Baryon Spectroscopy at LHCb

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Exotic Hadron Spectroscopy 2017
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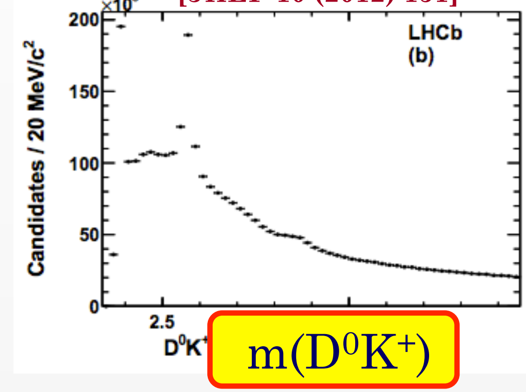
How to Do Spectroscopy?

Prompt Production: (e.g. pp → $D_s^{**}(\rightarrow D^0K) + X$)

- ✓ Large cross sections
- ✗ Large combinatorial background
- ✗ Hard to disentangle broad structures
- ✗ Difficult to assess spin
- ✗ Presence of "reflections"/"feed-downs"

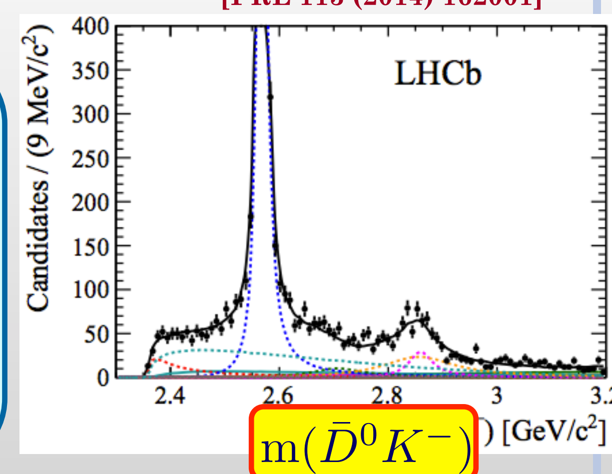
[JHEP 10 (2012) 151]



b-hadron decays (e.g. $B_s \rightarrow D_s^{**}(\rightarrow D^0K)\ \pi$)

- ✓ Small background
- ✓ Access to the phase of the amplitude and spin-parity
- ✗ Limited cross sections
- ✗ High spin resonances suppressed
- ✗ Presence of "shadows"

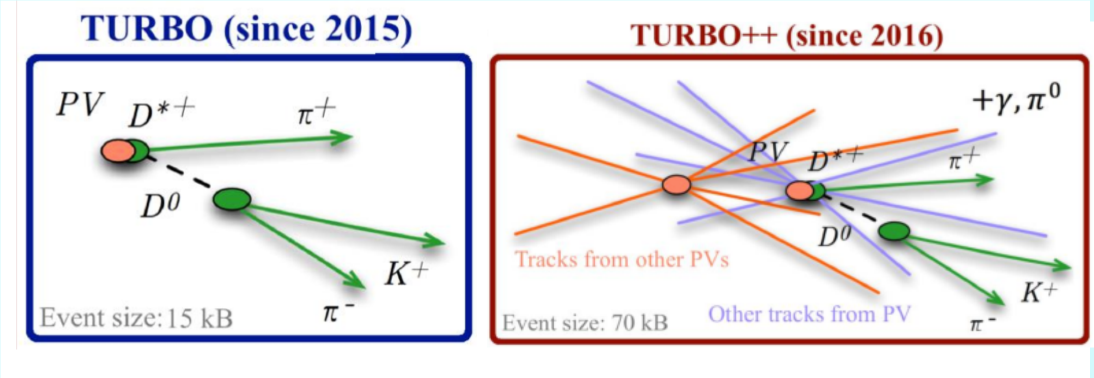
[PRL 113 (2014) 162001]



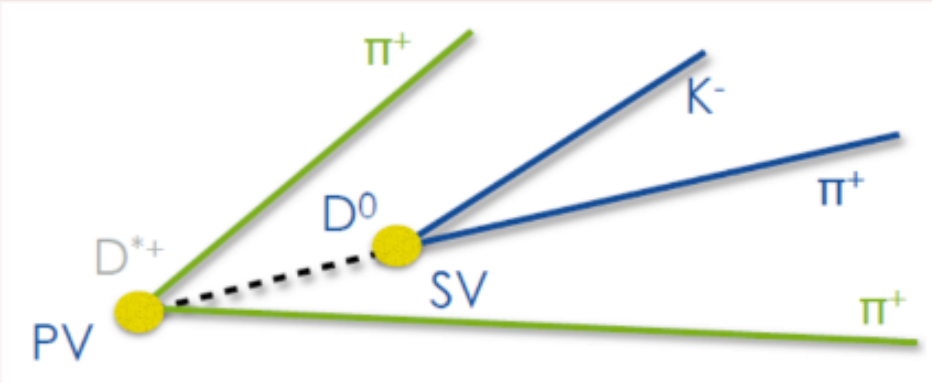
TRIGGER: TURBO STREAM

[Comput. Phys. Commun. 208 (2016) 35]

- Novel approach in Run 2 that exploits the LHCb real-time alignment capabilities
- Crucial for states with large production cross-sections (i.e. charmed hadrons, hyperons,...)
- Large disk space saving



- New intermediate solution in 2017: Turbo SP (Selective Persistence) that allows to save candidates and a subset of the reconstruction
- Allows particles nearby the PV to be chosen for further analysis



THE *bqq* (*q=u,d,s*) BARYONS (B=1, C=0)

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
Λ_b	$b[ud]$	$1/2^+$	3*	(0, 0)	0	1
Ξ_b^0	$b[su]$	$1/2^+$	3*	(1/2, 1/2)	-1	1
Ξ_b^-	$b[sd]$	$1/2^+$	3*	(1/2, -1/2)	-1	1
Σ_b^+	buu	$1/2^+$	6	(1, 1)	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	(1, 0)	0	1
Σ_b^-	bdd	$1/2^+$	6	(1, -1)	0	1
$\Xi_b^{0\prime}$	$b\{su\}$	$1/2^+$	6	(1/2, 1/2)	-1	1
$\Xi_b^{-\prime}$	$b\{sd\}$	$1/2^+$	6	(1/2, -1/2)	-1	1
Ω_b^-	bss	$1/2^+$	6	(0, 0)	-2	1
Σ_b^{*+}	buu	$3/2^+$	6	(1, 1)	0	1
Σ_b^{*0}	bud	$3/2^+$	6	(1, 0)	0	1
Σ_b^{*-}	bdd	$3/2^+$	6	(1, -1)	0	1
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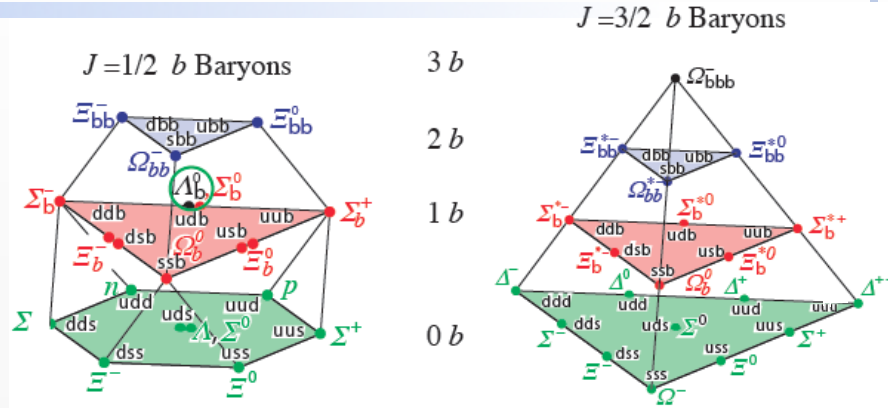


The system of baryons containing a *b* quark remains largely unexplored, despite recent progress made at the experiments at the Tevatron

Missing states before LHC era

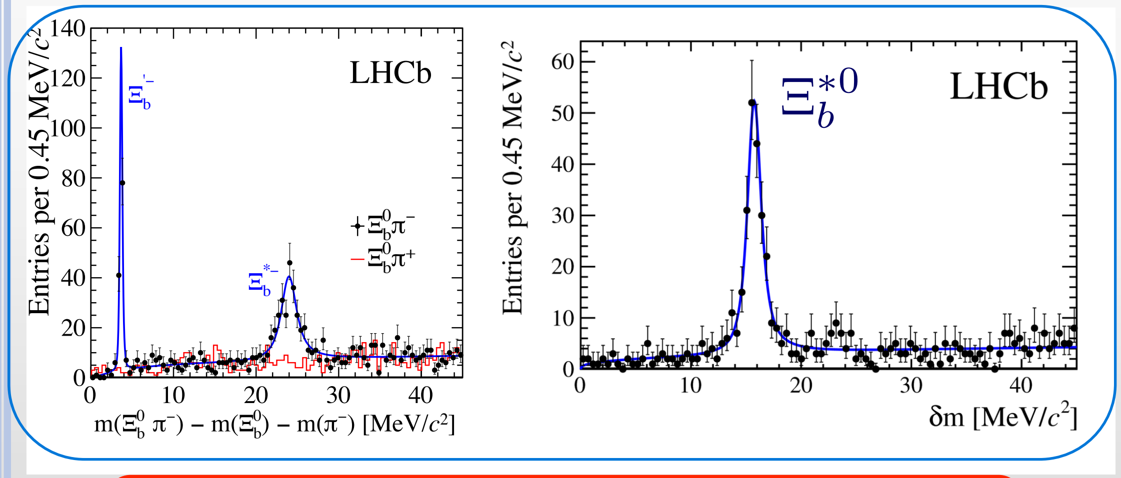
"Spin excited states"

Beauty Baryon Spectroscopy

- ✓ Filling the gaps of the missing ground states
- ✓ First observation of excited beauty baryons

[PRL 114 (2015) 062004, JHEP 05 (2016) 161]

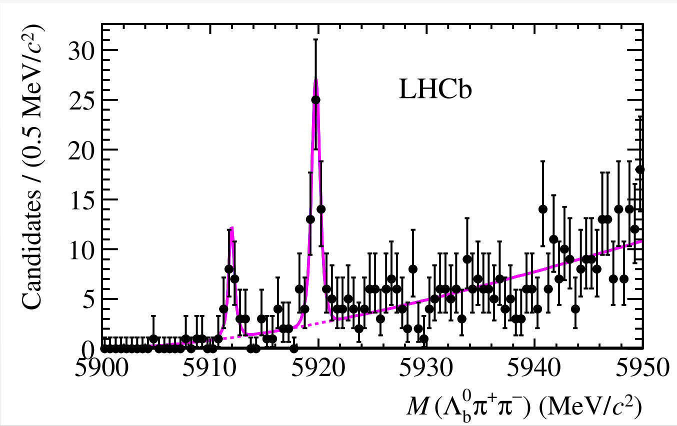
$\Xi_b^{**} \rightarrow \Xi_b\pi$, where $\Xi_b \rightarrow \Xi_c\pi$



Three narrow peaks interpreted as $\Xi_b'^{-}$ ($J^P = 1/2^+$), Ξ_b^{*-} ($J^P = 3/2^+$), Ξ_b^{*0} ($J^P = 3/2^+$)

[PRL 109 (2012) 172003]

$\Lambda_b^{**0} \rightarrow \Lambda_b^0\pi^+\pi^-$, where $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$

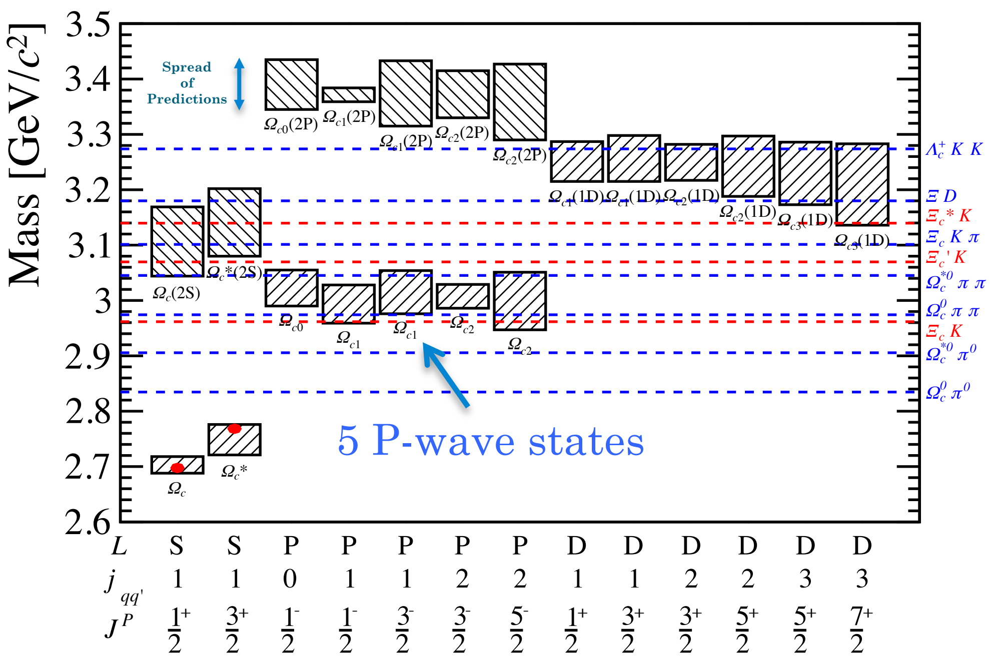


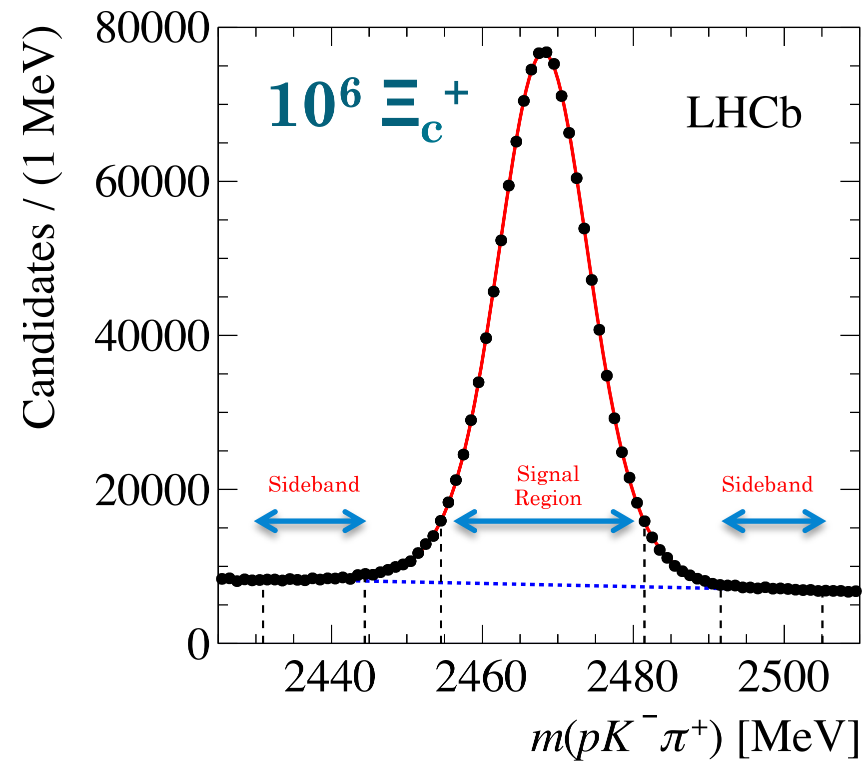
Two new peaks are interpreted as the orbitally L=1 excited Λ_b^0 states

Excited Ω^0_c States Decaying to $\Xi_c^+ K^-$

[PRL 118 (2017) 182001]

- Only the ground states Ω^0_c ($J^P=1/2^+$) and Ω^{*0}_c($J^P=3/2^+$) are known so far
- Reconstruction of Cabibbo suppressed $\Xi_c^+ \rightarrow pK^-\pi^+$ decays
- 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)

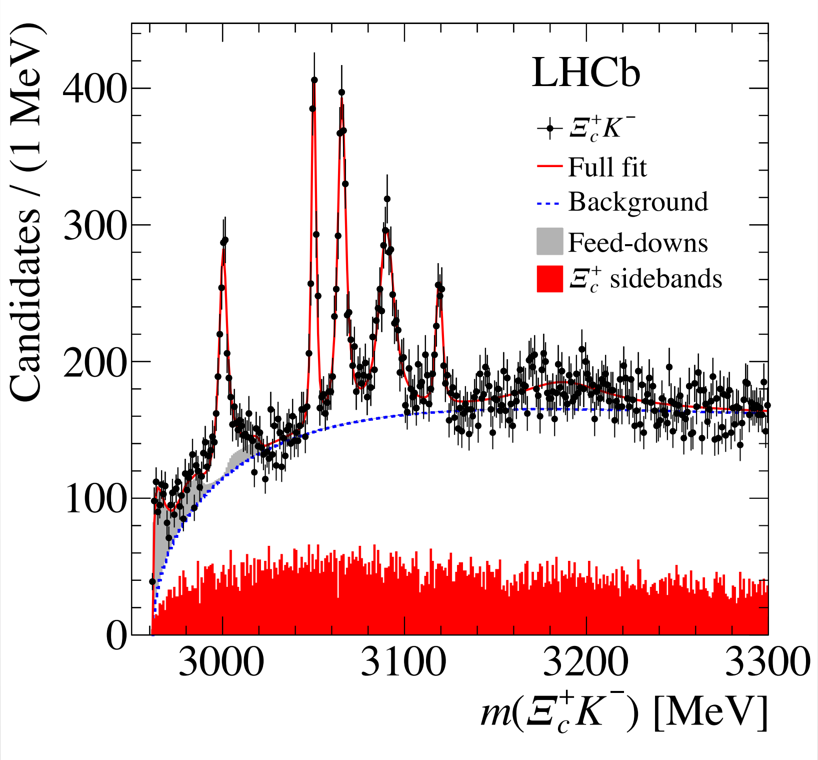




Five New Excited Ω^0_c States!

[PRL 118 (2017) 182001]

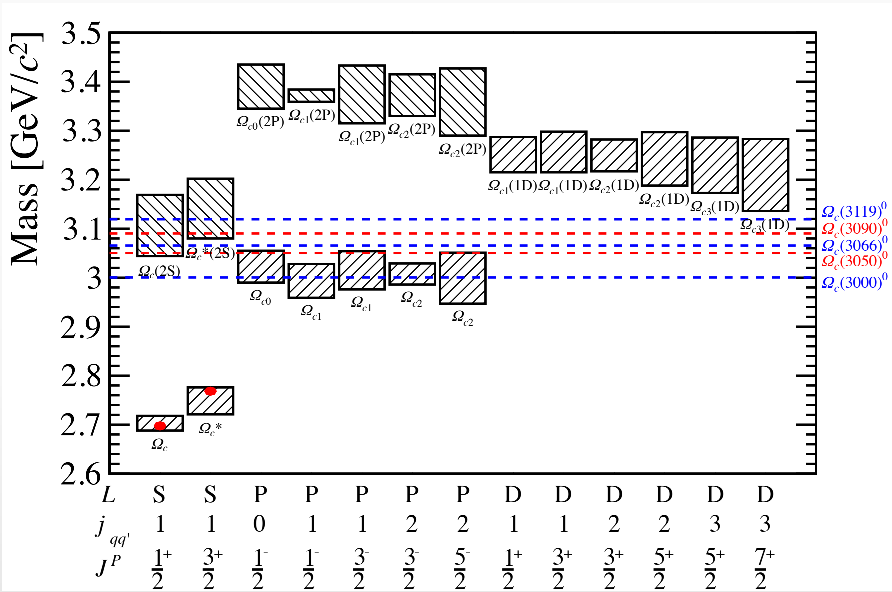
- Observation of **5** new excited Ω_c states! Two of them extremely narrow
- Many interpretations proposed (including pentaquarks)
- The broad state could be a superposition of several states
- Threshold enhancement consistent with being due to the partially reconstructed decay $\Omega_c(3066)^0 \rightarrow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

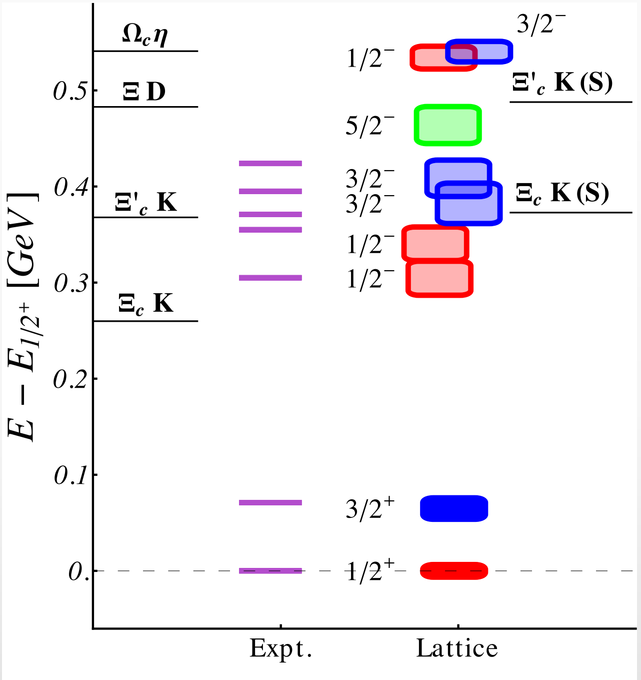


Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		< 1.2 MeV, 95% CL
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		< 2.6 MeV, 95% CL
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$

WHAT ARE THEY? WHY ARE THEY SO NARROW?

Most of the authors identified these states as the orbitally or radially excitations of the Ω^0_c baryon





The narrowness of the states might be a hint that it is difficult to get apart the two *s* quark in a *c(ss)* system. The decays ΞD would have been favored (if allowed kinematically)

What are They? Why are they so narrow?

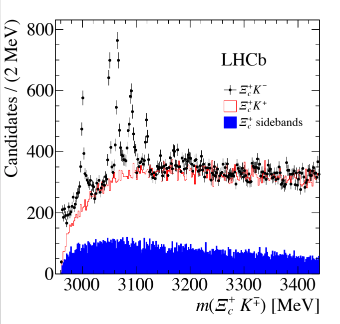
Are they orbitally excited (L=1) states? Or radiatally excitations? Or…

TABLE II: Spin-parity (J^P) numbers of the newly observed Ω_c states suggested in various works.

State	[19]	[20]	[21]	[23]	[29]	[25]	[27]	[28]	[32]	[26]	This work
$\Omega_c(3000)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^-$	$1/2^+$ or $3/2^+$	$1/2^-$		$1/2^-$
$\Omega_c(3050)$		$1/2^-$	$1/2^-$ $(3/2^-)$	$1/2^-$	$5/2^-$	$3/2^-$	$1/2^-$	$5/2^+$ or $7/2^+$	$3/2^-$		$3/2^-$
$\Omega_c(3066)$	$1/2^+$	$1/2^+$ or $1/2^-$	$3/2^-(5/2^-)$	$3/2^-$	$3/2^-$	$5/2^-$	$3/2^-$	$3/2^-$	$1/2^+$		$3/2^-$
$\Omega_c(3090)$			$3/2^-$ $(1/2^+)$	$3/2^-$	$1/2^-$	$1/2^+$	$3/2^-$	$5/2^-$	$1/2^+$		$5/2^-$
$\Omega_c(3119)$	$3/2^+$	$3/2^+$	$5/2^-$ $(3/2^+)$	$5/2^-$	$3/2^-$	$3/2^+$	$5/2^-$	$5/2^+$ or $7/2^+$	$3/2^+$	$1/2^-$	$1/2^+$ or $3/2^+$

[K.-L. Wang, L.-Y. Xiao, X.-H. Zhong, Q. Zhao, Phys. Rev. D95 (2017) 116010]

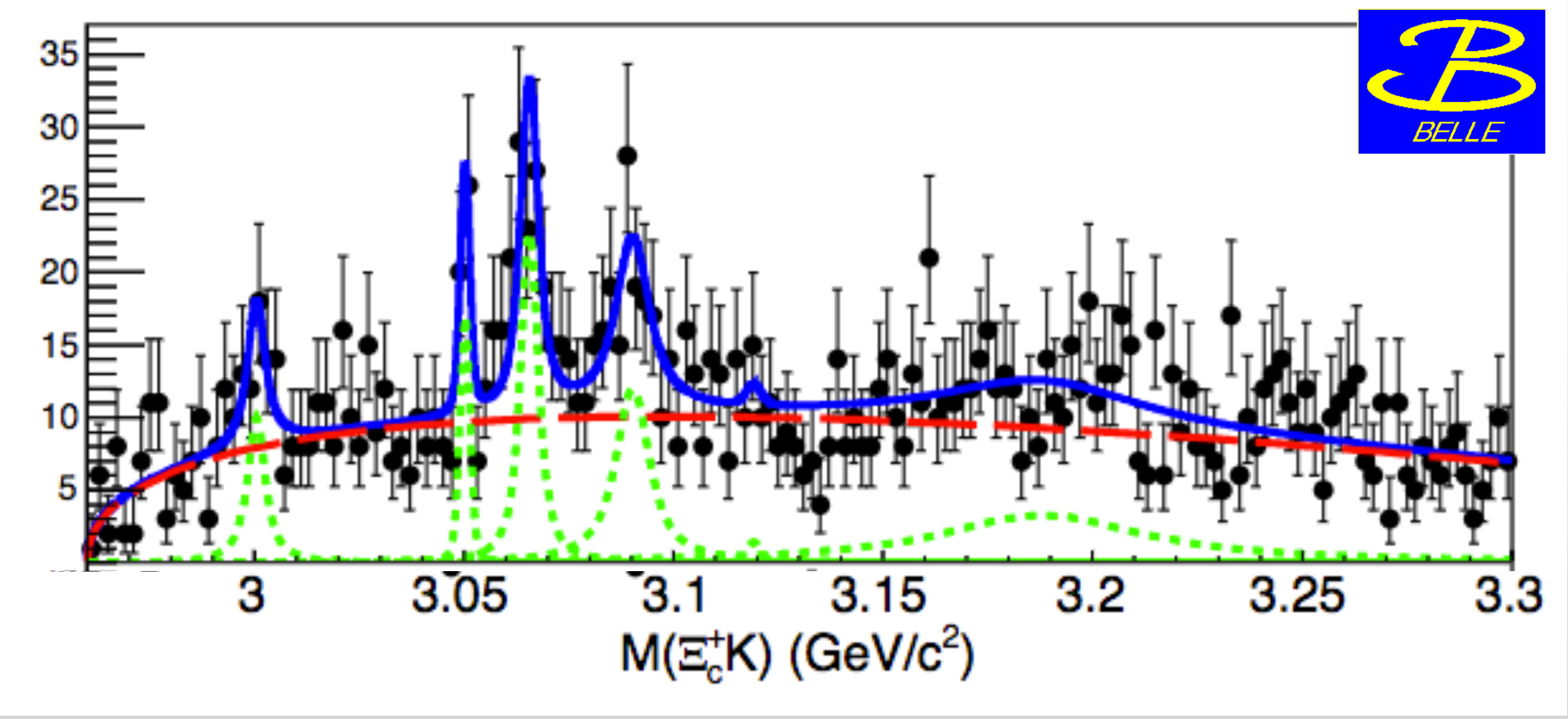
…or are they pentaquarks? (N.B. The lack of signals in the $\Xi_c^+K^+$ spectrum should be addressed in the latter scenario)



Confirmation of Excited Ω^0_c at Belle

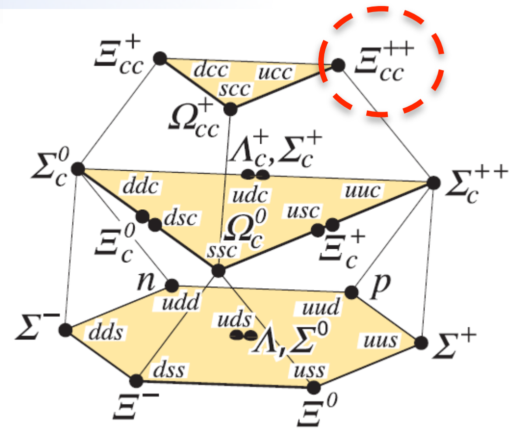
arXiv:1711.07927

- 4 out of 5 states confirmed
- The narrow state at high mass is missing (not in disagreement with the LHCb observation)
- If the 5th state is a pentaquark, suppression expected in the e^+e^- production



Observation Of The Doubly Charmed Baryon Ξ_{cc}^{++} [PRL 119 (2017) 112001]

- All of the ground states with C=0 or C=1 have been observed
- Three weakly decaying C=2 states expected: Ξ_{cc} isodoublet and Ω_{cc} isosinglet
- SELEX reported signals of $\Xi_{cc}^{+} \rightarrow \Lambda_c^+ K^- \pi^+$, pD^+K^- [PRL 89 (2002) 112001, PLB 628 (2005) 18]
- Not confirmed by BaBar [PRD 74 (2006) 011103], Belle [PRL 97 (2006) 162001] nor LHCb [JHEP 12 (2013) 090]



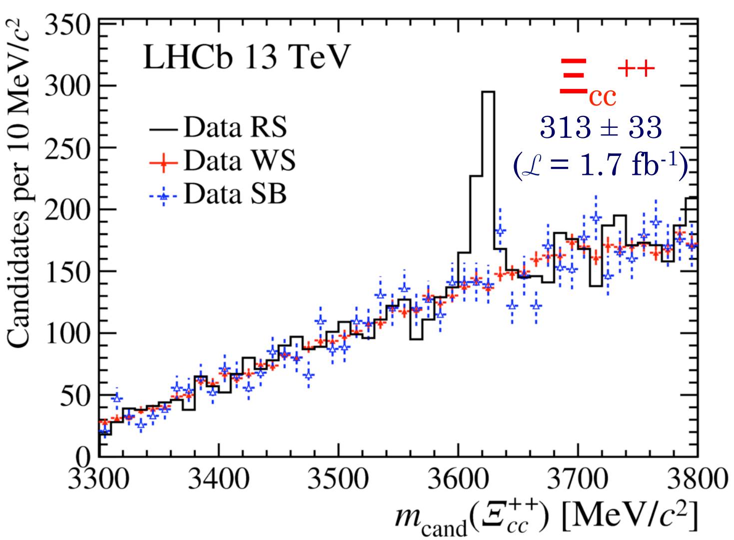
Search for Ξ_{cc}^{++} in the decay chain (2016 data):

$$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+, \ \Lambda_c^+ \rightarrow p K^- \pi^+$$

Turbo stream

Highly significant signal observed (>12σ) consistent with a state decaying weakly

$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(stat) \pm 0.27\,(syst) \pm 0.14\,(\Lambda_c^+)$ MeV



Inconsistent with being isospin partner of the SELEX state: $m(\Xi_{cc}^{++})-m(\Xi_{cc}^{+}) = 103 \pm 2$ MeV

Amplitude Analysis of $\Lambda_b \to D^0 p \pi^-$

[JHEP 05 (2017) 30]

- The spectrum of the excited Λ_c baryon is still incomplete
- 5D amplitude analysis of $\Lambda_b \to D^0 p \pi^-$ aiming to study the excited $\Lambda_c^{**} \to D^0 p$

$\Lambda_c(2860)^+$ with $J^P = 3/2^+$ (preferred)

$$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV}$$

$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}$$

$\Lambda_c(2880)^+$ with $J^P = 3/2$ (preferred)

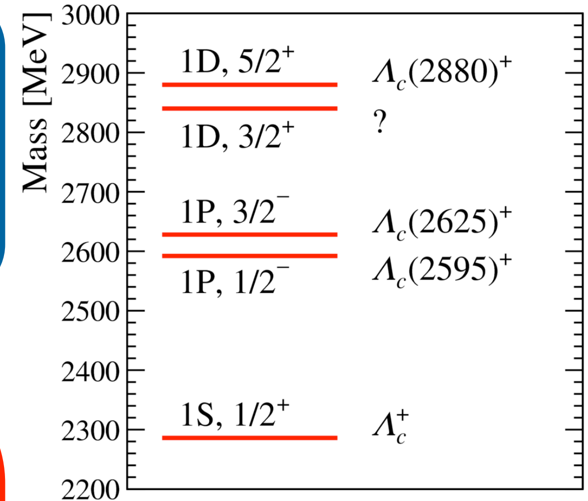
$$m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})\ \text{MeV}$$

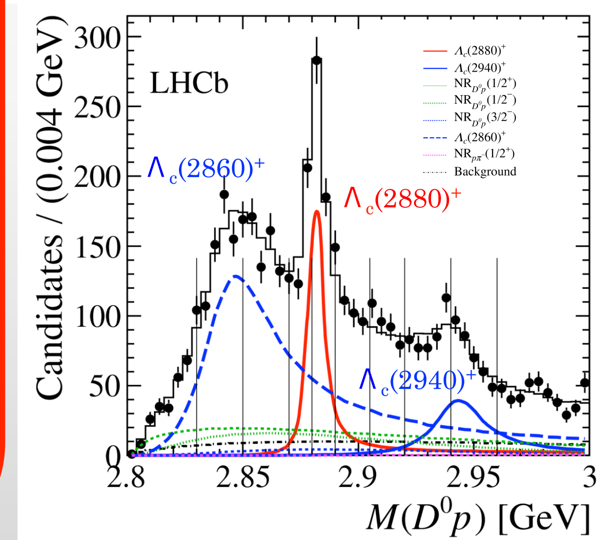
$$\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})\ \text{MeV}$$

$\Lambda_c(2940)^+$ with $J^P = 3/2^-$ (preferred)

$$m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5}(\text{stat}) \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})\ \text{MeV}$$

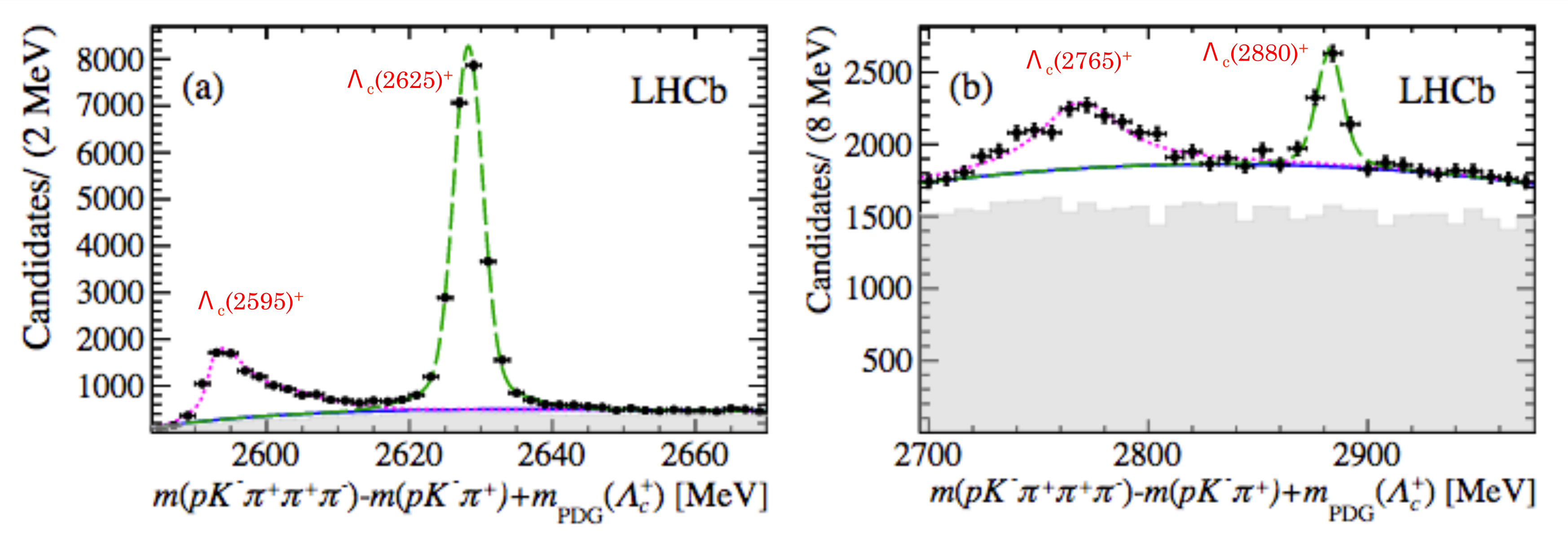
$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0}(\text{stat}) \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model})\ \text{MeV}$$





$\Lambda_c^{**} \rightarrow \Lambda_c \pi\pi$ IN SEMILEPTONIC DECAYS

arXiv:1709.01920



- Observation of 4 excited Λ_c baryons
- Searches for dipion decays are challenging in prompt production

PLAN & PROSPECTS

LHCb Going to Upgrade

Upgrade I

- Main limitation that prevents exploiting higher luminosity with the present detector is the Level-0 (hardware) trigger
  - ✓ – Level-0 output rate < 1 MHz (readout rate) requires raising thresholds
- This is particularly problematic for hadronic final states
- Running at 2×10^{33} cm^{-2} s^{-1} with full software trigger, running at 40 MHz

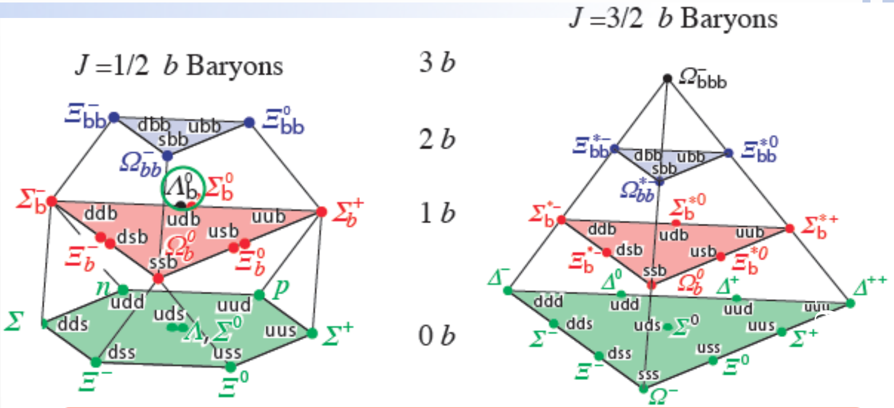
Upgrade II

To be installed in Long Shutdown 4 of the LHC:

- Subsystems redesigned to operate at a luminosity of 1-2 x 10^{34} cm^{-2} s^{-1}
- Integrated luminosity of > 300 fb^{-1}
- Extension of the experiment's capabilities into selecting π^0, η, γ and low-momentum tracks [CERN−LHCC−2017−003]

LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1}
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

THE *bqq (q=u,d,s)* BARYONS (B=1, C=0)



Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
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Ξ_b^-	$b[sd]$	$1/2^+$	3^*	(1/2, -1/2)	-1	1
Σ_b^+	buu	$1/2^+$	6	(1, 1)	0	1
Σ_b^0	$b\{ud\}$	$1/2^+$	6	(1, 0)	0	1
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Ω_b^{*-}	bss	$3/2^+$	6	(0, 0)	-2	1

The system of baryons containing a *b* quark remains largely unexplored, despite recent progress made at the experiments at the Tevatron

Missing states

"Spin excited states"

SEARCH FOR $\Sigma_b^{(*)0} \rightarrow \Lambda_b^0 \pi^0$

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
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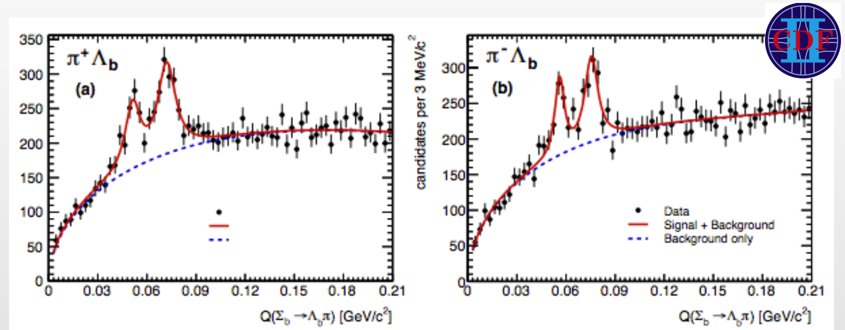
Ξ_b^{*-}	bds	$3/2^+$	6	(1/2, -1/2)	-1	1
Ω_b^{*-}	bss	$3/2^+$	6	(0, 0)	-2	1

$$m(\Sigma_b^0) \sim 5813\,\mathrm{MeV}$$
$$m(\Sigma_b^{*0}) \sim 5833\,\mathrm{MeV}$$

- Large Λ_b sample available
- Suppression of background is challenging, even more than $\Sigma^{(*)\pm}_b$



[PRD85 (2012) 092011]

Search For $\Xi_b^{'}$ and Ω_b^{*}

Notation	Quark content	J^P	SU(3)	(I, I_3)	S	B
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Ξ_b^{*0}	bus	$3/2^+$	6	(1/2, 1/2)	-1	1
Ξ_b^{*-}	bds	$3/2^+$	6	(1/2, -1/2)	-1	1
Ω_b^{*-}	bss	$3/2^+$	6	(0, 0)	-2	1

$$\Xi_b' - \Xi_b \sim 120\,\mathrm{MeV}$$
$$\Downarrow$$
$$\mathcal{B}(\Xi_b' \to \Xi_b\gamma) \sim 100\%$$

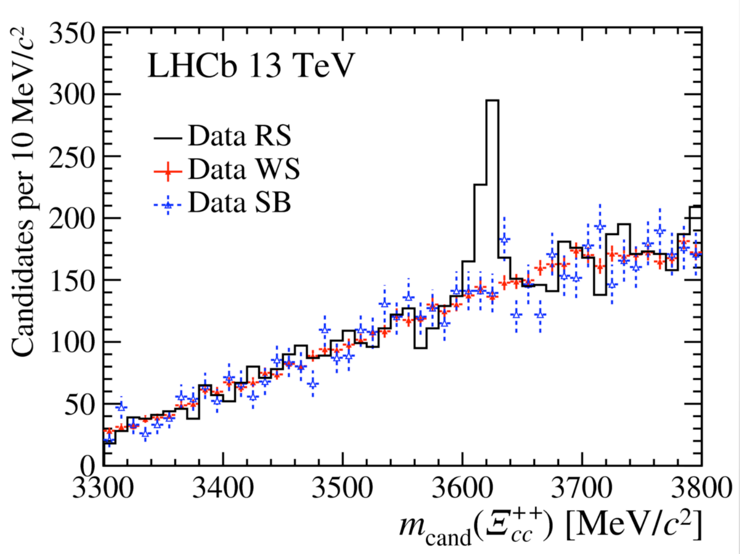
$$\Omega_b^* - \Omega_b \sim 20\mathrm{MeV}$$
$$\Downarrow$$
$$\mathcal{B}(\Omega_b^* \to \Omega_b\gamma) \sim 100\%$$

- Soft photon →Low efficiency
- Small Ω_b sample

Doubly Heavy Baryons

- Observations of Ξ_{cc}^{+} and Ω_{cc} expected with RUN II data or during the upcoming upgrade
- The Phase II upgrade will be useful into studying their production, BR's lifetime and excited spectra: Ξ^{**}_{cc} and Ω^{**}_{cc}. Ω_{ccc} is also likely to be observed

PRL 119 (2017) 112001



What about Ξ_{bc}?

- The B_c meson was discovered almost two decades ago
  In LHCb, ~5000 $B_c \rightarrow J/\psi\,\pi$ in Run I

So, why have we not yet seen bcq baryons (Ξ_{bc})?

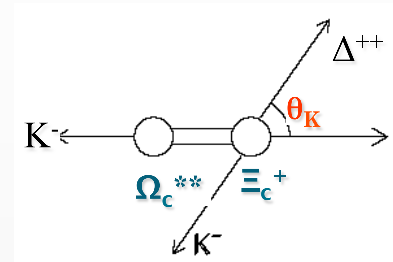
Lower production rates, guess $\sigma(X_{bc}) \sim (0.1\text{ -}0.5) \times \sigma(B_c^+)$
In J/ψ modes, (usually) get a charm baryon: yield reduced by $BF(X_c) \times \varepsilon_{sel}(X_c)$
Shorter lifetime (~0.15 – 0.4 ps range, compared to ~0.5 ps for B_c)

$$
\begin{aligned}
(e.g.)\, N(\Xi^0_{bc} \to J/\psi \Lambda_c^+ K^-; \mathrm{Run1}) = & N(B_c^+ \to J/\psi D_s^{(*)+}; \mathrm{Run1}) \\
& \times \frac{\sigma(pp \to \Xi_{bc} X)}{\sigma(pp \to B_c^+ X)} \times f_{\Xi_{bc} \to \Xi^0_{bc}} \\
& \times \frac{Br(\Xi^0_{bc} \to J/\psi \Lambda_c^+ K^-)}{Br(B_c^+ \to J/\psi D_s^{(*)+})} \\
& \times \epsilon_{K^-} \\
& \simeq 3\,\mathrm{candidates}
\end{aligned}
$$

$$N(\Xi^0_{bc} \to J/\psi \Lambda_c^+ K^-; \mathrm{Run\,5}) \simeq 6 \times 10^2$$

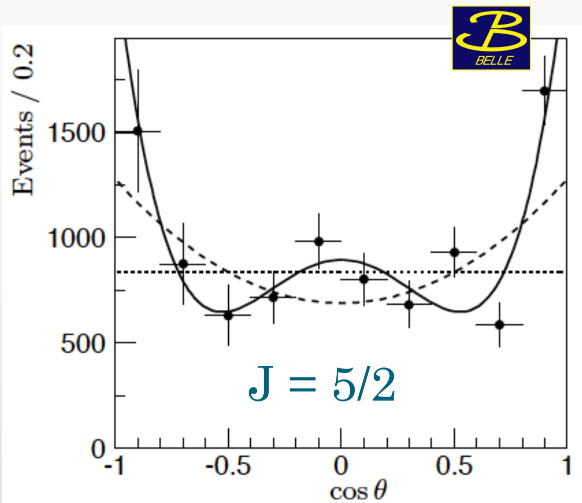
EXCITED Ω_c: DETERMINATION OF SPIN J

(E.g.) Decay chain $\Omega_c^{**} \rightarrow \Xi_c (\rightarrow \Delta^{++} K^- \text{ or } pK^*) K$

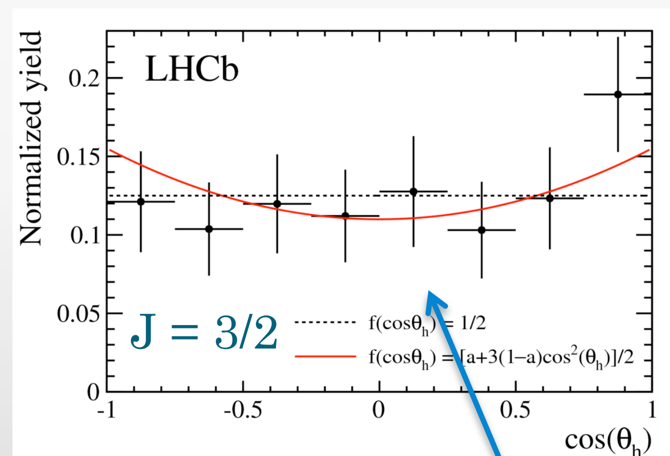


Helicity angle θ_K distributions may be used to distinguish between spin hypotheses for resonances.

$\Lambda_c(2880)^+ \rightarrow \Sigma_c(2455) (\rightarrow \Lambda_c \pi) \pi$
[Belle:Phys. Rev. Lett. 98 (2007) 262001]



$\Xi_b^{*-} \rightarrow \Xi_b^0 (\rightarrow \Xi_c^+ \pi^-) \pi^-$
[LHCb:Phys. Rev. Lett. 114 (2015) 062004]



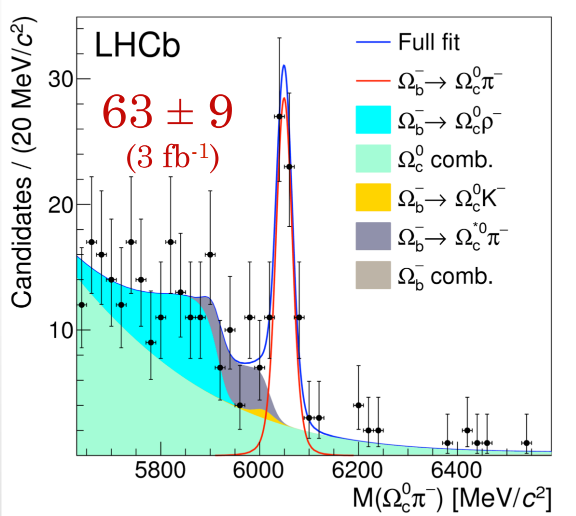
The method is not sensitive to the parity
(neither to the spin if the resonances are produced unpolarized)

Excited Ω_c: Determination of Spin-Parity J^P

Study of Ω_c^{**} in fully reconstructed decays: (e.g.) $\Omega_b^- \to \Xi_c^+ K^- \pi^-$

The decays $\Omega_b^- \to \Omega_c^0 (\to pKK\pi)\, \pi^-$ already observed.
Same number and type of tracks in the final state

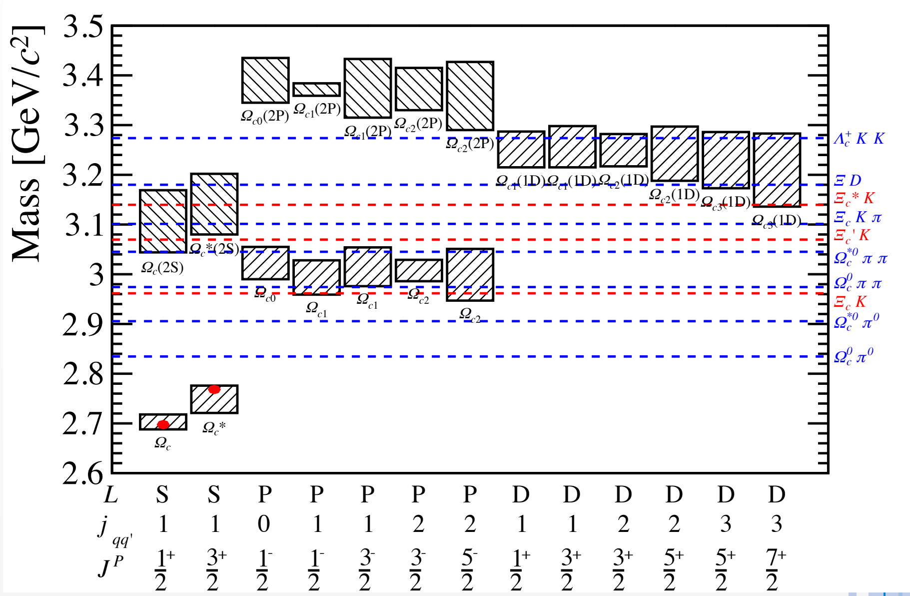
[Phys. Rev. D 93 (2016) 092007]



- ✓ Angular distributions might sligthly affected by $\Xi_c^{**0} \to \Xi_c^+ \pi^-$
- ✓ No resonances expected in the $K^- \pi^-$ system

Excited Ω_c: New Decay Modes

The nature of Ω_c^{**0} states can be probed by looking for new decay modes which can constrain the quantum numbers as well



✓ $\Omega_c^0\pi^+\pi^-$ and $\Omega_c^0\gamma$

Cabibbo suppressed decays $\Omega_c^0 \to pKK\pi$ are suitable to these searches. Low efficiency due to the large number of tracks or presence of a photon

✓ $\Xi_c' K$

Since $m(\Xi_c') - m(\Xi_c) \approx 110$ MeV, low efficiency into detecting the soft photons from $\Xi_c' \to \Xi_c\gamma$ decays. However possibility to study the feed-downs in the prompt search and from $\Omega_b^- \to \Xi_c'^+ K^- \pi^-$ decays

Excited Ω_c: Search for Exotic Pentaquark

The structure of pentaquarks Ω_c^0 in the chiral quark model

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Recently, the experimental results of LHCb Collaboration suggested the existence of five new excited states of Ω_c^0, $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$ and $\Omega_c(3119)^0$, the quantum numbers of these new particles are not determined now. To understand the nature of the states, a dynamical calculation of 5-quark systems with quantum numbers $IJ^P = 0(\frac{1}{2})^-$, $0(\frac{3}{2})^-$ and $0(\frac{5}{2})^-$ is performed in the framework of chiral quark model with the help of gaussian expansion method. The results show the $\Xi\bar{D}$, $\Xi_c K$ and $\Xi_c^* K$ are possible the candidates of these new particles. The distances between quark pairs suggest that the nature of pentaquark states.

The observed Ω_c^0 resonances as pentaquark states

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(Dated: May 25, 2017)

Abstract

In present work, we investigate the spectrum of several low-lying $sscq\bar{q}$ pentaquark configurations employing the constituent quark model, within which the hyperfine interaction between quarks is taken to be mediated by Goldstone boson exchange. Our numerical results show that four $sscq\bar{q}$ configurations with $J^P = 1/2^-$ or $J^P = 3/2^-$ lie at energies very close to the recently observed five Ω_c^0 states by LHCb collaboration, this indicates that the $sscq\bar{q}$ pentaquark configurations may form sizable components of the observed Ω_c^0 resonances.

Narrow pentaquarks as diquark-diquark-antiquark systems

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June 6, 2017

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Abstract

The diquark-diquark-antiquark model describes pentaquark states both in terms of quarks and hadrons. The latest LHCb data for pentaquarks with open charm emphasize the importance of hadron components in the structure of pentaquarks. We discuss pentaquark states with hidden charm $P(\bar{c}cuud)$ and those with open charm $P(\bar{u}ussc)$ which were discovered recently in LHCb data ($J/\Psi p$ and $\Xi_c^+ K^-$ spectra correspondingly). Considering the observed states as members of the lowest (s-wave) multiplet we discuss the mass splitting of states and the dumping of their widths.

On a possibility of charmed exotica

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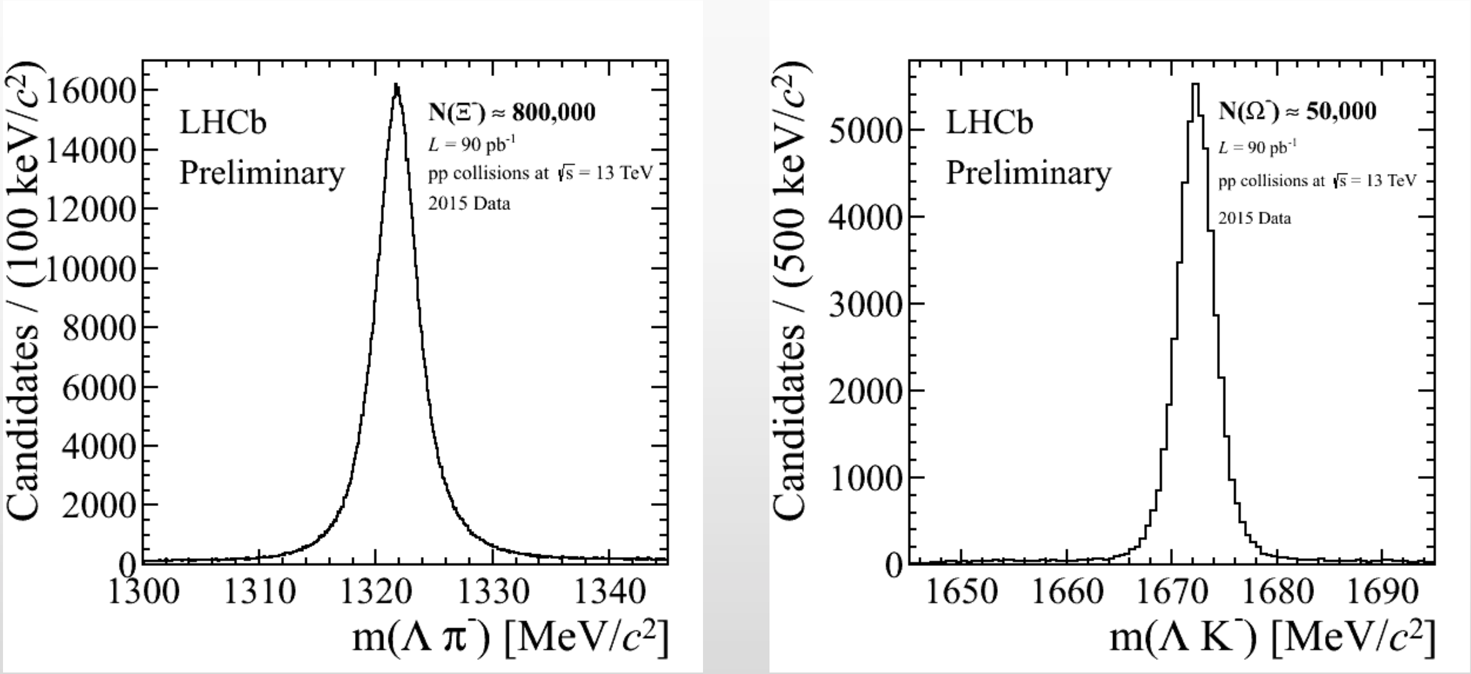
We employ the chiral quark-soliton model to describe excited baryons with one heavy quark. Identifying known charmed baryons with multiplets allowed by the model, we argue that apart from regular excitations of the ground state multiplets, some of recently reported by the LHCb collaboration narrow Ω_c^0 states, may correspond to the exotic pentaquarks. This interpretation can be easily verified experimentally, since exotic Ω_c^0 states – contrary to the regular excitations – form isospin triplets, rather than singlets.

- No peaks in the $\Xi_c^+ K^+$ spectrum
- Search for exotic $\Omega_c^{**-} \to \Xi_c^0 K^-$ by $\Xi_c^0 \to pKK\pi$
- Similar selection to $\Omega_c^{**0} \to \Xi_c^+ K^-$

Light Baryon Spectroscopy

- The poor knowledge of the light sector (Λ*, N*, etc…) has had a large impact on the amplitude analyses aiming to the search for the pentaquarks
- LHCb can contribute to study the spectroscopy of the light sector as well



Summary

- LHCb experiment very active in spectroscopy filling the gaps in many spectra
- Turbo stream will exploit data at the best

Excited Ω_c: Many interpretations proposed. Determination of spin-parity in prompt production of from Ω_b decays

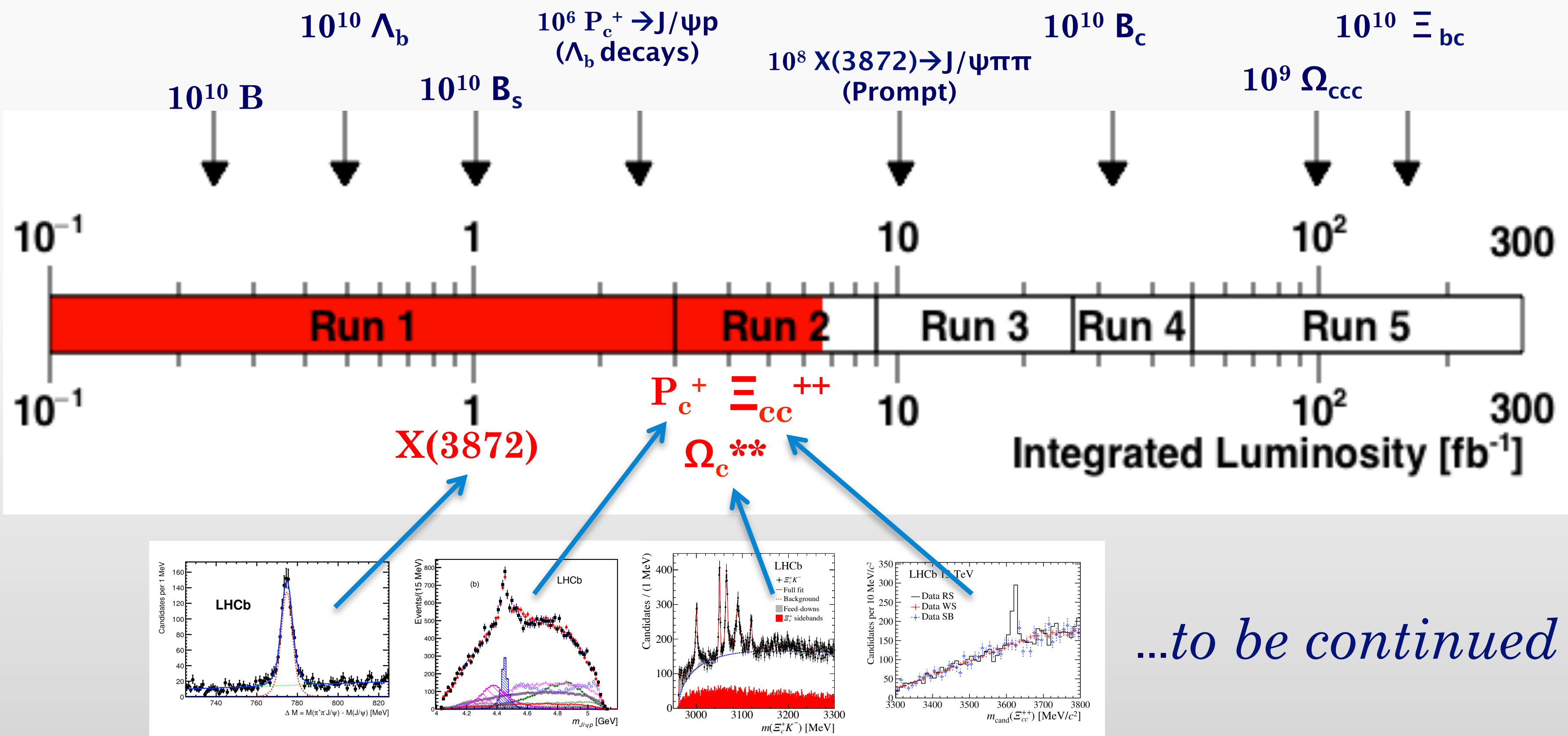
Excited Ω_b: Narrow peaks expected according to HQS

Ξ_{cc}^{++} : Measurement of the lifetime, search for Ξ_{cc}^{+} and Ω_{cc}^{+}

Λ^*, N^*: Study of light baryon spectroscopy from amplitude analysis of charmed baryons

Summary II

- Great interest into spectroscopy
- The observation of the two pentaquarks is the most cited LHCb paper
- The large data set collected, together with an upgraded detector, will boost sensitivity in searches for heavy states with small production cross sections and/or small decay rates

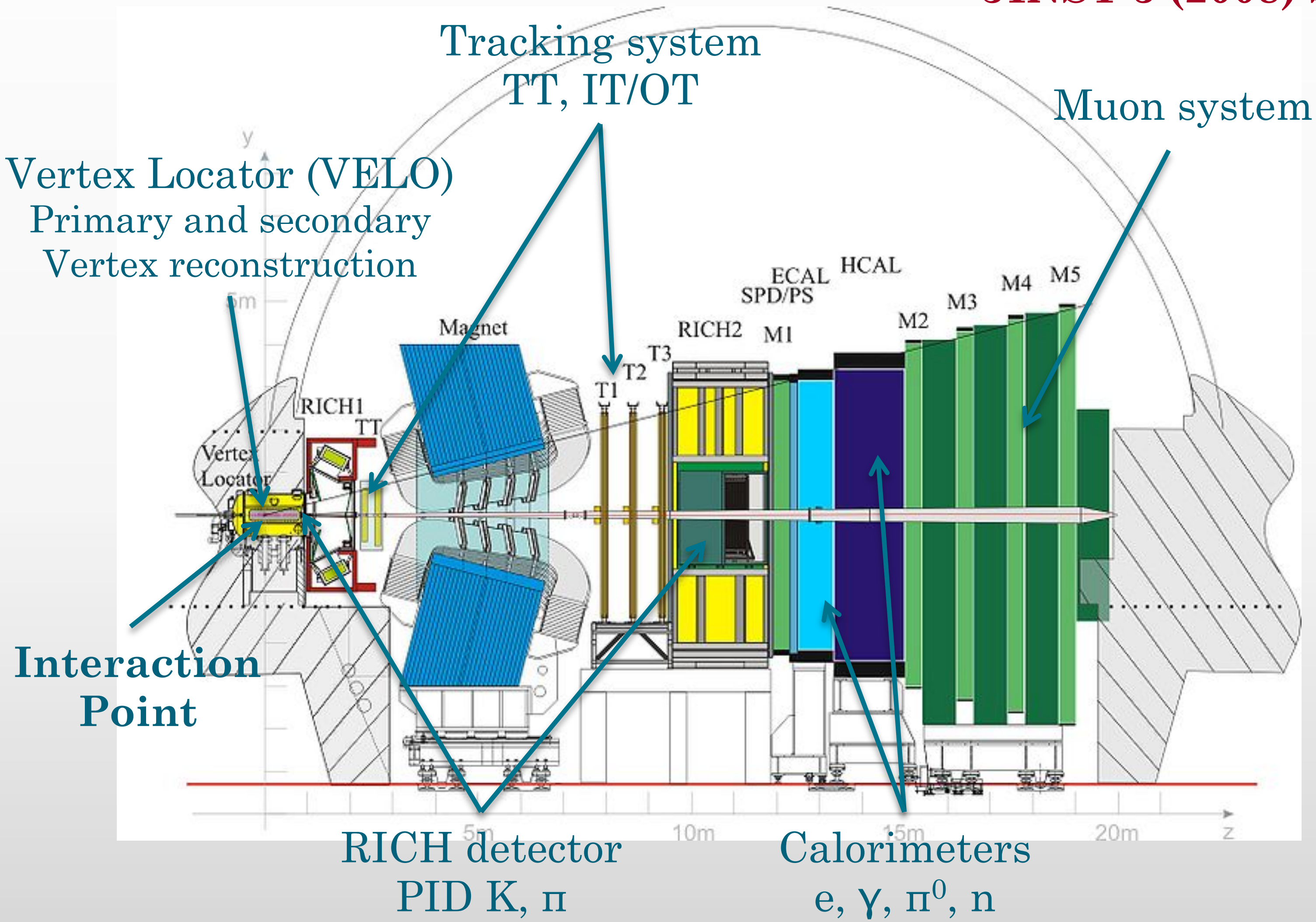


...to be continued

Back Up

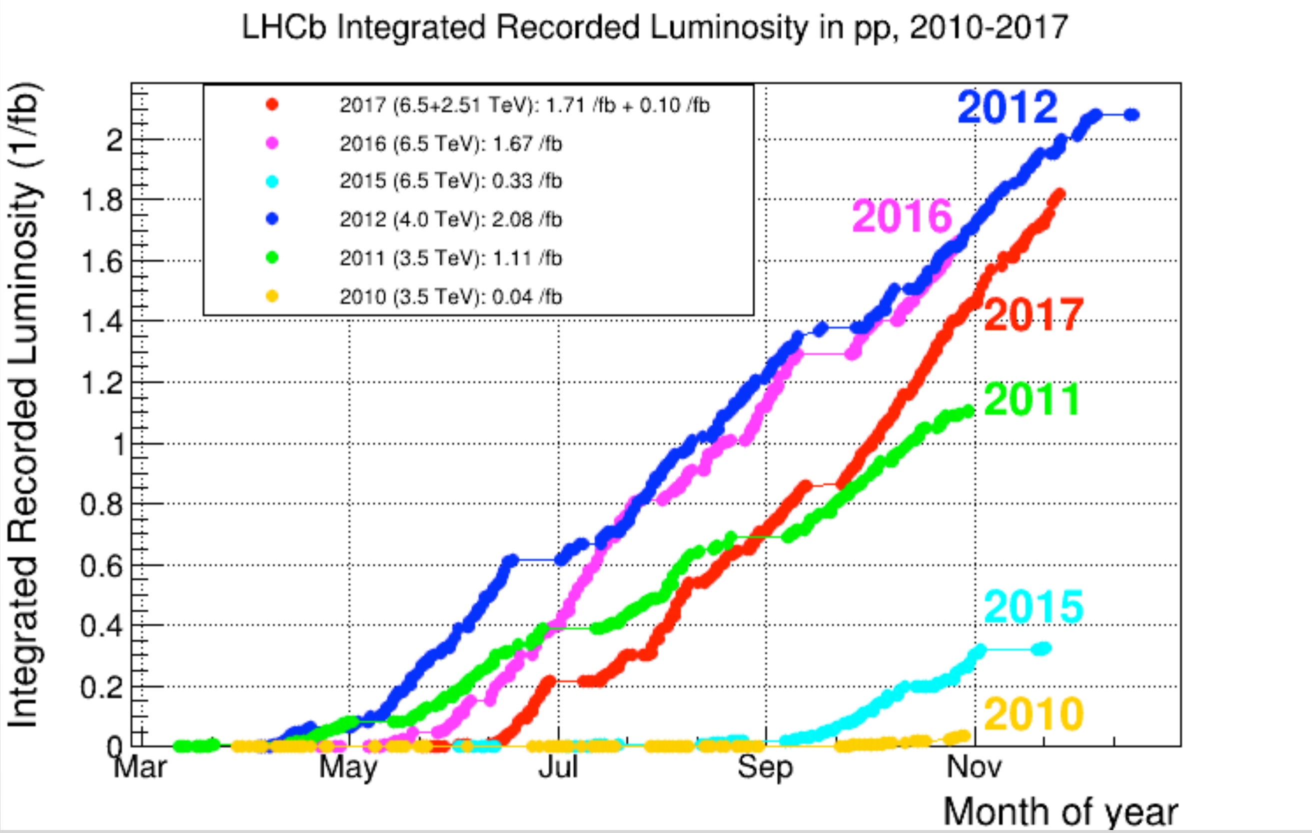
THE LHCb DETECTOR

JINST 3 (2008) S08005



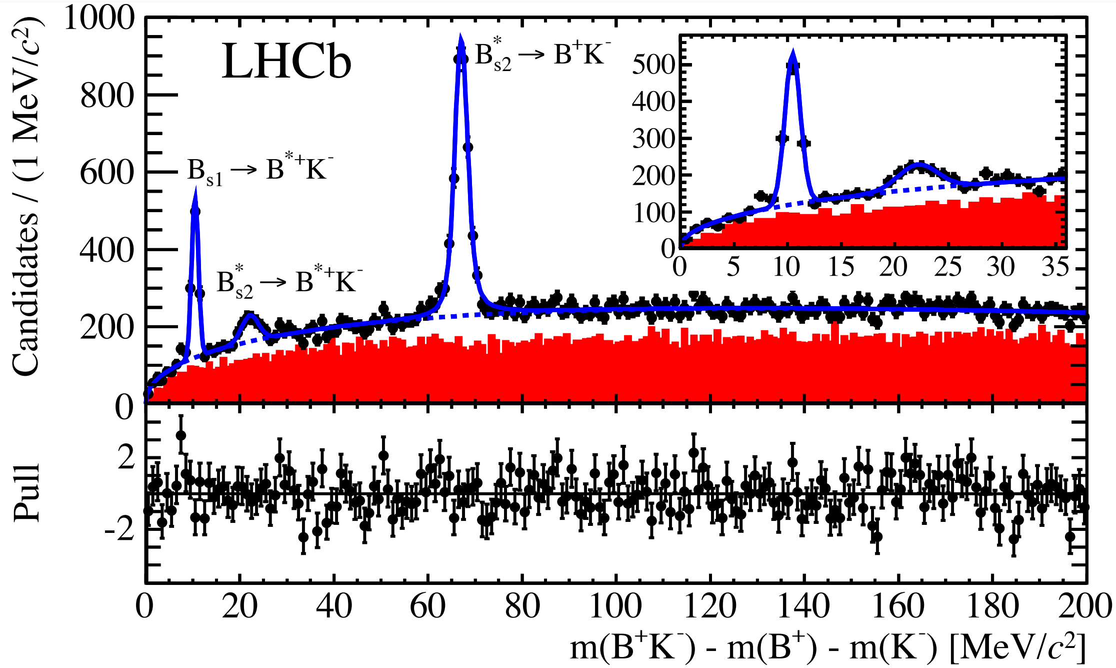
DATASETS

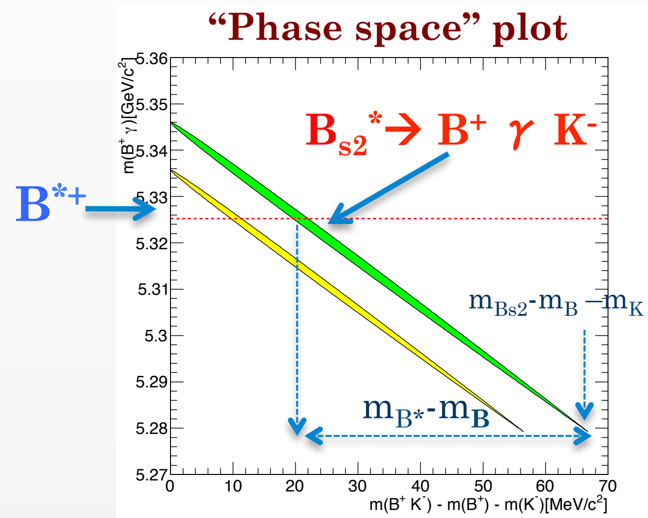
LHCb has just doubled the RUN I (2010-2012) dataset.
So far 1 fb^{-1} at 7 TeV + 2 fb^{-1} at 8 TeV + 3.7 fb^{-1} at 13 TeV



INTERMEZZO

[LHCb: PRL 113, 162001 (2014)]





$B_{s1}/B_{s2} \to B^*K$ decays appears in the BK spectrum due to small value of $m(B^{*+})$-$m(B^+)$ ~ 45 MeV