Exotic Hadron Spectroscopy in LHCb

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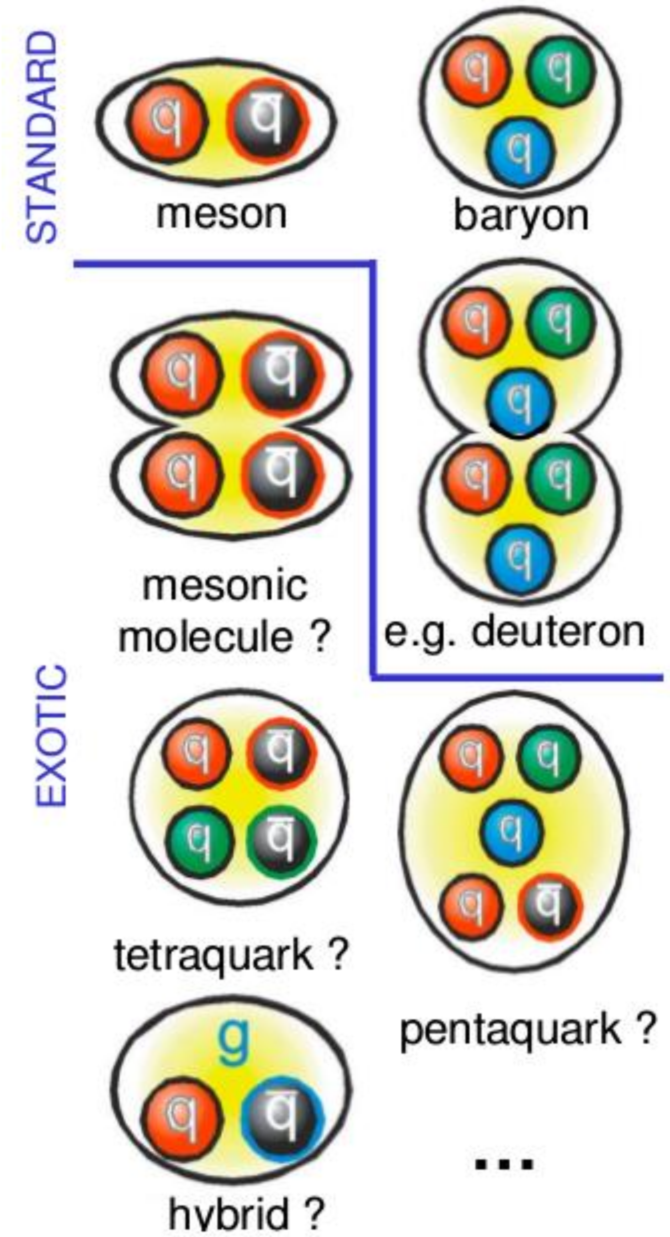
On behalf of the LHCb Collaboration

Exotic Hadrons

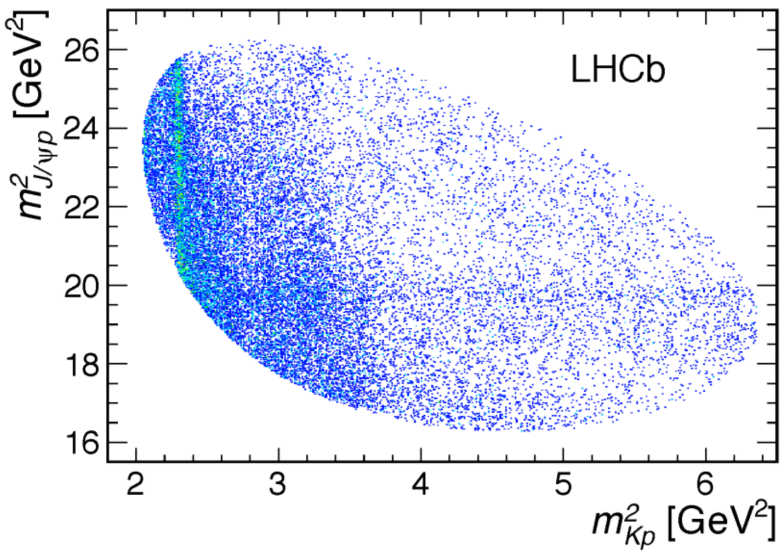
- Since the inception of the quark model in the 60’s with Gell-Mann (64) and Zweig (64), hadrons beyond the $q\bar{q}$ mesons and qqq baryons have been hypothesized.
- These could be molecular bound states with mesons, tetraquarks, pentaquarks, or hybrids.



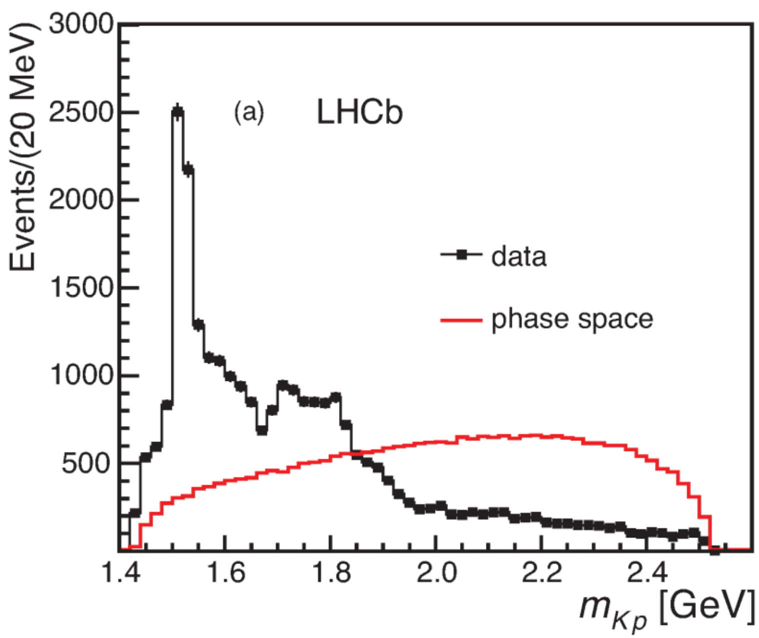
Outline

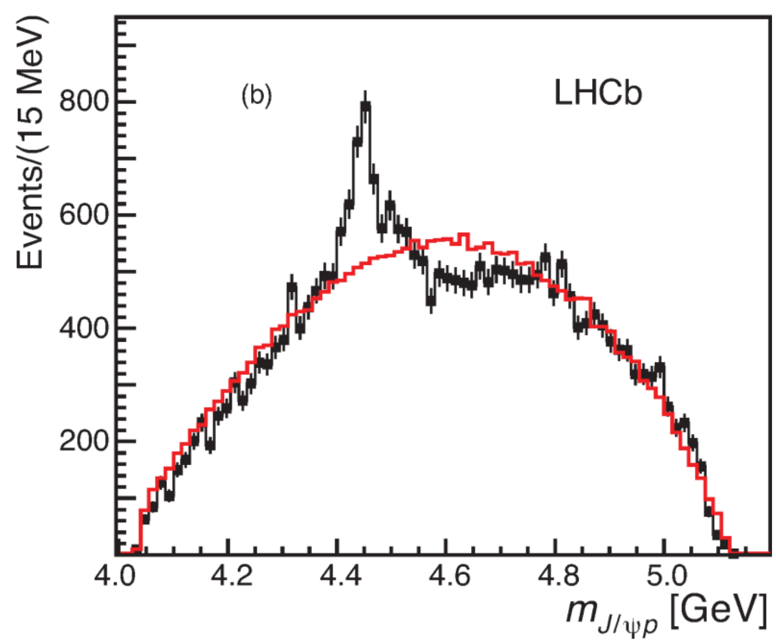
- In recent years strong candidates for these exotic hadrons been observed with contributions from multiple experiments.
- In this talk I will cover new results from LHCb for:
  - $P_c(4450)$, $P_c(4380)$: Recently observed pentaquark candidates LHCb-PAPER-2015-029, arXiv:1507.03414
  - X(3872): mesonic molecule, conventional charmonium, or a mixture. Phys Rev D 92, 011102 (2015)
  - $Z(4430)^{-}$: tetraquark candidate LHCb-PAPER-2015-038, in preparation. Confirmed by LHCb in Phys. Rev. Lett. 112, 222002 (2014),

Pentaquarks In $\Lambda_b \to J/\psi\, pK$



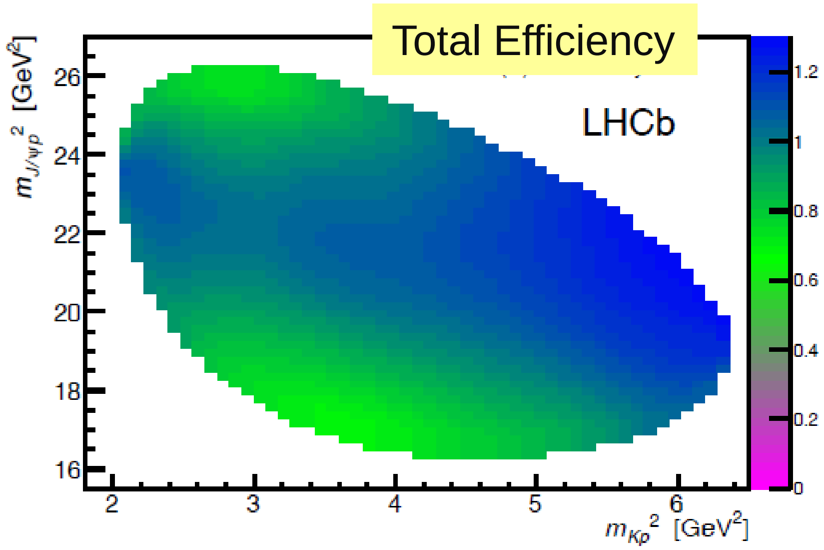
- In studying this decay, the expected Kp resonances were found. But also a surprising feature was found in the $J/\psi\, p$ system.





Is the peak "an artifact"?

- Many checks done that show this is not the case:
  - Reflections of B^0 and B_s are vetoed
  - Ξ_b decays checked
  - Efficiency is smooth, can't create a peak
  - Λ_b sideband background doesn't peak
  - Clones & ghost tracks eliminated

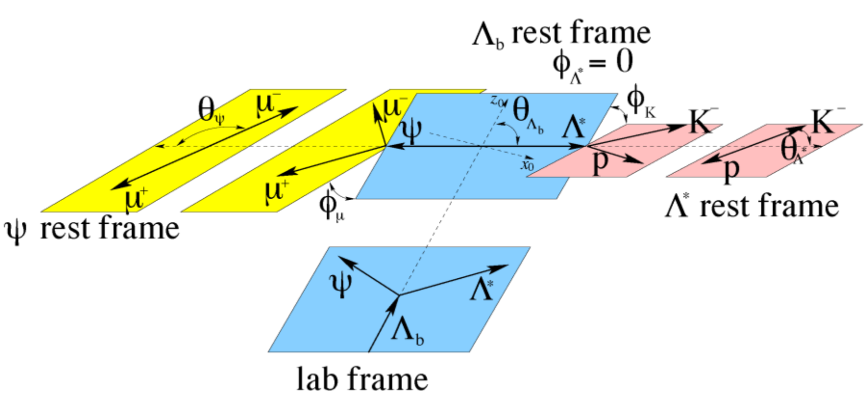


- Can interferences between Λ^* resonances generate a peak in the J/ψp mass spectrum? If not can the data be described in all relevant kinematic variables with the addiction of J/ψp resonances?
  - To answer these a full amplitude analysis is performed.

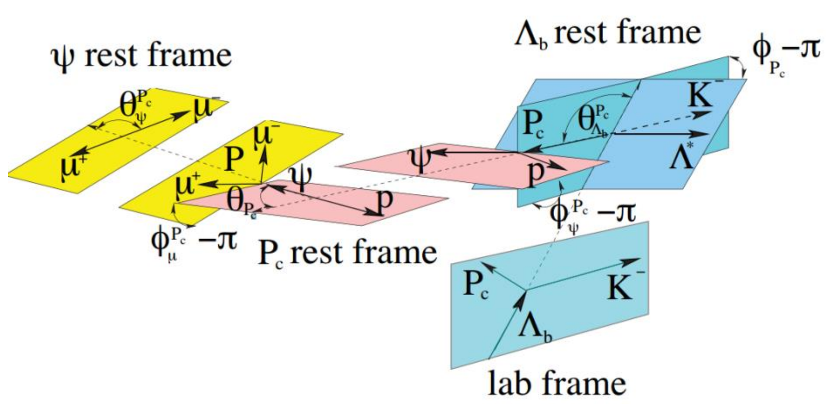
Amplitude Analysis Formalism

- The matrix element for $\Lambda_b \to J/\psi\, pK, J/\psi \to \mu^+\mu^-$ was written down in the helicity formalism. Allows for the conventional $\Lambda^* \to pK$ resonances to interfere with pentaquark states $P_c \to J/\psi\, p$.
- Dynamics of the Λ^* decay chain depend on 1 mass and 5 angles. For the P_c chain, they depend on 1 mass and 6 angles, which are not independent from the Λ^* variables.
  - We perform a 6-dimensional unbinned maximum likelihood fit to maximize sensitivity to underlying decay dynamics.

Λ^* Decay Chain



P_c Decay Chain



Amplitude Analysis Formalism II

- The matrix element for the Λ^* decay chain is:

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

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

- And for the P_c chain:

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

$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\,\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\;\; D^{1}_{\lambda_\psi^{P_c},\,\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

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

Amplitude Analysis Formalism II

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

- And for the P_c chain:

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

$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_j(m_{\psi p})\ D^{1}_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*$$

- $\mathcal{H}$ are complex helicity couplings determined from the fit to the data.

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- Wigner D-matrix arguments are Euler angles corresponding to the fitted angles.

Amplitude Analysis Formalism III

- They are added together 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 and θ_p are further rotation angles to align the final state helicity axes of the μ and p, as helicity frames used are different for the two decay chains.

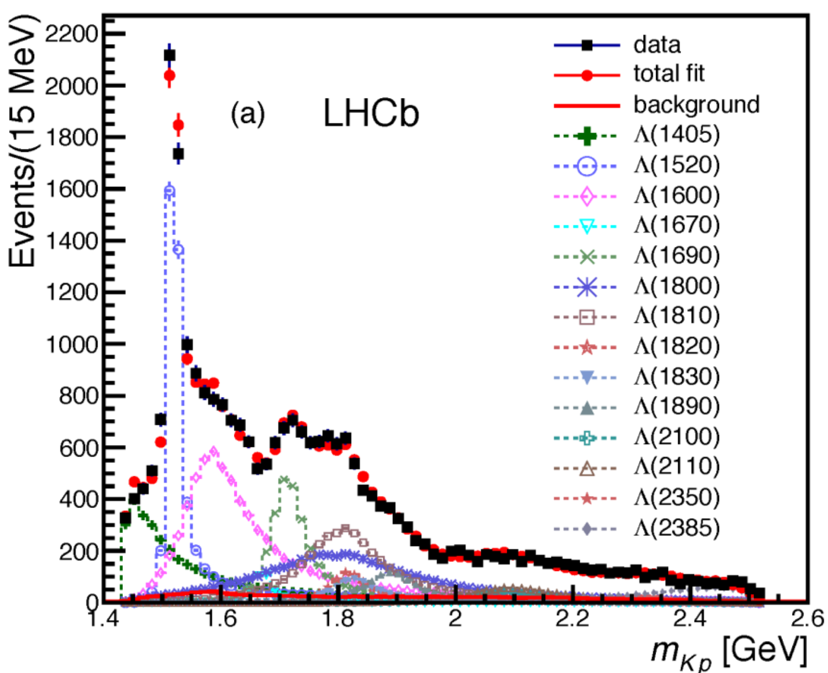
- Helicity couplings $\mathcal{H} \Rightarrow$ LS amplitudes *B* via:

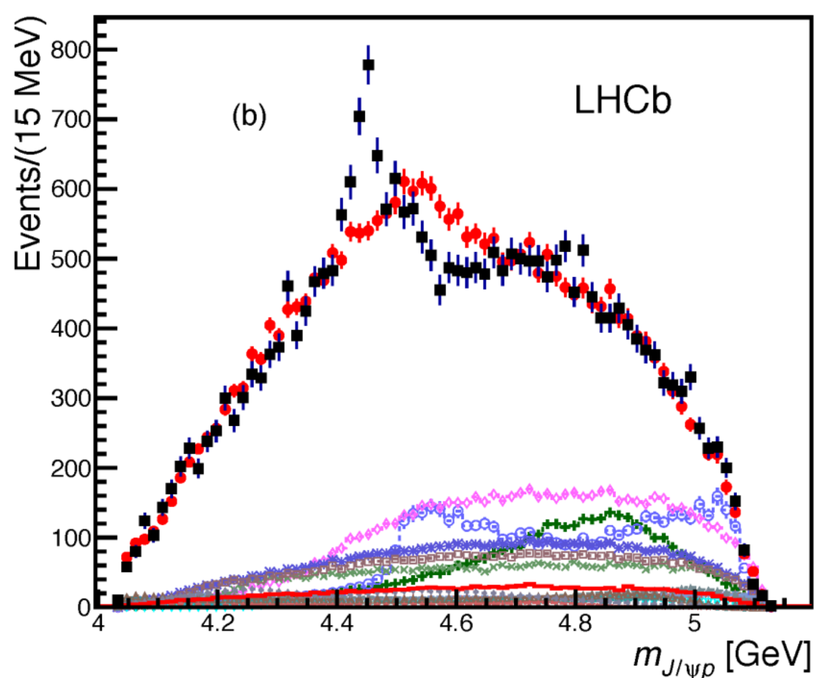
$$\mathcal{H}^{A\to BC}_{\lambda_B,\lambda_C} = \sum_L \sum_S \sqrt{\frac{2L+1}{2J_A+1}} B_{L,S} \left(\begin{array}{cc|c} J_B & J_C & S \\ \lambda_B & -\lambda_C & \lambda_B - \lambda_C \end{array} \right) \times \left(\begin{array}{cc|c} L & S & J_A \\ 0 & \lambda_B - \lambda_C & \lambda_B - \lambda_C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

  – Convenient way to enforce parity conservation in the strong decays via: $P_A = P_B P_C (-1)^L$

Fits With All Known Λ^* Resonances

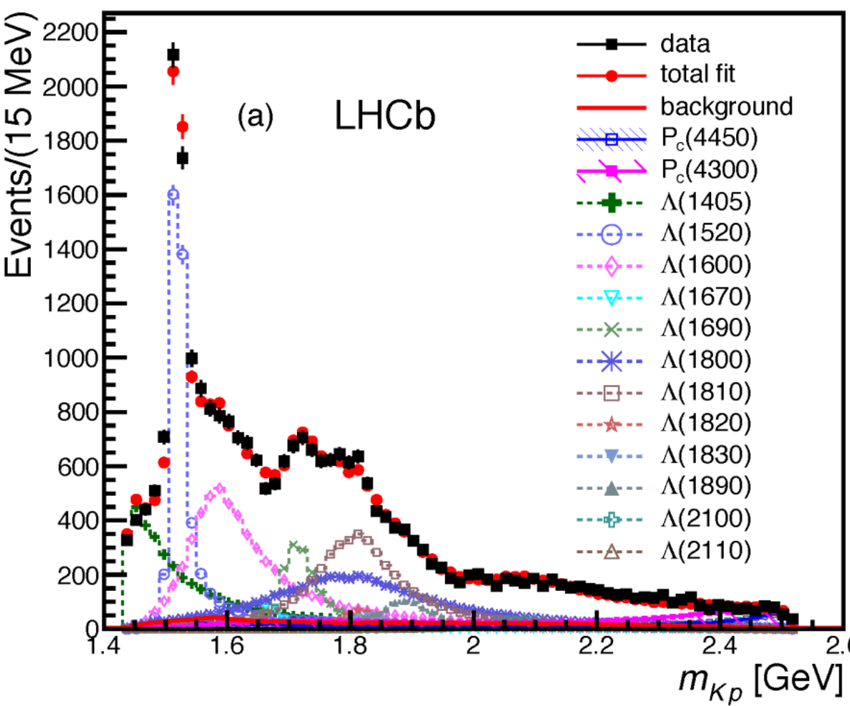
- Fitting with all known Λ^* does not reproduce the $M(J/\psi\, p)$ peaking structures!
- Also added the following, without being able to describe the peaks.
  - Σ^* contributions ($\Delta I = 1$ in Λ_b decays; expected to be small)
  - Additional Λ^* states with free mass and width
  - 4 non resonant Λ^*states with $J^P = 1/2^{\pm}, 3/2^{\pm}$

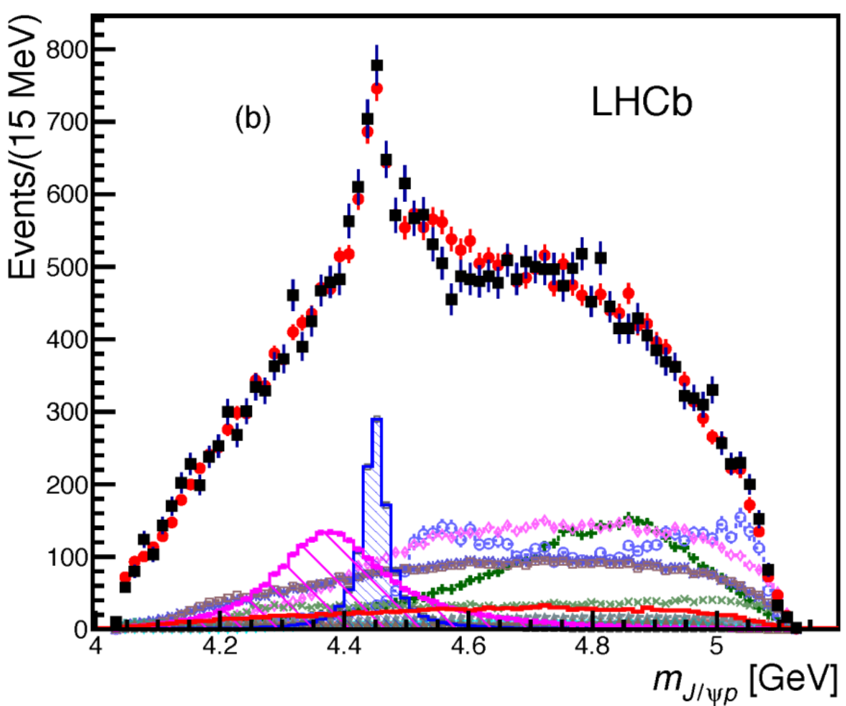




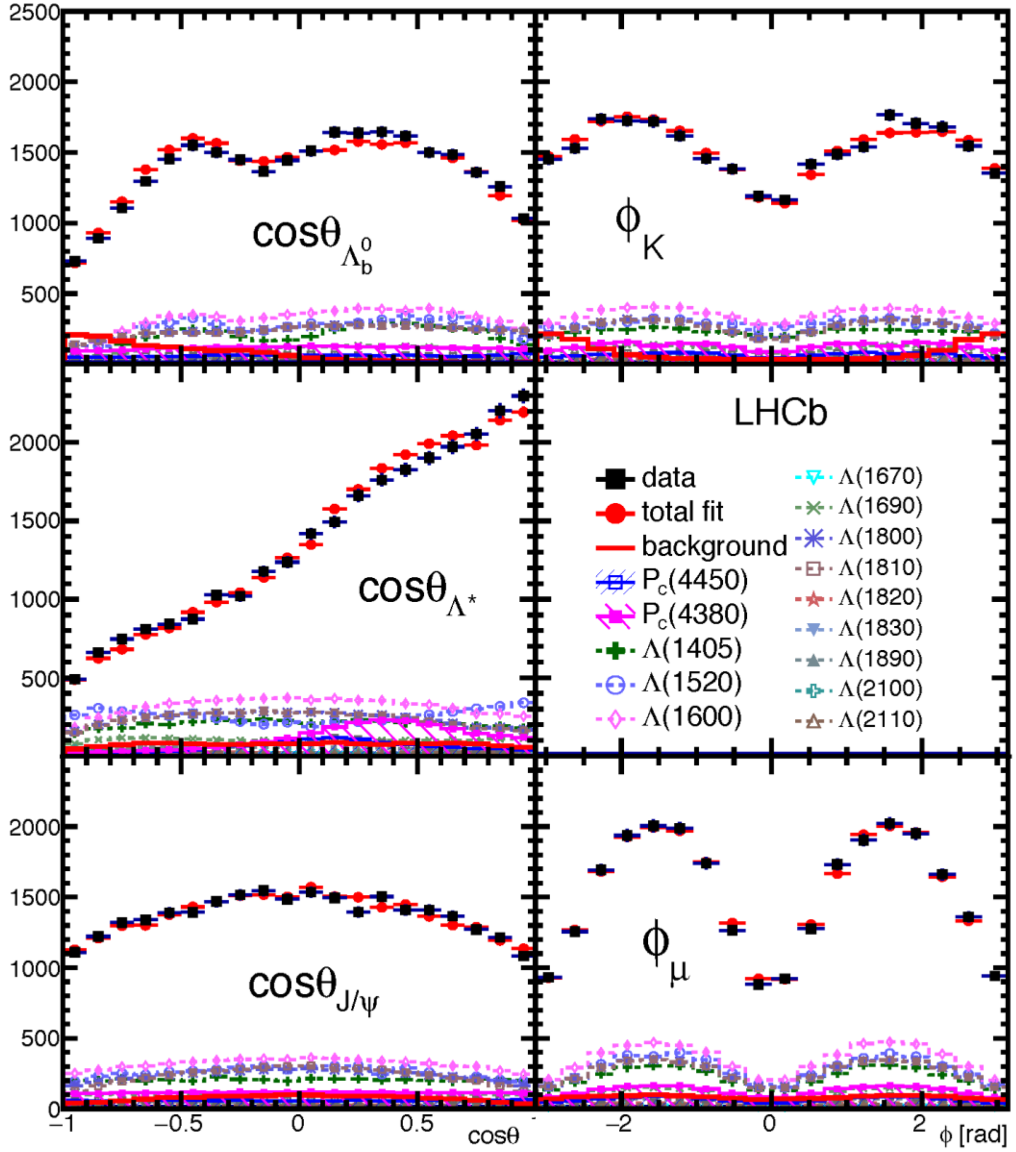
Fits With Two P_c Resonances

- With two P_c resonances, a good description of the data in all 6 dimensions is obtained (see next slide).
- Default model uses only well motivated Λ^* resonances.
- We fit all J^P combinations up to spin $^7/_2$.
- Best fit is with $J^P = (3/2^-, 5/2^+)$, but $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ not ruled out.

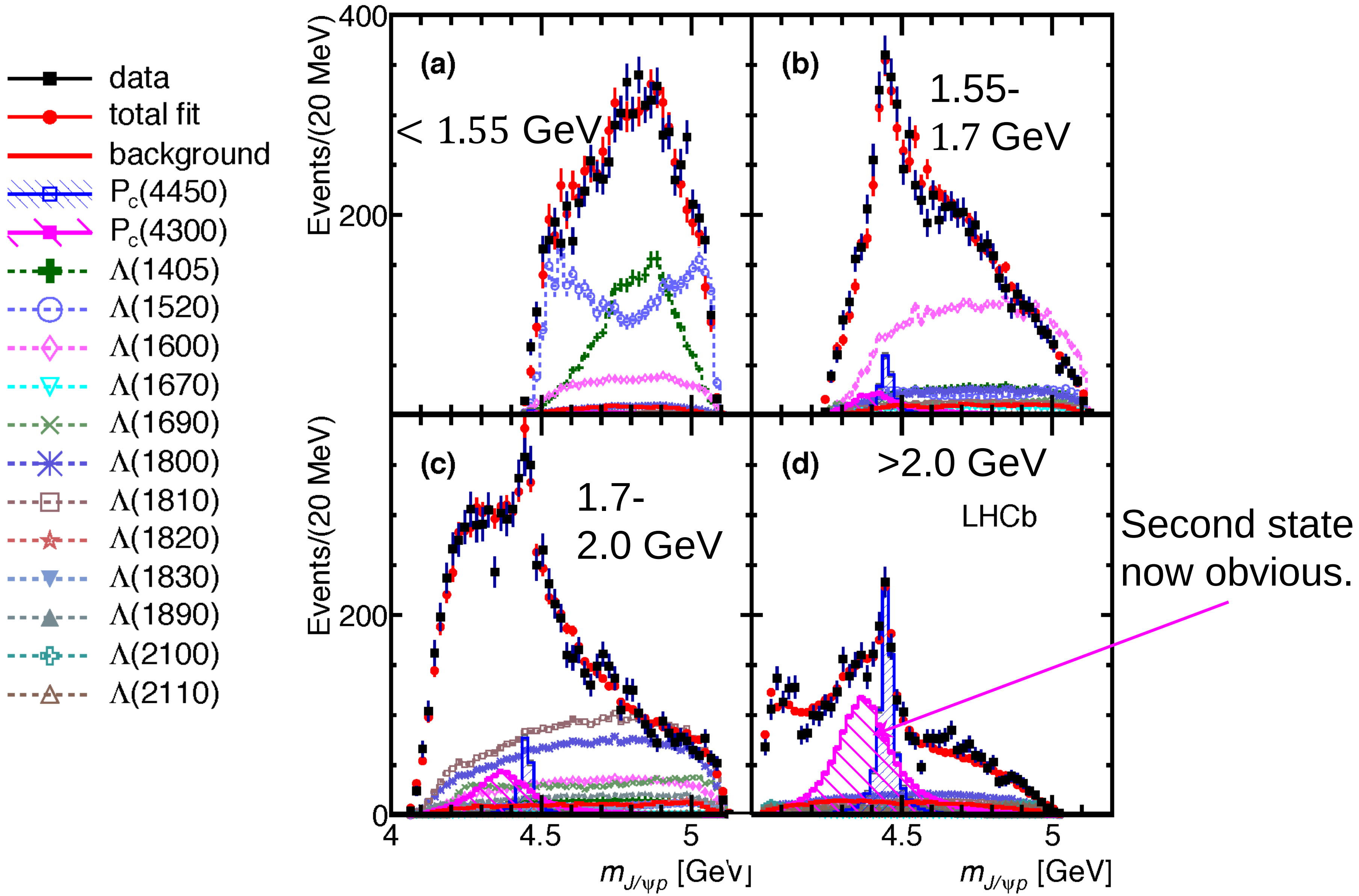




Angular Projections



$M(J/\psi\, p)$ in $M(Kp)$ Slices



Fit Results

- The observed states have masses, widths, and fit fractions of:

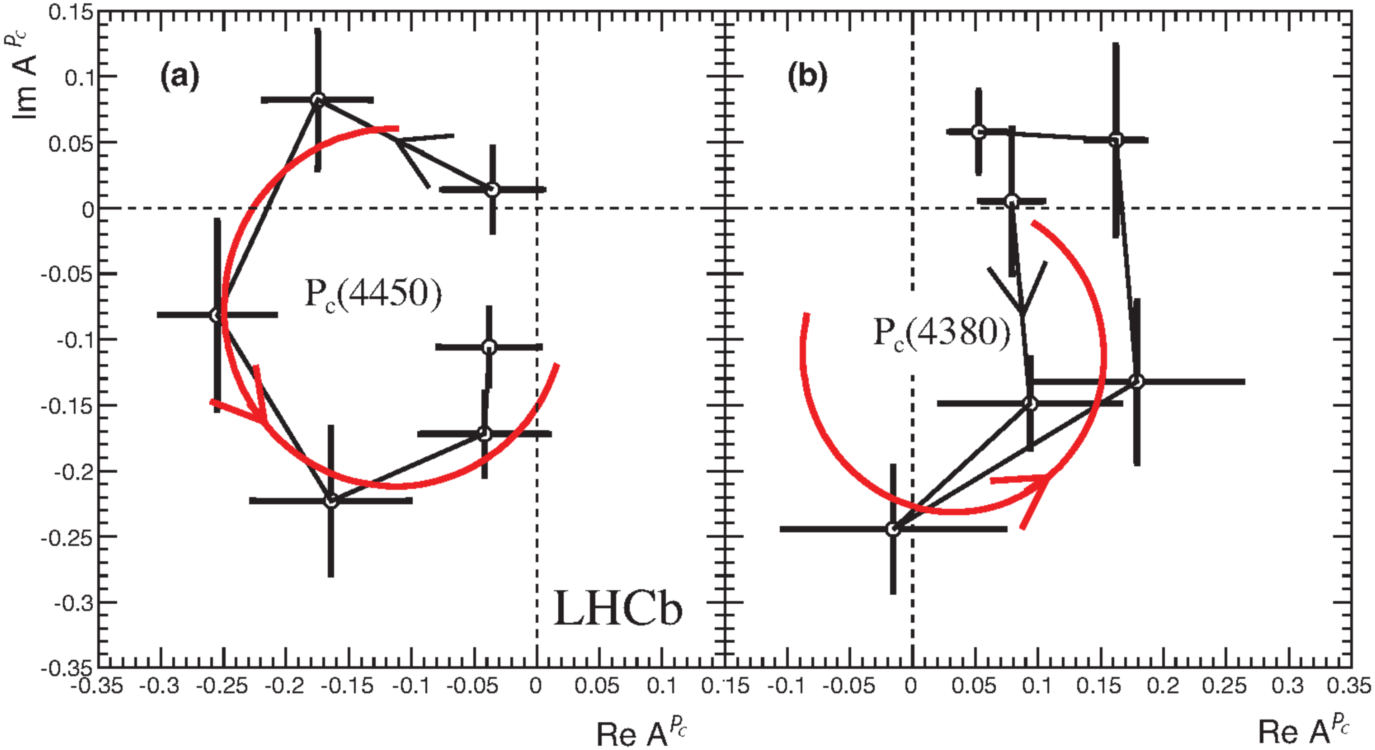
Resonance	Mass (MeV)	Width (MeV)	Fit Fraction (%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$
$\Lambda(1405)$			$15 \pm 1 \pm 6$
$\Lambda(1520)$			$19 \pm 1 \pm 4$

where the fit fractions of the more prominent Λ^* states are also listed

- The dominant systematic uncertainties come from the Λ^* model.

Resonance Phase Motion

- The Breit-Wigner shape for individual P_c's is replaced with 6 independent amplitudes in $M_0 \pm \Gamma_0$
- $P_c(4450)$: shows resonance behavior: a rapid counter-clockwise change of phase across the pole mass
- $P_c(4380)$: does show large phase change, but is not conclusive



Plot fitted values for amplitudes in an Argand diagram

Breit-Wigner Prediction

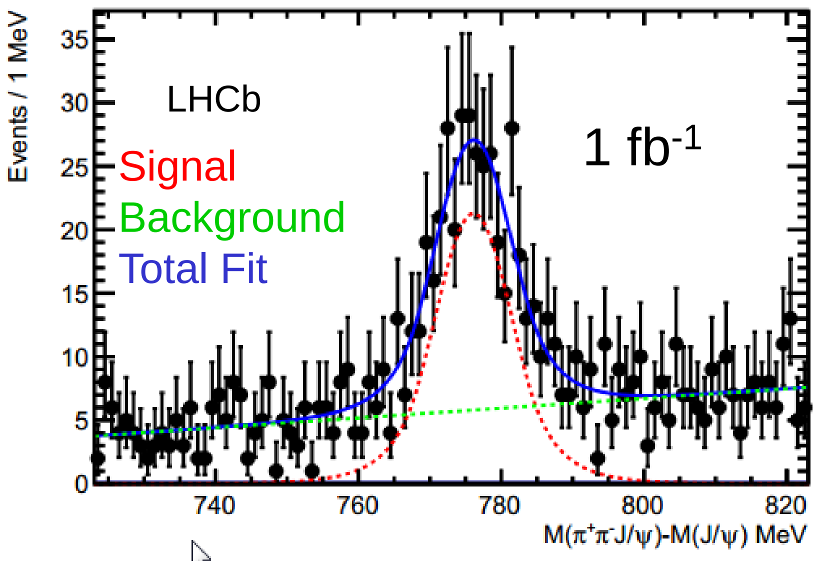
Fitted Values

X(3872) quantum numbers

Phys. Rev. Lett. 110, 222001 (2013)

- X(3872) is a long-lived state (Γ<1.2 MeV) with a mass within the errors off m(D^0)+m(D^{0*}).
- Currently unknown if it is a conventional charmonium state, something exotic (D^0D^{0*} molecule, tetraquark), or a mixture. Determination of its J^{PC} is important for narrowing down possible interpretations.
- Quantum numbers were narrowed down by CDF to be 1^{++} or 2^{-+}

- Using 1 fb^{-1} of 2011 data, LHCb used $B^+ \to X(3872)K^+$, with $X(3872) \to J/\psi\,\pi^+\pi^-$, and $J/\psi \to \mu^+\mu^-$ to pin down the J^{PC} to be 1^{++}.

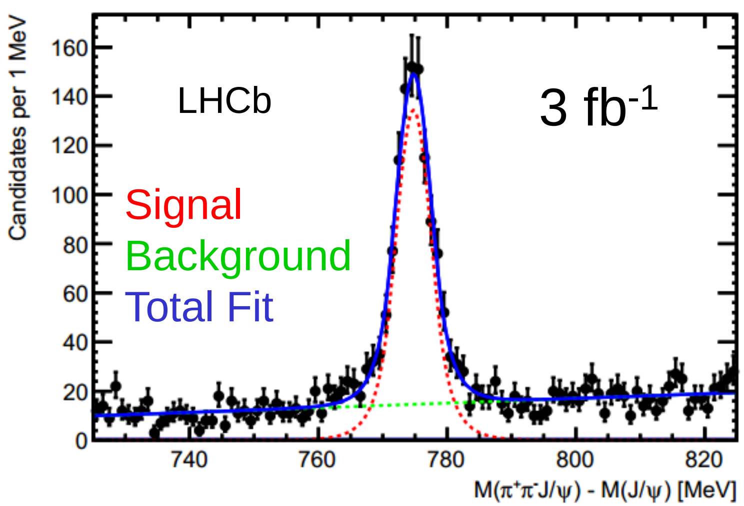


X(3872) quantum numbers

Phys Rev D 92, 011102 (2015)

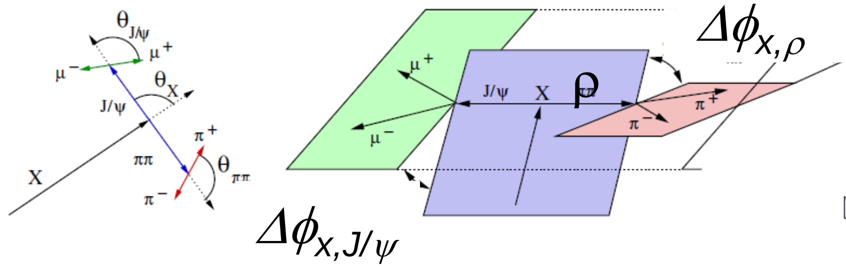
- All previous analyses had assumed the presence of only the lowest possible orbital angular momentum in the $X(3872) \to J/\psi\, \pi^+\pi^-$ decays.
- However a significant L > L_{min} could invalidate $J^P=1^+$ assignment and hint at molecular structure of X(3872)
  - It is important to check this!
  - Knowing the contribution of higher angular momentum is also interesting for better understanding these states.

- Using improved statistics from the full 3 fb^{-1} of Run 1 data, the analysis was done without any assumptions on orbital angular momentum present.



Determination of X(3872) J^{PC}: helicity formalism

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



5 independent angles describing the decay in helicity formalism

Ω – all 5 angles

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

Matrix element

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

Relation of the helicity couplings to LS amplitudes

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

Parity conservation

J^{PC}	B_{LS} all L	B_{LS} 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

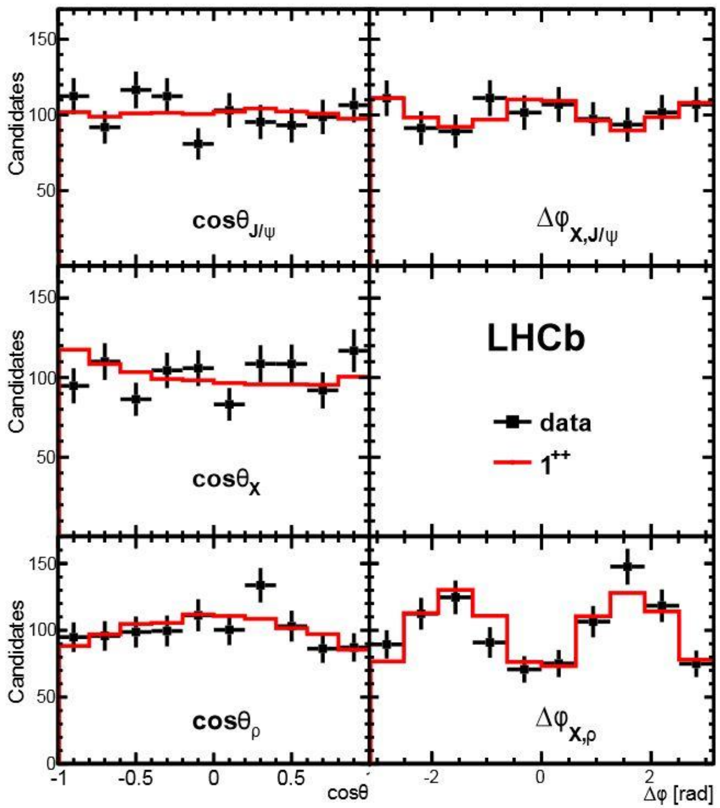
CDF 2007

LHCb 2013

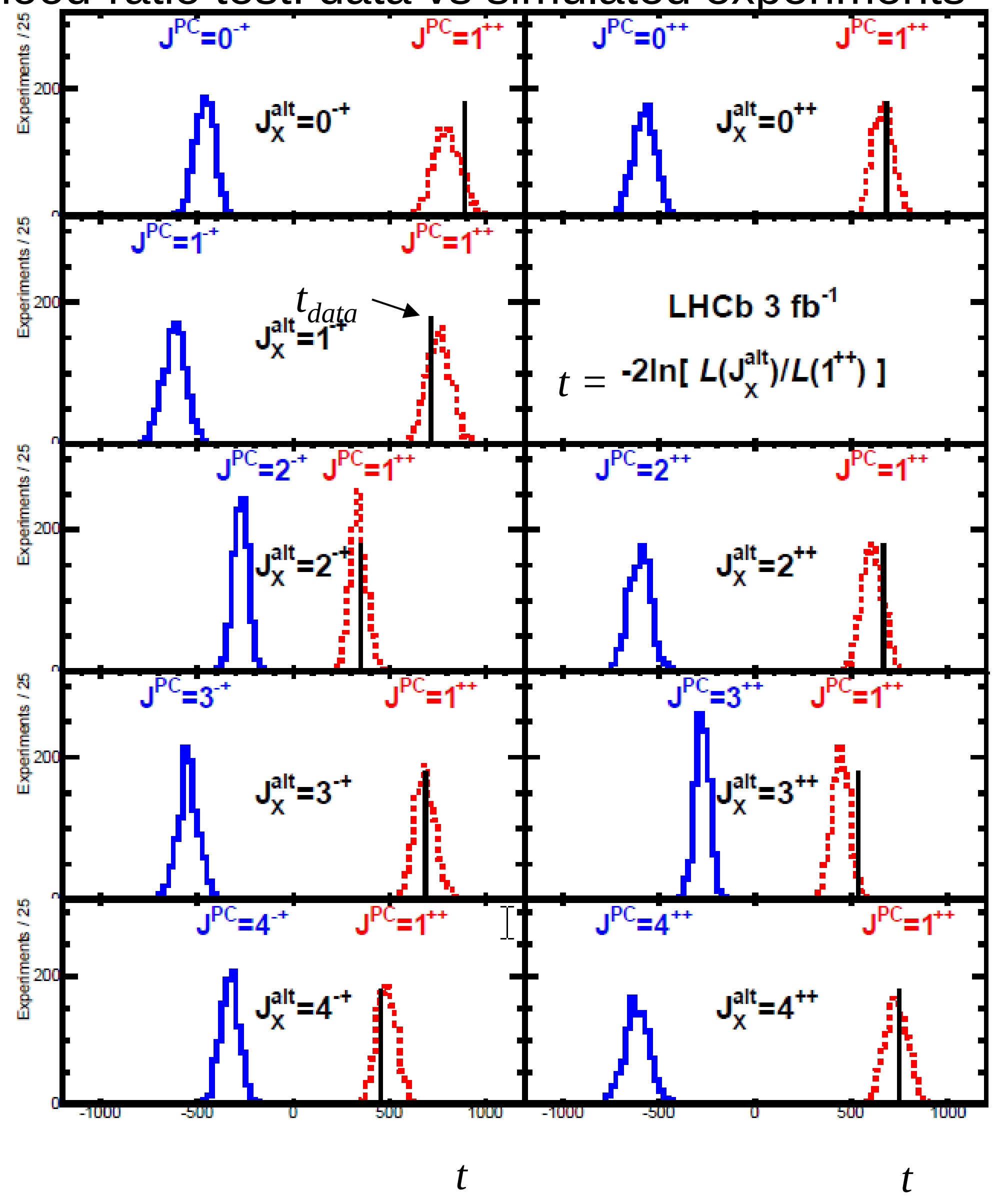
LS amplitudes to be determined from the data

Determination of X(3872) J^{PC}

Projection of all angles with 1^{++} hypothesis



Likelihood-ratio test: data vs simulated experiments



- Data unambiguously prefers 1^{++} hypothesis (new: no assumptions about L)

D-wave fraction in $X(3872)\to\rho^0 J/\psi$ for $J^{PC}=1^{++}$

- Fit to the real data:

$$\frac{|B_{21}|^2}{|B_{10}|^2} = 0.0018 \pm 0.0042 \qquad \frac{|B_{22}|^2}{|B_{10}|^2} = 0.0066 \pm 0.0081$$

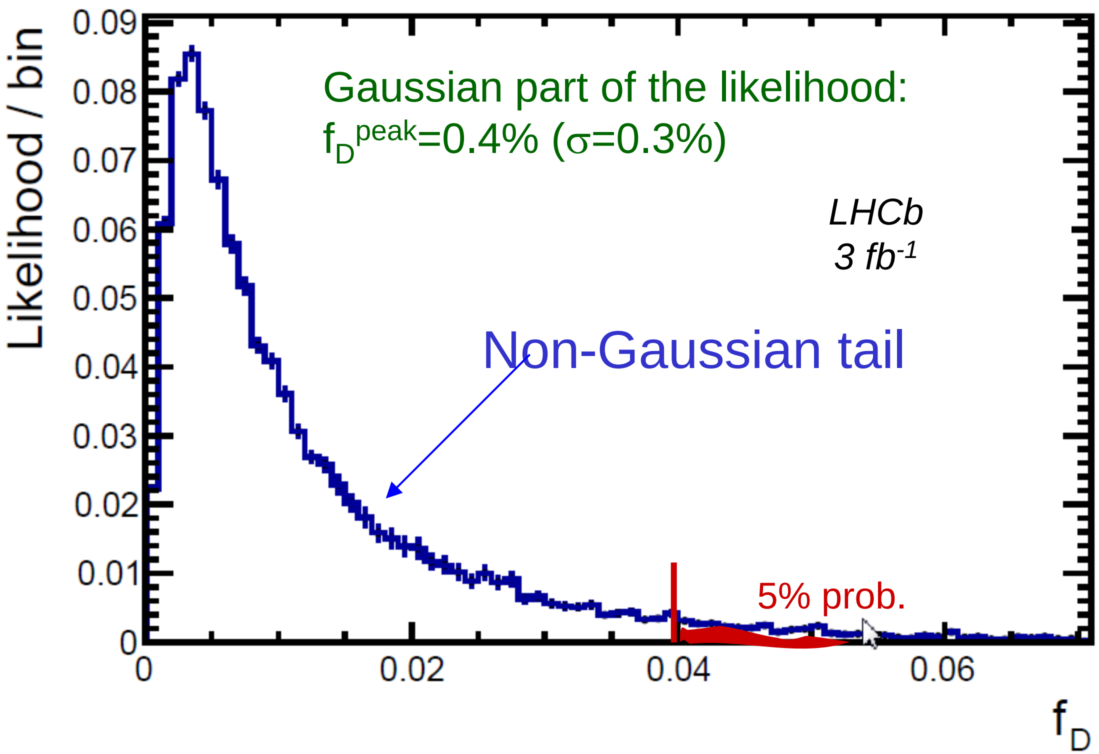
D-wave significance using Wilk's theorem applied to the likelihood ratio with/without D wave amplitudes: 0.8σ

D-wave amplitudes are consistent with zero

The likelihood was profiled as a function of the D-wave fraction:

$$f_D = \frac{\int |\mathcal{M}(\Omega)_D|^2 \, d\Omega}{\int |\mathcal{M}(\Omega)_{S+D}|^2 \, d\Omega}$$

$f_D<4\%$ at 95% CL



$Z(4430)^+$ previous measurements

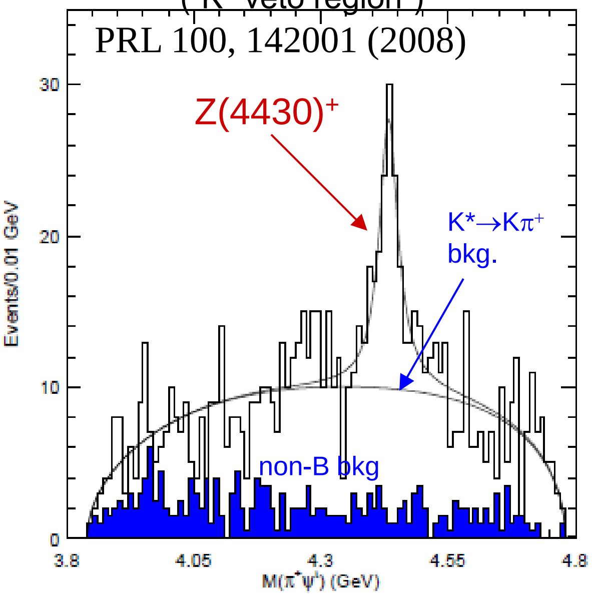
Z^+ K^*

$B \to \psi' \pi^+ K$

Belle 2008

1D $M(\psi'\pi^-)$ mass fit

("K* veto region")



$M(Z) = 4433 \pm 4 \pm 2$ MeV

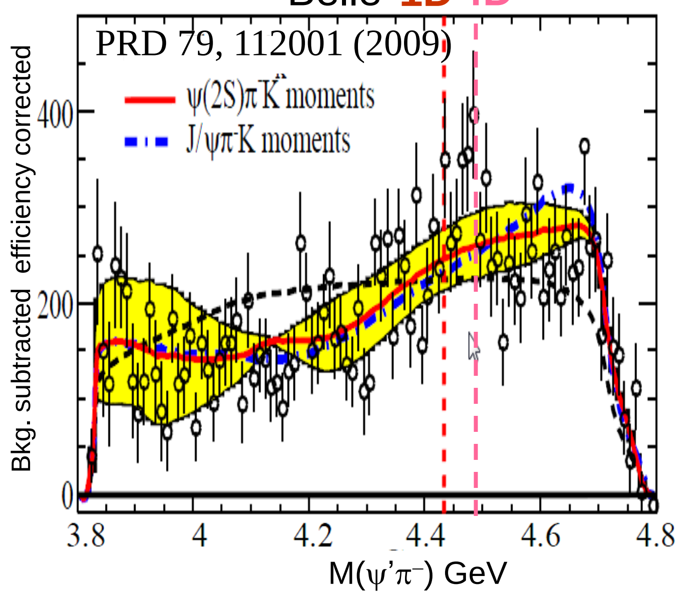
$\Gamma(Z) = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV

significance 6.5σ

BaBar 2009

Harmonic moments of K*s (2D) reflected to $M(\psi'\pi^+)$

Belle 1D 4D



BaBar did not confirm $Z(4430)^+$ in B sample comparable to Belle.

Did not numerically contradict the Belle results.

Belle 2013

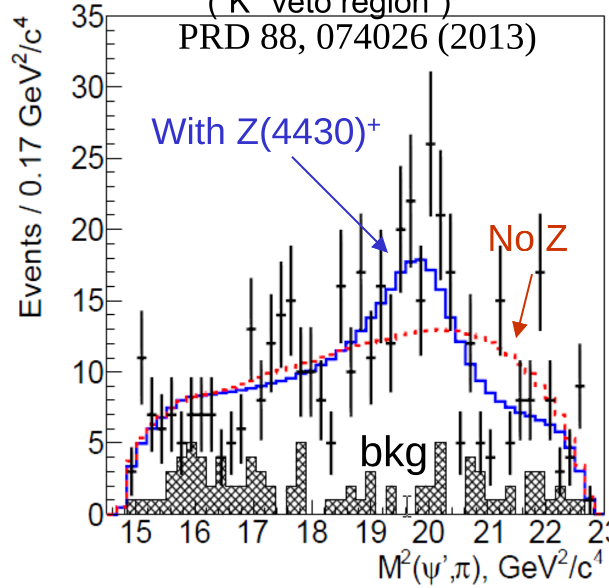
(2D amplitude fit in 2009)

4D amplitude fit

(subsample with $\psi' \to l^+l^-$)

0.996 GeV/c^2 < $M(K,\pi)$ < 1.332 GeV/c^2

("K* veto region")



$M(Z) = 4485^{+22}_{-22}{}^{+28}_{-11}$ MeV

$\Gamma(Z) = 200^{+41}_{-46}{}^{+26}_{-35}$ MeV

6.4σ (5.6σ with sys.)

$J^P=1^+$ preferred by $>3.4\sigma$

Ad hoc assumption about the $K^* \to K\pi^+$ background shape.

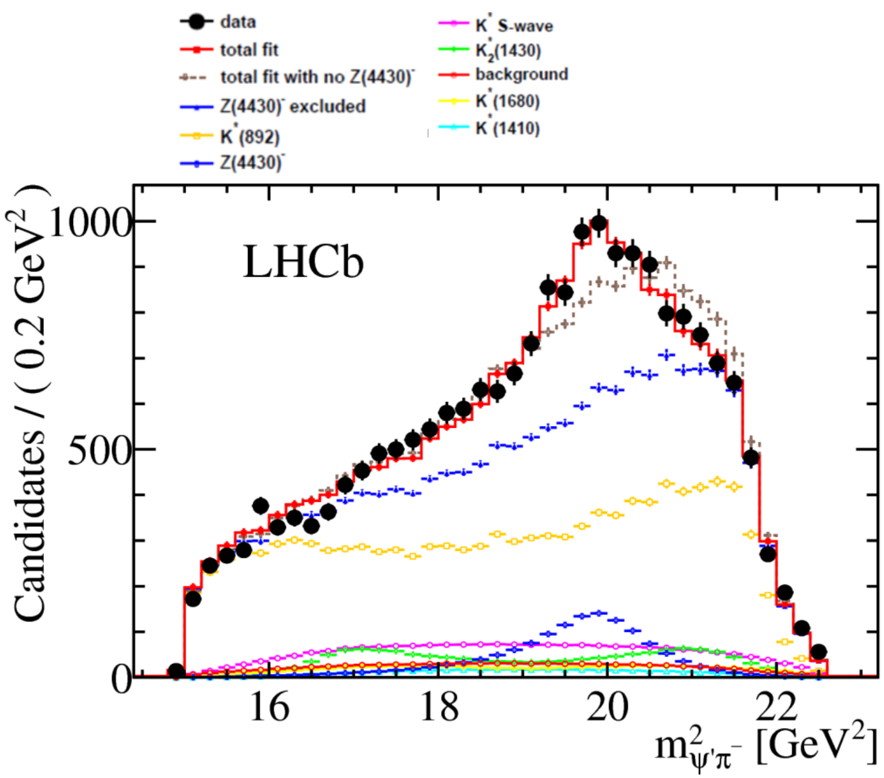
Almost **model independent** approach to $K^* \to K\pi^+$ backgrounds.

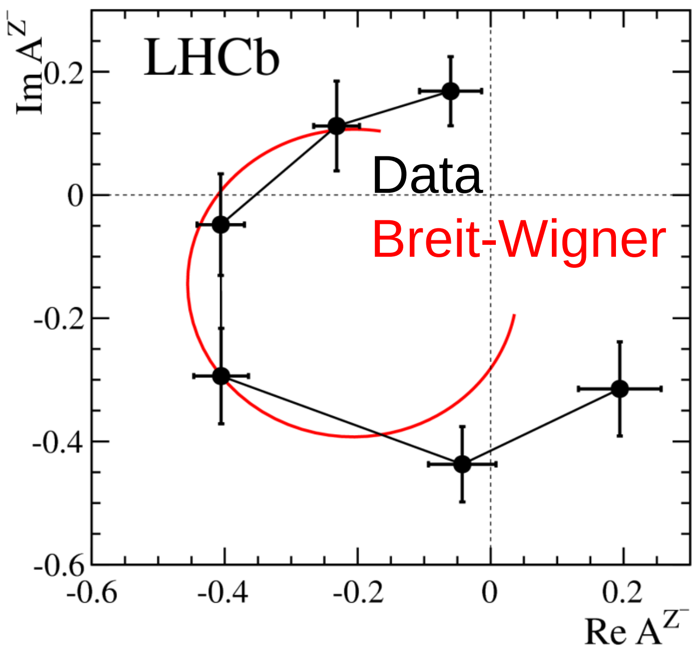
Model dependent approach to $K^* \to K\pi^+$ backgrounds. Higher statistical sensitivity.

$Z(4430)^+$ 4D Amplitude Analysis in LHCb

Phys Rev Lett 112, 222002 (2014)

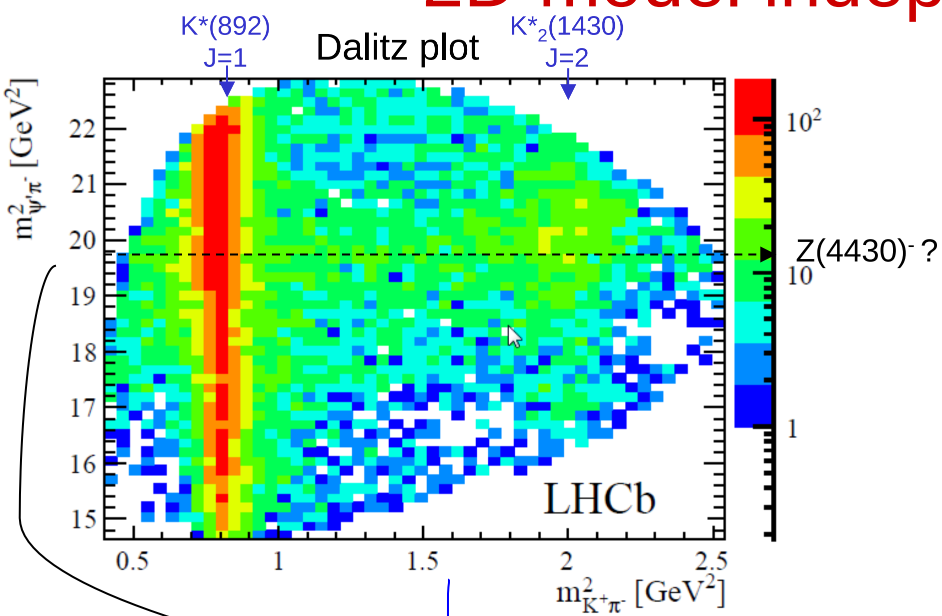
- With an order of magnitude larger statistics and smaller backgrounds, LHCb was well suited to settle the matter.





- In 2014 LHCb overwhelmingly confirmed the $Z(4430)^+$ and demonstrated its resonance phase motion.
- The quantum numbers were measured to be $J^P = 1^+$

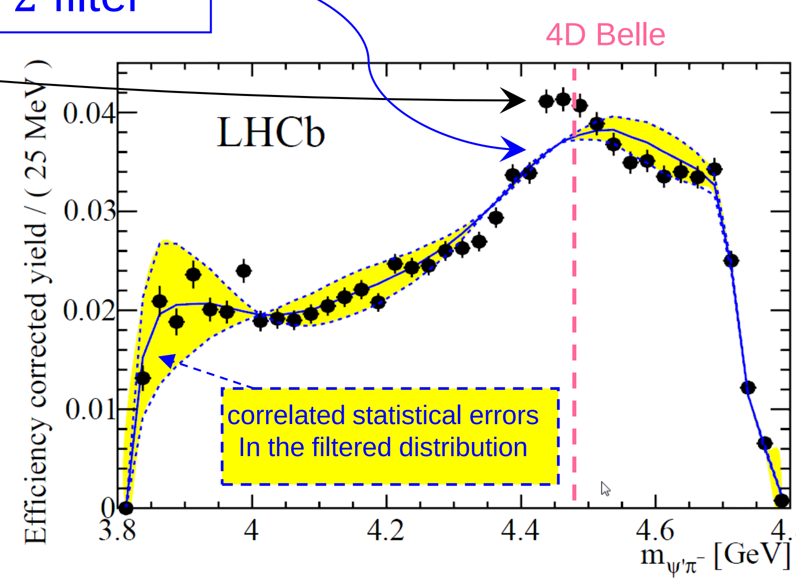
2D model independent analysis



This qualitative analysis was included in the 2014 paper. In the new analysis in preparation it is made quantitative.

actual distribution

K^* J≤ 2 filter



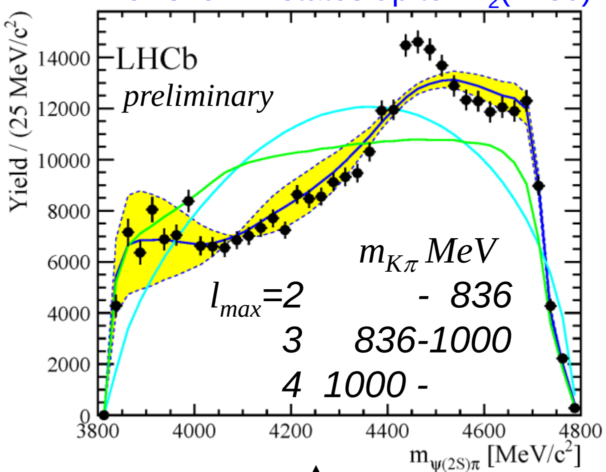
Excess of events over
the K* J$_{max}$=2 filtered
distribution
in the Z(4430)$^-$ region
is apparent !

Quantitative results from the model independent approach

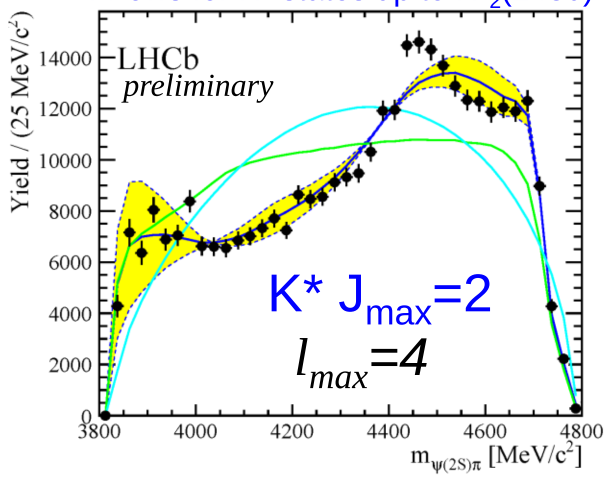
LHCb-PAPER-2015-038, in preparation

- The procedure on the previous slide is repeated for different J_{max} contributions.

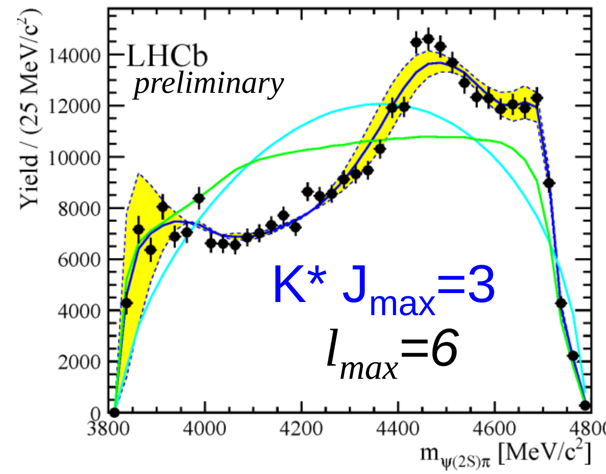
Allows for K* states up to K*$_2$(1430)



Allows for K* states up to K*$_2$(1430)



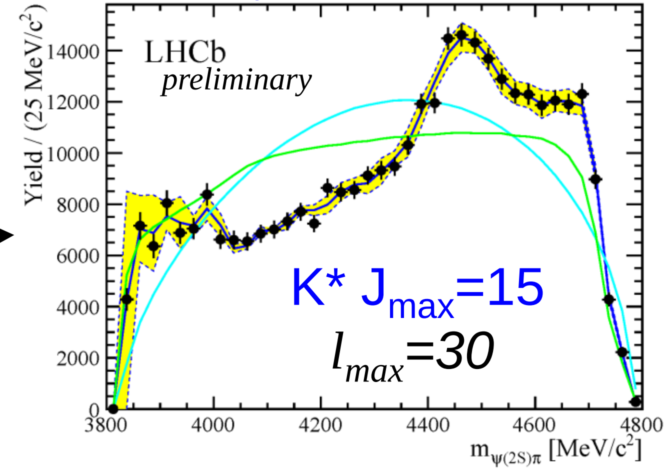
Allows for a tail of K*$_3$(1780)



J_{max} is K^* mass-dependent.

High moments wouldn't contribute except in presence of a Z

Allows implausible K* contributions



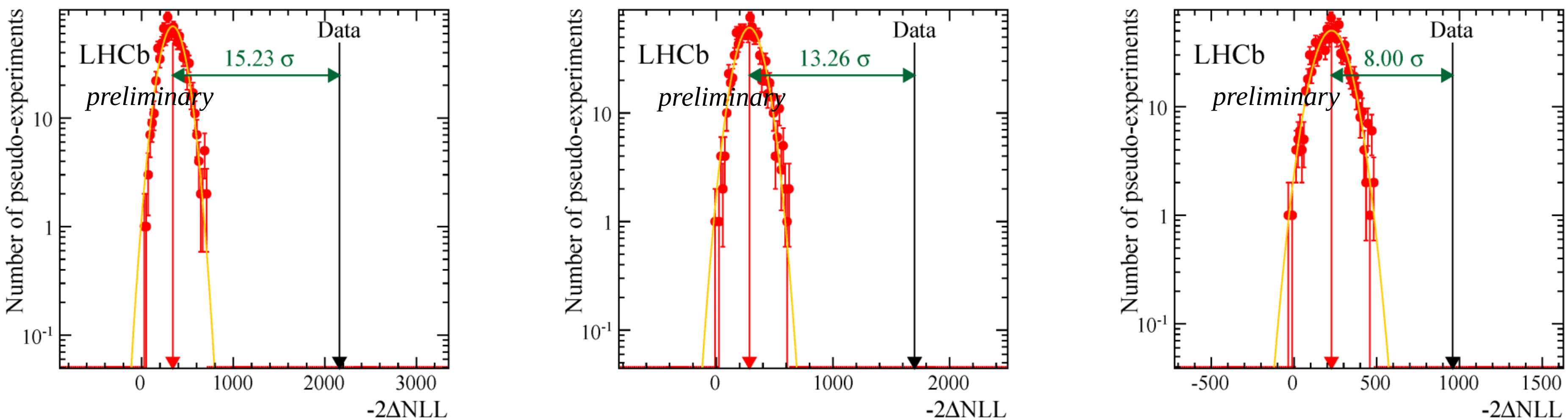
Quantitative results from the model independent approach

Test significance of implausible $l_{max} < l < 30$ $\cos(\theta_{K*})$ moments using the log-likelihood ratio:

$$\Delta(\text{-2NLL}) = -2\log\frac{\mathcal{L}_{l_{max}}}{\mathcal{L}_{30}} = -2\log\frac{\prod_i \mathcal{F}_{l_{max}}(m^i_{\psi'\pi})}{\prod_i \mathcal{F}_{30}(m^i_{\psi'\pi})}$$

Statistical simulations of pseudo-experiments were generated from the $l < l_{max}$ hypotheses, and $\Delta(-2\text{NLL})$ calculated:

K^* mass-dependent $J_{max} < 2$ $J_{max} < 2$ $J_{max} < 3$



Explanation of the data with plausible K* contributions is ruled out at high significance without assuming anything about K* resonance shapes or their interference patterns!

Conclusions

- Two states have been observed which are consistent with the long sought after pentaquarks.
  - The two states are necessary to provide a good description of the data in all 6 dimensions.
- The need for an exotic tetraquark contribution in $B_0 \to \psi(2S)K^-\pi^+$ decays was demonstrated in a quantitative way using a model independent analysis, supplementing the model dependent amplitude analysis of $Z(4430)^-$ published last year.
- The quantum numbers of X(3872) have been confirmed without any assumptions being made about the orbital angular momentum contributions present in the decay
  - The contribution of the higher waves was measured to be <4% at a 95% confidence level.
- We look forward to the discovery of more exotic hadrons and learning about their internal structure.

P_c Backup

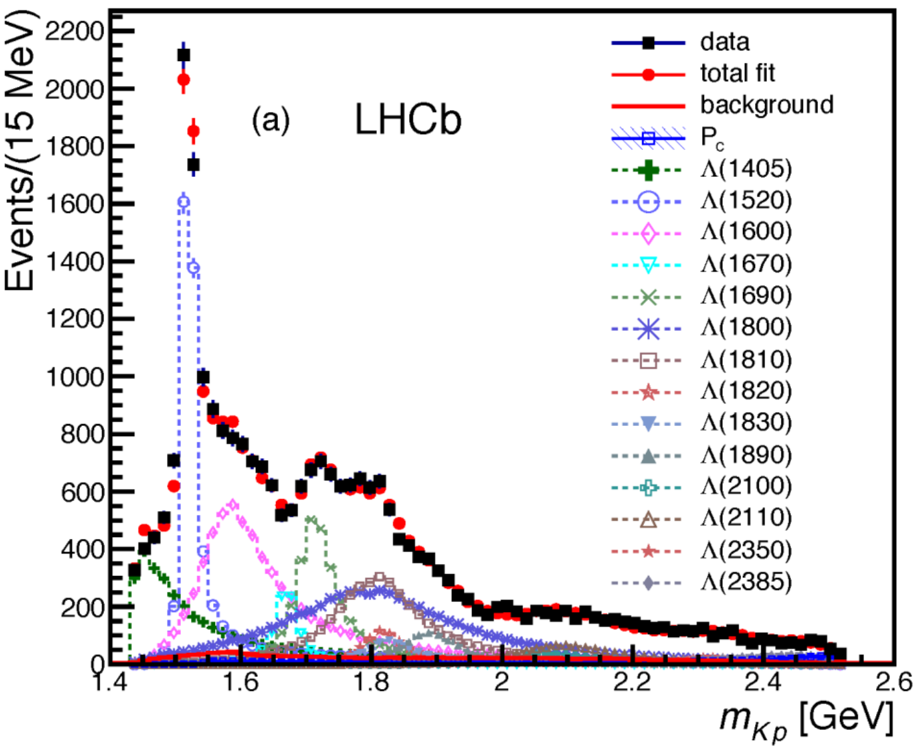
Λ^* Resonances

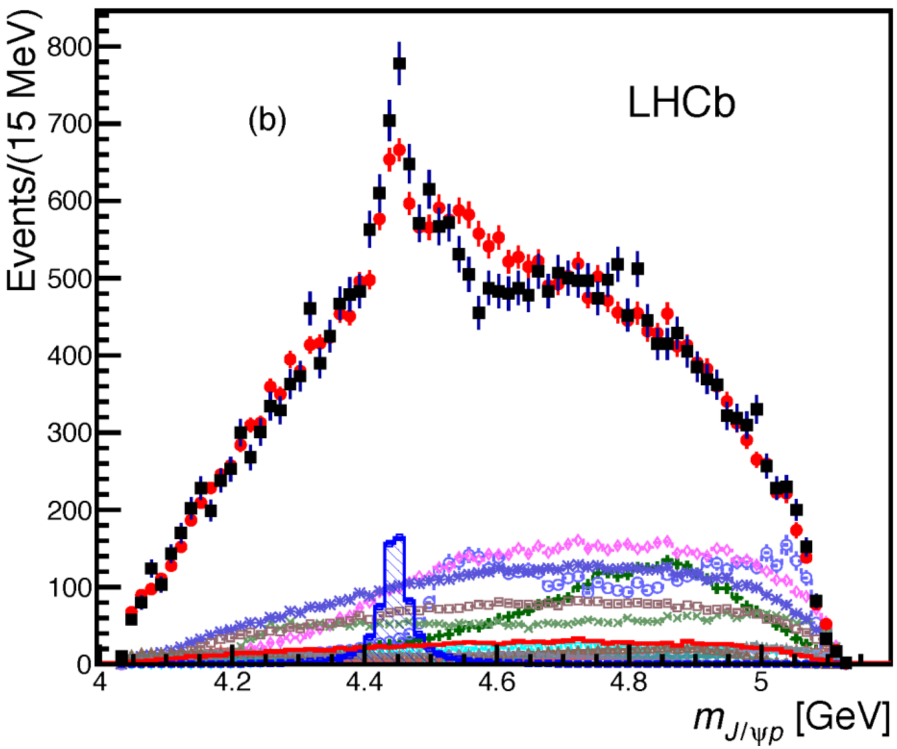
- Rich spectrum of possible resonances.
- We use two models, “reduced” and “extended” as part of tests on the dependence of the Λ^* model.
- Masses and widths are fixed to PDG values and varied in systematics.

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Amplitudes included # 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

Extended Model with a P_c

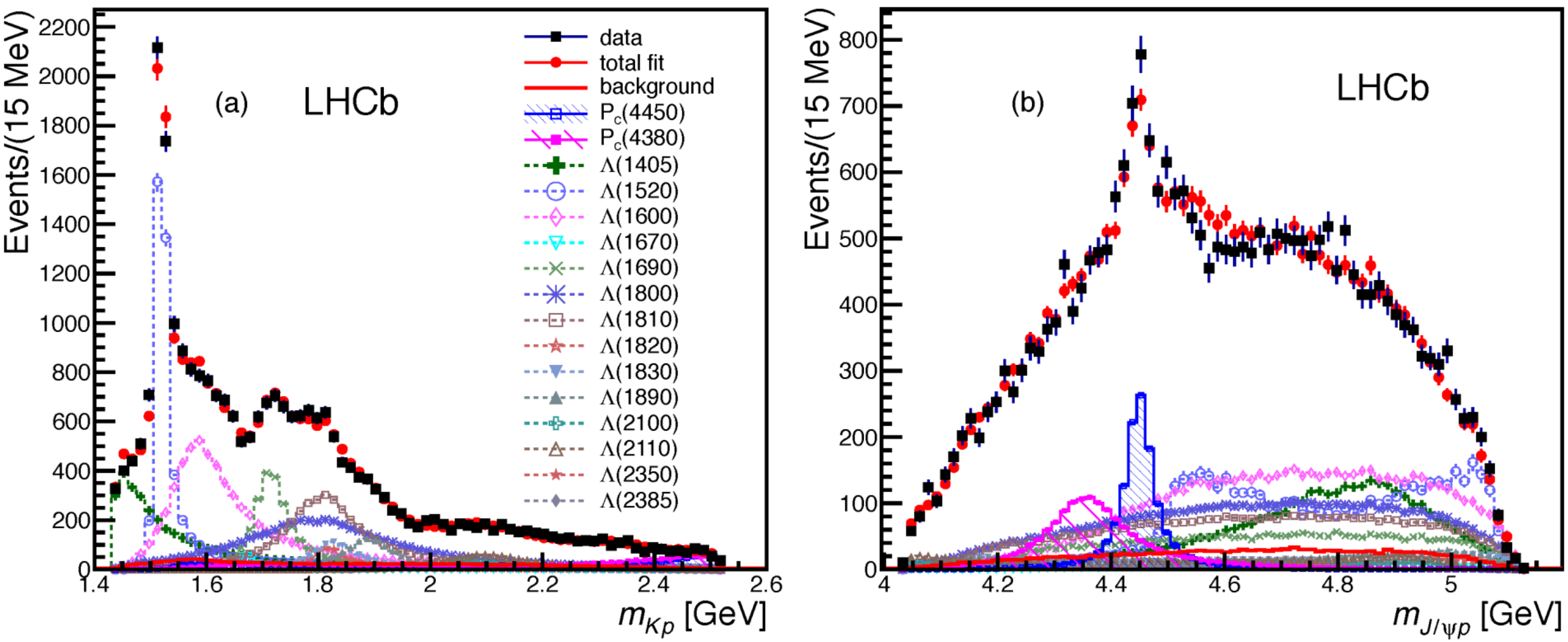
- We try all J^P up to $7/2^{\pm}$
- None give good fits, the best fit with $J^P = 5/2^+$ is shown.





Extended Model with Two P_c Resonances

- We add a second P_c and get a good fit!
- A good description of data is seen in all 6 dimensions.



Significance

- The significances are calculated using the extended model (the dominant source of systematic uncertainty).
- In the following scenarios, we see for: $\Delta(-2\ln\mathcal{L})$:
  - One P_c hypothesis verse no P_c: 14.7^2
  - Two P_c hypothesis verse one P_c: 11.6^2
  - Two P_c hypothesis verse no P_c: 18.7^2
- Toy experiments were run to properly obtain the significances:
  - One P_c hypothesis verse no P_c null hypothesis: 12σ
  - Two P_c hypothesis verse one P_c null hypothesis: 9σ
  - Two P_c hypothesis verse no P_c null hypothesis: 15σ

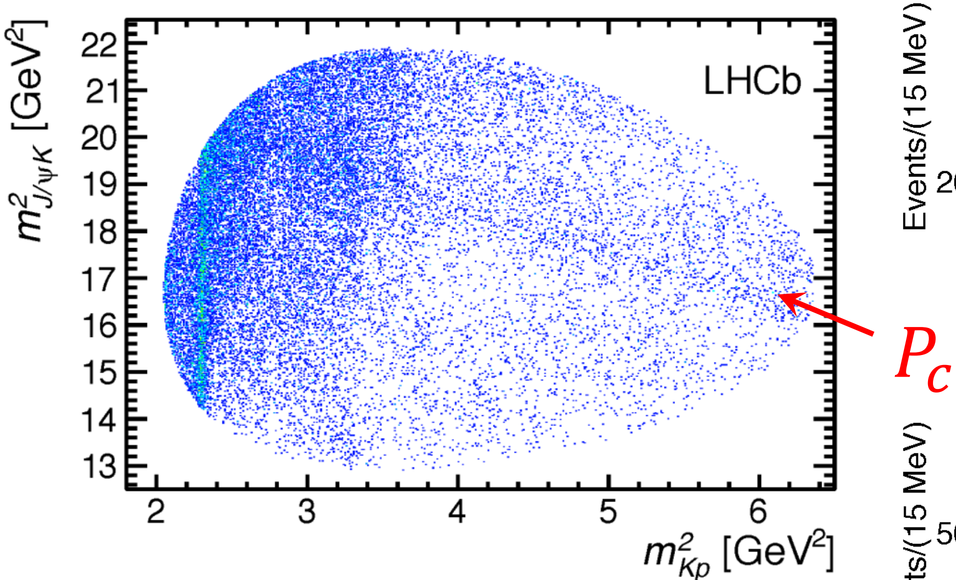
Systematic Uncertainties

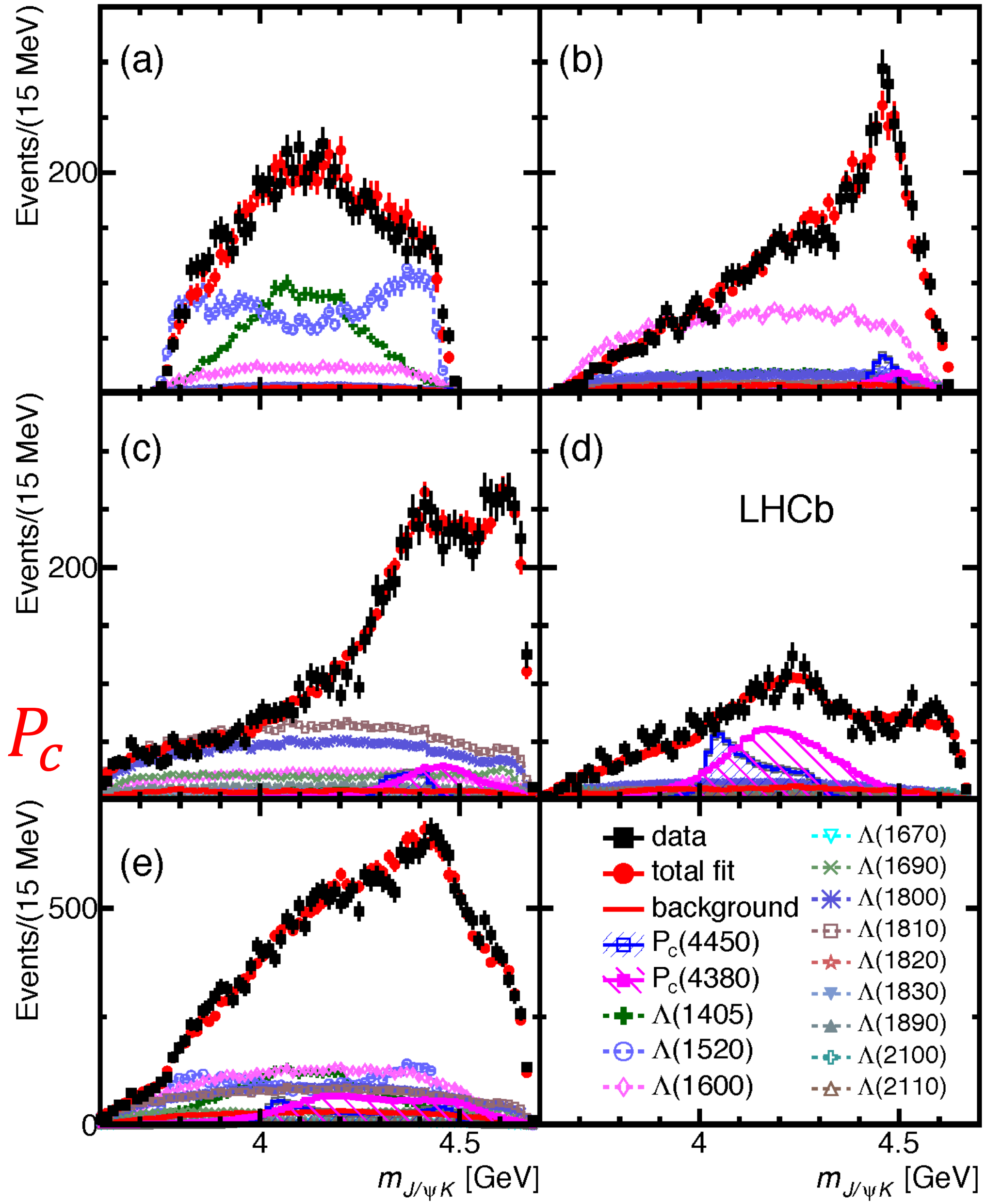
Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	low	high	low	high	low	high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	21	0.2	54	10	3.14	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	2.45
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	1.2	1	1	0.09	0.03	0.31	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

sFit/cFit comparison is included only as a cross-check and does not contribute to overall systematic uncertainty

$J/\psi\,K$ System

- $J/\psi\,K$ system is well described by the Λ^* and P_c reflections.





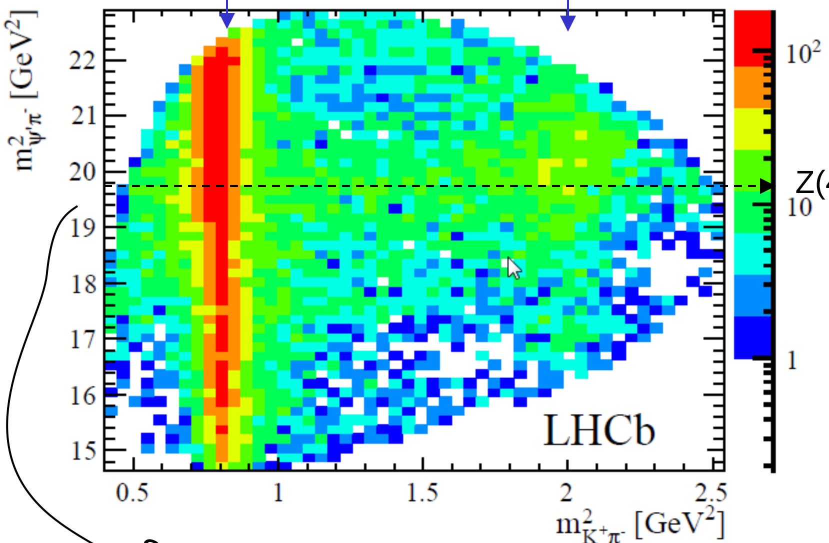
$Z(4430)^-$ Backup

$Z(4430)^+$ in LHCb: 2D model independent analysis (a la BaBar)

K*(892) J=1

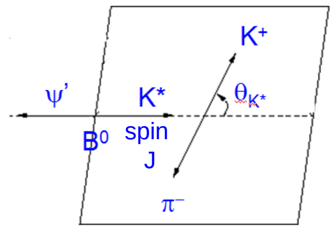
Dalitz plot

$K^*_2(1430)$ J=2



actual distribution

"Rectangular Dalitz plot"



⇨ $\cos(\theta_{K^*})$ vs. $m_{K+\pi-}$ ⇨

Decompose into Legendre moments

$$< P_l^U > = \sum_{i=1}^{N_{data}} \frac{1}{\varepsilon_i} P_l(\cos\theta_{K^*i})$$

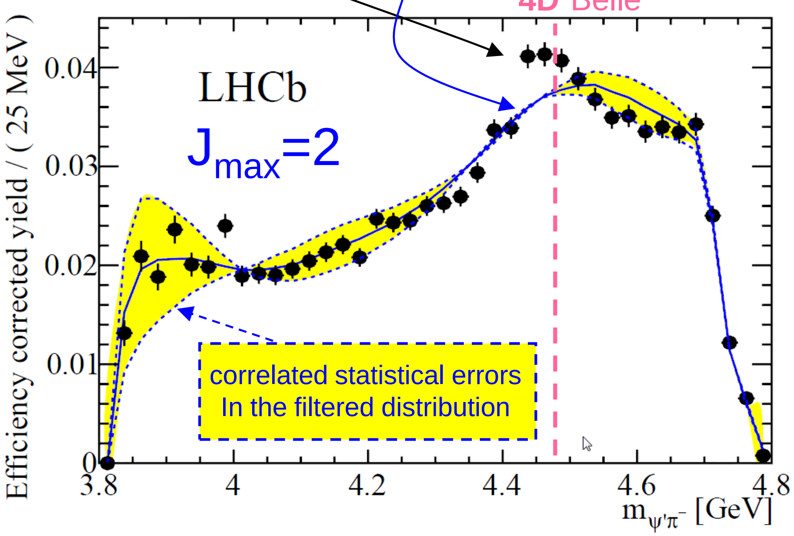
vs. $m_{K+\pi-}$

Pass only moments with l not more than $l_{max}=J_{max}/2$

"K* J_{max} filtered" $\cos(\theta_{K^*})$ vs. $m_{K+\pi-}$

"K* J_{max} filtered" Dalitz plot

4D Belle



Excess of events over
the K* J_{max}=2 filtered distribution
in the $Z(4430)^-$ region
is apparent !

This qualitative analysis was included in the 2014 paper