New results on exotic baryon resonances at LHCb

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On behalf of LHCb Collaboration

10th International Workshop on e^+e^- collisions from Phi to Psi

(USTC, Hefei, China)

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 (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 $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, 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".

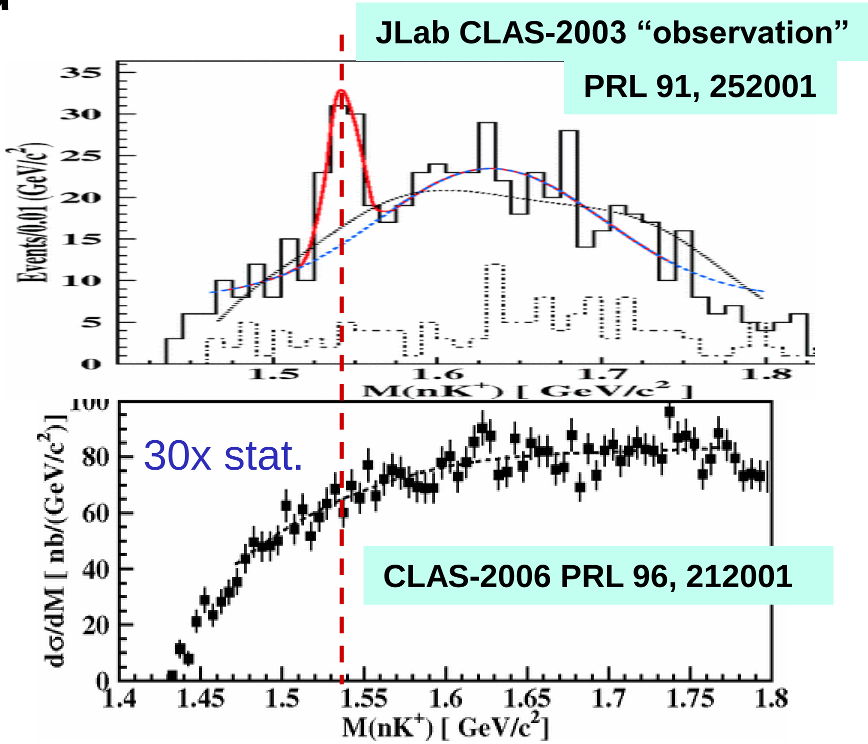
These multiquark states would be short-lived ~10^{-23} s "resonances" whose presences are detected by mass peaks & angular distributions showing the unique J^{PC} quantum numbers

Curious history of pentaquark Θ^+ search

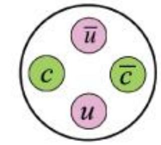
See summary by [K. H. Hicks, Eur. Phys. J. H37 (2012) 1]

- No convincing states 50 years after Gell-mann paper proposing $qqqq\bar{q}$ states
- Prediction: $\Theta^+(uudd\bar{s})$ could exist with m ≈1530 MeV
- In 2003,10 experiments reported seeing 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”

$\gamma d \to pK^-K^+n$

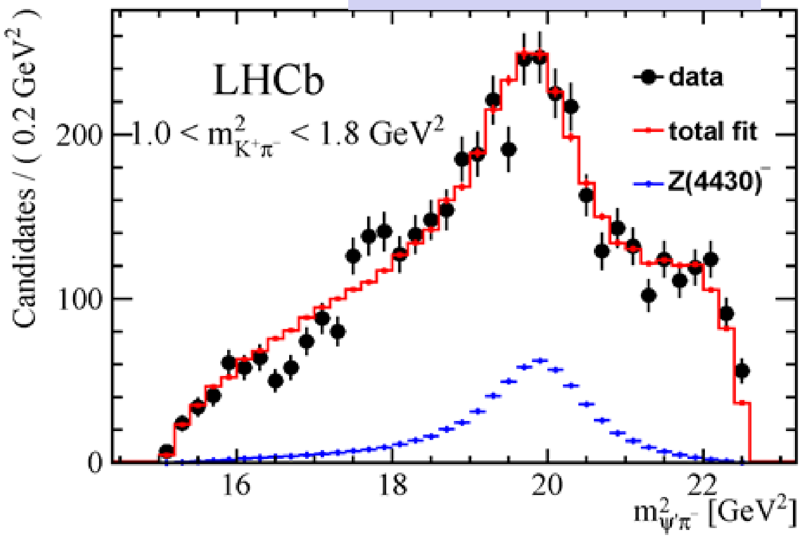


Tetraquark

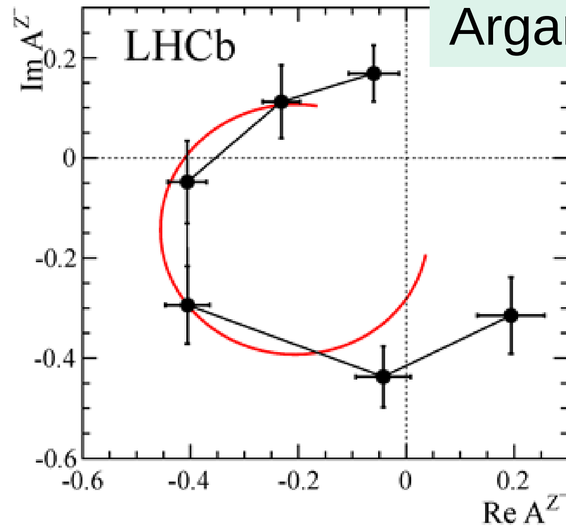


- Experimental evidence started to appear only recently
- $Z(4430)^+$ (Belle, LHCb)
  – Both analyses performed full amplitude fits

[PRL 112, 222002 (2014)]



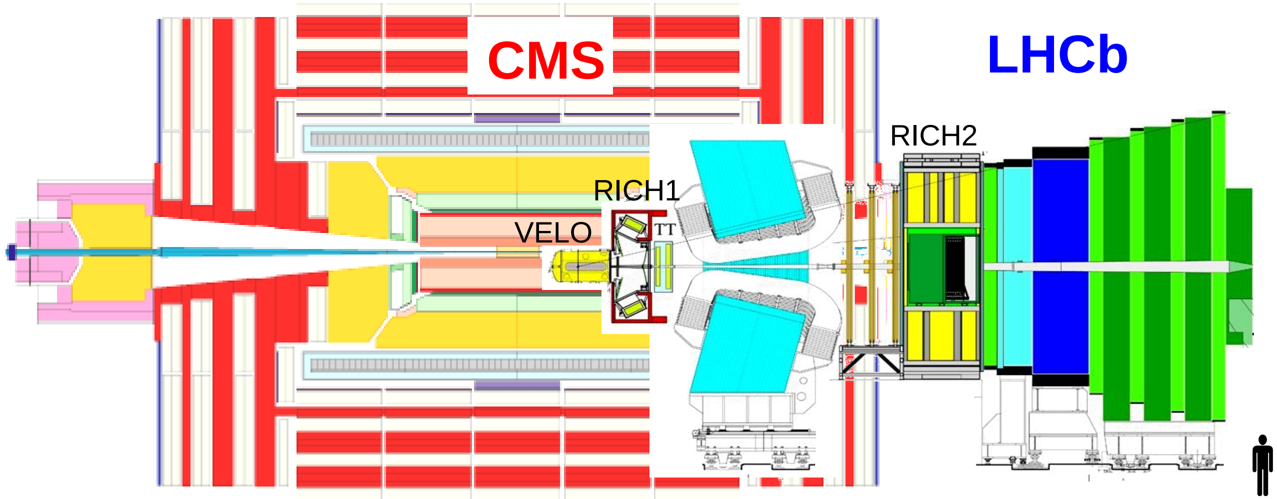
Argand diagram

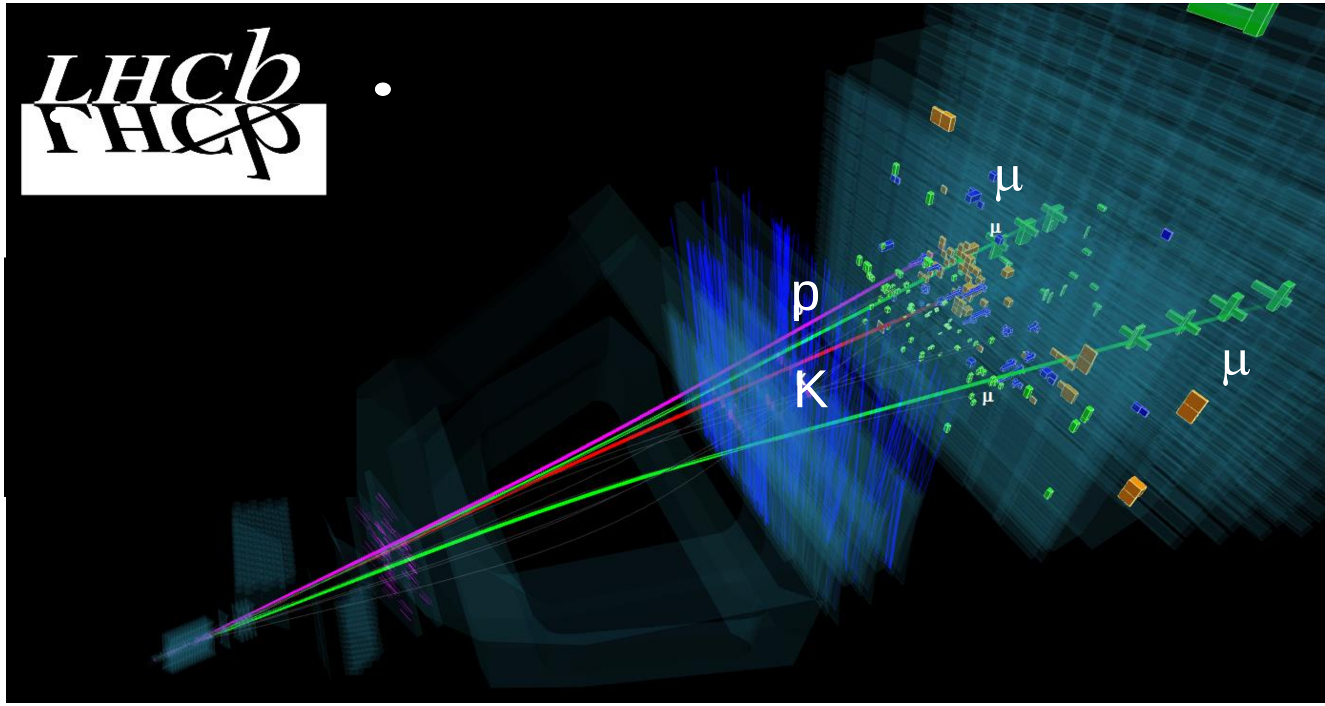


- $Z_c(3900)^+$and its families (BESIII)
- $Z_b(10610)^+$ and $Z_b(10650)^+$ (Belle)
- These give support to the possibility of pentaquark states

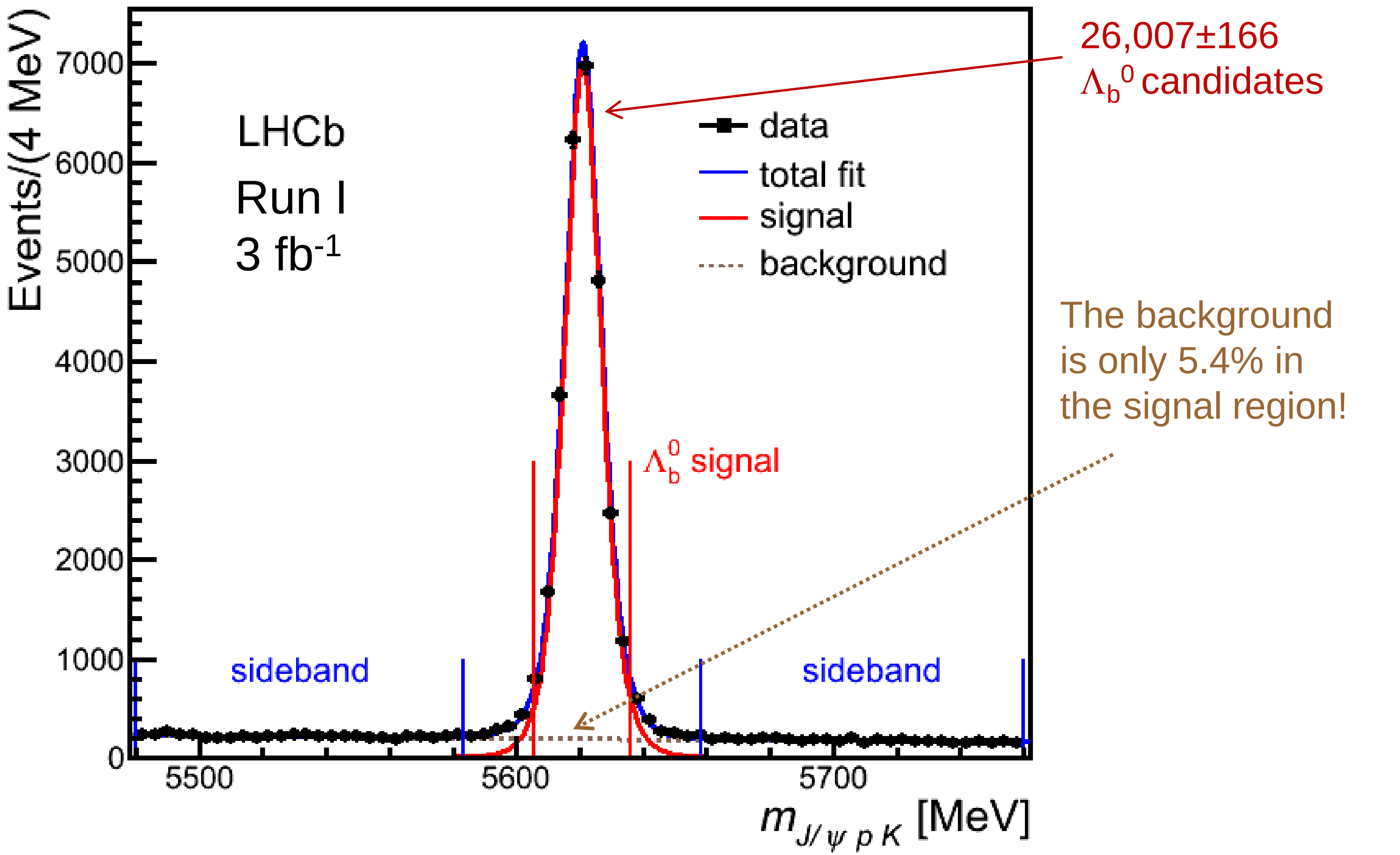
LHCb detector at LHC

- 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 π/K/p discrimination (smaller backgrounds)
  - Small event size allows large trigger bandwidth (up to 5 kHz in Run I); all devoted to flavor physics



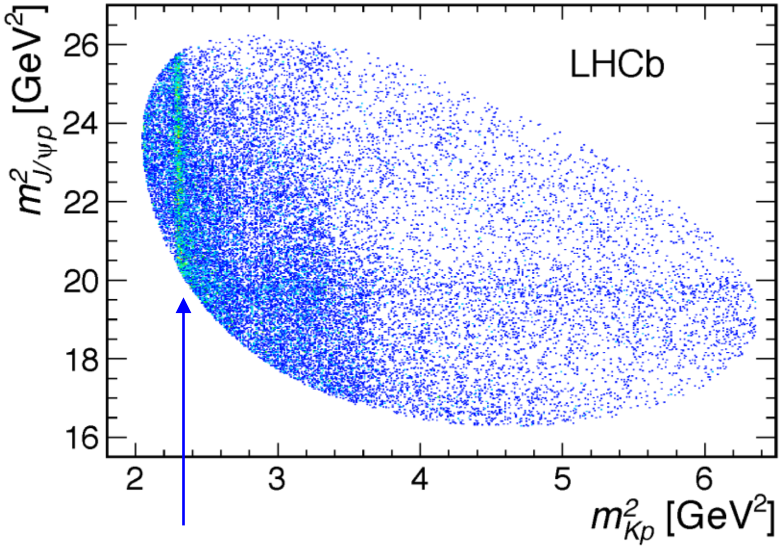


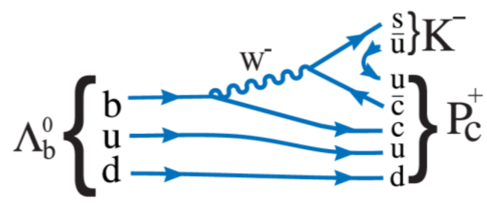
LHCb $\Lambda_b^0 \rightarrow J/\psi\ p\ K^-$



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

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

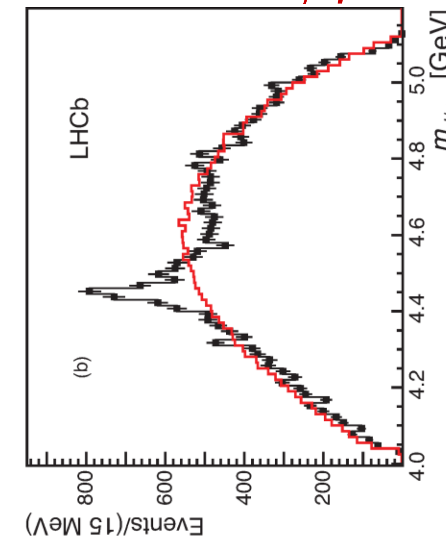




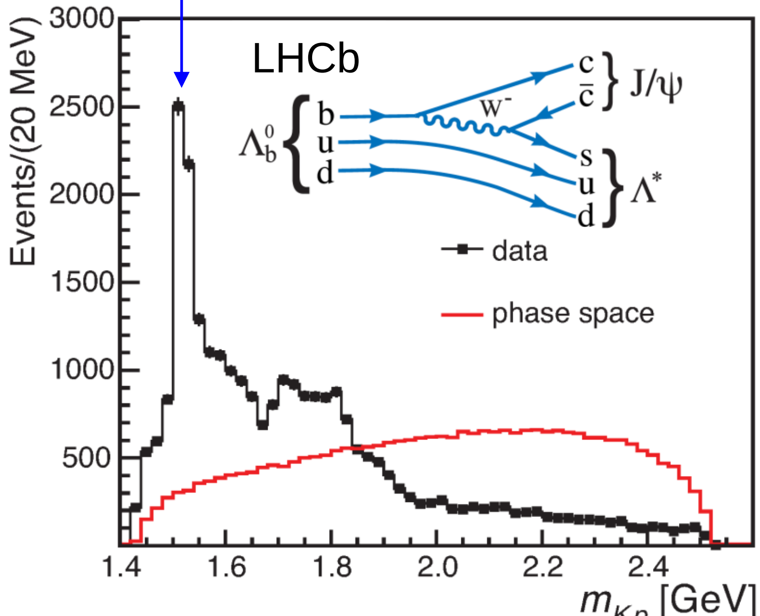
$P_c^+ \rightarrow J/\psi\ p$

?

$c\bar{c}uud$



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



- Unexpected, narrow peak in $m_{J/\psi p}$
- Many checks done to ensure it is not an "artifact" of selection:
  - Veto $B_s \rightarrow J/\psi K^- K^+$ & $B^0 \rightarrow J/\psi K^- \pi^+$ 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 $\rightarrow$ p K^- ?
  - Proper amplitude analysis absolutely necessary!

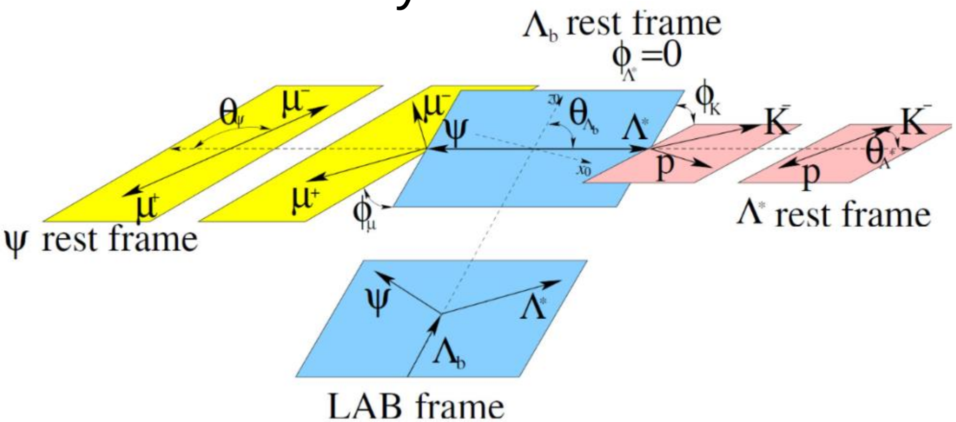
Amplitude Analysis Formalism

- Helicity formalism
  - Allows for the conventional $\Lambda^* \to pK$ resonances to interfere with pentaquark states $P_c^+ \to J/\psi\, p$
  - Use m(K⁻p) & 5 decay angles as fit parameters.

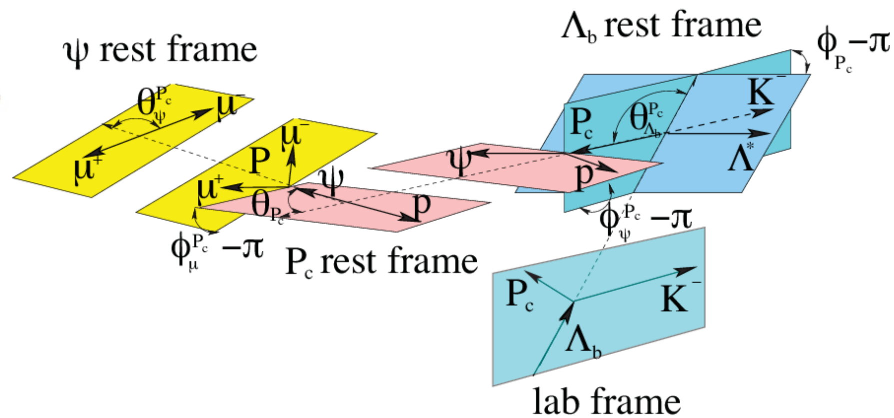
So 6D fit

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

Λ^* Decay Chain



P_c^+ Decay Chain



Λ^* resonance model

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

Helicity couplings

LS couplings

In Λ^* decay: $P_A = P_B P_C (-1)^L$

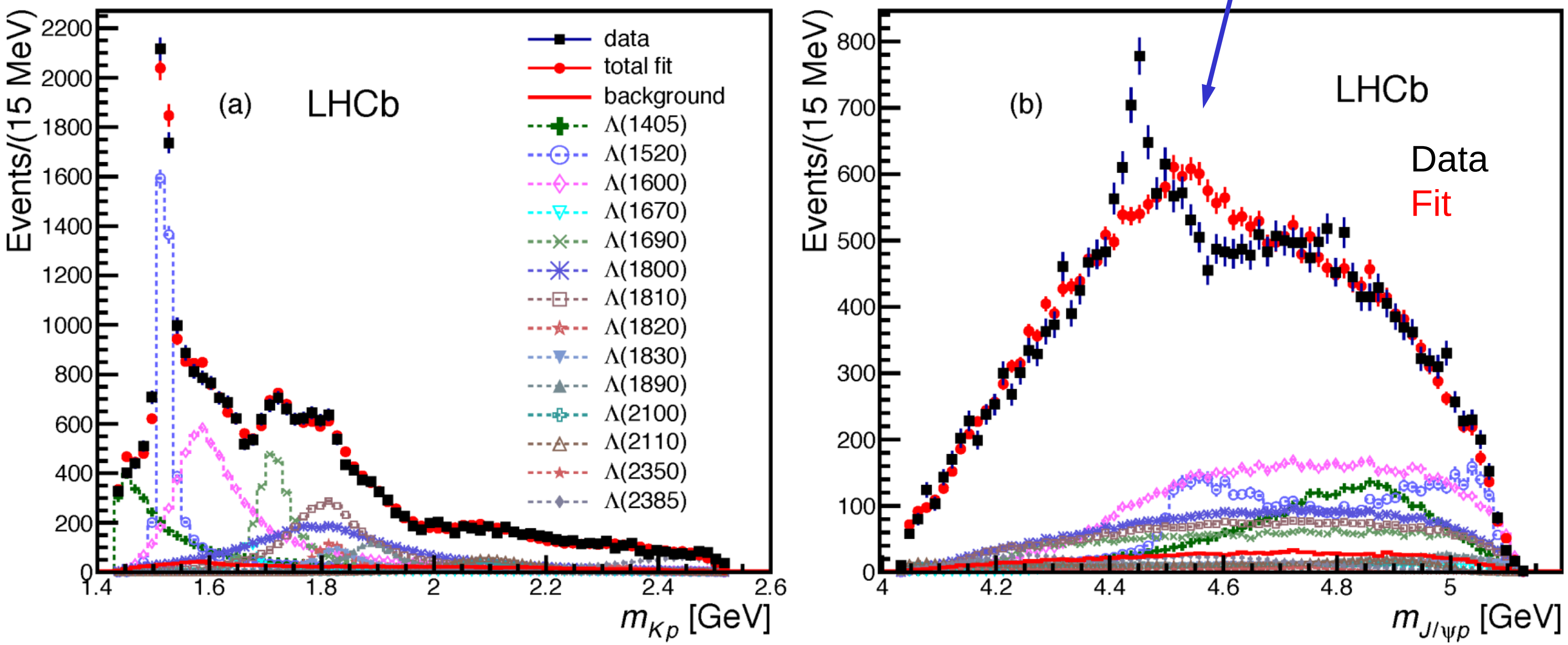
No high-J^P high-mass states

All known Λ^* states

				limit L	All states, all L
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

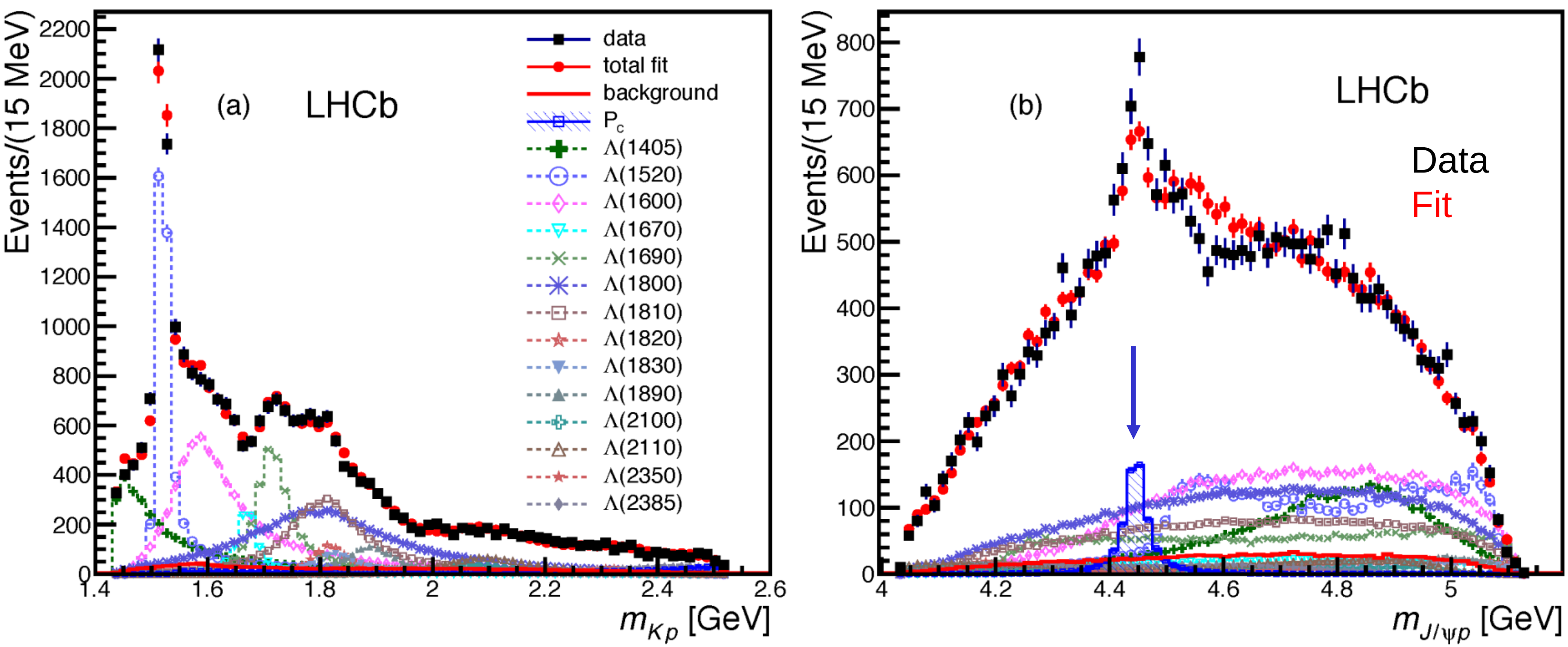
Extended model fits with only Λ^*

- Fails to reproduce the $M(J/\psi\, p)$ peaking structures!
- Other possibilities we have studied:
  - All Σ^{*0} (I=1), isospin violating decay
  - two new Λ^* with free m&Γ
  - 4 non-resonant Λ^* with $J^P = 1/2^{\pm}$ and $3/2^{\pm}$
- Still fail to describe the data



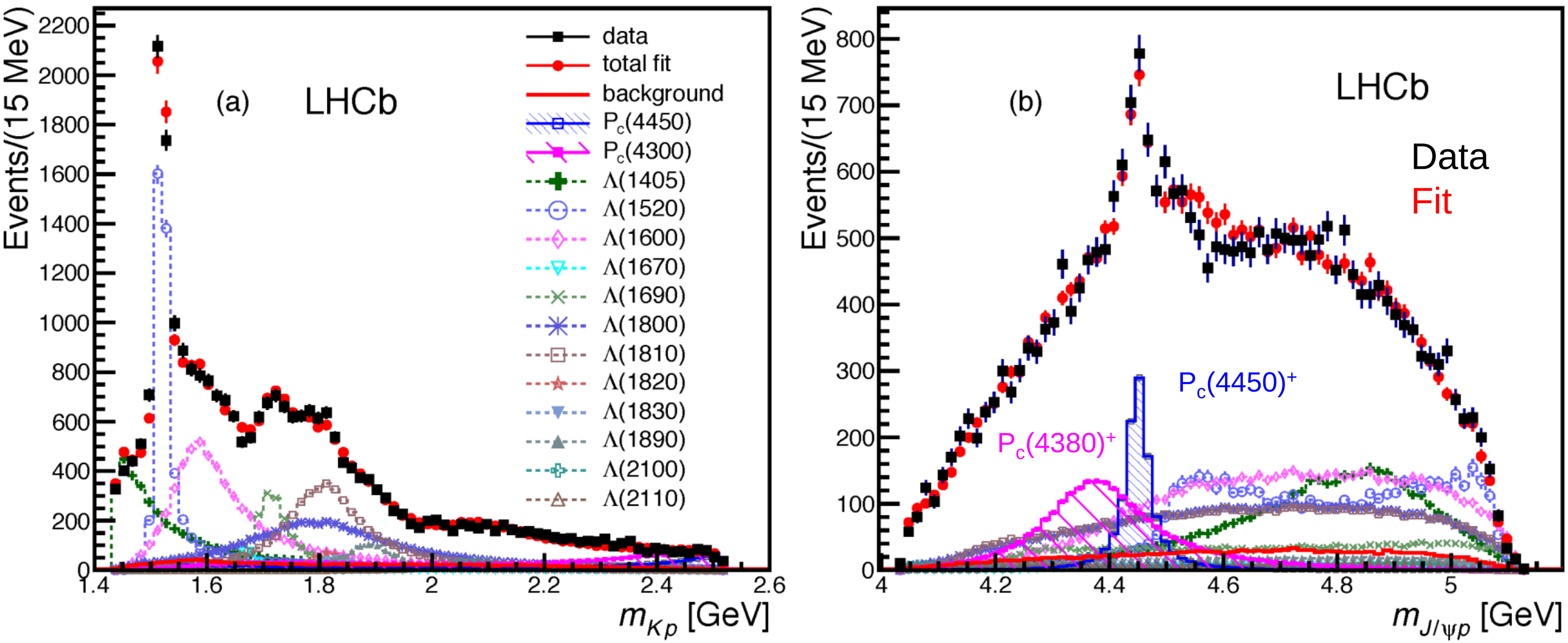
Extended model fits with 1 P_c^+

- Try all J^P up to 7/2$^\pm$. All don't give good fit

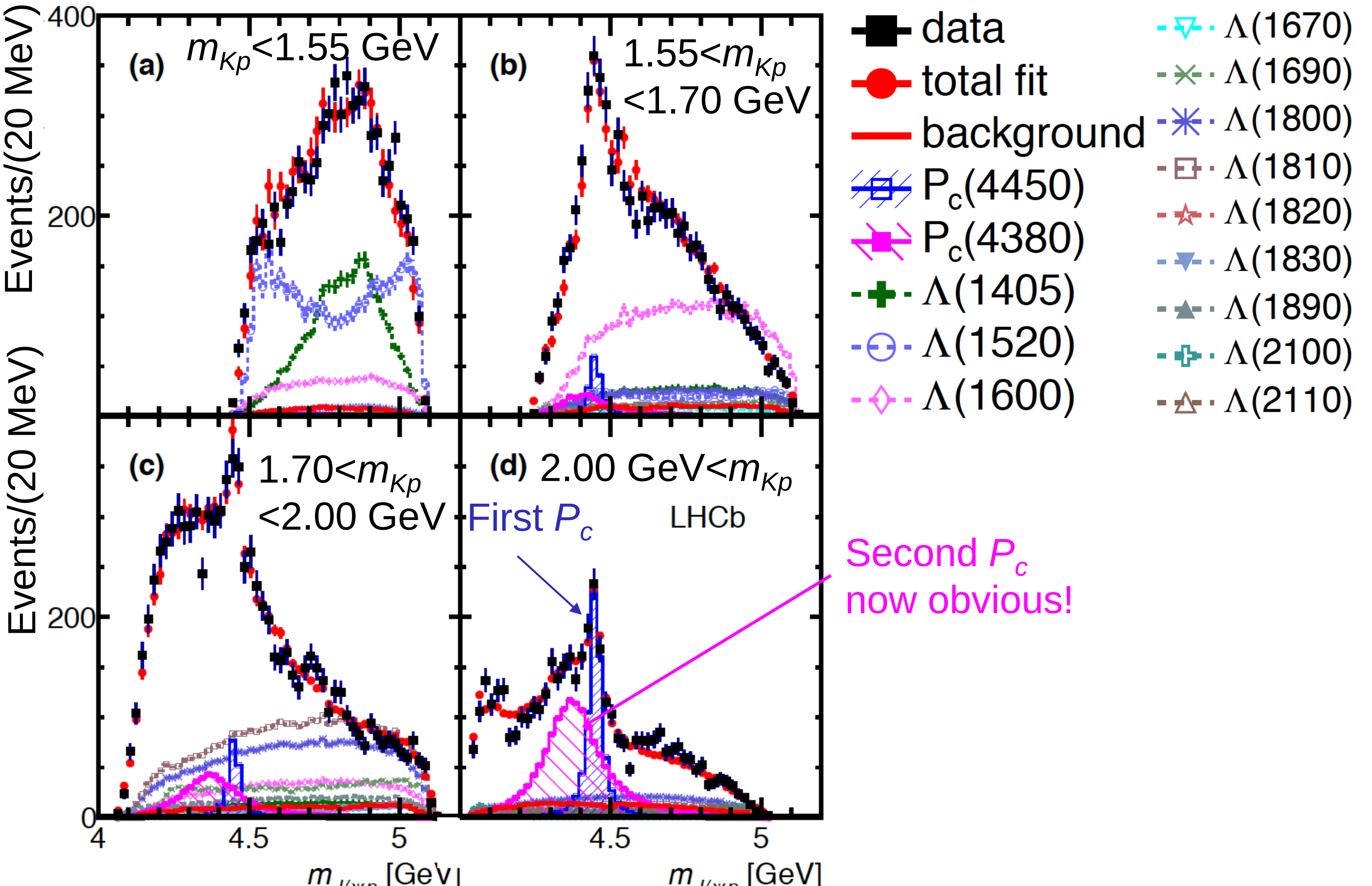


2 P_c^+ fit in reduced model

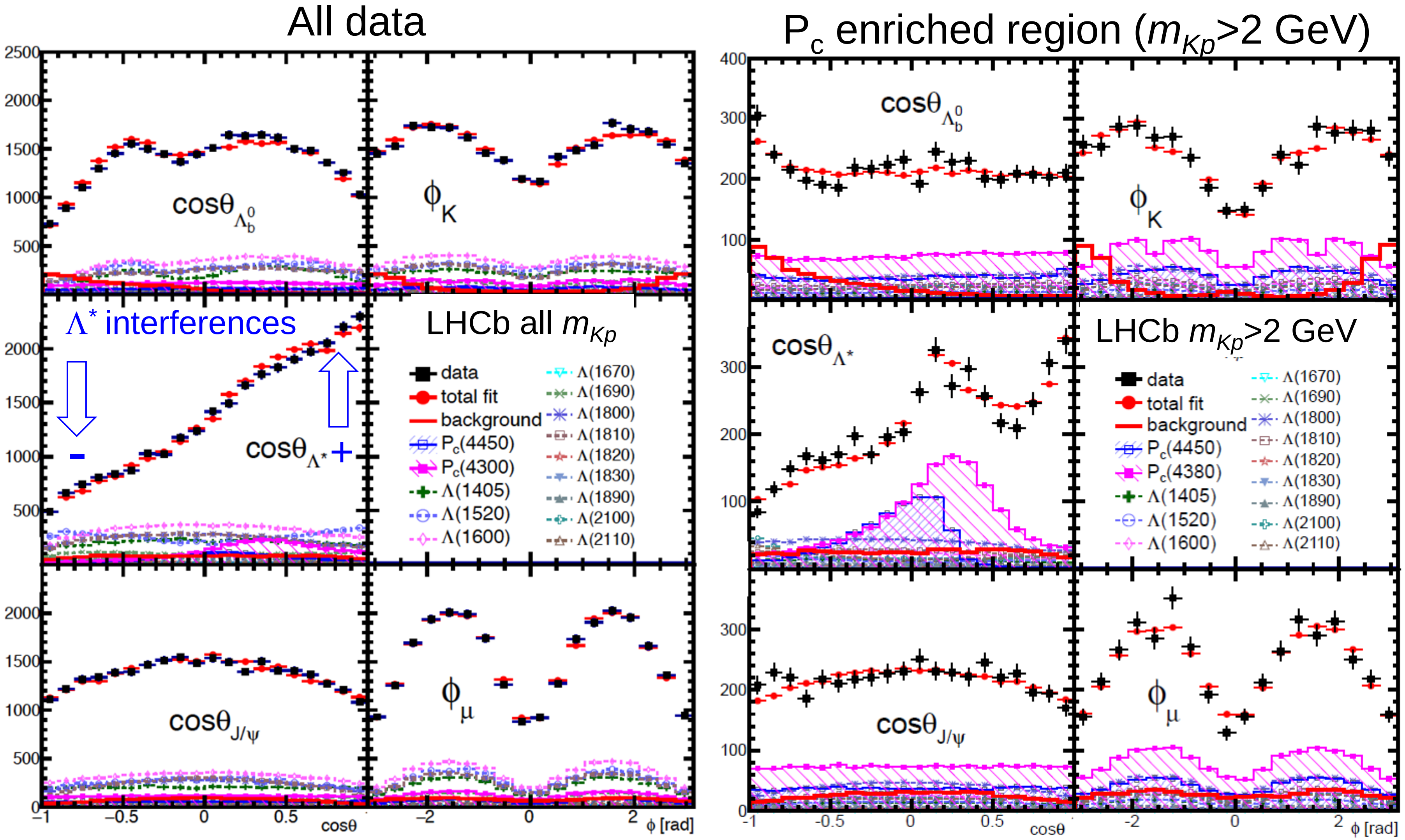
- Best fit has J^P= ($3/2^-$ (low), $5/2^+$(high)), also ($3/2^+$, $5/2^-$) & ($5/2^+$, $3/2^-$) are preferred



$M(J/\psi\, p)$ in $M(Kp)$ Slices

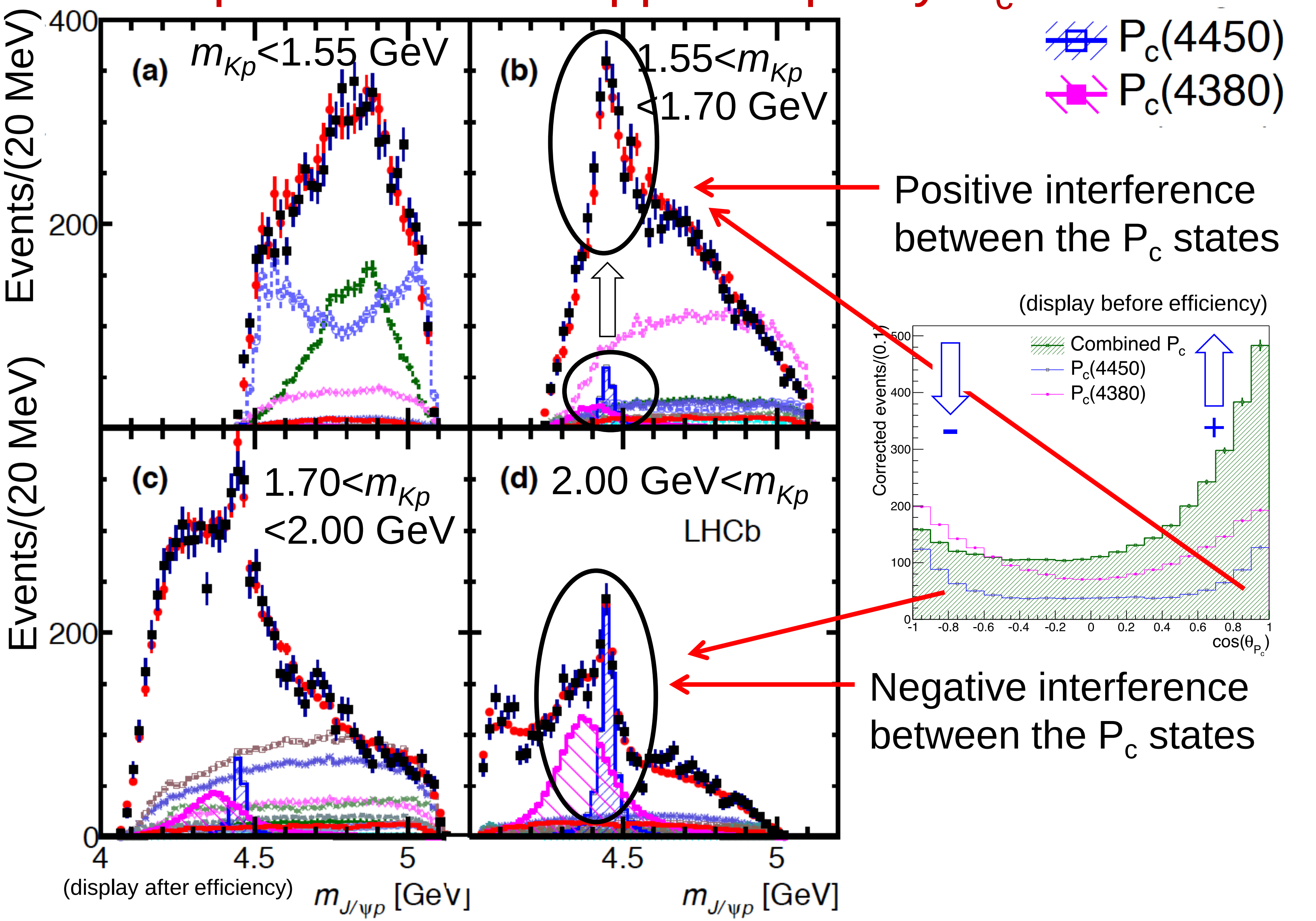


Angular distributions



- Good description of the data in all 6 dimensions!

Data preference for opposite parity P_c^+ states



- This interference pattern only for states with opposite parity

Significances and results

- Significance include systematic uncertainty
- Fit improves greatly, for 1 P_c^+ Δ(-2ln*L*)=216=14.7^2, adding the 2nd P_c^+ improves by 135=11.6^2
- Toy MCs used to obtain significances based on Δ(-2ln*L*)

	$P_c(4380)^+$	$P_c(4450)^+$
Significance	9σ	12σ
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit fraction(%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1
$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-;$ $P_c^+ \to J/\psi p)$	$(2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36})$ $\times 10^{-5}$	$(1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18})$ $\times 10^{-5}$

Branching ratio results are submitted to Chin. Phys. C (arXiv:1509.00292)

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

Cross-checks

- Two independently coded fitters using different background subtractions (sFit & cFit)

- Split data show consistency 2011/2012, magnet up/down, $\Lambda_b^0/\overline{\Lambda}_b^0$, two Λ_b^0 p_T bins

- Selection varied
  - BDTG>0.5 instead of 0.9 (default)
  - B^0 and B_s reflections modelled in the fit instead of veto

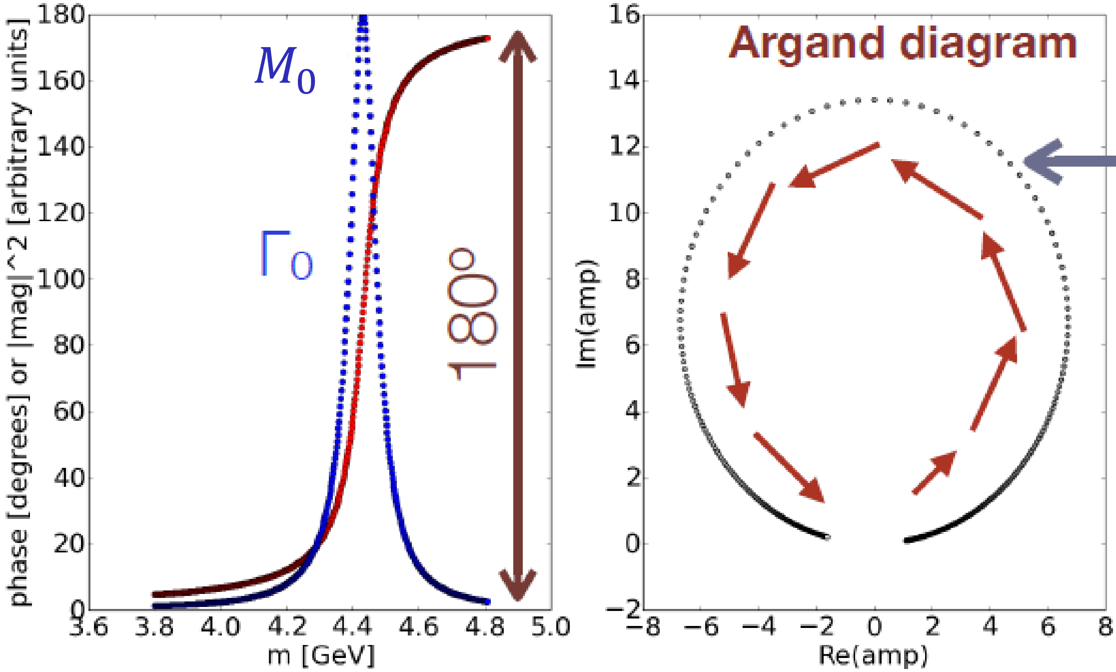
Breit-Wigner amplitude

- Often a relativistic Breig-Wigner function is used to model resonance
- q is daughter momentum in the resonance rest frame

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

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

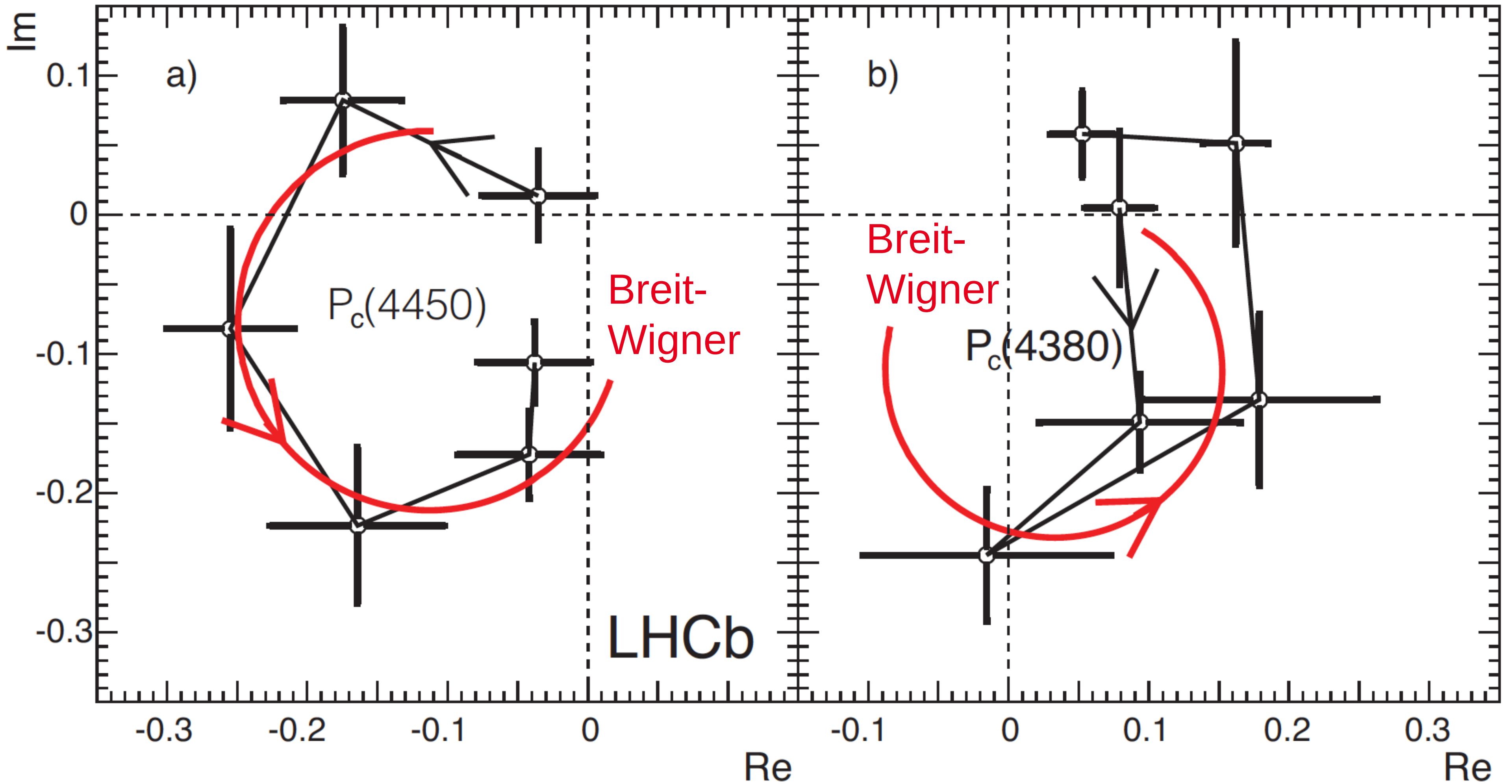
Blatt-Weisskopf function for orbital angular momentum (*L*) barrier factors



- 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

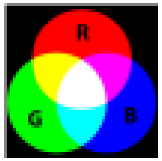
P_c^+ amplitudes for 6 $m_{J/\psi p}$ bins between $+\Gamma$ & $-\Gamma$ around the resonance mass

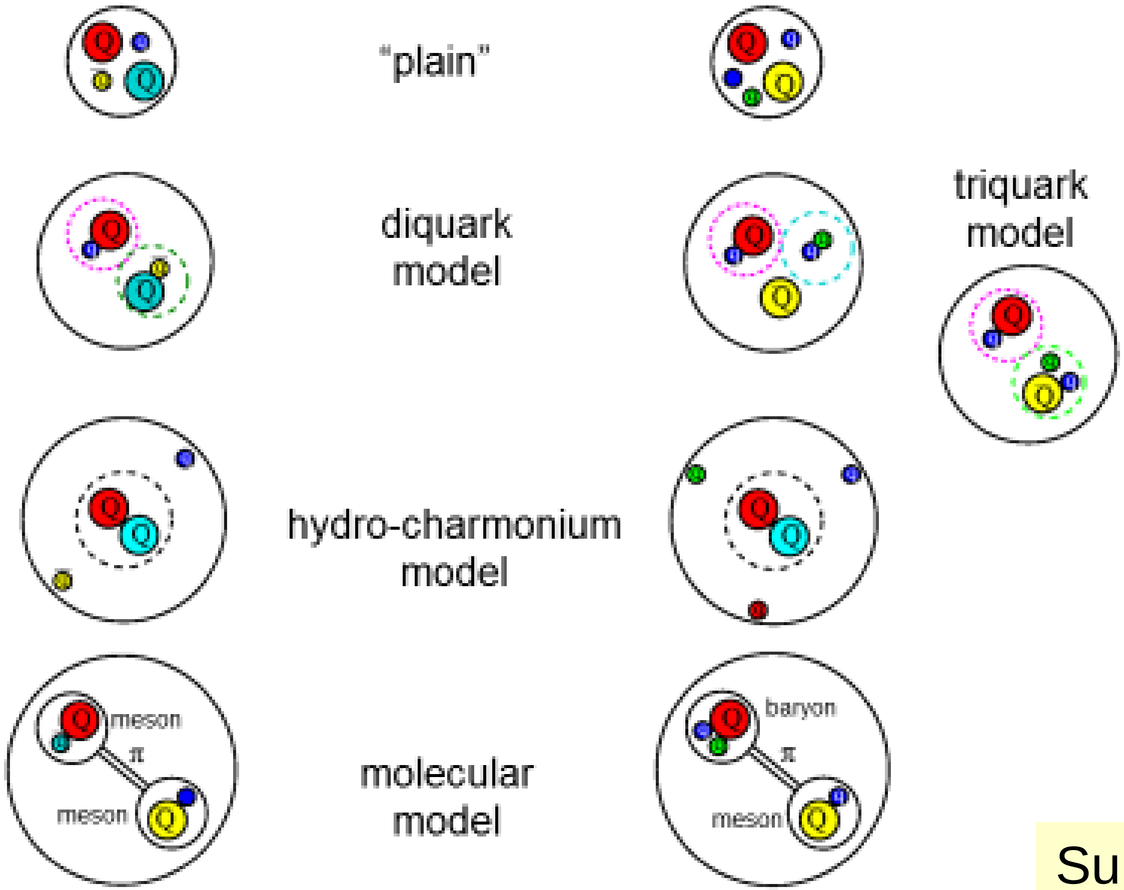


- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive

Different types of tetra- and penta-quarks

- Crucial for understanding QCD & points to other states.





Maiani, Polosa & Riquer [arXiv:1507.04980]

Summarized by Burns [arXiv:1509.02460]

+ kinematic effects

Conclusions

- LHCb has found two pentaquark candidates decaying to $J/\psi p$ with overwhelming significance in a state of the art amplitude analysis: they will not go away!
- The preferred J^P are of opposite parity, with one state having J=3/2 and the other 5/2
- Both the P_c^+ and $Z_{(c)}^+$ states contain $c\bar{c}$, strong binding due to this?
- Determination their internal binding mechanism will require more study
- We look forward to establishing the structure of many other states or other decay modes

Backup

sFit

- Signal PDF

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

$\vec{\omega}$: fitting parameters
Φ : phase-space = pq
ϵ: efficiency

$$I(\vec{\omega}) \propto \sum_{j}^{N_{\text{MC}}} w_j^{\text{MC}}\,|\mathcal{M}(m_{Kp\,j},\Omega_j|\vec{\omega})|^2$$

- Normalization calculated using simulated PHSP MC ($\Phi\epsilon$ included)
- w^{MC} discuss later

- sFit minimizes

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

W_i is sWeighs from m(J/ψKp) fits
$s_W = \Sigma_i W_i \,/\, \Sigma_i W_i^2$ constant factor to correct uncertainty

Constant (invariant of $\vec{\omega}$), is dropped
No need to know $\Phi\varepsilon$ paramerizaiton

cFit

- cFit uses events in ±2σ window (σ=7.52MeV)
- Total PDF $\mathcal{P}(m_{Kp},\Omega|\vec{\omega}) = (1-\beta)\,\mathcal{P}_{\rm sig}(m_{Kp},\Omega|\vec{\omega}) + \beta\,\mathcal{P}_{\rm bkg}(m_{Kp},\Omega)$
- Background is described by sidebands 5σ-13.5σ
- cFit minimizes

Background fraction β=5.4%

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

$$I_{\rm bkg} \propto \sum_j w_j^{\rm MC}\frac{\mathcal{P}^u_{\rm bkg}(m_{Kp\ j},\Omega_j)}{\Phi(m_{Kp\ i})\epsilon(m_{Kp\ j},\Omega_j)}$$

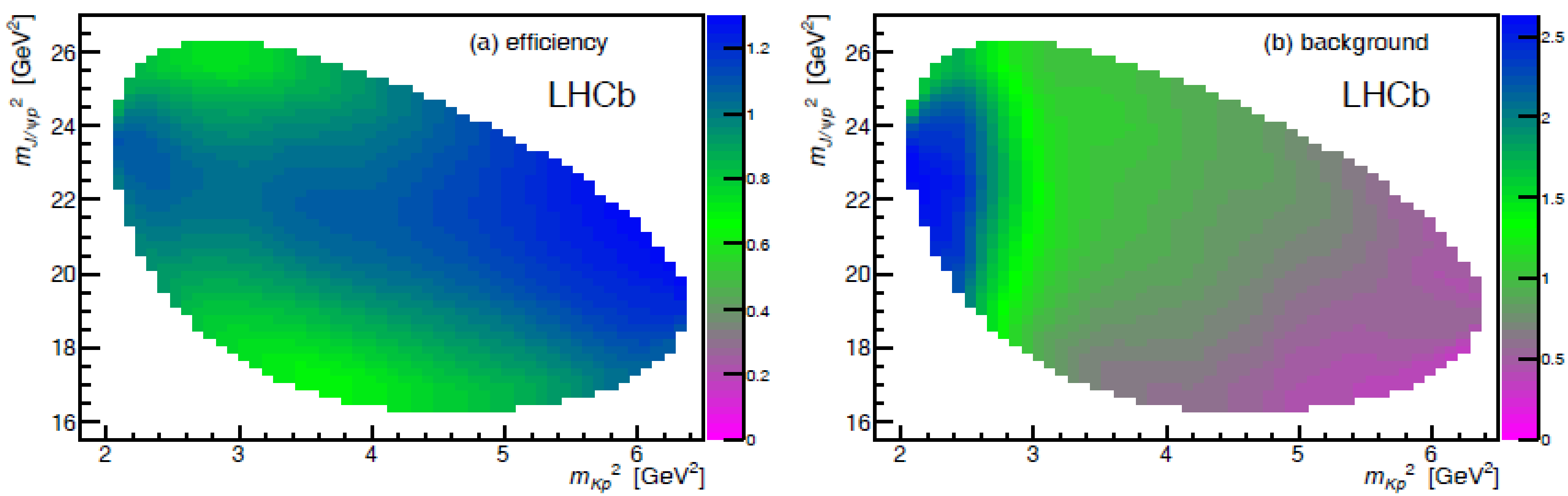
Signal efficiency parameterization becomes part of background parameterization,
effects only a tiny part of total PDF because of small β

cFit efficiency and background parameterizations

- Both use similar ways

$$\epsilon(m_{Kp},\Omega) = \epsilon_1(m_{Kp},\cos\theta_{\Lambda})\cdot\epsilon_2(\cos\theta_{\Lambda_b^0}|m_{Kp})\cdot\epsilon_3(\cos\theta_{J/\psi}|m_{Kp})\cdot\epsilon_4(\phi_K|m_{Kp})\cdot\epsilon_5(\phi_\mu|m_{Kp})$$

$$\frac{\mathcal{P}^u_{\rm bkg}(m_{Kp},\Omega)}{\Phi(m_{Kp})} = P_{{\rm bkg}_1}(m_{Kp},\cos\theta_\Lambda)\cdot P_{{\rm bkg}_2}(\cos\theta_{\Lambda_b^0}|m_{Kp})$$
$$\cdot P_{{\rm bkg}_3}(\cos\theta_{J/\psi}|m_{Kp})\cdot P_{{\rm bkg}_4}(\phi_K|m_{Kp})\cdot P_{{\rm bkg}_5}(\phi_\mu|m_{Kp}).$$



Amplitude Analysis Formalism II

- 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:

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

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

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

- 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 determined from the fit

Amplitude Analysis Formalism II

- 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 Formalism III

- They are added together as:

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

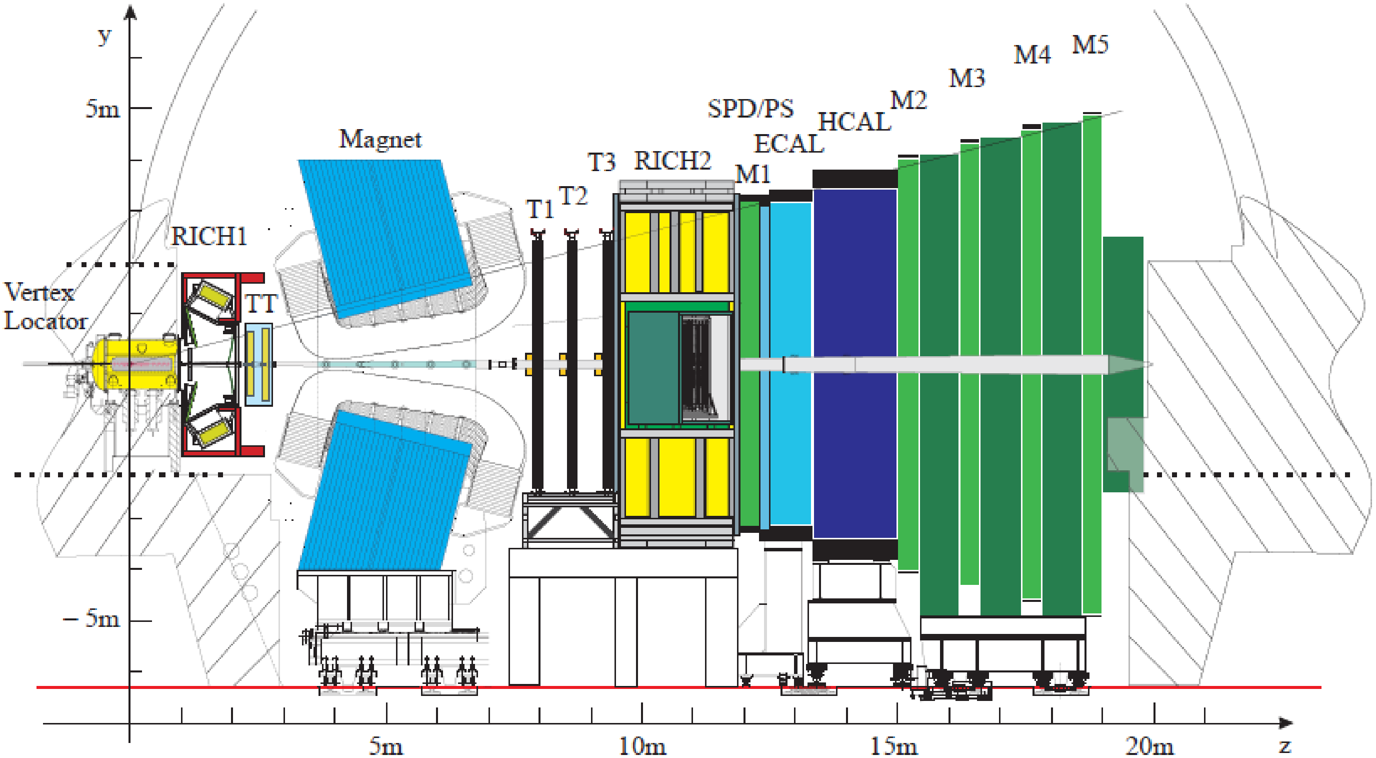
- α_μ and θ_p are rotation angles to align the final state helicity axes of the μ and p, as helicity frames used are different for the two decay chains.

- Helicity couplings $\mathcal{H} \Rightarrow$ LS amplitudes *B* via:

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

  - Convenient way to enforce parity conservation in the strong decays via: $P_A = P_B P_C (-1)^L$

LHCb detector



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: $\Delta p/p = 0.4 \sim 0.6\%$ ($5 - 100$ GeV$/c$)

Mass : $\sigma_m = 8$ MeV$/c^2$ for $B \to J/\psi X$ (constrained $\mathrm{m}_{J/\psi}$)

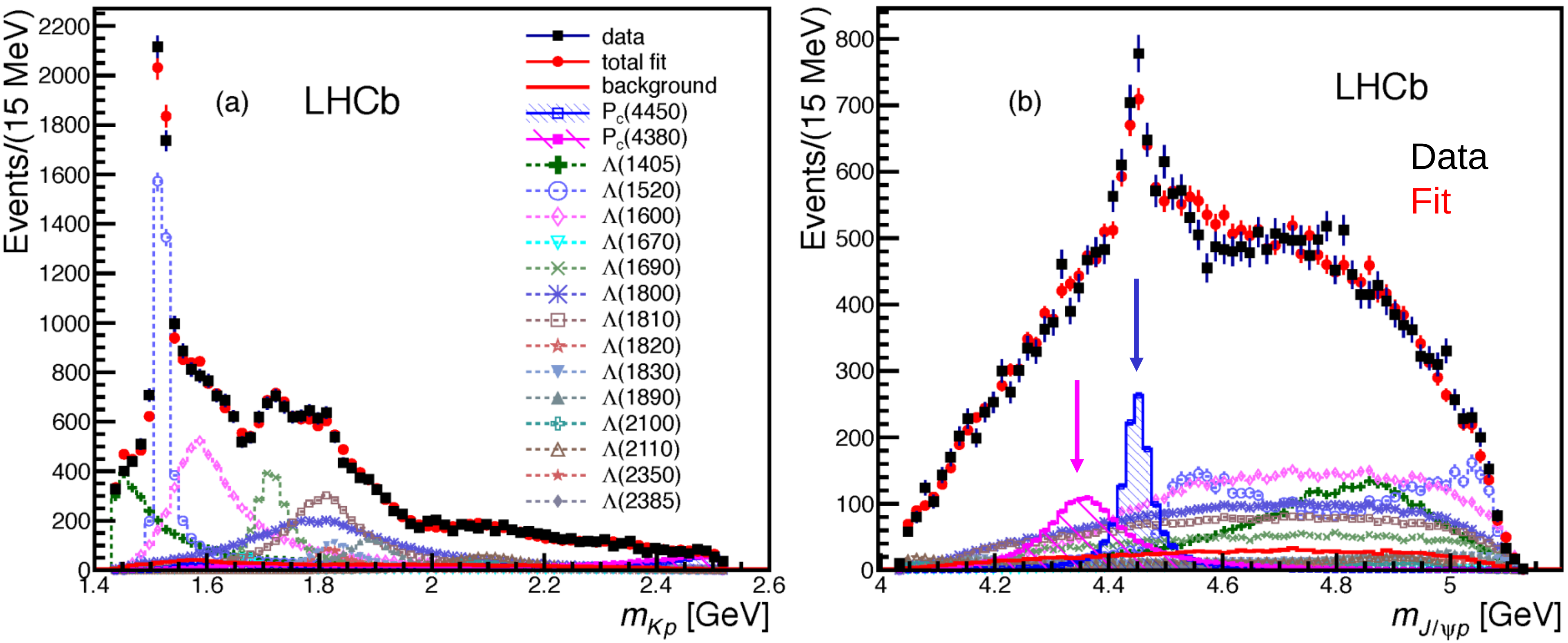
RICH $K - \pi$ separation: $\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$

Muon ID: $\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$

ECAL: $\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

Extended model fits with 2 P_c^+

- Leads to a good fit
- The second broad P_c^+ is visible in other projections (shown later)
- It also modifies the narrow P_c^+'s decay angular distribution via interference to match with the data distribution



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
$L_{\Lambda_b^0}^{P_c}$ $\Lambda_b^0 \to P_c^+$ (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		
$L_{\Lambda_b^0}^{\Lambda_n^*}$ $\Lambda_b^0 \to J/\psi\, \Lambda^*$	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

Λ^* modelling contributes the largest

Systematic Uncertainties

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Alternate J^P fits give sizeable uncertainty

Systematic Uncertainties

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Varying choices in mass depend function also give sizeable uncertainty

Systematic Uncertainties

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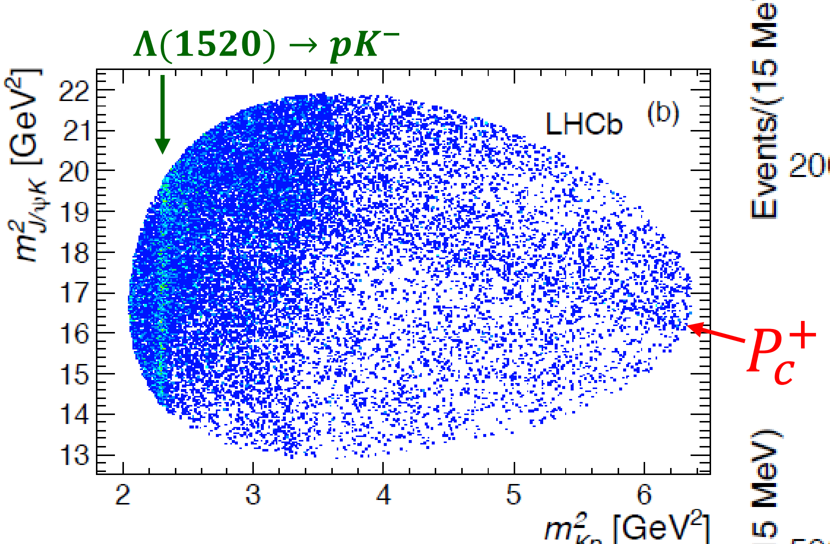
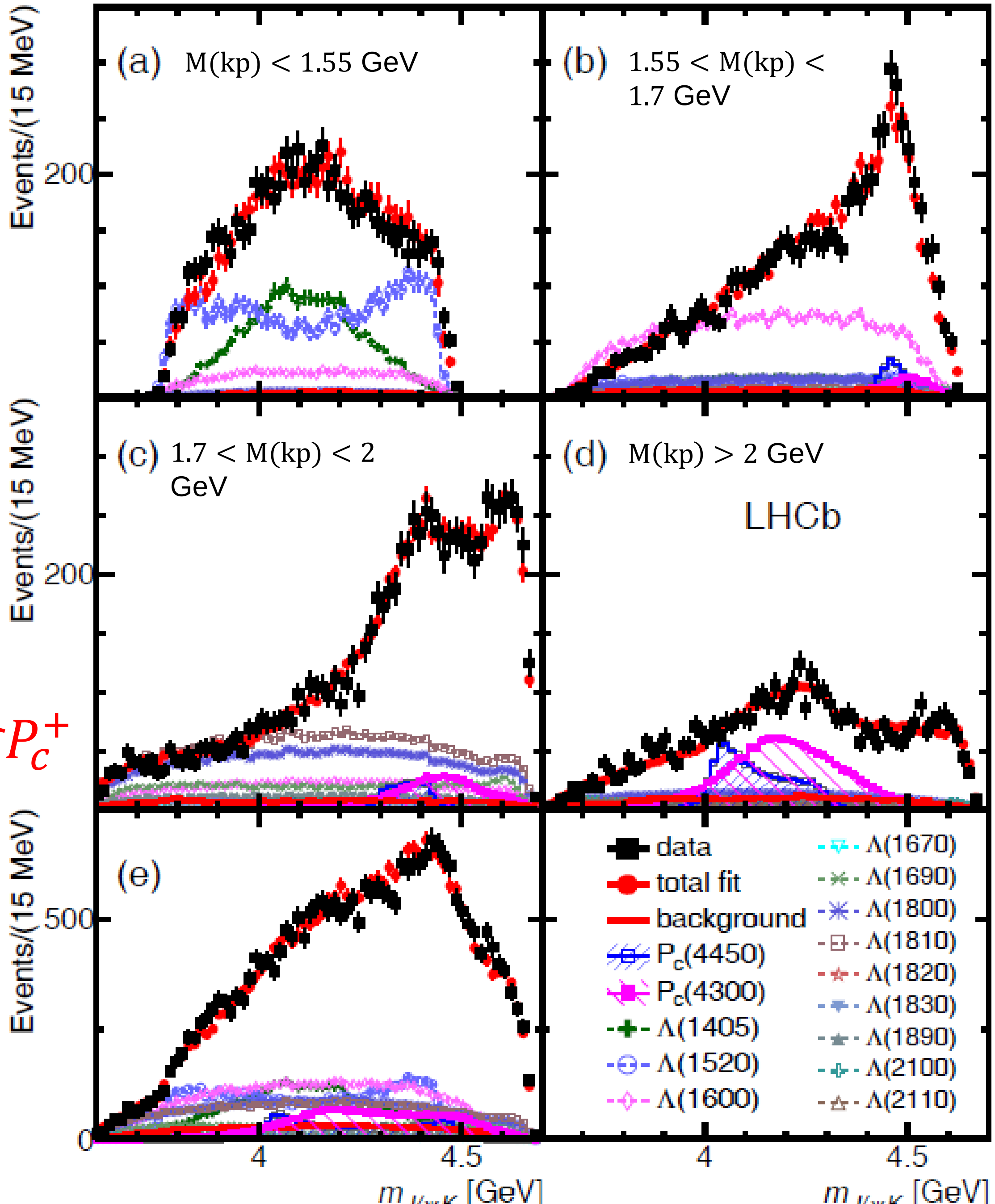
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

sFit/cFit give consistent results

$J/\psi\, K$ System

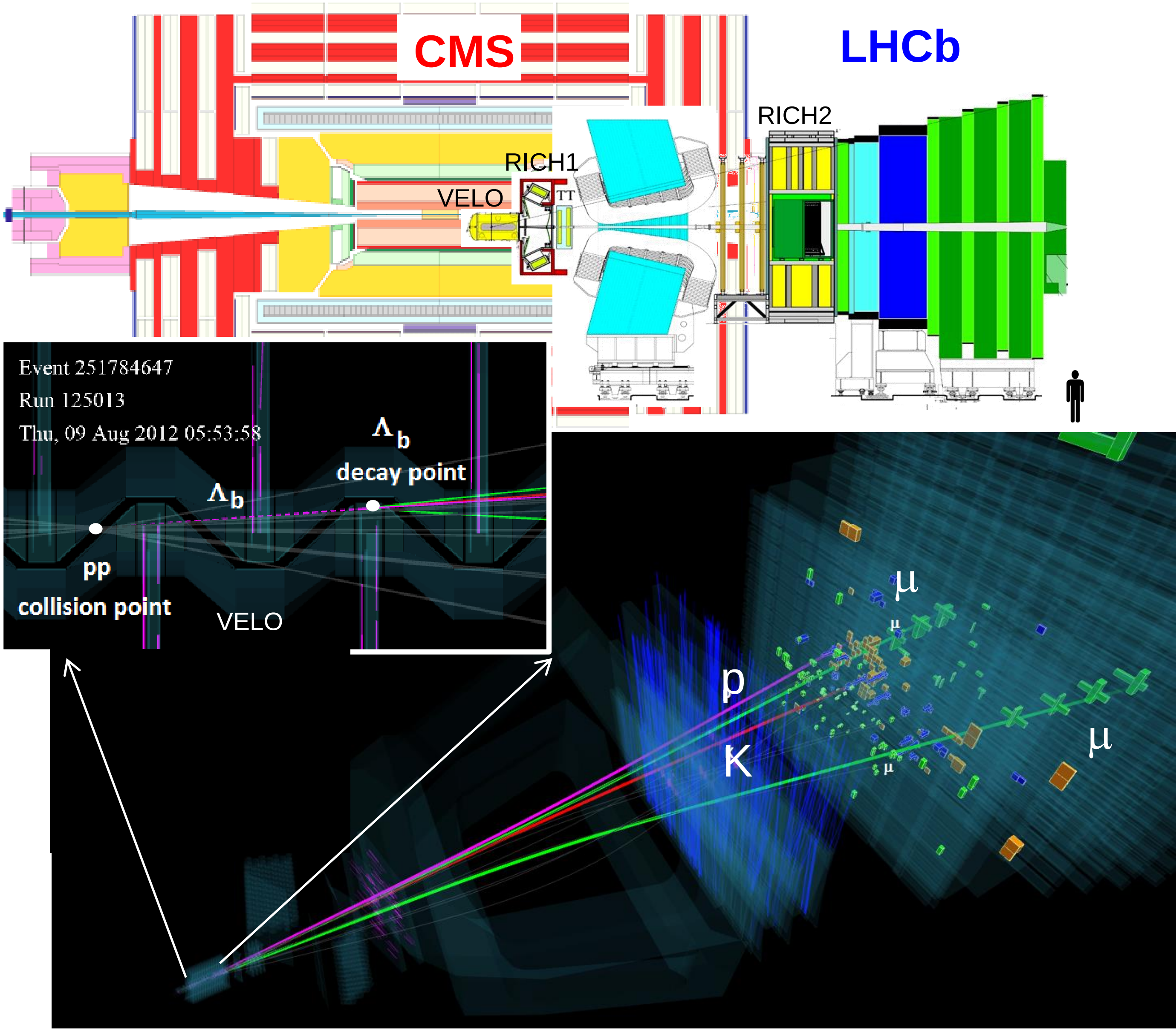
- $J/\psi\, K$ system is well described by the Λ^* and P_c reflections



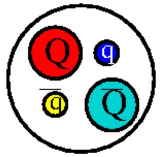


LHCb detector at LHC

- 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 π/K/p discrimination (smaller backgrounds)
  - Small event size allows large trigger bandwidth (up to 5 kHz in Run I); all devoted to flavor physics



Different types of tetra- and penta-quarks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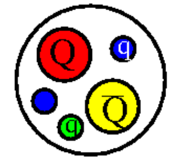
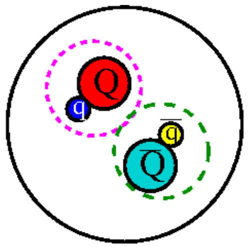
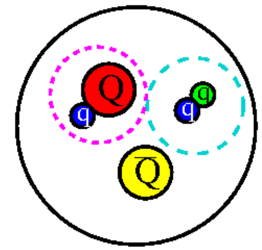
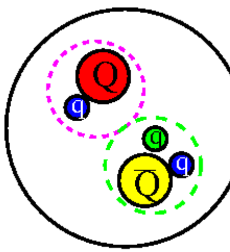
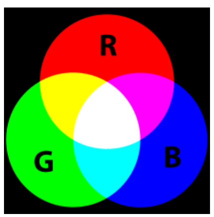
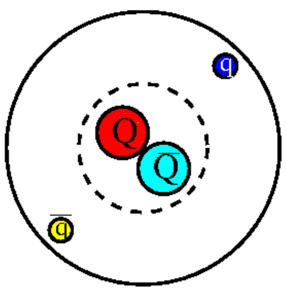
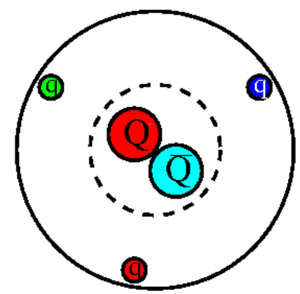


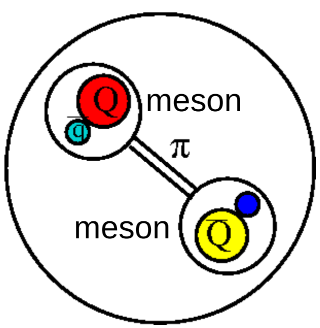

diquark model


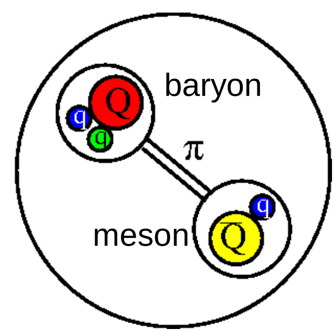
triquark model






hydro-charmonium model




molecular model


Prejudices against pentaquark

- No convincing states 50 years after Gell-mann paper proposing $qqqq\bar{q}$ states
- Previous "observations" of several pentaquark states have been refuted
- These included
  - $\Theta^+ \rightarrow K^0 p$, $K^+ n$, mass=1.54 GeV, Γ~10 MeV
  - Resonance in $D^{*-}p$ at 3.10 GeV, Γ=12 MeV
  - $\Xi^{--} \rightarrow \Xi^- \pi^-$, mass=1.862 GeV, Γ<18 MeV
- Generally they were found/debunked by looking for "bumps" in mass spectra circa 2004

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