University of Chinese Academy of Sciences

Prospect for singly and doubly charmed baryons

Jibo HE (UCAS), for the LHCb collaboration

presented at

INTENSITY frontier

Workshop on singly and doubly charmed baryons

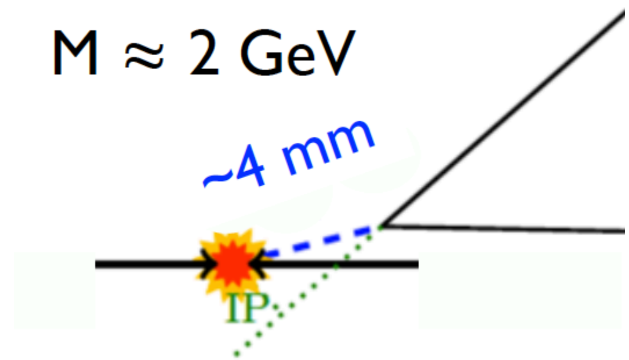
26-27 June 2018
LPNHE
Europe/Paris timezone

Outline

- Introduction
- Singly charmed baryon
  - Spectroscopy
  - Decay
  - CP violation
  - Rare decay
- Doubly charmed baryon
  - Spectroscopy
  - CP violation?

Charm production / signature

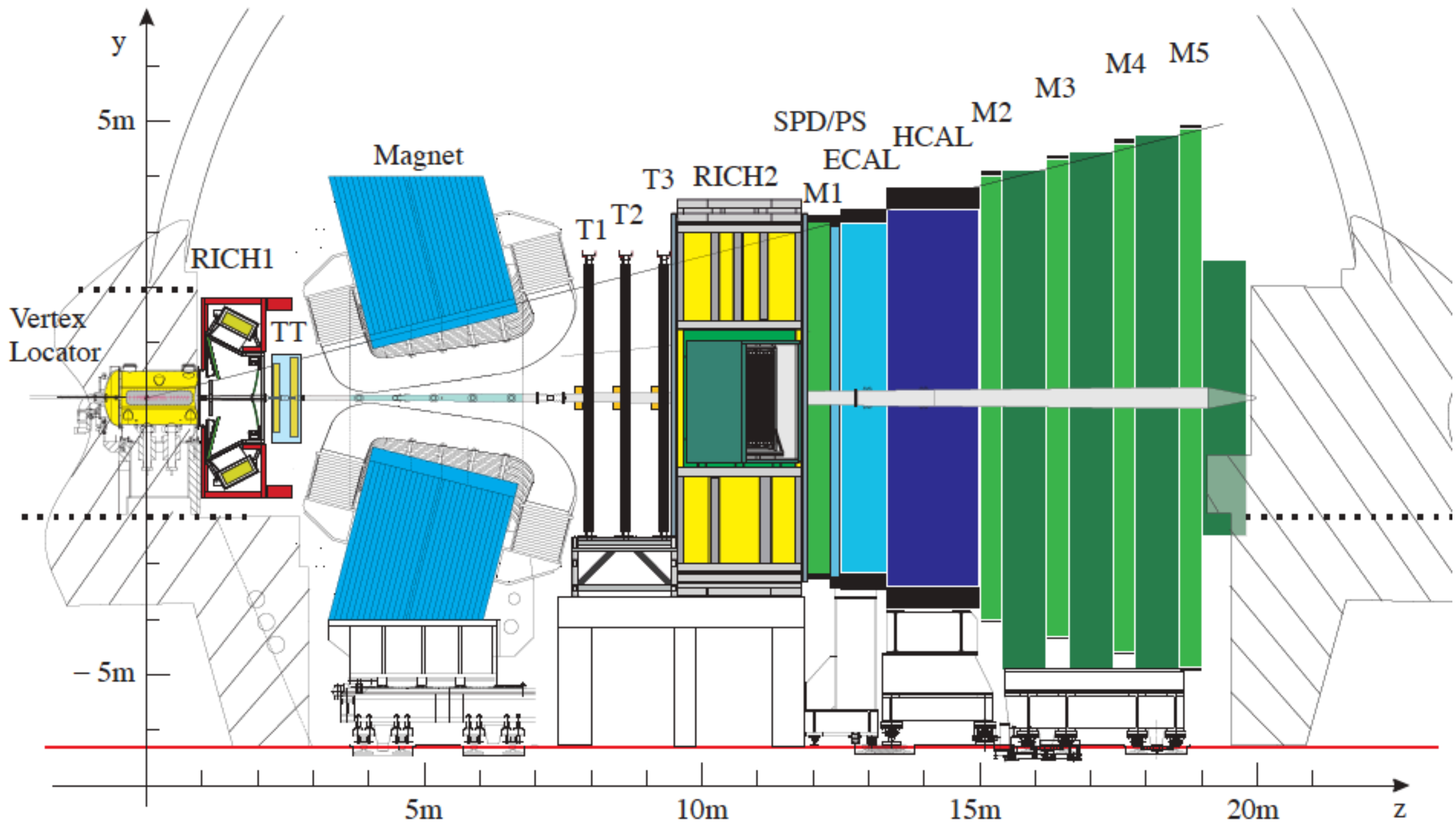
- Large production cross-section @ 7 TeV
  - Minibias ~60 mb
  - Charm ~6 mb



- Charm, compared to minibias (bkg)
  - Relatively high mass → high p_T
  - Relatively long lifetime → large IP
- Requires excellent vertexing, tracking, PID

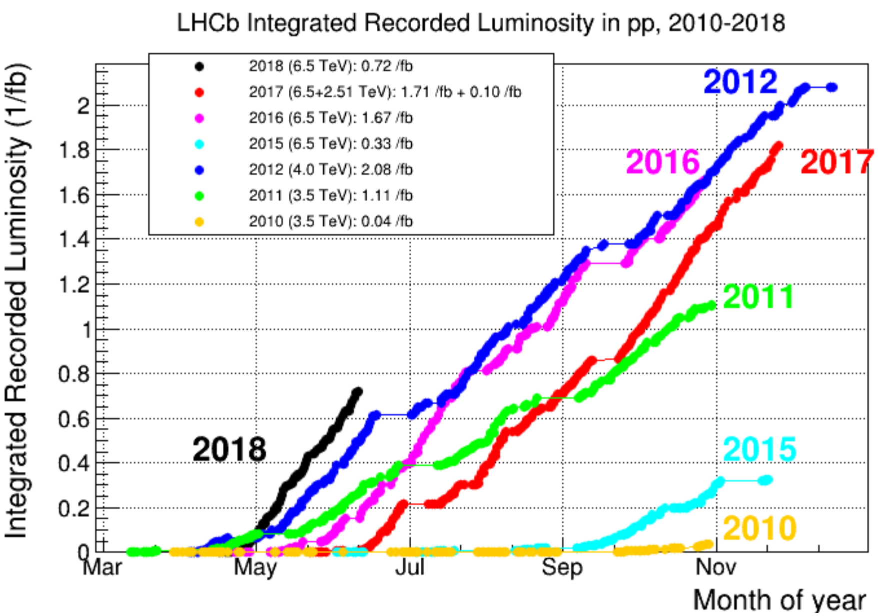
The LHCb experiment

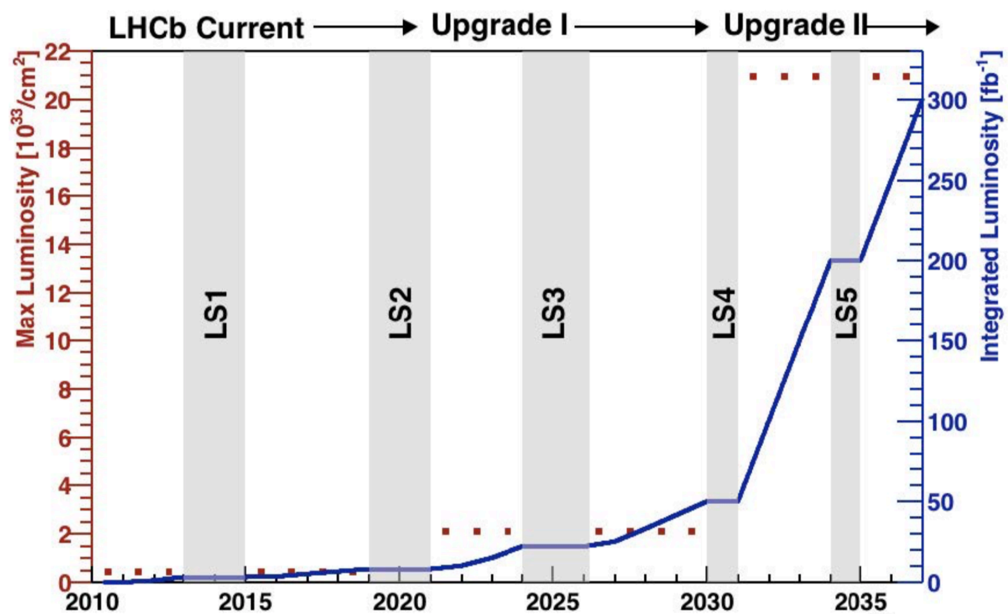
- Dedicated to precision study of *b/c*-hadrons



[JINST 3 (2008) S08005]

LHCb luminosity prospects





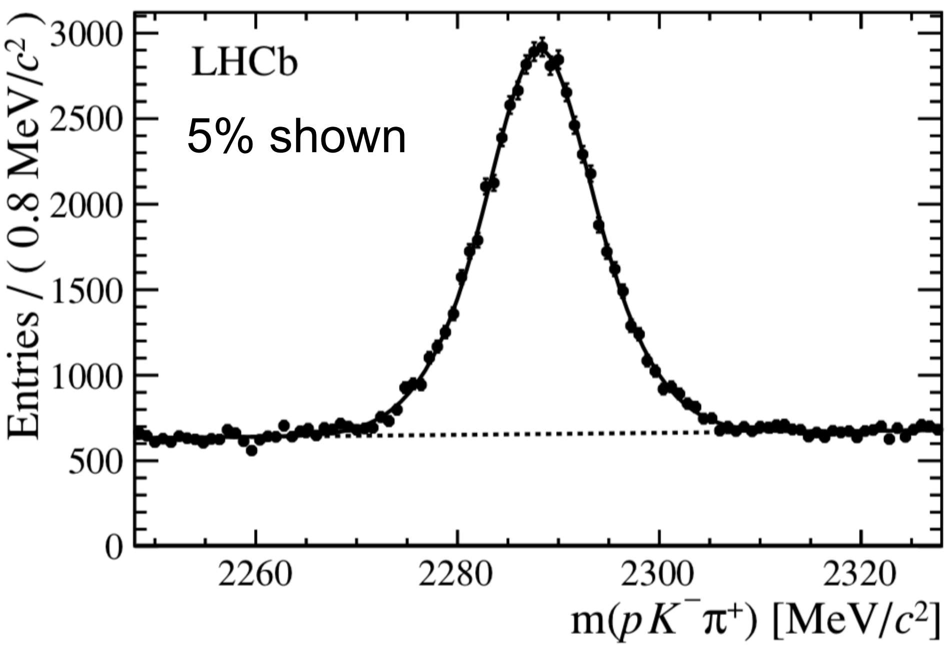
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	**6** fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

		Phase-1 Upgrade!!	**Phase-1b Upgrade!?**	**Phase-2 Upgrade??**

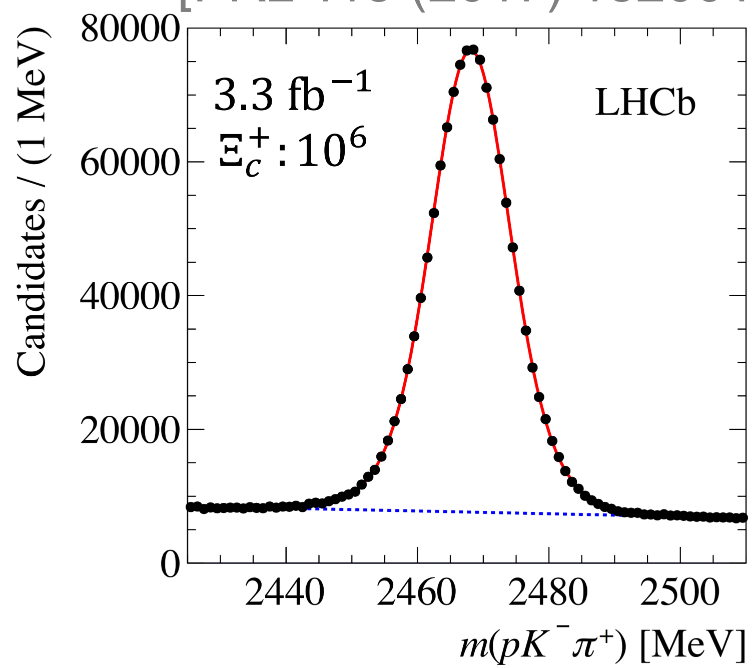
Lots of singly charmed baryons

- $\Lambda_c^+ \to pK^-\pi^+$: $\sim 1\times10^6$ per fb^{-1} @ 7 TeV
- $\Xi_c^+ \to pK^-\pi^+$: $\sim 3\times10^5$ per fb^{-1} @ 7 TeV

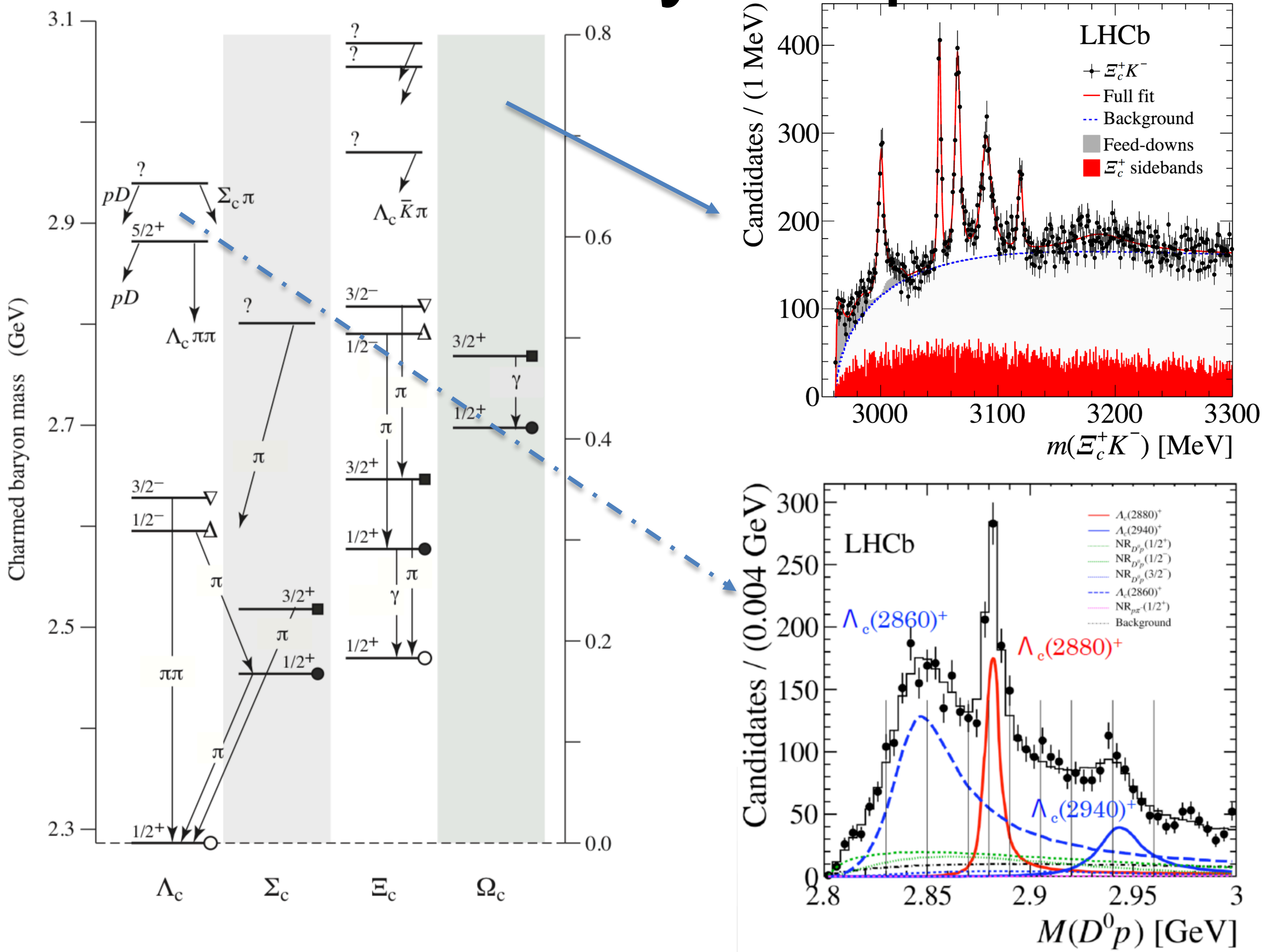
[JHEP 12 (2013) 90]



[PRL 118 (2017) 182001]



Charmed baryon spectroscopy

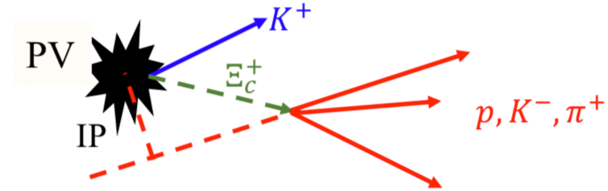


[PRL 118 (2017) 182001]

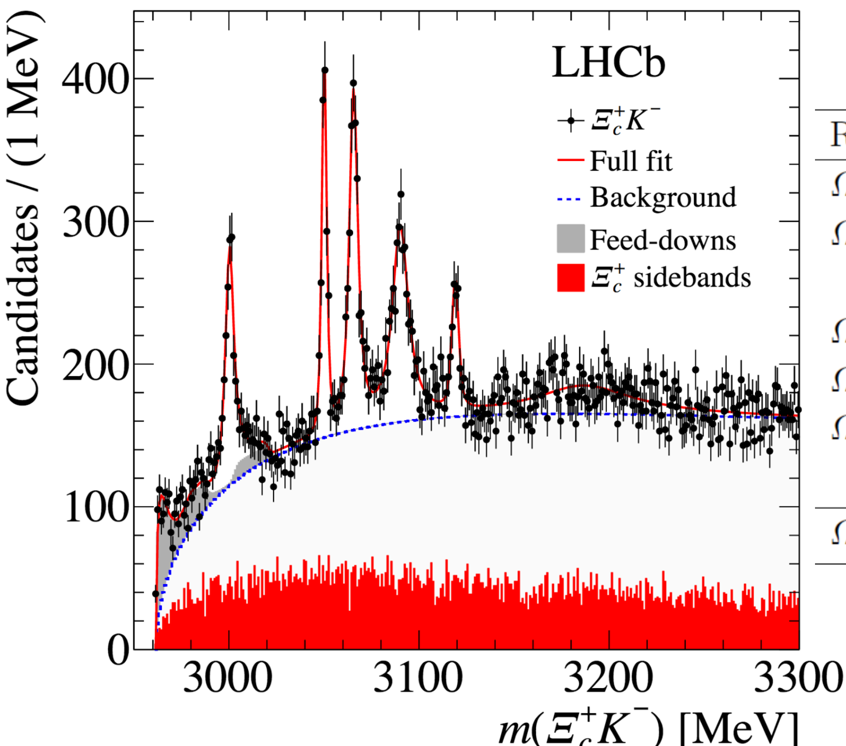
[JHEP 05 (2017) 030]

Observation of excited Ω_c states

- With $\Xi_c^+ K^-, \Xi_c^+ \to p K^- \pi^+$
- 5 narrow states + evidence of a broader one



[PRL 118 (2017) 182001]

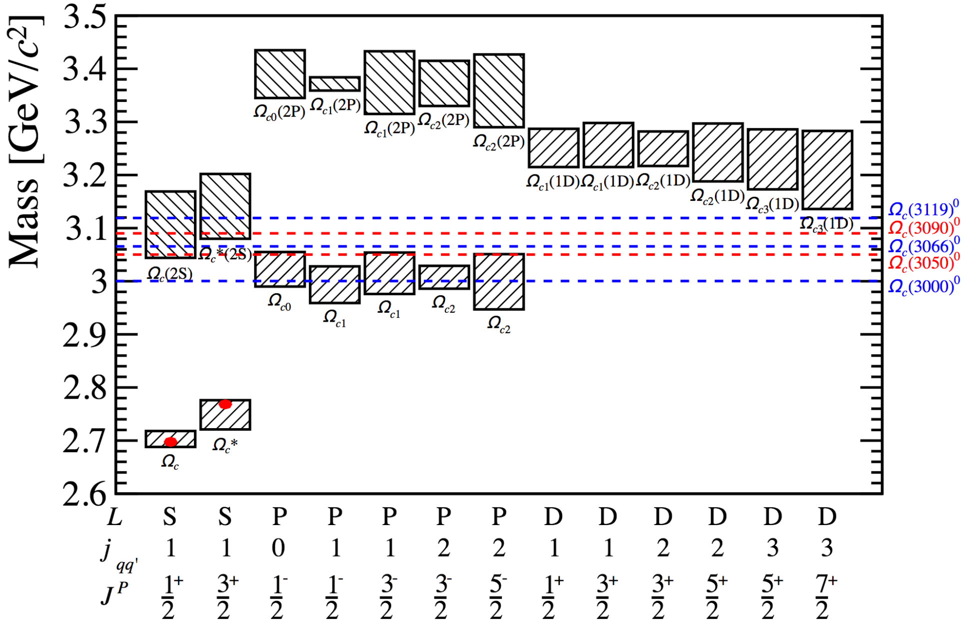


Resonance	Mass (MeV)	Γ (MeV)	$N_\sigma = \sqrt{\Delta\chi^2}$
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	20.4
		$< 1.2\,\mathrm{MeV}, 95\%$ CL	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	10.4
		$< 2.6\,\mathrm{MeV}, 95\%$ CL	
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	6.4

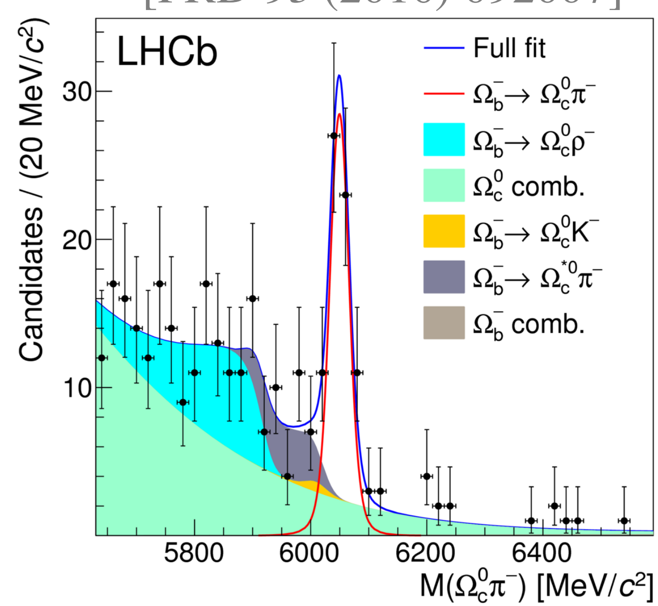
Understand these Ω_c states?

- Matching between observed peaks and predictions requires spin-parity info
  - Not easy in direct production due to unknown polarization, maybe try $\Omega_b \to \Omega_c^* \pi^-$?

[PRL 118 (2017) 182001]



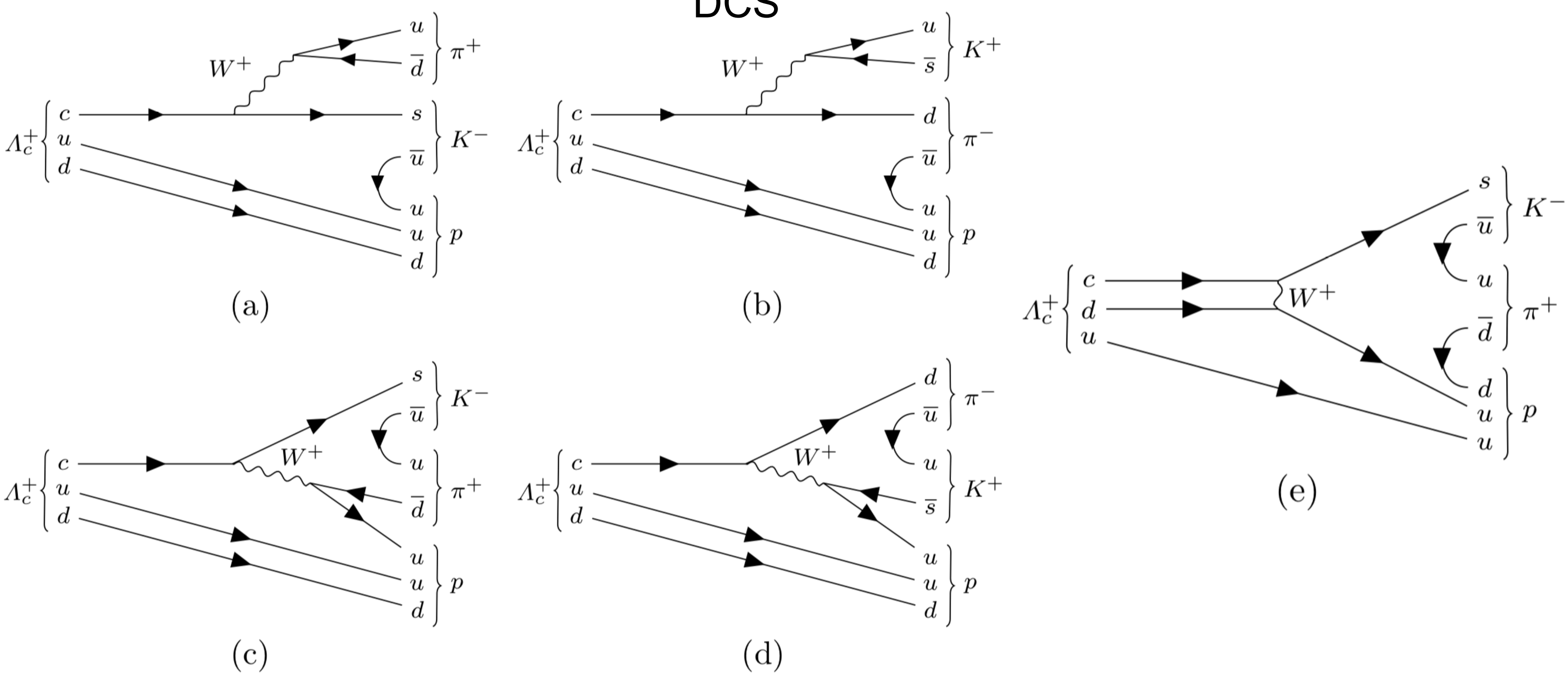
[PRD 93 (2016) 092007]



Nonleptonic decay

- Interplay between strong/weak interaction, internal dynamics, internal W-exchange

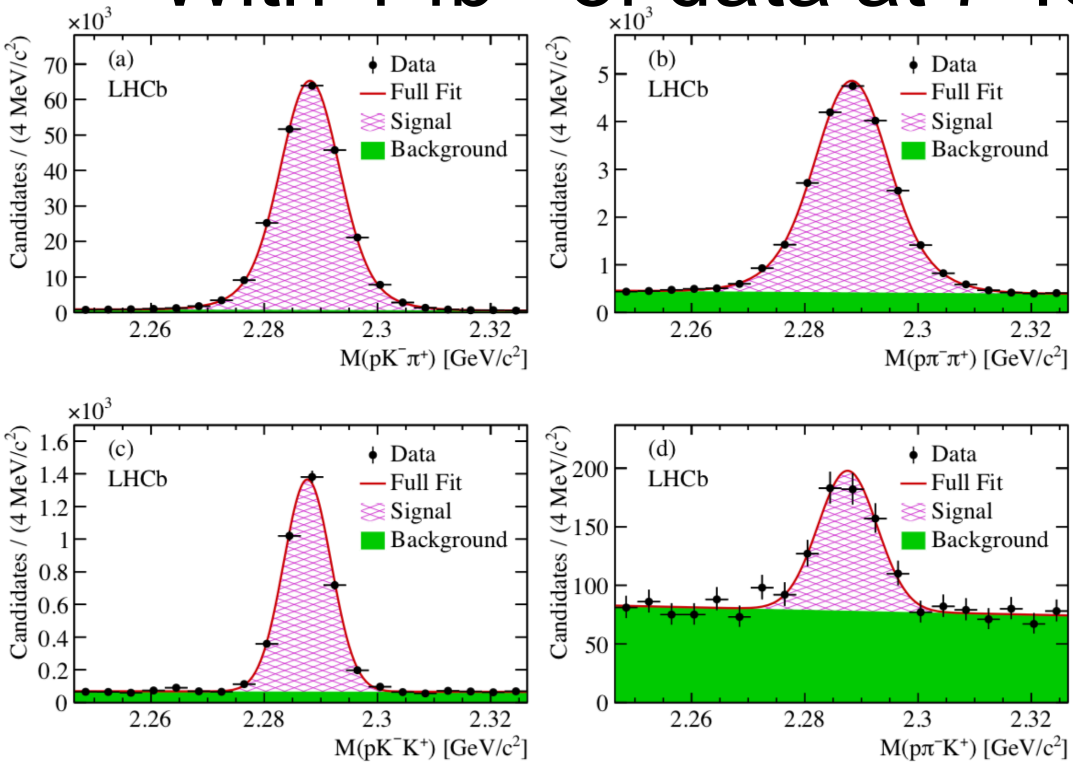
DCS



Measurement of $\mathcal{B}(\Lambda_c^+ \to phh')$

- With 1 fb^{-1} of data at 7 TeV

[JHEP 03 (2018) 043]



	Mode	Yield
SL	$\Lambda_c^+ \to pK^-\pi^+$	$226{,}851 \pm 522$
	$\Lambda_c^+ \to p\pi^-\pi^+$	$19{,}584 \pm 207$
	$\Lambda_c^+ \to pK^-K^+$	$3{,}420 \pm 62$
	$\Lambda_c^+ \to p\pi^-K^+$	392 ± 35
Prompt	$\Lambda_c^+ \to pK^-\pi^+$	$58{,}115 \pm 1{,}561$
	$\Lambda_c^+ \to p\pi^-\pi^+$	$7{,}480 \pm 328$
	$\Lambda_c^+ \to pK^-K^+$	766 ± 61

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (7.44 \pm 0.08 \pm 0.18)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.70 \pm 0.03 \pm 0.03)\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (0.165 \pm 0.015 \pm 0.005)\%,$$

$$\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+) = (4.72 \pm 0.05 \pm 0.11 \pm 0.25) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to pK^-K^+) = (1.08 \pm 0.02 \pm 0.02 \pm 0.06) \times 10^{-3},$$

DCS: $$\mathcal{B}(\Lambda_c^+ \to p\pi^-K^+) = (1.04 \pm 0.09 \pm 0.03 \pm 0.05) \times 10^{-4},$$

CPV in charmed baryon

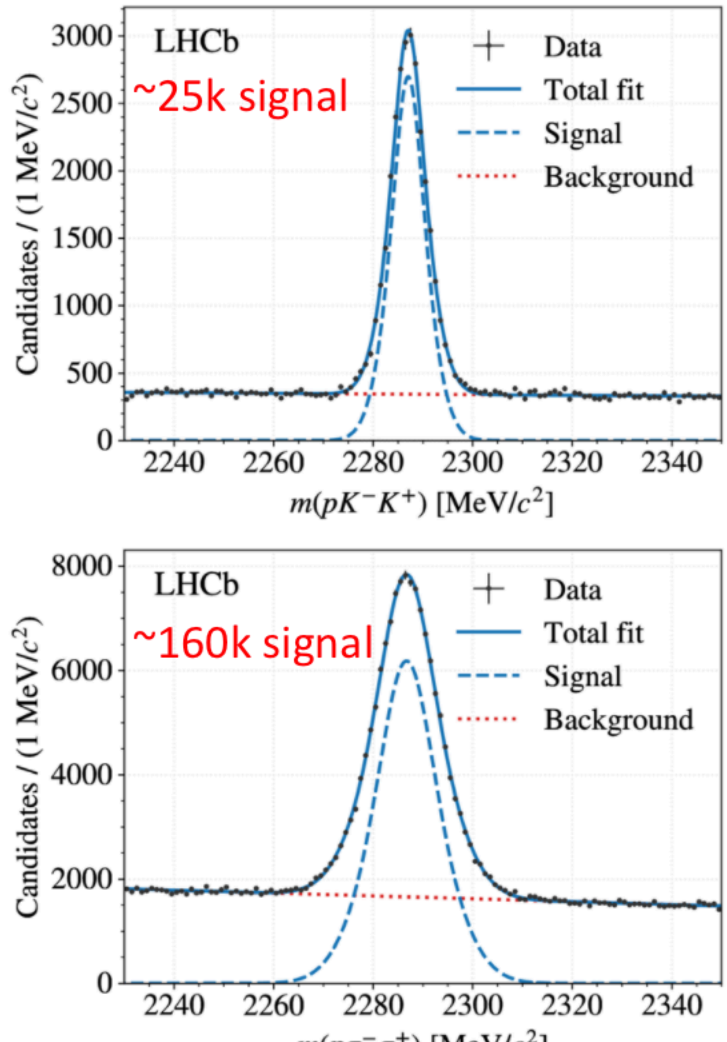
[See Alex's talk]

[JHEP 03 (2018) 182]

- $\Delta\mathcal{A}_{\text{CP}}(\Lambda_c^+ \to ph^+h^-)$ with Run-I data (3 fb^{-1})
- Corrected efficiency for 5-D ph^+h^- phase space
- Results

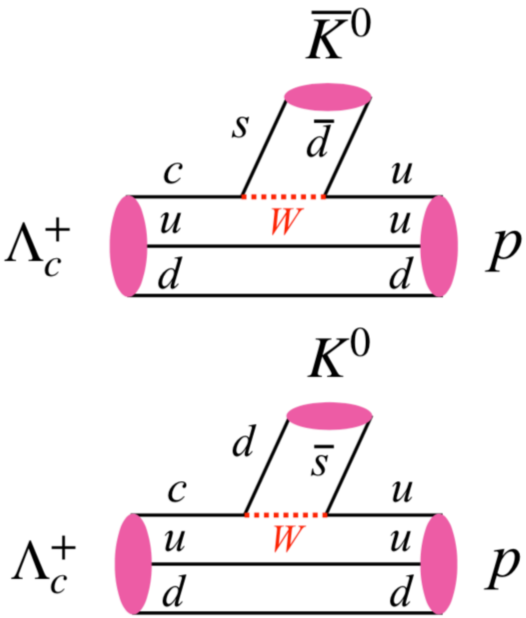
$$\Delta A_{CP}^{\rm wgt} = A_{CP}(pK^-K^+) - A_{CP}^{\rm wgt}(p\pi^-\pi^+) = (0.30 \pm 0.91 \pm 0.61)\,\%,$$

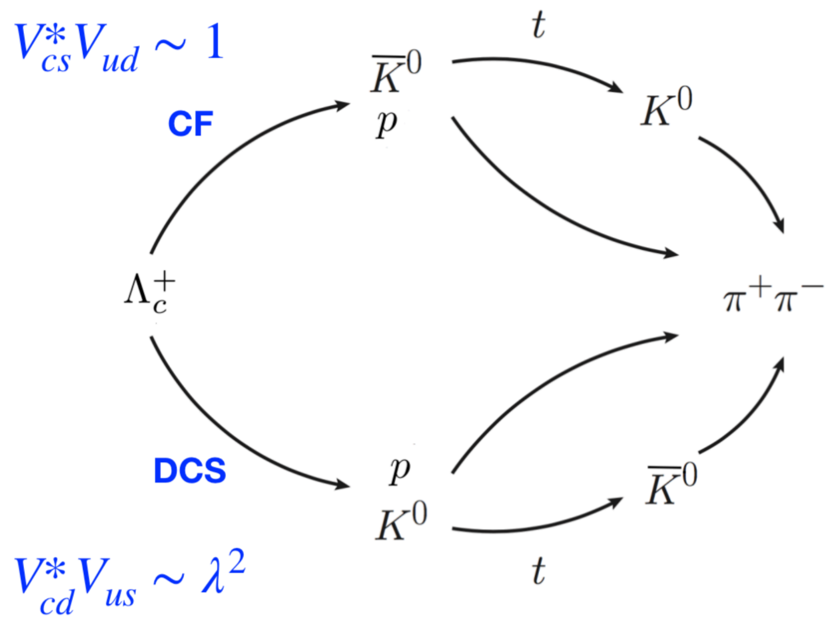
More data required to match the sensitivity of similar measurements using charm mesons



CPV in $\Lambda_c^+ \to p K_S^0$

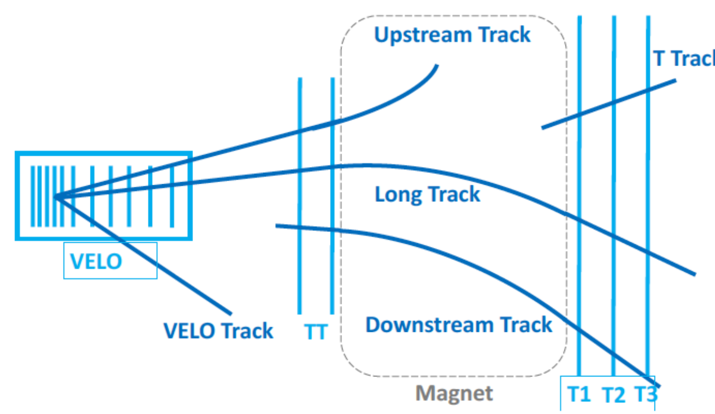
- Suggested by Fu-Sheng [See Fu-Sheng's talk]





- $\mathcal{B}(\Lambda_c^+ \to p K_S^0)_{\text{exp}} = (1.52 \pm 0.09)\%$

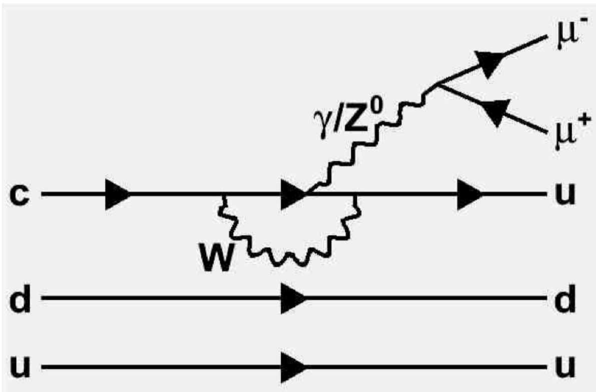
  suitable for LHCb upgrade



Rare decay

[PRD 97 (2018) 091101 (R)]

- FCNC $c \to u\ell^+\ell^-$

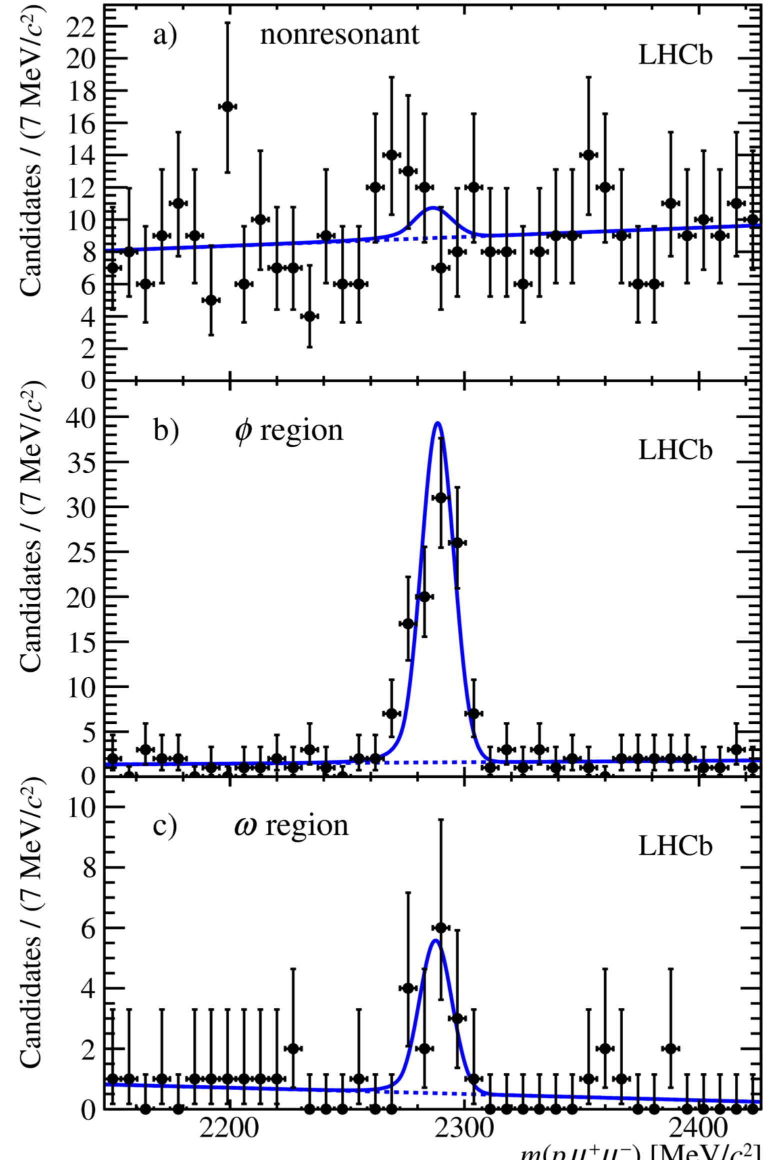


- $\mathcal{B}: \mathcal{O}(10^{-9})$ in SM
- $\Lambda_c^+ \to p\mu^+\mu^-$ searched with Run-I data (3 fb^{-1})

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7(9.6) \times 10^{-8} \text{ at } 90\%(95\%)$$

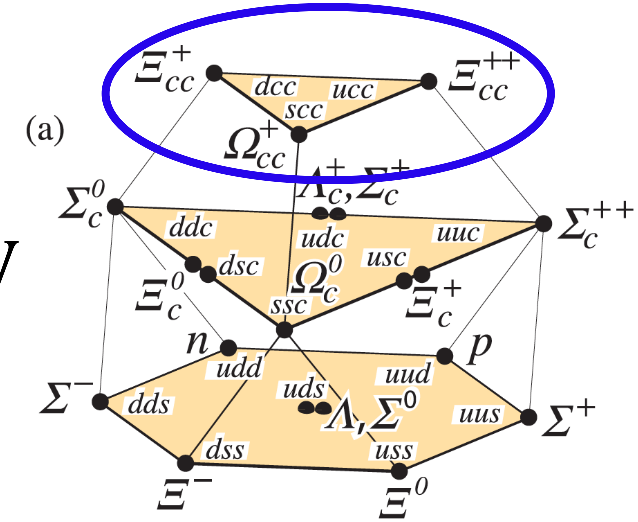
c.f. $< 10^{-5}$ at 90% CL by BaBar

Approaching SM value!

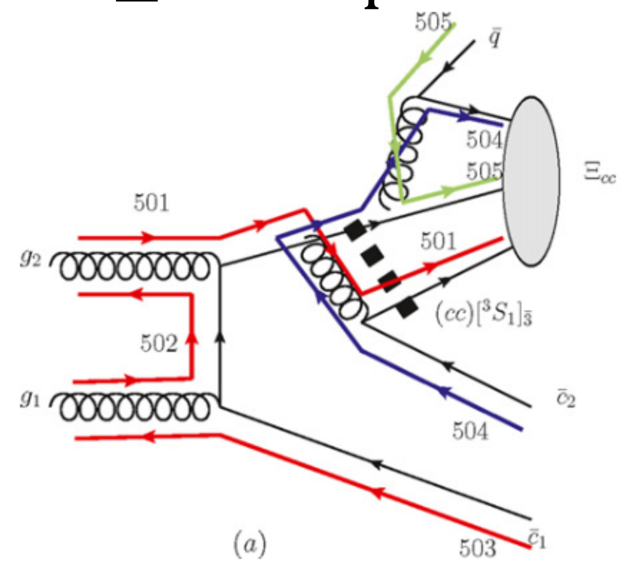


Doubly charmed baryon

- Mass [See J.M. Richard's talk]
  - $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$
    $= 3621.24 \pm 0.72$ MeV
  - $M(\Omega_{cc}^{+}) \approx M(\Xi_{cc}^{++}) + 100$ MeV



- Lifetime
  - $3\tau(\Xi_{cc}^{+}) \approx 3\tau(\Omega_{cc}^{+}) \approx \tau(\Xi_{cc}^{++}) = 0.256 \pm 0.027$ ps
- Production [PRD 83 (2011) 034026]
  - $\sigma(cc) = 90$ nb @ 13 TeV in LHCb
  - $f_{\mathrm{frag}}\ u{:}\,d{:}\,s \sim 1{:}\,1{:}\,0.3$
    $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) \sim 40$ nb
    $\sigma(\Omega_{cc}^{+}) \sim 13$ nb

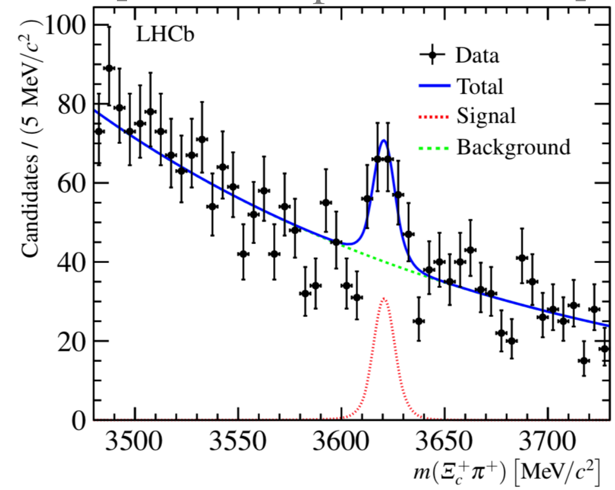


Ξ_{cc}^{++} status

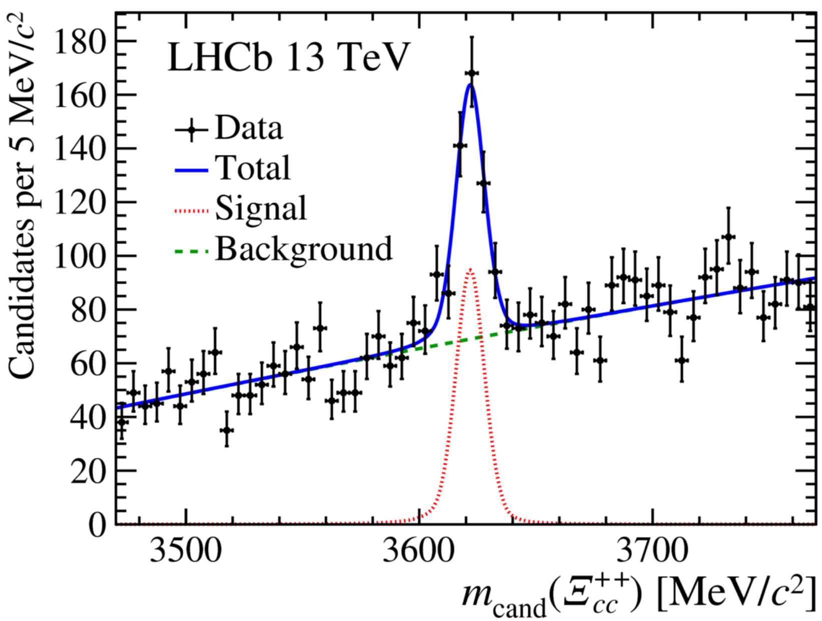
[See Murdo's talk]

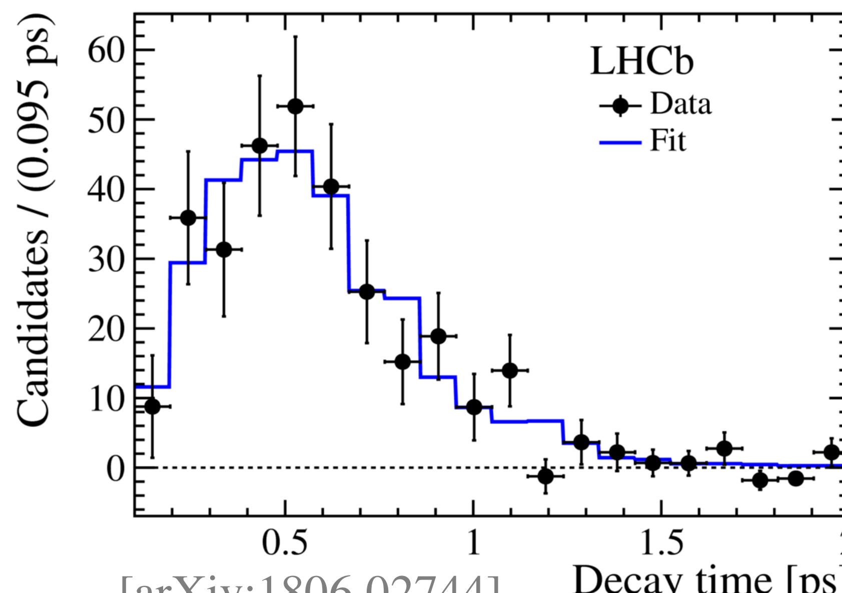
- $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+ (\Xi_c^+ \pi^+)$ observed, w/ 300 (100) signal. Mass/lifetime measured
- 2016 (1.7 fb^{-1}) used so far

[LHCb-Paper-2018-026]



[PRL 119 (2017) 112001]

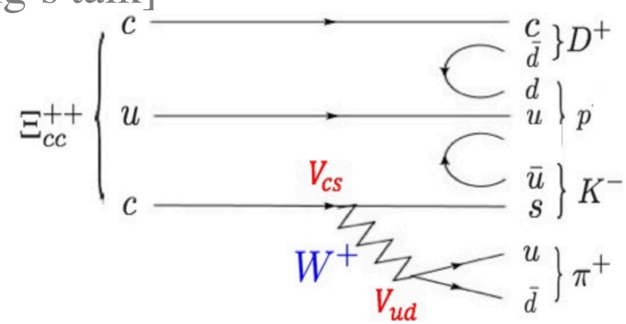


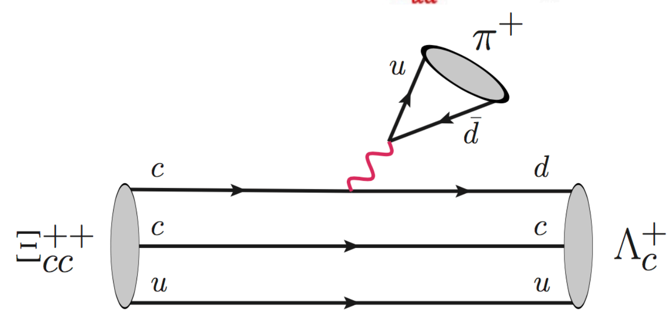


[arXiv:1806.02744]

Other Ξ_{cc}^{++} studies in pipeline

- Measurement of $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ production relative to prompt Λ_c^+
  - Constraint on intrinsic charm? [See S. Brodsky's talk]
- More decay modes [See Fu-Sheng's talk]
  - $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$
    - CF, $\tau(D^+)$ big
  - $\Xi_{cc}^{++} \to \Lambda_c^+ \pi^+$
    - BR: (0.1-0.6)%





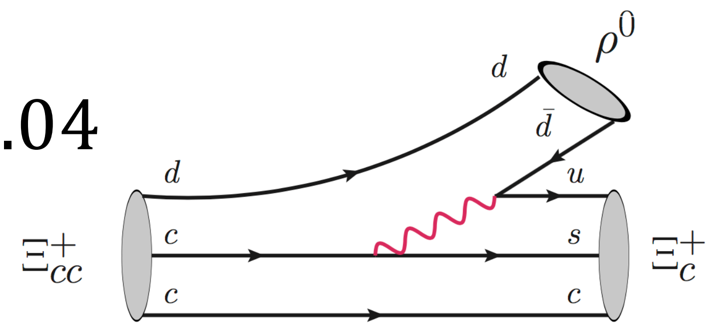
Search for Ξ_{cc}^{+}

- Gold mode: $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$
  - $\frac{\mathcal{B}(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} = \left(\frac{\mathcal{R}_\tau}{0.3}\right) \times 0.22$ [See Fu-Sheng's talk]
- Compared to $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
  - BR a factor of 5 smaller
  - $\tau(\Xi_{cc}^{+})$ a factor of 3 smaller, assuming selection efficiency has linear dependence
  - Production cross-section is the same

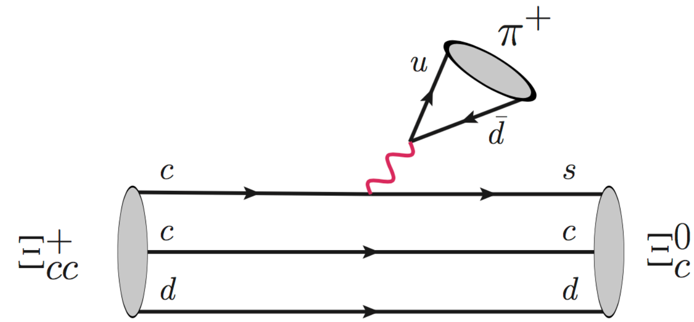
We would expect $300 \times \frac{7.5}{1.7} / 5. / 3. \approx 90$ signals in all data taken by the end of 2018

Other Ξ_{cc}^{+} modes

- $\Xi_{cc}^{+} \rightarrow \Xi_{c}^{+}\pi^{+}\pi^{-}$
  - $\frac{\mathcal{B}(\Xi_{cc}^{+}\rightarrow\Xi_{c}^{+}\pi^{+}\pi^{-})}{\mathcal{B}(\Xi_{cc}^{++}\rightarrow\Lambda_{c}^{+}K^{-}\pi^{+}\pi^{+})} = \left(\frac{\mathcal{R}_{\tau}}{0.3}\right)\times 0.04$
  - Smaller $\mathcal{B}(\Xi_{c}^{+} \rightarrow pK^{-}\pi^{+})$
  - $\tau(\Xi_{c}^{+}) \sim 0.442$ ps Vs. $\tau(\Lambda_{c}^{+}) \sim 0.200$ ps

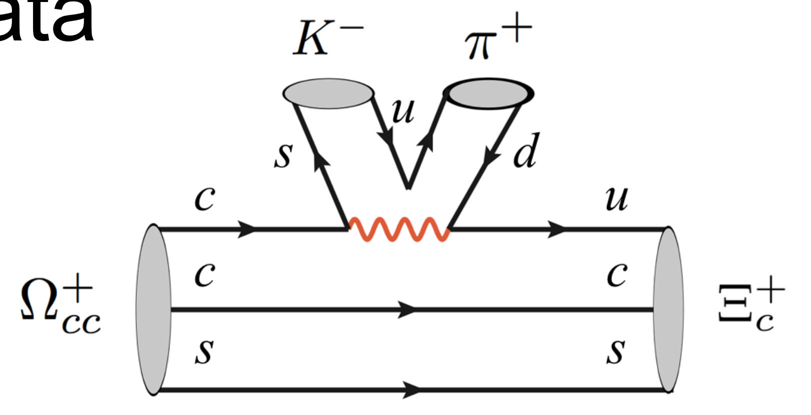


- $\Xi_{cc}^{+} \rightarrow \Xi_{c}^{0}\pi^{+}$
  - Smaller BR
  - $\tau(\Xi_{c}^{0}) \sim 0.112$ ps Vs.
    $\tau(\Xi_{c}^{+}) \sim 0.442$ ps



Ω_{cc}^{+}

- Production cross-section a factor of 3 smaller, with similar lifetime to Ξ_{cc}^{+}, more challenging
- Search with $\Omega_{cc}^{+} \to \Xi_{c}^{+} K^{-} \pi^{+}$
- Probably need to use data after the upgrade



Prospects of DCB in a nutshell

- LHCb ($7.5\ \mathrm{fb}^{-1}$)
  - Ξ_{cc}^{++} properties better known, >1k signal
  - Ξ_{cc}^{+} probably observed
  - Ω_{cc}^{+} evidence?
- LHCb upgrade ($50\ \mathrm{fb}^{-1}$)
  - Ξ_{cc}^{++}, $\mathcal{O}(10\mathrm{k})$ signals, search for excited states, more decay modes, CPV study?
  - Ξ_{cc}^{+}, $\mathcal{O}(1\mathrm{k})$ signals, properties better known
  - Ω_{cc}^{+}, observation
- LHCb upgrade-II, another factor of 6

Summary

- LHCb has done world-leading works on singly and doubly charmed baryons
  - Spectroscopy: Ω_c^*, Ξ_{cc}^{++}
  - Decay: $\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$
  - CPV: $\Delta\mathcal{A}_{\mathrm{CP}}(\Lambda_c^+ \to ph^+h^-)$
  - RD: $\Lambda_c^+ \to p\mu^+\mu^-$
- With LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1}), much more will be done
- Your suggestions are always welcome!