Pentaquarks and Tetraquarks at LHCb

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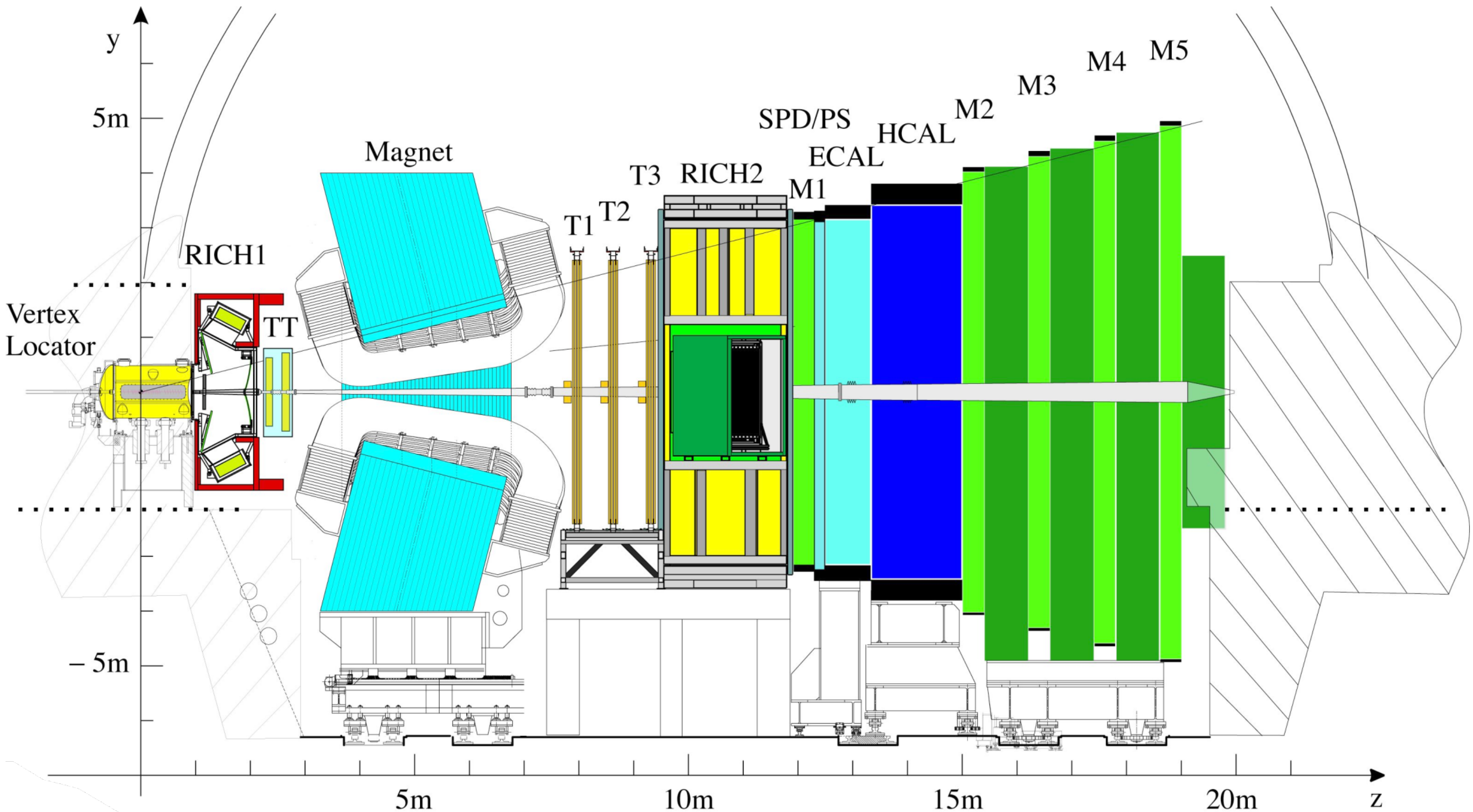
LHCb Detector

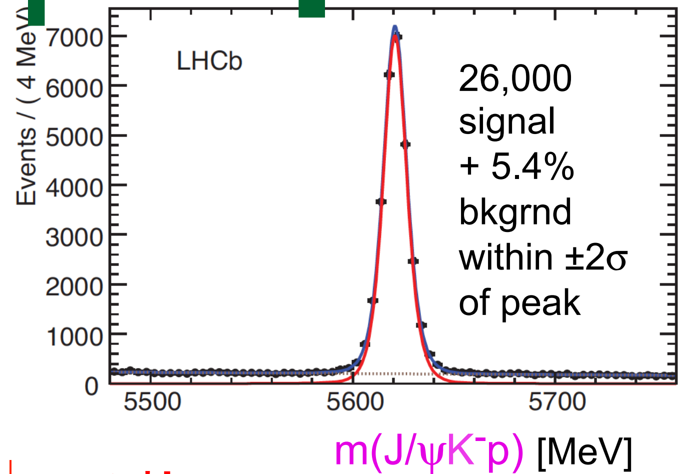


LHCb goals

- Find or establish limits on physics beyond the standard model using CP violating & rare beauty & charm decays
- Rare: $B_{(s)}\rightarrow\mu^+\mu^-$, $B^0\rightarrow K^*\mu^+\mu^-$, $B^-\rightarrow K\mu^+\mu^-/Ke^+e^-$
- CP violation: determine ∠'s: γ, β, ϕ_s
  - Use $B_{(s)}\rightarrow J/\psi K^+K^-$, $J/\psi\pi^+\pi^-$ decays
  - ϕ_s measured with $B_s\rightarrow J/\psi\phi$ & $J/\psi\pi^+\pi^-$ decays
  - Penguin pollution limited using $B^0\rightarrow J/\psi\rho^0$ decays
- Study of $B^0\rightarrow J/\psi K^+K^-$, turned not to be that interesting [arXiv:1308.5916] but

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

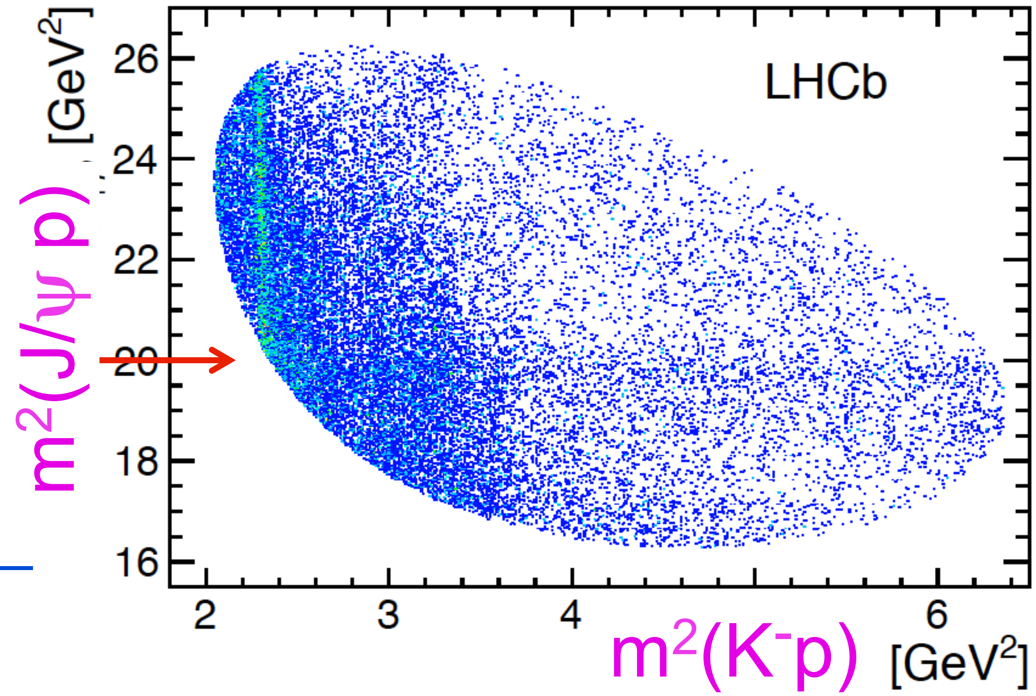
- First looked for in LHCb as a potential background for $B^0 \rightarrow J/\psi K^+ K^-$
- Large signal found, used for Λ_b lifetime [arXiv:1402.6242]



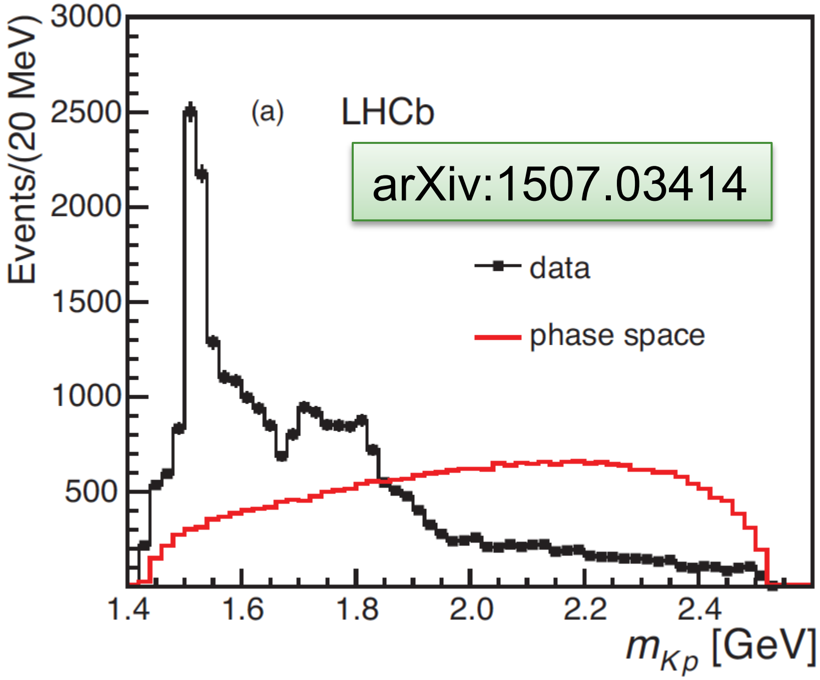
↓ ↓ ↓…Λ*'s

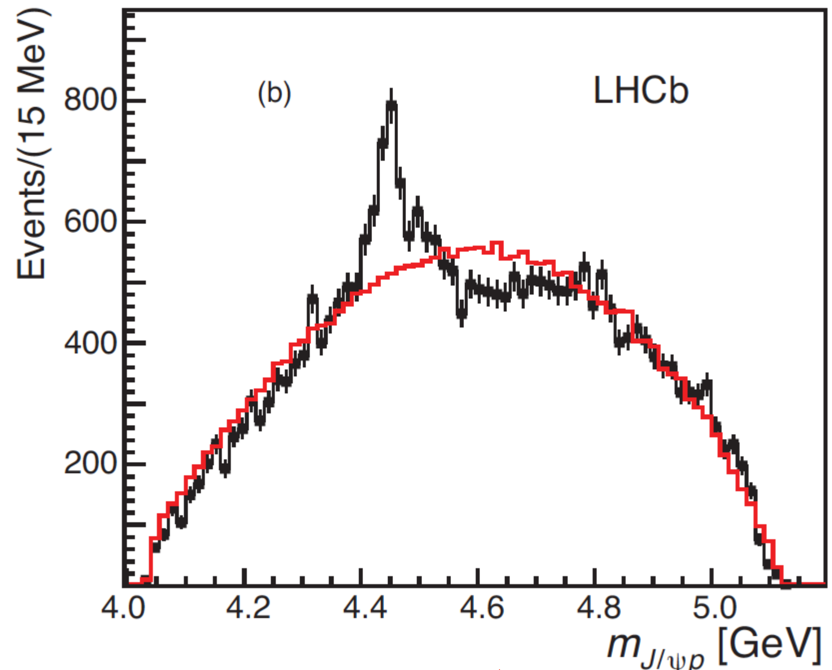
- Dalitz plot showed an unusual feature

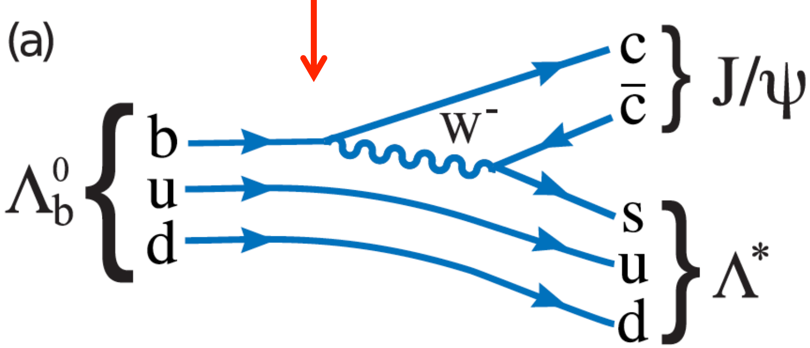
[arXiv:1507.03414]

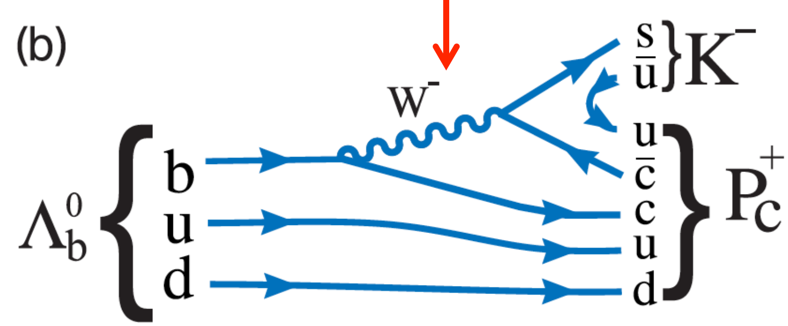


Projections









Does this diagram exist?

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.]

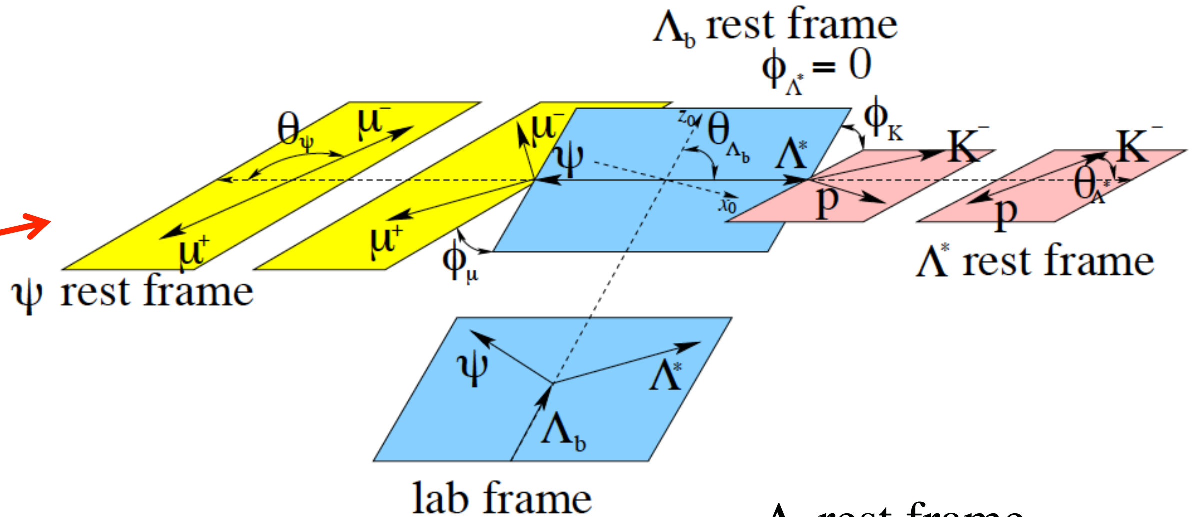
Decay amplitude analysis

- 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 $B_s \rightarrow J/\psi K^- K^+$ & $B^0 \rightarrow J/\psi K^- \pi^+$
  - 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

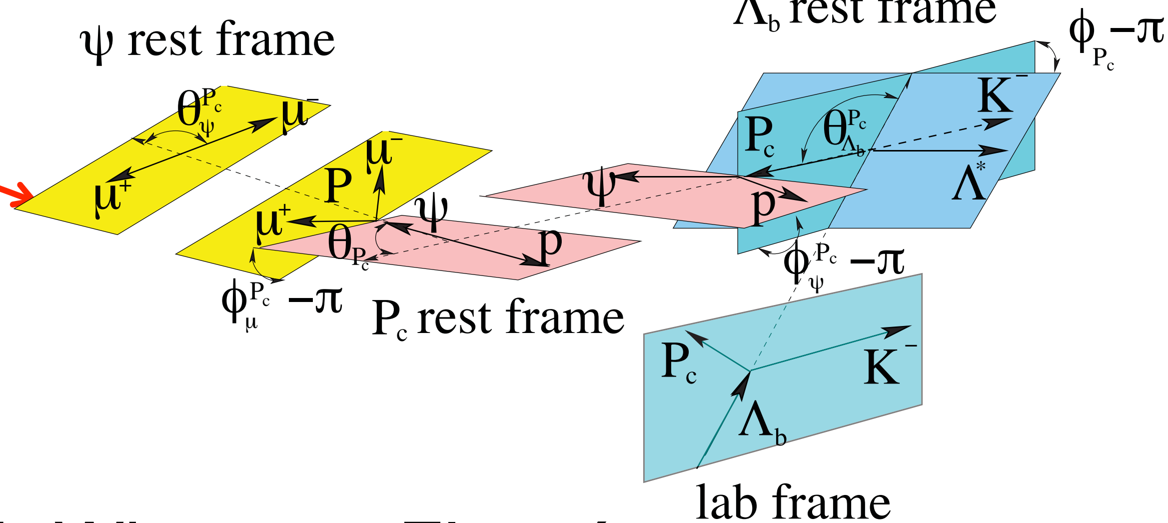
- Two interfering channels:

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



&

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



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

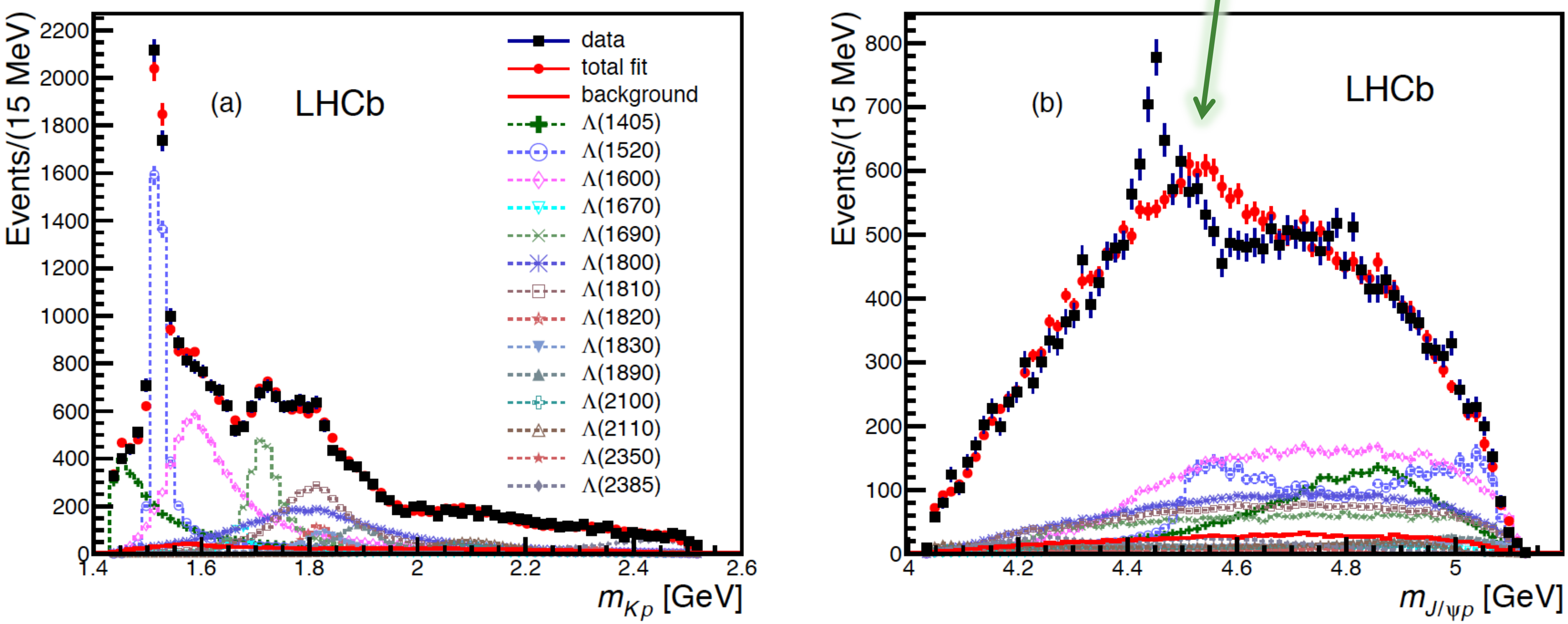
Models: extended & reduced

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

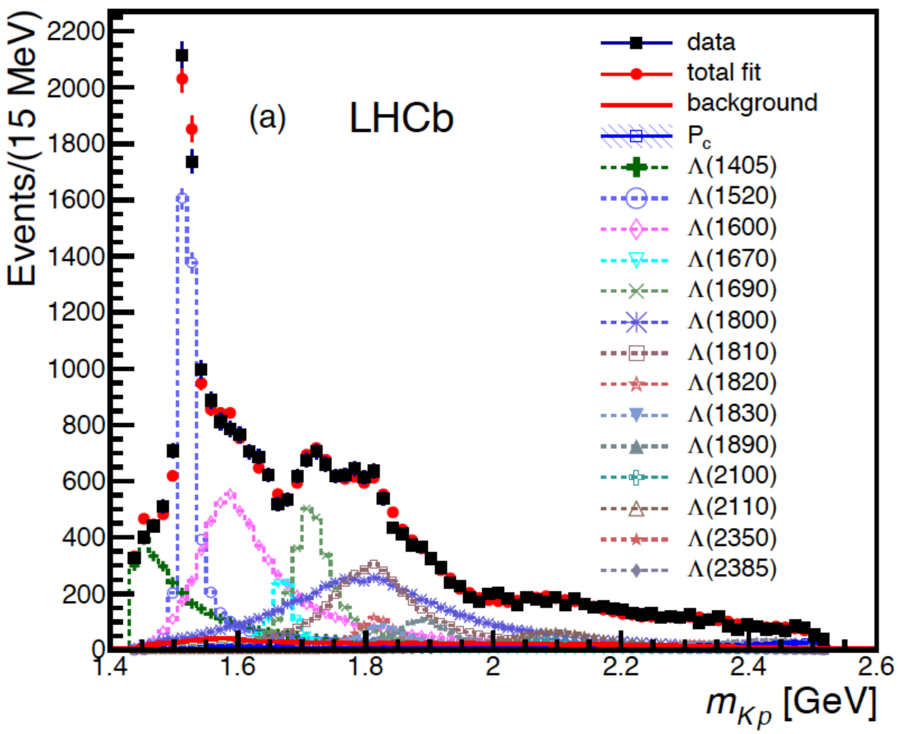
Results without P_c states

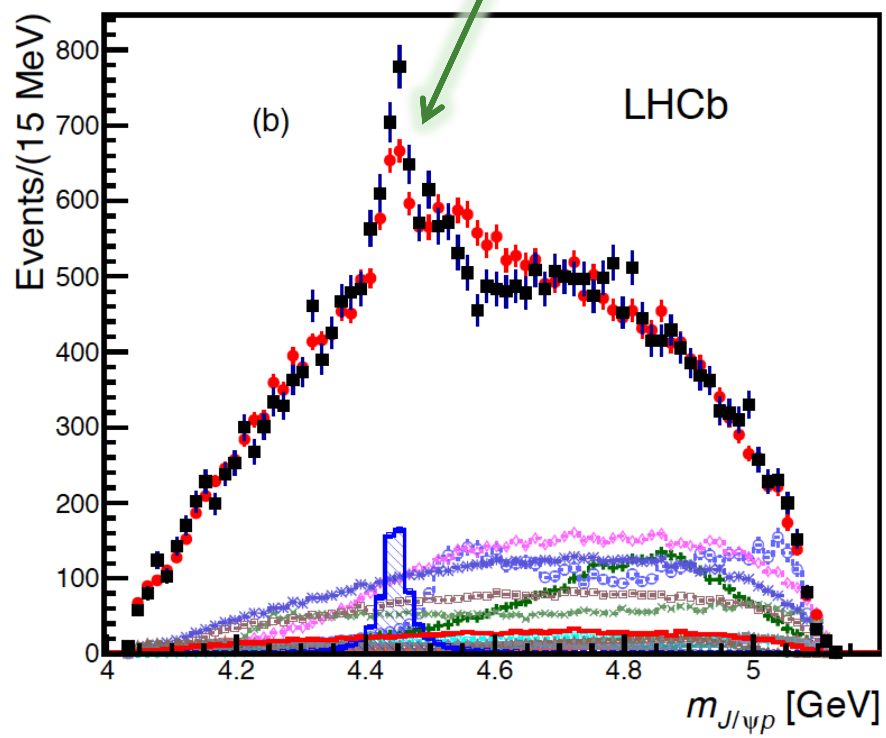
- Use extended model, so all possible known Λ^* amplitudes. m_{Kp} looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant, extra Λ^*'s doesn't help



Extended model with 1 P_c

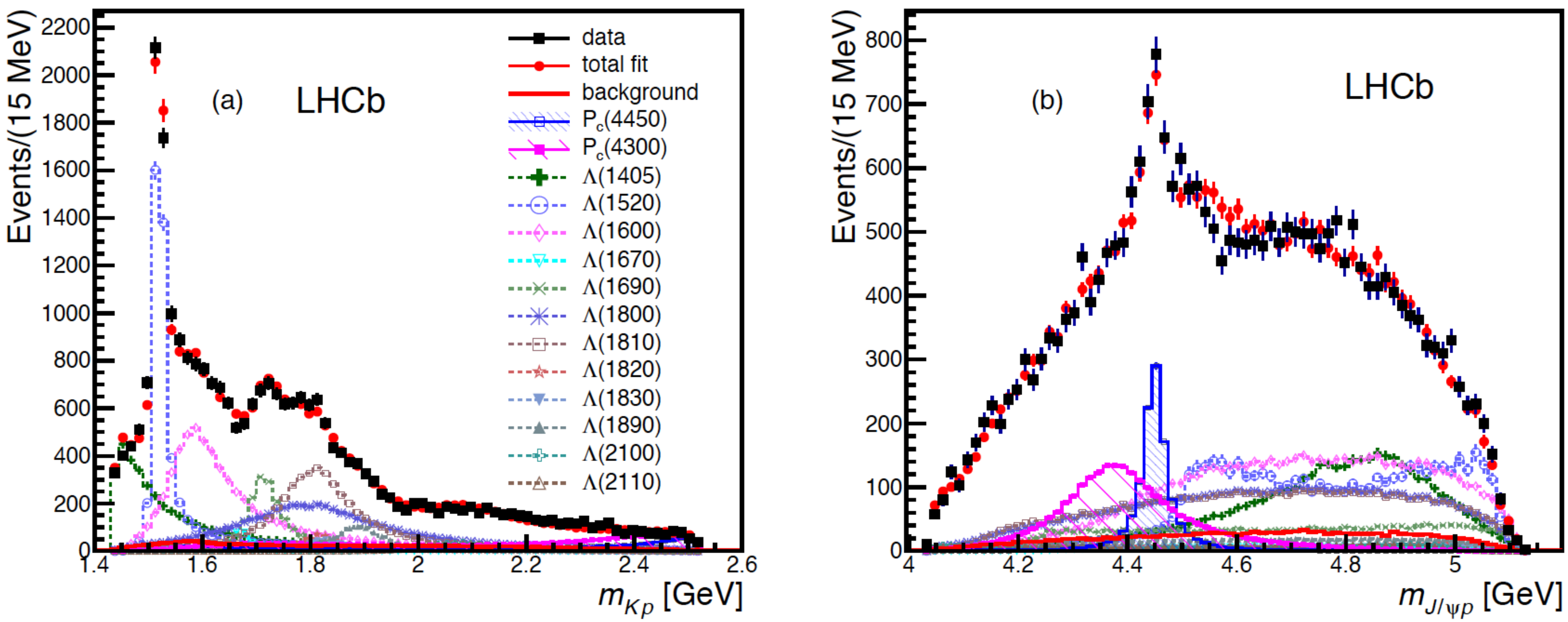
- Try all J^P up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit





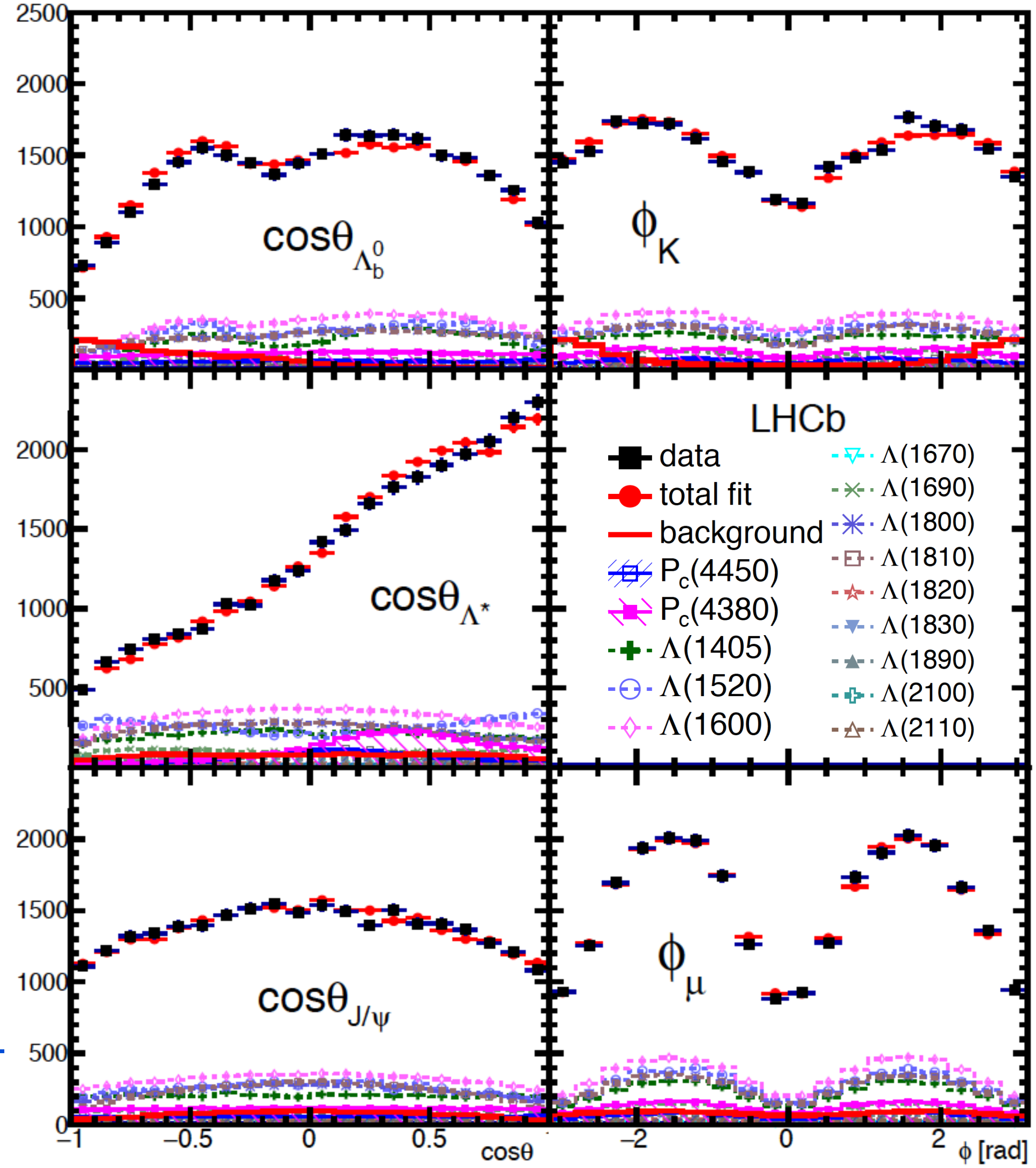
Reduced model with 2 P_c's

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



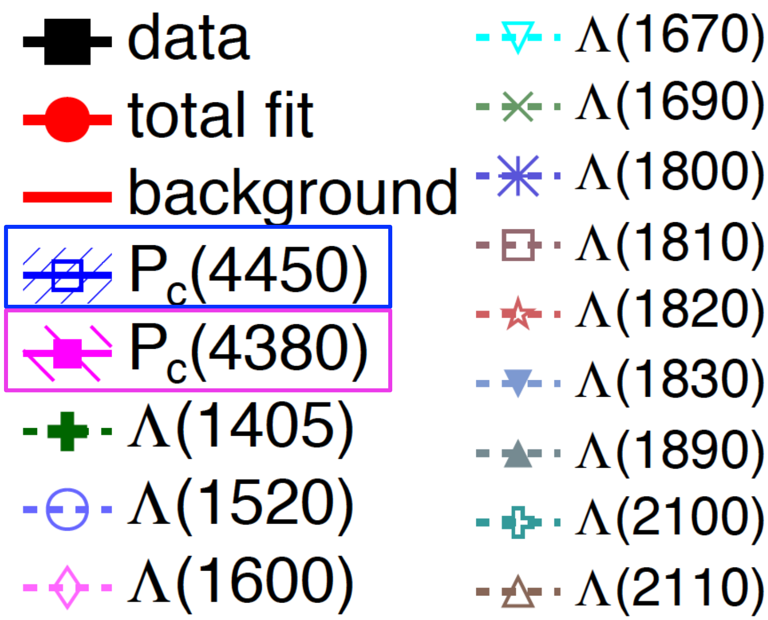
Angular distributions

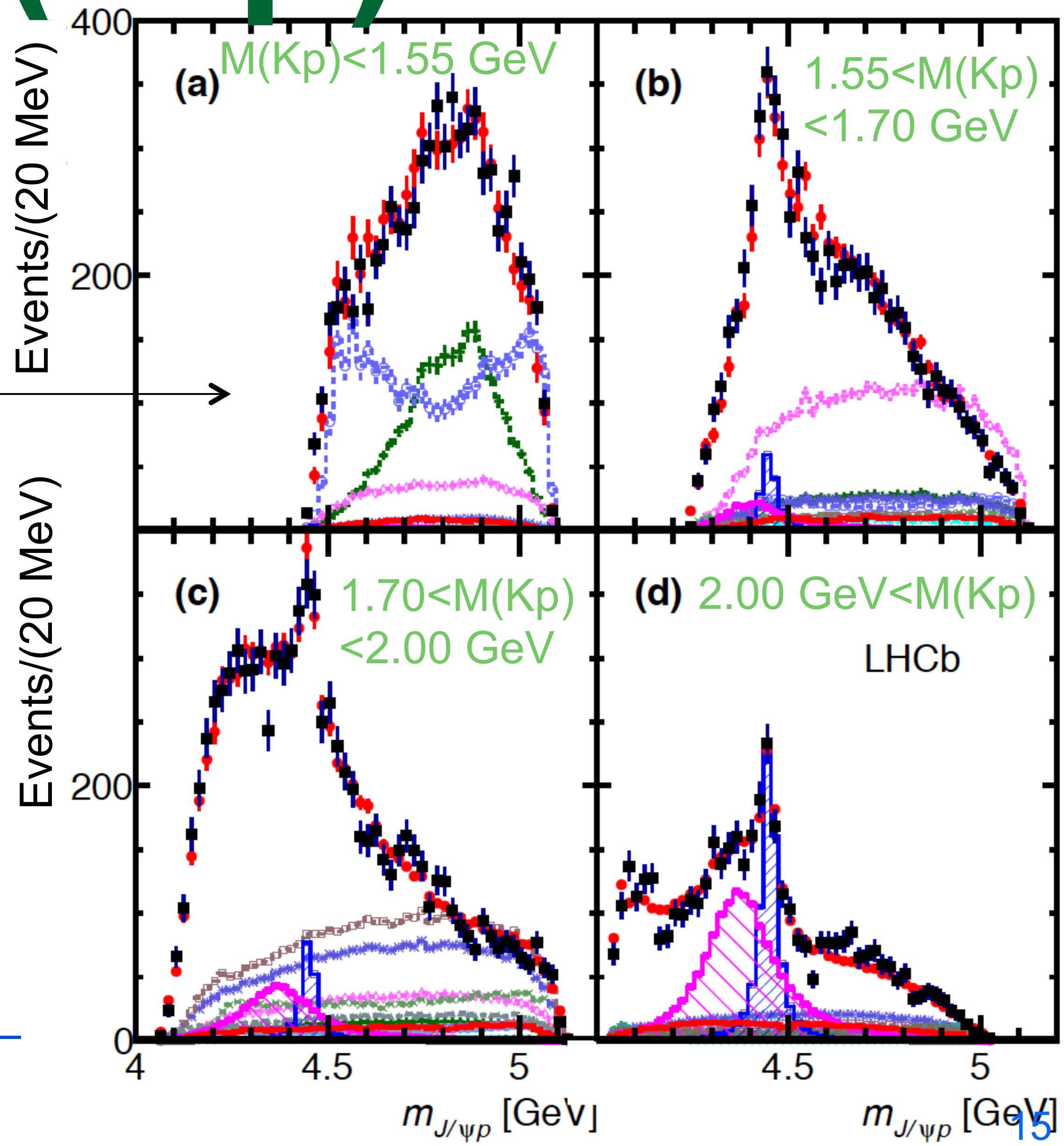
Good fits in the angular variables



In m(K^-p) slices

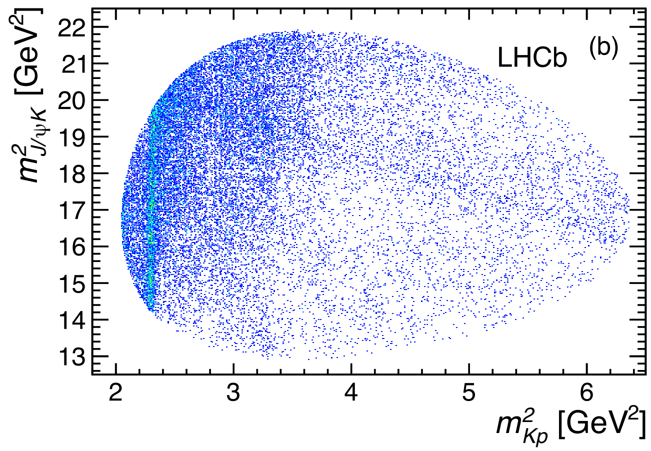
P_c's cannot appear in first interval as they would be outside of the Dalitz plot boundary

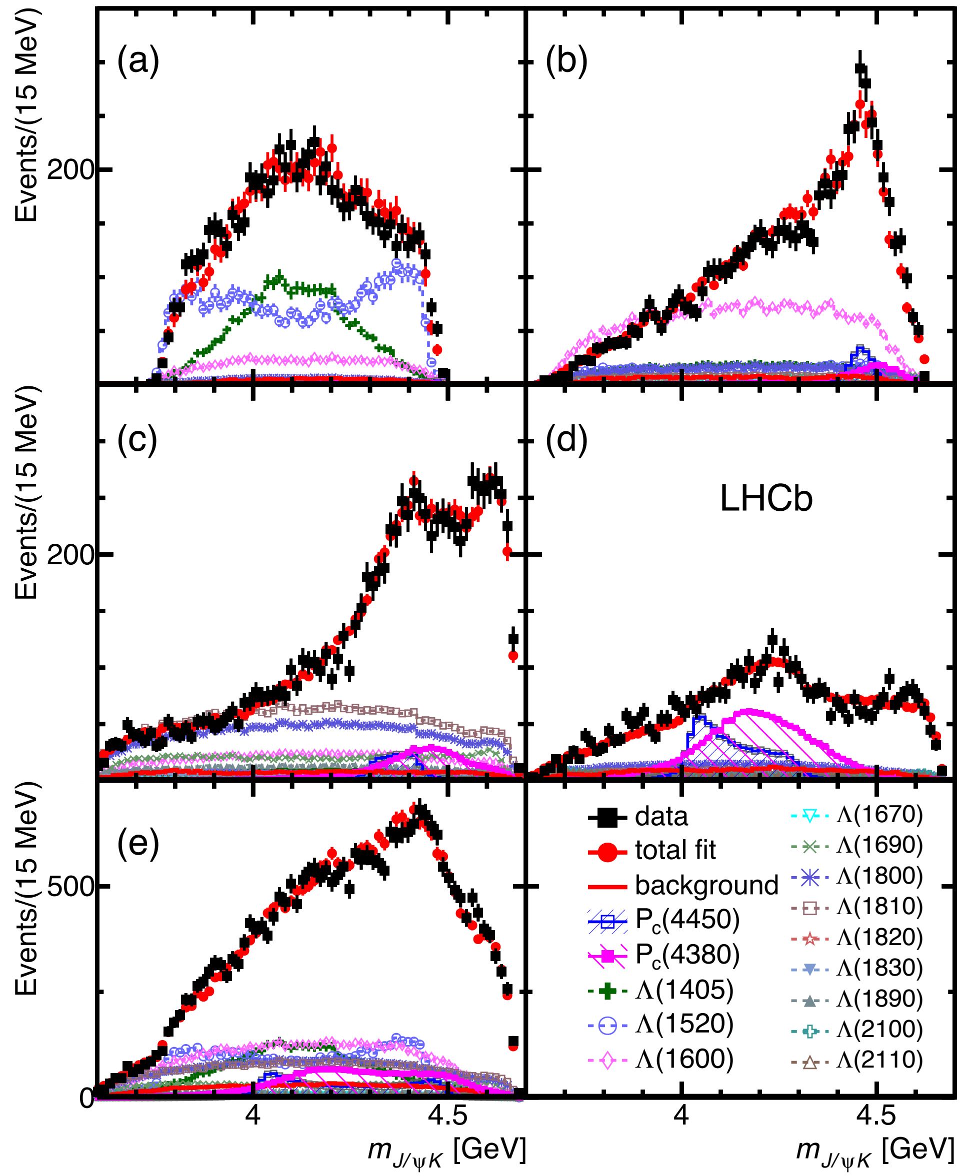




$m(J/\psi\ K^-)$

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





Significances

- Fit improves greatly, for 1 P_c $\Delta(-2\ln\mathcal{L})=14.7^2$, adding the 2^{nd} P_c improves by 11.6^2, for adding both together $\Delta(-2\ln\mathcal{L})=18.7^2$
- Using toy simulations 1^{st} state has significance of 9σ & 2^{nd} 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

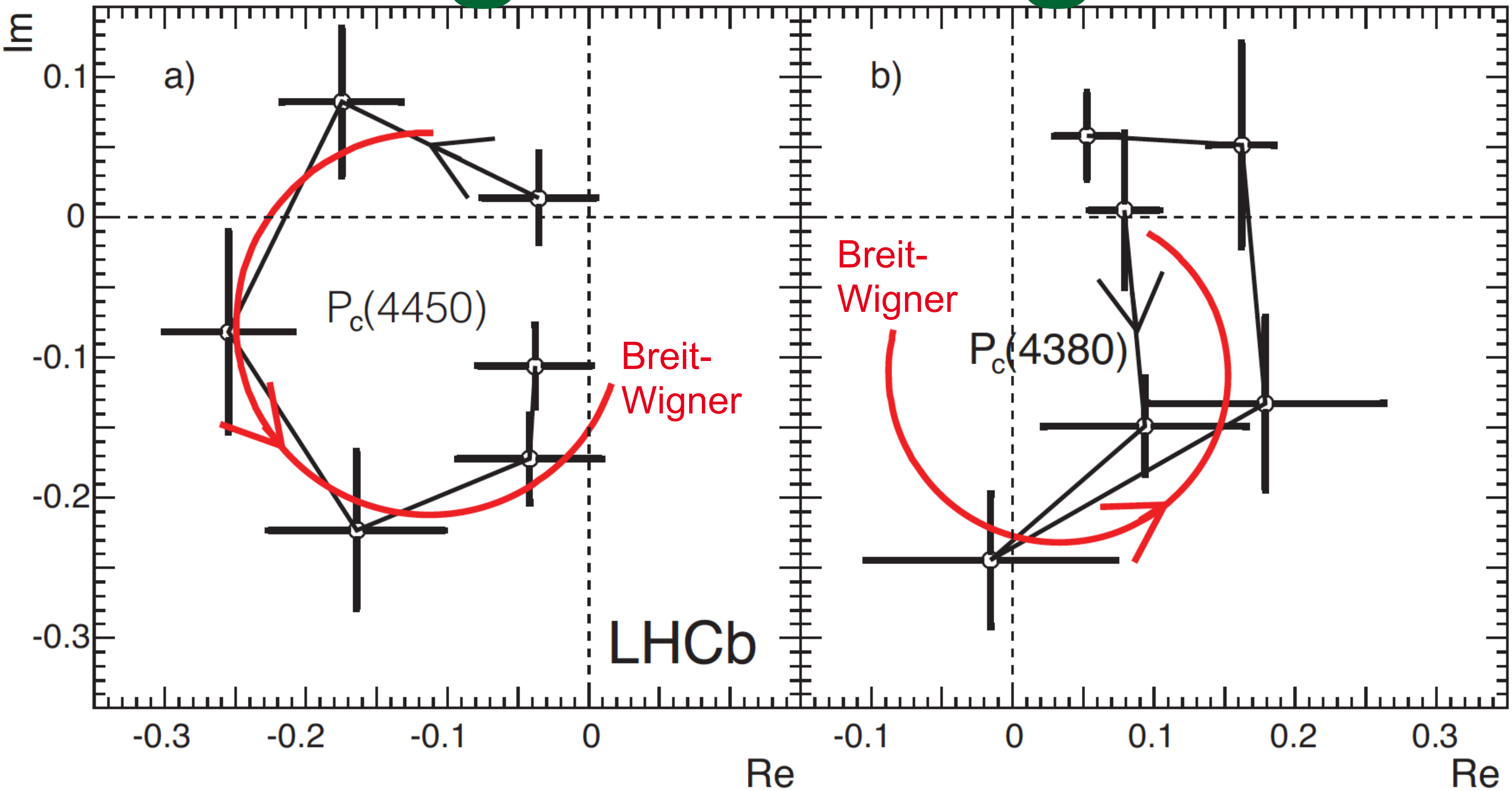
Systematic uncertainties

Source	M_0 (MeV)		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

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, $\overline{\Lambda}_b/\Lambda_b$, $\Lambda_b(p_T$ low$)/\Lambda_b(p_T$ 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

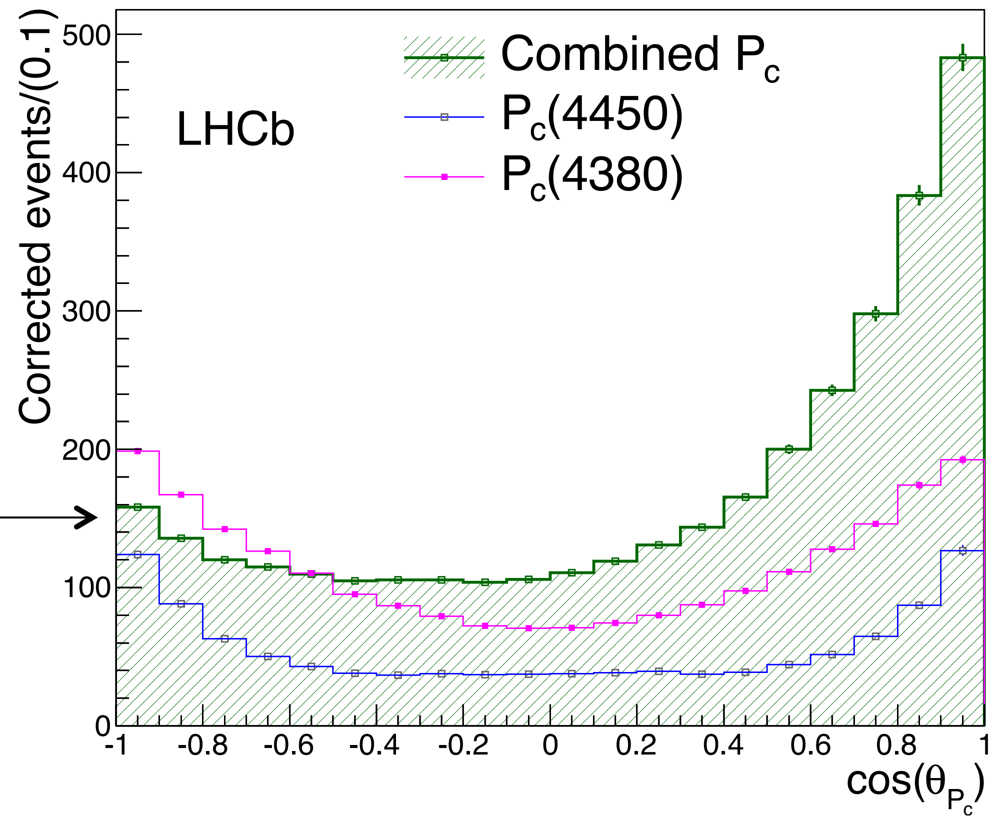
Argand diagrams



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

Data demands 2 states

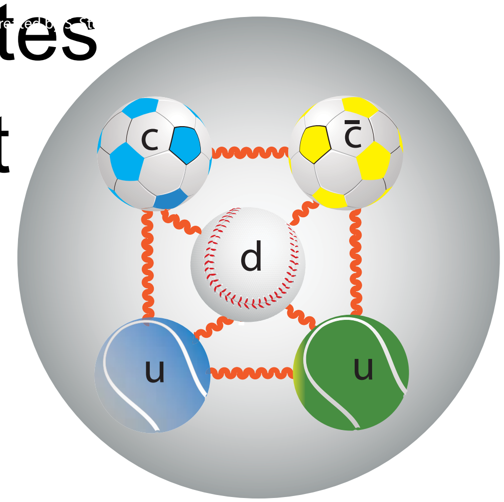
- Interference between opposite parity states needed to explain P_c decay angle distribution
- Fit projections



Large m(Kp) region negative interference

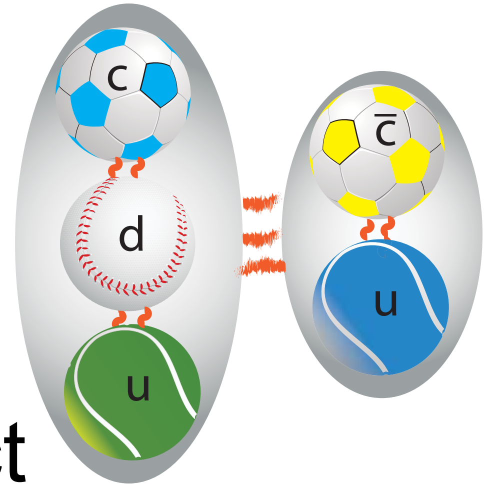
Small m(Kp) region positive interference

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



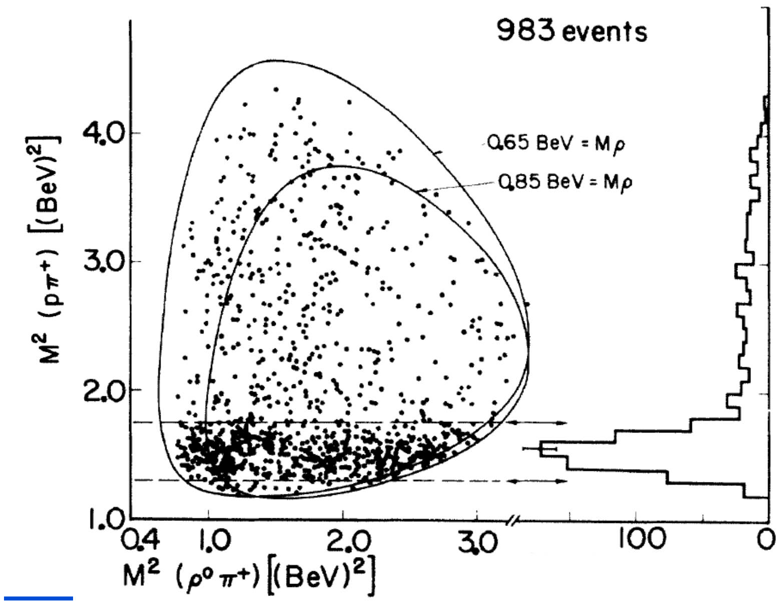
- Molecular models, generally with meson exchange for binding
- Ala' Törnqvist [Z. Phys. C61 (1994) 525]
- π exchange models usually predict only one state, mainly $J^P=1/2^+$, but could also include ρ exchange…
- Several authors consider $\Sigma_c\, D^{(*)}$ components (most of these are postdictions)

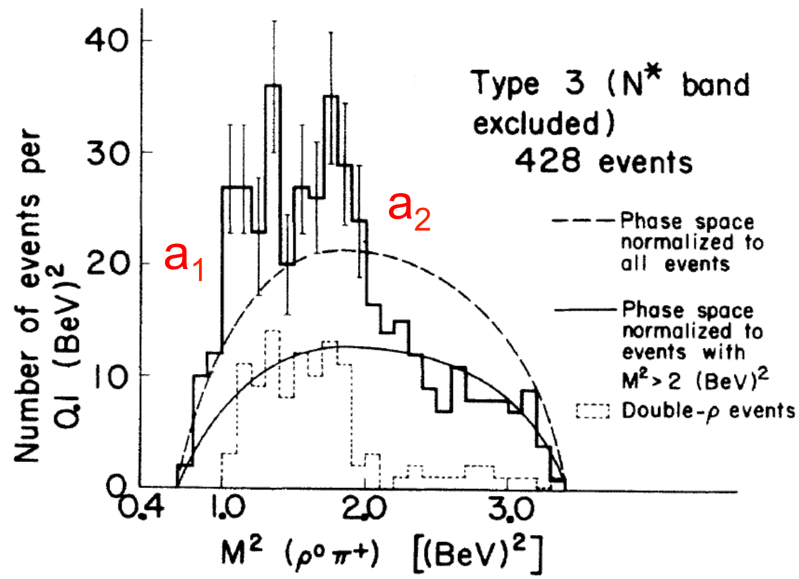
Rescattering

- These are all postdictions
- They construct non-BW amplitude that must mimic mass shape & phase variation of a BW
- eg. $\Lambda_b \to XY(Z) \to J/\psi p K^-$, 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)*

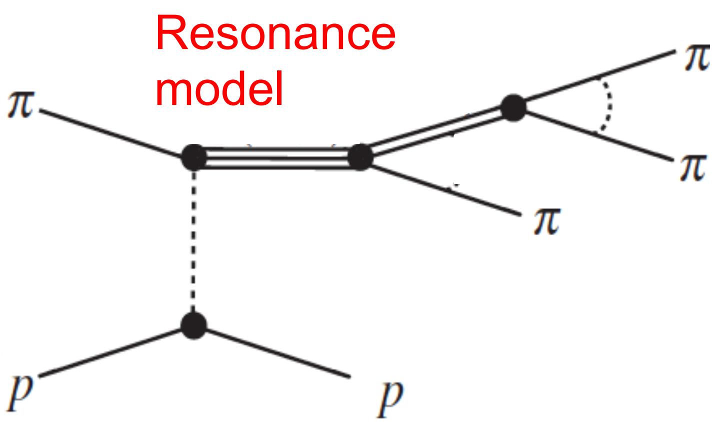


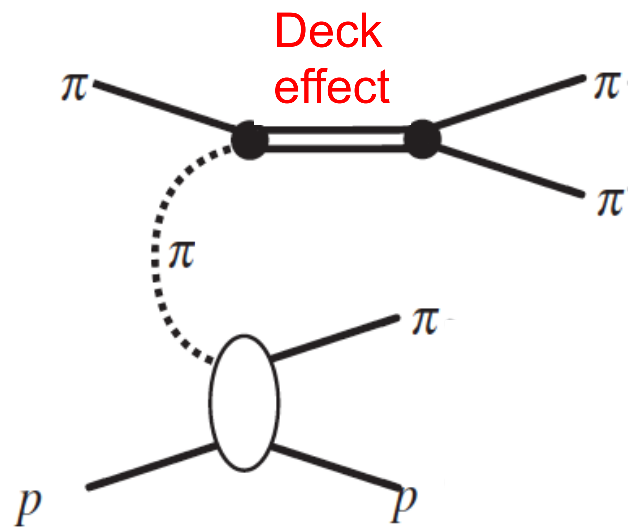


Note BeV≡GeV

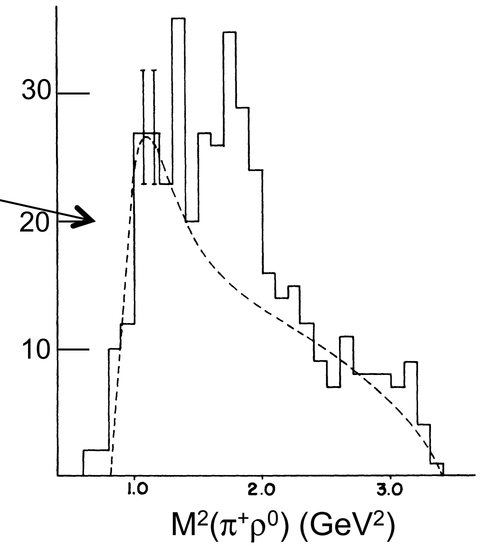
"Kinematical" effect

- 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)*





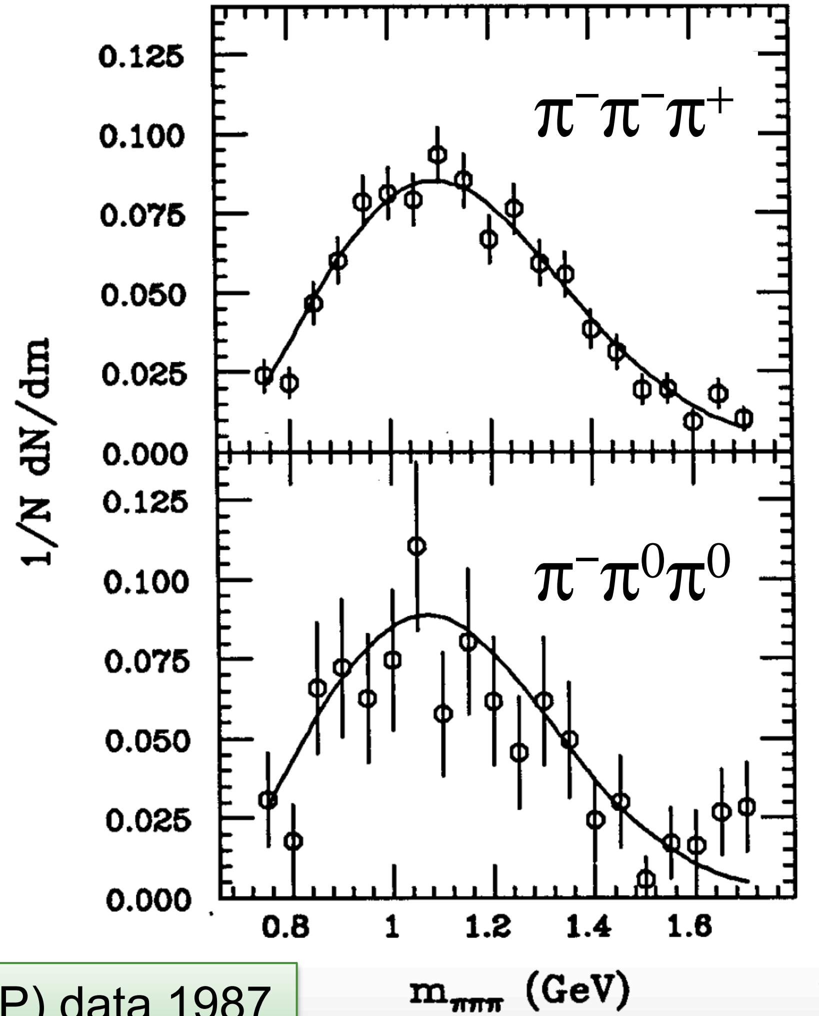
Deck Effect



- 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

$\tau^- \to (\pi\pi\pi)^- \nu$

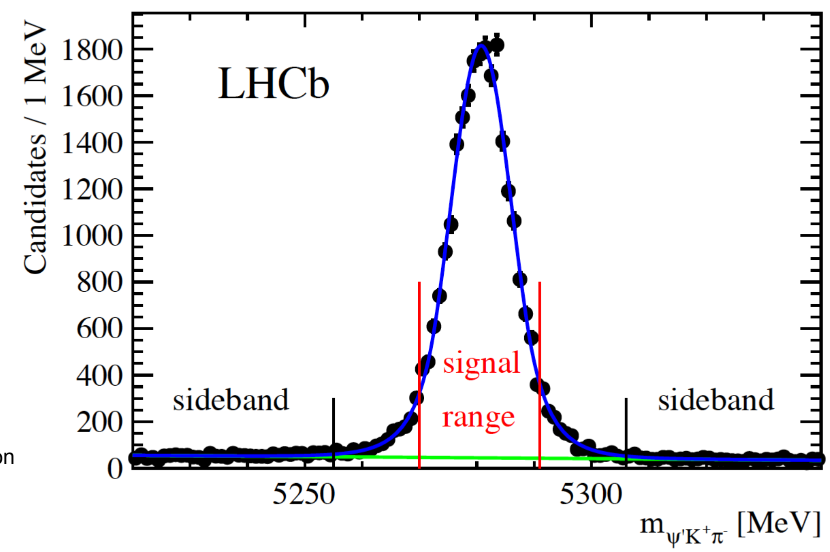
Surmises: a full amplitude analysis may have proved the resonant nature of the a_1 earlier. Important to see resonant states in several ways. There never was an unambiguous demonstration of the Deck effect.



MAC (PEP) data 1987

$Z(4430)^+$ tetraquark

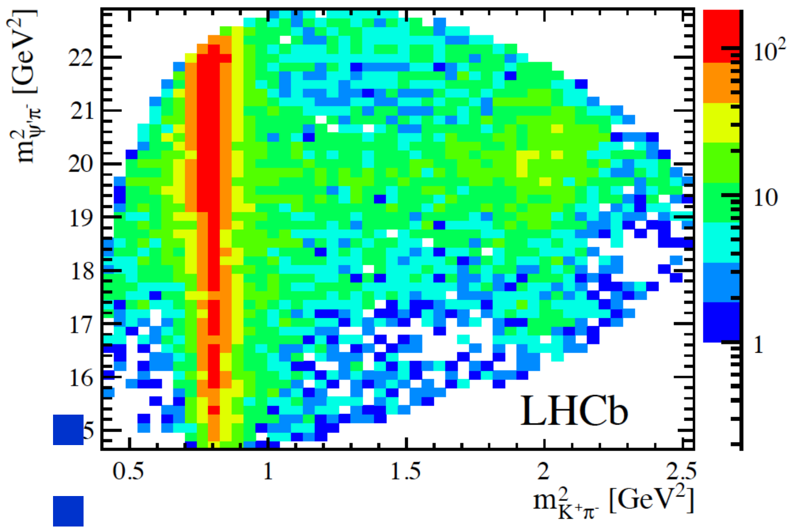
- $B^0 \to \psi' \pi^- K^+$, peak in $m(\psi'\pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle M=4433±5 MeV, Γ=45 MeV
  - Challenged by BaBar: explanation in terms of K*'s
  - Belle reanalysis using full amplitude fit: M= $4485 \pm 22^{+28}_{-11}$ MeV, Γ=200 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]

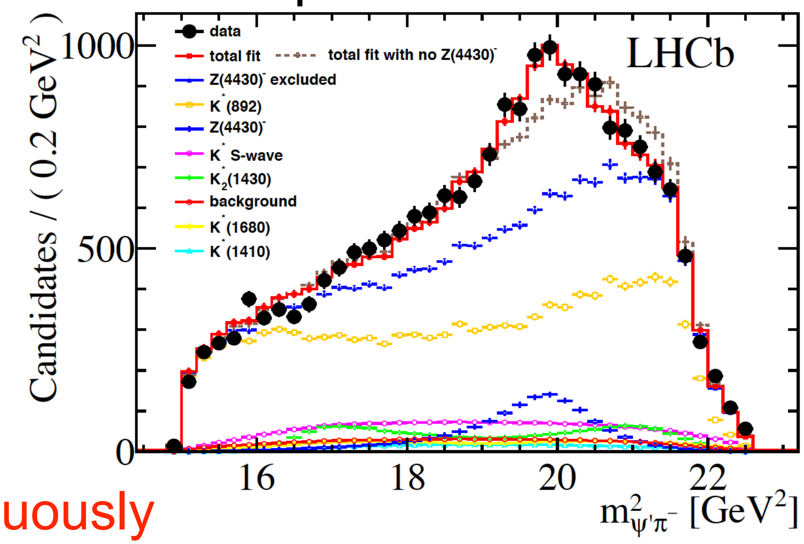


see also , LHCb-PAPER-2015-038 in preparation

LHCb Amplitude analysis

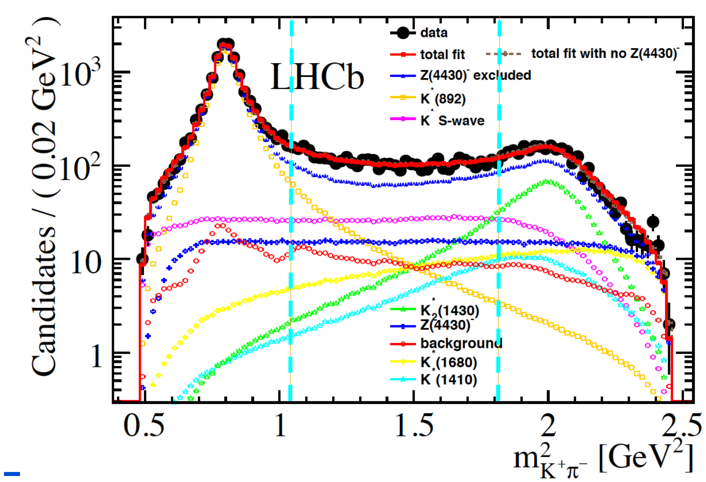
- Full 4D fit to both $K^* \to K^- \pi^+$ & $Z \to \psi' \pi^-$ states

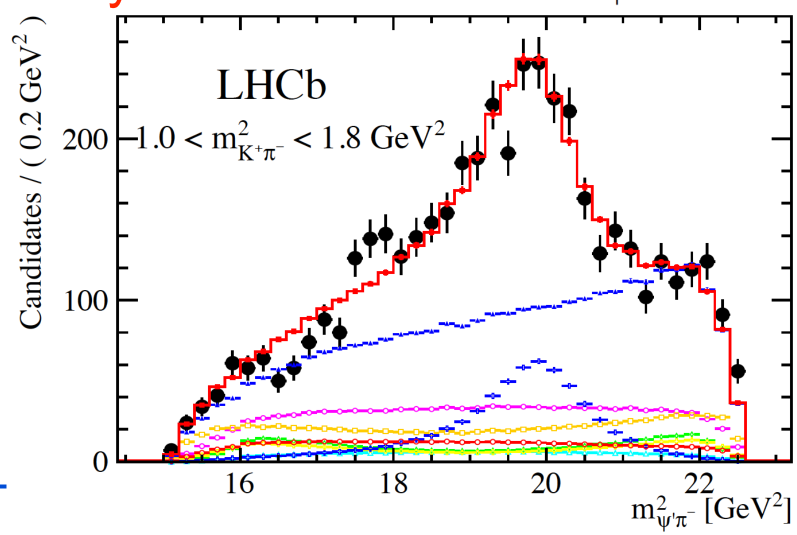




$J^P = 1^+$

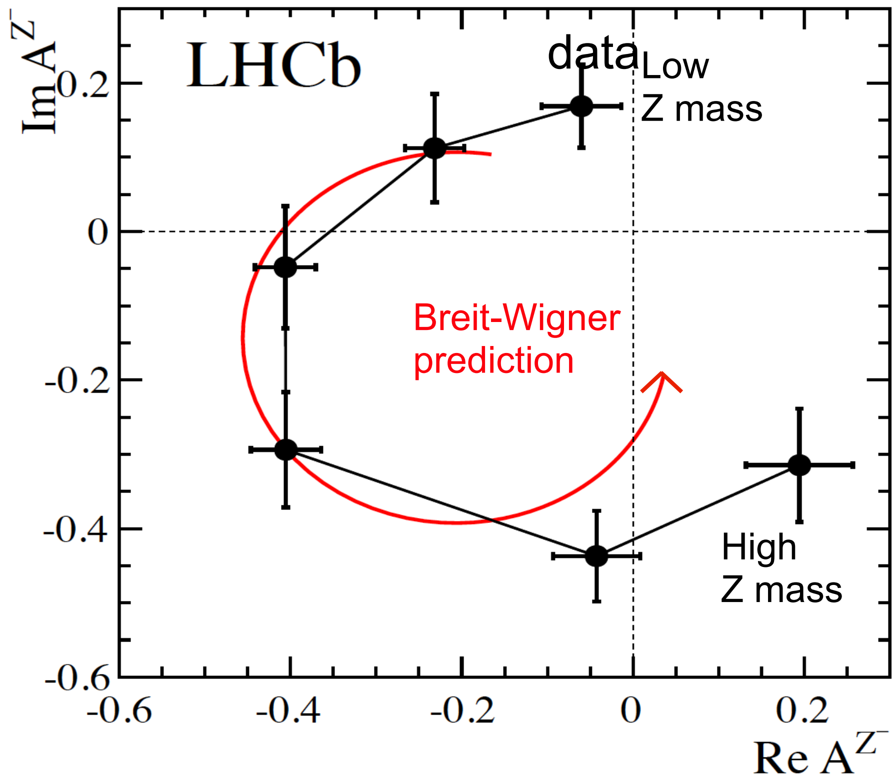
Unambiguously





Is it a resonance?

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



Other Explanations

- Molecule:

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

T. Barnes et.al, [arXiv:1409.6651

- Same scattering phase

as Breit-Wigner

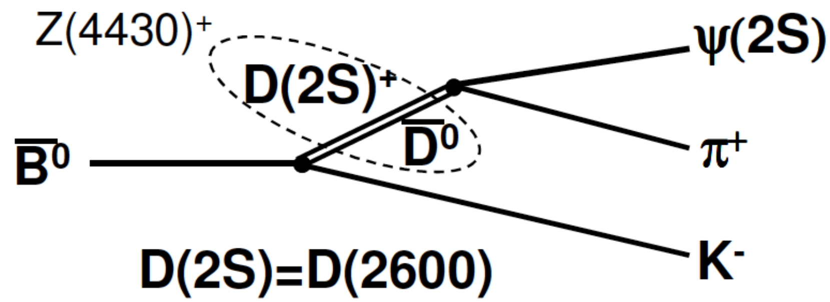
- Rescattering:

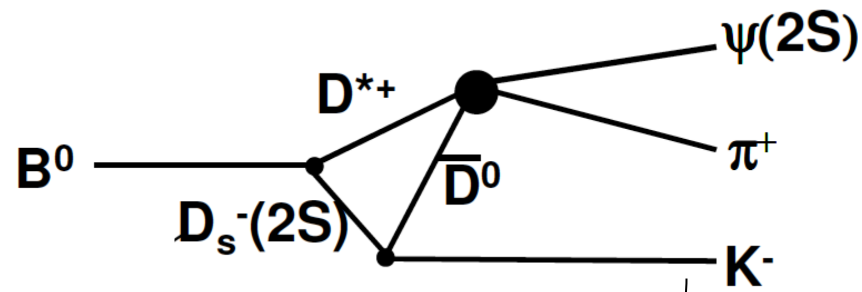
P. Pakhov & T. Uglov

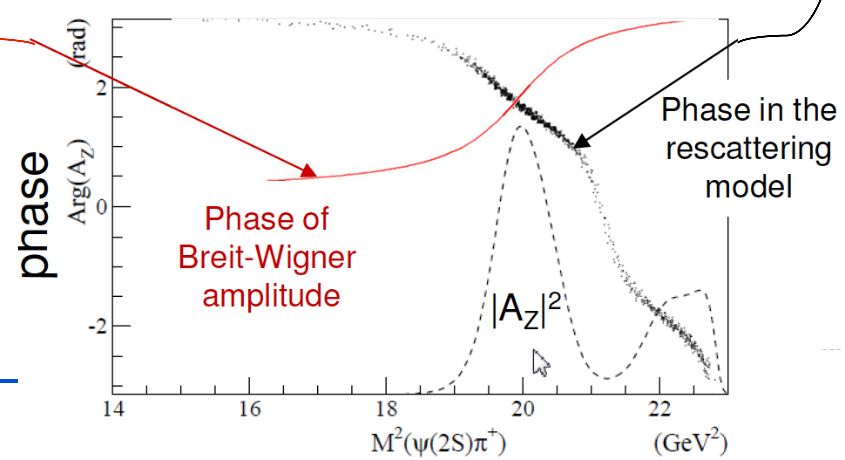
[arXiv:1408:5295]

- Opposite phase
- Ruled out by LHCb

Argand diagram



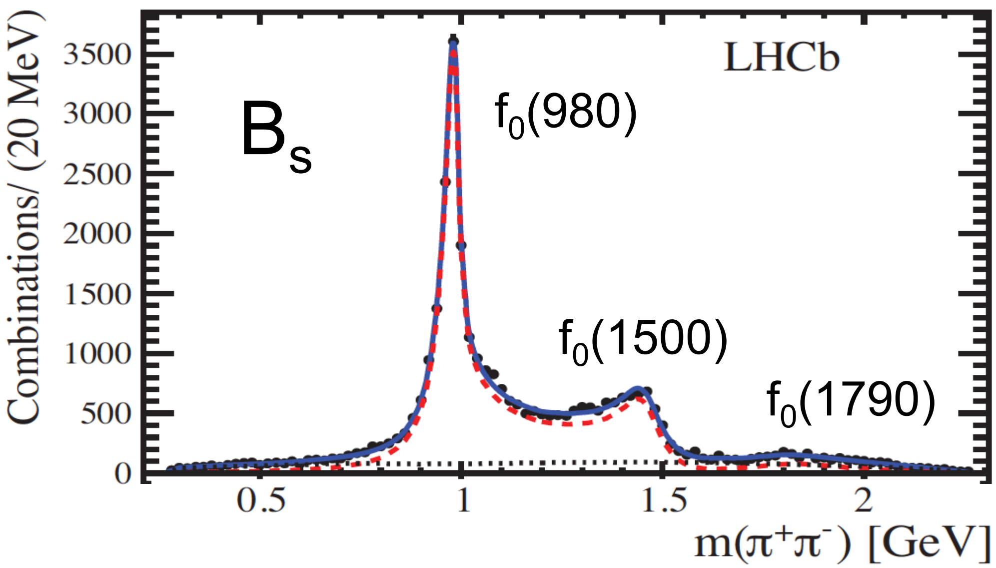


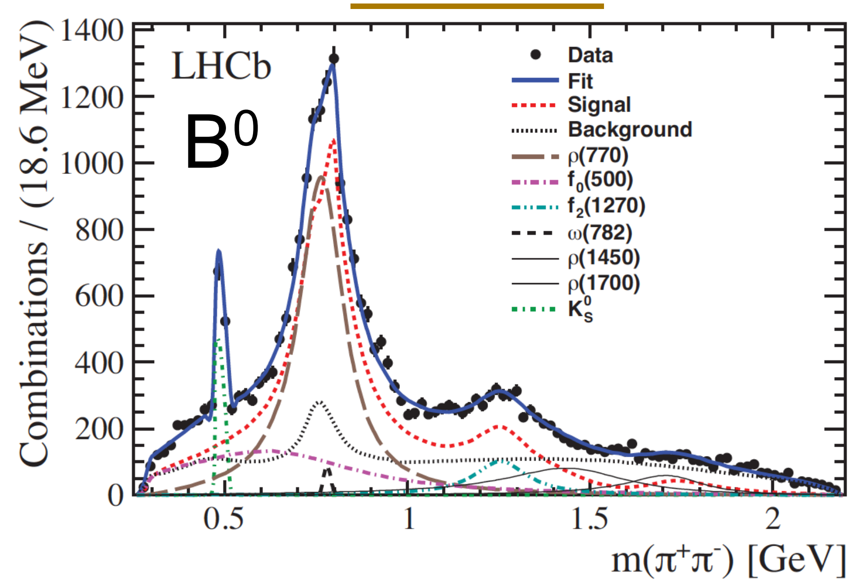


Light Scalar Mesons

$B \to J/\psi\pi^+\pi^-$ decays

- LHCb data arXiv:1402.6248 arXiv:1404.5673

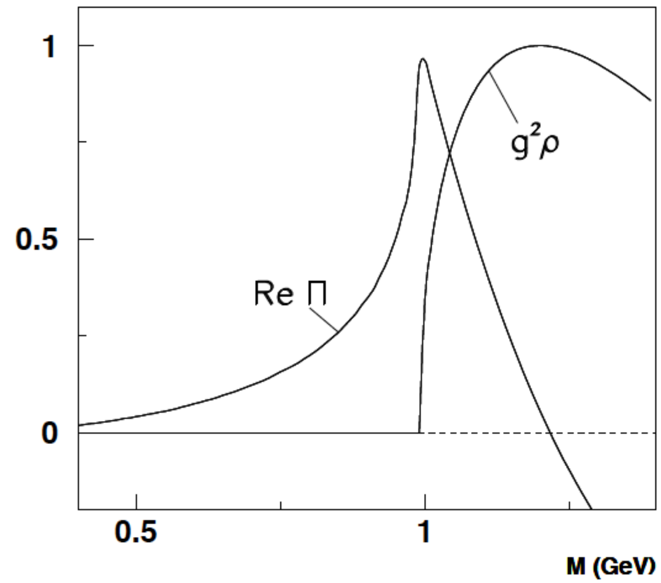




- Note large $f_0(980)$ in B_s & $f_0(500)\equiv\sigma$ in B^0
- Why is $f_0(980)$ so narrow? The mass is very close to threshold for K^+K^-, coupled channel decay into $\pi\pi$ & KK was parameterized by Flatte'

Thresholds & cusps

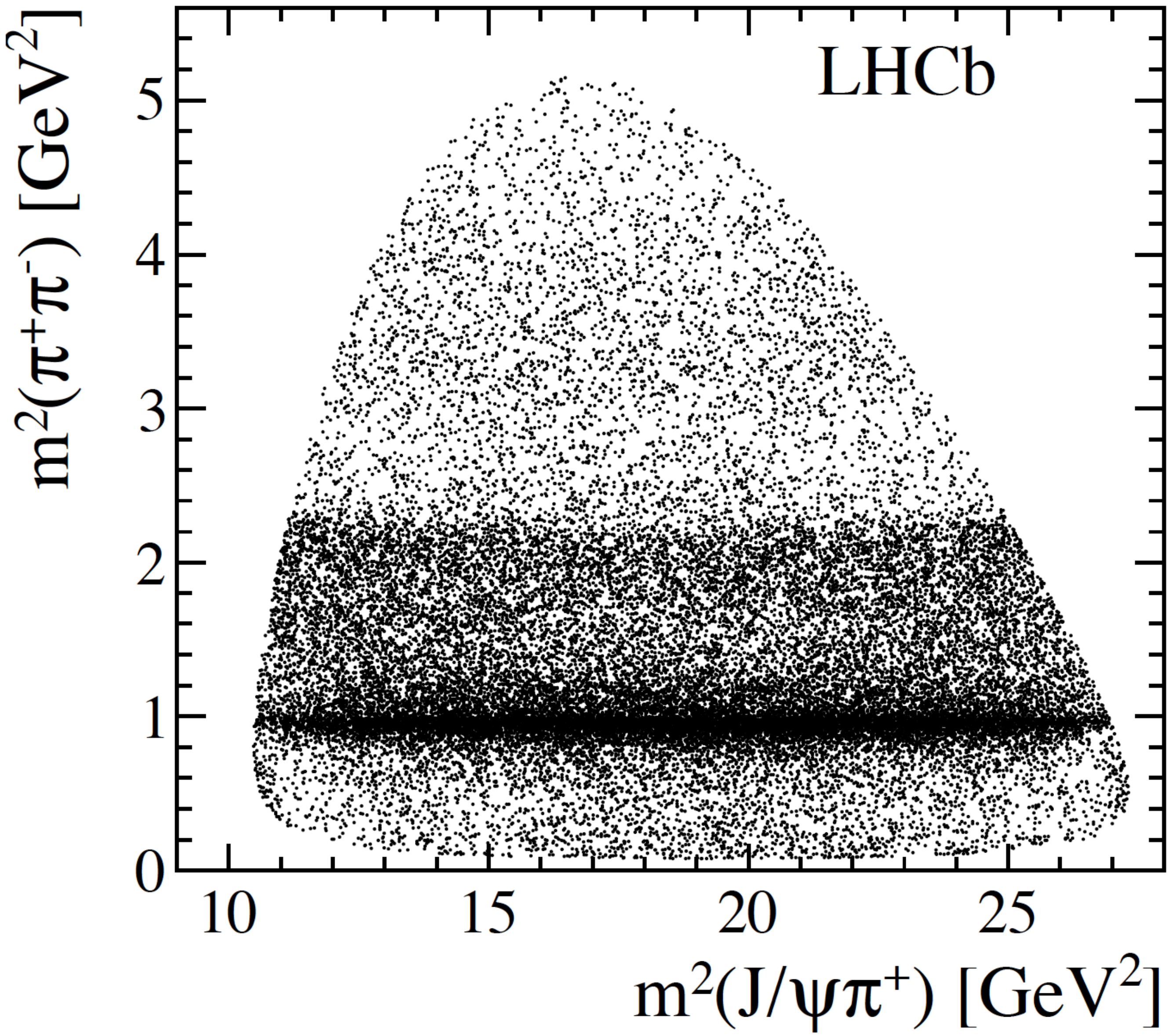
- In the context of a coupled channel model by Törnqvist, Bugg, arXiv: 0802.0934 has shown that the presence of a threshold can narrow down a resonance. The resonance is real, its structure is not important.



- Others have argued that the thresholds can mimic resonances. (See Swanson arXiv: 1409.3291). Even create a ~90^0 phase shift in Argand plane (Bugg arXiv:1105.5492)

Dalitz plot

No evidence for exotic structures in $J/\psi\pi^+$



Scalar meson quandry

- While 0^- and 1^- mesons follow a simple rule that adding an s-quark increases their mass, the 0^+ mesons are difficult to understand in this context

Isospin	1^- state	mass	$q\bar{q}$	0^+ state	mass
1	ρ	776 MeV	$(u\bar{u}+d\bar{d})\sqrt{2}$	$a_0(980)$	980 MeV
0	ω	783 MeV	$(u\bar{u}-d\bar{d})\sqrt{2}$	$f_0(500)$ or $\boldsymbol{\sigma}$	500 MeV
1/2	K*(892)	892 MeV	(u or d) $\bar{s}$	$\kappa(800)$	800 MeV
0	ϕ	1020 MeV	$s\bar{s}$	$f_0(980) \equiv f_0$	980 MeV

- σ & $f_0(980)$ may be mixed by angle ϕ
- Suggestions that scalars are tetraquarks

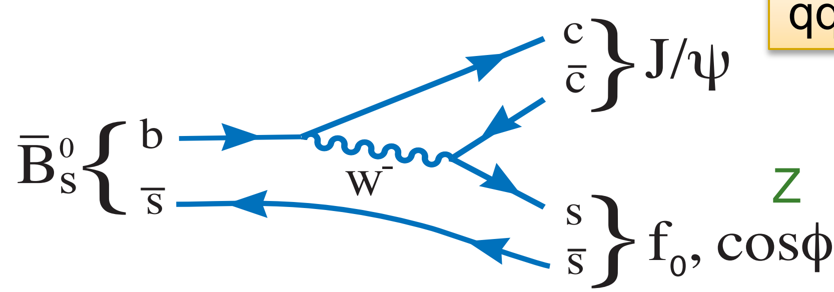
B_s decay diagrams

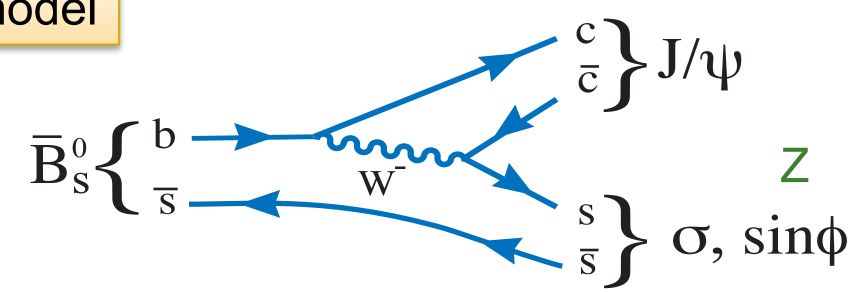
$$\Gamma(\bar{B}^0_s \to J/\psi f) = C\left|F^f_{B_s}\left(m^2_{J/\psi}\right)\right|^2 \left|V_{cs}\right|^2 \Phi Z^2$$

form factor phase space coupling

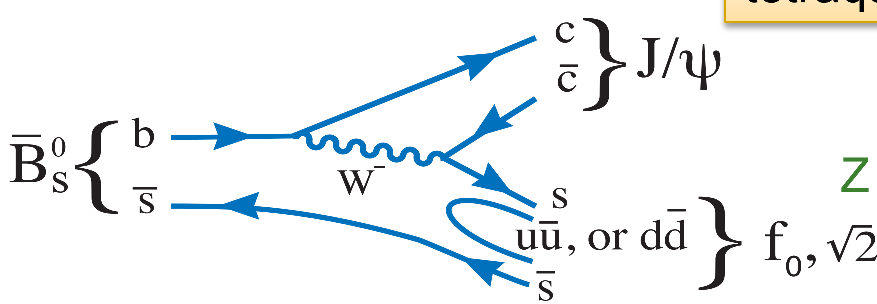
Stone & Zhang arXiv:1305.6554

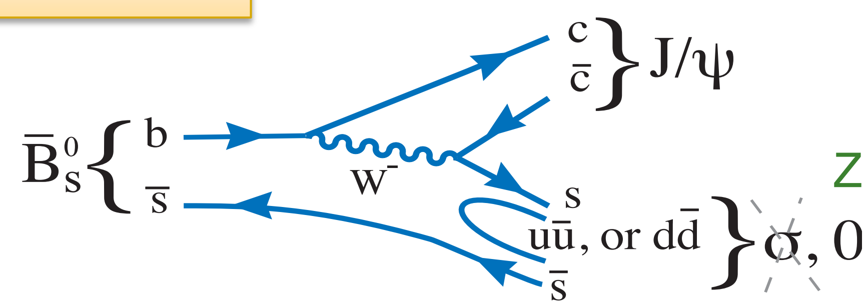
qq̄ model





tetraquark model



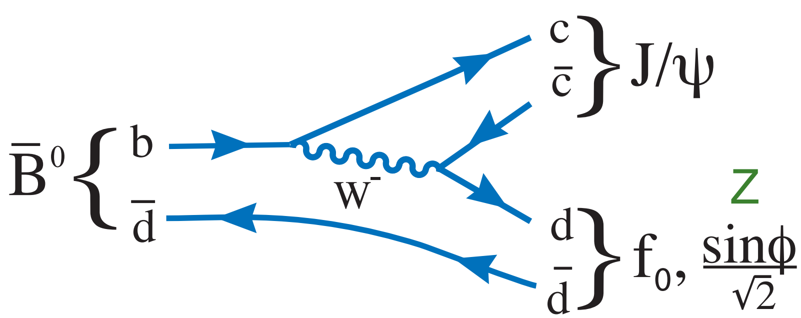


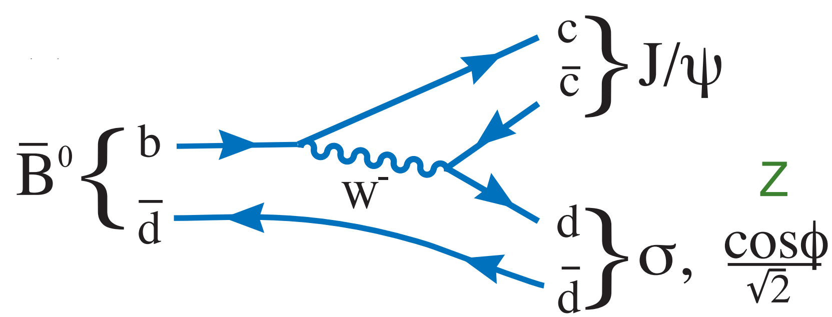
First prediction: If σ is a tetraquark it will not be seen in $B_s \to J/\psi\sigma$

B^0 decay diagrams

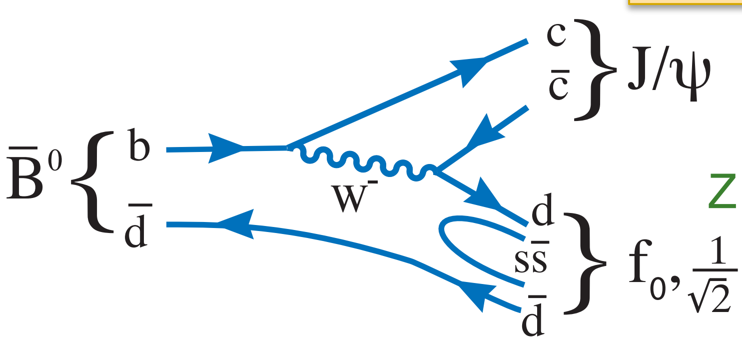
$$\Gamma(\bar{B}^0 \to J/\psi f) = C\left|F^f_{B^0}\left(m^2_{J/\psi}\right)\right|^2 \left|V_{cd}\right|^2 \Phi Z^2$$

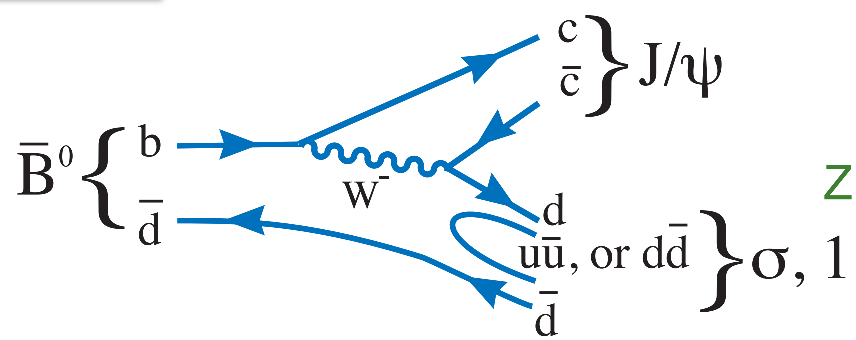
q$\bar{q}$ model





tetraquark model





Rate ratios

Label	Mode ratio	Rate ratio	$\mathcal{Z}^2$ $q\bar{q}$	$\mathcal{Z}^2$ tetraquark
$r^{0f_0}_{sf_0}$	$\dfrac{\Gamma(\bar{B}^0 \to J/\psi\, f_0)}{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)}$	$= \dfrac{\lvert F^{f_0}_{B^0}(m^2_{J/\psi})\rvert^2}{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2} \dfrac{\lvert V_{cd}\rvert^2 \Phi^{f_0}_{B^0}}{\lvert V_{cs}\rvert^2 \Phi^{f_0}_{B^0_s}}$	$\frac{1}{2}\tan^2\phi$	$\frac{1}{4}$
$r^{0f_0}_{0\sigma}$	$\dfrac{\Gamma(\bar{B}^0 \to J/\psi\, f_0)}{\Gamma(\bar{B}^0 \to J/\psi\, \sigma)}$	$= \dfrac{\lvert F^{f_0}_{B^0}(m^2_{J/\psi})\rvert^2}{\lvert F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert^2} \dfrac{\Phi^{f_0}_{B^0}}{\Phi^{\sigma}_{B^0}}$	$\tan^2\phi$	$\frac{1}{2}$
$r^{s\sigma}_{sf_0}$	$\dfrac{\Gamma(\bar{B}^0_s \to J/\psi\, \sigma)}{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)}$	$= \dfrac{\lvert F^{\sigma}_{B^0_s}(m^2_{J/\psi})\rvert^2}{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2} \dfrac{\Phi^{\sigma}_{B^0_s}}{\Phi^{f_0}_{B^0_s}}$	$\tan^2\phi$	0
$r^{sf_0}_{0\sigma}$	$\dfrac{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)}{\Gamma(\bar{B}^0 \to J/\psi\, \sigma)}$	$= \dfrac{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2}{\lvert F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert^2} \dfrac{\lvert V_{cs}\rvert^2 \Phi^{f_0}_{B^0_s}}{\lvert V_{cd}\rvert^2 \Phi^{\sigma}_{B^0}}$	2	2

Last ratio is independent of model, allows measurement of form factor ratio of $0.99^{+0.13}_{-0.04}$

LHCb results

- $r^{0 f_0}_{0\sigma}$ <0.098 @ 90% cl, should be ½ for tetraquark, suggests the f_0 & σ are $q\bar{q}$ states
- Possible deviations caused by tetraquark mixing, isospin violation, etc…
- If $q\bar{q}$, mixing angle $|\phi|$ <17^{o} at 90% cl arXiv: 1404.5673

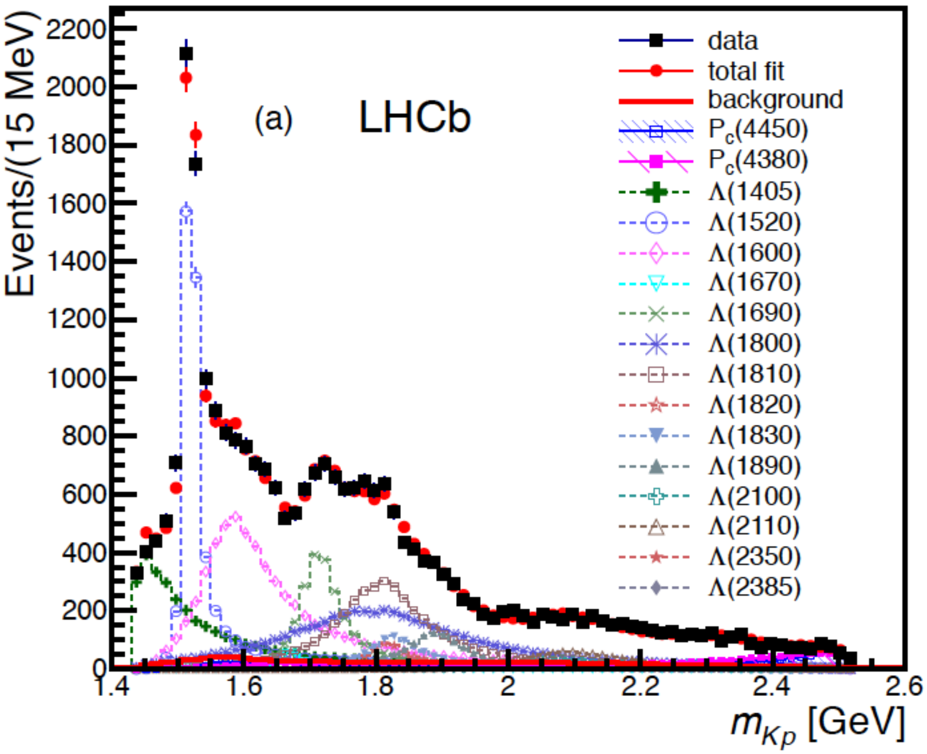
Conclusions

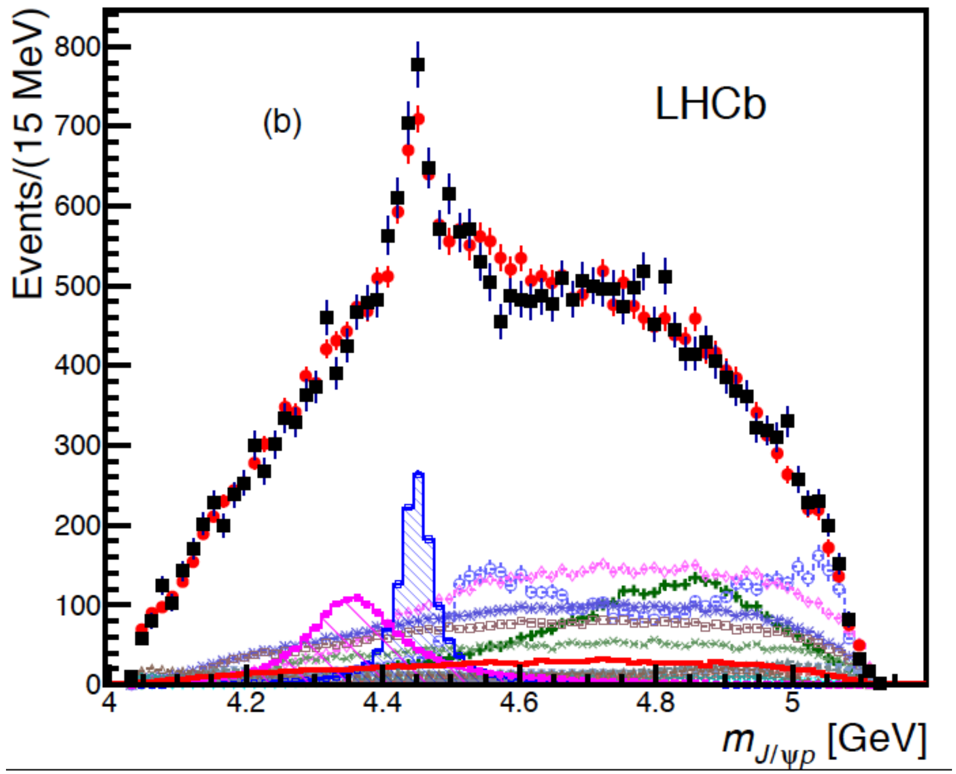
- LHCb has found two resonances decaying into $J/\psi p$ with pentaquark content of $uudc\bar{c}$ arXiv:1507.03414.
- Determination of their internal binding will require more study. They have spin 3/2 & 5/2 & opposite P
- Other exotic states have appeared containing $c\bar{c}$ quarks: the $Z^+(4430)\rightarrow\psi' K^-\pi^+$ 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
- The 0^+ f_0 & σ appear to be $q\bar{q}$
- We look forward to further searches for exotics

The End

US LHCb groups gratefully acknowledge support from the NSF

Extended model with 2 P_c's





Amplitude formalism

- The amplitude for the Λ^* decay sequence is given by

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

- For the P_c:

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

Amplitude formalism II

- The amplitude for the Λ^* decay sequence is given by

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

- For the P_c:

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

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

Amplitude formalism III

- The amplitude for the Λ^* decay sequence is given by

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

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

- 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 formalism IV

- Λ^* decay sequence is given by

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

- 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 formalism V

- They are summed 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 & θ_p are rotation angles needed to align the final state helicity axes of the μ & p, as the initial helicity frames 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