

Heavy Flavor Baryons at LHCb

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on behalf of the LHCb collaboration

Heidelberg University

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The LHC as a Heavy Baryon Factory

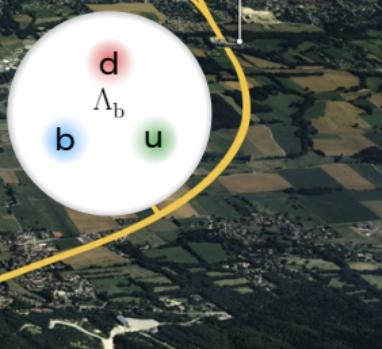
Proton-Proton Collisions at $\sqrt{s} = 13 \text{ TeV}$
 $\sim 20\,000 b\bar{b}$ -pairs per second

High B-baryon production fraction

— Mesons —

$$\begin{array}{c} B^+ \\ (u\bar{b}) \end{array} + \begin{array}{c} B^0 \\ (d\bar{b}) \end{array} : \begin{array}{c} B_s^0 \\ (s\bar{b}) \end{array} : \begin{array}{c} \Lambda_b \\ (u\bar{d}\bar{b}) \end{array} \quad 4 : 1 : 2$$

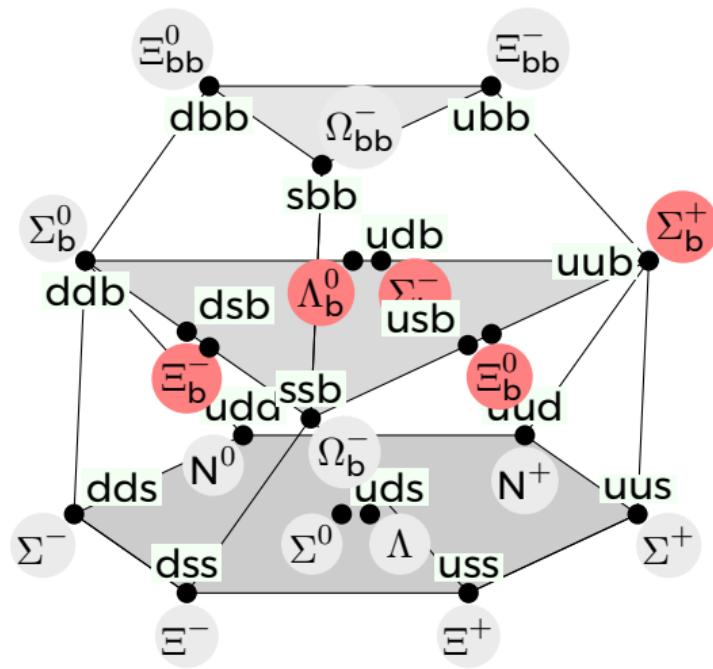
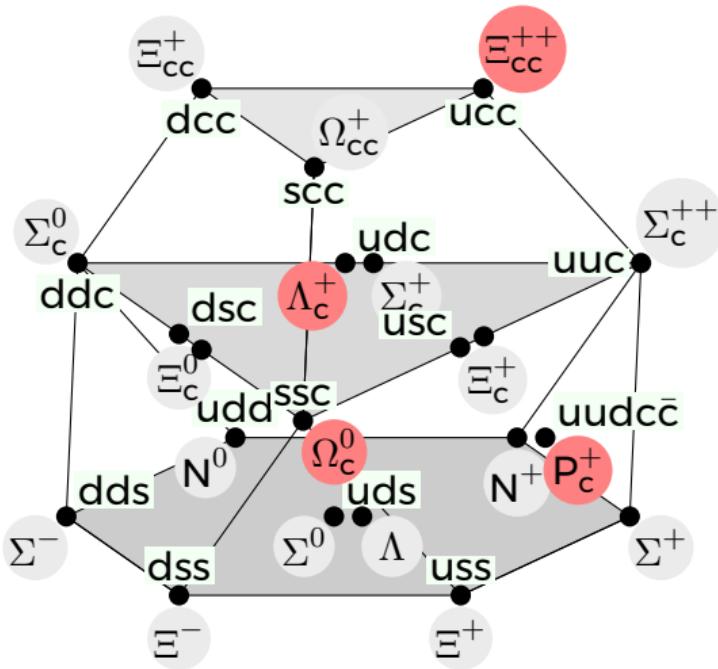
Unique dataset



LHC 27 km



$J = 1/2$ Baryon Multiplets





Outline

1 Beauty Baryons

2 Charmed Baryons

3 Baryons with Hidden Charm



Beauty Baryons

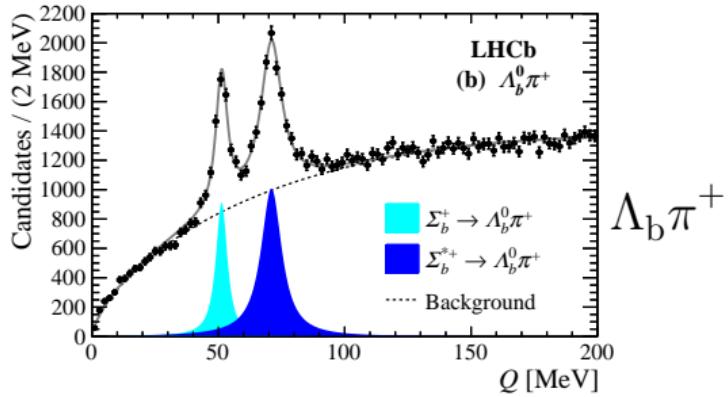
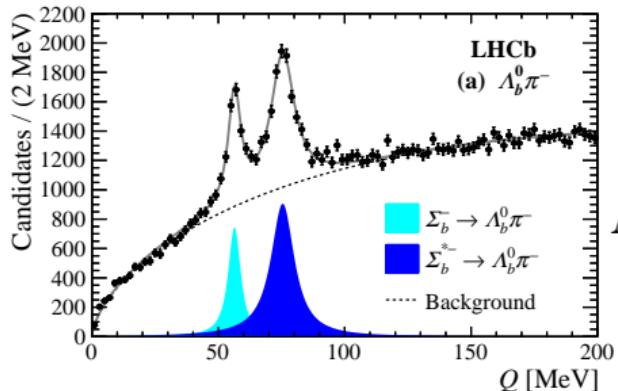
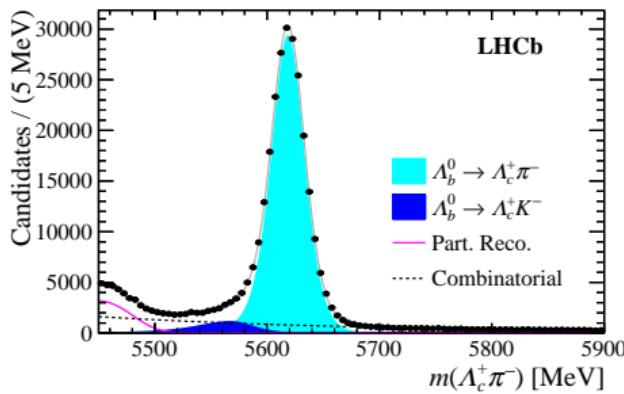
$$\Lambda_b^0 = udb, \Xi_b^0 = usb, \Xi_b^- = dsb, \Omega_b^- = ssb$$

Λ_b^0	1/2 ⁺	***
$\Lambda_b(5912)^0$	1/2 ⁻	***
$\Lambda_b(5920)^0$	3/2 ⁻	***
Σ_b	1/2 ⁺	***
Σ_b^*	3/2 ⁺	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ_b^0, Ξ_b^-	1/2 ⁺	***
$\Xi_b'(5935)^-$	1/2 ⁺	***
$\Xi_b(5945)^0$	3/2 ⁺	***
$\Xi_b(5955)^-$	3/2 ⁺	***
$\Xi_b(6227)$		***
Ω_b^-	1/2 ⁺	***



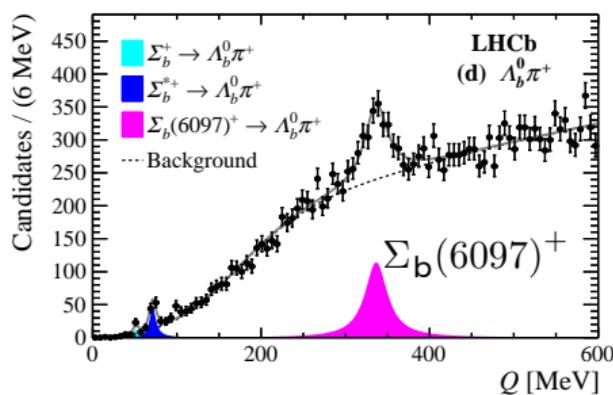
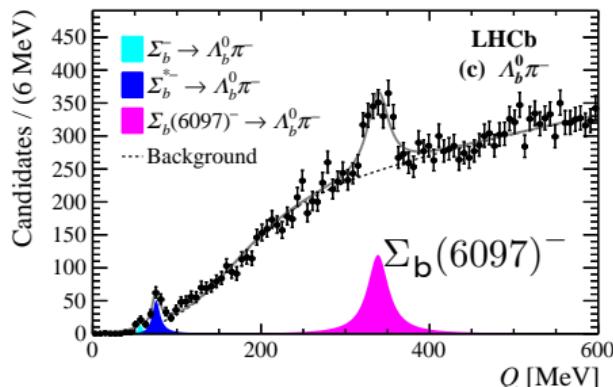
Σ_b and Σ_b^* at LHCb

- $\Lambda_b^0 \pi^\pm$ spectrum
- with $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ (displaced vertex)
- with $\Lambda_c^+ \rightarrow p K \pi$
- combined with pions from PV
- $234\,270 \pm 900$ Λ_b candidates in 3 fb^{-1}





A new Σ_b excitation



[PRL122(2019)012001]

Quantity Value [MeV]

$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$

$\Sigma_b^{(*)}$ masses and widths
in agreement with CDF

$m(\Sigma_b^{*-}) - m(\Sigma_b^-)$	$19.09 \pm 0.22 \pm 0.02$
$m(\Sigma_b^{*+}) - m(\Sigma_b^+)$	$19.73 \pm 0.18 \pm 0.01$
$\Delta(\Sigma_b(6097)^{\pm})$	$-2.2 \pm 2.4 \pm 0.3$
$\Delta(\Sigma_b^{\pm})$	$-5.09 \pm 0.18 \pm 0.01$
$\Delta(\Sigma_b^{*\pm})$	$-4.45 \pm 0.22 \pm 0.01$

- 5 $\Sigma_b(1P)$ states expected in heavy-quark limit
e. g. [Nucl. Phys. A965(2017)57]
- $\Sigma_b(6097)$ might be a superposition of several resonances



A doublet of strangely beautiful baryons: Ξ_b^-

Groundstate parameters (PDG)

State	M [MeV/c ²]	Mean life [10 ⁻¹² s]
Ξ_b^-	5797.0 ± 0.9	1.572 ± 0.040
Ξ_b^0	5791.9 ± 0.5	1.477 ± 0.030

New mass measurement from LHCb:

$$m(\Xi_b^-) = 5796.70 \pm 0.39 \pm 0.15 \pm 0.17 \text{ MeV}/c^2$$

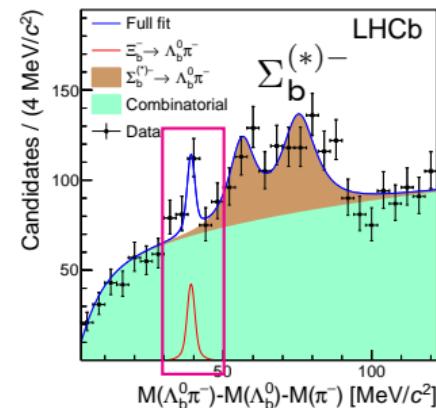
[PRD99(2019)052006]

in agreement with previous results

- Lifetimes benchmark for HQET
- Good agreement with HQE prediction

[Int.J.Mod.Phys.A30(2015)1543005]

Evidence for a strangeness changing decay $\Xi_b^- \rightarrow \Lambda_b \pi^-$ [PRL115(2015)241801]



$$\mathcal{B}(\Xi_b^- \rightarrow \Lambda_b^0 \pi^-) = 0.2 \cdots 0.6\%$$

in agreement with [PLB750(2015)653]

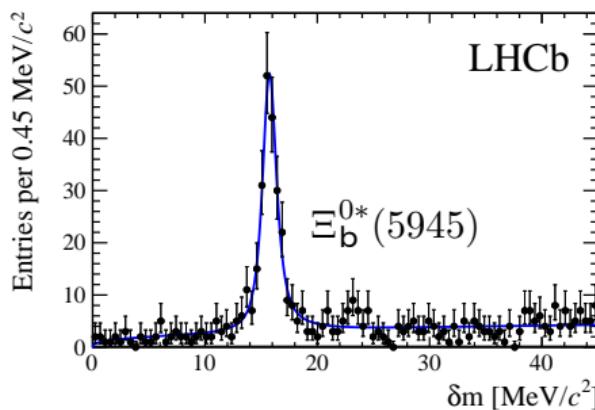


Ξ_b excitation spectrum overview

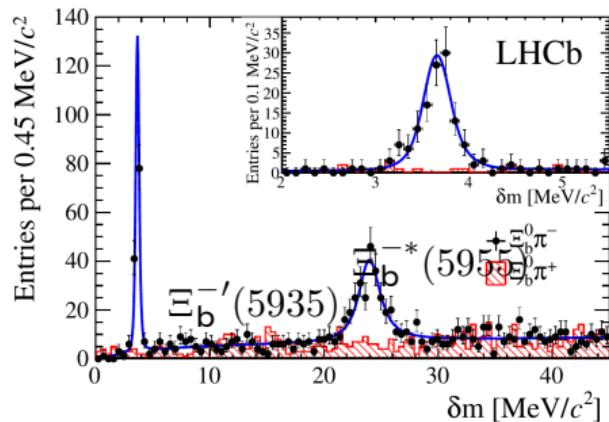
- 4 excited states known
- Isospin partner of the $1/2^+$ excitation missing
- heaviest Baryon observed so far

J^P	$I_3 = -\frac{1}{2}$	$I_3 = +\frac{1}{2}$
$\frac{1}{2}^+$	Ξ_b^- (5935)	missing
$\frac{3}{2}^+$	Ξ_b^- (5955)	Ξ_b^- (5945)
?	Ξ_b^- (6227)	

[JHEP05(2016)161]



[PRL114(2015)062004]

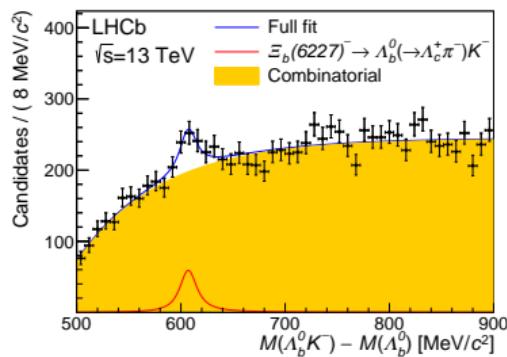




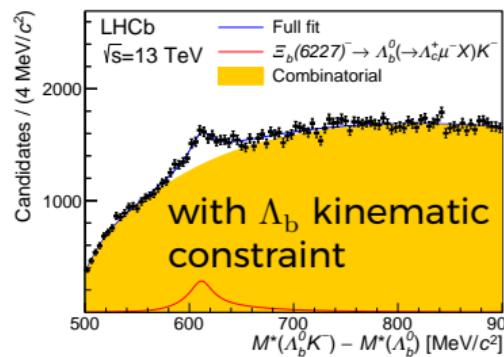
The heaviest Baryon

[PRL121(2018)072002]

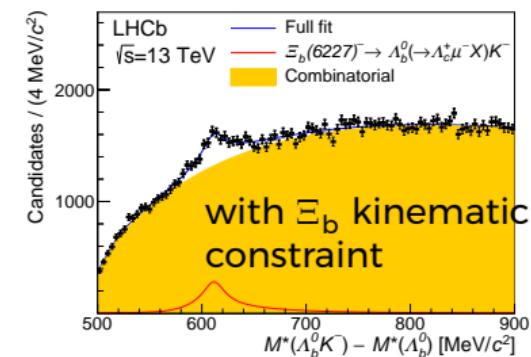
Exclusive $\Lambda_b K$
with $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$



Semileptonic $\Lambda_b K$
with $\Lambda_b \rightarrow \Lambda_c^+ \mu^- X$



Semileptonic $\Xi_b \pi$
with $\Xi_b \rightarrow \Xi_c \mu^- X$



- Mass: $m(\Xi_b(6227)^-) = 6226.9 \pm 2.0 \pm 0.3 \pm 0.2 \text{ MeV}/c^2$
- Width: $\Gamma(\Xi_b(6227)^-) = 18.1 \pm 5.4 \pm 1.8 \text{ MeV}/c^2$

The most massive
baryon observed so
far!



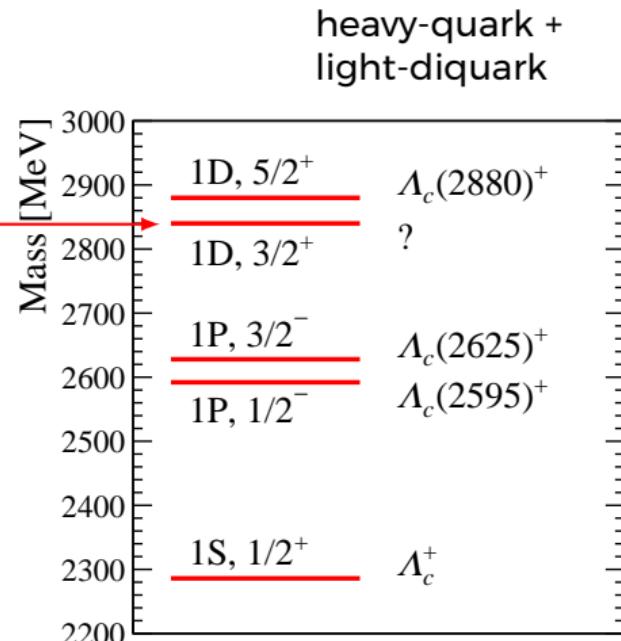
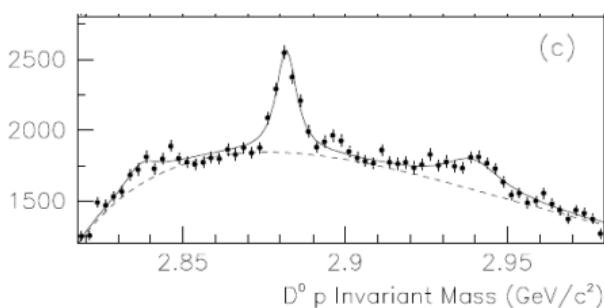
Charmed Baryons



The Λ_c^+ excitation spectrum

Well studied heavy-light-light system

- Orbitally excited states
- D-wave doublet predicted
more states in other models
- Missing state? —
- Indication by BaBar for structure in
 $D^0 p$ at 2.84 GeV
[PRL98(2007)012001]

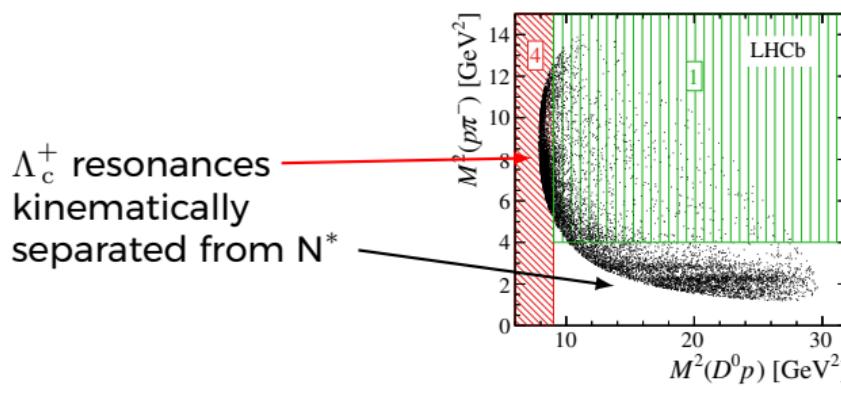
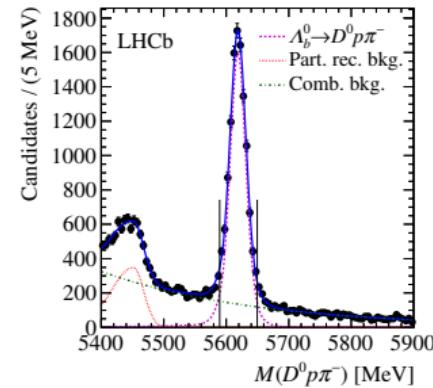


Predictions from [EPJ A51(2015)82]

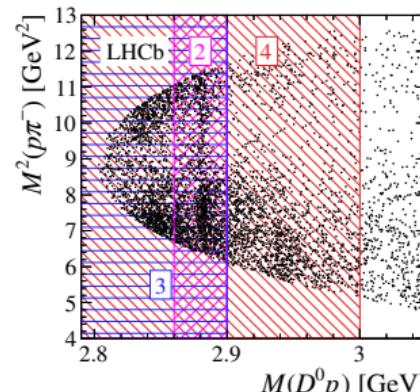
Amplitude analysis of $\Lambda_b \rightarrow D^0 p \pi^-$ at LHCb

[JHEP05(2017)030]

- Data set 3 fb^{-1} (Run I)
 $\sim 11\,000 \Lambda_b$ decays
- 5D amplitude analysis in helicity formalism
- Investigating $D^0 p$ resonances



Λ_c^+ resonances
kinematically
separated from N^*





The missing $\Lambda_c^* 1D$ state

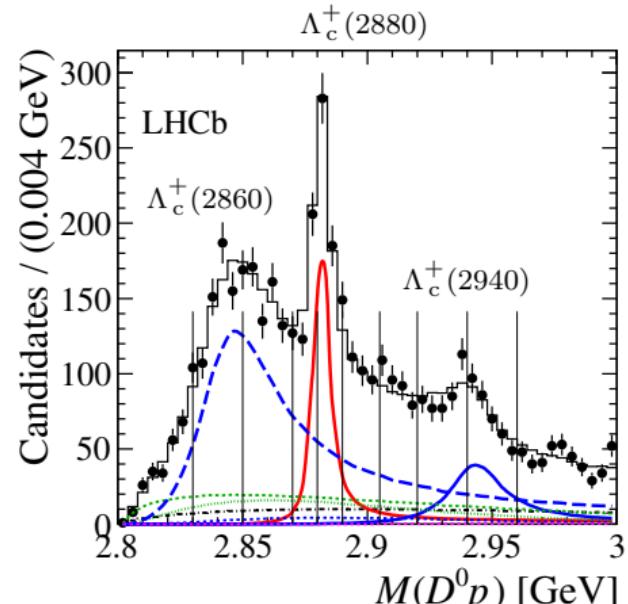
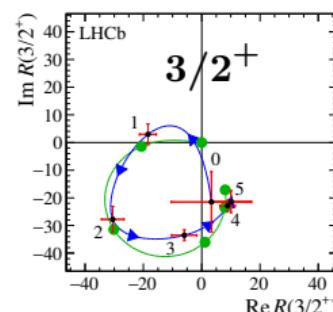
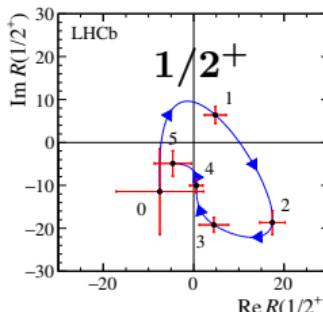
[JHEP05(2017)030]

■ Three Λ_c^+ resonances

State	M[MeV]	Γ [MeV]	J^P
$\Lambda_c^+(2860)$	2856	67	$3/2^+$
$\Lambda_c^+(2880)$	2881	5.4	$5/2^+$
$\Lambda_c^+(2940)$	2945	28	$3/2^-$ fav.

■ First constraint on $\Lambda_c^+(2940)$ spin

■ $\Lambda_c^+(2880), \Lambda_c^+(2940)$ in agreement with previous measurements



Only $3/2^+$ gives physical phase motion

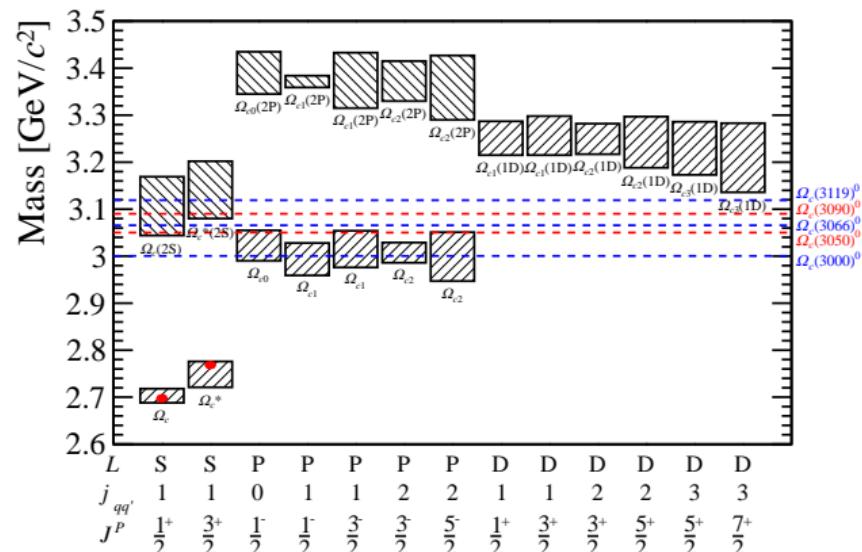


Strangely charming baryons: The Ω_c

[PRL118(2017)182001]

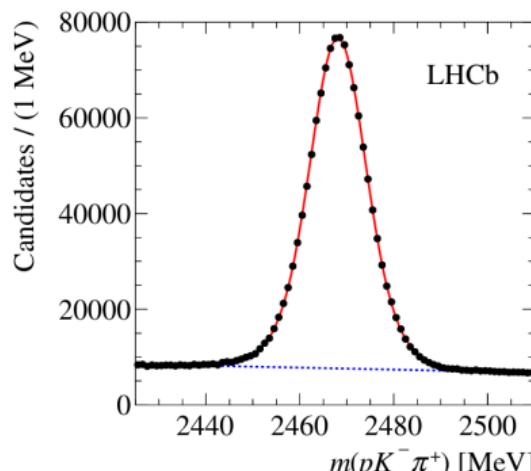
- The $|css\rangle$ system is a proving ground for HQET
- Popular model: heavy quark + light diquark
- Two S-wave ground states Ω_c^0 and $\Omega_c^0(2770)$ observed
- 5 P-wave states predicted

Summary of theoretical predictions



Five new Ω_c states in the decay $\Xi_c^+ K^- \pi^+$

[PRL118(2017)182001]

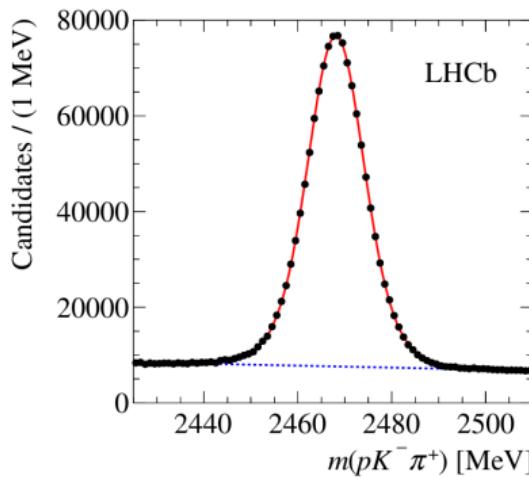
Reconstruct $\Xi_c \rightarrow p K^- \pi^+$ 

- Ξ_c detached from primary vertex
- PID of daughter tracks
- pointing to primary vertex



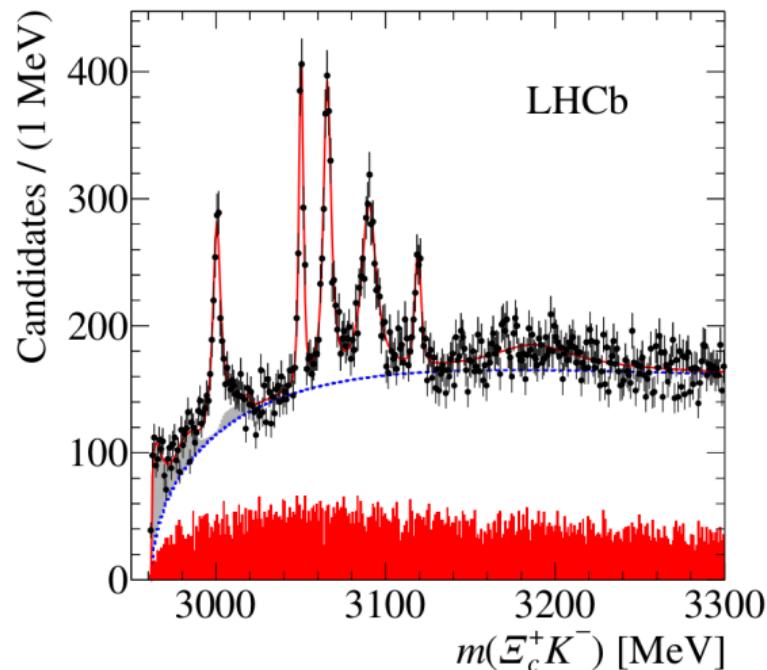
Five new Ω_c states in the decay $\Xi_c^+ K^-$

[PRL118(2017)182001]

Reconstruct $\Xi_c \rightarrow p K^- \pi^+$ 

- Ξ_c detached from primary vertex
- PID of daughter tracks
- pointing to primary vertex

Adding another kaon:

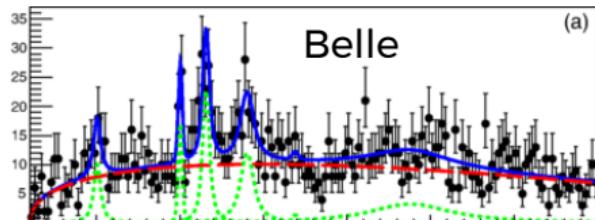


Five new Ω_c states in $\Omega_c \rightarrow \Xi_c^+ K^-$

[PRL]118(2017)182001

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2 \text{ MeV}, 95\% \text{ CL}$		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6 \text{ MeV}, 95\% \text{ CL}$		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	

- Are these the 5 P-wave states? [PRD95(2017)114012]
- Why two very narrow states? [PRD96(2017)014009]
- **Next steps: quantum numbers and multiplet**
- **4 states confirmed by Belle [PRD97(2018)051102]**





Ω_c lifetime

[PRL121(2018)092003]

■ HQE: lifetime hierarchy

$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^0} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$$

■ $\tau_{\Omega_c^0}$ considered smallest due to constructive interference between s-quark in $c \rightarrow s$ transition and spectator s

■ HQE allows inverted hierarchy depending on treatment of higher orders [hep-ph/9311331]

■ $\tau_c = 69 \pm 12 \text{ fs}$ from small statistics, fixed target experiments, consistent with hierarchy

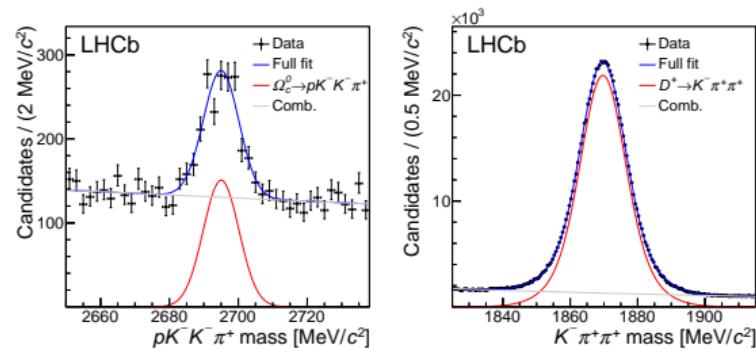
New measurement by LHCb

■ Measure lifetime ratio

$$r_{\Omega_c^0} = \frac{\tau_{\Omega_c^0}}{\tau_{D^+}}$$

■ Using semileptonic decays

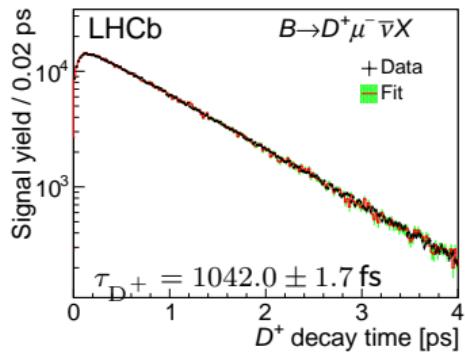
$$\Omega_b^- \rightarrow \Omega_c^0 \mu^- \bar{\nu}_\mu X \text{ and } B^0 \rightarrow D^+ \mu^- \bar{\nu}_\mu X$$





Ω_c lifetime

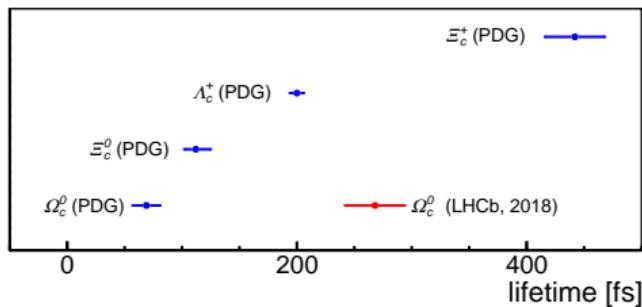
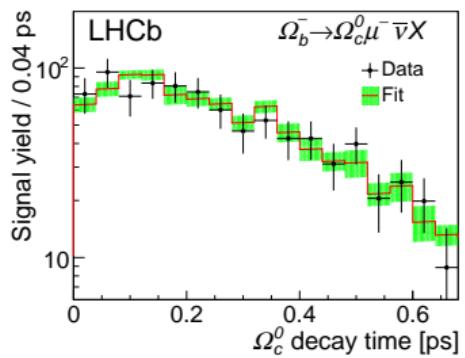
[PRL121(2018)092003]



- Calibrated on $B^0 \rightarrow D^+ \mu^- \bar{\nu}_\mu X$

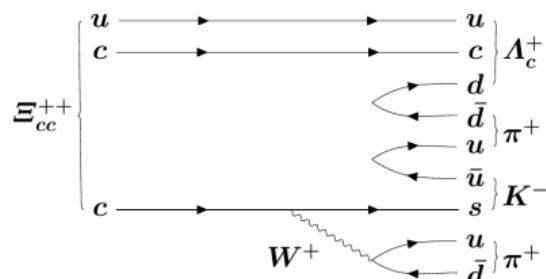
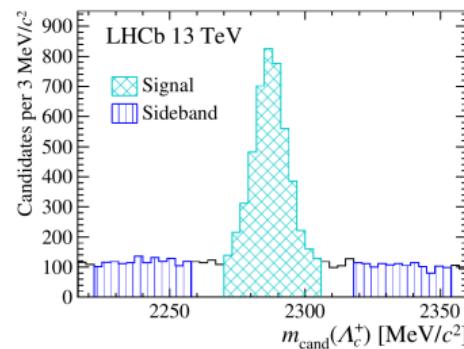
$$r_{\Omega_c^0} = \frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$
$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs}$$

- ~ 4 times larger than world average
- new hierarchy:



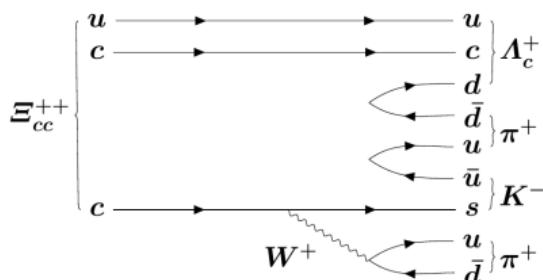
A Doubly Charmed Baryon Ξ_{cc}^{++} at LHCb

[PRL119(2017)112001]

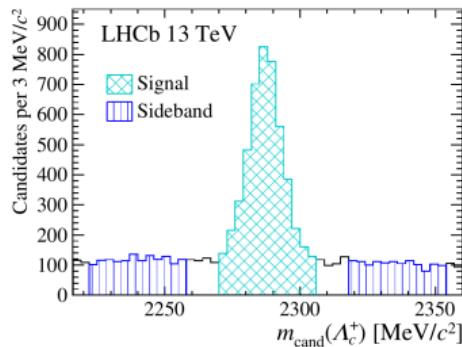
with $\Lambda_c^+ \rightarrow p K^- \pi^+$ 



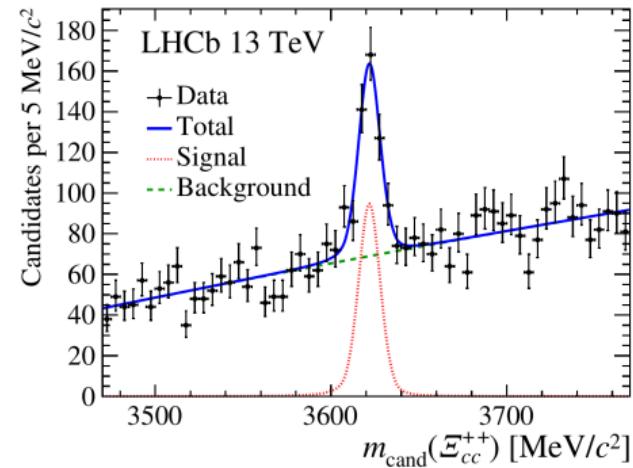
A Doubly Charmed Baryon Ξ_{cc}^{++} at LHCb [PRL119(2017)112001]



with $\Lambda_c^+ \rightarrow p K^- \pi^+$



Adding $K^- \pi^+ \pi^+$, background suppression using neural network



- 2016 Dataset: 1.7 fb^{-1} , 13 TeV
- Ξ_{cc}^{++} reconstructed entirely online in the trigger



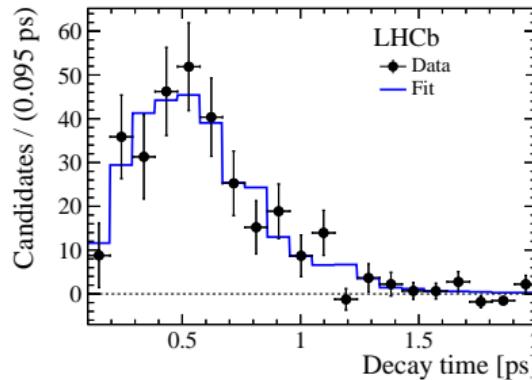
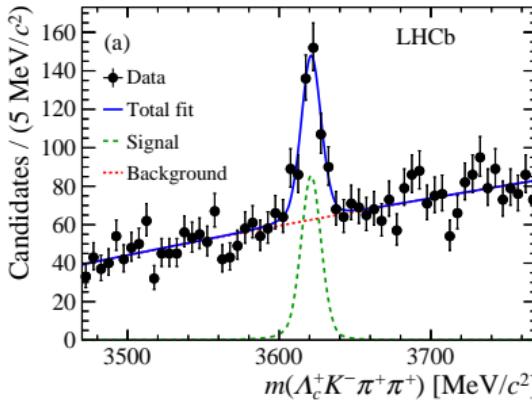
Comparison with Selected Theory Predictions

Method	$m_{\Xi_{cc}^{++}} [\text{MeV}/c^2]$	Reference
Experiment	$3621.40 \pm 0.72 \pm 0.27 \pm 0.14$	[PRL119(2017)112001]
Effective potential	3627 ± 12	[PRD90(2014)094007]
Relativized Quark Model	3613	arXiv:1708.04468
Relativistic Quark Model	3620	[PRD66(2002)014008]
Lattice QCD	$3610 \pm 23 \pm 22$	[PRD90(2014)094507]
HQ effective theory	3610	[Pr. Part. Nucl. Phys. 33(1994)787]

- Excellent agreement in several theoretical approaches!
- Comment on Selex observation:
 - Observation of Ξ_{cc}^+ at $m = 3519 \pm 2 \text{ MeV}/c^2$ can't be Isospin partner
[PRL89(2002)112001][PLB628(2005)18]
 - Low statistics (yields 15.9 and 5.62 events)
 - Short lifetime 33 fs and too large production xsection

Lifetime of Ξ_{cc}^{++}

[PRL121(2018)052002]



- Calibrated on $\Lambda_b \rightarrow \Lambda_c^+ \pi \pi \pi$

- Result:

$$\tau_{\Xi_{cc}^{++}} = 0.256^{+0.024}_{-0.022} (\text{stat}) \pm 0.014 (\text{syst}) \text{ ps.}$$

- On the low side of theoretical predictions

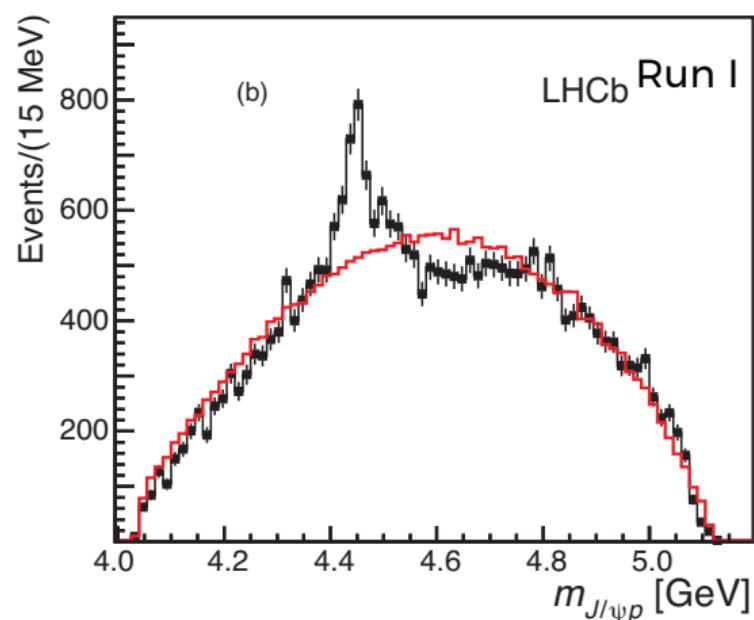
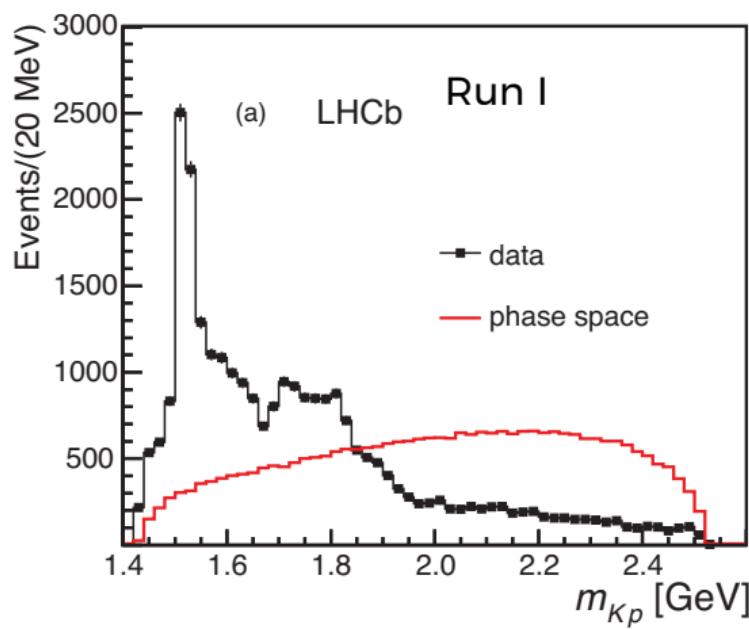
Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014



Heavy Baryons with Hidden Charm

Updating $\Lambda_b \rightarrow J/\psi p K$

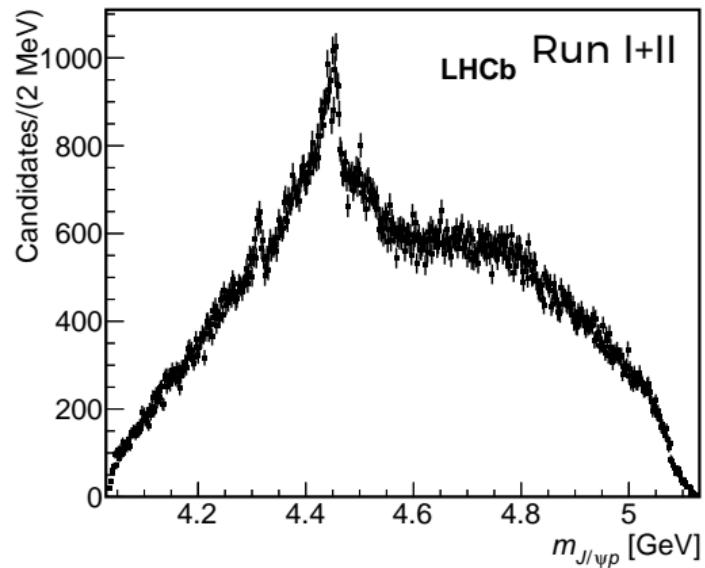
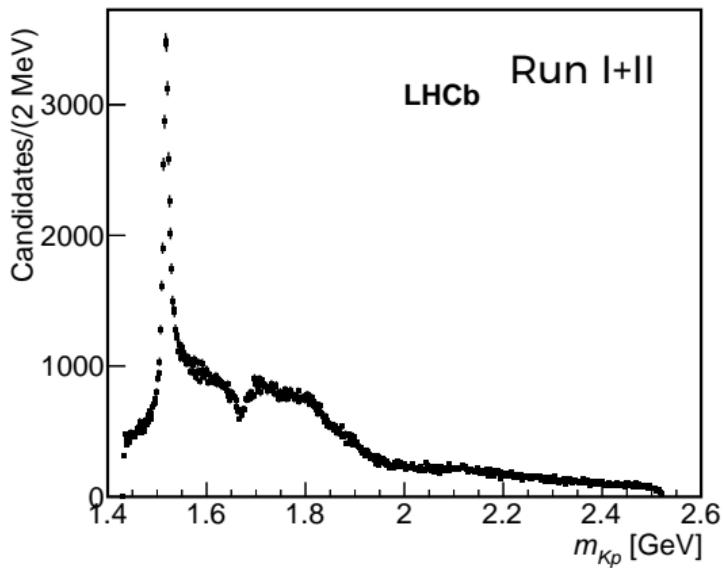
[PRL122(2019)222001]



Updating $\Lambda_b \rightarrow J/\psi p K$

[PRL122(2019)222001]

Improved selection and adding Run II data \Rightarrow
increased sample size by factor 9 to 246 000 candidates (total: $3 + 6 \text{ fb}^{-1}$)



Improved selection: include PID information in multivariate classifier
 $\Rightarrow 2\times$ better signal efficiency





Narrow structures

[PRL122(2019)222001]

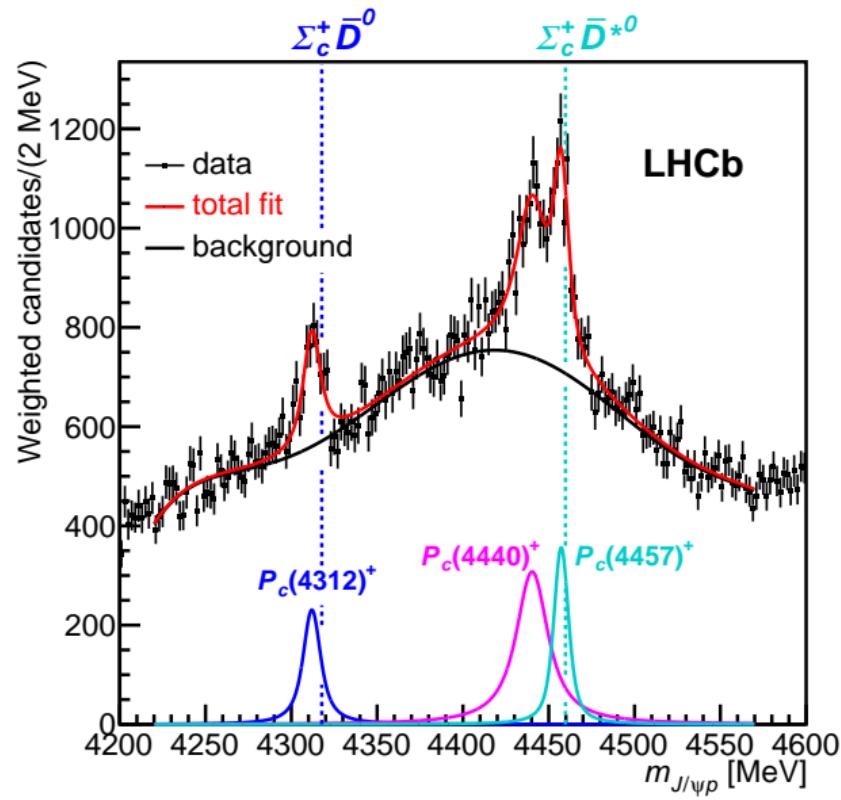
Fine binning reveals

- **New narrow structure at $m = 4312 \text{ MeV}$**
- **Peak at 4450 MeV split into two peaks**

investigated in $J/\psi p$ projection alone (no angular analysis)

Reflections from Λ^* occur mainly at $\cos \theta_{P_c} > 0$ (P_c helicity angle). Reweighting data in this variable reduces this background. Difference to unweighted results is taken as a systematic.

Without amplitude analysis broad $P_c(4380)^+$ can neither be confirmed nor excluded





Narrow Pentaquarks

[PRL122(2019)222001]

Results with relativistic Breit-Wigner fits:

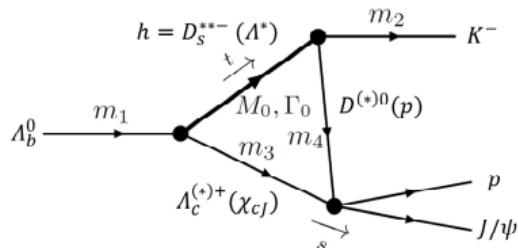
State	M [MeV]	Γ [MeV]	(95% CL)	\mathcal{R} [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

- Observed widths are consistent with experimental resolution.
- Significance of two-peak structure: 5.4σ
- Largest systematic uncertainty: unknown interference terms
- Determination of spin and parity quantum numbers requires amplitude analysis.



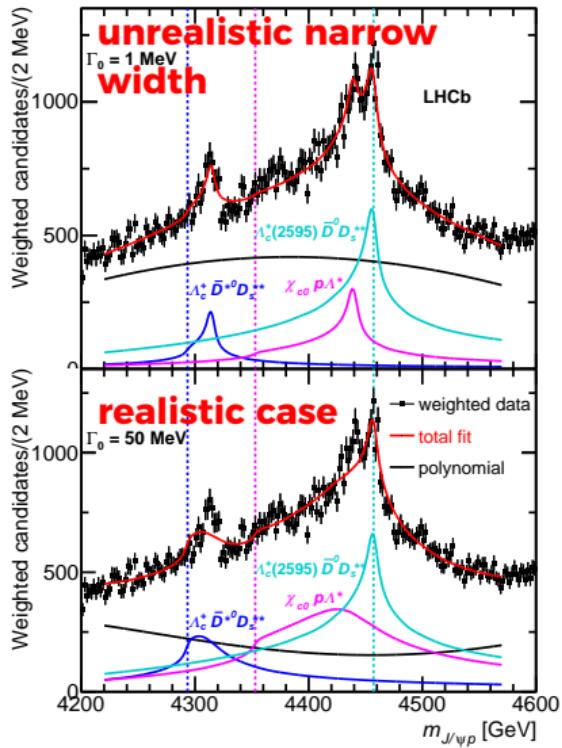


Triangle singularities?

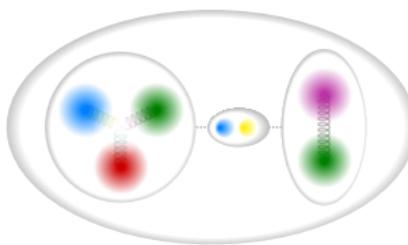


- To fully fit data intermediate particles need to be given unrealistically narrow width.
- For realistic width **only one peak can be generated by triangle.**
- Need to take hadronic loops into account when building amplitude model

[PRL122(2019)222001]



The pentaquarks as meson-baryon molecules?



- $\Lambda_c + \bar{D}^0$, $\Sigma_c^{*+} \bar{D}^0$ and $\Sigma_c \bar{D}^{0*}$ close two-body thresholds
- **Predictions of narrow baryon resonances with hidden charm** in dynamical coupled channel models

[Nucl.Phys.A776(2006)17] (octet of narrow resonances)

[PRC 84 (2011) 015202] (six narrow resonances)

[PRC 85 (2012) 044002] A narrow $J^P = 1/2^-$ state at

$$M - \frac{i}{2}\Gamma = 4314.531 - 1.448i$$



Theory response (post observation)

See next talk by
Bing-Song Zou

- All molecular models predict $P_c(4413)$ to have $J^P = 1/2^-$.
- Different multiplet structures possible

Model	$P_c(4312)$	$P_c(4440)$	$P_c(4457)$	$P_c(4380)$	notes	references
Molecular	$\Sigma_c^{++} D^-$ $1/2^-$	$\Sigma_c^{++*} D^-$ $3/2^-$	$\Sigma_c^+ D^0$ $3/2^-$		alt. for $P_c(4440/57)$	1903.11001
Molecule OBE	$\Sigma_c^+ \bar{D}^0$ $1/2^-$	$\Sigma_c \bar{D}^*$ $1/2^-$	$\Sigma_c \bar{D}^*$ $3/2^-$	$\Sigma_c^* \bar{D}$ $3/2^-$	$1/2^-, 3/2^-$ no more states	1903.11013
Molecule	$\Sigma_c^+ \bar{D}^0$	$\Sigma_c \bar{D}^*$	$\Sigma_c \bar{D}^*$			1904.00221
QDCS	$1/2^-$	$3/2^-$	$1/2^-$			
Molecule + HQSS	$\Sigma_c^+ \bar{D}^0$ $1/2^-$	$\Sigma_c \bar{D}^*$ $1/2^-$	$\Sigma_c \bar{D}^*$ $3/2^-$	$\Sigma_c^* \bar{D}$ $3/2^-$	septett $1/2^-, 3/2^-, (5/2^-)$	1903.11506 1904.01296
alt. QPSS multiplet	$1/2^-$	$3/2^-$ singlet	$3/2^-$ triplet			1904.00587
$\bar{c}[cu]_{s=1}[ud]_{s=0}; \ell$	$\ell = 0$	$\ell = 1$	$\ell = 1$	difficult		1904.00446
compact	$3/2^-$	$3/2^+$	$5/2^+$			

- **Clear distinction between compact and molecule $P_c(4312)$**
- Determination of quantum numbers is crucial \Leftrightarrow future amplitude analysis.





Summary

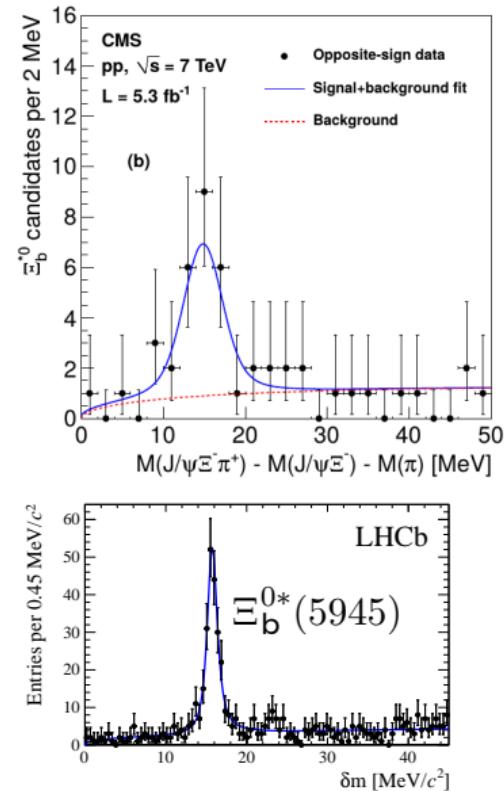
- LHC is a heavy quark baryon factory
- Precision measurements: properties of charm and bottom groundstate baryons
 - masses and lifetimes
- Exploring the excitation spectra
- Large Ω_c lifetime
- First doubly charmed baryon
- Updated analysis: we now have 3 pentaquark candidates

Backup



Ξ_b Excitations: The $\Xi_b^{0*}(5945)$

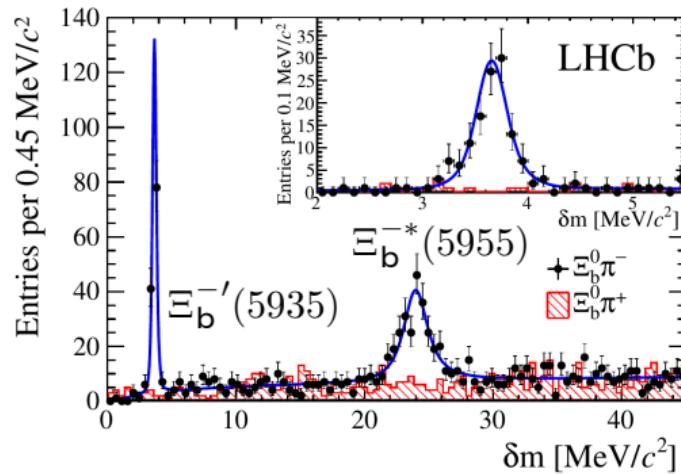
- Discovered by CMS [PRL108(2012)252002]
 - in $\Xi_b^{0*} \rightarrow \Xi_b^- \pi^+$ with $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Xi^- \rightarrow \Lambda^0 \pi^-$
 - Compatible with $J^+ = 3/2^+$ state
No other states seen in $\Xi_b^- \pi^+$
 - Precise measurement of mass and width at LHCb [JHEP05(2016)161]
 - in $\Xi_b^{0*} \rightarrow \Xi_b^- \pi^+$ with $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$ and $\Xi_c^0 \rightarrow p K^- K^- \pi^+$
- $$m(\Xi_b^{0*}) - m(\Xi_b^-) - m(\pi^+) = 15.727 \pm 0.068 \pm 0.023 \text{ MeV}$$
- $$\Rightarrow m(\Xi_b^{0*}) = 5952.3 \pm 0.1 \pm 0.9 \text{ MeV}$$
- $$\Gamma(\Xi_b^{0*}) = 0.90 \pm 0.16 \pm 0.08 \text{ MeV}$$





Isospin partners: Two Ξ_b^- Excitations [PRL114(2015)062004]

- Two excited Ξ_b^- states found at LHCb
- in $\Xi_b^{-*} \rightarrow \Xi_b^0 \pi^-$ with $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$ and $\Xi_c^+ \rightarrow p K^- \pi^+$
- decay angle distributions compatible with quark-model spin assignments
- $\Xi_b^{-*}(5955)$ and $\Xi_b^{0*}(5945)$ isospin partners Isospin-splitting $\delta m_{\text{iso}} \approx 2.3 \text{ MeV}$
- Isospin partner to $\Xi_b^{-'}(5935)$ missing below $\Xi_b^- \pi^+$ threshold?



	$\delta M [\text{MeV}]$	$\Gamma [\text{MeV}]$	J^P
$\Xi_b^{-'}$	$3.653 \pm 0.018 \pm 0.006$	$< 0.0895\% \text{C.L.}$	$1/2^+$
Ξ_b^{-*}	$23.96 \pm 0.12 \pm 0.06$	$1.65 \pm 0.31 \pm 0.10$	$3/2^+$



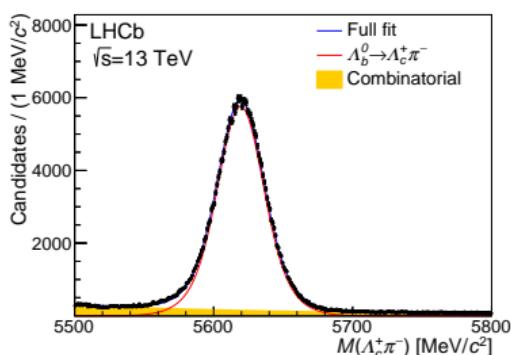
The heaviest Baryon

[PRL121(2018)072002]

Search for excited Ξ_b in three decays:

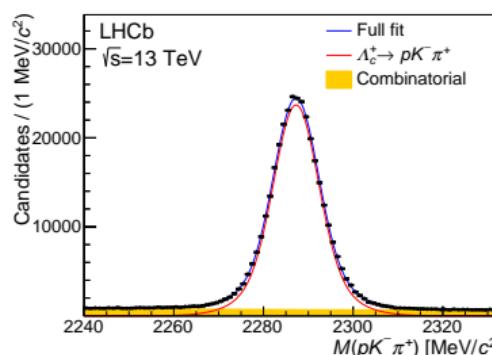
Exclusive $\Lambda_b K$
with $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$

$$\Lambda_b \rightarrow \Lambda_c^+ \pi^-$$



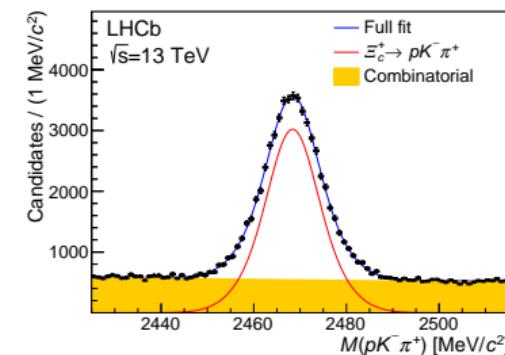
Semileptonic $\Lambda_b K$
with $\Lambda_b \rightarrow \Lambda_c^+ \mu X$

$$\Lambda_c^+ \rightarrow p K \pi$$



Semileptonic $\Xi_b \pi$
with $\Xi_b \rightarrow \Xi_c \mu X$

$$\Xi_c \rightarrow p K \pi$$



- Analysis uses data taken at $\sqrt{s} = 7, 8$ and 13 TeV corresponding to 4.5 fb^{-1}





More Theory Predictions

compiled in [PRD90(2014)094007]

Reference	Value (MeV)	Method
[Karliner and Rosner, 2014]	3627 ± 12	
[De Rujula et al., 1975]	$3550 - 3760$	QCD-motivated quark model
J. Bjorken (unpublished draft, 1986)	3668 ± 62	QCD-motivated quark model
[Anikeev et al., 2001]	3651	QCD-motivated quark model
[Fleck and Richard, 1989]	3613	Potential and bag models
[Richard, 1994]	3630	Potential model
[Korner et al., 1994]	3610	Heavy quark effective theory
[Roncaglia et al., 1995]	3660 ± 70	Feynman-Hellmann + semi-empirical
[Lichtenberg et al., 1996]	3676	Mass sum rules
[Ebert et al., 1997]	3660	Relativistic quasipotential quark model
[Silvestre-Brac, 1996]	3607	Three-body Faddeev equations.
[Gerasyuta and Ivanov, 1999]	3527	Bootstrap quark model + Faddeev eqs.
[Itoh et al., 2000]	ucc: 3649 ± 12 , dcc: 3644 ± 12	Quark model
[Kiselev and Likhoded, 2002a]	3480 ± 50	Potential approach + QCD sum rules
[Narodetskii and Trusov, 2002]	3690	Nonperturbative string
[Ebert et al., 2002]	3620	Relativistic quark-diquark





More Theory Predictions

compiled in [PRD90(2014)094007]

Reference	Value (MeV)	Method
[He et al., 2004]	3520	Bag model
[Richard and Stancu, 2005]	3643	Potential model
[Migura et al., 2006]	3642	Relativistic quark model + Bethe-Salpeter
[Albertus et al., 2007b]	3612^{+17}	Variational
[Roberts and Pervin, 2008]	3678	Quark model
[Weng et al., 2011]	3540 ± 20	Instantaneous approx. + Bethe-Salpeter
[Zhang and Huang, 2008]	4260 ± 190	QCD sum rules
[Lewis et al., 2001]	$3608(15)(\frac{13}{35}),$ $3595(12)(\frac{21}{22})$	Quenched lattice
[Flynn et al., 2003]	3549(13)(19)(92)	Quenched lattice
[Liu et al., 2010]	$3665 \pm 17 \pm 14^{+0}_{-78}$	Lattice, domain-wall + KS fermions
[Namekawa, 2012]	3603(15)(16)	Lattice, $N_f = 2 + 1$
[Alexandrou et al., 2012]	3513(23)(14)	LGT, twisted mass ferm., $m_\pi = 260$ MeV
[Briceno et al., 2012]	3595(39)(20)(6)	LGT, $N_f = 2 + 1$, $m_\pi = 200$ MeV
[Alexandrou et al., 2014]	3568(14)(19)(1)	LGT, $N_f = 2 + 1$, $m_\pi = 210$ MeV

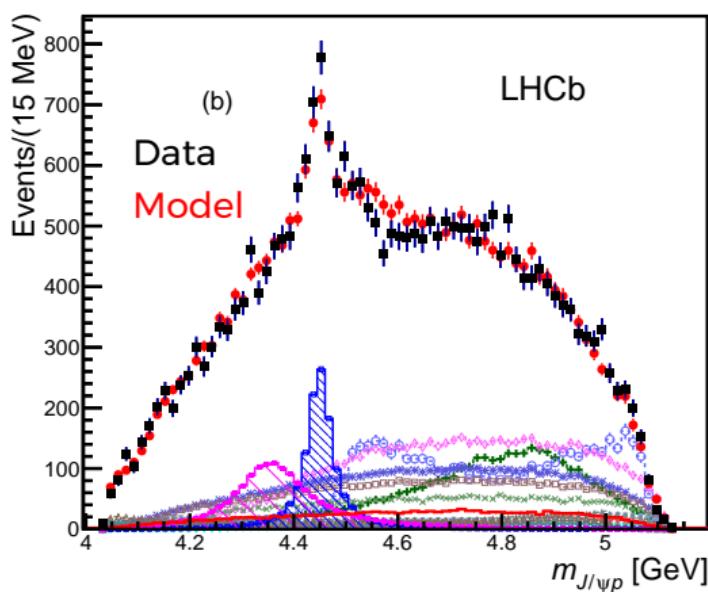




Pentaquarks in $J/\psi p$ at LHCb in Run I

[PRL115(2015)072001]

6D amplitude analysis of $\Lambda_b \rightarrow J/\psi p K$ needs two Breit-Wigner resonances in $J/\psi p$ to describe the data



Best fit:

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
- Also allowed:
 $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$
- Exotic contributions needed in two subsequent analyses
 - $\Lambda_b \rightarrow J/\psi p K$ moments analysis
[PRL117(2016)082002]
 - $\Lambda_b \rightarrow J/\psi p \pi$ amplitude analysis
[PRL117(2016)082003]



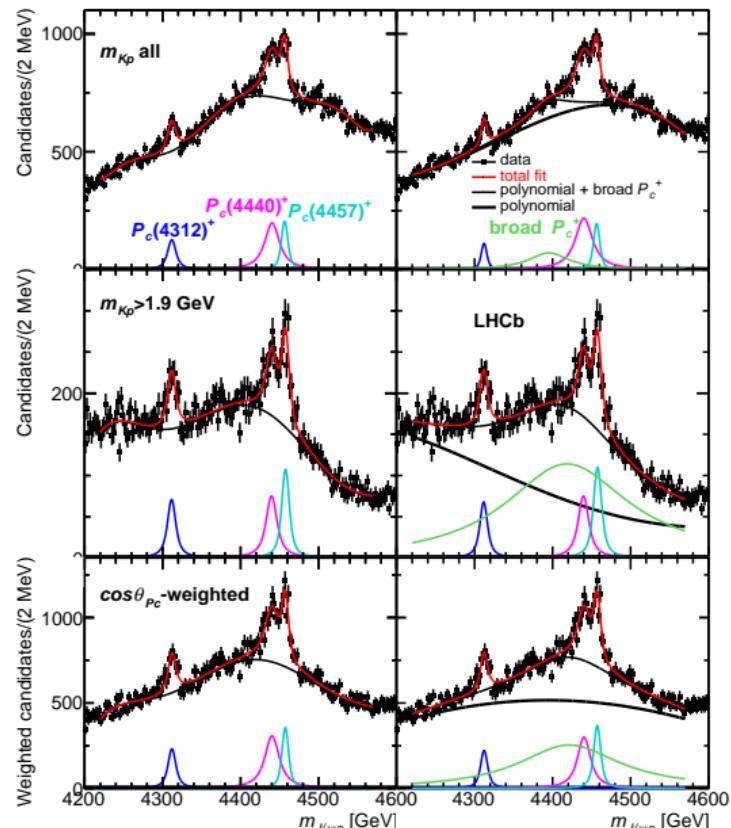
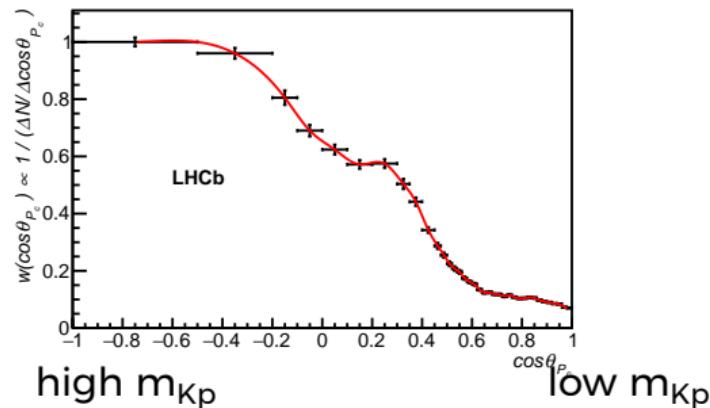
Angular weighting

PRL122(2019)222001

Reflections from Λ^* occur mainly at $\cos \theta_{P_c} > 0$ (P_c helicity angle).

Reweighting data with inverse of density in this variable reduces this background. Difference to unweighted results is taken as a systematic.

Weighting function:



J/ ψ pK Dalitz Plot

PRL122(2019)222001

