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First determination of the spin-parity of the $\Xi_c(3055)^{+(0)}$ baryons

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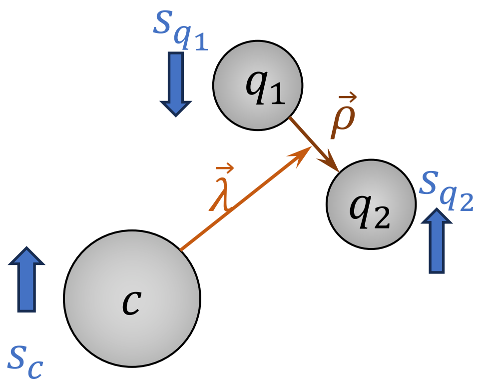
in representative of the LHCb Collaboration

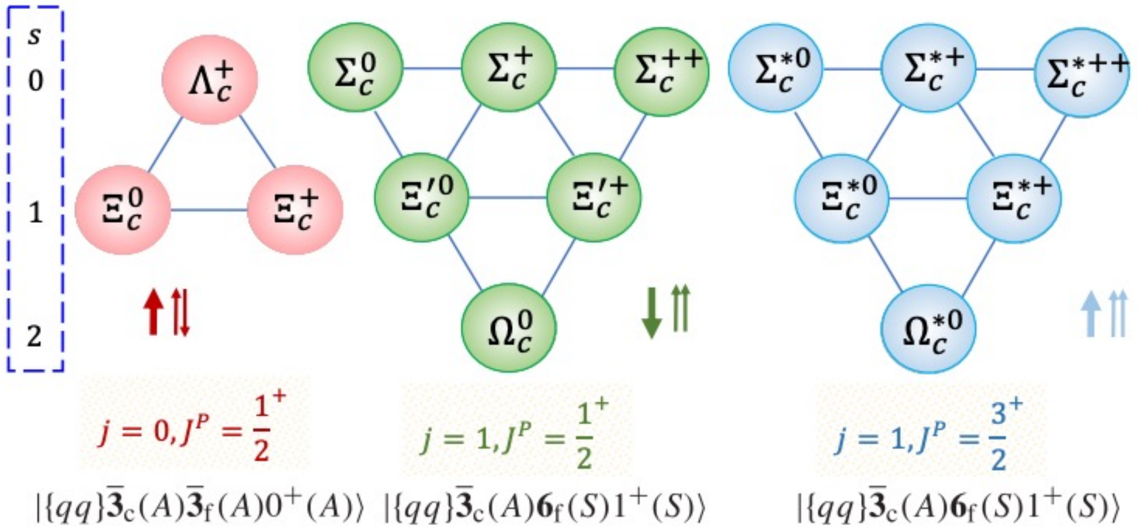
Outline

- Motivation & overview
- Event selection
- Mass fit & signal extraction
- Amplitude analysis
- J^P determination of $\Xi_c(3055)^{+(0)}$
- Systematics
- Summary

Singly heavy baryons

- Singly heavy baryon:
  - A heavy quark ($\boldsymbol{c}, \boldsymbol{b}$) and two light quarks ($\boldsymbol{u}, \boldsymbol{d}, \boldsymbol{s}$)
  - In the relative frame:
    - Dynamics governed by the light quark pairs (*di-quark*)
- Rich spectrum:
  - Ground states: $\bar{3}_F$ (Λ, Ξ) / $6_F(\Sigma, \Xi', \Omega)$
  - Excitation: λ/ρ orbital excitation modes
- Good lab for non-perturbative QCD





Spectroscopy of $\Xi_c^{(*)}$

State	J^{PC}	Mass (MeV)	Width (MeV)	Observed modes
Ξ_c^+	$1/2^+$	$2467.94^{+0.17}_{-0.20}$	$1/[(4.56\pm0.05)\times10^{-13}s]$	$pK^-\pi^+, \Xi^0\pi^+(0.55)$,
Ξ_c^0	$1/2^+$	$2470.90^{+0.22}_{-0.29}$	$1/[(1.53\pm0.06)\times10^{-13}s]$	$pK^-K^-\pi^+(0.005), \Xi^-\pi^+(0.01), \Omega^-K^+(0.004$
$\Xi_c'^+$	$1/2^+$	2578.4 ± 0.5	keV	$\Xi_c^+\gamma$ (Σ_c^+ analogy)
$\Xi_c'^0$	$1/2^+$	2579.2 ± 0.5	keV	$\Xi_c^0\gamma$
$\Xi_c^+(2645)$	$3/2^+$	$2645.56^{+0.24}_{-0.30}$	2.14 ± 0.19	$\Xi_c^0\pi^+$ only, Σ_c^{++} analogy)
$\Xi_c^0(2645)$	$3/2^+$	$2646.38^{+0.20}_{-0.23}$	2.35 ± 0.22	$\Xi_c^+\pi^-$ only
$\Xi_c^+(2790)$	$1/2^-$	2792.4 ± 0.5	8.9 ± 1.0	$\Xi_c'^0\pi^+$ ($\Lambda_c^+(2595)$ analogy)
$\Xi_c^0(2790)$	$1/2^-$	2794.1 ± 0.5	10.0 ± 1.1	$\Xi_c'^+\pi^-$
$\Xi_c^+(2815)$	$3/2^-$	$2816.74^{+0.20}_{-0.23}$	2.43 ± 0.26	$\Xi_c'^0\pi^+, \Xi_c^0(2645)\pi^+$ ($\Lambda_c^+(2625)$ analogy)
$\Xi_c^0(2815)$	$3/2^-$	$2820.25^{+0.25}_{-0.31}$	2.54 ± 0.25	$\Xi_c'^+\pi^-, \Xi_c^+(2645)\pi^-$
$\Xi_c^+(2930)$	?	2942 ± 5	15 ± 9	$B^0\to\Lambda_c^-(\Lambda_c^+K^0)$ only an evidence (by Belle)
$\Xi_c^0(2930)$	?	$2929.7^{+2.8}_{-5.0}$	26 ± 8	$B^-\to\Lambda_c^-(\Lambda_c^+K^-)$ Split into two by LHCb
$\Xi_c^+(2970)$	?	$2966.34^{+0.17}_{-1.00}$	$20.9^{+2.4}_{-3.5}$	$\Lambda_c^+\pi^+(\Sigma_c(2455))K^-, \Xi_c^+\pi^+\pi^-, \Xi_c'^0\pi^+$; Λ_c^+K not seen
$\Xi_c^0(2970)$	?	$2970.9^{+0.4}_{-0.6}$	$28.1^{+3.4}_{-4.0}$	$\Lambda_c^+\pi^+(\Sigma_c(2455))K^0, \Xi_c^0\pi^+\pi^-, \Xi_c'^+\pi^-$; Λ_c^+K not seen
$\Xi_c^+(3055)$	?	3055.9 ± 0.4	7.8 ± 1.9	$\Sigma_c^{++}K^-, D^+\Lambda$
$\Xi_c^0(3055)$	?	3059.0 ± 0.7	6.4 ± 2.3	$\Sigma_c^{++}K^0, D^0\Lambda$
$\Xi_c^+(3080)$	?	3077.2 ± 0.4	3.6 ± 1.1	$\Lambda_c^+\pi^+K^-, \Sigma_c^{(*)++}K^-, D^+\Lambda$; Λ_c^+K not seen
$\Xi_c^0(3080)$	?	3077.2 ± 0.4	5.6 ± 2.2	$\Lambda_c^+\pi^+K^0, \Sigma_c^{(*)++}K^0, D^0\Lambda$; Λ_c^+K not seen
$\Xi_c^+(3123)$	?	2122.9 ± 1.3	4 ± 4	$\Sigma_c^{++}(2520)K^-$ only 3.6σ, not confirmed by Belle

Table: Experimentally discovered Ξ_c excited states

Two 1P excitation of Ξ_c^+ in λ mode

Not matched

- Undetermined excitations
  - Various theoretical explanations
- **Pinning down the state:**
  - Mass, width, decay modes
  - **Spin-parity**
  - **Decay parameter**

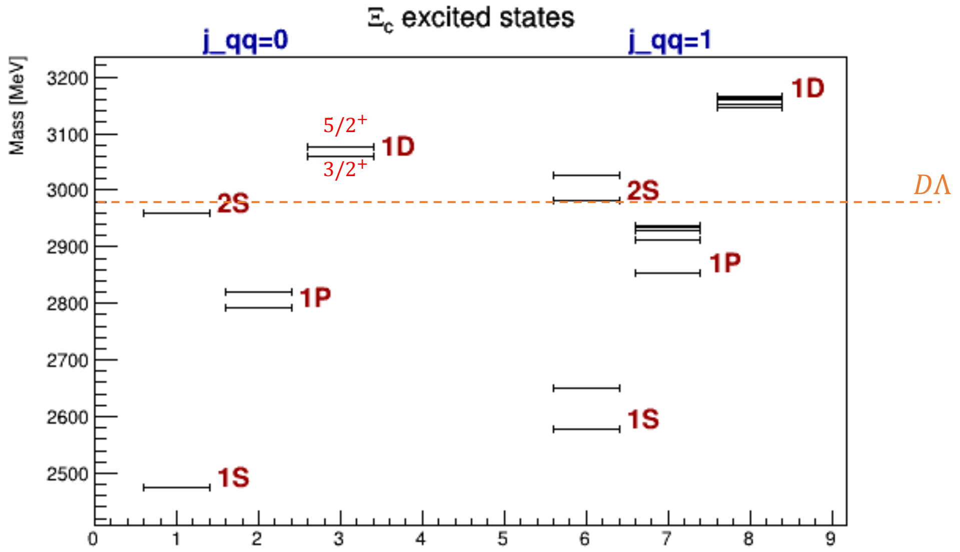


Figure: Theoretical predictions of the Ξ_c excited states (λ mode only)

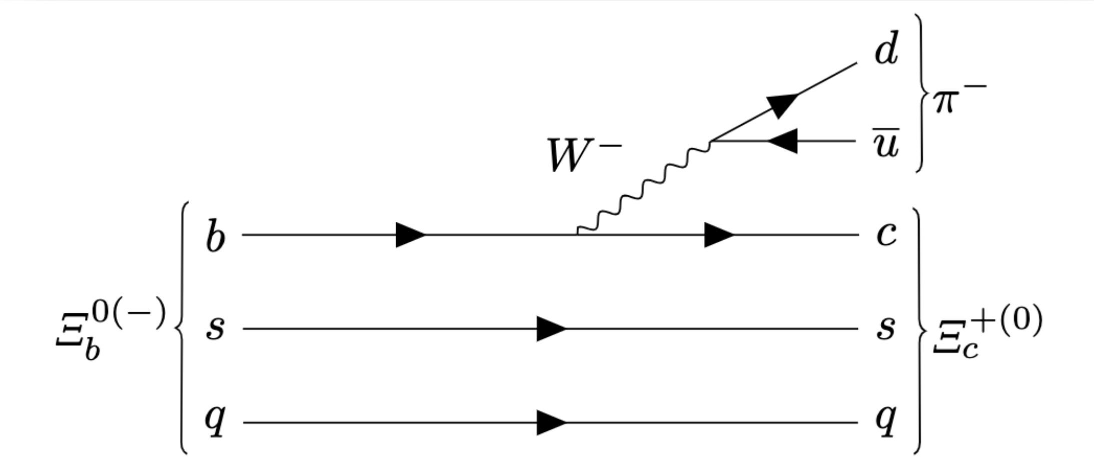
Ref : A review of the open charm and open bottom systems

Decay parameter

- Under helicity basis:

$$\alpha_{\Xi_b \to \Xi_c^{**}\pi} \equiv \frac{|H_\uparrow|^2 - |H_\downarrow|^2}{|H_\uparrow|^2 + |H_\downarrow|^2}$$

  - Reflect parity violation in the transition



- If the initial (Ξ_b) & final (Ξ_c^{**}) particle have similar structure:
  - Governed by $b \to c$ weak decay
  - Pure parity violation, $\alpha_{\Xi_b \to \Xi_c^{**}\pi} \sim -100\%$

- If not: deviation from -100%

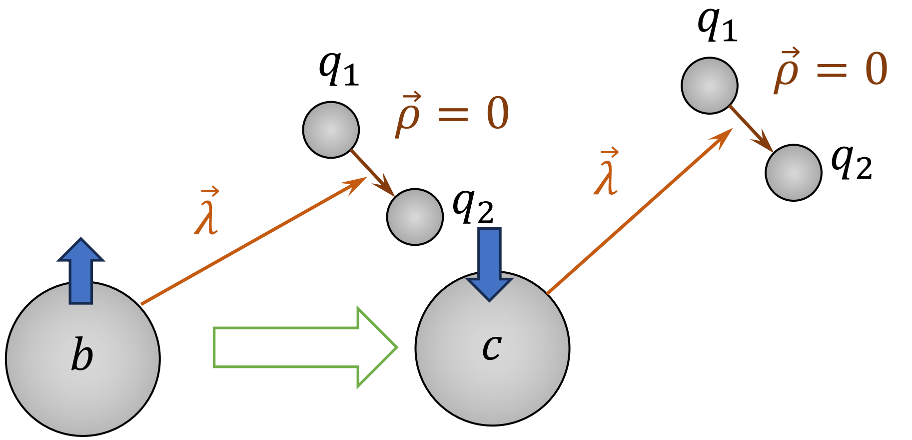


TABLE XIV: The predicted up-down asymmetries of $\mathcal{B}_b \to \mathcal{B}_c P$ decays. The asymmetries are given in unit of %. The asterisks in the first column indicate that the baryons in the final states are radial excited.

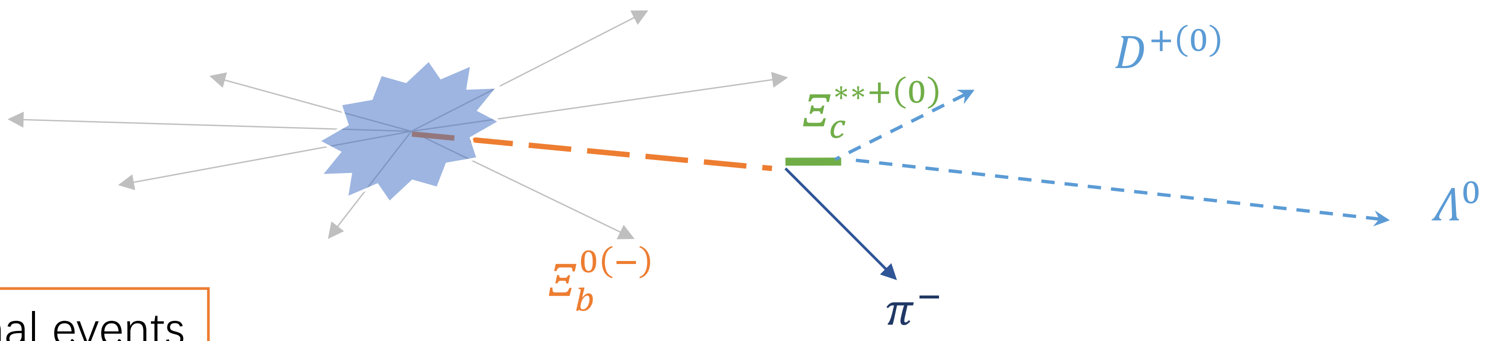
Type	Mode	$P = \pi^-$	$P = K^-$	$P = D^-$	$P = D_s^-$
(i)	$\alpha(\Lambda_b \to \Lambda_c P)$	$-99.99^{+2.24}_{-0.00}$	$-99.98^{+2.41}_{-0.00}$	$-98.47^{+8.91}_{-1.52}$	$-98.06^{+9.41}_{-1.87}$
(i)	$\alpha(\Xi_b^0 \to \Xi_c^+ P)$	$-99.99^{+2.24}_{-0.00}$	$-99.97^{+2.41}_{-0.00}$	$-98.40^{+9.01}_{-1.59}$	$-97.96^{+9.52}_{-1.96}$
(i)	$\alpha(\Xi_b^- \to \Xi_c^0 P)$	$-99.99^{+2.24}_{-0.00}$	$-99.97^{+2.41}_{-0.00}$	$-98.39^{+9.01}_{-1.59}$	$-97.96^{+9.53}_{-1.96}$
(i)*	$\alpha[\Lambda_b \to \Lambda_c(2765)P]$	$-100.00^{+2.14}_{-0.00}$	$-99.98^{+2.39}_{-0.00}$	$-96.61^{+10.76}_{-3.32}$	$-95.54^{+11.49}_{-4.46}$
(ii)	$\alpha(\Omega_b \to \Omega_c P)$	$59.92^{+9.88}_{-9.22}$	$59.93^{+9.88}_{-9.22}$	$59.95^{+14.95}_{-13.54}$	$59.90^{+14.95}_{-13.53}$
(ii)*	$\alpha[\Omega_b \to \Omega_c(3090)P]$	$60.02^{+9.88}_{-9.23}$	$60.02^{+9.88}_{-9.23}$	$59.49^{+14.93}_{-13.47}$	$59.23^{+14.92}_{-13.43}$
(iii)	$\alpha[\Lambda_b \to \Lambda_c(2595)P]$	$-98.86^{+4.77}_{-1.04}$	$-98.84^{+4.79}_{-1.05}$	$-97.86^{+9.63}_{-2.03}$	$-97.57^{+9.93}_{-2.25}$
(iii)	$\alpha[\Xi_b^0 \to \Xi_c^+(2790)P]$	$-99.13^{+4.44}_{-0.84}$	$-99.12^{+4.44}_{-0.84}$	$-98.58^{+8.77}_{-1.42}$	$-98.39^{+9.02}_{-1.59}$
(iii)	$\alpha[\Xi_b^- \to \Xi_c^0(2790)P]$	$-99.13^{+4.44}_{-0.84}$	$-99.12^{+4.44}_{-0.84}$	$-98.58^{+8.76}_{-1.42}$	$-98.39^{+9.02}_{-1.59}$
(iii)*	$\alpha[\Lambda_b \to \Lambda_c(2940)P]$	$-98.86^{+4.76}_{-1.03}$	$-98.84^{+4.78}_{-1.05}$	$-97.04^{+10.41}_{-2.81}$	$-96.36^{+10.94}_{-3.60}$

Unit : %

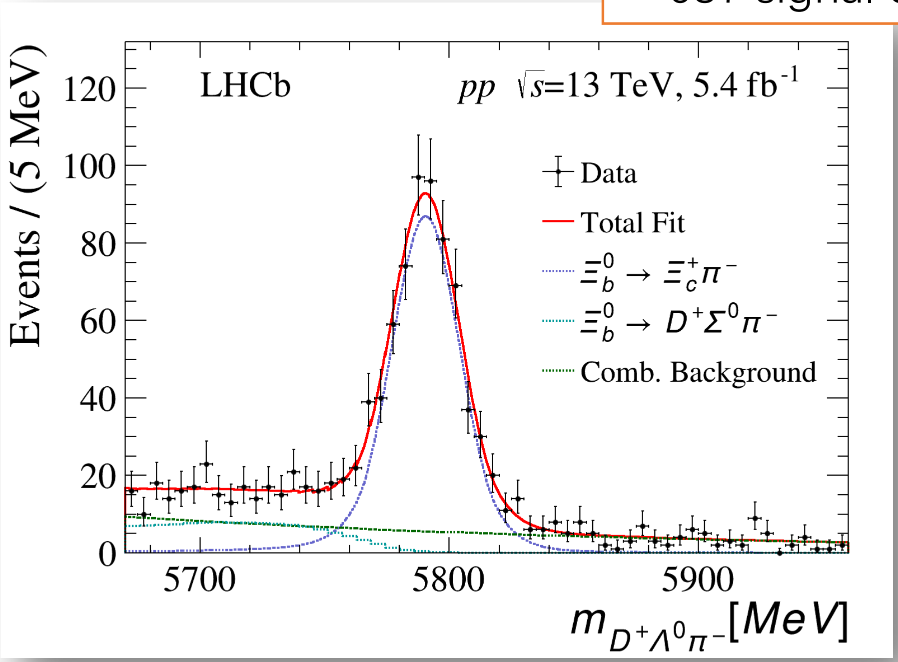
Ref:1811.09265

Analysis overview

- In $\Xi_b^{0(-)} \to \Xi_c^{**+(0)} \pi^-$ decay, where $\Xi_c^{**+(0)} \to D^{+(0)} \Lambda^0$ [Ref: PhysRevD.94.032002]
  - $D^{+(0)} \to K\pi\pi(K\pi)$
  - $\Lambda^0 \to p\pi$
- Run2 2016-18 data sample



~ 637 signal events



- Strategy:
  1. Event selection with pre-selection & MVA
  2. Signal extraction with Ξ_b mass fit
  3. Amplitude analysis
  4. Spin-parity determination
     - Validation with toy study
  5. Systematic uncertainties

The LHCb Detector (Run2)

Large **H**adron **C**ollider **b**eauty experiment：

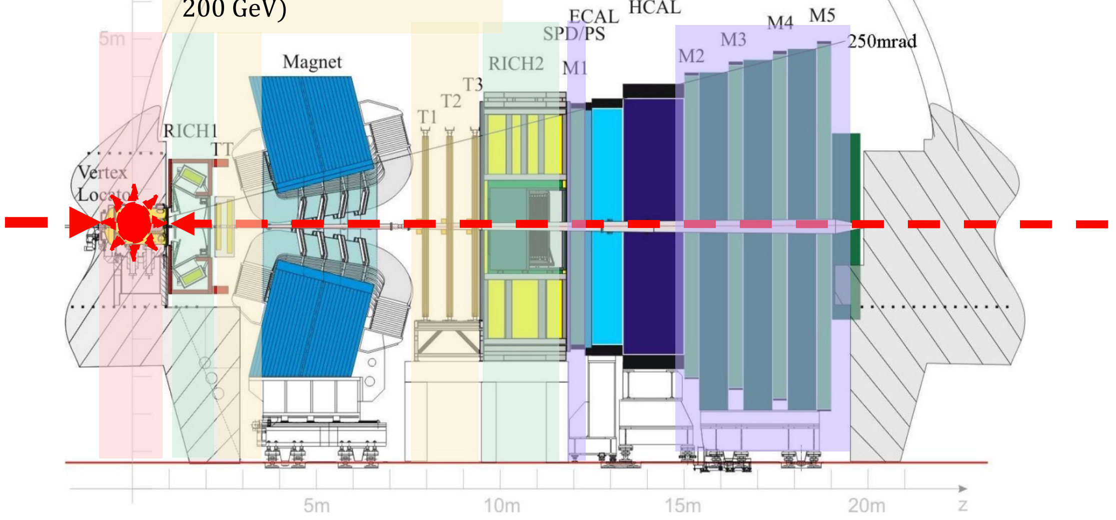
- Single-arm forward region:
  - Designed for heavy flavor study
- Dedicated vertex detector
- Tracking system: good momentum resolution
- PID system: hadron and muon identification
- Hardware & Software trigger system

Vertex Locator
σ_{IP}~20 μm
σ_{τ}~45 fs

Tracking System
$\epsilon_{\mathrm{tracking}}$~96%
σ_p/p~0.5% – 1% (5 – 200 GeV)

PID System
$\epsilon(K \to K) \sim 95\%$
mis-ID $\epsilon(\pi \to K) \sim 5\%$

Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
mis-ID $\epsilon(\pi \to \mu)$ ~1 – 3%



JINST 3 (2008) S08005 IJMPA 30 (2015) 1530022

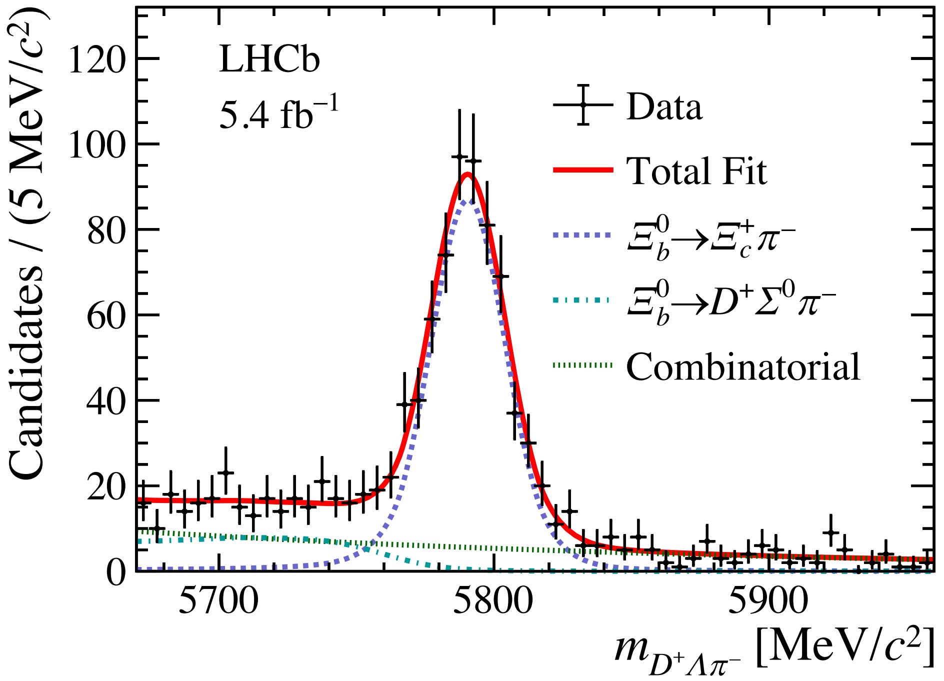
Event selection

Data processing

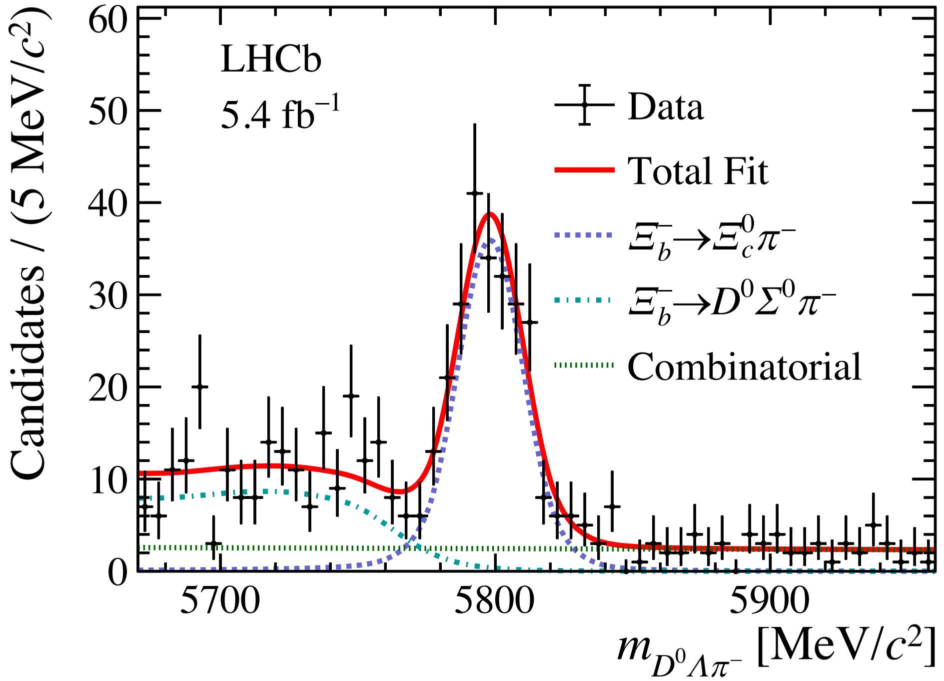
- Trigger level requirement:
  - Hardware trigger: transverse energy deposited in calorimeter
  - Software level: high-momentum track with sufficient impact parameter, displaced secondary vertex…
- Offline reconstruction:
  - Good quality vertices displaced from PV
  - Invariant mass of $D^{+(0)}, \Lambda$ within nominal ranges
  - Kinematic refit with mass & PV constrains
- Offline selection:
  - Multivariate analysis selection
    - Multi-layer perceptron (MLP) trained
    - Utilizing kinematics and vertex information of Ξ_b baryons and its decay product

Ξ_b mass fit

Ξ_b^0 channel



Ξ_b^- channel

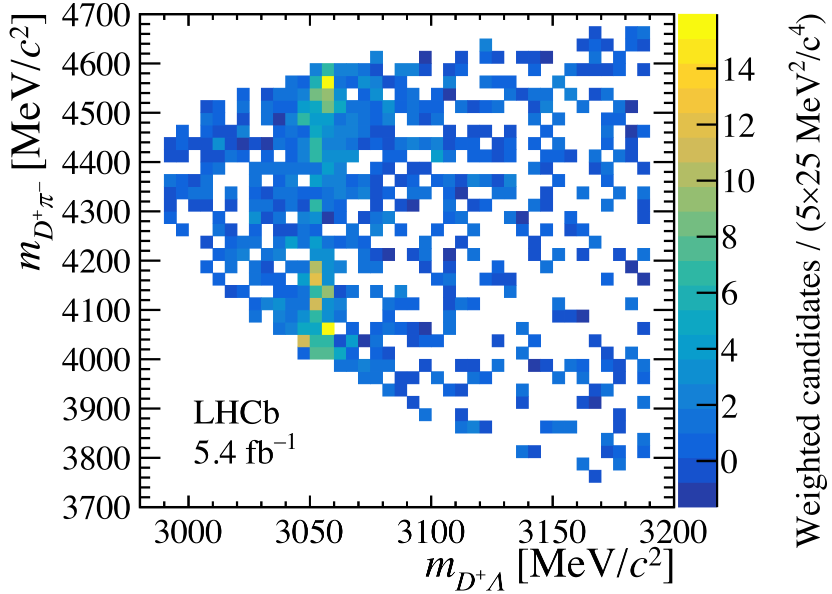


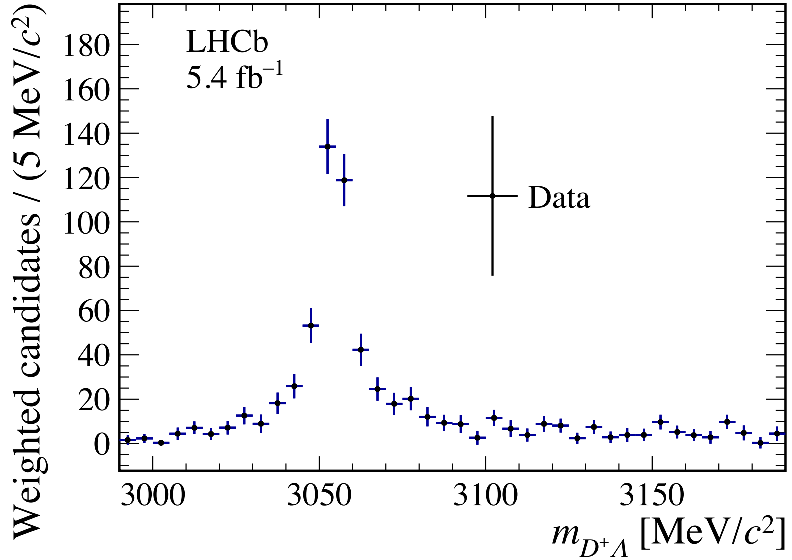
- Signal model: Gaussian + DSCB (parameters determined from MC)
- Partial reconstruction: shape from simulation
- Combinatorial background: exponential
- Signal then extracted with sPlot method 10.1016/j.nima.2005.08.106

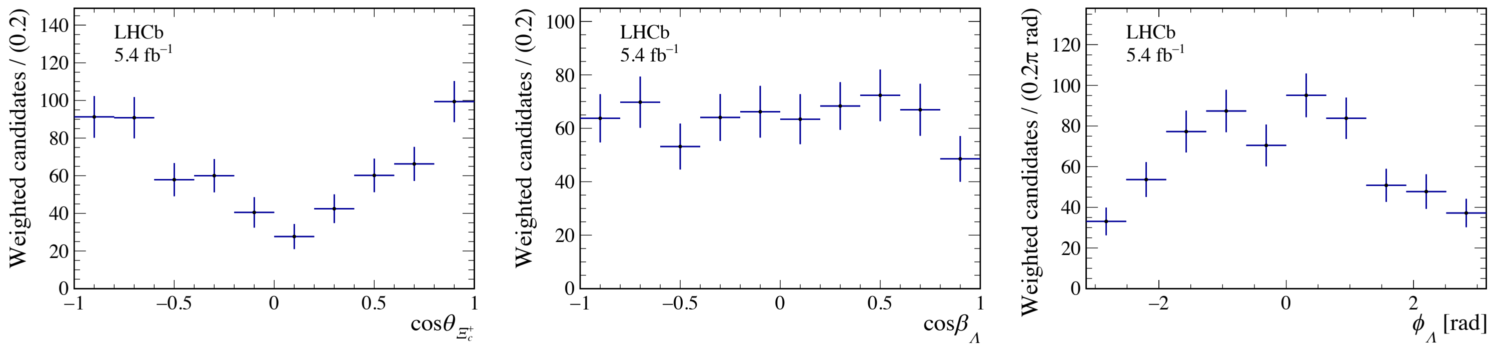
Channel	$\Xi_b^0 \to \Xi_c^{**+} \pi^-$	$\Xi_b^- \to \Xi_c^{**0} \pi^-$
Signal yields	637 ± 31	232 ± 19

Extracted spectrum

- Distributions weighted with sPlot method 10.1016/j.nima.2005.08.106
  - $\Xi_c(3055)^{+(0)}$ observed
  - Evidence of $\Xi_c(3080)^{+(0)}$
  - Non-resonance component
- Dalitz variable distributions extracted





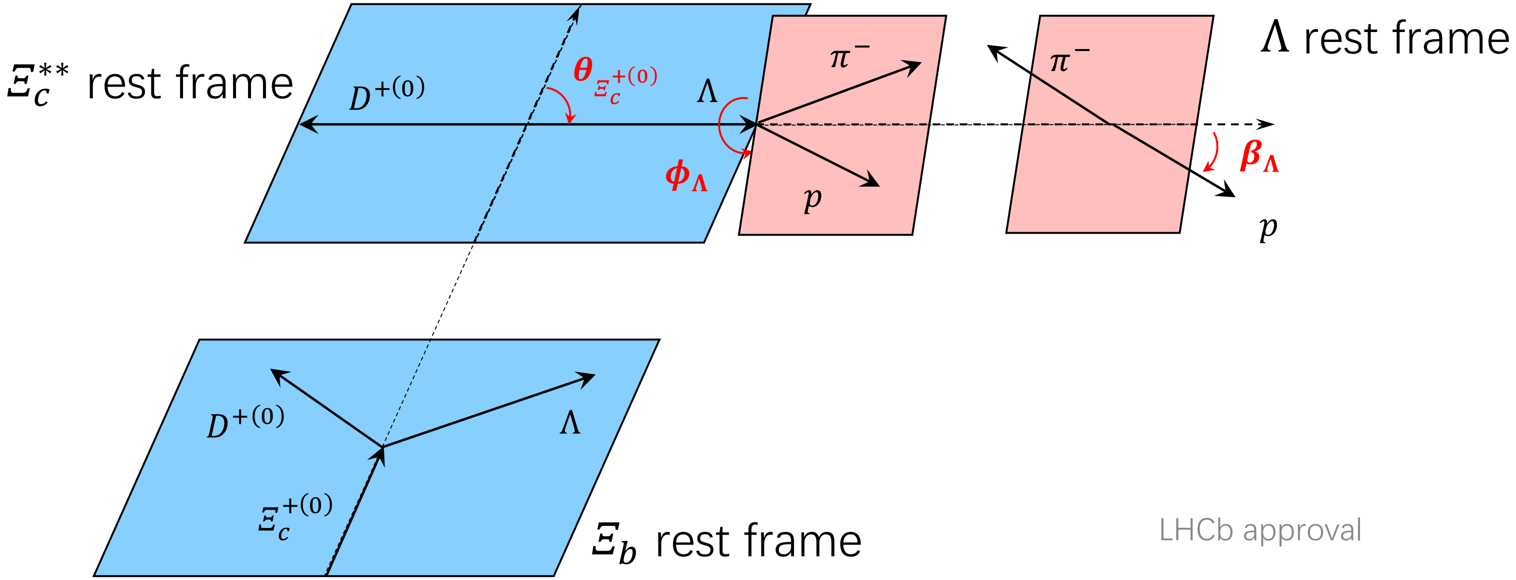


Helicity amplitude analysis

Helicity amplitude

- Helicity couplings in the $\Xi_b \to \Xi_c\pi,\ \Xi_c^{**} \to D\Lambda,\ \Lambda \to p\pi$ decay chain:

- $\Xi_b \to \Xi_c^{**}\pi^-$ $\quad$ $A^{\Xi_b\to\Xi_c\pi^-}_{\lambda_{\Xi_b},\lambda_{\Xi_c},\lambda_\pi} = H^{\Xi_b\to\Xi_c\pi^-}_{\lambda_{\Xi_c}}\delta_{\lambda_{\Xi_b},\lambda_{\Xi_c}}$ $\quad$ Floated for each resonance
- $\Xi_c^{**} \to D\Lambda$ $\quad$ $A^{\Xi_c\to D\Lambda}_{\lambda_{\Xi_c},\lambda_D,\lambda_\Lambda} = H^{\Xi_c\to D\Lambda}_{\lambda_\Lambda} d^{J_{\Xi_c}}_{\lambda_{\Xi_c},\lambda_\Lambda}(\theta)$ $\quad$ Strong decay, only phase term: $\eta^{P_{\Xi_c}}(-1)^{J_{\Xi_c}+1/2}$
- $\Lambda \to p\pi^-$ $\quad$ $A^{\Lambda\to p\pi^-}_{\lambda_\Lambda,\lambda_p,\lambda_\pi} = H^{\Lambda\to p\pi^-}_{\lambda_p} D^{j_\Lambda}_{\lambda_\Lambda,\lambda_p}(\phi,\beta,0)$ $\quad$ Fixed from input



$$\alpha_{\Xi_b\to\Xi_c^{**}\pi} \equiv \frac{\left|H^{\Xi_b}_{\lambda_{\Xi_c}=+\frac{1}{2}}\right|^2 - \left|H^{\Xi_b}_{\lambda_{\Xi_c}=-\frac{1}{2}}\right|^2}{\left|H^{\Xi_b}_{\lambda_{\Xi_c}=+\frac{1}{2}}\right|^2 + \left|H^{\Xi_b}_{\lambda_{\Xi_c}=-\frac{1}{2}}\right|^2}$$

LHCb approval

Amplitude model

- Coherent and incoherent sum:

$$|M|^2 = \sum_{\lambda_{\Xi_b},\lambda_p} \left| \sum_{\lambda_{\Xi_c},\lambda_\Lambda} A_{\Xi_c^{**}(3055)} + \sum_{\lambda_{\Xi_c},\lambda_\Lambda} A_{\Xi_c^{**}(3080)} + \sum_{\lambda_{\Xi_c},\lambda_\Lambda} A_{Non-resonance} \right|^2$$

- Probability Density Function:

$$\mathcal{P}(m_{D\Lambda}, \vec{\Omega}|\vec{\nu}) = \frac{1}{I(\vec{\nu})} \sum_{\lambda_{\Xi_b},\lambda_p} \left| \mathcal{M}(m_{D\Lambda}, \vec{\Omega}|\vec{\nu}) \right|^2 \times \Phi(m_{D\Lambda}, \vec{\Omega}) \epsilon(m_{D\Lambda}, \vec{\Omega}),$$

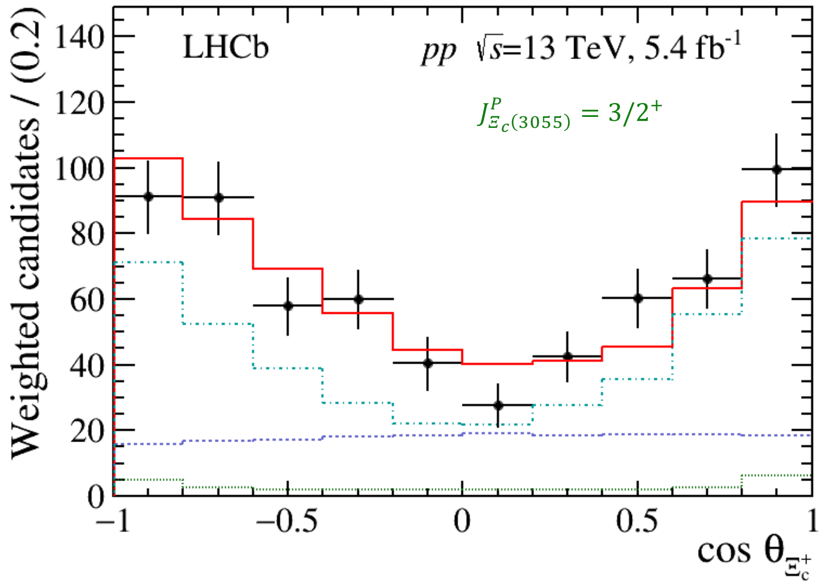
- Fit parameters $\vec{\nu}$:
  - $H^{\Xi_c}_{\lambda_{\Xi_c}=\pm 1/2}$: helicity couplings of $\Xi_c^{**}(3055)$, $\Xi_c^{**}(3080)$, non-resonances
  - m_0, Γ_0 of $\Xi_c^{**}(3055)$
  - $J^P_{\Xi_c^{**}(3055)}$: discrete parameter

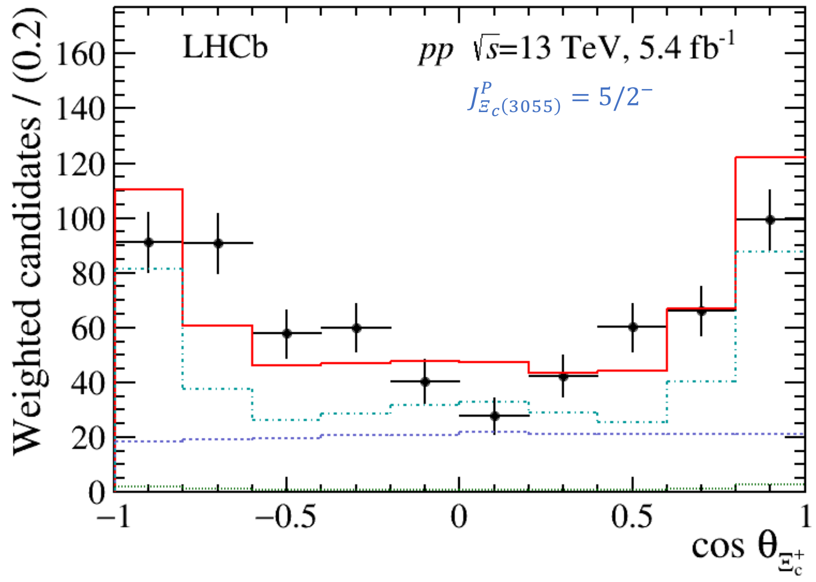
Hypotheses tests

- $J^P_{\Xi_c^{**}(3055)} = 3/2^+$ favored
  - among all tested hypotheses: $1/2^{\pm}, 3/2^{\pm}, 5/2^{\pm}, 7/2^{\pm}$
  - with rejection significance $n_\sigma \geq 6.5\sigma$ (from toy study)

	$J^P_{\Xi_c(3055)^+}$	$\alpha_{\Xi_b^0 \to \Xi_c(3055)^+\pi^-}$	n_σ
Favored	$\mathbf{3/2^+}$	$\mathbf{-0.92 \pm 0.10}$	-
	$1/2^-$	-0.10 ± 0.17	12.9σ
	$1/2^+$	$+0.31 \pm 0.13$	11.0σ
	$3/2^-$	$+0.18 \pm 0.14$	7.3σ
	$5/2^-$	-0.12 ± 0.14	6.5σ
	$5/2^+$	$+0.52 \pm 0.14$	9.8σ
	$7/2^-$	$+0.41 \pm 0.16$	10.7σ
	$7/2^+$	$+0.12 \pm 0.14$	10.9σ

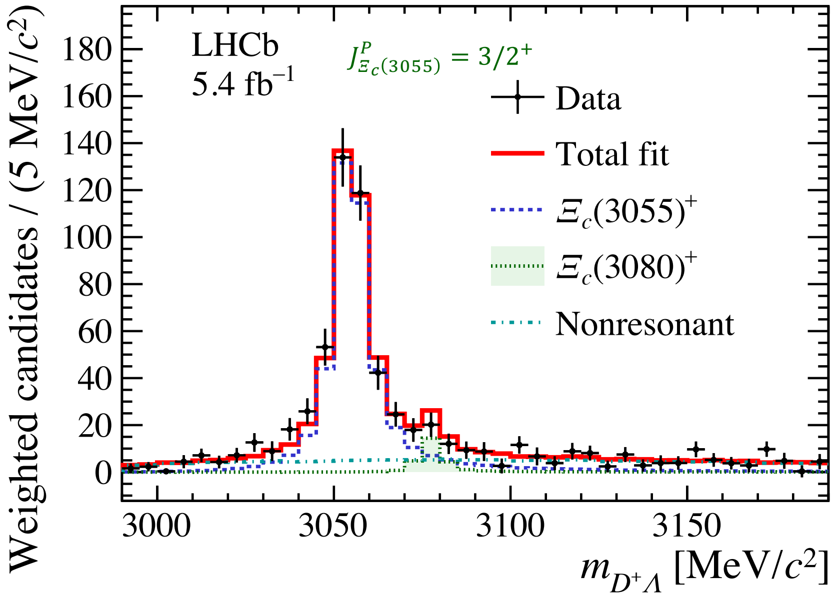
Projections to $\cos\theta$ for different hypothesized fits:

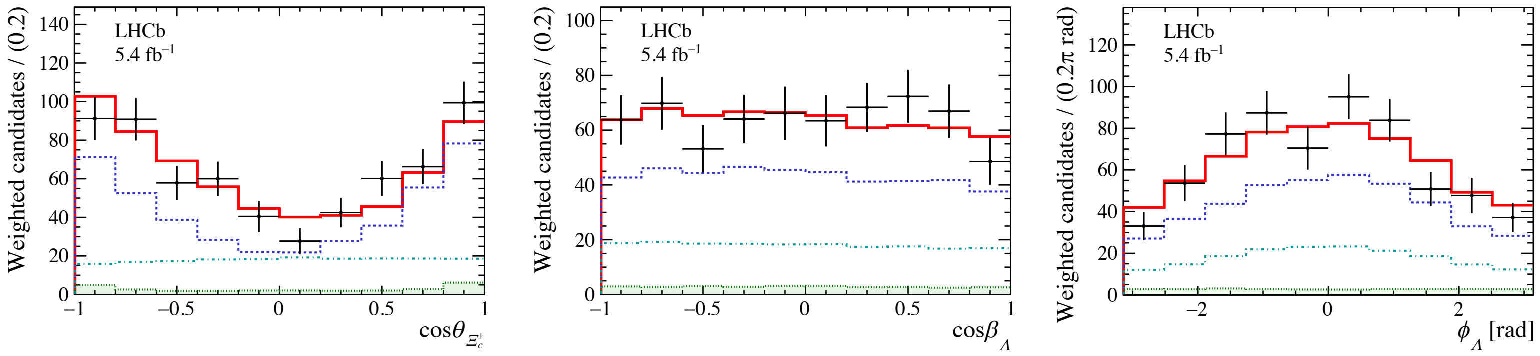




Run2, $\Xi_b^0 \to \Xi_c^{**+}\pi^-$ channel

Best fit projections: $J^P_{\Xi_c^{**}(3055)} = 3/2^+$





- $J^P_{\Xi_c^{**}(3055)} = 3/2^+, J^P_{\Xi_c^{**}(3080)} = 5/2^+, J^P_{NR} = 1/2^-$ (S-wave) as default

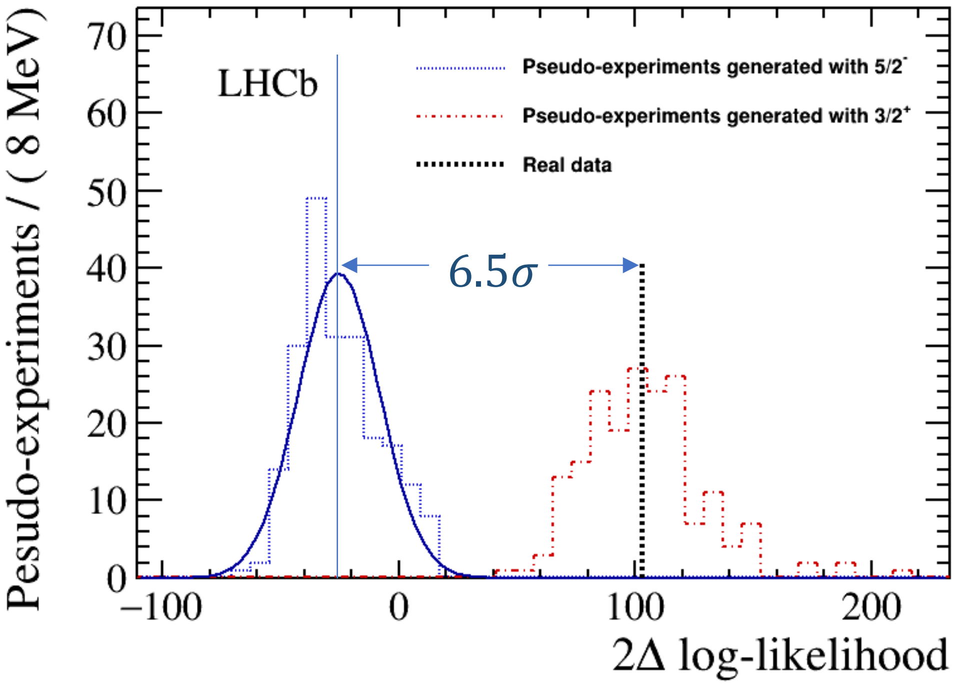
Table 1: Measured $\Xi_c^{**}(3055)$ properties

μ_0[MeV]	Γ_0[MeV]	$\alpha_{\Xi_b \to \Xi_c^{**}\pi}$
3054.52 ± 0.36	8.01 ± 0.76	-0.92 ± 0.10

PDG : $\mu_0 = 3055.9 \pm 0.4$ $\Gamma_0 = 7.8 \pm 1.9$

LHCb approval

Rejection significance



- Toys samples generated for alternative J^P hypotheses (J^P_{dis})
  - Parameters optimized
- Using test statistics:

$$t \equiv 2\ln\left[\mathcal{L}(J^P = 3/2^+)/\mathcal{L}(J^P_{\text{disfavor}})\right] = 2\Delta\log\mathcal{L}(3/2^+,\text{dis}),$$

- Significance rejecting J^P_{dis} is determined with:

$$n_\sigma(J_{\text{disfavor}}) = \frac{t_{\text{data}} - \mu(t_{J_{\text{disfavor}}})}{\sigma(t_{J_{\text{disfavor}}})},$$

$J^P_{\Xi_c(3055)^+}$	n_σ
$\mathbf{3/2^+}$	-
$1/2^-$	12.9σ
$1/2^+$	11.0σ
$3/2^-$	7.3σ
$5/2^-$	6.5σ
$5/2^+$	9.8σ
$7/2^-$	10.7σ
$7/2^+$	10.9σ

Systematics

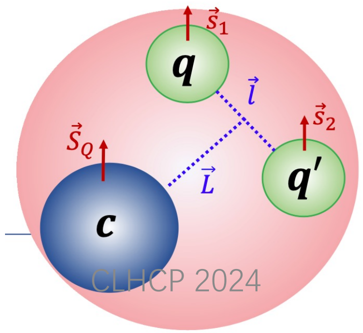
Table 3: Biases and systematic uncertainties for the $\Xi_b^0 \to \Xi_c(3055)^+\pi^-$ channel.

Source	σ_m [MeV/c^2]	σ_Γ [MeV/c^2]	σ_α	$\sigma_{R_\mathcal{B}}$
Amplitude fit bias	–	–	–	–
Hadron masses	±0.05	–	–	–
Momentum scale	±0.01	–	–	–
Resolution	±0.00	±0.07	±0.00	±0.000
Simulation sample	±0.15	±0.30	±0.02	±0.002
Trigger correction	±0.01	±0.03	±0.02	±0.000
Λ categories	±0.03	±0.04	±0.01	±0.002
Ξ_b^0 mass fit model	±0.03	±0.13	±0.01	±0.001
Angular momentum	±0.00	±0.00	±0.04	±0.002
Nonresonant model	±0.00	±0.00	±0.00	±0.000
$\Xi_c(3080)^+$ width	±0.01	±0.01	±0.00	±0.003
$\Xi_c(3080)^+$ mass	±0.00	±0.02	±0.00	±0.000
Clone tracks	±0.02	±0.03	±0.01	±0.003
Total	±0.17	±0.34	±0.05	±0.006

Summary

Theoretical interpretations of $\Xi_c(3055)$

References	Theoretical model	J^P of $\Xi_c(3055)$
Eur. Phys. J. A 37 (2008) 217–225	Faddeev method	$5/2^+$ (1D)
Phys. Rev. D 78 (2008) 056005	Regge phenomenology	$5/2^+$ (1D)
Phys. Rev. D 84 (2011) 014025	QCD-motivated relativistic quark model	$3/2^+$ (1D)
Phys. Rev. D 86 (2012) 034024	Chiral quark model	$3/2^+$ (1D)
Eur. Phys. J. A 82 (2015) 51	Relativistic flux tube model	$3/2^+$ (1D)
Phys. Rev. D 94 (2016) 114016	QCD sum rules within HQET	$3/2^+$ (1D)
Phys. Rev. D 96 (2017) 114003	3P0 model	$1/2^+(\bar{3}_F), 3/2^+(6_F)$ (2S)
Eur. Phys. J. C 79 (2019)167	Hadron molecular state	$1/2^-, 3/2^-$ (molecular)



Summarized in Rept.Prog.Phys. 80 (2017) no.7, 076201

Or see our paper draft

Decay parameter

$$\alpha_{\Xi_b\to\Xi_c^{**}\pi} \equiv \frac{\left|H^{\Xi_b}_{\lambda_{\Xi_b}=+}\right|^2 - \left|H^{\Xi_b}_{\lambda_{\Xi_b}=-}\right|^2}{\left|H^{\Xi_b}_{\lambda_{\Xi_b}=+}\right|^2 + \left|H^{\Xi_b}_{\lambda_{\Xi_b}=-}\right|^2}$$

- Our measurement: $\alpha_{\Xi_b\to\Xi_c(3055)^+\pi} = -0.92 \pm 0.10 \pm 0.05$
  - Consistent with pure parity violation
- Validating the factorization approximation
  - in $\bar{3}_F \to \bar{3}_F$ beauty to charm transitions
- Hint the structure of $\Xi_c(3055)^+$ (consistent with J^P)

$J^P_{\Xi_c(3055)^+}$	$\alpha_{\Xi_b^0\to\Xi_c(3055)^+\pi^-}$
$3/2^+$	**-0.92 ± 0.10**
$1/2^-$	-0.10 ± 0.17
$1/2^+$	$+0.31 \pm 0.13$
$3/2^-$	$+0.18 \pm 0.14$
$5/2^-$	-0.12 ± 0.14
$5/2^+$	$+0.52 \pm 0.14$
$7/2^-$	$+0.41 \pm 0.16$
$7/2^+$	$+0.12 \pm 0.14$

TABLE XIV: The predicted up-down asymmetries of $\mathcal{B}_b \to \mathcal{B}_c P$ decays. The asymmetries are given in unit of %. The asterisks in the first column indicate that the baryons in the final states are radial excited.

Type	Mode	$P=\pi^-$	$P=K^-$	$P=D^-$	$P=D_s^-$
(i)	$\alpha(\Lambda_b\to\Lambda_c P)$	$-99.99^{+2.24}_{-0.00}$	$-99.98^{+2.41}_{-0.00}$	$-98.47^{+8.91}_{-1.52}$	$-98.06^{+9.41}_{-1.87}$
(i)	$\alpha(\Xi_b^0\to\Xi_c^+ P)$	$-99.99^{+2.24}_{-0.00}$	$-99.97^{+2.41}_{-0.00}$	$-98.40^{+9.01}_{-1.59}$	$-97.96^{+9.52}_{-1.96}$
(i)	$\alpha(\Xi_b^-\to\Xi_c^0 P)$	$-99.99^{+2.24}_{-0.00}$	$-99.97^{+2.41}_{-0.00}$	$-98.39^{+9.01}_{-1.59}$	$-97.96^{+9.53}_{-1.96}$
(i)*	$\alpha[\Lambda_b\to\Lambda_c(2765)P]$	$-100.00^{+2.14}_{-0.00}$	$-99.98^{+2.39}_{-0.00}$	$-96.61^{+10.76}_{-3.32}$	$-95.54^{+11.49}_{-4.46}$
(ii)	$\alpha(\Omega_b\to\Omega_c P)$	$59.92^{+9.88}_{-9.22}$	$59.93^{+9.88}_{-9.22}$	$59.95^{+14.95}_{-13.54}$	$59.90^{+14.95}_{-13.53}$
(ii)*	$\alpha[\Omega_b\to\Omega_c(3090)P]$	$60.02^{+9.88}_{-9.23}$	$60.02^{+9.88}_{-9.23}$	$59.49^{+14.93}_{-13.47}$	$59.23^{+14.92}_{-13.43}$
(iii)	$\alpha[\Lambda_b\to\Lambda_c(2595)P]$	$-98.86^{+4.77}_{-1.04}$	$-98.84^{+4.79}_{-1.05}$	$-97.86^{+9.63}_{-2.03}$	$-97.57^{+9.93}_{-2.25}$
(iii)	$\alpha[\Xi_b^0\to\Xi_c^+(2790)P]$	$-99.13^{+4.44}_{-0.84}$	$-99.12^{+4.44}_{-0.84}$	$-98.58^{+8.77}_{-1.42}$	$-98.39^{+9.02}_{-1.59}$
(iii)	$\alpha[\Xi_b^-\to\Xi_c^0(2790)P]$	$-99.13^{+4.44}_{-0.84}$	$-99.12^{+4.44}_{-0.84}$	$-98.58^{+8.76}_{-1.42}$	$-98.39^{+9.02}_{-1.59}$
(iii)*	$\alpha[\Lambda_b\to\Lambda_c(2940)P]$	$-98.86^{+4.76}_{-1.03}$	$-98.84^{+4.78}_{-1.05}$	$-97.04^{+10.41}_{-2.81}$	$-96.36^{+10.94}_{-3.60}$

Unit : %

Ref:1811.09265

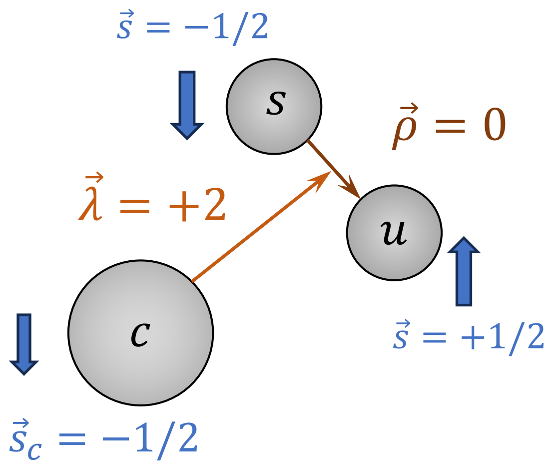
Conclusion

The $\Xi_b^0 \rightarrow D^+\Lambda^0\pi^-$ and $\Xi_b^- \rightarrow D^0\Lambda^0\pi^-$ decays are observed for the first time:

- $\Xi_c(3055)^{+(0)}$ mass and width are measured
- $\Xi_c(3055)^{+(0)}$ spin-parity measured to be $3/2^+$
  - With significance of $6.5(3.5)\sigma$
  - First determination with significance over 5σ of a charm-strange baryons
- Decay parameter in $\Xi_b^{0(-)} \rightarrow \Xi_c(3055)^{+(0)}\pi^-$ measured to be:

$$-0.92 \pm 0.10 \pm 0.05(-0.92 \pm 0.16 \pm 0.22)$$

  - First time in beauty to charm + pseudoscalar decays
- Consistent with first D-wave, λ-mode excitation of $\overline{3}_F$ category

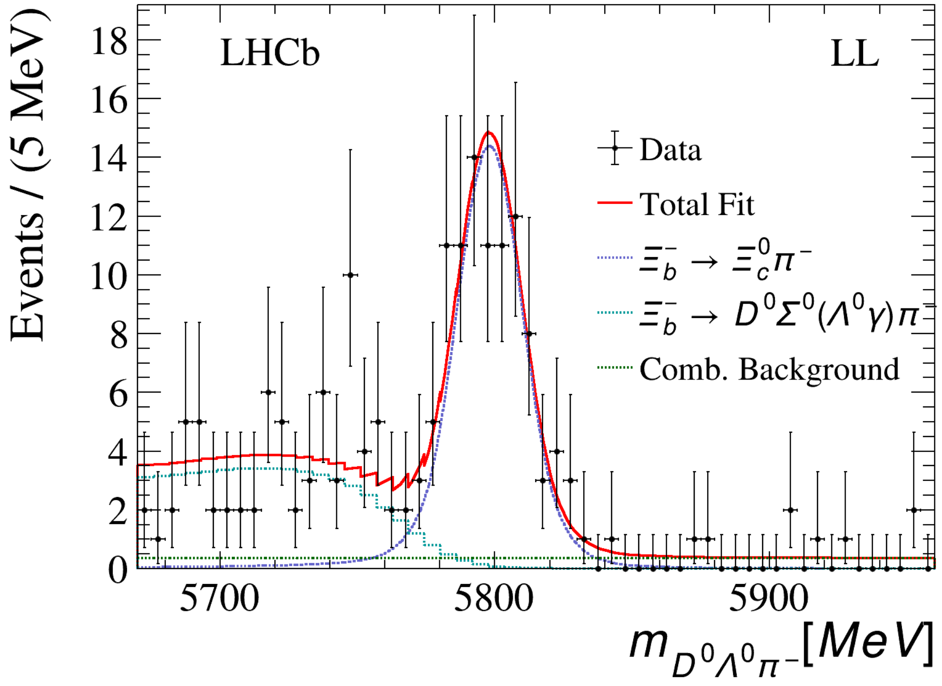


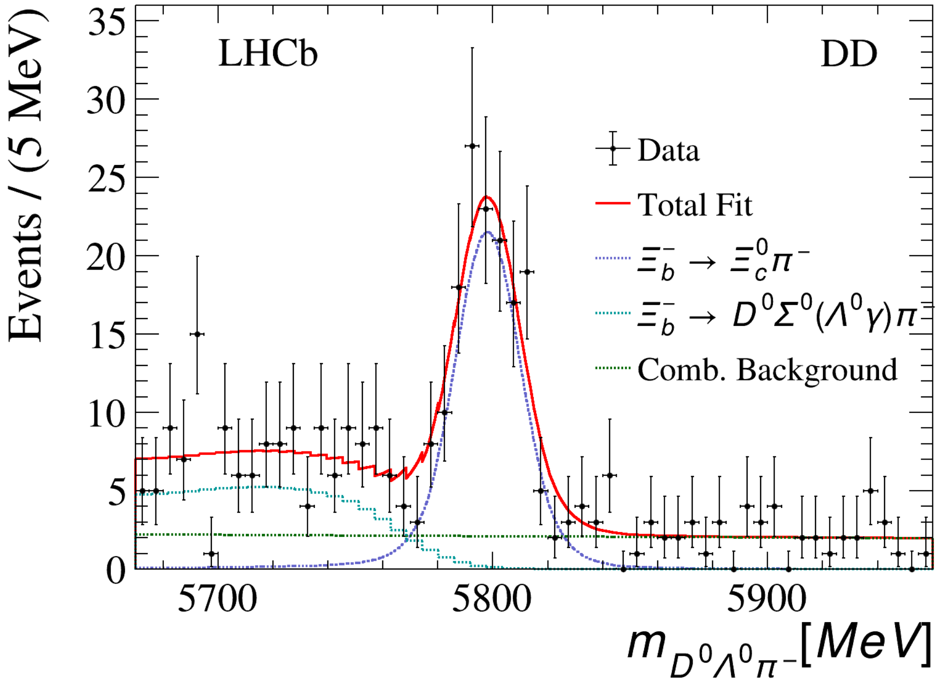
Paper can be found on arXiv: https://arxiv.org/abs/2409.05440

Thanks for your attention!

$\Xi_b^- \to \Xi_c^{**0}\pi^-$ channel results

Ξ_b mass fit



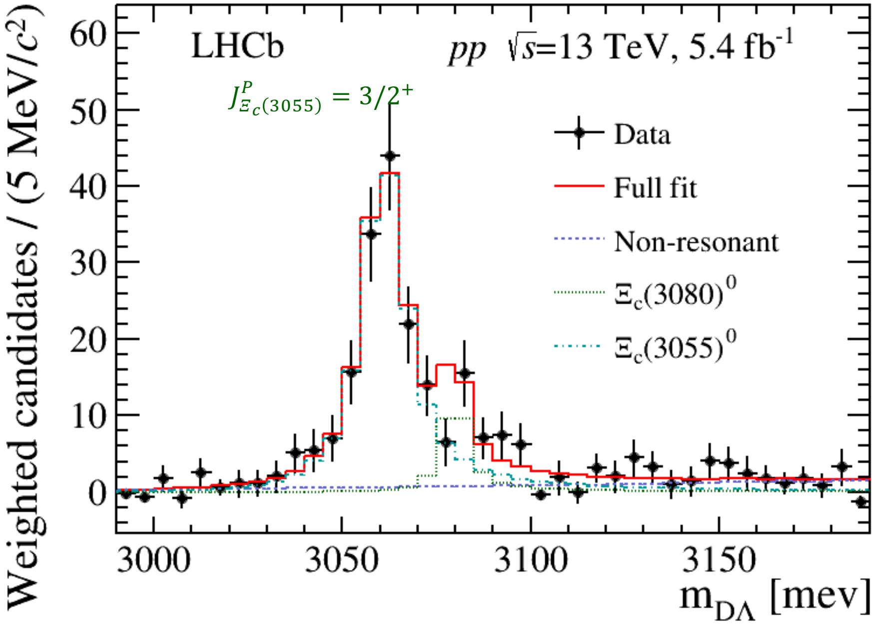


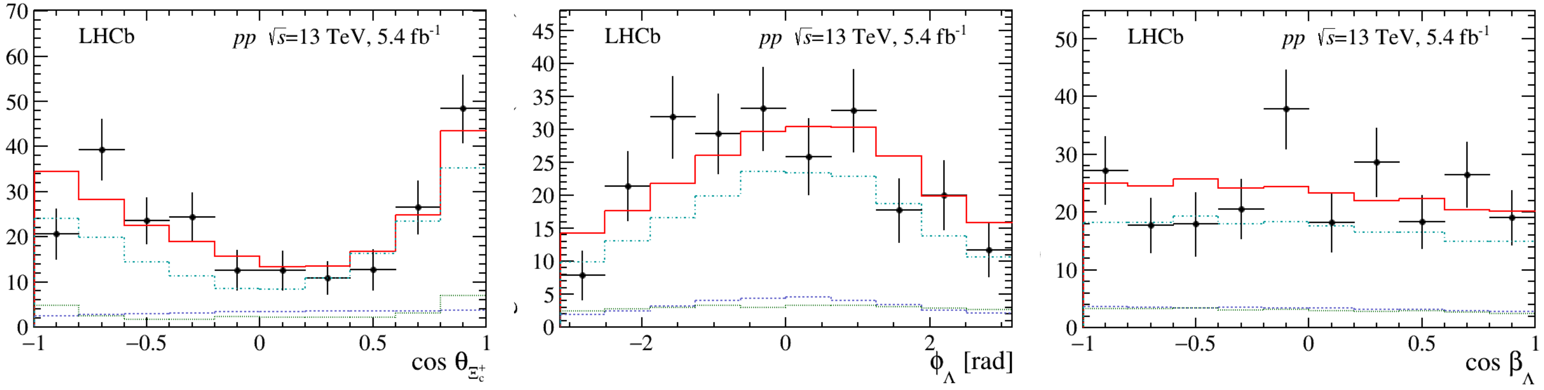
- Signal model: Gaussian + DSCB (parameters determined from MC)
- Partial reconstruction: shape from fast simulation
- Combinatorial background: exponential

➢ Simultaneously for LL & DD

Parameters	Fit Result(DD)	Fit Result(LL)
$\mu_{\Xi_b^-}$	5798.2±1.0 MeV	
$\sigma_{\Xi_b^-}$	12.5±1.0 MeV	
signal yield	139±16	93±10

Best fit projections: $J^P_{\Xi_c^{**}(3055)} = 3/2^+$





JP hypotheses	significance
3/2 +	-
1/2 −	5.5σ
1/2 +	6.5σ
3/2 −	3.5σ
5/2 −	4.8σ
5/2 +	4.8σ
7/2 −	6.0σ
7/2 +	6.2σ

Table 1: Measured $\Xi_c^{**}(3055)$ properties

μ_0[MeV]	Γ_0[MeV]	$\alpha_{\Xi_b \to \Xi_c^{**}\pi}$
3061.00 ± 0.80	12.4 ± 2.0	-0.92 ± 0.16

Systematics

Table 4: Biases and systematic uncertainties for the $\Xi_b^- \to \Xi_c(3055)^0\pi^-$ channel.

Source	σ_m[MeV/c^2]	σ_Γ[MeV/c^2]	σ_α	$\sigma_{R_\mathcal{B}}$
Amplitude fit bias	–	−0.46	–	–
Hadron masses	±0.05	–	–	–
Momentum scale	±0.03	–	–	–
Resolution	±0.00	±0.10	±0.00	±0.001
Simulation sample	±0.13	±0.38	±0.02	±0.006
Trigger correction	±0.01	±0.03	±0.00	±0.001
Λ categories	±0.04	±0.12	±0.05	±0.004
Ξ_b^- mass fit model	±0.00	±0.19	±0.02	±0.003
Angular momentum	±0.01	±0.15	±0.21	±0.014
Nonresonant model	±0.00	±0.03	±0.00	±0.001
$\Xi_c(3080)^0$ width	±0.08	±0.69	±0.01	±0.032
$\Xi_c(3080)^0$ mass	±0.03	±0.20	±0.01	±0.006
Clone tracks	±0.13	±0.04	±0.04	±0.008
Total	±0.23	±1.11	±0.22	±0.038

Backup

Status of $\Xi_c(3055)$

- Firstly observed by BABAR in the $\Xi_c^+(3055) \to \Sigma_c^{++}K^-$ channel [Ref: PhysRevD.77.012002]
- Later confirmed by Belle in the $\Sigma_c^{++}K^-$ mode [Ref: PhysRevD.89.052003] and $D^+\Lambda$ mode [Ref: PhysRevD.94.032002]
  - $\Xi_c^0(3055)$ is also found in the $D^0\Lambda$ mode [Ref: PhysRevD.94.032002]
- Various theoretical interpretations exist

Spectroscopy of $\Xi_c^{(*)}$

[Ref: 10.1088](#)

- ➢ Undetermined excitations
  - Various theoretical explanations
- ➢ **Pinning down the state:**
  - Mass, width, decay modes
  - **Spin-parity**
  - **Decay parameter**

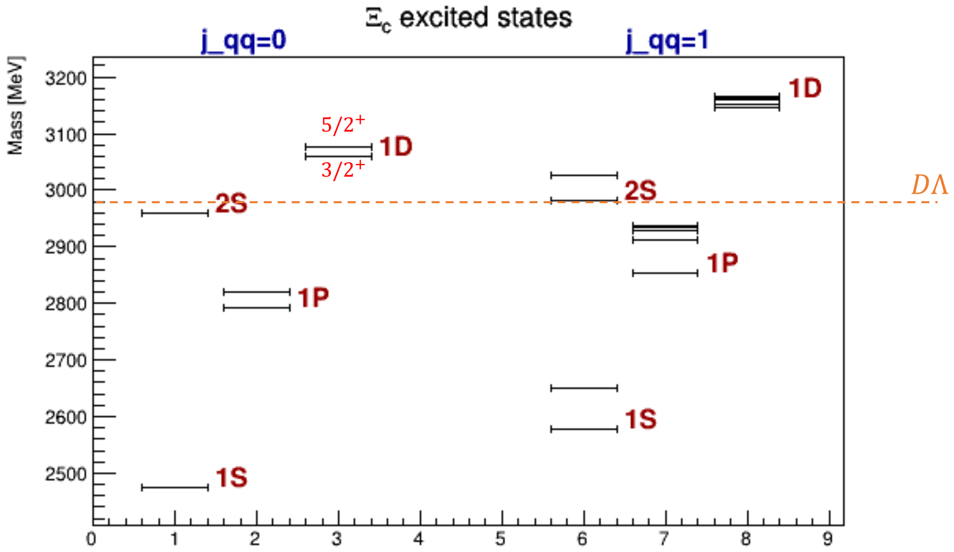


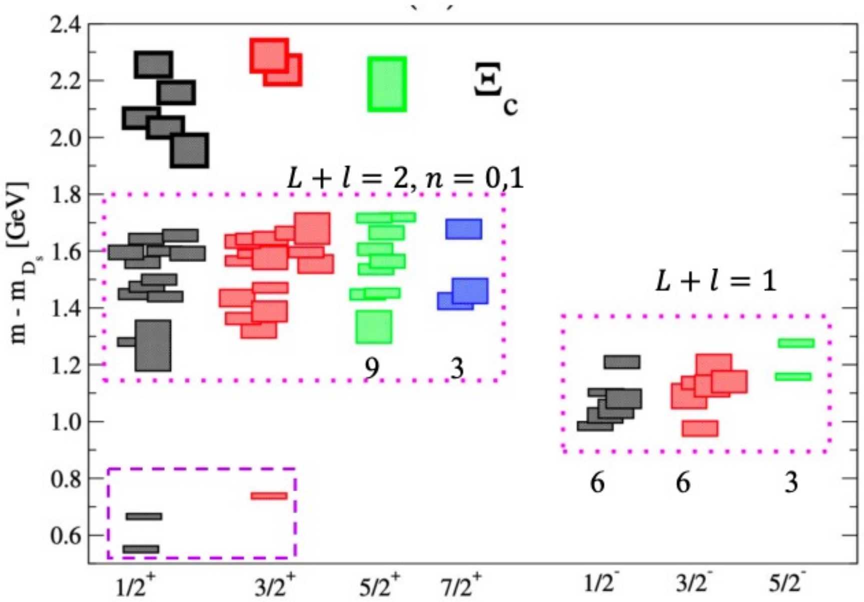
Figure : Theoretical predictions of the Ξ_c excited states (λ mode only)

Table: Experimental results of Ξ_c (until 2017)

State	Status	$I(J^P)$
Ξ_c^+	$***$	$\frac{1}{2}(\frac{1}{2}^+)$
Ξ_c^0	$***$	$\frac{1}{2}(\frac{1}{2}^+)$
$\Xi_c^{\prime +}$	$***$	$\frac{1}{2}(\frac{1}{2}^+)$
$\Xi_c^{\prime 0}$	$***$	$\frac{1}{2}(\frac{1}{2}^+)$
$\Xi_c(2645)^+$	$***$	$\frac{1}{2}(\frac{3}{2}^+)$
$\Xi_c(2645)^0$	$***$	$\frac{1}{2}(\frac{3}{2}^+)$
$\Xi_c(2790)^+$	$***$	$\frac{1}{2}(\frac{1}{2}^-)$
$\Xi_c(2790)^0$	$***$	$\frac{1}{2}(\frac{1}{2}^-)$
$\Xi_c(2815)^+$	$***$	$\frac{1}{2}(\frac{3}{2}^-)$
$\Xi_c(2815)^0$	$***$	$\frac{1}{2}(\frac{3}{2}^-)$
$\Xi_c(2930)^0$	$*$	$?(?^?)$
$\Xi_c(2980)^+$	$***$	$\frac{1}{2}(?^?)$
$\Xi_c(2980)^0$	$***$	$\frac{1}{2}(?^?)$
$\Xi_c(3055)^+$	$***$	$?(?^?)$
$\Xi_c(3080)^+$	$***$	$\frac{1}{2}(?^?)$
$\Xi_c(3080)^0$	$***$	$\frac{1}{2}(?^?)$
$\Xi_c(3123)^+$	$*$	$?(?^?)$

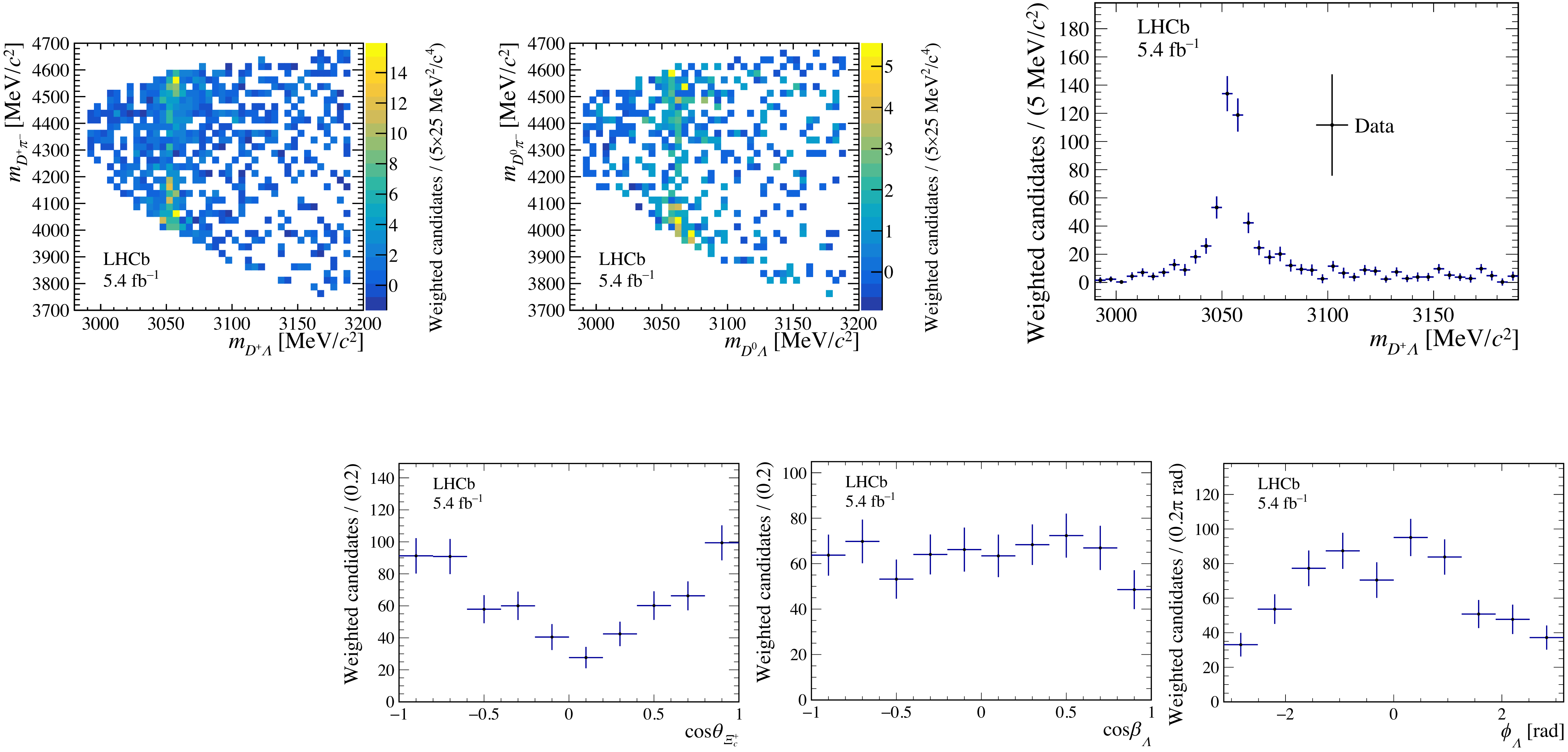
Status of $\Xi_c(3055)$

State	Status	$I(J^P)$	Mass (MeV)	Width (MeV)	Experiment	Decay modes
Λ_c^+	$****$	$0(\frac{1}{2}^+)$	2286.46 ± 0.14	$(200 \pm 6) \times 10^{-15}$ s	Fermilab [404]	weak
$\Lambda_c(2595)^+$	$***$	$0(\frac{1}{2}^-)$	2592.25 ± 0.28	2.59 ± 0.56	CLEO [405]	$\Lambda_c\pi\pi, \Sigma_c\pi$
$\Lambda_c(2625)^+$	$***$	$0(\frac{3}{2}^-)$	2628.11 ± 0.19	< 0.97	ARGUS [406]	$\Lambda_c\pi\pi, \Sigma_c\pi$
$\Lambda_c(2765)^+$	$*$	$?(?^?)$	2766.6 ± 2.4	50	CLEO [407]	$\Sigma_c\pi, \Lambda_c\pi\pi$
$\Lambda_c(2880)^+$	$***$	$0(\frac{5}{2}^+)$	2881.53 ± 0.35	5.8 ± 1.1	CLEO [407]	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p$
$\Lambda_c(2940)^+$	$***$	$0(?^?)$	$2939.3^{+1.4}_{-1.5}$	17^{+8}_{-6}	BaBar [408]	$\Sigma_c^{(*)}\pi, \Lambda_c\pi\pi, D^0p$
$\Sigma_c(2455)^{++}$	$****$	$1(\frac{1}{2}^+)$	2453.97 ± 0.14	$1.89^{+0.09}_{-0.18}$	BNL [409]	$\Lambda_c\pi$
$\Sigma_c(2455)^+$	$****$	$1(\frac{1}{2}^+)$	2452.9 ± 0.4	< 4.6	TST [410]	$\Lambda_c\pi$
$\Sigma_c(2455)^0$	$****$	$1(\frac{1}{2}^+)$	2453.75 ± 0.14	$1.83^{+0.11}_{-0.19}$	BNL [409]	$\Lambda_c\pi$
$\Sigma_c(2520)^{++}$	$***$	$1(\frac{3}{2}^+)$	$2518.41^{+0.21}_{-0.19}$	$14.78^{+0.30}_{-0.40}$	SKAT [411]	$\Lambda_c\pi$
$\Sigma_c(2520)^+$	$***$	$1(\frac{3}{2}^+)$	2517.5 ± 2.3	< 17	CLEO [412]	$\Lambda_c\pi$
$\Sigma_c(2520)^0$	$***$	$1(\frac{3}{2}^+)$	2518.48 ± 0.20	$15.3^{+0.4}_{-0.5}$	CLEO [413]	$\Lambda_c\pi$
$\Sigma_c(2800)^{++}$	$***$	$1(?^?)$	2801^{+4}_{-6}	75^{+22}_{-17}	Belle [414]	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^+$	$***$	$1(?^?)$	2792^{+14}_{-5}	62^{+60}_{-40}	Belle [414]	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
$\Sigma_c(2800)^0$	$***$	$1(?^?)$	2806^{+5}_{-7}	72^{+22}_{-15}	Belle [414]	$\Lambda_c\pi, \Sigma_c^{(*)}\pi, \Lambda_c\pi\pi$
Ξ_c^+	$***$	$\frac{1}{2}(\frac{1}{2}^+)$	$2467.93^{+0.28}_{-0.40}$	$(442 \pm 26) \times 10^{-15}$ s	CERN [415]	weak
Ξ_c^0	$***$	$\frac{1}{2}(\frac{1}{2}^+)$	$2470.85^{+0.28}_{-0.40}$	$(112^{+13}_{-10}) \times 10^{-15}$ s	CLEO [416]	weak
$\Xi_c'^+$	$***$	$\frac{1}{2}(\frac{1}{2}^+)$	2575.7 ± 3.0	–	CLEO [417]	$\Xi_c\gamma$
$\Xi_c'^0$	$***$	$\frac{1}{2}(\frac{1}{2}^+)$	2577.9 ± 2.9	–	CLEO [417]	$\Xi_c\gamma$
$\Xi_c(2645)^+$	$***$	$\frac{1}{2}(\frac{3}{2}^+)$	2645.9 ± 0.5	2.6 ± 0.5	CLEO [418]	$\Xi_c\pi$
$\Xi_c(2645)^0$	$***$	$\frac{1}{2}(\frac{3}{2}^+)$	2645.9 ± 0.5	< 5.5	CLEO [419]	$\Xi_c\pi$
$\Xi_c(2790)^+$	$***$	$\frac{1}{2}(\frac{1}{2}^-)$	2789.1 ± 3.2	< 15	CLEO [420]	$\Xi_c'\pi$
$\Xi_c(2790)^0$	$***$	$\frac{1}{2}(\frac{1}{2}^-)$	2791.9 ± 3.3	< 12	CLEO [420]	$\Xi_c'\pi$
$\Xi_c(2815)^+$	$***$	$\frac{1}{2}(\frac{3}{2}^-)$	2816.6 ± 0.9	< 3.5	CLEO [421]	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2815)^0$	$***$	$\frac{1}{2}(\frac{3}{2}^-)$	2819.6 ± 1.2	< 6.5	CLEO [421]	$\Xi_c^*\pi, \Xi_c\pi\pi, \Xi_c'\pi$
$\Xi_c(2930)^0$	$*$	$?(?^?)$	2931 ± 6	36 ± 13	BaBar [422]	$\Lambda_c\bar{K}$
$\Xi_c(2980)^+$	$***$	$\frac{1}{2}(?^?)$	2970.7 ± 2.2	17.9 ± 3.5	Belle [423]	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, \Xi_c\pi\pi$
$\Xi_c(2980)^0$	$***$	$\frac{1}{2}(?^?)$	2968.0 ± 2.6	20 ± 7	Belle [423]	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, \Xi_c\pi\pi$
$\Xi_c(3055)^+$	$***$	$?(?^?)$	3055.1 ± 1.7	11 ± 4	BaBar [424]	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3080)^+$	$***$	$\frac{1}{2}(?^?)$	3076.94 ± 0.28	4.3 ± 1.5	Belle [423]	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3080)^0$	$***$	$\frac{1}{2}(?^?)$	3079.9 ± 1.4	5.6 ± 2.2	Belle [423]	$\Sigma_c\bar{K}, \Lambda_c\bar{K}\pi, D\Lambda$
$\Xi_c(3123)^+$	$*$	$?(?^?)$	3122.9 ± 1.3	4.4 ± 3.8	BaBar [424]	$\Sigma_c^*\bar{K}, \Lambda_c\bar{K}\pi$
Ω_c^0	$***$	$0(\frac{1}{2}^+)$	2695.2 ± 1.7	$(69 \pm 12) \times 10^{-15}$ s	WA62 [425]	weak
$\Omega_c(2770)^0$	$***$	$0(\frac{3}{2}^+)$	2765.9 ± 2.0	–	Belle [426]	$\Omega_c\gamma$

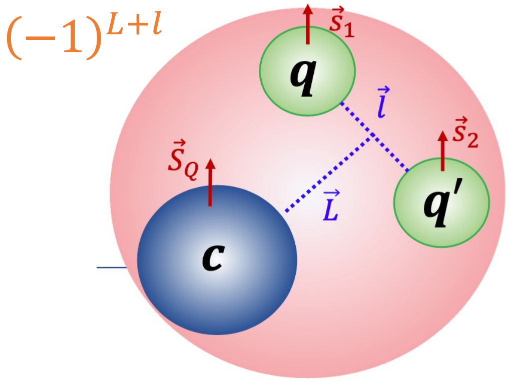


Run2, $\Xi_b^0 \to \Xi_c^{**+}\pi^-$ channel

Extracted sample



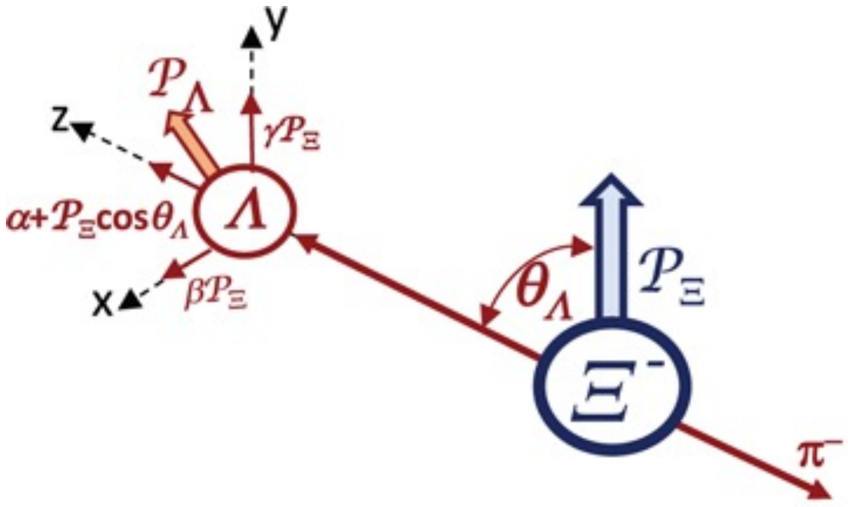
Decay Parameter



- **Decay parameter:**

$$\alpha = \frac{2|S||P|cos(\delta \pm \phi)}{|S|^2 + |P|^2}$$

- Relative transition possibility between up & down parity

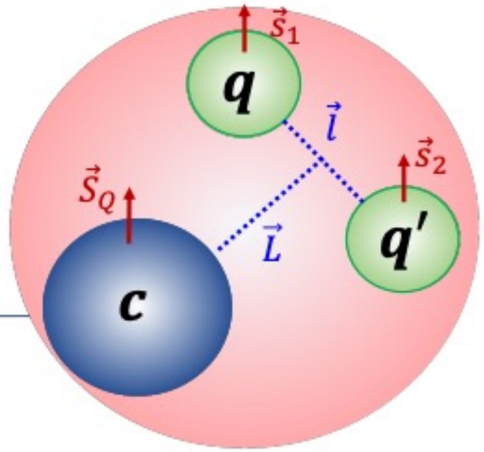


(a)

Orbital angular momenta

ρ modes: $l \neq 0$
λ modes: $L \neq 0$

Can happen at the same time



For only λ modes

1P Negative parity

$(S_l, \quad J)$

There are two P-wave states for $\Xi_c(0,1/2)$ $1/2^-$ and $3/2^-$
another two P-wave states for $\Xi_c'(1,1/2)$ $1/2^-$ and $3/2^-$,
and another three P-wave states for $\Xi_c^*(1,3/2)$ $1/2^-$, $3/2^-$ and $5/2^-$.

7 in total

2D positive parity

There are two D-wave states for $\Xi_c(0,1/2)$ $3/2^+$ and $5/2^+$,
another two D-wave states for $\Xi_c'(1,1/2)$ $3/2^+$ and $5/2^+$,
and another four D-wave states for $\Xi_c^*(1,3/2)$ $1/2^+$, $3/2^+$, $5/2^+$ and $7/2^+$.

8 in total

$S: 0$
$P: 1$
$D: 2$
$F: 3$

Likelihood construction

- sFit likelihood:

$$\log \mathcal{L}(\vec{\nu}) = \frac{\sum_{i \in data} w_i}{\sum_{i \in data} w_i^2} \sum_{i \in data} w_i \times \log \left[\mathcal{P}(m_{D\Lambda}^i, \vec{\Omega}^i | \vec{\nu}) \right],$$

where PDF is matrix element mode square:

$$\mathcal{P}(m_{D\Lambda}, \vec{\Omega}|\vec{\nu}) = \frac{1}{I(\vec{\nu})} \sum_{\lambda_{\Xi_b}, \lambda_p} \left| \mathcal{M}(m_{D\Lambda}, \vec{\Omega}|\vec{\nu}) \right|^2 \times \Phi(m_{D\Lambda}, \vec{\Omega}) \epsilon(m_{D\Lambda}, \vec{\Omega}),$$

efficiency encoded with MC integral:

$$I(\vec{\nu}) \equiv \int \sum_{\lambda_{\Xi_b}, \lambda_p} \left| \mathcal{M}(m_{D\Lambda}, \vec{\Omega}|^2 \vec{\nu}) \right| \Phi \epsilon(m_{D\Lambda}, \vec{\Omega}) dm_{D\Lambda} d\vec{\Omega}$$

Toy study

1. Construct model $f\left(m_{D\Lambda},\vec{\Omega};\vec{v}',J^P_{dis}\right)$ for disfavored $J^P_{dis}=1/2^{\pm},3/2^{-},5/2^{\pm},7/2^{\pm}$
   - Parameters $\vec{v}'$ are optimized from hypothesized fit
2. Sampling component from PDF=$f\left(m_{D\Lambda\pi};\vec{v}_{\Xi_b}\right)\times\epsilon_i(m_{D\Lambda\pi})\times f\left(m_{D\Lambda},\vec{\Omega};\vec{v}_{\Xi_c}',J^P_{dis}\right)\times\epsilon_i(m_{D\Lambda},\vec{\Omega})$
   - Variable space: $m_{D\Lambda\pi}$, $m_{D\Lambda}$, $\vec{\Omega}(\cos\theta,\cos\beta,\phi)$
   - Poisson randomized entries
   - Efficiency from MC (Legendre expansion)
3. sFit with disfavored model (J^P_{dis}), and favored model ($J^P_{fav}=3/2^{+}$)

LHCb approval

Components : partial reconstruction

- $\Xi_b \to D\Sigma^0(\to \Lambda^0\gamma)\pi^-$ samples generated with RapidSim , invariant mass of $D\Lambda^0\pi^-$ (Ξ_b with a γ lost) calculated
- Influence of preselection neglectable

Resolution

- Resolution of Ξ_c^{**} evaluated with MC samples :
  - Fit $(M_{True} - M_{Reconstruction})$ in each m(DΛ) bin with :

$$f \times Gaussian_1 + (1 - f) Gaussian_2$$

  - Choose constant resolution
  - Convolute to PDF

Trigger Efficiency

- MC errors in L0 trigger efficiency for :
  - TIS : $L0\_Photon|Electron|Muon|DiMuon\_TIS$

    Calibrated using TISTOS method

  - TOS : $L0\_Hadron\_TOS$

    Calibrated using E_T dependent data driven L0 efficiency for each trach

TIS Efficiency Calibration

- TIS efficiency as a function of Ξ_b transverse momentum:

$$\epsilon_{TIS} = \frac{N_{TIS\&TOS}(p_T)}{N_{TOS}(p_T)}$$

- Evaluated for data and MC in each p_T bins
- MC corrected according to differences

➢ Data efficiency is evaluated with $\Xi_b \to \Xi_c \pi^-$ decay, with larger statistics

TOS Efficiency Calibration

- L0 TOS efficiency is tabulated with respect to E_T of final tracks
- Fitting variables distribution in two MC samples are compared:
  - Cut with L0_Hadron_TOS decision
  - Weighted with L0 efficiency table
- The first sample is calibrated to the second sample
  - With GBReweighter method
  - Concerning fitting variables $m(D\Lambda)$, $\cos\theta$, $\cos\beta$ and α
- Events triggered with TIS/TOS are separately weighted

Selection Bias

- Effects of Pre-selection & MVA :
  - Evaluated with MC
  - Distribution of $\Delta M = M_{\text{reconstruction},\Xi_c} - M_{\text{true},\Xi_c}$ is fitted
  - μ evaluated for samples before and after selection
  - $\Delta\mu$ taken as bias, all within $\pm 0.001 MeV$

PDG Bias & Uncertainty

- *DecayTreeFitter* constrained D, Λ masses to known values in LHCb database

➢ Differences with PDG :

$$\Delta\mu = \sum_{D,\Lambda,\pi} (m_{PDG} - m_{LHCb})$$

➢ Uncertainties :

$$\sigma_{\mu_0} = \sqrt{\sum_{D,\Lambda,\pi} |\sigma_{PDG}|^2}$$

Particle	PDG [MeV]	LHCb [MeV]	Particle	PDG [MeV]	LHCb [MeV]
Λ	1115.683 ± 0.006	1115.683	D^+	1869.66 ± 0.05	1869.62
D^0	1864.84 ± 0.05	1864.86	π^-	139.57039 ± 0.00018	139.57018

Momentum Scale

- Track momenta have been calibrated (MS)
  - With precision 0.03%
- Evaluated by varying calibration by $\pm 0.03\%$
  - Event-by-event mass difference is fitted (with triple Gaussian)
  - Maximum taken as uncertainties

Resolution Uncertainty

- Vary within $\mu_0 \pm \Gamma$
- Maximum differences taken as uncertainties

MC Fluctuation

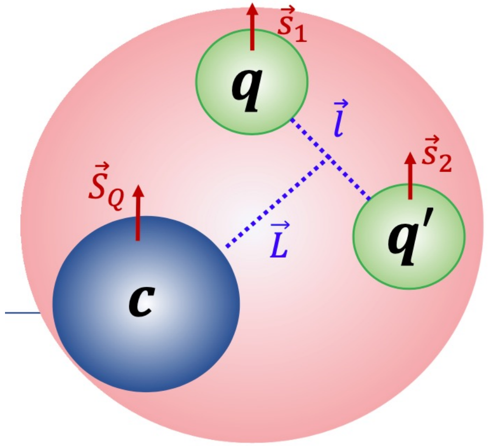
- MC integral over phase-space to implement signal efficiency
- Limited statistics in MC will introduce uncertainty to fit results
- Using bootstrap toy MC method

LL/DD Differences

- In default fit, LL&DD samples are merged
- LL and DD samples are fitted simultaneously

Contribution of $\Xi_c(3080)$

ρ modes: $l \neq 0$
λ modes: $L \neq 0$



- The $\Xi_c(3080)^{+/0}$ components are introduced to the amplitude model.
- $\Xi_c(3080)^{+/0}$ assumed to have $J = l_\lambda + s_c$, with $J = l_\lambda - s_c$ for $\Xi_c(3055)^{+/0}$
- With $l_\lambda = 2$, the J^P is fixed to $5/2^+$
- The uncertainties of $\Xi_c(3080)^{+/0}$ mass & width input are evaluated

Uncertainties of sWeights

- Uncertainty in Ξ_b mass fit can be introduced to amplitude fit
- Three variations of the $\mathrm{m}(\Xi_b)$ fit models are checked:
  - ➢ Extra component of $\Xi_b^- \to D^{*0}(\to D^0\gamma)\Lambda^0\pi^-$ partial reconstruction
  - ➢ Signal model :

$$Gauss + DSCB \to Gauss_1 + Gauss_2$$

  - ➢ Background model :

Exponential → 2nd order Chebychev polynomial

LS couplings

- Possible orbital angular momentums in $\Xi_b \to \Xi_c \pi$ weak decay.
- Only lower state considered in default model
- Alternative $l - s$ couplings are considered, with l expanded:

$$H^{A\to B+C}_{\lambda_B,\lambda_C} q^{l_{\min}} B_{l_{\min}}(q,q_0,d) \to \sum_{ls} g_{ls}\sqrt{\frac{2l+1}{2J_A+1}} \langle l0; s\delta | J_A\delta\rangle \langle J_B\lambda_B; J_C - \lambda_C | s\delta\rangle q^l B_l(q,q_0,d)$$

$$= \sum_{l=\frac{1}{2}+J_{\Xi_c}, J_{\Xi_c}-\frac{1}{2}} g_{l,s=J_{\Xi_c}} \sqrt{\frac{2l+1}{2}} \left\langle l0; J_{\Xi_c}\lambda_{\Xi_c} | \frac{1}{2}\lambda_{\Xi_c} \right\rangle q^l B_l(q,q_0,d)$$