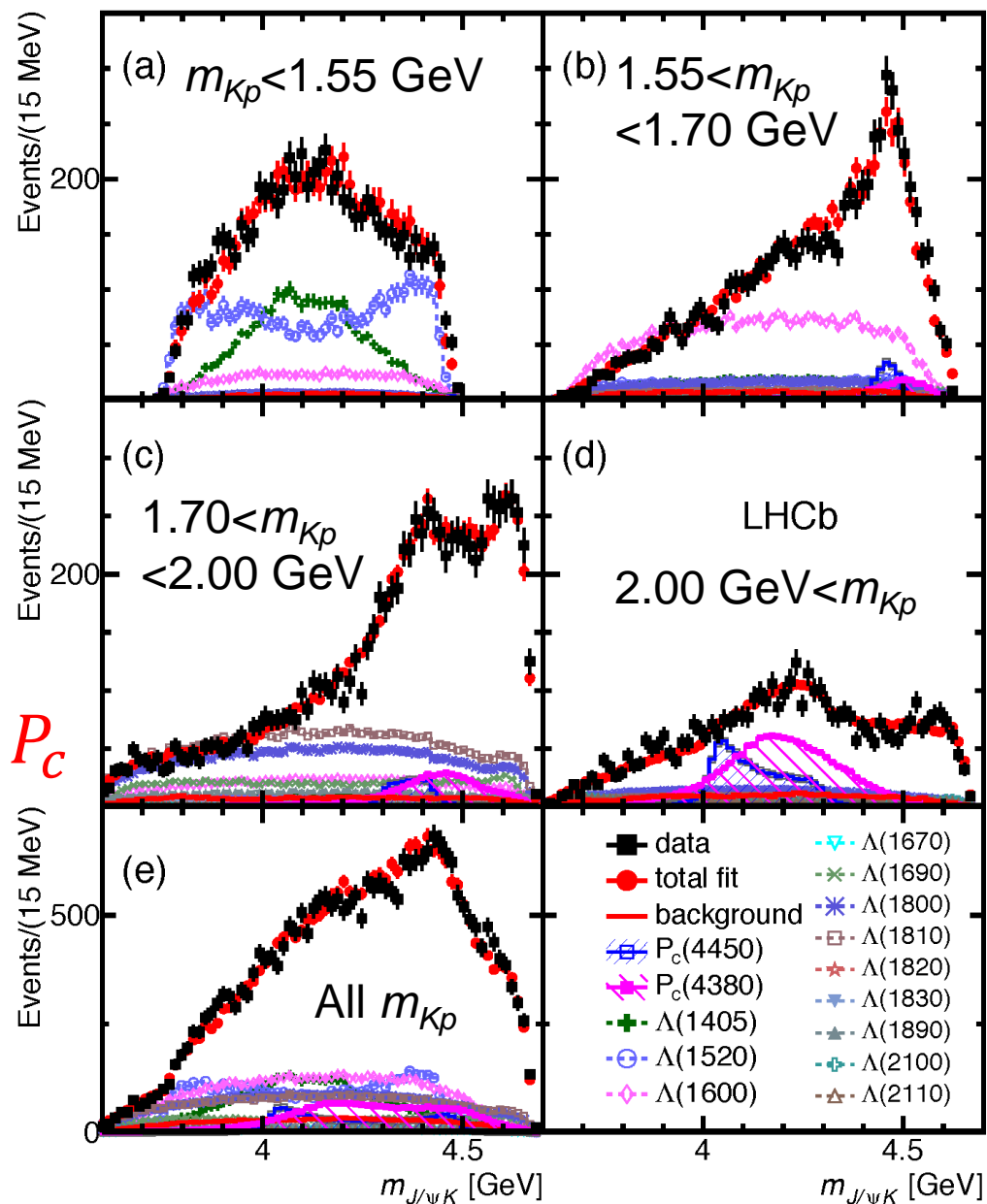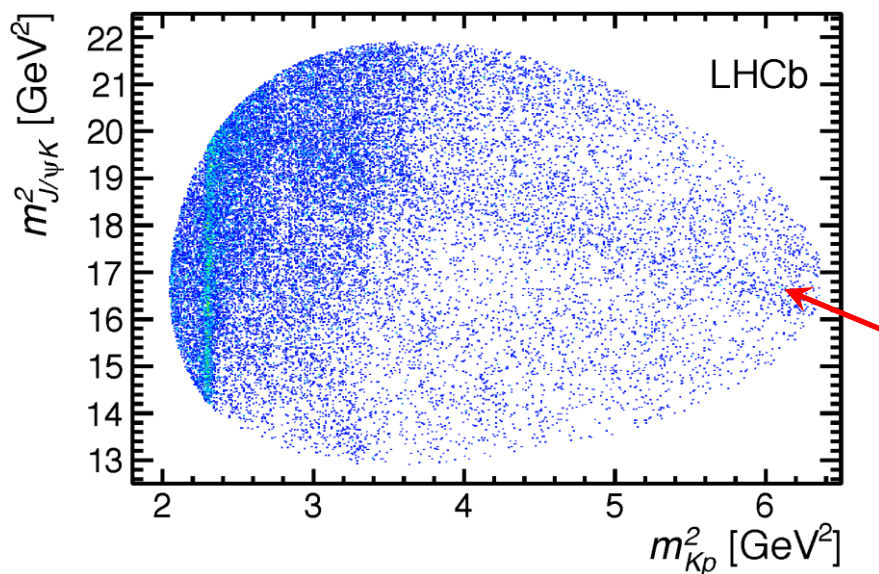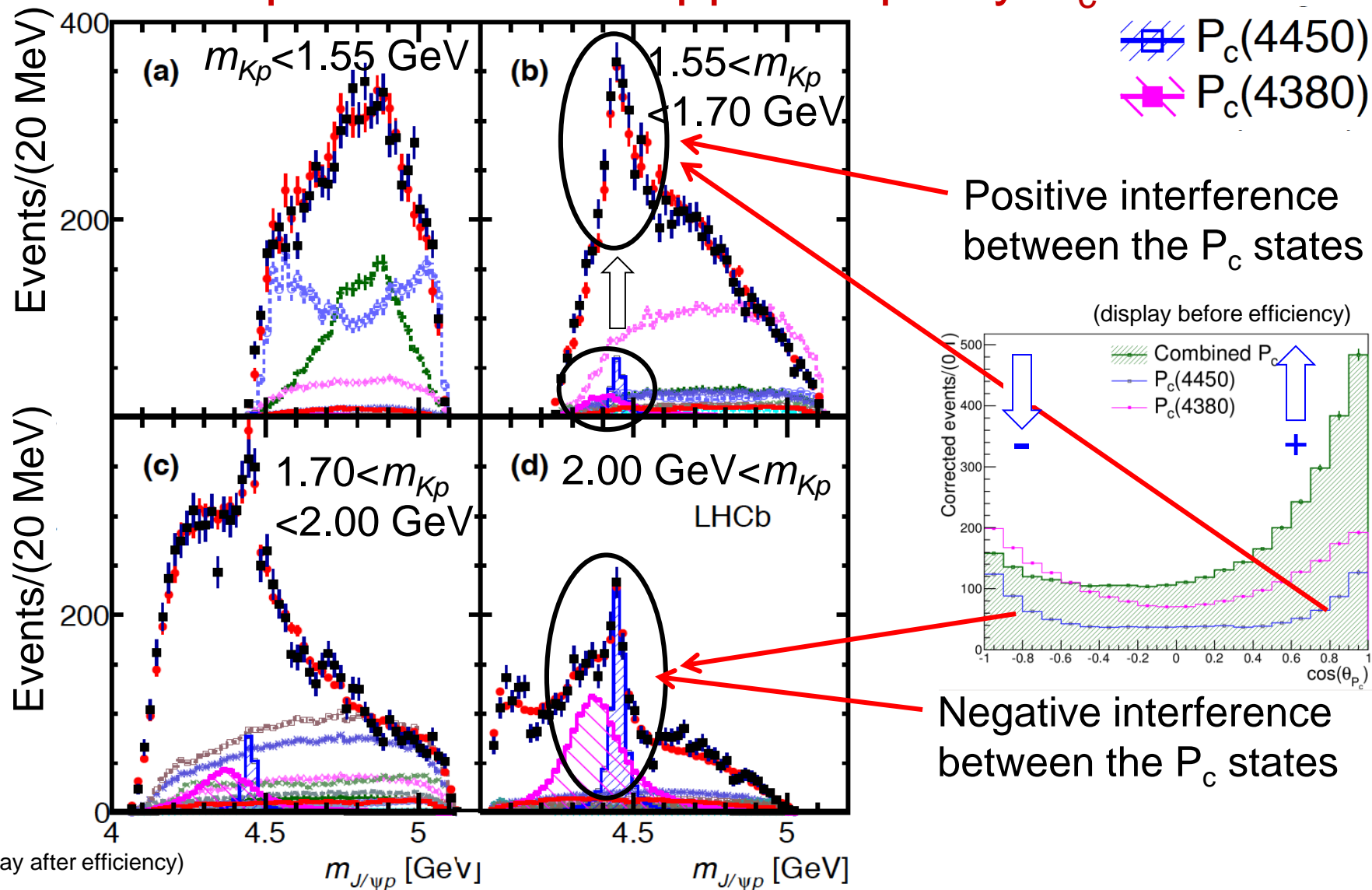
Angular distributions

All data

P_c enriched region

- Good description of the data in all 6 dimensions!

No need for exotic J/ψK⁻ contributions

- J/ψK⁻ system is well described by the Λ^* and P_c^+ reflections.

Data preference for opposite parity P_c^+ states

$P_c(4450)$
$P_c(4380)$

(a) $m_{Kp} < 1.55$ GeV

(b) $1.55 < m_{Kp} < 1.70$ GeV

(c) $1.70 < m_{Kp} < 2.00$ GeV

(d) 2.00 GeV $< m_{Kp}$

LHCb

Positive interference between the P_c states

(display before efficiency)

Combined P_c
$P_c(4450)$
$P_c(4380)$

Negative interference between the P_c states

(display after efficiency)

Events/(20 MeV)

$m_{J/\psi p}$ [GeV]

- Two opposite parity states necessary to generate the interference pattern

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Systematic uncertainties

Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	low	high	low	high	low	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

- Uncertainties in the Λ^* model dominate

- Quantum number assignment and resonance parametrization are also sizeable.

Results

- Parameters of the P_c^+ states (and F.F. of well isolated Λ^*'s)

State	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	4380 ± 8 ± 29	205 ± 18 ± 86	8.4 ± 0.7 ± 4.2
$P_c(4450)^+$	4449.8 ± 1.7 ± 2.5	39 ± 5 ± 19	4.1 ± 0.5 ± 1.1
$\Lambda(1405)$			15 ± 1 ± 6
$\Lambda(1520)$			19 ± 1 ± 4

- With the $\mathcal{B}(\Lambda_b^0 \to J/\psi\, p\, K^-)$ measurement (arXiv:1509.00292) we can also calculate the branching fractions:

$$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = \begin{cases} (2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5} & \text{for} \quad P_c(4380)^+ \\ (1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5} & \text{for} \quad P_c(4450)^+ \end{cases}$$

Significances

- Significances assessed using the extended model.

- This includes the dominant systematic uncertainties, coming from difference between extended and reduced Λ^* model results.

- Fit quality improves greatly, and simulations of pseudoexperiments are used to turn the $\Delta(-2\ln\mathcal{L})$ values to significances

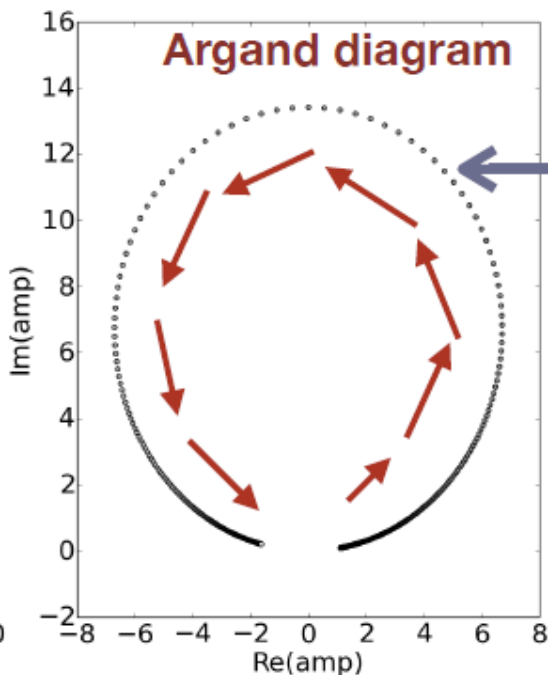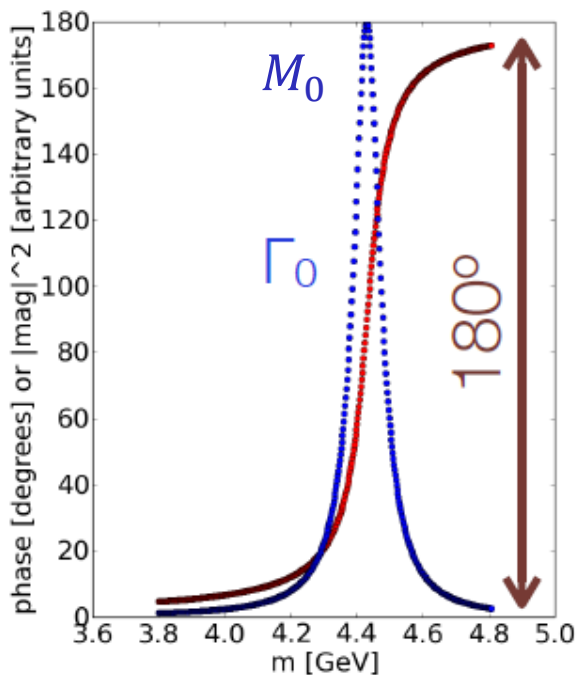|	$\Delta(-2\ln\mathcal{L})$	Significance
$0 \to 1\ P_c$	14.7^2	12σ
$1 \to 2\ P_c$	11.6^2	9σ
$0 \to 2\ P_c$	18.7^2	15σ

- Each of the states is overwhelmingly significant.

Resonance Phase Motion

- Relativistic Breit-Wigner function is used to model resonances

$$BW(m|M_0, \Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0\Gamma(m)} \quad , \qquad \Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L+1} \frac{M_0}{m} B'_L(q, q_0, d)^2$$

- The complex function $BW(m|M_0, \Gamma_0)$ displayed in an Argand diagram exhibits a circular trajectory.

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

Resonance Phase Motion

- The Breit-Wigner shape for individual P_c's is replaced with 6 independent amplitudes in $M_0 \pm \Gamma_0$

- $P_c(4450)$: shows resonance behavior: a rapid counter-clockwise change of phase across the pole mass

- $P_c(4380)$: does show large phase change, but is not conclusive.
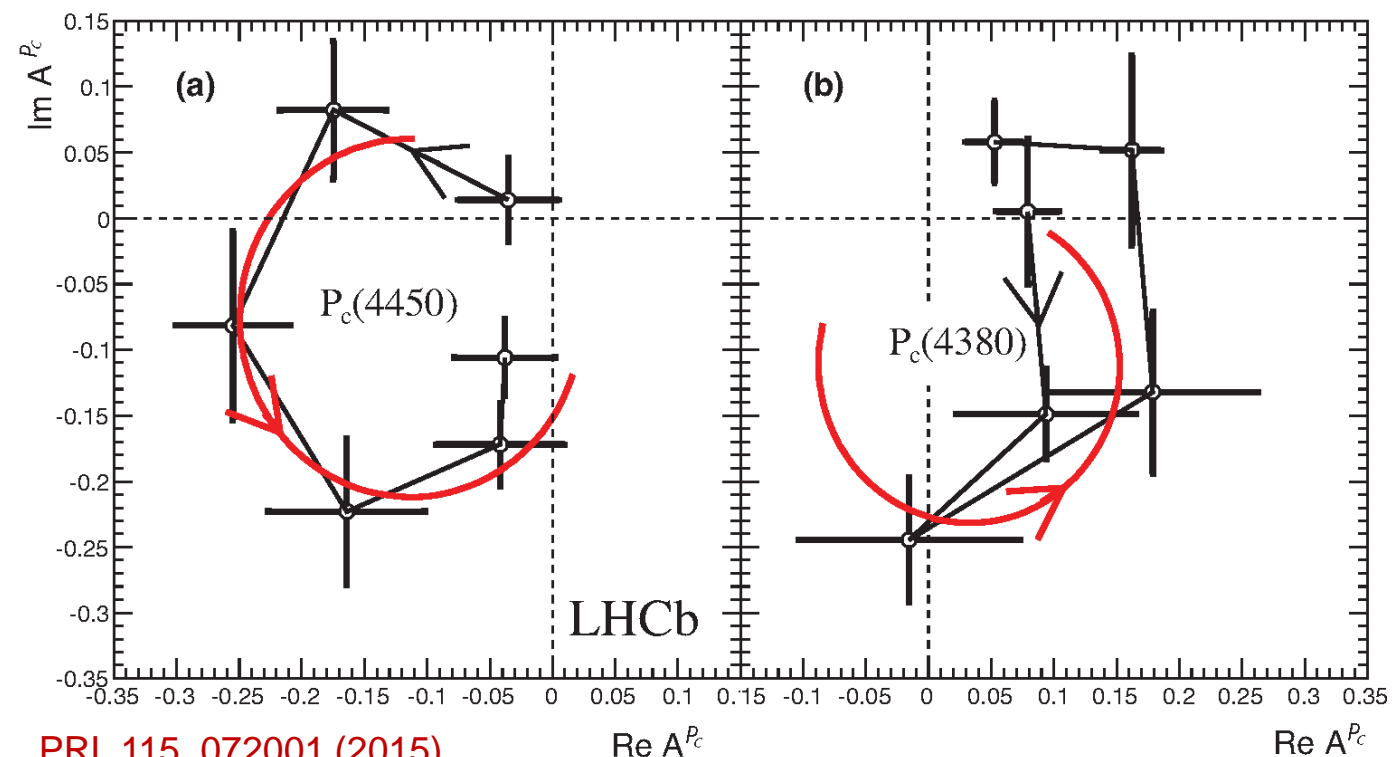
Plot fitted values for amplitudes in an Argand diagram

Breit-Wigner Prediction

Fitted Values

Interpretations of the states

"plain"   hydro-charmonium   diquarks   molecular   triquark
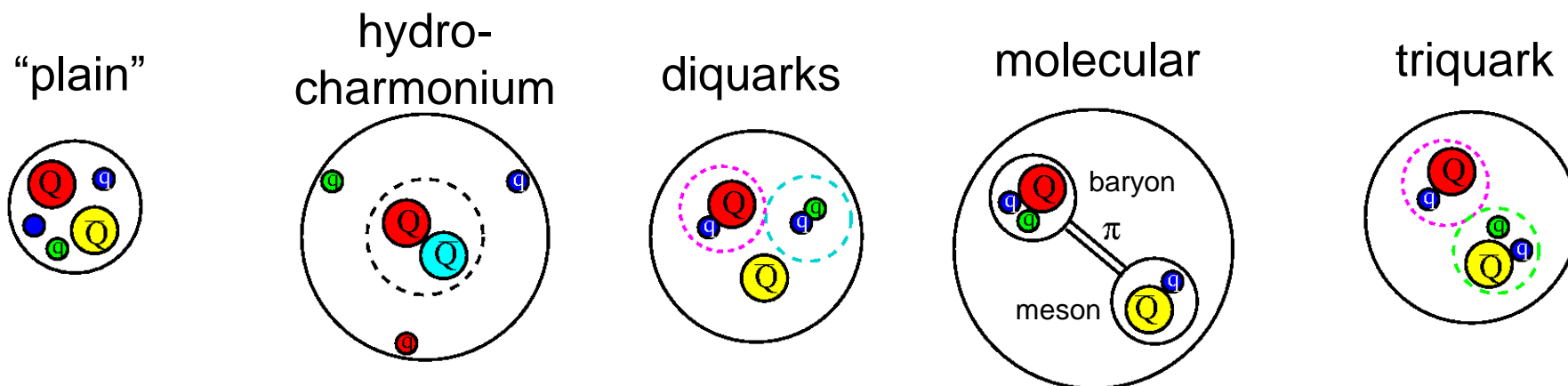
- Already ~50 citations on the arXiv, with a variety of models being proposed.

- Most common models employ molecular binding or additional hadron building blocks of diquarks or triquarks.

- Additional explanations have been offered in terms of kinematical effects. However these cannot explain two states.

Where else to look for these pentaquarks?

- There are many ideas on where to look. None will be as ideal as the clean J/ψ signature plus two charged tracks forming a secondary vertex. This was a good channel to accidentally find this in.

- They can be looked for in decays to other charmonium states: ηp, $\chi_c p$

- Or to open charm pairs: $\Lambda_c \overline{D}, \Lambda_c \overline{D^*}, \Sigma \overline{D}$

- Would be very interesting to see them from different sources:

  - Direct production: However there is a difficulty from huge number of protons coming from primary vertices

  - It's been proposed to look for these states in $\gamma p \rightarrow J/\psi\, p$ (arXiv:1508.00339,1508.00888, and 1508.01496)

And for other pentaquarks?

- Discovery of further states is crucial for shedding light on internal bindings and the nature of these states.

- Should look for more $c\bar{c}uud$ resonances: with different charge, spin-parity, isospin

- Huge number of possibilities. One could look for them decaying to many combinations of a baryon + meson.

- Given the trend of finding exotic hadron candidates with heavy quark content, finding them in decays of Λ_b's or other b-baryons is an attractive possibility.

- A systematic search should be done, as we also learn from non-observations.

Conclusions

- Two pentaquark candidates decaying to J/ψp have been observed with overwhelming significance in a state of the art amplitude analysis. Both are absolutely needed to obtain a good description of the data.
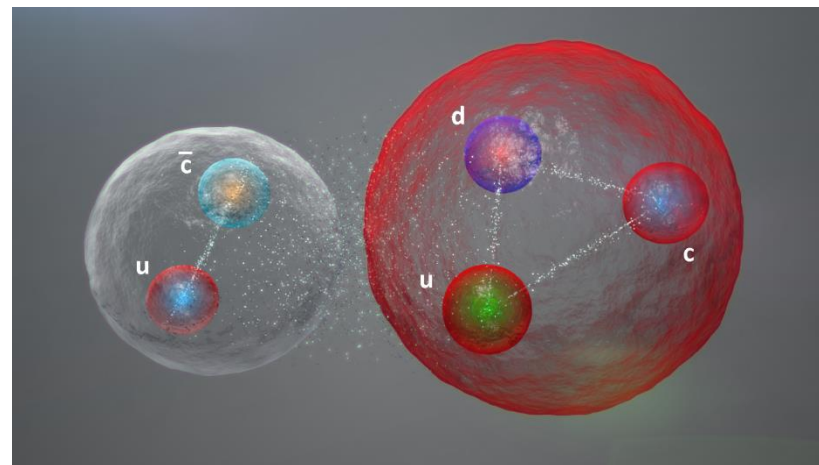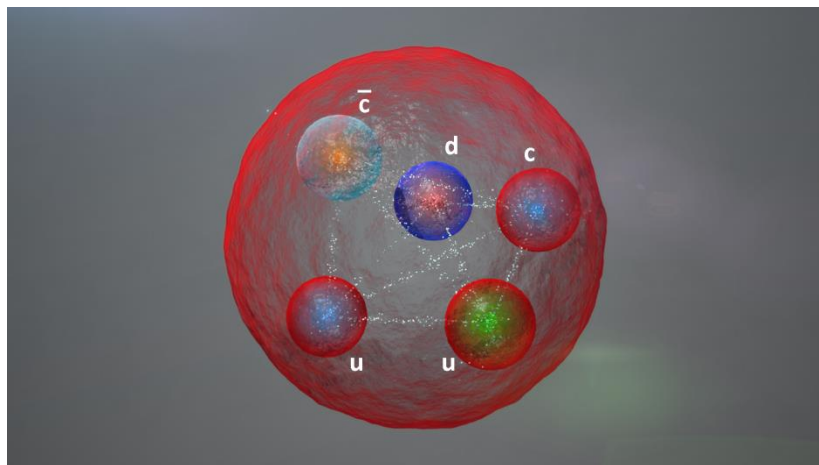
- The nature of the states is unknown. For elucidation, more sensitive studies as well as searches for other pentaquark candidates will be absolutely necessary.

- Towards this effort we continue to fully utilize the Run 1 data, and have increased statistics on the way. LHCb expects 8 fb^{-1} in Run 2 (-2018) followed by the detector/luminosity upgrade which will bring ~50 fb^{-1} by 2028.

- We look forward to more input from theory and other experiments.

BACKUP SLIDES

Complete set of fit fractions

Table 3: Fit fractions of the different components from cFit and sFit for the default $(3/2^-, 5/2^+)$ model. Uncertainties are statistical only.

Particle	Fit fraction (%) cFit	Fit fraction (%) sFit
$P_c(4380)^+$	8.42 ± 0.68	7.96 ± 0.67
$P_c(4450)^+$	4.09 ± 0.48	4.10 ± 0.45
$\Lambda(1405)$	14.64 ± 0.72	14.19 ± 0.67
$\Lambda(1520)$	18.93 ± 0.52	19.06 ± 0.47
$\Lambda(1600)$	23.50 ± 1.48	24.42 ± 1.36
$\Lambda(1670)$	1.47 ± 0.49	1.53 ± 0.50
$\Lambda(1690)$	8.66 ± 0.90	8.60 ± 0.85
$\Lambda(1800)$	18.21 ± 2.27	16.97 ± 2.20
$\Lambda(1810)$	17.88 ± 2.11	17.29 ± 1.85
$\Lambda(1820)$	2.32 ± 0.69	2.32 ± 0.65
$\Lambda(1830)$	1.76 ± 0.58	2.00 ± 0.53
$\Lambda(1890)$	3.96 ± 0.43	3.97 ± 0.38
$\Lambda(2100)$	1.65 ± 0.29	1.94 ± 0.28
$\Lambda(2110)$	1.62 ± 0.32	1.44 ± 0.28

Extended Model with Two P_c Resonances