Spectroscopy of Baryons at LHCb

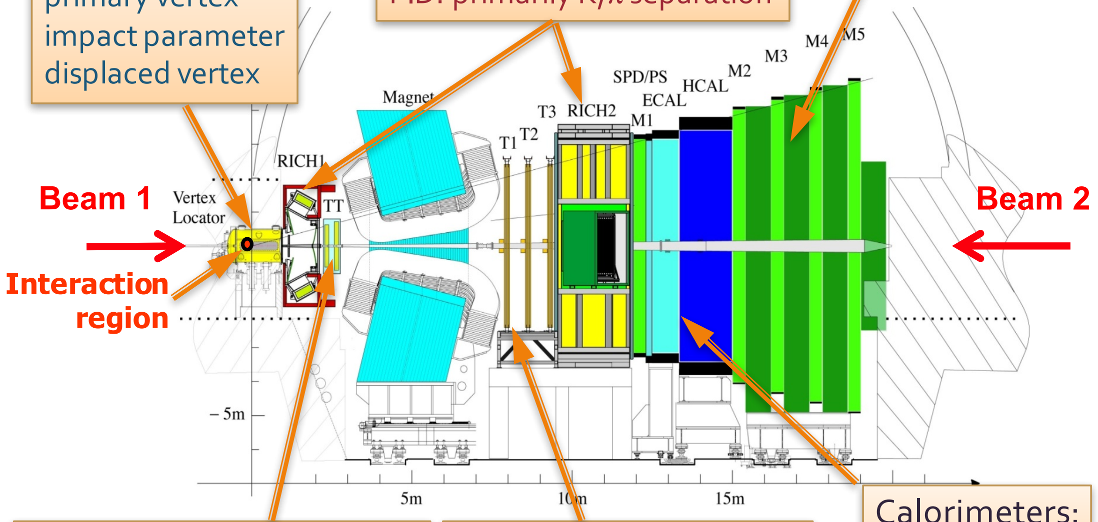
Liming Zhang

(Tsinghua University)

On behalf of the LHCb Collaboration

LHCb detector and performance

The LHCb detector described in JINST 3 (2008) S08005



VELO:
primary vertex
impact parameter
displaced vertex

RICH:
PID: primarily K,π separation

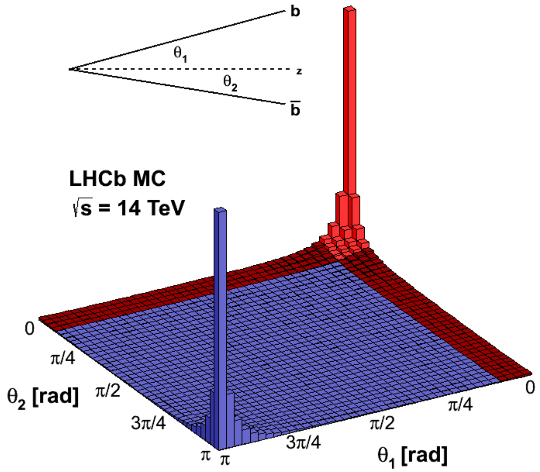
Muon System

Tracking Station: p for lower energy tracks and long lived V° reconstruction

Tracking Stations:
p of charged particles that traverse the magnet

Calorimeters:
PID: h,e,γ, π°

- $2 < \eta < 5$ range: $\sim 25\%$ of $b\bar{b}$ pairs inside LHCb acceptance



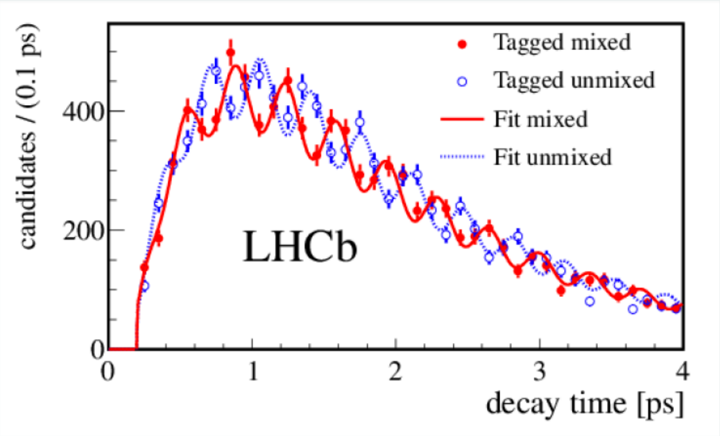
Int. J. Mod. Phys. A 30 (2015) 1530022

Impact parameter:	$\boldsymbol{\sigma_{IP} = 20\ \mu\mathrm{m}}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ \mathrm{GeV}/c)$
Mass :	$\boldsymbol{\sigma_m = 8\ \mathrm{MeV}/c^2}$ **for** $\boldsymbol{B \to J/\psi X}$ **(constrained** $\boldsymbol{\mathrm{m}_{J/\psi}}$**)**
RICH $K - \pi$ separation:	$\boldsymbol{\epsilon(K \to K) \sim 95\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to K) \sim 5\%}$
Muon ID:	$\boldsymbol{\epsilon(\mu \to \mu) \sim 97\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to \mu) \sim 1 - 3\%}$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

LHCb detector and performance

Vertexing

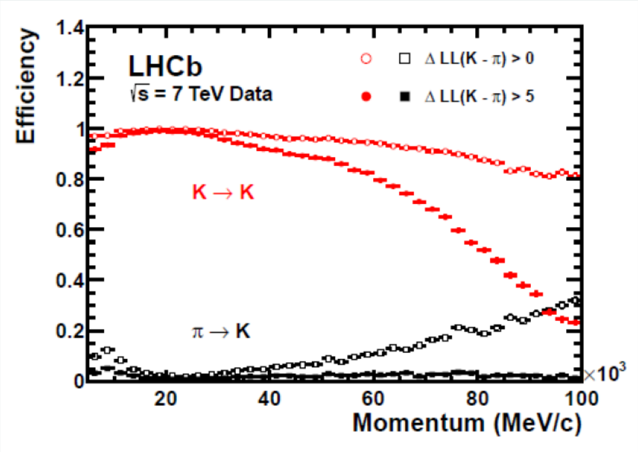
B_s^0 oscillations with $B_s^0 \to D_s\pi$



[New J. Phys. 15 (2013) 053021]

PID

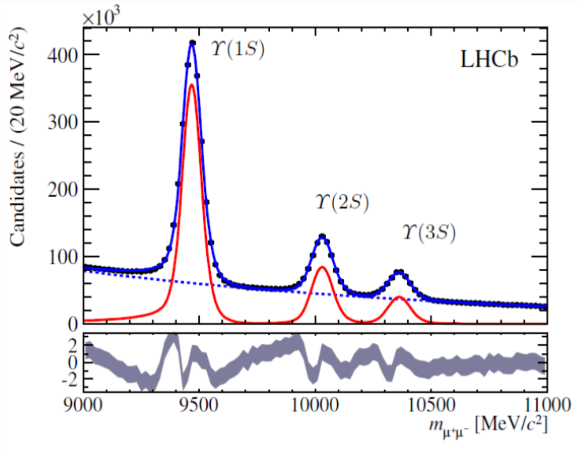
K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

Tracking

$\mu^+\mu^-$ mass spectrum



[PRL 111 (2013) 101805]

Int. J. Mod. Phys. A 30 (2015) 1530022

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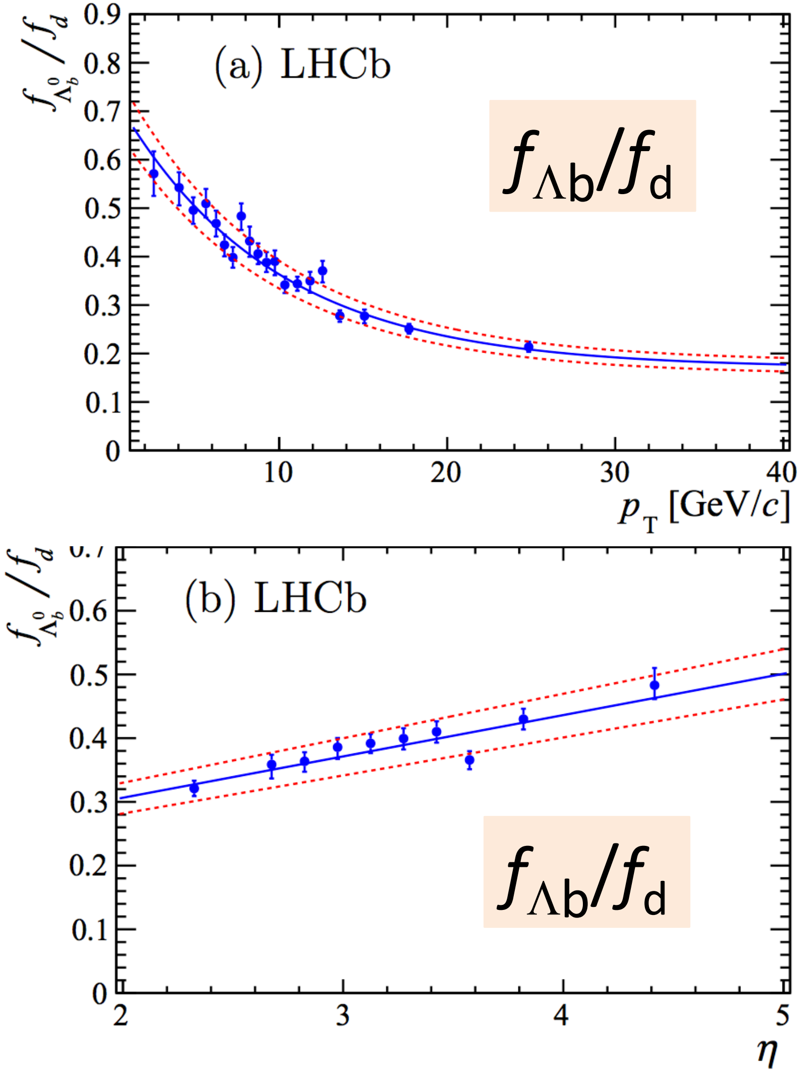
Mass : **$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrained $\mathrm{m}_{J/\psi}$)**
RICH $K - \pi$ separation: **$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$**
Muon ID: **$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$**
ECAL: $\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

LHCb advantage and disadvantage



[LHCb, JHEP 08(2014) 143]

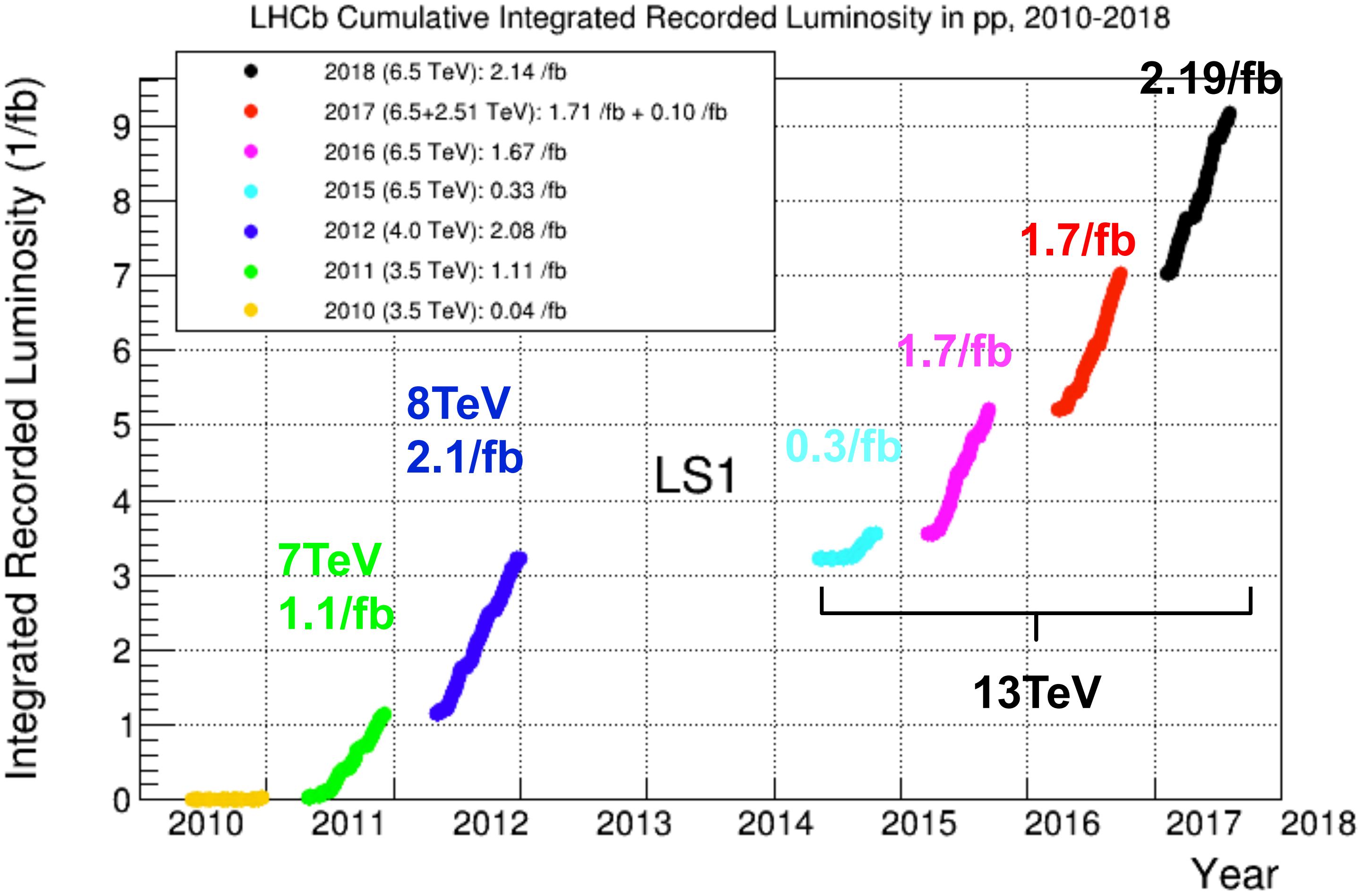
- Advantage at LHCb:
  - Huge *b*-production cross-section

    $\sigma(pp \to b\bar{b}X) \approx 72$ μb @7 TeV ≈ 144 μb @13 TeV in LHCb acceptance **PHYS. REV. LETT. 118, 052002 (2017)**
  - Can also access Λ_b^0, B_s^0, B_c^+

    B^0:Λ_b:B_s = 4:2:1

- Disadvantage at LHCb:
  - Efficiency of one track ~50% (not good for large number of finial states)
  - Inefficiency for K_S^0, Λ^0, γ

LHCb collected luminosity

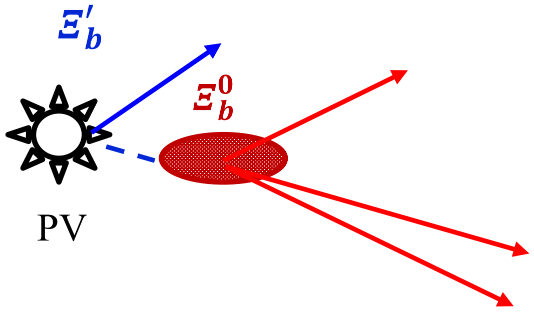


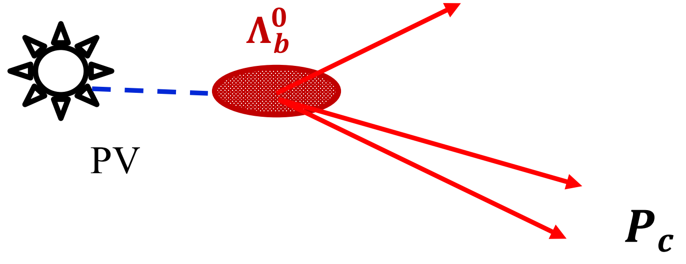
$\sigma(pp \to b\bar{b}X) \approx 72\ \mu b$ @7 TeV vs $\approx 144\ \mu b$ @13 TeV in LHCb acceptance

Expect Yield(Run1+2) ≈ 4.5 Yield(Run1)

Two methods for spectroscopy

- Direct production in pp collisions
  - Combine a heavy flavour hadron with one or more light particles
  - Pros: High statistics, in principle can study all states
  - Cons: Large combinatorial background, hard to determine J^P
- Production by a heavier particle decay
  - Usually with amplitude analysis
  - Pros: Low background, Better determination of J^P
  - Cons: Low cross-section, limited states and limited J

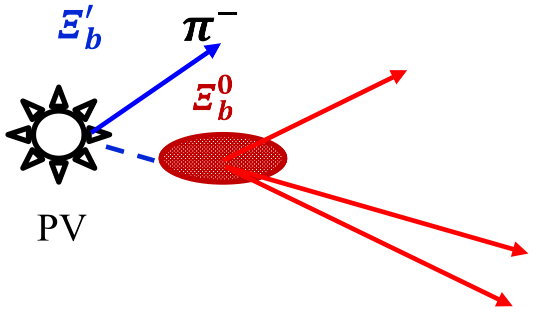


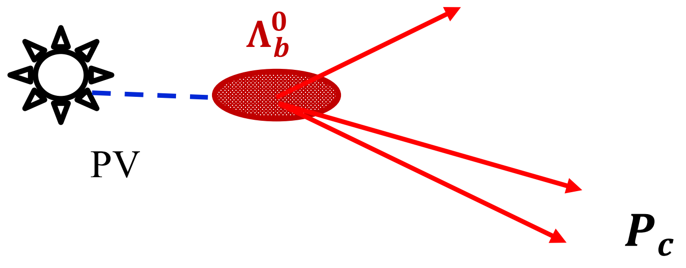


Two methods for spectroscopy

- Direct production in pp collisions
  - ❑ Ξ_{cc}^{++}, $\Omega_c^* \rightarrow \Xi_c K$
  - ❑ All excited B, $\Xi_b^* \rightarrow \Xi_b \pi; \Lambda_b K$

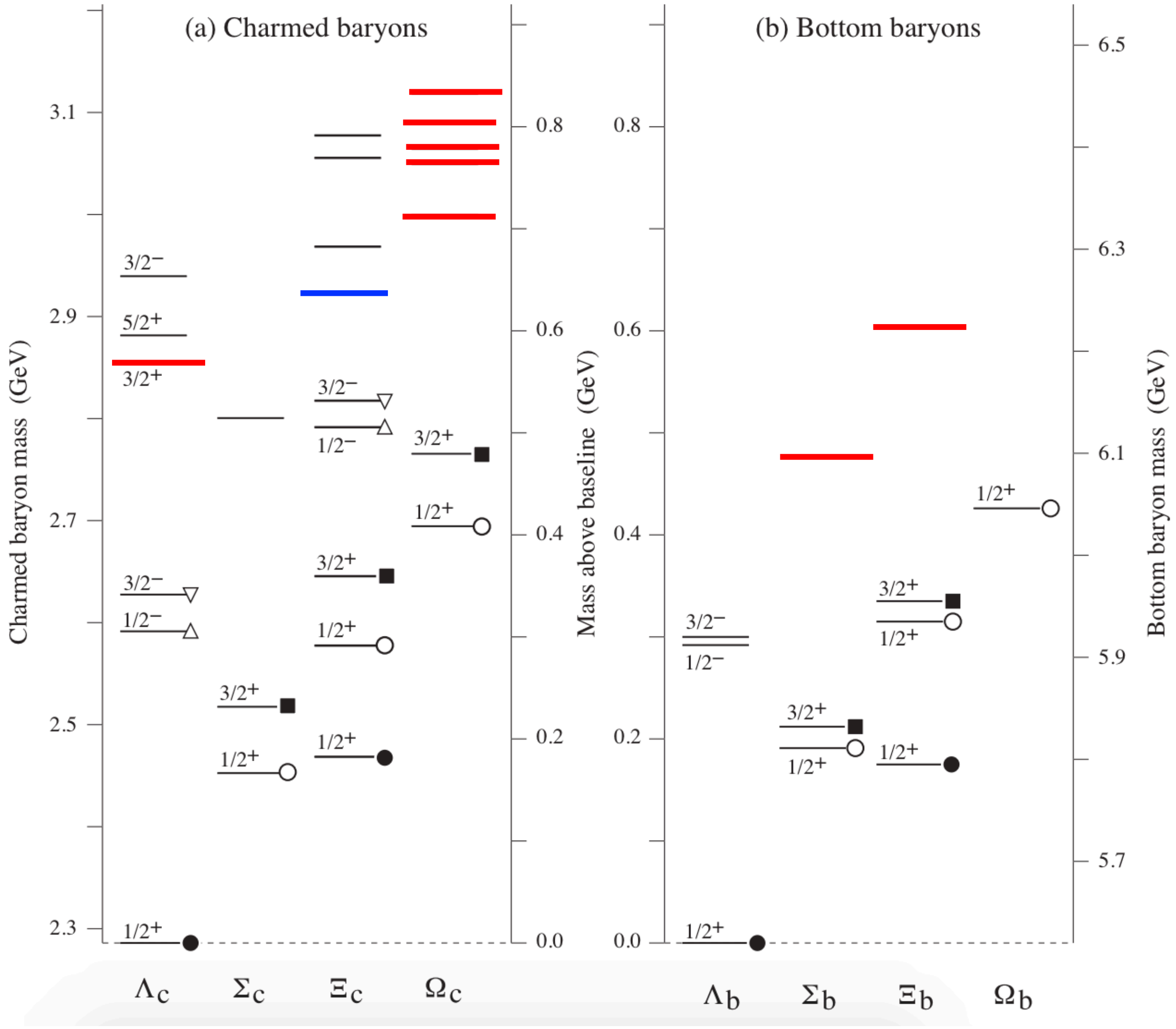
- Production by a B or D decays
  - ❑ X(3872) J^P
  - ❑ $Z_c(4430)$
  - ❑ X(4140) ….
  - ❑ $P_c(4450)$, $P_c(4380)$
  - ❑ $D_{(s)J}$





Charmed and bottom baryons

- 25 charmed baryons observed
  - Missing many Σ_c^*?
- 11 bottom baryons observed
- Bottom are very similar to charmed baryons



Bottom baryons

- ✓ Direct production

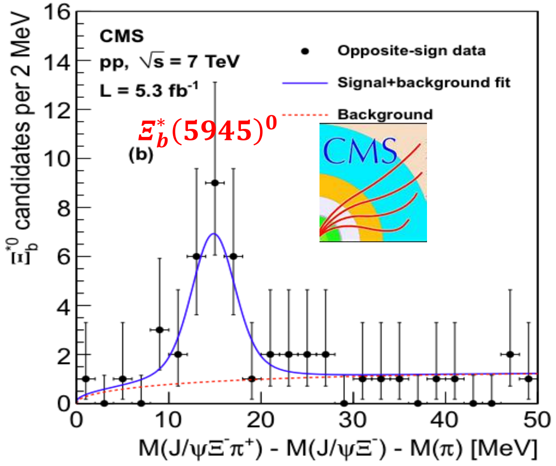
Ξ_b baryon spectroscopy

- Numbers of excited *b*-baryons have already been discovered
  - $\Xi_b^*(5945)^0 \to \Xi_b^- \pi^+$ [CMS'12]
  - $\Xi_b'(5935)^-, \Xi_b^*(5955)^- \to \Xi_b^0 \pi^-$ [LHCb'15]
  - $\Xi_b'^{\,0}$ not yet observed

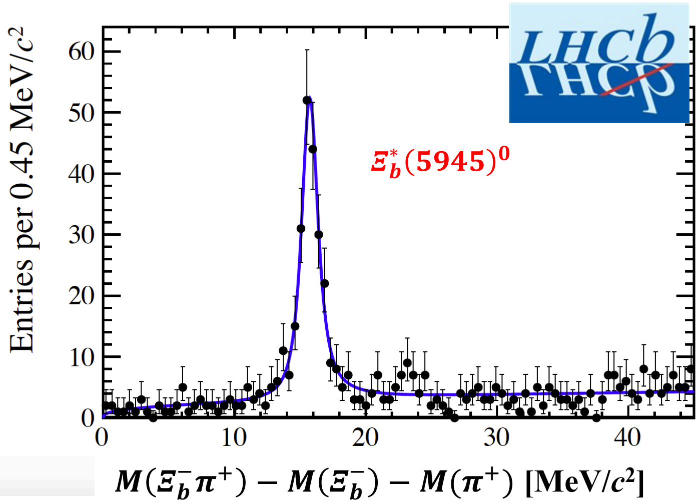
State	J^P	$b(sq)$
Ξ_b	$1/2^+$	$\uparrow(\uparrow\downarrow)$
Ξ_b'	$1/2^+$	$\downarrow(\uparrow\uparrow)$
Ξ_b^*	$3/2^+$	$\uparrow(\uparrow\uparrow)$

Neutral Ξ_b^*

PRL 108, 252002 (2012)

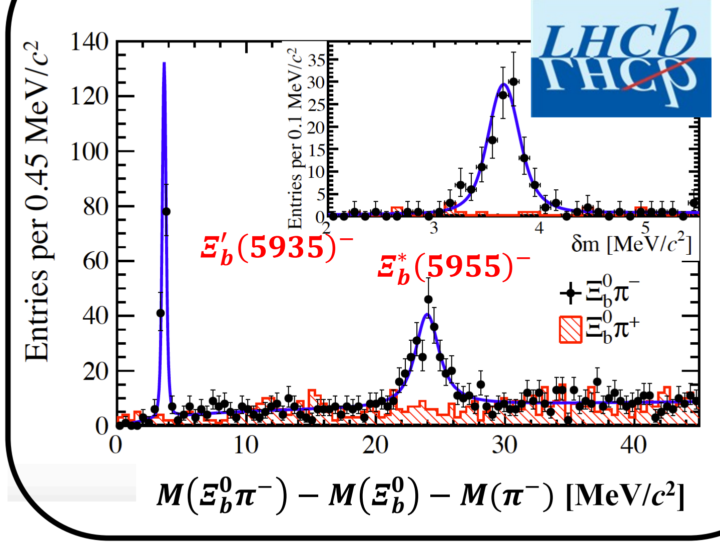


JHEP 05 (2016) 161



Charged $\Xi_b'^{(*)}$

PRL 114 (2015) 062004



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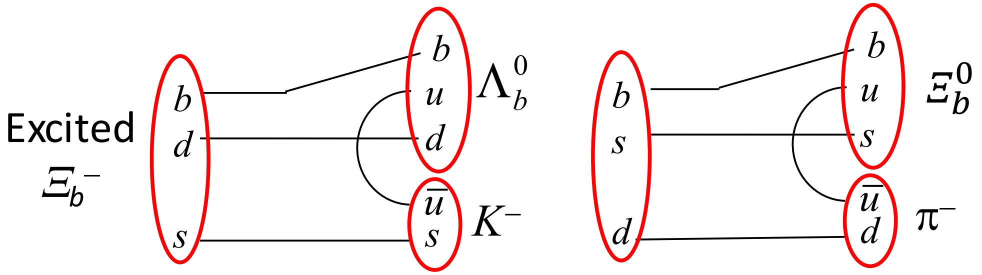
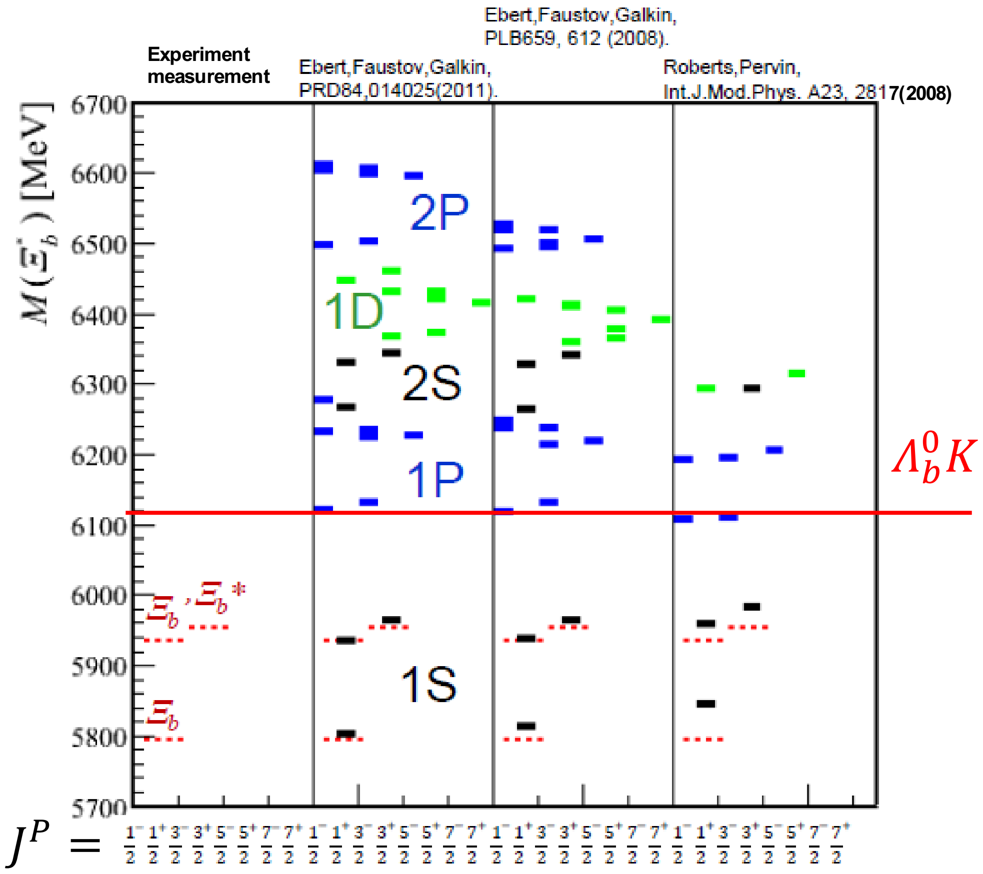
  - ☐ $\Xi_b'^{\,0}$ not yet observed

- More higher excited states are expected to be above $\Lambda_b^0 K$ threshold





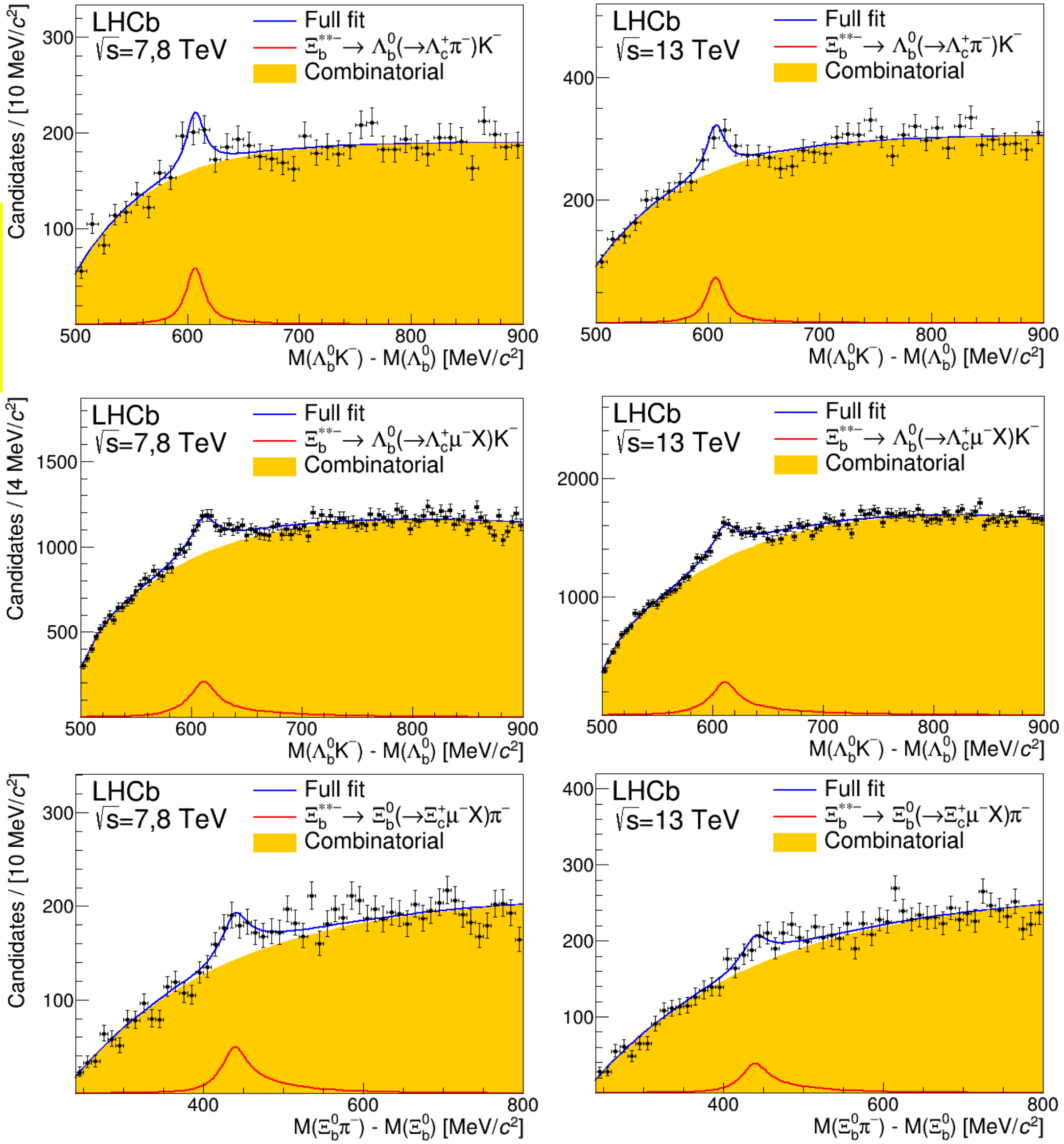
Observation of a new Ξ_b^{**-} state

- Hadronic $\Lambda_b^0 \to \Lambda_c^+\pi^-$:
  - Resolution: 2 MeV
  - 7.9σ

New method using SL gives 15x yield than that in HD, largely increase search power of excited bottom hadrons

- Semileptonic (SL)
  $\Lambda_b^0 \to \Lambda_c^+\mu^- X\bar{\nu}_\mu$
  - Resolution: ~18 MeV
  - Yields ~15 larger
  - 25σ
- Semileptonic (SL)
  $\Xi_b^0 \to \Xi_c^+\mu^- X\bar{\nu}_\mu$
  - 9.2σ

PRL 121 (2018) 072002



The Ξ_b^{**-} properties

PRL 121 (2018) 072002

- With hadronic mode

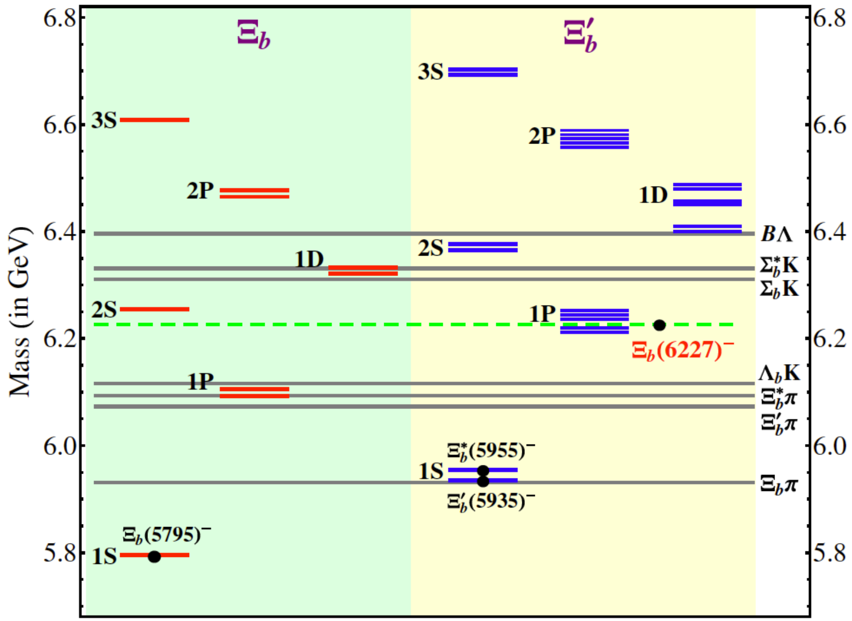
$$M(\Xi_b^{**-}) - M(\Lambda_b^0) = 607.3 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst})\ \text{MeV}/c^2,$$
$$\Gamma = 18.1 \pm 5.4\,(\text{stat}) \pm 1.8\,(\text{syst})\ \text{MeV}/c^2,$$
$$M(\Xi_b^{**-}) = 6226.9 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV}/c^2,$$

Mass peak position is consistent between the three decay channels

- Production ratios are measured with SL modes

Quantity	7+8 TeV	13 TeV
$(\sigma_{\Xi_b^{**-}}/\sigma_{\Lambda_b^0})\mathcal{B}(\Xi_b^{**-} \to \Lambda_b^0 K^-)$	$(3.0 \pm 0.4 \pm 0.4)\times 10^{-3}$	$(3.4 \pm 0.4 \pm 0.4)\times 10^{-3}$
$(\sigma_{\Xi_b^{**-}}/\sigma_{\Xi_b^0})\mathcal{B}(\Xi_b^{**-} \to \Xi_b^0 \pi^-)$	$(47 \pm 9 \pm 7)\times 10^{-3}$	$(22 \pm 6 \pm 3)\times 10^{-3}$

- Consistent with 1P states



Bing Chen et. al. PRD 98, (2018) 031502(R)

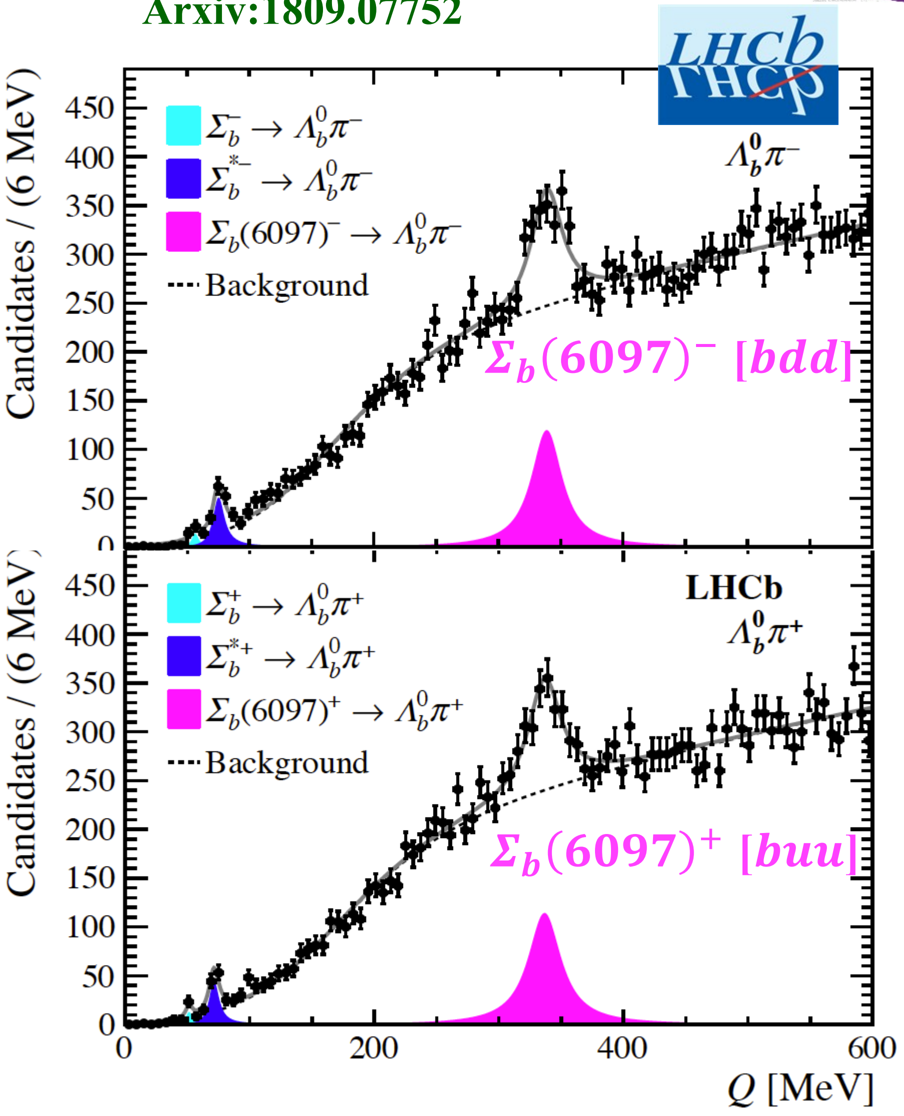
Σ_b spectroscopy: Observation of $\Sigma_b(6097)^{\pm}$

- $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ combined with $\pi^{\pm}$ from PV
- $p_T(\pi^{\pm}) > 1$ GeV to suppress backgd
- Relativistic BW convoluted with resolutions of 1.0, 1.1, 2.4 MeV for Σ_b, Σ_b^*, $\boldsymbol{\Sigma_b(6097)}$

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

$\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ parameters are measured, 5x more precise than the previous CDF values

Arxiv:1809.07752



Charmed baryons

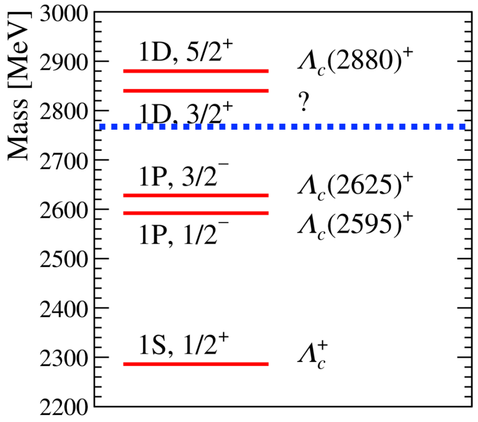
- ✓ Direct production
- ✓ From B decay

$\Lambda_c^{(*)}$ spectroscopy

- Status

B.Chen, K.-W. Wei and A. Zhang, EPJA 51 (2015) 82

– experimental observations / nonrelativistic *heavy quark-light diquark* model



D^0p

states seen with confirmed properties

Λ_c(2765) or Σ_c

threshold structure near 2840 MeV

Λ_c(2940)

- $\mathcal{B}(\Lambda_b \to D^0 p\pi^-)$ measured with 1fb^{-1}

LHCb-PAPER-2013-056
PRD 89 (2014) 032001

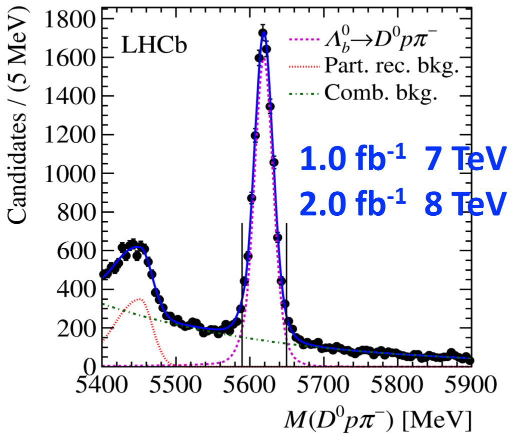
Amplitude analysis with 3 fb-1

LHCb-PAPER-2016-061
JHEP 05 (2017) 030

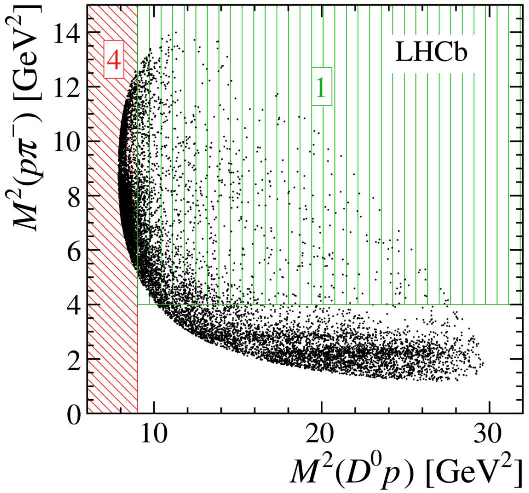
Amplitude analysis $\Lambda_b \rightarrow D^0 p \pi^-$

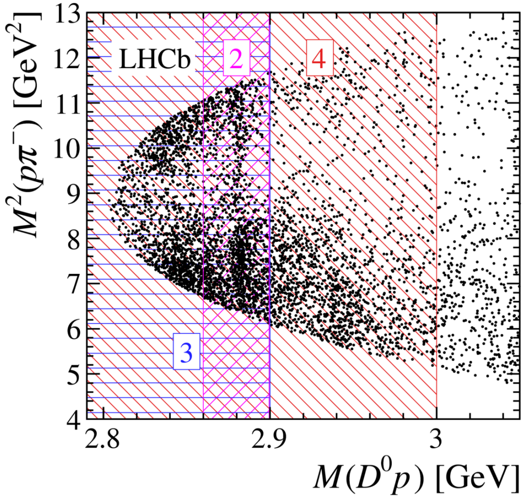
LHCb-PAPER-2016-061
JHEP 05 (2017) 030

- Clean sample with ~11K signal events



1.0 fb^{-1} 7 TeV
2.0 fb^{-1} 8 TeV





fit in different phase space regions to reduce complexities

Yield	Phase space region Full	1	2	3	4
$\Lambda_b^0 \rightarrow D^0 p \pi^-$	$11\,212 \pm 126$	$2\,250 \pm 61$	$1\,674 \pm 46$	$3\,141 \pm 63$	$4\,750 \pm 79$
Combinatorial	$14\,024 \pm 224$	$4\,924 \pm 132$	968 ± 78	$2\,095 \pm 96$	$4\,188 \pm 127$
Partially rec.	$4\,106 \pm 167$	$1\,344 \pm 96$	321 ± 64	691 ± 75	$1\,204 \pm 96$
Signal in box	10 233	2 061	1 500	2 803	4 261
Background in box	1 616	598	89	192	427

Amplitude analysis $\Lambda_b \to D^0 p \pi^-$

LHCb-PAPER-2016-061
JHEP 05 (2017) 030

- $\Lambda_c(2880)$ $J^P = \frac{5}{2}^+$ confirmed

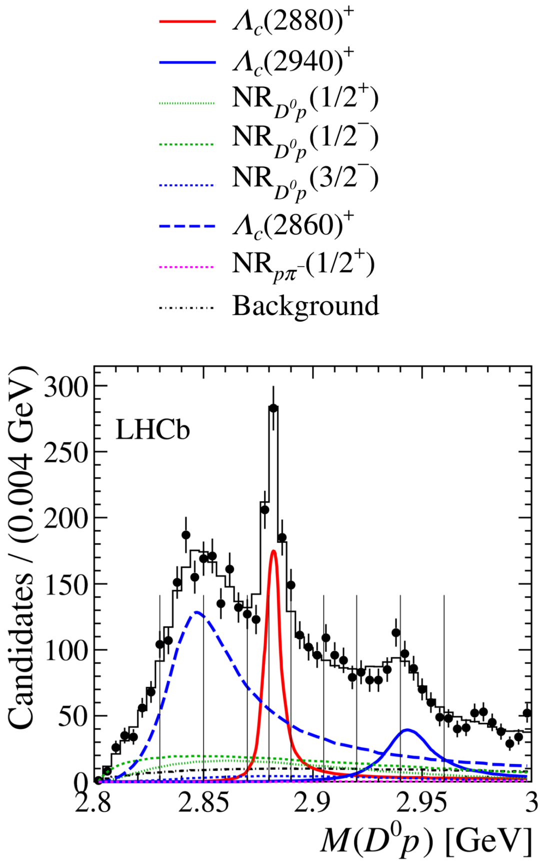
$$m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29(\text{stat}) \pm 0.07(\text{syst})^{+0.14}_{-0.20}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71}(\text{stat}) \pm 0.29(\text{syst})^{+0.75}_{-0.00}(\text{model})\ \text{MeV}.$$

- $\Lambda_c(2860)$ $J^P = \frac{3}{2}^+$ confirmed

$$m(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7}(\text{stat}) \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\ \text{MeV},$$
$$\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1}(\text{stat}) \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\ \text{MeV}.$$

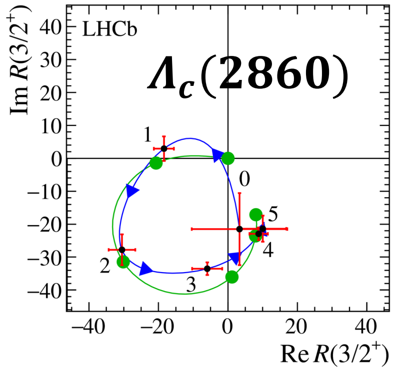
- $\Lambda_c(2940)$ $J^P = \frac{3}{2}^-$ favored , ($\frac{3}{2}^+, \frac{5}{2}^-, \frac{5}{2}^+$ ~3σ)

$$m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5}(\text{stat}) \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})\ \text{MeV}$$
$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0}(\text{stat}) \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model})\ \text{MeV}.$$



Argand plot —

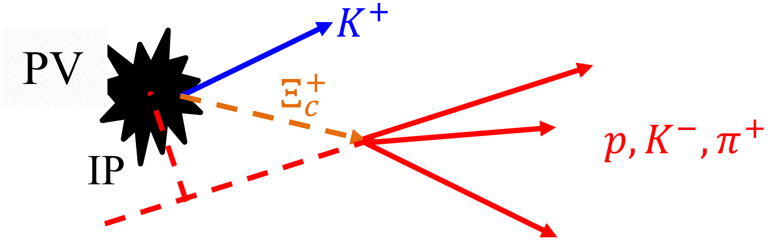
Breit-Wigner —



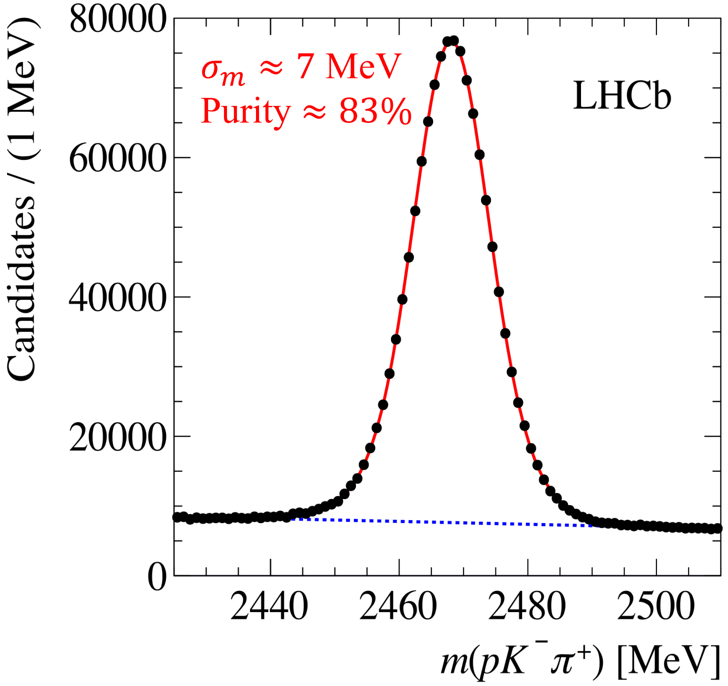
Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

- **Excited $\Lambda_c^+, \Sigma_c, \Xi_c$ states have been reported but no excited Ω_c^0 states were observed before LHCb**
- **3 fb^{-1} Run I + 0.3 fb^{-1} Run II pp collisions data**
- **Decay: $\Omega_c^{**0} \to \Xi_c^+ K^-$, $\Xi_c^+ \to pK^-\pi^+$**



Cabibbo suppressed decay, but much higher reconstruction efficiency

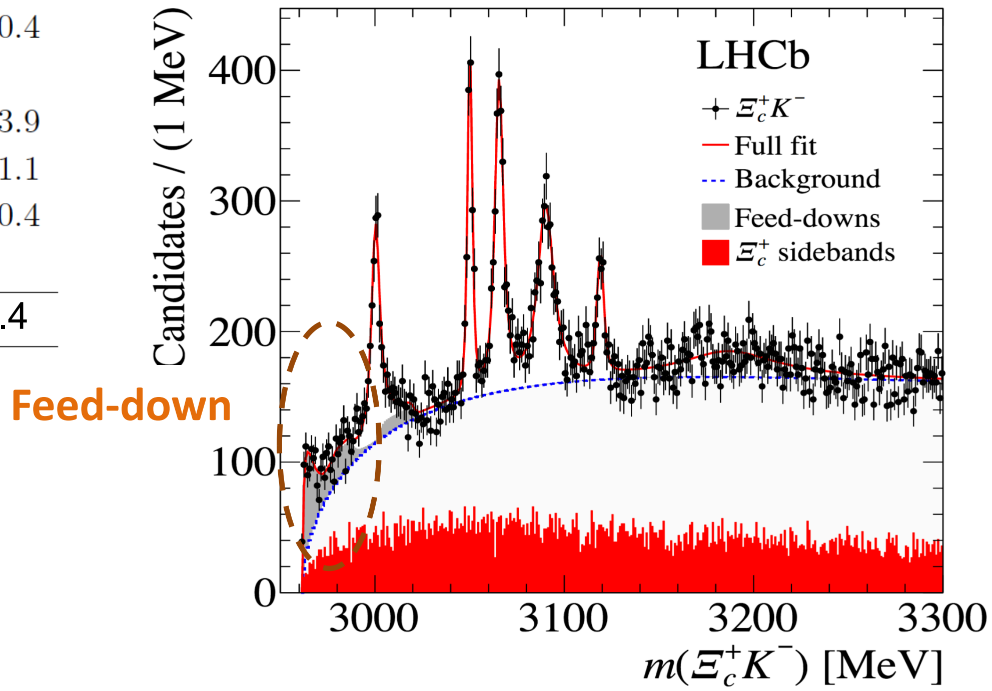


Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

- **5 narrow states & evidence for 6th broader state at high mass**

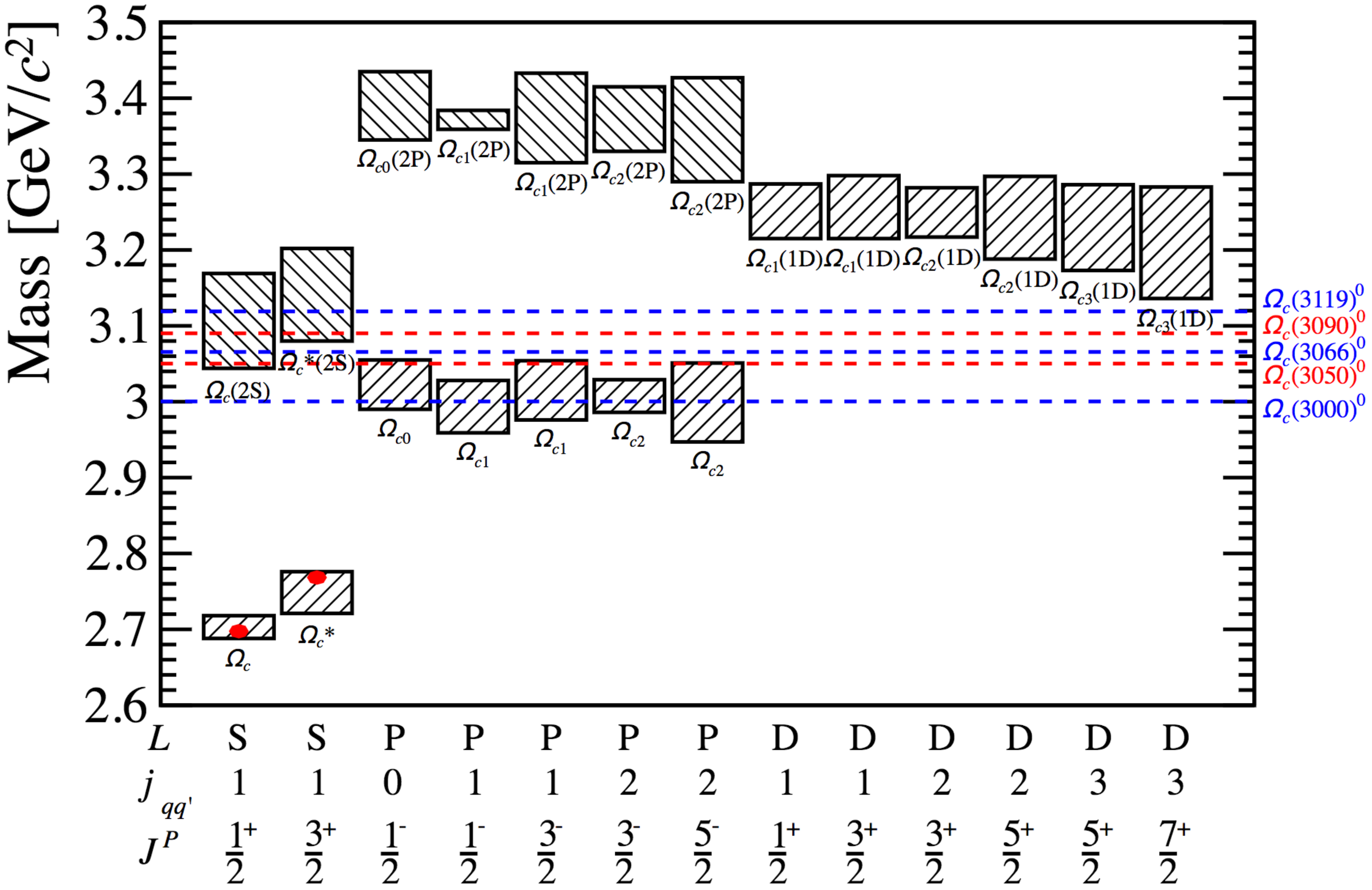
Resonance	Mass (MeV)	Γ (MeV)	$N_\sigma = \sqrt{\Delta\chi^2}$
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$ < 1.2 MeV, 95% CL	20.4
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$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



> Even at the most powerful particle accelerator on Earth, the discovery of a new particle is a big deal. Finding five new baryons in one go, as the Large Hadron Collider beauty experiment (LHCb) has done, is truly historical.
>
> \- Matteo Rini *Physics*

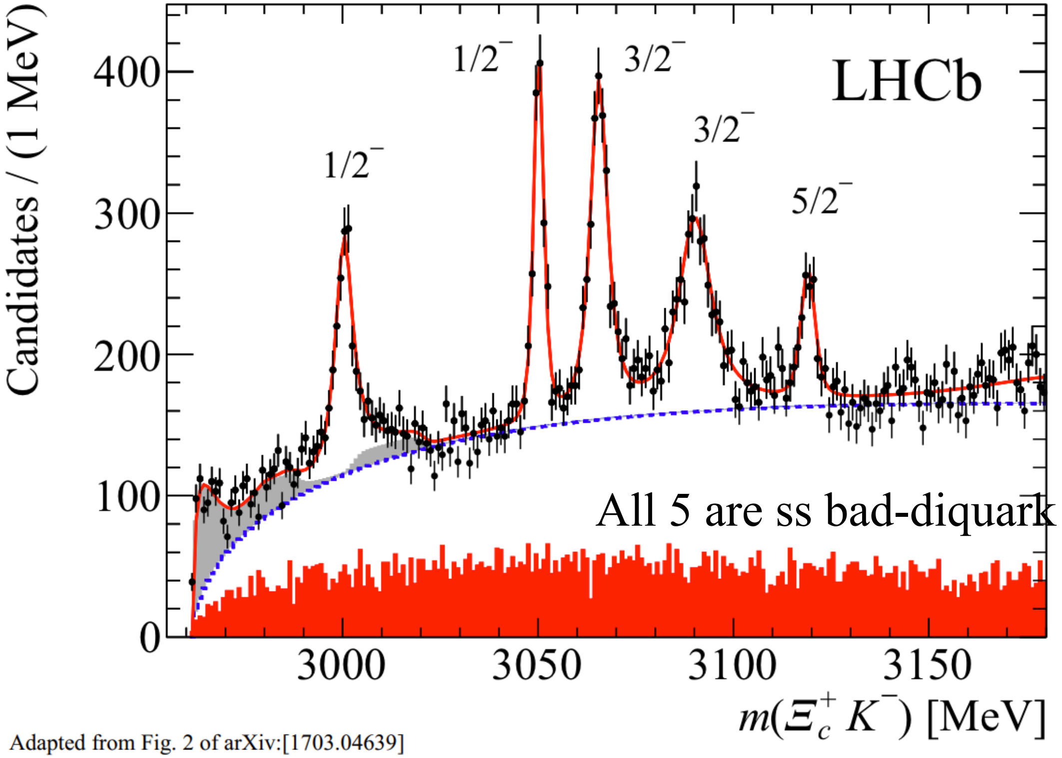
Feed-down: $\Omega_c^{**0} \rightarrow K^- \Xi_c'^+, \Xi_c'^+ \rightarrow \gamma \Xi_c^+$,
$m(\Xi_c^+ K^-)$ mass peaks shifted

Interpretation of exited Ω_c states



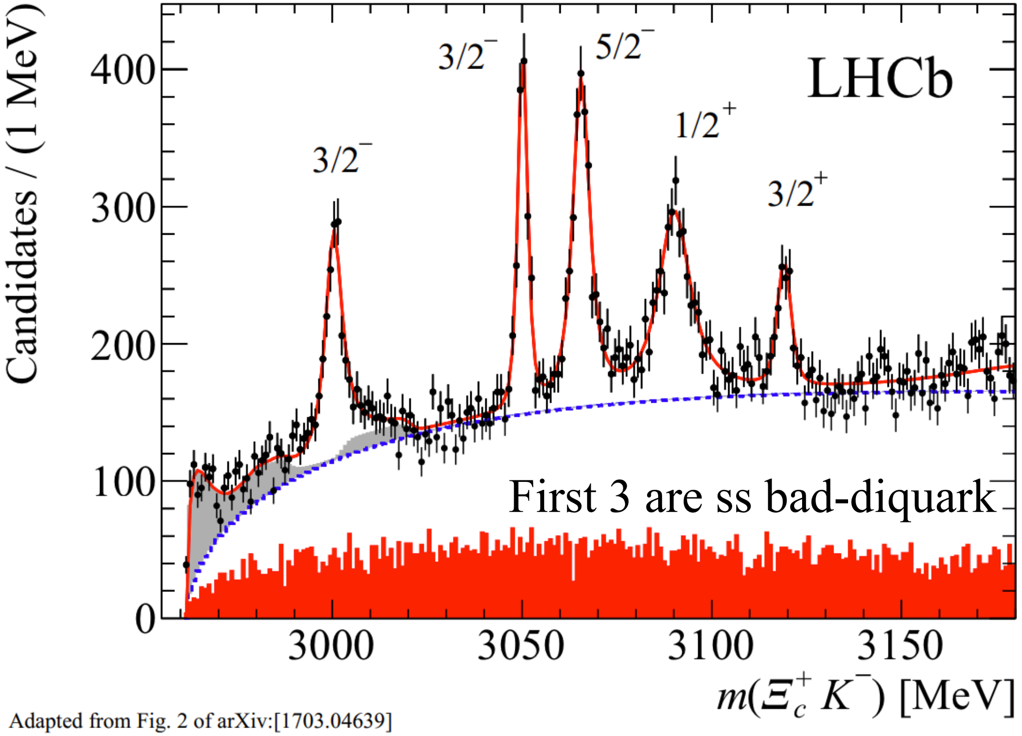
Interpretation of exited Ω_c states

- Quark model



All 5 are ss bad-diquark

Adapted from Fig. 2 of arXiv:[1703.04639]



First 3 are ss bad-diquark

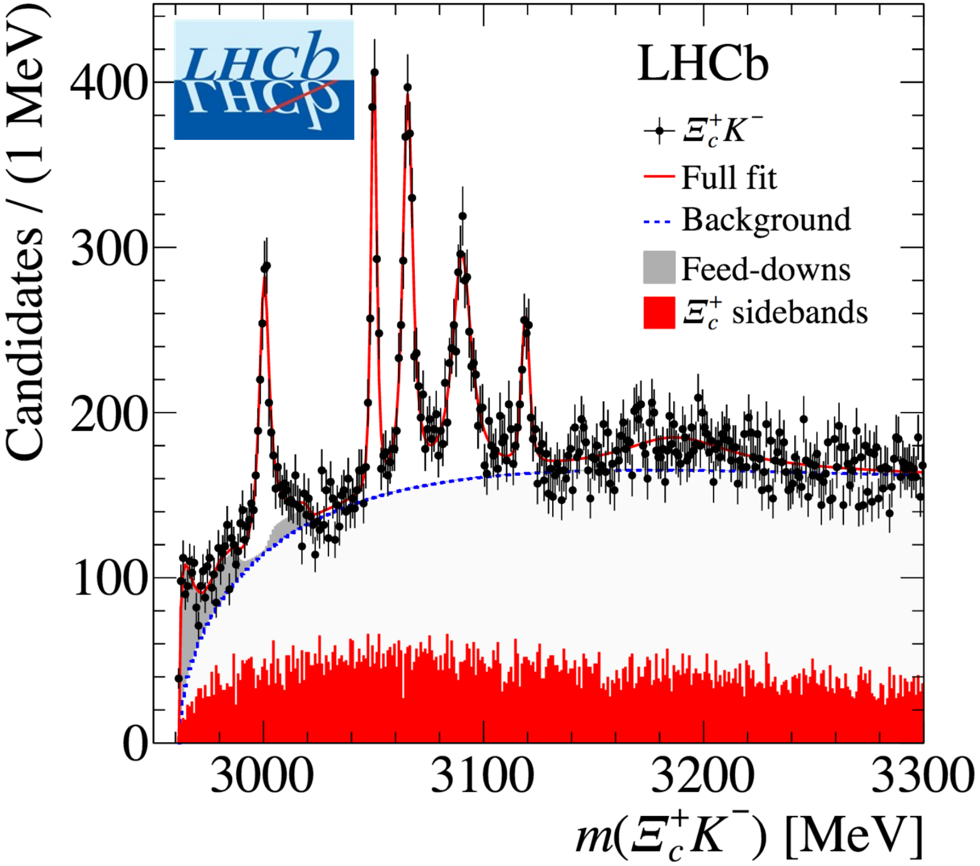
Adapted from Fig. 2 of arXiv:[1703.04639]

- Some theorists also consider 3050 & 3090 are $D\Xi$ molecular

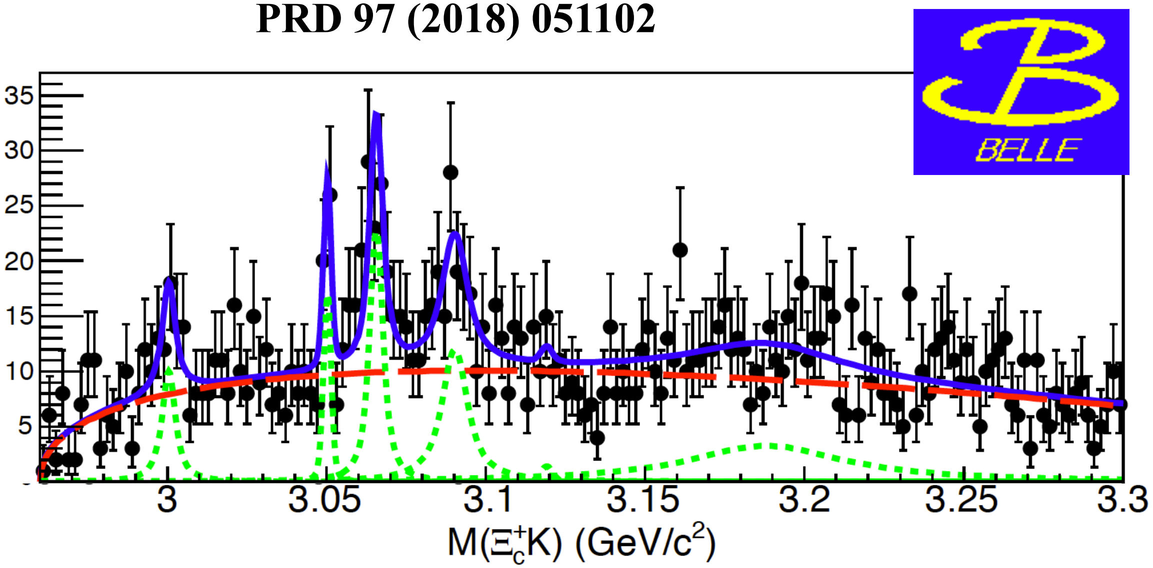
Excited Ω_c states

- LHCb observed 5 narrow states (+ a possible wide one) in 2017
- Belle confirmed the first four states this year

PRL 118 (2017) 182001



PRD 97 (2018) 051102



The measured masses are consistent with LHCb values

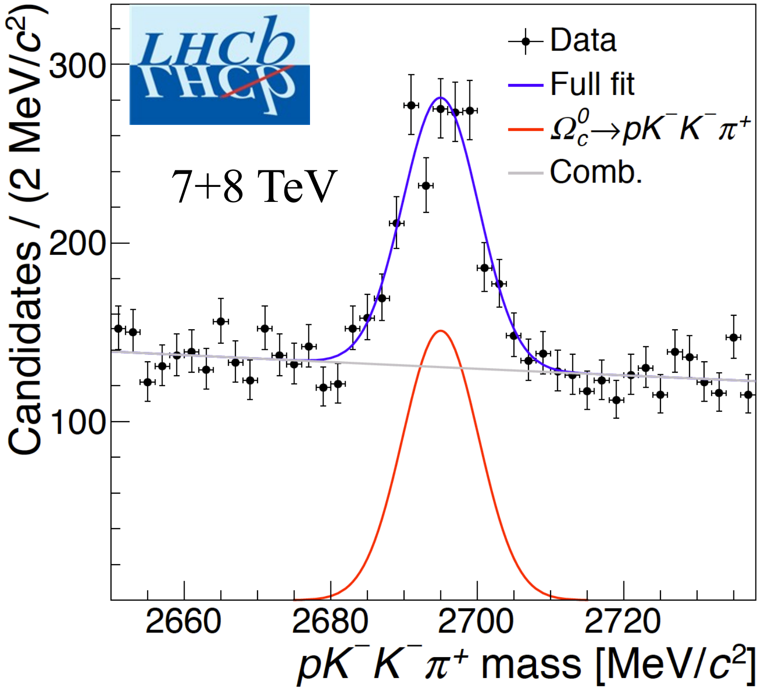
Measurement of Ω_c^0 lifetime

PRL 121 (2018) 092003

- *Charm*-hadron lifetimes probe high-order corrections in HQE
- *Charm*-baryon lifetimes are not well measured, in particular Ω_c^0 (69 ± 12 fs)
- Current measurements

Precision 17%

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



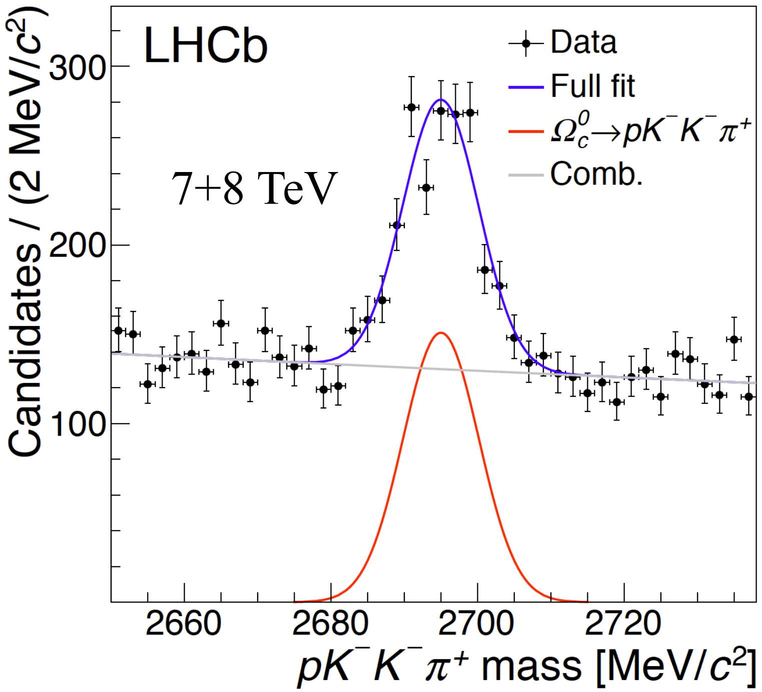
- LHCb uses $b \to c$ semileptonic decays to avoid bias on charm
  - Signal: $\Omega_b^- \to \Omega_c^0(\to pK^-K^-\pi^+)\mu^-\bar{\nu}_\mu X$
  - Control: $B \to D^+(\to K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$

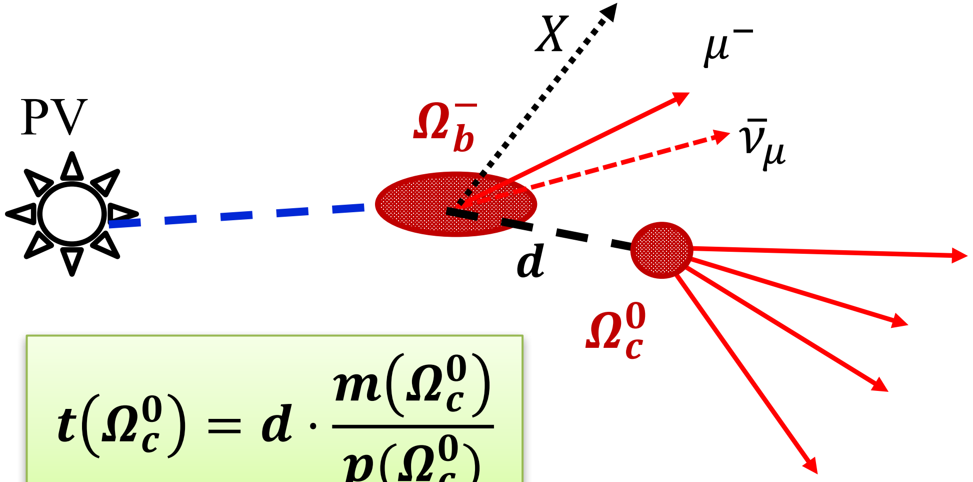
Yields:
$\Omega_c^0\mu^-$: 978 ± 60
(~10 times larger than any previous sample used for τ)

Signal and control channels

- Use $b \to c$ semileptonic decays to avoid bias from trigger and offline selections
  - Muon trigger
  - Tracks well separated from PV
- Signal: $\Omega_b^- \to \Omega_c^0(\to pK^-K^-\pi^+)\mu^-\bar{\nu}_\mu X$
- Control: $B \to D^+(\to K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$

PRL 121 (2018) 092003





$$t(\Omega_c^0) = d \cdot \frac{m(\Omega_c^0)}{p(\Omega_c^0)}$$

Yields:

$\Omega_c^0\mu^-$: 978 ± 60

(~10 times larger than any previous sample used for τ)

$D^+\mu^-$: $(809 \pm 1) \times 10^3$

(used only 10% of LHCb Run-I data)

Lifetime fits

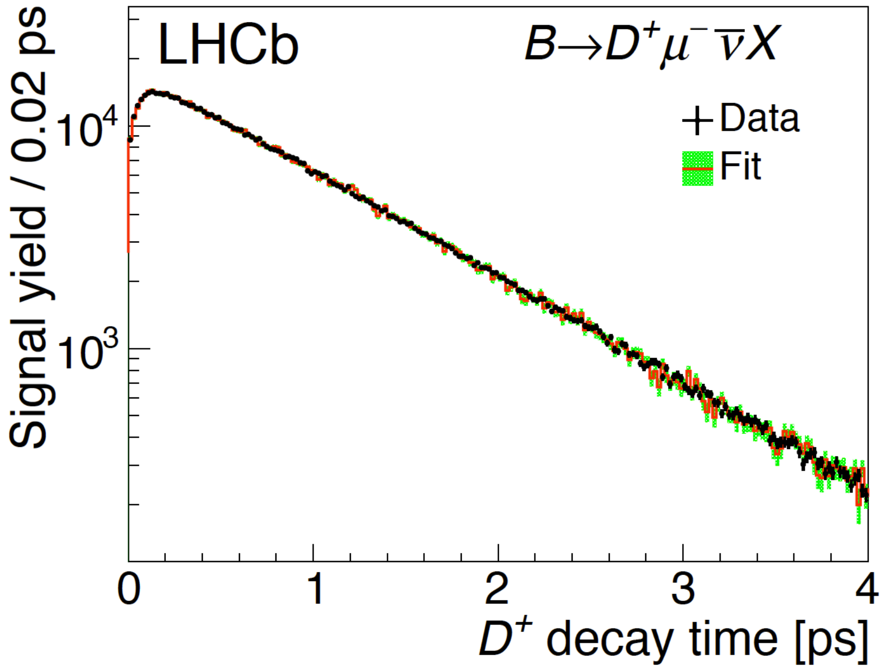
PRL 121 (2018) 092003

- Fit background-subtracted distribution obtained with sPlot technique
- Signal PDF:

$$S(t_{\text{rec}}) = \boxed{f(t_{\text{rec}})}\exp\left(-\frac{t_{\text{rec}}}{\tau_{\text{fit}}}+\frac{t_{\text{rec}}}{\tau_{\text{sim}}}\right)\boxed{\beta(t_{\text{rec}})}$$

Binned Template from simulation
✓ **Corresponding to efficiency**

Correction for small efficiency different between data and MC
✓ **Obtained from D^+ and used for Ω_c^0**



If without $\beta(t_{\text{rec}})$ correction, about 1.2σ below the PDG value

- Check fit procedure with D^+ events

Consistent with PDG value: 1040 ± 7 fs

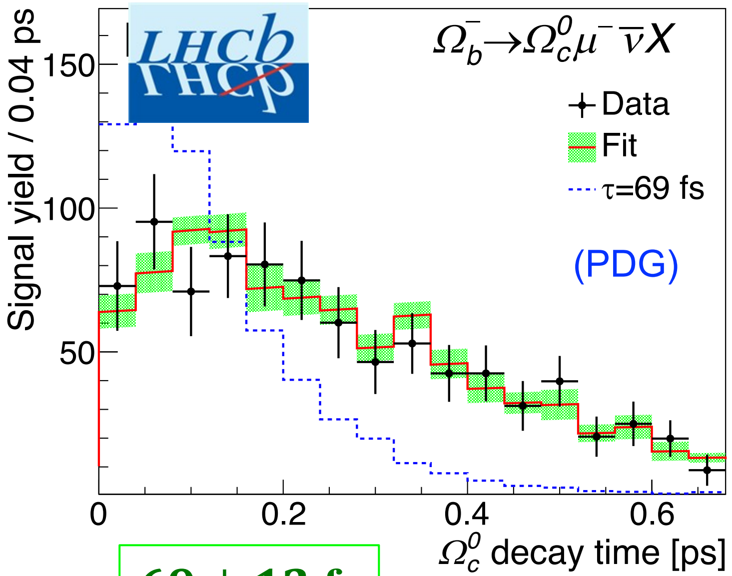
Ω_c^0 lifetime result

PRL 121 (2018) 092003

- Simultaneous fit signal and control samples

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

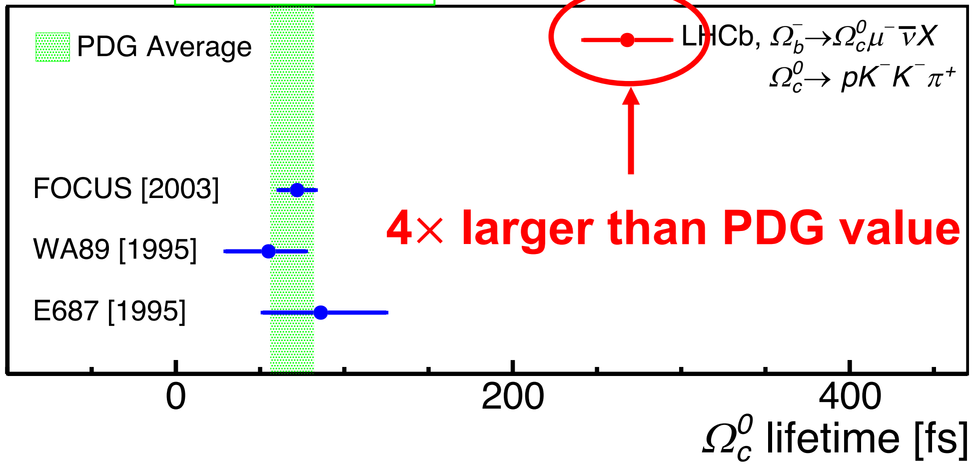
Precision 9.7%



(PDG)

69 ± 12 fs

- Many cross-checks
  - 13 TeV 2016 data
  - An additional $D^0 \to K3\pi$ lifetime measurement



4× larger than PDG value

- LHCb result gives

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

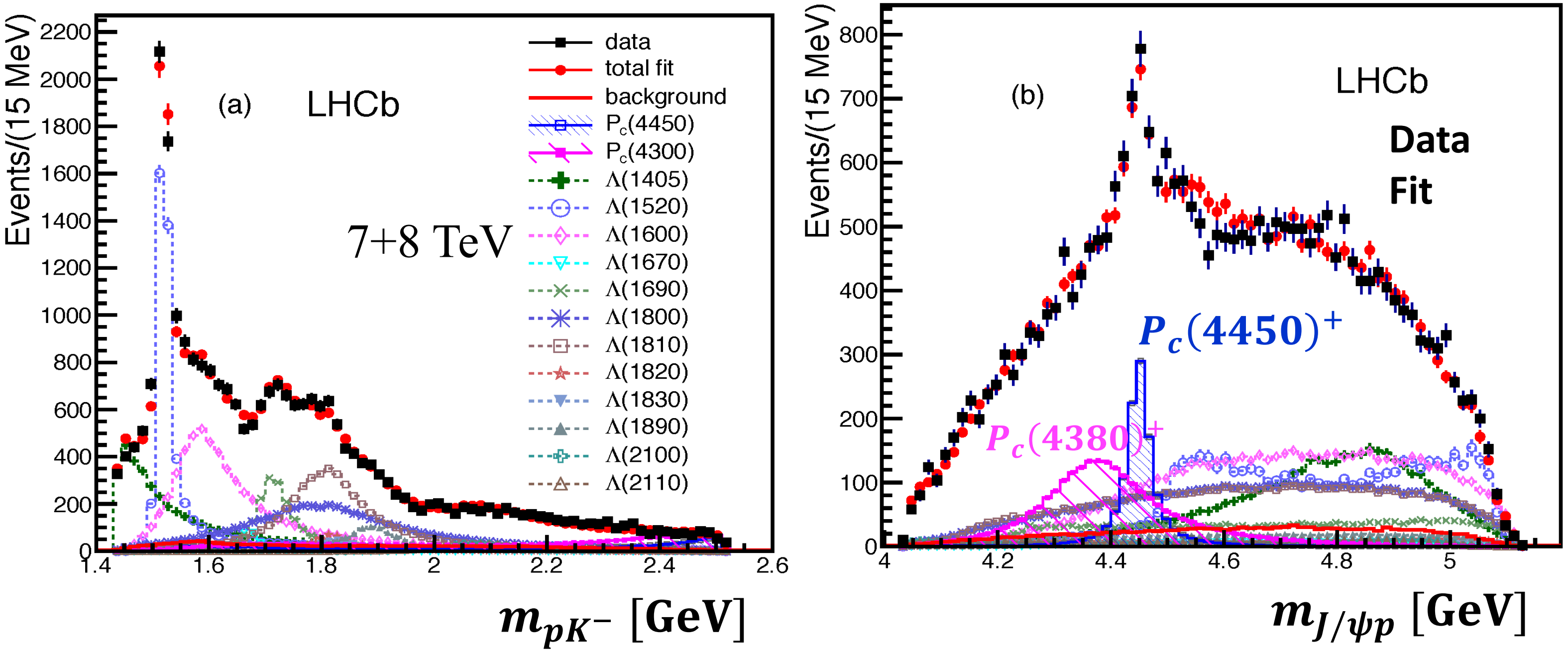
Verifications are needed from the other experiments and LHCb study using prompt Ω_c^0

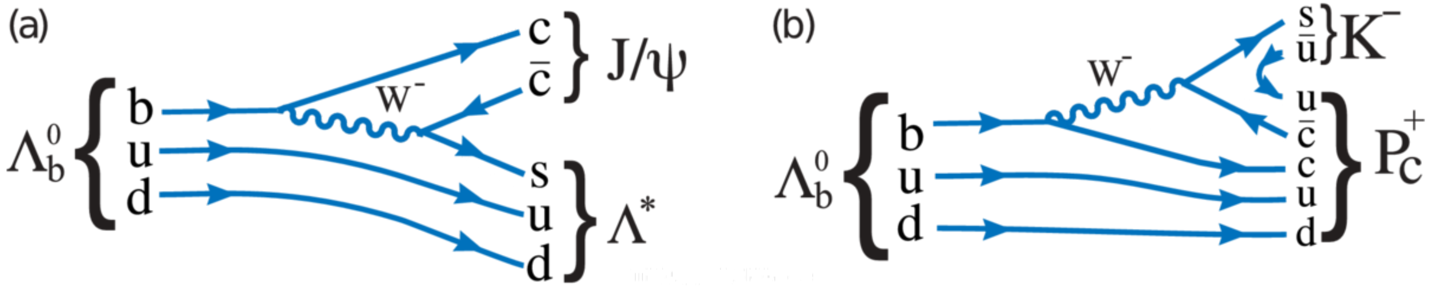
Exotic baryons

Discovery of pentaquark states

PRL 115, 072001 (2015)

- Two pentaquark states observed in 26,000 $\Lambda_b^0 \to J/\psi p K^-$ decays

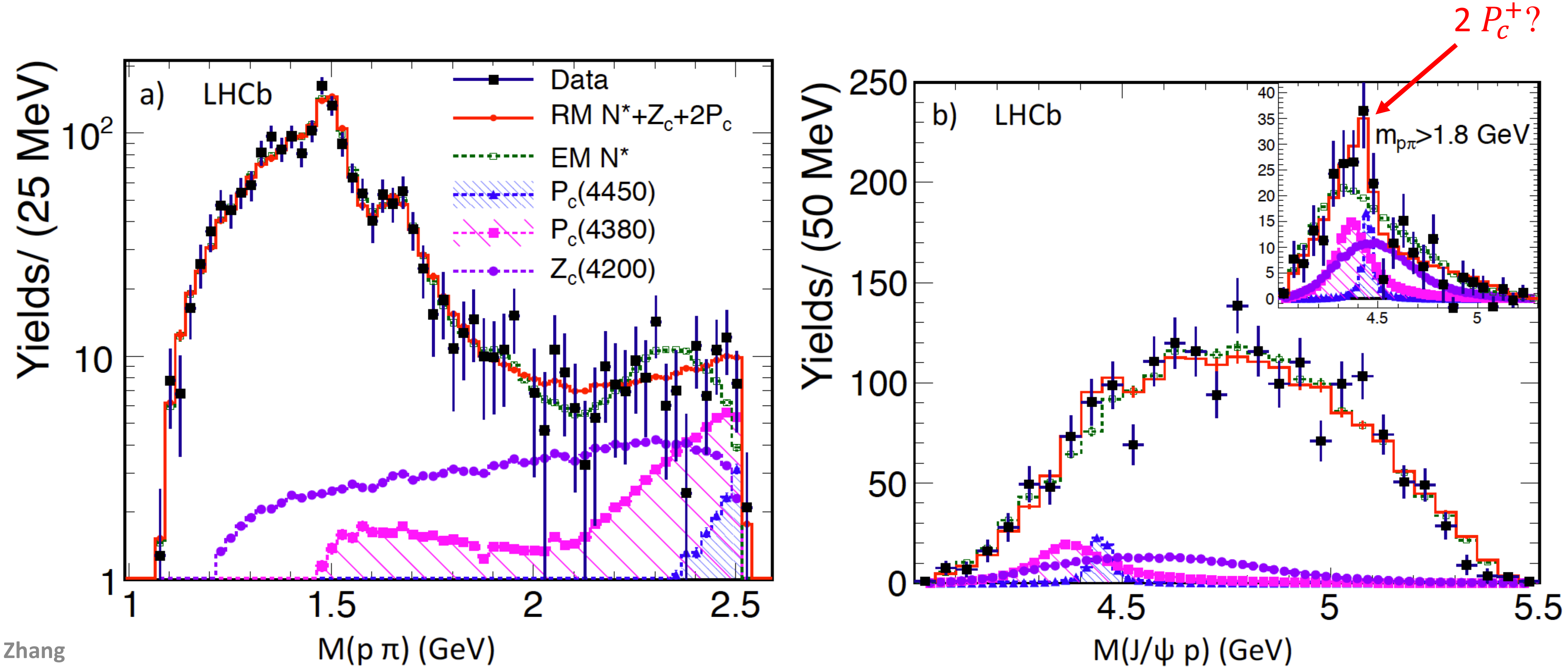




Full amplitude fits to $\Lambda_b^0 \to J/\psi p \pi^-$

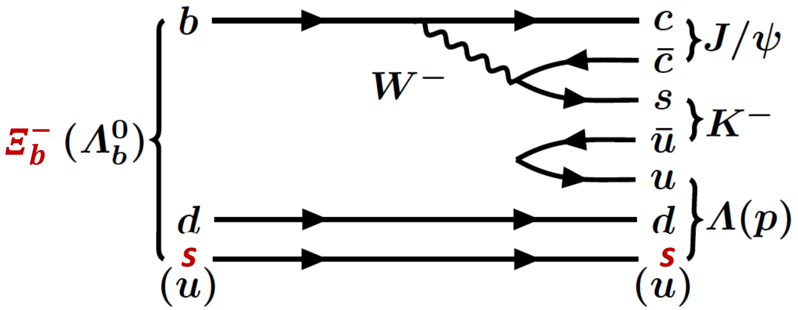
- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ take together is 3.1 σ including syst.
- First evidence!

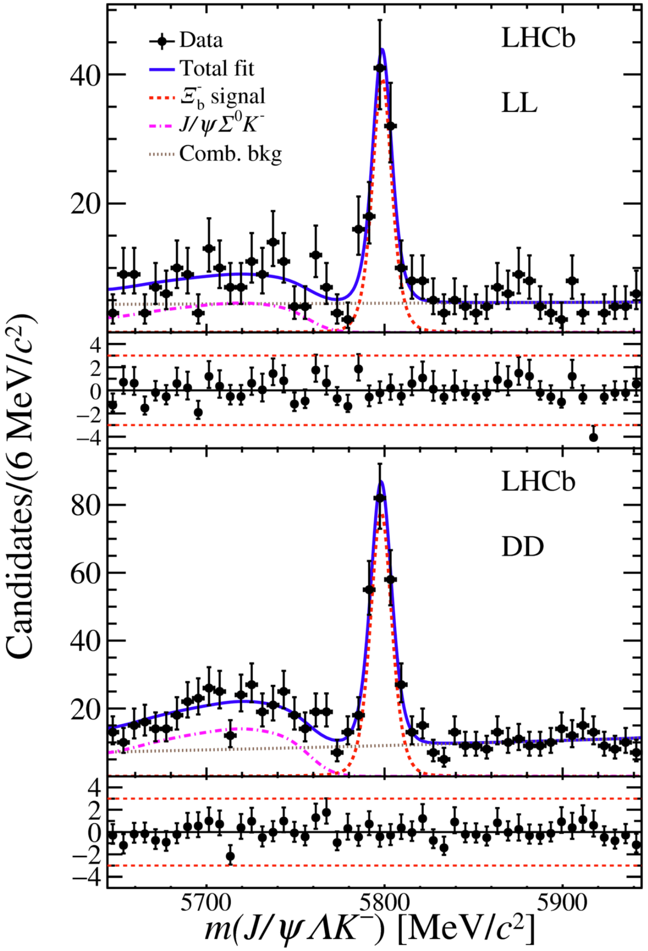
PRL 117, 082003 (2016)



Observation of $\Xi_b^- \to J/\psi \Lambda K^-$

- Strange pentaquark ($udsc\bar{c}$) predicted in **[PRL 105, 232001 (2010)]**
- Can be searched for in the Ξ_b^- decay **[PRC 93, 065203 (2016)]**





$N_{\rm sig} = 308 \pm 21$ (21σ)

PLB 772 (2017) 265-273

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15)\times 10^{-2}$$

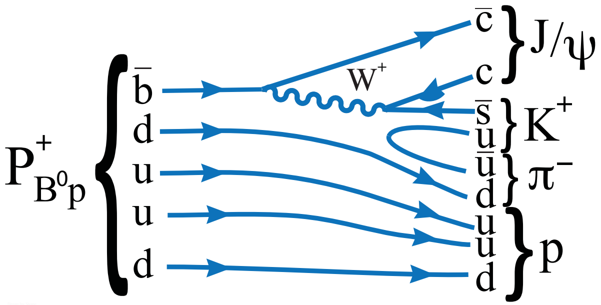
Expect ~1700 signals, amplitude analysis is in good progress

Weakly decaying *b*-flavoured pentaquarks

PRD 97 (2018) 032010

- Skyrme model: heavy quarks give tightly bound pentaquark

PLB 590(2004) 185; PLB 586(2004)337; PLB 331(1994)362



- Search for mass peaks below strong decay threshold

Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0p} \to J/\psi K^+\pi^- p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda^0_b\pi^-} \to J/\psi K^-\pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda^0_b\pi^+} \to J/\psi K^-\pi^+ p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B^0_sp} \to J/\psi \phi p$	5055–6305 MeV

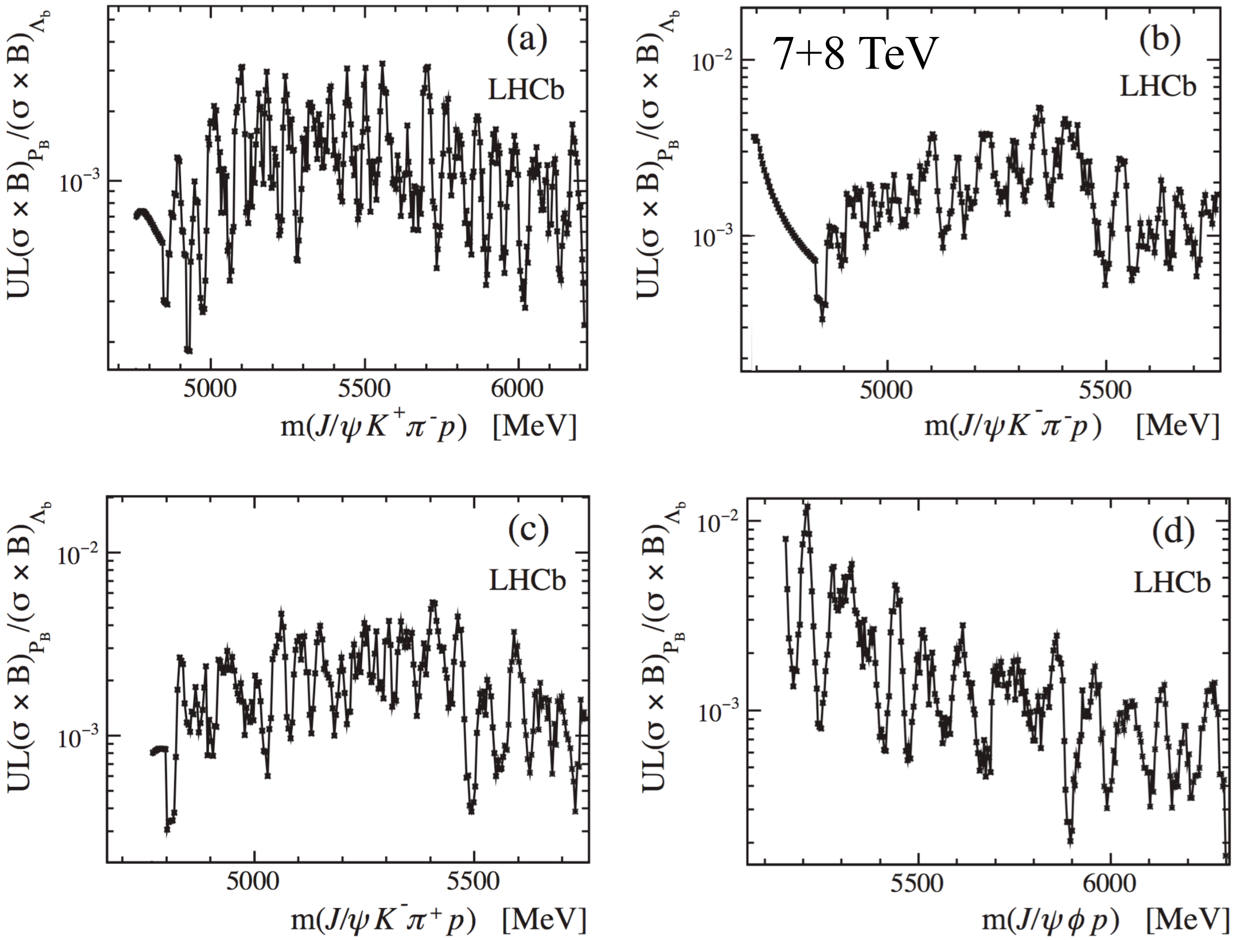
- Upper limit on production ratio $\sigma \cdot \mathcal{B}$ wrt $\Lambda^0_b \to J/\psi K^- p$

$$R = \frac{\sigma(pp \to P_B X) \cdot \mathcal{B}(P_B \to J/\psi\, X)}{\sigma(pp \to \Lambda^0_b X) \cdot \mathcal{B}(\Lambda^0_b \to J/\psi\, K^- p)}$$

Weakly decaying *b*-flavoured pentaquarks

PRD 97 (2018) 032010

- No evidence for signal, 90% CL limits on $R < 10^{-2} - 10^{-3}$



Summary

- LHCb have made contributions to charm baryon spectroscopy

- LHCb shows unique power to explore heavier states:
  - ☐ including excited *b*-baryons, doubly-heavy baryons & exotic baryons

- 欢迎理论家给我们指导，寻找底重子激发态
  - ☐ $\Lambda_b^*, \Sigma_b^* \to \bar{B}p?$
  - ☐ $\Xi_b^* \to \Xi_b\pi^+\pi^-, \bar{B}\Lambda?$

谢谢！

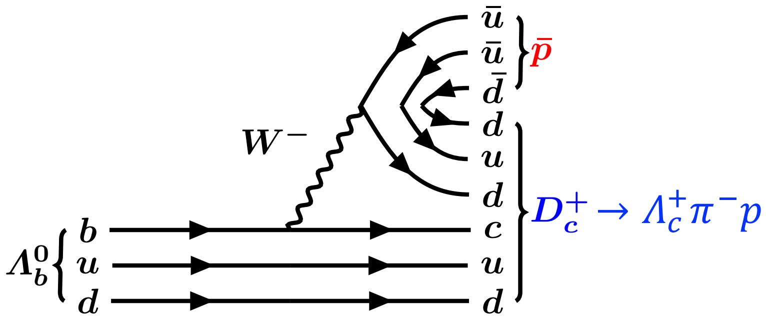
Search for dibaryon state

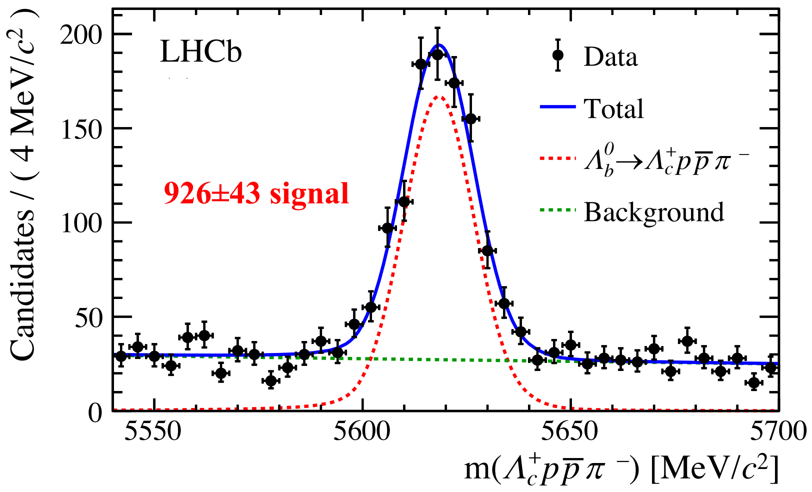
- A dibaryon state $[cd][ud][ud]$ could be produced in Λ_b^0 decays to final state $\Lambda_c^+\pi^-p\bar{p}$

L. Maiani, et al. PLB 750 (2015) 37

- LHCb has discovered the decay $\Lambda_b^0 \to \Lambda_c^+\pi^-p\bar{p}$

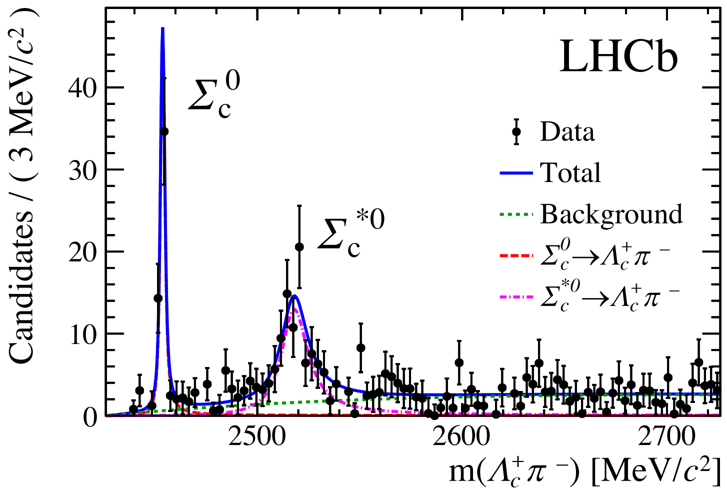
LHCb-PAPER-2018-005
arXiv:1804.09617 submitted to PLB





926±43 signal

Resonance contributions



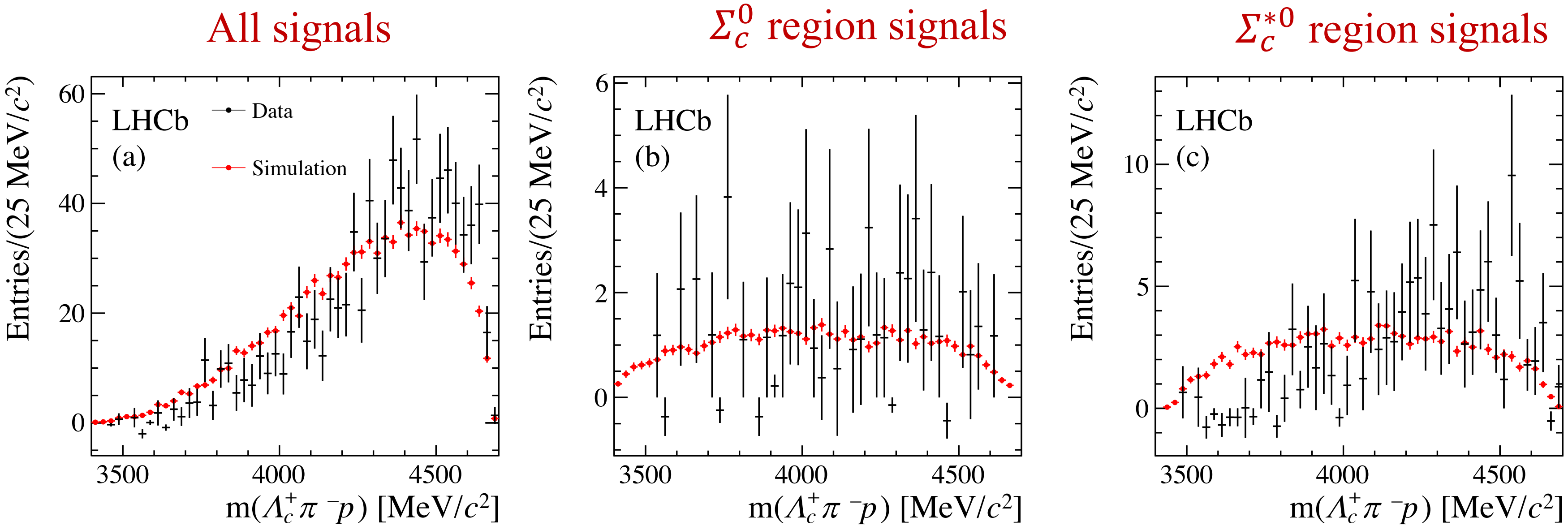
Search for dibaryon state

LHCb-PAPER-2018-005
arXiv:1804.09617 submitted to PLB

- Ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p \bar{p} \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032$$

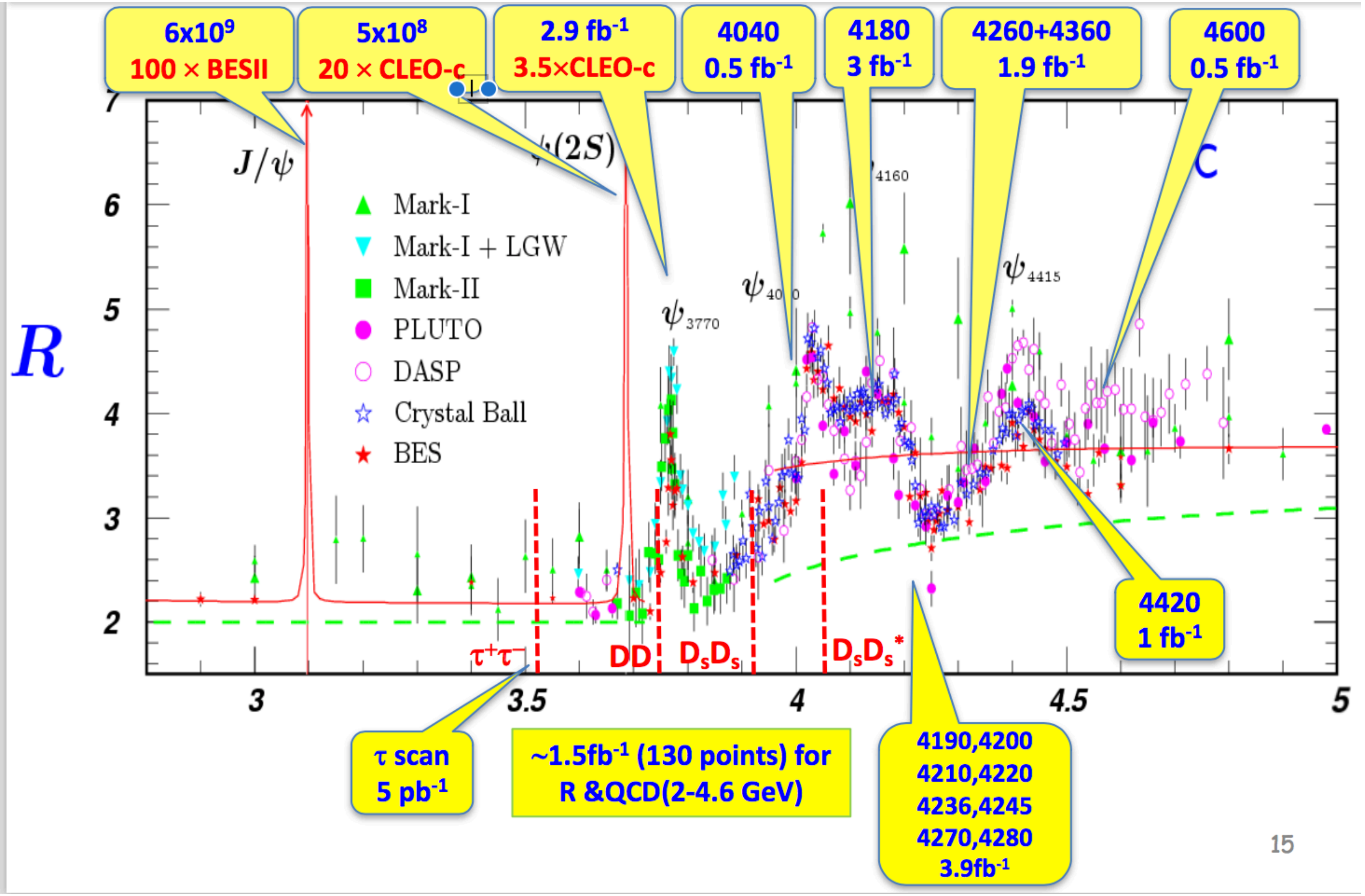
- No obvious dibaryon peak in $m(\Lambda_c^+ \pi^- p)$ spectra


All signals

Σ_c^0 region signals

Σ_c^{*0} region signals

BESIII data samples



6×10^9
100 × BESII

5×10^8
20 × CLEO-c

2.9 fb^{-1}
3.5×CLEO-c

4040
0.5 fb^{-1}

4180
3 fb^{-1}

4260+4360
1.9 fb^{-1}

4600
0.5 fb^{-1}

4420
1 fb^{-1}

τ scan
5 pb^{-1}

~1.5fb^{-1} (130 points) for
R &QCD(2-4.6 GeV)

4190,4200
4210,4220
4236,4245
4270,4280
3.9fb^{-1}

Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$

- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \boxed{\chi_{c(1,2)} p} K^-$ decays
  $\Rightarrow$Test hypothesis of kinematic rescattering effect

PRD 92 (2015) 071502

- First step: observe the decays, measure $\mathcal{B}$
- Use $\chi_{c(1,2)} \to J/\psi\gamma$, constrain $J/\psi\gamma$ mass to known χ_{c1} mass

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

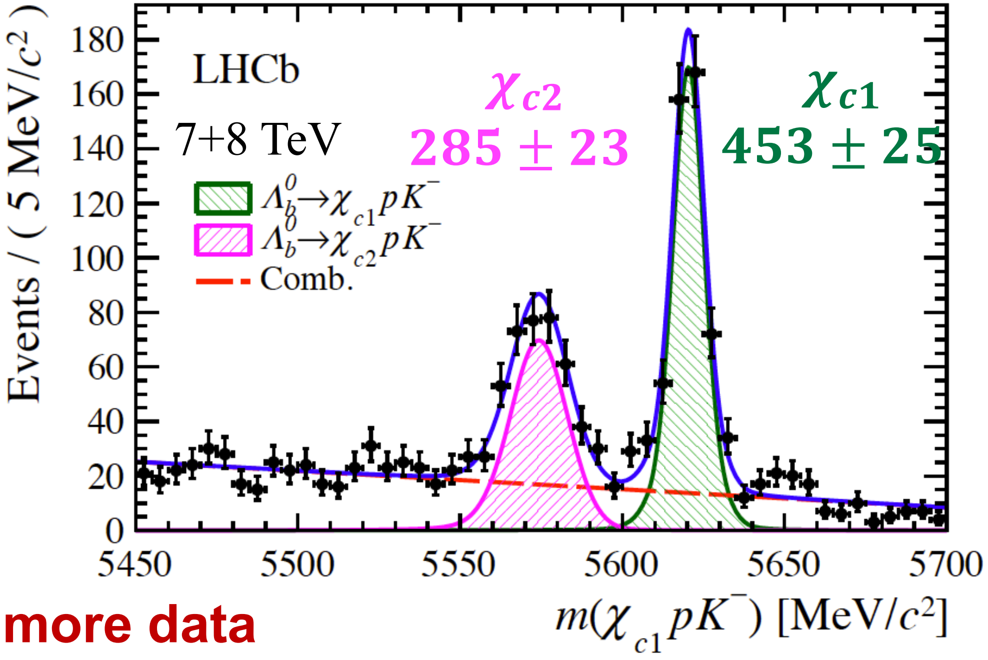
$$0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

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

$$\mathcal{B}(\chi_{cJ})$$

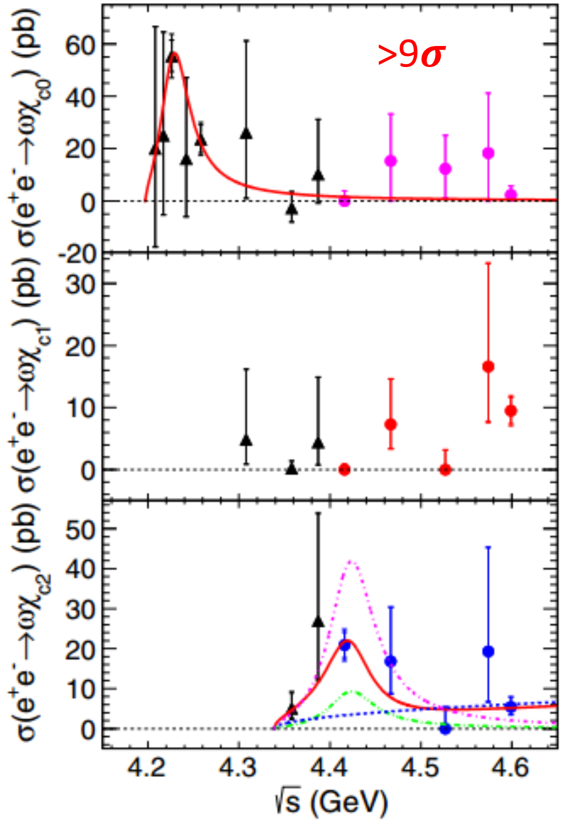
$$0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

PRL 119 (2017) 062001



Next step: full amplitude analysis with more data

Cross sections of $e^+e^-\rightarrow\omega/\phi\chi_{cJ}$ (J=0,1,2)



The triangle black data points are from

Phys. Rev. Lett. 114,092003(2015)

Other data points are from

Phys. Rev. D 93, 011102 (2016)

$e^+e^-\rightarrow\omega\chi_{c0}$:

Fit with a single BW

Mass = 4226±8±6 MeV

Width = 39±12±2 MeV

Significance > 9σ

$e^+e^-\rightarrow\omega\chi_{c2}$:

Agree with from ψ(4415) with

BR=$(1.4\pm0.5)\times10^{-3}$ (sol. I), or

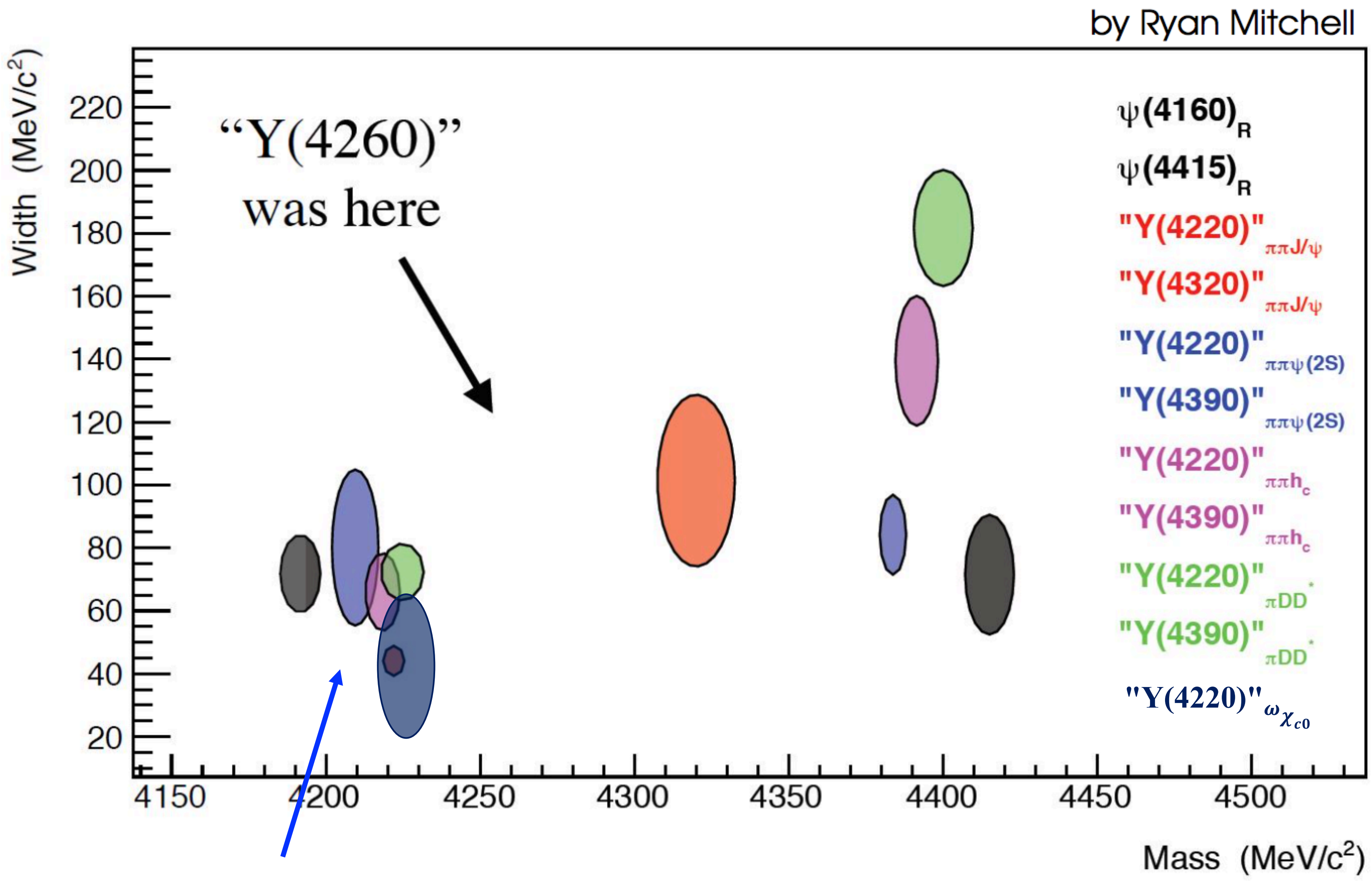
BR=$(6\pm1)\times10^{-3}$ (sol. II)

While BESIII measures $e^+e^-\rightarrow\phi\chi_{cJ}$ at 4.6GeV *PRD97, 032008 (2018)*

- $\sigma\,(e^+e^-\rightarrow\phi\chi_{c0}) < 5.4$ pb
- $\sigma\,(e^+e^-\rightarrow\phi\chi_{c1}) < (4.2^{+1.7}_{-1.0}\pm0.3)$ pb
- $\sigma\,(e^+e^-\rightarrow\phi\chi_{c2}) < (6.7^{+3.4}_{-1.7}\pm0.5)$ pb

Need data beyond 4.6 GeV to check structure in $\omega\chi_{c1}$ and $\phi\chi_{cJ}$

Y(4220) and the new Y's



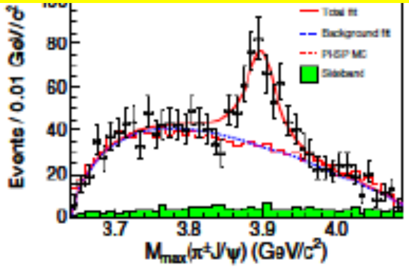
"Y(4260)" was here

Mass~4220 MeV, Width~ 60 MeV!

The Z_c Family at BESIII

$Zc(3900)^+$?

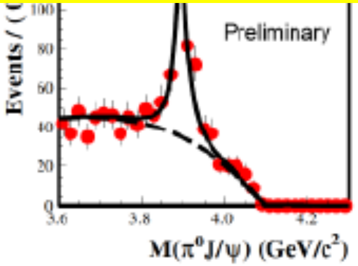
PRL 110, 252001 (2013)



$e^+e^- \to \pi^-\pi^+J/\psi$

$Zc(3900)^0$?

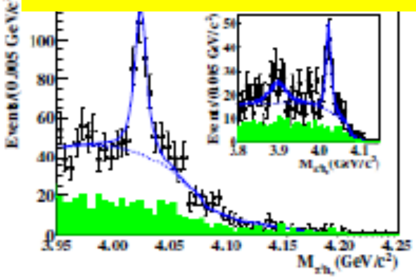
PRL 115, 112003 (2015)



$e^+e^- \to \pi^0\pi^0J/\psi$

$Zc(4020)^+$?

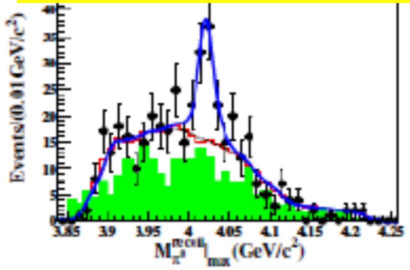
PRL 111, 242001(2013)



$e^+e^- \to \pi^-\pi^+h_c$

$Zc(4020)^0$?

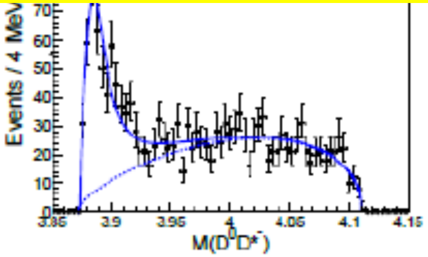
PRL113,212002 (2014)



$e^+e^- \to \pi^0\pi^0h_c$

$Zc(3885)^+$?

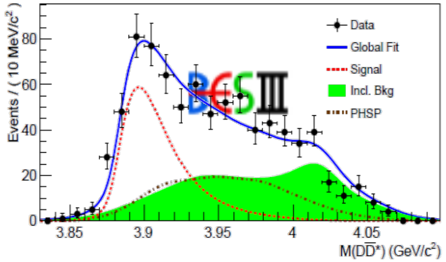
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



$e^+e^- \to \pi^-(D\bar{D}^*)^+$

$Zc(3885)^0$?

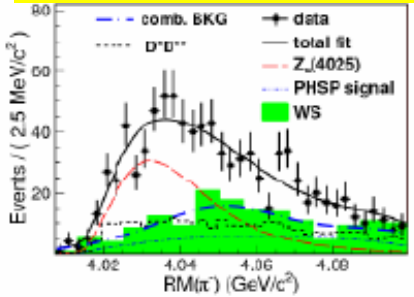
PRL 115, 222002 (2015)



$e^+e^- \to \pi^0(D^*\bar{D}\;)^0$

$Zc(4025)^+$?

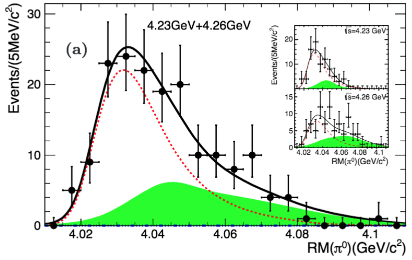
PRL 112, 132001 (2014)



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

$Zc(4025)^0$?

PRL115, 182002 (2015)



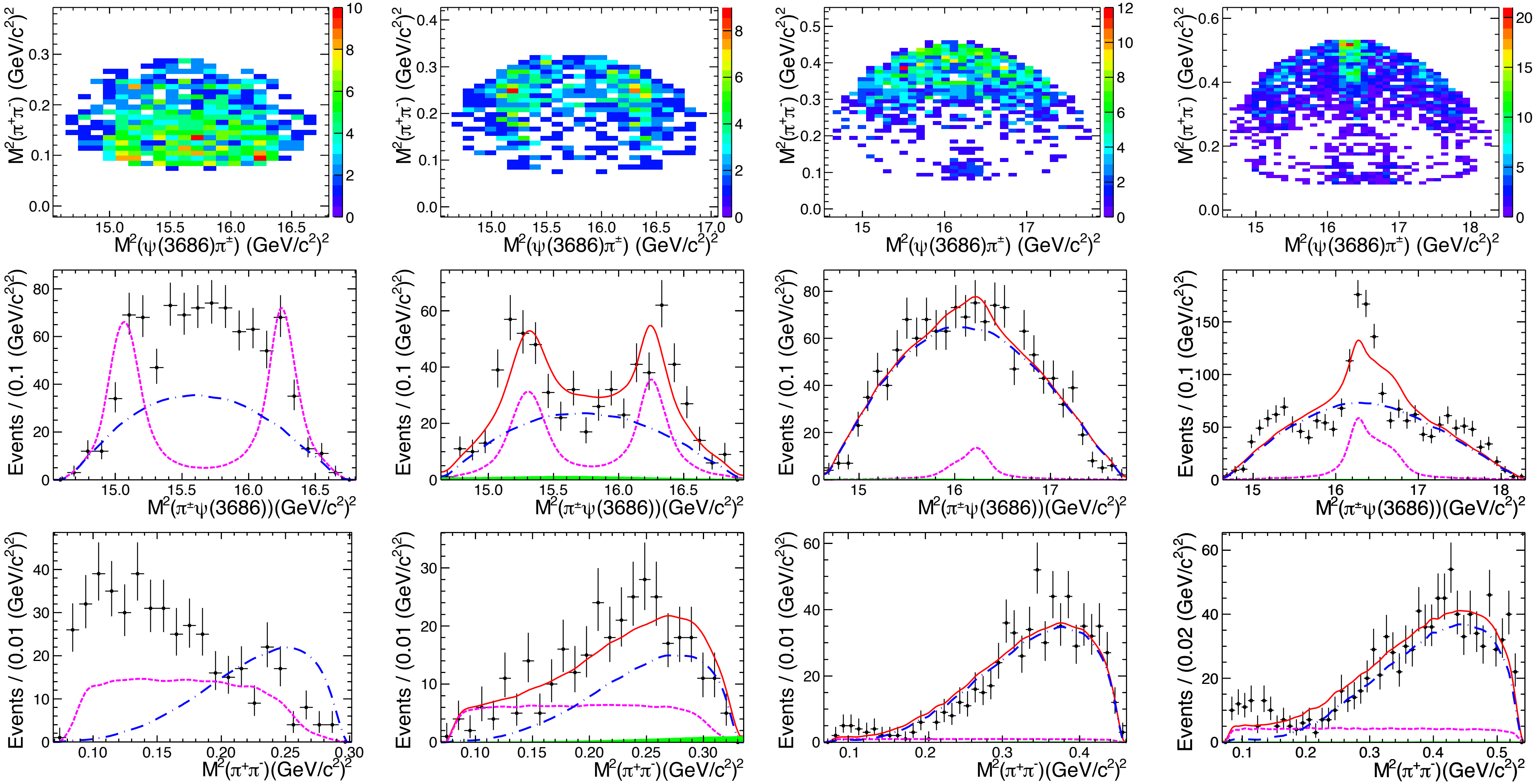
$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

Which is the nature of these states?

Different decay channels of the same observed states? Other decay modes?

$e^+e^- \to \psi(2S)\pi^+\pi^-$ Dalitz-plot

PRD 96 (2017) 032004



LHCb results on tetra and pentaquarks

- Confirmation of $Z(4430)$

  PRL 112 (2014) 222002

- Observation of two charmonium pentaquarks

  PRL 115 (2015) 072001

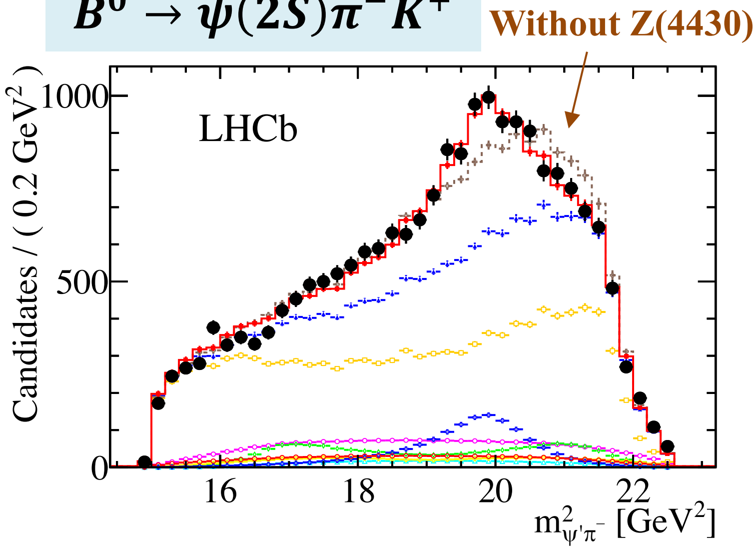
- Observation of four $J/\psi\phi$ structures

  PRL 118 (2017) 022003

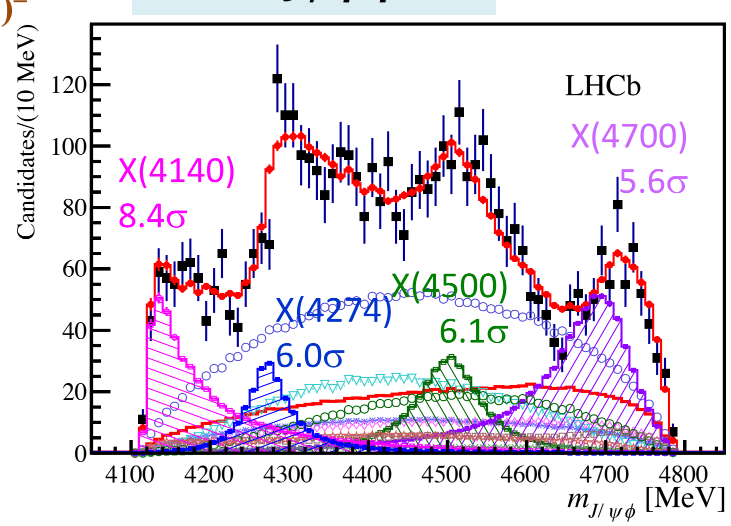
- Evidence of exotic contribution in Cabibbo-suppressed decays

  PRL 117 (2016) 082003

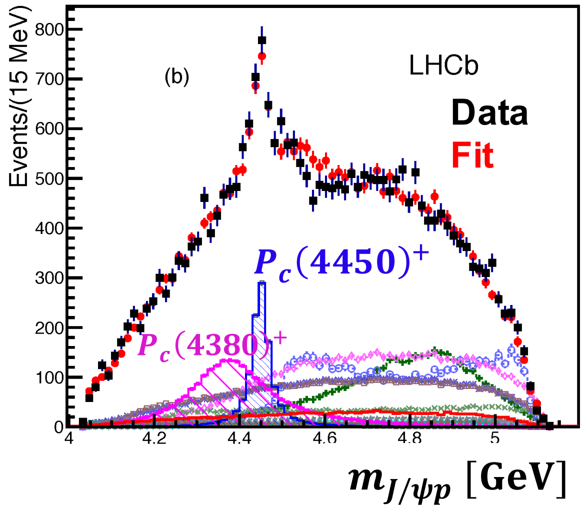
$B^0 \rightarrow \psi(2S)\pi^- K^+$



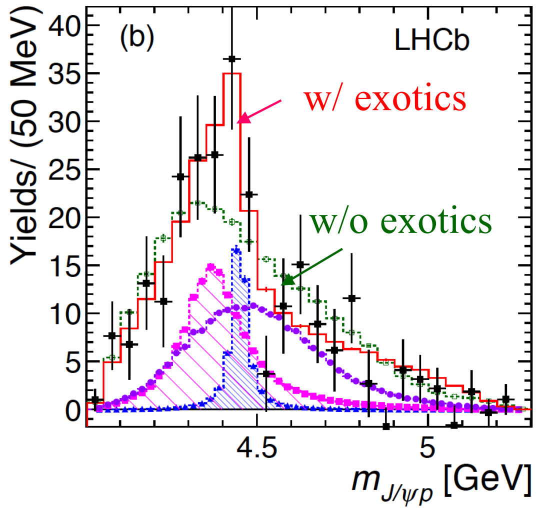
$B^+ \rightarrow J/\psi\phi K^+$



$\Lambda_b^0 \rightarrow J/\psi p K^-$



$\Lambda_b^0 \rightarrow J/\psi p \pi^-$

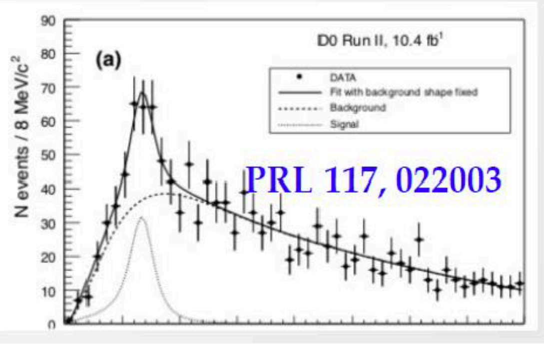


X(5568) – puzzle ?

- Possible tetraquark candidate of four different quarks
- Seen by D0 with **4. 8 σ** significance

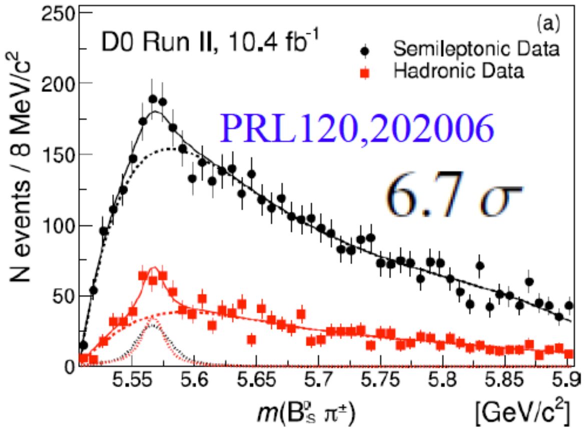
$$m = 5567.8 \pm 2.9\,(\mathrm{stat})^{+0.9}_{-1.9}\,(\mathrm{syst})\ \mathrm{MeV}/c^2$$

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



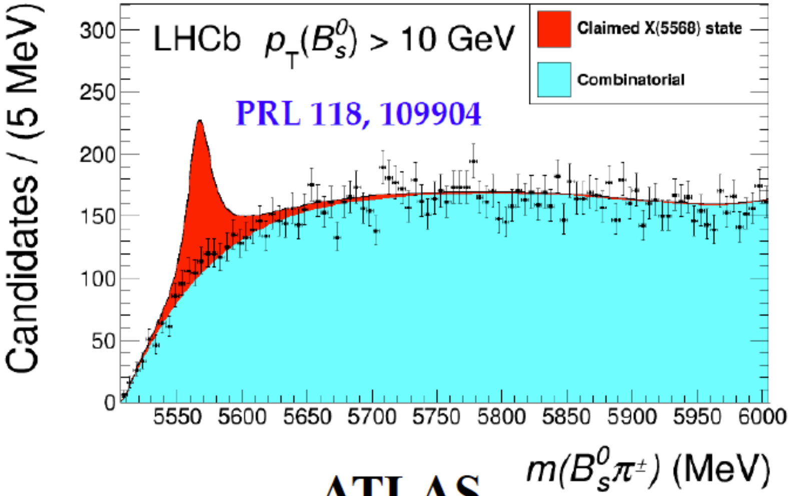
PRL 117, 022003

If confirmed, would be unique with 4 different flavors



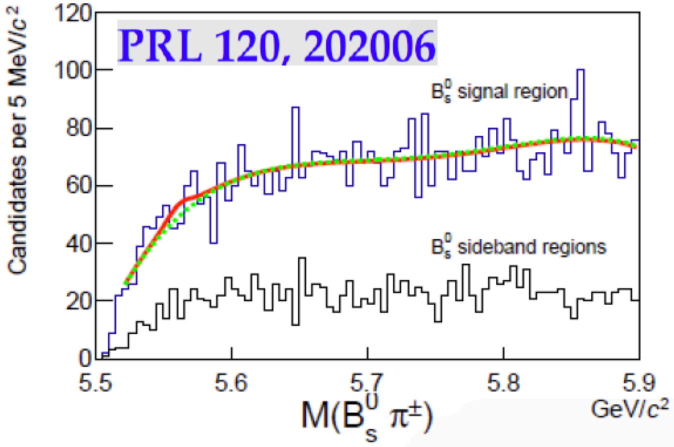
PRL120,202006

6.7 σ



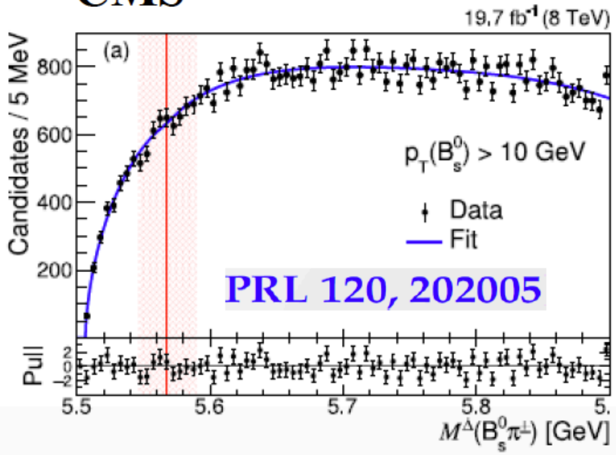
PRL 118, 109904

CDF



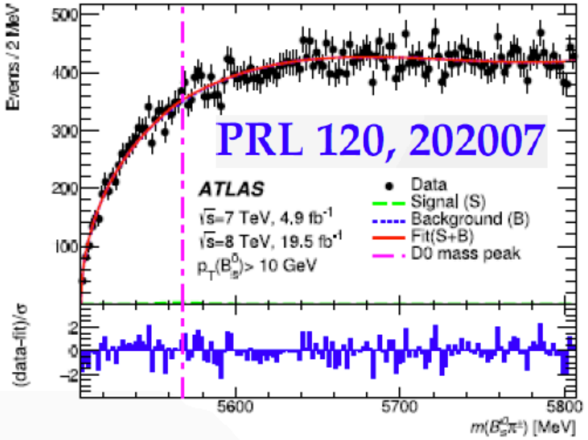
PRL 120, 202006

CMS



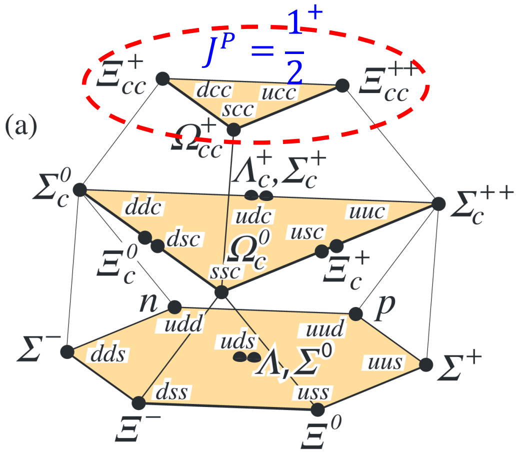
PRL 120, 202005

ATLAS

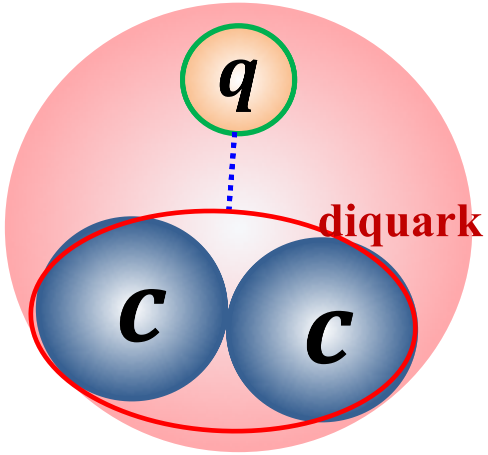


PRL 120, 202007

Doubly charmed baryons: motivation

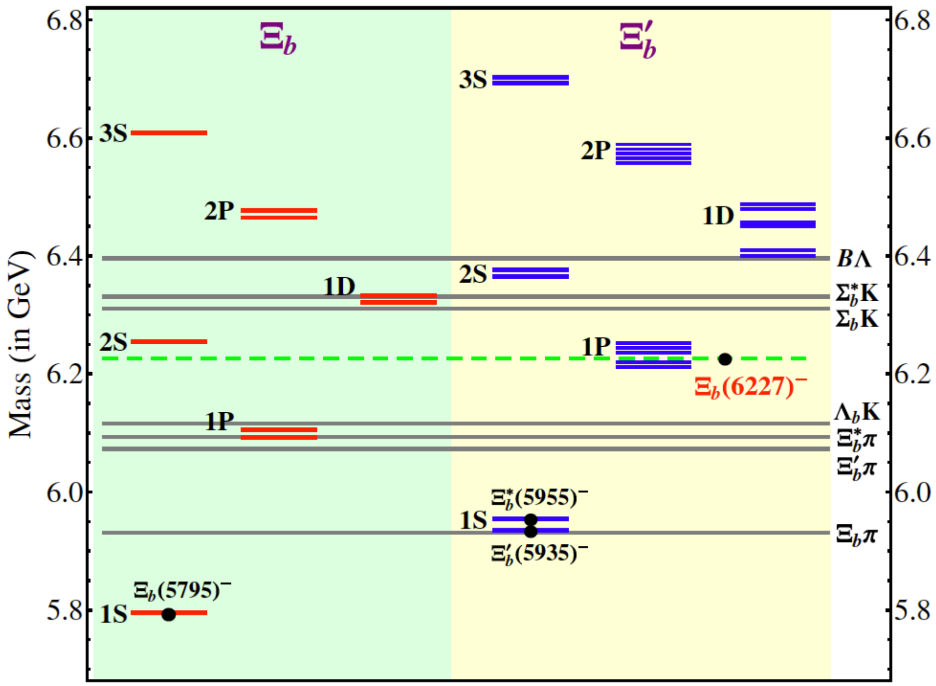


- Doubly charmed baryons are not observed or established
- Doubly heavy baryons' mass and decay width to test QCD motivated models
- Baryons with two heavy quarks probe the QCD potential in a different way than baryons with a single heavy quark [hep-ph/9811212]
  - **HQET: two charm quarks considered as a heavy diquark, doubly heavy baryon similar to a heavy meson $\bar{Q}q$**
  - **Such diquark can naturally extend to $\bar{Q}\bar{q}\bar{q} = cc\bar{q}\bar{q}$ exotic system**

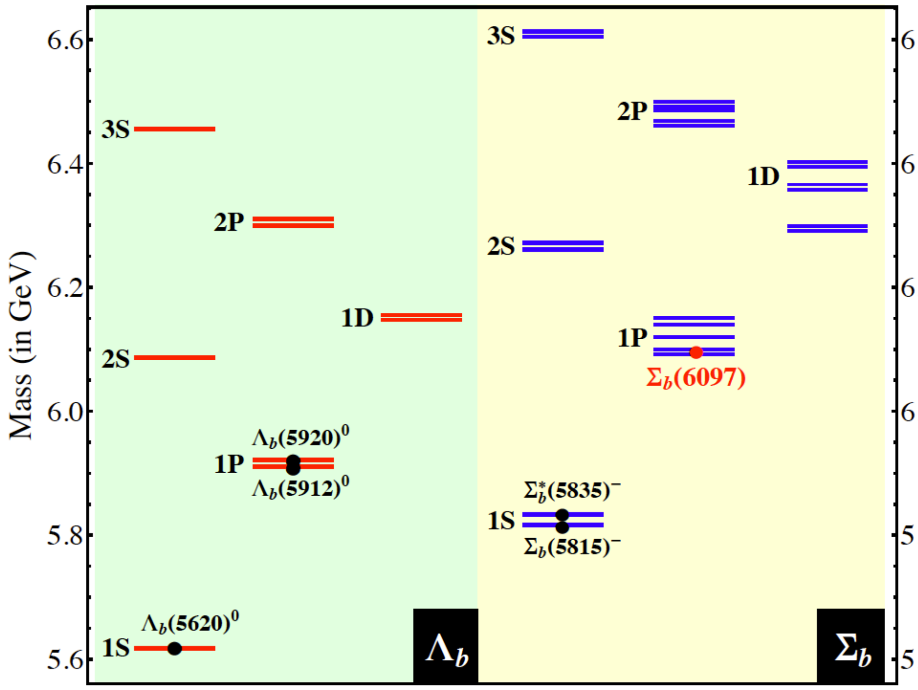


Theoretical interpretations

- $\Xi_b^{**}(6227)^-$: good candidate for 1P 5/2⁻ or 3/2⁻ state
  - Not 2S state, since 2S state doesn't decay into $\Lambda_b K$
- $\Sigma_b(6097)^\pm$: good candidates for 1P 5/2⁻ or 3/2⁻ state



Bing Chen et. al. PRD 98 (2018) 031502(R)



Bing Chen, Xiang Liu arxiv:1810.00389

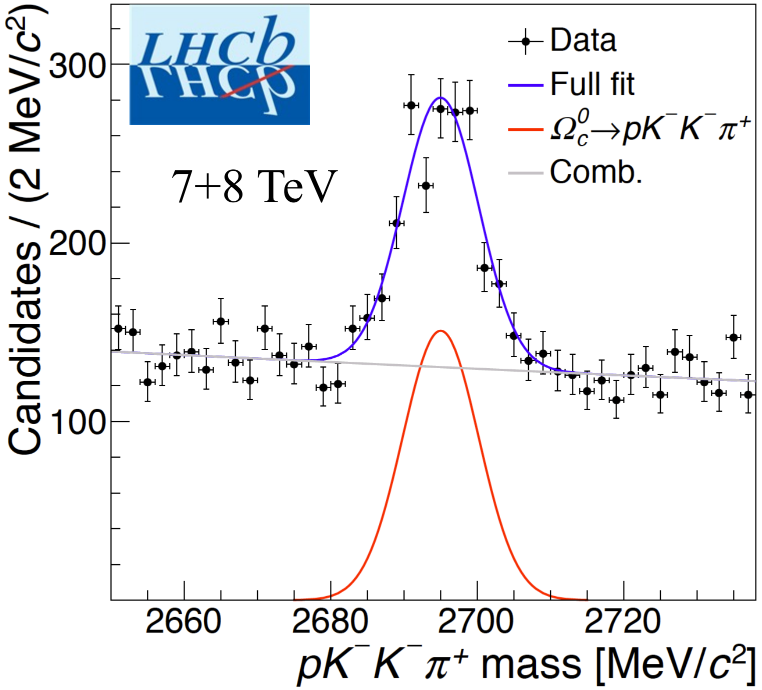
Measurement of Ω_c^0 lifetime

PRL 121 (2018) 092003

- *Charm*-hadron lifetimes probe high-order corrections in HQE
- *Charm*-baryon lifetimes are not well measured, in particular Ω_c^0 (69 ± 12 fs)
  Precision 17%
- Current measurements

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

- LHCb uses $b \rightarrow c$ semileptonic decays to avoid bias on charm
  - ☐ Signal: $\Omega_b^- \rightarrow \Omega_c^0(\rightarrow pK^-K^-\pi^+)\mu^-\overline{\nu}_\mu X$
  - ☐ Control: $B \rightarrow D^+(\rightarrow K^-\pi^+\pi^+)\mu^-\overline{\nu}_\mu X$



Yields:

$\Omega_c^0\mu^-$: 978 ± 60

(~10 times larger than any previous sample used for τ)

Ω_c^0 lifetime result

PRL 121 (2018) 092003

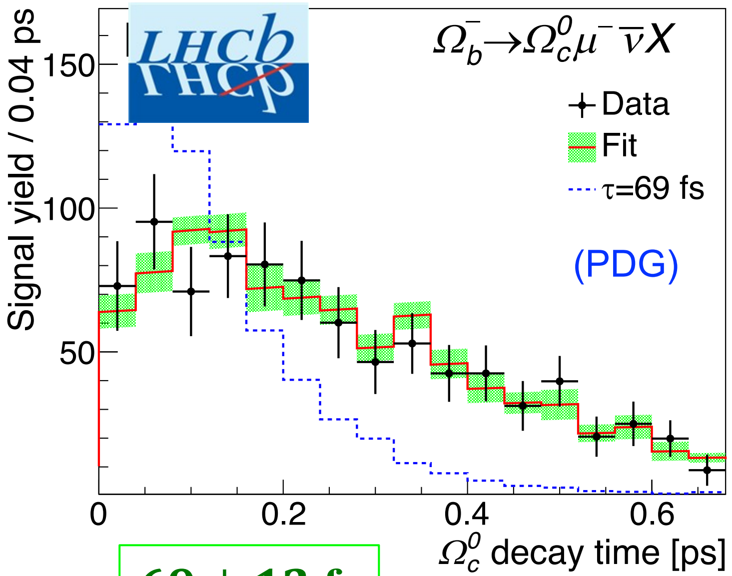
- Simultaneous fit signal and control samples

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

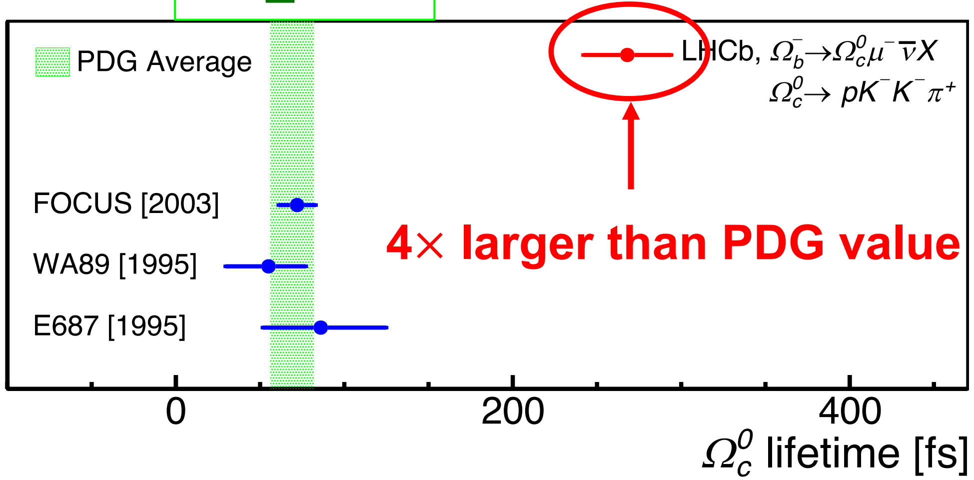
Precision 9.7%

- Many cross-checks
  - 13 TeV 2016 data
  - An additional $D^0 \to K3\pi$ lifetime measurement
- LHCb result gives

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



69 ± 12 fs



4× larger than PDG value

Verifications are needed from the other experiments and LHCb study using prompt Ω_c^0