Heavy Quark Baryons and Exotica

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XVII INTERNATIONAL CONFERENCE
ON HADRON SPECTROSCOPY AND STRUCTURE

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Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

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CAMPUS DE EXCELENCIA INTERNACIONAL

The LHC as a Heavy Baryon Factory

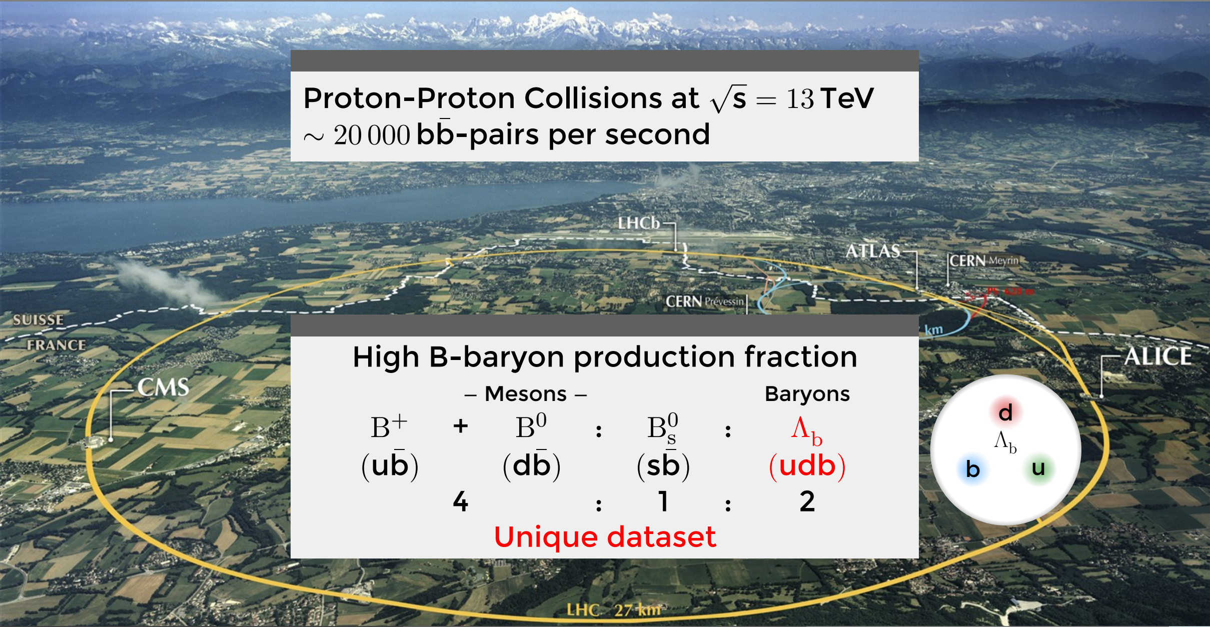
Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

$\sim 20\,000$ $b\bar{b}$-pairs per second

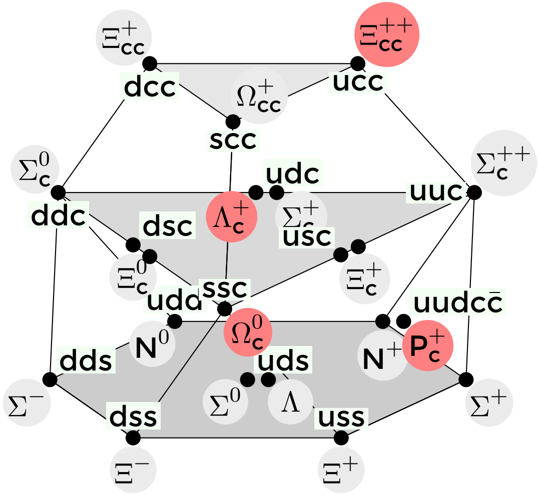
High B-baryon production fraction

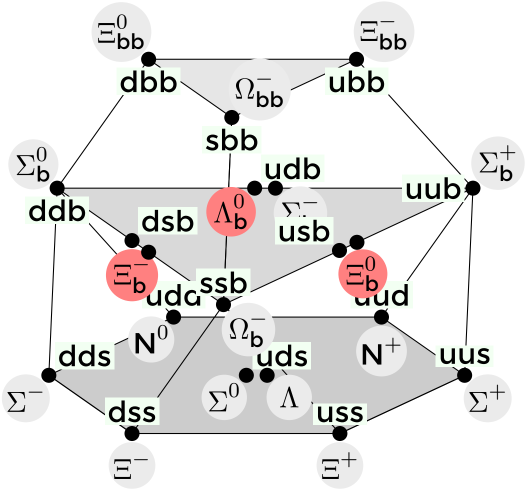
– Mesons –				Baryons
B^+ +	B^0	: B^0_s	:	Λ_b
$(u\bar{b})$	$(d\bar{b})$	$(s\bar{b})$		(udb)
4		: 1	:	2

Unique dataset



$J = 1/2$ Baryon Multiplets





Charmed Baryons

The Λ_c^+ excitation spectrum

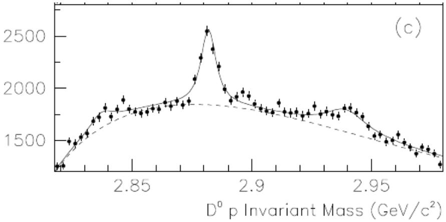
Well studied heavy-light-light system

- Orbitally excited states
- D-wave doublet predicted

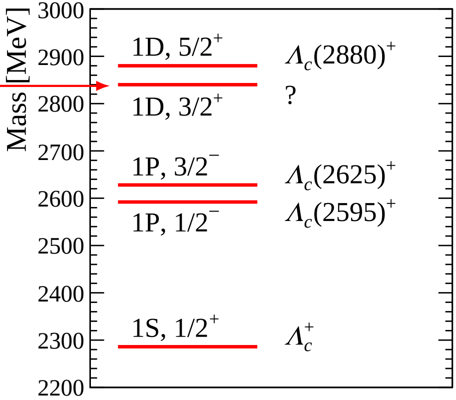
  more states in other models
- Missing state?

- Indication by BaBar for structure in $D^0 p$ at 2.84 GeV

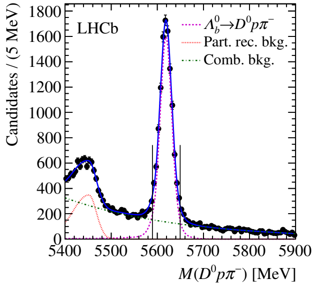
  [PRL98(2007)012001]



heavy-quark + light-diquark

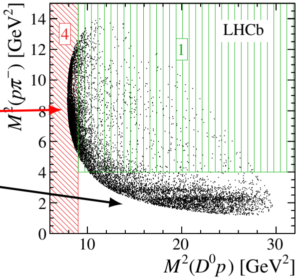


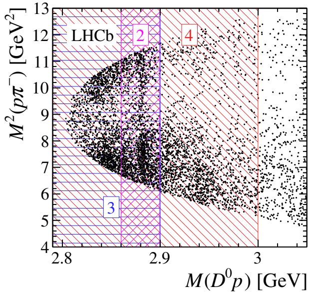
Predictions from [EPJ A51(2015)82]



- Data set $3\,\mathrm{fb}^{-1}$ (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*



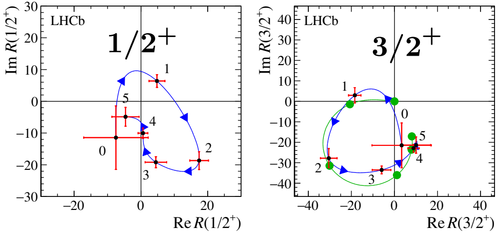


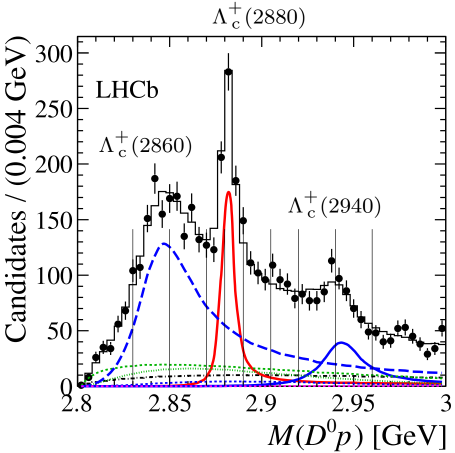
S. N. Friday 10:05h
Session: Baryons

- 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



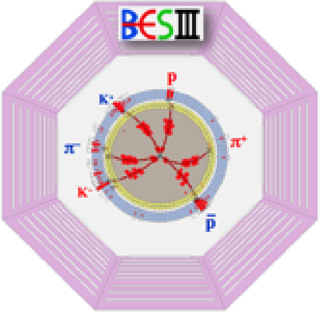


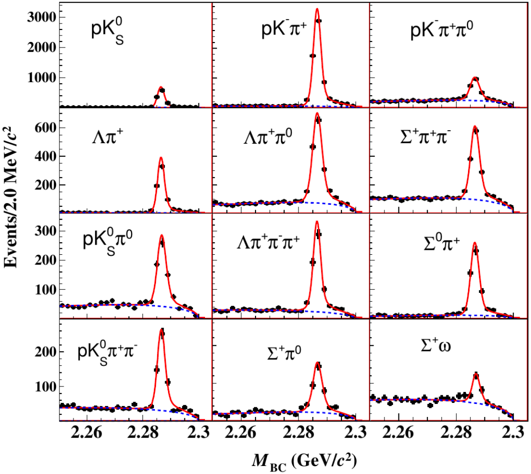
Only $3/2^+$ gives physical phase motion

Exclusive $e^+e^- \to \Lambda_c^+\Lambda_c^-$ production at threshold

P. Yue Thu 17:10h
Session: Hadron decays

- Data sample corresponding to $567\,\text{pb}^{-1}$ at $\sqrt{s} = 4.599$ GeV
- Beam energy-momentum constraint





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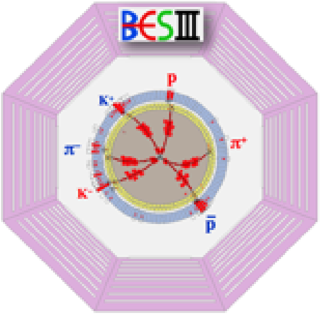


Mode	This work (%)	PDG (%)
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35
$pK^-\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0

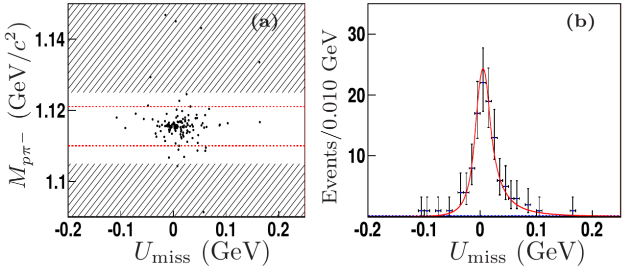
- Tag one Λ_c^+ hadronically
- Lepton PID (dE/dx + TOF + EMC)
- Use beam constraint to infer missing energy

$$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$$

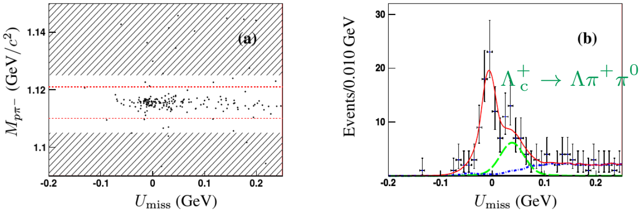
$$\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu) = (3.49 \pm 0.46 \pm 0.27)\%$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+ \nu_e)}{\mathcal{B}(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)} = 0.96 \pm 0.16 \pm 0.04$$

$\Lambda_c^+ \to \Lambda e^+ \nu_e$ [PRL115(2015)221805]

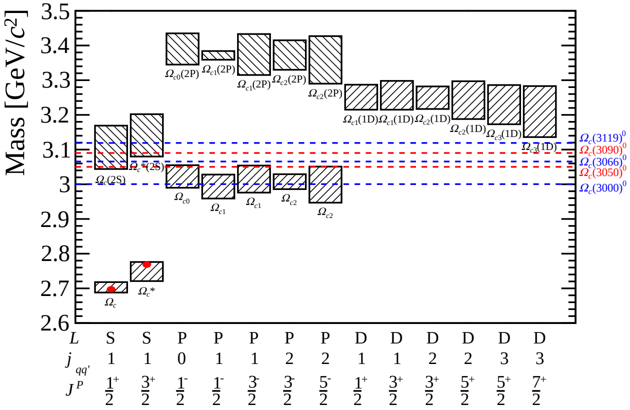


$\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$ [PLB767(2017)42]



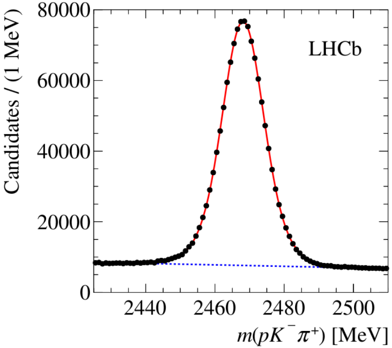
- The $|css>$ system is a proving ground for HQET
- Popular model: heavy quark + light diquark
- Two S-wave ground states Ω_c^0 and $\Omega_c^0(2770)$ observed
- 5 P-wave states predicted

Summary of theoretical predictions



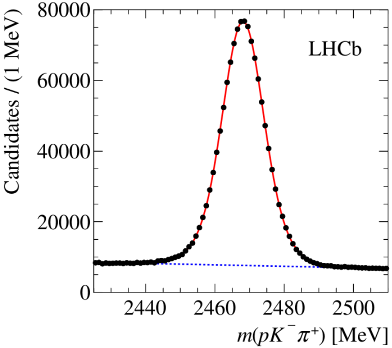
Five new Ω_c states in the decay $\Xi_c^+ K^-$ [PRL118(2017)182001]

Reconstruct $\Xi_c \to pK^-\pi^+$



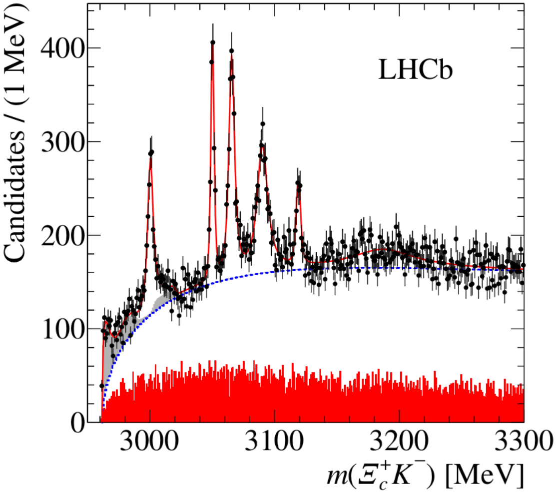
- Ξ_c detached from primary vertex
- PID of daughter tracks
- pointing to primary vertex

Reconstruct $\Xi_c \to pK^-\pi^+$



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

Adding another kaon:

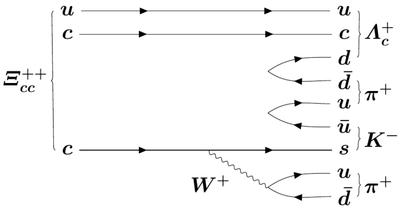


Five new Ω_c states in $\Omega_c \to \Xi_c^+ K^-$ [PRL118(2017)182001]

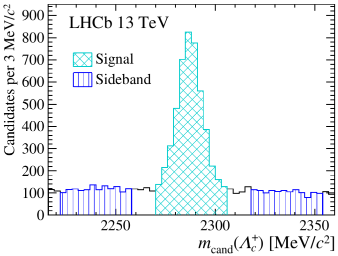
Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}$, 95% CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	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
		$< 2.6\,\mathrm{MeV}$, 95% CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	

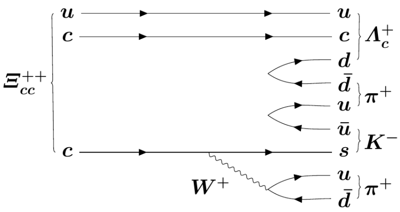
- Are these the 5 P-wave states? [PRD95(2017)114012]
- Why two very narrow states? [PRD96(2017)014009]
- Next steps: quantum numbers and Isospin multiplet

V. Belyaev Friday 09:45h
Session: Baryons



with $\Lambda_c^+ \to pK^-\pi^+$





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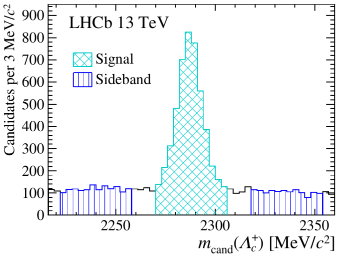
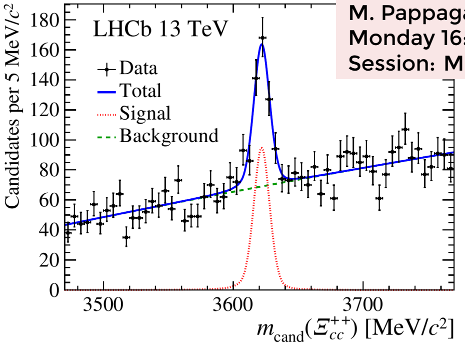


Adding $K^-\pi^+\pi^+$, background suppression using neural network

M. Pappagallo.
Monday 16:45h
Session: Mesons



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

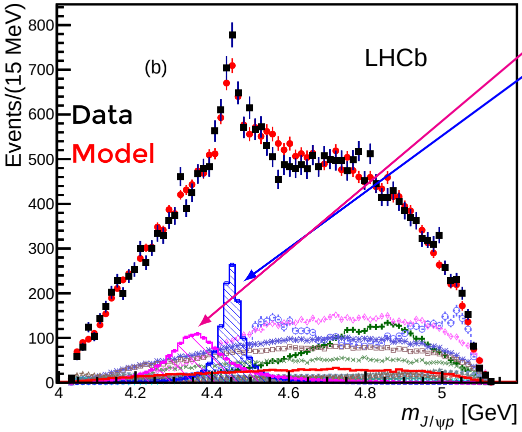
Comparison with Selected Theory Predictions

Method	$m_{\Xi_{cc}^{++}}$ [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 $= 3519 \pm 2$ 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

Heavy Baryons with Hidden Charm

6D Amplitude analysis allows to measure resonance parameters

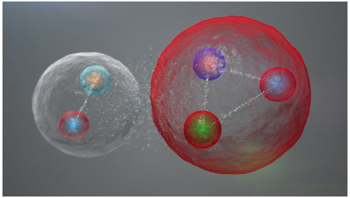


State	Mass [MeV]	Width [MeV]	J^P
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+$

- 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]

Pentaquark Models

- Proximity of thresholds suggests two-body contributions



Closeby thresholds

[MeV]	$P_c(4380)^+$	$P_c(4450)^+$
Mass	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
$\Sigma_c^{*+}\overline{D}^0$	4382.3 ± 2.4	
$\chi_{c1}(1P)p$		4448.93 ± 0.07
$\Lambda_c^{+*}\overline{D}^0$		4457.09 ± 0.35
$\Sigma_c\overline{D}^{0*}$		4459.9 ± 0.5
$\Sigma_c\overline{D}^0\pi^0$		4452.7 ± 0.5

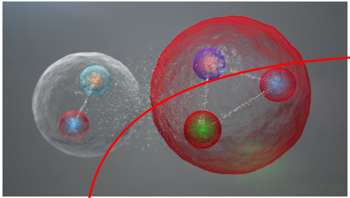
[EPJ A51(2015)11,152]

Rescattering	Hadronic molecules	Tightly bound states
kinematic effect	loosely bound system of color-singlets	constituents carrying color (di-quarks)
above threshold	below threshold	no association
–	S-wave binding restricts J^P	large multiplets

Pentaquark Models

Many contributions
Session: Exotics

- Proximity of thresholds suggests two-body contributions



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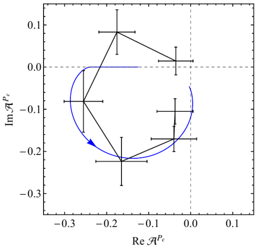
Testing Rescattering Models: $\Lambda_b \to \chi_{c1}(1P)\ p\ K$ at LHCb

- Even in amplitude analyses cusps are difficult to distinguish from real resonances

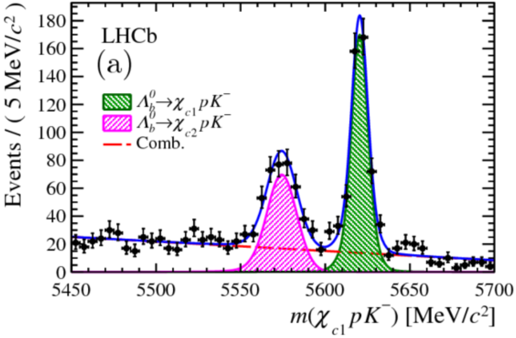
[PRD92(2015)071502]



- phase motion: resonance vs cusp

- Add complementary data: Rescattering can be ruled out if there is a narrow enhancement in the elastic channel $\chi_{c1}(1P)\ p$

First observation of $\Lambda_b \to \chi_{c1(2)} pK$



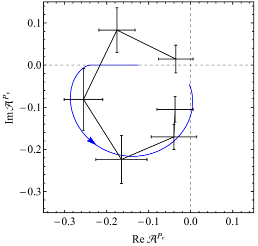
kinematic constraint $\chi_c = \chi_{c1} \to J/\psi\gamma$

[PRL119(2017)062001]

Testing Rescattering Models: $\Lambda_b \to \chi_{c1}(1P)$ p K at LHCb

- Even in amplitude analyses cusps are difficult to distinguish from real resonances

[PRD92(2015)071502]



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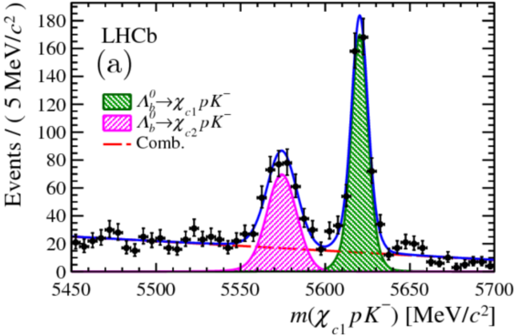


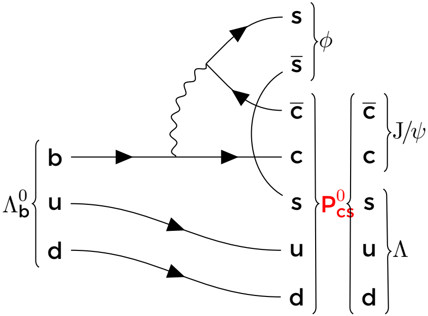
kinematic constraint
$\chi_c = \chi_{c1} \to J/\psi\gamma$
[PRL119(2017)062001]

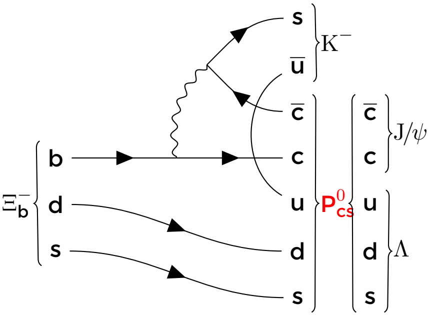
Next step: amplitude analysis

Pentaquarks with Strangeness?

V. Magas. Friday 10:25h
Session: Exotics

Both final states provide access to strange pentaquarks usdc$\bar{c}$





- $J/\psi\phi$ system $\rightarrow$ c$\bar{c}$s$\bar{s}$ Tetraquarks
- LHCb Analyse $B \rightarrow J/\psi\phi K$:
  [PRL118(2017)022003]
  [PRD95(2017)012002]

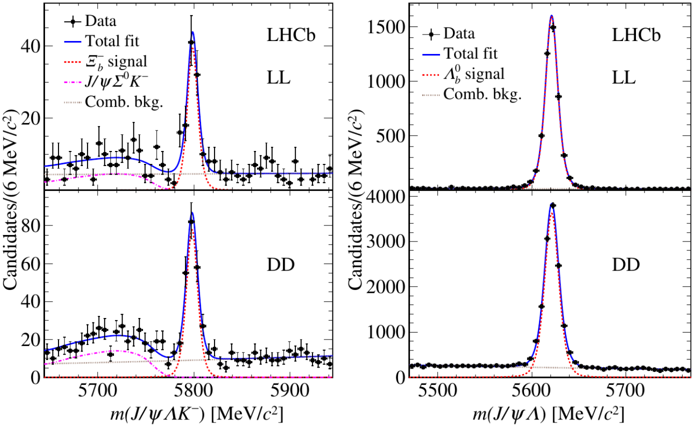
- Less tracks reconstruct
- Lower Ξ_b production cross section
- Expect comparable statistics

First Observation of $\Xi_b^- \to J/\psi \Lambda K^-$ [PLB772(2017)265]

$$\frac{f_{\Xi_b} \mathcal{B}(\Xi_b \to J/\psi \Lambda K)}{f_{\Lambda_b} \mathcal{B}(\Lambda_b \to J/\psi \Lambda)}$$
$$= (4.19 \pm 0.29 \pm 0.14) \times 10^{-2}$$

$$m(\Xi_b^-) - m(\Lambda_b)$$
$$= 177.08 \pm 0.47 \pm 0.16 \, \mathrm{MeV}/c^2$$

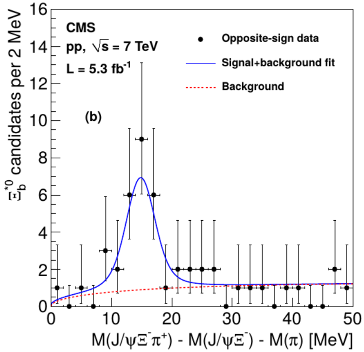
- Use Run II data set to study $J/\psi \Lambda K^-$ amplitudes



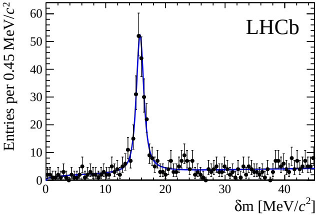
Beauty Baryons

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

- Discovered by CMS [PRL108(2012)252002]
- in $\Xi_b^{0*} \to \Xi_b^- \pi^+$ with $\Xi_b^- \to J/\psi \Xi^-$ and $\Xi^- \to \Lambda^0 \pi^-$
- Compatible with $J^+ = 3/2^+$ state
  No other states seen in $\Xi_b^- \pi^+$

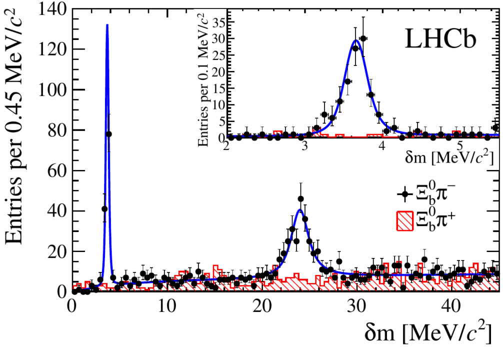


- Precise measurement of mass and width at LHCb [JHEP05(2016)161]
- in $\Xi_b^{0*} \to \Xi_b^- \pi^+$ with $\Xi_b^- \to \Xi_c^0 \pi^-$ and $\Xi_c^0 \to pK^-K^-\pi^+$



$$m(\Xi_b^{0*}) - m(\Xi_b^-) - m(\pi^+) = 15.727 \pm 0.068 \pm 0.023 \text{ MeV}$$
$$\Gamma(\Xi_b^{0*}) = 0.90 \pm 0.16 \pm 0.08 \text{ MeV}$$

- Two excited Ξ_b^- states found at LHCb
- in $\Xi_b^{-*} \to \Xi_b^0\pi^-$ with $\Xi_b^0 \to \Xi_c^+\pi^-$ and $\Xi_c^+ \to pK^-\pi^+$
- decay angle distributions compatible with quark-model spin assignments
- Ξ_b^{-*} and Ξ_b^{0*} isospin partners
  Isospin-splitting $\delta m_{iso} \approx 2.3$ MeV
- Isospin partner to $\Xi_b^{-\prime}$ below $\Xi_b^-\pi^+$ threshold?



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

Summary

- LHC is a heavy quark baryon factory
- Discovery of 5 new Ω_c states and
- Doubly charmed Ξ_{cc}^{++} this year's highlight
- Impressive success for theory
- More puzzles to solve – which role do multiquark states play in the baryon spectrum?

Backup

More Theory Predictions

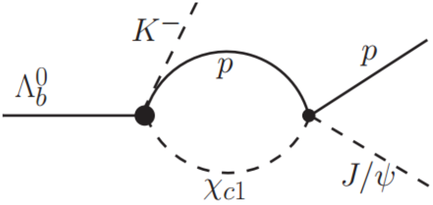
compiled in [PRD90(2014)094007]

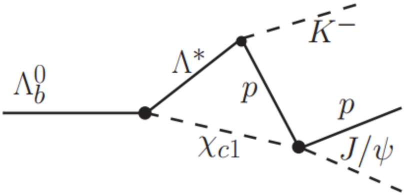
Reference	Value (MeV)	Method
[Karliner and Rosner, 2014]	3627 ± 12	
[De Rujula et al., 1975]	$3550 - 3760$	QCD-motivated quark model
J. Bjorken (unpublished draft, 1986)	3668 ± 62	QCD-motivated quark model
[Anikeev et al., 2001]	3651	QCD-motivated quark model
[Fleck and Richard, 1989]	3613	Potential 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]	$3608(15)(^{13}_{35})$, $3595(12)(^{21}_{22})$	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_π=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





Nonrelativistic loop integral:

$$G_\Lambda(E) = \int \frac{d^3q}{(2\pi)^3} \frac{\vec{q}^2 f_\Lambda(\vec{q}^2)}{E - m_1 - m_2 - \vec{q}^2/2\mu}$$

with a form factor $f_\Lambda(\vec{q}^2)$.

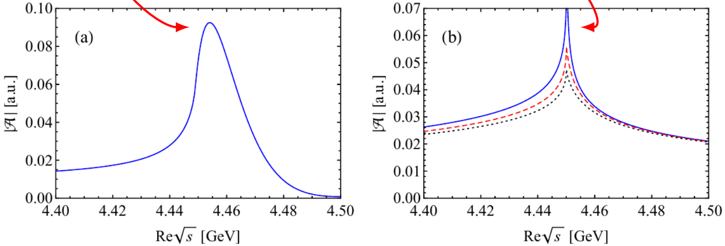
Triangle Singularity given by Landau-equation

$$1 + 2y_{12}y_{23}y_{13} = y_{12}^2 + y_{23}^2 + y_{13}^2$$

$$y_{ij} = \left(m_i^2 + m_j^2 - (p_i + p_j)^2\right)/2m_im_j$$

Rescattering: hadronic loops

Cusps just **above** threshold



But: no cusp in elastic channel here: $p\chi_{c1}$

Nonrelativistic loop integral:

$$G_\Lambda(E) = \int \frac{d^3q}{(2\pi)^3} \frac{\vec{q}^2 f_\Lambda(\vec{q}^2)}{E - m_1 - m_2 - \vec{q}^2/2\mu}$$

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