

LHCb exotics

M.Shapkin

Institute for High Energy Physics, Protvino, Russia

On behalf of the LHCb Collaboration



THE THIRD ANNUAL CONFERENCE ON
LARGE HADRON COLLIDER PHYSICS

Outline

- Observation of pentaquarks in J/ψ p channel

LHCb-PAPER-2015-029, arXiv:1507.03414, Phys.Rev.Lett. 115(2015) 072001

- Model independent confirmation of the $Z(4430)^-$ state

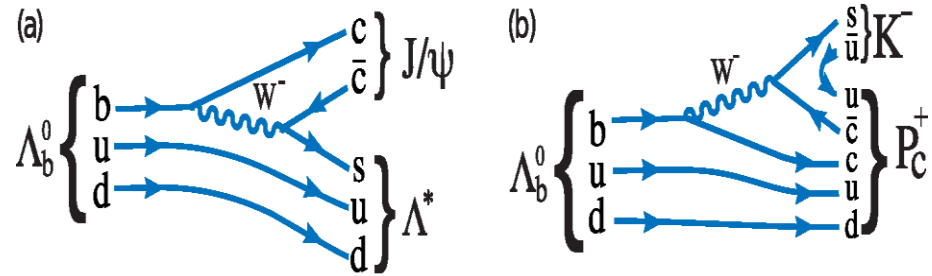
LHCb-PAPER-2015-029

- Quantum numbers of $X(3872)$ without assuming a value of orbital angular momentum in the decay $X(3872) \rightarrow \rho^0 J/\psi$

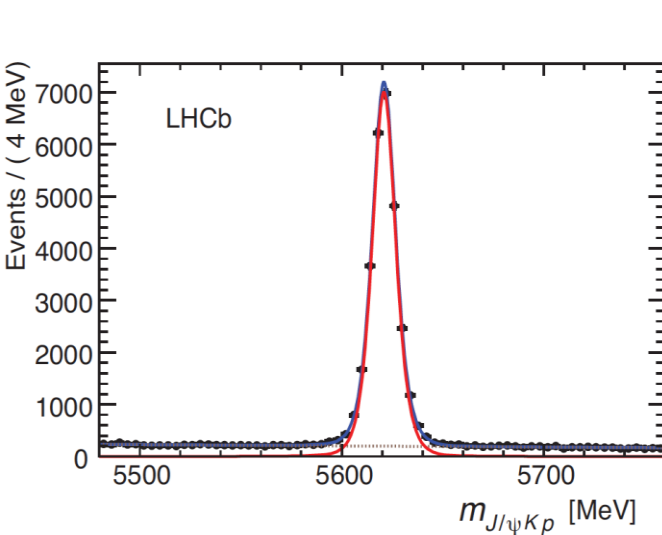
LHCb-PAPER-2015-029, arXiv:1504.06639

Pentaquarks

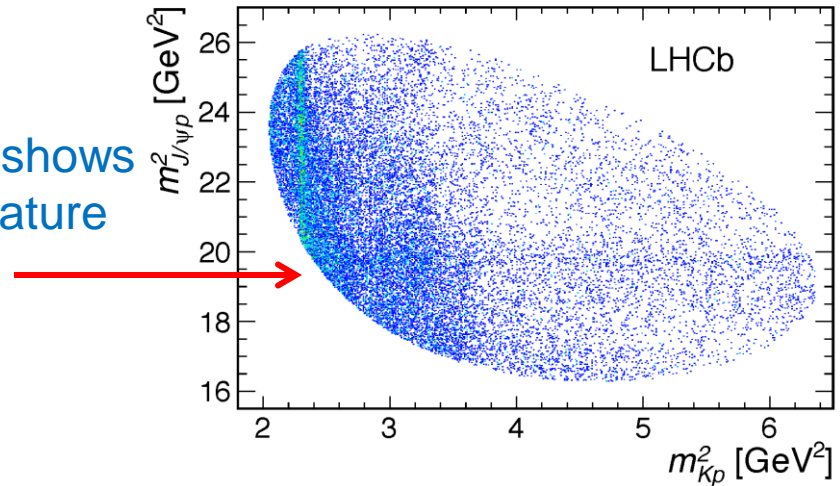
For 3 fb^{-1} LHCb has ~ 26000 of the $\Lambda_b \rightarrow J/\psi K^+ p$ decays



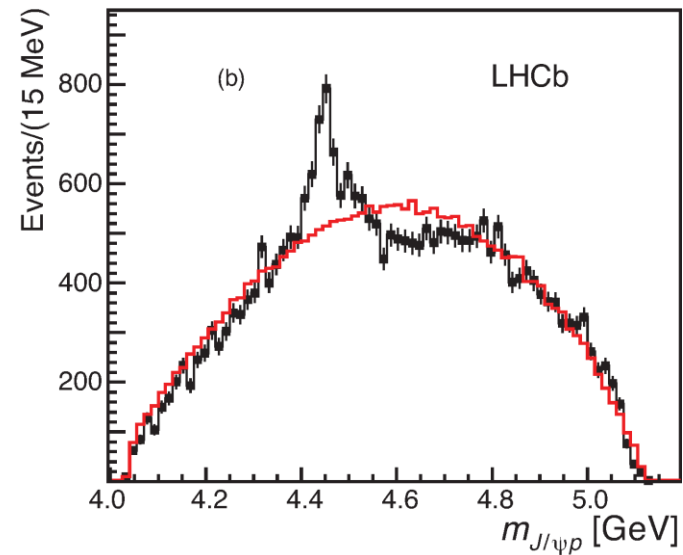
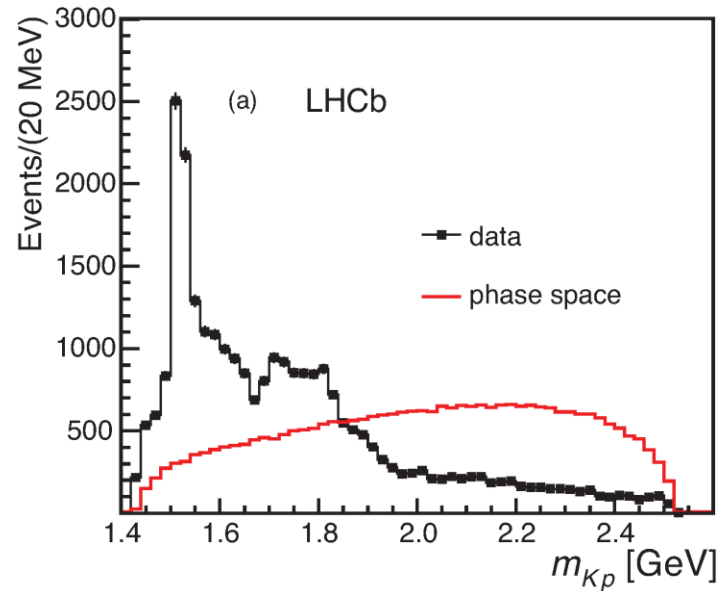
This decay can proceed by the diagram (a) or have exotic contribution shown in diagram (b)



Dalitz plot shows unusual feature



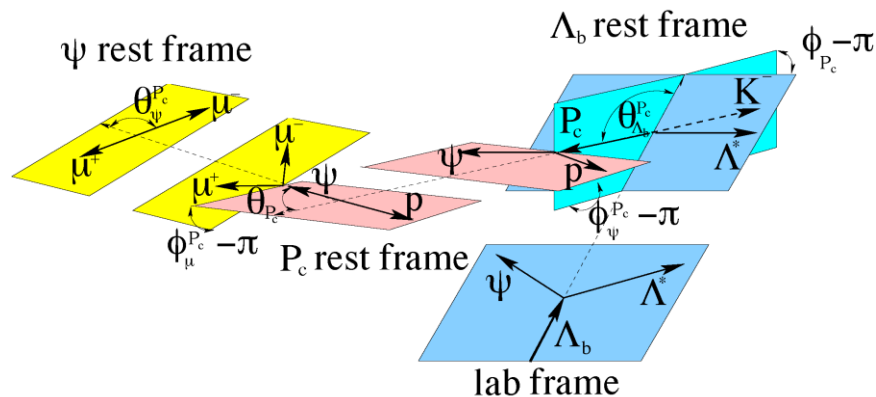
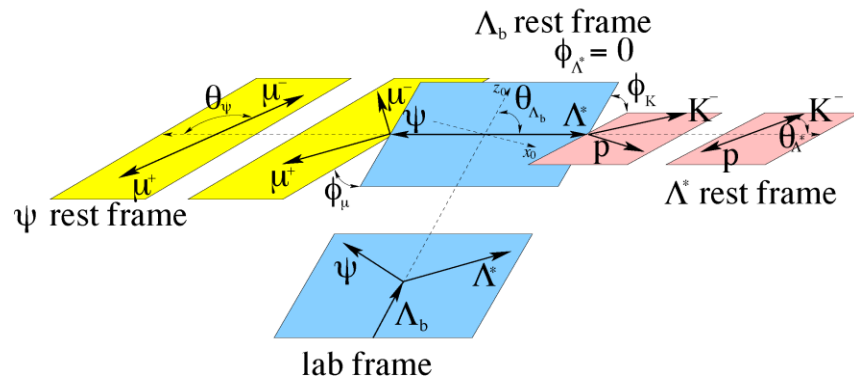
m_{Kp} and $m_{J/\psi p}$ projections



Unexpected narrow peak in $m_{J/\psi p}$ spectrum at ~ 4.4 GeV

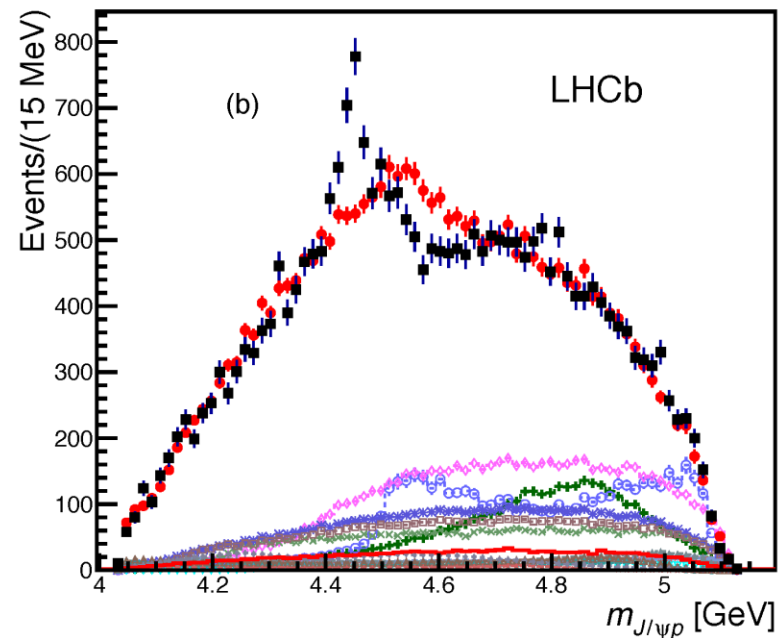
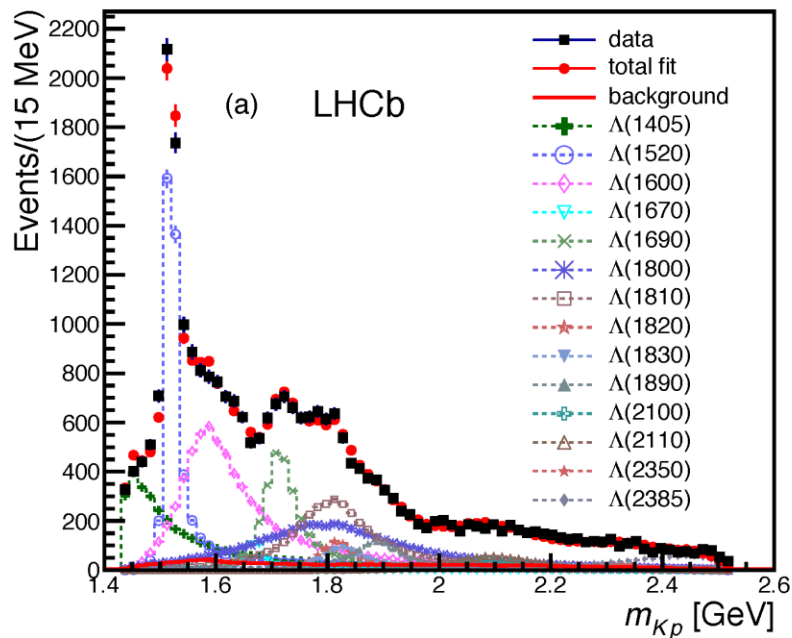
Decay amplitude analysis

- First we tried to fit the data with an amplitude model that contains 14 Λ^* states listed in PDG
- As this did not give a satisfactory description of the data we added one P_c^+ state, and when that was not sufficient we included a second state
- We use two interfering channels: $\Lambda_b \rightarrow J/\psi \Lambda^*$, $\Lambda^* \rightarrow K^- p$ and $\Lambda_b \rightarrow P_c^+ K^-$, $P_c^+ \rightarrow J/\psi p$
- Use $m(K^- p)$ and five angles as fit parameters



Results without P_c states

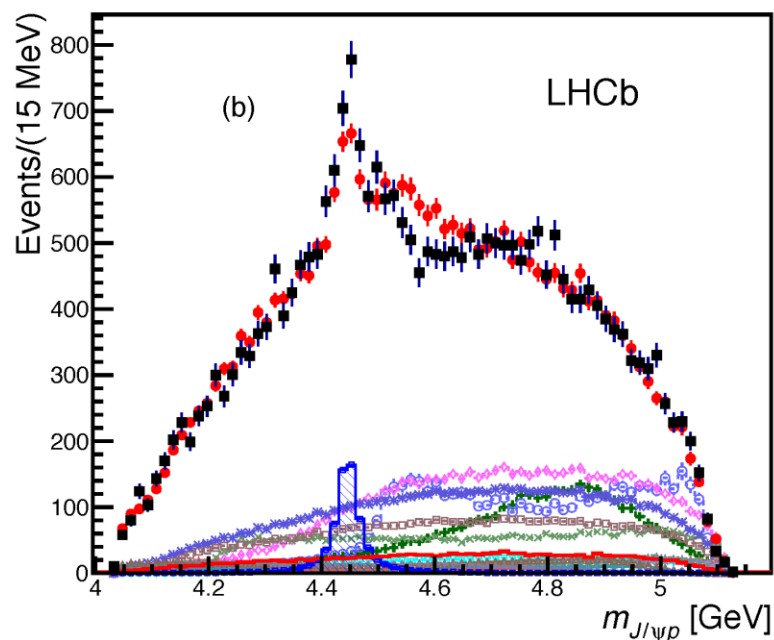
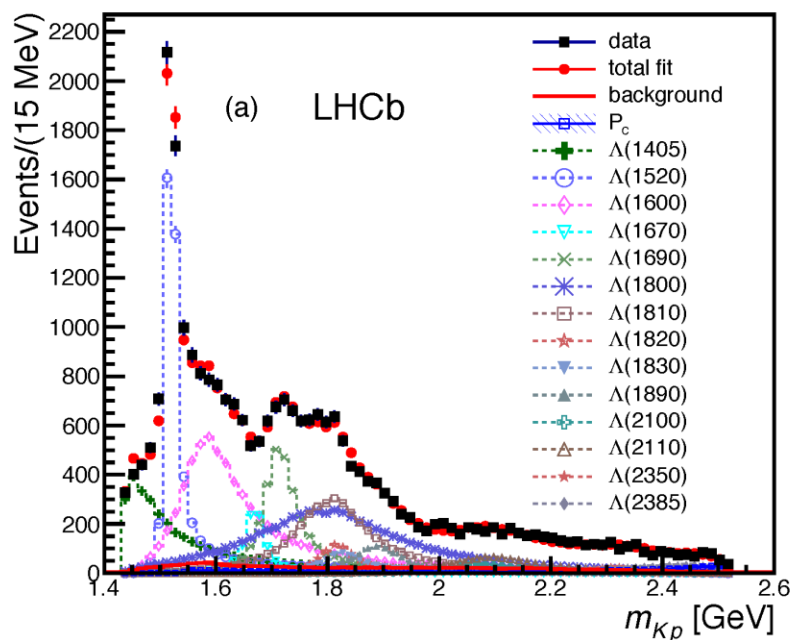
All possible known Λ^* describe $m(Kp)$ well but $m(J/\psi p)$ is not described
 Additions of non-resonant or extra Λ^* doesn't help



Extended model with 1 P_c

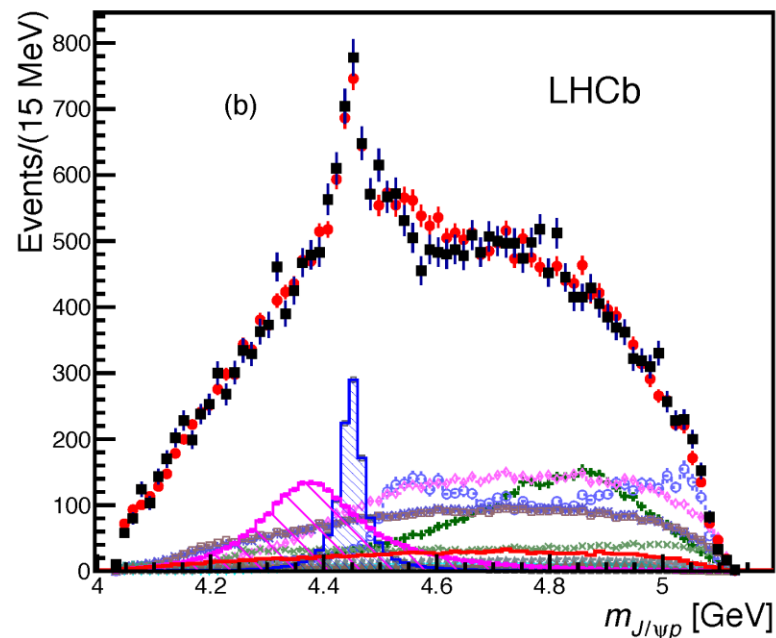
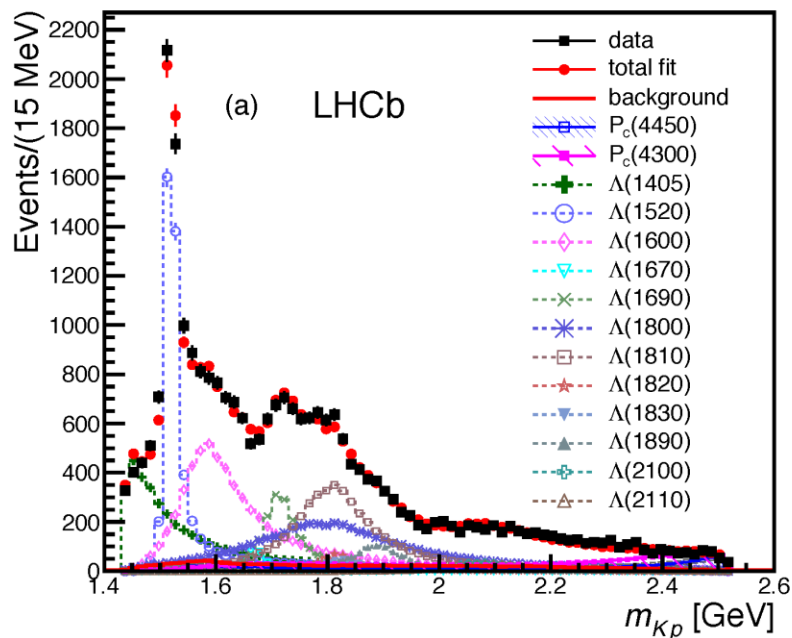
Try all J^P up to $7/2^\pm$

Best fit has $J^P=7/2^\pm$. Still not a good fit



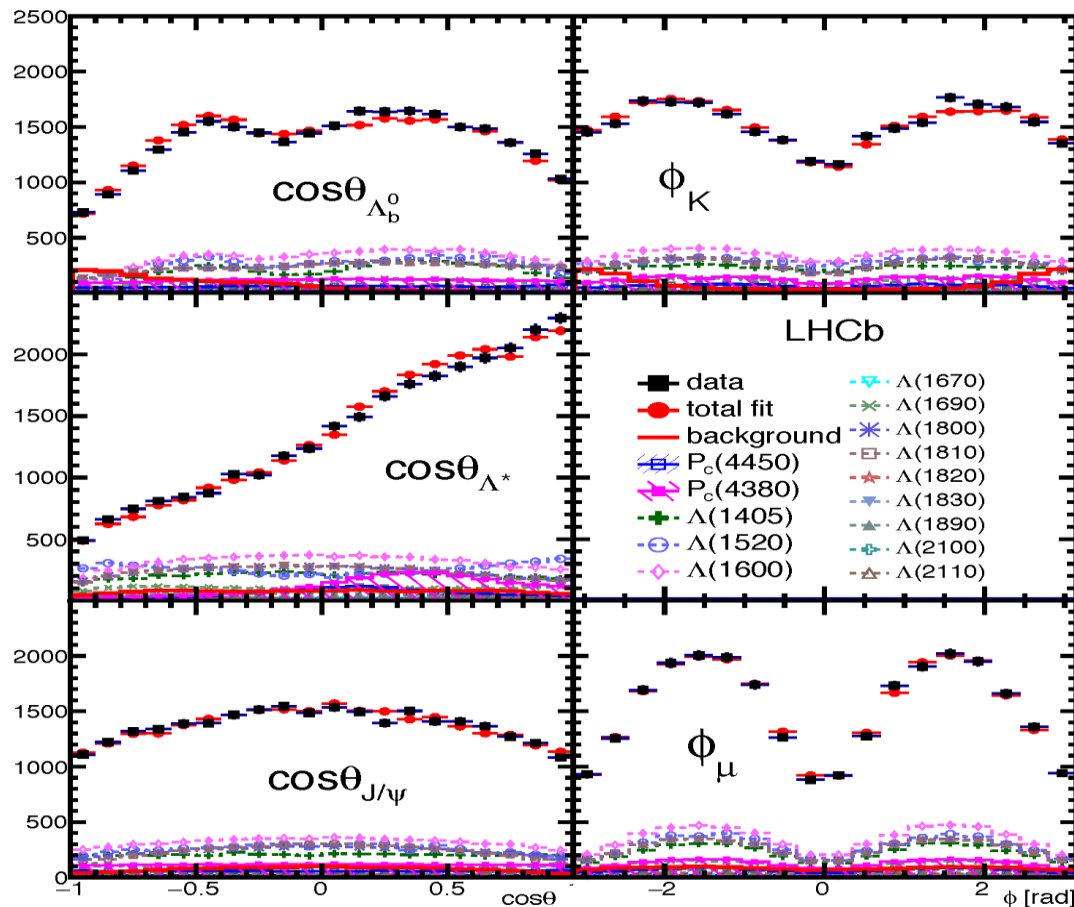
Reduced model with 2 P_c

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



Angular distributions

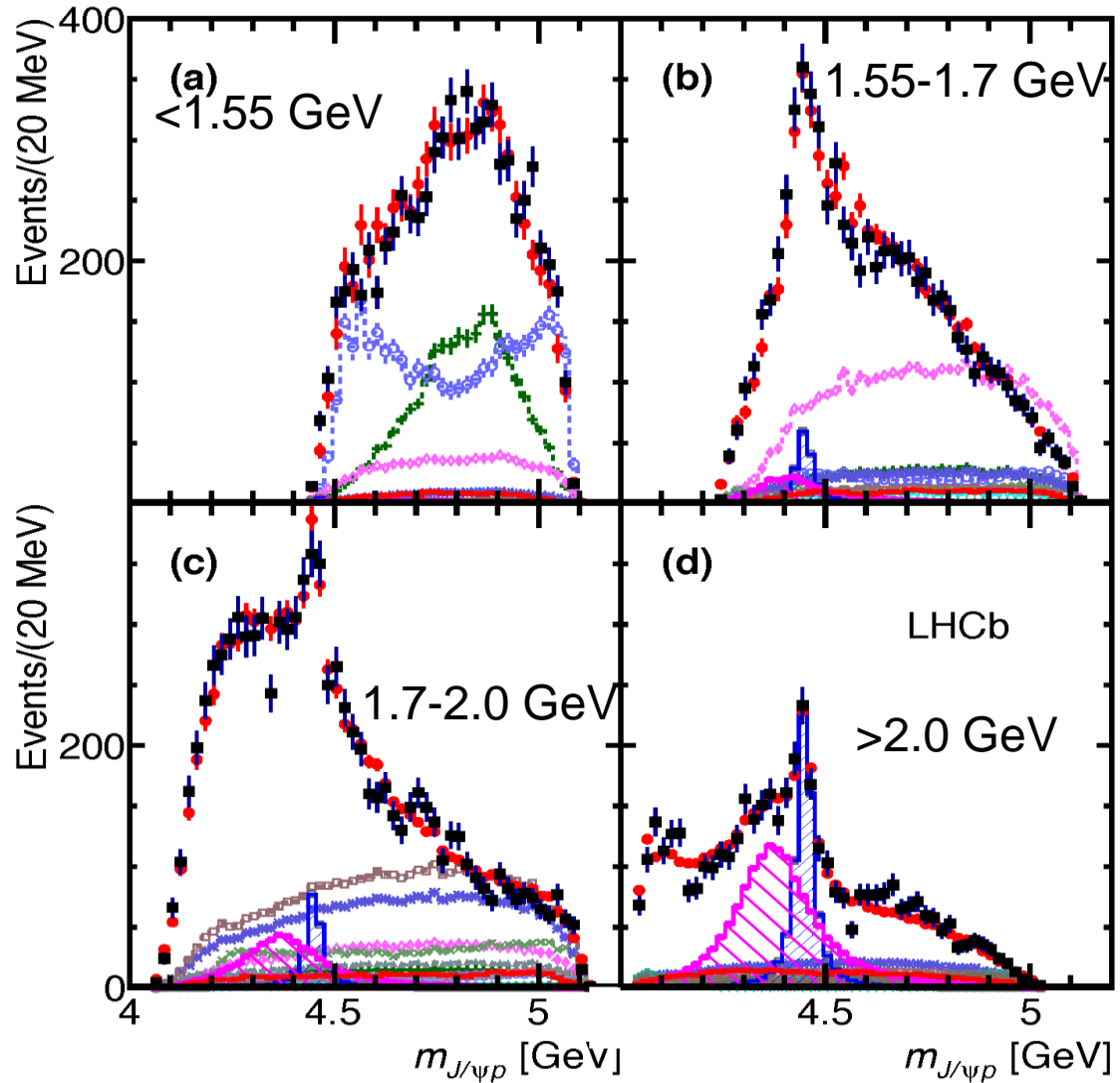
Good fits in the angular variables



M(K-p) slices

Negative interference between two P_c 's is evident in fig.(d)

No P_c 's in fig.(a)



Significances

- For 1 P_c fit improves by $-\Delta(2\ln(L))=14.7^2$, adding the second PC improves by 11.6^2 , for adding both together $-\Delta(2\ln(L))=18.7^2$
- Using toy simulations first state has significance 9σ , the second state 12σ , including systematic uncertainties, coming from difference between extended and reduced model results

Fit results

| Mass (MeV) | Width (MeV) | Fit fraction (%) |
|--------------------------|---------------------|-----------------------|
| $4380 \pm 8 \pm 29$ | $205 \pm 18 \pm 86$ | $8.4 \pm 0.7 \pm 4.2$ |
| $4449.8 \pm 1.7 \pm 2.5$ | $39 \pm 5 \pm 19$ | $4.1 \pm 0.5 \pm 1.1$ |
| $\Lambda(1405)$ | | $15 \pm 1 \pm 6$ |
| $\Lambda(1520)$ | | $19 \pm 1 \pm 4$ |

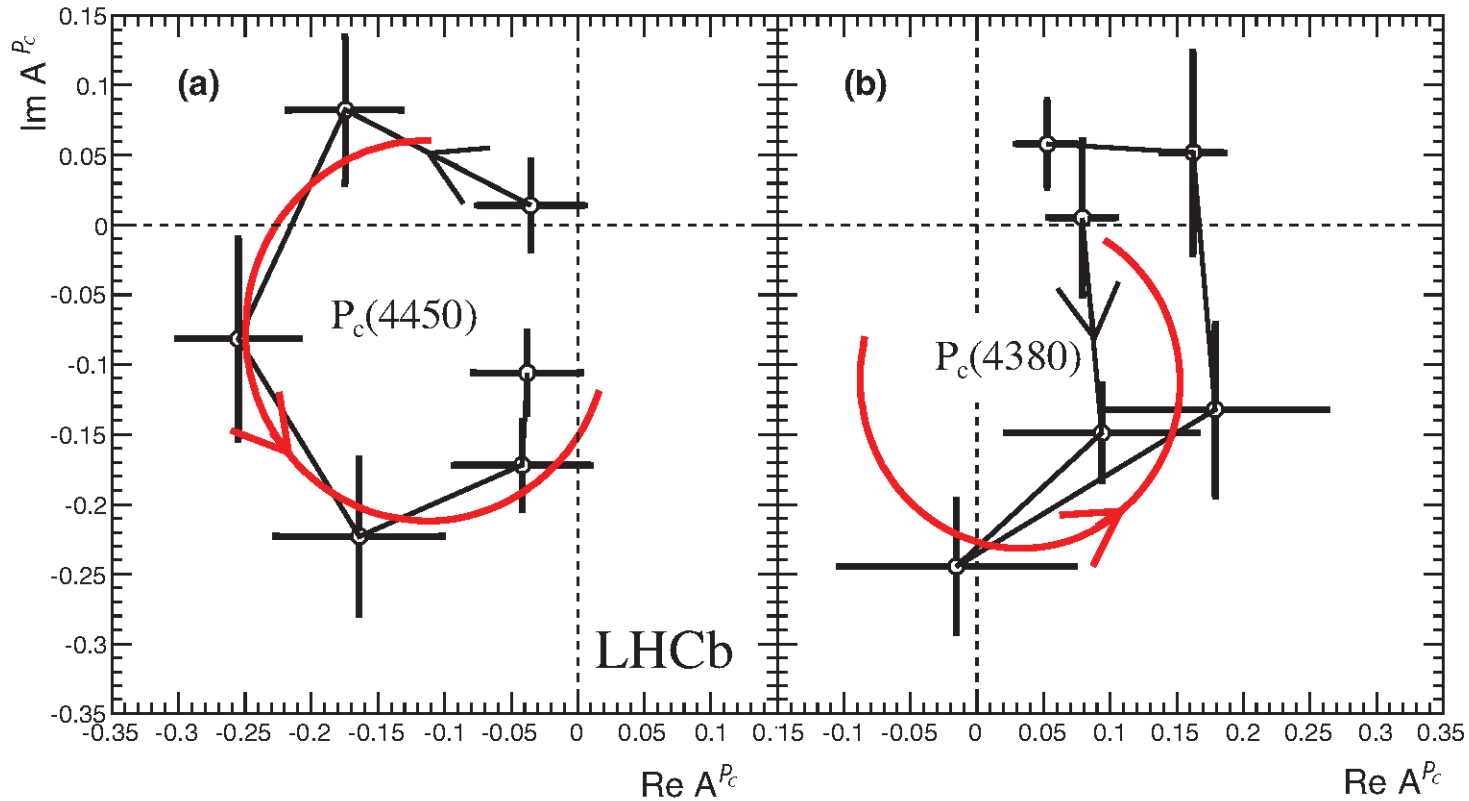
Cross-checks

Two independent coded fitters using different background subtractions (sFit & cFit) give consistent result.

Split of the data into 2011 and 2012 parts, magnet up/down, $\Lambda_b/\bar{\Lambda}_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$ give consistent result.

Extended model fits tried without Pc states, but two additional high mass Λ^* resonances allowing mass and width to vary, or 4 non-resonant terms of J up to 3/2.

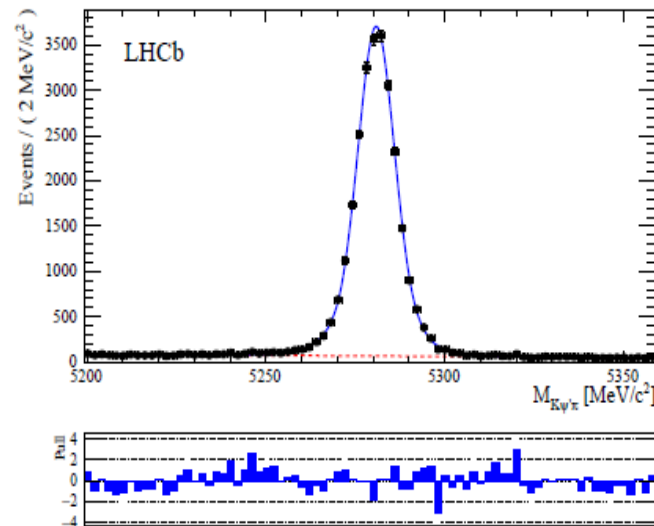
Argand diagrams



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

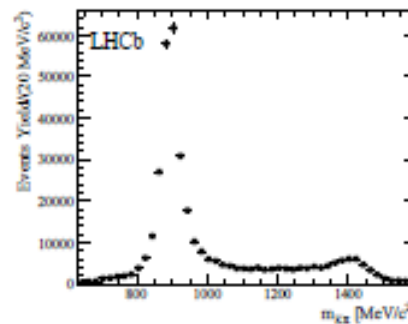
Model independent confirmation of the $Z(4430)^-$ state

- $B^0 \rightarrow \psi' \pi^- K^+$, peak in $m(\psi' \pi^-)$, charged charmonium state must be exotic (not $q\bar{q}$)
- First observed by Belle $M=4433 \pm 5$ MeV, $\Gamma=45$ MeV Phys.Rev.Lett. 100 (2008)142001
- Challenged by BaBar: explanation in terms of K^* 's Phys.Rev. D79 (2009) 112001
- Belle analysis using full amplitude fit: $M=4485^{+22+28}_{-11}$ MeV, $\Gamma=200$ MeV, 1^+ preferred but 0^- and 1^- not excluded
- LHCb full amplitude fit: $M=4475 \pm 7^{+15}_{-25}$ MeV, $\Gamma=172$ MeV, $J^P=1^+$ unambiguously Phys.Rev.Lett. 112 (2014) no.22142001 222002
- New LHCb analysis follows the BaBar strategy to reproduce the $m(\psi' \pi^-)$ spectrum by the reflections from $\pi^- K^+$ system
Use 23801 ± 63 $B^0 \rightarrow \psi' \pi^- K^+$ events

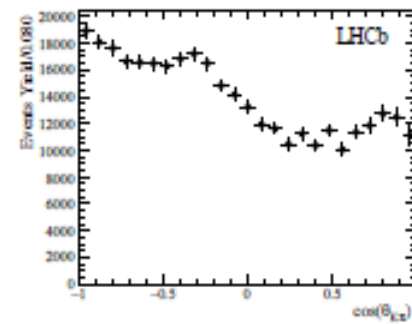


K* resonances after background subtraction and efficiency correction

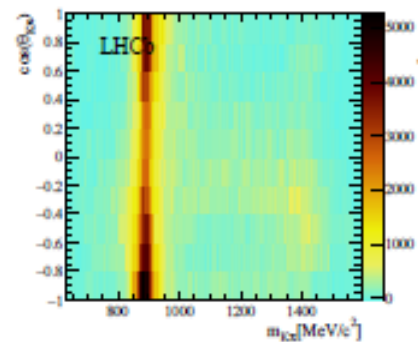
- The observed $K\pi$ spectrum (a) is dominated by $K^*(892)$, structures in $K^*(1410)$, $K^*_0(1430)$ and $K^*_2(1430)$ are also visible
- Non-resonant component between these two regions is evident
- $\text{Cos}(\theta_{K^*})$ distribution highlights the rich angular structure of the $K\pi$ system



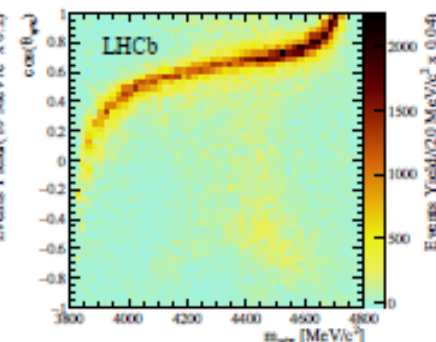
(a)



(b)



(c)



(d)

Extraction of the moments of the $K\pi$ system

- Data are subdivided by bins of $m(K\pi)$ 30 MeV width
- For each $m(K\pi)$ bin the $\cos(\theta_{K^*})$ distribution after integration over ψ' decay angles can be written as

$$\frac{dN}{d \cos \theta_{K^*}} = \sum_{j=0}^{j=l_{\max}} \langle P_J^U \rangle P_J(\cos \theta_{K^*})$$

For sufficiently large samples coefficients $\langle P_J^U \rangle$ can be extracted from data as

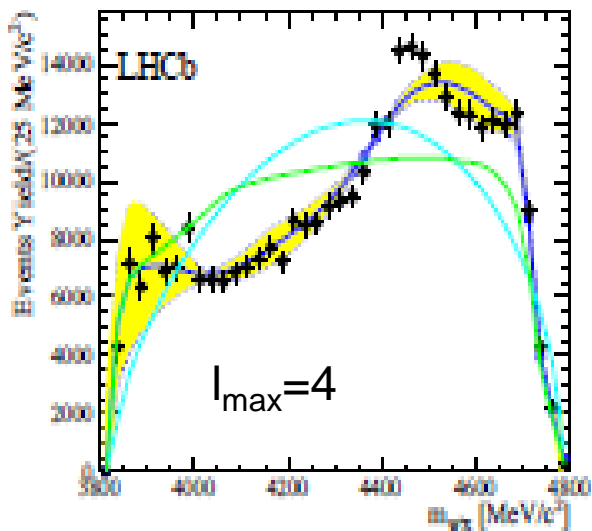
$$\langle P_J^U \rangle \approx \sum_{i=1}^{N_{\text{reco}}} W^i \text{sig} / \varepsilon_i * P_J(\cos \theta_{K^*}^i)$$

$$\varepsilon_i = \varepsilon(m_{K\pi i}, \cos \theta_{K^* i}, \cos \theta_{\psi' i}, \Delta \phi_{K\pi \psi' i})$$

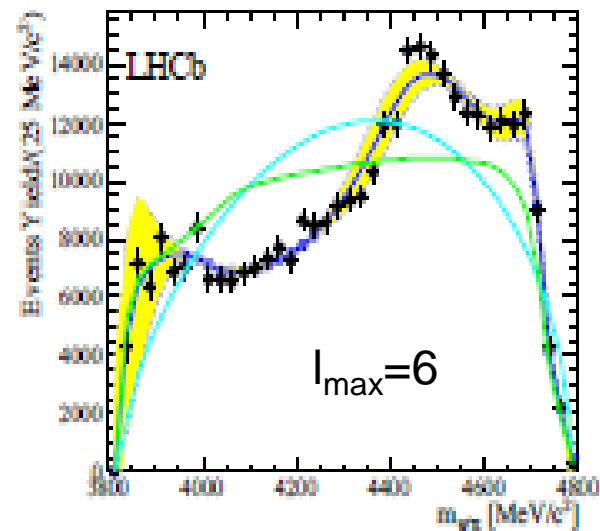
The resonances of the $K\pi$ system with spin s contribute to the moments $\langle P_{2s}^U \rangle$ in the region of $m_{K\pi}$ where they are lying

Analysis of the $m_{\psi'\pi}$ system

The $m_{\psi'\pi}$ is not well described by $K\pi$ angular structure with $l_{\max}=4$ (a) and $l_{\max}=6$ (b) (good description for $L_{\max}=30$)



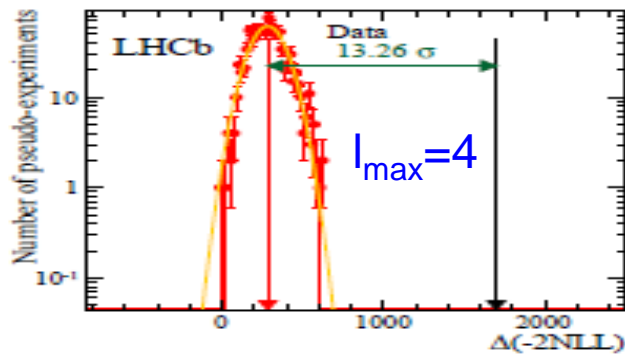
(a)



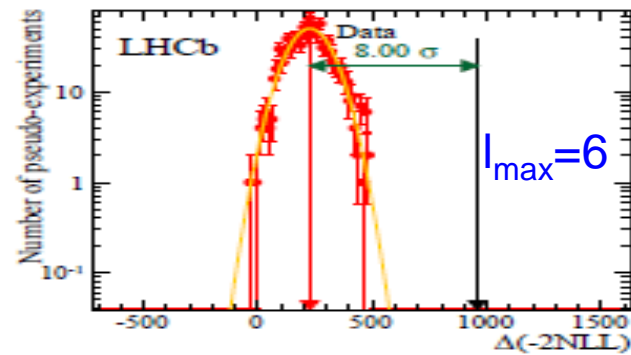
(b)

Significances

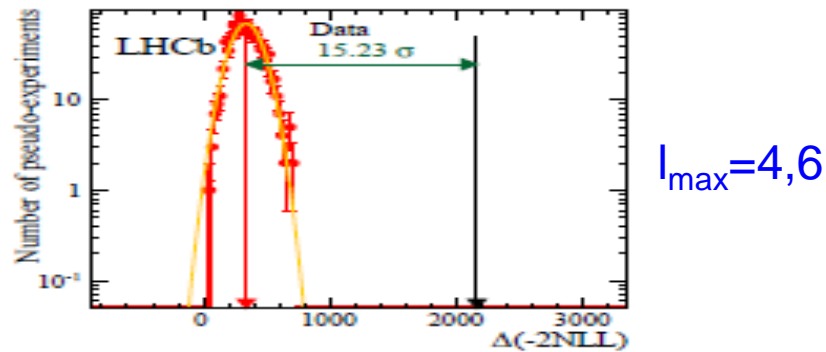
$$-2\Delta\text{NLL}_{l_{\text{max}}} = -2\log(L_{l_{\text{max}}}/L_{30})$$



(a)



(b)



(c)

Orbital angular momentum in the decay $X(3872) \rightarrow \rho^0 J/\psi$ and quantum numbers of $X(3872)$

- The nature of the state $X(3872)$ remains unclear
- It is narrow, has a mass very close the $D^0 \bar{D}^{*0}$ threshold and decays to $\rho^0 J/\psi$ and $\omega J/\psi$ with comparable branchings, violating isospin symmetry
- Observation of the decays $X \rightarrow \gamma J/\psi$ and $X \rightarrow \gamma \psi(2S)$ imply positive C
- This requires the total angular momentum of dipion system in $X \rightarrow \pi^+ \pi^- J/\psi$ to be odd
- $M(\pi^+ \pi^-)$ is limited to be less than 775 MeV, so $J_{\pi\pi} \geq 3$ can be ruled out
- In fact the distribution of $M(\pi^+ \pi^-)$ is consistent with $X \rightarrow \rho^0 J/\psi$
- LHCb ruled out $J^{PC} = 2^{-+}$ in favor of 1^{++} assignment for the decay $X \rightarrow \pi^+ \pi^- J/\psi$ using 1.0 fb^{-1} data
- It was assumed that the lowest angular momentum L_{min} between the $X(3872)$ decay products dominated the matrix element
- Significant contributions from $L_{\text{min}} + 2$ amplitudes could invalidate 1^{++} assignment
- It is important to probe the $X(3872)$ spin-parity without any assumptions about L

Data sample and allowed LS couplings

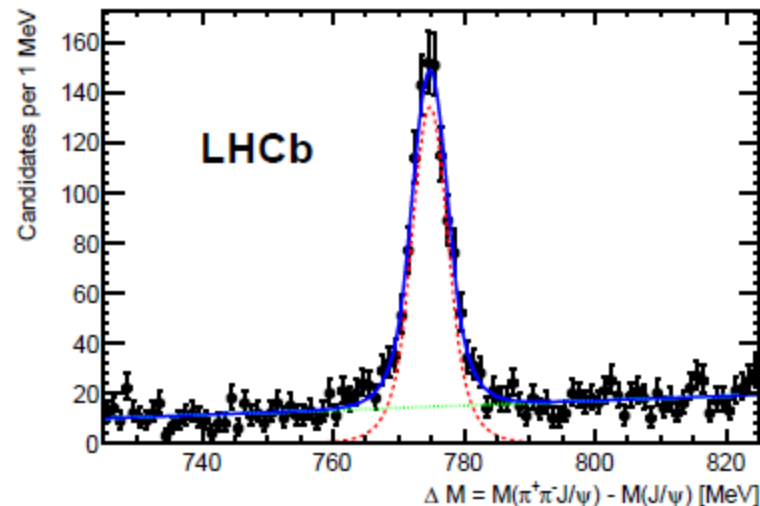
Parity-allowed LS couplings in $X \rightarrow \rho^0 J/\psi$ decay

For comparison a subset of these couplings corresponding to the lowest L is listed which used in previous determination of J^{PC} of X

| J^{PC} | B_{LS} | |
|----------|--|--------------------------|
| | Any L value | Minimal L value |
| 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} |

Present analysis is based on 3fb^{-1} data sample

1011 ± 38 decays of $X \rightarrow \pi^+ \pi^- J/\psi$



Fraction of D-wave

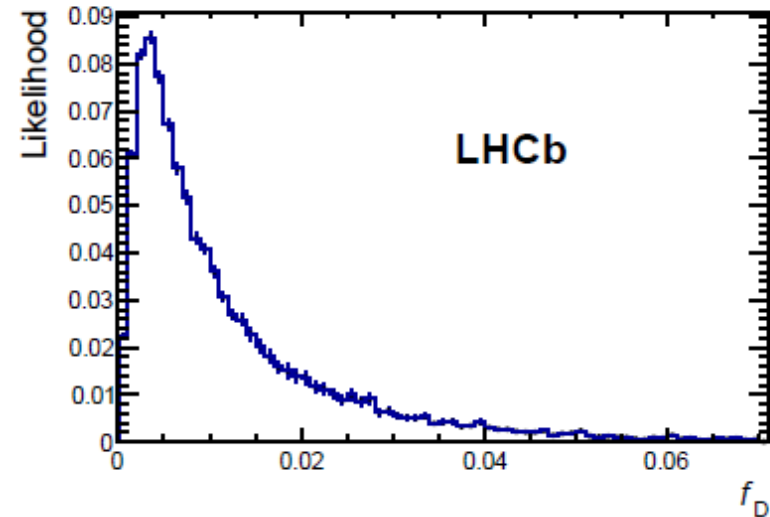
$$|B_{21}|^2/|B_{01}|^2=0.002\pm 0.004$$

$$|B_{22}|^2/|B_{01}|^2=0.007\pm 0.008$$

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

$f_D < 4\%$ at 95% C.L.

Likelihood weighted distribution of D-wave fraction



Conclusions

- LHCb has found two resonances decaying into $J/\psi p$ with pentaquark content of $uudc\bar{c}$ Phys.Rev.Lett. 115(2015) 072001
- The preferred J^P are $(3/2^-, 5/2^+)$, $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$
- Other exotic tetraquark state $Z^+(4430) \rightarrow \psi' \pi^+$ containing $c\bar{c}$ pair is evident in a model independent way with significance more than 8σ LHCb-PAPER-2015-029
- The J^{PC} of $X(3872)$ equal to 1^{++} are determined without any assumption about the orbital momentum of $\pi^+\pi^-$ system with respect to J/ψ . $X(3872)$ is found to decay predominantly through S-wave, upper limit on D-wave fraction is 4% at 95% C.L. arXiv:1504.06639



Backup slides

Systematic uncertainties

| Source | M_0 (MeV) | | Γ_0 (MeV) | | Fit fractions (%) | | | |
|--|-------------|------|------------------|------|-------------------|------|-----------------|-----------------|
| | low | high | low | high | low | high | $\Lambda(1405)$ | $\Lambda(1520)$ |
| Extended vs. reduced | 21 | 0.2 | 54 | 10 | 3.14 | 0.32 | 1.37 | 0.15 |
| Λ^* masses & widths | 7 | 0.7 | 20 | 4 | 0.58 | 0.37 | 2.49 | 2.45 |
| Proton ID | 2 | 0.3 | 1 | 2 | 0.27 | 0.14 | 0.20 | 0.05 |
| $10 < p_p < 100$ GeV | 0 | 1.2 | 1 | 1 | 0.09 | 0.03 | 0.31 | 0.01 |
| Nonresonant | 3 | 0.3 | 34 | 2 | 2.35 | 0.13 | 3.28 | 0.39 |
| Separate sidebands | 0 | 0 | 5 | 0 | 0.24 | 0.14 | 0.02 | 0.03 |
| J^P ($3/2^+$, $5/2^-$) or ($5/2^+$, $3/2^-$) | 10 | 1.2 | 34 | 10 | 0.76 | 0.44 | | |
| $d = 1.5 - 4.5$ GeV $^{-1}$ | 9 | 0.6 | 19 | 3 | 0.29 | 0.42 | 0.36 | 1.91 |
| $L_{\Lambda_b^0}^{P_c} \Lambda_b^0 \rightarrow P_c^+ (low/high) K^-$ | 6 | 0.7 | 4 | 8 | 0.37 | 0.16 | | |
| $L_{P_c} P_c^+ (low/high) \rightarrow J/\psi p$ | 4 | 0.4 | 31 | 7 | 0.63 | 0.37 | | |
| $L_{\Lambda_b^0}^{\Lambda^*} \Lambda_b^0 \rightarrow J/\psi \Lambda^*$ | 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 |