Observation of $J/\psi p$ Resonances Consistent With Pentaquark States

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On behalf of the LHCb Collaboration

Aug 17, 2015

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

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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ 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 $\bar{A}$AAAA, $\bar{A}\bar{A}$AAAAA, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}$A, $\bar{A}\bar{A}$AA etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}$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)

$Z_0(1780)$ → P_{01}

```
95  Z*0(1780, JP=1/2+) I=0
SEE THE MINI-REVIEW PRECEDING THIS LISTING.

WILSON 72 AND GIACOMELLI 74 FIND SOME SOLUTIONS
WITH RESONANT-LIKE BEHAVIOR IN THE P01 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)

M        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 P01 WAVE       3/72
M   W  ESTIMATE OF PARAMETERS FROM BW + QUADRATIC BACKGROUND FIT TO P01. 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.)                 GIACCMEL  74  PWA    .38-1.51 GEV/C    10/74*
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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

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

OMITTED FROM SUMMARY TABLE

PENTAQUARK UPDATE

Written February 2006

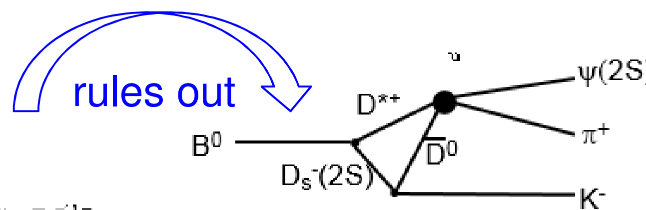
In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997 paper [1], considering only u, d, and s quarks, Diakonov *et*

. . .

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.

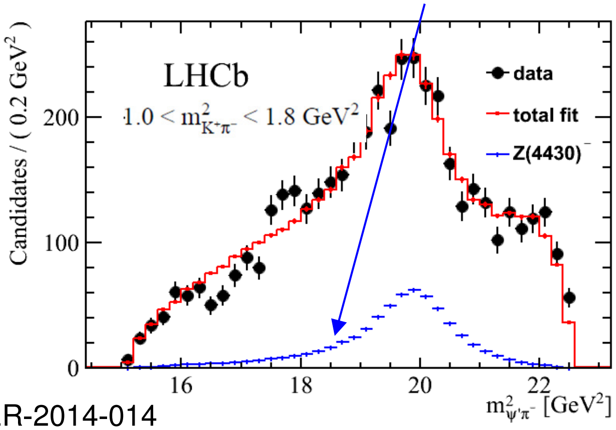
Charmonium and Quark Model

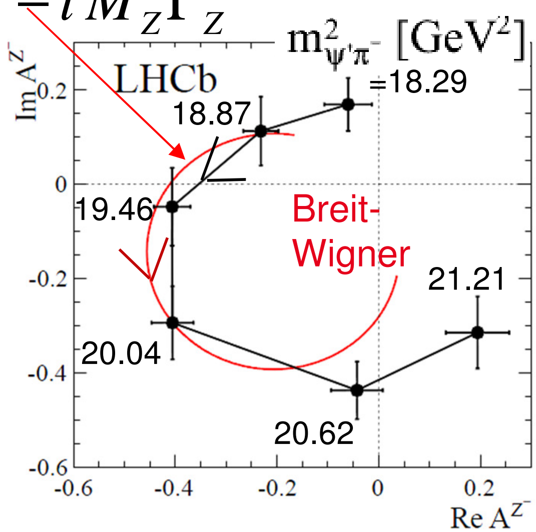
- November revolution 1974: discovery of J/ψ and other charmonium states convinces remaining skeptics that the quarks are real and mesons are made out of $q\bar{q}$.
- Discovery of the super narrow (Γ<1.2 MeV) X(3872) state ($\rightarrow J/\psi\pi^+\pi^-$) at the $D^0\bar{D}^{0*}$ threshold in 2003 by Belle renews hopes for establishing tetraquark states (molecular or tightly bound), but $\chi_c(2^3P_{1++})$ is likely in the mix.
- Discovery of the charged $Z(4430)^+$ ($\rightarrow\psi'\pi^+$) in 2007 by Belle provides “smoking gun” for 4-quark effect. However, not confirmed until the last year.
- 4D amplitude analysis by LHCb of $B^0\rightarrow\psi'\pi^+K^-$, $\psi'\rightarrow\mu^+\mu^-$ with interfering $K^{0*}\rightarrow\pi^+K^-$ and $Z(4430)^+\rightarrow\psi'\pi^+$ contributions confirms $Z(4430)^+$ and provides evidence for its resonant character via Argand diagram:

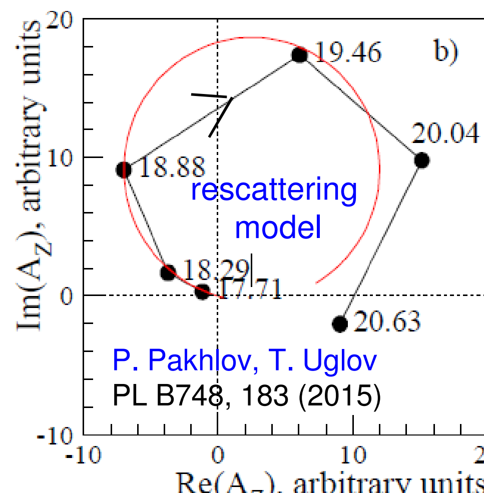


$4475 \pm 7^{+15}_{-25}$	$M(Z)$ [MeV]
$172 \pm 13^{+37}_{-34}$	$\Gamma(Z)$ [MeV]
$5.9 \pm 0.9^{+1.5}_{-3.3}$	f_Z [%]

$$\frac{1}{M_Z^{\ 2} - m_{\psi'\pi^+}^{\ \ 2} - i\, M_Z \Gamma_Z}$$





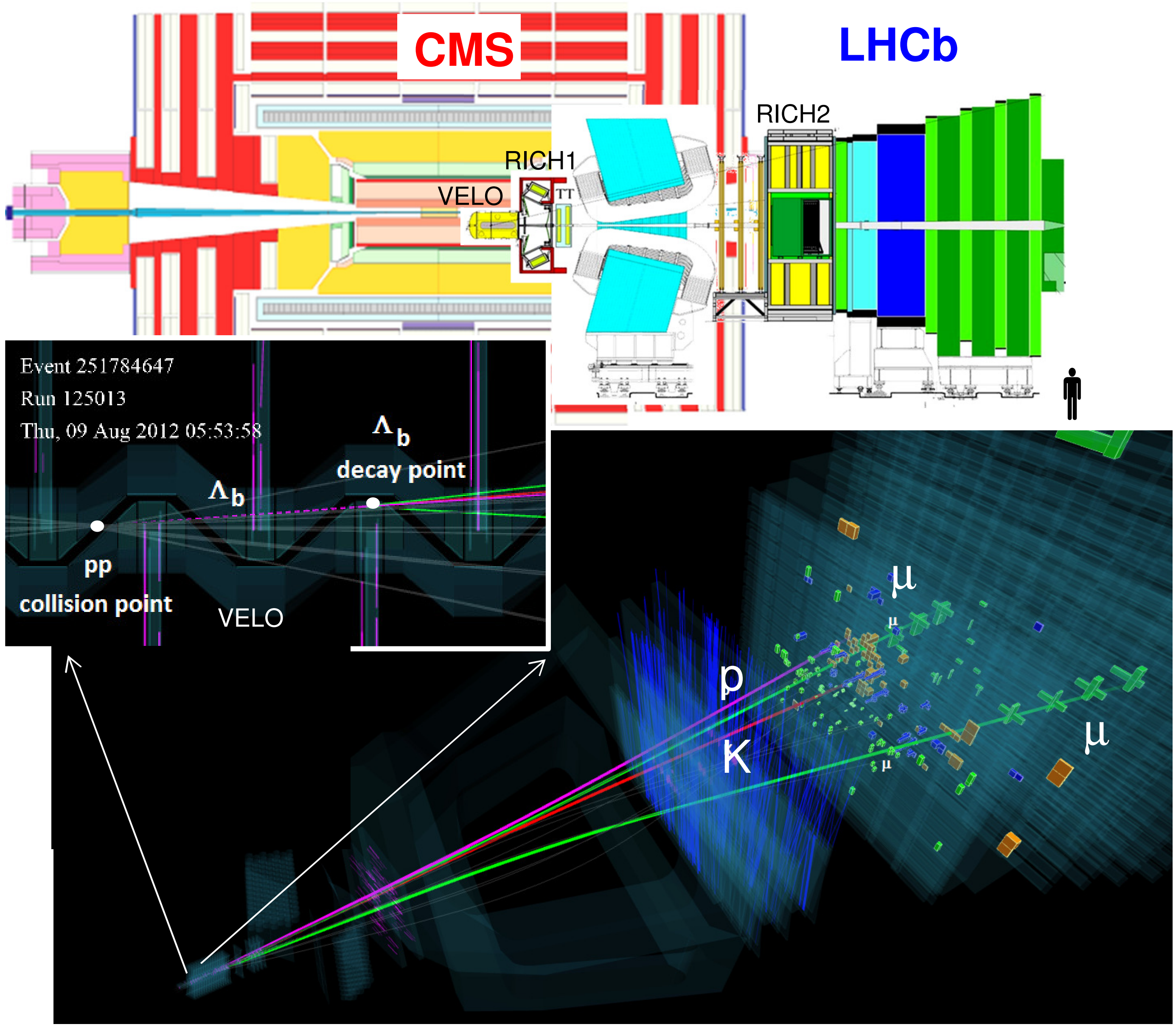


LHCb-PAPER-2014-014
PRL 112, 222002
See also LHCb-PAPER-2015-038

LHCb has 12.5 times more events than Belle with better purity thanks to…

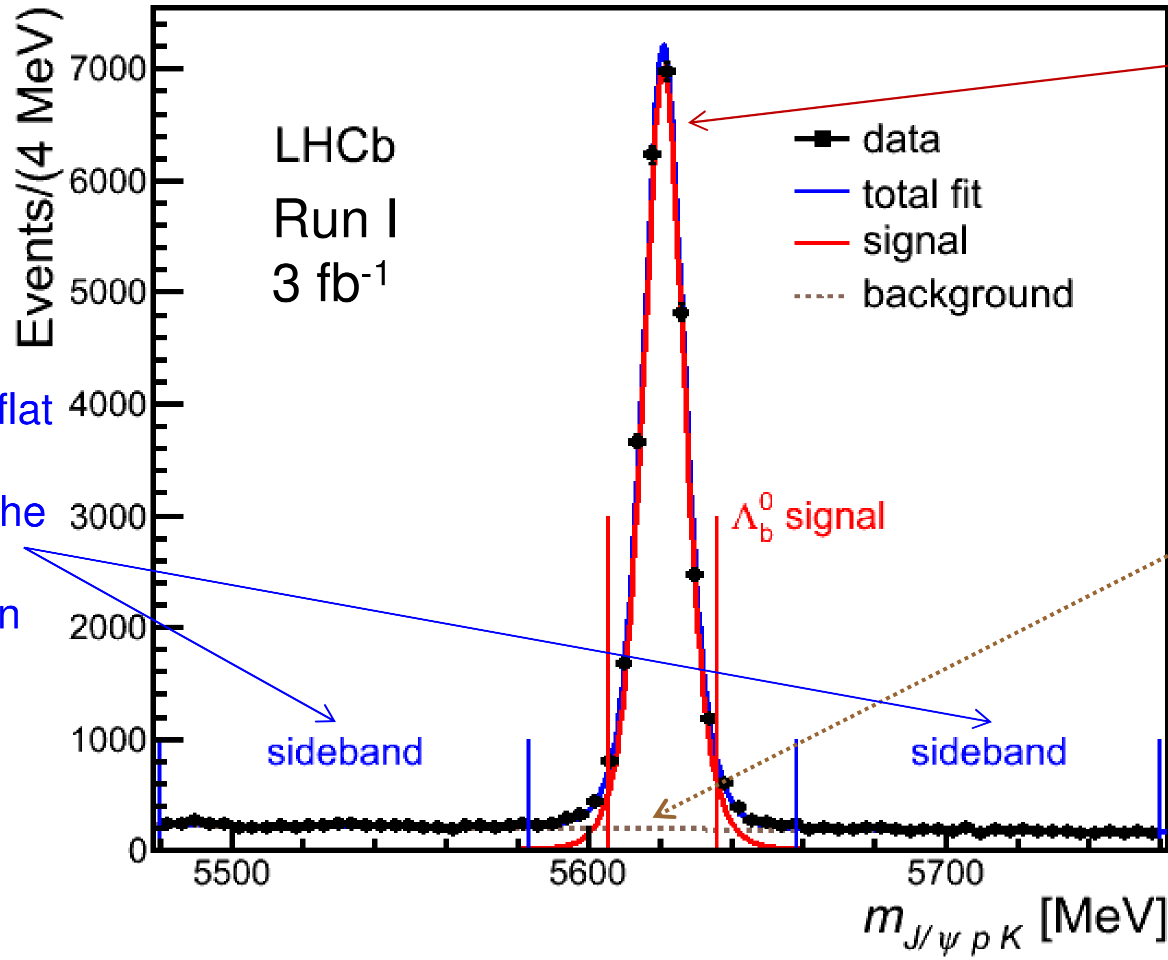
LHCb detector at LHC

- Advantages over e^+e^- B-factories:
  - ~1000x larger b production rate
  - **produce b-baryons at the same time as B-mesons**
  - long visible lifetime of b-hadrons (no backgrounds from the other b-hadron)
- Advantages over GPDs:
  - RICH detectors for $\pi/K/p$ discrimination (smaller backgrounds)
  - Small event size allows large trigger bandwidth (up to 5 kHz in Run I); all devoted to flavor physics



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

LHCb-PAPER-2015-029, arXiv:1507.03414, PRL 115, 07201



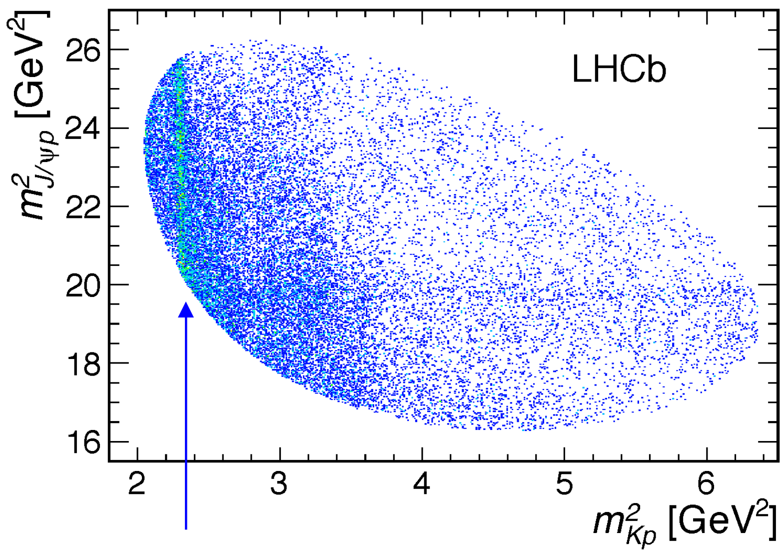
26,007±166 Λ_b^0 candidates

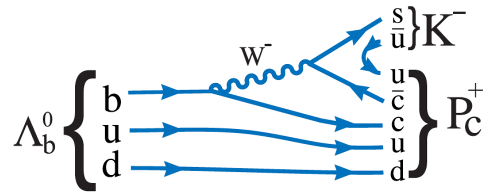
The sideband distributions are flat → no major reflections from the other b-hadrons after the selection

The background is only 5.4% in the signal region!

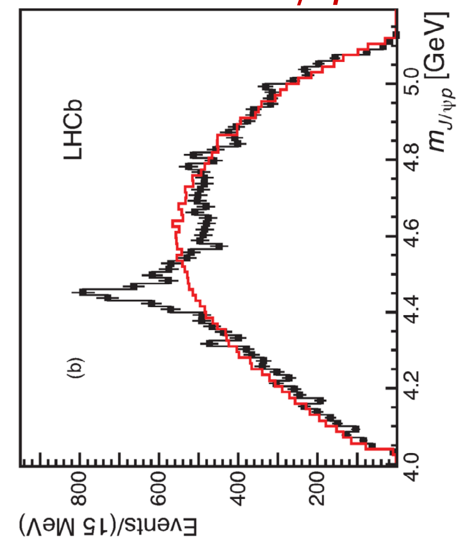
- The decay first observed by LHCb and used to measure Λ_b^0 lifetime:
  - LHCb-PAPER-2013-032 (PRL 111, 102003)

$\Lambda_b^0 \to J/\psi p K^-$: unexpected structure in $m_{J/\psi\, p}$

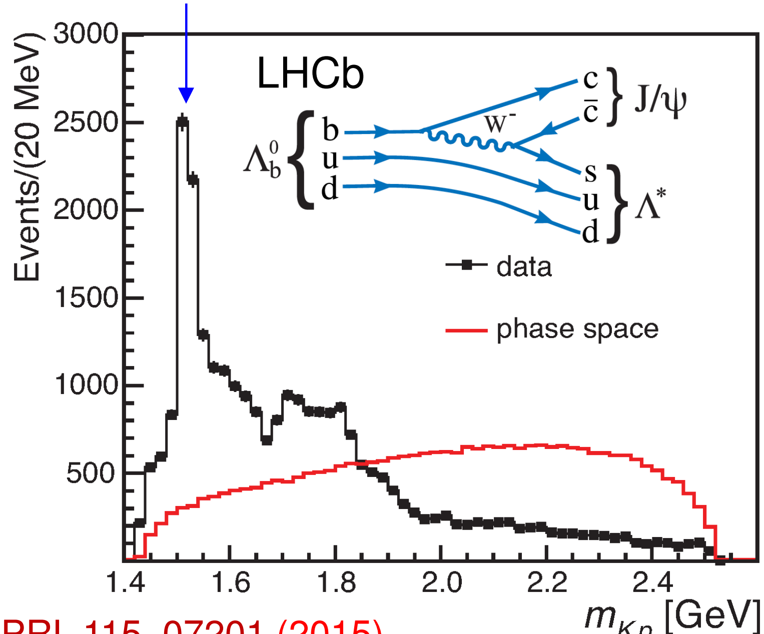




$P_c^+ \to J/\psi\, p$?



$\Lambda(1520)$ and other Λ^*'s $\to$ p K^-

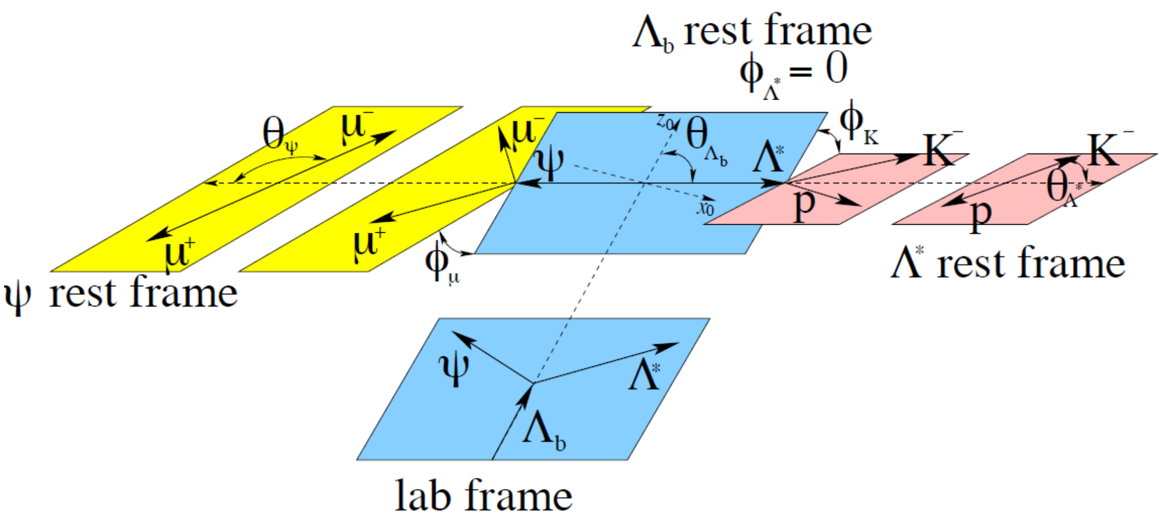


PRL 115, 07201 (2015)

- Unexpected, narrow peak in $m_{J/\psi\, p}$
- Many checks done to ensure it is not an "artifact" of selection:
  - Veto $B_s \to J/\psi K^- K^+$ & $B^0 \to J/\psi K^- \pi^+$ after changing p to K, or K to π
  - Clone and ghost tracks carefully eliminated
  - Exclude Ξ_b decays as a possible source
- Could it be a reflection of interfering Λ^*'s $\to$ p K^- ?
  - Proper amplitude analysis absolutely necessary!

Amplitude Analysis of $\Lambda_b^0 \to J/\psi p K^-$, $J/\psi \to \mu^+\mu^-$

- Follows in footsteps of the $Z(4430)^+$ 4D amplitude analysis in $B^0 \to J/\psi \pi^+ K^-$, $J/\psi \to \mu^+\mu^-$
- Analyze all dimensions of the $\Lambda_b^0 \to J/\psi p K^-$, $J/\psi \to \mu^+\mu^-$ decay kinematics:
  - to maximize sensitivity to the decay dynamics
  - to avoid biases due to averaging over some dimensions in presence of the non-uniform detector efficiency
  - two additional dimensions (6D) because Λ_b^0 has a spin



6 independent data variables:
1 mass (m_{Kp}), 5 angles

4-6 independent **complex** helicity couplings per Λ_n^* resonance to fit depending in its J^P

- Use 6D unbinned maximum likelihood fit of the matrix element parameters
- Two different background subtraction methods:
  - parametrized $m_{J/\psi\, p\, K}$ sidebands (cFit) or sWeighted log-likelihood (sFit)

Λ^* resonance model

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

Helicity couplings

LS couplings

In Λ^* decay: $P_A = P_B P_C (-1)^L$

No high-J^P high-mass states

limit L

All states, all L

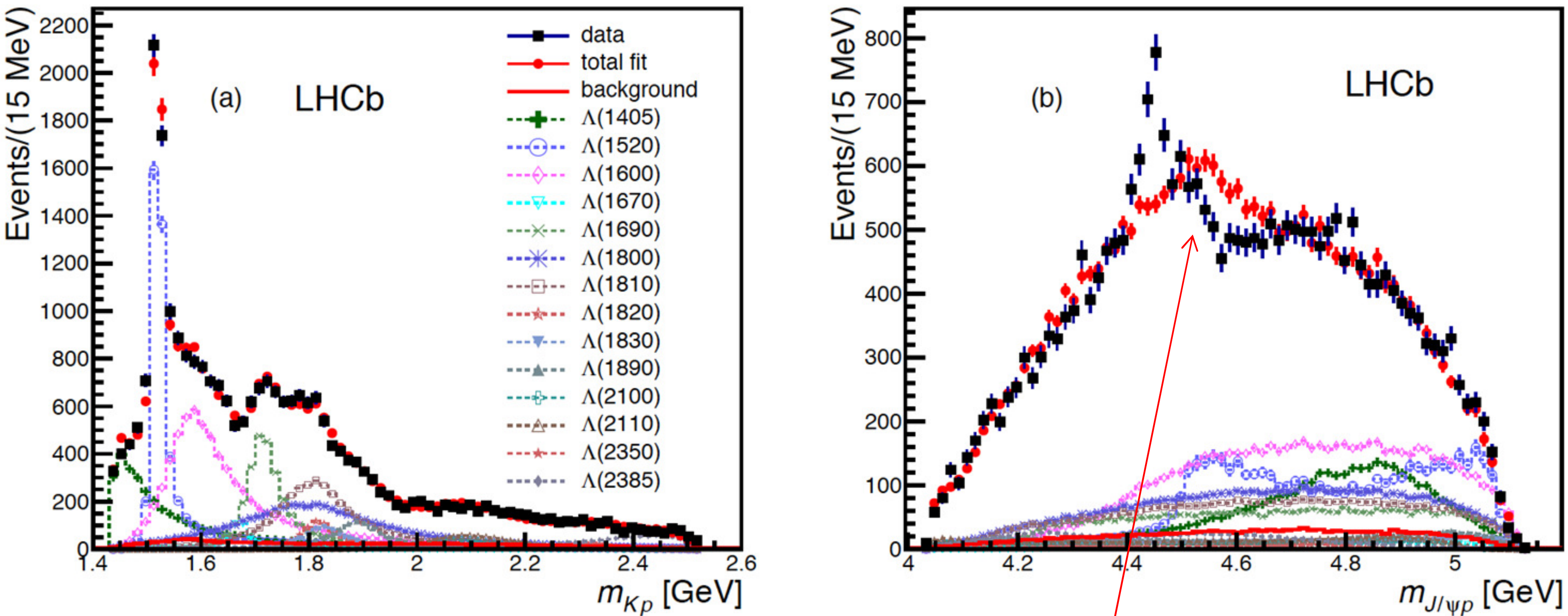
All known Λ^* states

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

# of fit parameters: 64 146

PRL 115, 07201 (2015)

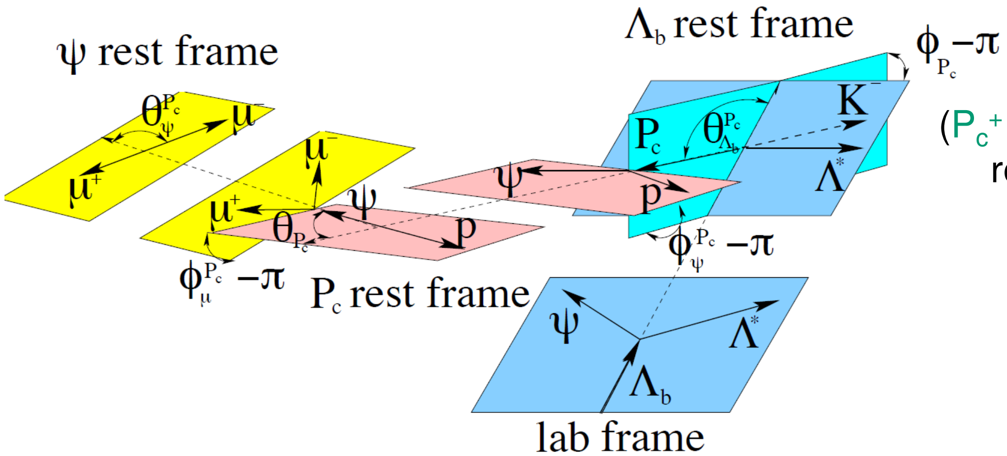
Fit with $\Lambda^{*} \rightarrow pK^{-}$ contributions only



- Use extended model, so all possible known Λ^{*} amplitudes: m_{Kp} looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant term, Σ^{*}'s or extra Λ^{*}'s doesn't help

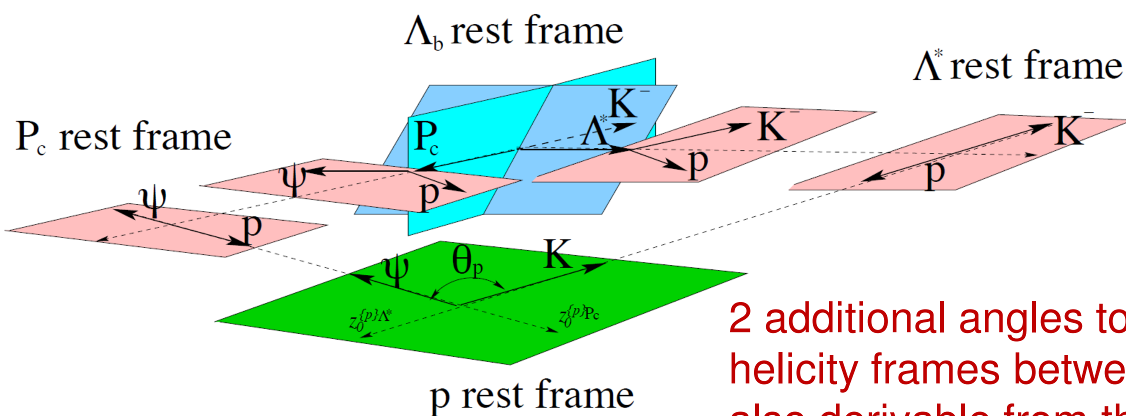
PRL 115, 07201 (2015)

P_c^+ Matrix Element



(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

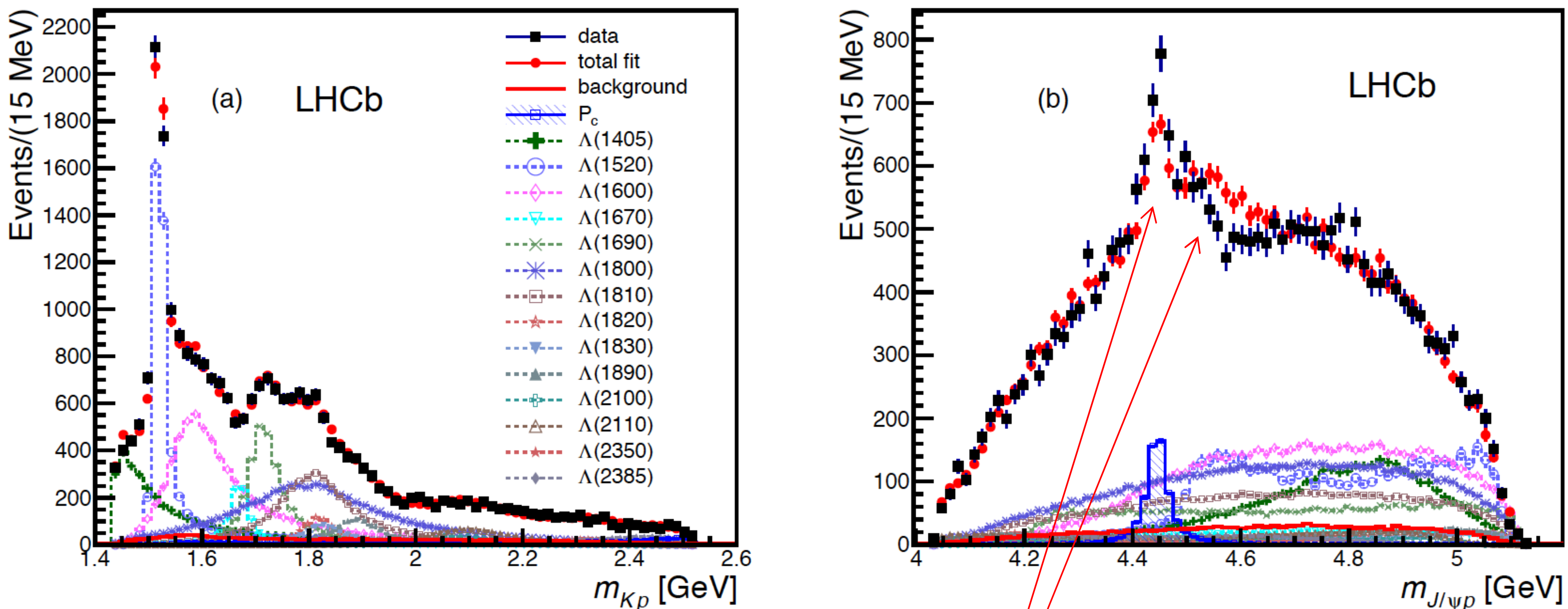


2 additional angles to align the muon and proton helicity frames between the Λ^* and P_c^+ decay chains also derivable from the Λ^* decay variables

3-4 independent **complex** helicity couplings per $P_{c\,j}^+$ resonance depending on its J^P plus its mass and width to fit

PRL 115, 07201 (2015)

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

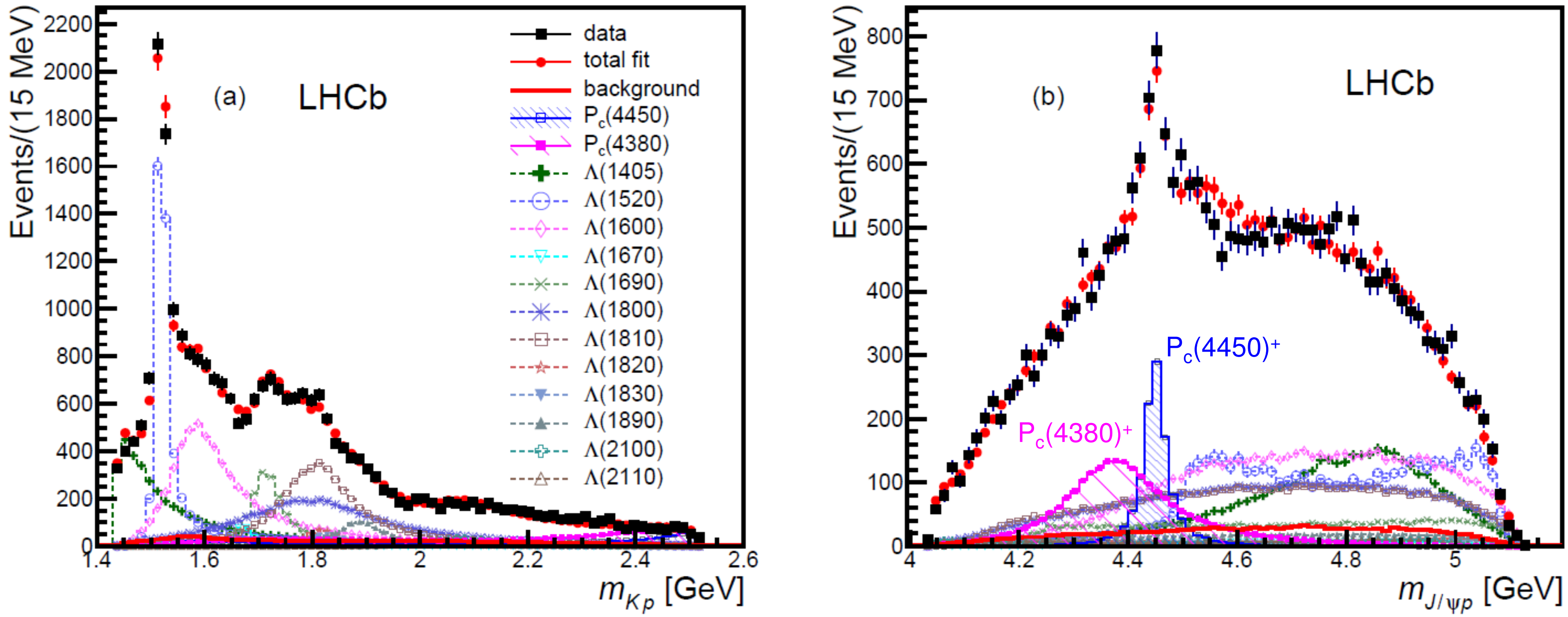


(extended Λ^* model)

- 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

PRL 115, 07201 (2015)

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

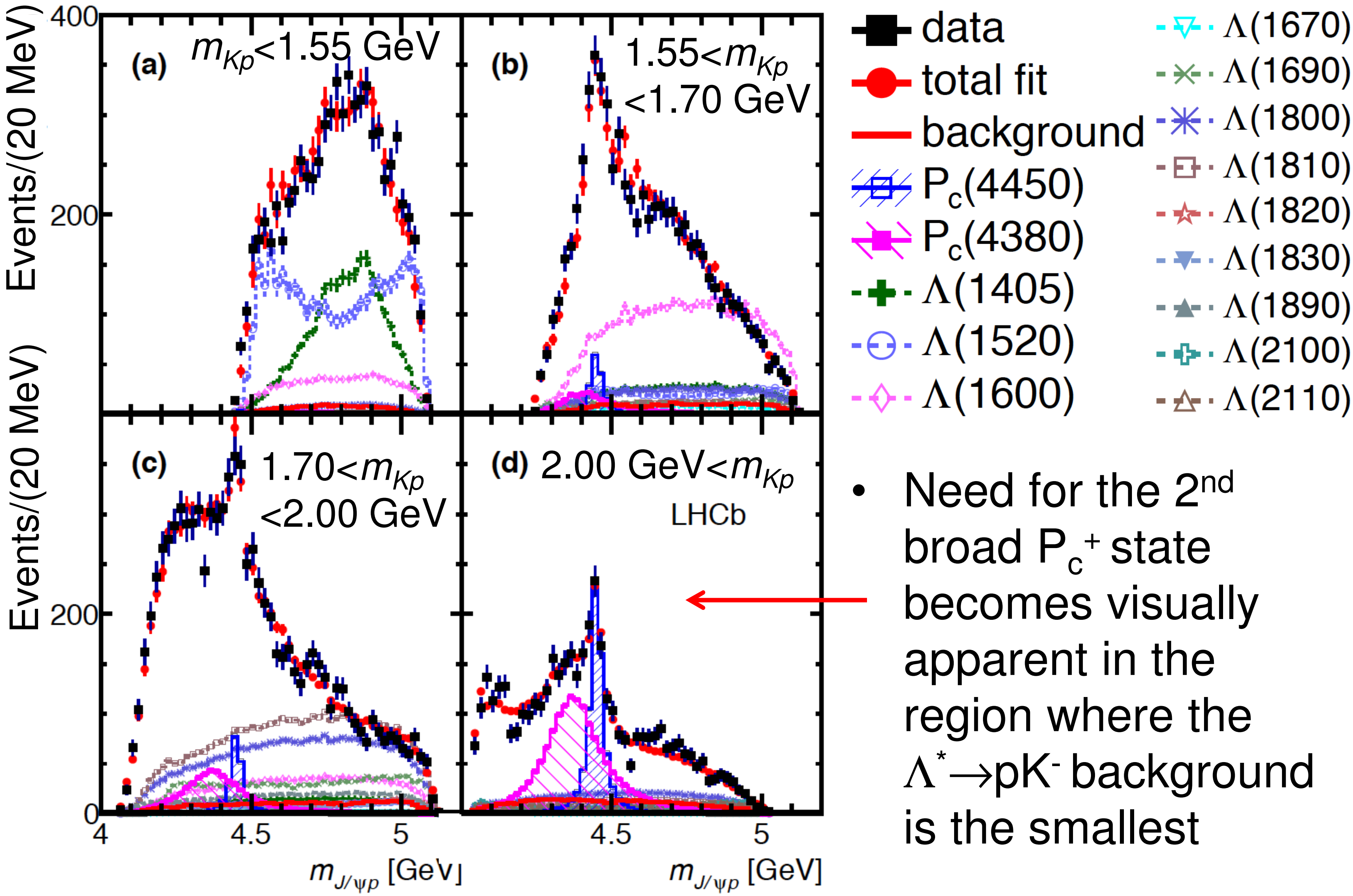


(reduced Λ^* model)

- Obtain good fits even with the reduced Λ^* model
- Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred

PRL 115, 07201 (2015)

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

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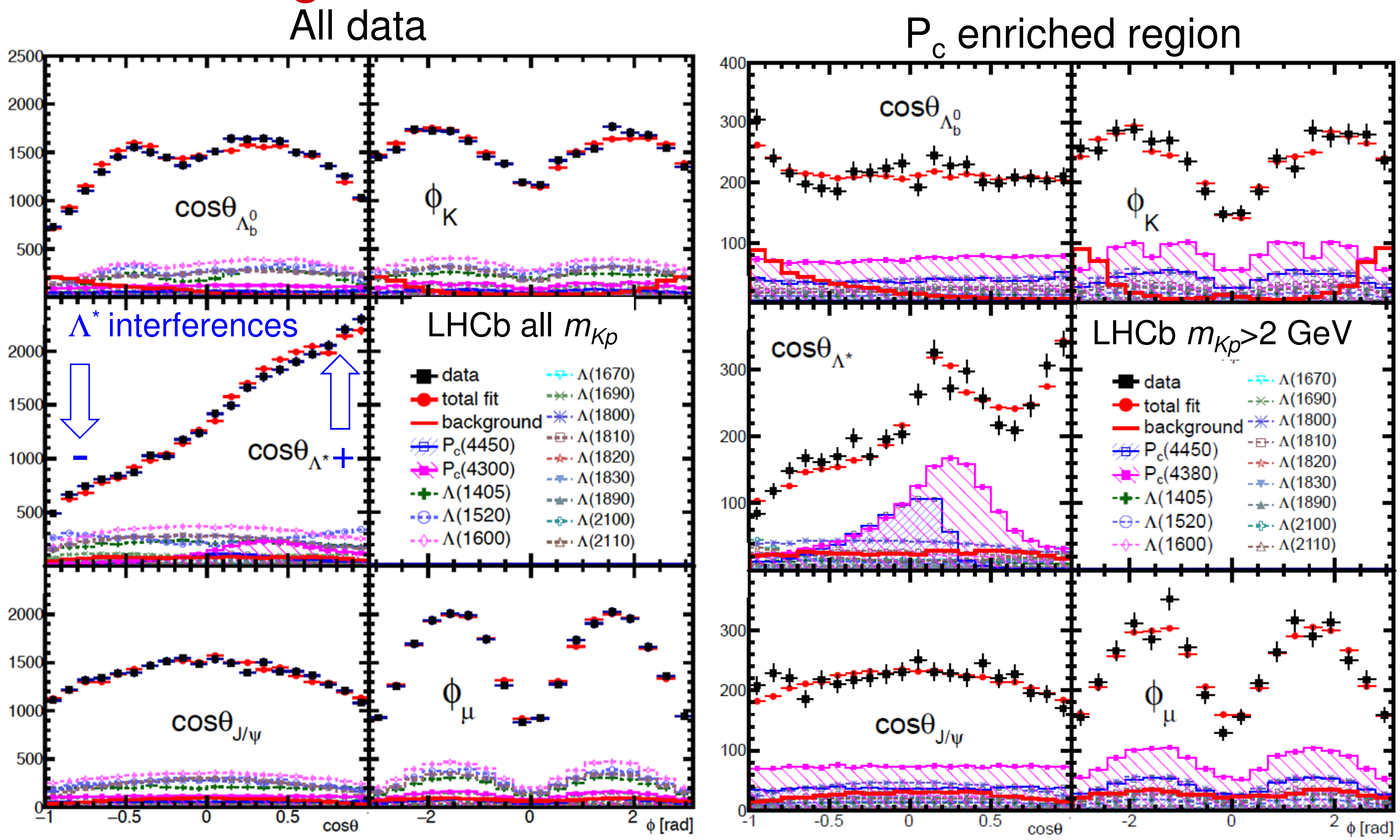
Angular distributions

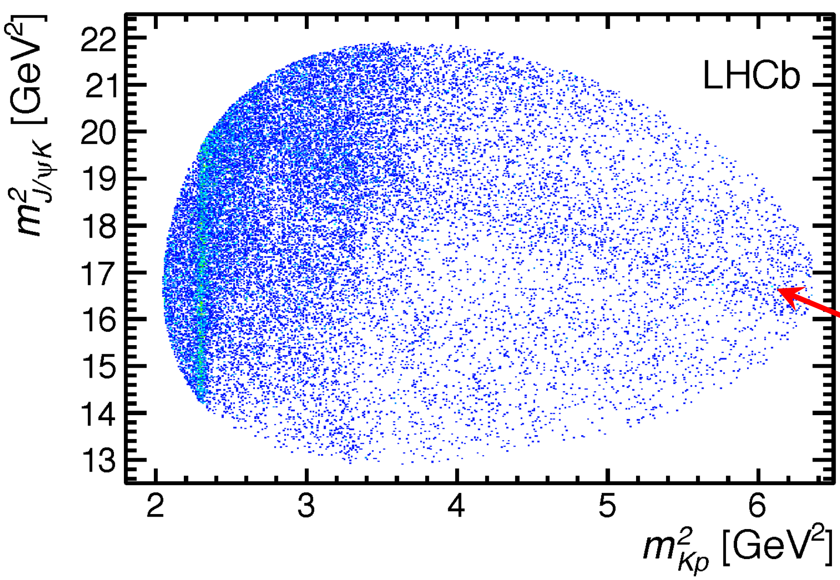


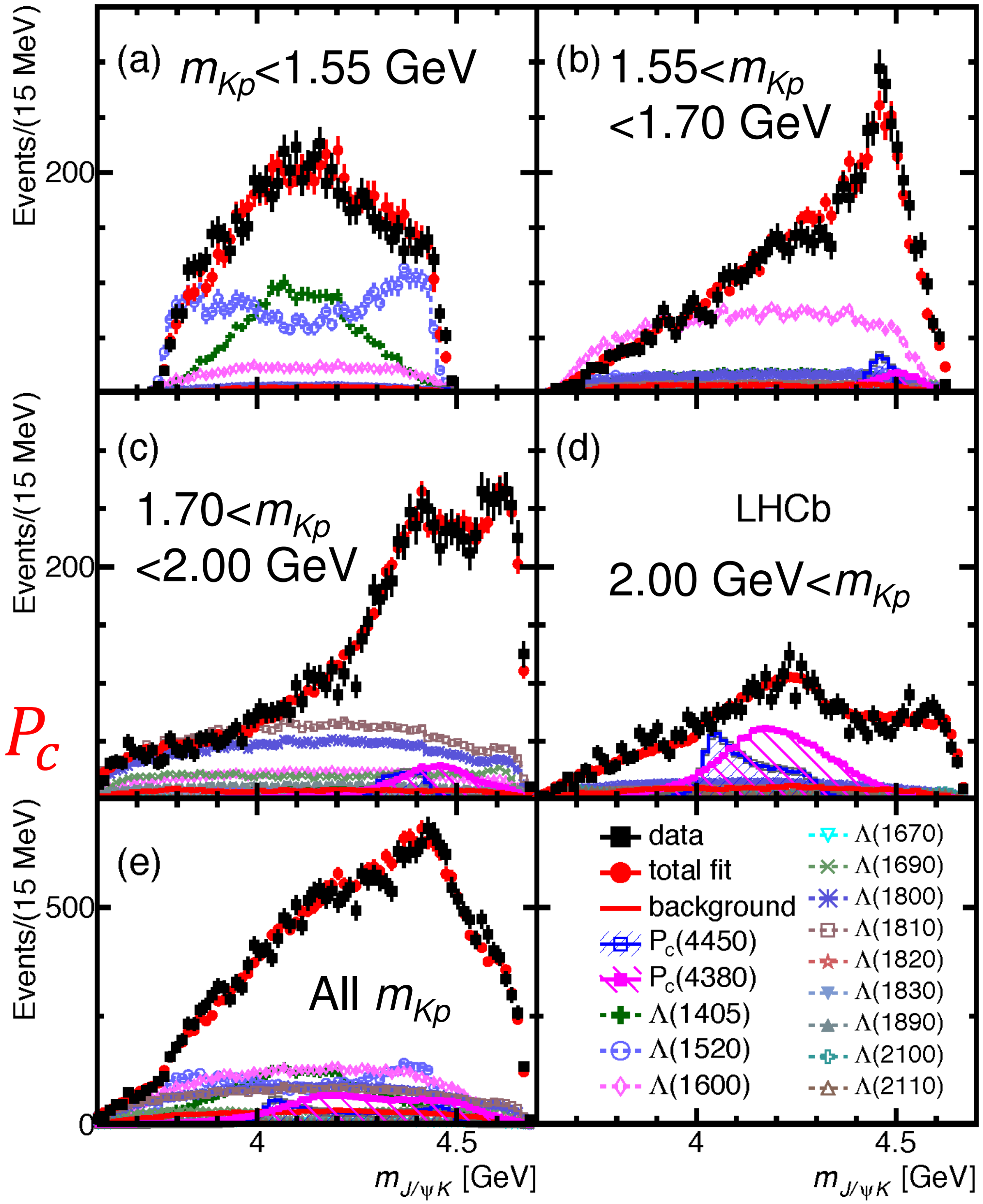
- Good description of the data in all 6 dimensions!

PRL 115, 07201 (2015)

No need for exotic $J/\psi K^-$ contributions

- $J/\psi K^-$ system is well described by the Λ^* and P_c^+ reflections.





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Significances and the results

- 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 $\Delta(-2\ln\mathcal{L})=18.7^2$
- Simulations of pseudoexperiments are used to turn the $\Delta(-2\ln\mathcal{L})$ values to significances:
  - significance of $P_c(4450)^+$ state is 12σ
  - significance of $P_c(4380)^+$ state is 9σ
  - combined significance of the two P_c^+ states is 15σ
- This includes the dominant systematic uncertainties, coming from difference between extended and reduced Λ^* model results.
- Parameters of the P_c^+ states (and F.F. of well isolated Λ^*'s)

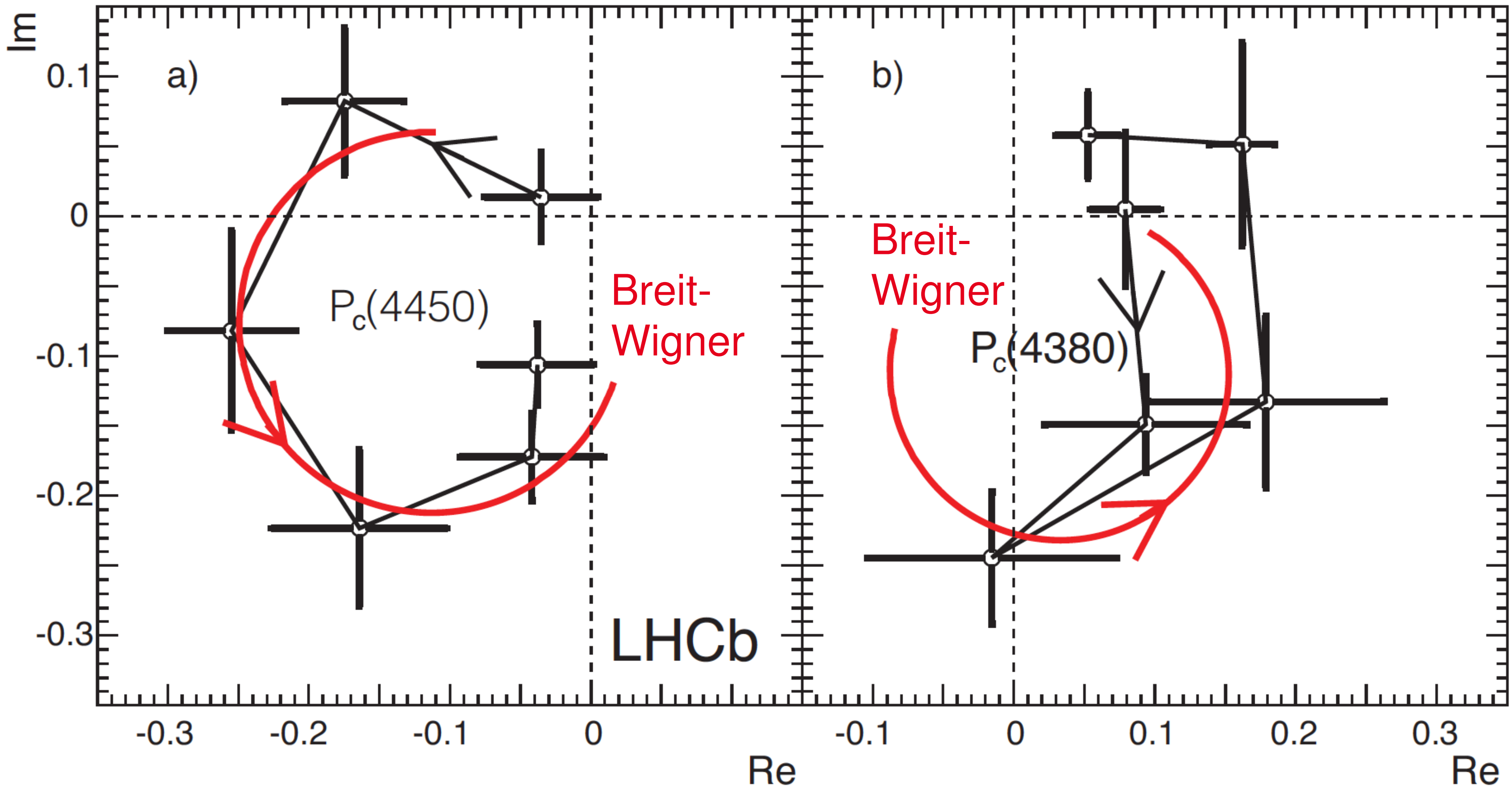
State	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	**4380 ±8±29**	**205±18±86**	**8.4±0.7±4.2**
$P_c(4450)^+$	**4449.8±1.7±2.5**	**39± 5±19**	**4.1±0.5±1.1**
$\Lambda(1405)$			15±1±6
$\Lambda(1520)$			19±1±4

LHCb-PAPER-2015-029, arXiv:1507.03414, PRL 115, 07201

Argand diagrams

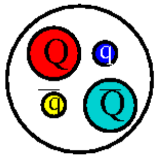
PRL 115, 07201 (2015)

P_c^+ amplitudes for 6 $m_{J/\psi p}$ bins between $+\Gamma$ & $-\Gamma$ around the resonance mass

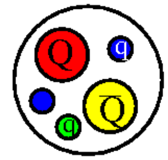


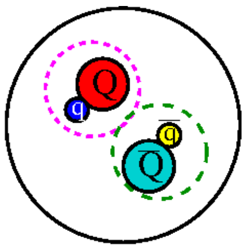
- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive

Different types of tetra- and penta-quarks

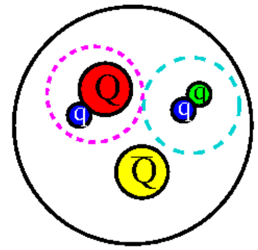


“plain”

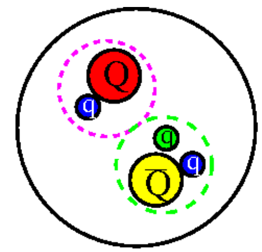


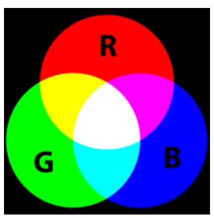


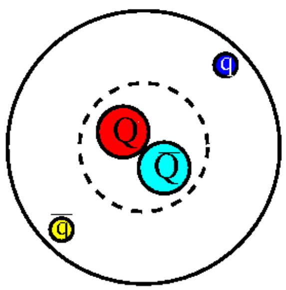
diquark model



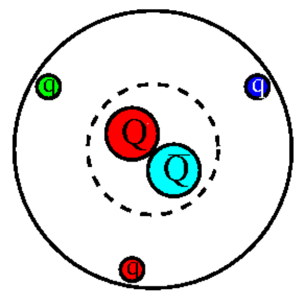
triquark model

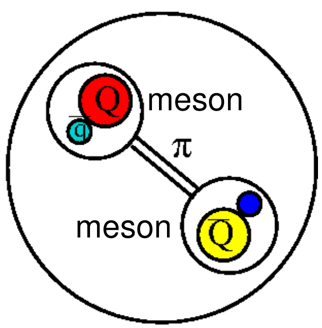




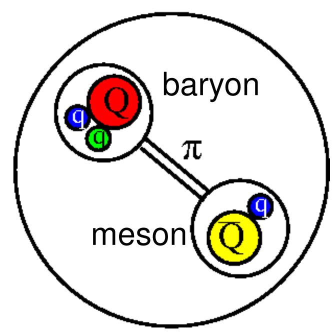


hydro-charmonium model





molecular model



Conclusion

- Two pentaquark candidates decaying to J/ψp observed by LHCb with overwhelming significance in a state of the art amplitude analysis: they will not go away!

Frank Wilczek's twit on 7/14/15: "Pentaquarks rise from the ashes: a phoenix pair"

Pentaquark candidates rise from the ashes for the 2nd time.

- LHC resurrects them: should not be a surprise given baryon cross-sections!

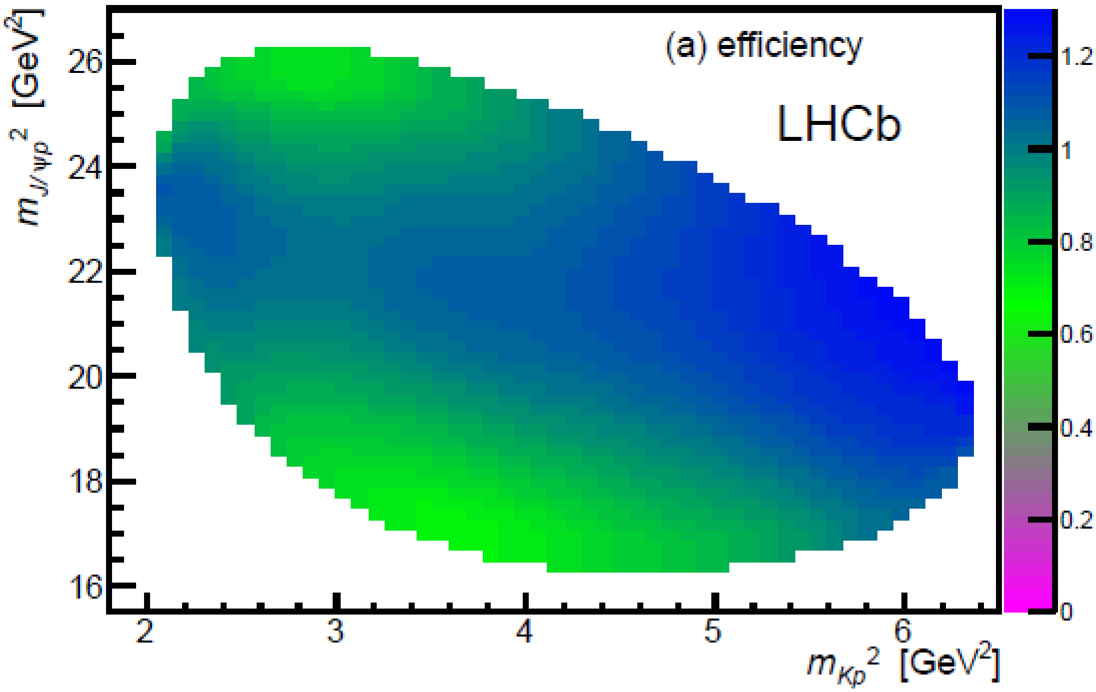
$c\bar{c}$ pair inside:

- Given the history of Quark Model should not be a surprise either.
- Hopefully true July 2015 revolution!

- However, what kind of 5-quark effects are they? 24 paper published in 1 month. Loosely bound meson-baryon molecules? Tightly bound (diquarks,triquarks,..)? Can we decisively rule out rescattering effects?
- Need more statistics for more sensitive tests. Need to identify the other elements of the new periodic table.
  - LHCb expects 8 fb^{-1} in Run 2 (-2018) followed by the detector/luminosity upgrade which will bring ~50 fb^{-1} by 2028.
  - Other experiments/colliders should be able to contribute (photoproduction?)

BACKUP SLIDES

Efficiency is smooth



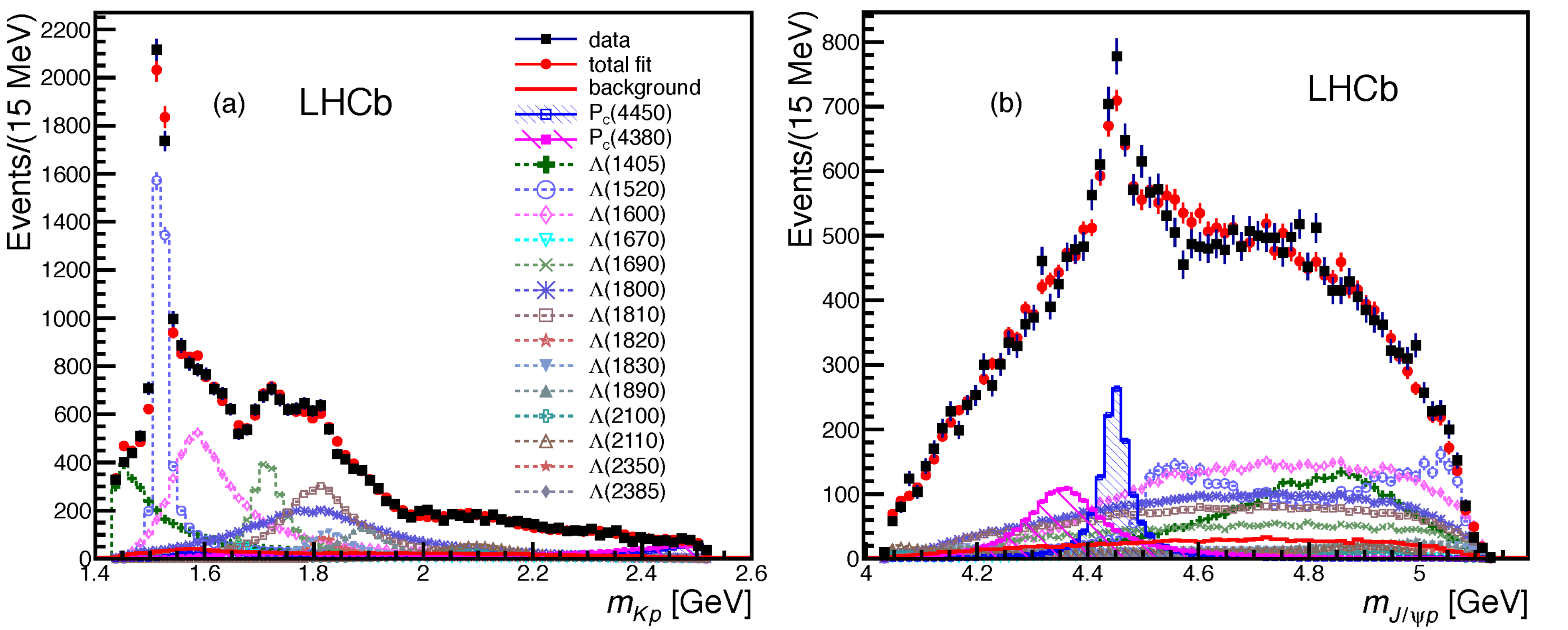
- The Dalitz plane contains the dominant efficiency variations
- Relative changes in efficiency smaller for the other fit variables
- Smooth, cannot be responsible for peaking structures.

Complete set of fit fractions

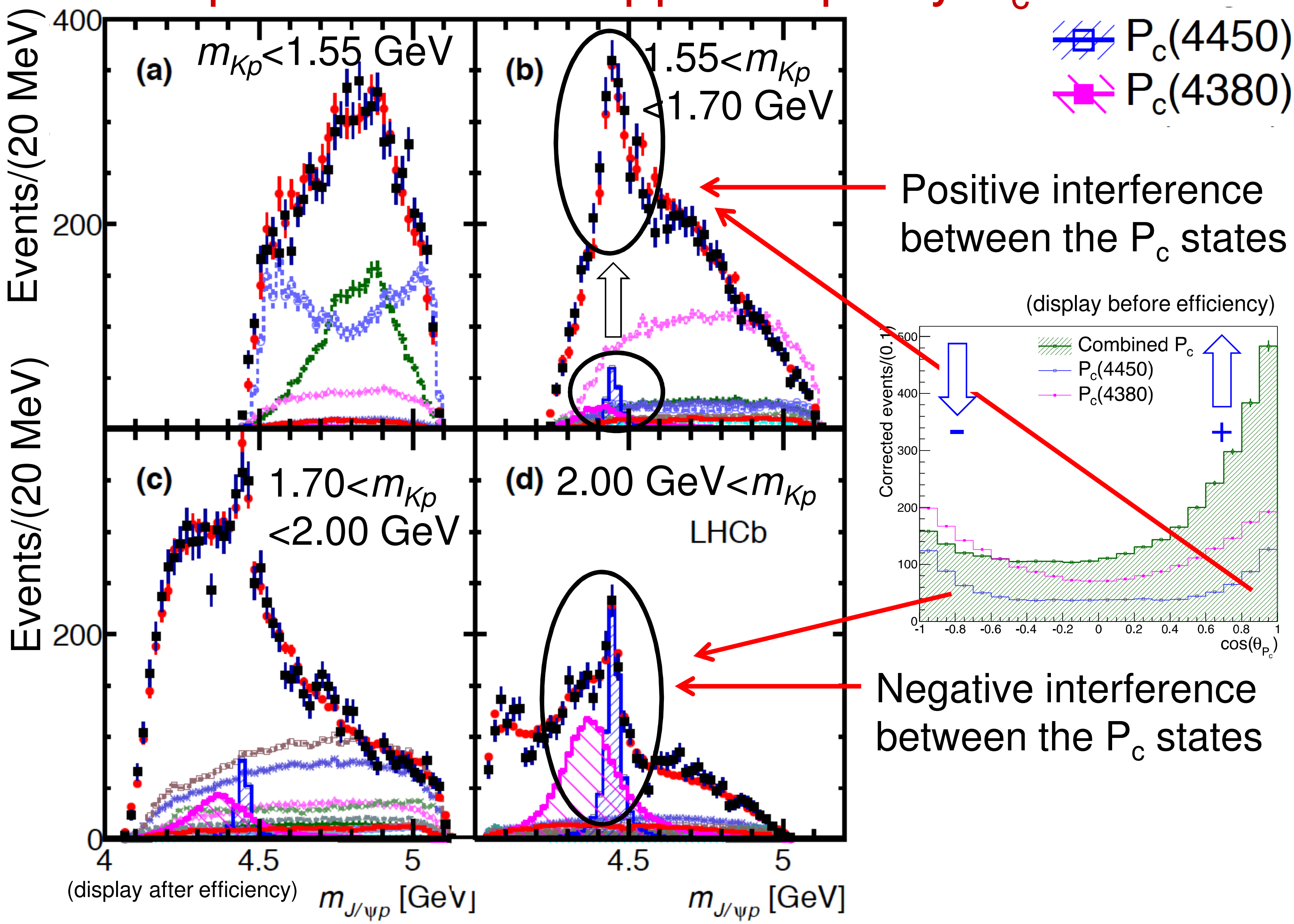
Table 3: Fit fractions of the different components from cFit and sFit for the default $(3/2^-, 5/2^+)$ model. Uncertainties are statistical only.

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



Data preferrence for opposite parity P_c^+ states



- This interference pattern only for states with opposite parity

Systematic uncertainties

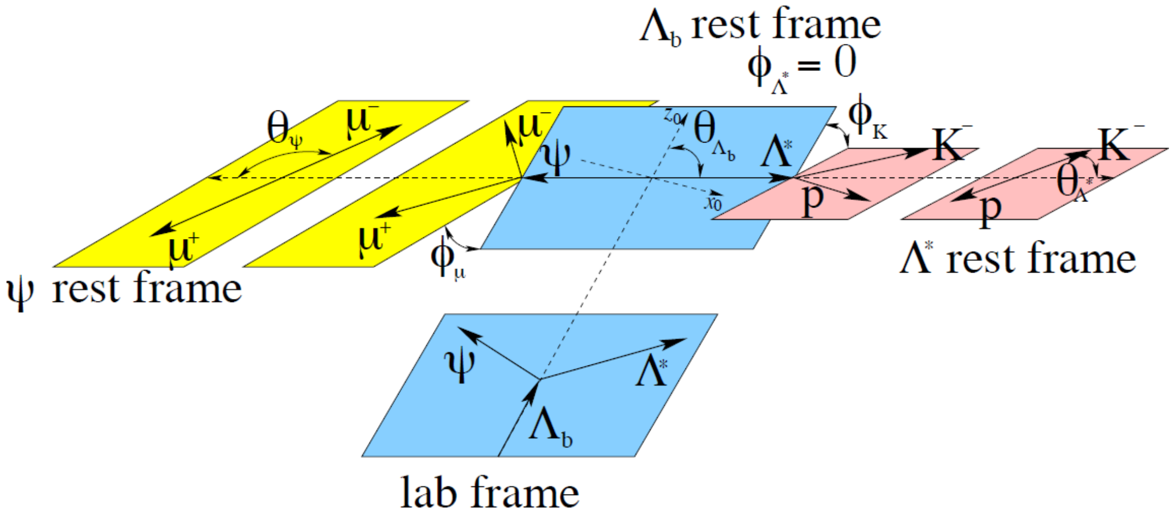
Source	M_0 (MeV) low	M_0 (MeV) high	Γ_0 (MeV) low	Γ_0 (MeV) high	Fit fractions (%) low	Fit fractions (%) high	Fit fractions (%) $\Lambda(1405)$	Fit fractions (%) $\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	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

Additional cross-checks

- Many additional cross-checks have been done. Some are listed here:
  - The same P_c^+ structure found using very different selections by different LHCb teams
  - Two independently coded fitters using different background subtractions (cFit & sFit)
  - Split data shows consistency: 2011/2012, magnet up/down, $\overline{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
  - Extended model fits tried without P_c states, but with two additional high mass Λ^* resonances allowing masses & widths to vary, or 4 non-resonant terms of J up to 3/2

Λ^* Matrix Element



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

6 independent data variables: 1 mass, 5 angles

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

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

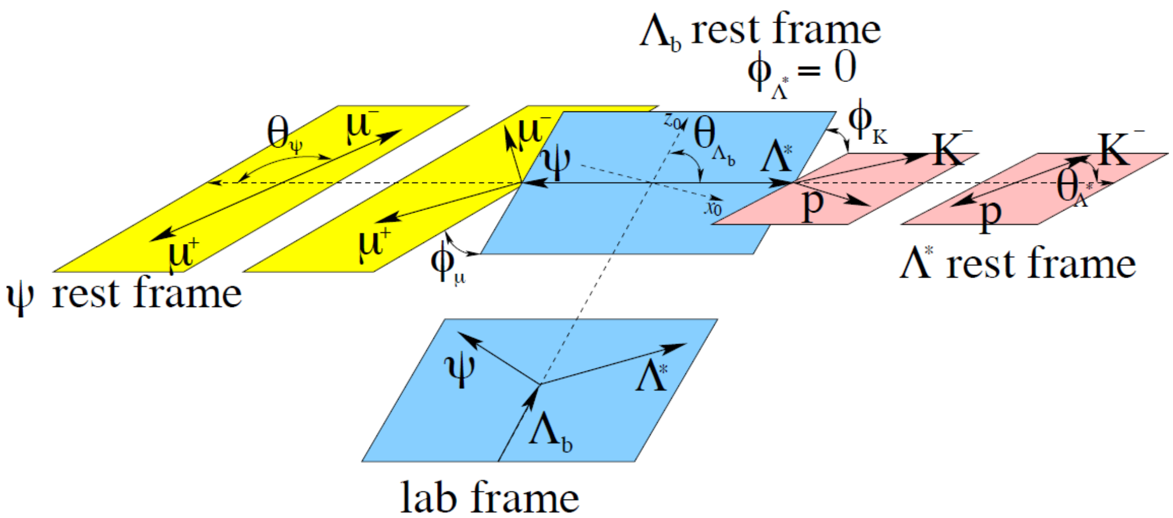
$$R_X(m) = B'_{L^X_{\Lambda_b^0}}(p,p_0,d)\left(\frac{p}{M_{\Lambda_b^0}}\right)^{L^X_{\Lambda_b^0}} \mathrm{BW}(m|M_{0X},\Gamma_{0X})\, B'_{L_X}(q,q_0,d)\left(\frac{q}{M_{0X}}\right)^{L_X}$$

Blatt-Weisskopf functions

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

Breit-Wigner

Λ^* Matrix Element



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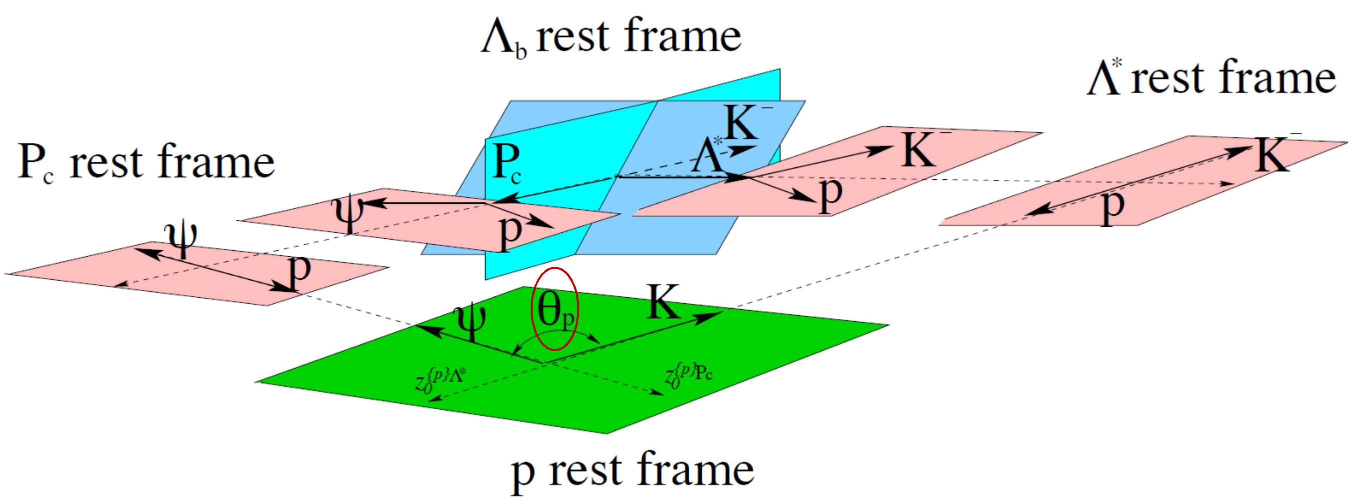
Breit-Wigner

Λ^* Plus P_c^+ Matrix Element

2 additional angles to align the muon and proton helicity frames between the Λ^* and P_c^+ decay chains

also derivable from the Λ^* decay variables

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



- Without this realignment can't describe Λ^* plus P_c^+ interferences properly
- They integrate out to zero in full phase-space but present in the differential 6D fit-PDF

Unbinned 6D maximum likelihood fit

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

$$\mathcal{P}_{\rm sig}(m_{Kp},\Omega|\vec{\omega}) = \frac{1}{I(\vec{\omega})}\left|\mathcal{M}(m_{Kp},\Omega|\vec{\omega})\right|^2 \Phi(m_{Kp})\epsilon(m_{Kp},\Omega), \qquad (69)$$

where $\Phi(m_{Kp})$ is the phase space function equal to $p\,q$, where p is the momentum of the Kp system (*i.e.* Λ^*) in the Λ_b^0 rest frame, and q is the momentum of K^- in the Λ^* rest frame, and $I(\vec{\omega})$ is the normalization integral.

$$\begin{aligned} I(\vec{\omega}) &\equiv \int \left|\mathcal{M}(m_{Kp},\Omega|\vec{\omega})\right|^2 \Phi(m_{Kp})\epsilon(m_{Kp},\Omega)\, dm_{Kp}\, d\Omega \\ &\propto \sum_j^{N_{\rm MC}} w_j^{\rm MC} \left|\mathcal{M}(m_{Kp\,j},\Omega_j|\vec{\omega})\right|^2, \end{aligned}$$

Corrections improving MC simulations

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

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

Possible data event weights (see next).

sFit

W_i- sWeights based on the fit to $m_{J/\psi pK}$ distribution
The data in the extended $m_{J/\psi pK}$ range passed to the amplitude fit.

Since the events are weighted in the log-likelihood this is “quasi” maximum-likelihood fit

$$
\begin{aligned}
-2\ln\mathcal{L}(\overrightarrow{\omega}) &= -\,2s_W\sum_i W_i \ln\mathcal{P}_{\rm sig}(m_{Kp\ i},\Omega_i|\overrightarrow{\omega}) \\
&= -\,2s_W\sum_i W_i \ln|\mathcal{M}(m_{Kp\ i},\Omega_i|\overrightarrow{\omega})|^2 + 2s_W\ \ln I(\overrightarrow{\omega})\sum_i W_i \\
&\qquad \cancel{-\,2s_W\sum_i W_i \ln[\Phi(m_{Kp\ i})\epsilon(m_{Kp\ i},\Omega_i)]}.
\end{aligned}
$$

No need for parameterization of the signal efficiency

cFit (default)

$W_i=1$ no event weights; true maximum likelihood fit
Data only in the Λ_b^0 peak region passed to the amplitude fit.
Sideband data used to construct 6D model of the background: $\mathcal{P}^u_{\rm bkg}(m_{Kp\ j}, \Omega_j)$

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

$\beta = 5.4\%$ background fraction

$$
\begin{aligned}
-2\ln\mathcal{L}(\overrightarrow{\omega}) = & \\
& -2\sum_i \ln\left[(1-\beta)\,\frac{|\mathcal{M}(m_{Kp\ i}, \Omega_i|\overrightarrow{\omega})|^2\,\Phi(m_{Kp\ i})\epsilon(m_{Kp\ i}, \Omega_i)}{I(\overrightarrow{\omega})} + \beta\,\frac{\mathcal{P}^u_{\rm bkg}(m_{Kp\ i}, \Omega_i)}{I_{\rm bkg}}\right] \\
= & -2\sum_i \ln\left[|\mathcal{M}(m_{Kp\ i}, \Omega_i|\overrightarrow{\omega})|^2 + \frac{\beta\, I(\overrightarrow{\omega})}{(1-\beta)I_{\rm bkg}}\,\frac{\mathcal{P}^u_{\rm bkg}(m_{Kp\ i}, \Omega_i)}{\Phi(m_{Kp\ i})\epsilon(m_{Kp\ i}, \Omega_i)}\right] \\
& + 2N\ln I(\overrightarrow{\omega}) + \cancel{\text{constant}},
\end{aligned}
$$

$$I_{\rm bkg} \equiv \int \mathcal{P}^u_{\rm bkg}(m_{Kp}, \Omega)\, dm_{Kp}\, d\Omega \propto \sum_j w_j^{\rm MC}\,\frac{\mathcal{P}^u_{\rm bkg}(m_{Kp\ j}, \Omega_j)}{\Phi(m_{Kp\ j})\epsilon(m_{Kp\ j}, \Omega_j)}.$$

The background term is then efficiency-corrected so it can be added to the efficiency-independent signal probability expressed by $|\mathcal{M}|^2$. This way the efficiency parametrization, $\epsilon(m_{Kp}, \Omega)$, influences only the background component which affects only a tiny part of the total PDF