



---

# Hadron spectroscopy study at LHCb

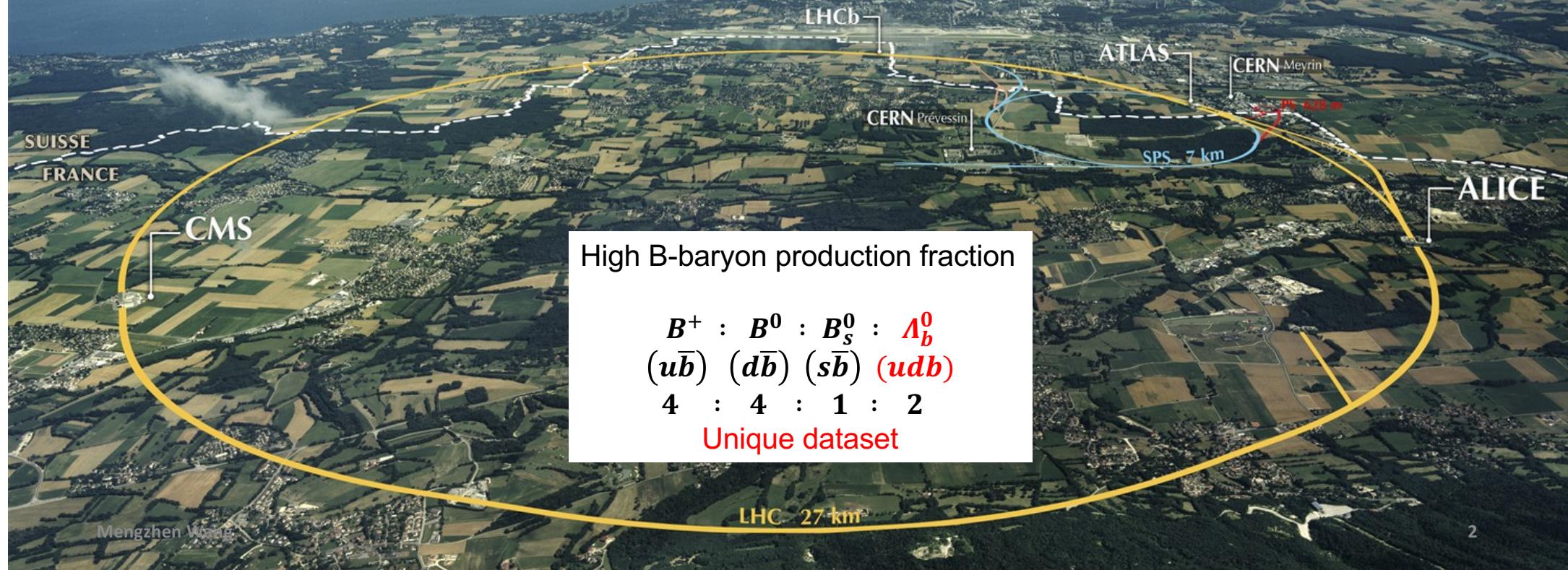
Mengzhen Wang  
(Tsinghua University)



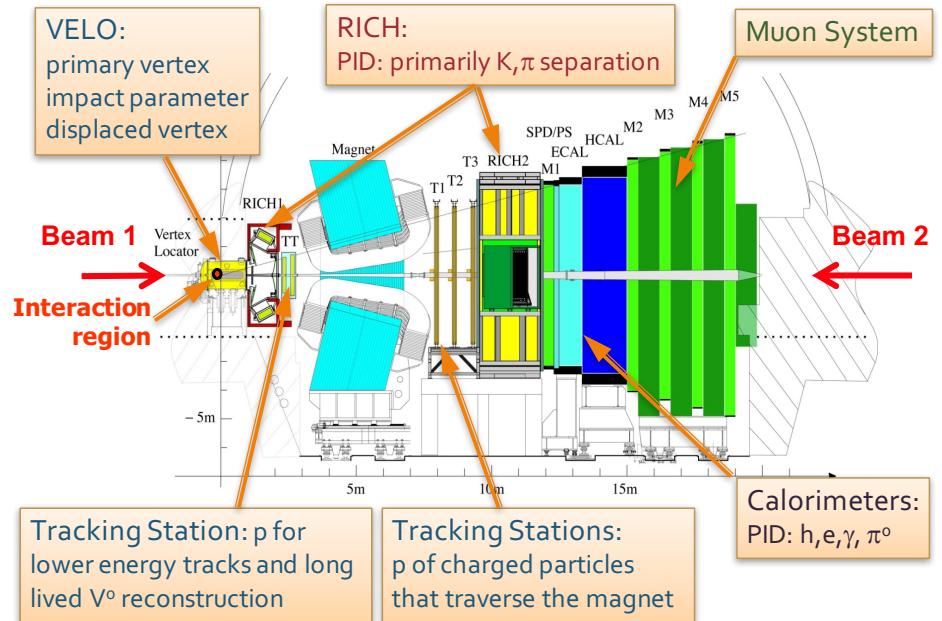
**BESIII-BELLE-LHCb 粱强子物理联合研讨会 2019**  
**(31/Oct – 03/Nov, 2019, 山西师范大学)**

# The LHC as a Beauty and Charm factory

Proton-Proton Collisions at  $\sqrt{s} = 13$  TeV  
~ 20 000  $b\bar{b}$  pairs per second, x 20 of  $c\bar{c}$  pairs

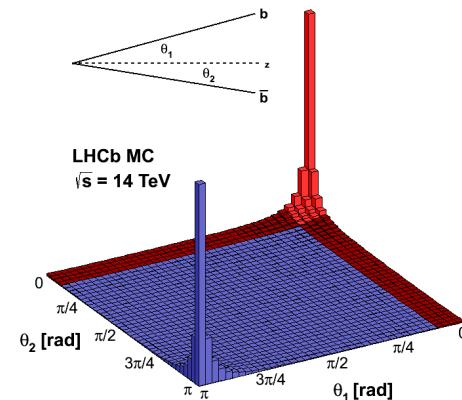


# LHCb detector and performance



The LHCb detector described in [JINST 3 (2008) S08005]

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



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

Impact parameter:

$$\sigma_{IP} = 20 \text{ }\mu\text{m}$$

Proper time:

$$\sigma_\tau = 45 \text{ fs for } B_s^0 \rightarrow J/\psi \phi \text{ or } D_s^+ \pi^-$$

Momentum:

$$\Delta p/p = 0.4 \sim 0.6\% \text{ (5 - 100 GeV/c)}$$

Mass :

$$\sigma_m = 8 \text{ MeV}/c^2 \text{ for } B \rightarrow J/\psi X \text{ (constrained } m_{J/\psi})$$

RICH  $K - \pi$  separation:

$$\epsilon(K \rightarrow K) \sim 95\% \text{ mis-ID } \epsilon(\pi \rightarrow K) \sim 5\%$$

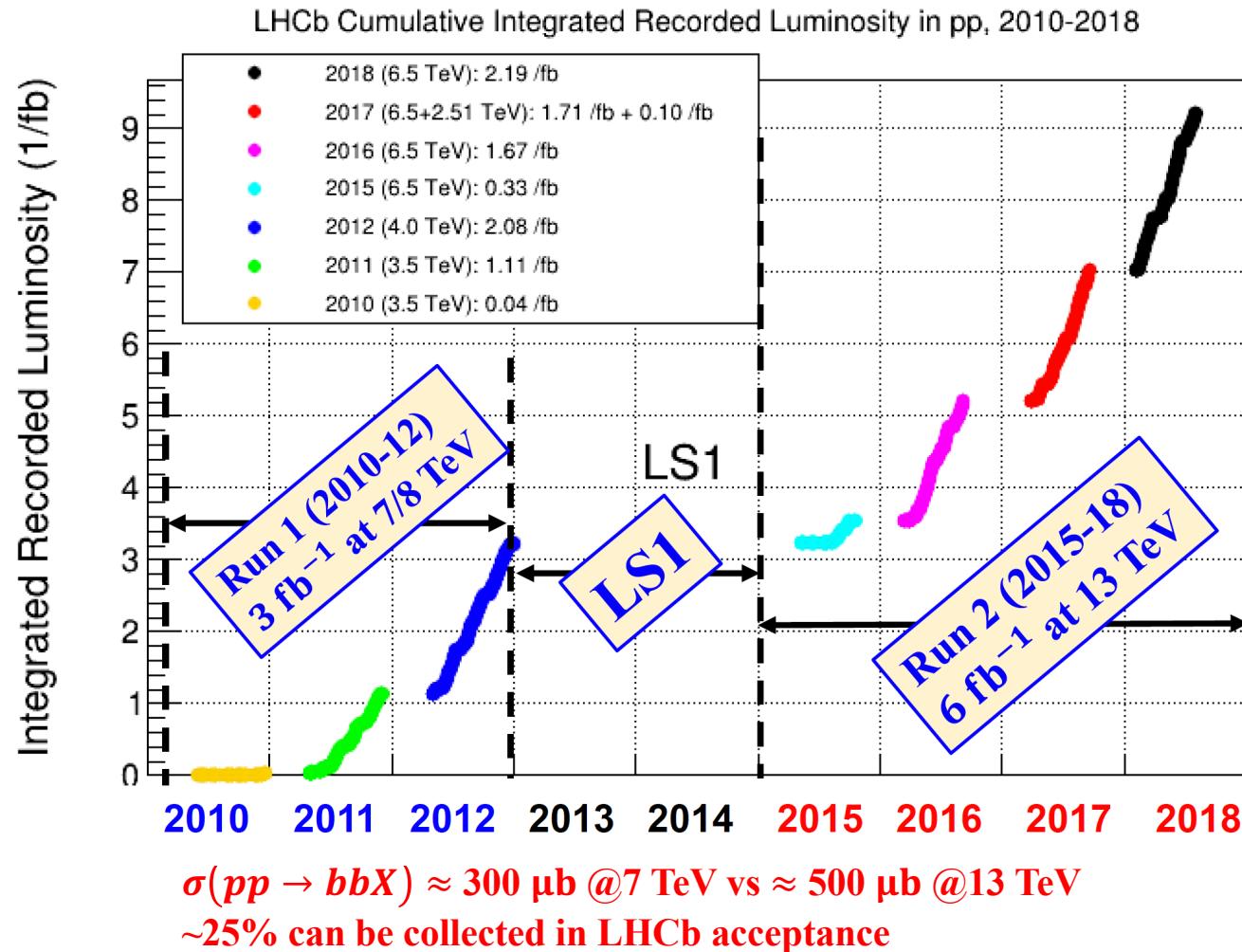
Muon ID:

$$\epsilon(\mu \rightarrow \mu) \sim 97\% \text{ mis-ID } \epsilon(\pi \rightarrow \mu) \sim 1 - 3\%$$

ECAL:

$$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$$

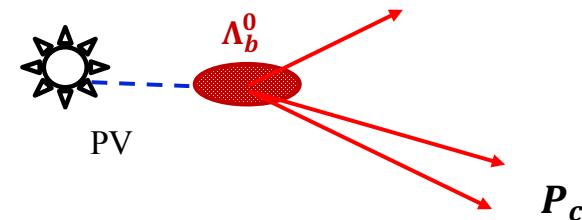
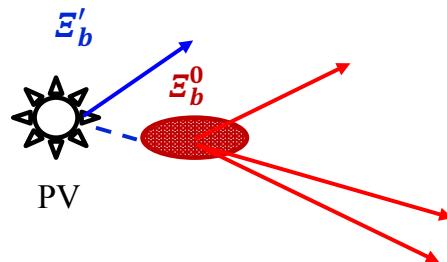
# LHCb collected luminosity



# Two methods for spectroscopy



- Direct production in  $p\bar{p}$  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  $J$



# Outline

---



- Excited heavy flavour baryons
- Lifetime strangely charming baryons
- Charmonia and Charmonium-like exotics
- Heavy baryons with hidden charm



---

# Excited heavy flavour baryons

# Bottom baryons



## BOTTOM BARYONS ( $B = -1$ )

$$\Lambda_b^0 = udb, \Xi_b^0 = usb, \Xi_b^- = dsb, \Omega_b^- = ssb$$

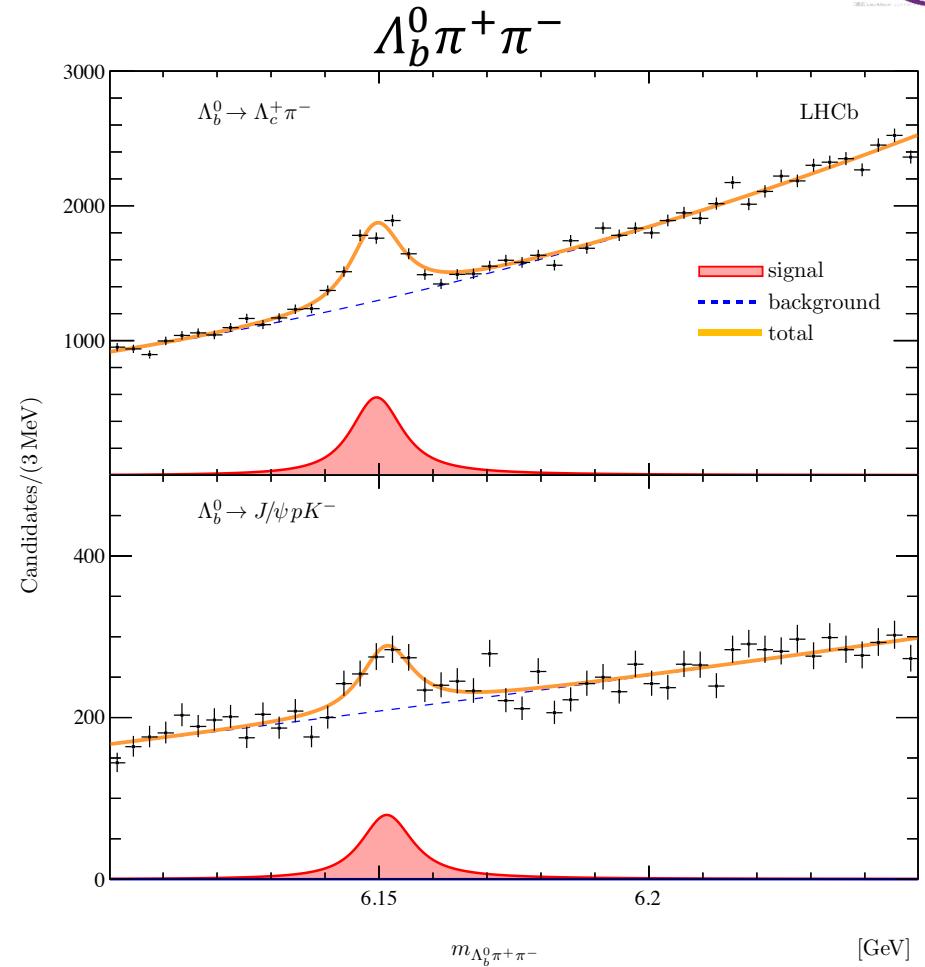
$\Lambda_b^0$	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
$\Sigma_b$	$1/2^+$	***
$\Sigma_b^*$	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
$\Xi_b^0, \Xi_b^-$	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6227)$		***
$\Omega_b^-$	$1/2^+$	***

# $\Lambda_b^0$ excitations in $\Lambda_b^0\pi^+\pi^-$

PRL 123 (2019) 152001



- Adding  $\pi^+\pi^-$  to the  $\Lambda_b^0$   
 $\Rightarrow$  probe  $\Lambda_b^0$  excitations
- $\Lambda_b^0$  is reconstructed in
  - $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  and
  - $\Lambda_b^0 \rightarrow J/\psi p K^-$
- Structure around 6.15GeV
- Investigate substructure of decays  
 $(\Sigma_b^{(*)} \rightarrow \Lambda_b \pi)\pi$

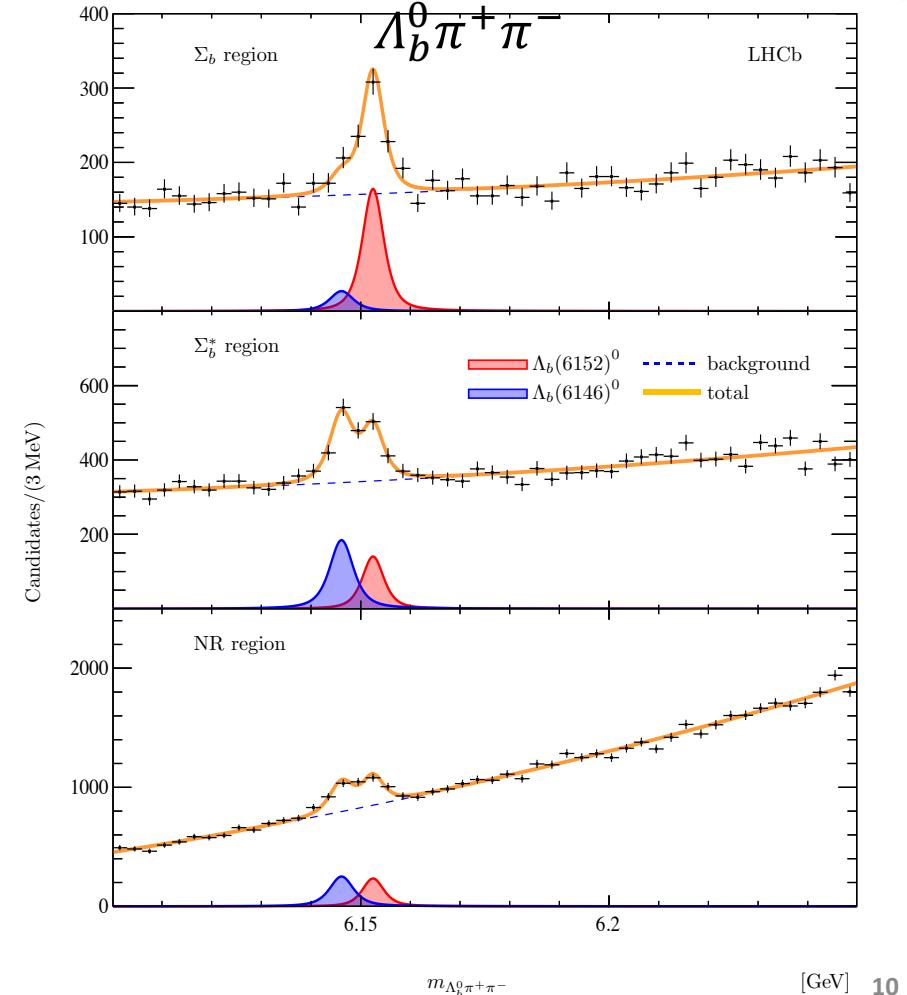


# $\Lambda_b^0$ excitations in $\Lambda_b^0\pi^+\pi^-$

PRL 123 (2019) 152001

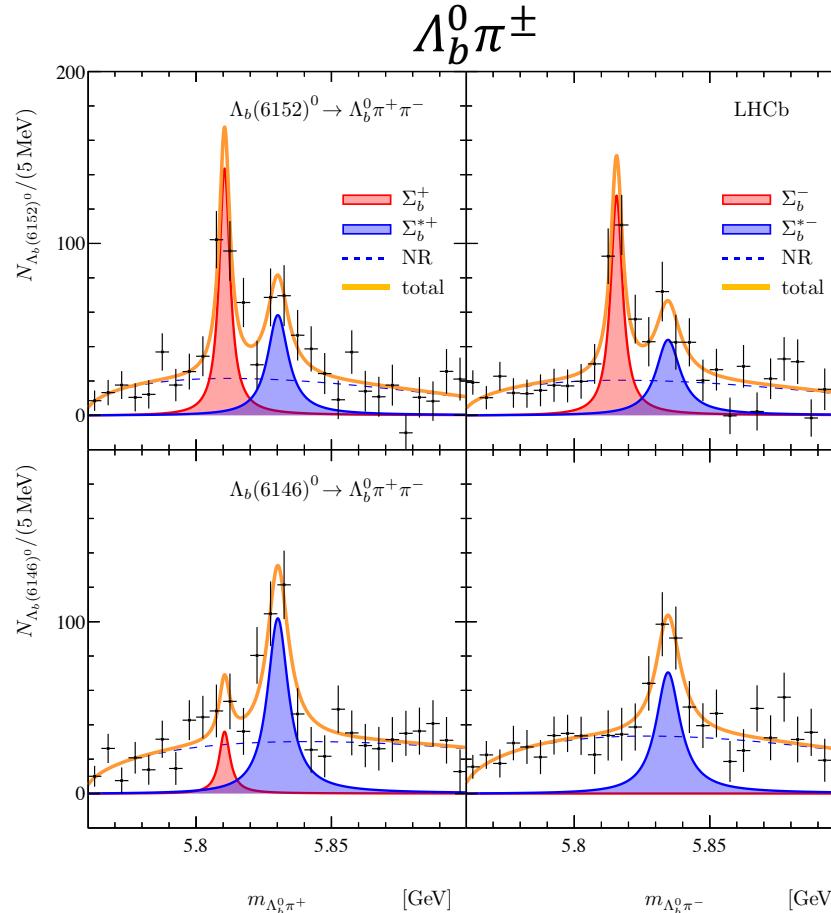


- Adding  $\pi^+\pi^-$  to the  $\Lambda_b^0$   
 $\Rightarrow$  probe  $\Lambda_b^0$  excitations
- $\Lambda_b^0$  is reconstructed in
  - $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$  and
  - $\Lambda_b^0 \rightarrow J/\psi p K^-$
- Structure around 6.15GeV
- Investigate substructure of decays  
 $(\Sigma_b^{(*)} \rightarrow \Lambda_b\pi)\pi$

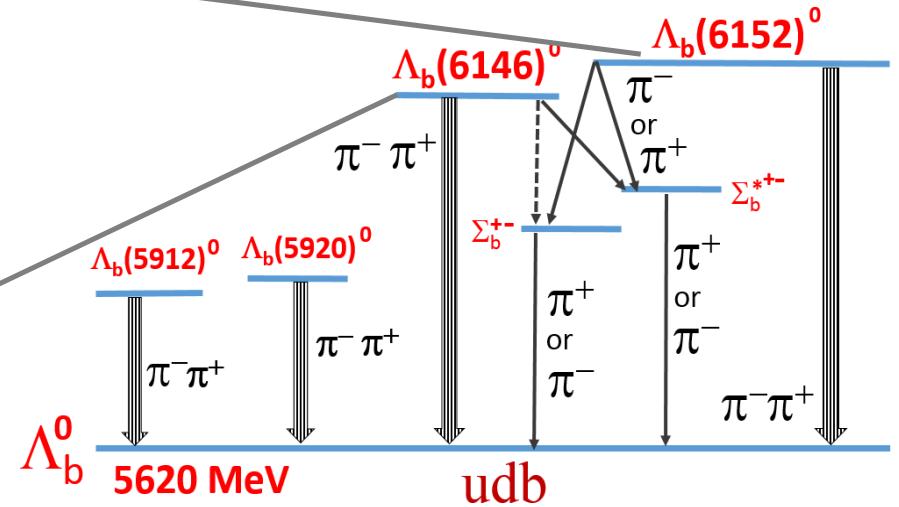


# Two new $\Lambda_b^0$ excitations

PRL 123 (2019) 152001



$$\begin{aligned} m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \pm 0.22 \pm 0.16 \text{ MeV}, \\ m_{\Lambda_b(6152)^0} &= 6152.51 \pm 0.26 \pm 0.22 \pm 0.16 \text{ MeV}, \\ \Gamma_{\Lambda_b(6146)^0} &= 2.9 \pm 1.3 \pm 0.3 \text{ MeV}, \\ \Gamma_{\Lambda_b(6152)^0} &= 2.1 \pm 0.8 \pm 0.3 \text{ MeV}, \end{aligned}$$



Interpretation as neutral  $\Sigma_b^0$  states cannot be excluded

Different coupling to the  $\Sigma_b$  and  $\Sigma_b^*$

Mengzhen Wang

11

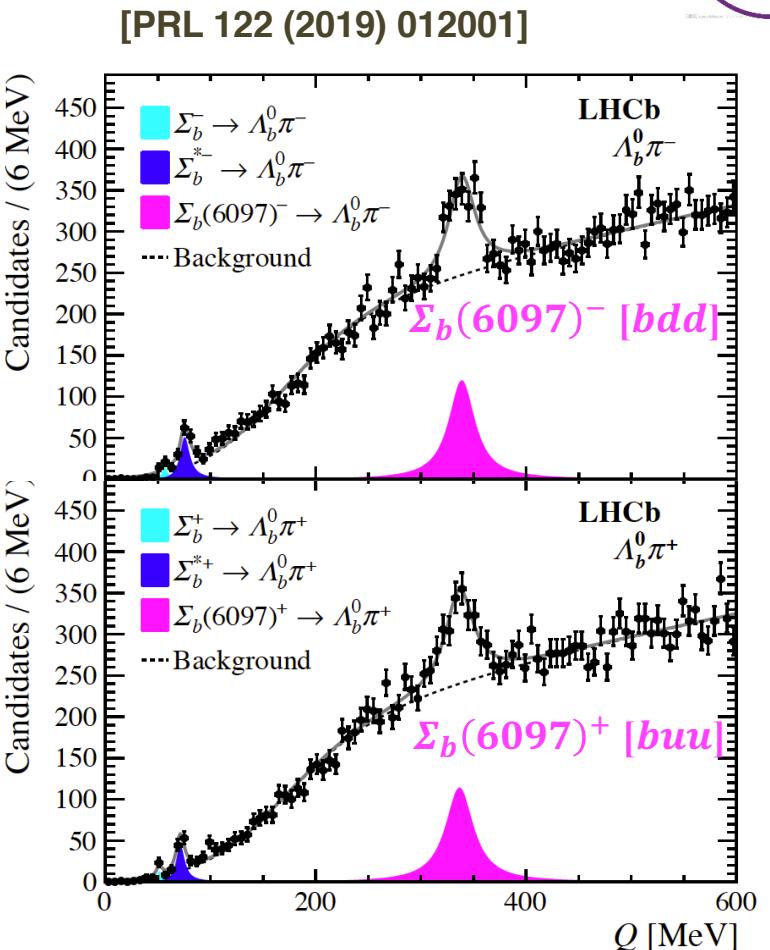
# $\Sigma_b$ spectroscopy: Observation of $\Sigma_b(6097)^\pm$



- $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  combined with  $\pi^\pm$  from PV
- Fit: relativistic BW convoluted with resolutions of 1.0-2.4 MeV

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



# Observation of a new $\Xi_b^{**}(6227)^-$ state



[PRL 121 (2018) 072002]

- Reconstruct  $\Xi_b^{**-} \rightarrow \Lambda_b^0 K^-$  and  $\Xi_b^0 \pi^-$ 
  - Hadronic (HD) and Semileptonic (SL) decays for  $\Lambda_b^0$
  - SL decays for  $\Xi_b^0 \rightarrow \Xi_c^+ \mu^- X \bar{\nu}_\mu$

- With hadronic mode

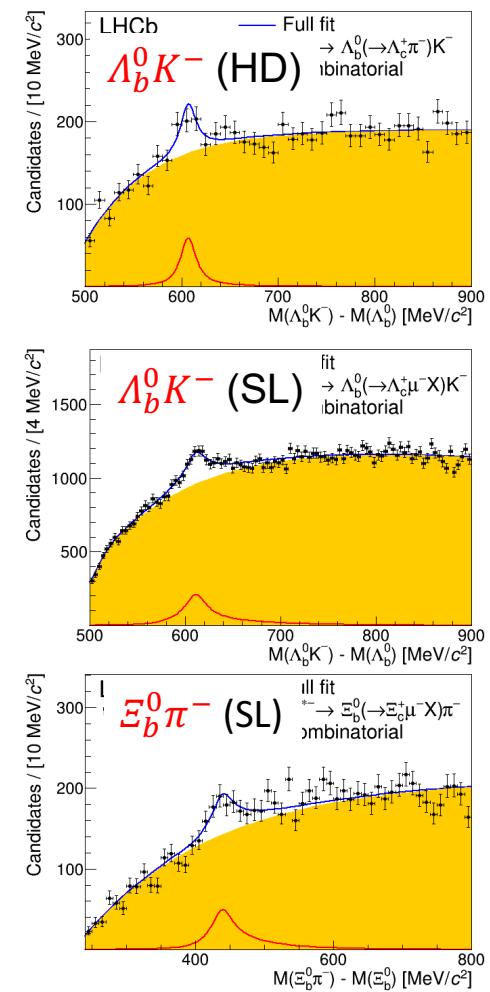
$$M(\Xi_b^{**-}) - M(\Lambda_b^0) = 607.3 \pm 2.0 \text{ (stat)} \pm 0.3 \text{ (syst)} \text{ MeV}/c^2,$$

$$\Gamma = 18.1 \pm 5.4 \text{ (stat)} \pm 1.8 \text{ (syst)} \text{ MeV}/c^2,$$

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

Mass peak position is consistent between the three decay channels

The most massive baryons observed so far!

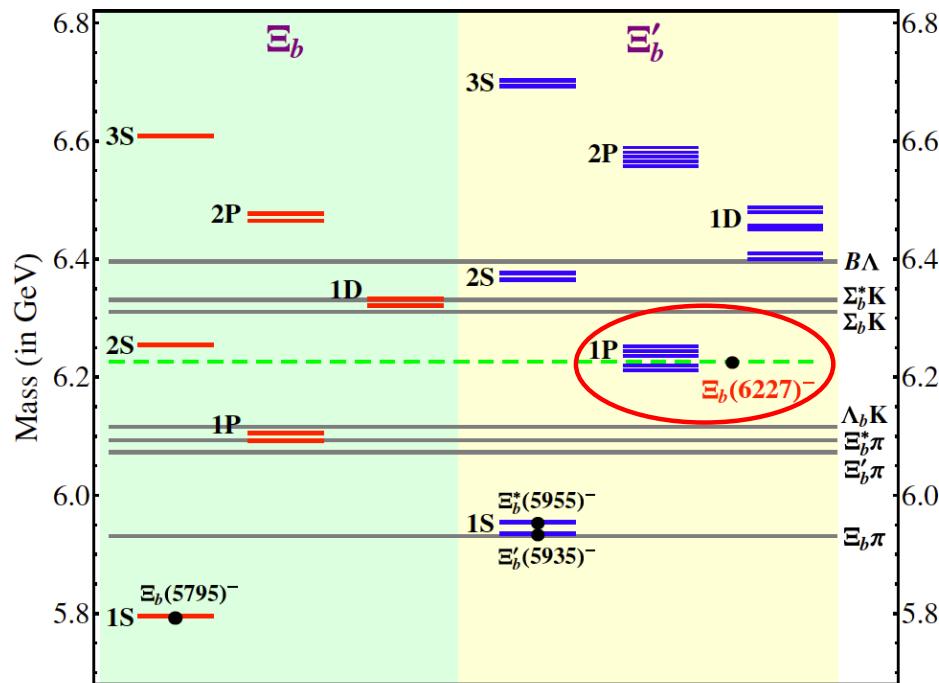


# Theoretical explanations



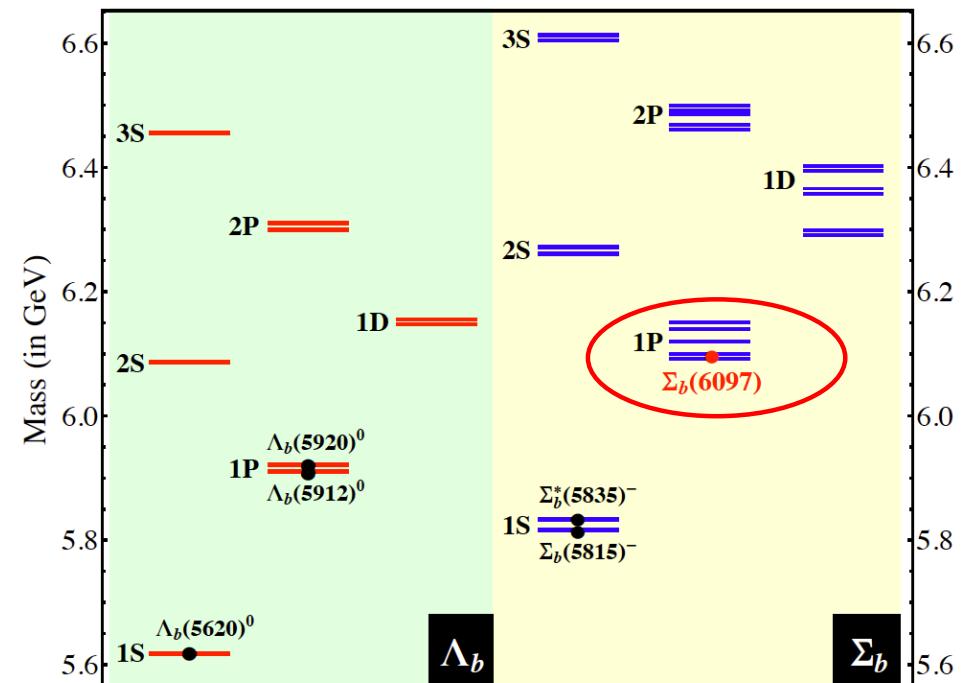
- $\Xi_b^{**}(6227)^-$  is good candidate for 1P  $5/2^-$  or  $3/2^-$  state
- $\Sigma_b(6097)^\pm$  is good candidates for 1P  $5/2^-$  or  $3/2^-$  state

Or superposition of several states?



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

Mengzhen Wang



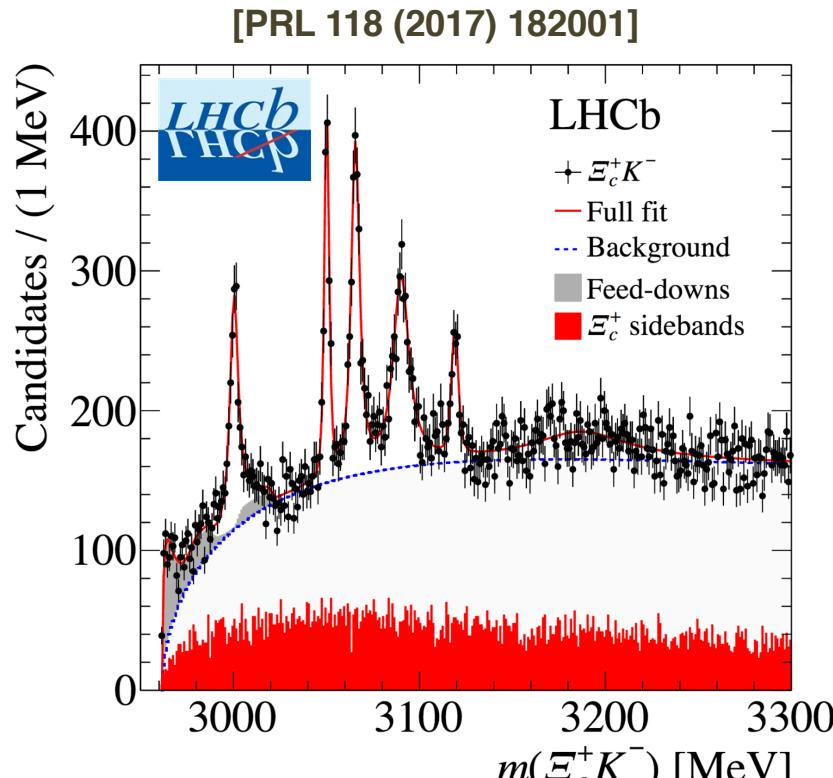
[Bing Chen, Xiang Liu PRD 98 (2018) 074032]

14

# Excited $\Omega_c \rightarrow \Xi_c^+ K^-$ states, prospect for $\Omega_b$



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



Mengzhen Wang

Resonance	Mass (MeV)	$\Gamma$ (MeV)	Yield	$N_\sigma$
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	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
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$<1.2$ MeV, 95% C.L. $3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	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
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$<2.6$ MeV, 95% C.L. $60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\text{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\text{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\text{fd}}$			$190 \pm 70 \pm 20$	

Analogical search applicable to  $b$ -sector

	$\Xi_c^+/\Xi_b^0$	$\Omega_c^*/\Omega_b^*$
$\Omega_c^* \rightarrow \Xi_c^+ K^-$	1M ( $3\text{fb}^{-1}$ )	1000-2000
$\Omega_b^* \rightarrow \Xi_b^0 K^-$	0.02M ( $9\text{fb}^{-1}$ ) [PRL 113 (2014) 032001 ( $3\text{fb}^{-1}$ )]	20-40 (scaled from charm result)



---

# Surprising lifetime of strangely charming baryons

Playground for Heavy Quark Expansion (HQE)

# $\Omega_c^0$ lifetime

[PRL 121(2018) 092003]

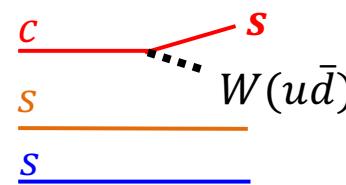


- HQE: lifetime hierarchy

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

- $\tau_{\Omega_c^0}$  considered smallest due to constructive Pauli interference

[Nucl. Phys. B248 (1984) 261]



- High order corrections in HQE allows inverted hierarchy [hep-ph/9311331]
- $\tau_{\Omega_c^0} = 69 \pm 12$  fs [PDG] from small statistics, consistent with predicted hierarchy

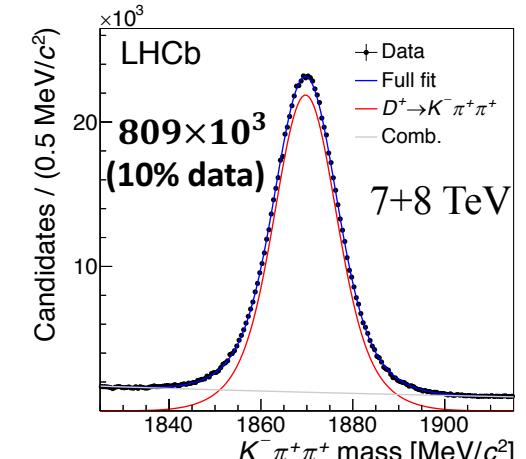
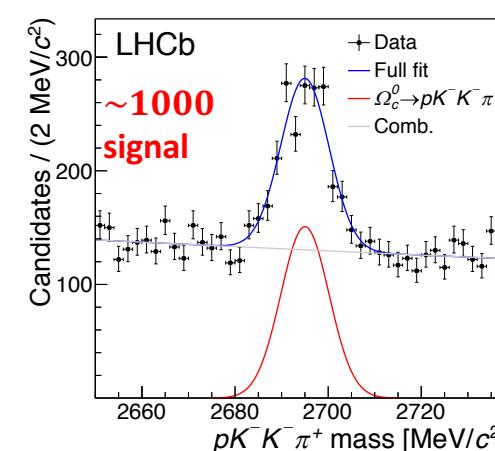
Mengzhen Wang

A measurement by LHCb

- Measure lifetime ratio

$$r_{\Omega_c^0} = \frac{\tau_{\Omega_c^0}}{\tau_{D^+}}$$

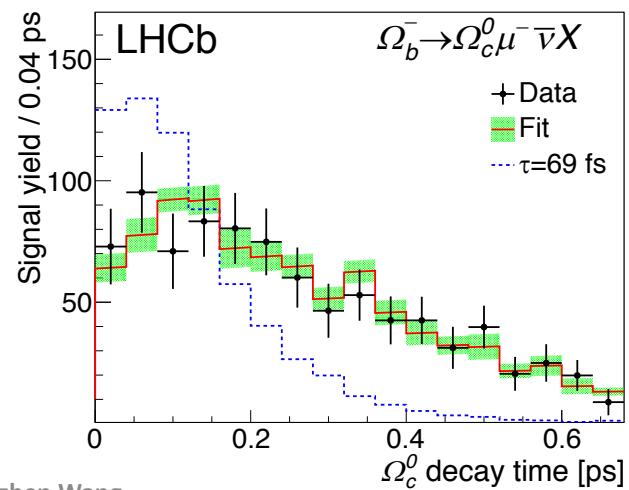
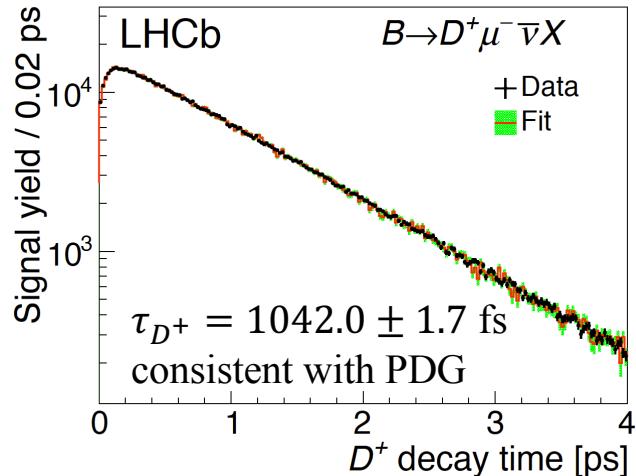
- Use  $b \rightarrow c$  semileptonic decays  $\Omega_b^- \rightarrow \Omega_c^0 \mu^- \bar{\nu}_\mu X$  and  $B \rightarrow D^+ \mu^- \bar{\nu}_\mu X$



Signal ~10x any previous sample

# $\Omega_c^0$ lifetime

[PRL 121(2018) 092003]



Mengzhen Wang

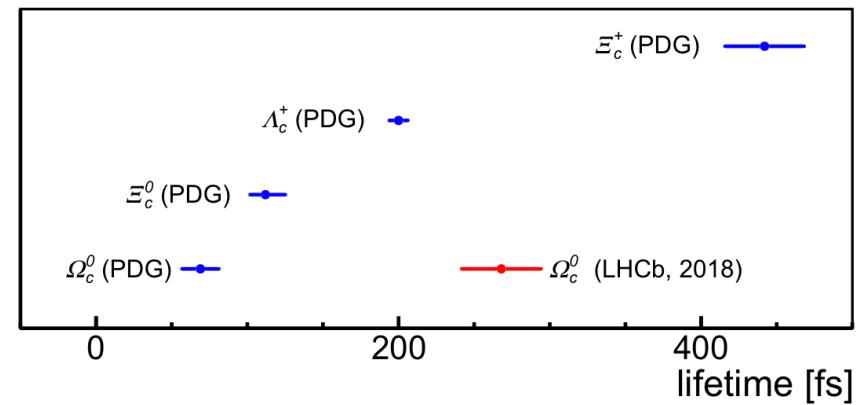
Simultaneous fit signal and control samples

$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$

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

$\sim 4 \times$  larger than PDG value  
Precision 9.7%

New hierarchy:



# Lifetimes of $\Lambda_c^+$ , $\Xi_c^+$ and $\Xi_c^0$ at LHCb

[PRD 100 (2019) 032001]



Same analysis procedure as for the  $\Omega_c^0$

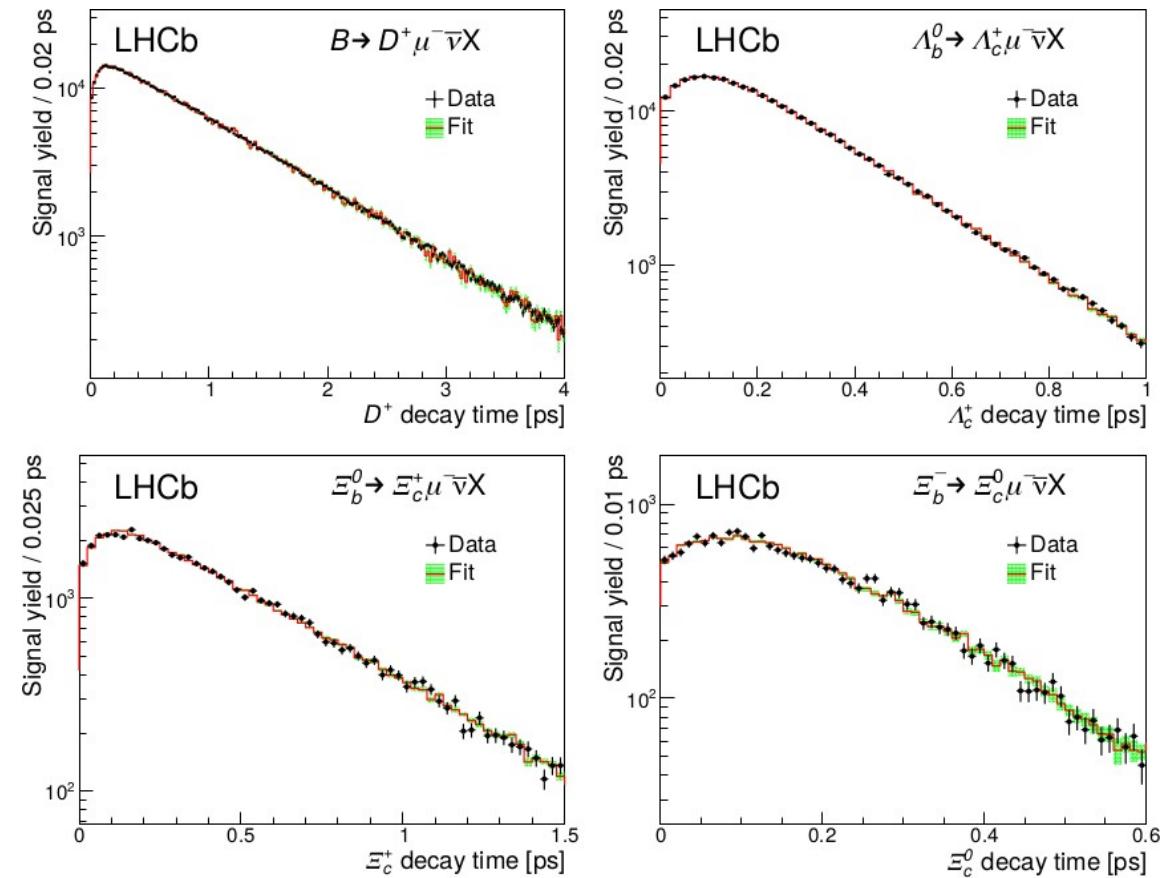
$$\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \pm 1.3 \pm 1.4 \text{ fs},$$

$$\tau_{\Xi_c^+} = 456.8 \pm 3.5 \pm 2.9 \pm 3.1 \text{ fs},$$

$$\tau_{\Xi_c^0} = 154.5 \pm 1.7 \pm 1.6 \pm 1.0 \text{ fs},$$

- $\Lambda_c^+$ ,  $\Xi_c^+$  consistent with world average
- 3.3 $\sigma$  tension for  $\Xi_c^0$
- **Confirms the new hierarchy:**

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





---

# Charmonia and Charmonium-like exotics

# The $c\bar{c}$ spectrum at LHCb

$B^\pm \rightarrow p\bar{p}K^\pm$

First observation of  $\eta_c(2S) \rightarrow p\bar{p}$

Limit (95% C. L.) on  $\chi_{c1}(3872) \rightarrow p\bar{p}$

$$\frac{\mathcal{B}(B^+ \rightarrow XK^+) \times \mathcal{B}(X \rightarrow p\bar{p})}{\mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \mathcal{B}(J/\psi \rightarrow p\bar{p})} < 0.25 \times 10^{-2}$$

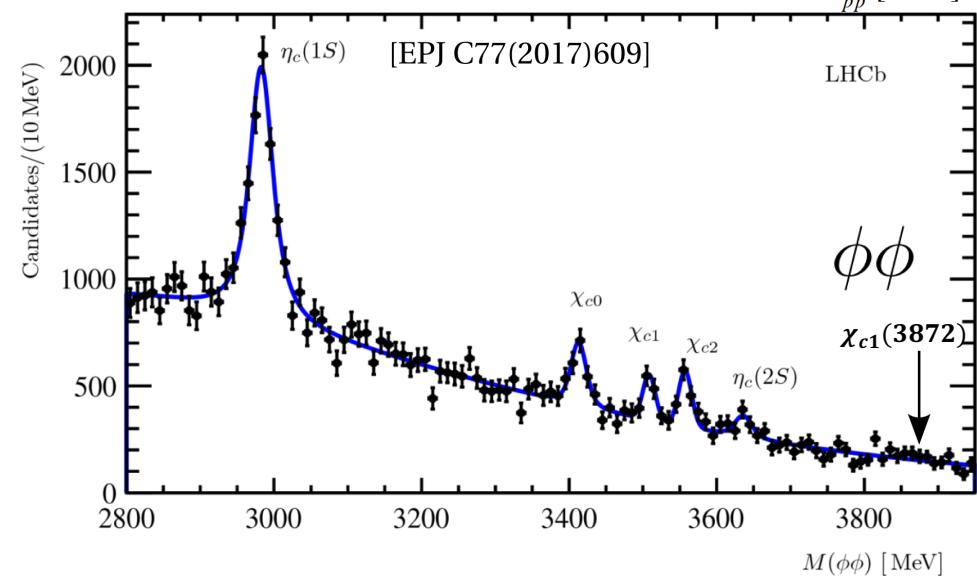
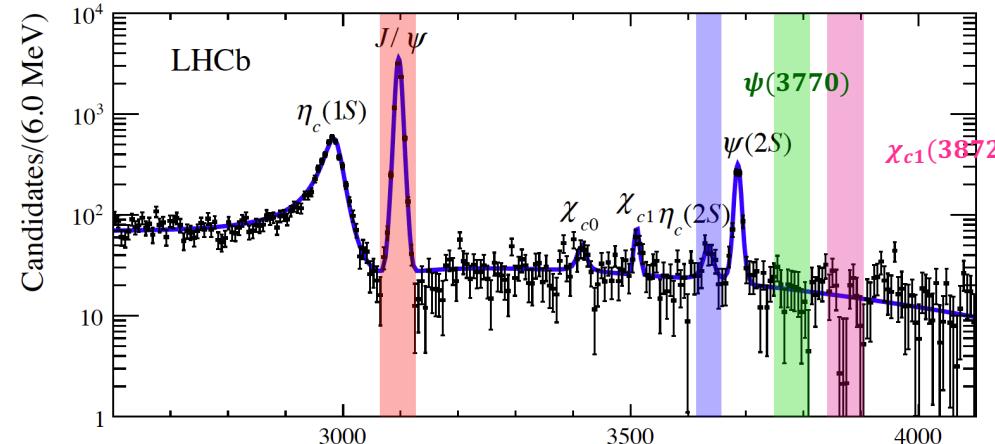
[PLB 769 (2017) 305]

Inclusive charmonia to  $\phi\phi$   
from B decays

First evidence of  $B_s^0 \rightarrow \phi\phi\phi$

[EPJ C77 (2017) 609]

Mengzhen Wang

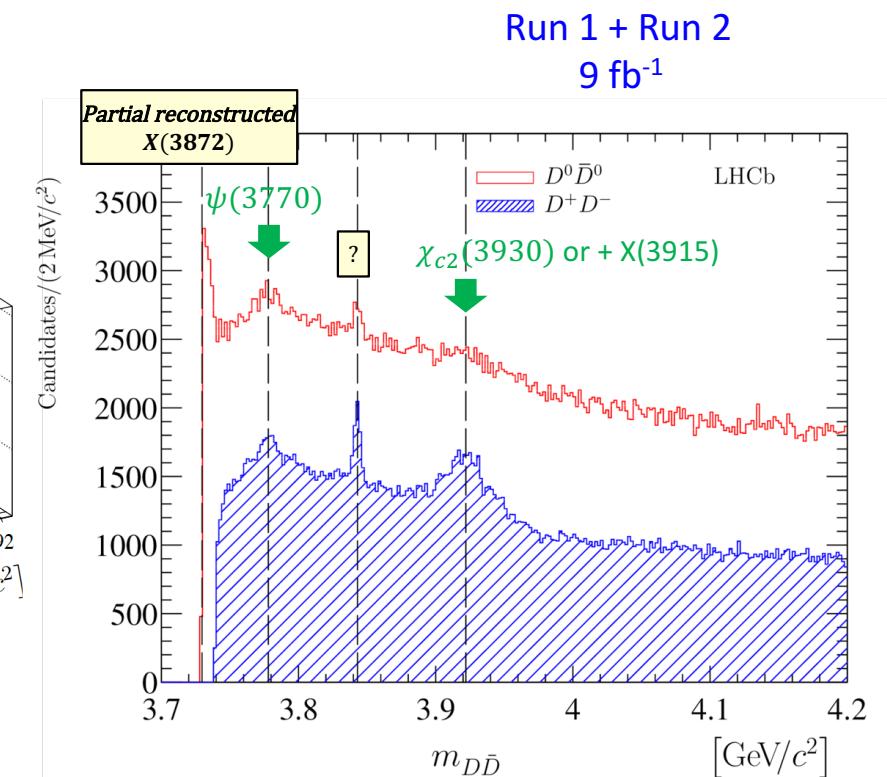
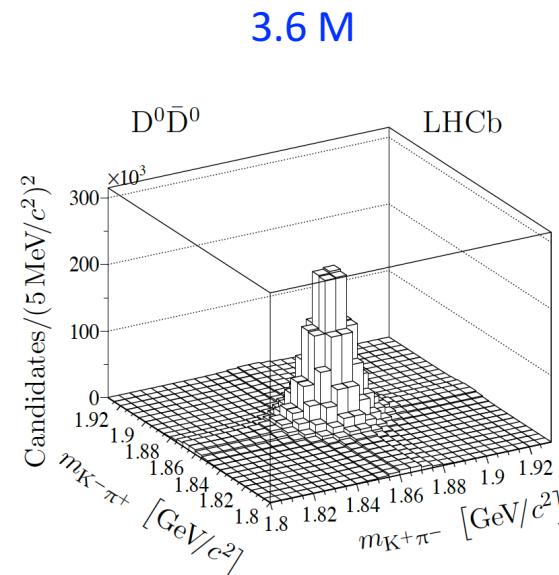
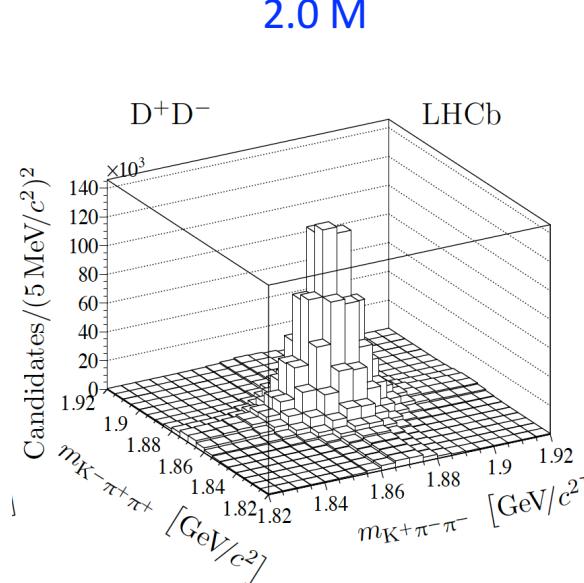


# New narrow structure X(3842)

[JHEP 07 (2019) 035]



- Promptly produced  $D^+D^-$  and  $D^0\bar{D}^0$  candidates selected for the near-threshold spectroscopy studies

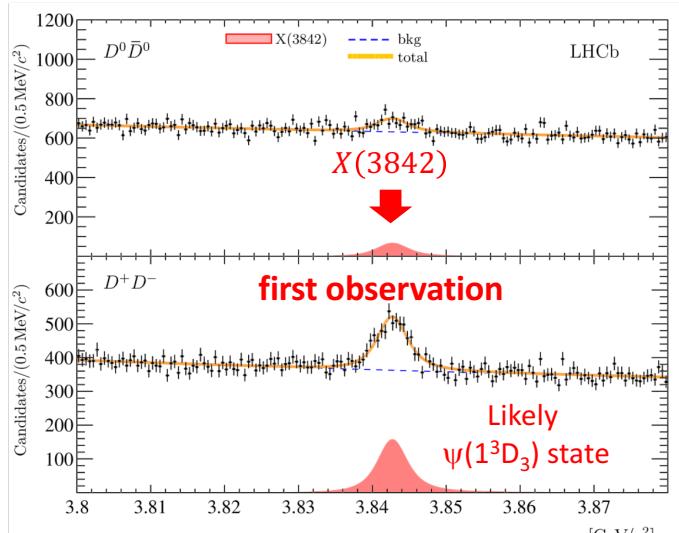


# New narrow structure X(3842)

[JHEP 07 (2019) 035]

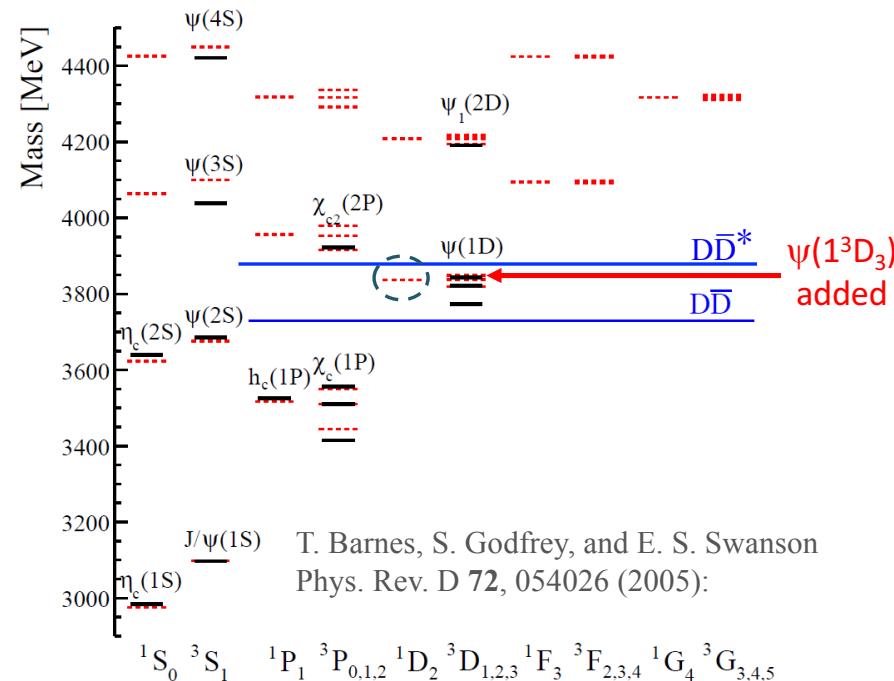


- First observation of X(3842), very narrow
- Mass and narrow width suggest it is spin-3  $\psi_3(1^3D_3)$  state
- Under  $D\bar{D}^*$  threshold, only missed one is  $\eta_{c2}\,{}^1D_2\,(2^{-+})$  state



$$M = 3842.71 \pm 0.16 \pm 0.12 \text{ MeV}$$

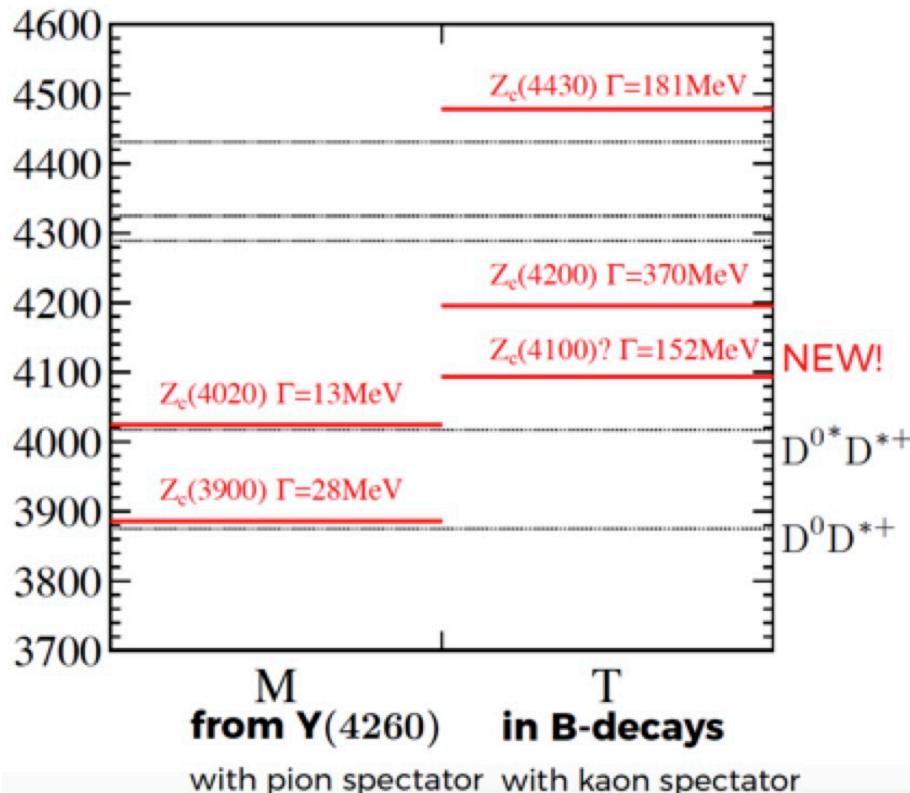
$$\Gamma = 2.79 \pm 0.51 \pm 0.35 \text{ MeV}$$



# Charged exotic mesons with hidden charm



All Z states have at least  $c\bar{c}q\bar{q}$  quark content



All  $Z_c$  observed so far have  $J^P=1^+$

LHCb has an evidence of  
 $Z_c(4100) \rightarrow \eta_c \pi$  that cannot be  $1^+$

## Tightly bound tetraquarks?

- Far from thresholds
- Large width

## Hadronic molecules

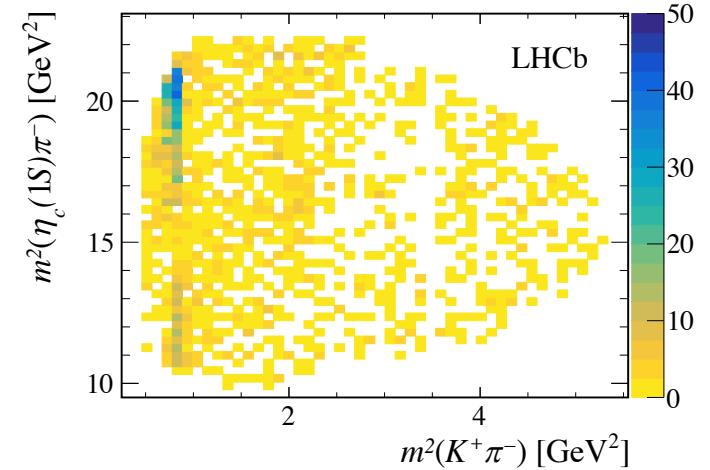
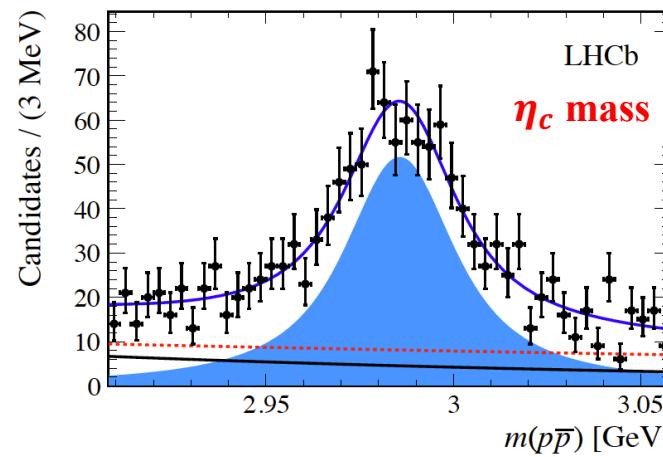
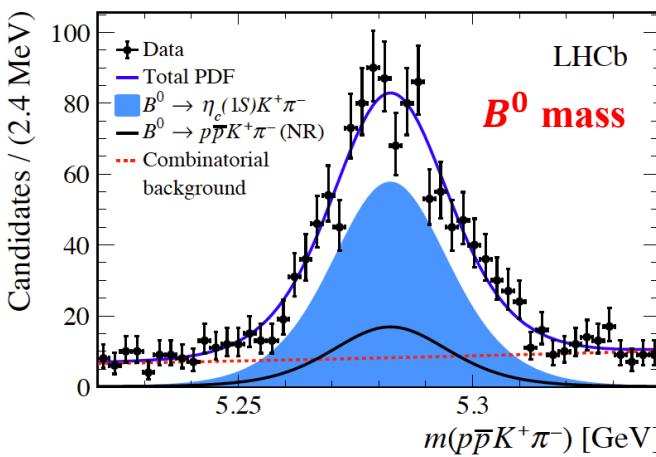
- At 2-body thresholds
- Narrow

# Evidence of $Z_c(4100)^-$ in $B^0 \rightarrow \eta_c \pi^- K^+$

[EPJ C78 (2018) 1019]



- $\mathcal{L} = 4.7 \text{ fb}^{-1}$ , run1 + 2016 data
- 2D fit to  $m(p\bar{p}K^+\pi^-)$  and  $m(p\bar{p})$  distribution  $N_{\text{sig}} = 1870 \pm 74$

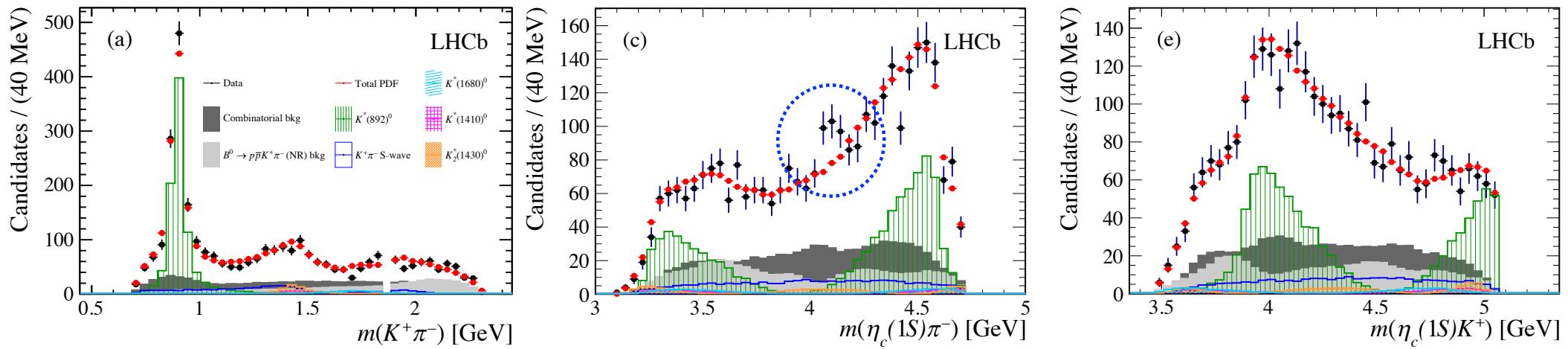


- Dalitz plot dominated by  $K^*(892)$  signal

# Evidence of $Z_c(4100)^-$ in $B^0 \rightarrow \eta_c \pi^- K^+$

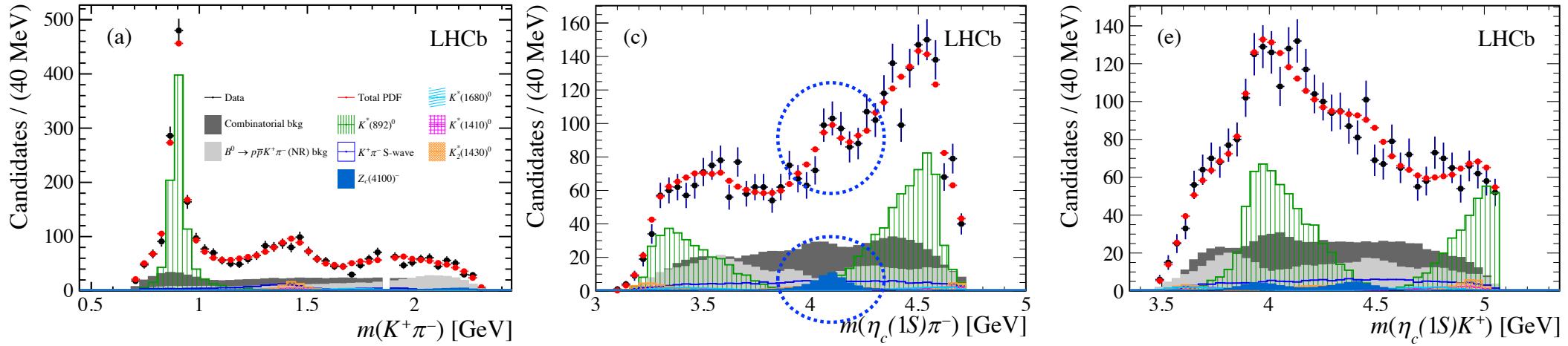


[EPJ C78 (2018) 1019]



# Evidence of $Z_c(4100)^-$ in $B^0 \rightarrow \eta_c \pi^- K^+$

[EPJ C78 (2018) 1019]



Adding a  $J^P = 1^-$  resonance in  $\eta_c \pi$  with

$$m_Z = 4096 \pm 20^{+18}_{-22} \text{ MeV} \quad \Gamma_Z = 152 \pm 58^{+60}_{-35} \text{ MeV}$$

improves fit by  $\Delta(-2\ln\mathcal{L}) = 41.4$  ( $4.8\sigma$ )

$J^P = 0^+$  is also allowed by the data

## Systematic effects on significance

Source	$\Delta(-2\ln\mathcal{L})$	Significance
Nominal fit	41.4	$4.8\sigma$
Fixed yields	45.8	$5.2\sigma$
Phase-space border veto	44.6	$5.1\sigma$
$\eta_c$ width	36.6	$4.3\sigma$
$K^+ \pi^-$ S-wave	31.8	$3.9\sigma$
Background	27.4	$3.4\sigma$



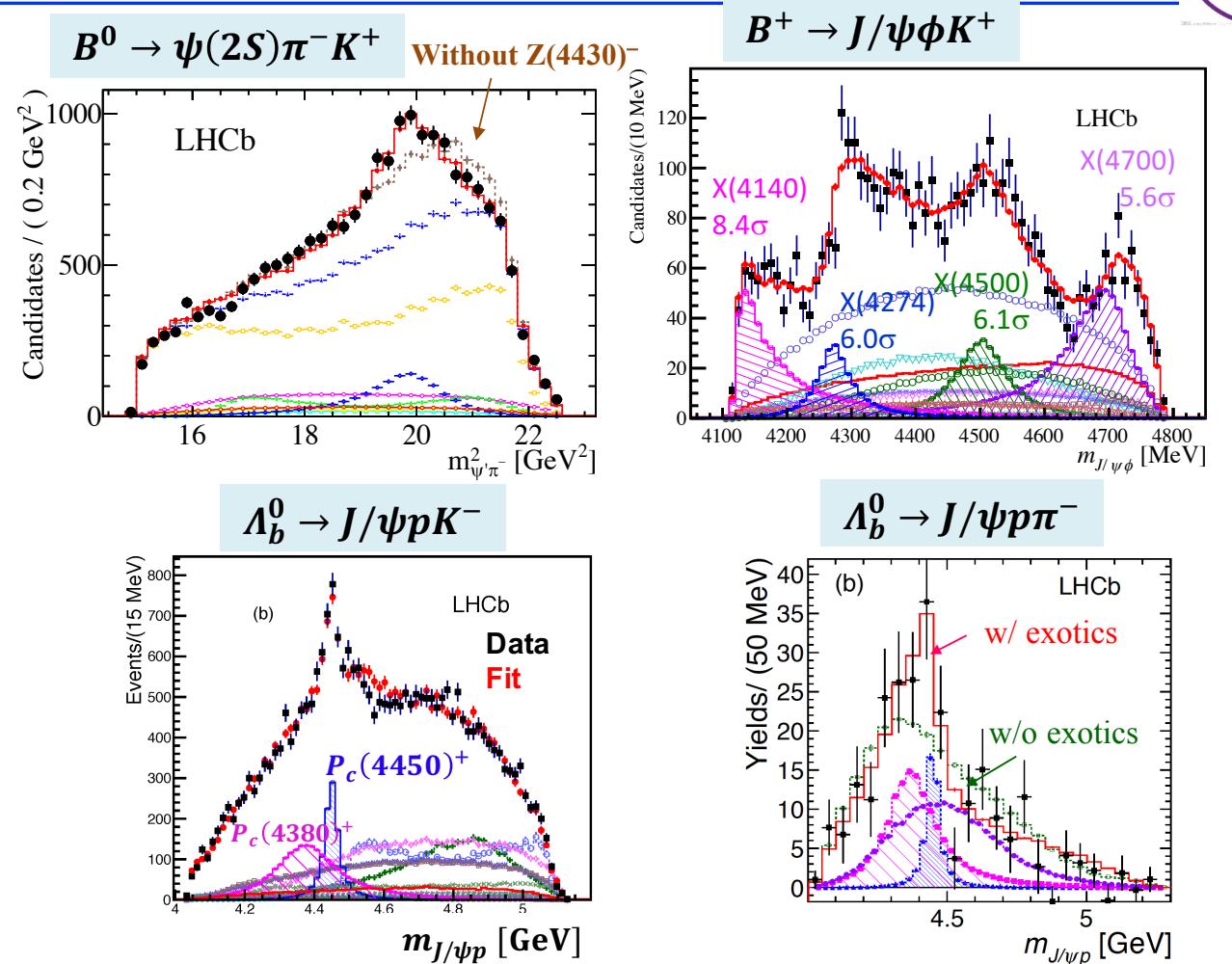
---

# Heavy Baryons with hidden-charm

# Tetra and pentaquark candidates ( $3\text{fb}^{-1}$ )



- Confirmation of  $Z(4430)$   
[PRL 112 (2014) 222002]
- Observation of two charmonium pentaquarks  
[PRL 115 (2015) 072001]
- Evidence of exotic contribution in Cabibbo-suppressed decays  
[PRL 117 (2016) 082003]
- Observation of four  $J/\psi\phi$  structures  
[PRL 118 (2017) 022003]

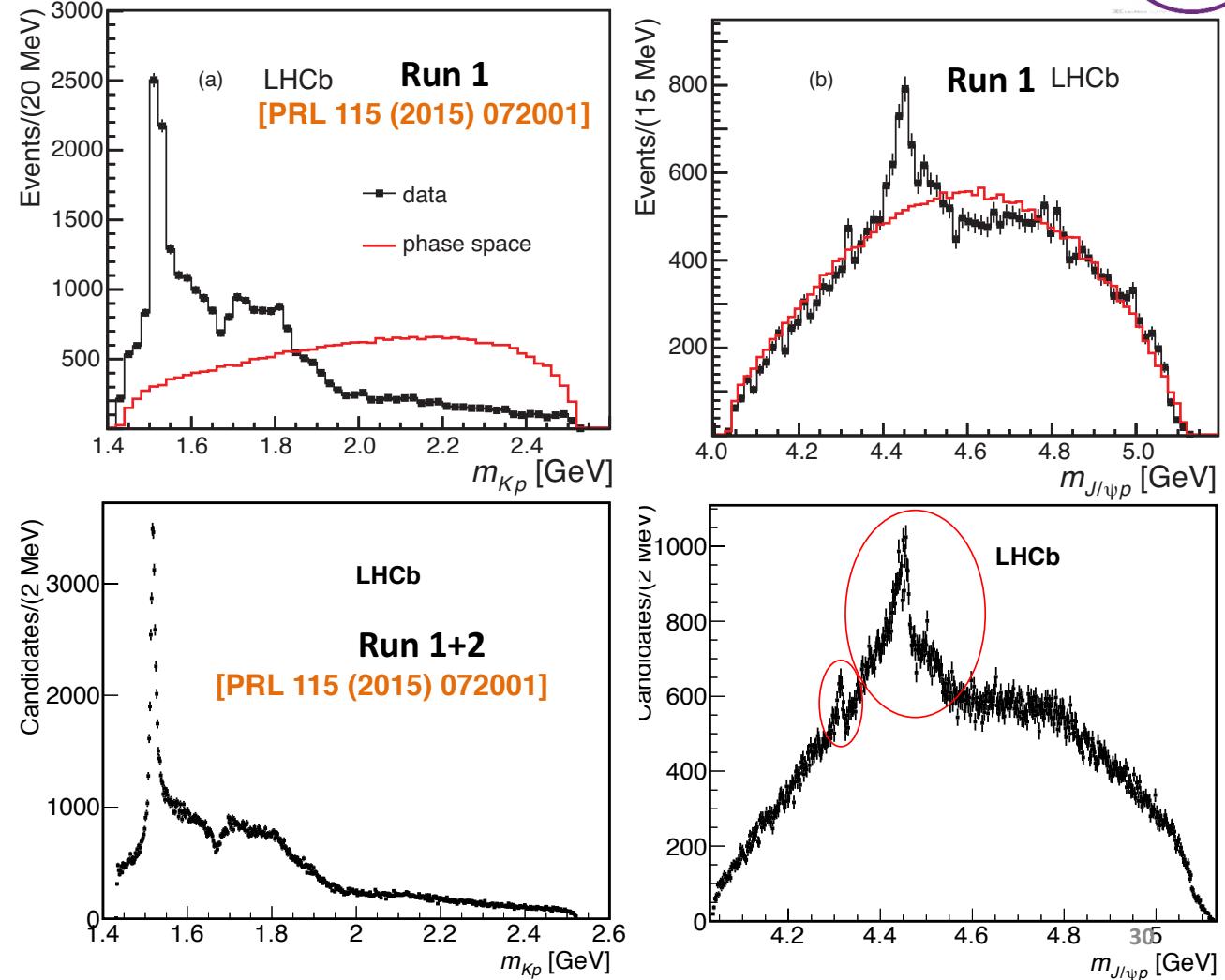


# Update $\Lambda_b^0 \rightarrow J/\psi p K^-$ (3+6fb $^{-1}$ )

[PRL 122 (2019) 222001]



- An order of magnitude increases in signal yield
  - Inclusion of Run 2 data ( $\times 5$ )
  - Improved data selection ( $\times 2$ )
- Consistent distributions between old and new samples
- More structures appear



# Narrow structures

[PRL 122 (2019) 222001]



Fine binning reveals

- New narrow structure at  $m = 4312$  MeV
- Peak at 4450 MeV splits into two peaks

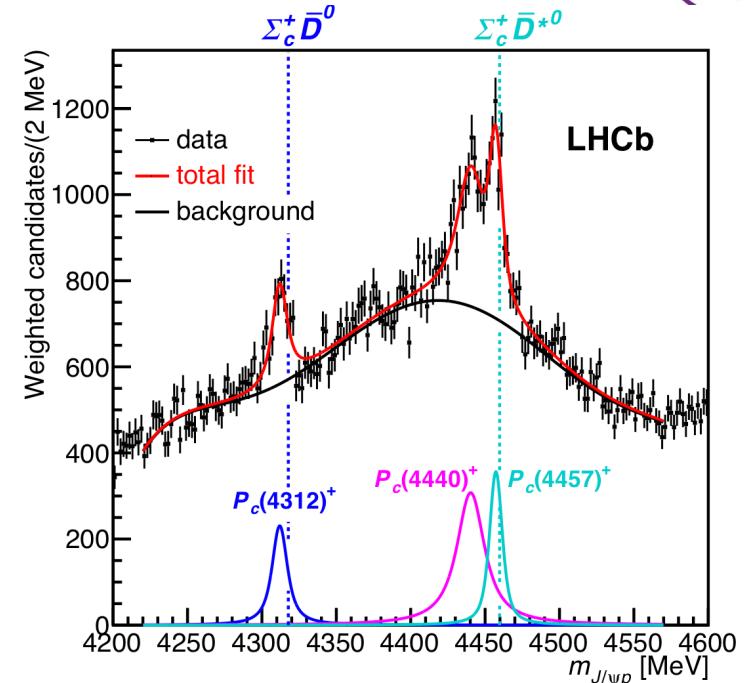
Fit 1D  $m_{J/\psi p}$  distribution

- Significance of two-peak structure vs one-peak hypothesis at 4450 MeV:  $5.4\sigma$
- Largest systematic uncertainty: unknown interference terms

$J^P$  measures and information of  $P_c(4380)^+$  require amplitude analysis

Broad  $P_c(4380)$  is neither be confirmed nor excluded

State	$M$ [MeV]	$\Gamma$ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	( $< 27$ )	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	( $< 49$ )	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	( $< 20$ )	$0.53 \pm 0.16^{+0.15}_{-0.13}$

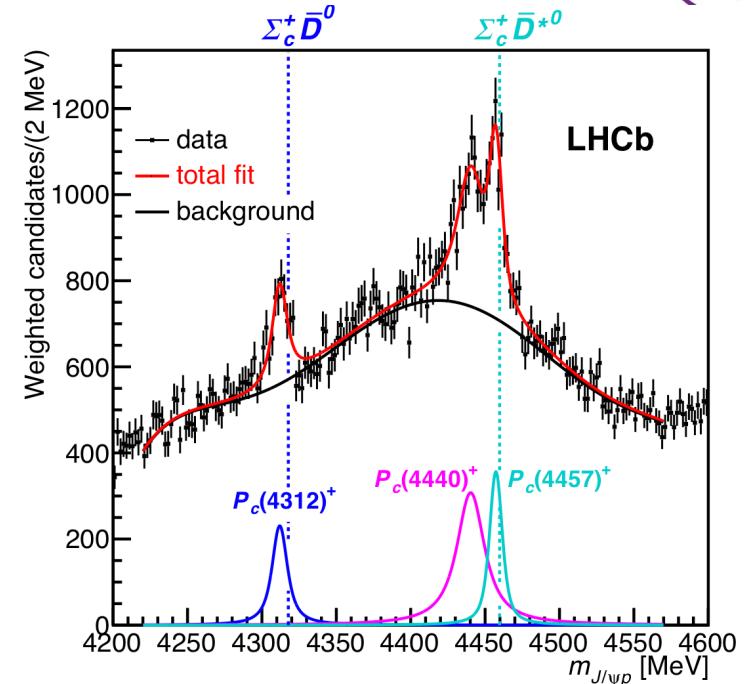


# Prospect for pentaquarks

- Regardless of the binding mechanism, the new pentaquarks suggest the existence of a whole new family of such particles
- A lot of open questions:
  - $J^P$ , mode decay modes,...?
  - hidden-bottom pentaquarks?
- An incomplete list of decays for pentaquark studies
 

$\checkmark \Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-$ $\checkmark \Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-$ $\checkmark \Lambda_b^0 \rightarrow \Lambda_c^+ D^- K^*$ $\checkmark \Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- \phi$ $\checkmark \Lambda_b^0 \rightarrow J/\psi \pi^+ \pi^- K^-$ $\checkmark \Lambda_b^0 \rightarrow \Sigma_c^{++} D^- K^-$ $\checkmark \Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ $\checkmark \Lambda_b^0 \rightarrow J/\psi \Lambda \eta^{(')}$	$\checkmark B_c^+ \rightarrow J/\psi p \bar{p} \pi^+$ $\checkmark Y(1S) \rightarrow J/\psi p \bar{p}$ $\checkmark B_s^0 \rightarrow J/\psi p \bar{p}$ $\checkmark B^+ \rightarrow J/\psi p \bar{\Lambda}$ $\checkmark$ Prompt $J/\psi p, J/\psi \Lambda, Y p$ $\checkmark \Lambda_b^0 \rightarrow \eta_c p K^-$ $\checkmark \Lambda_b^0 \rightarrow \chi_{c1} p K^-$ $\checkmark \Xi_b^- \rightarrow J/\psi \Lambda K^-$
---	---

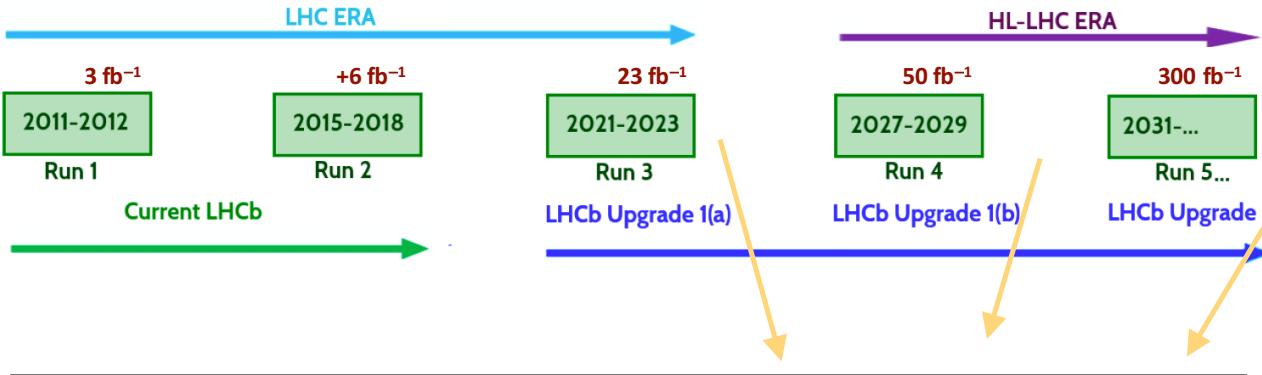
[PRL 122 (2019) 222001]



Similar strategy  
for tetraquarks

# Expected yields in future

arXiv:1808.08865



Decay mode	LHCb 23 fb <sup>-1</sup>	LHCb 50 fb <sup>-1</sup>	LHCb 300 fb <sup>-1</sup>
$B^+ \rightarrow X(3872)(\rightarrow J/\psi \pi^+ \pi^-) K^+$	14k	30k	180k
$B^+ \rightarrow X(3872)(\rightarrow \psi(2S) \gamma) K^+$	500	1k	7k
$B^0 \rightarrow \psi(2S) K^- \pi^+$	340k	700k	4M
$B_c^+ \rightarrow D_s^+ D^0 \bar{D}^0$	10	20	100
$\Lambda_b^0 \rightarrow J/\psi p K^-$ [*]	680k	1.4M	8M
$\Xi_b^- \rightarrow J/\psi \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k
$\Xi_{bc}^+ \rightarrow J/\psi \Xi_c^+$	50	100	600

- **LHCb is now boosting the data to a new level**
  - Expect to **7x more data (14x hadronic events)** by 2029 than current, half of these by 2023
  - Could have another **6x increase** from Upgrade II

$\chi_{c1}(3872)$  lineshape from multi-channels

$Z_c(4430)$ , also explore  $B \rightarrow D_{(s)}^{(*)} \bar{D}_{(s)} K^-$ ?

Doubly-charmed tetraquark  $T_{cc}^+ \rightarrow D_s^+ D^0$

More information for pentaquarks

[\*] updated according to the latest result

# Summary

---



- LHC is a heavy-quark hadron factory
- Precision measurements: properties of charm and bottom ground-state hadrons
- Exploring meson and baryon excitation spectra
- Studying exotic hadron spectroscopy
  
- Large  $\Omega_c$  lifetime
- New charmonium state  $X(3842)$  compatible with  $\psi_3(1^3D_3)$
- Update analysis: 3 new pentaquark candidates



---

# Backup

# Introduction



- QCD describing strong interaction between quarks and gluons is not well understood due to its non-perturbative nature at low energy scale
- Hadron spectroscopy provides opportunities to test QCD and its effective models
  - e.g. lattice QCD, diquark model, potential model ...
- Exotic hadrons provide unique probe to QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence



mesonic  
molecule ?



tetraquark ?



pentaquark ?



hybrid ?

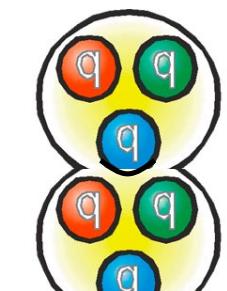


meson



baryon

...  
EXOTIC



e.g. deuteron

STANDARD

# $\Omega_c^0$ lifetime result

[PRL 121(2018) 092003]



- Simultaneous fit signal and control samples

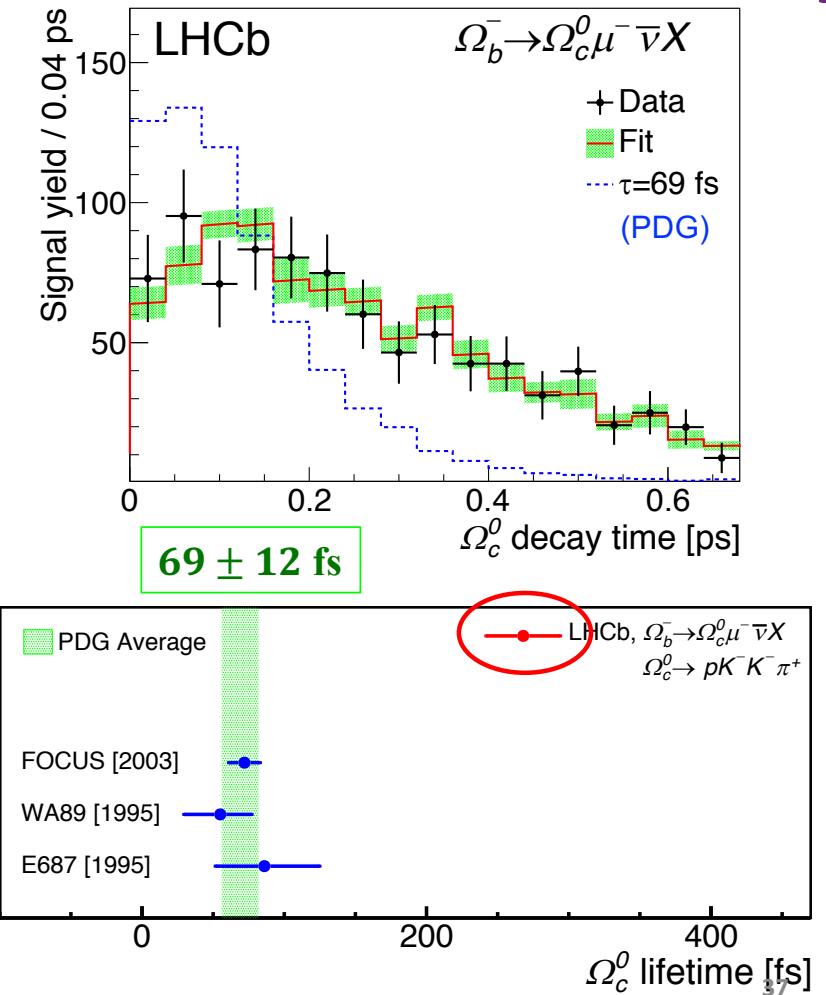
$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$

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

4× larger than PDG value  
Precision 9.7%

- Systematic uncertainties on lifetime ratio
  - Dominated by MC size (0.0098)
  - Background subtraction (0.0019)
  - Decay time acceptance (0.0013)
  - Physics background (0.0008)
- Many cross-checks
  - 13 TeV 2016 data
  - An additional  $D^0 \rightarrow K3\pi$  lifetime measurement

Mengzhen Wang



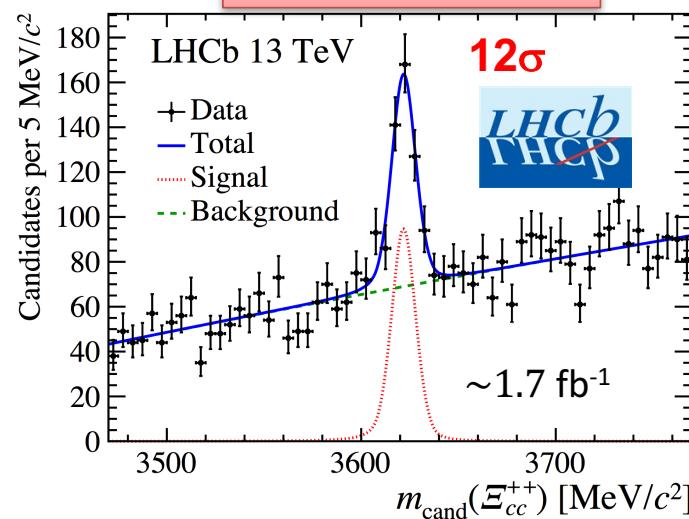
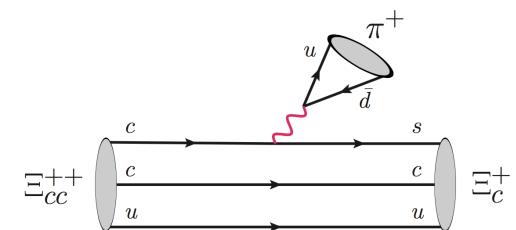
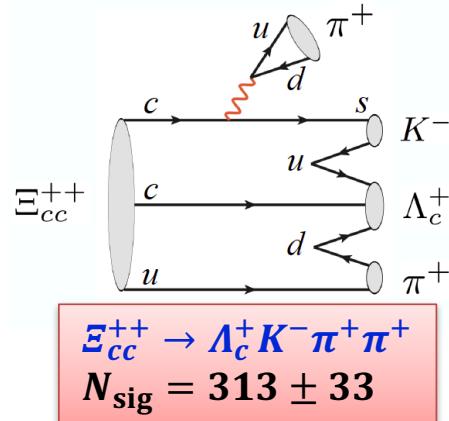
# Observation of $\Xi_{cc}^{++}$ from two decay modes



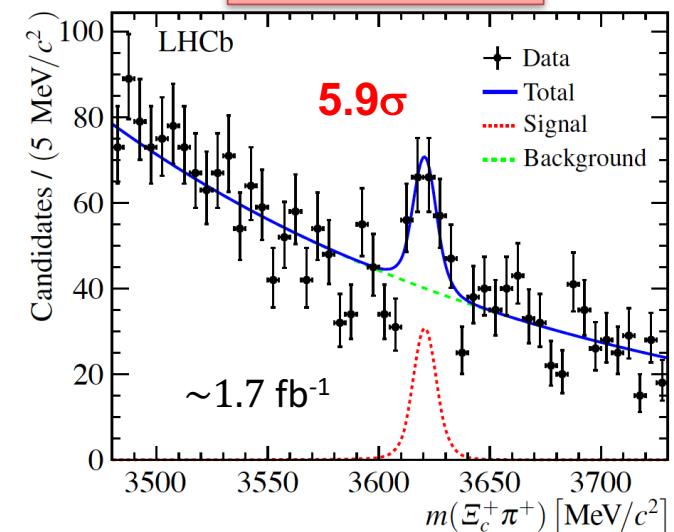
- Expect  $\Xi_{cc}^{++}(ucc)$  has higher sensitivity at LHCb due to longer lifetime [larger  $\mathcal{B}$  and higher efficiency]

[Yu et al., arXiv:1703.09086, CPC 42 (2018) 051001]

- Observed two suggested decay modes
  - Reconstruct  $\Lambda_c^+$  and  $\Xi_c^+$  (singly Cabibbo-suppressed) by decay  $pK^-\pi^+$
  - $\varepsilon(\Lambda_c^+ K^-\pi^+\pi^+)/\varepsilon(\Xi_c^+\pi^+) = 0.110$  due to two more tracks in former decay



[PRL 119 (2017) 112001]



[PRL 121 (2018) 162002]

# Observation of new decay mode $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$



- Ratio of branching fractions

[PRL 121 (2018) 162002]

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+; \Xi_c^+ \rightarrow p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+; \Lambda_c^+ \rightarrow p K^- \pi^+)} = (3.5 \pm 0.9 \pm 0.3) \times 10^{-2}$$

- $\mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+) = (6.28 \pm 0.32)\%$  [PDG] and  $\mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$   
[1<sup>st</sup> absolute measurement, Belle, arXiv:1904.12093]

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} = 0.49 \pm 0.13(\mathcal{R}) \pm 0.24(\mathcal{B}_{\Xi_c^+}) \quad [\text{my computation}]$$

- $\Xi_c^0 \pi^+$  would be a good mode to search for  $\Xi_c^+$ , but the most efficient decay  $\Xi_c^0 \rightarrow p K^- K^- \pi^+$  suffers low  $\mathcal{B}(\Xi_c^0 \rightarrow p K^- K^- \pi^+) = (0.58 \pm 0.23 \pm 0.05)\%$  [Belle, PRL 122 (2019) 082001]

# Observation of new decay mode $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$



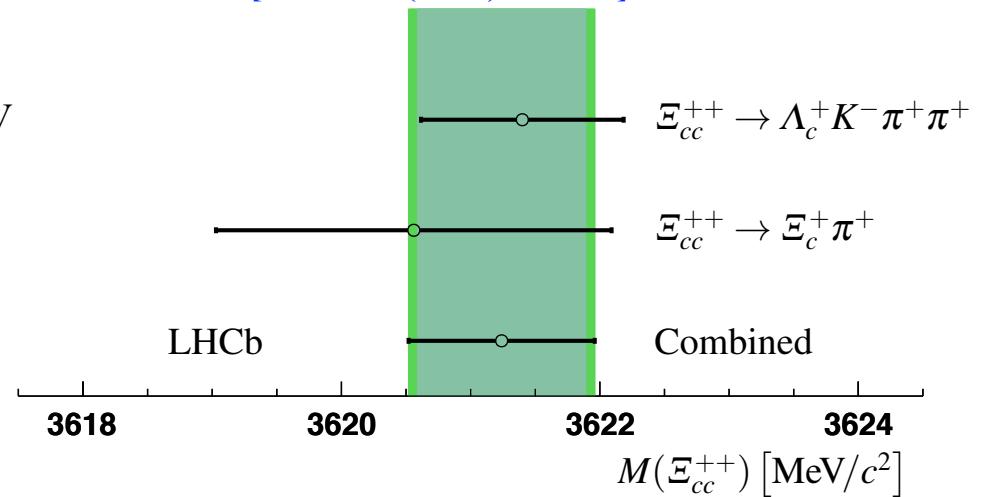
- Consistent mass measurements

$3621.40 \pm 0.72 \pm 0.27 \pm 0.14(\Lambda_c^+) \text{ MeV}$

$3620.56 \pm 1.5 \pm 0.4 \pm 0.3(\Xi_c^+) \text{ MeV}$

$3621.24 \pm 0.65 \pm 0.31 \text{ MeV}$

[PRL 121 (2018) 162002]



Mass difference:  $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_c^+)_{\text{SELEX}} = 103 \pm 2 \text{ MeV}$

➤ Inconsistent with being isospin partners

# Search for $\Xi_{cc}^{++} \rightarrow D^+ p K^- \pi^+$

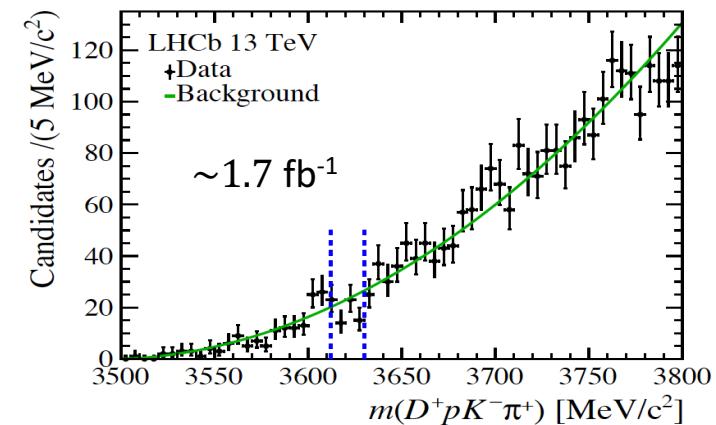
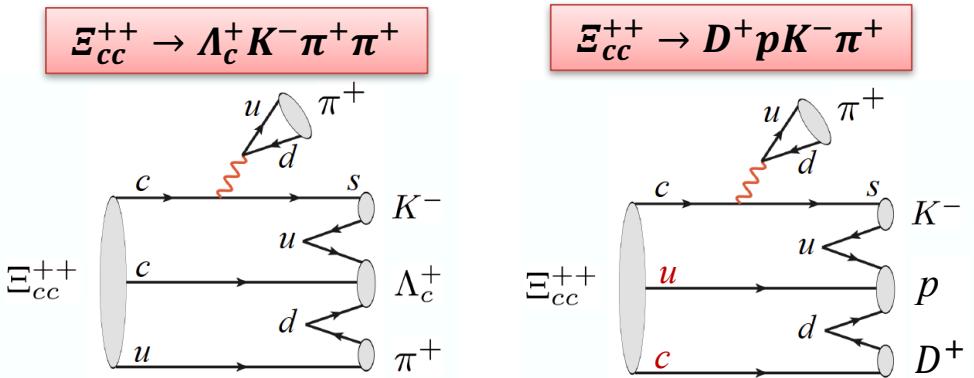
new



- Decay diagram is similar to that of  $\Lambda_c^+ K^- \pi^+ \pi^+$ , but smaller phase space
  - Just swap  $u$  and  $c$  quarks
- Efficiency is similar
- No evident signal
- Very stringent upper limit is obtained

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} < \mathbf{0.021@95\% C.L.}$$

[arXiv:1905.02421]

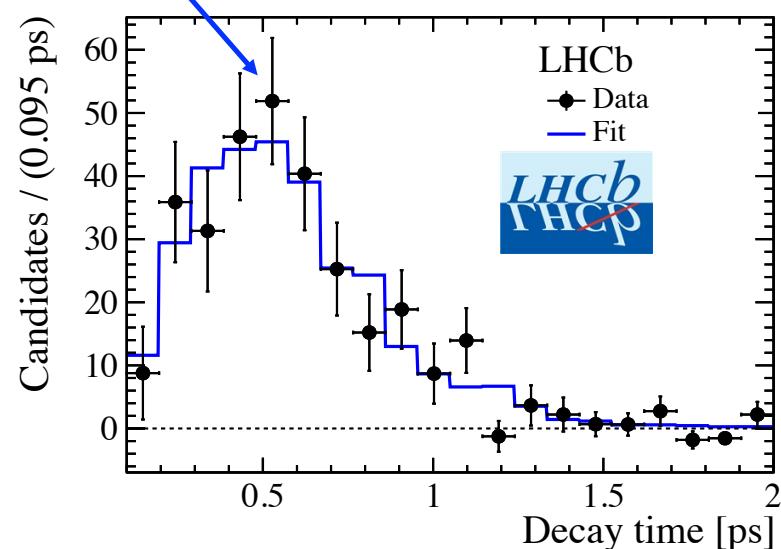


# First measurement of $\Xi_{cc}^{++}$ lifetime



- Using  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  decays

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$



[PRL 121 (2018) 052002]

$$\tau_{\Xi_{cc}^{++}} = 256^{+24}_{-22} \pm 14 \text{ fs}$$

Precision 10.5%

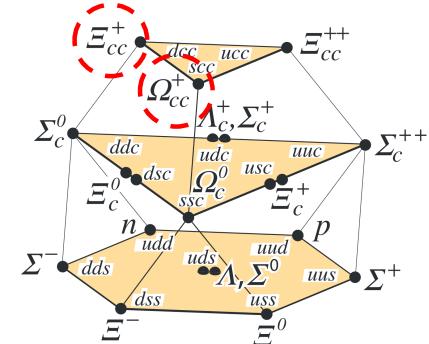
Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated $\Xi_{cc}^{++}$ lifetime	0.002
$\Lambda_b^0$ lifetime uncertainty	0.001
Sum in quadrature	0.014

Confirmed it is weakly decaying  $J = 1/2$  ground state

# Prospects on $\Xi_{cc}^+$ and $\Omega_{cc}^+$ searches at LHCb



- Mass  $m(\Xi_{cc}^+) \approx m(\Xi_{cc}^{++}) = 3621.24 \pm 0.72 \text{ MeV}$   
 $m(\Omega_{cc}^+) \approx m(\Xi_{cc}^{++}) + 100 \text{ MeV}$
- Lifetime  $3\tau(\Xi_{cc}^+) \approx 3\tau(\Omega_{cc}^+) \approx \tau(\Xi_{cc}^{++}) = 0.256 \pm 0.027 \text{ ps}$
- Production  $\sigma(\Xi_{cc}^{++}): \sigma(\Xi_{cc}^+): \sigma(\Omega_{cc}^+) \approx 1:1:0.3$
- Shorter lifetime in  $\Xi_{cc}^+$  and  $\Omega_{cc}^+$  makes numbers of drawbacks
  - Smaller  $\mathcal{B}$ , lower efficiency and larger background
- $\Xi_{cc}^+$ : uncertain with current full LHCb data
  - Expect  $\sim 200$  reconstructed  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$  with full LHCb data, **but how about the background level?**  
**exponentially increases?** assuming  $\mathcal{R}_\tau = \frac{\tau(\Xi_{cc}^+)}{\tau(\Xi_{cc}^{++})} = \frac{1}{3}$
- $\Omega_{cc}^+$ : More challenge



Estimation of golden mode  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$

$$\frac{\mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} = \left( \frac{\mathcal{R}_\tau}{0.3} \right) \times 0.22 \quad [\text{Fu et. al.}]$$

Compared to  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

- BR a factor of 1/5
- Similar efficiency: a factor of 1/3 due to  $\tau$  & a factor of 2 larger due to one less track
- Production cross-section is the same
- Full luminosity is a factor of 4 as 2016 data

# $J^P$ of $Z_c(4100)^-$ and $\mathcal{B}$

arXiv:1809.07416



- The default fit has  $4.3\sigma$  for  $J^P = 1^-$  over  $0^+$
- Systematic uncertainty reduces to  $1.2\sigma$ 
  - Alternative  $K^+\pi^-$  S-wave model  
(NR +  $\kappa$  +  $K_0^*(1430)^0$ )
- So  $J^P = 1^-$  and  $0^+$  are both consistent with the data
- Fit fraction of  $Z_c(4100)^-$  is  $(3.3 \pm 1.1^{+1.2}_{-1.1})\%$

Source	$\Delta(-2 \ln \mathcal{L})$	Significance
Default	18.6	$4.3\sigma$
Fixed yields	23.8	$4.9\sigma$
Phase-space border veto	24.4	$4.9\sigma$
$\eta_c$ width	4.2	$2.0\sigma$
Background	3.4	$1.8\sigma$
$K^+\pi^-$ S-wave	1.4	$1.2\sigma$

$$\mathcal{B}(B^0 \rightarrow Z_c(4100)^- K^+, Z_c(4100)^- \rightarrow \eta_c(1S) \pi^-) = (1.89 \pm 0.64^{+0.73}_{-0.67}) \times 10^{-5}$$

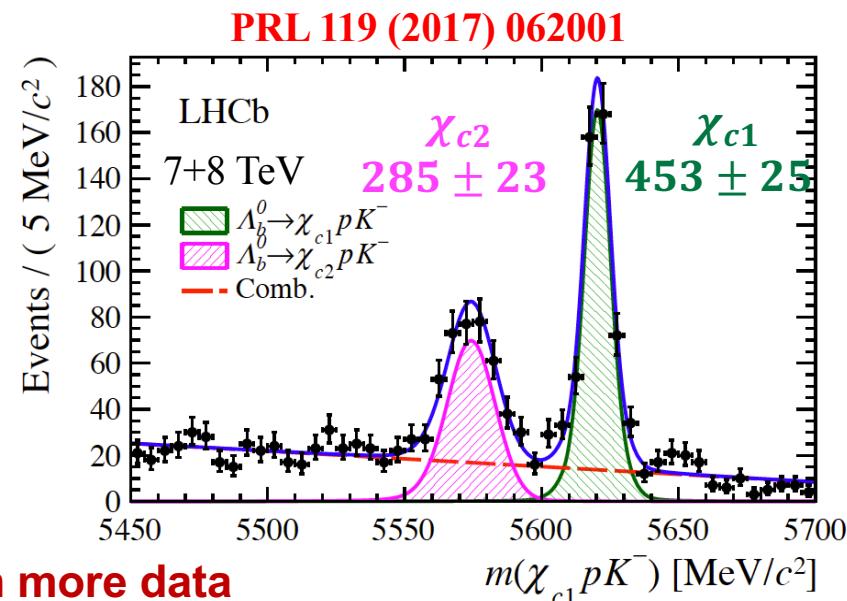
$$\mathcal{B}(B^0 \rightarrow \eta_c(1S) K^+ \pi^-) = (5.73 \pm 0.24 \pm 0.13 \pm 0.66) \times 10^{-4}$$

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

- Search for  $P_c(4450)^+$  in  $\Lambda_b^0 \rightarrow \chi_{c(1,2)} p K^-$  decays  
⇒ Test hypothesis of kinematic rescattering effect
- First step: observe the decays, measure  $\mathcal{B}$
- Use  $\chi_{c(1,2)} \rightarrow J/\psi \gamma$ , constrain  $J/\psi \gamma$  mass to known  $\chi_{c1}$  mass

PRD 92 (2015) 071502

$$\begin{aligned} \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)} &= \\ 0.242 \pm 0.014 \pm 0.013 \pm 0.009 & \\ \uparrow & \\ \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)} &= \\ 0.248 \pm 0.020 \pm 0.014 \pm 0.009 & \\ \downarrow & \end{aligned}$$



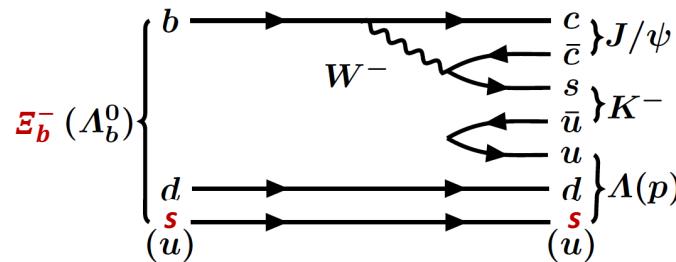
Next step: full amplitude analysis with more data

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

PLB 772 (2017) 265-273



- Strange pentaquark ( $ud\textcolor{red}{sc}\bar{c}$ ) predicted in [PRL 105 (2010) 232001]
- Can be searched for in the  $\Xi_b^-$  decay [PRC 93 (2016) 065203]

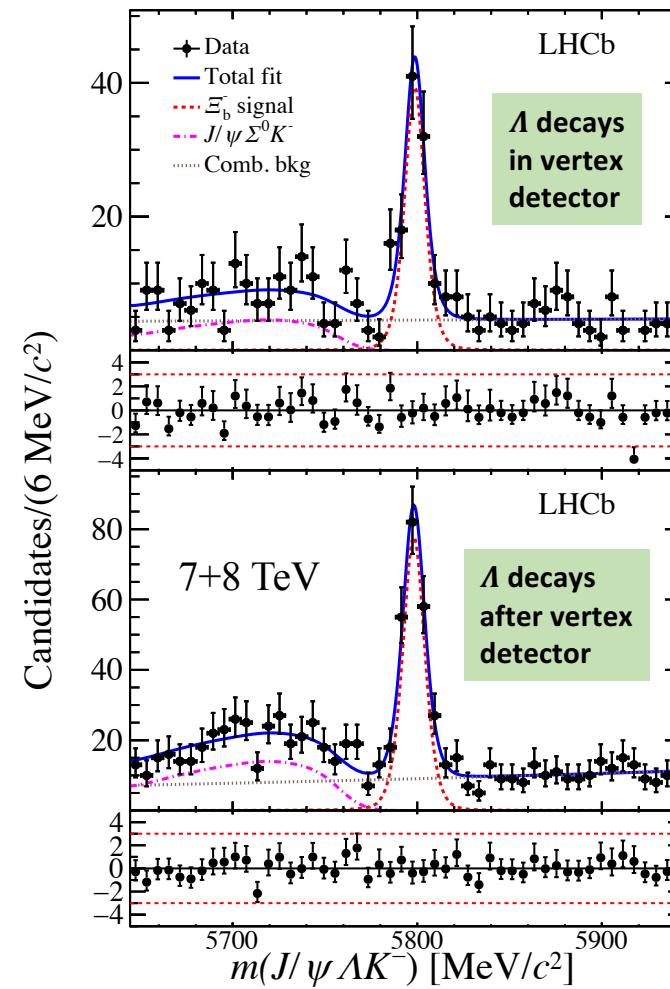


$$N_{\text{sig}} = 308 \pm 21 \text{ (21}\sigma\text{)}$$

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

Expect ~1500 signals after 2018 for amplitude analysis

Mengzhen Wang



# Weakly decaying $b$ -flavoured pentaquarks

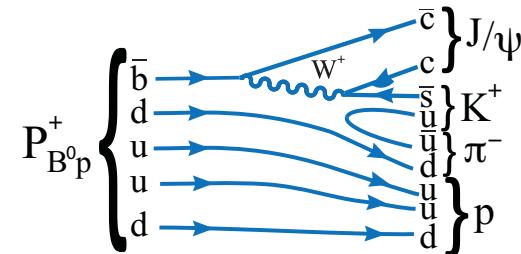
PRD 97 (2018) 032010



- 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	$\bar{b}duud$	$P_{B^0 p}^+ \rightarrow J/\psi K^+ \pi^- p$	4668–6220 MeV
II	$b\bar{u}udd$	$P_{\Lambda_b^0 \pi^-}^- \rightarrow J/\psi K^- \pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P_{\Lambda_b^0 \pi^+}^+ \rightarrow J/\psi K^- \pi^+ p$	4668–5760 MeV
IV	$\bar{b}s uud$	$P_{B_s^0 p}^+ \rightarrow J/\psi \phi p$	5055–6305 MeV

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

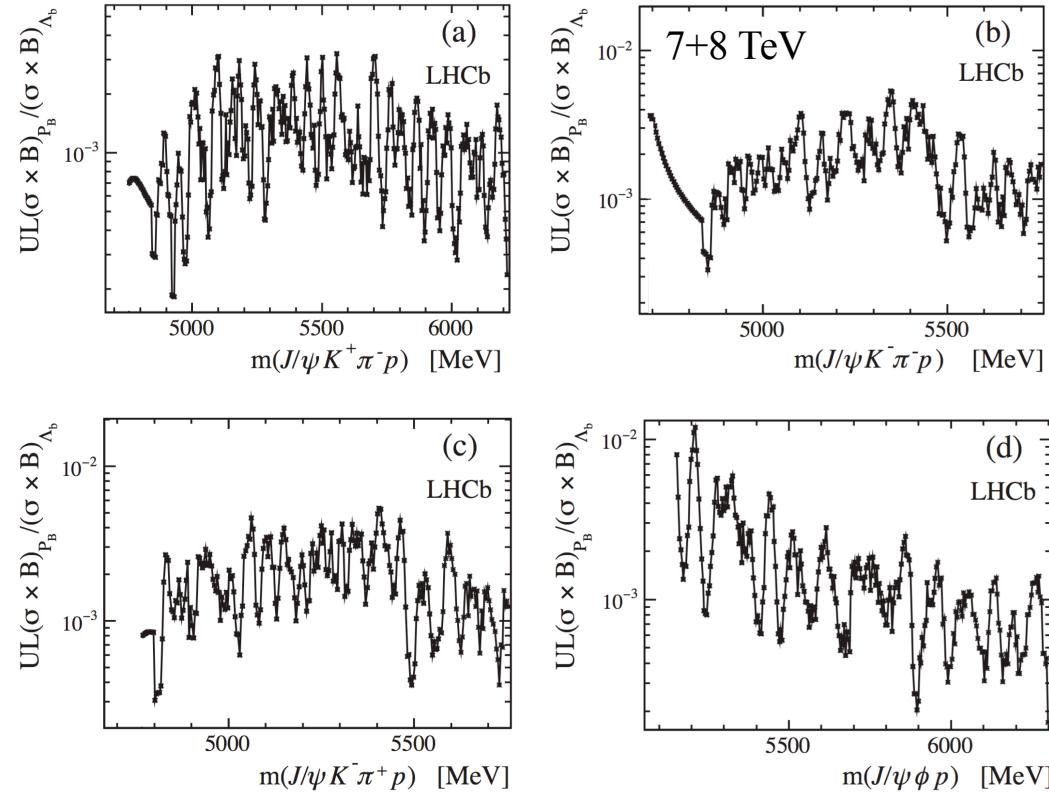
$$R = \frac{\sigma(pp \rightarrow P_B X) \cdot \mathcal{B}(P_B \rightarrow J/\psi X)}{\sigma(pp \rightarrow \Lambda_b^0 X) \cdot \mathcal{B}(\Lambda_b^0 \rightarrow J/\psi K^- p)}$$

# Weakly decaying $b$ -flavoured pentaquarks

PRD 97 (2018) 032010



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



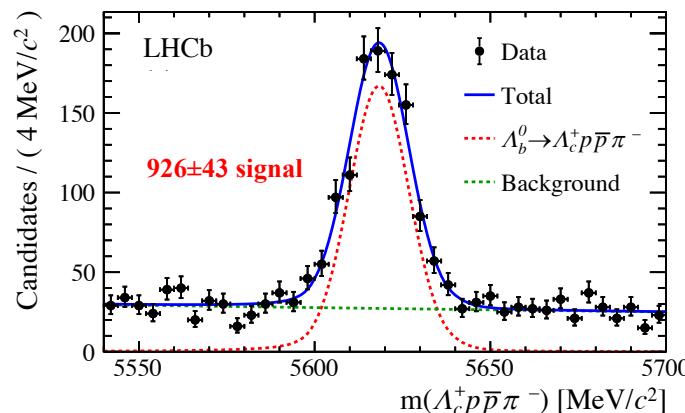
# Search for dibaryon state



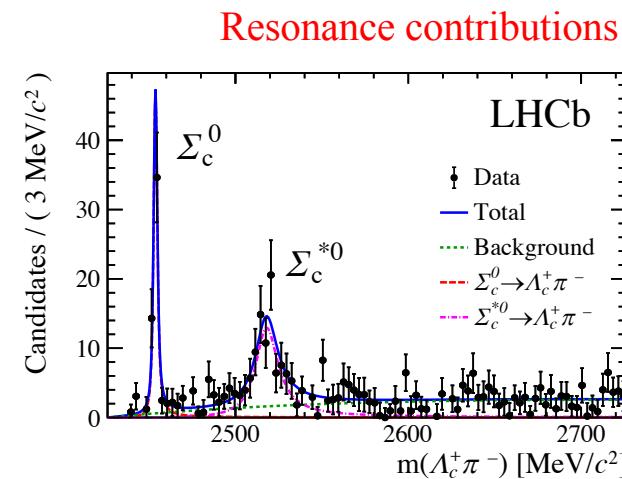
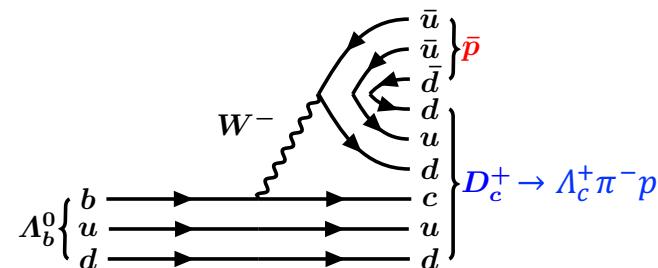
- A dibaryon state  $[cd][ud][ud]$  could be produced in  $\Lambda_b^0$  decays to final state  $\Lambda_c^+ \pi^- p\bar{p}$

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

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



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



# Search for dibaryon state

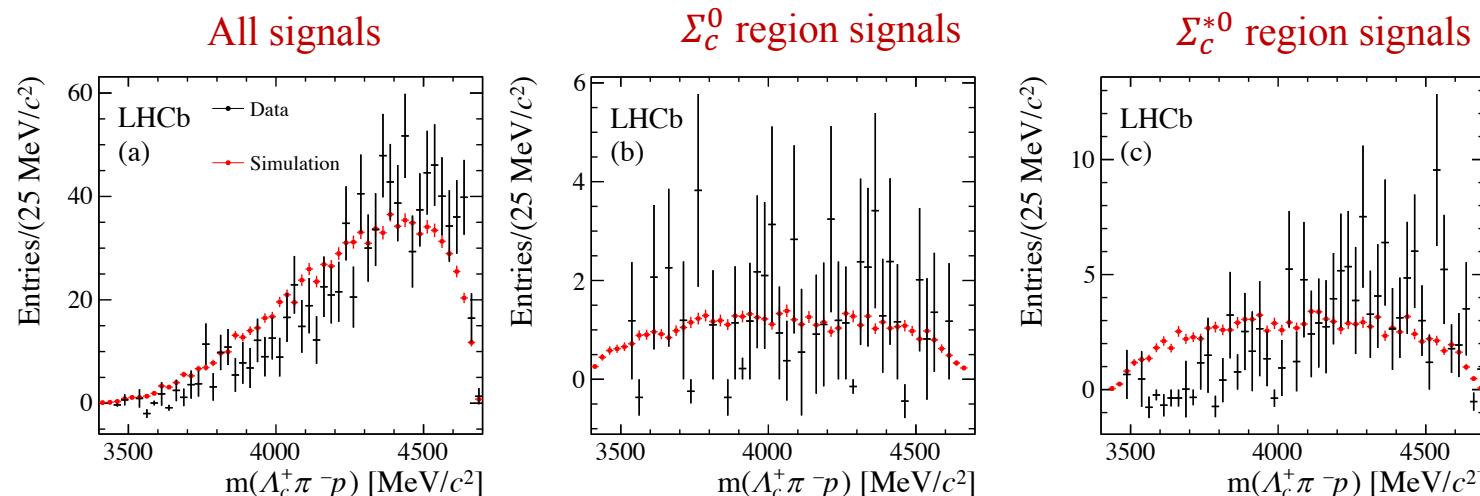


- Ratio of branching fractions

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

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

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



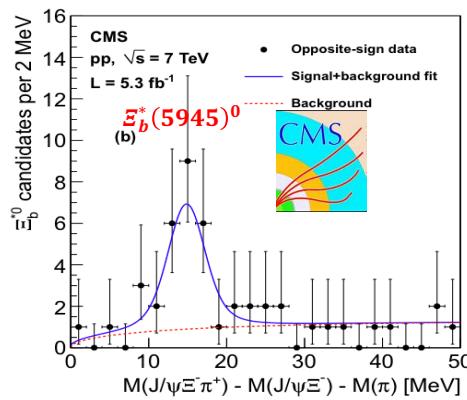
# $\Xi_b$ baryon spectroscopy



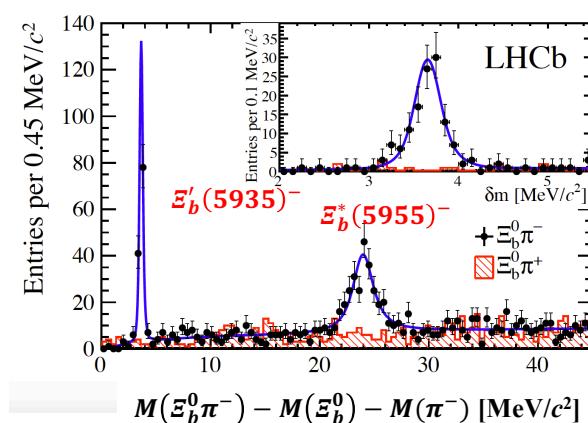
- Numbers of excited  $b$ -baryons have already been discovered
  - $\Xi_b^*(5945)^0 \rightarrow \Xi_b^- \pi^+$  [CMS'12]
  - $\Xi_b'(5935)^-, \Xi_b^*(5955)^- \rightarrow \Xi_b^0 \pi^-$  [LHCb'15]
  - $\Xi_b'^0$  not yet observed

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

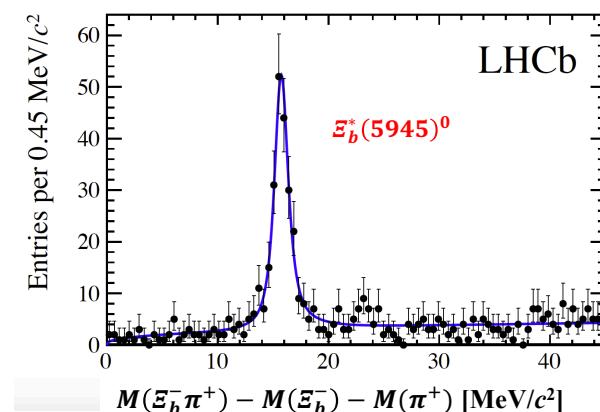
PRL 108, 252002 (2012)



PRL 114 (2015) 062004



JHEP 05 (2016) 161



# Amplitude analyses of exotic states



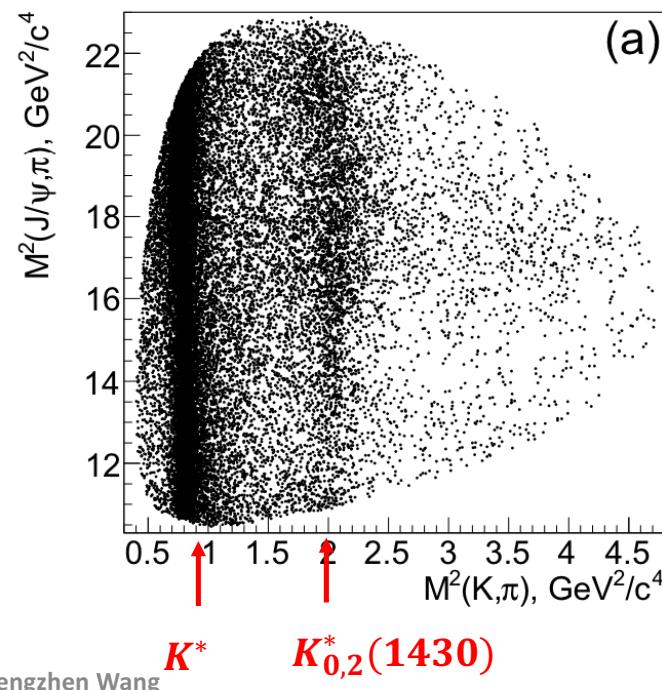
- Many puzzling exotic meson and baryon candidates were detected in  $B$ -hadron decays
  - Charged exotic mesons  $\rightarrow J/\psi, \psi(2S), \eta_c$  or  $\chi_{c1} + \pi^+$
  - The hidden-charmed mesons  $\rightarrow J/\psi\phi$
  - Charged exotic baryons  $\rightarrow J/\psi p$
- The determination of their properties, or even the claim for their existence, rely on advanced amplitude analyses
- Large contributions to these  $B$ -hadron decays are from production of  $K^*$ ,  $\Lambda^*$  or  $N^*$ , that are not well measured
- Improved knowledge of these conventional states are important for exotic study

# $Z_c^-$ in $B^0 \rightarrow J/\psi K^+ \pi^-$ from Belle

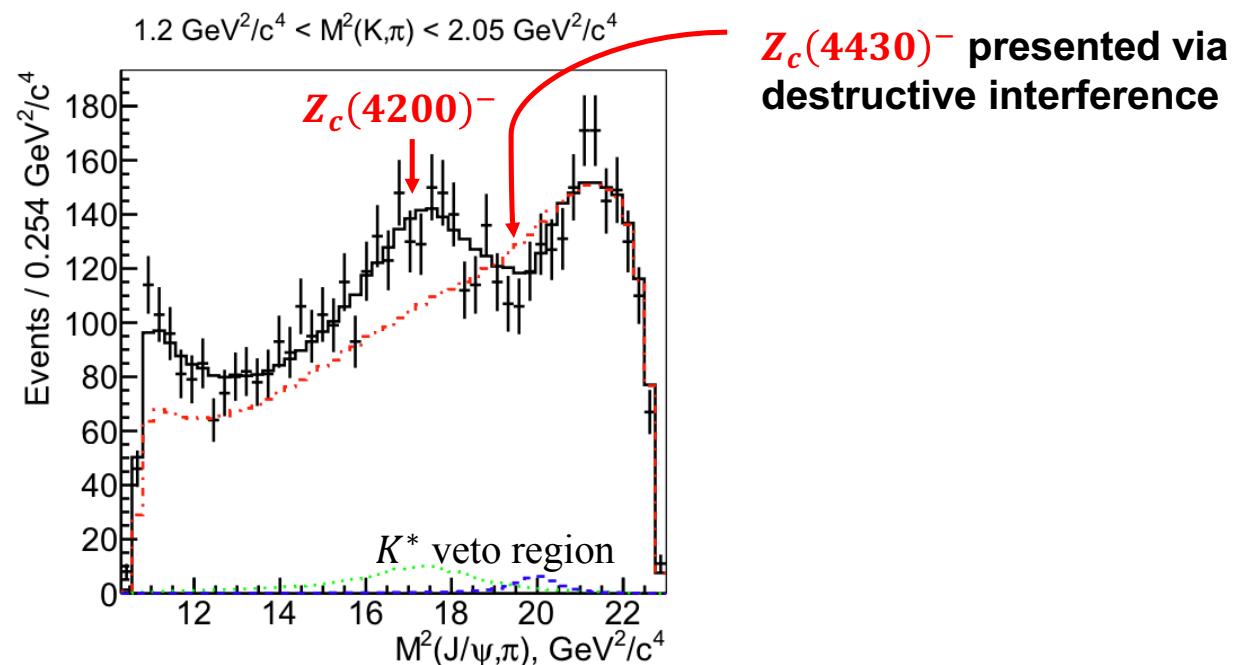
PRD 90, 112009 (2014)



- With  $\sim 30k$  signal, Belle observed a new  $Z_c(4200)^-$  and evidence for  $Z_c(4430)^-$  in  $B^0 \rightarrow J/\psi K^+ \pi^-$  decays
- Exotic fit fractions are small,  $(1.9^{+0.7}_{-0.5})\%$   $Z_c(4200)^-$  &  $(0.5^{+0.4}_{-0.1})\%$   $Z_c(4430)^-$



Mengzhen Wang

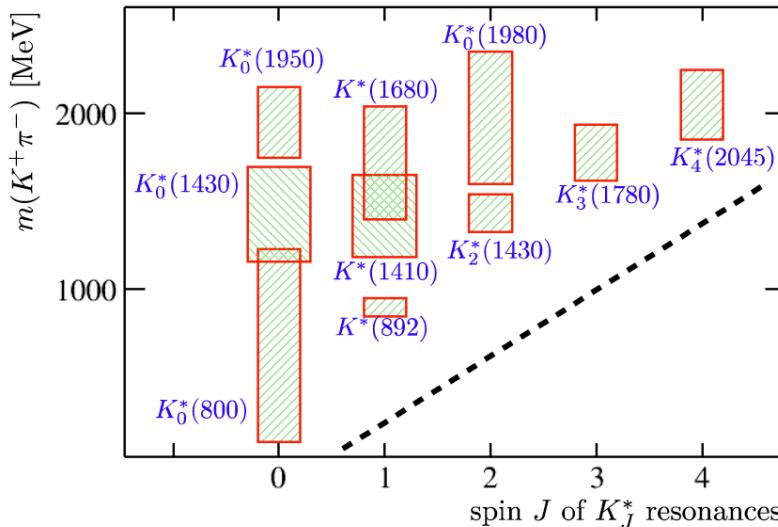


53

# Model-independent confirmation from LHCb



- Run-1 data,  $\times 20$  Belle signal yield  $m_{K\pi} \in [745, 1545]$  MeV: yield is  $554530 \pm 770$ .



- Several broad overlapping states
- Higher spins at higher masses
- $f_z \sim 1 - 2\%$ . Must veto the dominant  $K^*(892)$  and  $K_2^*(1430)$  regions.
- If data has only  $K_J^*$  states, assign:  $J_{\max} = \begin{cases} 2, & m_{K\pi} \in [1085, 1265] \text{ MeV} \\ 3, & m_{K\pi} \in [1265, 1445] \text{ MeV} \end{cases}$
- Exotics in  $[J/\psi \pi^-]$  or  $[J/\psi K^+]$ :  $J_{\max} \rightarrow \infty$ . Take  $J_{\max}^k = 15$  as proxy.

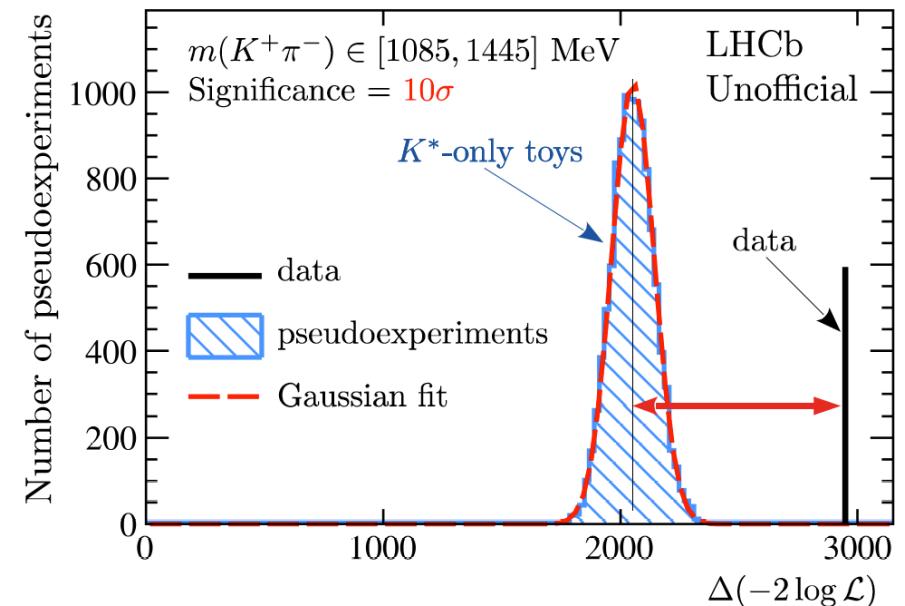
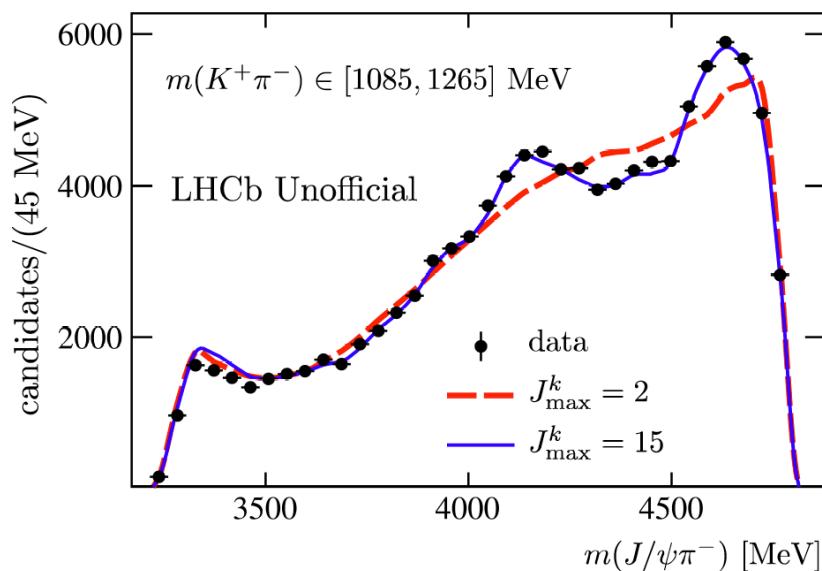
LHCb-PAPER-2018-043, presented at Implication Workshop <https://indico.cern.ch/event/743635/timetable/>

# Model-independent confirmation from LHCb



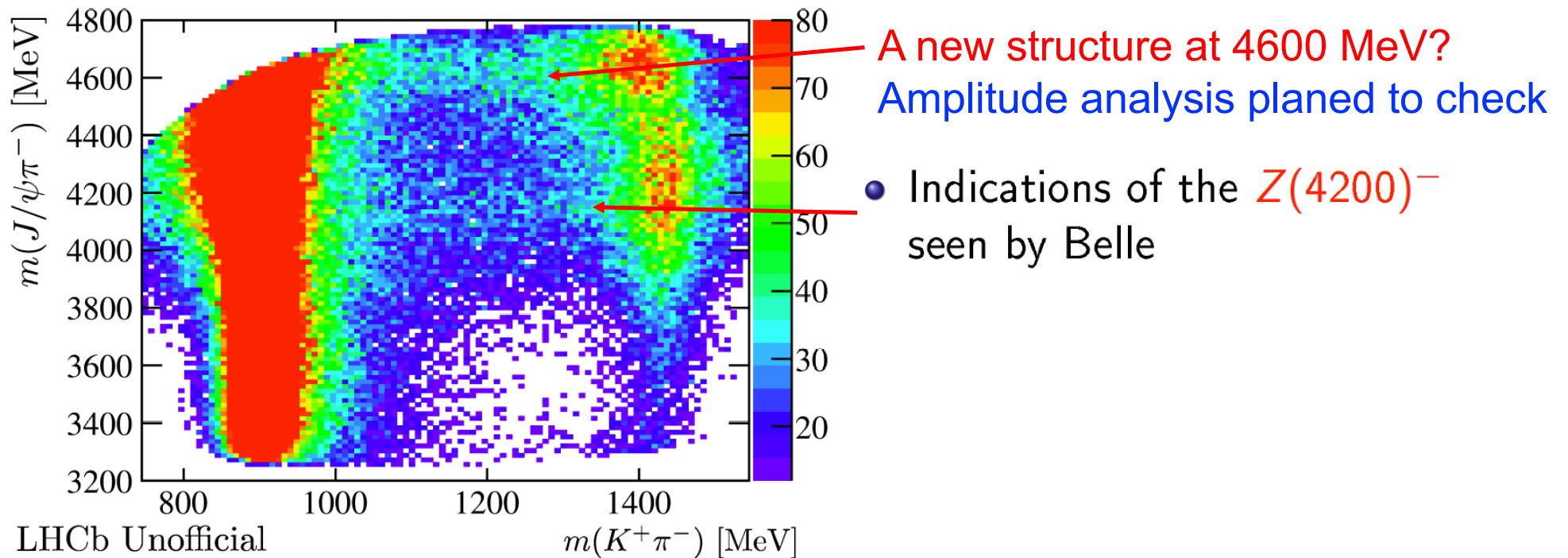
- Used novel “3D” angular moments to boost sensitivity
- $K^*$  only contributions ruled out by  $10\sigma$

In each  $m_{K\pi}$  bin:  $K^*$ -only model pdf doesn't describe data.



LHCb-PAPER-2018-043, presented at Implication Workshop <https://indico.cern.ch/event/743635/timetable/>

# Exotic interpretation



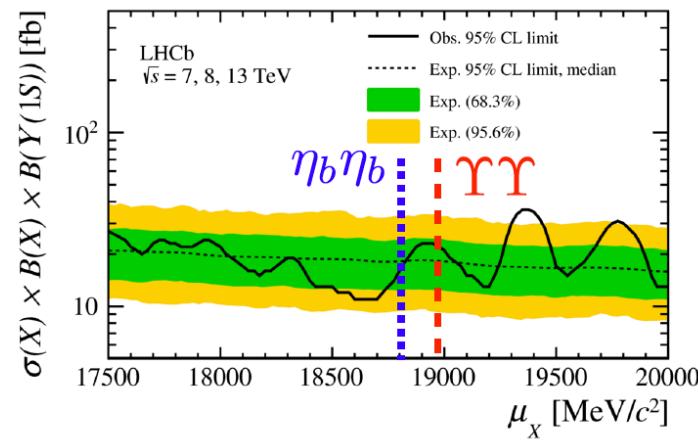
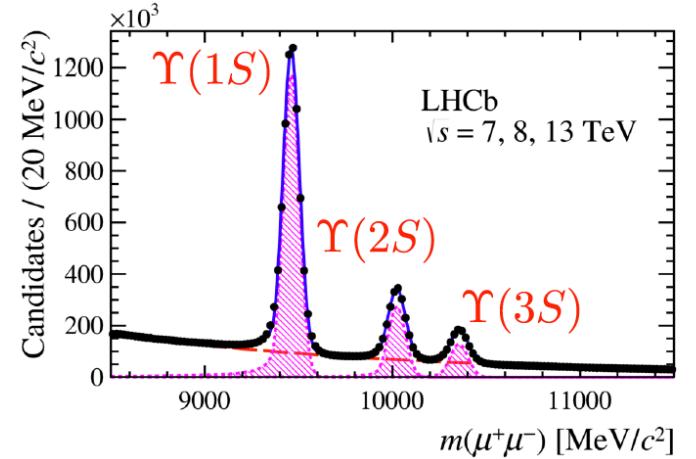
LHCb-PAPER-2018-043, presented at Implication Workshop <https://indico.cern.ch/event/743635/timetable/>

# Search for $X_{bb\bar{b}\bar{b}} \rightarrow \Upsilon(1S)\mu^+\mu^-$

JHEP 10 (2018) 086



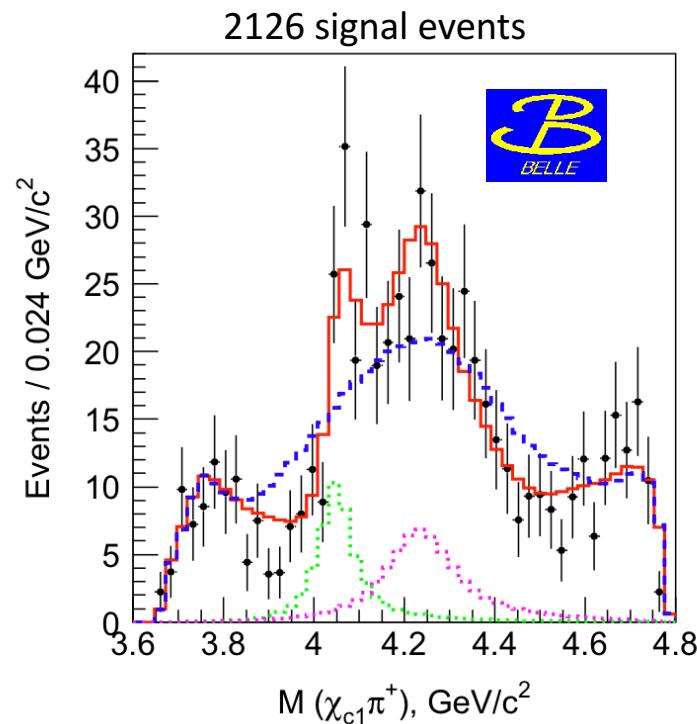
- Binding of **double-heavy  $b\bar{b}$  pairs** quite different to  $c\bar{c}$ +light meson cloud
- Ground state **bound  $bbbb\bar{b}$**  tetraquark  $\sim 18 - 19$  GeV in many phenomenological models.
- Typically **below  $\eta_b\eta_b$  threshold**. Can decay to  $\Upsilon(1S)\mu^+\mu^-$
- **No hint** of a structure in LHCb search with 2011-2016 data. **Upper limits** placed.



# Ongoing LHCb analyses for exotics



- Full amplitude analysis of  $B^0 \rightarrow \chi_{c1} K^+ \pi^-$  (~10,000 signals in Run1)
- Pentaquarks
  - $\Lambda_b^0 \rightarrow J/\psi p K^-$
  - $\Lambda_b^0 \rightarrow J/\psi p \pi^-$
  - $\Lambda_b^0 \rightarrow \chi_{c1} p K^-$
  - $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^-$
  - $\Xi_b^- \rightarrow J/\psi \Lambda^0 K^-$



Belle, PRD 78, 072004 (2008)