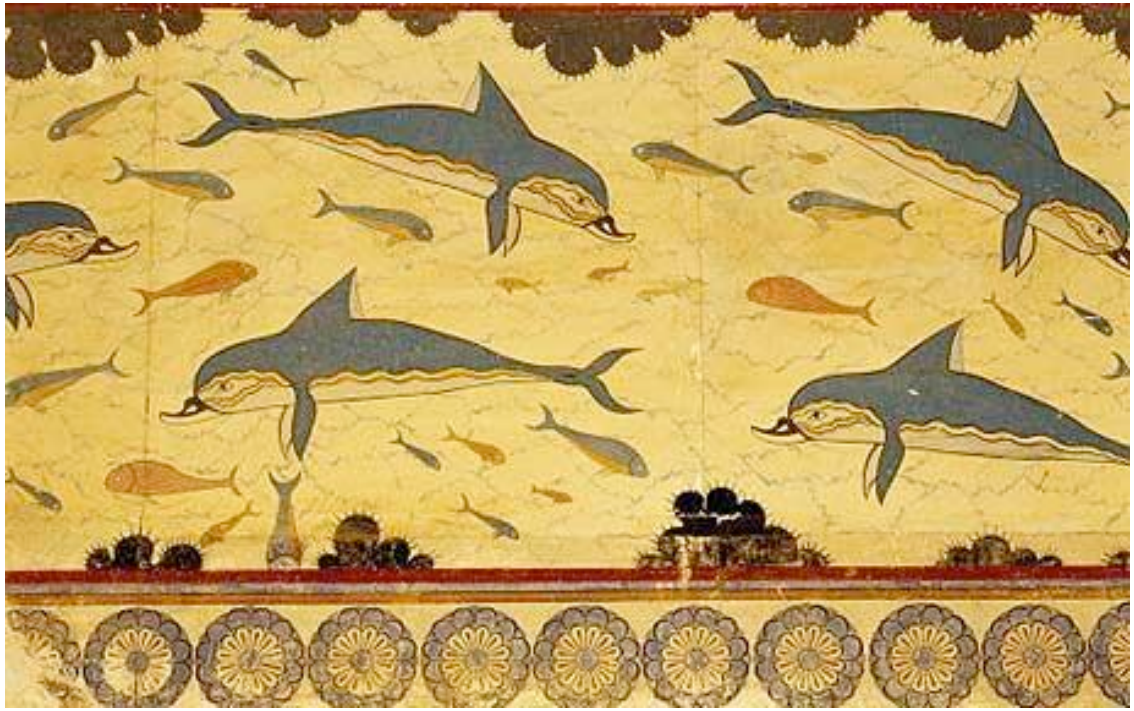
Observation of pentaquark resonances in $\Lambda_b \to J/\psi K p$ decays



ICNFP 2015 : 4th International Conference on New Frontiers in Physics

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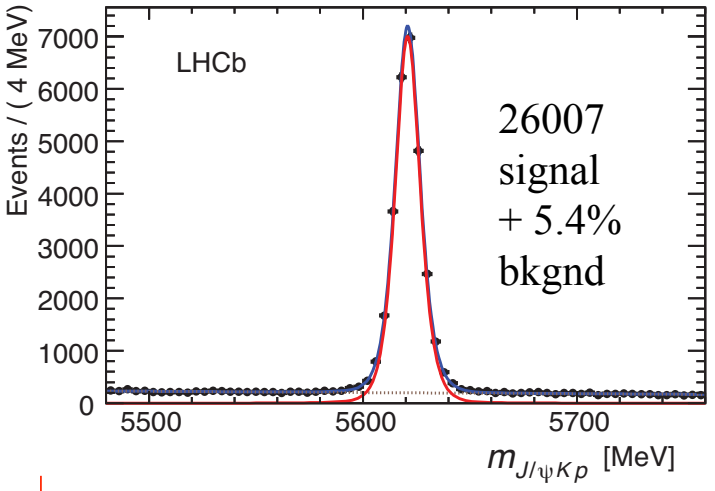
on behalf of the LHCb Collaboration

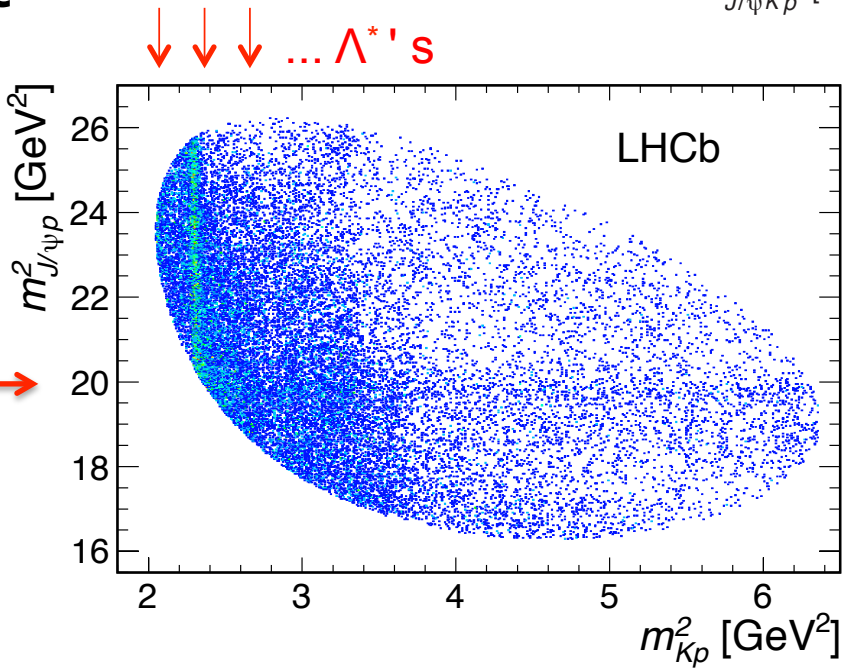
A chronicle of the pentaquark

- New states of matter beyond the simple quark picture: an inspiring case of QCD
- No reason why they should not exist
  - predicted by Gell-mann (64) and Zweig (64), specific QCD models Jaffe (76), Strottman (79), Hogaasen & Sorba (78), Lipkin (87)
- No convincing states 50 years after Gell-mann paper proposing qqq and qqqq$\bar{q}$ states
  - Various enhancements observed in mass spectra, including $\theta^+ \rightarrow K^+n$, $D^{*-}p$, and $\Xi^{--} \rightarrow \Xi^- \pi^-$ mostly "demystified", see recent review K. H. Hicks Eur. Phys. J. H37 (2012).

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

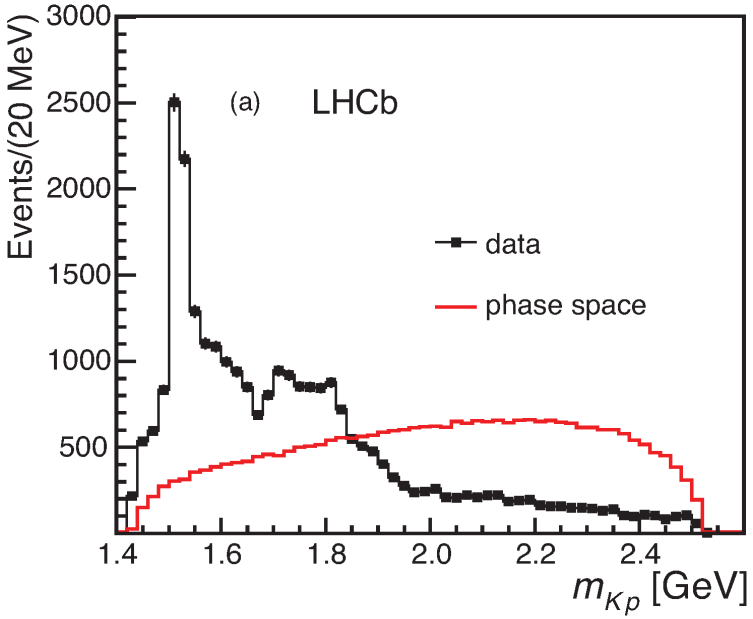
- Great Λ_b signal over very small background at LHCb, due to trigger on displaced vertices, large acceptance for low p_T $J/\Psi \rightarrow \mu^+\mu^-$, and excellent mass resolution
- Dalitz plot shows resonant Λ^* structures in $K^- p$ mass and unexpected feature in J/Ψ p mass

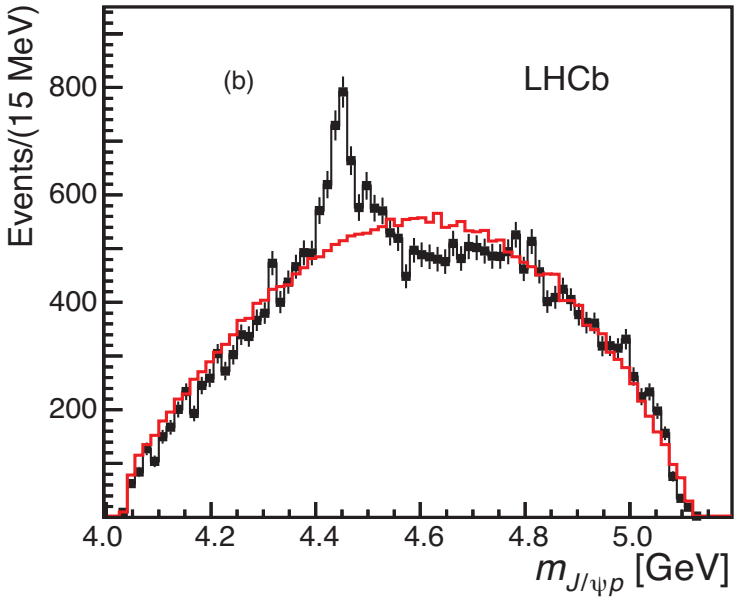


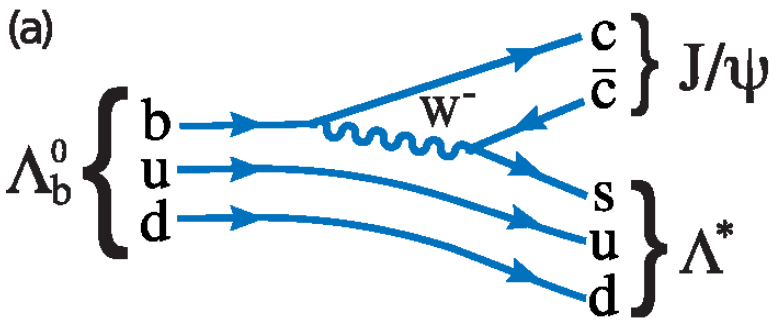


Projections

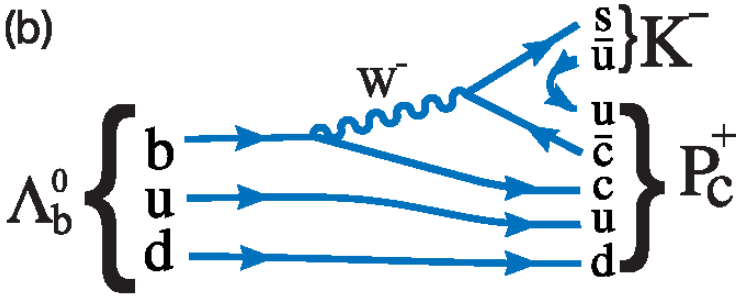
Phys. Rev. Lett. 115, 072001 (2015), published Aug. 12, 2015







minimal quark content: uudcc̄



Is this diagram real ?

Amplitude analysis

- Interference between two channels:

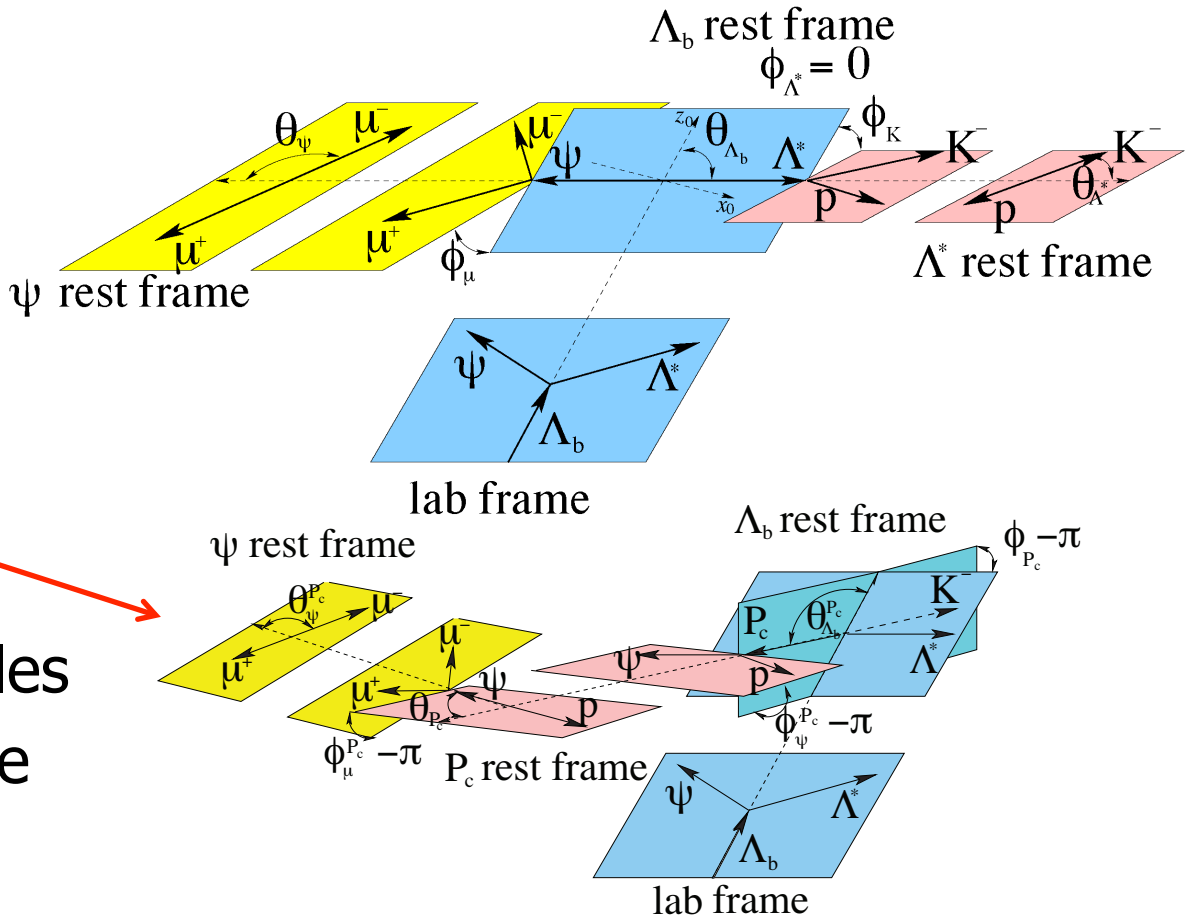
  $\Lambda_b \to J/\psi \Lambda^*$,

  $\Lambda^* \to K^- p$

  and

  $\Lambda_b \to P_c^+ K^-$,

  $P_c^+ \to J/\psi\, p$



- m(K^-p) & 5 decay angles are independent phase space dimensions
- Sequential weak/strong decay helicity amplitudes
- Parity conservation assumed in strong decays and Λ_b production

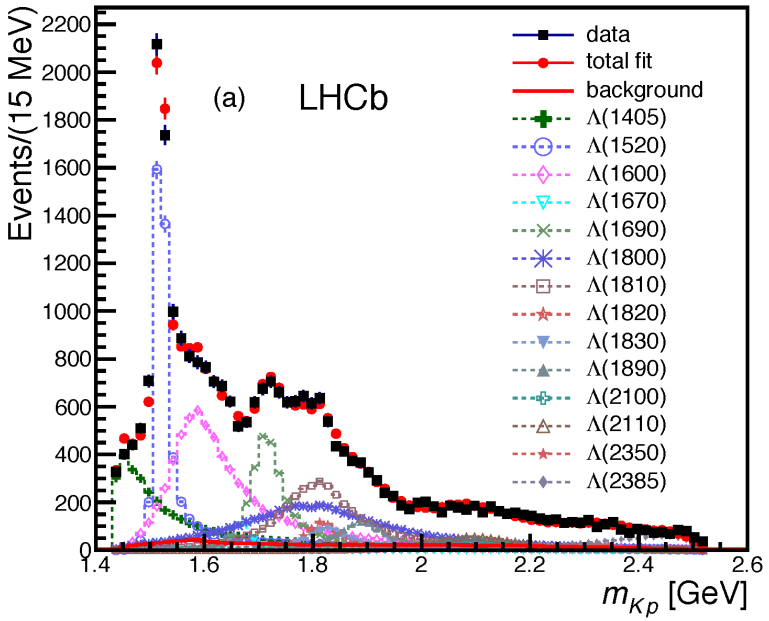
Models: extended & reduced

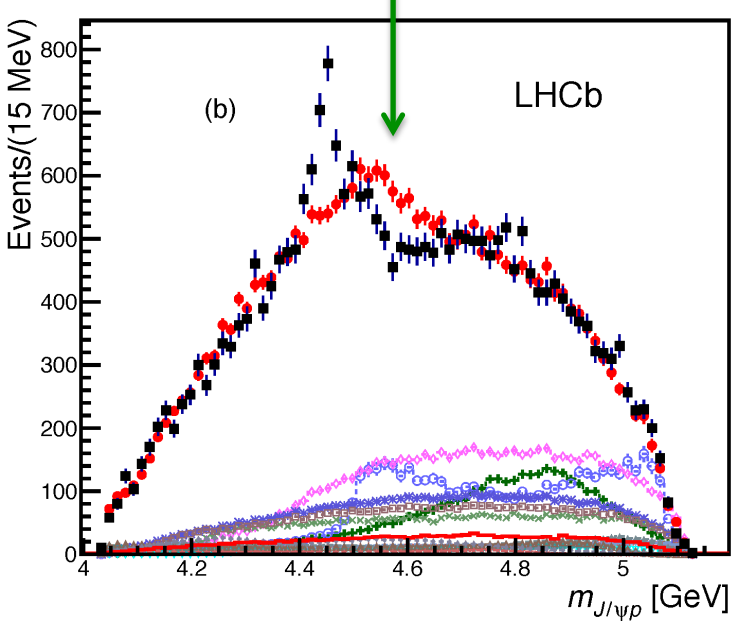
- Consider up to 13 Λ* states & allowed L values

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx$2585	200	0	6
			# parameters	64	146

Results without P_c states

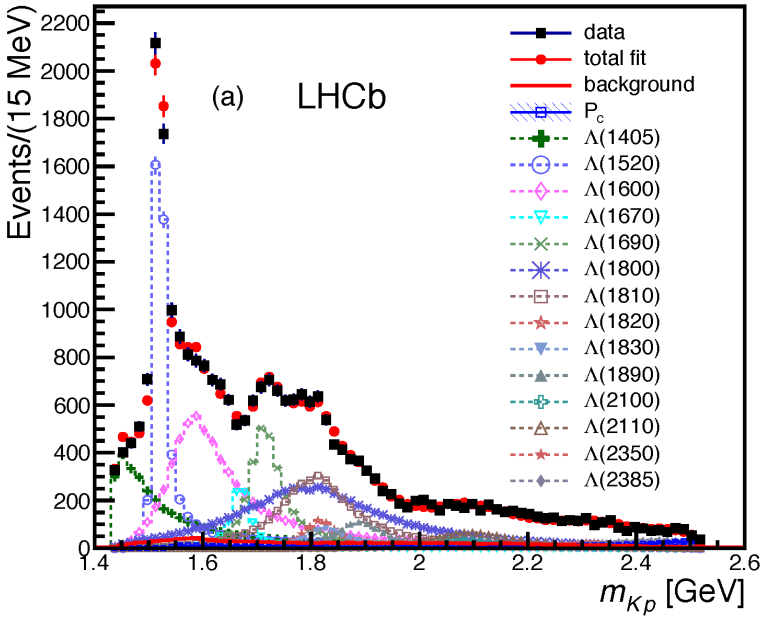
- Use extended model, so all possible known Λ* amplitudes. m_{Kp} looks fine but not $m_{J/\psi p}$
- Additions of non-resonant, or extra Λ*'s do not help

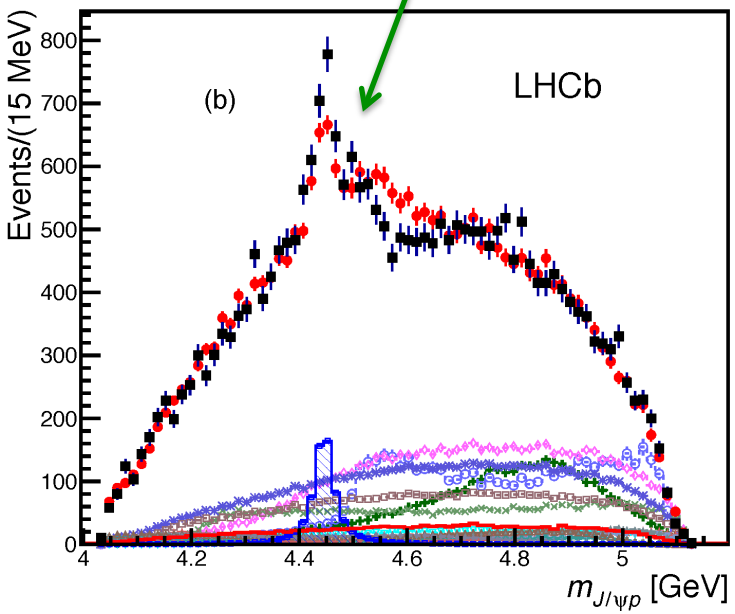




Extended model with one P_c

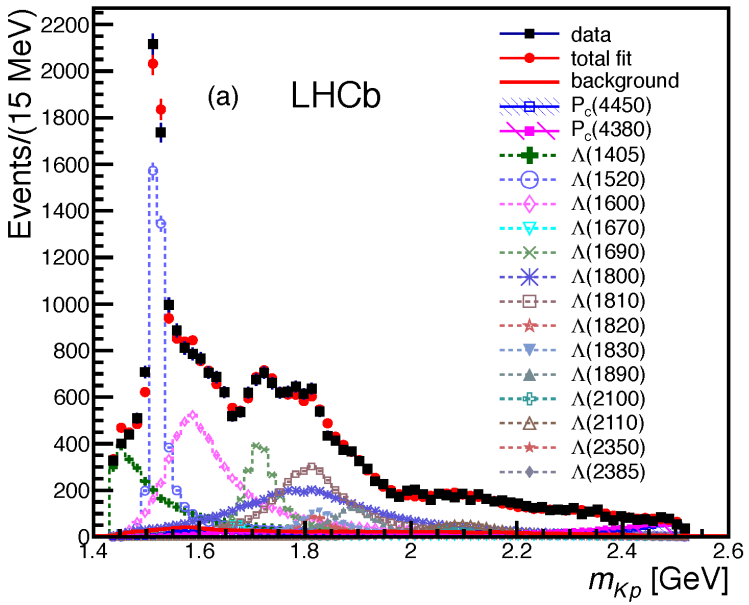
- Try all J^P up to $7/2^{\pm}$
- Best fit has $J^P = 5/2^{\pm}$. Still not a good fit

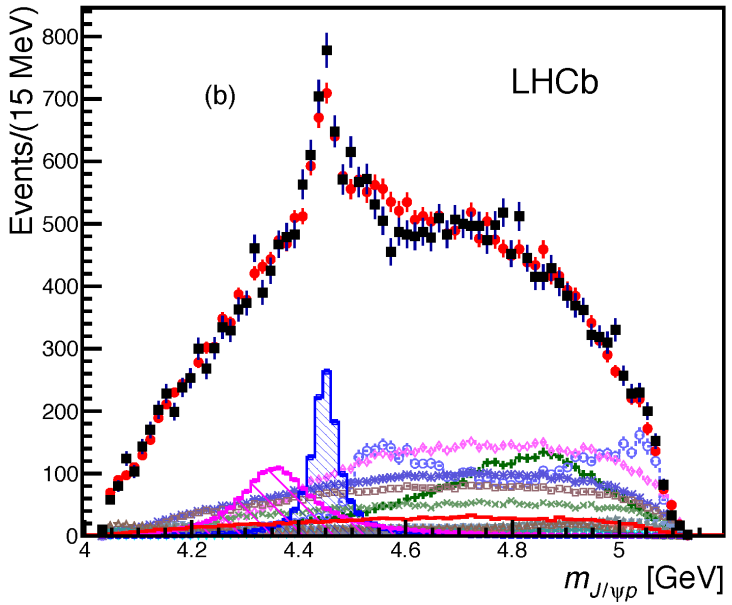




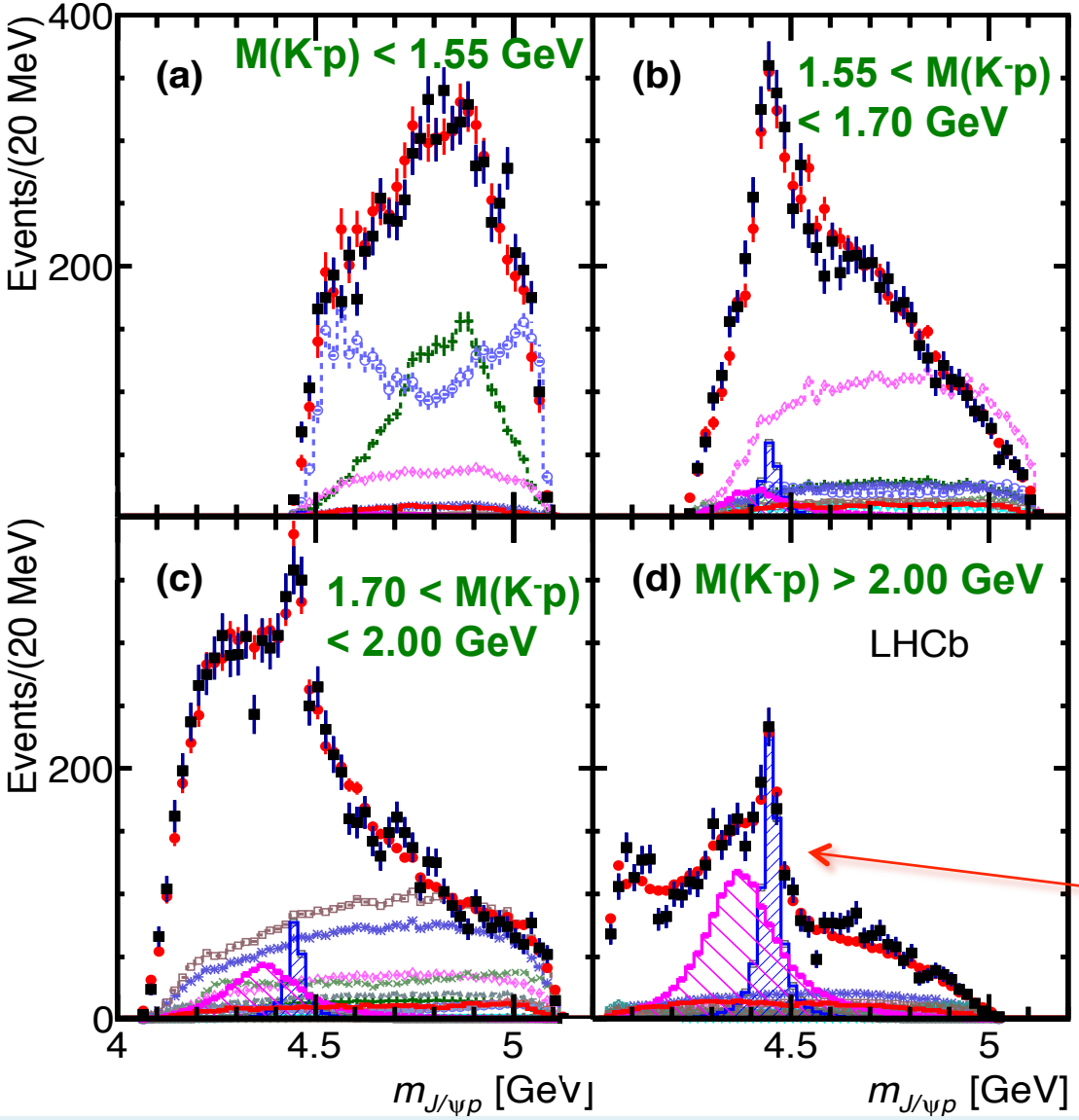
Reduced model with two P_c's

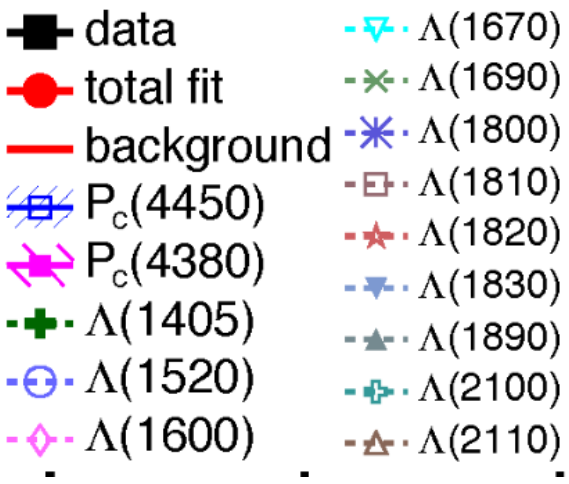
- Best fit has $J^P = (3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred





Intervals of m(K^-p)





Signal more prominent as m(K^-p) becomes large, away from Λ*'s

Results and significance

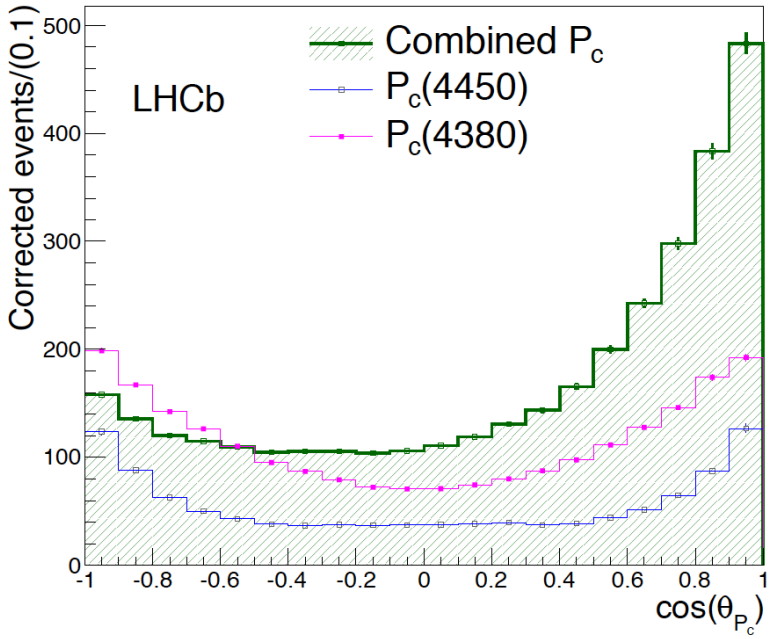
	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c^+(4380)$	4380 ± 8 ± 29	205 ± 18 ± 86	8.4 ± 0.7 ± 4.2
$P_c^+(4450)$	4449.8 ± 1.7 ± 2.5	39 ± 5 ± 19	4.1 ± 0.5 ± 1.1
	Λ(1405)		15 ± 1 ± 6
	Λ(1520)		19 ± 1 ± 4

- Fit improves after adding 1 P_c by $\Delta(-2\ln\mathcal{L})=14.7^2$, then adding the 2nd P_c by 11.6^2, and adding both together $\Delta(-2\ln\mathcal{L})=18.7^2$
- Alternatively from toy simulations: 1st state has significance of 9σ and 2nd state 12σ, including systematic uncertainties

Data demands two states

- Interference between opposite parity P_c^+ states needed to explain decay angular distribution
- θ_{Pc} is the J/ψ angle in P_c^+ rest frame
- Fit projections are shown

NEGATIVE INTERFERENCE (LARGE M_{KP})



POSITIVE INTERFERENCE (SMALL M_{KP})

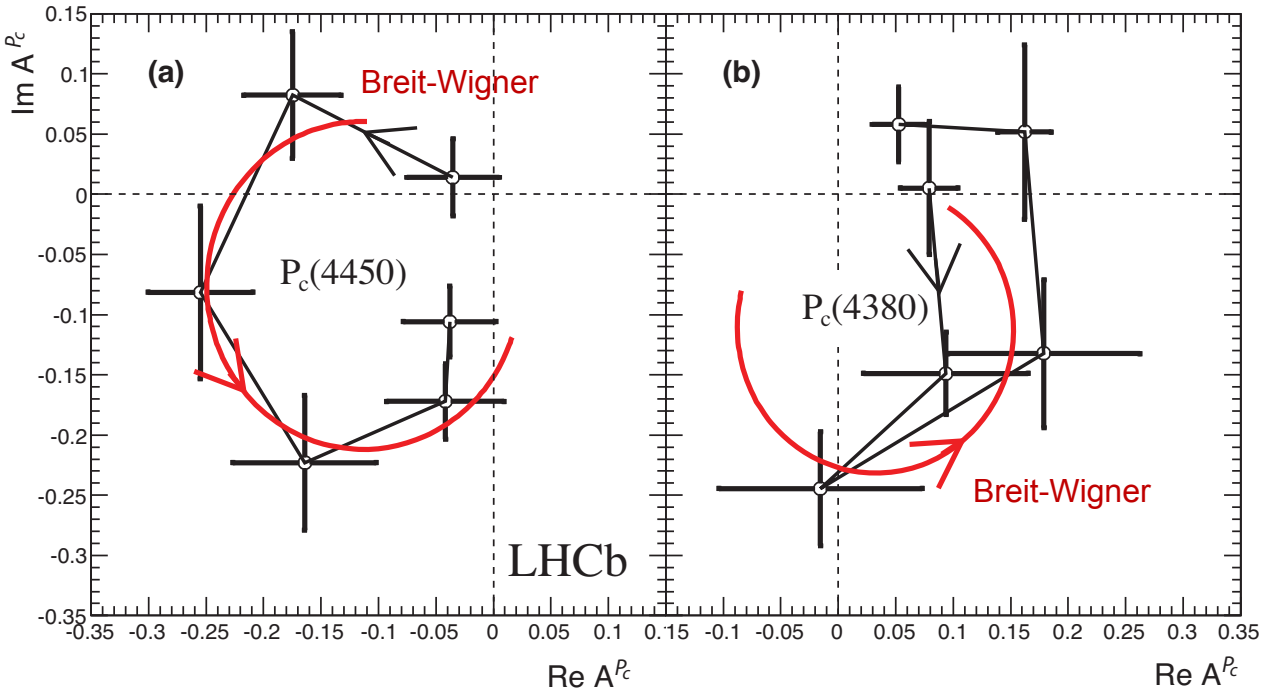
INDIVIDUALLY SYMMETRIC RATES

Phase behaviour

- Breit-Wigner amplitudes determined for 6 bins in (M_X-Γ, M_X+Γ)

$$\frac{1}{M_X^2 - m^2 - iM_X\Gamma(m)}$$

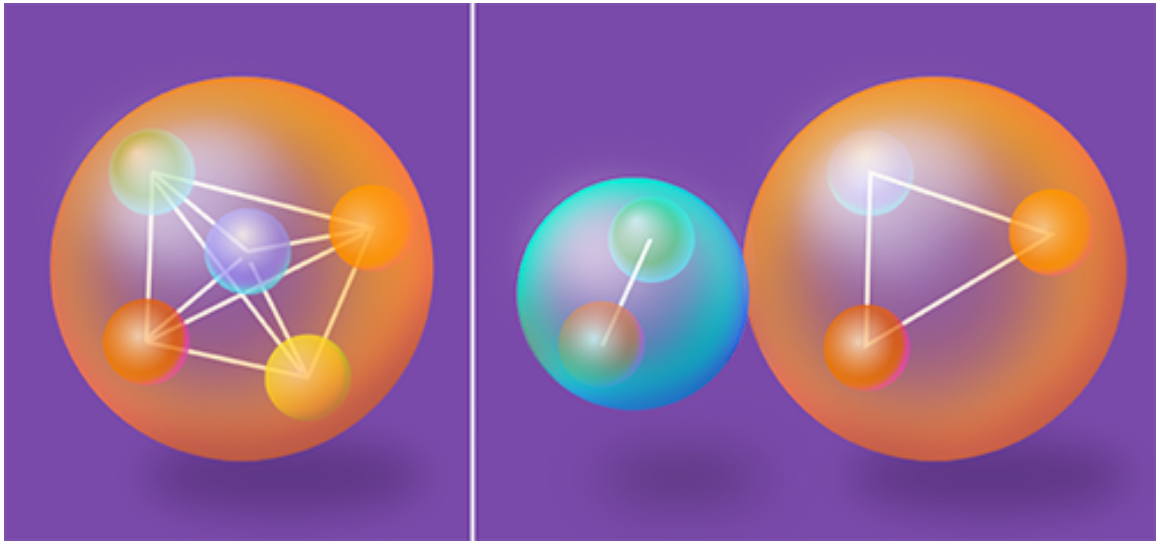
Canonical resonance unitary amplitude.
The phase should run counter-clockwise.



Conclusions

- LHCb has found two resonances coupled to J/ψ p with pentaquark content $uudc\bar{c}c$. Phys. Rev. Lett. 115, 072001 (2015) August, 2015.
- Determination of their binding mechanism will require more study. The preferred J^P are $(3/2^-,5/2^+)$, $(3/2^+,5/2^-)$ or $(5/2^+,3/2^-)$. Opposite parity is significant.
- Tetraquarks $Z^+(4430)$ have also appeared (Belle arXiv: 1306.4894, LHCb arXiv: 1404.1903, BES Phys. Rev. Lett. 110, 252001 (2013) with $J^P=1^+$ showing $c\bar{c}$ content. Is $c\bar{c}$ more strongly bound?
- Lattice QCD calculations would be most welcome to provide masses
- Some reactions have appeared pointing at hadronic molecule interpretation M. Karliner, J.L. Rosner arXiv:1506.06386
- We look forward to establishing the structure of many similar states

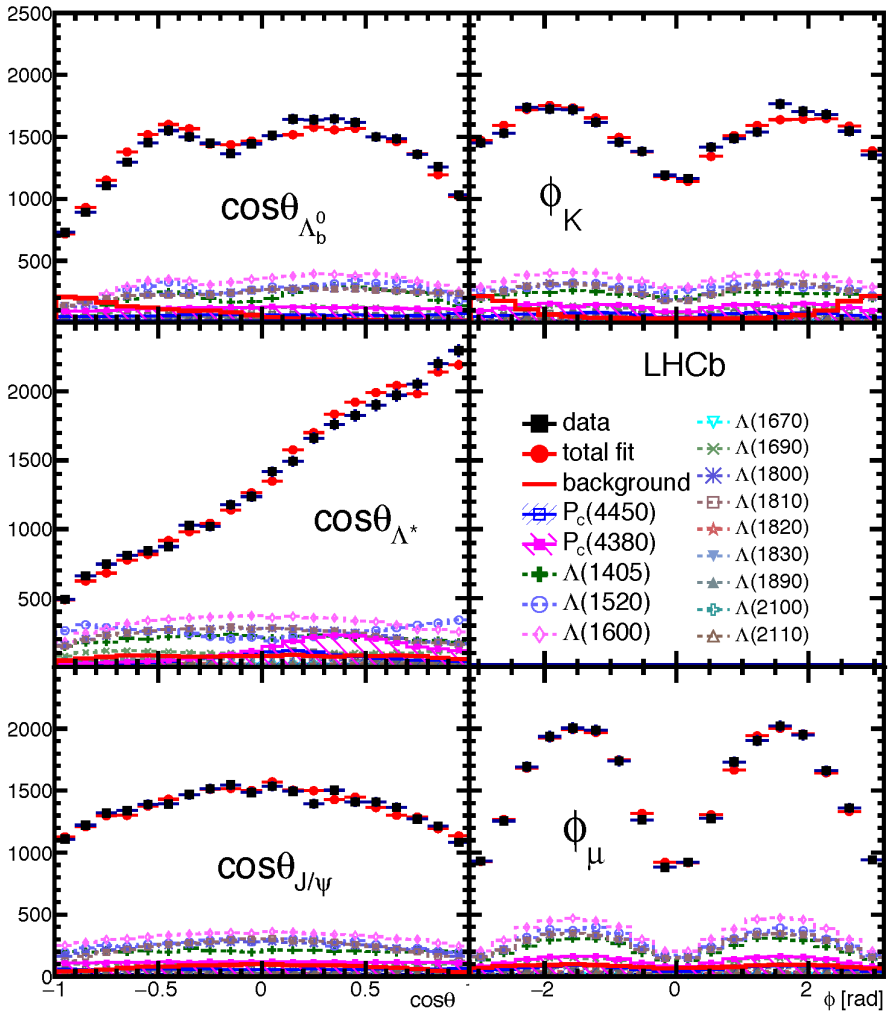
THANK YOU



BACKUPS

Angular distribution

- Good angular fits



Cross-checks

- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data shows consistency: 2011/2012, magnet up/down, Λ_b, Λ_b, Λ_b (p_T low)/Λ_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

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