Tetraquarks and pentaquarks

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28 Recontres de Blois, June 2, 2016

Why interest in exotics?

- Interest in tetraquarks, pentaquarks, hybrids & glueballs 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
  - Tetraquarks & pentaquarks Predicted by Gell-Mann (64), Zweig (64)
  - No time to speak about hybrids & glueballs

Themes

- Modern searches cannot be content just observing “bumps” in mass spectra. Especially in 3 body decay modes amplitude analysis is essential. Argand plots can show BW type behavior.
- Eventual observation of states in different production modes is essential
- Note that the 2004 pentaquark searches failed these criteria [see Hicks Eur. Phys. J. H37 (2012) 1.]
- I start with pentaquarks

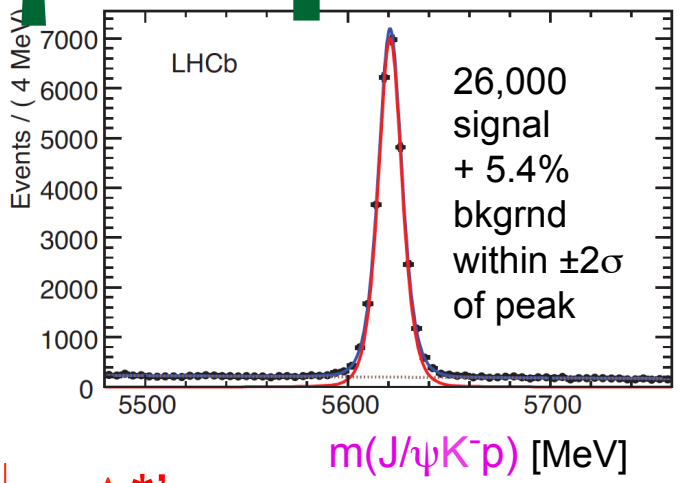
$\Lambda_b \rightarrow J/\psi K^- p$

- This decay had not been seen before
- Large signal found, used for Λ_b lifetime measurement [arXiv:1402.6242]
- 3 body decay,

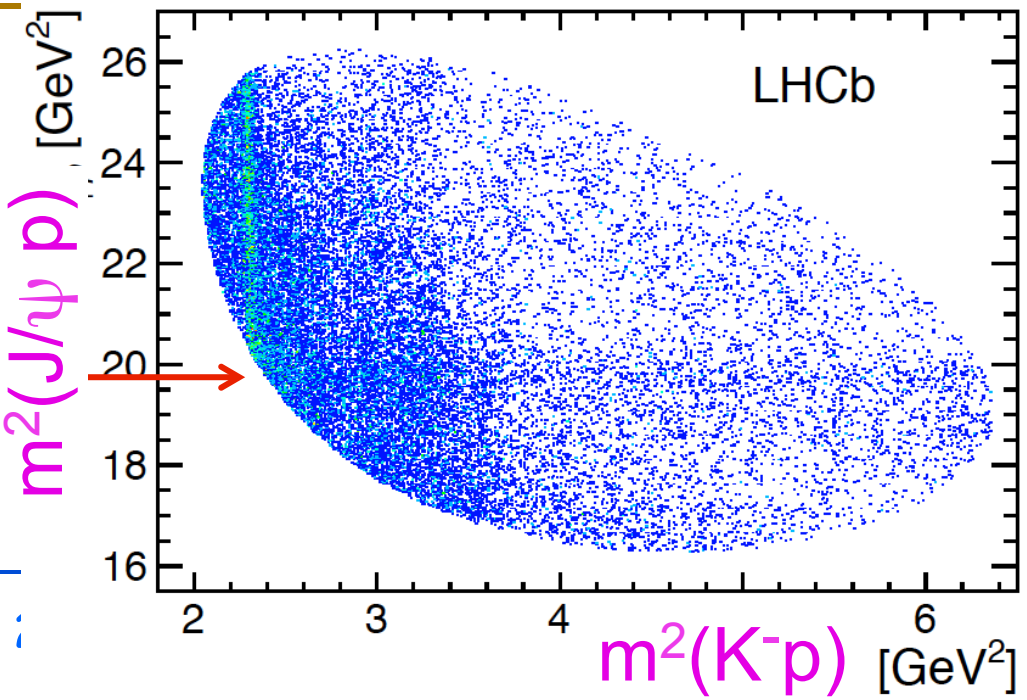
Make a Dalitz plot.

Showed an unusual feature

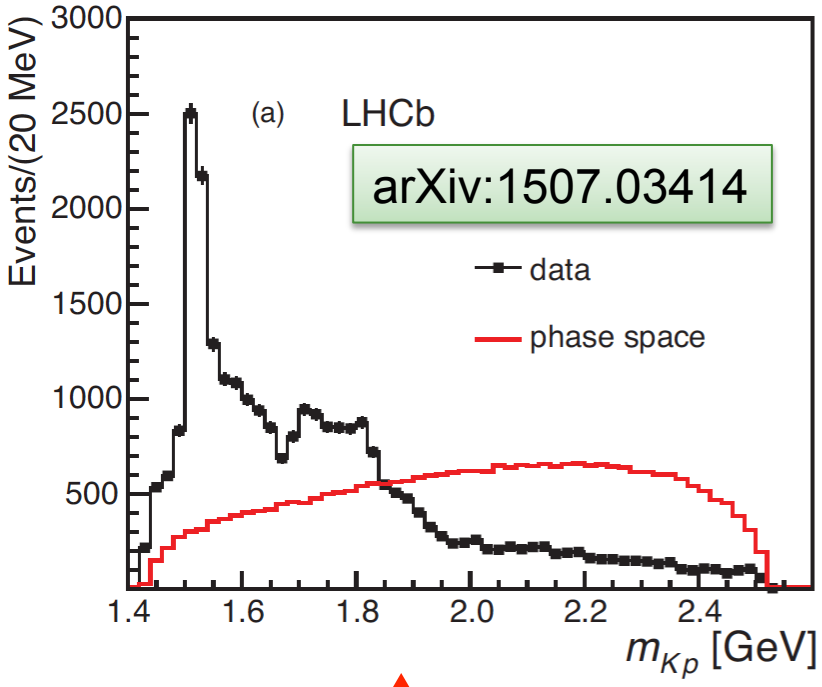
[arXiv:1507.03414]

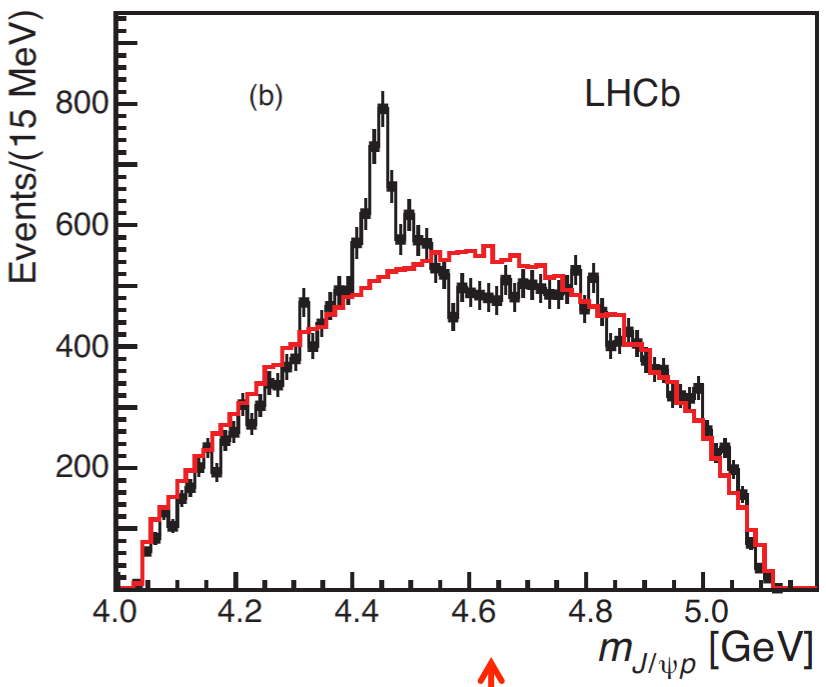


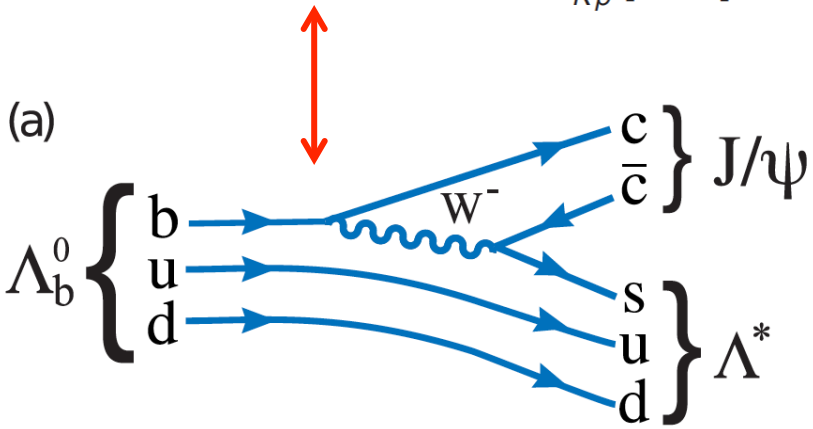
↓ ↓ ↓ …Λ*'s

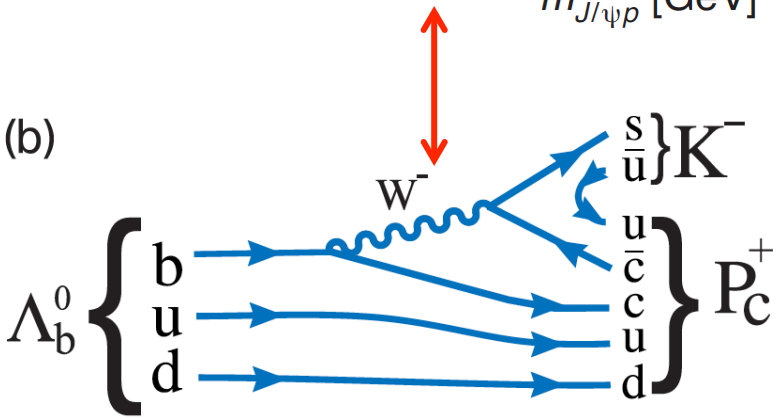


Projections









Does a 4 quark +$\overline{q}$ state 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:

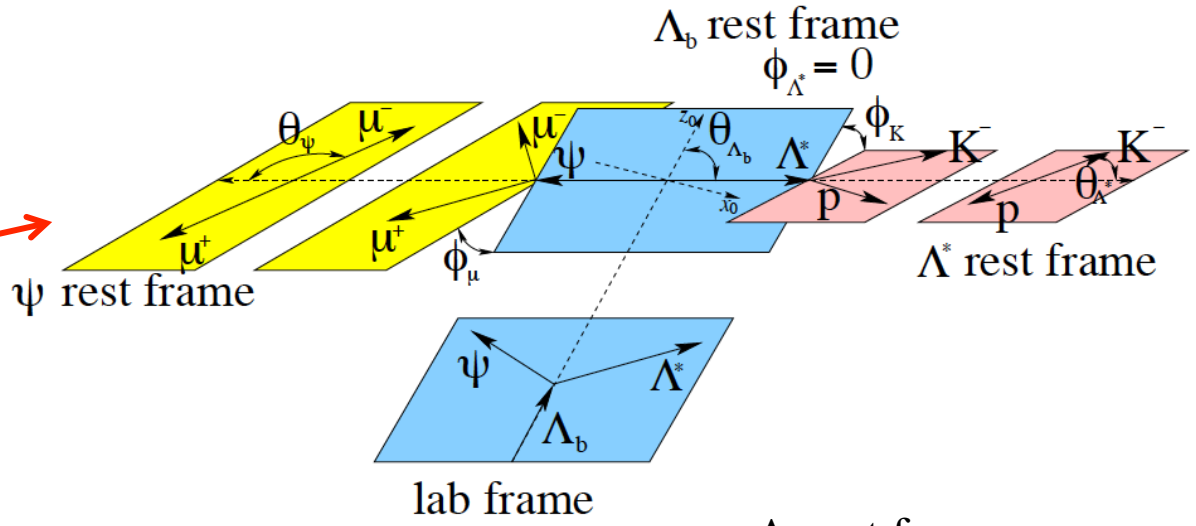
Matrix Element

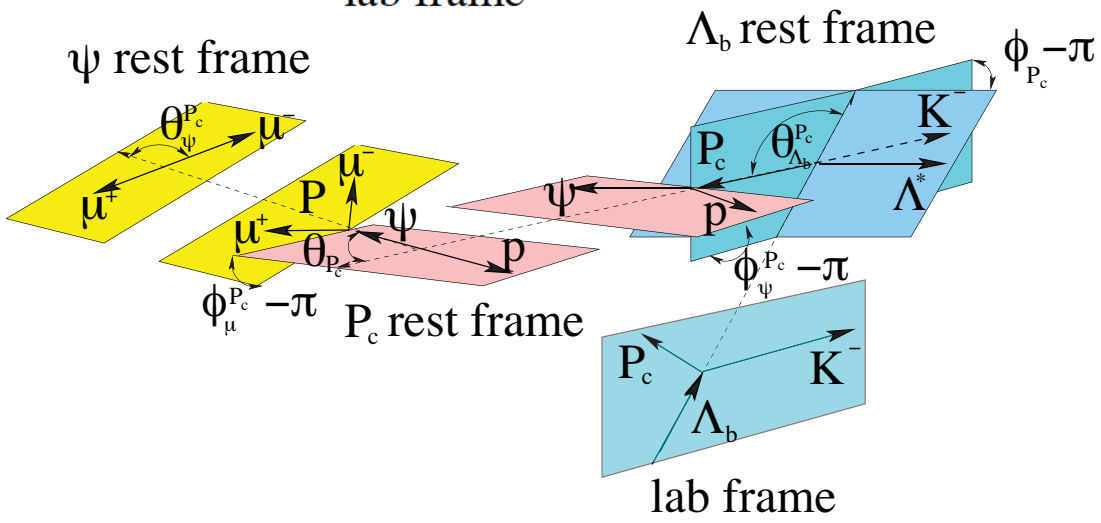
- Two interfering channels:

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

&

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





- Use m(K^-p) & 5 decay ∠'s as fit parameters
- Resonance mass shapes: Breit-Wigner or Flatte′

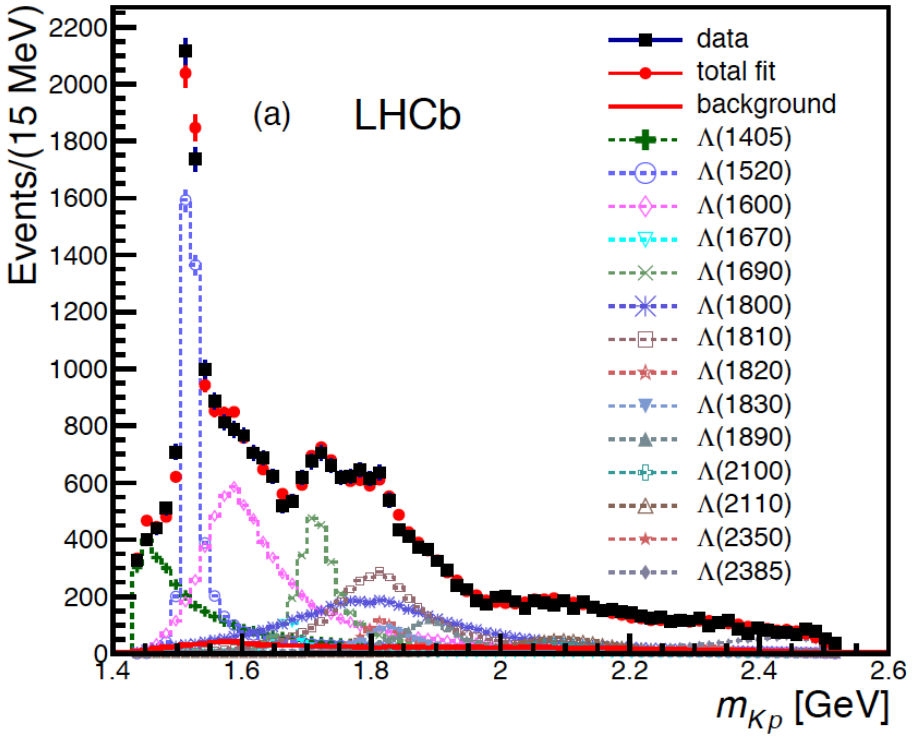
Models: extended & reduced

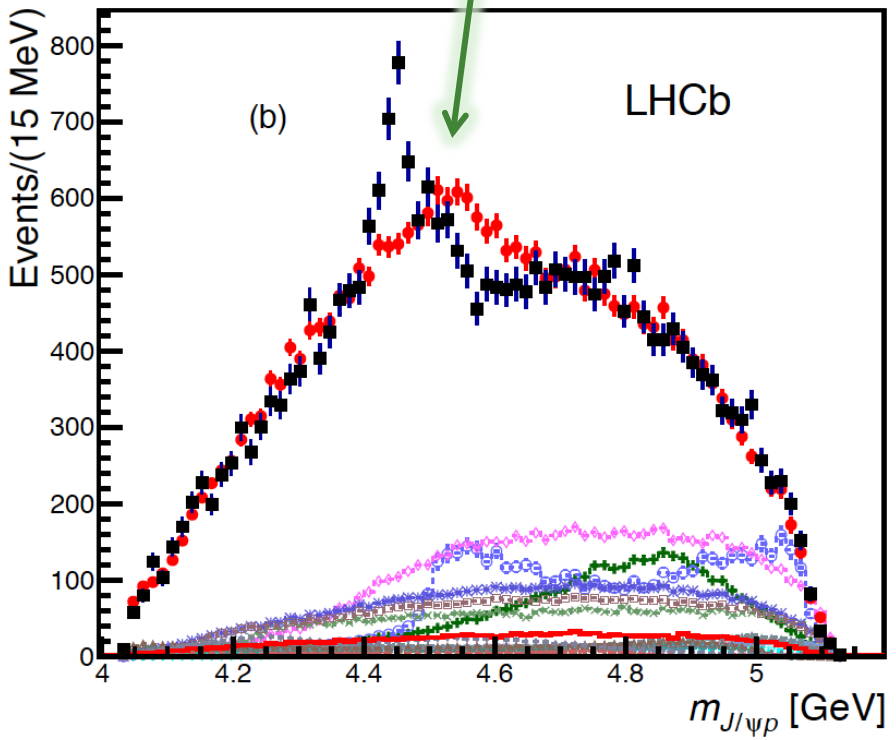
- Consider all Λ* states & all allowed L values

	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

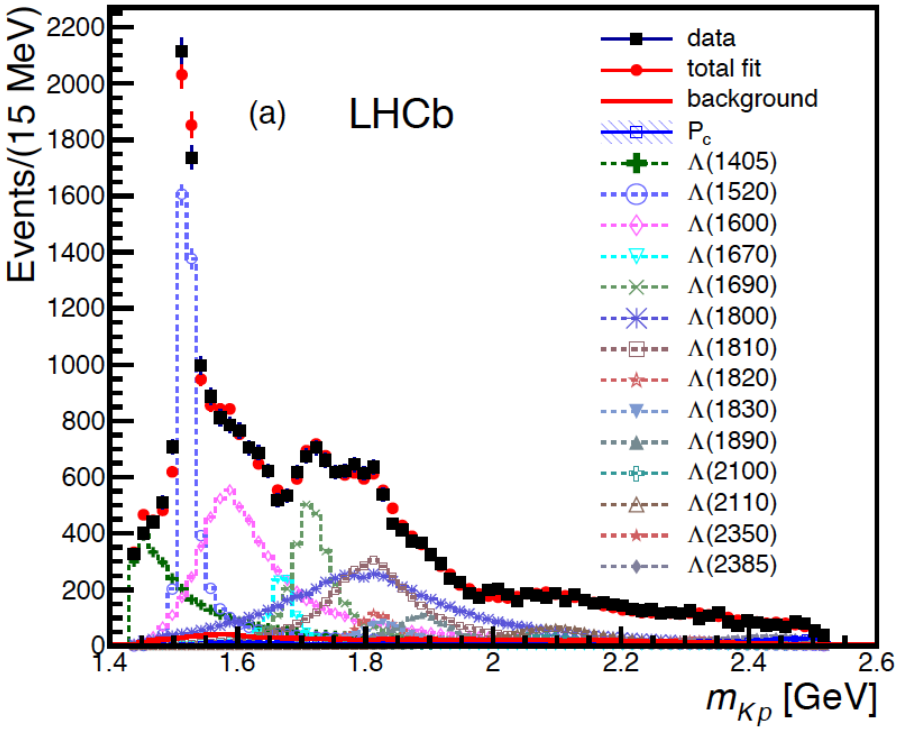
- Use extended model, so all possible known Λ^* amplitudes. m_{Kp} looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant, extra Λ^*'s doesn't help

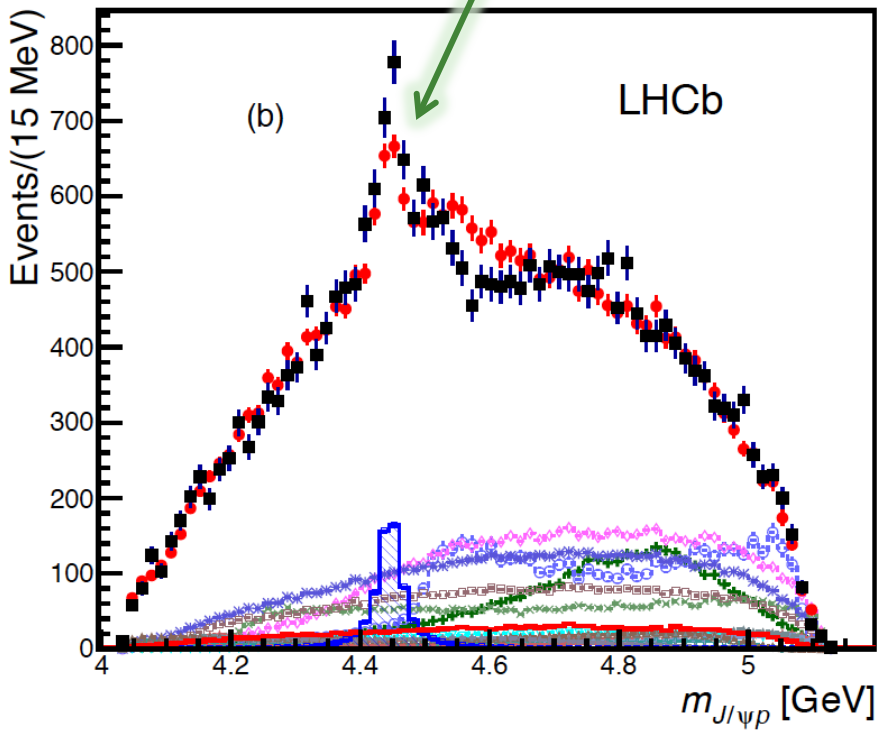




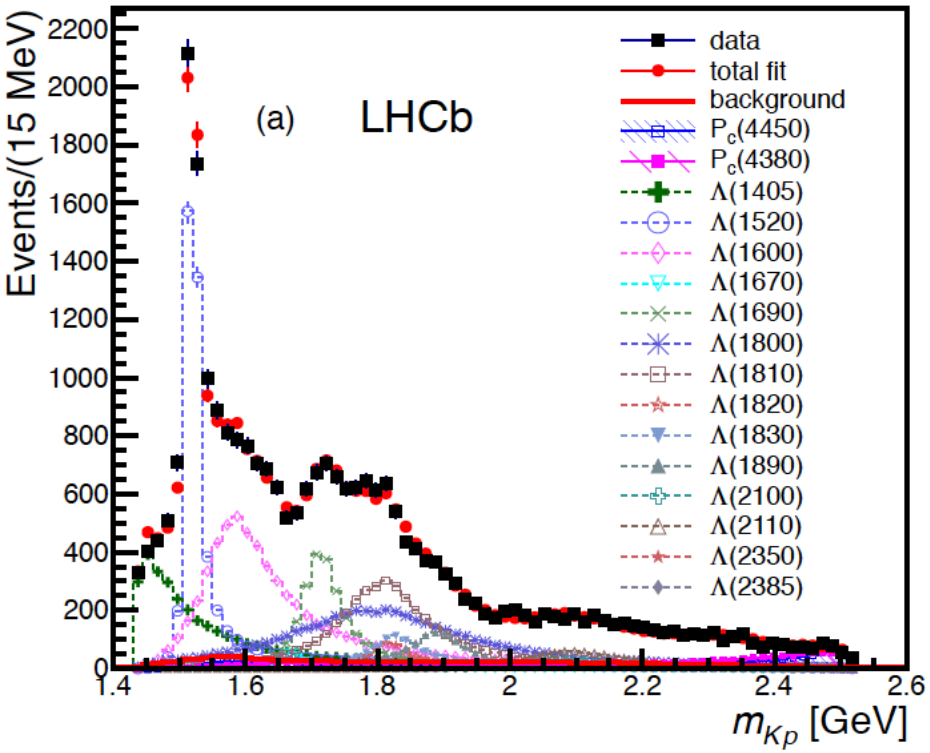
Extended model with 1 P_c

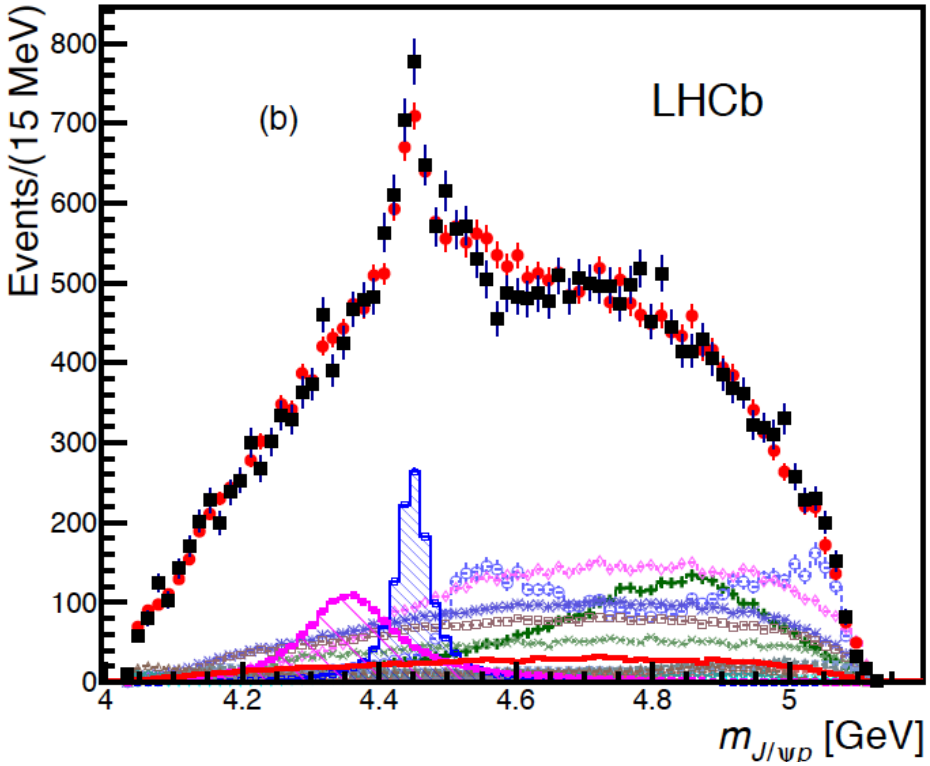
- Try all J^P up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit





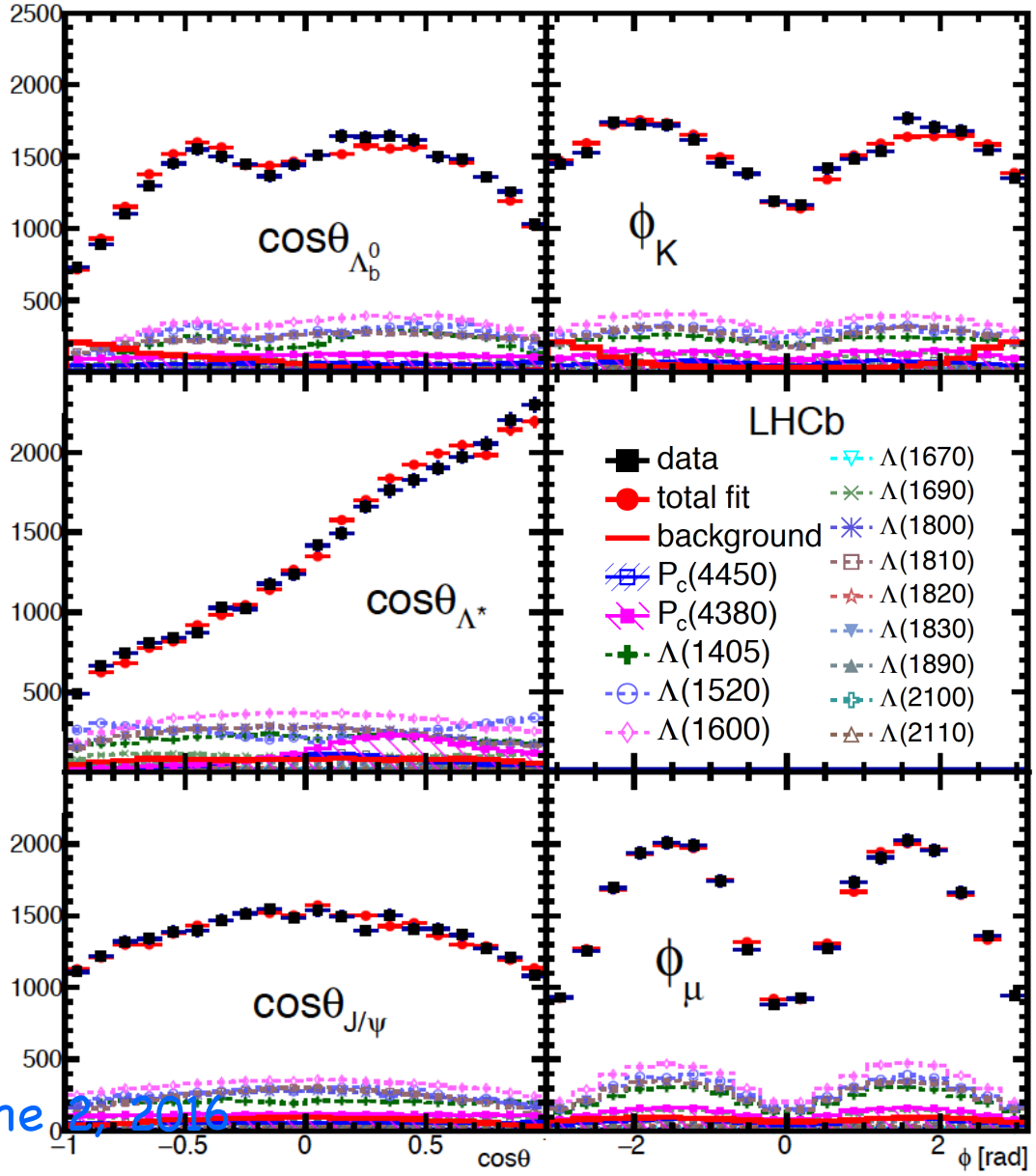
Extended model with 2 P_c's





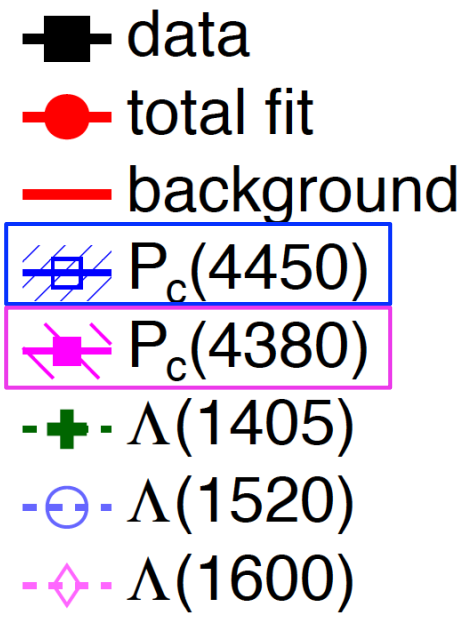
Angular distributions

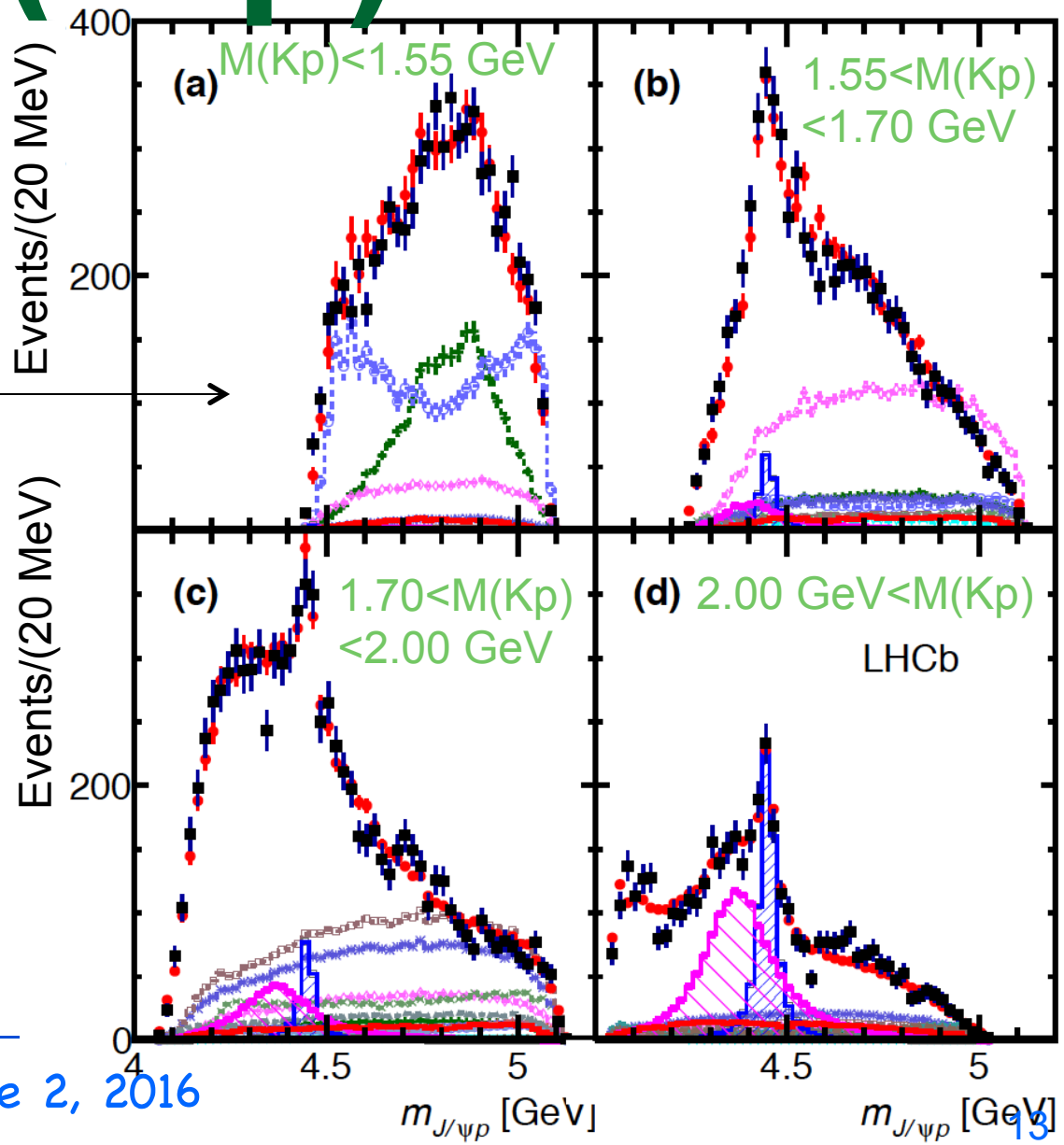
Good fits in the angular variables



In $m(K^-p)$ slices

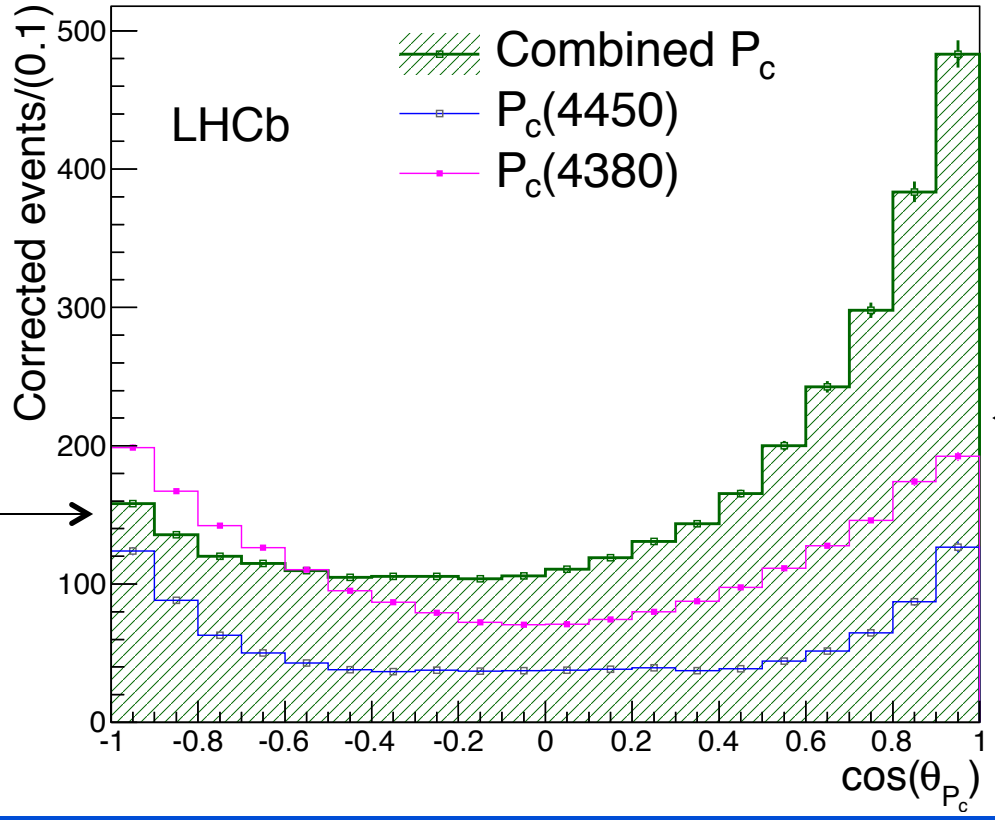
P_c's cannot appear in first interval as they would be outside of the Dalitz plot boundary





Data demands 2 states

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

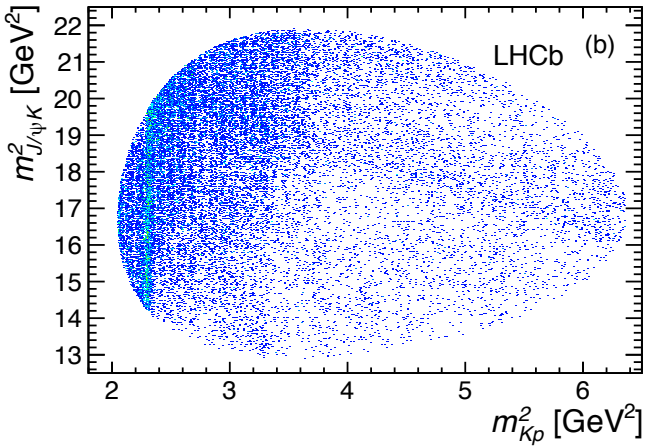


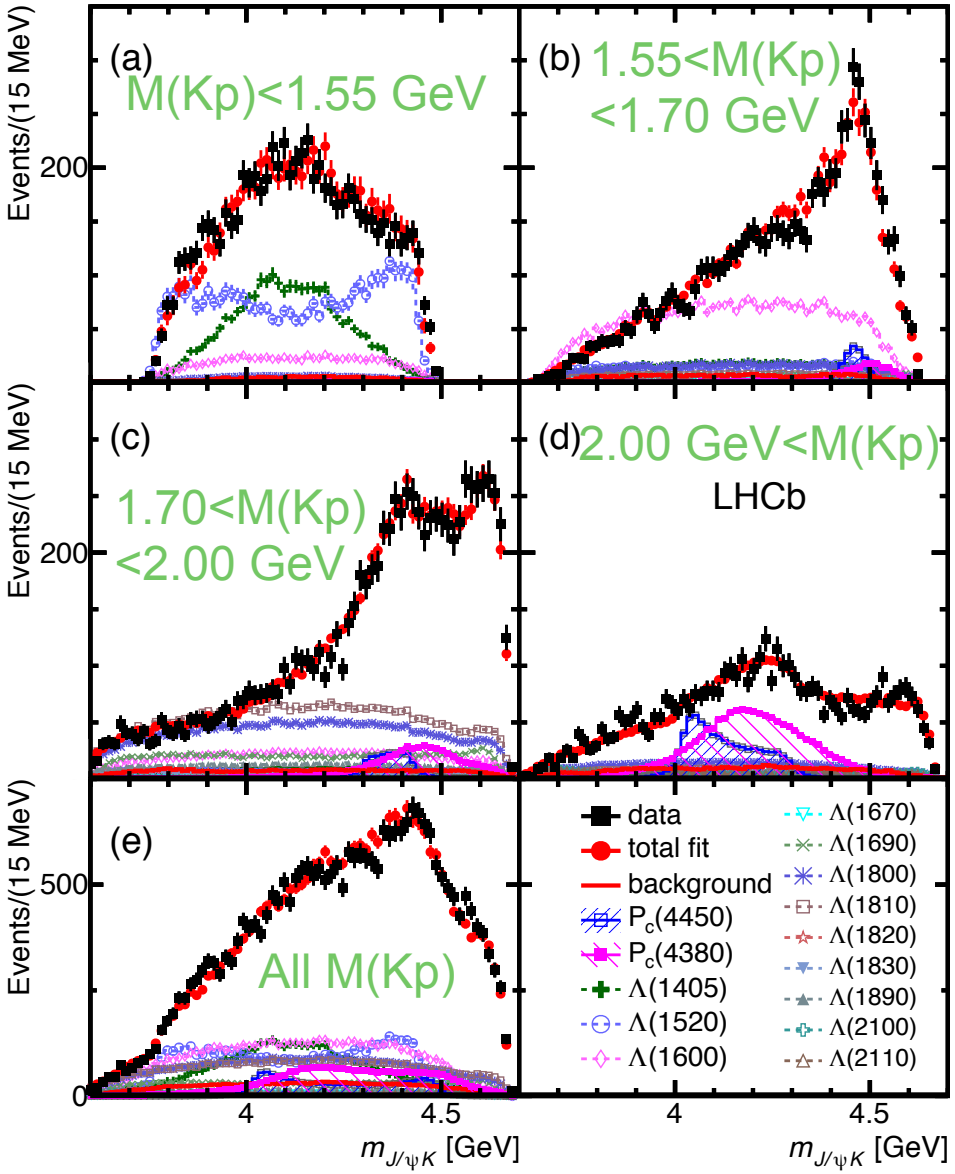
Large m(Kp) region negative interference

Small m(Kp) region positive interference

m(J/ψ K-)

- Our fit explains m(J/ψ K-)



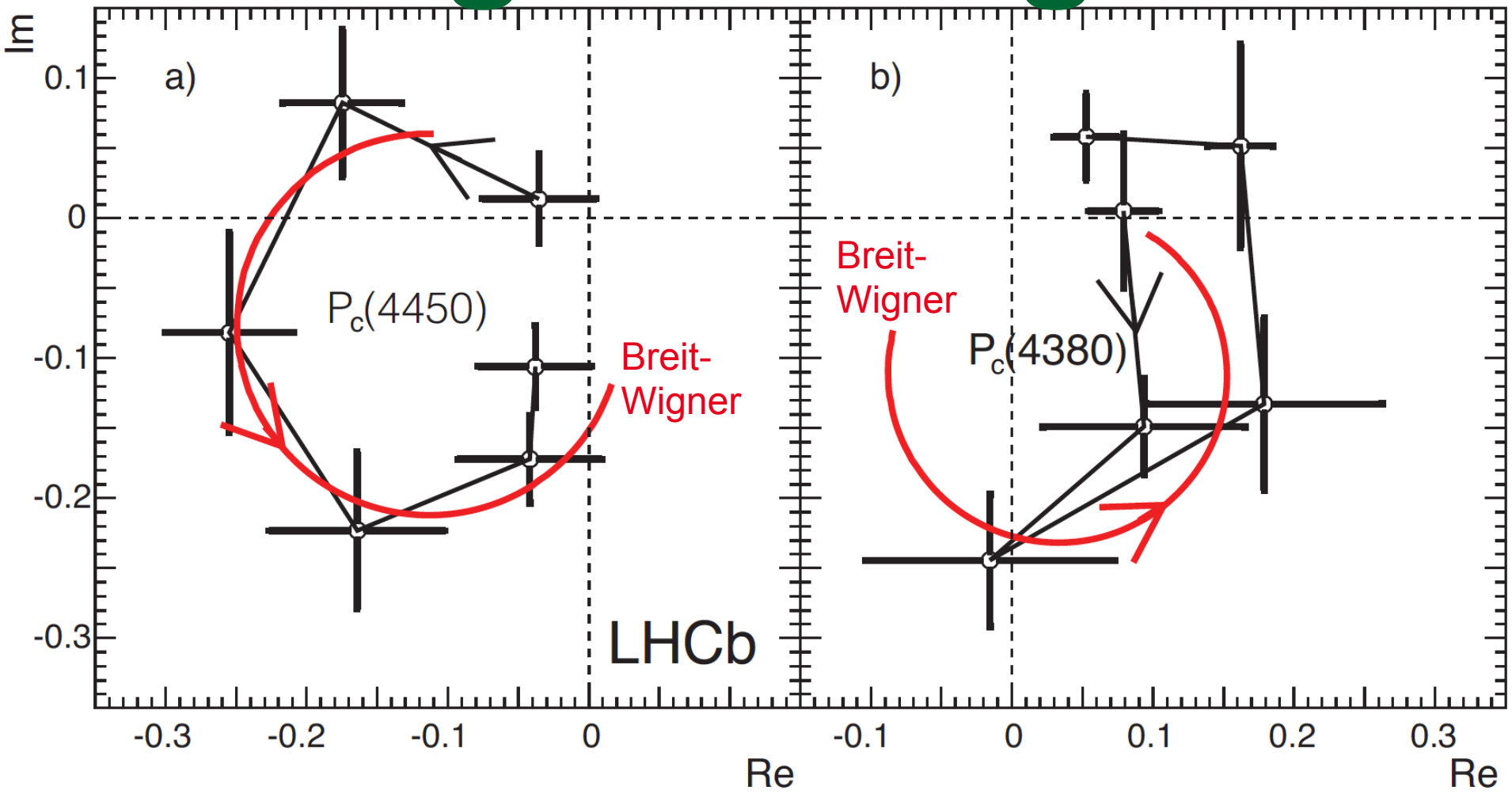


Fit results

Using toy simulations 1st state has significance of 9σ & 2nd state 12σ, including systematic uncertainties. (See G. Cowen's talk for model independent analyses, [arXiv:1604.05708])

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

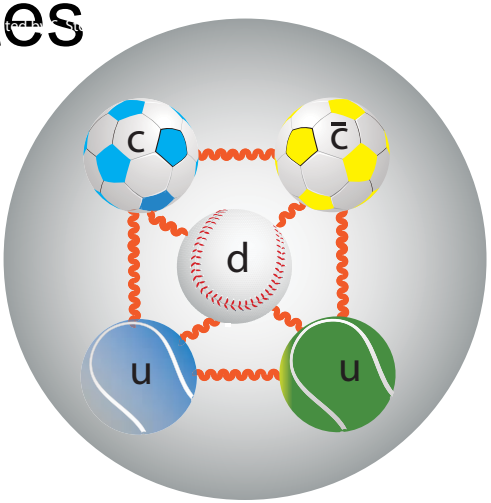
Argand diagrams



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

Pentaquark models

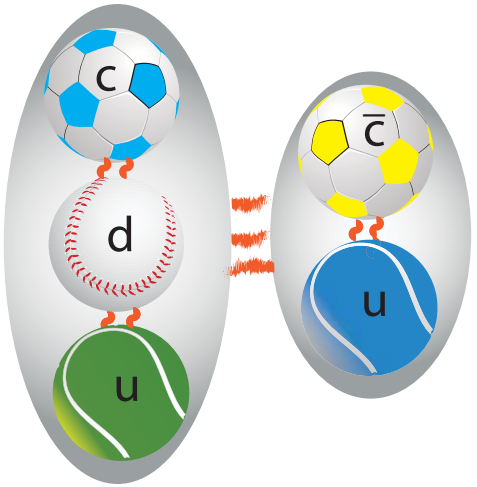
- All models must explain J^P of two states not just one. They also should predict properties of other states: masses, widths, J^P. Many models: Lets start with **tightly bound quarks** ala' Jaffe



  - 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]
  - Based on Bag model, Jaffe; Strings, Rossi & Veneziano [Nucl. Phys. B123 (1977) 507]

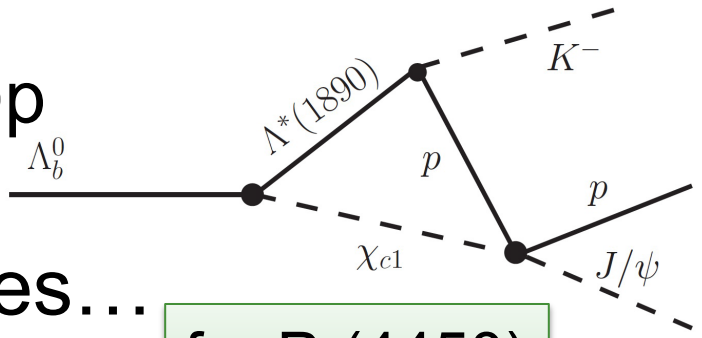
Molecular models

- Molecular models, generally with meson exchange for binding
- Ala′ Törnqvist [Z. Phys. C61 (1994) 525]
- Several authors consider Σ_c $D^{(*)}$ components (most of these are postdictions)
- Baryocharmonium which is a molecular like state of J/ψ N [arXiv:1508.00888]



Rescattering

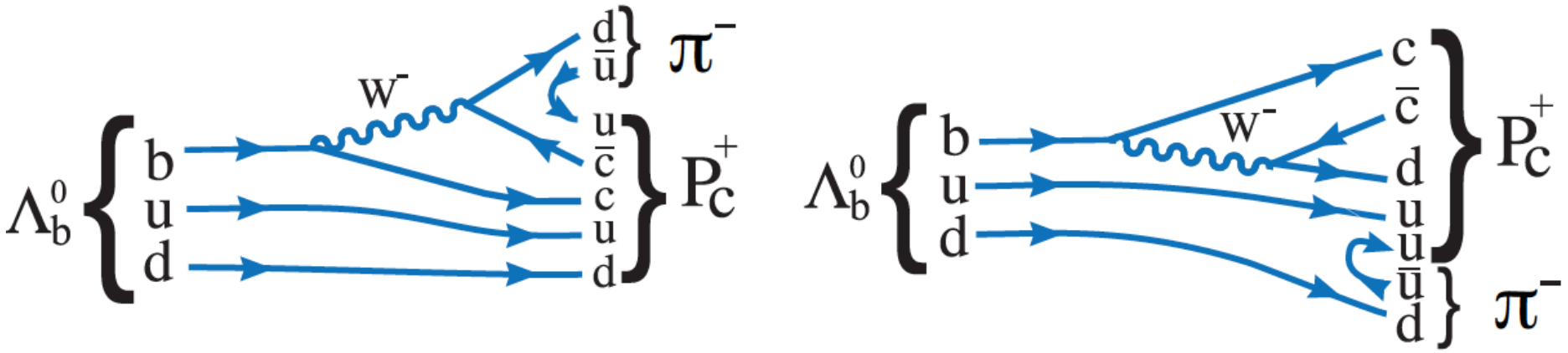
- These are mostly postdictions
- They construct an amplitude that must mimic mass shape & phase variation of a BW
- eg. $\Lambda_b \to XY(Z) \to J/\psi p K^-$, especially when $m(XY)=m(P_c)$, hence the word "cusp"
- These models have so far not predicted the size of the rescattering amplitude
- In one model $\Lambda_b \to K^- \chi_{c1} p \to K^- J/\psi p$
  Guo et. al [arXiv:1507.04950, 1605.05113]
- Also difficult to predict two states…



for $P_c(4450)$ only

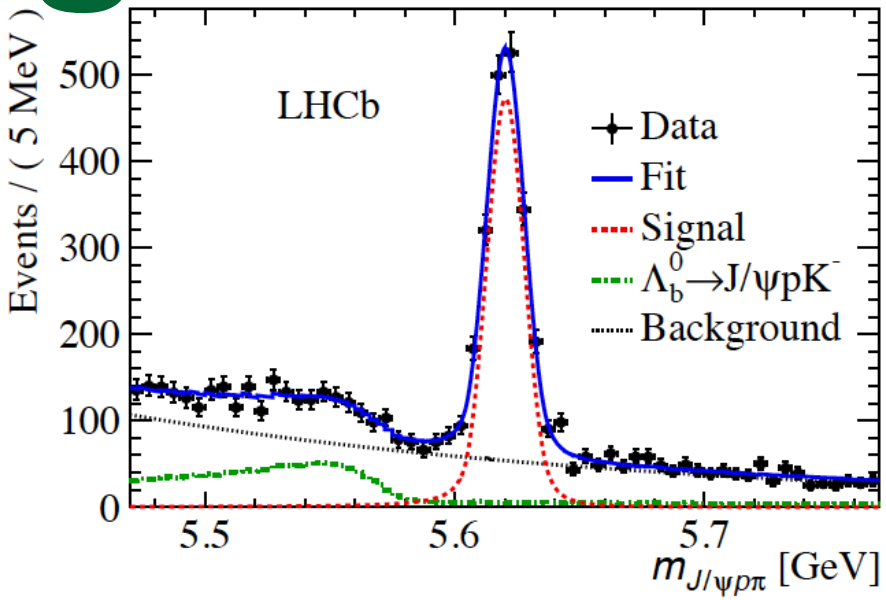
$\Lambda_b \rightarrow J/\psi\pi^- p$

- Expect the Λ_b branching fractions to the pentaquark states to be on the order of 5% of $J/\psi K^- p$ due to Cabibbo suppression ($W^- \rightarrow \bar{c}d/\bar{c}s$).
- However, in $J/\psi\pi^- p$ there is an additional pentaquark diagram, & these can interfere, altering somewhat the P_c state yields



Signal

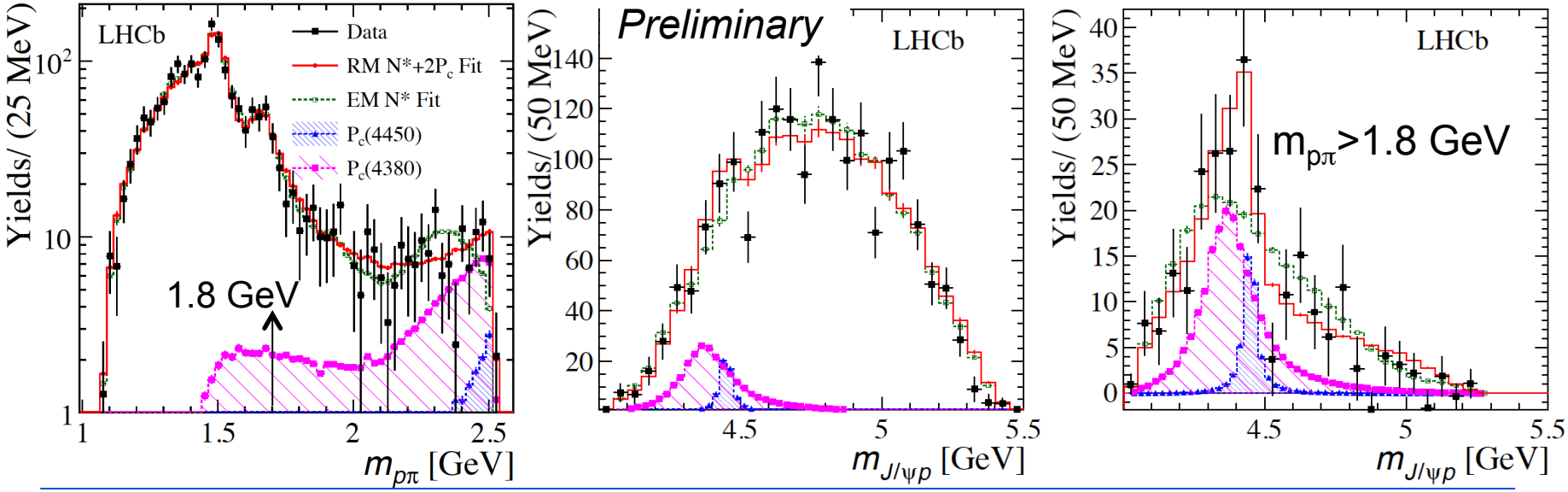
- Invariant mass distribution 1885±50 signal events
- Overall: [arXiv:1406.0755]



$$\frac{\mathcal{B}(\Lambda_b \to J/\psi \pi^- p)}{\mathcal{B}(\Lambda_b \to J/\psi K^- p)} = 0.082 \pm 0.002 \pm 0.004$$

Amplitude fits

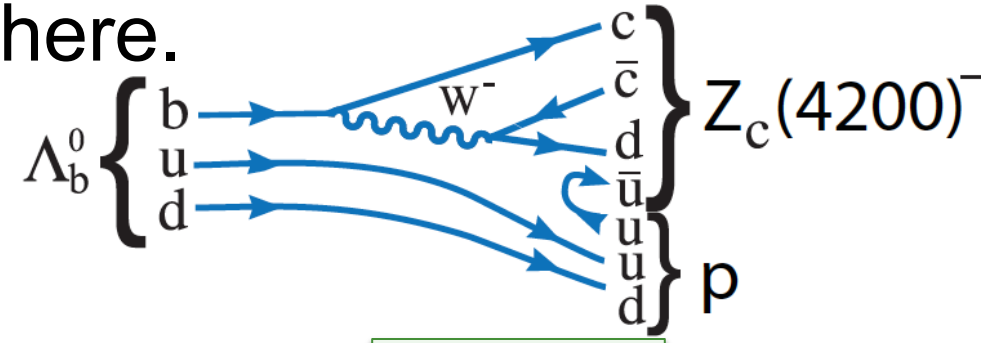
- Amplitude fits done similar to J/ψ K^-p, with N* replacing Λ^*. Here 7 N* (reduced model) 13 N* (extended model)
- Good fits with 3.3σ evidence of both P_c states
- Large part of the P_c rate is above $m_{p\pi}$ of 1.8 GeV



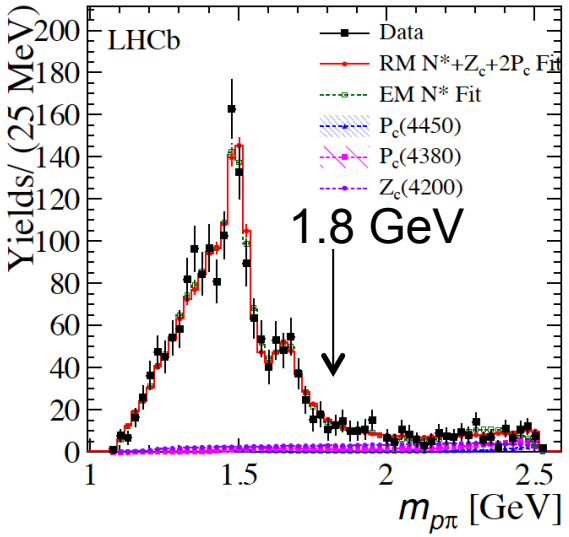
One more concern

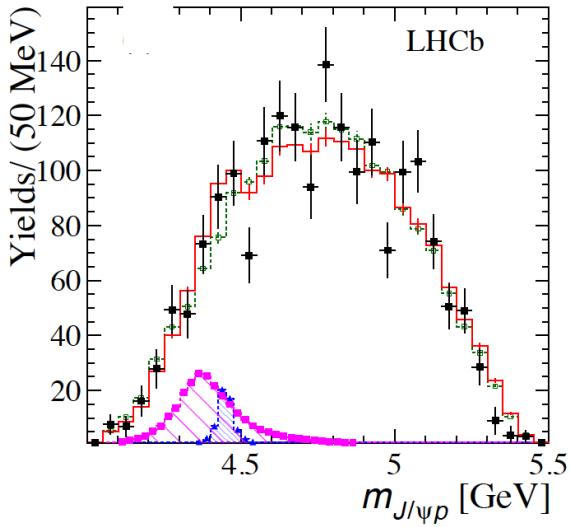
- Possible exotic $Z_c(4200)^- \rightarrow J/\psi\pi^-$ state, reported could occur here.
- So include in fit.

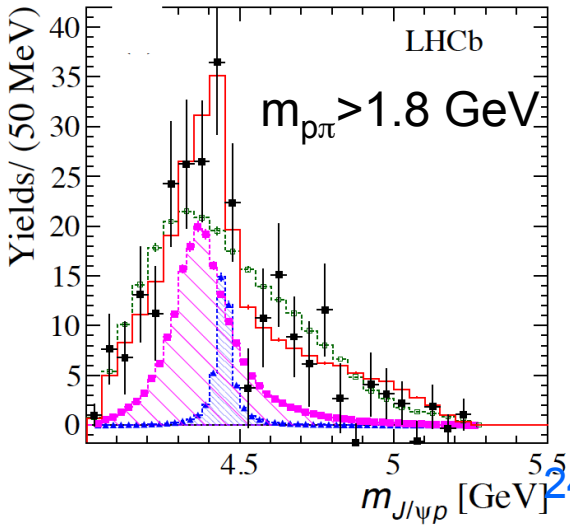
Z_c insignificant but reduces P_c significance to 2.3σ



Preliminary







Summary of J/ψ π⁻p

- Data are consistent with the two P_c states [LHCb-2016-016]

$$\frac{\mathcal{B}(\Lambda_b \to P_c(4380)^+ \pi^-)}{\mathcal{B}(\Lambda_b \to P_c(4380)^+ K^-)} = 0.050 \pm 0.016^{+0.020}_{-0.016} \pm 0.004 \pm 0.025$$

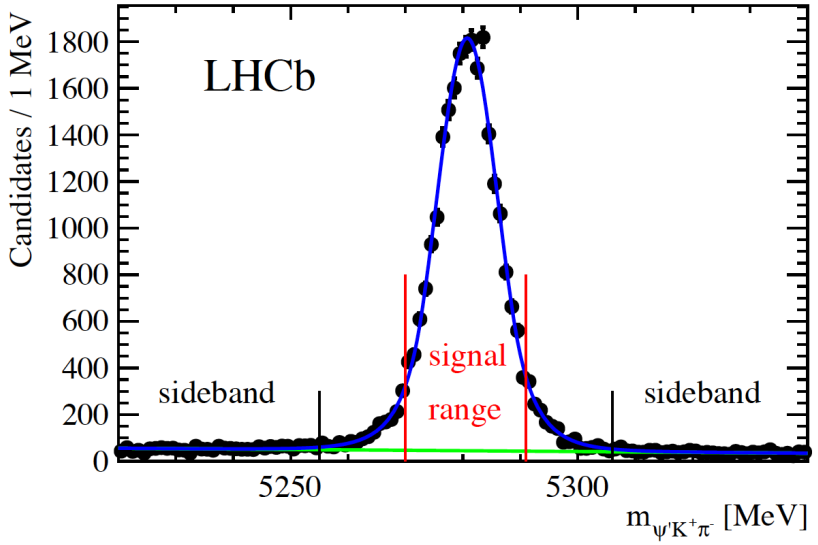
$$\frac{\mathcal{B}(\Lambda_b \to P_c(4450)^+ \pi^-)}{\mathcal{B}(\Lambda_b \to P_c(4450)^+ K^-)} = 0.033^{+0.016+0.011}_{-0.014-0.009} \pm 0.004 \pm 0.009$$

- Relative rates within expectations
- More statistics is needed to prove their existence. Would to tend disprove scattering theories

Z(4430)$^-$ tetraquark

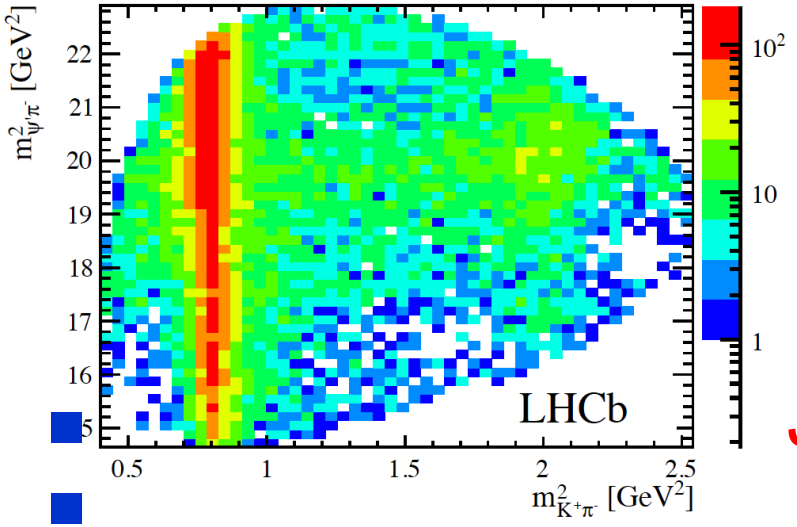
- $B^0 \to \psi' \pi^- K^+$, peak in $m(\psi' \pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle M=4433±5 MeV, Γ=45 MeV
  - Challenged by BaBar: explanation in terms of K*'s
  - Belle reanalysis using full amplitude fit: M= $4485 \pm 22^{+28}_{-11}$ MeV, Γ=200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



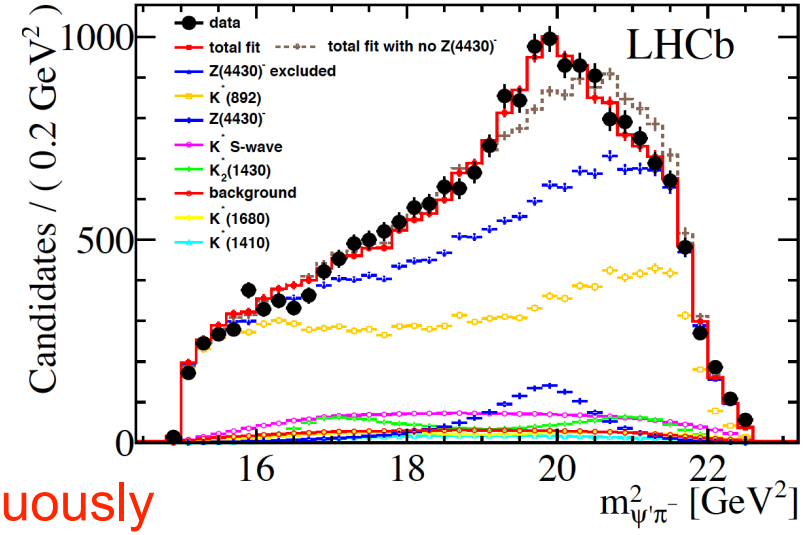
LHCb Amplitude analysis

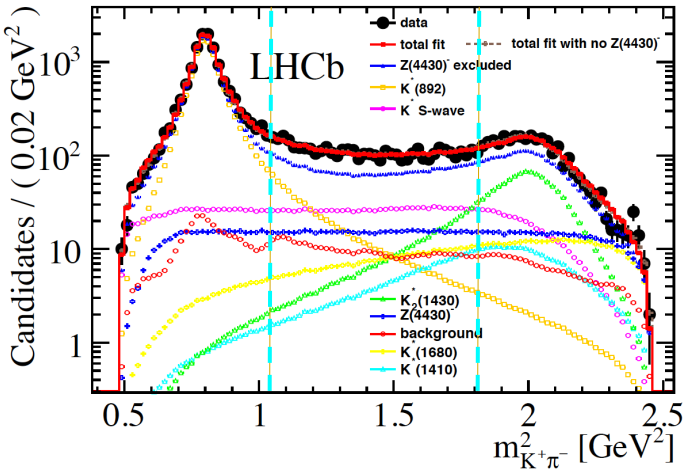
- Full 4D fit to both $K^* \to K^-\pi^+$ & $Z \to \psi'\pi^-$ states

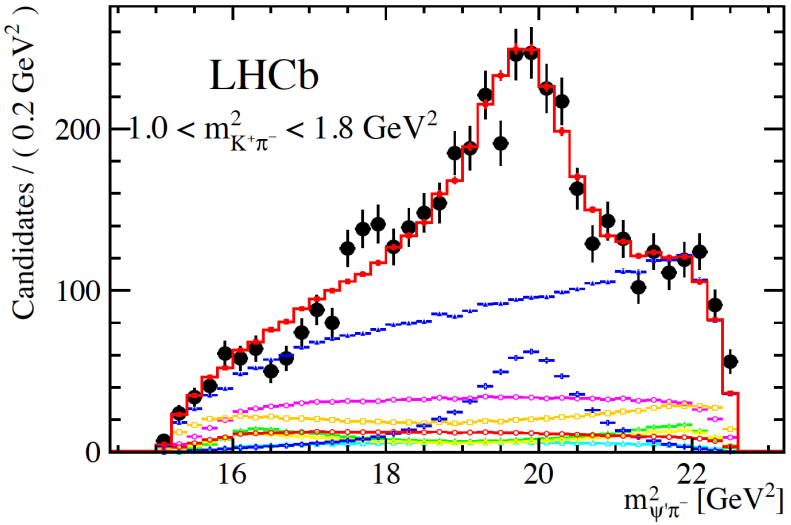


$J^P = 1^+$

Unambiguously

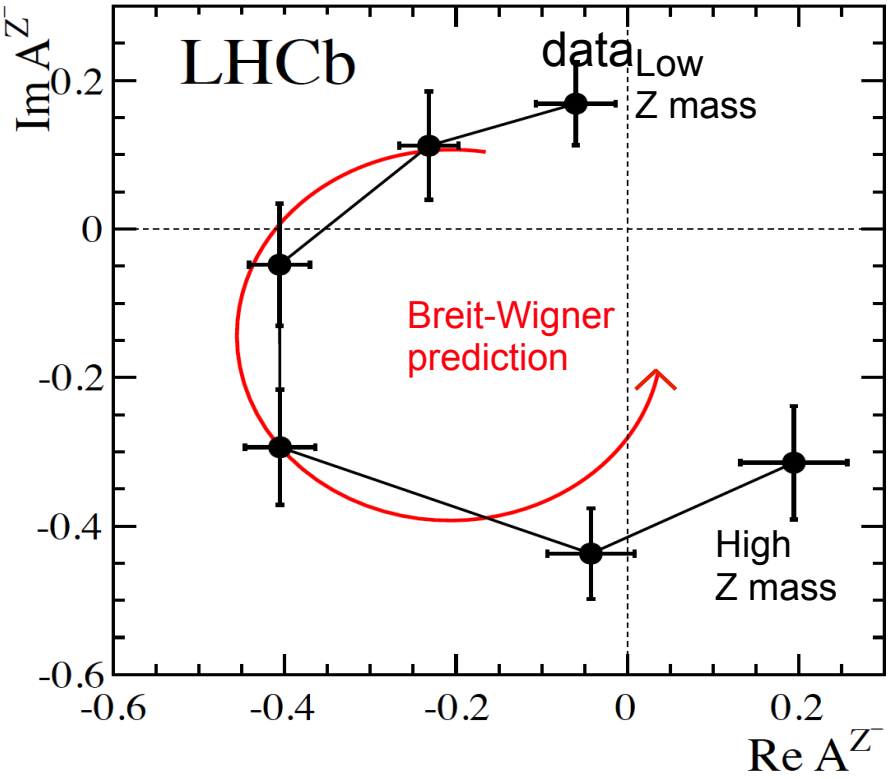






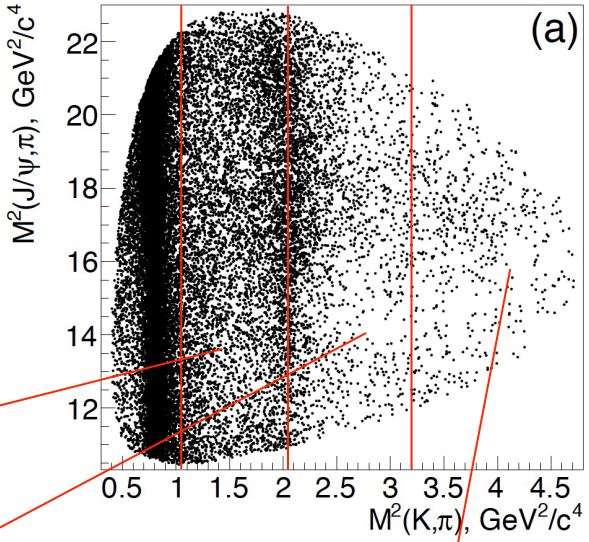
Is it a resonance?

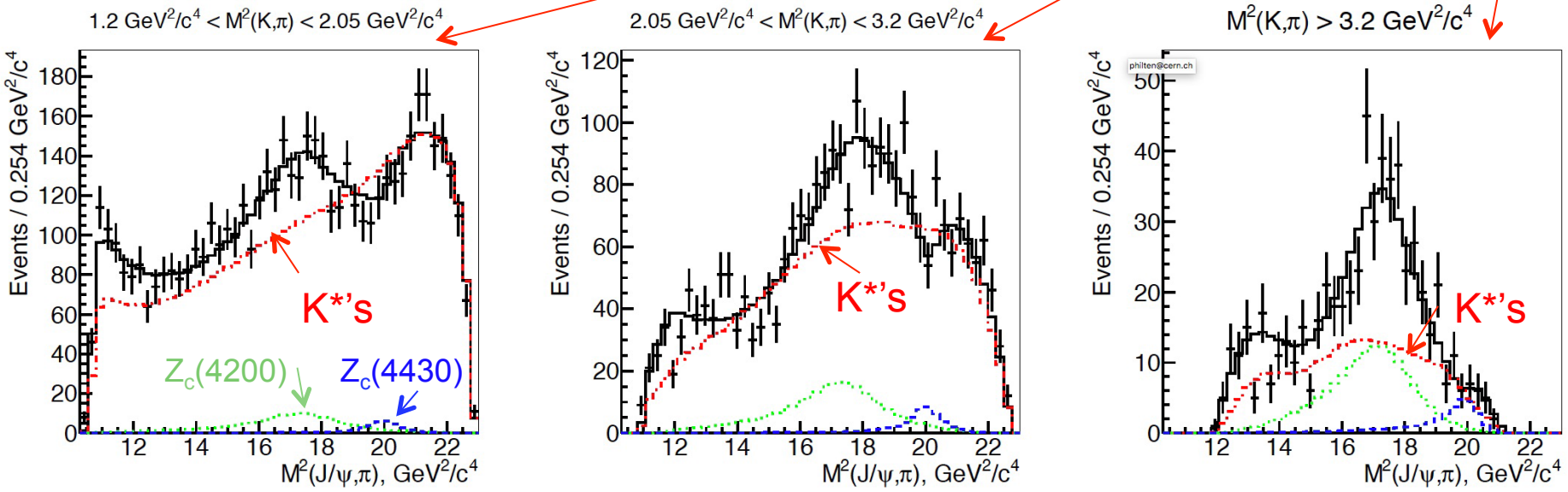
- LHCb produced an Argand plot that shows a clear & large phase change
- There are also attempts at rescattering explanations



$B^0 \to J/\psi\, \pi^- K^+$

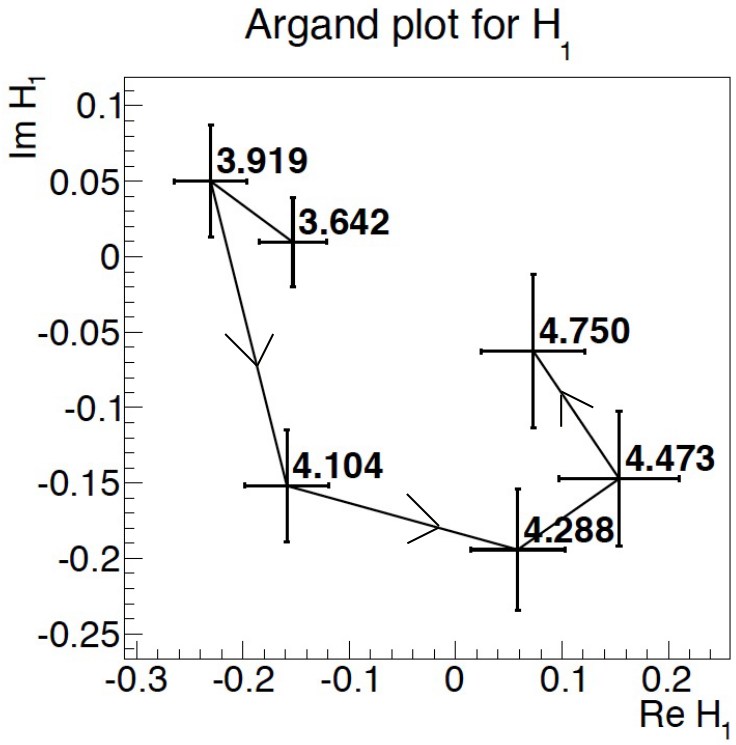
- Belle does a full amplitude analysis [arXiv:1408.6457]
- Sees $Z_c(4430) \to J/\psi\, \pi^-$, at 4σ level with $B(Z_c \to J/\psi\, \pi^-)/\, B(Z_c \to \psi' \pi^-) \sim 0.1$
- Plus a new state $Z_c(4200)$, $\Gamma \sim 370$ MeV at 6σ

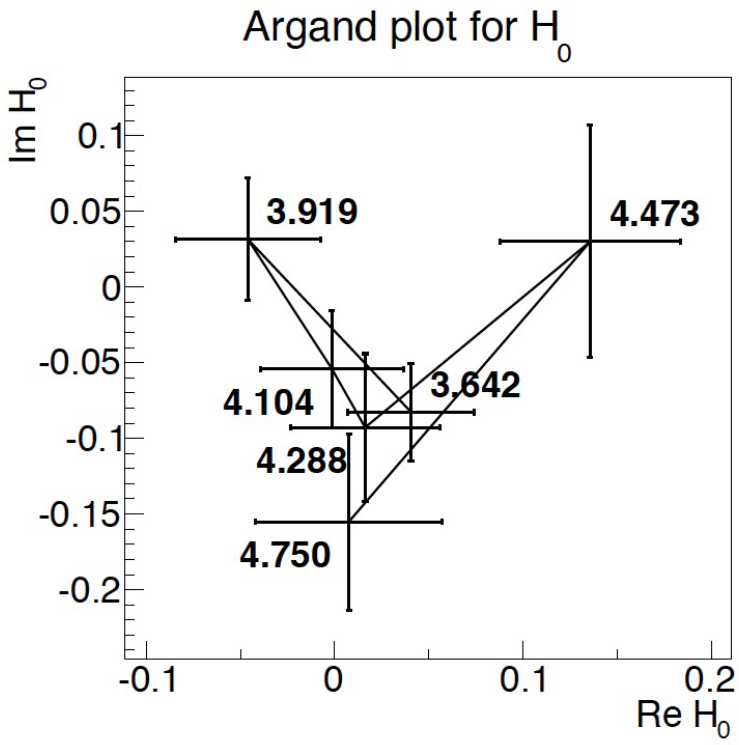




$Z_c(4200)^-$

- Also provides Argand plots for the two different helicity amplitudes in the decay

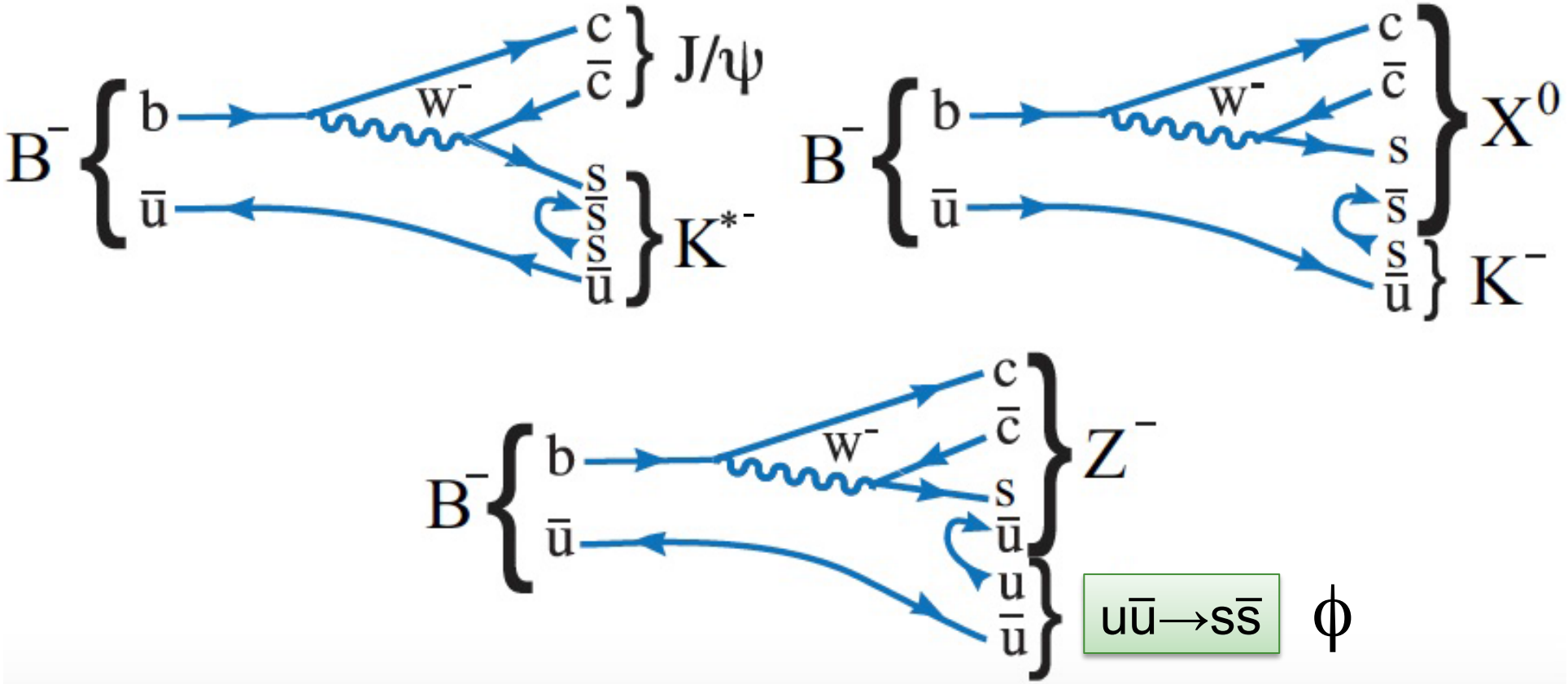




- Needs confirmation from another experiment

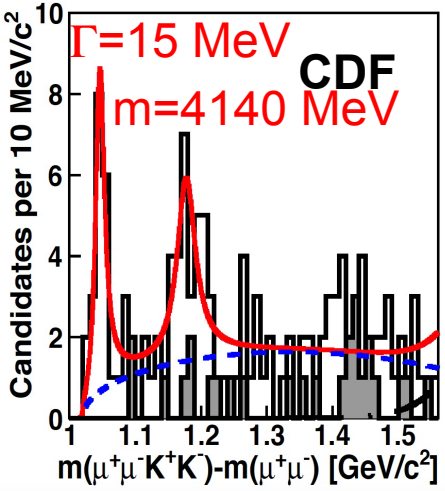
$B^- \to J/\psi\, \phi\, K^-$

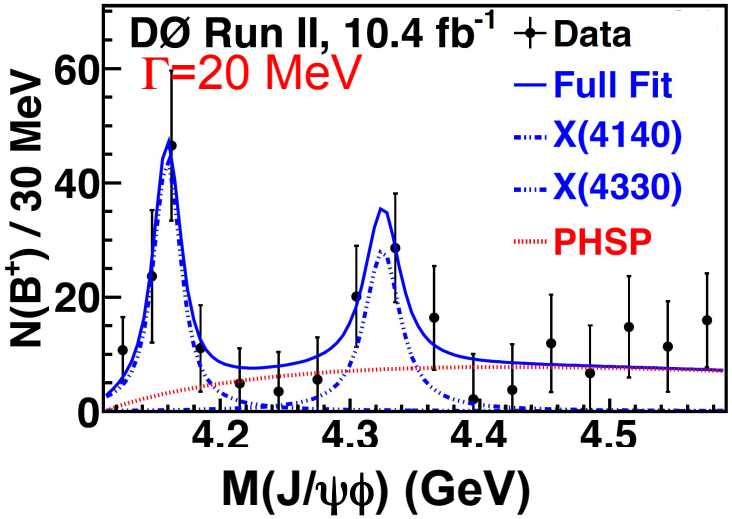
- Possible diagrams:

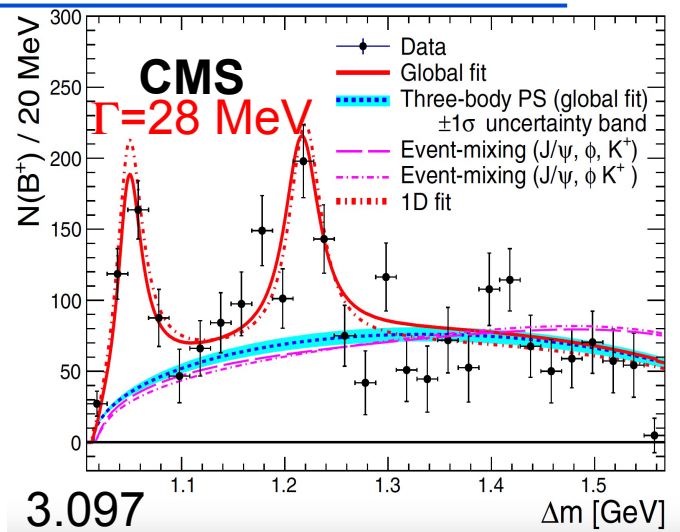


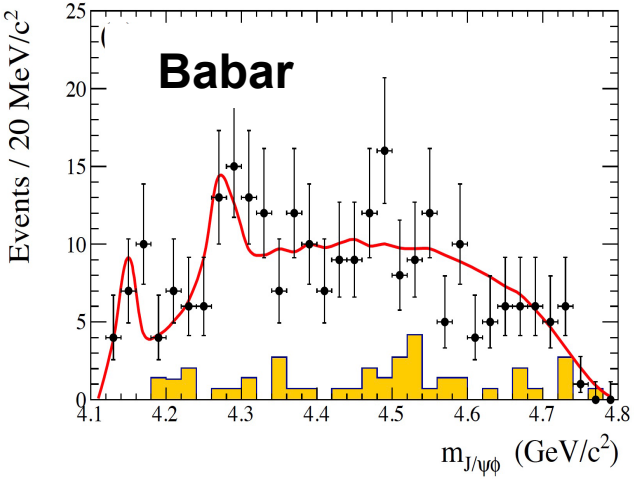
- Note $J/\psi\ \phi$ ($c\bar{c}s\bar{s}$) is not prima facie exotic

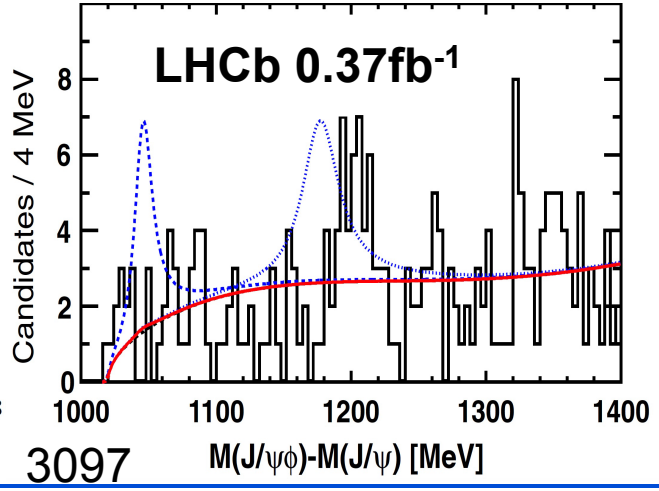
Some past results

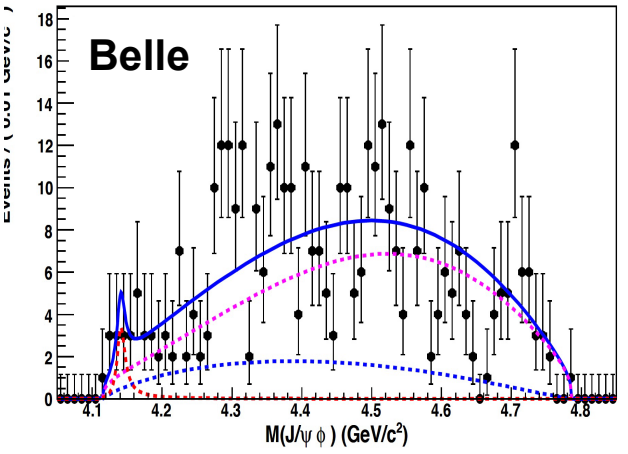












Detailed history

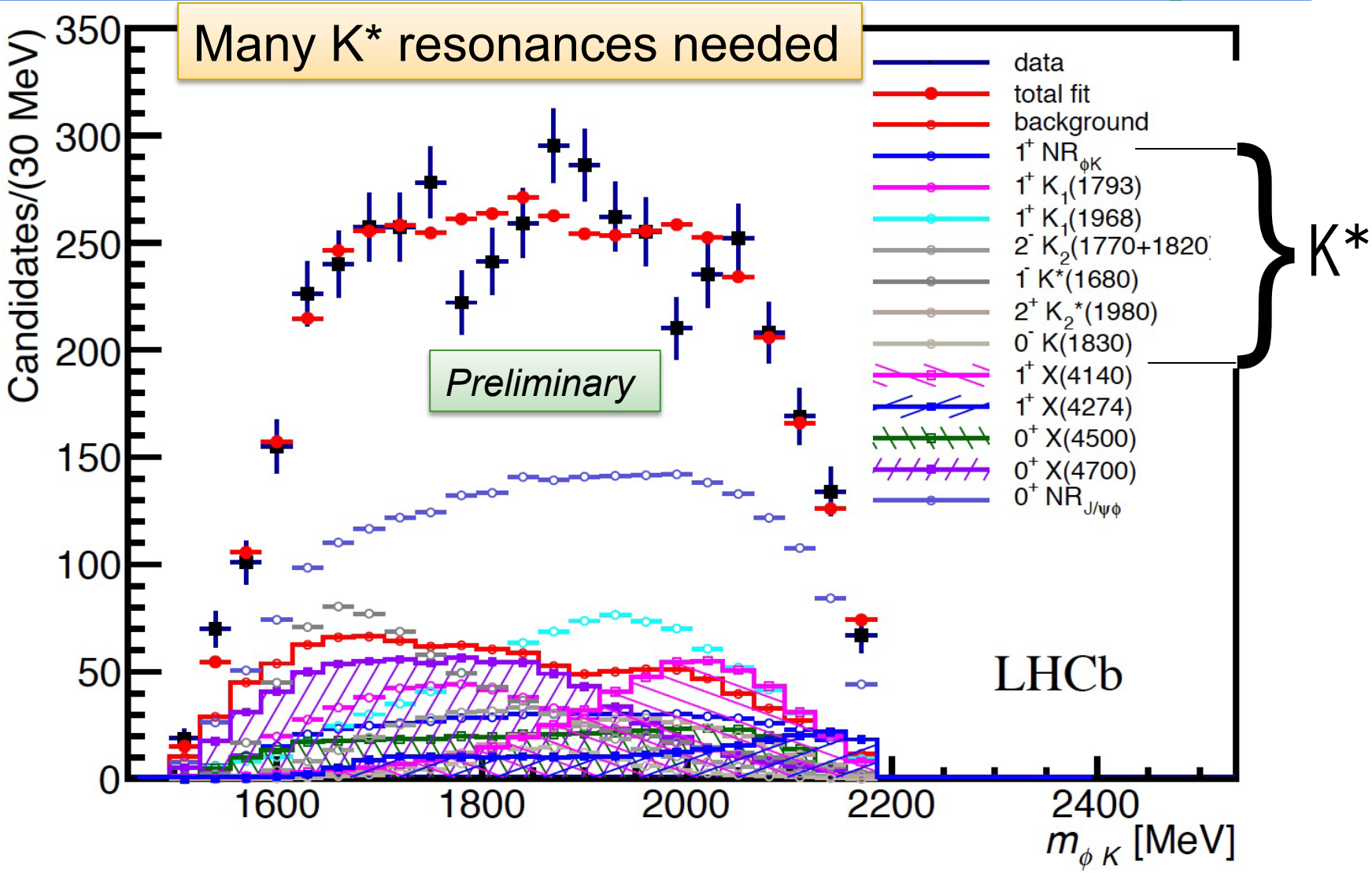
- One or two new resonant states claimed

Year	exp. (/fb)	# B^-	mass (MeV)	Γ (MeV)	σ	mass (MeV)	Γ (MeV)	σ
2008	CDF (2.7)	58±10	4143.0	11.7	3.8			
2009	Belle	325±21	4143 fix	11.7 fix	1.9			
2011	CDF (6.0)	115±12	4143.4	15.3	5.0	4274.4	32.3	3.1
2011	LHCb (0.37)	346±20	4143.4 fix	15.3 fix	ul	4274.4 fix	32.3 fix	
2013	CMS (5.2)	2480±160	4148.0	28.0	5.0	4313.8	38	
2013	D0 (10.4)	215±37	4159.0	19.9	3.1	4328.5	30 fix	
2014	Babar (422)	189±14	4143.4 fix	15.3 fix	1,6	4274.4 fix	32.3 fix	1.2

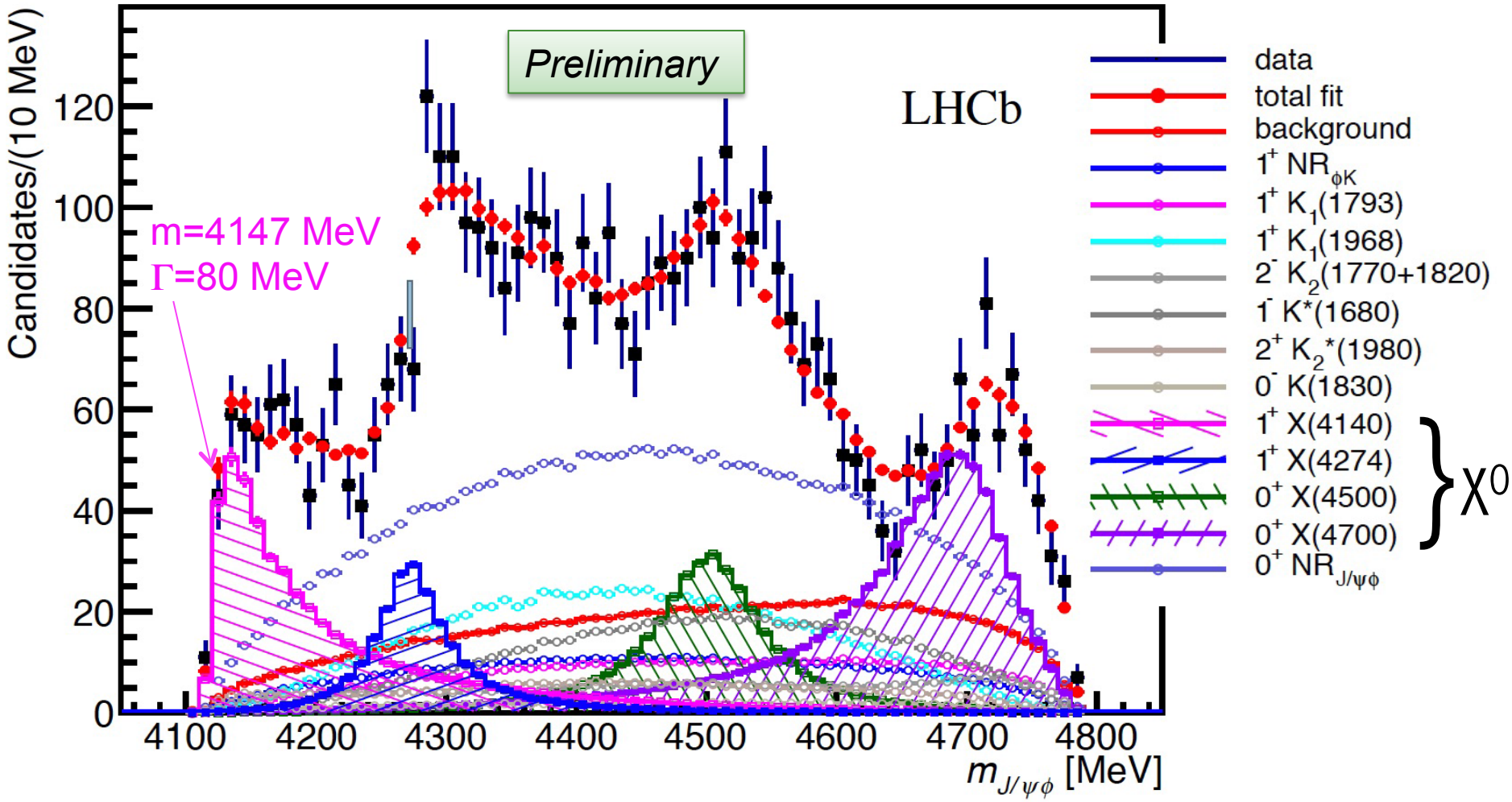
New LHCb (3/fb)

- LHCb has 4289±150 events [arXiv:1406.0755]
- Again do a full amplitude fit including interferences between $B^- \to J/\psi K^{*-}$, $K^{*-} \to \phi K^-$, and $B^- \to X^0 K^-$, $X^0 \to J/\psi\phi$.
- $B^- \to \phi Z^-$, $Z^- \to J/\psi K^-$ is also included in the amplitude fit, but used only as a source of systematic uncertainty

Results of fit: m(φK)



Results of fit: m(J/ψφ)



- 4 visible structures fit with BW amplitudes

Results of fit

- J^P also measured all with >4σ significances

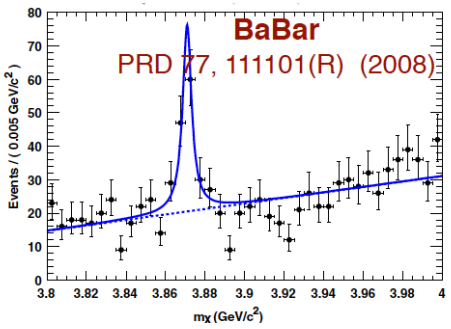
Particle	J^P	Signif-icance	Mass (MeV)	Γ (MeV)	Fit Fraction (%)
X(4140)	1^+	8.4 σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
X(4274)	1^+	6.0 σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
X(4500)	0^+	6.1 σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+3.5}_{-2.3}$
X(4700)	0^+	5.6 σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$
NR	0^+	6.4 σ			$46 \pm 11^{+11}_{-21}$

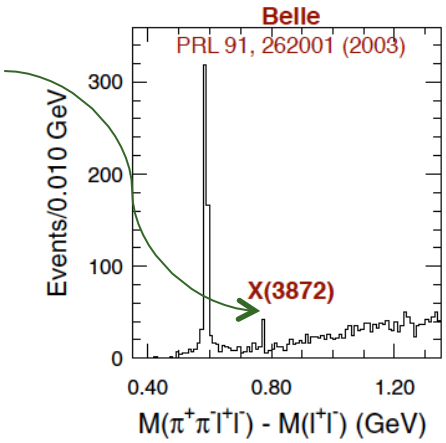
Rescattering?

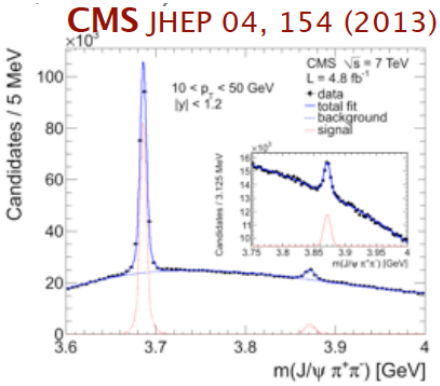
- Since 4 states in this decay channel seems rather odd, fits were tried using the "CUSP" model of Swanson that may explain other Z states just above $D^{(*)}D^{(*)}$ thresholds [arXiv: 1504.07952].
- The X(4140) has a 1.6σ better fit using this model than a BW. The other states have worse fits
- Note, no one predicted observable rescattering states in this mode

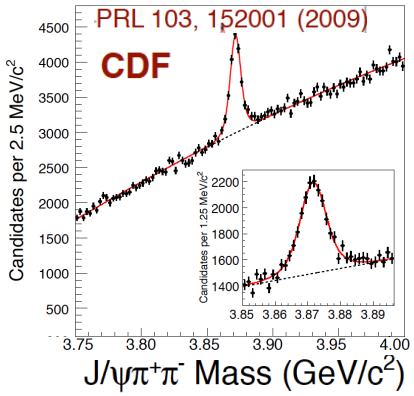
X(3872)

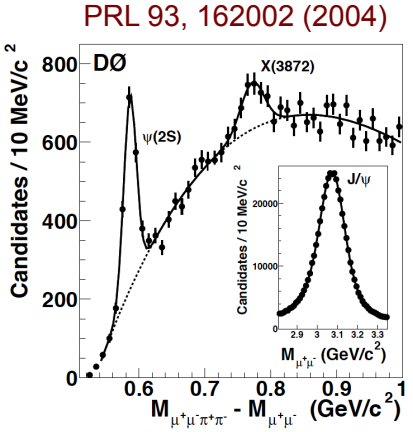
- First seen by Belle using $B \to (J/\psi \pi^+ \pi^-) K$
- Confirmed by BaBar
- Observed in direct production by CDF, D0 CMS, & LHCb







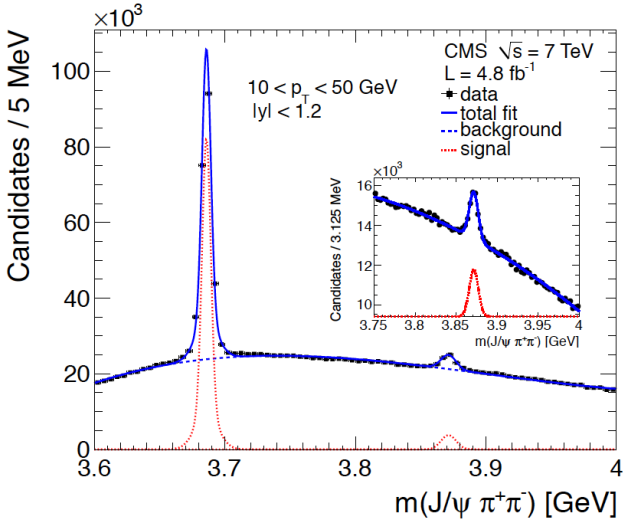


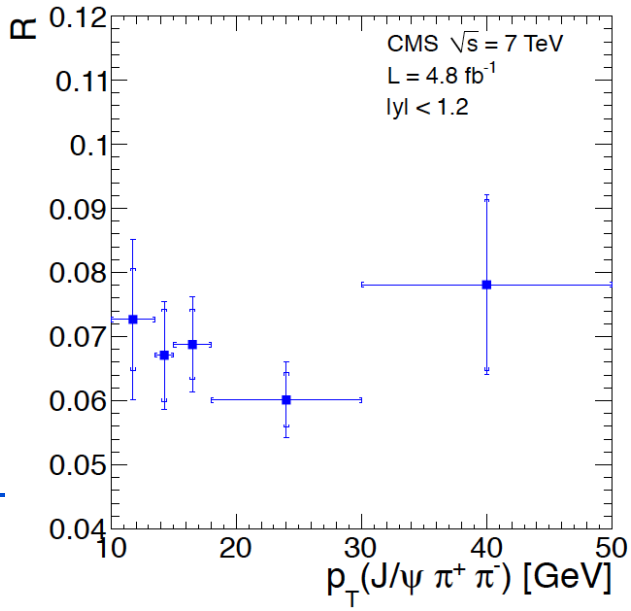


- At $D^{*0}D^0$ threshold: $\Delta m = -0.17 \pm 0.26$ MeV

Production characteristics

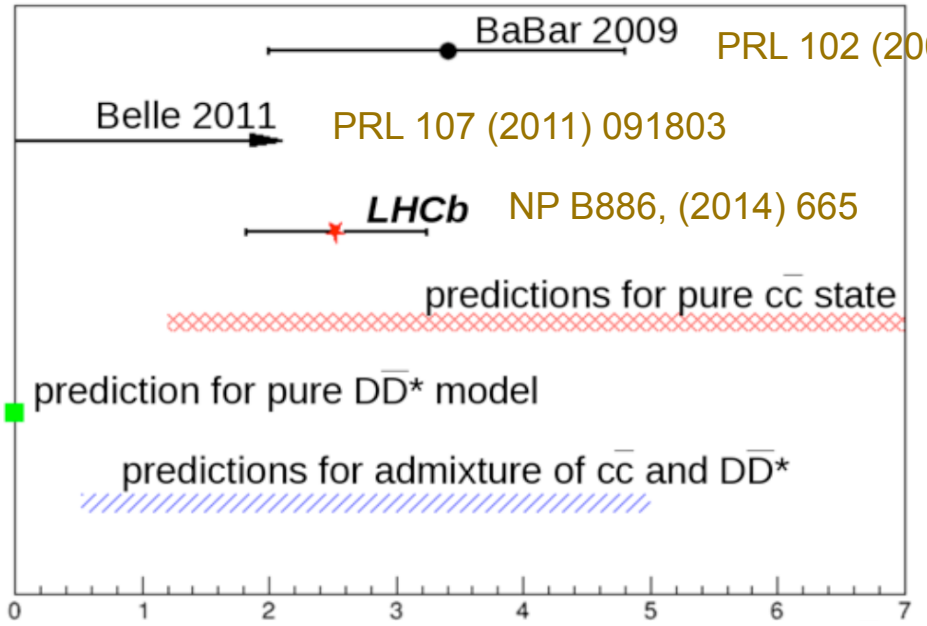
- CMS measures the p_t spectrum relative to that of the ψ' [arXiv:1302.3968]
- 11,910±490 X(3872) & 178,540±850 ψ' events
- Ratio of p_t distributions is flat, indicating that the X(3872) has a similar internal structure as the ψ'

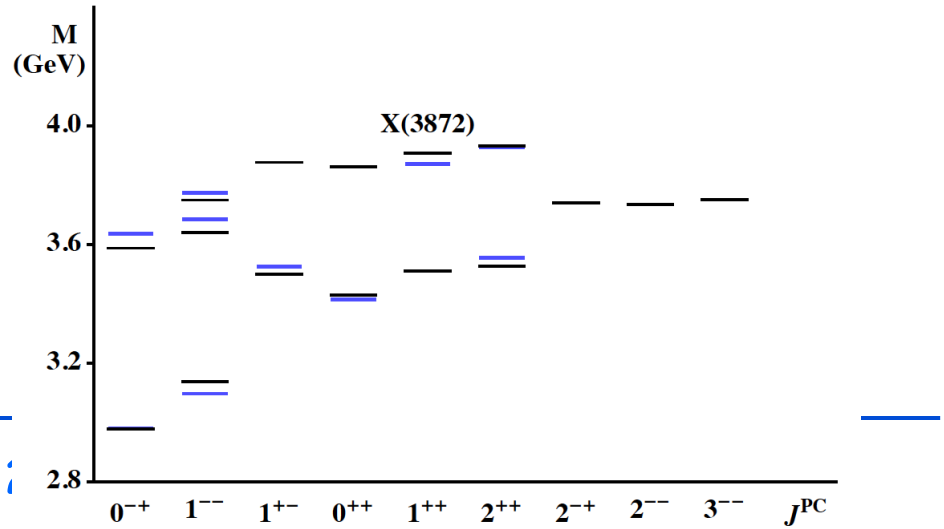




$R \equiv \Gamma(X \to \psi' \gamma)/\Gamma(X \to J/\psi\gamma)$

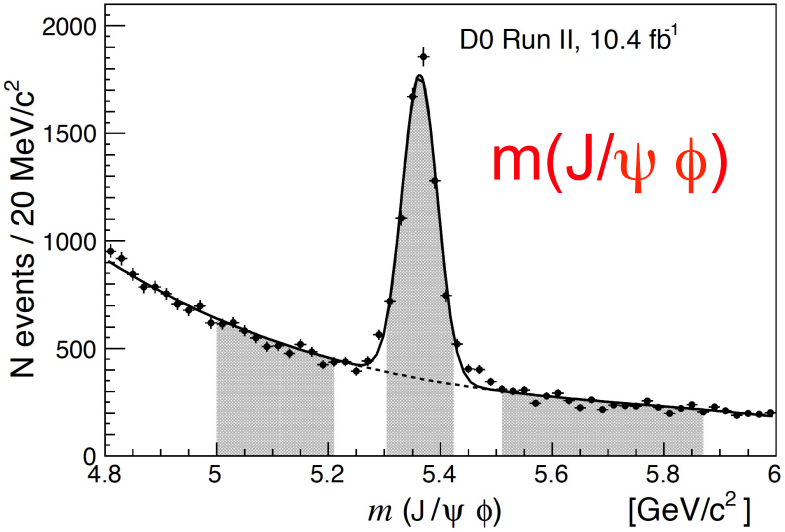
- Rules out purely molecular interpretation
- Consistent with $c\bar{c}$ state where the presence of the threshold has lowered the mass & width

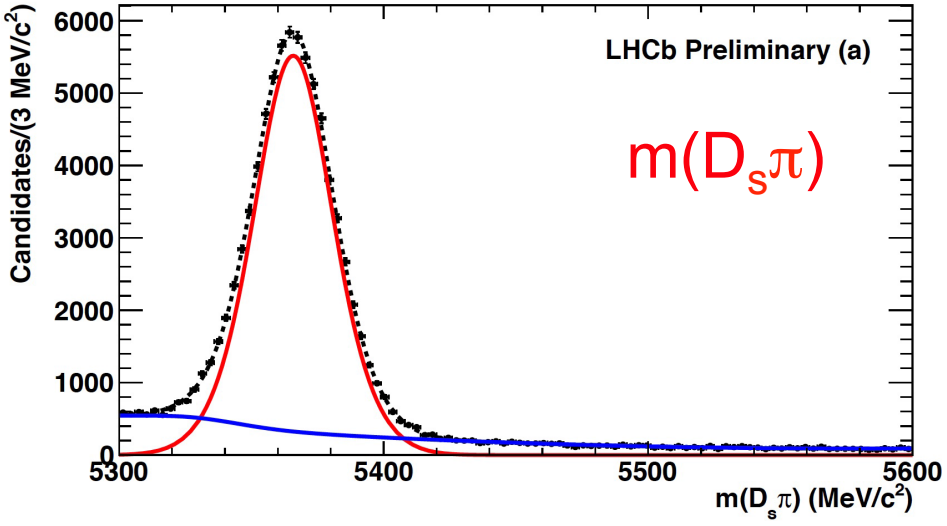


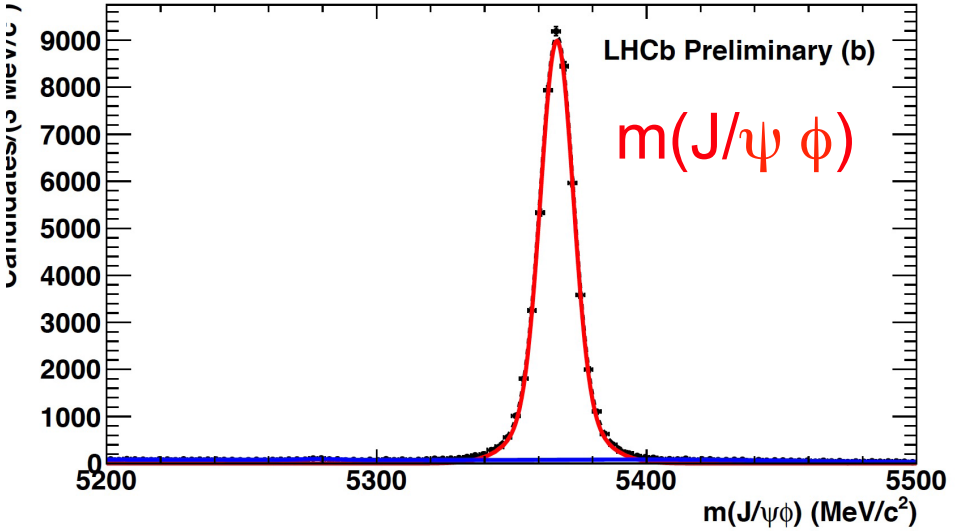


X(5568): B_s signals

- D0: 5,582±100 $B_s \rightarrow J/\psi\phi$
- LHCb: 66,300±300 $B_s \rightarrow D_s\pi$
- 46,300±200 $B_s \rightarrow J/\psi\phi$
- Sum 20 x D0 signal sample

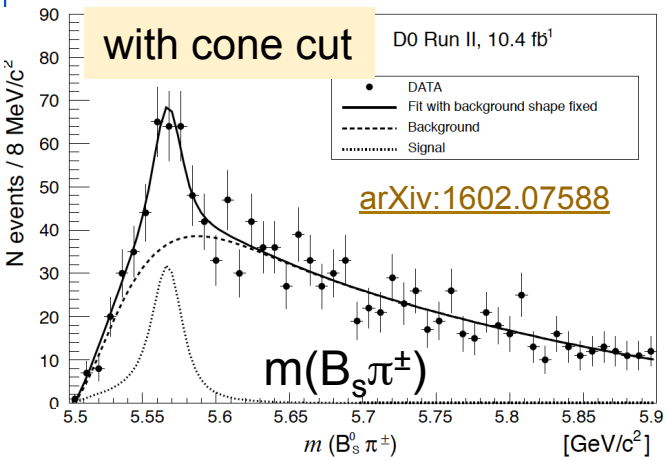


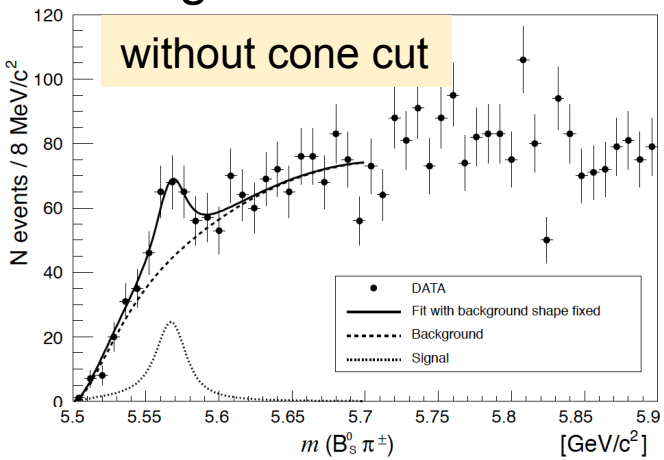


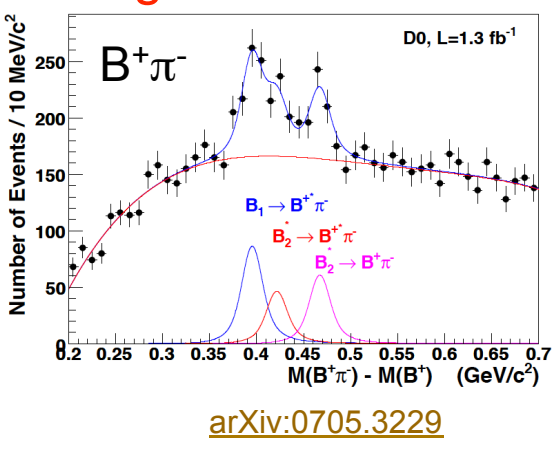


X(5568) results

- D0 uses 5582±100 B_s events to form $B_s\pi^{\pm}$ mass



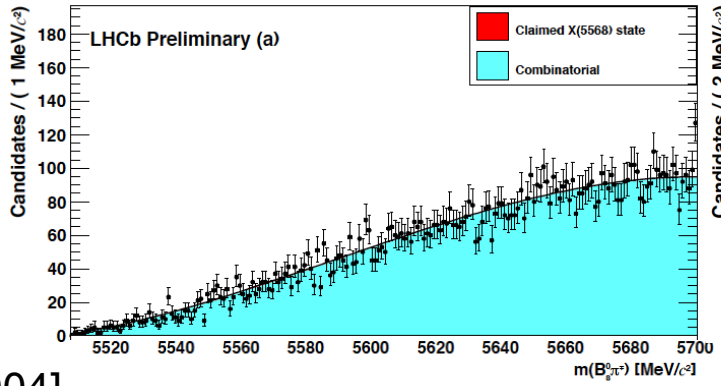




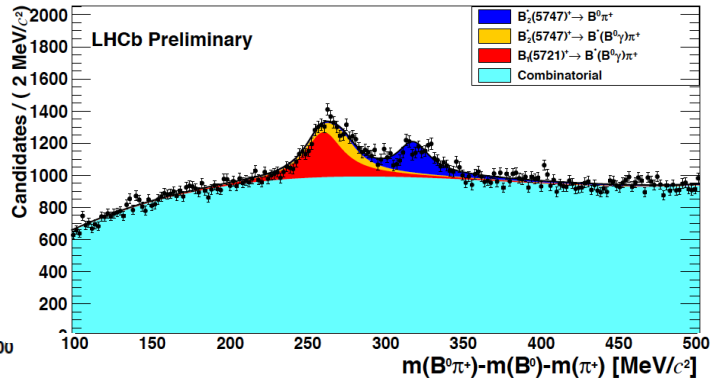
arXiv:0705.3229

- Rates: X(5568)/B_s =(8.6±1.9±1.4)%, B**/B+=(13.9±1.9±3.2)%

- LHCb sees nothing, limit <0.010@95% cl [LHCb-CONF-2016-004]

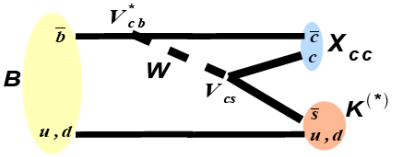


m($B_s\pi^{\pm}$)



m($B^0\pi^-$)-m(B^0)-m(π^-)

Other tetraquark candidates

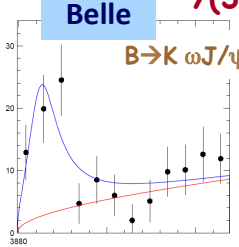


Thus far, no amplitude analyses for these states

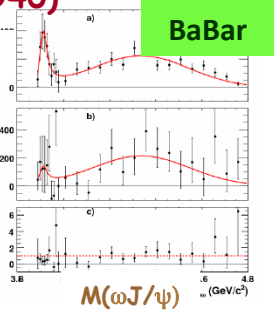
Belle

Y(3940)

B→K ωJ/ψ



M(ωJ/ψ)

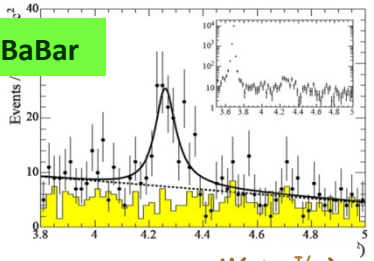


M(ωJ/ψ)

Z(4430)

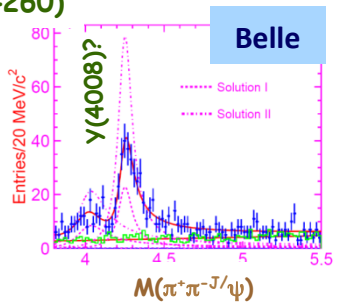
BaBar

Y(4260)



M(π⁺π⁻J/ψ)

Belle



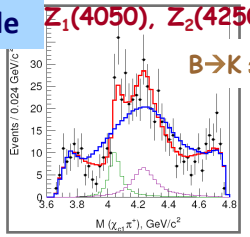
M(π⁺π⁻J/ψ)

Y(4350) & Y(4660)

Belle

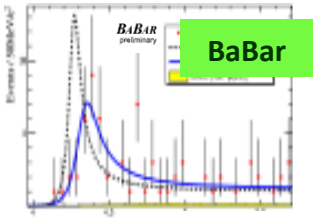
$Z_1(4050)$, $Z_2(4250)$

B→K π⁺χc1



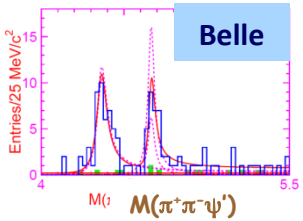
M(π±χc1)

BaBar



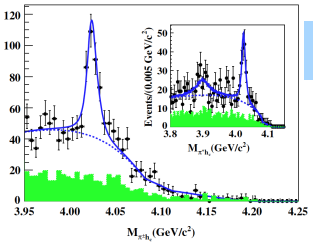
M(π⁺π⁻ψ')

Belle



M(π⁺π⁻ψ')

All current candidates contain a cc̄ or bb̄



M(π±hc)

BES

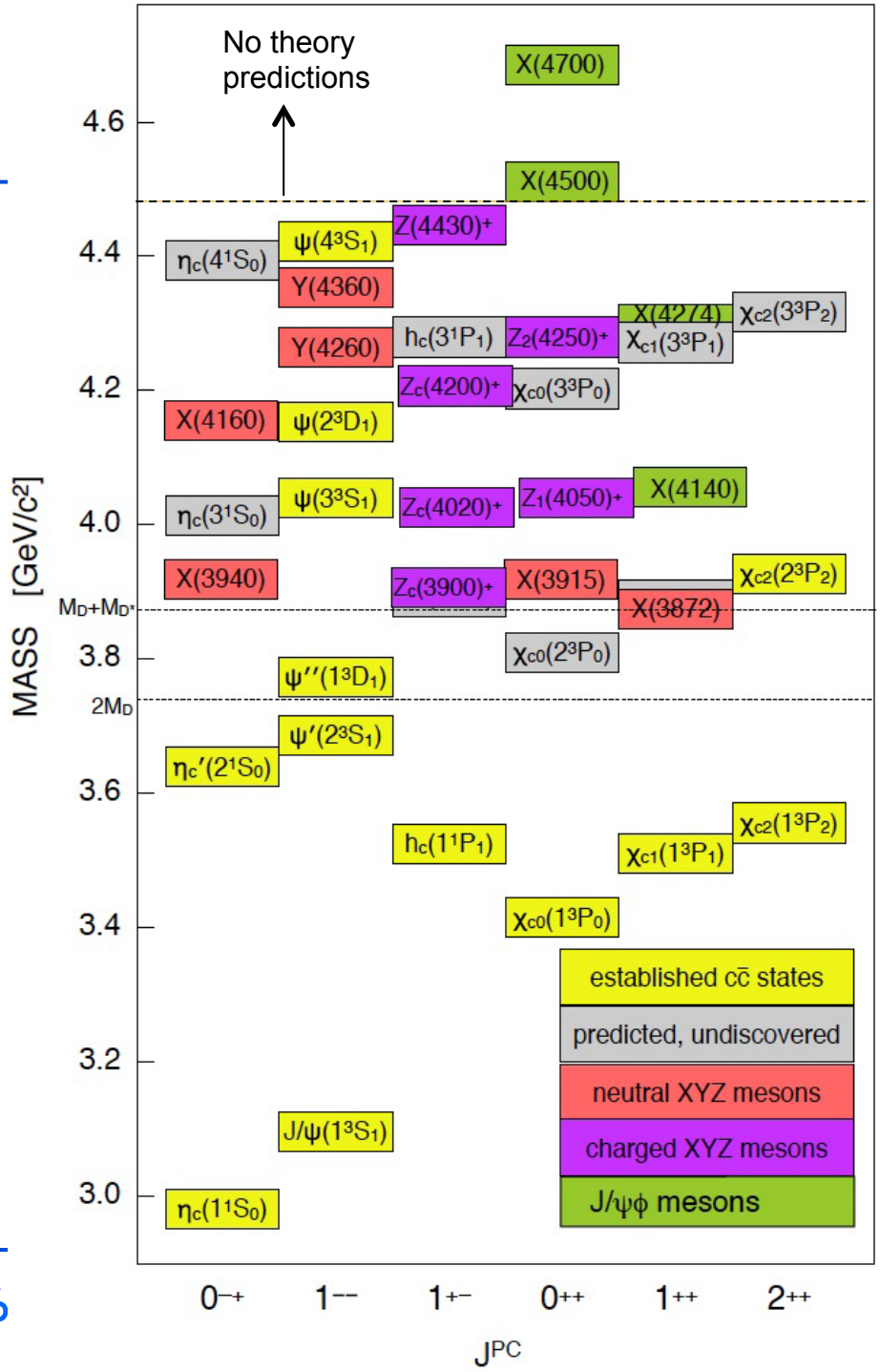
$e^+e^- \to Y(4260) \to \pi^+ Z_c(4020)^- \to \pi^- h_c$

Tetraquark summary

- Predicted neutral charmonium states compared with found $c\bar{c}$ states, & both neutral & charged exotic candidates

- Based on Olsen [arXiv:1511.01589]

- Added 4 new J/ψφ states



Conclusions I

- LHCb has found two resonances decaying into $J/\psi p$ with pentaquark content of $uudc\bar{c}$ in $\Lambda_b \rightarrow J/\psi K^- p$ [arXiv: 1507.03414]. They have spin 3/2 & 5/2 & opposite Parity
- Supporting evidence appears in $\Lambda_b \rightarrow J/\psi \pi^- p$
- Determination of their internal binding, the "color chemistry" will require more study.
- Other exotic states have appeared containing $c\bar{c}$ (or $b\bar{b}$) quarks: the $Z^+(4430) \rightarrow \psi' K^- \pi^+$ appears to be a tetraquark with $J^P=1^+$. Is binding stronger for c & b?
- Four states seen in $J/\psi\phi$. What are they?

Conclusions II

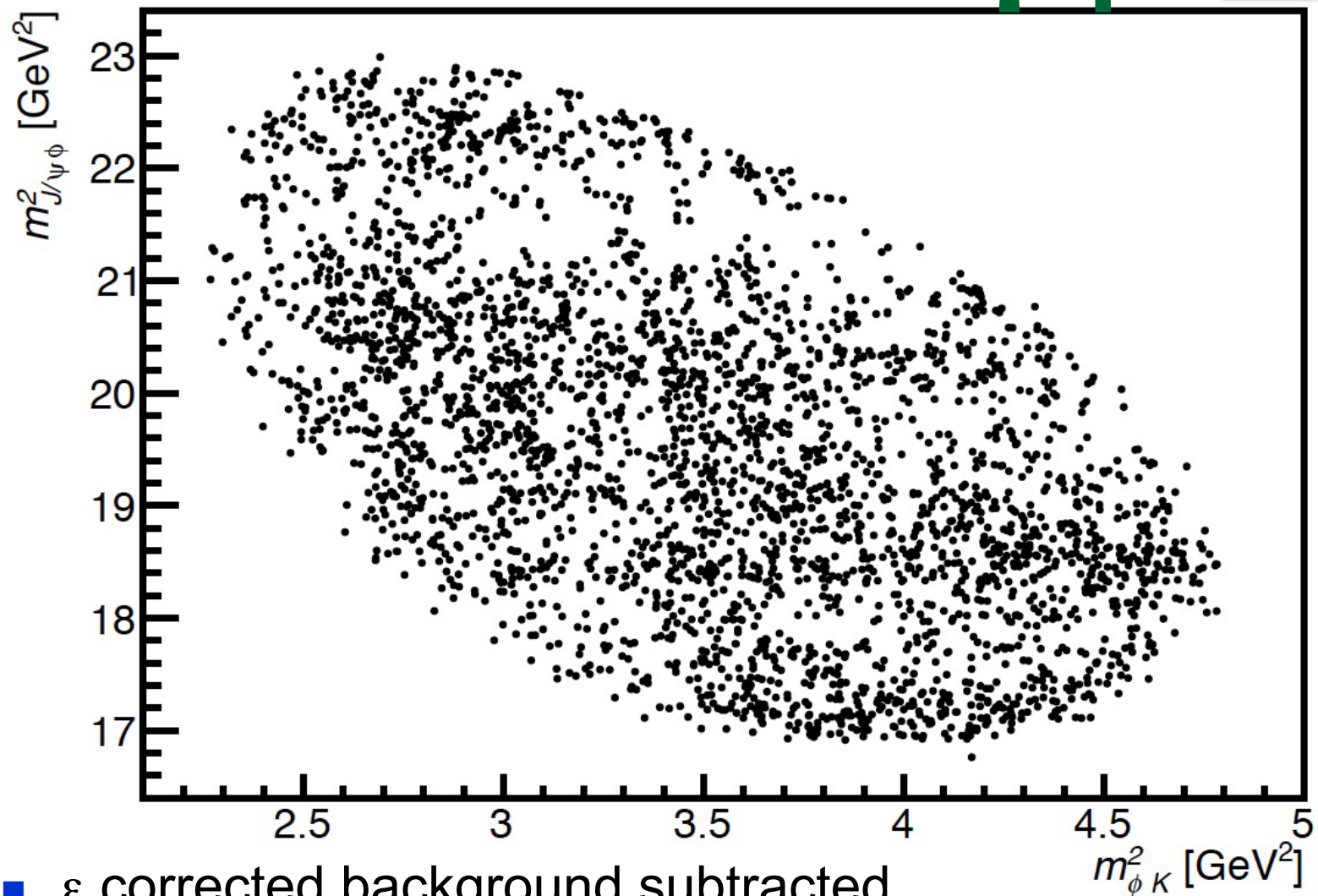
- Amplitude analysis is crucial to interpret data. (Do not just rely on bumps in mass spectra)
- Lattice QCD calculations providing masses would be most welcome
- We look forward to further searches for exotics and their interpretations.

The End

Backup material

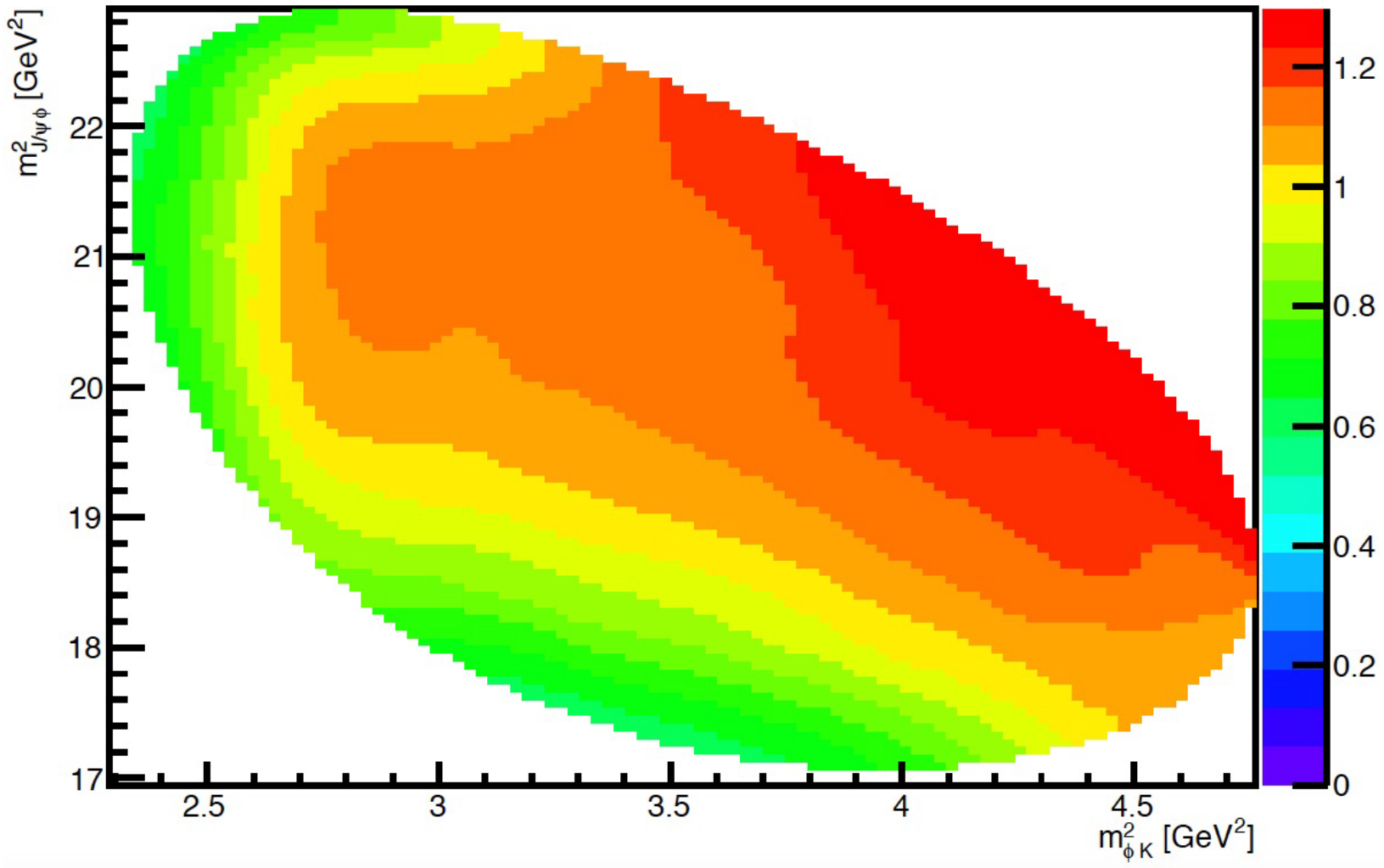
28 Recontres de Blois, June 2, 2016

Dalitz $J/\psi\phi K^-$

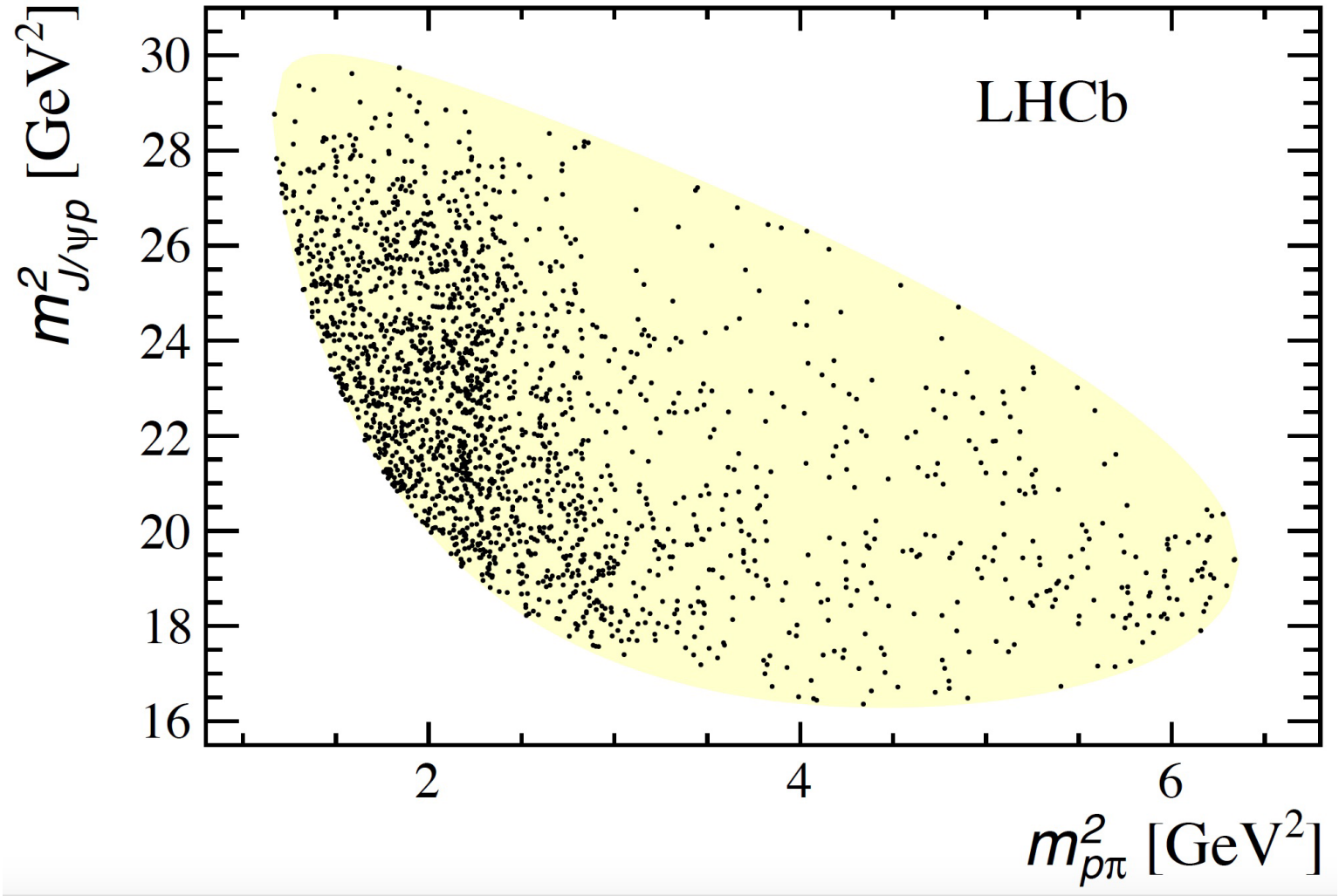


- ε corrected background subtracted

ε J/ψφK⁻

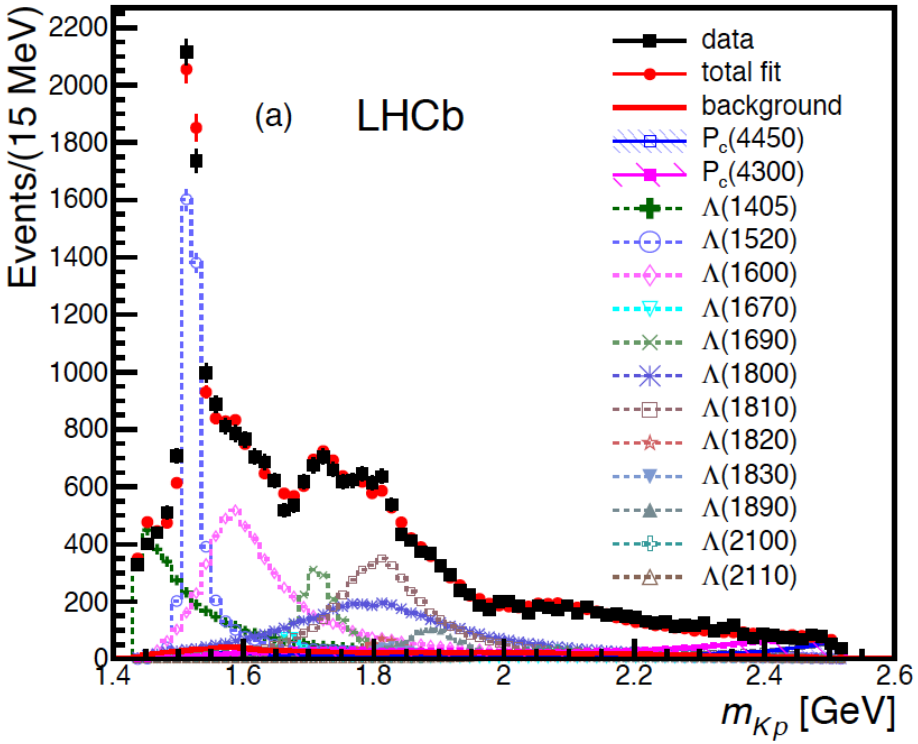

$m^2_{J/\psi\phi}$ [GeV^2]
22
21
20
19
18
17
2.5
3
3.5
4
4.5
$m^2_{\phi K}$ [GeV^2]
1.2
1
0.8
0.6
0.4
0.2
0

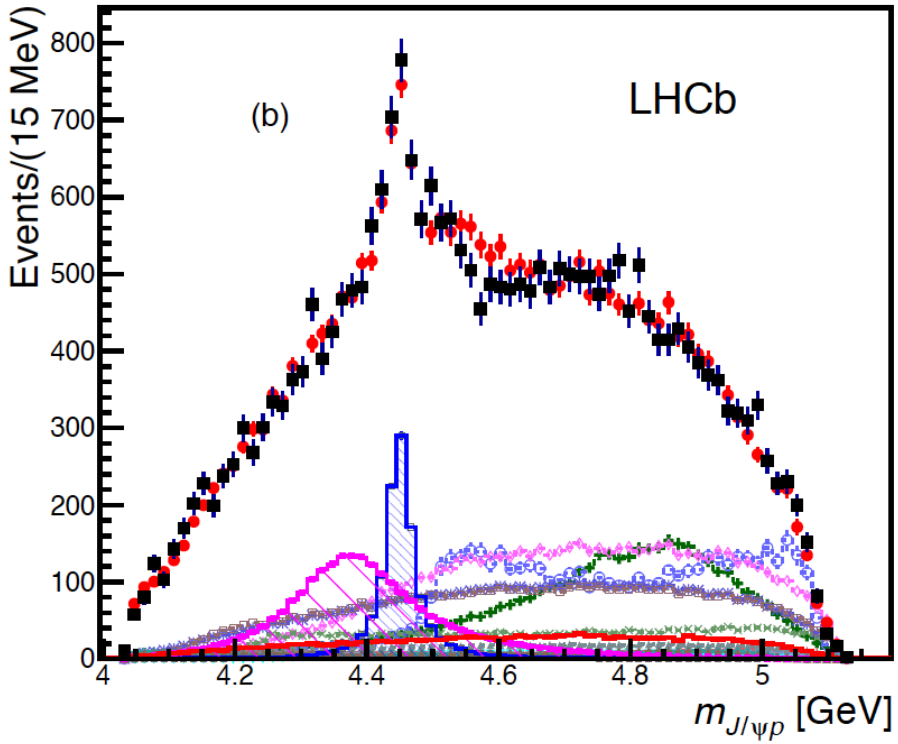
$\Lambda_b \rightarrow J/\psi \pi^- p$



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





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
$L^{P_c}_{\Lambda_b^0}$ $\Lambda_b^0 \to P_c^+$ (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

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.

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

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:

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

- Convenient way to enforce parity conservation in the strong decays via: P_A

Other Explanations

- Molecule:

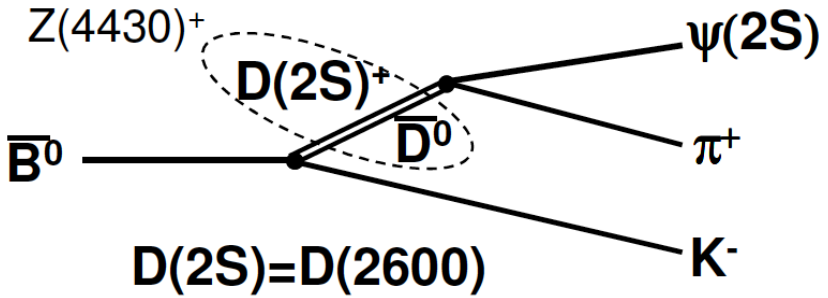
L. Ma et.al, [arXiv:1404.3450]

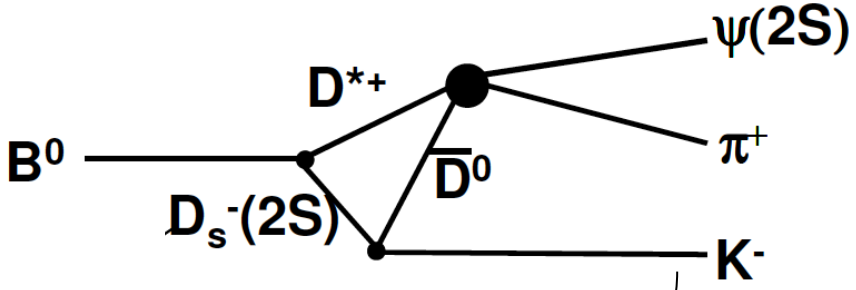
T. Barnes et.al, [arXiv:1409.6651

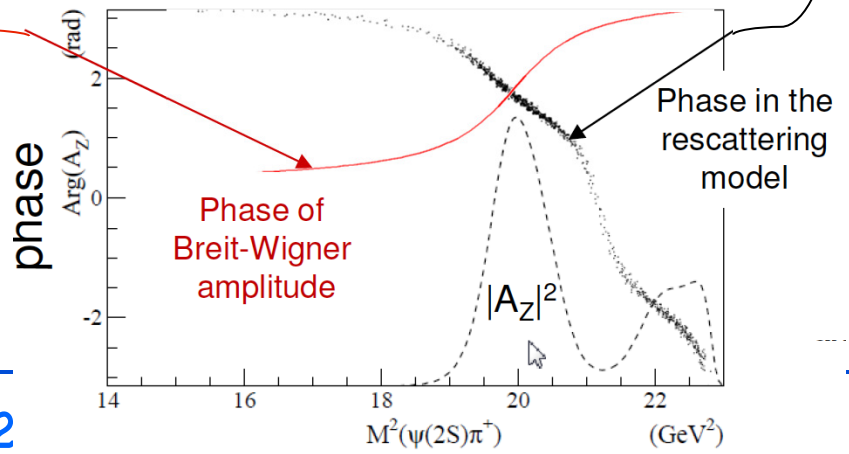
- Same scattering phase as Breit-Wigner
- Rescattering:

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

- Opposite phase
- Ruled out by LHCb Argand diagram

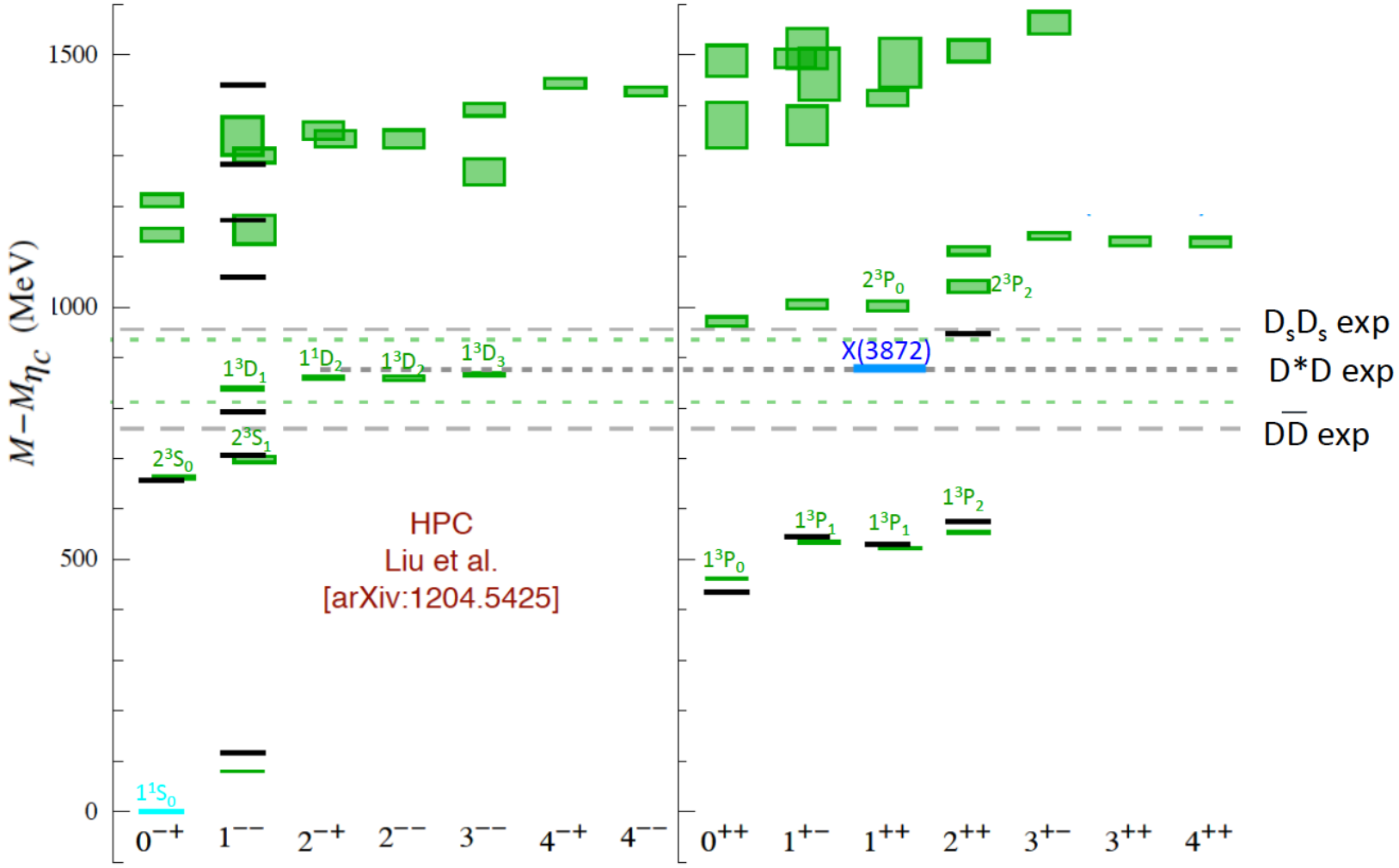






Charmonium like exotics

Predicted states and measurements

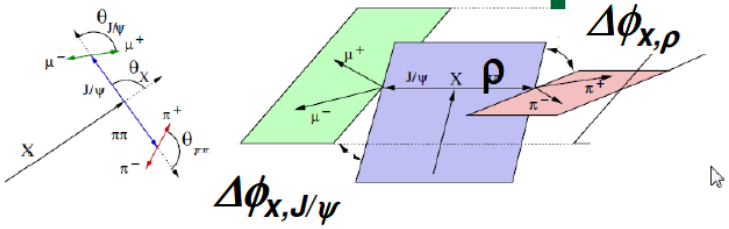


Properties

- Decay modes: $J/\psi\pi^+\pi^-$ dominated by ρ^0, also seen in $J/\psi\gamma$, $\psi'\gamma$, which implies C=+, $D^{*0}D^0$ where the mass appears to be higher and the width larger (For other modes Γ<1.2 MeV, but here $\Gamma = 3.4^{+1.7}_{-1.2}$ MeV)
- What is its internal structure? $q\bar{q}$ charmonium state, tetraquark state, molecular state binding D^{*0} & D^0 but would have large size due to weak binding 0.17±0.26 MeV
- J^{PC} measured by CDF to be 1^{++} or 2^{-+} [hep-ex/0612053]. New measurements by LHCb

LHCb full amplitude analysis

$B^+ \to X(3872) K^+$,
$X(3872) \to J/\psi\, \pi^+\pi^-$,
$J/\psi \to \mu^+\mu^-$



5 independent angles describing the decay in helicity formalism

$$|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \Big| \sum_{\lambda_{J/\psi},\lambda_\rho=-1,0,+1} A_{\lambda_{J/\psi},\lambda_\rho} \times D^{J_X}_{0,\lambda_{J/\psi}-\lambda_\rho}(0,\theta_X,0)^* \times D^1_{\lambda_\rho,0}(\Delta\phi_{X,\rho},\theta_\rho,0)^* \times D^1_{\lambda_{J/\psi},\Delta\lambda_\mu}(\Delta\phi_{X,J/\psi},\theta_{J/\psi},0)^* \Big|^2$$

Matrix element

$$A_{\lambda_{J/\psi},\lambda_\rho} = \sum_L \sum_S B_{LS} \times \left(\begin{matrix} J_{J/\psi} & J_\rho \\ \lambda_{J/\psi} & -\lambda_\rho \end{matrix} \middle| \begin{matrix} S \\ \lambda_{J/\psi} - \lambda_\rho \end{matrix} \right) \times \left(\begin{matrix} L & S \\ 0 & \lambda_{J/\psi} - \lambda_\rho \end{matrix} \middle| \begin{matrix} J_X \\ \lambda_{J/\psi} - \lambda_\rho \end{matrix} \right)$$

Relation of the helicity couplings to LS amplitudes

$$P_X = P_{J/\psi}\, P_\rho\, (-1)^L = (-1)^L$$

Parity conservation

	B_{LS}	
J^{PC}	all L	minimal L
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

LHCb 2015

Many more amplitudes to fit

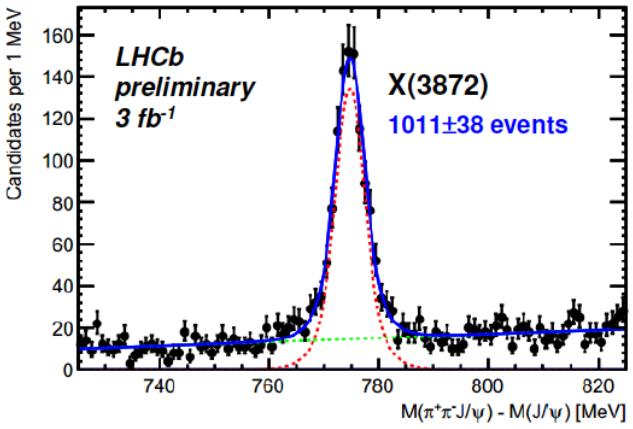
LHCb 2013

CDF 2007

LS amplitudes to be determined from the data

J^{PC} Results

- LHCb data (3/fb)



- State is only 1^{++} with mainly S-wave decay

arXiv:1504.06339

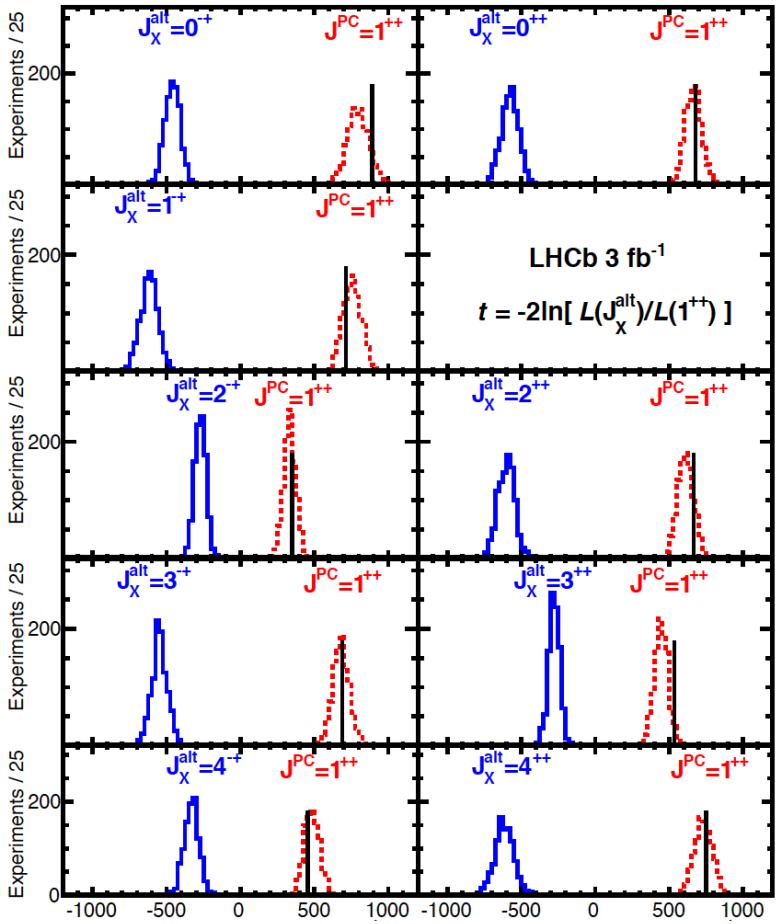
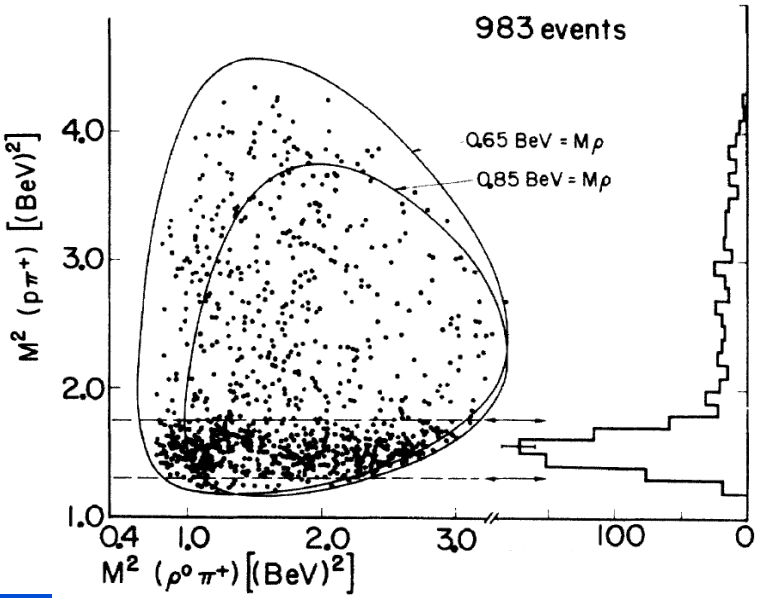
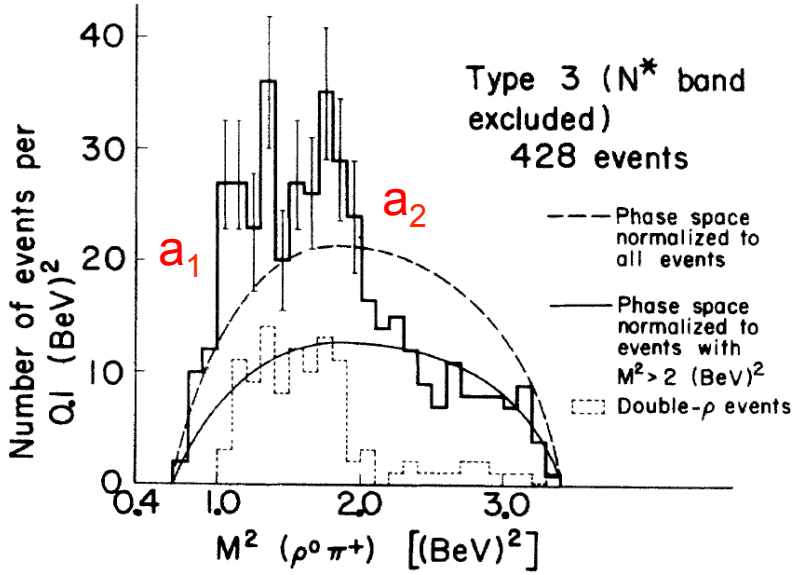


Figure 3: Distributions of the test statistic $t \equiv -2\ln[\mathcal{L}(J_X^{\rm alt}))/\mathcal{L}(1^{++})]$, for the simulated experiments under the $J^{PC} = J_X^{\rm alt}$ hypothesis (blue solid histograms) and under the $J^{PC} = 1^{++}$ hypothesis (red dashed histograms). The values of the test statistics for the data, $t_{\rm data}$, are shown by the solid vertical lines.

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)*

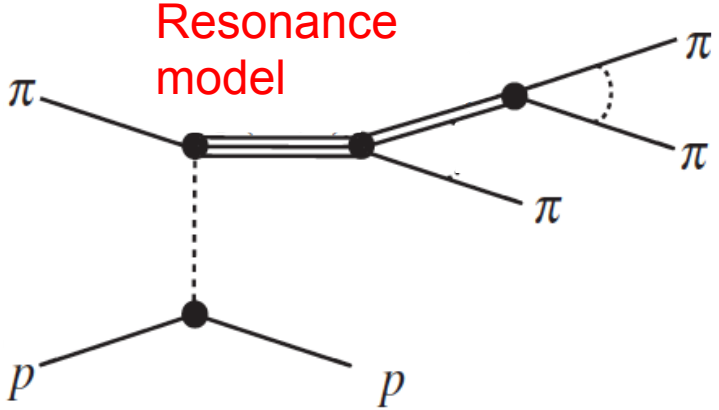


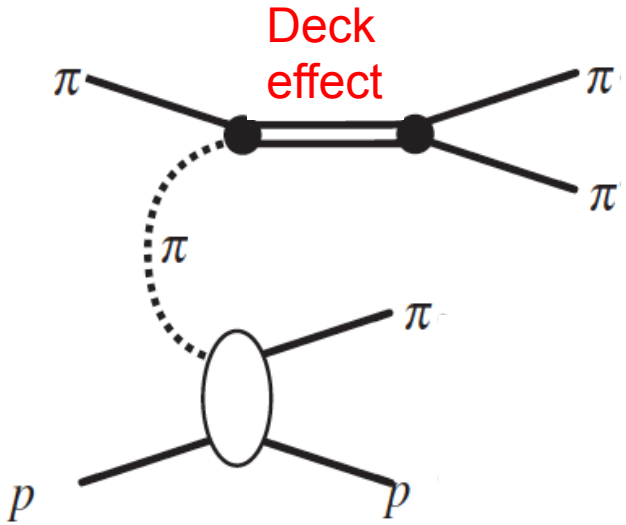


Note BeV≡GeV

"Kinematical" effect

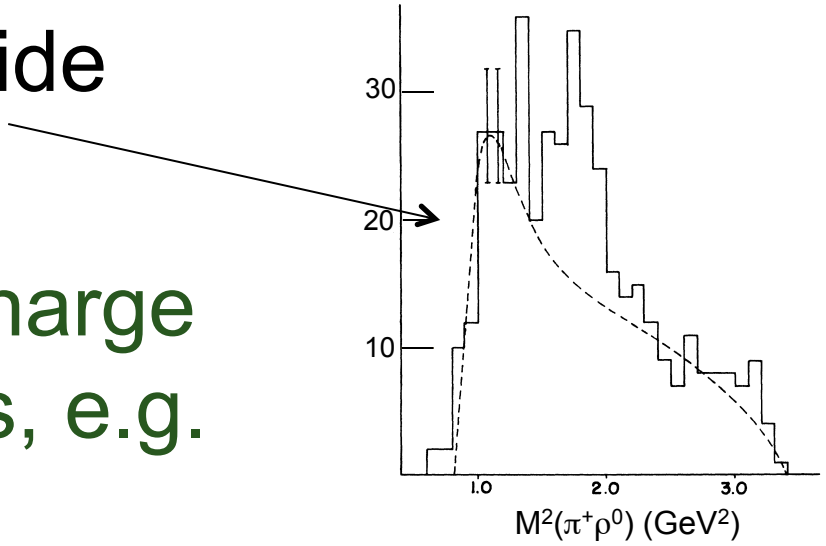
- Clear enhancement near threshold. Is it a new resonance as suggested in original paper?
- Theorists, first Deck, suggest that the threshold enhancement can be due to off shell πp scattering *R.T. Deck, PRL 13, 169 (1964)*





Deck Effect

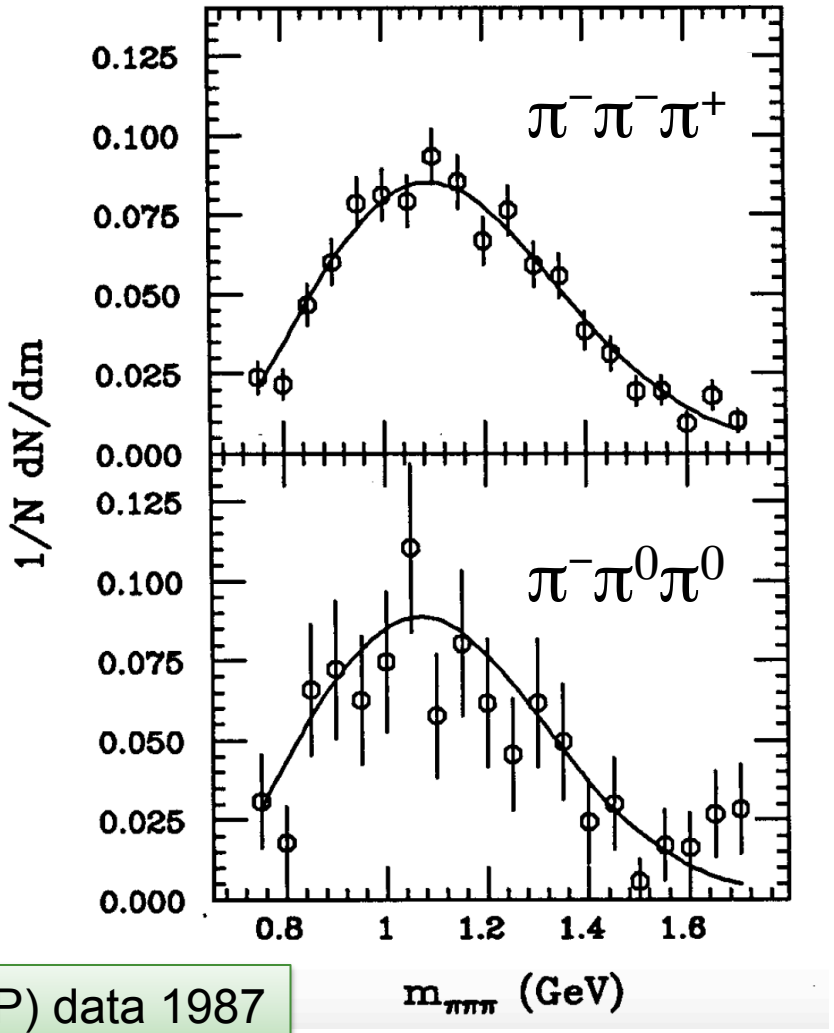
- Deck's fit to data can provide adequate explanation



- 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

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

Surmises: a full amplitude analysis may have proved the resonant nature of the a_1 earlier. Important to see resonant states in several ways.

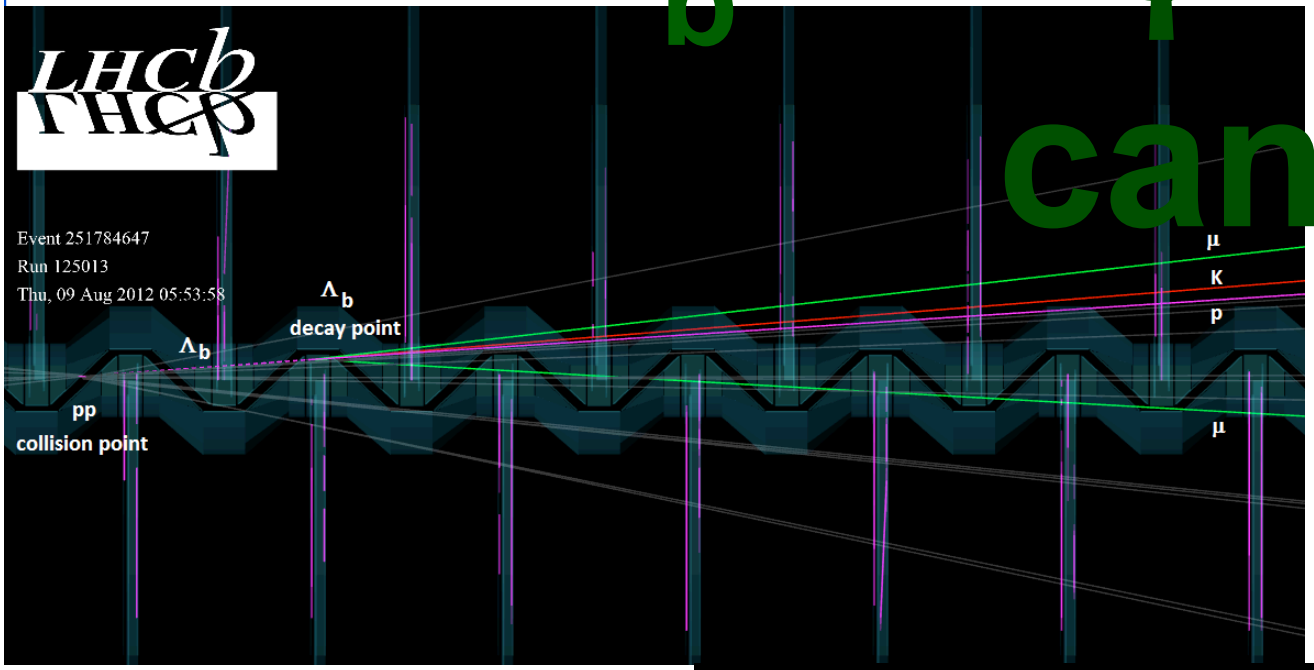


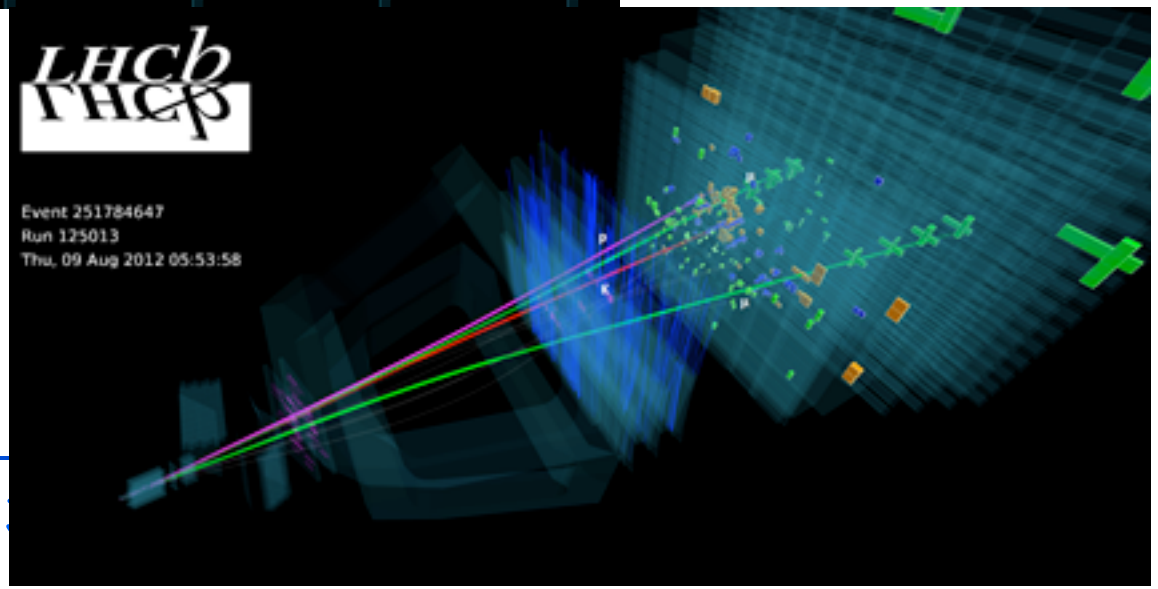
MAC (PEP) data 1987

Interest in multiquark objects

- Provides important lessons for QCD
- Are these objects tightly bound where the quarks are bound by color forces with each other?
- Or are they loosely bound where a subset of quarks form “normal” mesons or baryons that are then loosely bound together?
- As for glueballs, they have no quarks only gluons, and I will not speak further about them due to lack of time

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





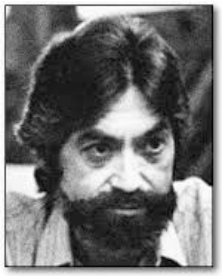
Quark model

In the beginning multiquark objects were predicted- now called exotic

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN – Geneva

8182/TH.401
17 January 1964



ABSTRACT

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The break-

Volume 8, number 3 PHYSICS LETTERS

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

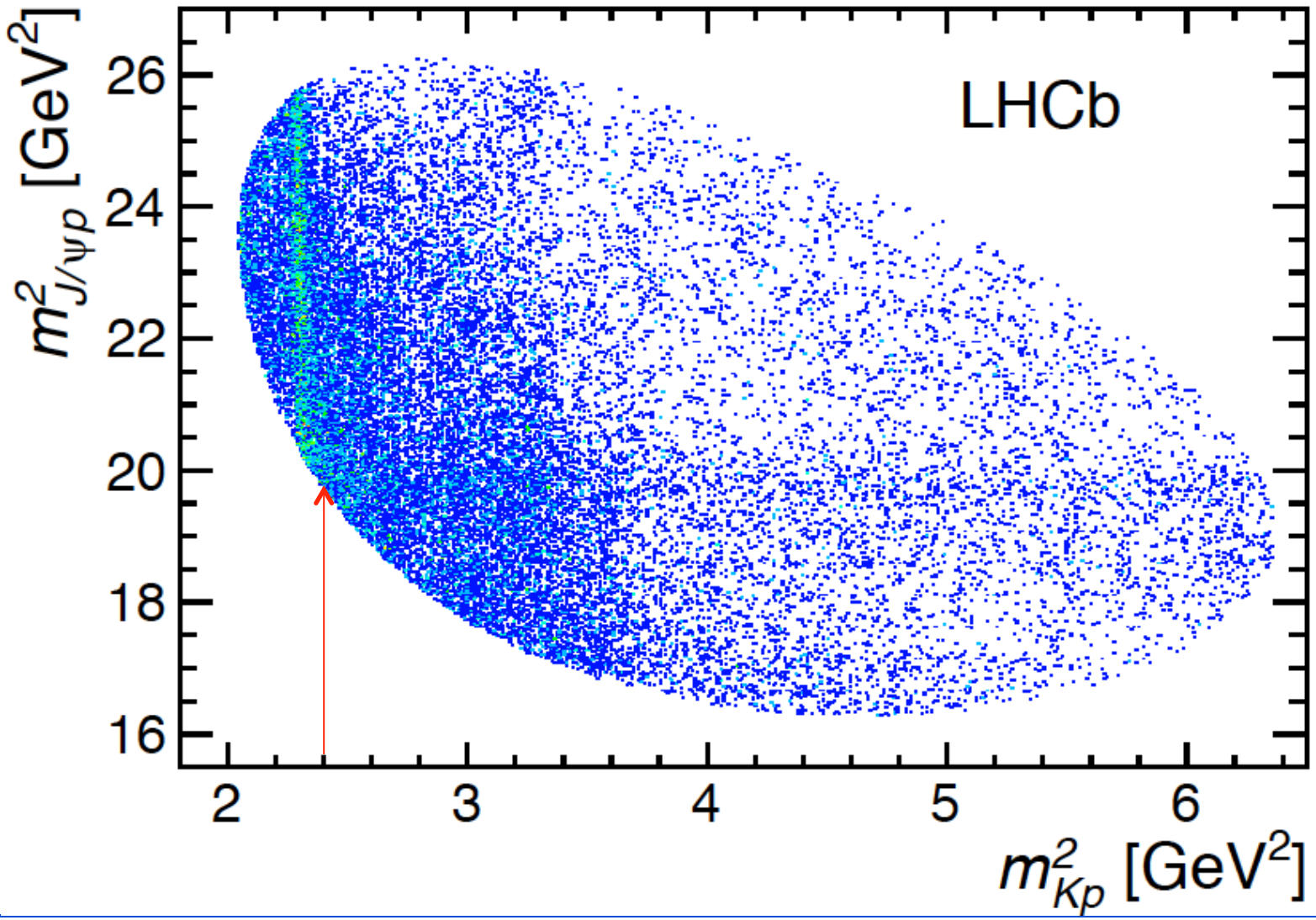
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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), $(qqq\bar{q})$, 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 the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

qqqq̄ baryons later called “pentaquarks”; qqq̄q̄ meson called “tetraquarks”

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.]

Dalitz Plot