Pentaquarks & Tetraquarks at LHCb

Sheldon Stone on behalf of LHCb

EPS Vienna, July 2015

Why pentaquarks?

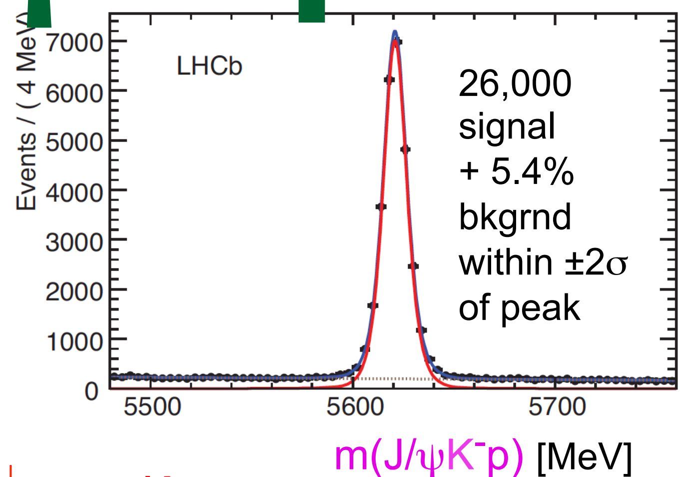
- Interest in pentaquarks arises from the fact that they would be new states of matter beyond the simple quark picture. Could teach us a lot about QCD.
- There is no reason they should not exist
  - Predicted by Gell-Mann (64), Zweig (64), others later in context of specific QCD models: Jaffe (76), Strottman (79)
- 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

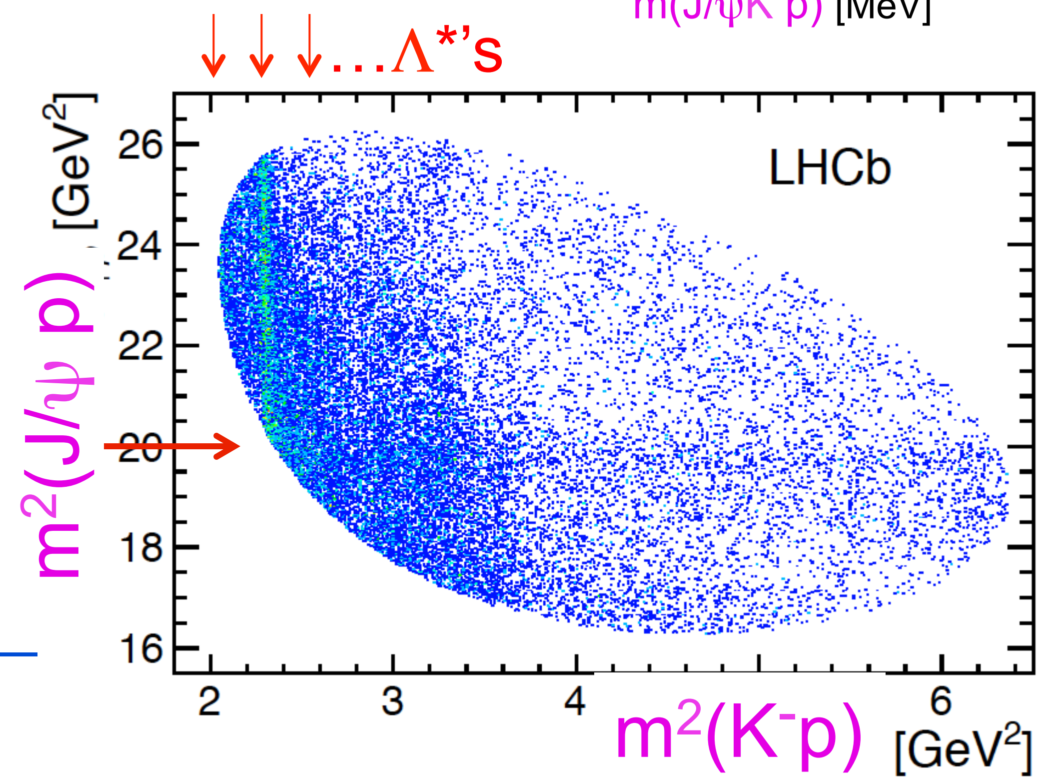
Prejudices

- No convincing states 50 years after Gell-mann paper proposing qqq and 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

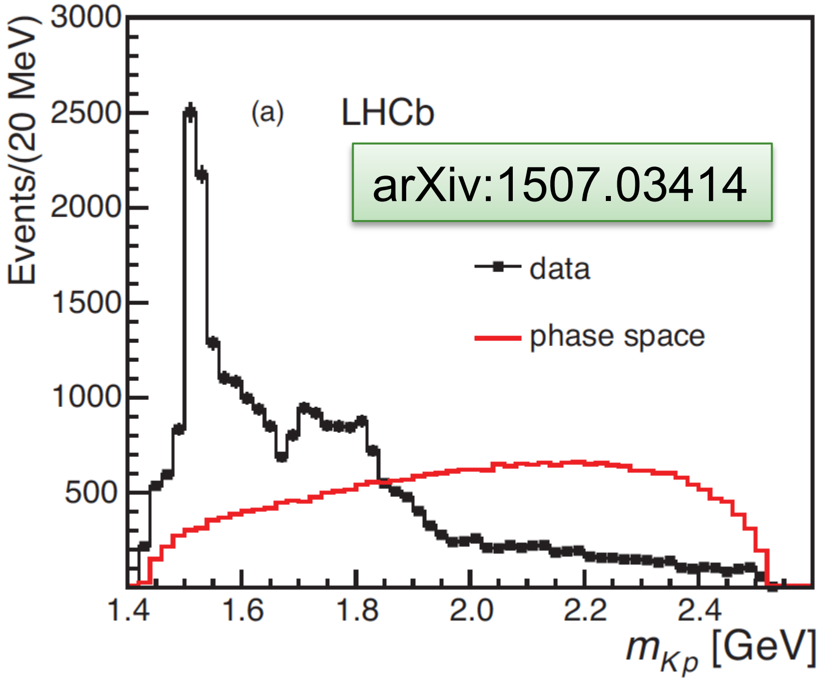
$\Lambda_b \to J/\psi K^- p$

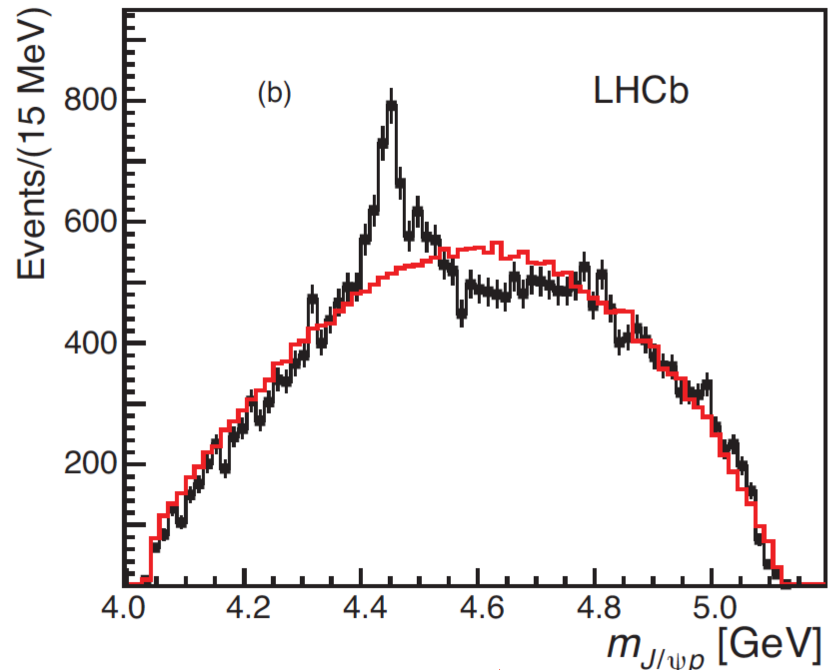
- First looked for in LHCb as a potential background for $B^0 \to J/\psi K^+ K^-$
- Large signal found, used for Λ_b lifetime
- Dalitz plot showed an unusual __________ feature

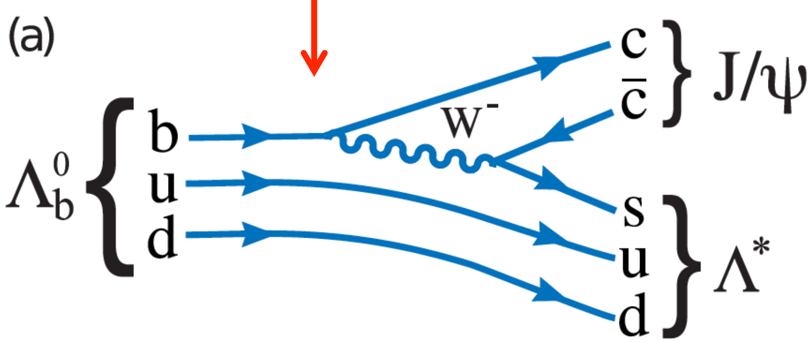


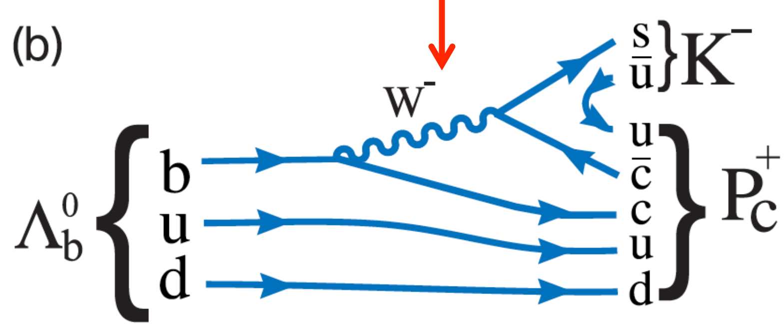


Projections









Does this diagram exist?

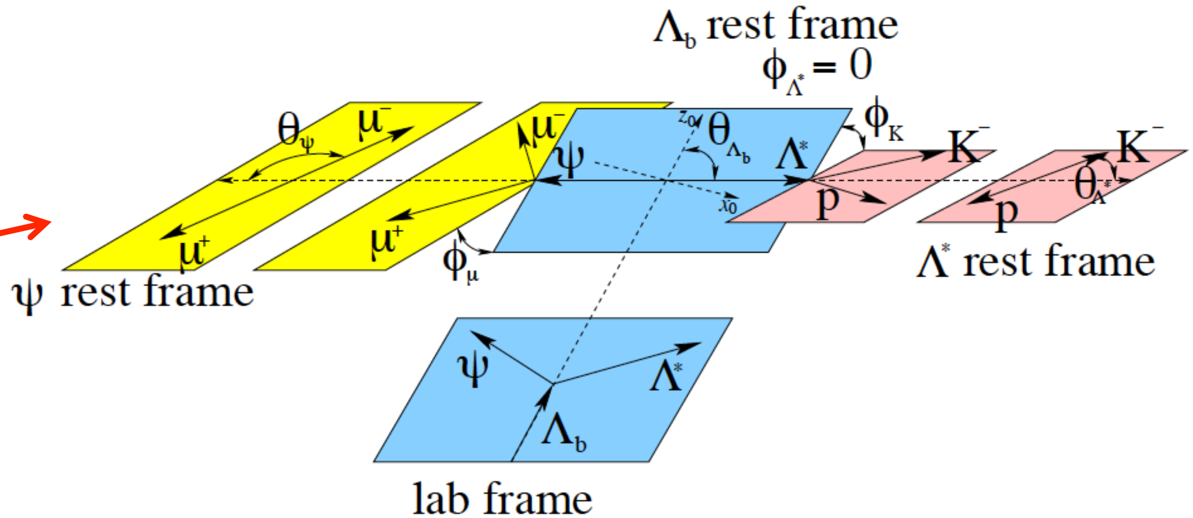
Decay amplitude analysis

- Are there "artifacts" that can produce a peak?
  - Many checks done that shows this is not the case: e.g. changing p to K, or π to K allows us to veto misidentified $B_s \to J/\psi K^- K^+$ & $B^0 \to J/\psi K^- \pi^+$
  - Clones & ghost tracks eliminated
  - Ξ_b decays checked as a source
- Can interferences between Λ^* resonances generate a peak in the $J/\psi p$ mass spectra?
  - Implemented a decay amplitude analysis that incorporates both decay sequences:

Matrix Element

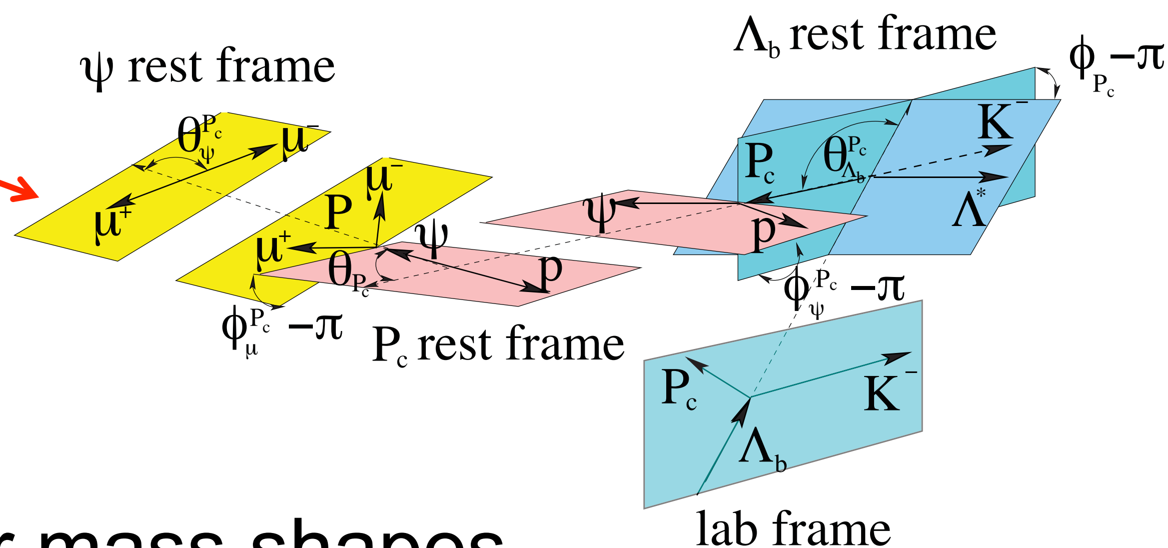
- Two interfering channels:

$\Lambda_b \rightarrow J/\psi \Lambda^*$,
$\Lambda^* \rightarrow K^- p$



&

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



- Use m(K⁻p) & 5 decay ∠'s as fit parameters
- Breit-Wigner's for mass shapes

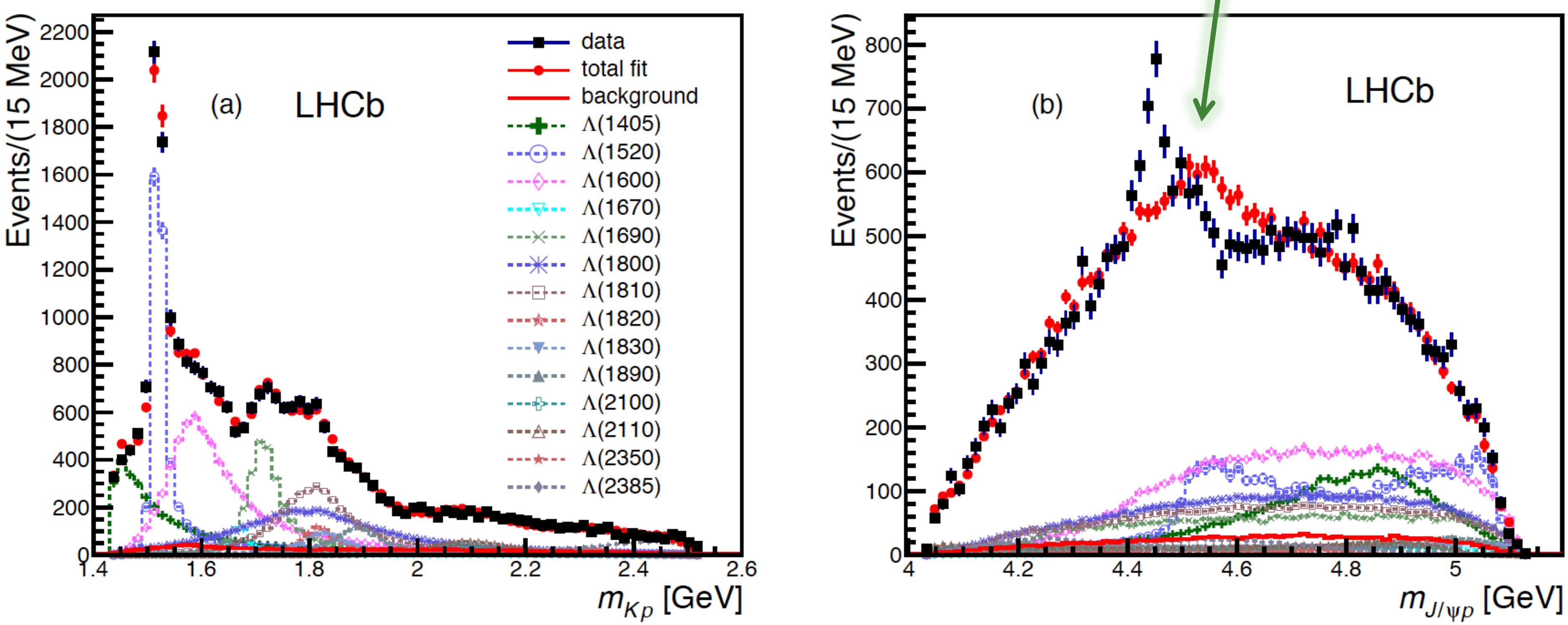
Models: extended & reduced

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

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
$\Lambda(2585)$	?	$\approx$2585	200	0	6
			# parameters	64	146

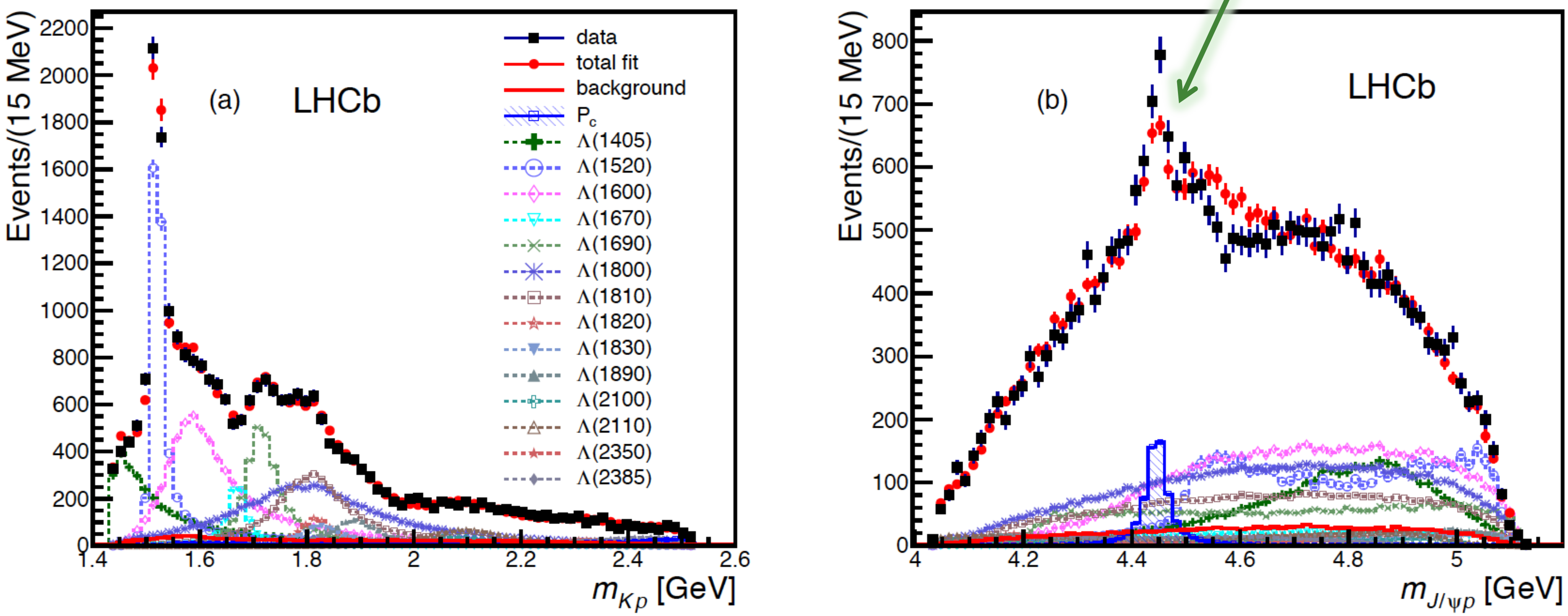
Results without P_c states

- 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^*'s doesn't help



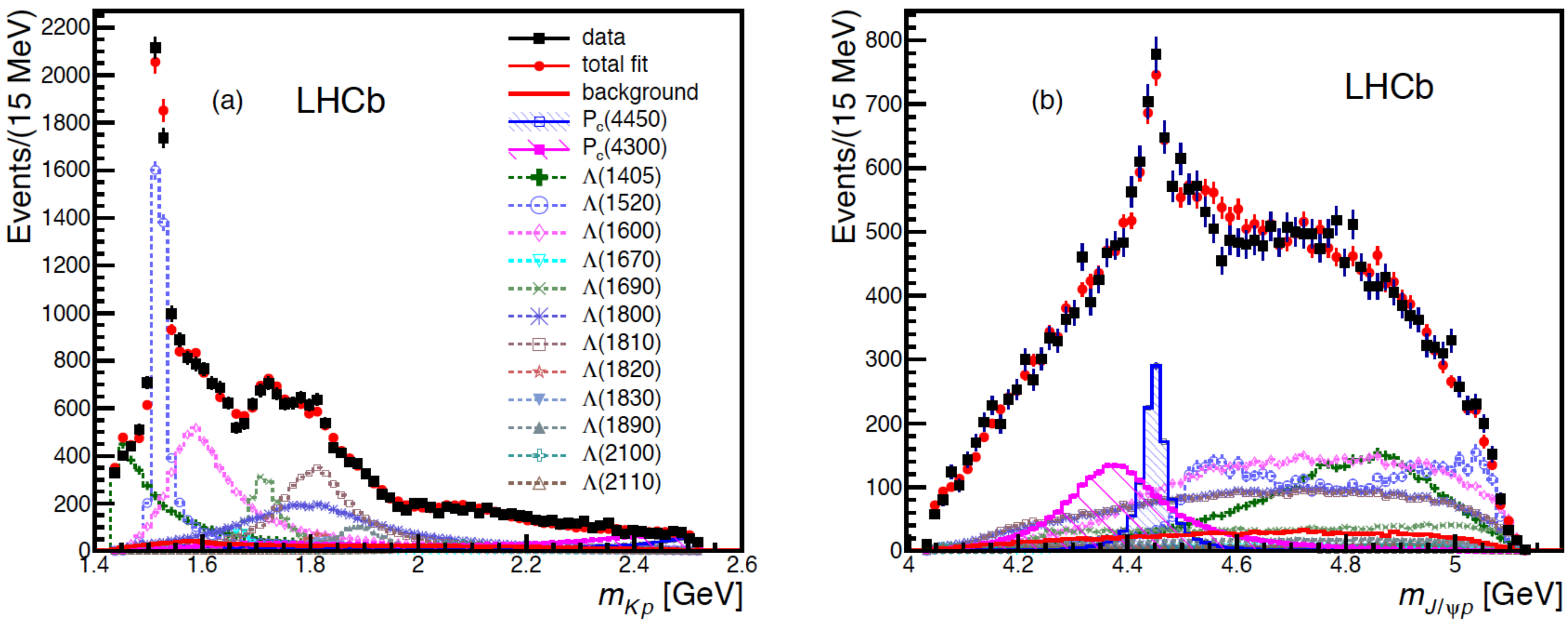
Extended model with 1 P_c

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



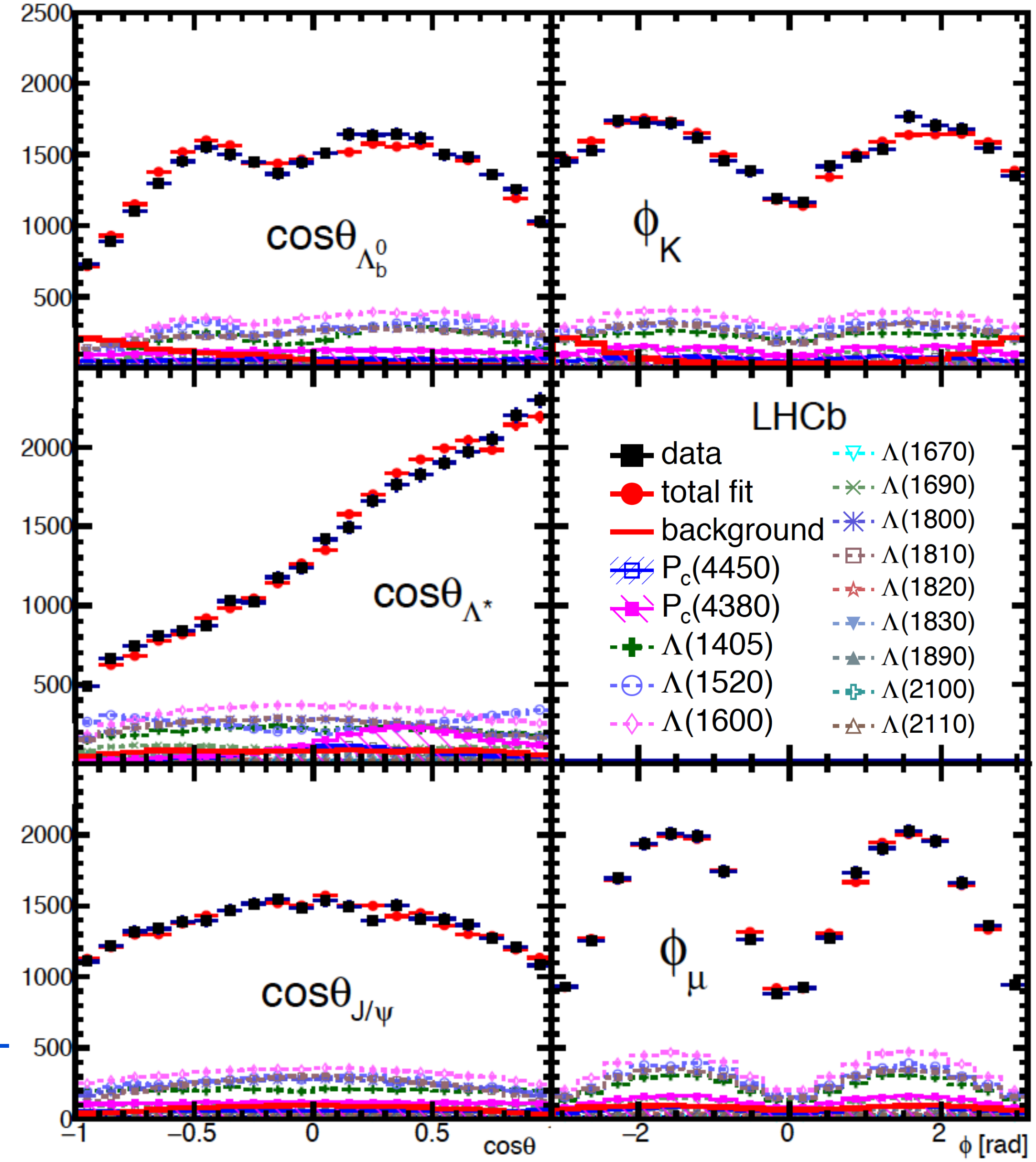
Reduced model with 2 P_c's

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



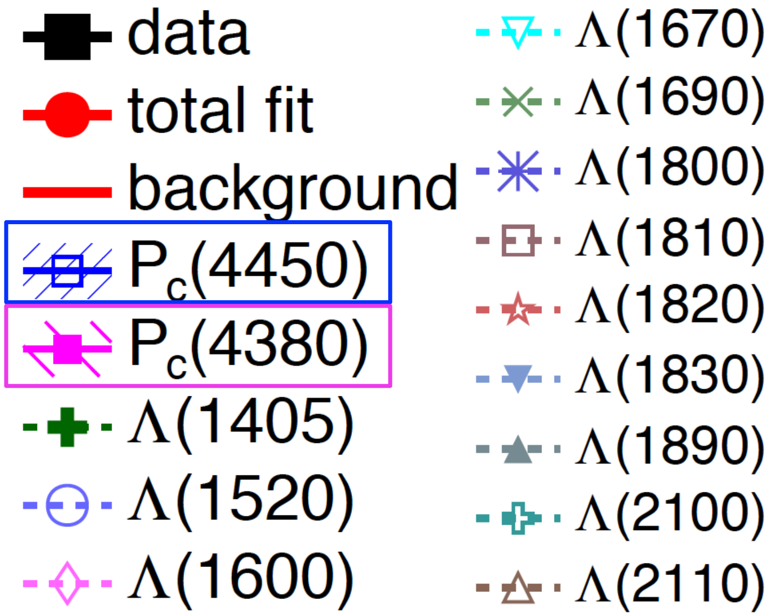
Angular distributions

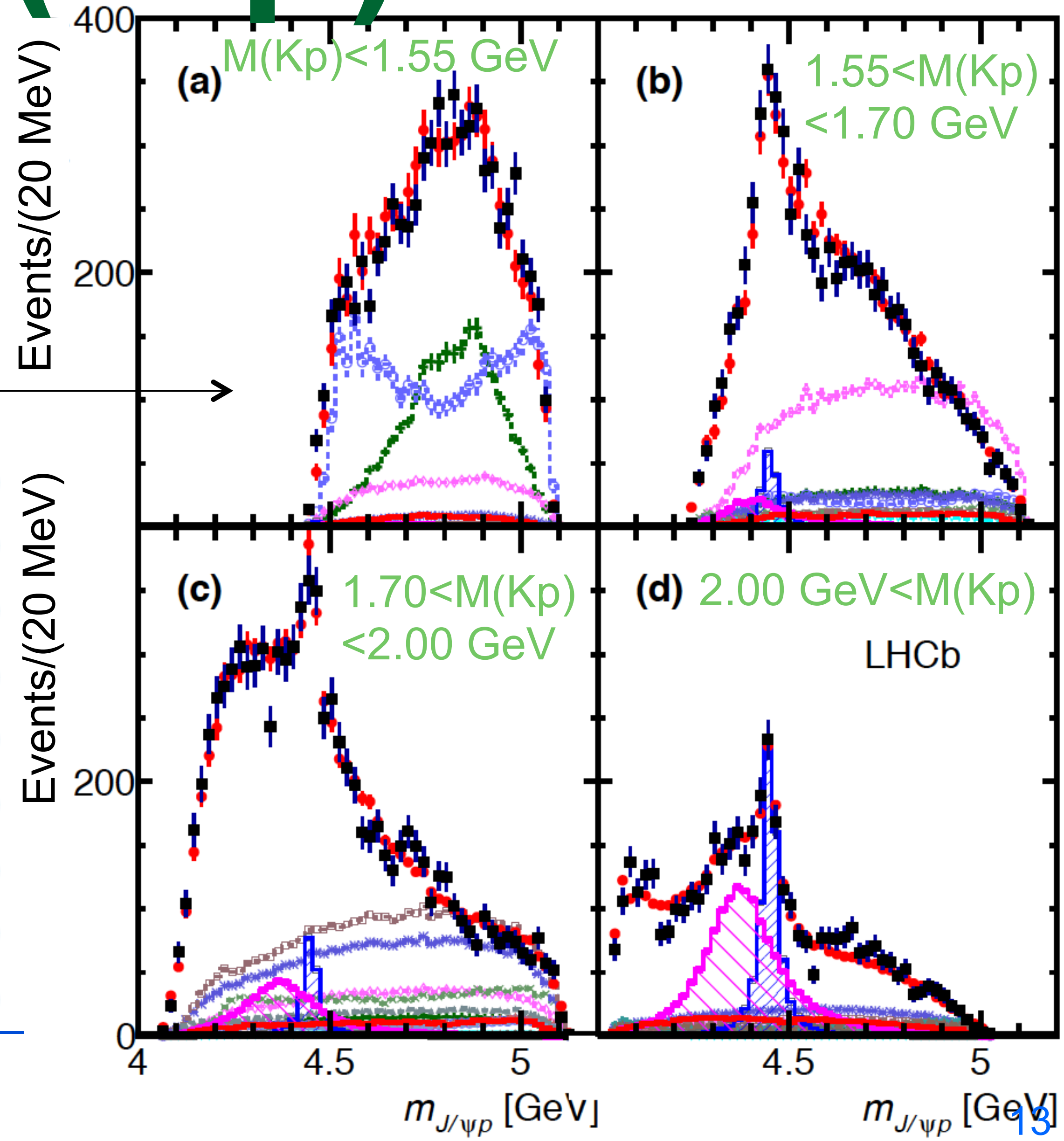
Good fits in the angular variables



In m(K⁻p) slices

Pc's cannot appear in first interval as they would be outside of the Dalitz plot boundary





Significances

- 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 $\Delta(-2\ln\mathcal{L})=18.7^2$
- Using toy simulations 1st state has significance of 9σ & 2nd state 12σ, including systematic uncertainties, coming from difference between extended & reduced model results.

Fit results

Mass (MeV)	Width (MeV)	Fit fraction (%)
4380±8±29	205±18±86	8.4±0.7±4.2
4449.8±1.7±2.5	39±5±19	4.1±0.5±1.1
Λ(1405)		15±1±6
Λ(1520)		19±1±4

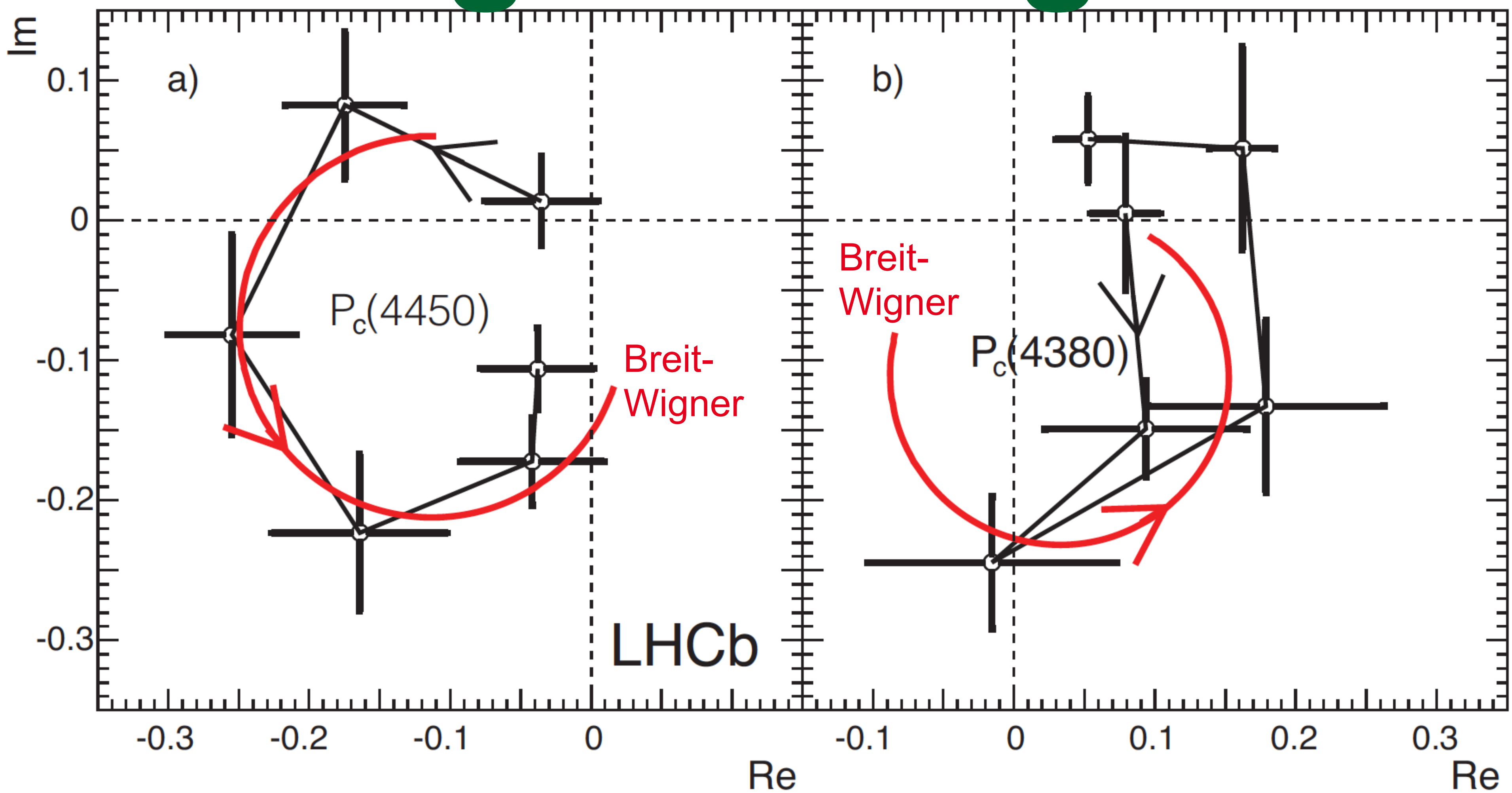
Systematic uncertainties

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
$L_{\Lambda_b^0}^{P_c}$ $\Lambda_b^0 \to P_c^+$ (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

Cross-checks

- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data shows consistency: 2011/2012, magnet up/down, $\overline{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
- Extended model fits tried without P_c states, but two additional high mass Λ^* resonances allowing masses & widths to vary, or 4 non-resonant terms of J up to 3/2

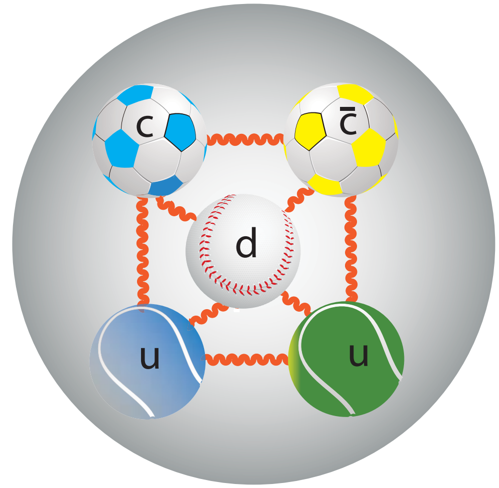
Argand diagrams

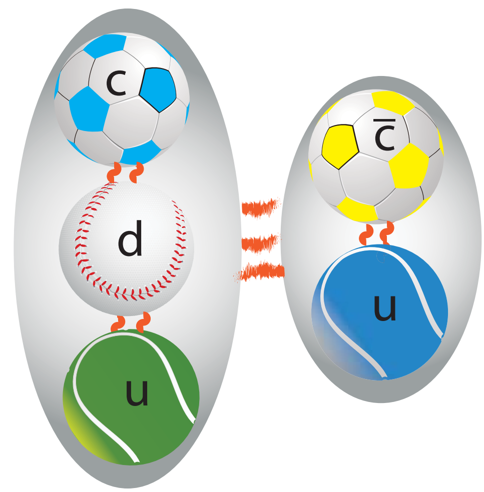


- Amplitudes for 6 bins between $+\Gamma$ & $-\Gamma$

Pentaquark models

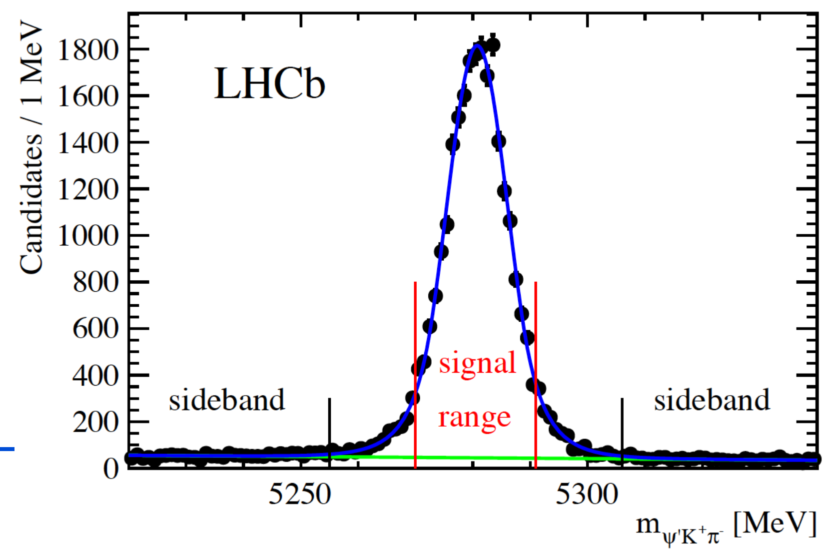
- Many models
  - Tightly bound ala' Jaffe [PRD15 (1977) 267], Strottman [PRD20(1979) 748], L.Maiani, et. al, [PRD71, (2005) 014028]
  - Molecular models, some with meson exchange for binding ala' Törnqvist [Z. Phys. C61 (1994) 525]
  - Postdictions: Rescattering or "Cusp" models, eg. $\Lambda_b \to XY \to J/\psi p K^-$, especially when $m(XY)=m(P_c)$





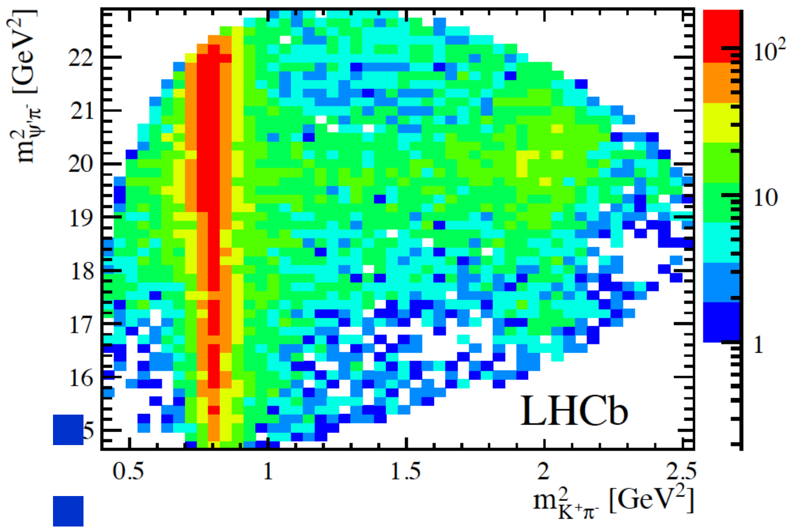
$Z(4430)^+$

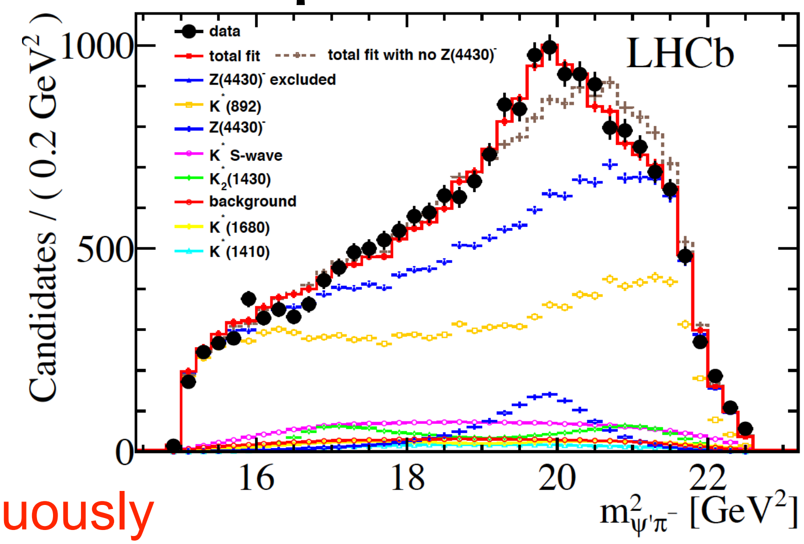
- $B^0 \to \psi' \pi^- K^+$, peak in $m(\psi' \pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle M=4433±5 MeV, Γ=45 MeV
  - Challenged by BaBar: explanation in terms of K*'s
  - Belle reanalysis using full amplitude fit: M= $4485 \pm 22^{+28}_{-11}$ MeV, Γ=200 MeV, 1^+ preferred but 0^- & 1^- not excluded [arXiv:1306.4894], LHCb-PAPER-2015-038 in preparation
- LHCb analysis also uses full amplitude fit
  - M= $4475 \pm 7^{+15}_{-25}$ MeV
  - Γ=172 MeV [arXiv:1404.1903]



LHCb Amplitude analysis

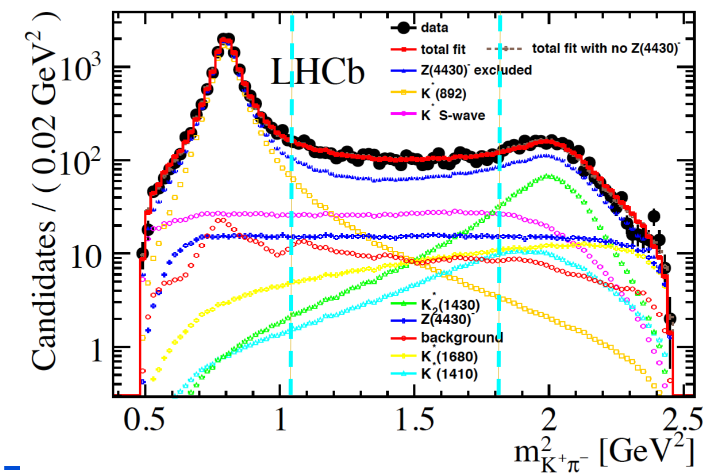
- Full 4D fit to both $K^* \to K^- \pi^+$ & $Z \to \psi' \pi^-$ states

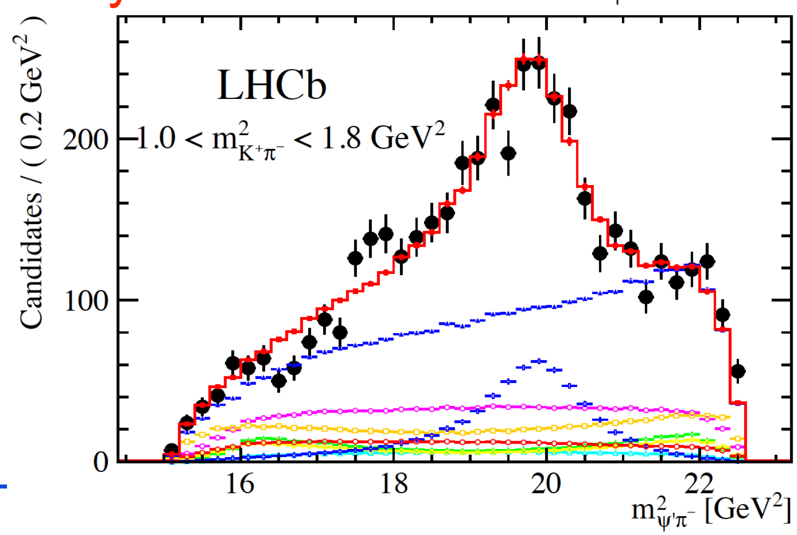




$J^P=1^+$

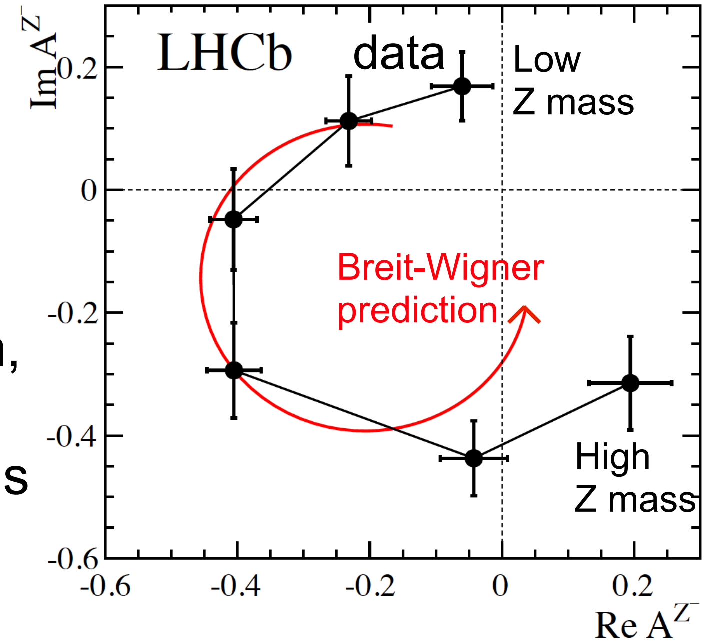
Unambiguously





Is it a resonance?

- LHCb produced an Argand plot that
- shows a clear & large phase change
- Problem with quoted mass



In the default fit we follow the approach of Belle who use a running mass M_R in the $(p_R / M_R)^{L_R}$ term, where M_R is the invariant mass of the two daughters of the resonance R; p_R is the daughter's momentum in the R rest frame & L_R is the orbital angular momentum of the decay. The more conventional formulation [PDG] is to use $(p_R)^{L_R}$ (equivalent to a fixed M_R mass). This changes the Z parameters via the K* terms in the amplitude model: M_Z varies by -22 MeV & Γ_Z by +29 MeV

← From LHCb paper

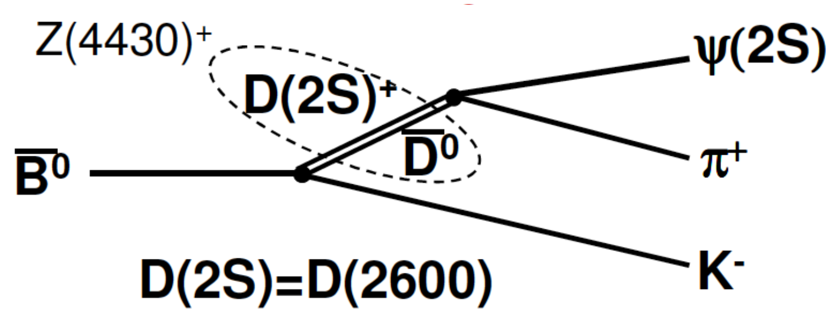
Believe now that old formula is wrong: m_Z=4456 MeV, Belle – LHCb average

Other Explanations

- Molecule:

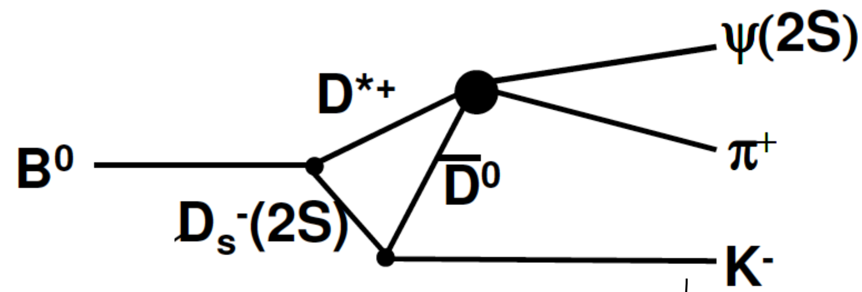
L. Ma et.al, [arXiv:1404.3450]

T. Barnes et.al, [arXiv:1409.6651

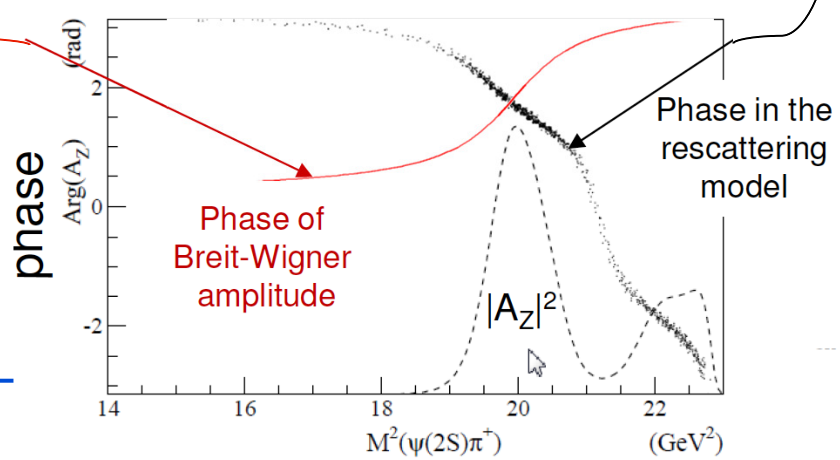


- Same scattering phase as Breit-Wigner
- Rescattering:

P. Pakhov & T. Uglov [arXiv:1408:5295]



- Opposite phase
- Ruled out by LHCb Argand diagram



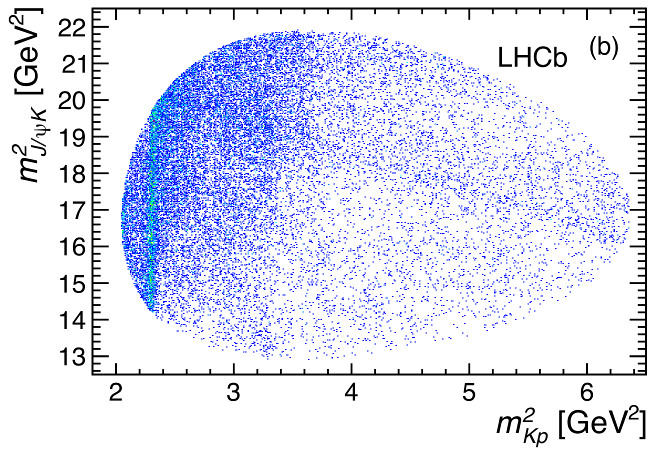
Conclusions

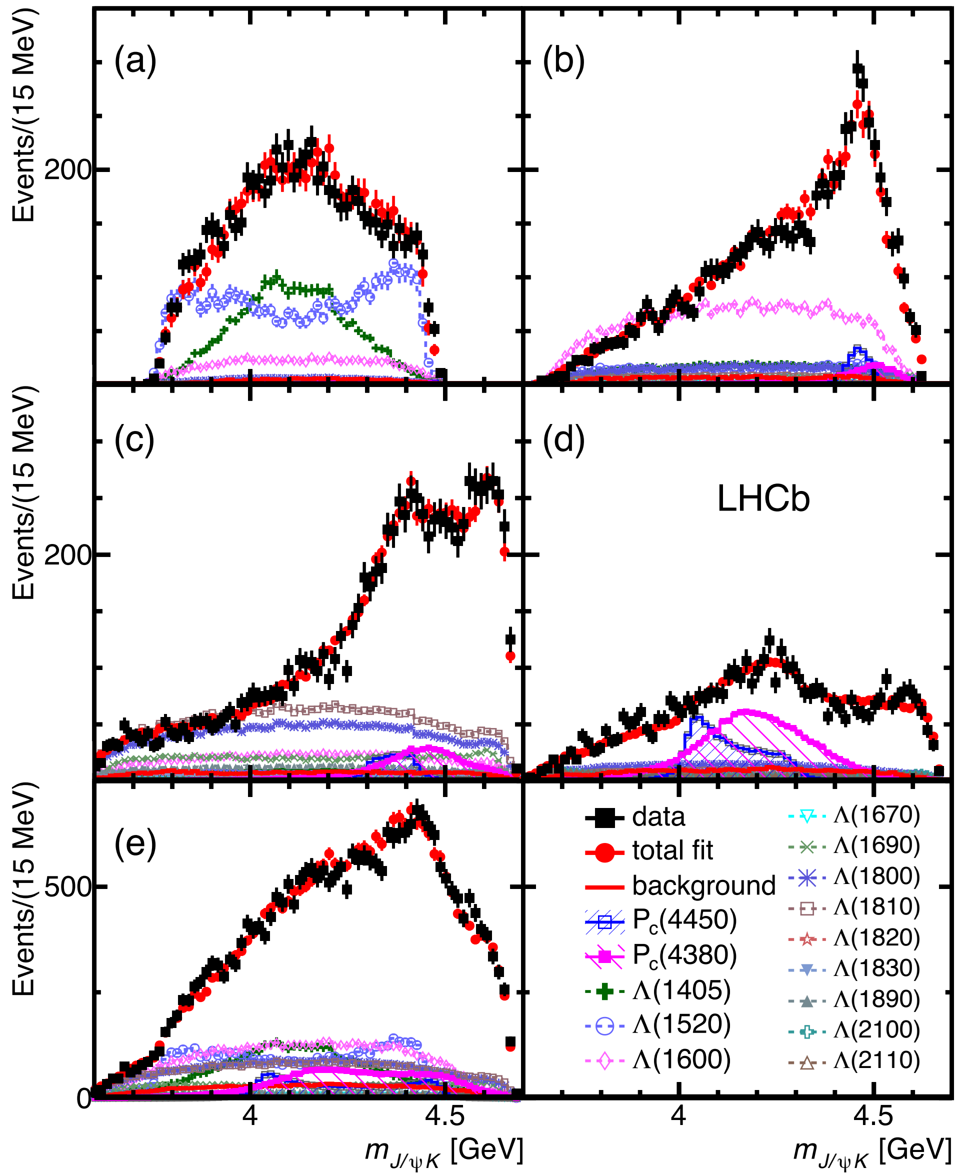
- LHCb has found two resonances decaying into $J/\psi p$ with pentaquark content of $uudc\bar{c}$ arXiv:1507.03414.
- Determination of their internal binding mechanism will require more study. The preferred J^P are $(3/2^-, 5/2^+)$, $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$
- The $Z^+(4430)$ appears to be a viable exotic tetraquark with $J^P=1^+$
- Both the P_c^+ & Z^+ states contain J/ψ. Stronger binding due to this?
- We look forward to establishing the structure of many other states

The End

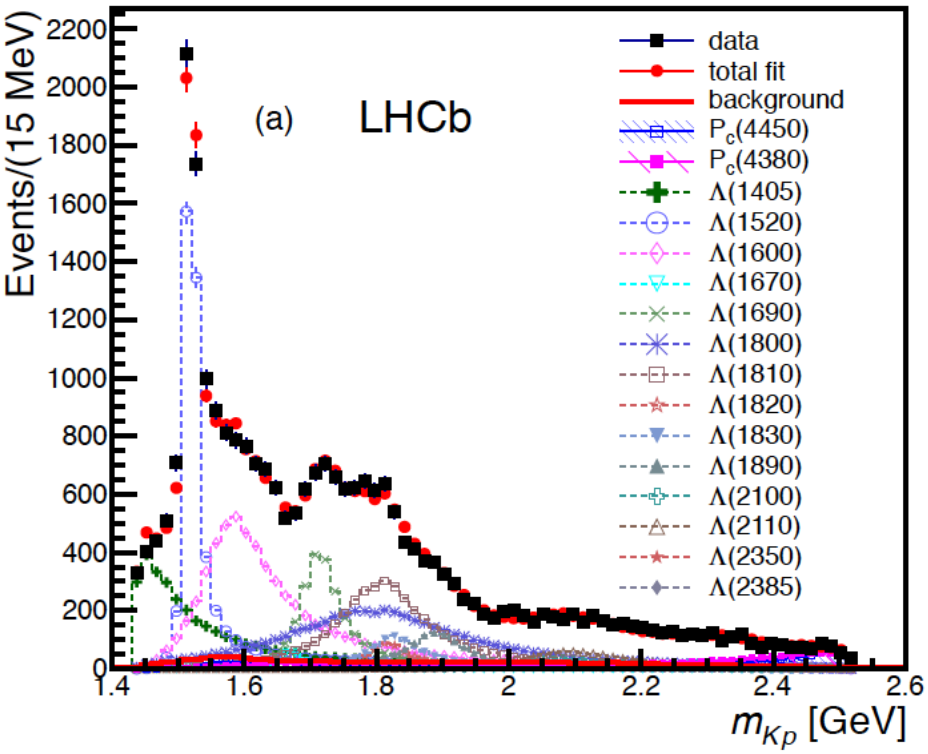
m(J/ψ K⁻)

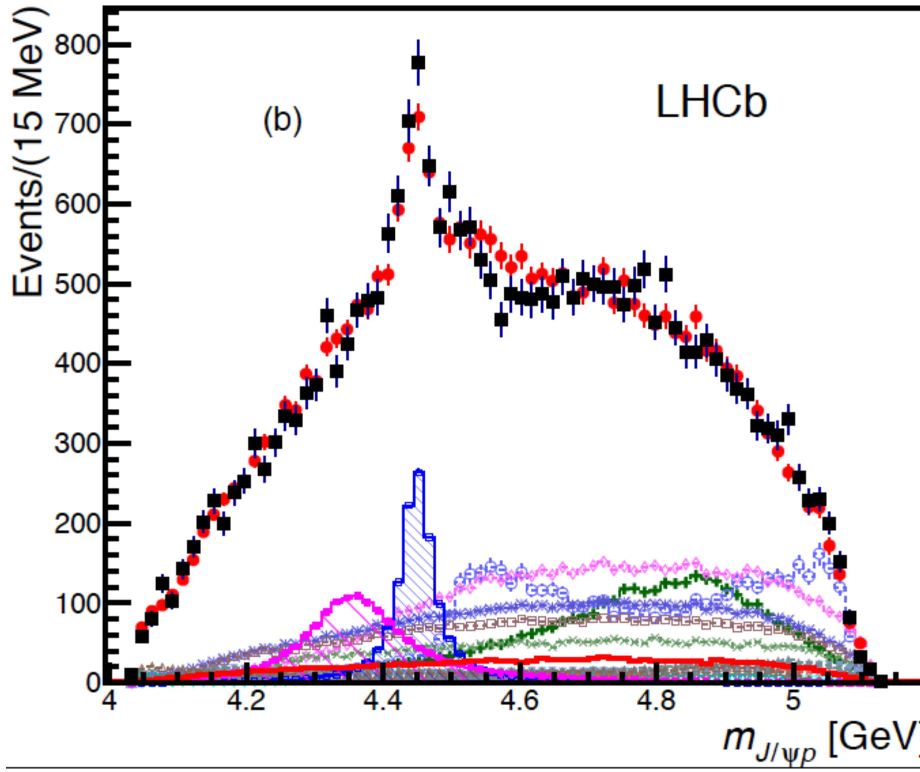
- Our fit explains m(J/ψ K⁻)





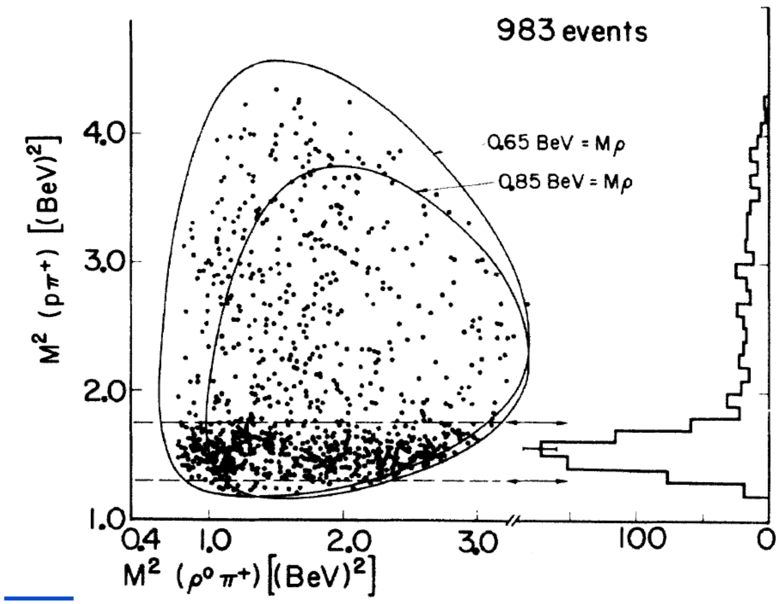
Extended model with 2 P_c's

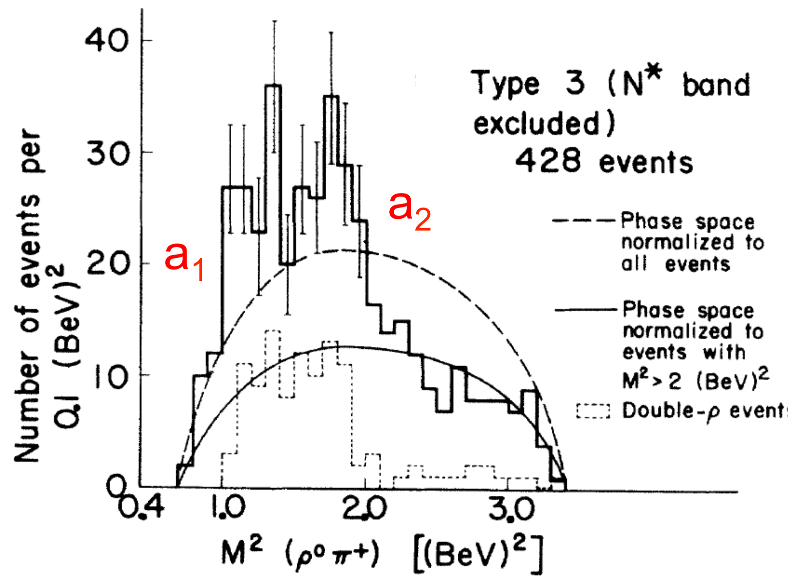




Some History: The a_1

- It is also possible for other processes to mimic resonant effects
- Example: The Deck effect, a lesson in confusion: $\pi^+ p \rightarrow \pi^+ \rho^0 p$, $\rho^0 \rightarrow \pi^+ \pi^-$, using a 3.65 GeV π^+ beam, *G. Goldhaber et. al, PRL 12, 336 (1964)*





Note BeV≡GeV

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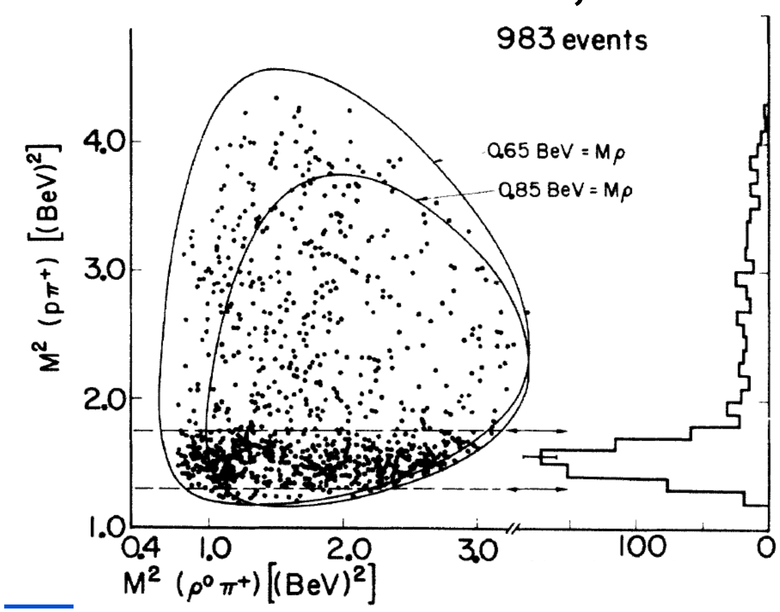
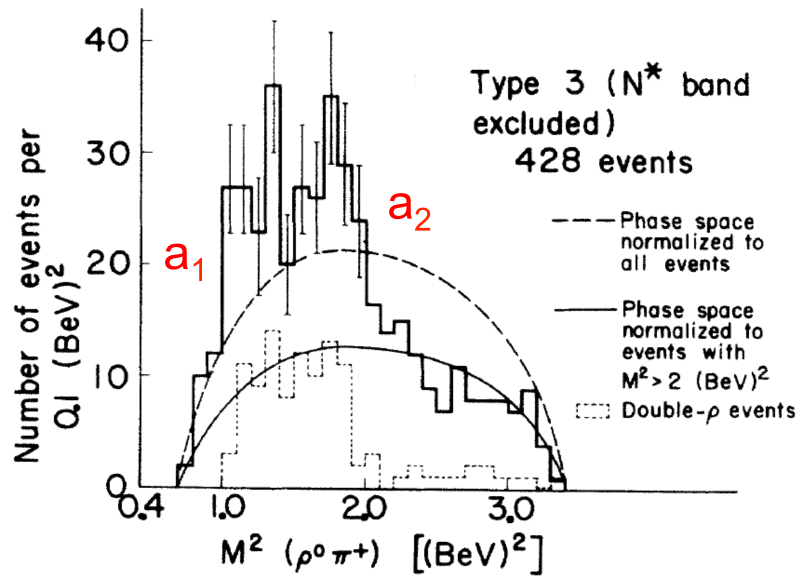
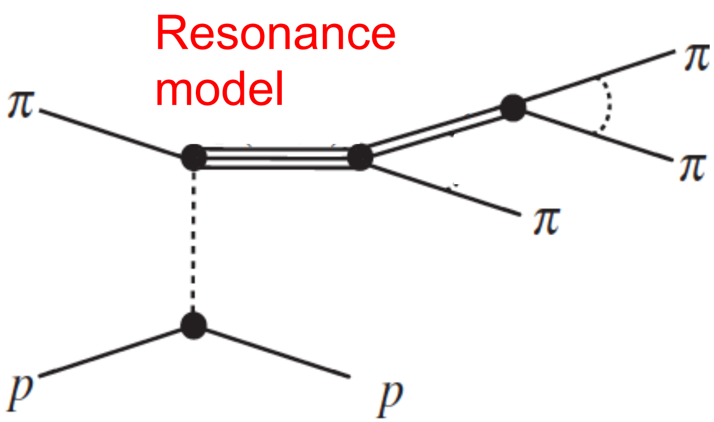


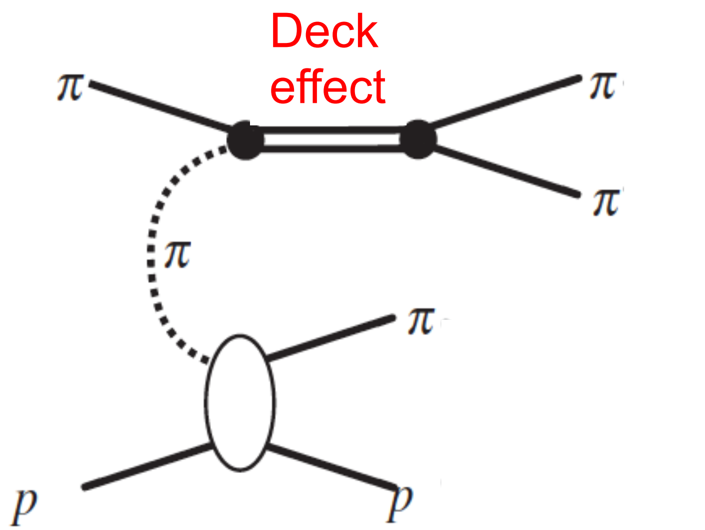


Note BeV≡GeV

"Kinematical" effect

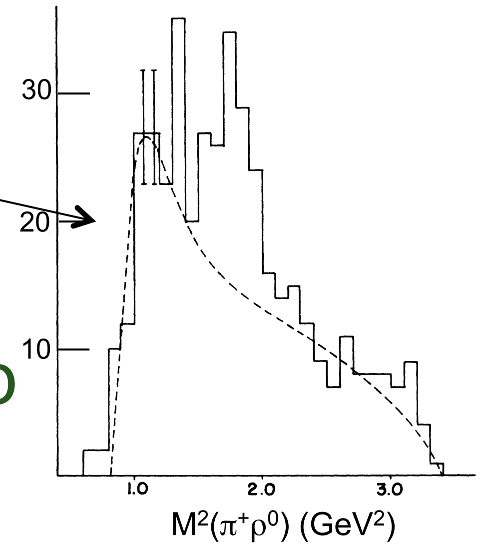
- Clear enhancement near threshold. Is it a new resonance as suggested in original paper?
- Theorists, first Deck, suggest that the threshold enhancement can be due to off shell πp scattering *R.T. Deck, PRL 13, 169 (1964)*





Deck Effect

- Deck's fit to data can provide adequate explanation
- a_1 seen in different charge states & different channels, e.g. $K^+p \rightarrow K^+\pi^+\pi^-\pi^0\, p$



- Many more sophisticated theory papers
- Controversy continued until observation of a_1 in $\tau^- \rightarrow \pi^+\pi^-\pi^-\nu$ decays
- Lesson: a real state should be seen in several ways. Even though the a_1 is a real state, the Deck effect maybe there to some extent.