Amplitude Analysis for Baryon Spectroscopy at LHCb

Sebastian Neubert

on behalf of the LHCb collaboration

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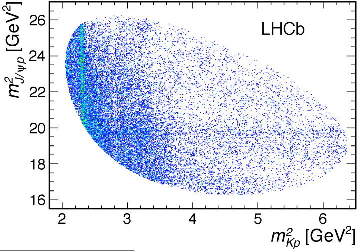
Baryonic Amplitude Analysis in LHCb

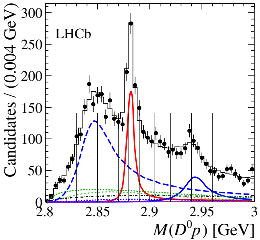
Still a new topic for LHCb – but a very successful tool:

- $\Lambda_b \to J/\psi p K$
  $\Rightarrow$ Discovery of $J/\psi p$ pentaquark candidates $P_c(4380)^+$ and $P_c(4450)^+$
  [PRL115(2015)072001]

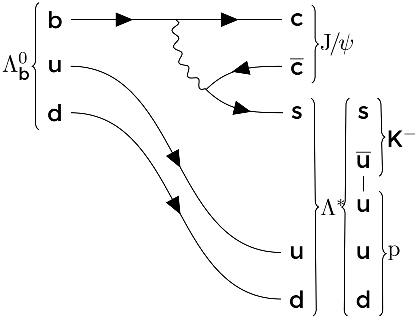
- $\Lambda_b \to J/\psi p \pi$
  $\Rightarrow$ Confirmation of P_c candidates
  [PRL117(2016)082003]

- NEW: $\Lambda_b \to D^0 p \pi$
  $\Rightarrow$ A new resonance in $D^0 p$
  [JHEP05(2017)030]





Amplitude Analysis as Interference Experiment



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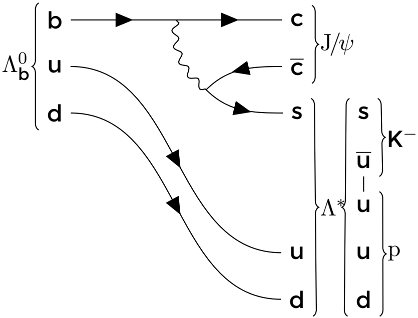
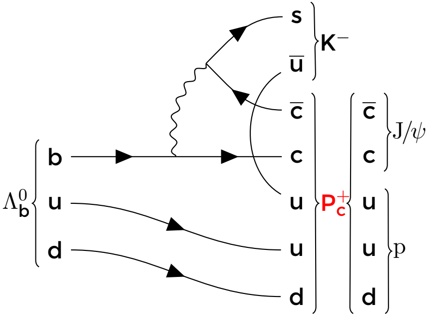
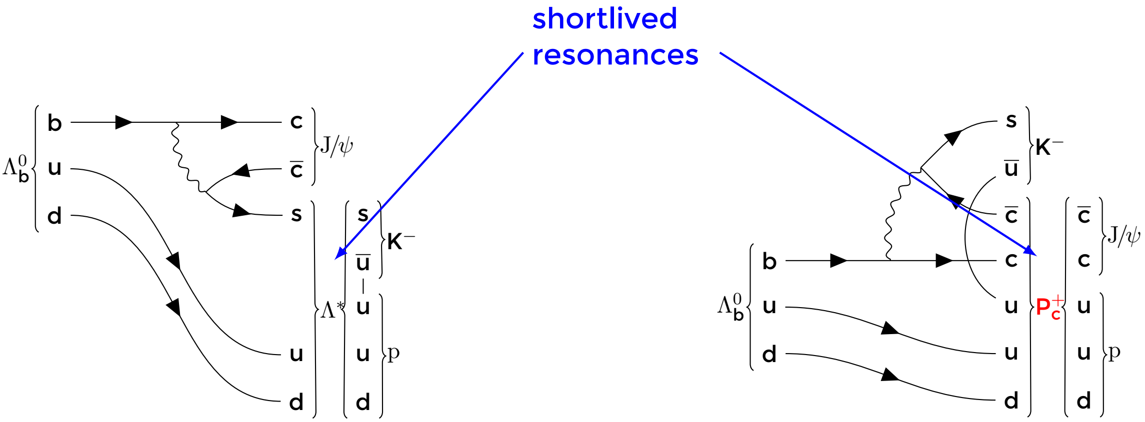
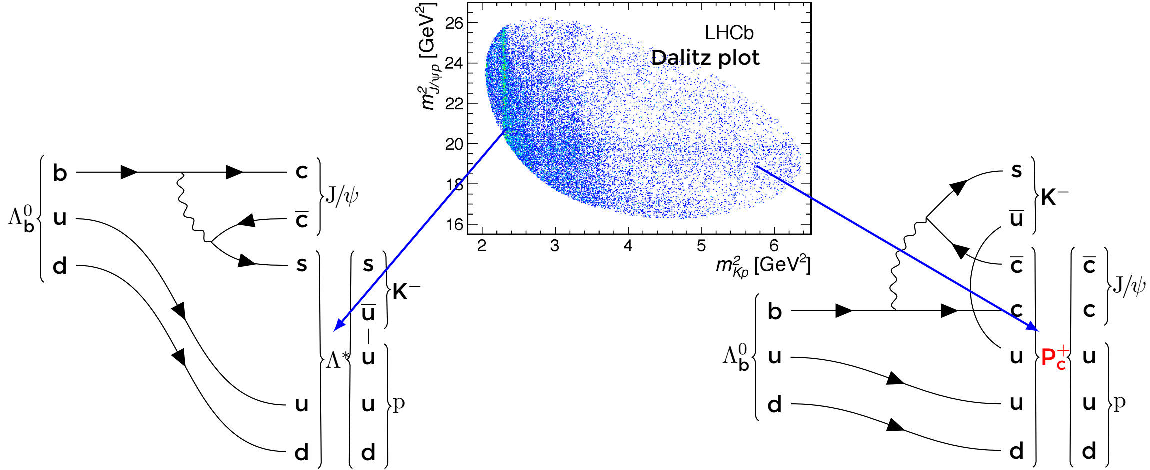




Amplitude Analysis as Interference Experiment



Amplitude Analysis as Interference Experiment

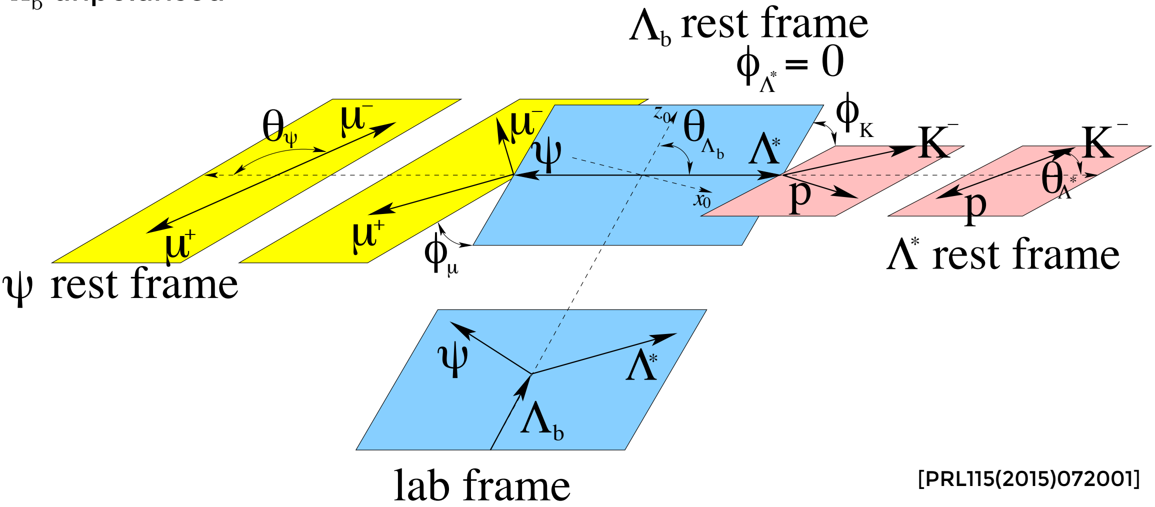


$\Rightarrow$ **Interference-patterns** (in angular distributions of decay products)

Isobar Model Helicity Amplitudes for $\Lambda_b \to J/\psi \Lambda^*$

Matrix Element $\mathcal{M}^{\Lambda^*}$ parametrized as a function of 5 angles and one mass m^2_{pK}

Λ_b **unpolarised**



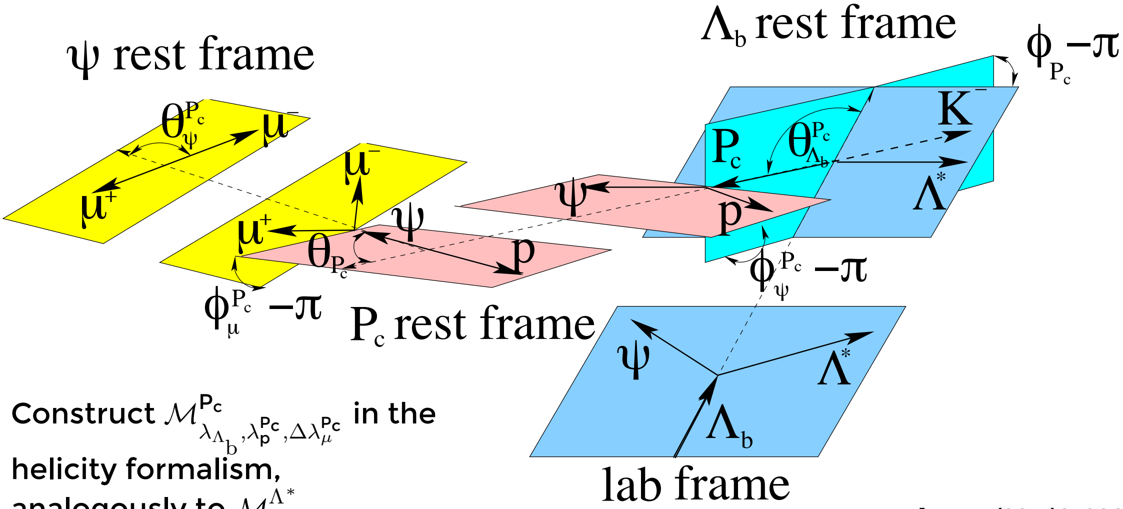
[PRL115(2015)072001]

Isobar Model Helicity Amplitudes for $\Lambda_b \to J/\psi \Lambda^*$

- Angular structures (no free parameters)
- Helicity couplings $\leftarrow$ complex numbers, floating in fit
- Λ^* partial waves variety of possible parametrizations (Breit-Wigner, Flatté, Polynomials, Splines)

$$\mathcal{M}^{\Lambda^*} = \sum_n R_n(m_{Kp}) \; \Lambda^*_n \to Kp_{\lambda_p} \; \sum_{\lambda_\psi} e^{i\,\lambda_\psi \phi_\mu} \, d^{1}_{\lambda_\psi, \Delta\lambda_\mu}(\theta_\psi) \times$$

$$\sum_{\lambda_{\Lambda^*}} \Lambda_b \to \Lambda^*_n \psi_{\lambda_{\Lambda^*},\, \lambda_\psi} \; e^{i\,\lambda_{\Lambda^*} \phi_K} \; d^{\frac{1}{2}}_{\lambda_{\Lambda_b},\, \lambda_{\Lambda^*} - \lambda_\psi}(\theta_{\Lambda_b}) \; d^{J_{\Lambda^*_n}}_{\lambda_{\Lambda^*},\, \lambda_p}(\theta_{\Lambda^*})$$

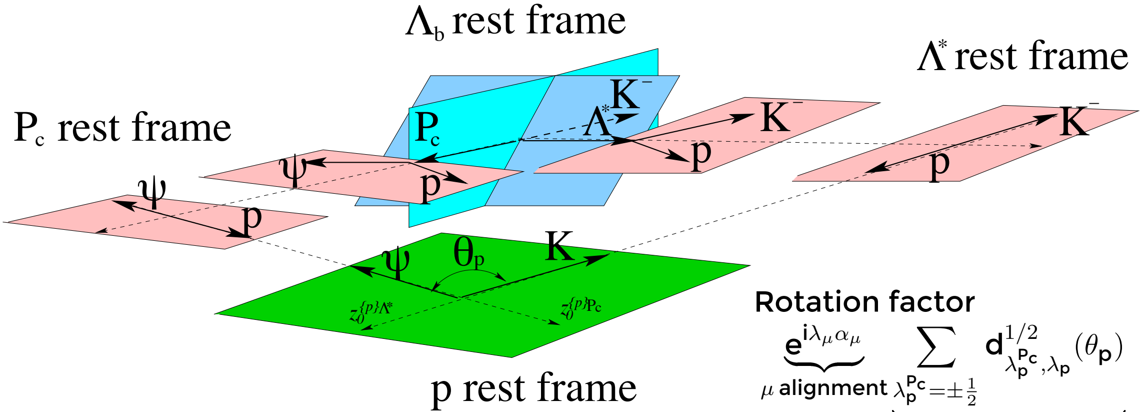


Construct $\mathcal{M}^{P_c}_{\lambda_{\Lambda_b},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}}$ in the helicity formalism, analogously to $\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu}$

[PRL115(2015)072001]

An important detail: Aligning reference frames

Quantisation axes of proton (and muon) spins need to be defined in the same frame.

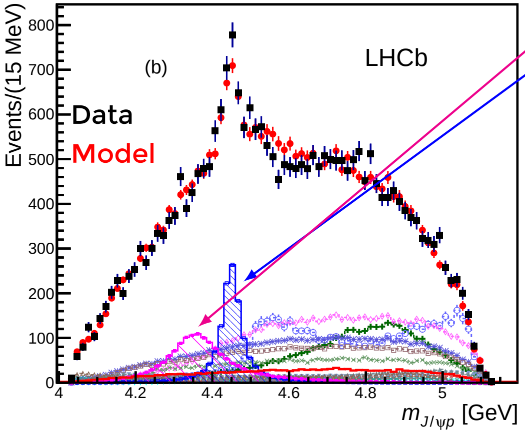


Rotation factor

$$\underbrace{e^{i\lambda_\mu \alpha_\mu}}_{\mu\text{ alignment}} \underbrace{\sum_{\lambda_p^{P_c}=\pm\frac{1}{2}} d^{1/2}_{\lambda_p^{P_c},\lambda_p}(\theta_p)}_{\text{proton align.}}$$

[PRL115(2015)072001]

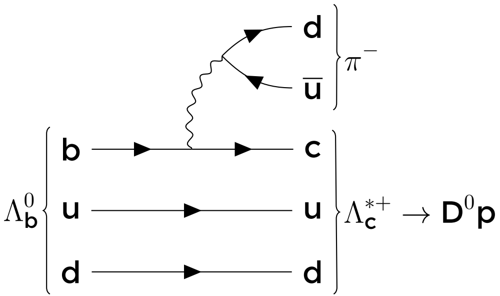
6D Amplitude analysis allows to measure resonance parameters



State	Mass [MeV]	Width [MeV]	J^P
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+$

- Spin parity assignment not unique
- Excluded: same parity solution
- Results confirmed in two subsequent analyses
  - $\Lambda_b \to J/\psi p K$ moments analysis [PRL117(2016)082002]
  - $\Lambda_b \to J/\psi p \pi$ amplitude analysis [PRL117(2016)082003]

New Analysis: $\Lambda_b \to D^0 p\pi$



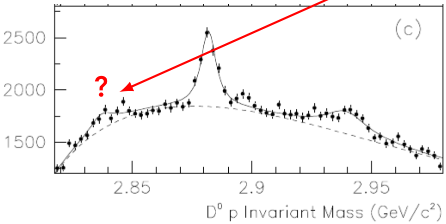
The Λ_c^+ spectrum

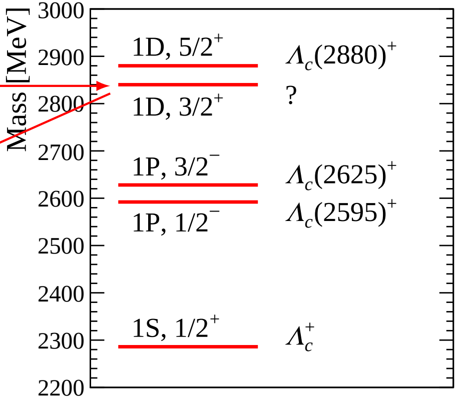
Well studied heavy-light-light system

- Orbitally excited states
- D-wave doublet predicted

  more states depending on model
- Missing state?
- Indication by BaBar for structure in $D^0 p$ at 2.84 GeV

  [PRL98(2007)012001]





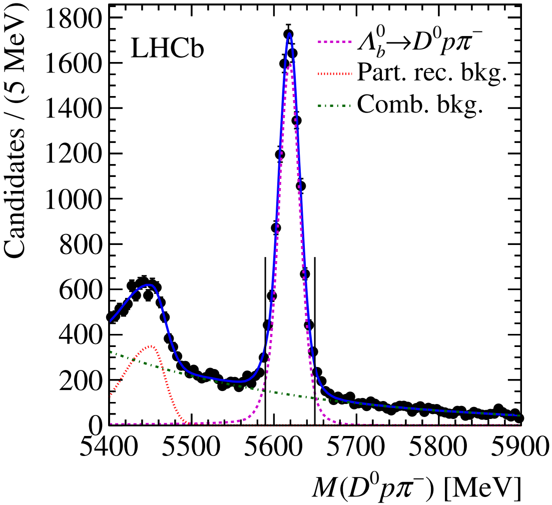
Predictions from [EPJ A51(2015)82]

$\Lambda_b \to D^0 p\pi$ Analysis strategy

[JHEP05(2017)030]

- Data set $3\,\text{fb}^{-1}$ (Run I)
- Select $D^0 \to K\pi$ using PID
- Kinematic fit to improve resolution
- Combinatoric background suppressed with a BDT

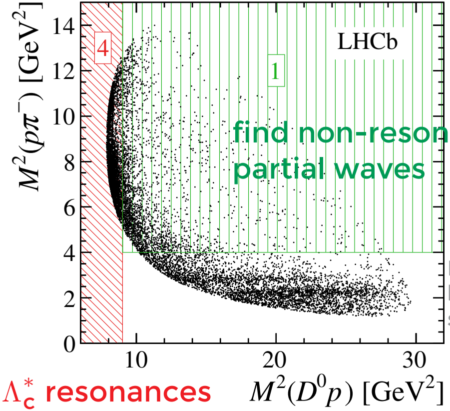
- 5D amplitude analysis
- Helicity formalism
- Cross-checked with covariant tensor formalism
  [Comput. Phys. Comm. 180(2009)1847]
  part of systematic uncertainty



$\Lambda_b \to D^0 p \pi$ Phase Space Regions

Performing fits in increasingly larger regions

Full phase space

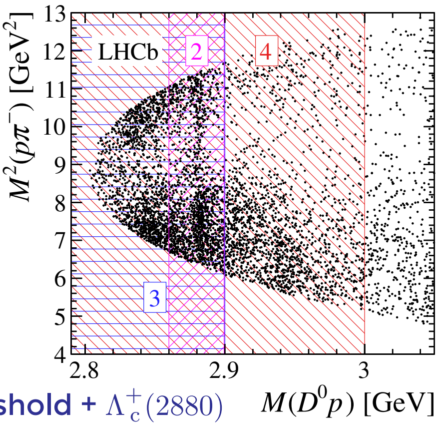


find non-resonant partial waves

N^* resonances kinematically separated

4) Λ_c^* resonances

Zoom to small D^0p masses

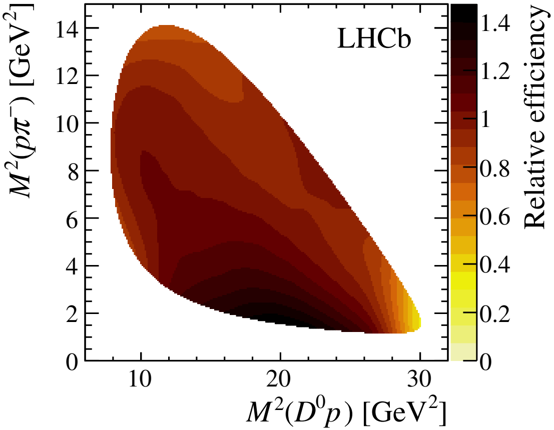


3) Threshold + $\Lambda_c^+(2880)$

2) $\Lambda_c^+(2880)$ region

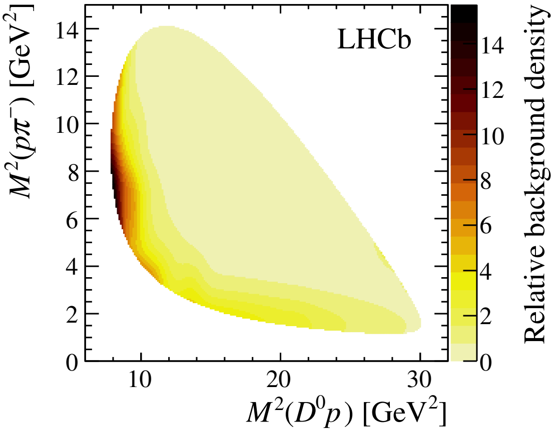
Efficiency and background distribution [JHEP05(2017)030]

Efficiencies from Monte-Carlo



calibrated on control samples

Background from Λ_b sidebands

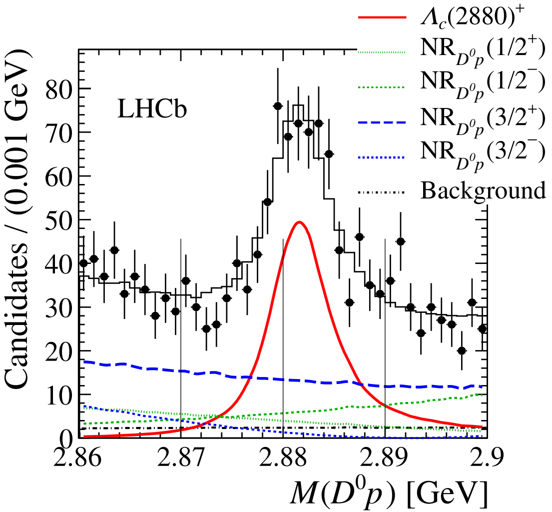


cross-checked with wrong-sign sample

Extracting $\Lambda_c^+(2880)$ Resonance parameters [JHEP05(2017)030]

- Non-resonant $D^0 p$ partial waves inferred from region (1)
- $J^P = 1/2^-, 1/2^+, 3/2^-, 3/2^+$ needed
- Linear parametrization in $\Lambda_c^+(2880)$ mass window

- Relativistic Breit-Wigner
- Positive parity of $\Lambda_c^+(2880)$ fixed
- Modelling uncertainty includes spin formalism, lineshape, background parametrization



m $= 2881.75 \pm 0.29$(stat) ± 0.07(sys)$^{+0.14}_{-0.20}$(model) MeV

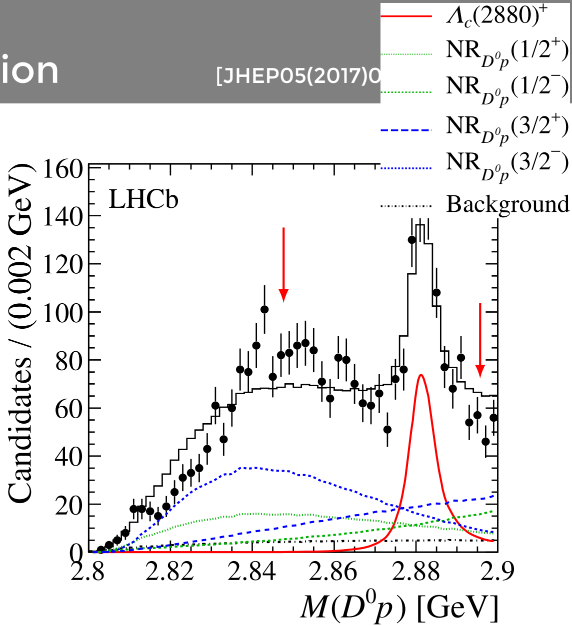
$\Gamma = 5.43^{+0.77}_{-0.71}$(stat) ± 0.29(sys)$^{+0.75}_{-0.00}$(model) MeV

$J^P = 5/2^+$ favoured by 4σ over $7/2$

Including the threshold region

[JHEP05(2017)0

- $\Lambda_c^+(2880)$ fixed to PDG params.
- Region around 2.84 GeV not well described by broad background components

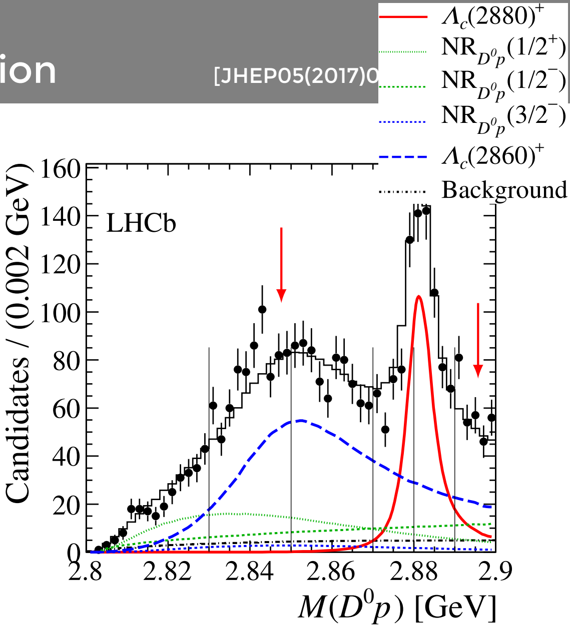


Including the threshold region

[JHEP05(2017)0

- $\Lambda_c^+(2880)$ fixed to PDG params.
- Region around 2.84 GeV not well described by broad background components

- Adding another Breit-Wigner
- BW vs Flattè and various J^P tested
- Evidence for new state $\Lambda_c^+(2860)$



m $= 2856.1^{+2.0}_{-1.7}$(stat) $\pm\, 0.5$(sys)$^{+1.1}_{-5.6}$(model) MeV

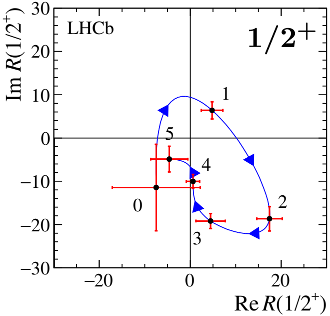
$\Gamma = 67.63^{+10.1}_{-8.1}$(stat) $\pm\, 0.29$(sys)$^{+5.9}_{-20.0}$(model) MeV

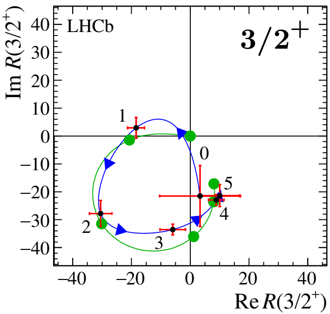
$J^P = 3/2^+$ favoured by 6.2σ over next best solution

Testing resonant nature of $\Lambda_c^+(2860)$ [JHEP05(2017)030]

- Both $J^P = 1/2^+$ and $3/2^+$ give reasonable description of data
  $J = 3/2$ favoured by 6.2σ
- Complex valued spline parametrization instead of Breit-Wigner

- $J^P = 1/2^+ \Rightarrow$ unphysical clockwise phase motion
- $J^P = 3/2^+ \Rightarrow$ good argeement with BW





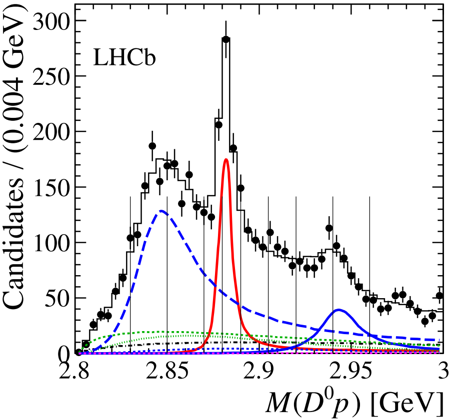
The full Λ_c^* resonance region

- Adding Breit-Wigner for $\Lambda_c^+(2940)$
- Exponential or polynomial background

m $= 2944.8^{+3.5}_{-2.5}$(stat)± 0.4(sys)$^{+0.1}_{-4.6}$(model) MeV

$\Gamma = 27.7^{+8.2}_{-6.0}$(stat) ± 0.9(sys)$^{+5.2}_{-10.4}$(model) MeV

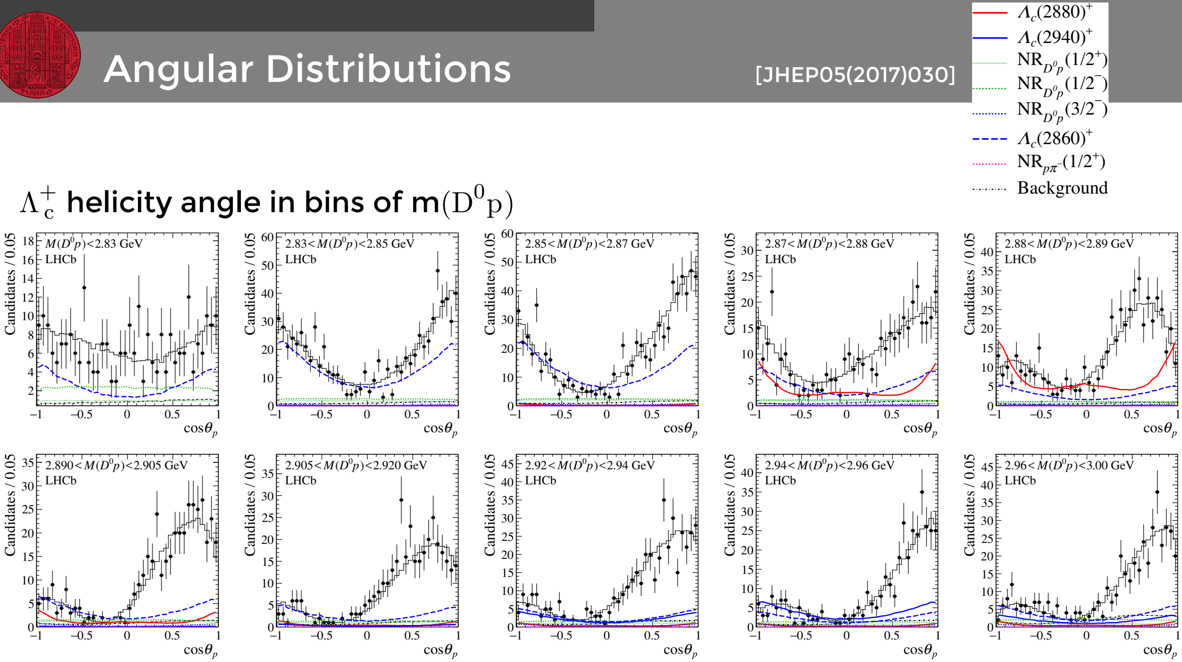
- $J^P = 3/2^-$ favoured
- other spin-parity assignments still allowed, dependent on background parametrization.



Bkg Model	$1/2^+$	$1/2^-$	$3/2^+$	$5/2^+$	$5/2^-$	$7/2^+$	$7/2^-$
Expo	7.9	5.6	3.7	4.4	4.5	6.1	6.1
Poly	4.1	4.5	3.6	3.1	2.2	6.2	4.0

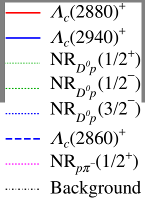
significance of $J^P = 3/2^-$ over alternative hypotheses

Λ_c^+ helicity angle in bins of m$(D^0 p)$

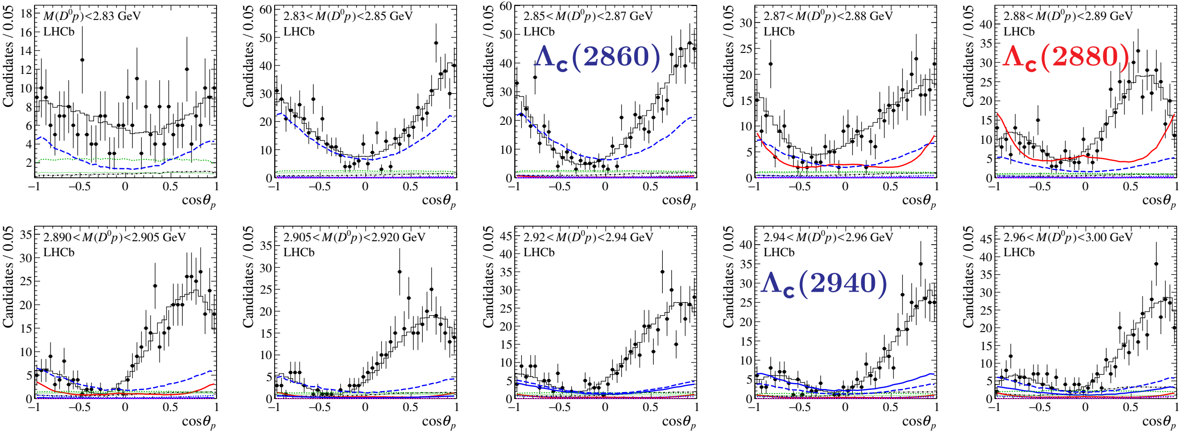


Angular Distributions

[JHEP05(2017)030]



Λ_c^+ helicity angle in bins of m$(\mathrm{D^0p})$



Summary

- Amplitude analyses yield invaluable information on heavy baryons
- Both helicity and covariant formalism in use
- Analysis of $\Lambda_b \to D^0 p\pi$:
  - New $J^P = 3/2^+$ resonance $\Lambda_c^+(2860)$

$$m = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{sys})^{+1.1}_{-5.6}(\text{model})\ \text{MeV}$$

$$\Gamma = 67.63^{+10.1}_{-8.1}(\text{stat}) \pm 0.29(\text{sys})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}$$

  - Compatible with missing D-wave state
  - $\Lambda_c^+(2880)$ and $\Lambda_c^+(2940)$ consistent with previous measurements
  - First constraints on $\Lambda_c^+(2940)$ spin and parity

Backup

Resonance parametrisation

Dynamical Terms $R_n(m_{Kp})$ given by

- Relativistiv, single-channel Breit-Wigner amplitudes $BW(M_{Kp}|M_0^{\Lambda_n^*}, \Gamma_0^{\Lambda_n^*})$

$$BW(M|M_0,\Gamma_0) = \frac{1}{M_0^2 - M^2 - iM_0\Gamma(M)},$$

where

$$\Gamma(M) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2\,\ell_{\Lambda^*}+1} \frac{M_0}{M} B'_{\ell_{\Lambda^*}}(q,q_0,d)^2 .$$

- Angular-momentum barrier factors $B'_\ell(p,p_0,d)$

$$R_n(m_{Kp}) = B'_{\ell_{\Lambda_b}}\left(\frac{p}{M_{\Lambda_b}}\right)^{\ell_{\Lambda_b}} \times BW(M_{Kp}) \times B'_{\ell_{\Lambda_n^*}}\left(\frac{q}{M_{\Lambda_n^*}}\right)^{\ell_{\Lambda_n^*}} .$$

- special case $\Lambda(1405)$ is subthreshold: Flatté ($K\,p$ and $\Sigma\,\pi$ channels)

$p(q)$ are momenta of the daughter particles in the rest-frame of the decaying particle.

$p_0(q_0)$ calculated on the nominal resonance mass