Pentaquarks and Tetraquarks at LHCb

Sheldon Stone on behalf of LHCb

DPF Ann Arbor, August 2015

Why pentaquarks?

- Interest in pentaquarks arises from the fact that they would be new states of matter beyond the simple quark-model picture. Could teach us a lot about QCD.
- There is no reason they should not exist
  - Predicted by Gell-Mann (64), Zweig (64), others later in context of specific QCD models: Jaffe (76), Högaasen & Sorba (78), Strottman (79)
- 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

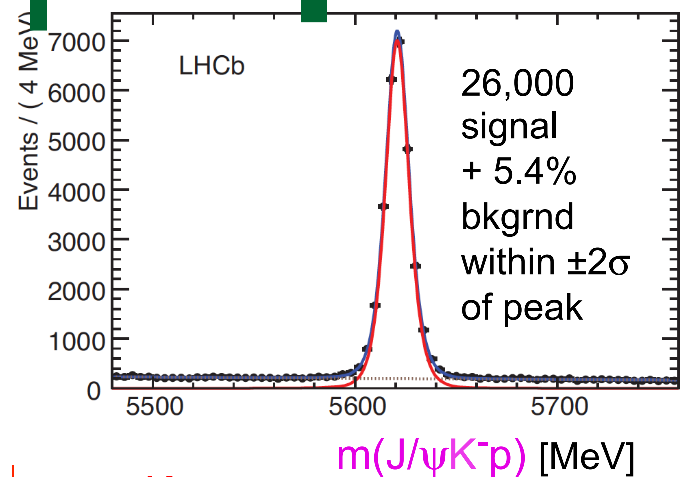
Prejudices

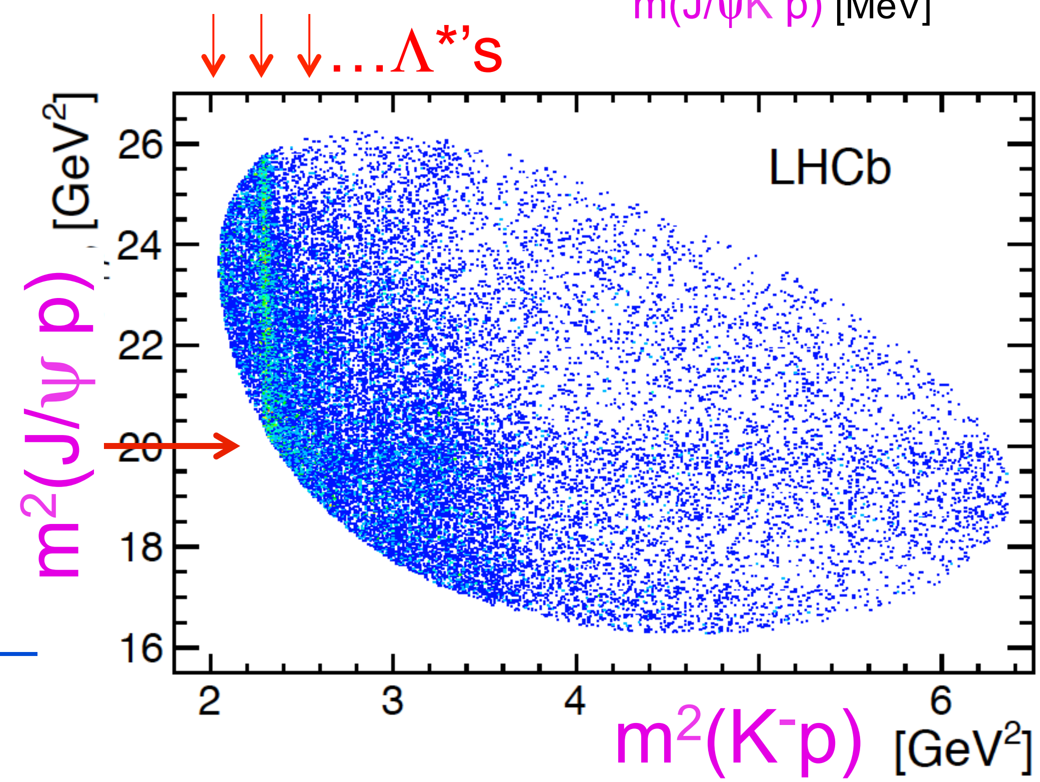
- No convincing states 51 years after Gell-mann & Zweig proposed qqq and qqqq$\bar{q}$ baryonic states
- Previous "observations" of several pentaquark states have been refuted
- These included
  - $\Theta^+ \rightarrow K^0 p$, $K^+ n$, mass=1.54 GeV, Γ~10 MeV
  - Resonance in $D^{*-}p$ at 3.10 GeV, Γ=12 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 Hicks Eur. Phys. J. H37 (2012) 1.]

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

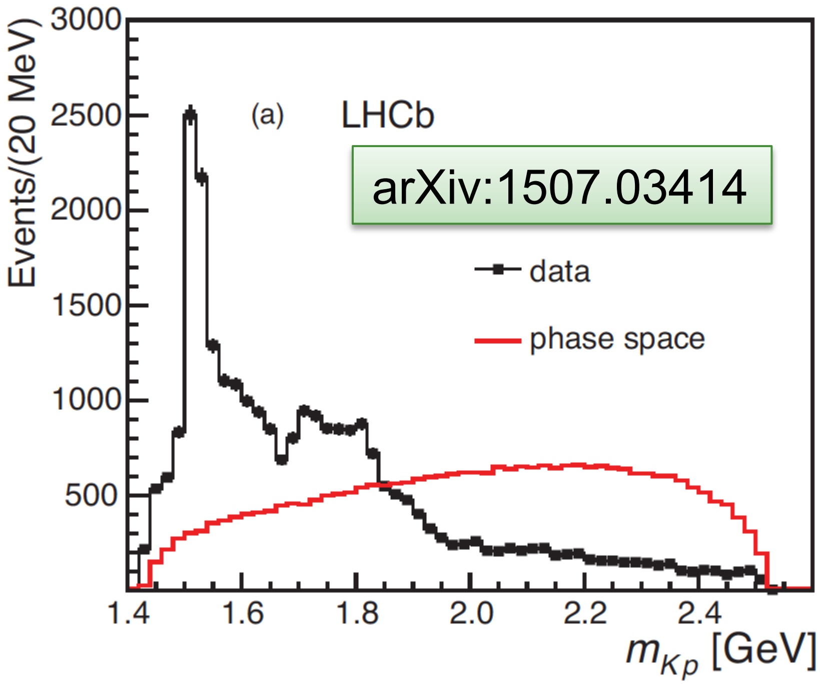
- First looked for in LHCb as a potential background for $B^0 \to J/\psi K^+ K^-$
- Large signal found, used for Λ_b lifetime
- Dalitz plot showed an unusual feature

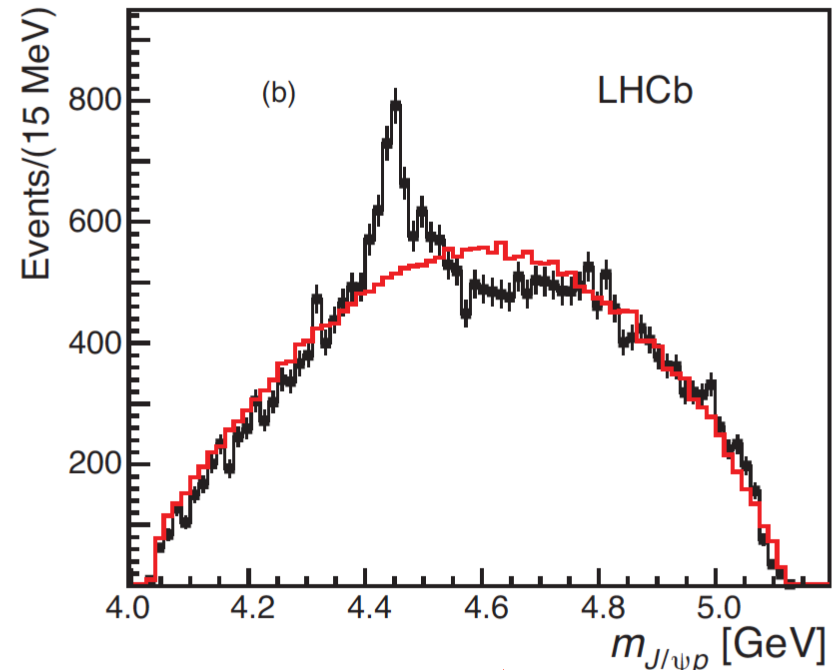
[arXiv:1507.03414]

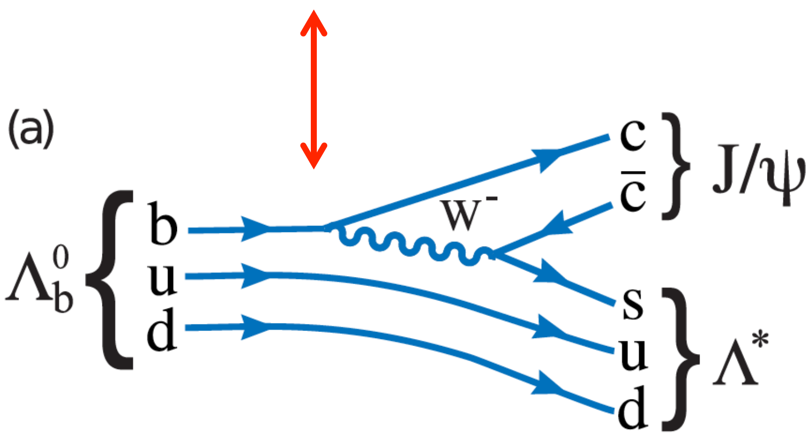


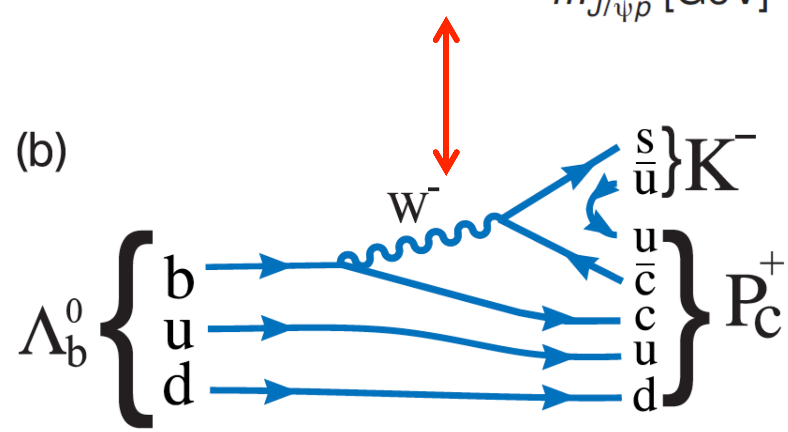


Projections









Does this diagram exist?

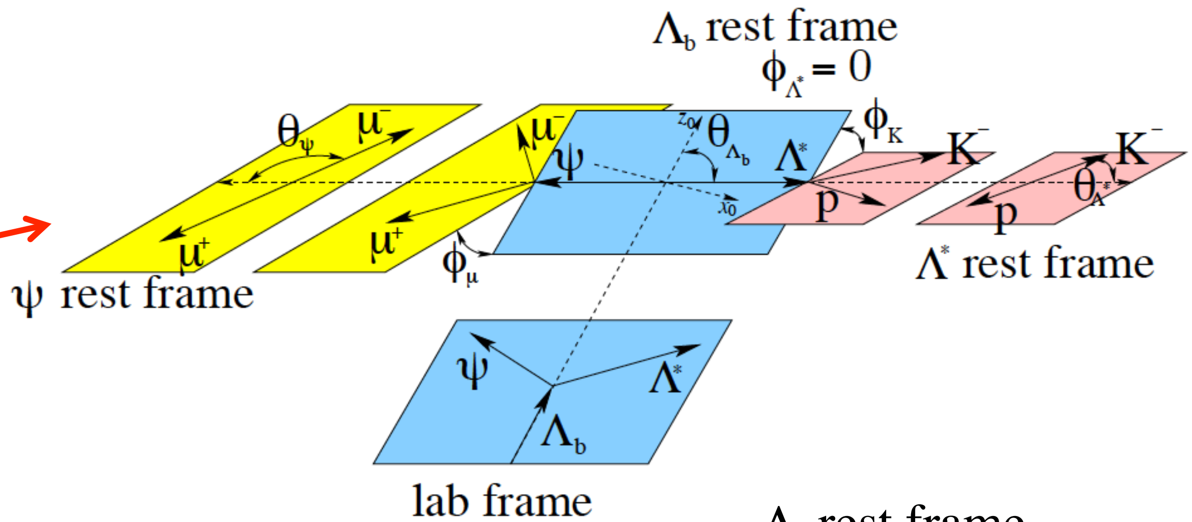
Decay amplitude analysis

- 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

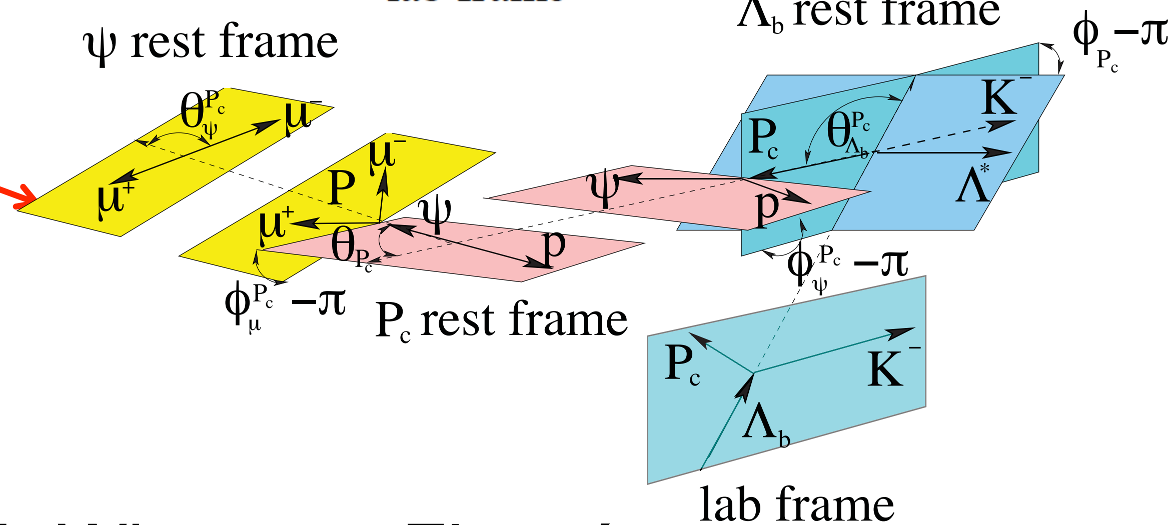
- Two interfering channels:

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



&

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



- Use $m(K^- p)$ & 5 decay ∠'s as fit parameters
- Mass shapes: Breit-Wigner or Flatte´

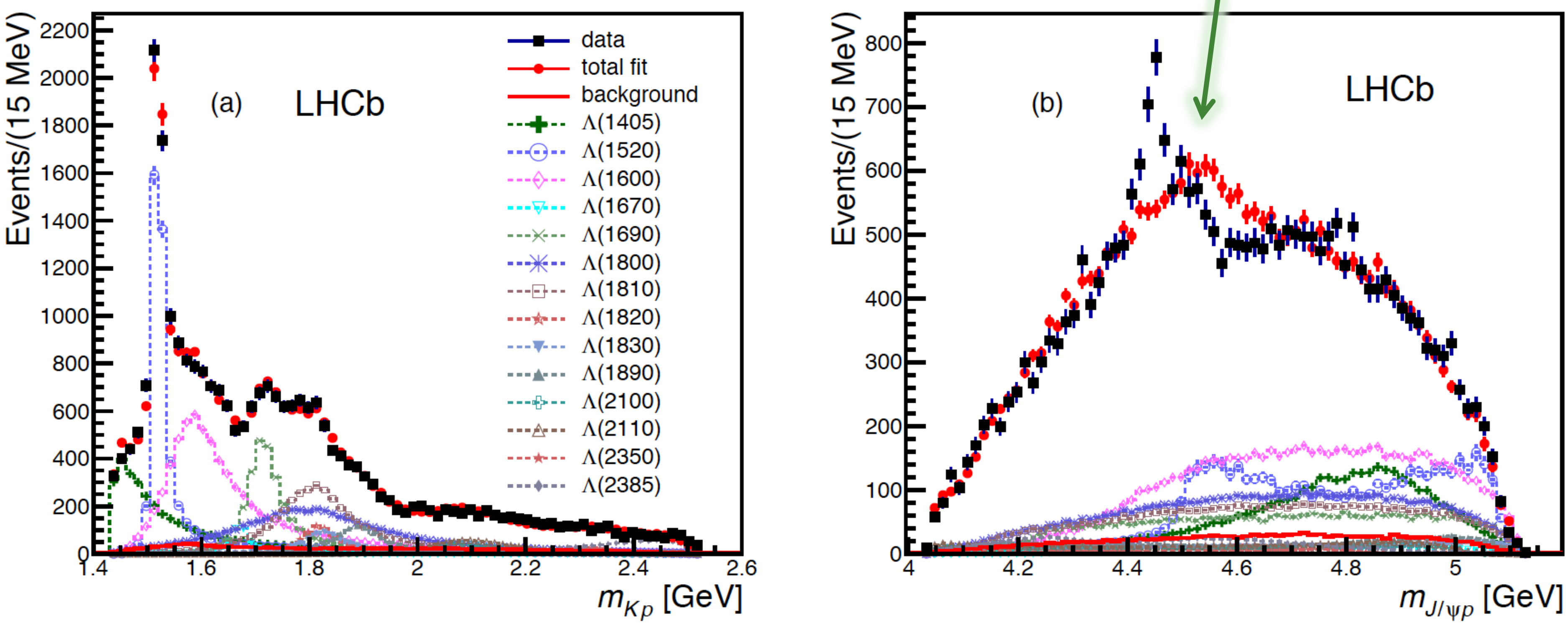
Models: extended & reduced

- Consider all Λ* states & all allowed L values

	State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
Flatte´	$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
BW	$\Lambda(1520)$	$3/2^-$	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

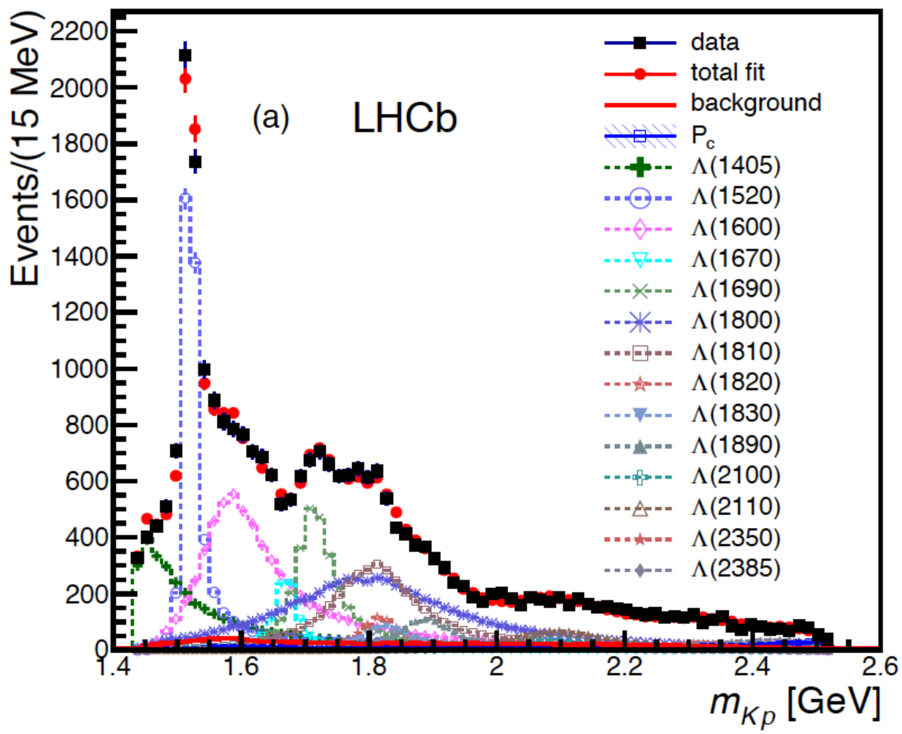
Results without P_c states

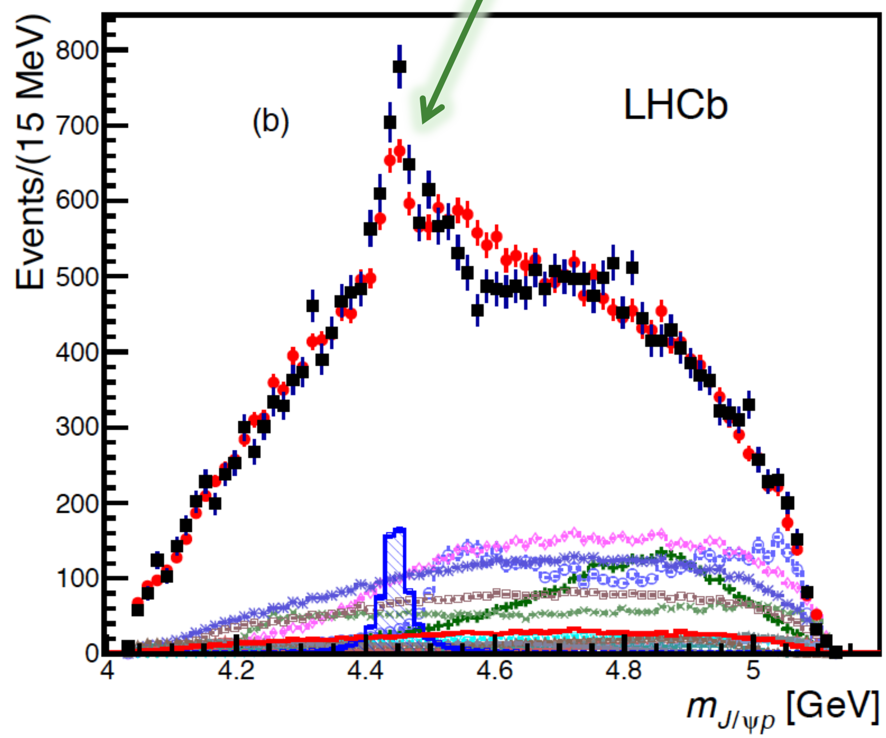
- Use extended model, so all possible known Λ^* amplitudes. m_{Kp} looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant, extra Λ^*'s doesn't help



Extended model with 1 P_c

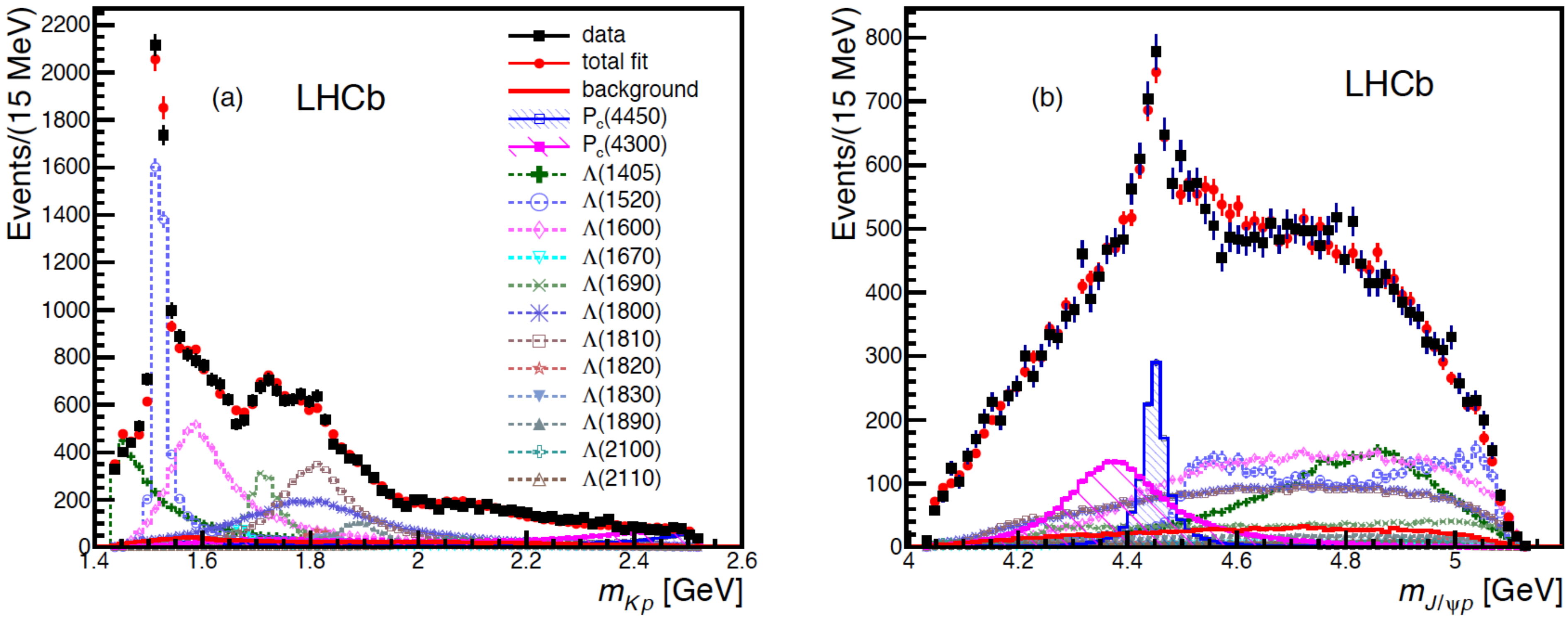
- Try all J^P up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit





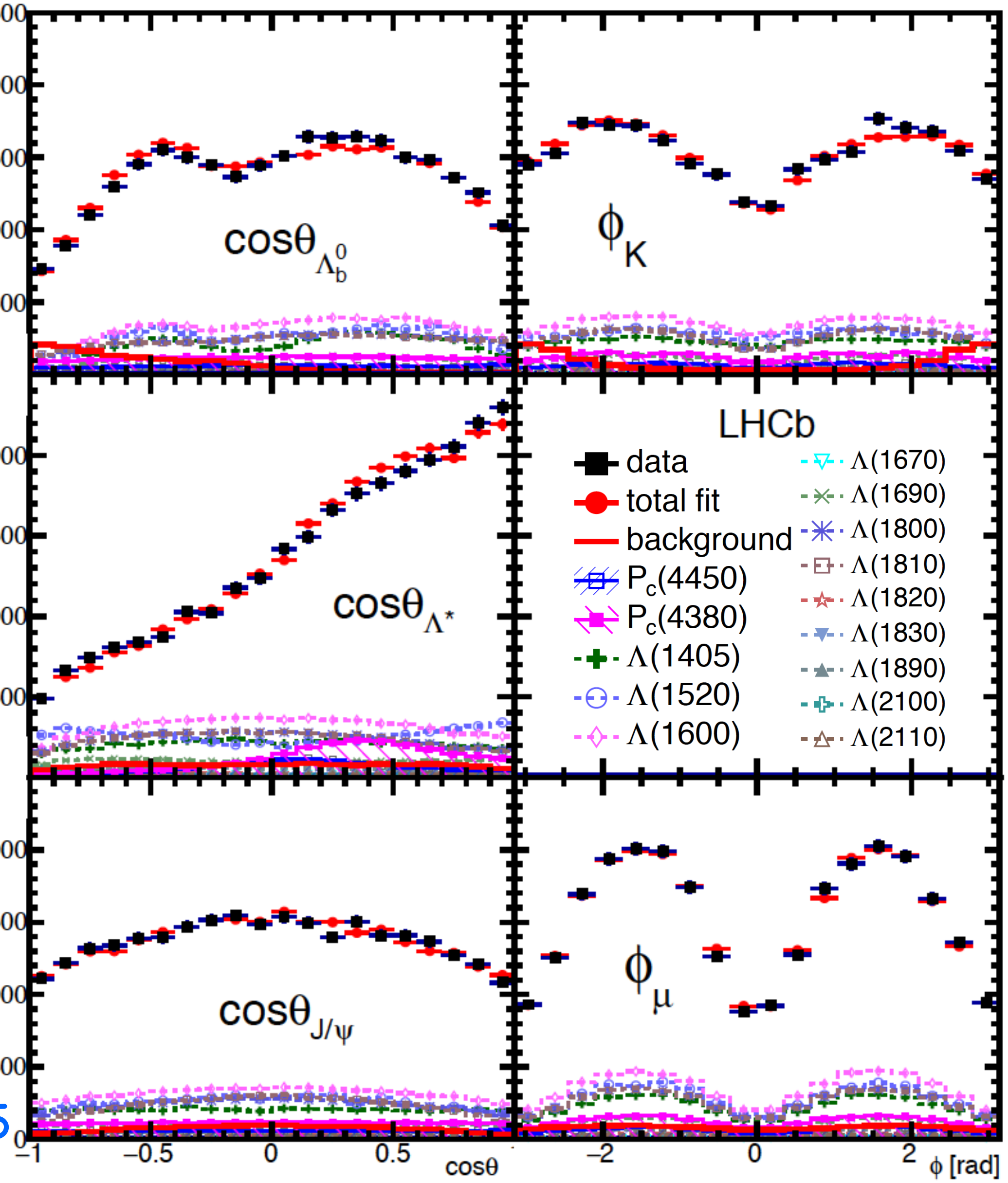
Reduced model with 2 P_c's

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



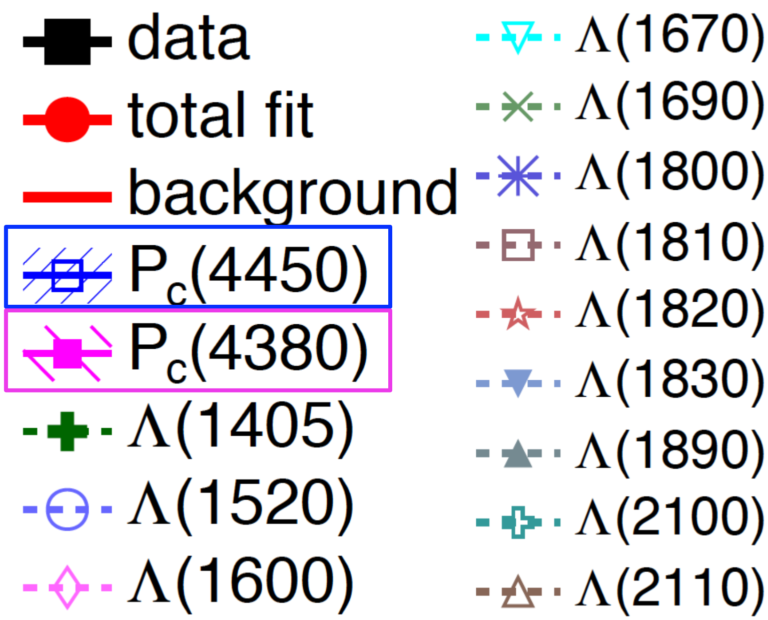
Angular distributions

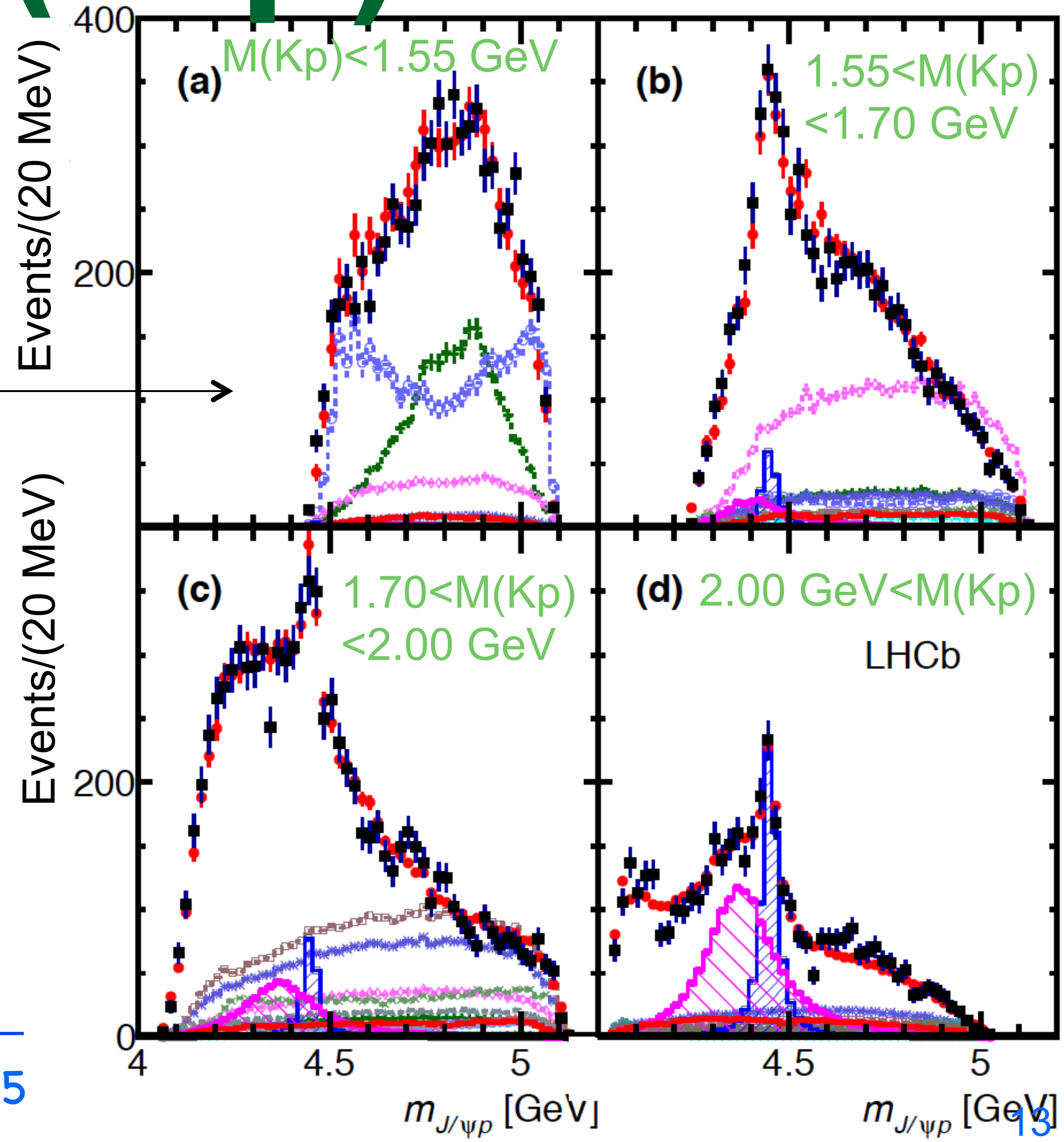
Good fits in the angular variables



In m(K⁻p) slices

P_c'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

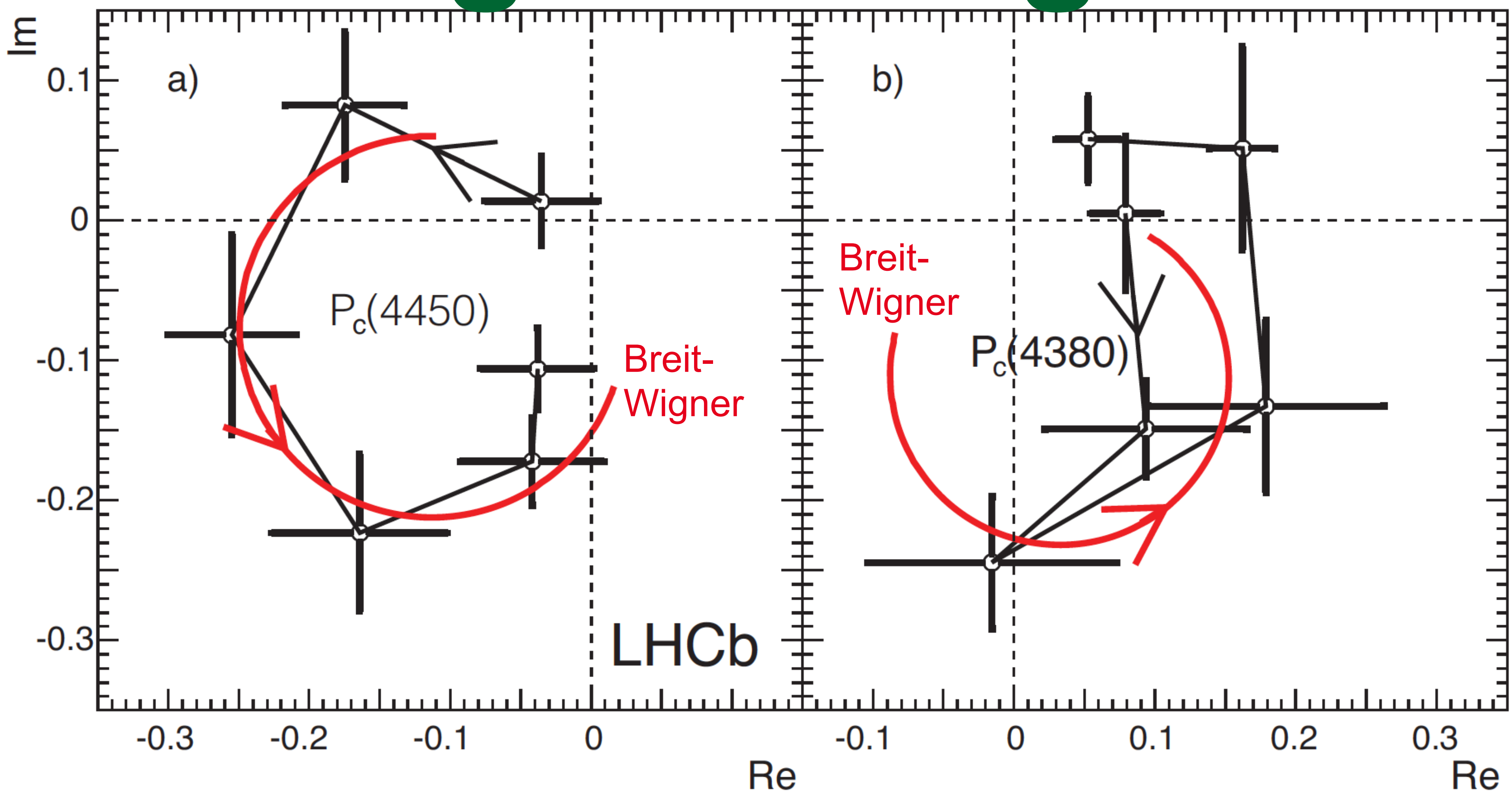
Systematic uncertainties

Source	M_0 (MeV) low	M_0 (MeV) high	Γ_0 (MeV) low	Γ_0 (MeV) high	Fit fractions (%) low	Fit fractions (%) high	$\Lambda(1405)$	$\Lambda(1520)$
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

Cross-checks

- Many done, some listed here:
- Signal found using different selections by others
- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data shows consistency: 2011/2012, magnet up/down, $\overline{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
- 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

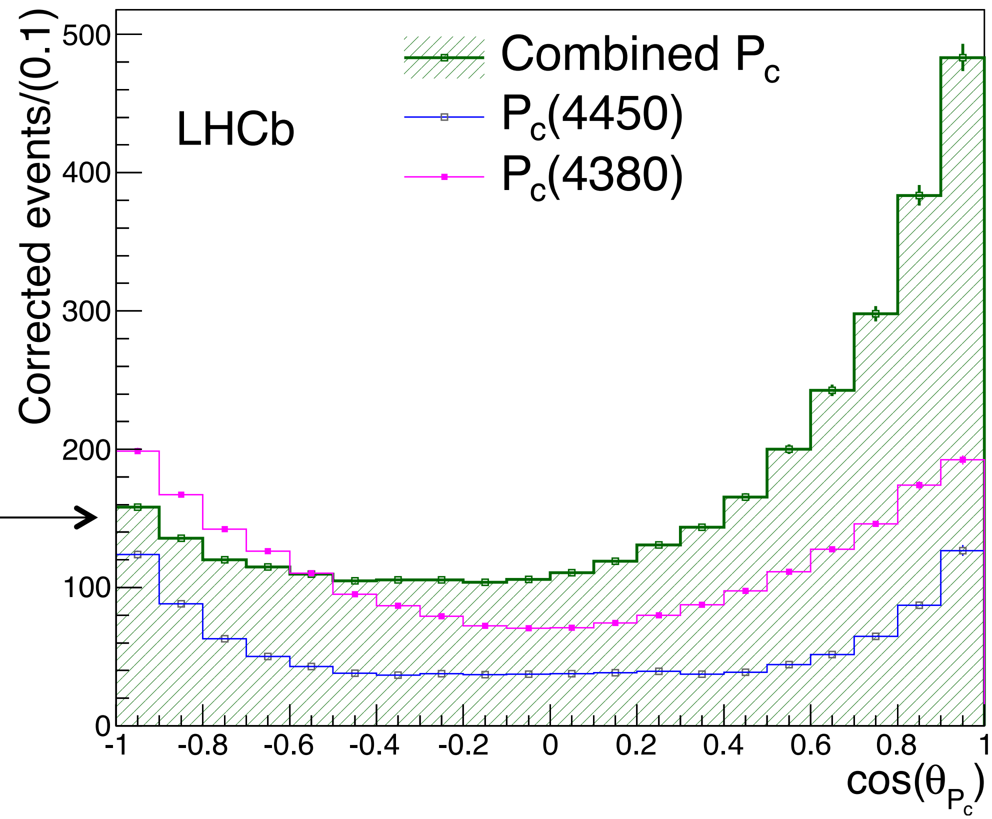


- Amplitudes for 6 bins between $+\Gamma$ & $-\Gamma$

Data demands 2 states

- Interference between opposite parity states needed to explain P_c decay angle distribution
- Fit projections

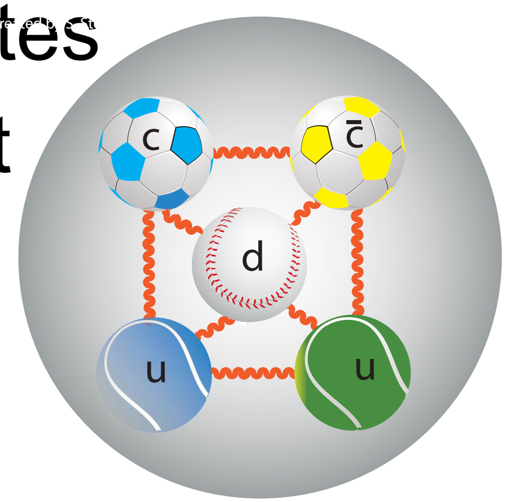
Large m(Kp) region negative interference



Small m(Kp) region positive interference

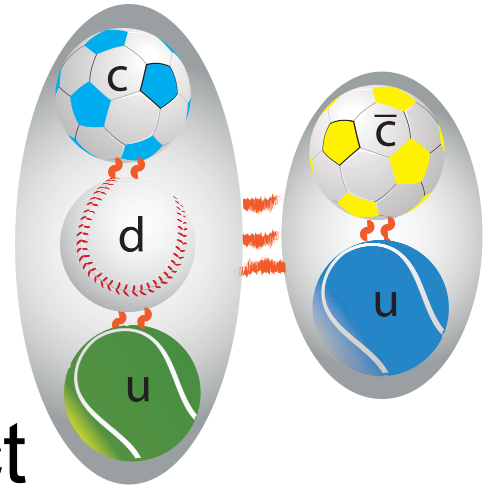
Pentaquark models

- All models must explain J^P of two states not just one. They also should predict properties of other states: masses, widths, J^P. Many models: Lets start with **tightly bound quarks** ala' Jaffe



  - Two colored diquarks plus the anti-quark, L.Maiani, et. al, [arXiv:1507.04980], ibid [PRD20(1979) 748]
  - Colored diquark + colored triquark, R. Lebed [arXiv: 1507.05867]
  - Bag model, Jaffe; Strings, Rossi & Veneziano [Nucl. Phys. B123 (1977) 507]

Molecular models



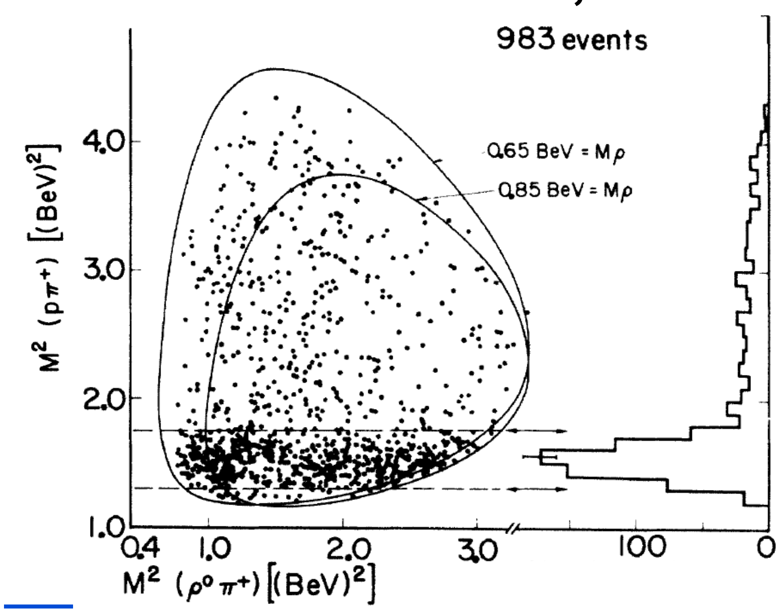
- Molecular models, generally with meson exchange for binding
- ala′ Törnqvist [Z. Phys. C61 (1994) 525]
- π exchange models usually predict only one state, mainly $J^P=1/2^+$, but could also include ρ exchange…
- Several authors consider $\Sigma_c\ D^{(*)}$ components (most of these are postdictions)

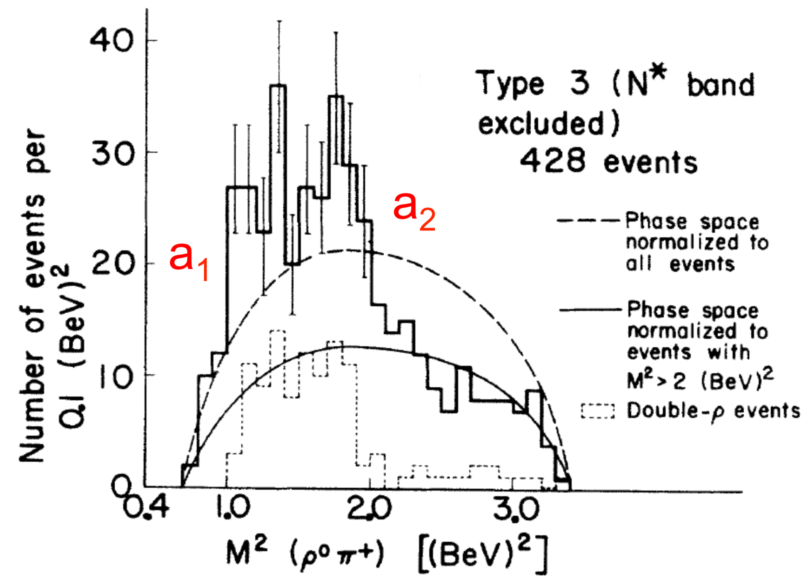
Rescattering

- These are all postdictions
- They construct non-BW amplitude that must mimic mass shape & phase variation of a BW
- eg. $\Lambda_b \rightarrow XY(Z) \rightarrow J/\psi p K^-$, especially when $m(XY)=m(P_c)$, hence the word "cusp"
- These models have so far not predicted the size of the rescattering amplitude
- Also difficult to predict two states…

Some History: The a_1

- Is it 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)*

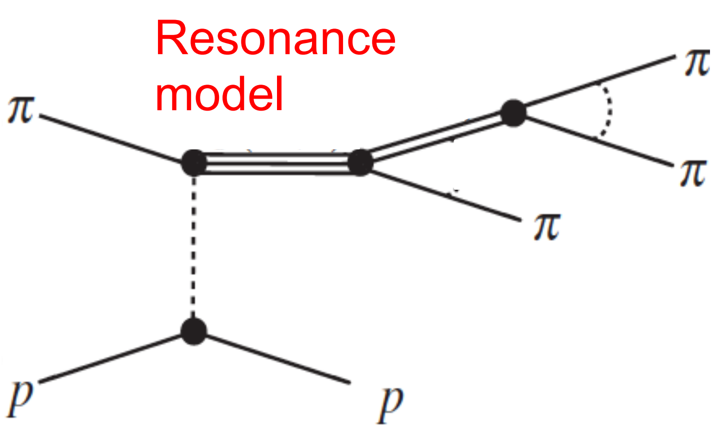


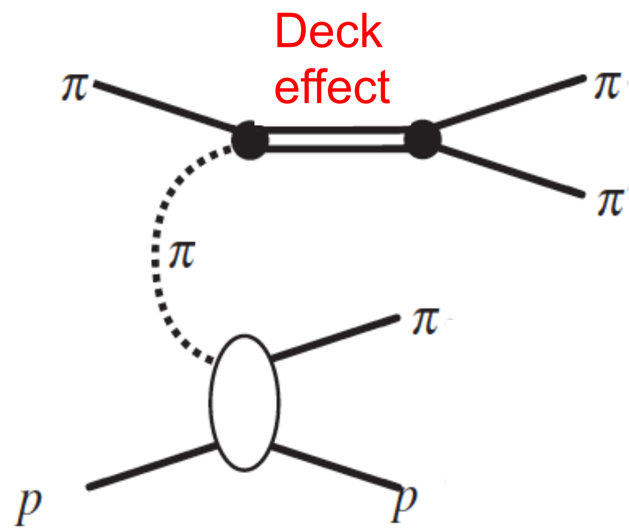


Note BeV≡GeV

"Kinematical" effect

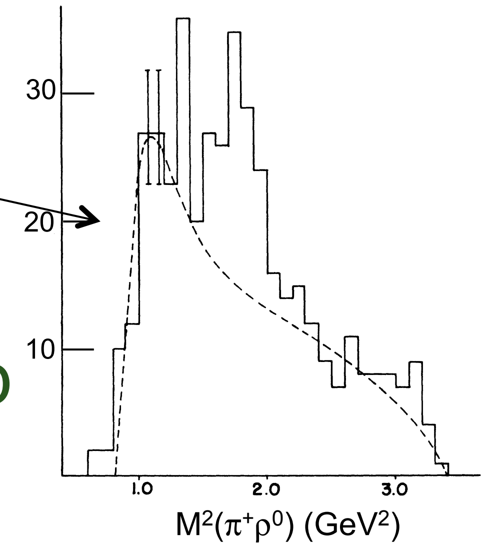
- Clear enhancement near threshold. Is it a new resonance as suggested in original paper?
- Theorists, first Deck, suggest that the threshold enhancement can be due to off shell πp scattering *R.T. Deck, PRL 13, 169 (1964)*





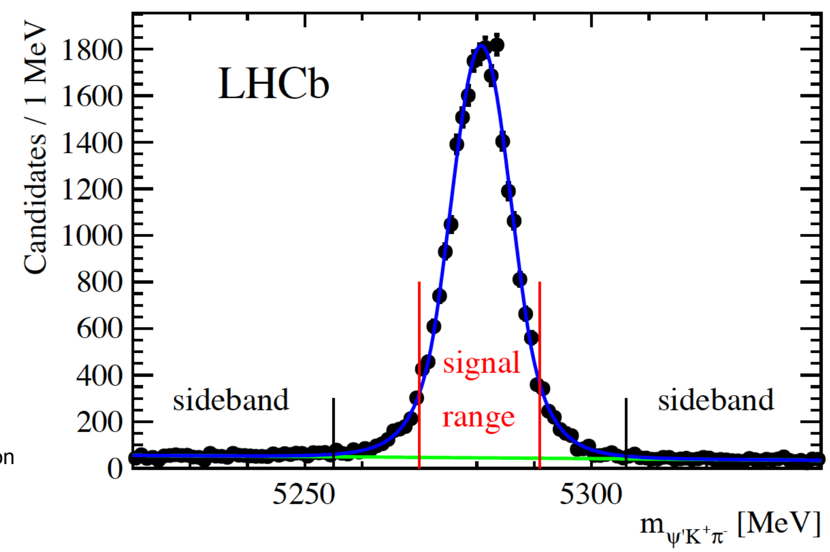
Deck Effect

- Deck's fit to data can provide adequate explanation
- a_1 then 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, ~1977
- Surmises: a full amplitude analysis may have proved the resonant nature of the a_1 earlier. Important to see resonant states in several ways. There never was an unambiguous demonstration of the Deck effect.



$Z(4430)^+$ tetraquark

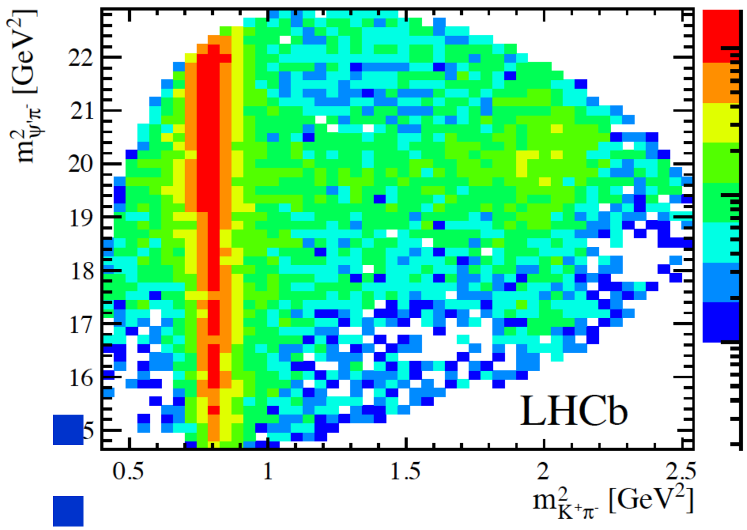
- $B^0 \to \psi' \pi^- K^+$, peak in $m(\psi'\pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle M=4433±5 MeV, Γ=45 MeV
  - Challenged by BaBar: explanation in terms of K*'s
  - Belle reanalysis using full amplitude fit: M= $4485 \pm 22^{+28}_{-11}$ MeV, Γ=200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

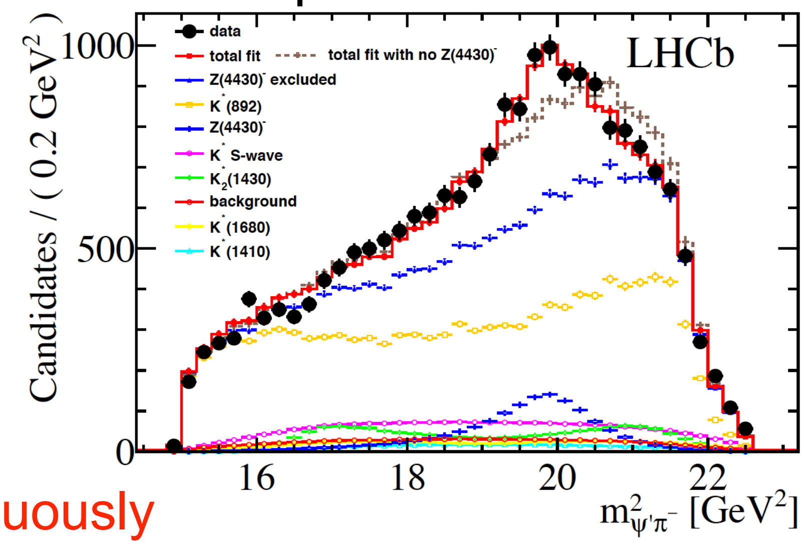


see also , LHCb-PAPER-2015-038 in preparation

LHCb Amplitude analysis

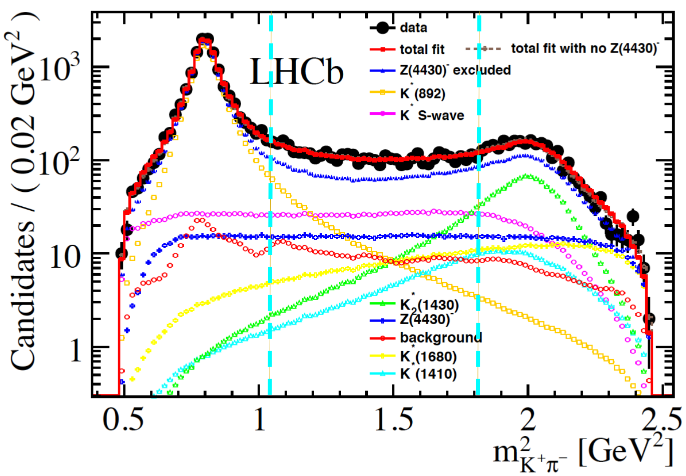
- Full 4D fit to both $K^* \to K^- \pi^+$ & $Z \to \psi' \pi^-$ states

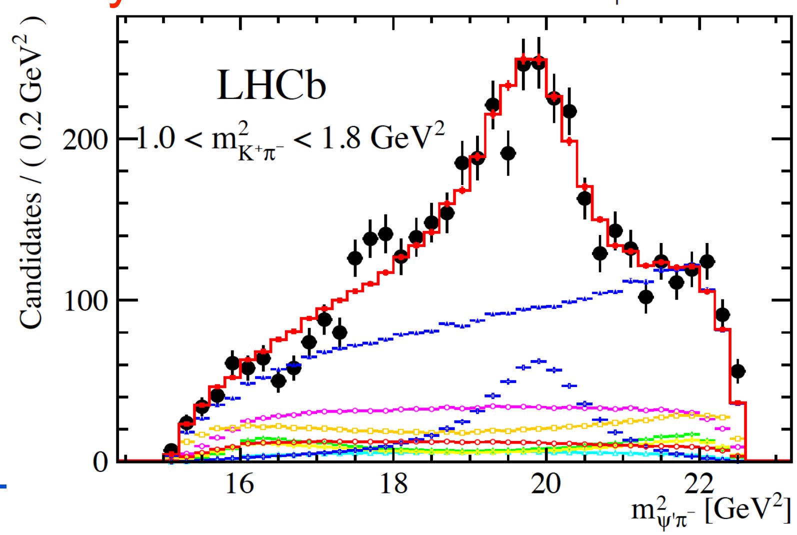




$J^P = 1^+$

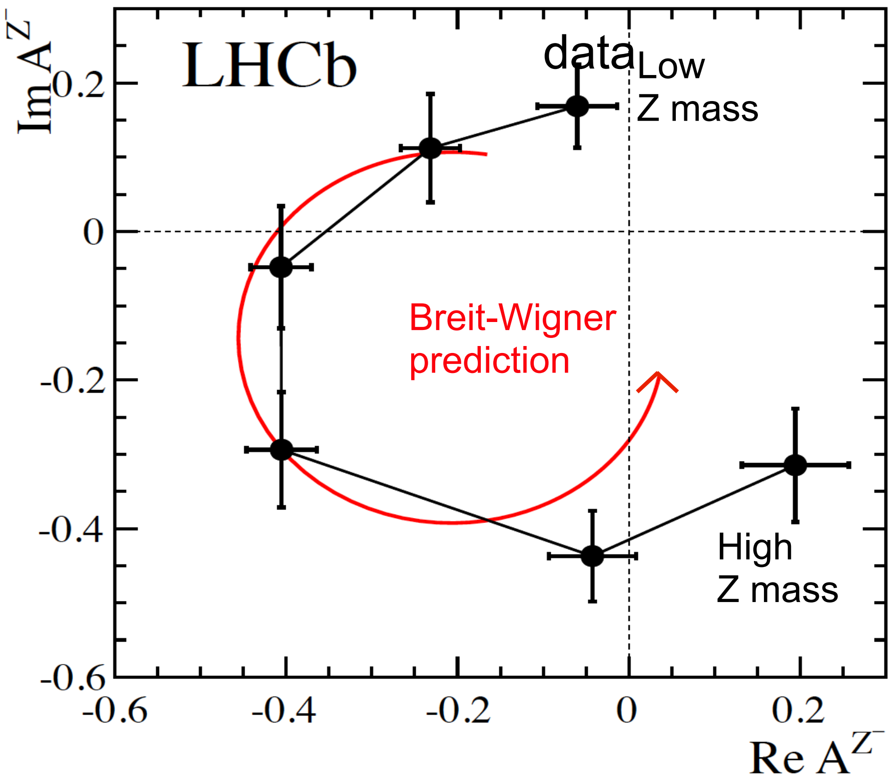
Unambiguously





Is it a resonance?

- LHCb produced an Argand plot that shows a clear & large phase change
- There are also attempts at rescattering explanations



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 $(5/2^+, 3/2^-)$
- Other exotic states have appeared containing $c\bar{c}$ quarks: the $Z^+(4430) \rightarrow \psi' K^- \pi^+$ appears to be a tetraquark with $J^P=1^+$. Is binding stronger for $c\bar{c}$?
- Lattice QCD calculations providing masses would be most welcome
- We look forward to establishing the structure of many other states

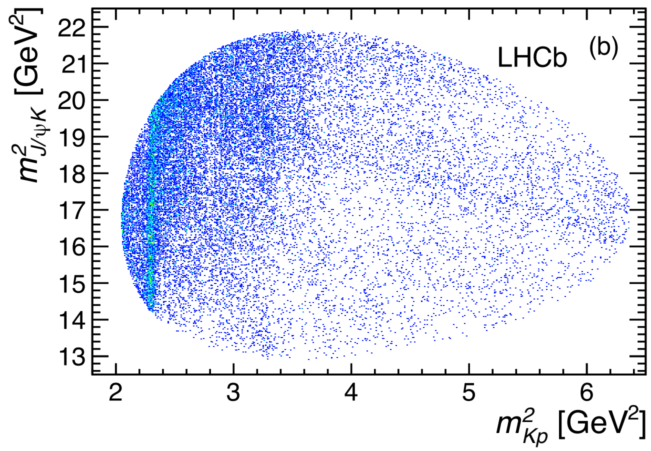
See parallel session talk of Nathan Jurik for more details

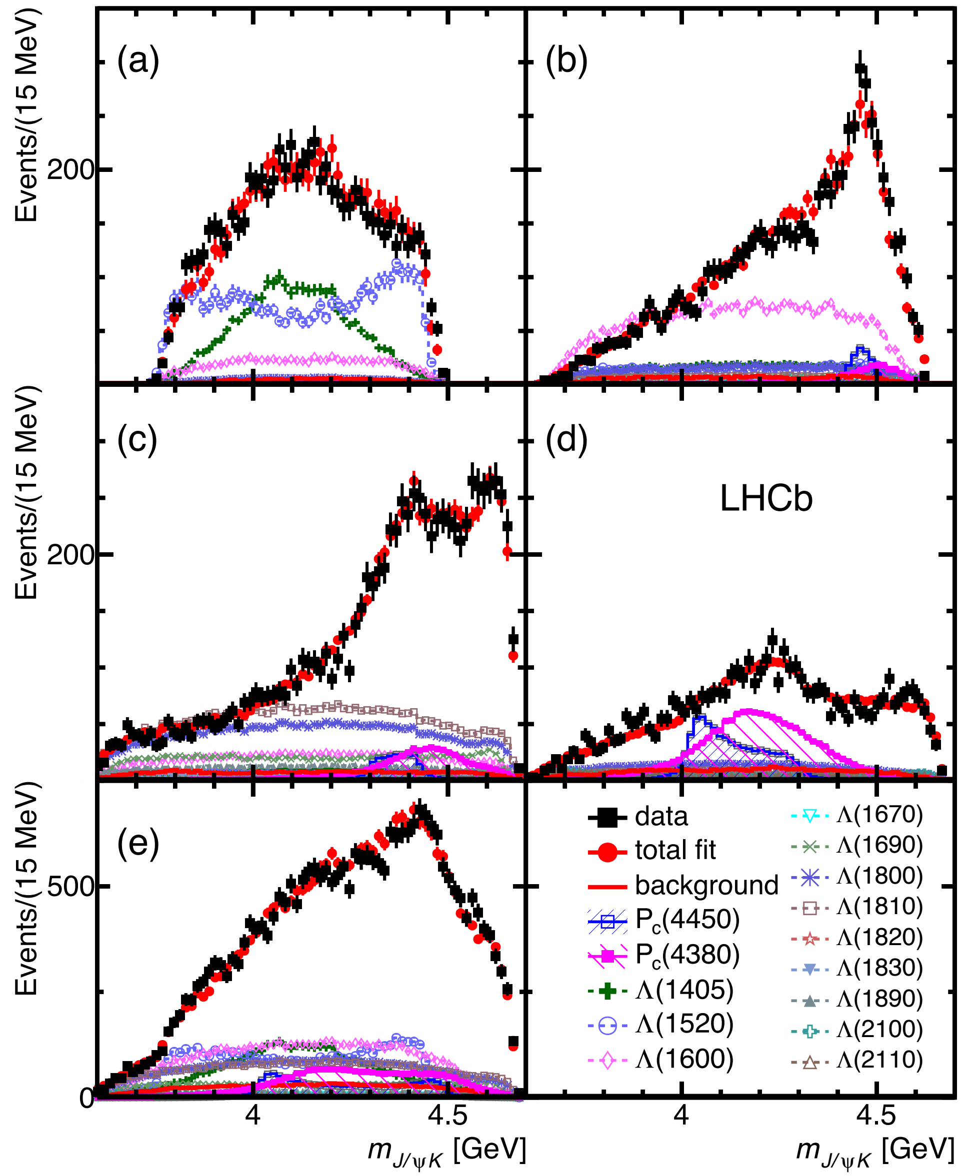
The End

US LHCb groups gratefully acknowledge support from the NSF

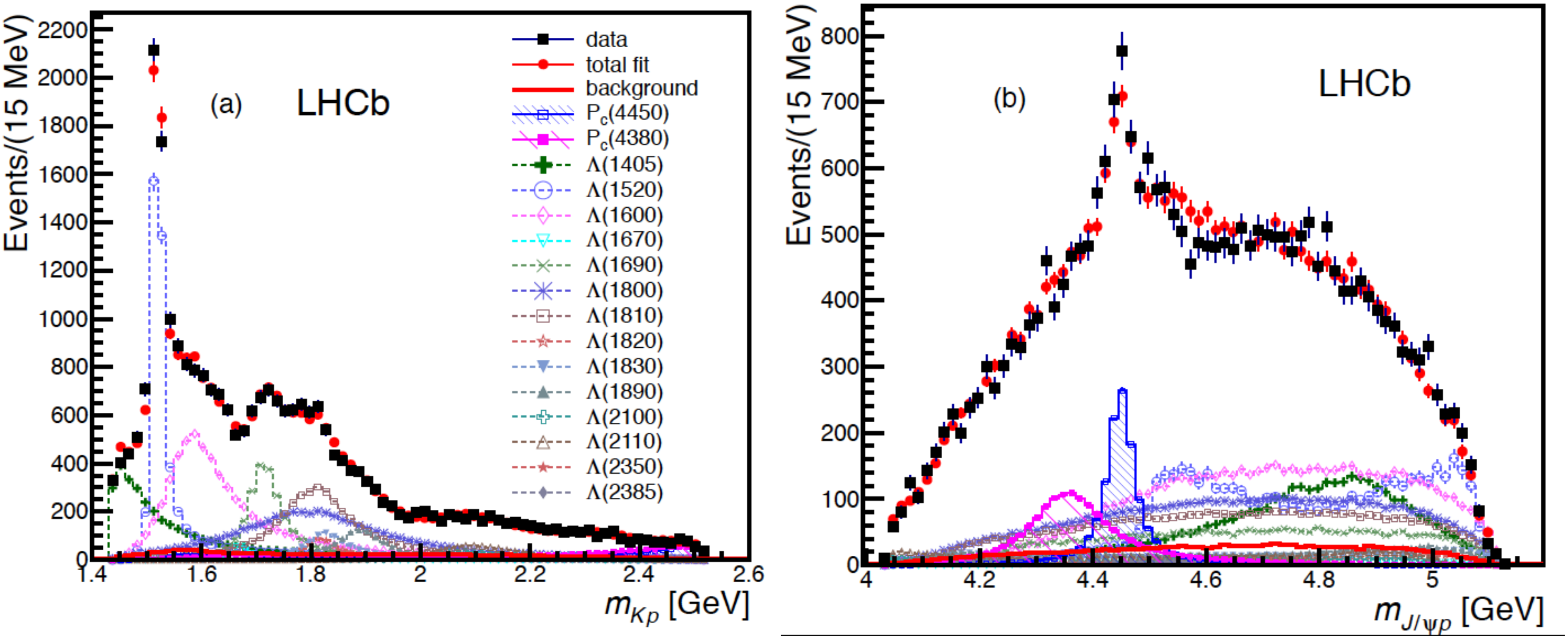
$m(J/\psi\ K^-)$

- Our fit explains $m(J/\psi\ K^-)$





Extended model with 2 P_c's

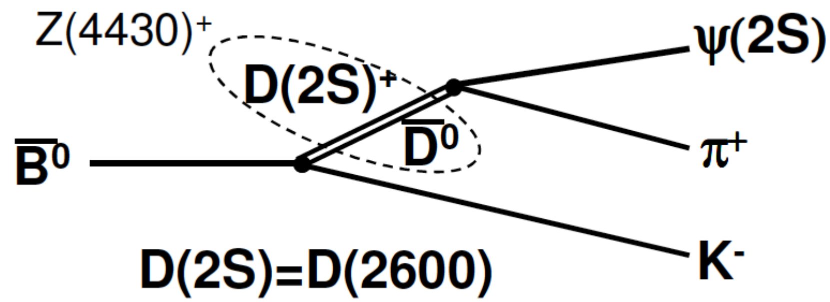


Other Explanations

- Molecule:

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

T. Barnes et.al, [arXiv:1409.6651



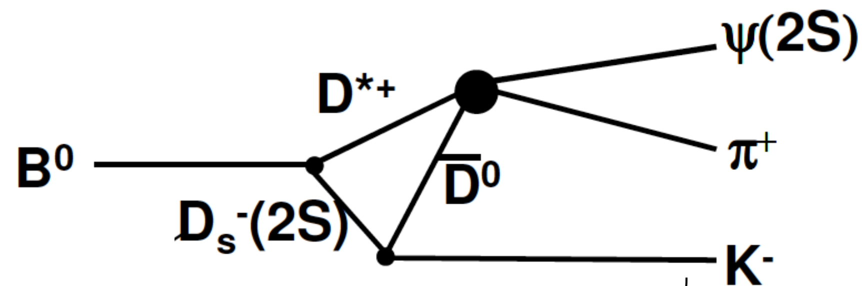
- Same scattering phase

as Breit-Wigner

- Rescattering:

P. Pakhov & T. Uglov

[arXiv:1408:5295]



- Opposite phase
- Ruled out by LHCb

Argand diagram