Hadron Spectroscopy and Exotic States at LHCb

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on behalf of LHCb collaboration

Recontres de Moriond
QCD and High Energy Interactions
25 March-1 April 2017, La Thuille, Italy

OUTLINE

- Observation of 5 new narrow Ω^0_c states **NEW**
  [arXiv: 1703.04639]
- Search for the tetraquark $X(5568)^{\pm}$
  [Phys. Rev. Lett. 117 (2016) 152003]
- Observation of $\Lambda^0_b \to \chi_{c1(2)}\, p\, K^-$ decays **NEW**
  [LHCb-PAPER-2017-011 in preparation]
- Observation of $\Xi_b^- \to J/\psi\, \Lambda\, K^-$ **[arXiv: 1701.05274]**

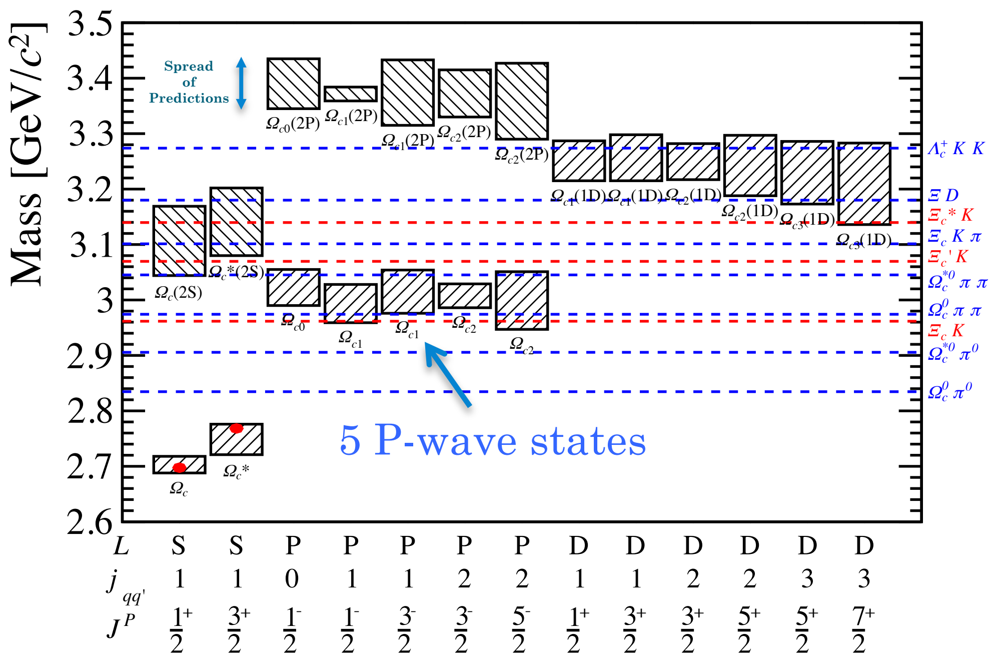
Observation of five new narrow Ω^0_c states decaying to $\Xi_c^+K^-$

[arXiv:1703.04639]
(Accepted by PRL)

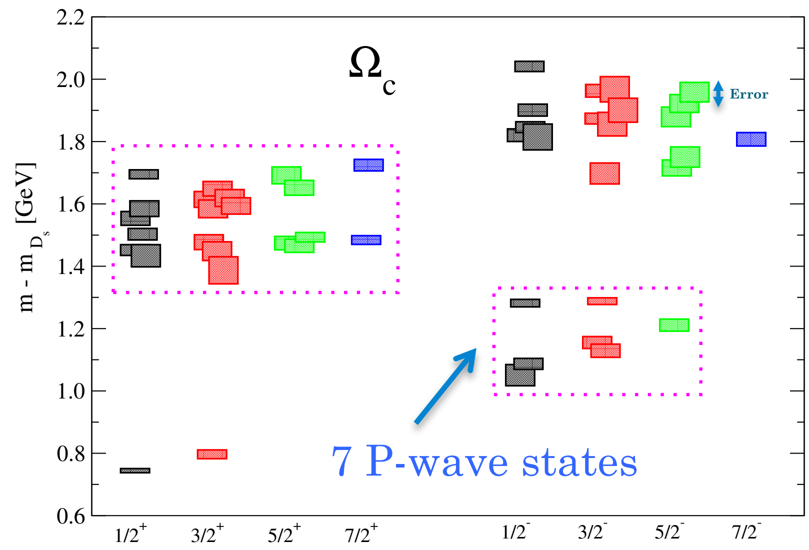
Excited Ω^0_c States

Only the ground states Ω^0_c ($J^P=1/2^+$) and Ω^{*0}_c($J^P=3/2^+$) are known so far

Excited modes between the two light quarks are not considered



Lattice QCD:
[M. Padmanath *et al.* arXiv:1311.4806]



Decays to $\Omega^0_c\,\pi^0$ and $\Omega^{*0}_c\pi^0$ final states are suppressed by isospin-violation
Investigation of the decays to the $\Xi_c^+K^-$ final state

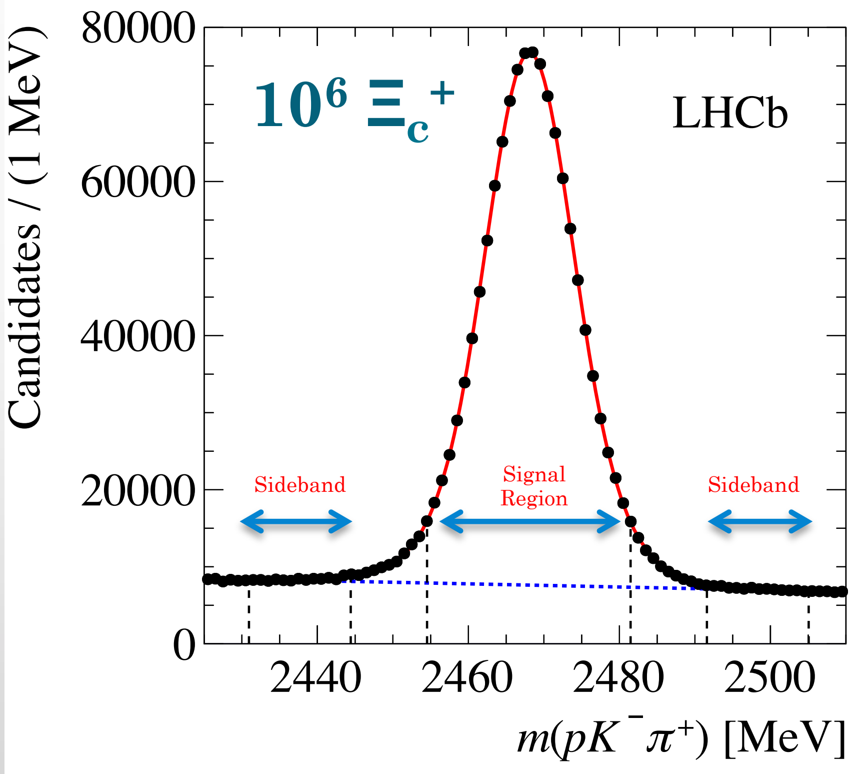
Selection of the Ξ_c^+ Sample

[arXiv:1703.04639]

Selection of $\Xi_c^+ \to pK^-\pi^+$ decays: though Cabibbo suppressed, they do not involve hyperons in the final state, which tend to decay beyond the vertex detector

Data sample: 1.0 fb^{-1} (7 TeV) + 2.0 fb^{-1} (8 TeV) + 0.3 fb^{-1} (13 TeV) = 3.3 fb^{-1}
A dedicated trigger (and the larger collision energy) boosted the number of the reconstructed Ξ_c^+ in the 13 TeV sample (x 3)

Data-driven multivariate selection based on likelihood ratios: vertex χ^2, proton and kaon PID, Ξ_c^+ flight distance, Ξ_c^+ p_T, …



Mass resolution: 6.8 MeV

The $\Xi_c^+K^-$ Mass Spectrum

[arXiv:1703.04639]

Ξ_c^+ candidates are combined to kaons with opposite charge
(tight PID requirement and $p_T(\Xi_c^+K^-) > 4.5$ GeV)

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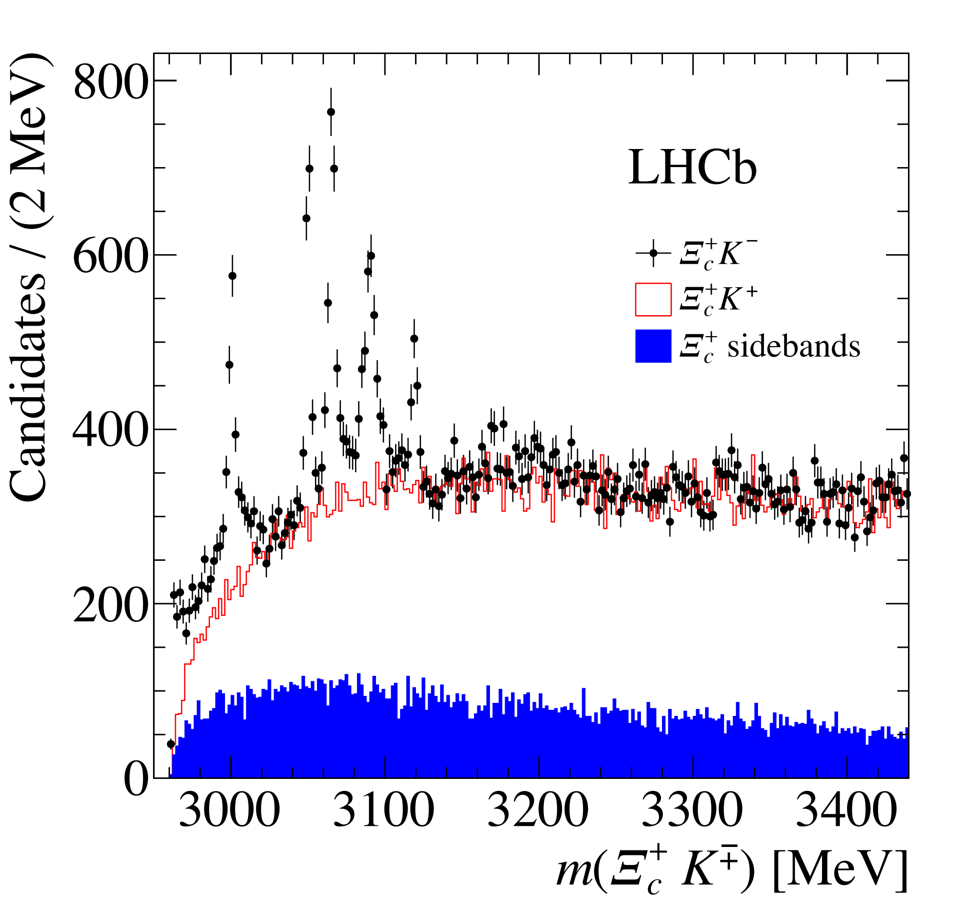

5 narrow peaks in $\Xi_c^+K^-$!

No peaks in the wrong sign sample $\Xi_c^+K^+$
No peaks in the Ξ_c^+ -sidebands K^- sample

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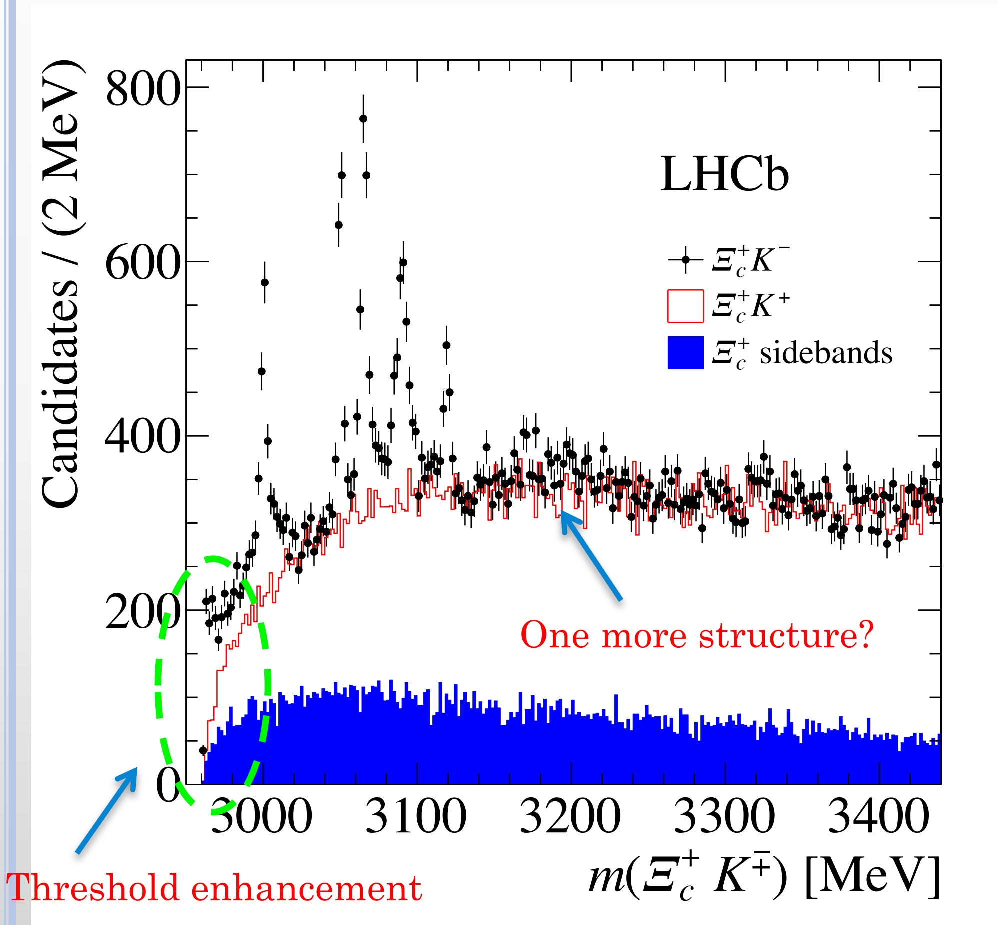

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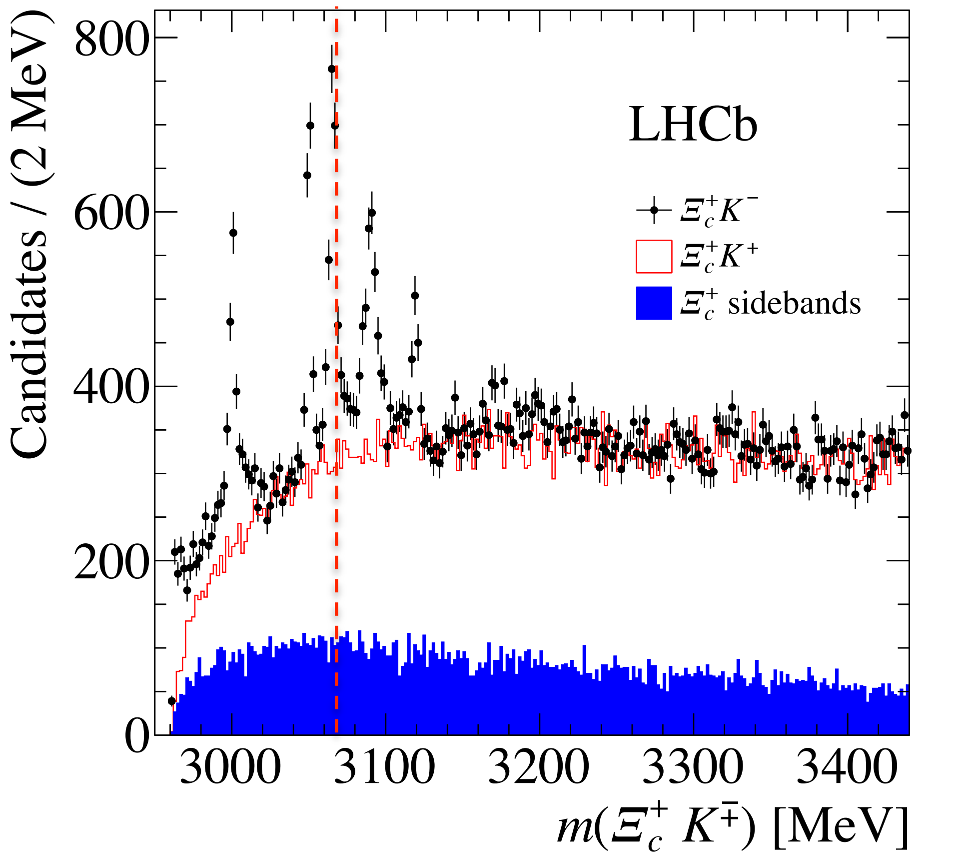
$\Xi_c'^+K^-$
Kinematic threshold



5 narrow peaks in $\Xi_c^+K^-$!

No peaks in the wrong sign sample $\Xi_c^+K^+$
No peaks in the Ξ_c^+ -sidebands K^- sample

States with masses $M > m(\Xi_c') + m(K)$ could decay to $\Xi_c'^+K^-$ as well and appear into Ξ_cK as partially reconstructed decays (i.e. feed-downs)

FIT MODEL

[arXiv:1703.04639]

Signals:
- 6 Relativistic Breit-Wigner convolved with Gaussian functions
- Mass resolutions: 0.7-1.7 MeV
- 3 Feed-downs:

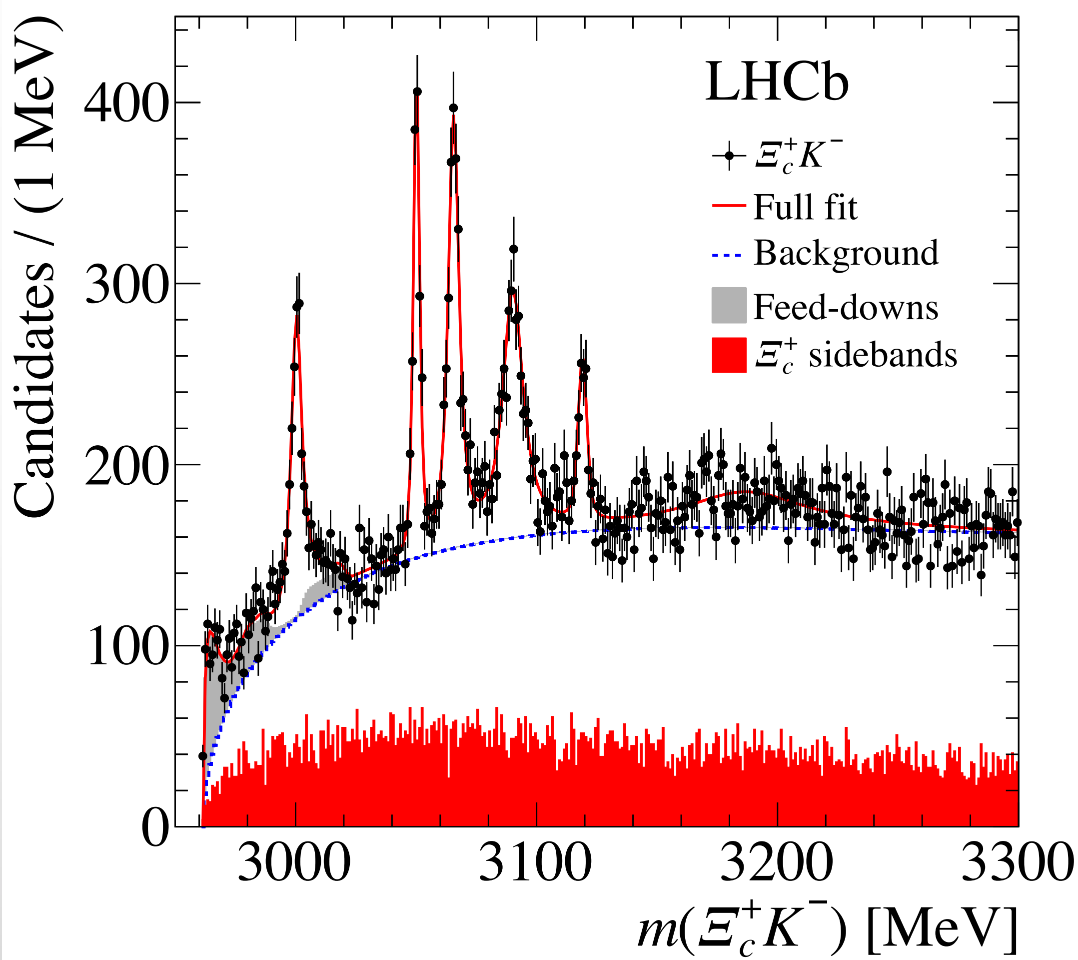
$\Omega_c(X)^0 \to \Xi_c'^+ K^-$ where $\Xi_c'^+ \to \Xi_c^+ \gamma$

Background:

$$B(m) = \begin{cases} P(m) e^{a_1 m + a_2 m^2} & \text{for } m < m_0, \\ P(m) e^{b_0 + b_1 m + b_2 m^2} & \text{for } m > m_0, \end{cases}$$

Momentum in the two-body reference frame

Binned χ^2 fit



SYSTEMATICS

[arXiv:1703.04639]

Source	$\Omega_c(3000)^0$ (m, Γ)	$\Omega_c(3050)^0$ (m, Γ)	$\Omega_c(3066)^0$ (m, Γ)	$\Omega_c(3090)^0$ (m, Γ)	$\Omega_c(3119)^0$ (m, Γ)	$\Omega_c(3188)^0$ (m, Γ)
Fit bias	(0.00, 0.10)	(0.03, 0.00)	(0.01, 0.00)	(0.04, 0.00)	(0.00, 0.00)	(0.55, 0.00)
Background model	(0.03, 0.25)	(0.00, 0.05)	(0.00, 0.10)	(0.00, 0.49)	(0.01, 0.21)	(1.81, 4.92)
Interference	(0.05, 0.09)	(0.09, 0.08)	(0.27, 0.15)	(0.48, 0.49)	(0.89, 0.17)	(8.19, 6.56)
Feed-down shift	(0.13, 0.09)	(0.00, 0.02)	(0.00, 0.03)	(0.00, 0.09)	(0.00, 0.03)	(0.21, 0.82)
Mass scale at 7–8 TeV	(0.01, 0.00)	(0.03, 0.00)	(0.03, 0.00)	(0.04, 0.00)	(0.05, 0.00)	(0.07, 0.00)
Mass scale at 13 TeV	(0.00, 0.00)	(0.01, 0.00)	(0.01, 0.00)	(0.01, 0.00)	(0.02, 0.00)	(0.02, 0.00)
Data-MC discrepancy	(0.00, 0.08)	(0.00, 0.01)	(0.00, 0.06)	(0.00, 0.15)	(0.00, 0.02)	(0.00, 0.00)
High-mass description	(0.00, 0.11)	(0.00, 0.00)	(0.00, 0.03)	(0.10, 0.37)	(0.00, 0.30)	(9.50, 7.20)
Total	(0.14, 0.31)	(0.10, 0.10)	(0.27, 0.19)	(0.48, 0.80)	(0.89, 0.40)	(12.7, 10.9)

The largest contribution is found to be from possible interference, while the feed-down shift has a sizeable effect only on the $\Omega_c(3000)^0$ parameters

Fit Results

[arXiv:1703.04639]

Significances $N_\sigma = \sqrt{\Delta\chi^2}$

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
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	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		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\mathrm{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\mathrm{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\mathrm{fd}}$			$190 \pm 70 \pm 20$	

- Observation of **5** new excited Ω_c states! Two of them extremely narrow
- The broad state could be a superposition of several states
- Threshold enhancement consistent with being due to the partially reconstructed decay $\Omega_c(3066)^0 \rightarrow \Xi_c'^+ K^-$

Search for structure in the $B_s^0\pi^\pm$ invariant mass spectrum

[Phys. Rev. Lett. 117 (2016) 152003]

SEARCH FOR X(5568)$^{\pm}$ AT LHCb

[PRL 117 (2016) 152003]

Claimed observation/evidence of an exotic state ($\bar{b}s\bar{u}d$) by DØ collaboration

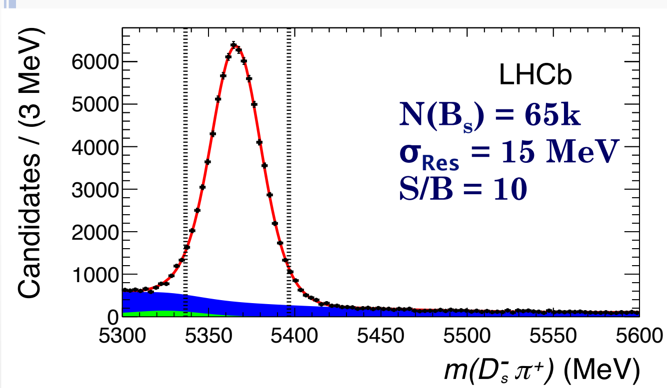
- ✓ X(5568)$^{\pm}\to B_s^0\pi^{\pm}$, $B_s^0\to J/\psi\,\phi$, $J/\psi\to\mu^+\mu^-$, $\phi\to K^+K^-$

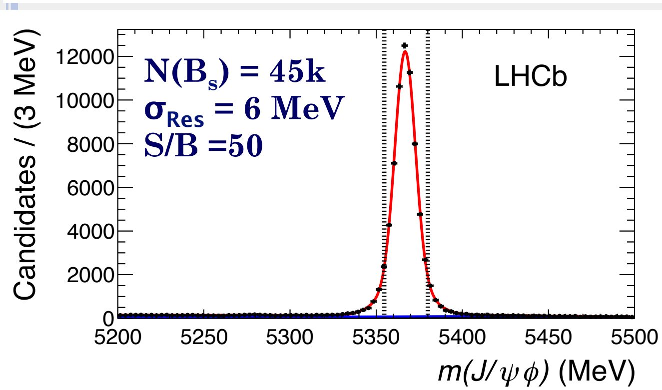
$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV}/c^2$$

N.B. m(Ξ_b) ~ 5790 MeV

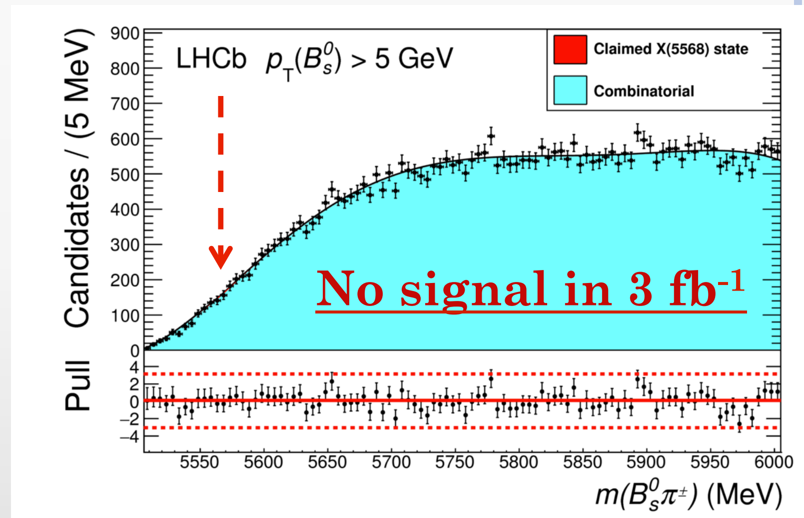
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \mathrm{MeV}/c^2$$

- ✓ Fraction of B_s^0 from $X^{\pm}$ decay: $\rho_X^{D\text{Ø}} = (8.6 \pm 1.9 \pm 1.4)$ %





$B_s + \pi^{\pm}$



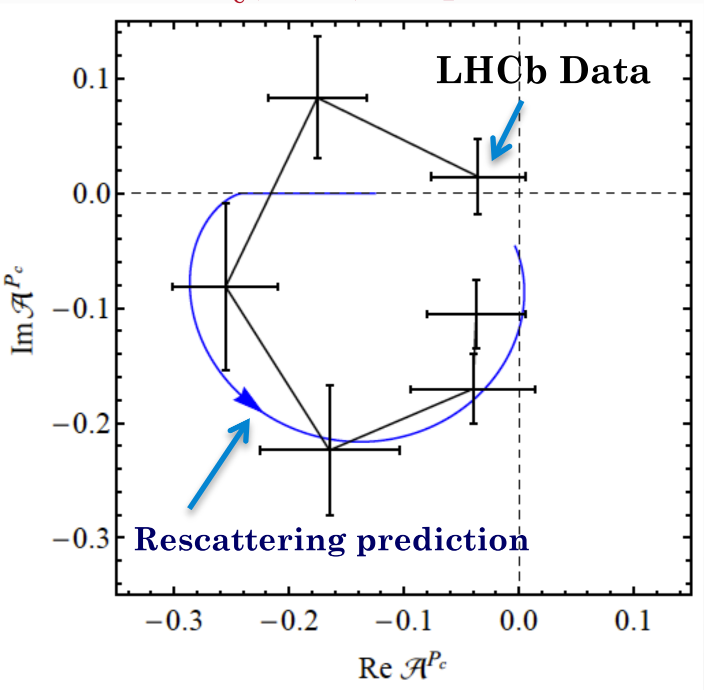
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T > 5\ \mathrm{GeV}/c) < 0.011\,(0.012)\ @\ 90\,(95)\ \%\ \mathrm{CL}$$
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T > 10\ \mathrm{GeV}/c) < 0.021\,(0.024)\ @\ 90\,(95)\ \%\ \mathrm{CL}$$
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_T > 15\ \mathrm{GeV}/c) < 0.018\,(0.020)\ @\ 90\,(95)\ \%\ \mathrm{CL}$$

Observation of $\Lambda^0_b \rightarrow \chi_{c1(2)} pK^-$ decays and measurements of the Λ^0_b mass

[LHCb-PAPER-2017-011 in preparation]

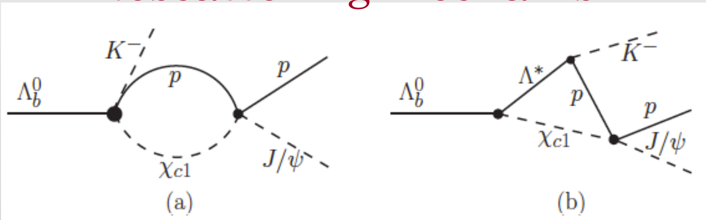
Motivation: Test Exotic Nature of $P_c(4450)$

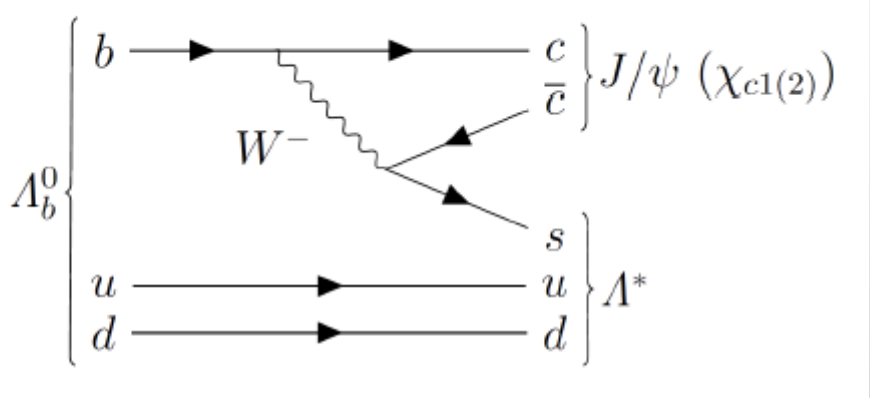
Argard diagram for the $P_c(4450)$ amplitude



- $P_c(4450)$ just above the χ_{c1} p threshold
- Could it be explained by kinematic rescattering effects
  [Meißner et al. PLB 751 (2015) 59-62] [Guo et al. PRD 92 (2015) 071502(R)]
- Would not explain narrow enhancement in χ_{c1} p

Rescattering mechanism



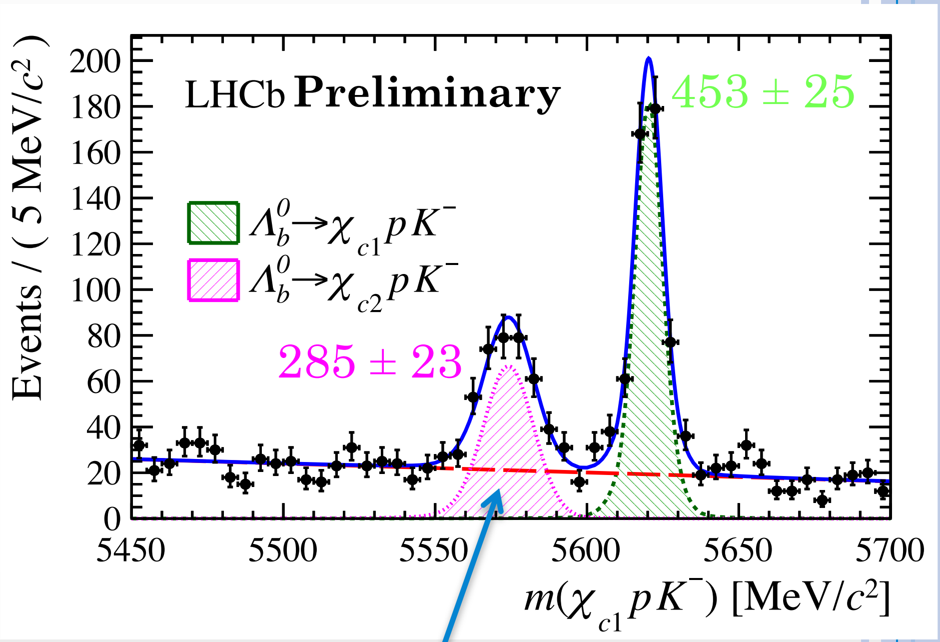


The $\Lambda^0_b \to \chi_{c1(2)}$ p K Decays

[LHCb-PAPER-2017-011 in preparation]

$\Lambda^0_b \to \chi_{c1(2)}$ p K candidates reconstructed using the decays $\chi_{c1(2)} \to J/\psi\, \gamma$

- Dataset: 3 fb^{-1}
- $J/\psi\, \gamma$ invariant mass constrained to the mass of χ_{c1}
- Selection consisting of a multivariate classifier based on a gradient-boosted decision tree



Two new decay modes observed with high statistical significance:
$\Lambda^0_b \to \chi_{c1}$ p K (29σ) and $\Lambda^0_b \to \chi_{c2}$ p K (17σ)

Signal shifted down due to the χ_{c1} mass constraint

RESULTS

[LHCb-PAPER-2017-011 in preparation]

Branching ratios are measured relative to $\Lambda^0_b \to J/\psi\, p\, K$ decay mode:

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.243 \pm 0.014 \pm 0.012 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.246 \pm 0.020 \pm 0.014 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = 1.01 \pm 0.10 \pm 0.02 \pm 0.005$$

Preliminary

N.B. $\frac{\mathcal{B}(B^0 \to \chi_{c2} K^{*0})}{\mathcal{B}(B^0 \to \chi_{c1} K^{*0})} = (17.1 \pm 0.50 \pm 1.7 \pm 1.1) \times 10^{-2}$ [NPB 874 (2013) 663]

where the first uncertainty is statistical, the second systematic and the third due to the uncertainty on the branching fractions of the $\chi_{c1(2)} \to J/\psi\gamma$ decays

Using both decay modes, the mass of the Λ^0_b baryon is also measured

$$m(\Lambda^0_b) = 5619.44 \pm 0.28 \pm 0.25\ \text{MeV}/c^2$$

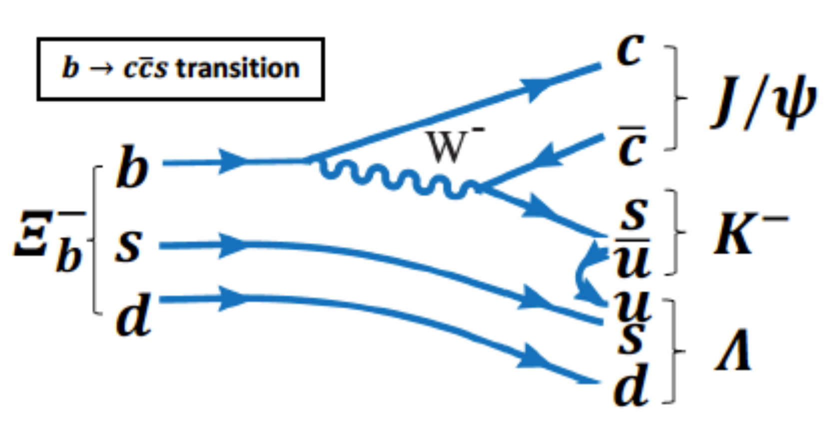
Preliminary

Observation of $\Xi_b^- \rightarrow J/\psi\, \Lambda\, K^-$ decays

[arXiv: 1701.05274]

Motivation

- Two hidden charm pentaquark states were found in $\Lambda^0_b \rightarrow J/\psi\, p\, K$ decays [PRL 115 (2015) 072001]
- A strangeness hidden charm pentaquark state, decaying to $J/\psi\, \Lambda$ is predicted with a mass of 4650 MeV and a width of order of 10 MeV which can be searched in $\Xi_b^- \rightarrow J/\psi\, \Lambda\, K$ decays [PRC 93 (2016) 065203]
- $\Xi_b^- \rightarrow J/\psi\, \Lambda\, K$ channel has similar topology to $\Lambda^0_b \rightarrow J/\psi\, p\, K$ mode by replacing the *u* by the *s* quark



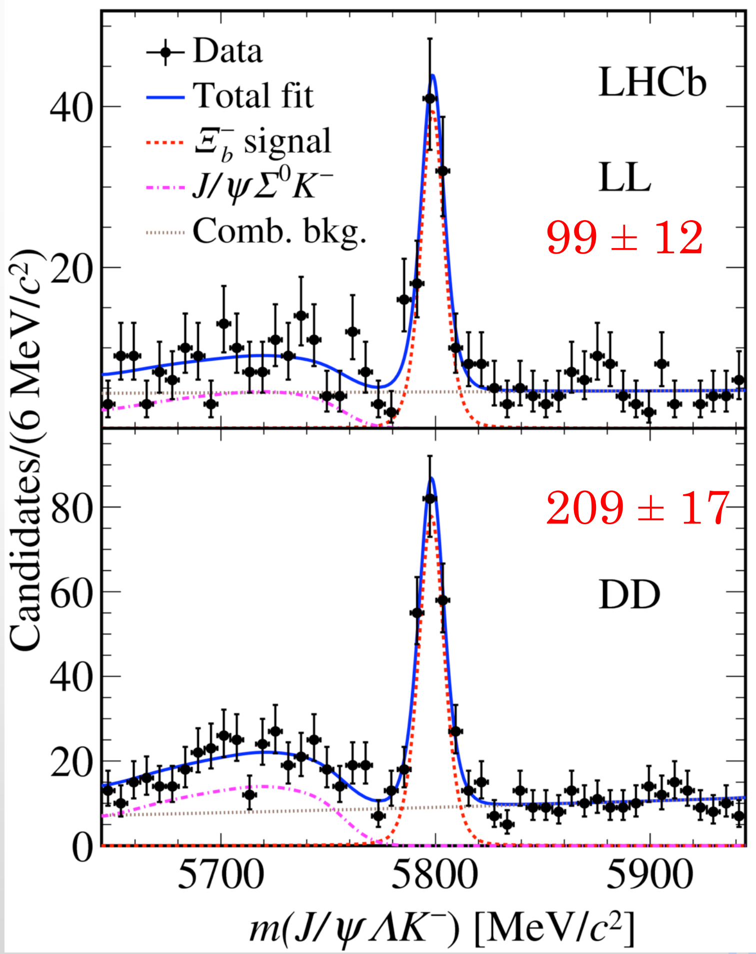
Leading order diagram of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$

THE Ξ_b^- → J/ψ Λ K⁻ DECAYS

[arXiv: 1701.05274]

Λ's can decay inside (LL) or outside (DD) of the vertex detector

- Dataset: 3 fb^{-1}
- J/ψ and Λ mass constrained
- First observation!



Branching ratios measured relative to $\Lambda^0_b \to J/\psi\,\Lambda$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \times \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = 0.0419 \pm 0.0029(\text{stat}) \pm 0.0014(\text{syst})$$

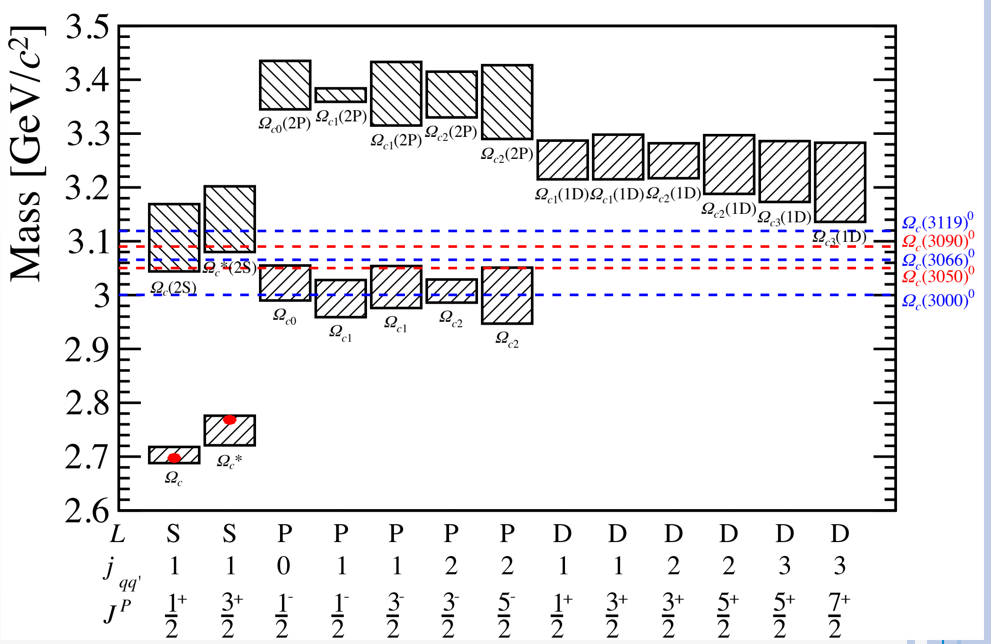
Fragmentation fractions of $b \to \Xi^0_b$ and $b \to \Lambda^0_b$ transitions

Summary

5 narrow peaks observed in $\Xi_c^+K^-$
Difficult to state if they are the orbitally or radially excitations of the Ω^0_c baryon

Determination of their quantum numbers from Ω_b decays might be possible in a near future

Search for other decay modes are ongoing



- ✓ The investigation of pentaquarks keeps going at LHCb by looking for new decay modes of $P_c(4450)$ and searching for new states decaying to $J/\psi\Lambda$
- ✓ The initial stage, presented here, focused on the first observations of new decay modes

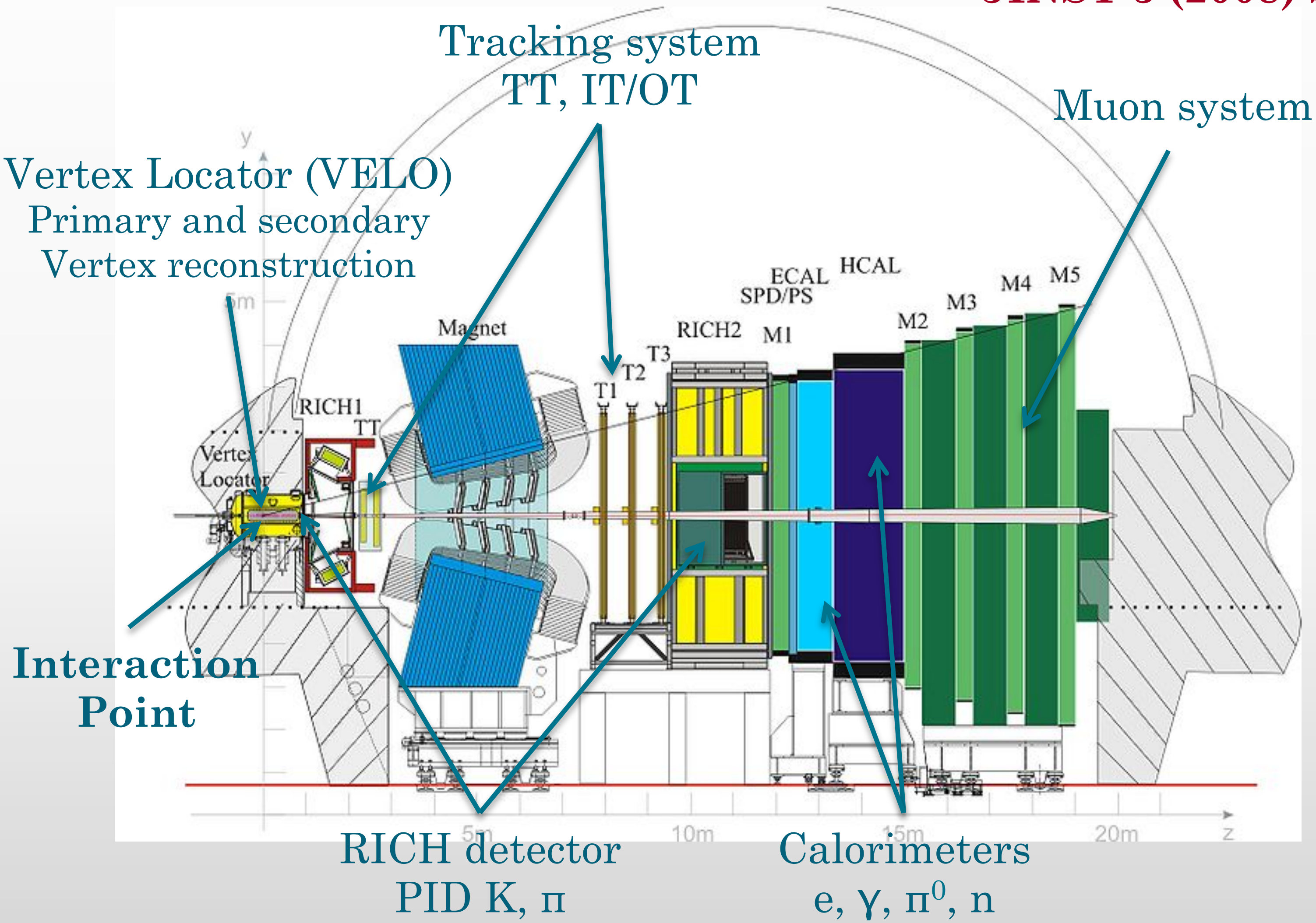
$\Lambda^0_b \to \chi_{c1(2)}\, p\, K^-$ $\Xi_b^- \to J/\psi\, \Lambda\, K^-$

The upcoming data taking will allow amplitude analyses of these decay modes aiming to the search for signals into the $\chi_{c1(2)}\, p$ and $J/\psi\Lambda$ mass spectra

Back-up slides

The LHCb Detector

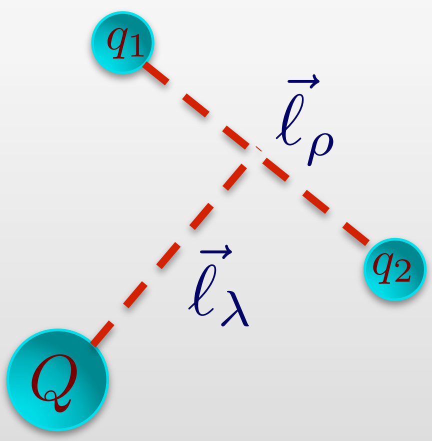
JINST 3 (2008) S08005



INTRODUCTION

- The heavy quark effective theories (HQET) predict the masses of the heavy mesons/baryons by a perturbative expansion of $\Lambda_{QCD}/m_Q \sim 0$
- Precise measurements of the excited heavy meson properties are a sensitive test of the validity of HQET

Heavy baryon often modeled as a system consisting of a static heavy quark Q surrounded by a diquark system comprised of the two light quarks



$\vec{\ell}_\rho$	Orbital angular momentum between the two light quarks
$\vec{\ell}_\lambda$	Orbital angular momentum between the heavy quark and the diquark system
$\vec{L} = \vec{\ell}_\rho + \vec{\ell}_\lambda$	Total orbital angular momentum
$\vec{s}_{qq} = \vec{s}_{q_1} + \vec{s}_{q_2}$	Sum of light quarks spins
$\vec{s}_{Q=b,c}$	Spin of the heavy quark
$\vec{j}_{qq} = \vec{L} + \vec{s}_{qq}$	Angular momentum of the diquark system
$\vec{J} = \vec{j}_{qq} + \vec{s}_Q$	Total angular momentum of the heavy meson

$$\text{Parity } P = (-1)^{\ell_\rho + \ell_\lambda}$$

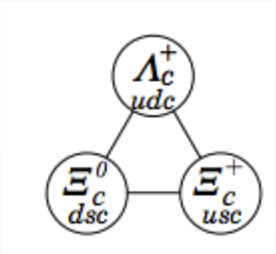
GROUND STATES

- Baryons made of 3 quarks (fermions)
- Wave function must be antisymmetric under interchange of any two equal-mass quarks

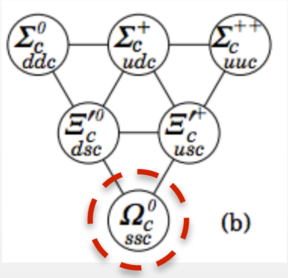
$$|qqq\rangle_A = |\text{color}\rangle_A \times |\text{space, spin, flavor}\rangle_S$$

SU(3) Multiplets

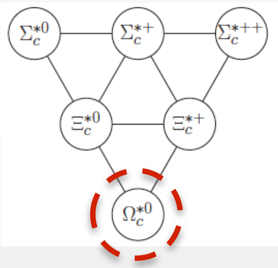
j=0⁺ J^P=1/2⁺



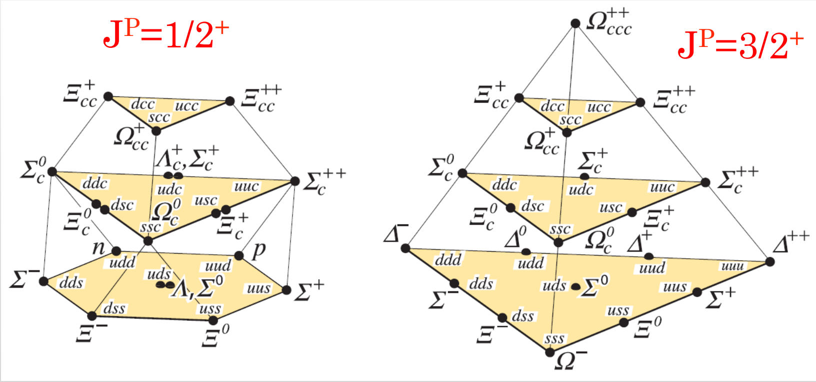
j=1⁺ J^P=1/2⁺



j=1⁺ J^P=3/2⁺



SU(4) Multiplets

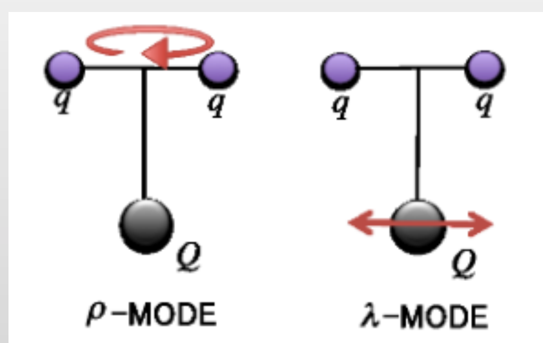


Excited P-wave Ω^0_c States

[X-H Chen *et al.* Phys. Rev. D 91 (2015) 054034]

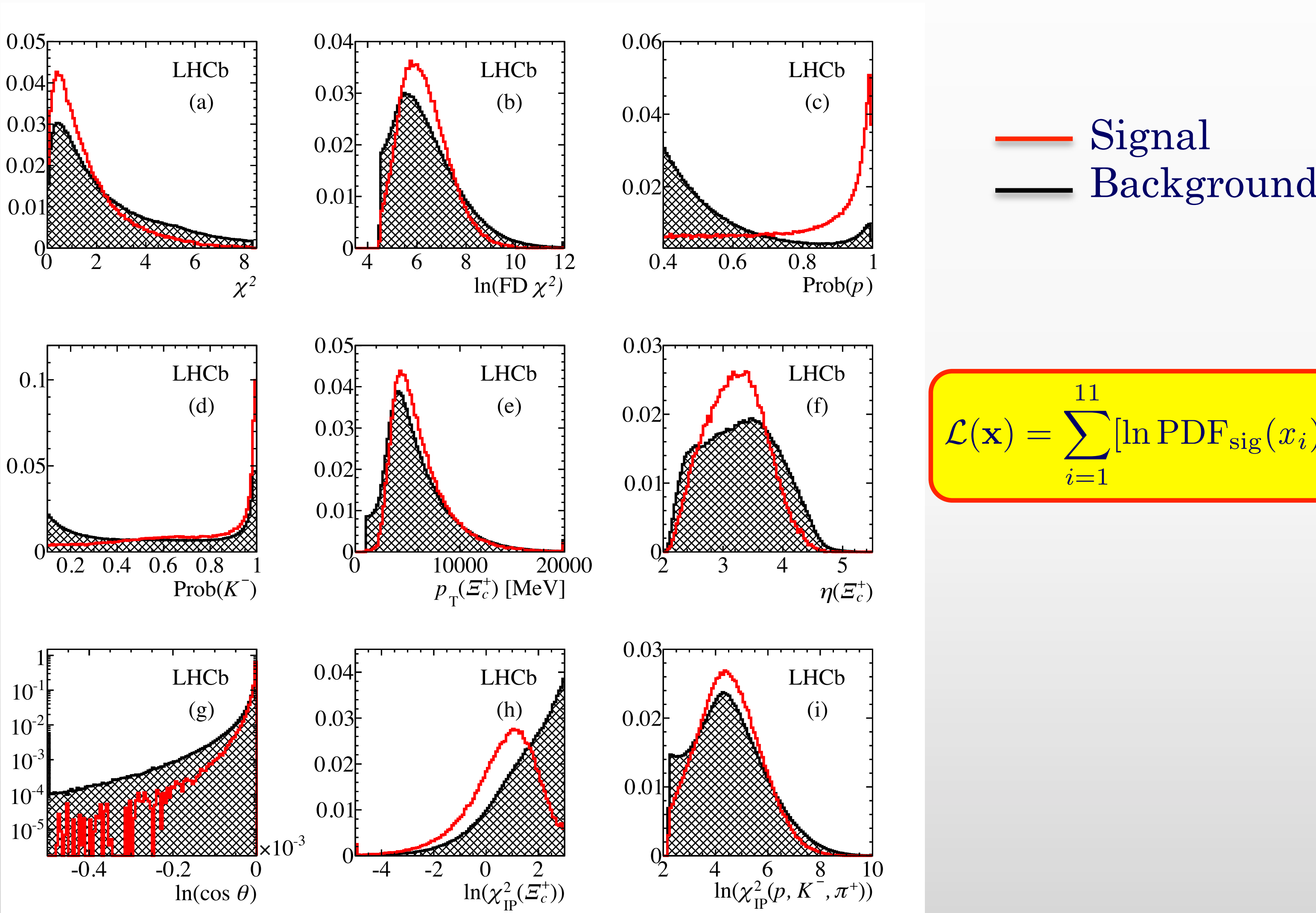
$\bar{\mathbf{3}}_C$ (A)

Orbital	s_l	Flavor	j_l	States			Label
$l_\rho = 1$ (A), $l_\lambda = 0$	$s_l = 0$ (A)	$\mathbf{6}_F$ (S)	$j_l = 1$:	$\Sigma_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	$\Xi'_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	$\Omega_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	(1-a) $[\mathbf{6}_F, 1, 0, \rho]$
	$s_l = 1$ (S)	$\bar{\mathbf{3}}_F$ (A)	$j_l = 0$:	$\Lambda_{c0}(\frac{1}{2}^-)$	$\Xi_{c0}(\frac{1}{2}^-)$		(1-b) $[\bar{\mathbf{3}}_F, 0, 1, \rho]$
			$j_l = 1$:	$\Lambda_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	$\Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$		(1-c) $[\bar{\mathbf{3}}_F, 1, 1, \rho]$
			$j_l = 2$:	$\Lambda_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$	$\Xi_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$		(1-d) $[\bar{\mathbf{3}}_F, 2, 1, \rho]$
$l_\rho = 0$ (S), $l_\lambda = 1$	$s_l = 0$ (A)	$\bar{\mathbf{3}}_F$ (A)	$j_l = 1$:	$\Lambda_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	$\Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$		(2-a) $[\bar{\mathbf{3}}_F, 1, 0, \lambda]$
	$s_l = 1$ (S)	$\mathbf{6}_F$ (S)	$j_l = 0$:	$\Sigma_{c0}(\frac{1}{2}^-)$	$\Xi'_{c0}(\frac{1}{2}^-)$	$\Omega_{c0}(\frac{1}{2}^-)$	(2-b) $[\mathbf{6}_F, 0, 1, \lambda]$
			$j_l = 1$:	$\Sigma_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	$\Xi'_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	$\Omega_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$	(2-c) $[\mathbf{6}_F, 1, 1, \lambda]$
			$j_l = 2$:	$\Sigma_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$	$\Xi'_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$	$\Omega_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$	(2-d) $[\mathbf{6}_F, 2, 1, \lambda]$



Search for Excited Ω^0_c States
Probability Density Functions

[arXiv:1703.04639]



$$\mathcal{L}(\mathbf{x}) = \sum_{i=1}^{11} [\ln \mathrm{PDF}_{\mathrm{sig}}(x_i) - \ln \mathrm{PDF}_{\mathrm{back}}(x_i)]$$

Just for curiosity…

[Phys. Rev. Lett. 117 (2016) 152003]

If $\rho_X^{\mathrm{LHCb}} = \rho_X^{\mathrm{D\O}} = 8.6\%$, how would the X(5568) signal look like?

(Both modes combined: $p_T(B_s) > 10$ GeV/c)