LHCb上重味强子谱学和奇特态

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5th Workshop on the XYZ particles
10/23/2018,郑州大学

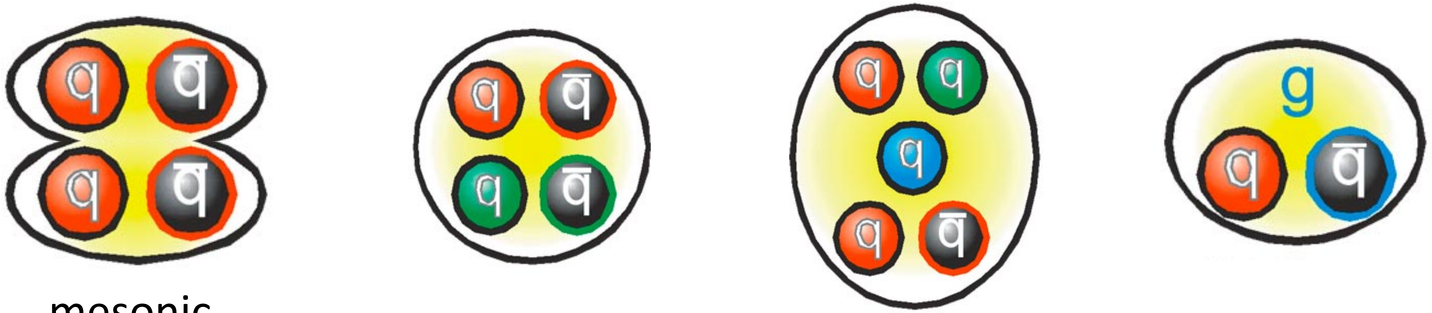
Outline

- Exotic states
  - Evidence of an $\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$
  - Model independent confirmation for Z_c^- in $B^0 \to J/\psi K^+\pi^-$
  - Other searches for exotic states

- Heavy flavour spectroscopy
  - Observation of a new Ξ_b^{**-} state
  - Observation of two new $\Sigma_b^{\pm}$ states

Introduction

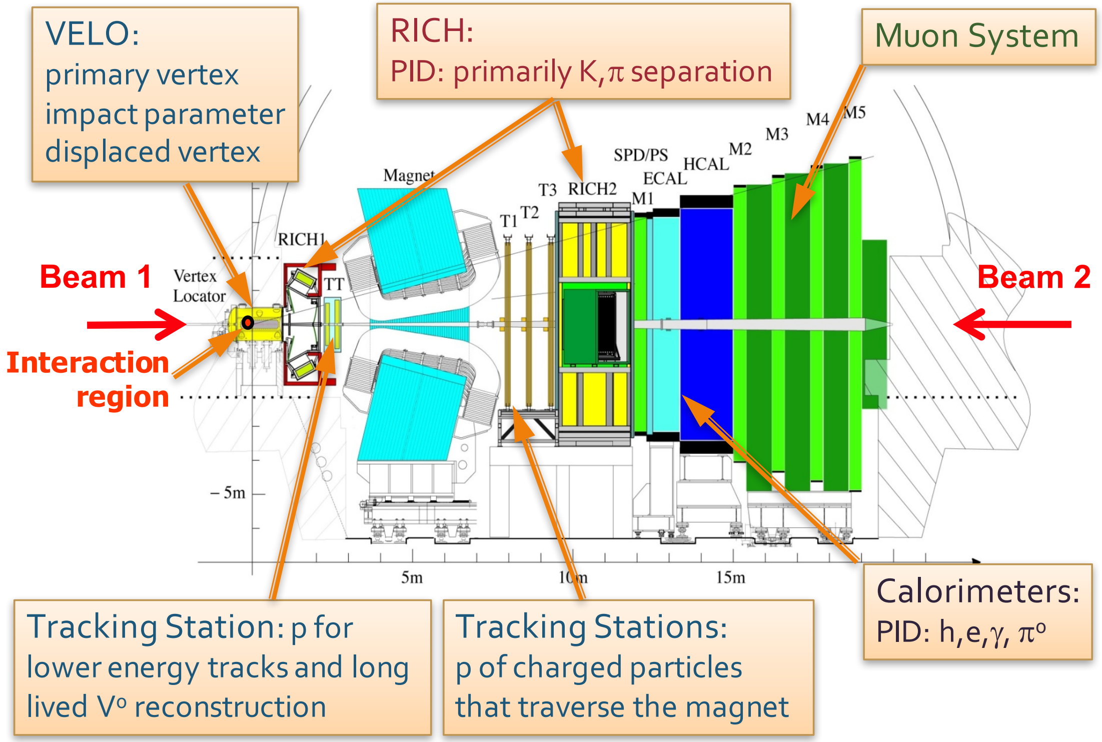
- QCD, describing strong interaction between quarks and gluons, at low energy scale is not well understood due to its non-perturbative nature
- Hadron spectroscopy provides opportunities to study QCD predictions
  - For various models e.g. lattice QCD, diquark model, potential model …
- Exotic states provide unique environment to understand strong force in QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence



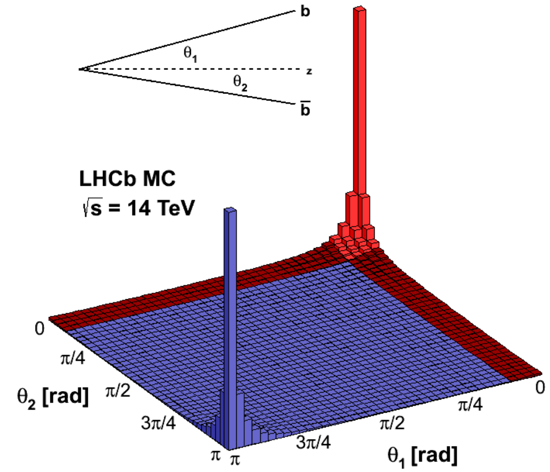
mesonic molecule ? tetraquark ? pentaquark ? hybrid ? …

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



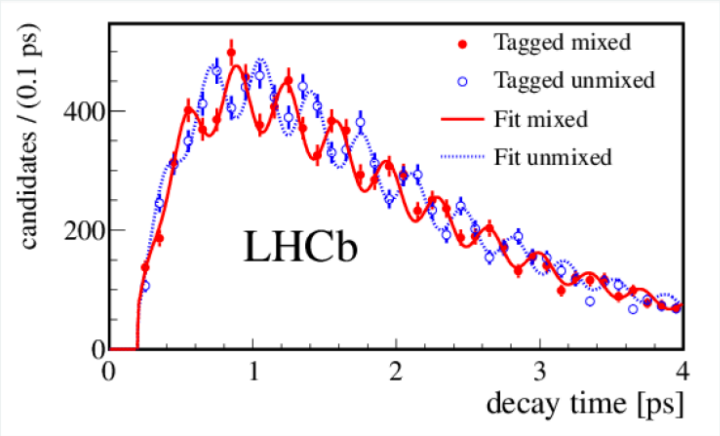
Int. J. Mod. Phys. A 30 (2015) 1530022

Impact parameter:	$\sigma_{IP} = 20\ \mu\text{m}$
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 GeV/c)
Mass :	$\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrained $m_{J/\psi}$)
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:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

LHCb detector and performance

Vertexing

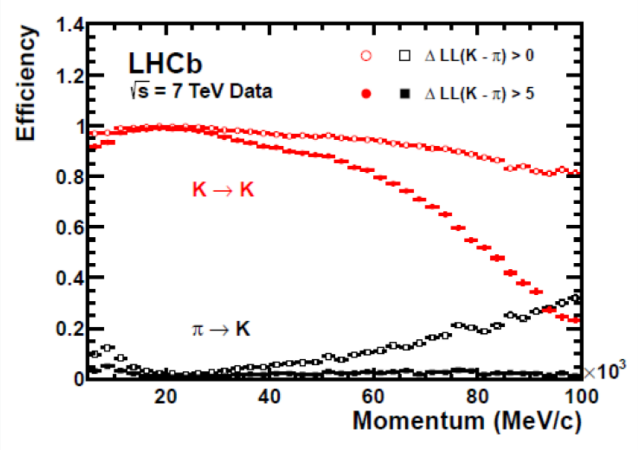
B_s^0 oscillations with $B_s^0 \to D_s\pi$



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

PID

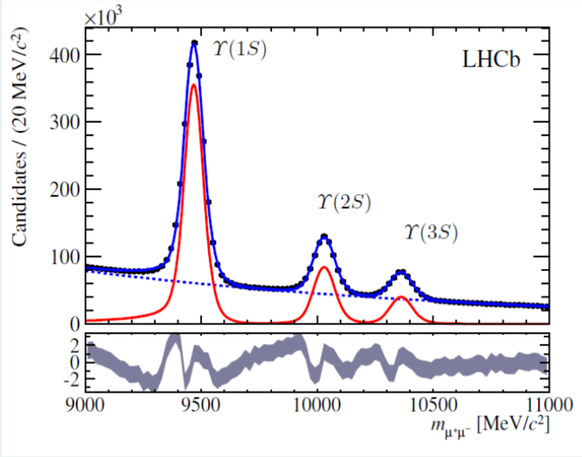
K/π ID efficiency and misID rate



[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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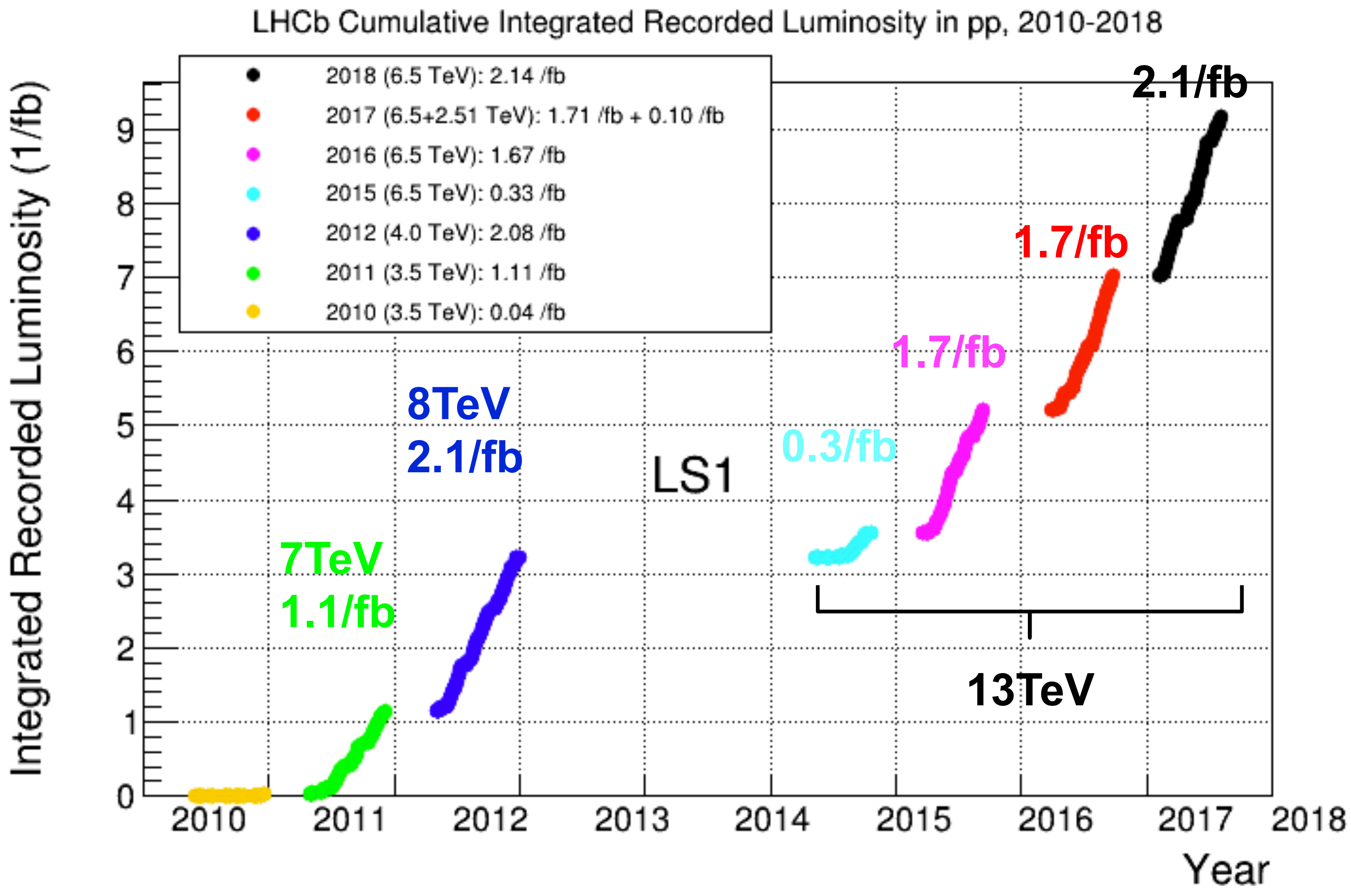
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

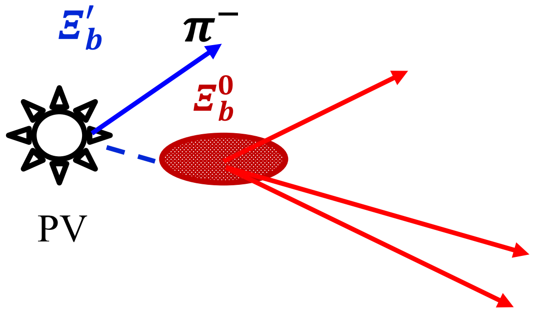
LHCb collected luminosity



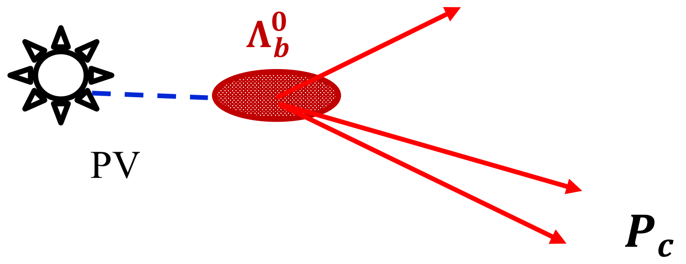
$\sigma(pp \rightarrow b\bar{b}X) \approx 300\ \mu b$ @7 TeV vs $\approx 500\ \mu b$ @13 TeV

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



Amplitude analyses of exotic states

- Many puzzling exotic meson and baryon candidates were detected in *B*-hadron decays
  - Charged exotic mesons → J/ψ, $\psi(2S)$, η_c or χ_{c1} $+ \pi^+$
  - The hidden-charmed mesons → $J/\psi\phi$
  - Charged exotic baryons → $J/\psi p$
- 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^*, Λ^* or N^*, that are not well measured
- Improved knowledge of these conventional states are important for exotic study

LHCb results on tetra and pentaquarks

- Confirmation of $Z(4430)$

  PRL 112 (2014) 222002

- Observation of two charmonium pentaquarks

  PRL 115 (2015) 072001

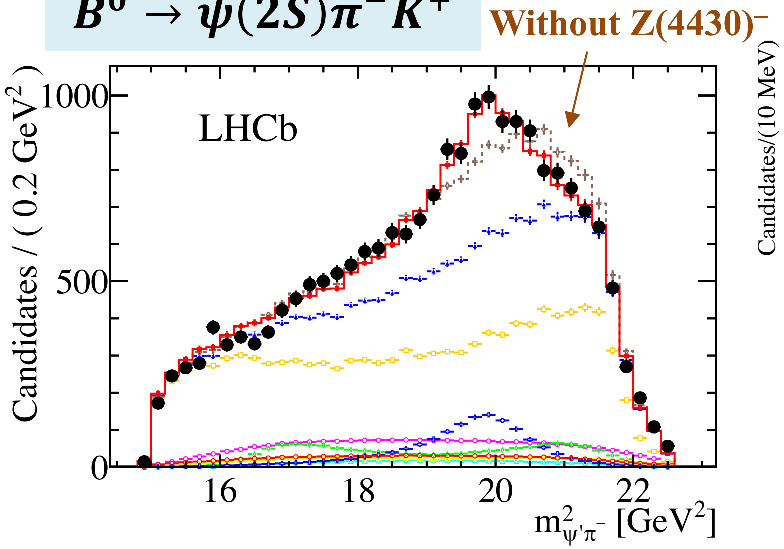
- Observation of four $J/\psi\phi$ structures

  PRL 118 (2017) 022003

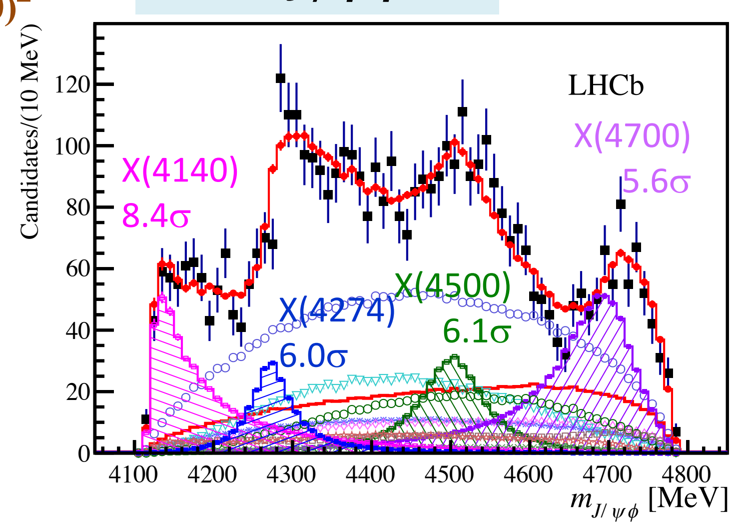
- Evidence of exotic contribution in Cabibbo-suppressed decays

  PRL 117 (2016) 082003

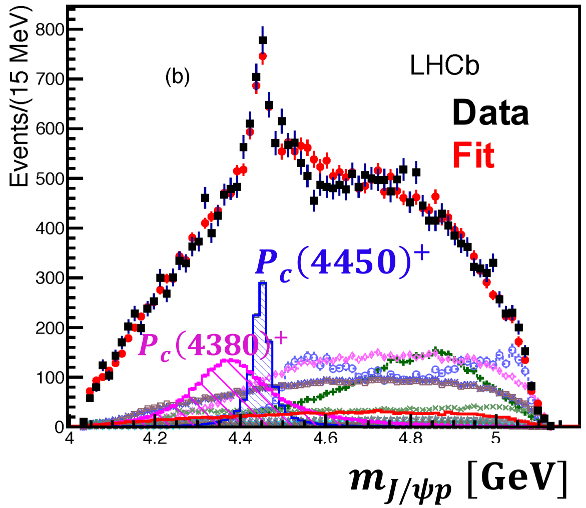
$B^0 \to \psi(2S)\pi^- K^+$



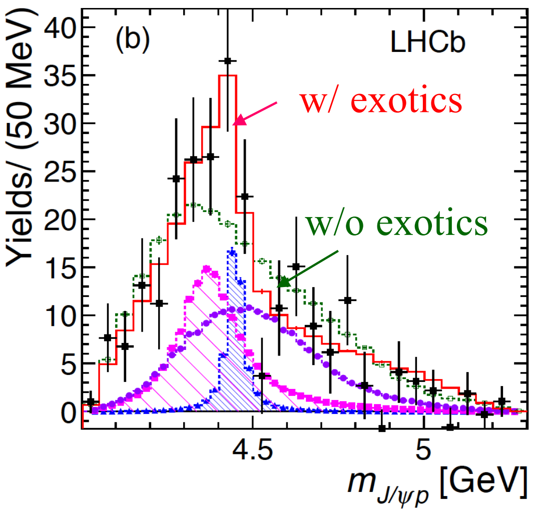
$B^+ \to J/\psi\phi K^+$



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

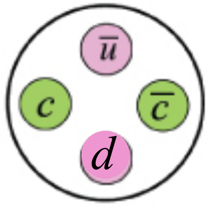


$\Lambda_b^0 \to J/\psi p \pi^-$



Evidence of an $\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$

- Charmonium-like charged states Z_c^-
  - Obviously exotic, since minimal four quark structure



- $\eta_c\pi^-$ acesses J^P other than 1^+, that several Z_c^- confirmed to be
  - "natural" $J^P = 0^+$, 1^- and 2^+ [$J = L$, $P = (-1)^L$]

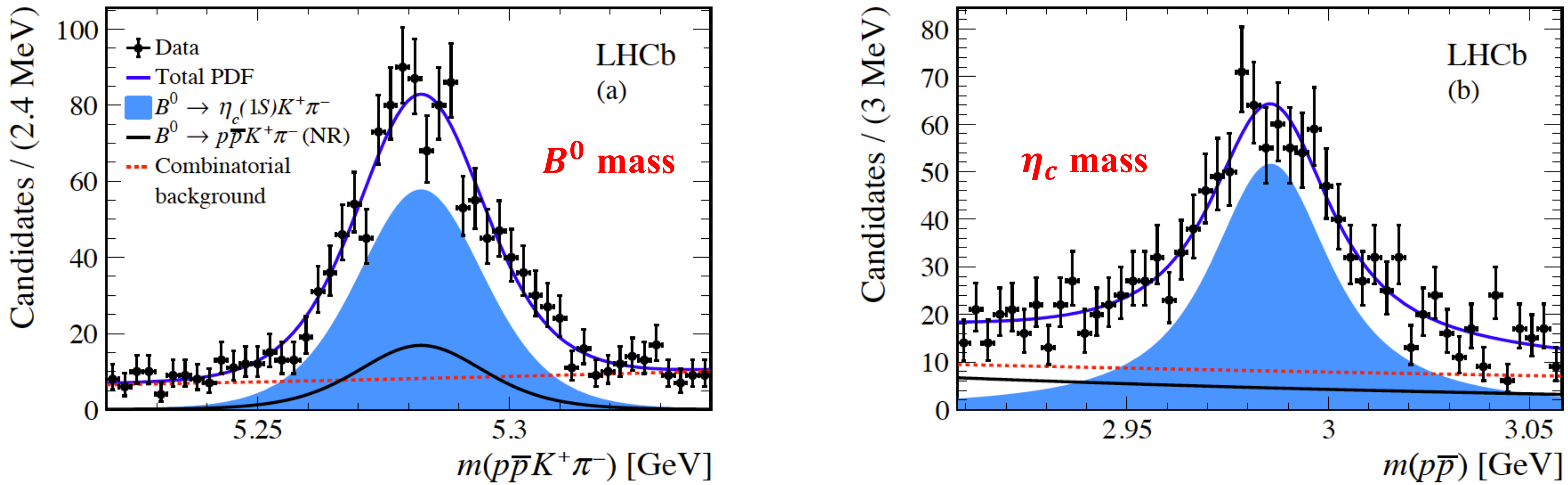
State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$Z_c^{+,0}(3900)$	3886.6 ± 2.4	28.1 ± 2.6	1^{+-}	$e^+e^- \to \pi^{-,0} + (J/\psi\,\pi^{+,0})$	BESIII (92; 101), Belle (88)
				$e^+e^- \to \pi^{-,0} + (D\bar{D}^*)^{+,0}$	BESIII (102; 103)
$Z_c^{+,0}(4020)$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e- \to \pi^{-,0} + (h_c\,\pi^{+,0})$	BESIII (93; 104)
				$e^+e^- \to \pi^{-,0} + (D^*\bar{D}^*)^{+,0}$	BESIII (105; 106)
$Z^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle (107), BaBar (108)
$Z^+(4200)$	4196^{+35}_{-32}	$370^{+\ 99}_{-149}$	1^+	$B \to K + (J/\psi\,\pi^+)$	Belle (51)
				$B \to K + (\psi'\pi^+)$	LHCb (46)
$Z^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle (107), BaBar (108)
$Z^+(4430)$	4477 ± 20	181 ± 31	1^+	$B \to K + (\psi'\,\pi^+)$	Belle (45; 109; 110), LHCb (46; 111)
				$B \to K + (J\psi\,\pi^+)$	Belle (51)

Rev. Mod. Phys. 90, 15003 (2018)

$B^0 \to \eta_c(1S)K^+\pi^-$: Signal

arXiv:1809.07416

- $\mathcal{L} = 4.7\text{fb}^{-1}$, including Run1+Run2(2011-2016) data
- 2D fit to $m(p\bar{p}K^+\pi^-)$ and $m(p\bar{p})$ distribution
  - Fit to obtain yields of signal, NR $p\bar{p}$ and combinatorial backgrounds
  - $N_{\text{sig}} = 1870 \pm 74$
  - Use sPlot to get two background PDFs in Dalitz-plot



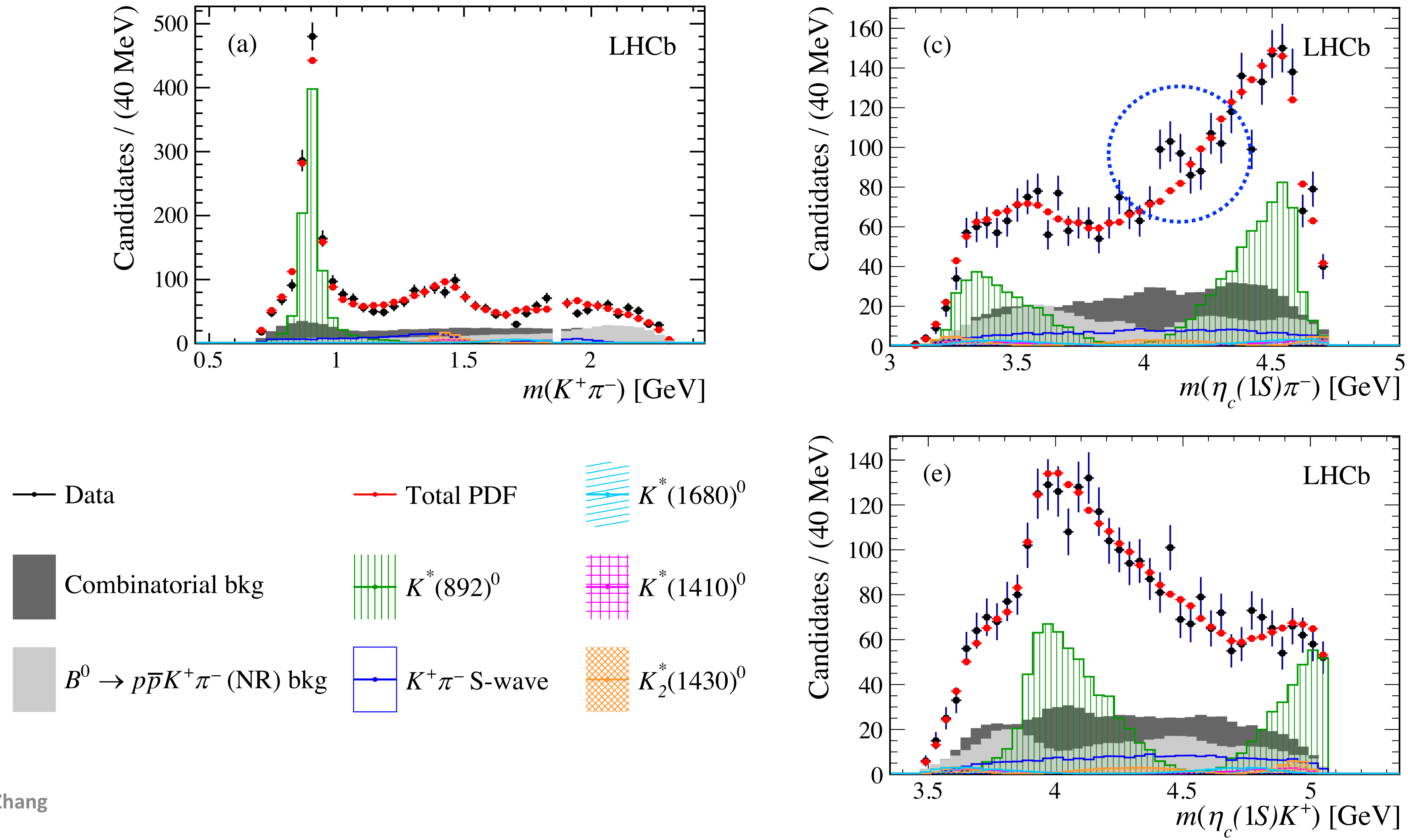
Dalitz-plot analysis

- Fit includes signal + two background components
- Seven K^{*0} resonances have significant contributions
  - Mass and width of each K^{*0} resonance are fixed, except for LASS
- Good description in all variables after adding an exotic Z_c component

Resonance	Mass [MeV]	Width [MeV]	J^P	Model
$K^*(892)^0$	895.55 ± 0.20	47.3 ± 0.5	1^-	RBW
$K^*(1410)^0$	1414 ± 15	232 ± 21	1^-	RBW
$K_0^*(1430)^0$	1425 ± 50	270 ± 80	0^+	LASS
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+	RBW
$K^*(1680)^0$	1717 ± 27	322 ± 110	1^-	RBW
$K_0^*(1950)^0$	1945 ± 22	201 ± 90	0^+	RBW

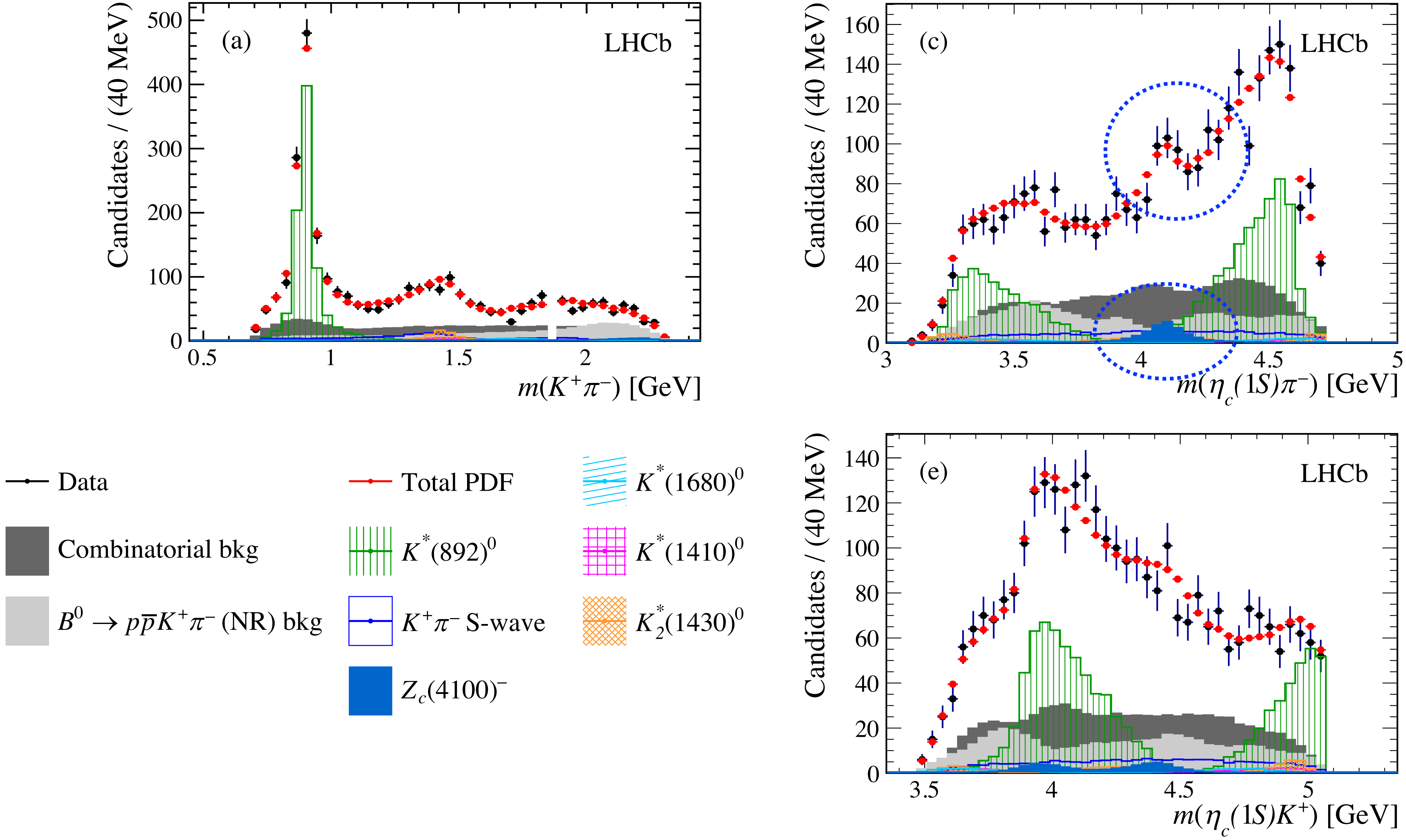
K^{*0} only fit

arXiv:1809.07416



$K^{*0} + Z_c^-$ fit

arXiv:1809.07416



Evidence for an exotic $Z_c(4100)^-$

arXiv:1809.07416

- Adding a Z_c^- improve the fit $-2\ln\mathcal{L}$ by 22.8, 41.4 and 7.0 for "natural" $J^P = 0^+, 1^-$ and 2^+
- Statistical significance is 4.8σ for nominal $J^P = 1^-$
  - ndof = 2 x N_{para} = 8 to take into account look-elsewhere effect
- Significance is reduced to 3.4σ after considering systematics

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

- $m_0 = 4096 \pm 20^{+18}_{-22}$ MeV and $\Gamma = 152 \pm 58^{+60}_{-35}$ MeV

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

arXiv:1809.07416

- The default fit has 4.3σ for $J^P = 1^-$ over 0^+
- Systematic uncertainty reduces to 1.2σ
  - Alternative $K^+\pi^-$ S-wave model (NR + κ + $K_0^*(1430)^0$)
- So $J^P = 1^-$ and 0^+ are both consistent with the data

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

- Fit fraction of $Z_c(4100)^-$ is $(3.3 \pm 1.1^{+1.2}_{-1.1})\%$

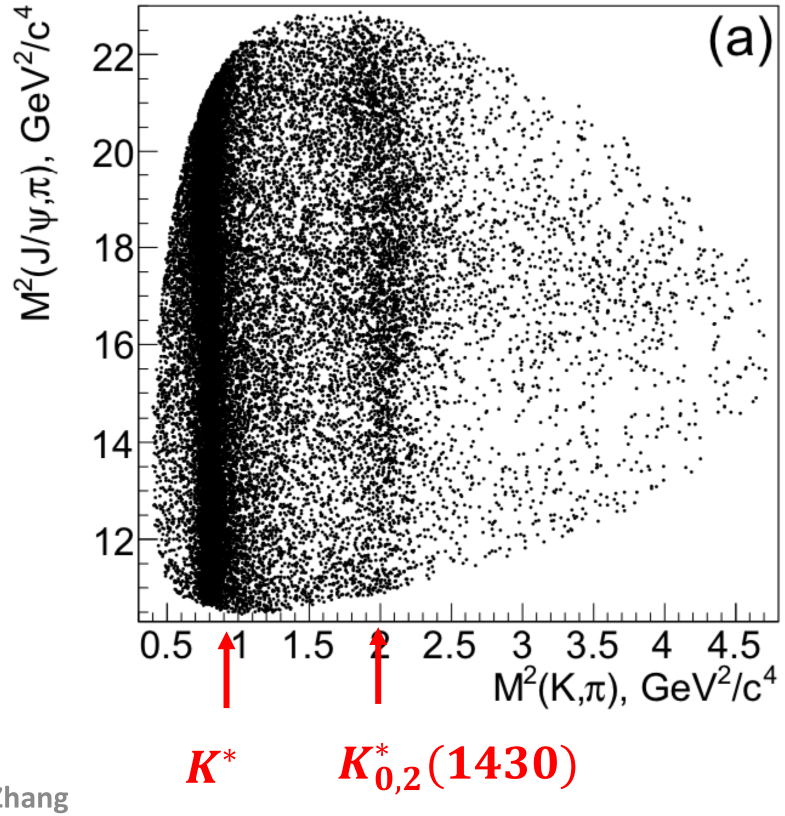
$$\mathcal{B}(B^0 \to Z_c(4100)^- K^+, Z_c(4100)^- \to \eta_c(1S)\pi^-) = (1.89 \pm 0.64^{+0.73}_{-0.67})\times 10^{-5}$$

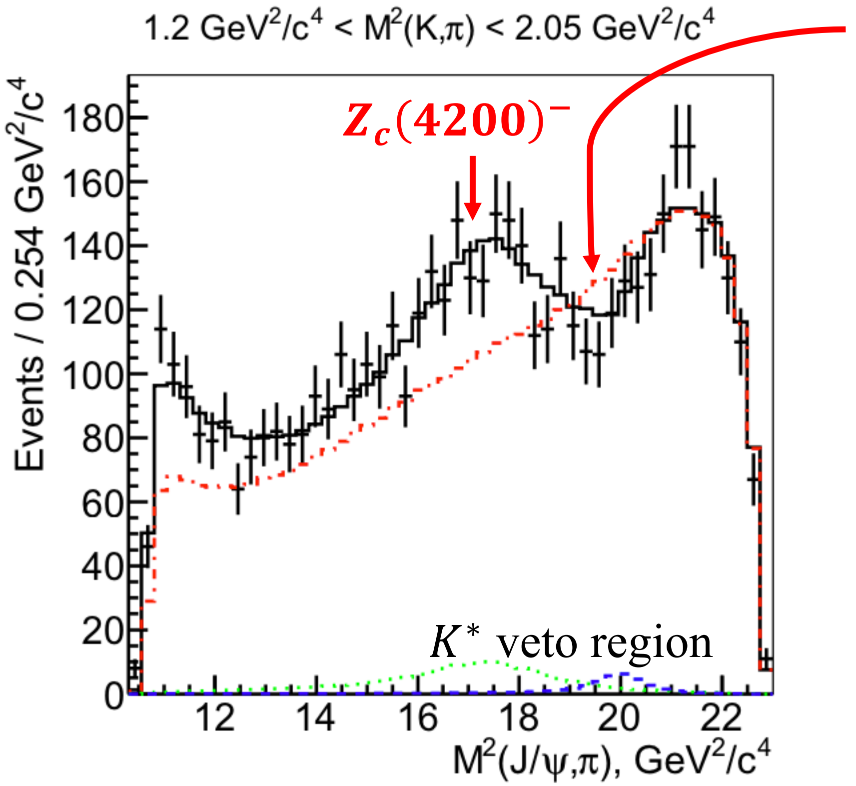
$$\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = (5.73 \pm 0.24 \pm 0.13 \pm 0.66)\times 10^{-4}$$

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

PRD 90, 112009 (2014)

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



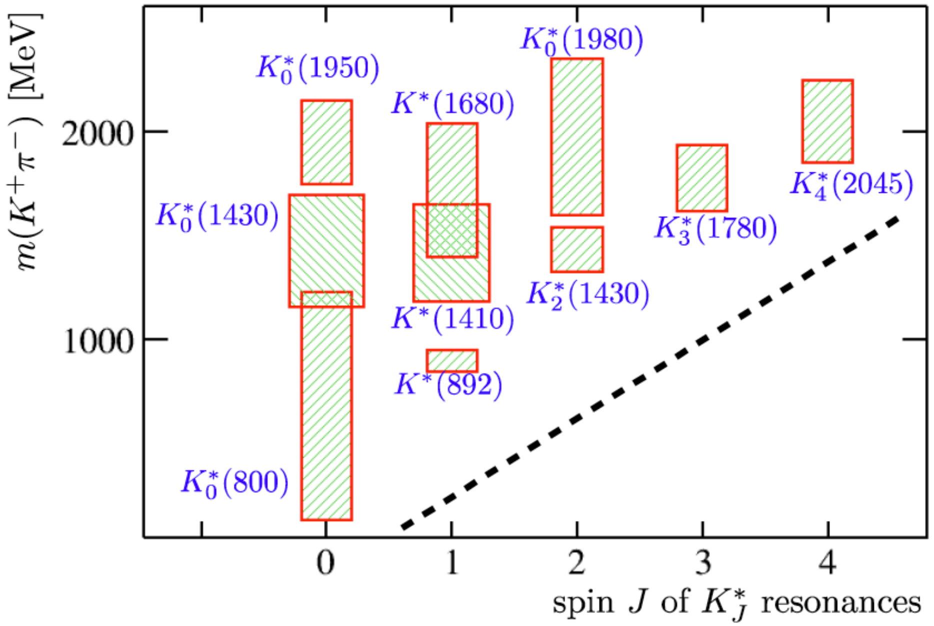


$Z_c(4430)^-$ **presented via destructive interference**

Model-independent confirmation from LHCb

- Run-1 data, x20 Belle signal yield

$m_{K\pi} \in [745, 1545]$ MeV: yield is 554530 ± 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:

$$J_{\max} = \begin{cases} 2, & m_{K\pi} \in [1085, 1265]\ \text{MeV} \\ 3, & m_{K\pi} \in [1265, 1445]\ \text{MeV} \end{cases}$$

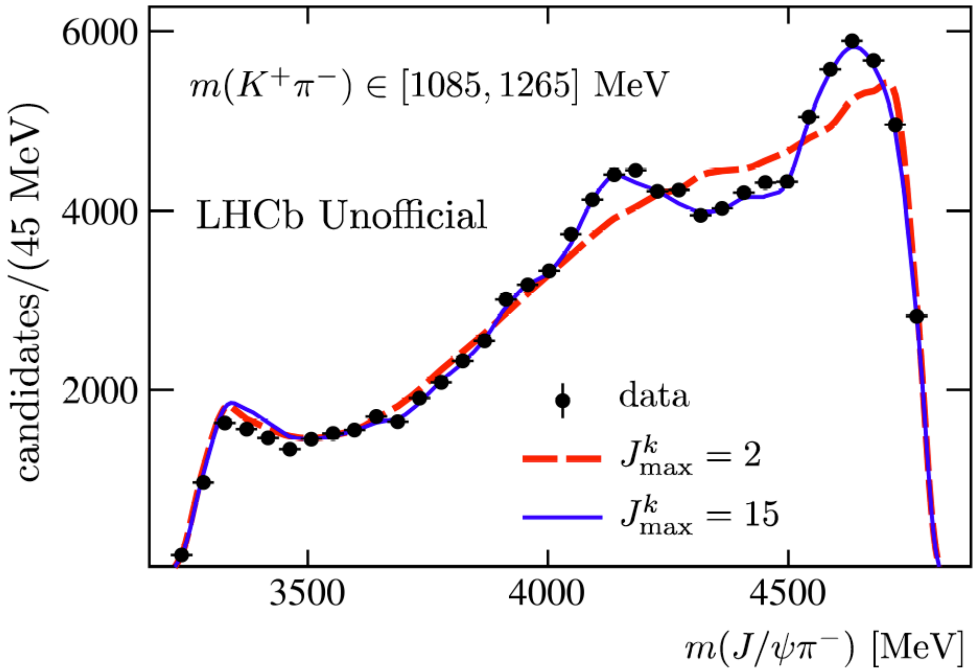
- Exotics in $[J/\psi\,\pi^-]$ or $[J/\psi\,K^+]$: $J_{\max} \to \infty$. Take $J^k_{\max} = 15$ as proxy.

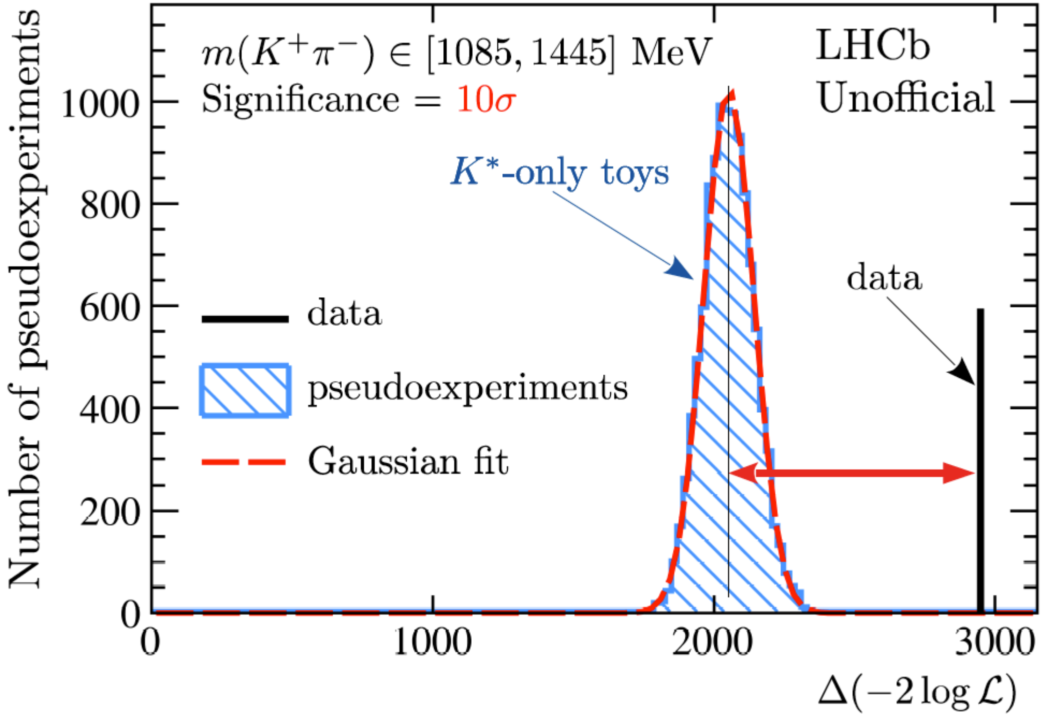
LHCb-PAPER-2018-043, presented at Implication Workshop https://indico.cern.ch/event/743635/timetable/

Model-independent confirmation from LHCb

- Used novel "3D" angular moments to boost sensitivity
- K^* only contributions ruled out by 10σ

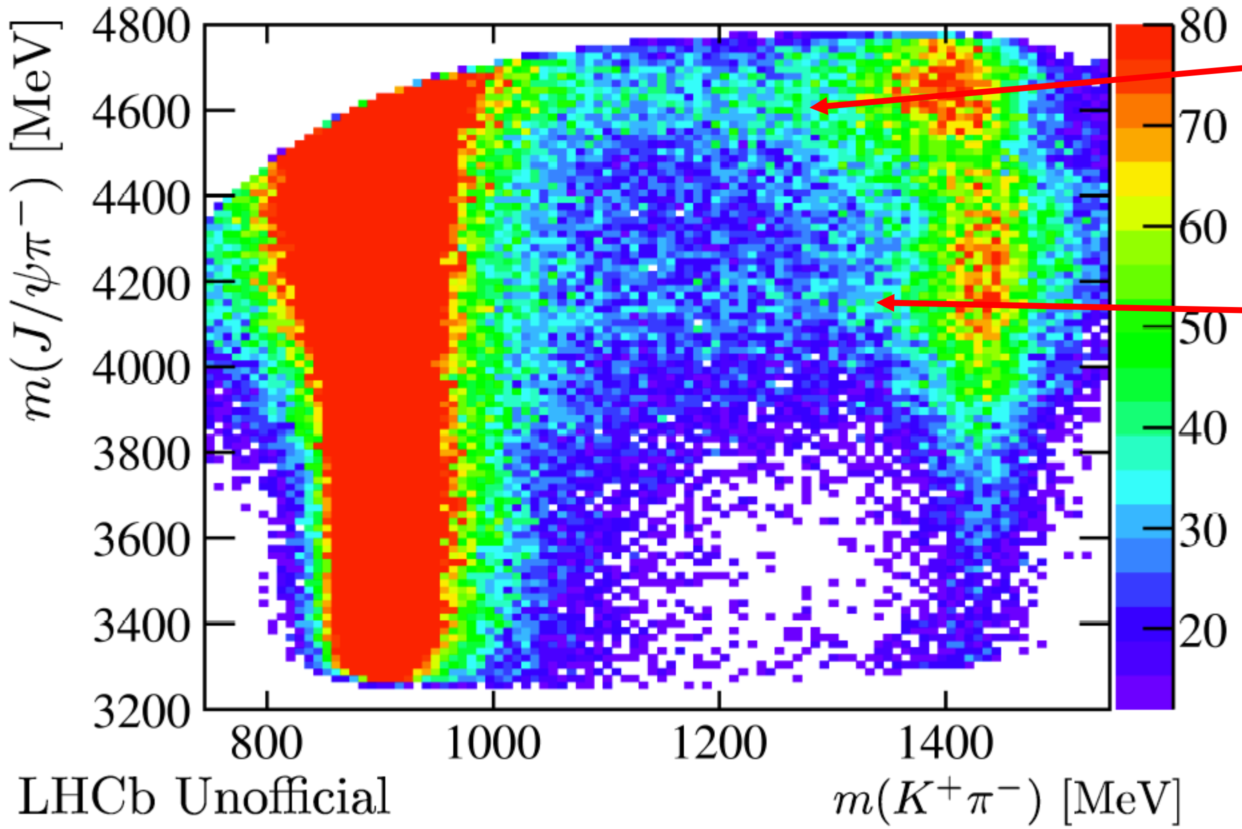
In each $m_{K\pi}$ bin: K^*-only model pdf doesn't describe data.





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

Exotic interpretation



A new structure at 4600 MeV?

Amplitude analysis planed to check

- Indications of the $Z(4200)^-$ seen by Belle

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

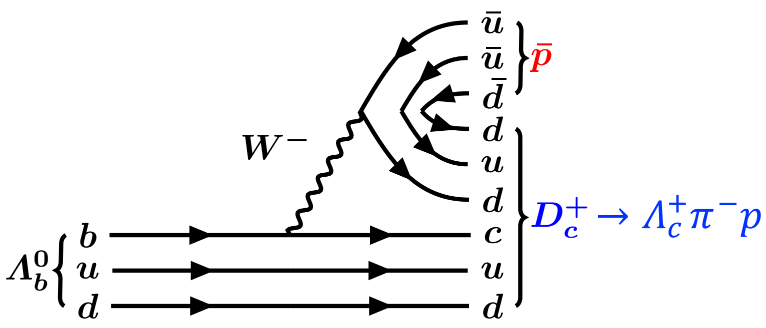
Search for dibaryon state

PLB 784 (2018) 101

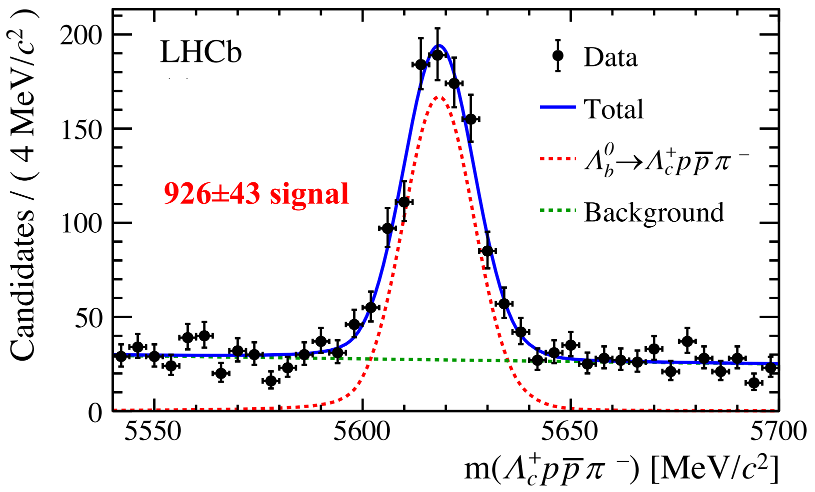
- A dibaryon state $[cd][ud][ud]$ could be produced in Λ_b^0 decays to final state $\Lambda_c^+\pi^- p\bar{p}$

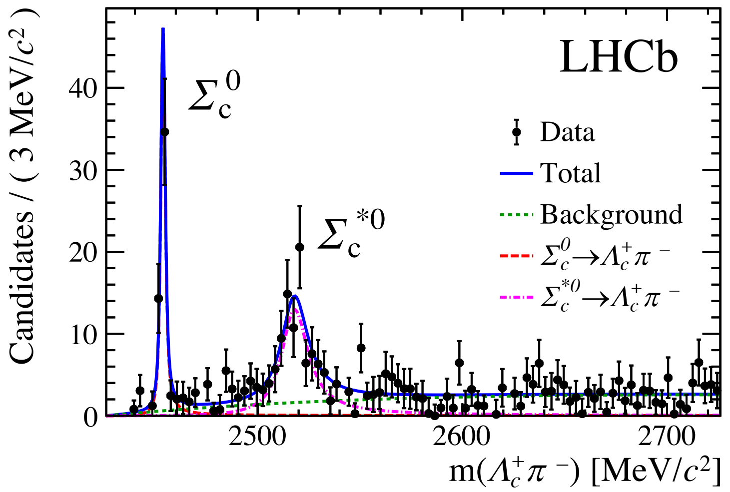
L. Maiani, et al. PLB 750 (2015) 37

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



Resonance contributions





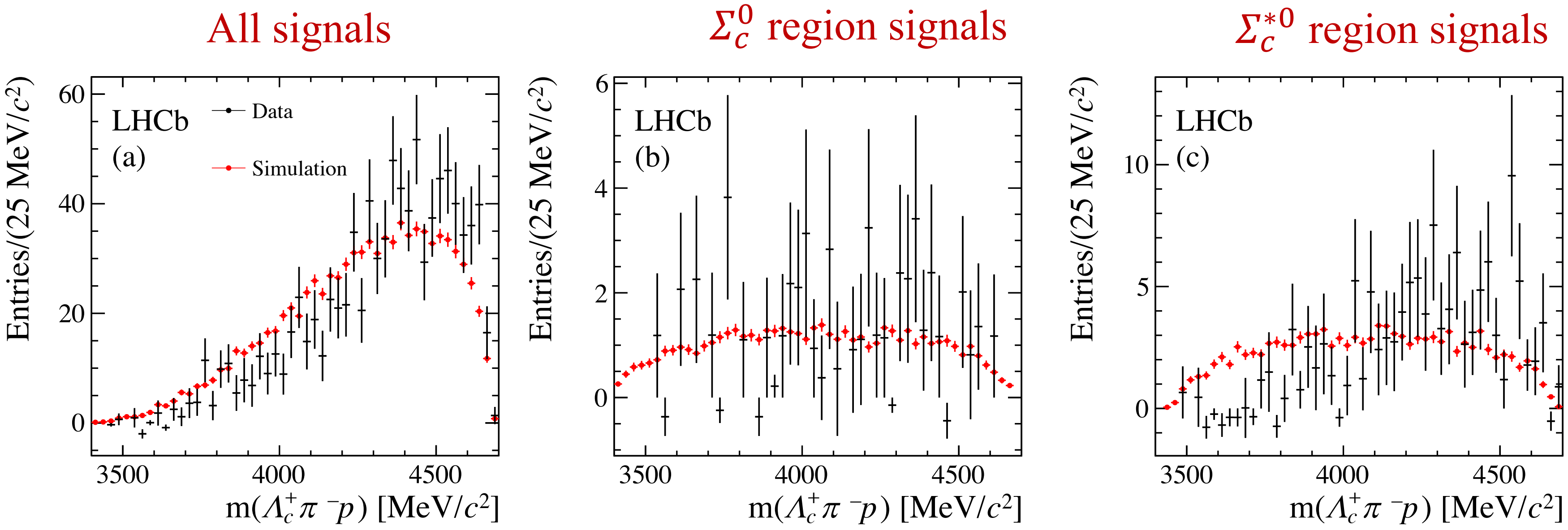
Search for dibaryon state

PLB 784 (2018) 101

- 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



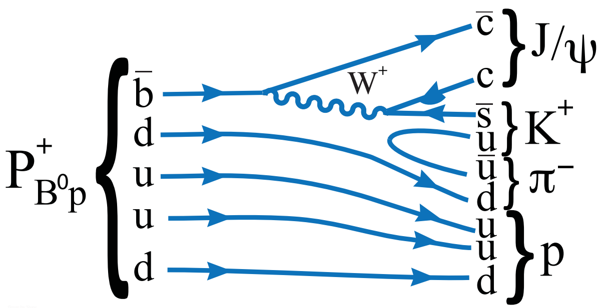
Weakly decaying *b*-flavoured pentaquarks

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	$\bar{b}suud$	$P^+_{B^0_s p} \to J/\psi \phi p$	5055–6305 MeV

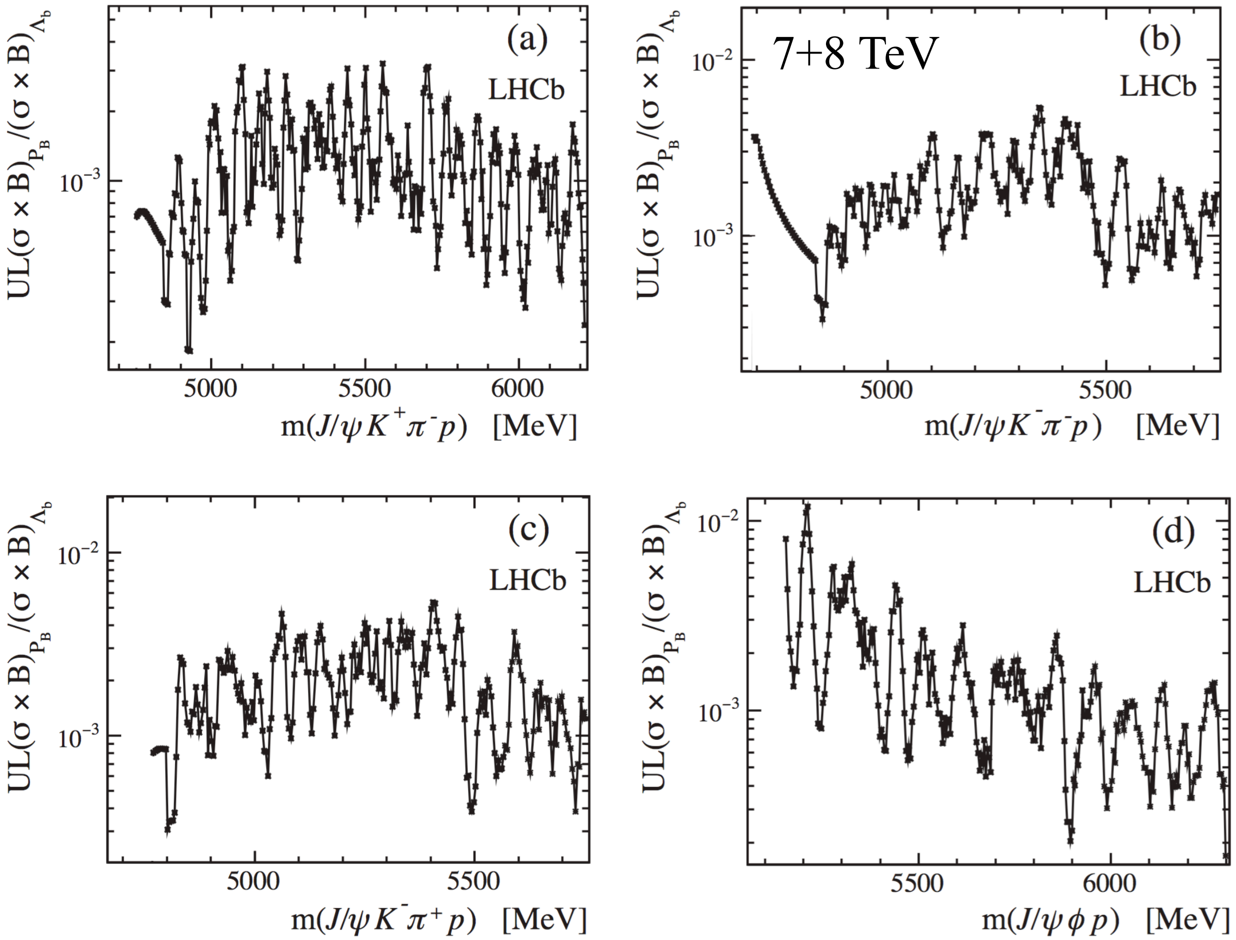
- Upper limit on production ratio $\sigma \cdot \mathcal{B}$ wrt $\Lambda_b^0 \to J/\psi K^- p$

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

Weakly decaying *b*-flavoured pentaquarks

PRD 97 (2018) 032010

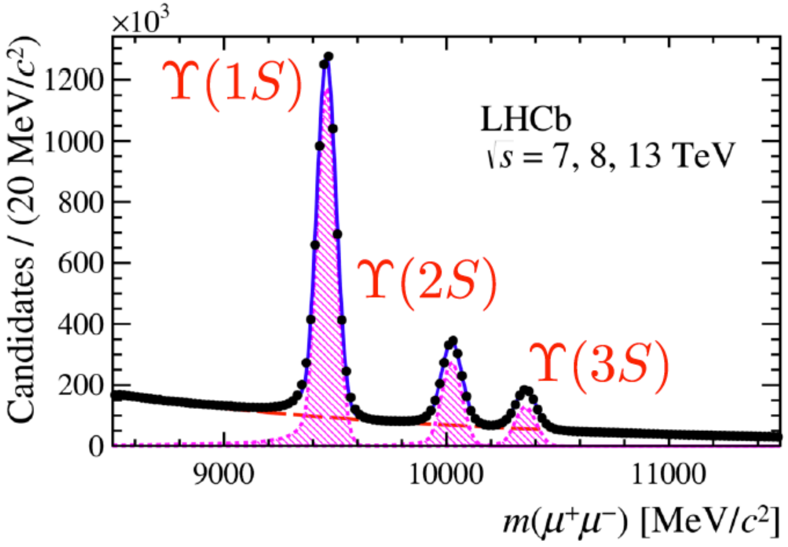
- No evidence for signal, 90% CL limits on $R < 10^{-2} - 10^{-3}$

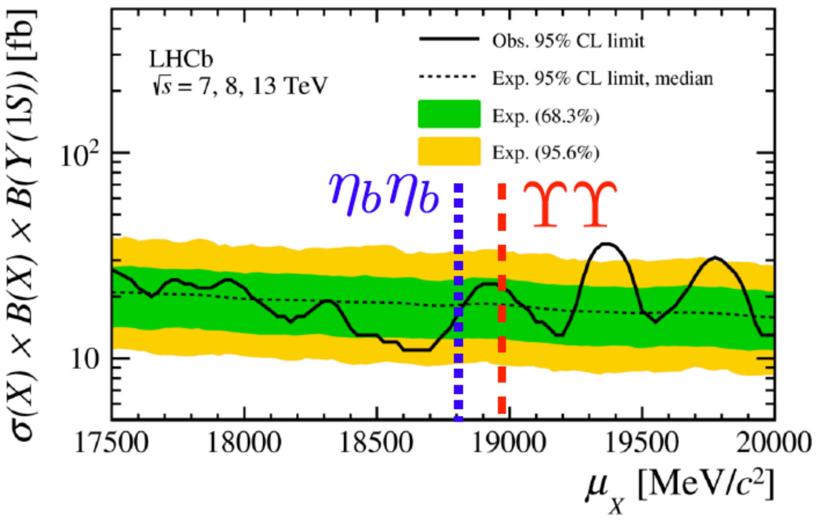


Search for $X_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$

JHEP 10 (2018) 086

- Binding of double-heavy $b\bar{b}$ pairs quite different to $c\bar{c}$+light meson cloud
- Ground state bound $b\bar{b}b\bar{b}$ 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.

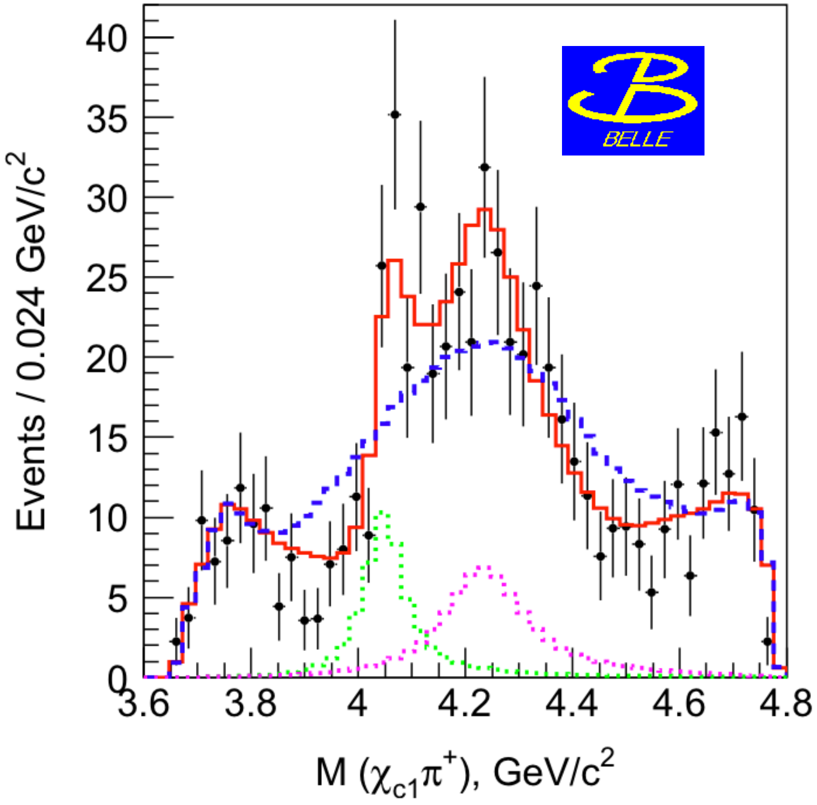




Ongoing LHCb analyses for exotics

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

2126 signal events



Belle, PRD 78, 072004 (2008)

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

PRL 121 (2018) 072002

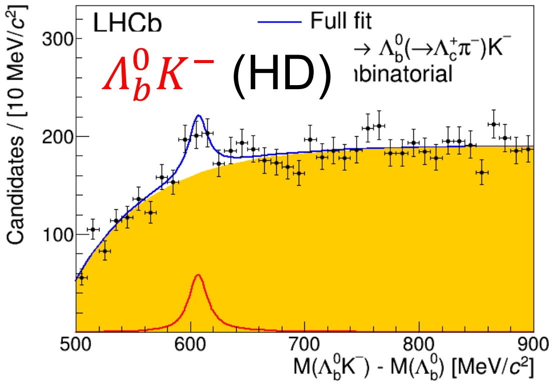
- Reconstruct $\Xi_b^- \to \Lambda_b^0 K^-$ and $\Xi_b^0 \pi^+$
  - Hadronic (HD) and Semileptonic (SL) decays for Λ_b^0
  - SL decays for $\Xi_b^0 \to \Xi_c^+ \mu^- X \bar{\nu}_\mu$
- With hadronic mode

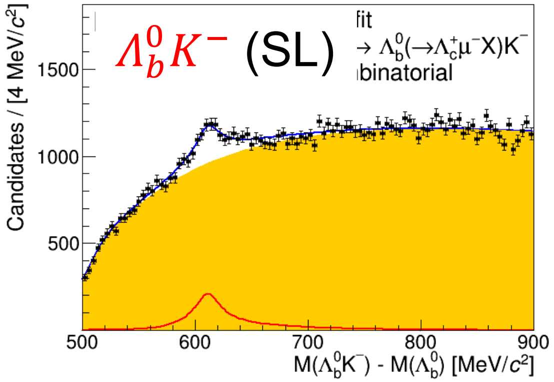
$$M(\Xi_b^{**-}) - M(\Lambda_b^0) = 607.3 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst})\ \text{MeV}/c^2,$$
$$\Gamma = 18.1 \pm 5.4\,(\text{stat}) \pm 1.8\,(\text{syst})\ \text{MeV}/c^2,$$
$$M(\Xi_b^{**-}) = 6226.9 \pm 2.0\,(\text{stat}) \pm 0.3\,(\text{syst}) \pm 0.2(\Lambda_b^0)\ \text{MeV}/c^2,$$

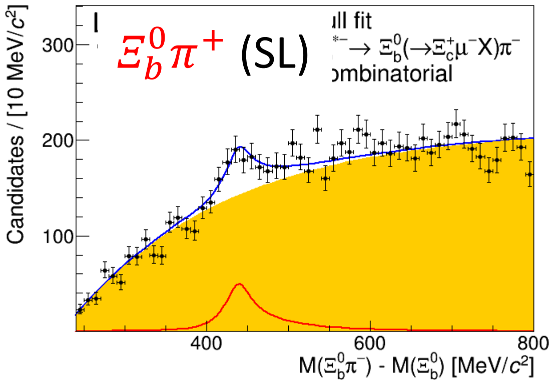
Mass peak position is consistent between the three decay channels

- Production ratios are measured with SL modes

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







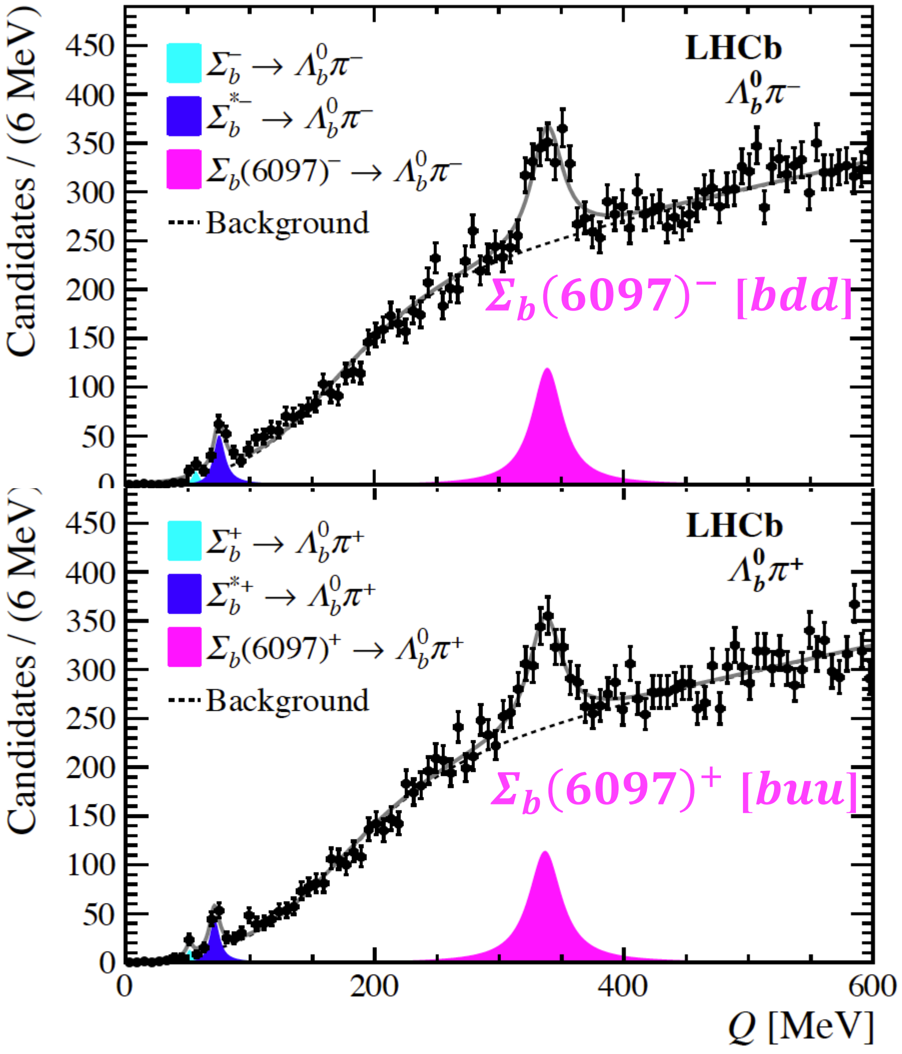
Σ_b spectroscopy: Observation of $\Sigma_b(6097)^{\pm}$

- $\Lambda_b^0 \to \Lambda_c^+ \pi^-$ combined with $\pi^\pm$ from PV
- $p_T(\pi^\pm) > 1$ GeV to suppress backgrd
- 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]
$m(\Sigma_b(6097)^-)$	$6098.0 \pm 1.7 \pm 0.5$
$m(\Sigma_b(6097)^+)$	$6095.8 \pm 1.7 \pm 0.4$
$\Gamma(\Sigma_b(6097)^-)$	$28.9 \pm 4.2 \pm 0.9$
$\Gamma(\Sigma_b(6097)^+)$	$31.0 \pm 5.5 \pm 0.7$

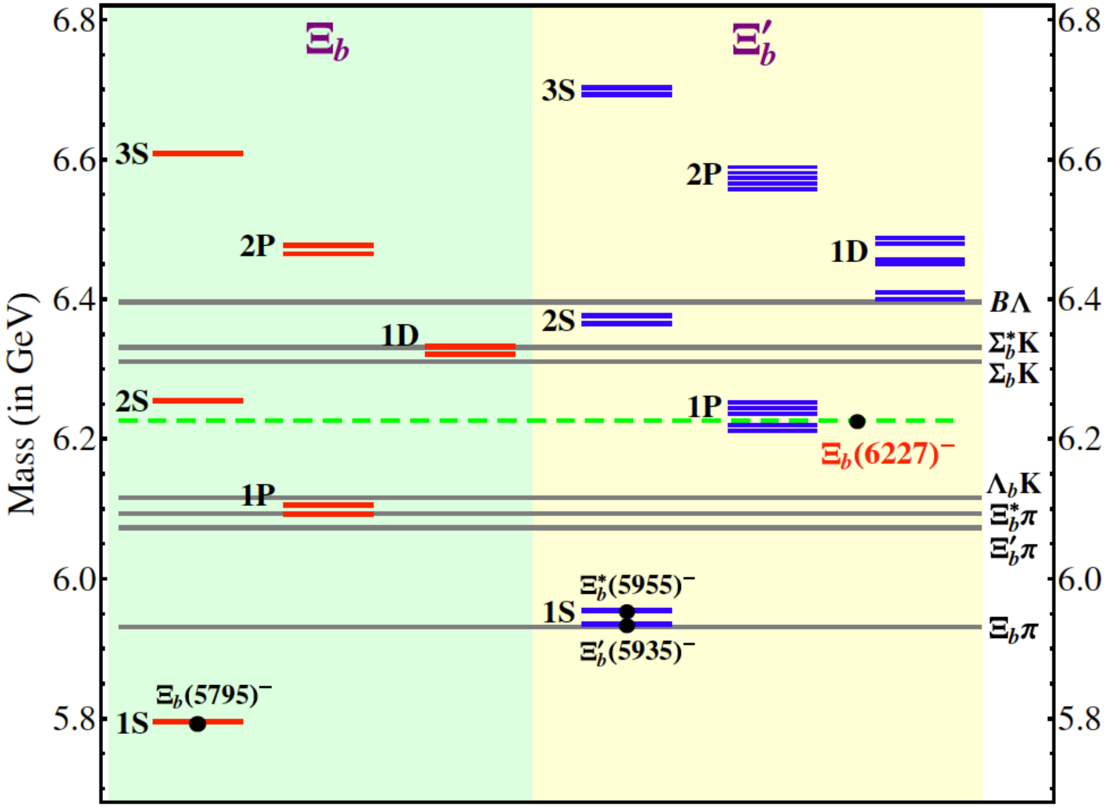
$\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ parameters are measured,
5x more precise than the previous CDF values

Arxiv:1809.07752

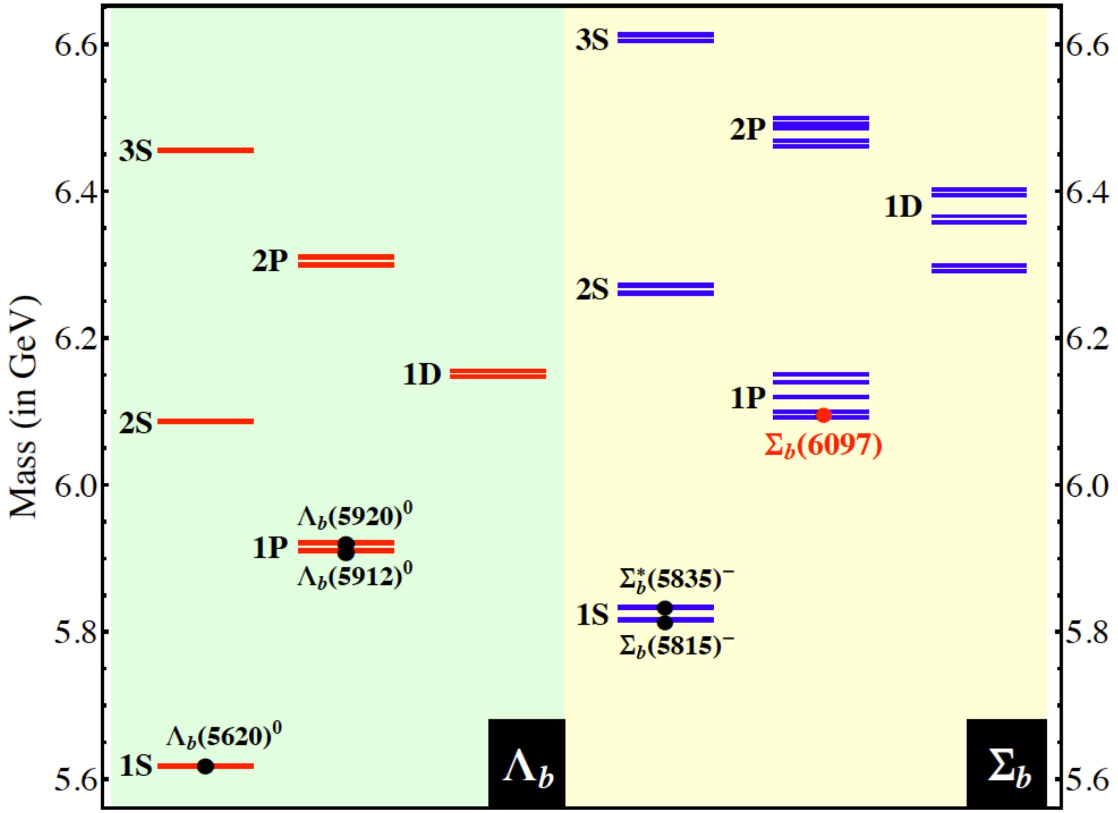


Theoretical explanations

- $\Xi_b^{**}(6227)^-$ 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



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



Bing Chen, Xiang Liu arxiv:1810.00389

Summary

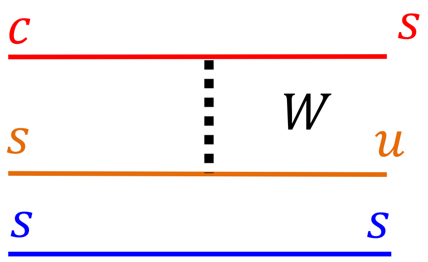
- LHCb has made important contributions to the knowledge of hadron spectroscopy
  - Evidence for $\boldsymbol{Z_c(4100)^- \to \eta_c\pi^-}$, $J^P = 1^-$ or 0^+
  - Model-independent confirmation of Z_c^- in $B^0 \to J/\psi K^+\pi^-$
  - Observations of $\boldsymbol{\Xi_b(6227)^-}$ and $\boldsymbol{\Sigma_b(6097)^\pm}$
- Stay tuned with new results from RUNI+RUNII
- LHCb data-taken plan:
  - Upgrade most all detectors (2019-2020)
  - Plan to take **50 fb^{-1}** data (2021-2030)

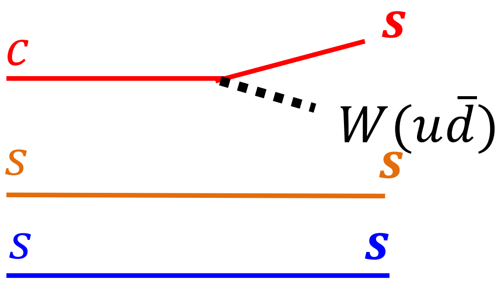
LHC时代		高亮度LHC时代		
一期 (2010-12)	二期 (2015-18)	三期 (2021-24)	四期 (2027-30)	五期以上 (2031+)
3 fb^{-1}	**9 fb^{-1}**	**23 fb^{-1}**	**50 fb^{-1}**	**>300 fb^{-1}**

Backup

Measurement of the lifetime of Ω_c^0

- Test theoretical approaches, e.g. Heavy Quark Expansion (HQET)
  - Higher order effects are important: expansion in powers of $1/m_Q$
  - *c*-hadrons: sizable high-order corrections
  - *c*-baryon decays: *W*-exchange and Pauli interference [Nucl. Phys. B**248** (1984) 261] larger than in *c*-meson decays

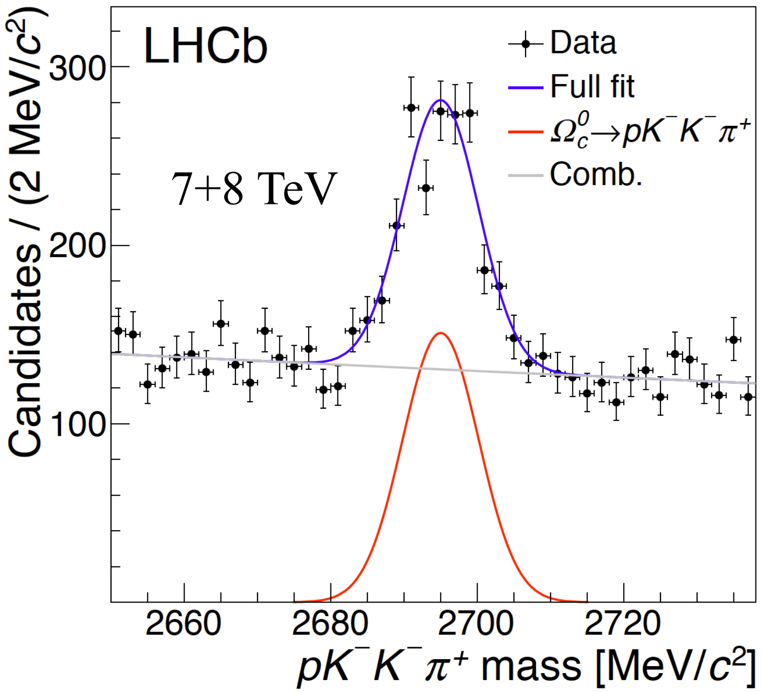




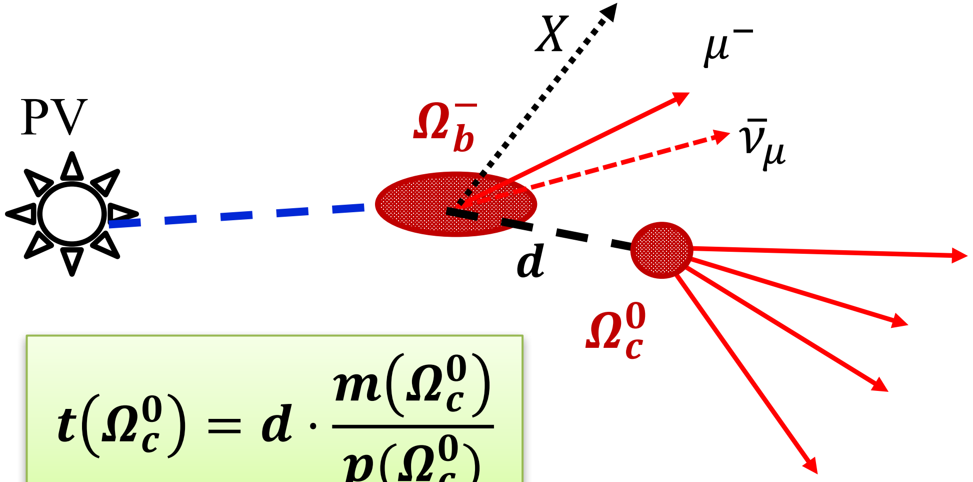
- *c*-baryon lifetimes are not well measured, in particular uncertainty for Ω_c^0 is 17%

Signal and control channels

PRL 121 (2018) 092003



- 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: $B \to D^+(\to K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$



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

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

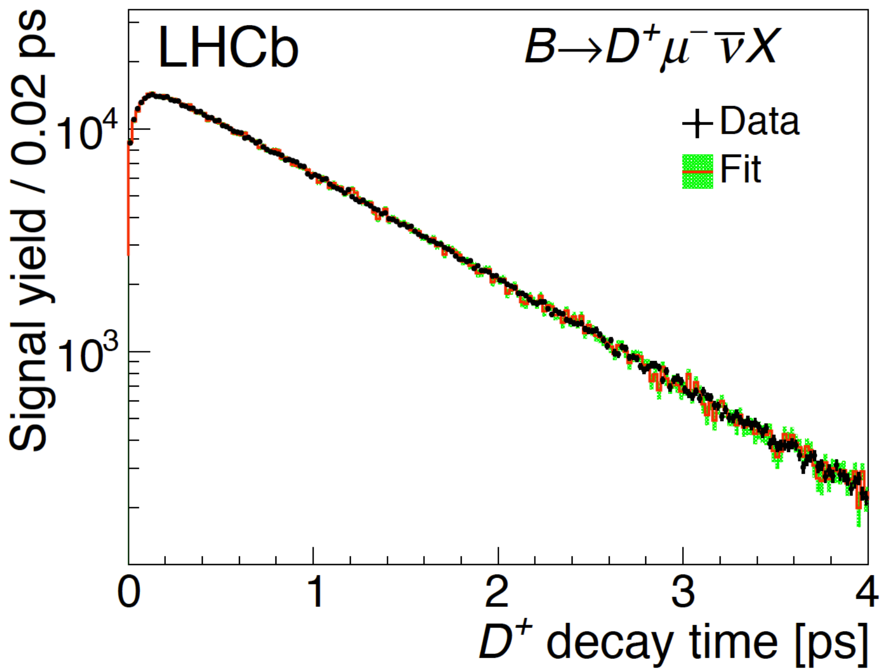
PRL 121 (2018) 092003

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

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

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 $\beta(t_{\mathrm{rec}})$ 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

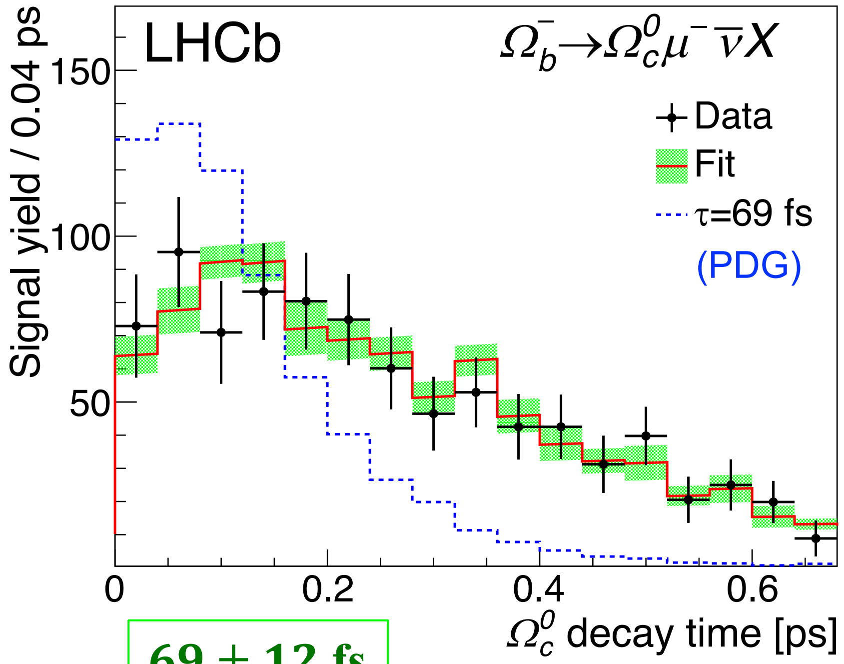
- Simultaneous fit signal and control samples

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

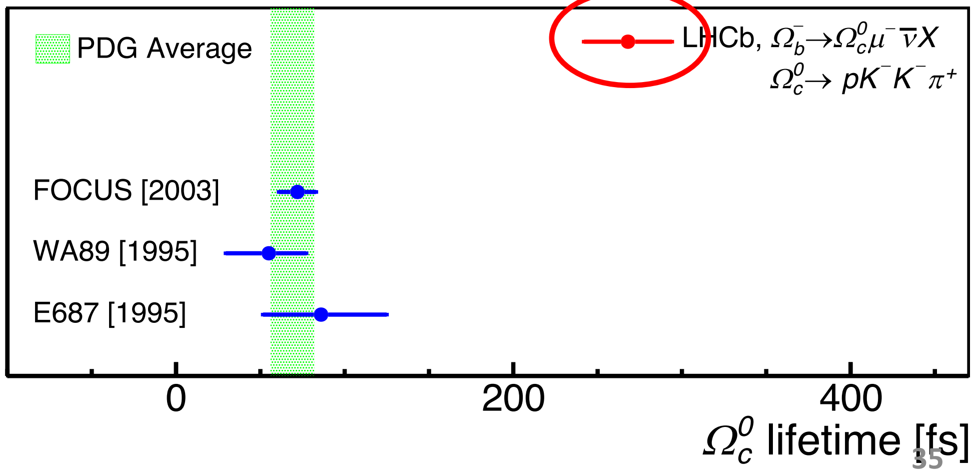
$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2\ (\tau_{D^+})\ \text{fs}$$

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 $D^0 \to K3\pi$ lifetime measurement



69 ± 12 fs



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

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

PRD 92 (2015) 071502

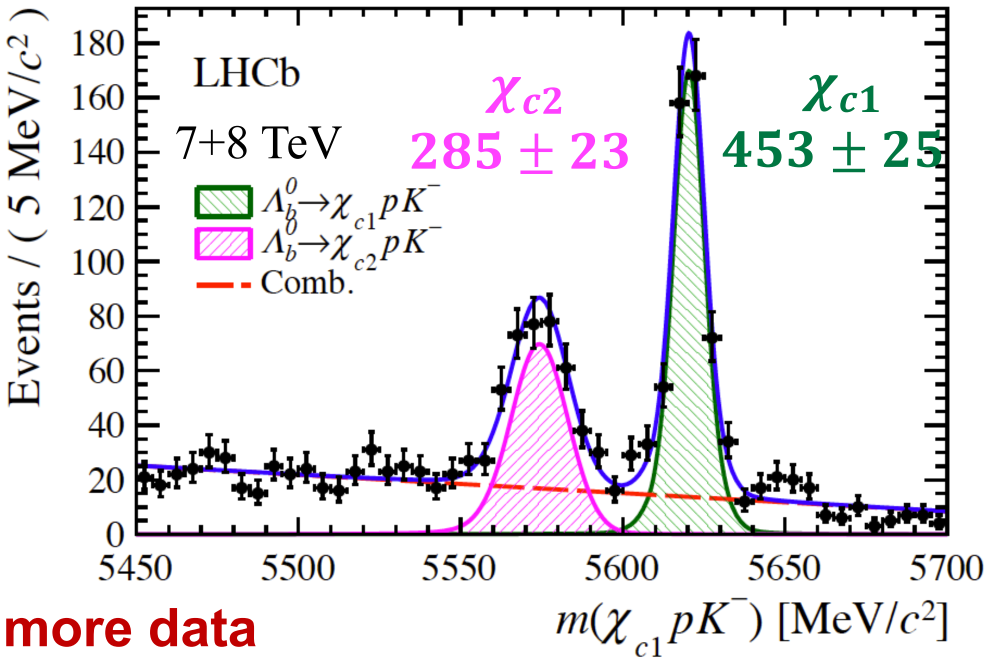
- First step: observe the decays, measure $\mathcal{B}$
- Use $\chi_{c(1,2)} \to J/\psi\gamma$, constrain $J/\psi\gamma$ mass to known χ_{c1} mass

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

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

PRL 119 (2017) 062001

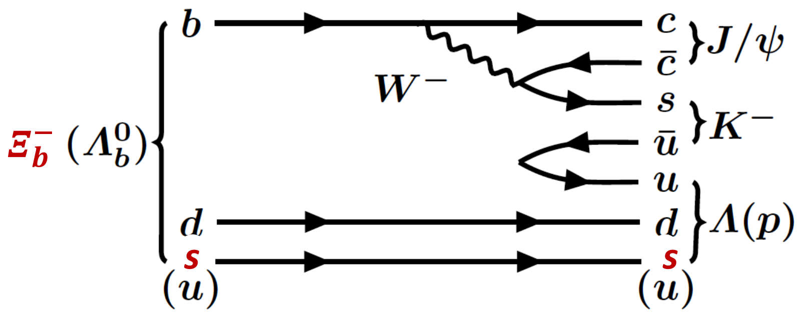


Next step: full amplitude analysis with more data

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

PLB 772 (2017) 265-273

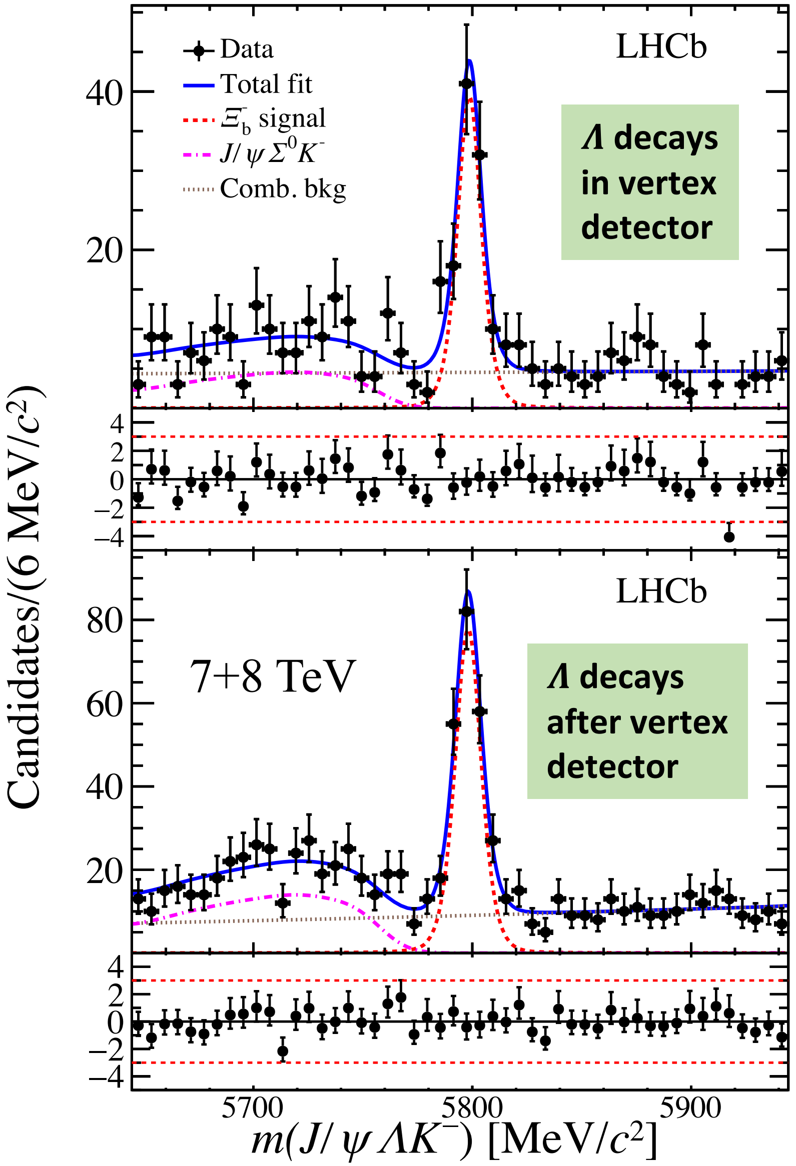
- Strange pentaquark ($uds c\bar{c}$) predicted in [PRL 105 (2010) 232001]
- Can be searched for in the Ξ_b^- decay [PRC 93 (2016) 065203]



$N_{sig} = 308 \pm 21$ (21σ)

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

Expect ~1500 signals after 2018 for amplitude analysis

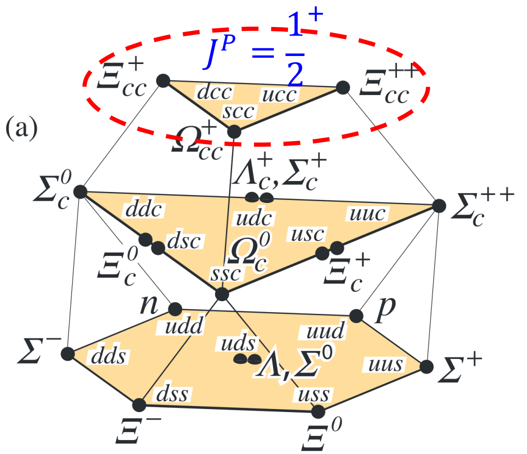


Physics program at LHCb

- Not only precision measurements in b, c sectors
  - CKM and *CP*-violation parameters
  - Rare decays
  - Testing lepton universality
  - …
- But also a general purpose detector
  - Electroweak measurments: $\sin\theta_W$, W/Z, top quark
  - Spectroscopy, exotic hadrons
  - Soft QCD
  - Heavy ions
  - …

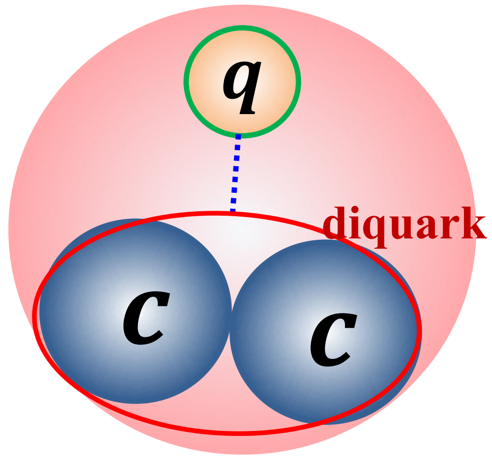
Doubly charmed baryons: motivation

- Doubly charmed baryons are not observed or established



- Doubly heavy baryons' mass and decay width to test QCD motivated models

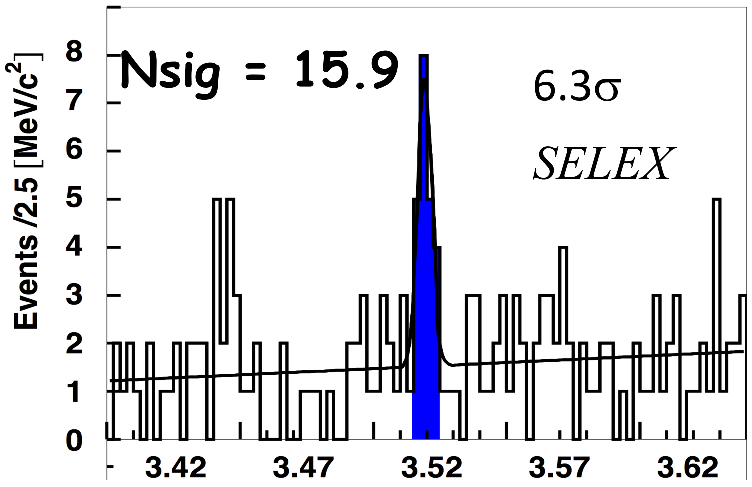
- Baryons with two heavy quarks probe the QCD potential in a different way than baryons with a single heavy quark [hep-ph/9811212]
  - **HQET: two charm quarks considered as a heavy diquark, doubly heavy baryon similar to a heavy meson $\bar{Q}q$**
  - **Such diquark can naturally extend to $\bar{Q}\bar{q}\bar{q} = cc\bar{q}\bar{q}$ exotic system**



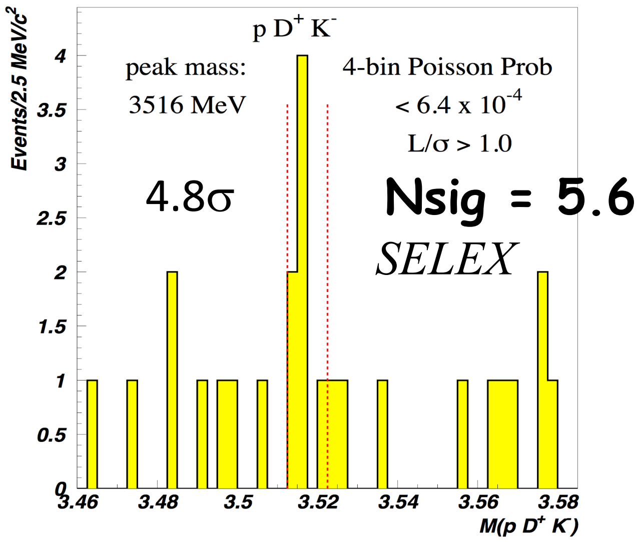
SELEX results on Ξ_{cc}^{+}

- Observation of $\Xi_{cc}^{+}(ccd)$ reported by SELEX
  - Mass: 3518.7 ± 1.7 MeV
  - Short lifetime: $\tau(\Xi_{cc}^{+}) < 33$ fs @90% CL, but not zero
  - Large production: $R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})}{\sigma(\Lambda_c^{+})} \sim 20\%$
- Not confirmed by Babar [PRD 74 (2006) 011103], Belle [PRL 97(2006) 162001] nor LHCb [JHEP 12 (2013) 090]

$\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ PRL 89 (2002) 112001



$\Xi_{cc}^{+} \to p D^{+} \pi^{-}$ PLB 628 (2005) 18

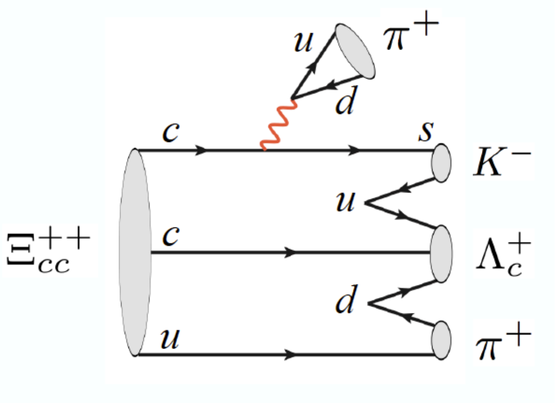


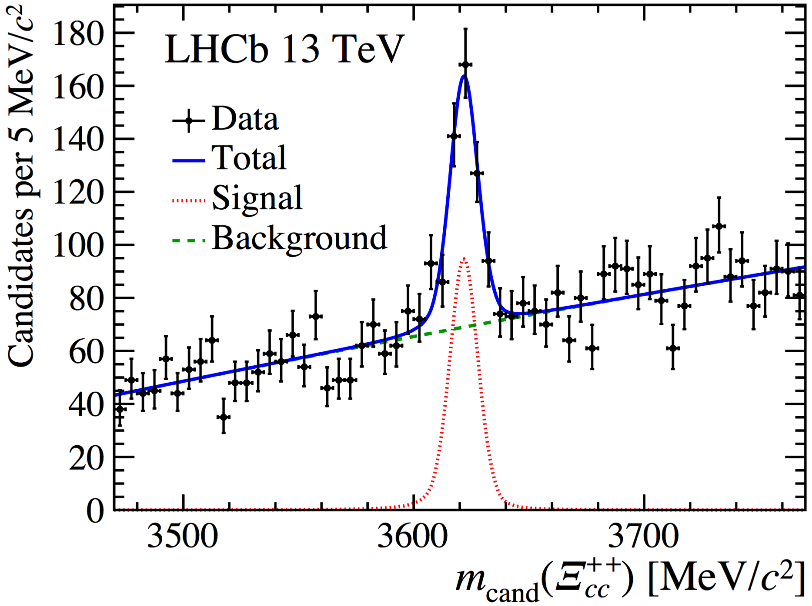
Observation of Ξ_{cc}^{++} at LHCb

PRL 119 (2017) 112001

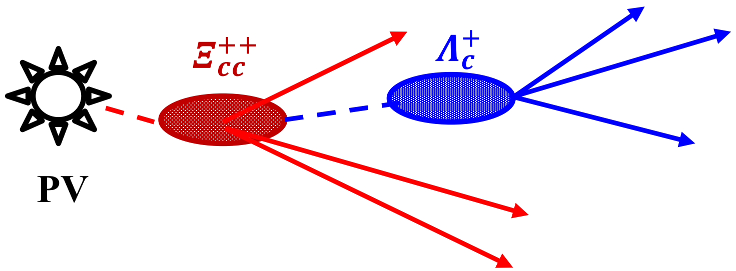
- Expected to have longer lifetime than Ξ_{cc}^{+}, higher sensitivity at LHCb
- Decay: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\mathcal{B}$ could be as large as 10% [Yu et al., arXiv:1703.09086, Chinese Phys. C **42** (2018) 051001]
- LHCb run II at $\sqrt{s} = 13$ TeV, ~1.7 fb^{-1}
  - 313 ± 33 events, 12σ
  - 8 TeV data analyzed for cross-check, 7σ

$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14(\Lambda_c^+)\ \mathrm{MeV}/c^2$$





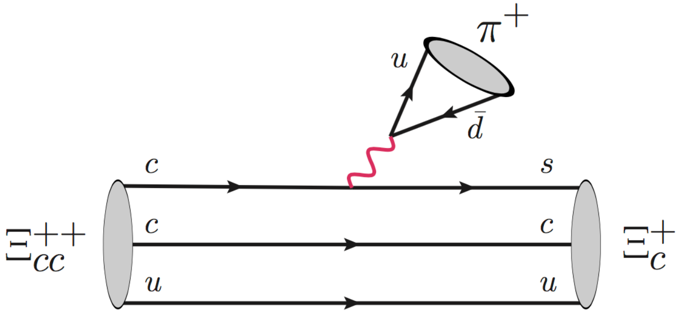
$$\Xi_{cc}^{++} \to K^- \pi^+ \pi^+ \Lambda_c^+ (\to p K^- \pi^+)$$



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

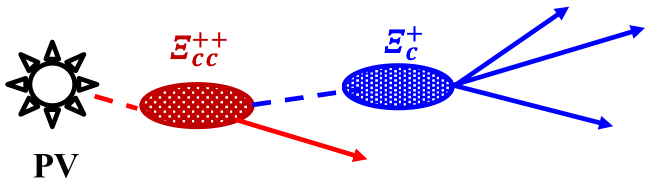
arXiv:1807.01919, submitted to PRL

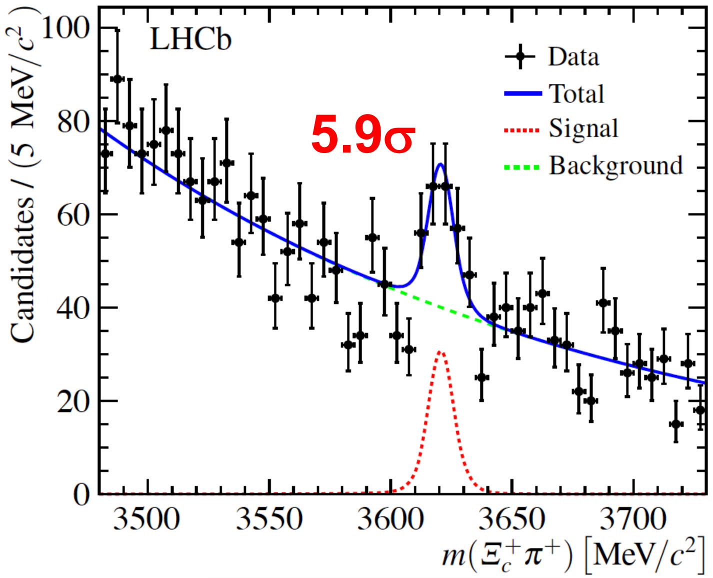
- Yu et al. also suggest to use $\Xi_c^+(\to pK^+\pi^-)\pi^+$ at LHCb
- LHCb run II, ~1.7 fb^{-1}
- Control mode:
  $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$
- Similar selections and triggers for signal and control modes
  - Good PID, high p_T, displacement
  - Multivariate selection



Signal mode

$\Xi_{cc}^{++} \to \pi^+ \Xi_c^+(\to pK^-\pi^+)$

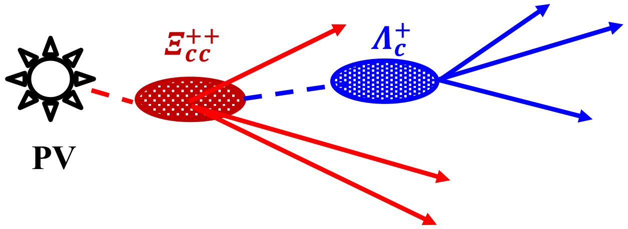


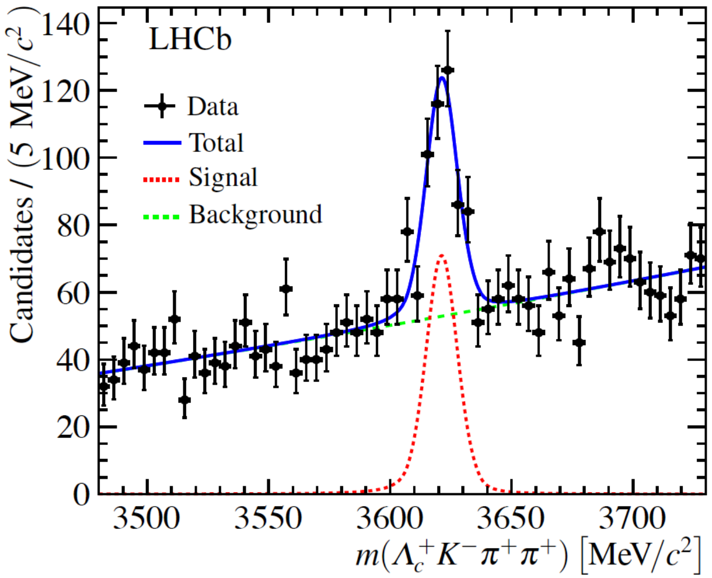


$N_{sig} = 91 \pm 20$

Control mode

$\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$





$N_{cont} = 298 \pm 35$

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

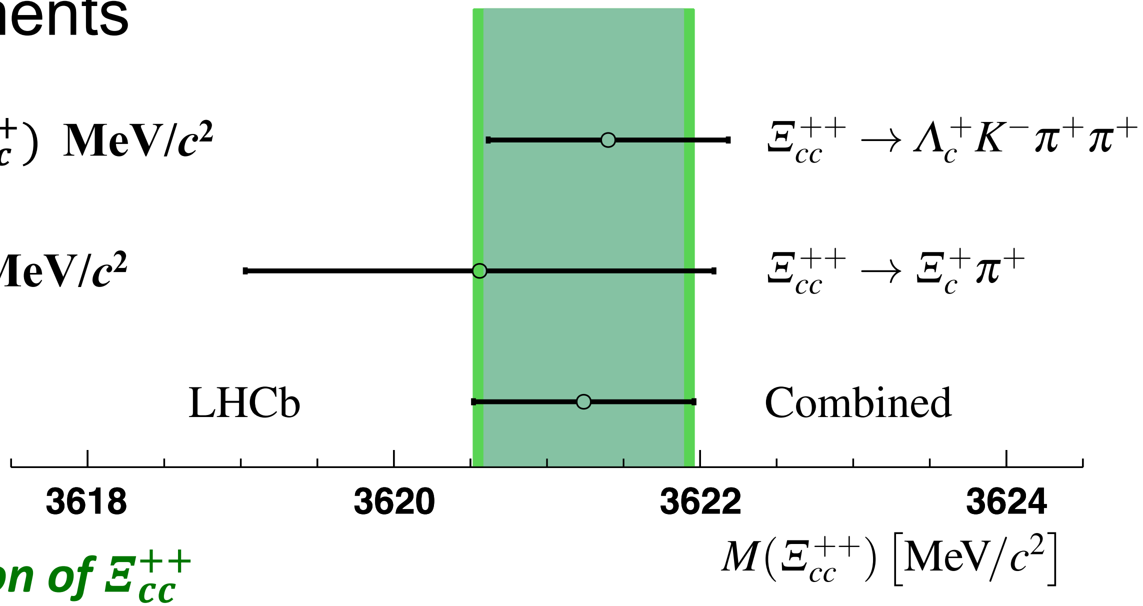
arXiv:1807.01919, submitted to PRL

- Consistent mass measurements

$\mathbf{3621.40 \pm 0.72 \pm 0.27 \pm 0.14(\Lambda_c^+)\ MeV/c^2}$

$\mathbf{3620.56 \pm 1.5 \pm 0.4 \pm 0.3(\Xi_c^+)\ MeV/c^2}$

$\mathbf{3621.24 \pm 0.65 \pm 0.31\ MeV/c^2}$



Confirm previous LHCb observation of Ξ_{cc}^{++}

- Ratio of branching fractions

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

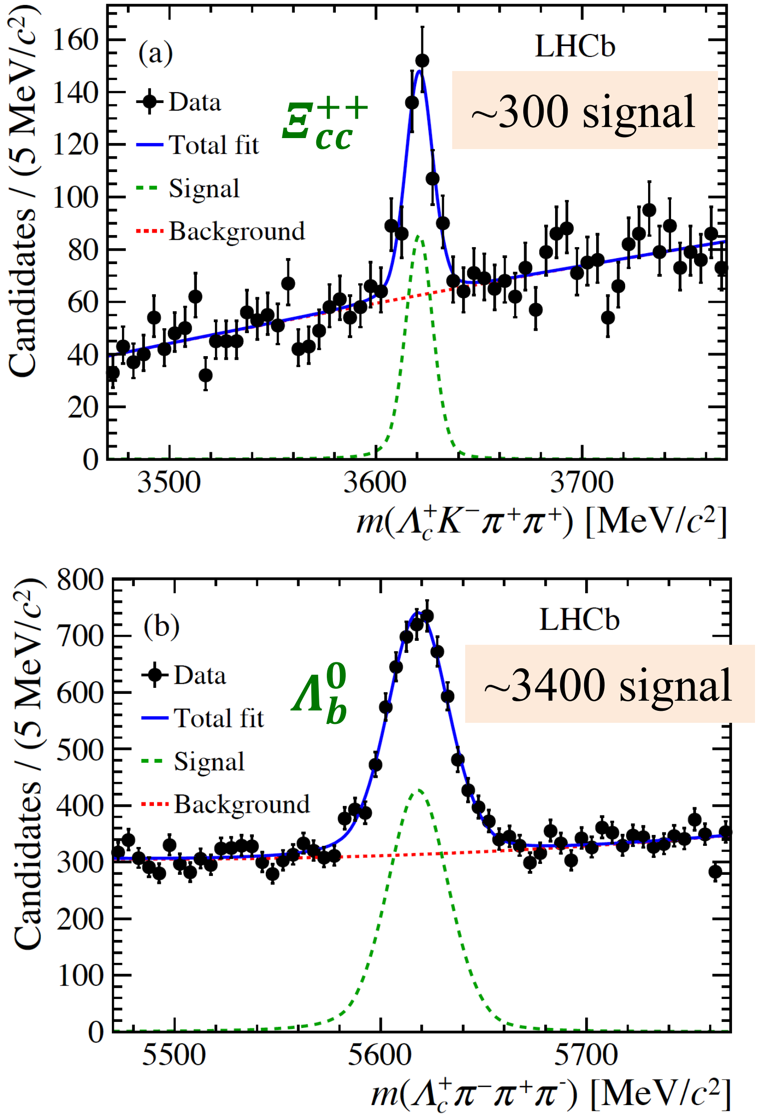
Consistent with prediction [Yu et al., arXiv:1703.09086, Chinese Phys. C **42** (2018) 051001]

Ξ_{cc}^{++} lifetime

arXiv:1806.02744, accepted by PRL

- A lifetime measurement is critical
  - Test whether it is weakly decaying J = ½ ground state
  - Necessary ingredient for theoretical prediction of $\mathcal{B}$
  - Important information for experimental exploration of other doubly-heavy baryons
  - Test various predictions of QCD models

- Analysis strategy
  - Same data sample, event selection as previous Ξ_{cc}^{++} observation
    - **Specific trigger requirement to simplify trigger efficiency determination**
  - Relative measurement to $\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$ decays



First measurement of Ξ_{cc}^{++} lifetime

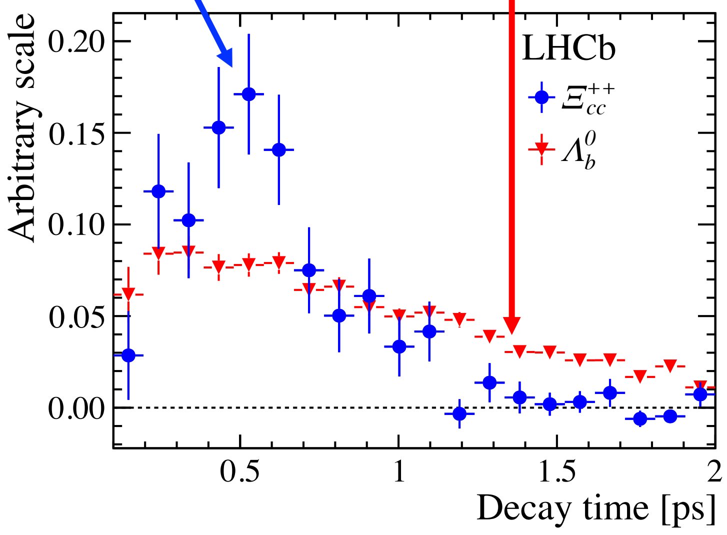
arXiv:1806.02744, accepted by PRL

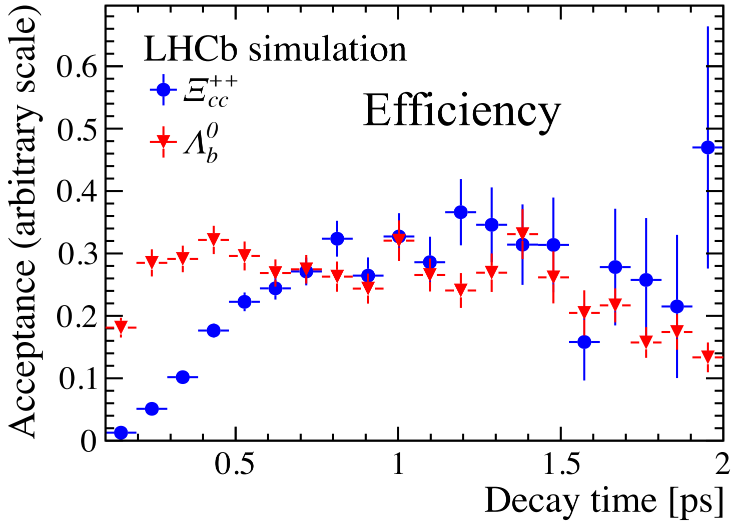
- Weighted unbinned maximum likelihood fit

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

$\tau_{\Lambda_b^0} = 1.470 \pm 0.010$ ps (PDG)

Free parameter





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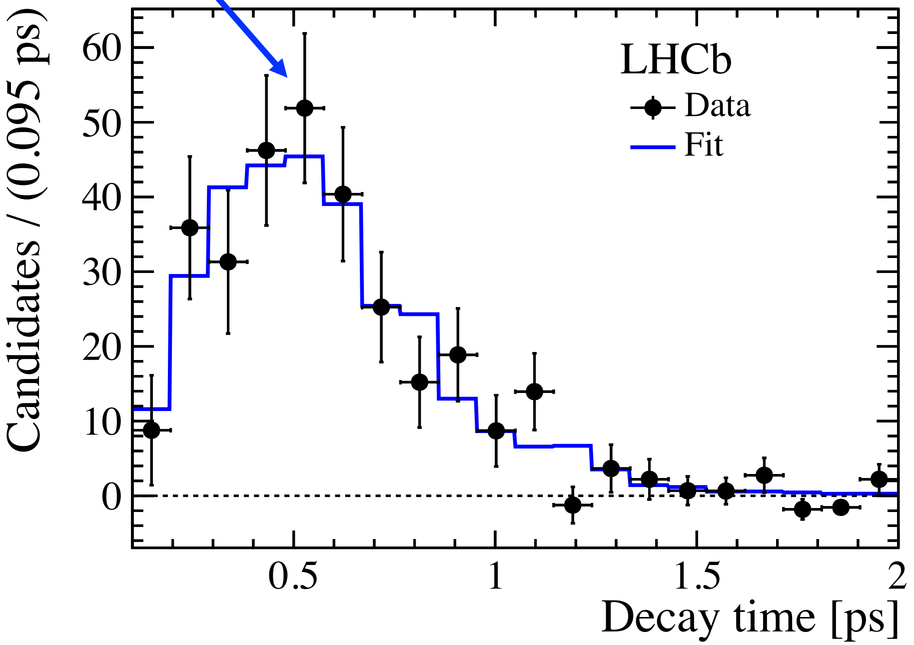
arXiv:1806.02744, accepted by PRL

- Weighted unbinned maximum likelihood fit

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



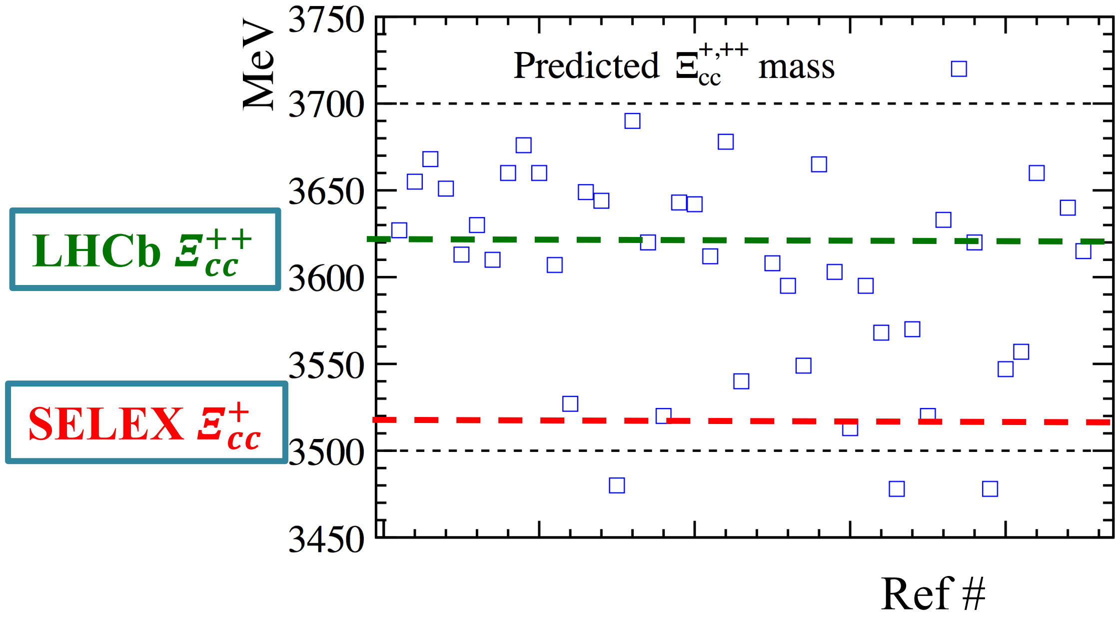
$$\tau_{\Xi_{cc}^{++}} = 256^{+24}_{-22} \pm 14 \text{ fs}$$

- ✓ Fit procedure is verified by toys
- ✓ Robust result against many checks

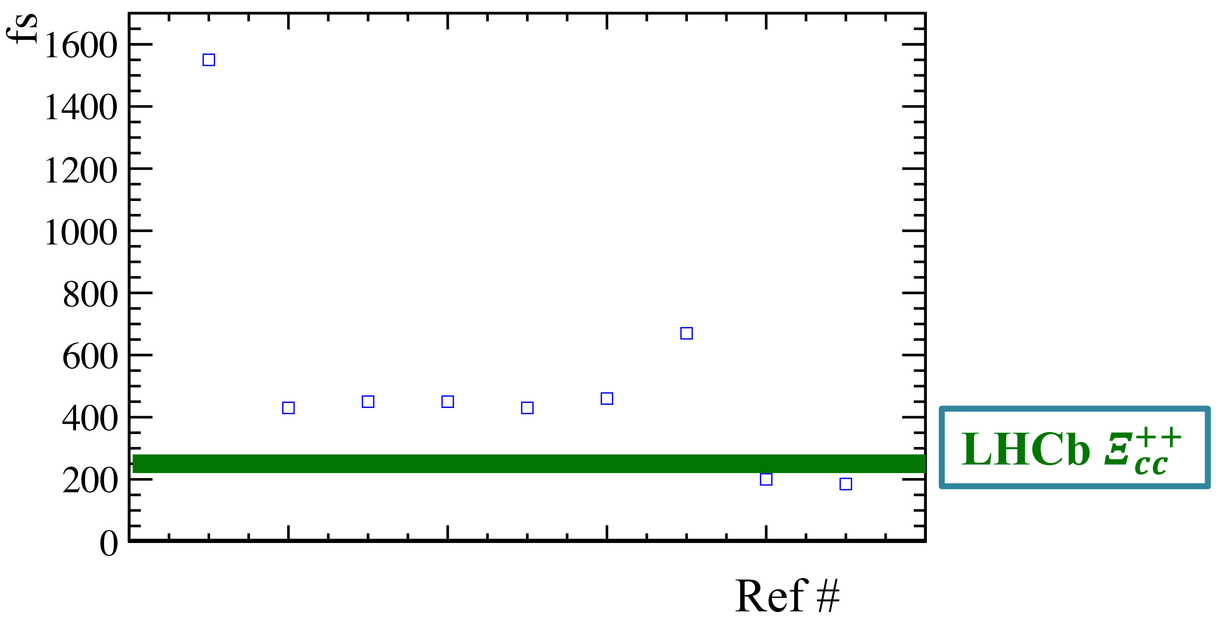
Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature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

Mass and lifetime predictions vs measurements

- Predicted $\Xi_{cc}^{+,++}$ masses in range 3.5 – 3.7 GeV
- Mass splitting between Ξ_{cc}^{+} and Ξ_{cc}^{++} only a few MeV due to u, d symmetry
- Expectation: $\tau(\Xi_{cc}^{++}) \simeq 4\times\tau(\Xi_{cc}^{+})$
- Calculations give $\tau(\Xi_{cc}^{++}) \in [\,200 - 1550]$ fs



Measured lifetime at low side of predictions



Exotic study with amplitude analyses at LHCb

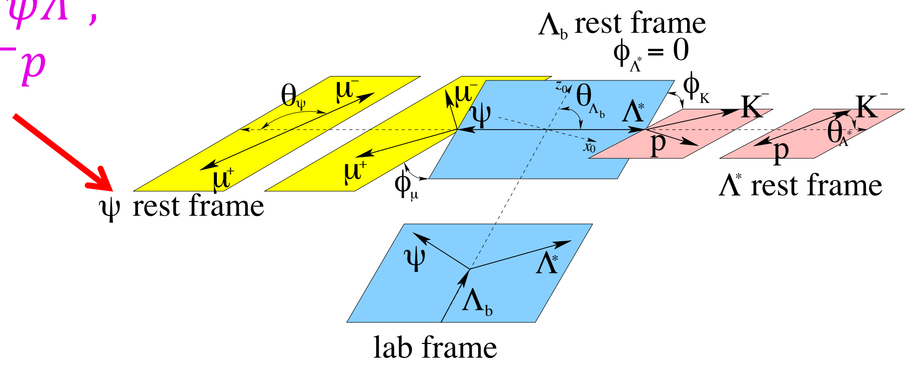
- Used Helicity formalism and isobar model
- Full amplitude fit uses all possible mass and angles to get maximum information for J^P of exotics
  - Different decay chains added coherently
  - Rotation angles introduced to align the helicity axes for non-scalar final state

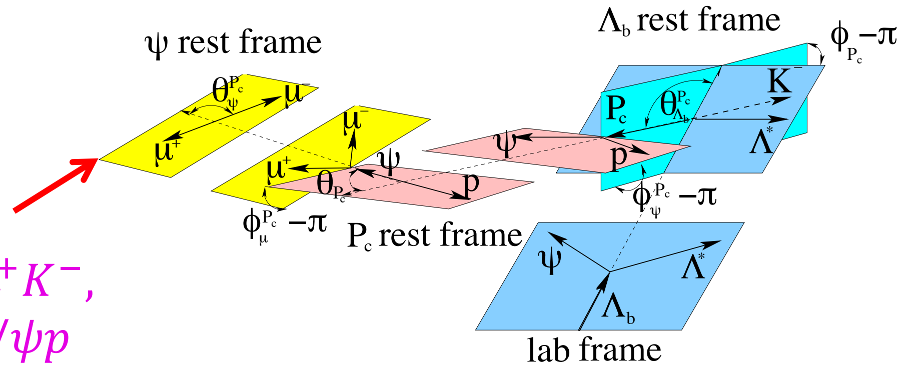
$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}} \sum_{\lambda_p} \sum_{\Delta\lambda_\mu} \left| \mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu} \right|^2$$

- Other formalism is also in the market [arXiv:1805.02113] to be explored

$\Lambda_b^0 \to J/\psi p K^-$ as an example

$\Lambda_b^0 \to J/\psi \Lambda^*$,
$\Lambda^* \to K^- p$





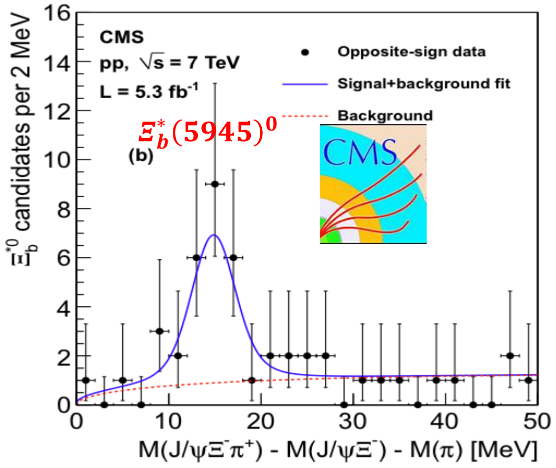
$\Lambda_b^0 \to P_c^+ K^-$,
$P_c^+ \to J/\psi p$

Ξ_b baryon spectroscopy

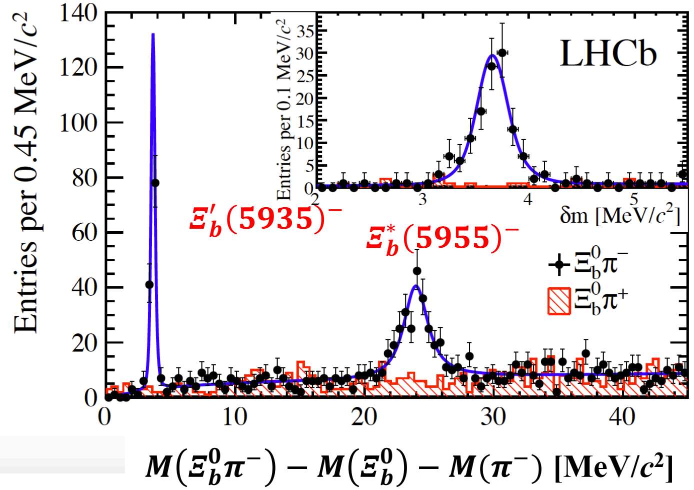
- Numbers of excited *b*-baryons have already been discovered
  - $\Xi_b^*(5945)^0 \to \Xi_b^- \pi^+$ [CMS'12]
  - $\Xi_b'(5935)^-, \Xi_b^*(5955)^- \to \Xi_b^0 \pi^-$ [LHCb'15]
  - $\Xi_b'^{\,0}$ not yet observed

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

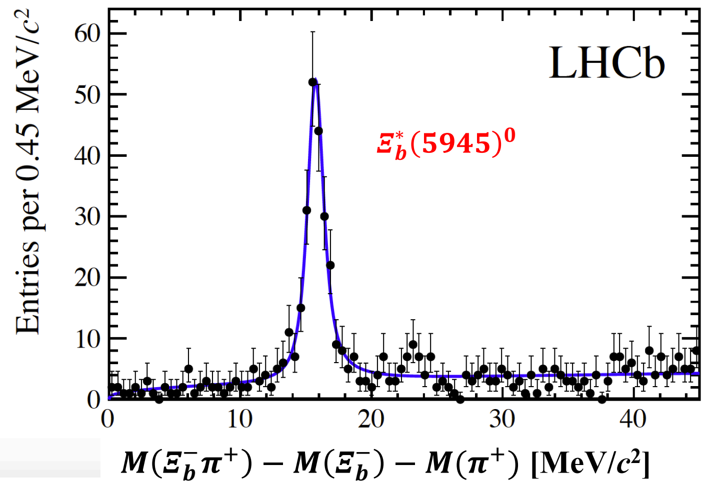
PRL 108, 252002 (2012)



PRL 114 (2015) 062004



JHEP 05 (2016) 161



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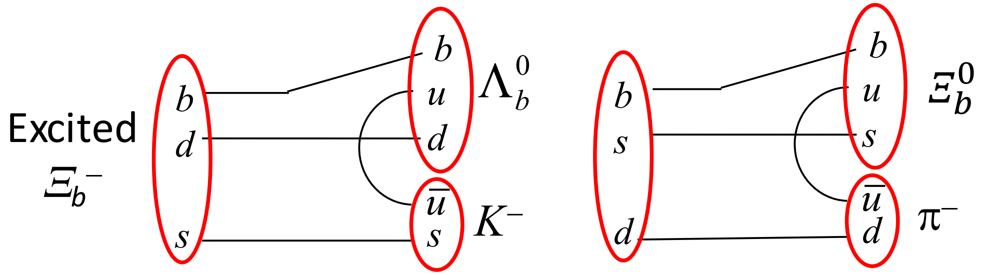
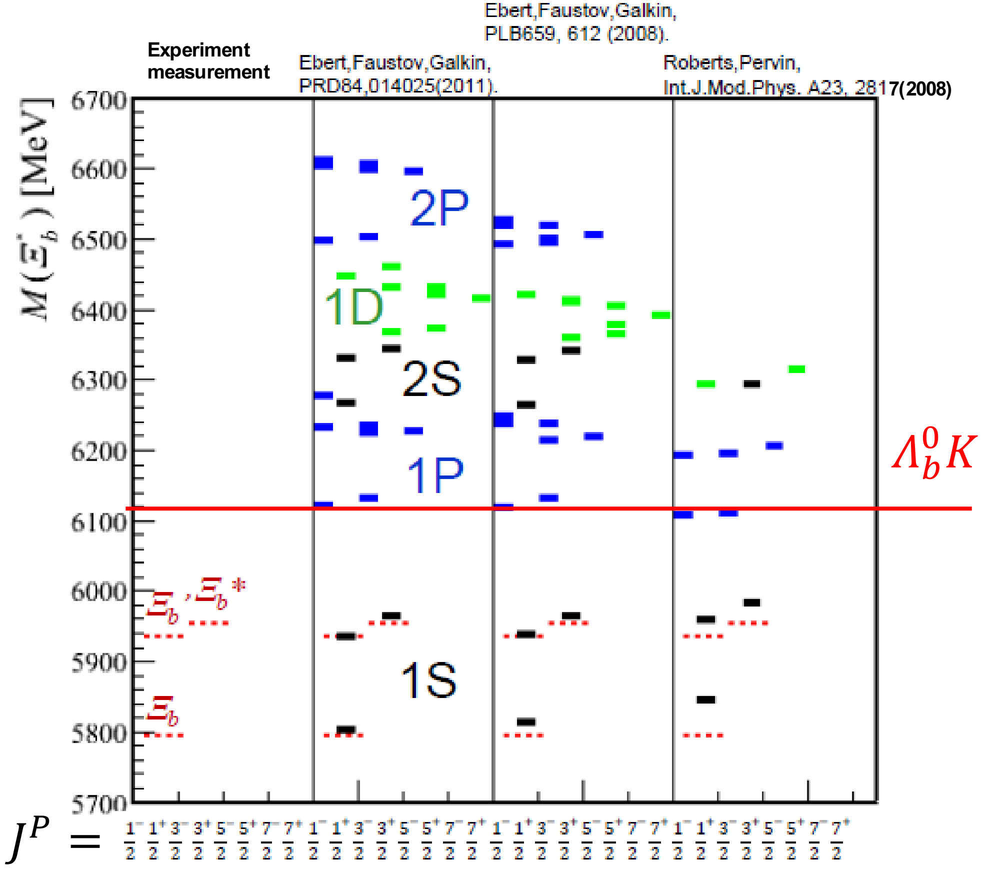
- More higher excited states are expected to be above $\Lambda_b^0 K$ threshold

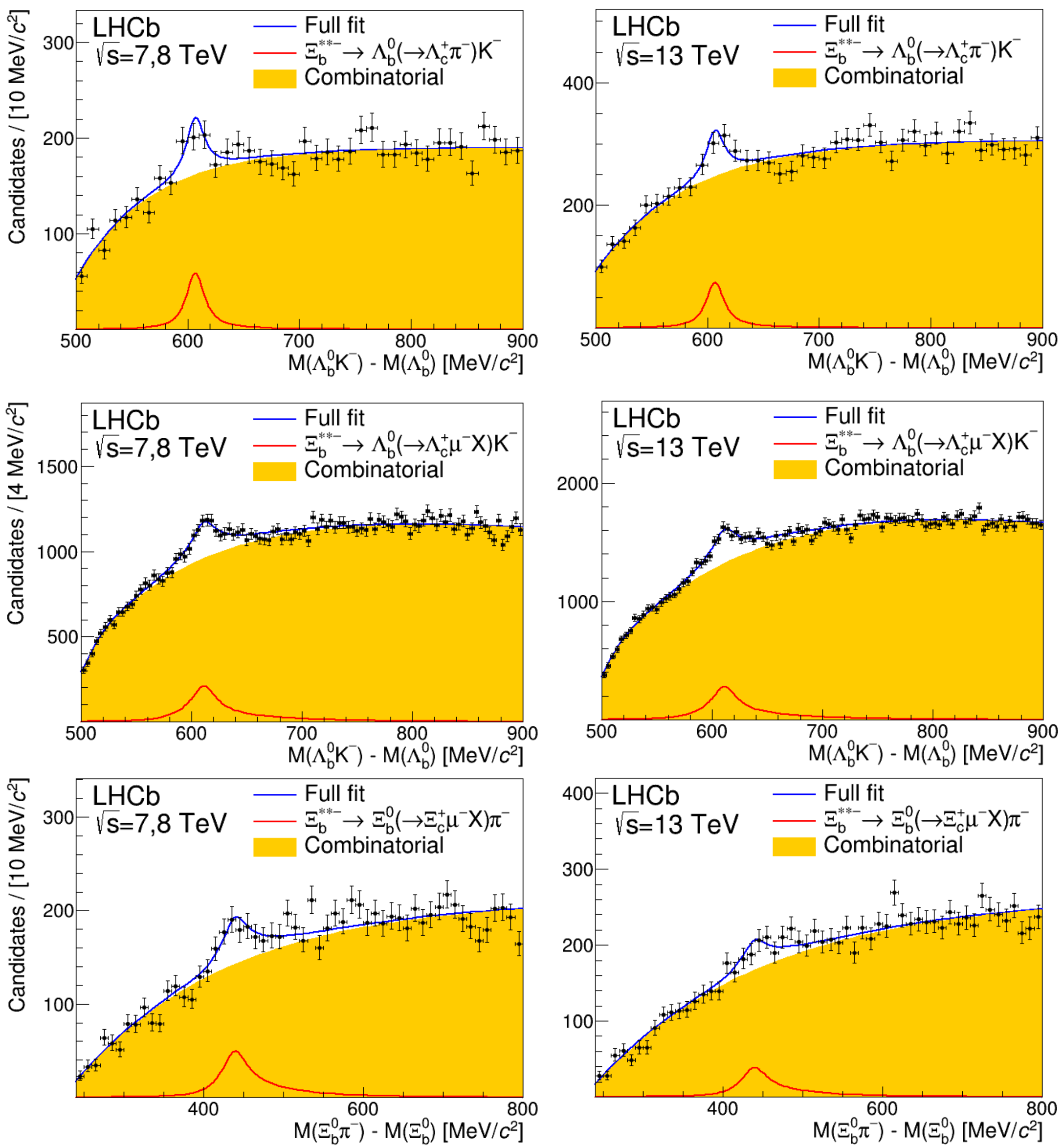




Observation of a new Ξ_b^{**-} state

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

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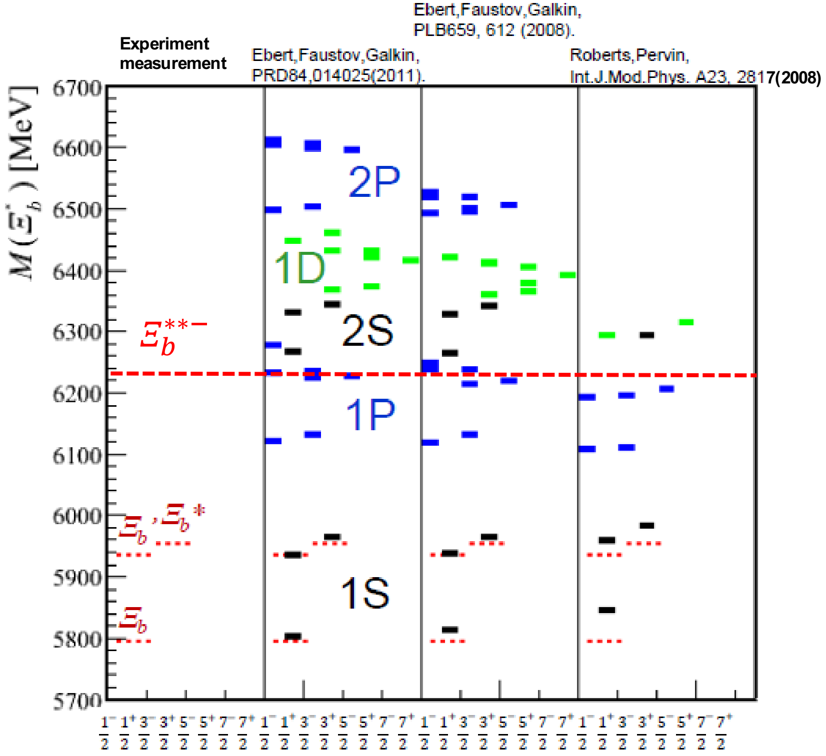
- With hadronic mode

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

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 ± 0.4 ± 0.4)×10^{-3}	(3.4 ± 0.4 ± 0.4)×10^{-3}
$(\sigma_{\Xi_b^{**-}}/\sigma_{\Xi_b^0})\mathcal{B}(\Xi_b^{**-} \to \Xi_b^0 \pi^-)$	(47 ± 9 ± 7)×10^{-3}	(22 ± 6 ± 3)×10^{-3}



- Many states are predicted at ~6230 MeV
  - To distinguish them further information needed (e.g. J^P, $\mathcal{B}$)