Spectroscopy at LHCb
Conventional states

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On behalf of the LHCb Collaboration
Beauty September 30th –October 4th 2019

BEAUTY 2019

Outline

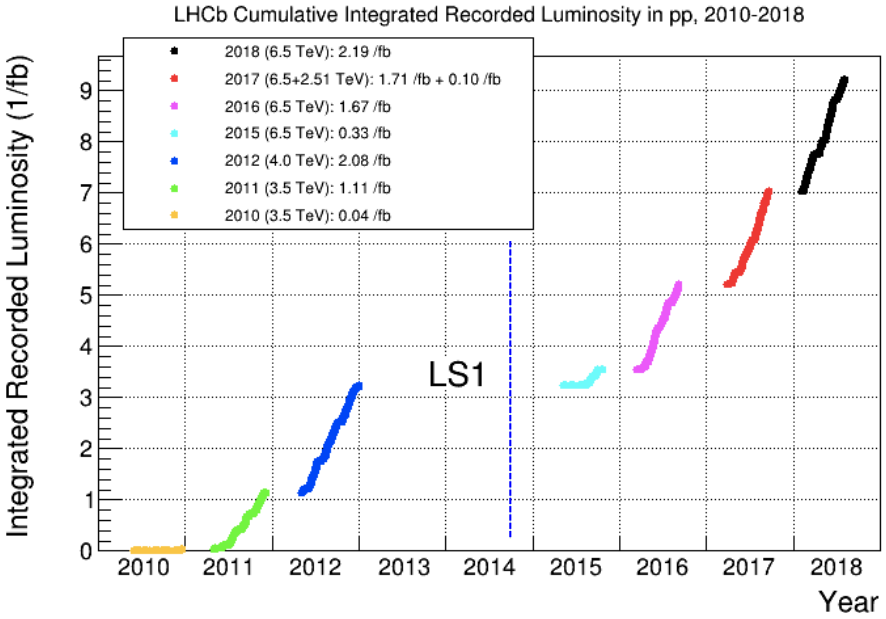
LHC era: New golden years for spectroscopy. Concentrate on a selection of recent results

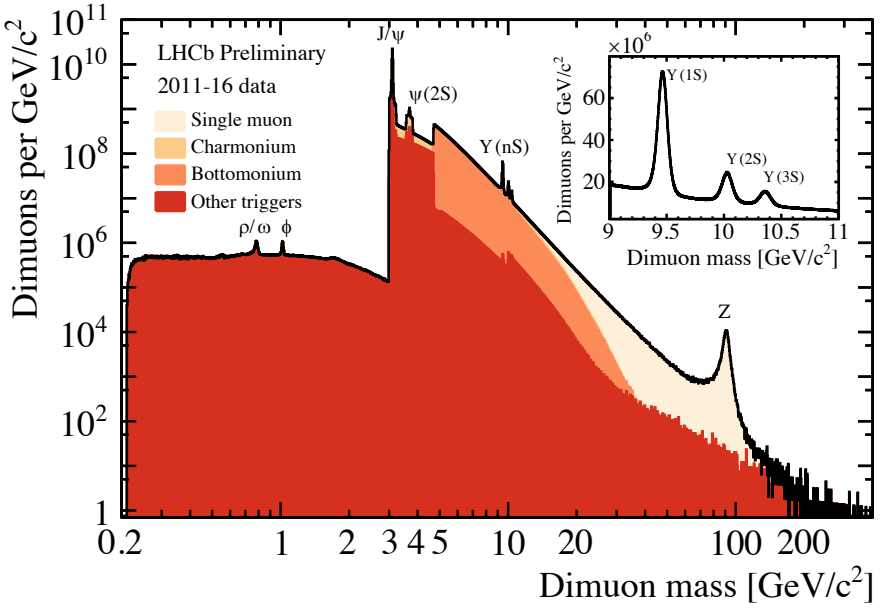
- Beautiful Baryons
- Double Charm baryons
- Hidden Charm

This talk focused on conventional states. See also LHCb talks:

Michel de Cian *Lifetime measurements* (Thursday afternoon)
Liming Zhang *Spectroscopy at LHCb: Exotic States (*Tuesday afternoon)
Marcello Rotondo *Heavy Flavour Production at LHCb (*Tuesday afternoon)

Introduction

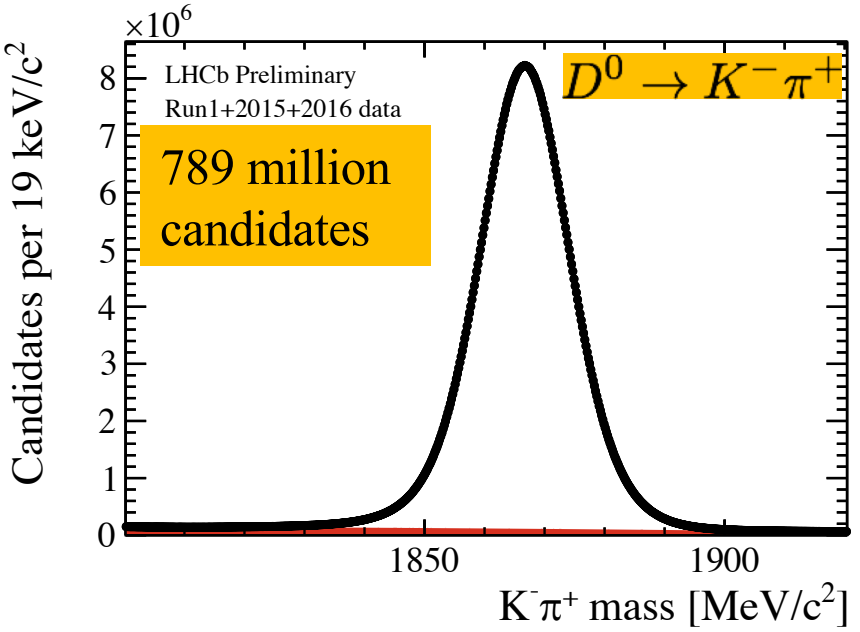




World largest heavy flavour dataset
(9 fb^{-1}) collected during Run1+Run2

- Precision tracking
- Excellent PID using RICH
- Trigger for fully hadronic decays

Int.J.Mod.Phys. A30 (2015) no.07, 1530022



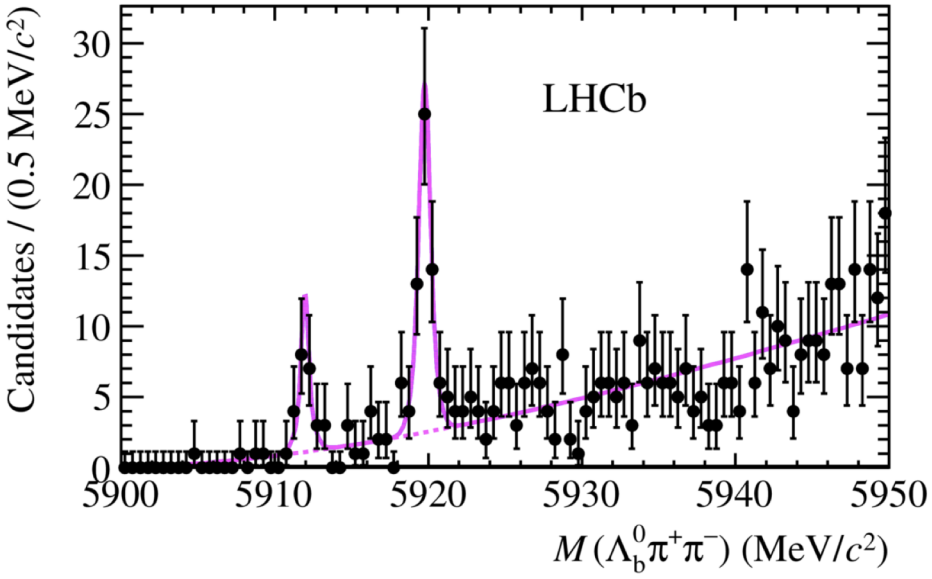
Beautiful Baryons

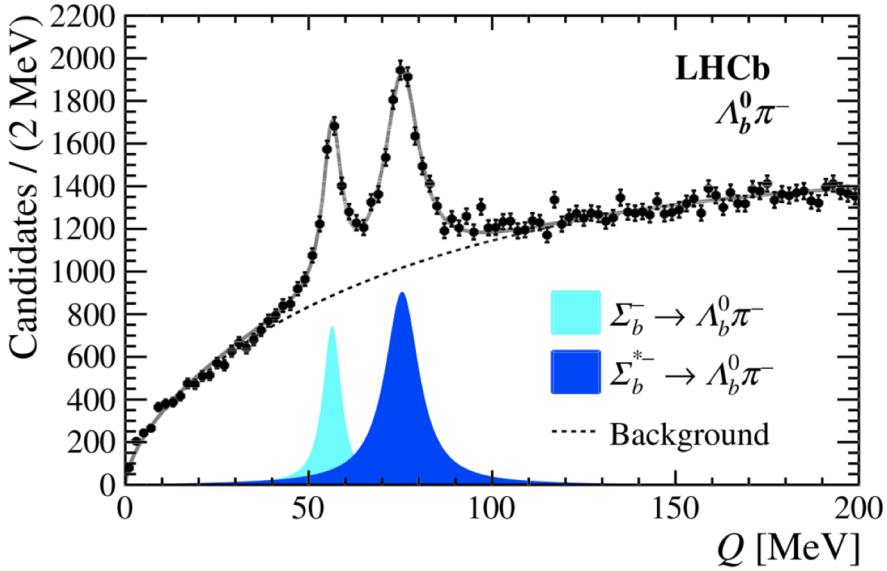
Excited Λ_b states

Large sample of Λ_b baryons collected by LHCb has provided rich starting point to explore b-baryon spectroscopy

Observation of $\Lambda_b(5912)$ and $\Lambda_b(5920)$ via decays to $\Lambda_b\ \pi^+\pi^-$ final state (PRL 109 (2012) 172003) [1 fb^{-1}]

Precise measurement of $\Sigma_b^{(*)\pm}$ states seen by CDF and observation of a new state $\Sigma_b(6097)^{\pm}$ (PRL 122 (2019) 012001) [3 fb^{-1}]





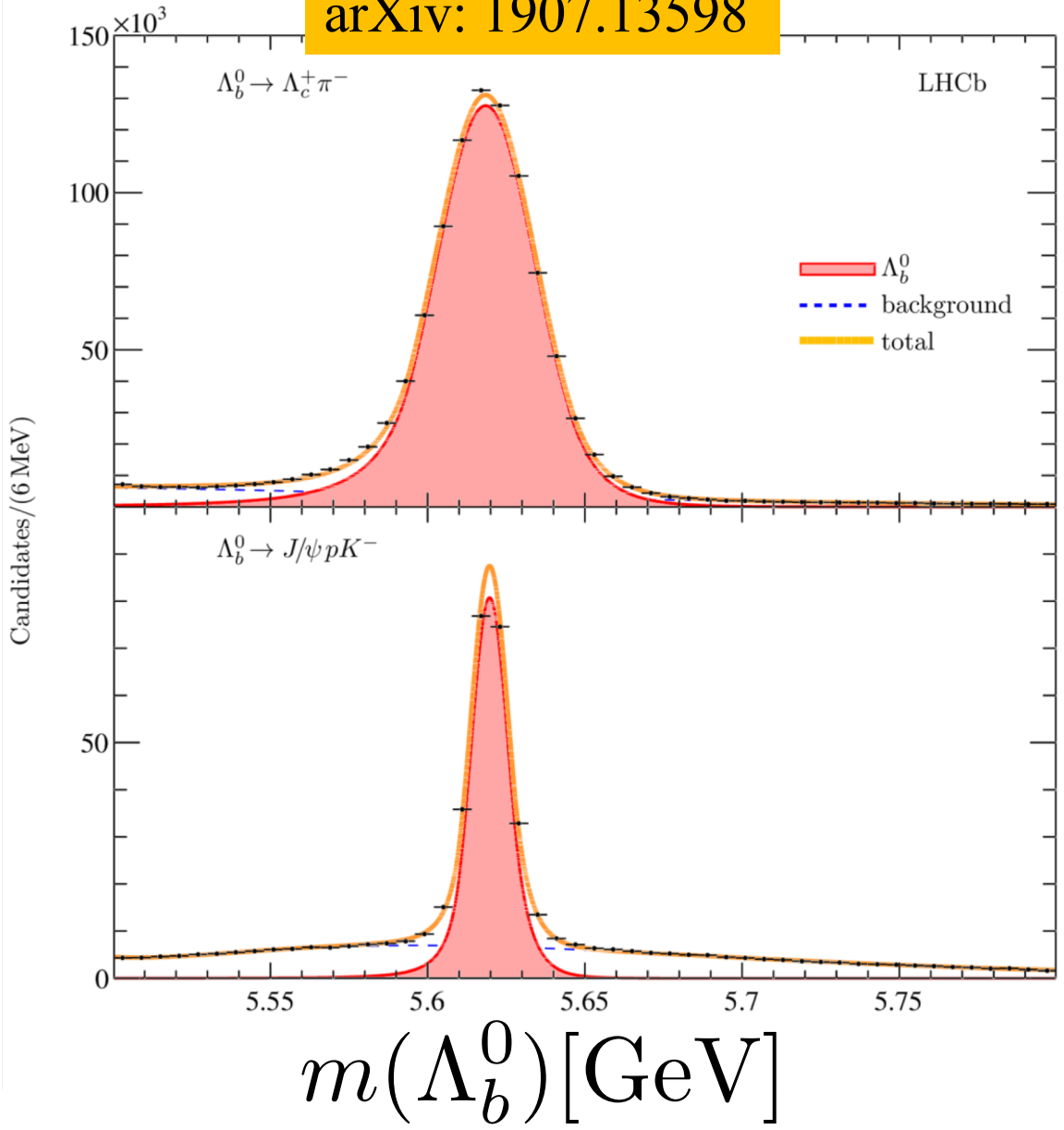
Excited Λ_b states

Full Run 1+2 dataset: 9 fb^{-1}

Exploit large clean samples of Λ_b decays to the $\Lambda_c\pi^-$ and J/ψpK$^-$ final states

Decay mode	N $[10^3]$
$\Lambda_b^0 \to \Lambda_c^+\pi^-$	892.8 ± 1.2
$\Lambda_b^0 \to J/\psi pK^-$	217.5 ± 0.7

arXiv: 1907.13598



Excited Λ_b states

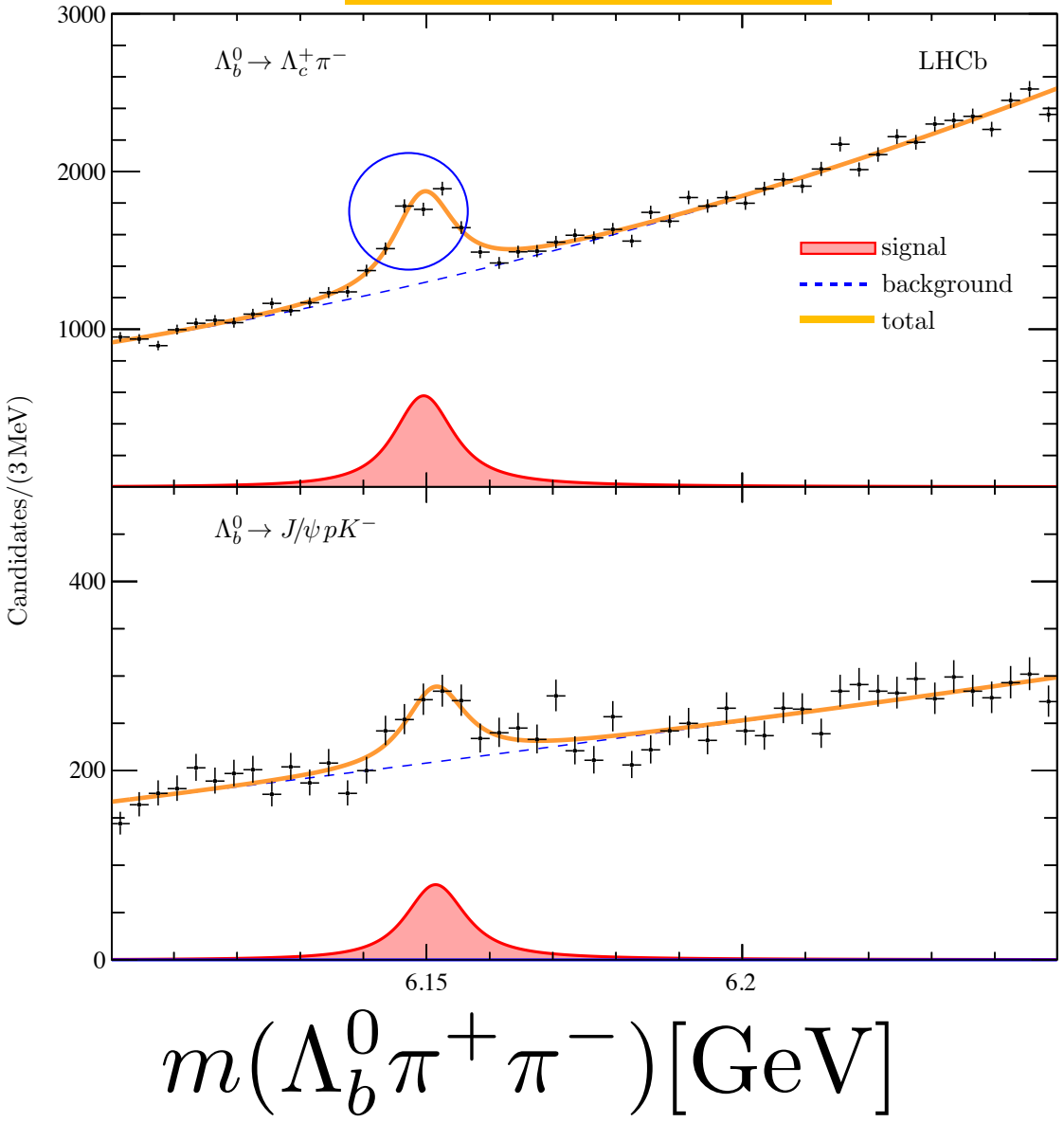
arXiv: 1907.13598

Add two prompt pions

Suppress combinatorial background with BDT

Study Λ_b $\pi^+\pi^-$ mass spectrum

New structure seen around 6.15 GeV above $\Sigma_b^{(*)\mp}\pi^{\pm}$ threshold



Excited Λ_b states

Split data into 3 regions of $\Lambda_b\pi^\pm$ invariant mass:

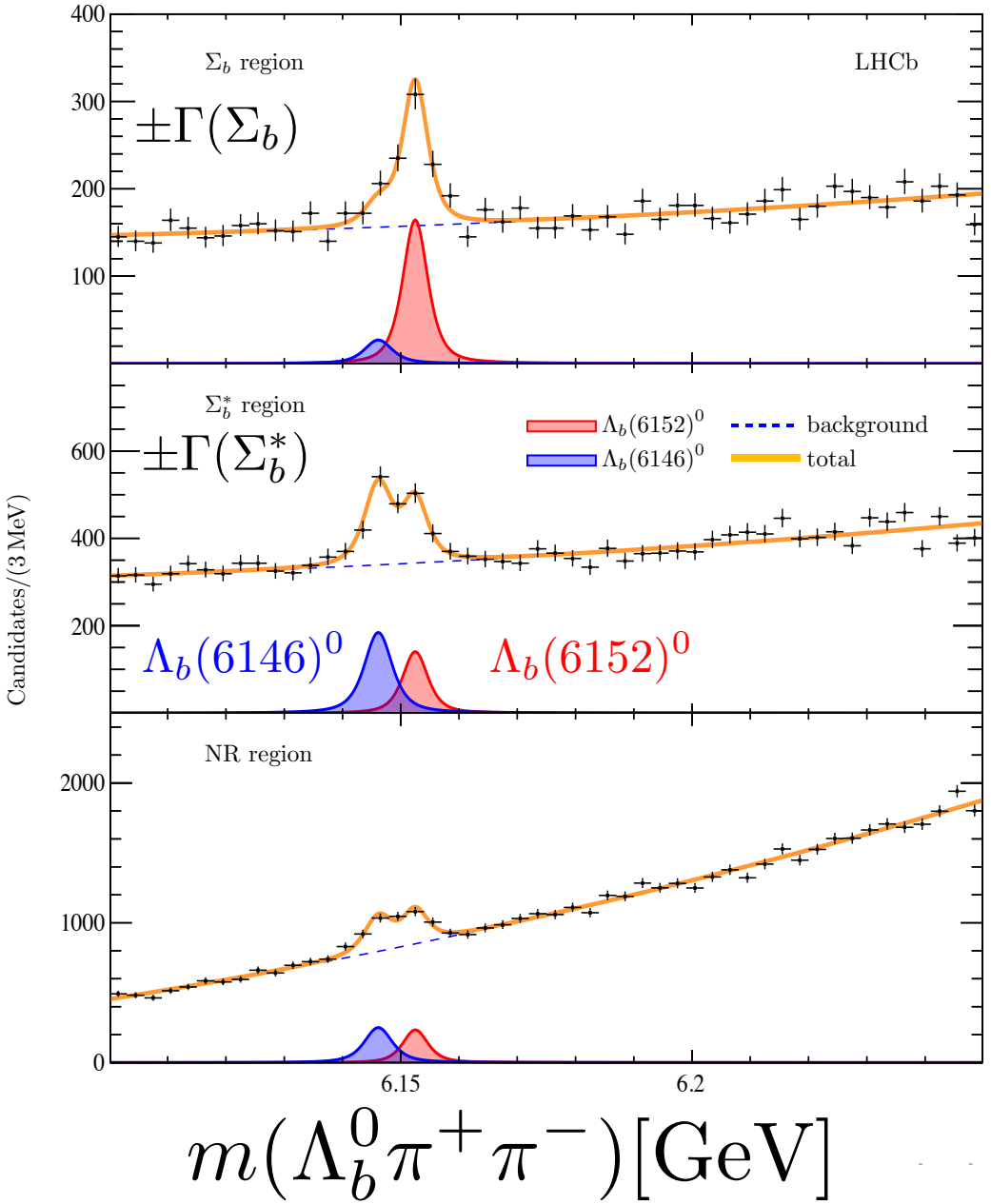
- Σ_b
- Σ_b^*
- Non-resonant

Simultaneous fit to data in 3 regions

Data favours hypothesis of 2 narrow near degenerate states at 7σ significance

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

arXiv: 1907.13598



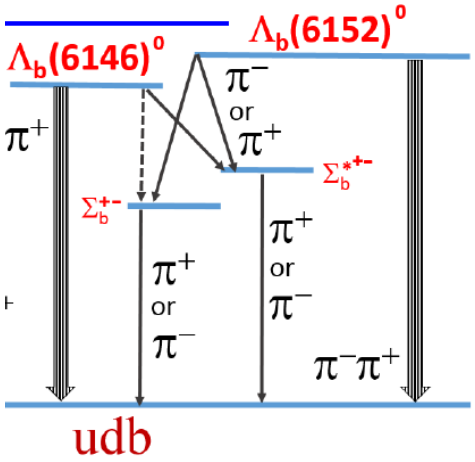
Excited Λ_b states

Fit $\Lambda_b\,\pi^+\pi^-$ then sPlot $\Lambda_b\pi^\pm$ mass

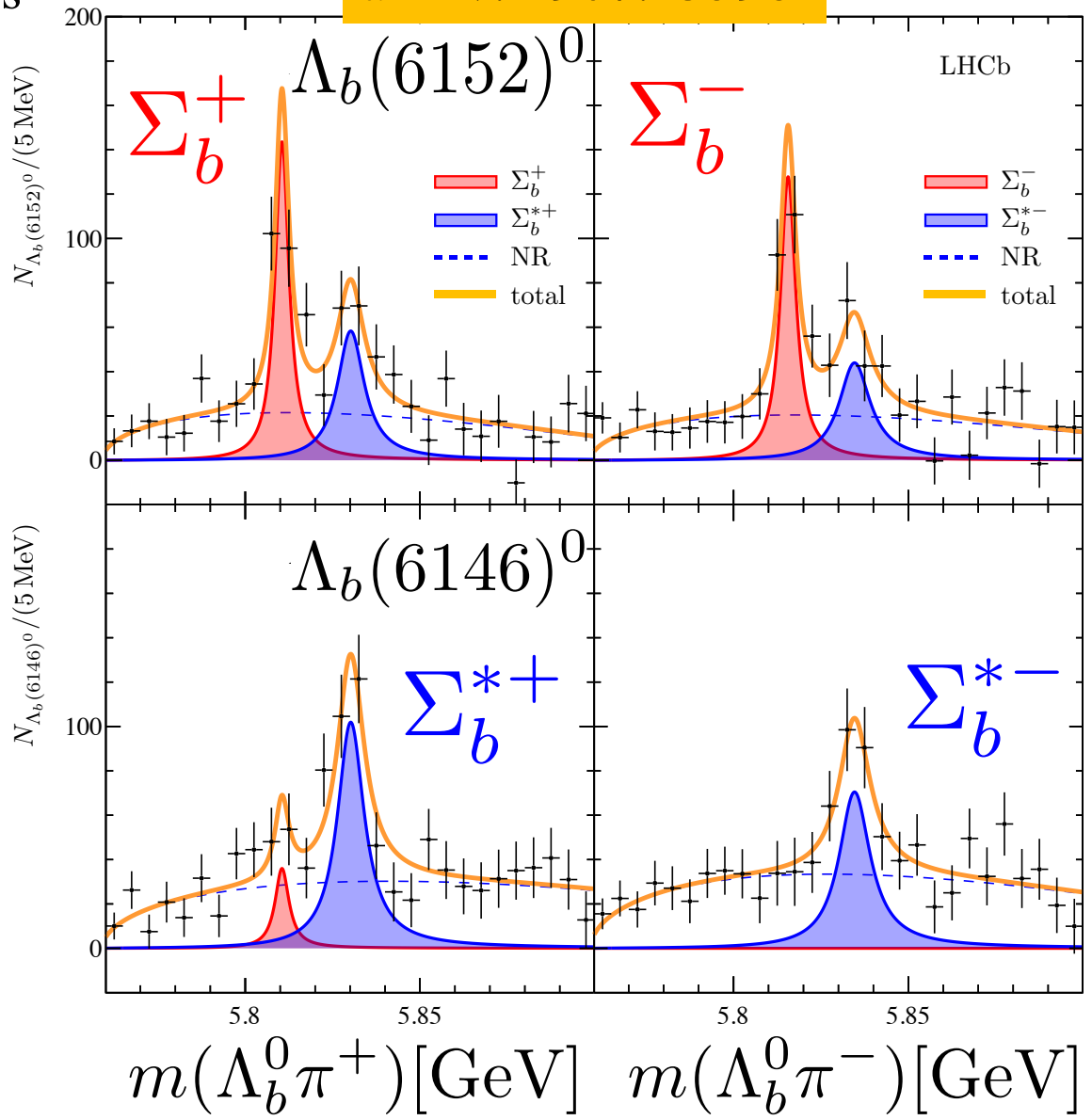
$\Lambda_b(6512)^0$ couples to both Σ_b^+ and Σ_b^{*+}

$\Lambda_b(6546)^0$ couples primarily to Σ_b^*

Observed masses, width + decay patterns consistent $\Lambda_b(1D)^0$ doublet with $J^P = 3/2^+$ and $5/2^+$



arXiv: 1907.13598



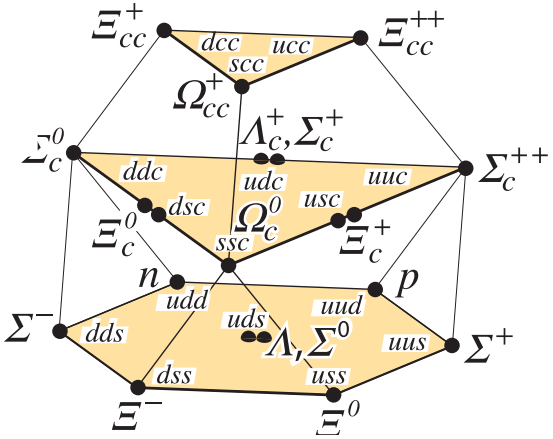
Doubly Charmed Baryons

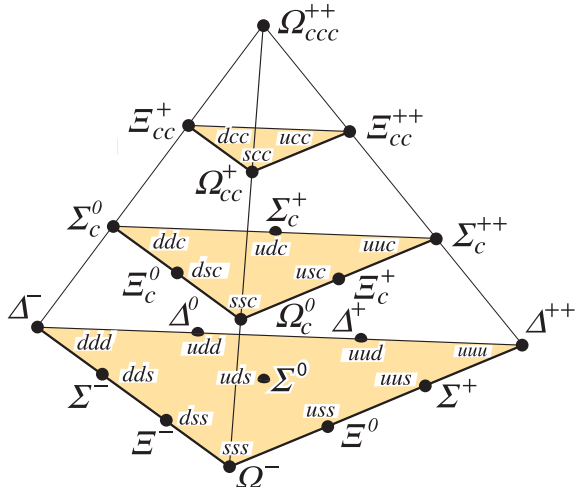
Doubly Charmed Baryons

Two SU(4) 20-plets containing SU(3) triplets

$$\Xi_{cc}^{+} = ccd,\ \Xi_{cc}^{++} = ccu,\ \Omega_{cc}^{+} = ccs$$

$J^P = \frac{1}{2}^+$





$J^P = \frac{3}{2}^+$

Ξ_{cc}^{++} first observed decaying to $\Lambda_c^+ K^- \pi^+ \pi^+$ by LHCb in 2017

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

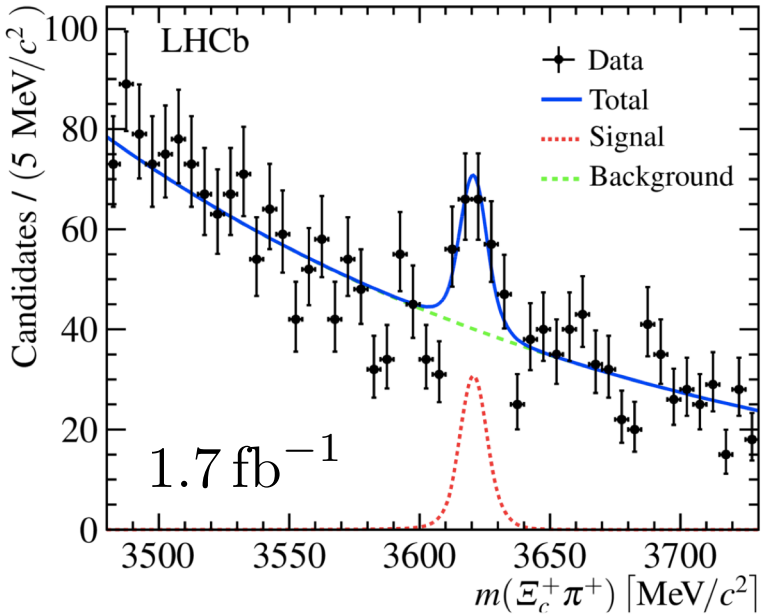
PRL 119 (2017) 112001

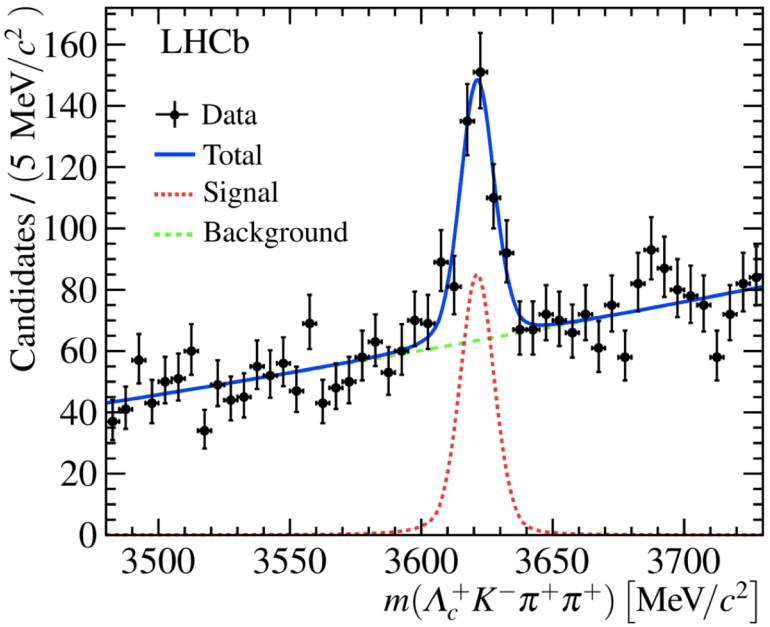
$$\tau(\Xi_{cc}^{++}) = (0.256^{+0.024}_{-0.022} \pm 0.014)\,\mathrm{ps}$$

PRL 121 (2018) 052002

See talk of Michel de Cian

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





State confirmed in $\Xi_c^+ \pi^+$ mode

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+; \Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+; \Lambda_c^+ \to pK^-\pi^+)}$$

$$\mathcal{R} = (3.5 \pm 0.9 \pm 0.3) \times 10^{-2}$$

Using recent Belle measurement:

$\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$

Phys.Rev. D100 031101

gives

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+)} \approx 0.5$$

Combining both modes

$$m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65 \pm 0.31\,\text{MeV}/c^2$$

PRL 121 (2018) 162002

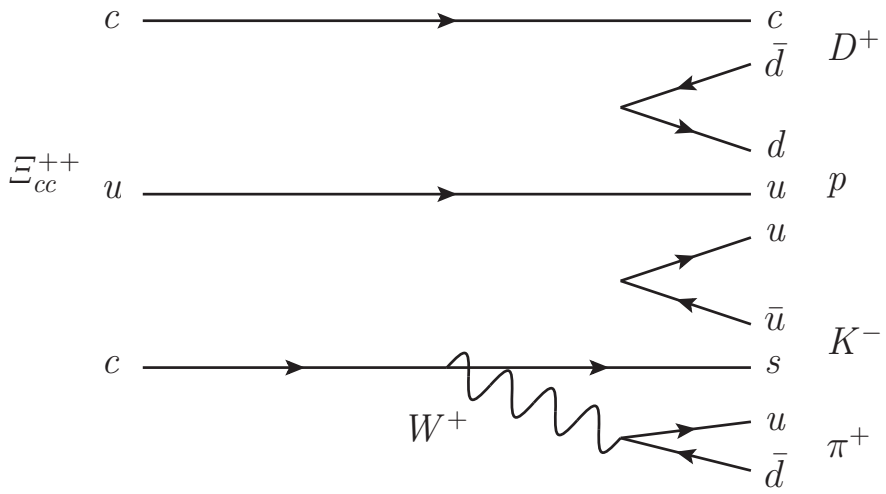
Search for $\Xi_{cc}^{++} \to D^+pK^-\pi^+$

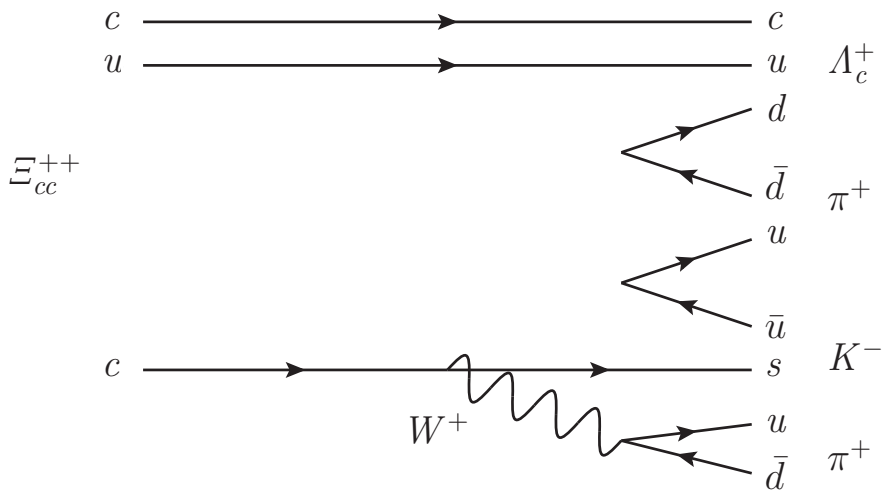
To further understand the dynamics of weak decays Ξ_{cc}^{++} need to explore other modes

Good trigger efficiency for $D^+ \to K^+K^-\pi^+$ ☺

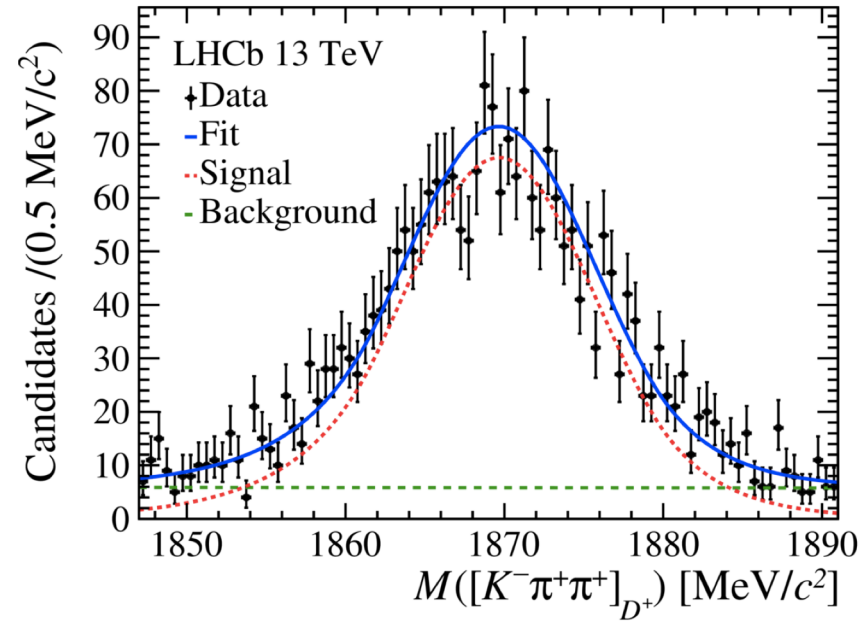
Lower phase space ☹

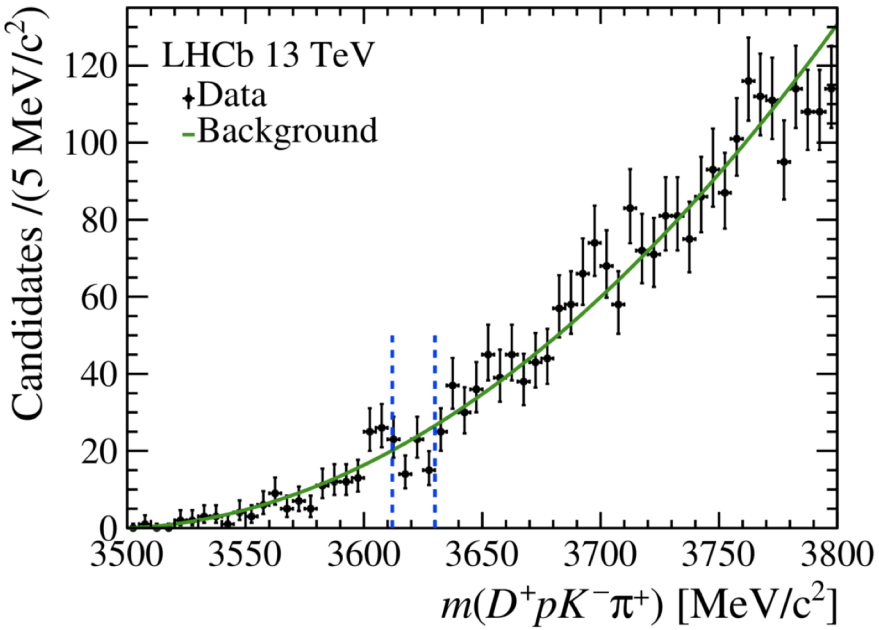
arXiv:1905.02421





Search for $\Xi_{cc}^{++} \to D^+pK^-\pi^+$





Study the $D^+pK^-\pi^+$ spectrum with 1.7 fb^{-1} of data collected in 2016

No significant signal seen

Limit set on:

$$\mathcal{R} \equiv \frac{\mathcal{B}\left(\Xi_{cc}^{++} \to D^+ pK^-\pi^+\right)}{\mathcal{B}\left(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+\right)}$$

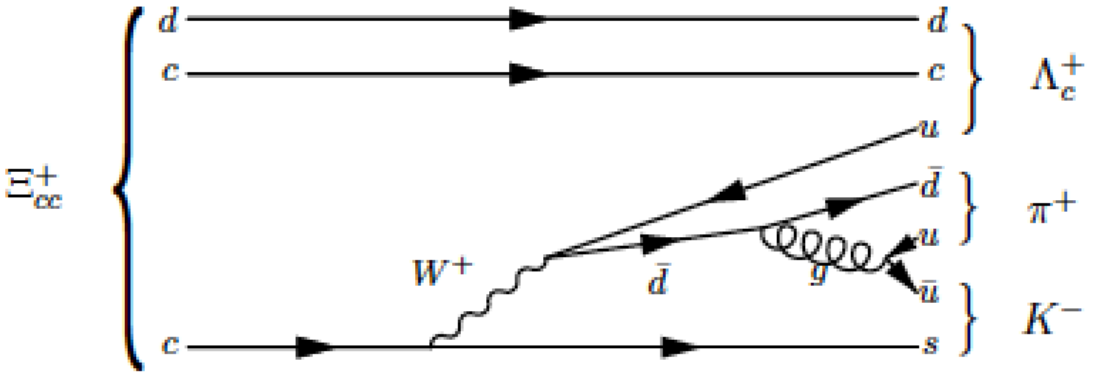
$$\mathcal{R} < 2.1\times10^{-2} \quad @\ 95\ \%\ \text{CL}$$

arXiv:1905.02421

Search for Ξ_{cc}^{+}

What about other doubly charmed baryons ? e.g Ξ_{cc}^{+}

Predicted to have similar mass to Ξ_{cc}^{++} but shorter lifetime



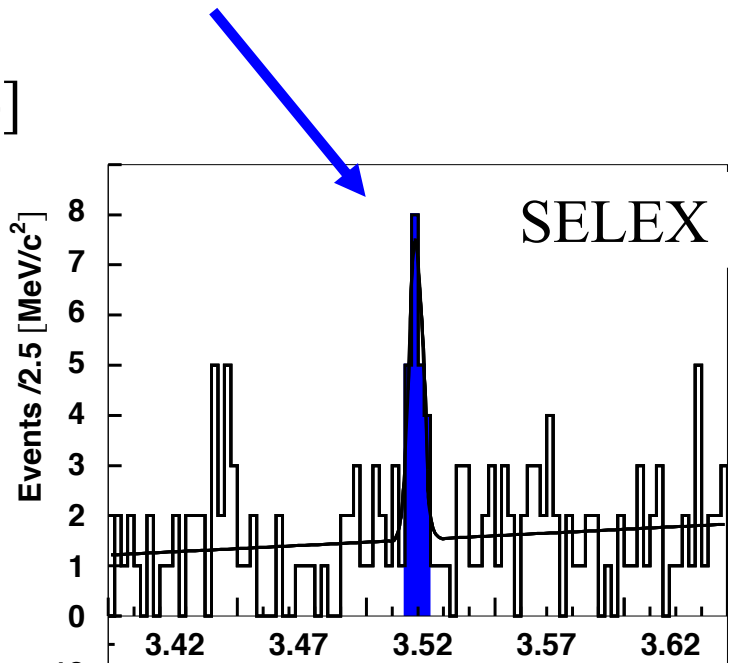
Longstanding unconfirmed observation by the SELEX experiment

PRL. 89 (2002) 112001, arXiv:hep-ex/0208014]

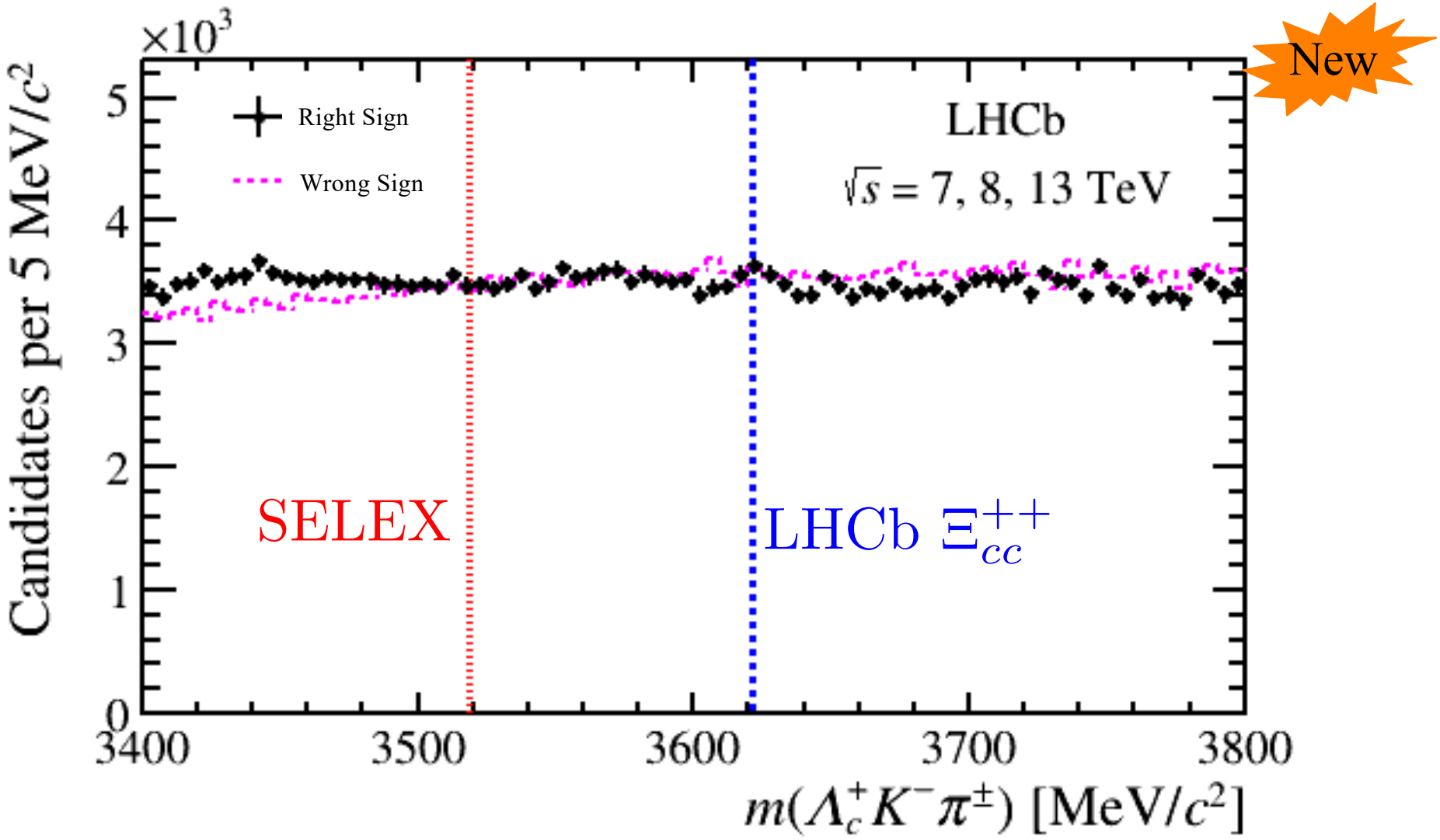
New

arXiv:1909.12273

LHCb search using $\Lambda_c^+ \pi^+ K^-$ mode and full Run 1+2 dataset



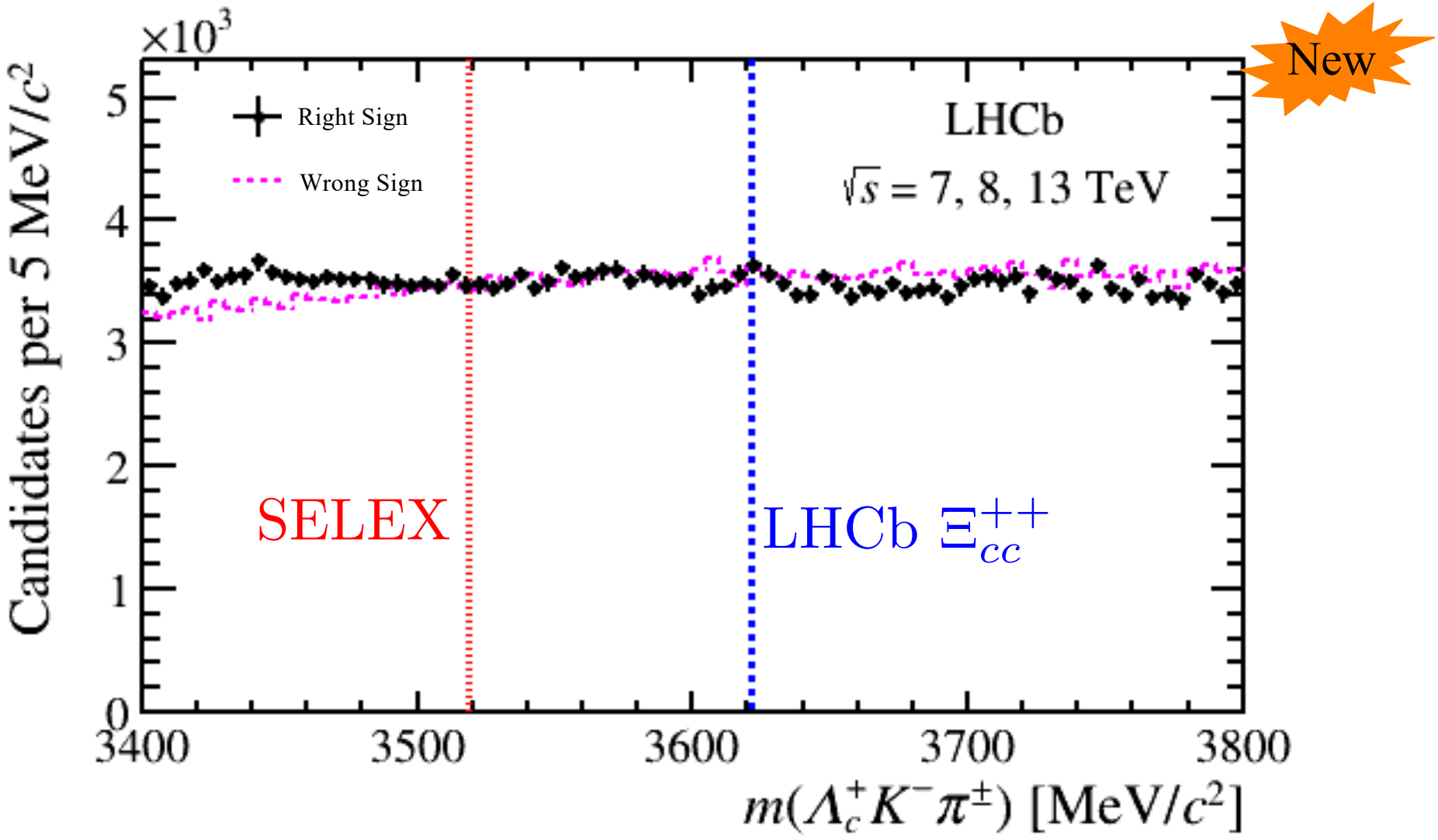
Search for Ξ_{cc}^{+}



No signal seen

arXiv:1909.12273

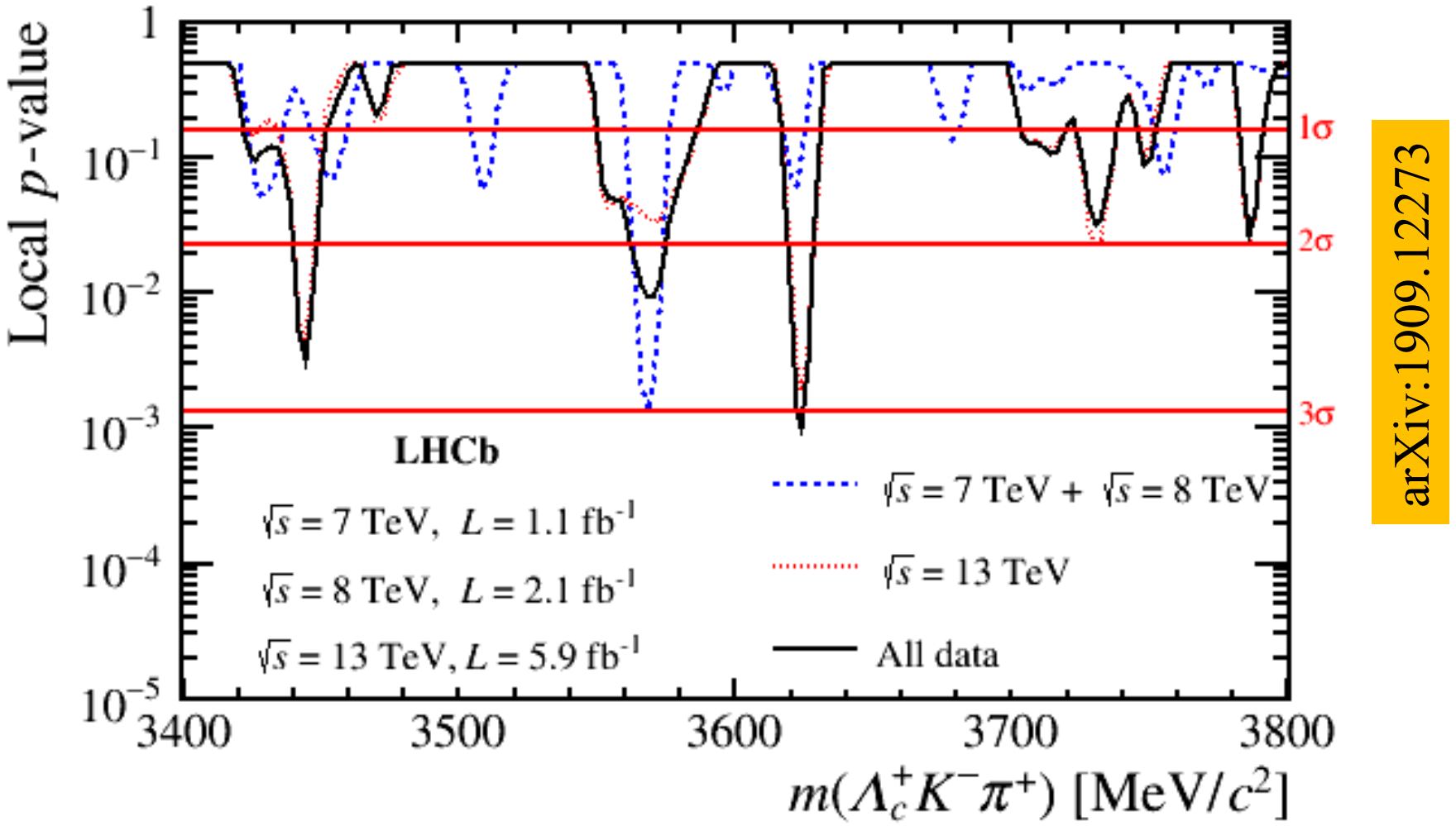
Search for Ξ_{cc}^{+}



No signal seen

arXiv:1909.12273

Search for Ξ_{cc}^{+}



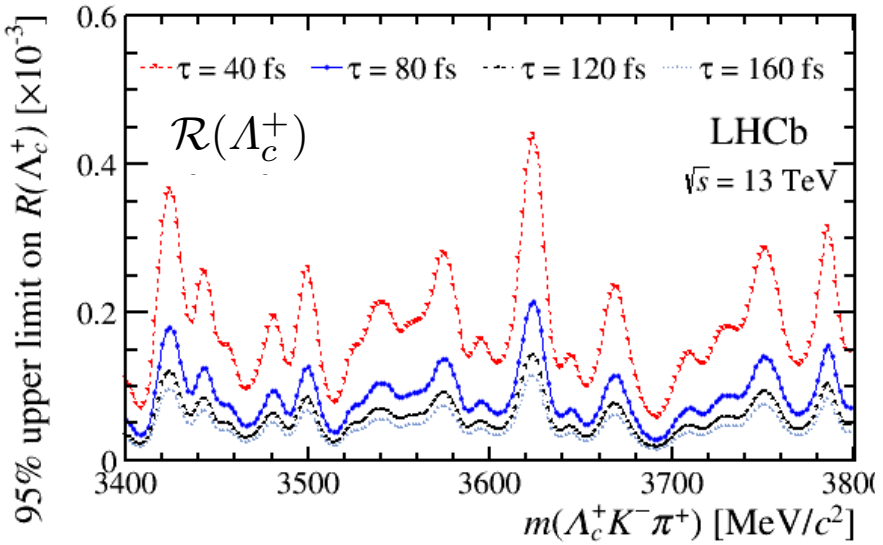
arXiv:1909.12273

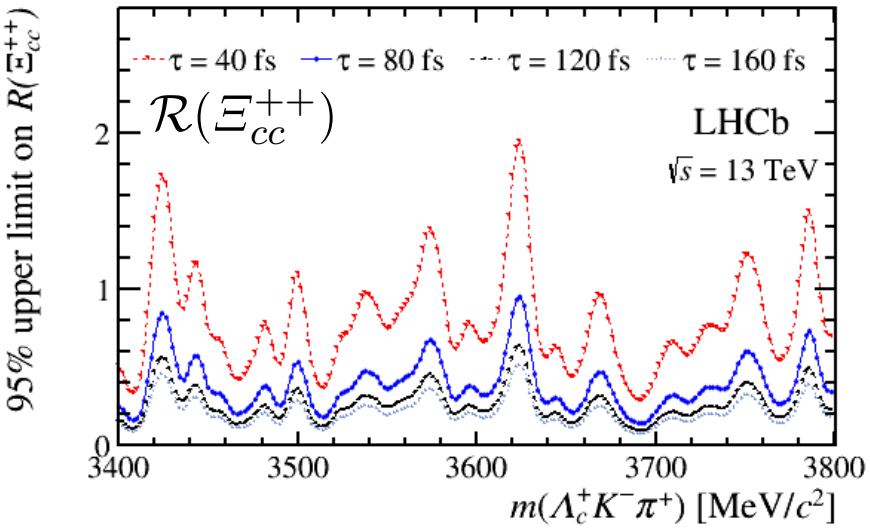
Largest local significance 3.1σ (statistical) around 3620 MeV/c^2
Global significance 1.7σ no evidence, limits set

New

Search for Ξ_{cc}^{+}

Set upper limits on R as a function of mass for different lifetime hypotheses





LHCb-PAPER-2019-029

New

$$R(\Lambda_c^+) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+)}{\sigma(\Lambda_c^+)}$$

$$R(\Xi_{cc}^{++}) \equiv \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^-\pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+)}$$

- Improve LHCb limits by order of magnitude compared to Run 1 analysis,
- Limits significantly below expectations from SELEX (caveat different environment)

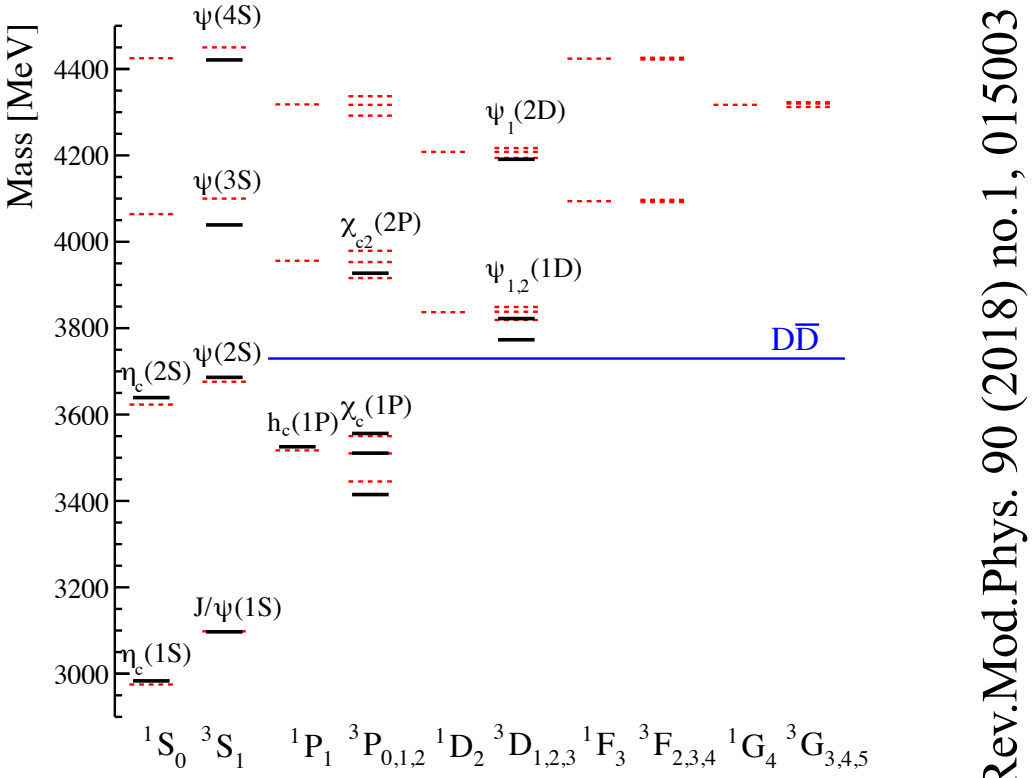
Missing Hidden Charm

Charmonium System

Since November revolution of 1974 hidden charm spectrum well mapped out over the last 45 years

Up to this year candidate for all but two of lowest states seen

Missing states $^3D_3$ and $^1D_2$



Rev.Mod.Phys. 90 (2018) no.1, 015003

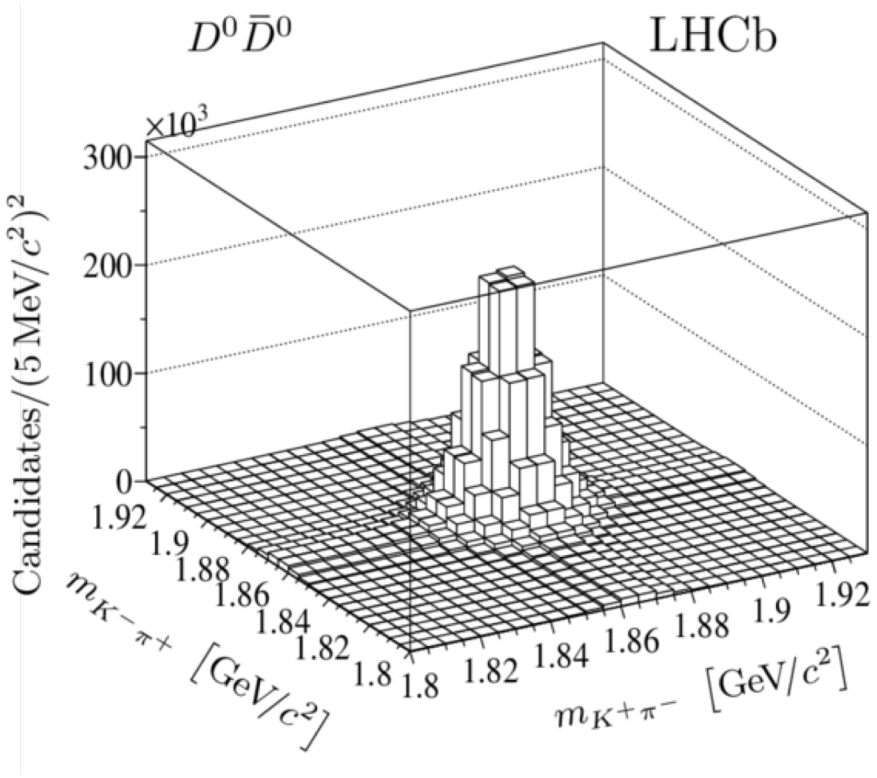
$^3D_3$ decays to open charm but expected to be narrow due to F-wave centrifugal barrier factor

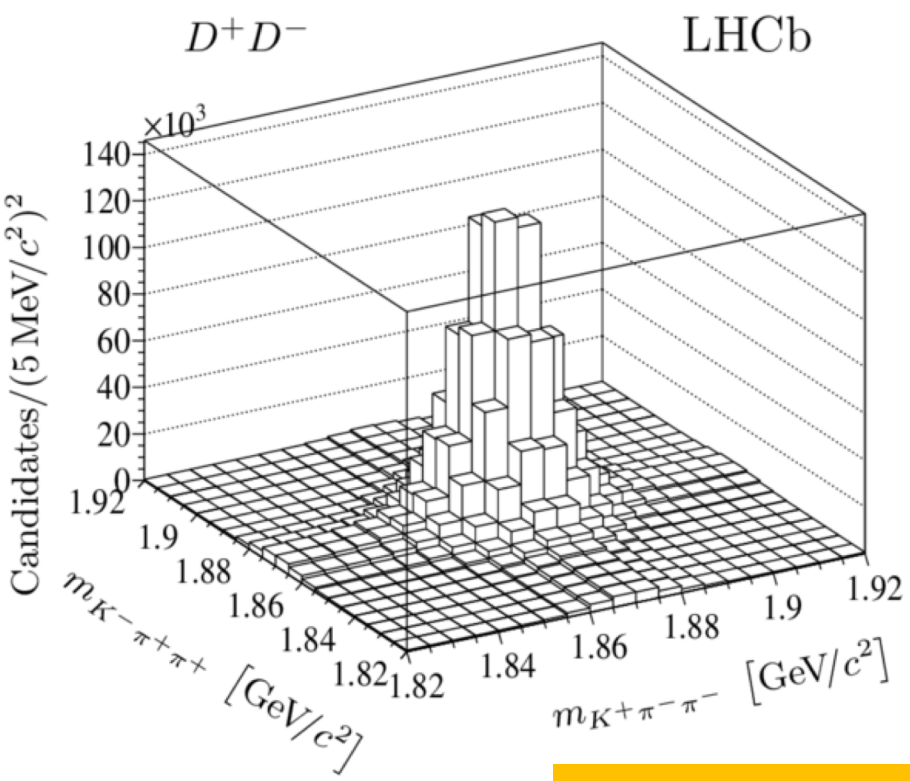
- (-) C, cannot be produced in gluon fusion or $\gamma\gamma$ See PRD 72 (2005) 054026

Near Threshold $D\bar{D}$ spectroscopy

Exploit large samples of open charm collected in full Run 1+2 datasets

Select events with 2 reconstructed charm mesons from same PV

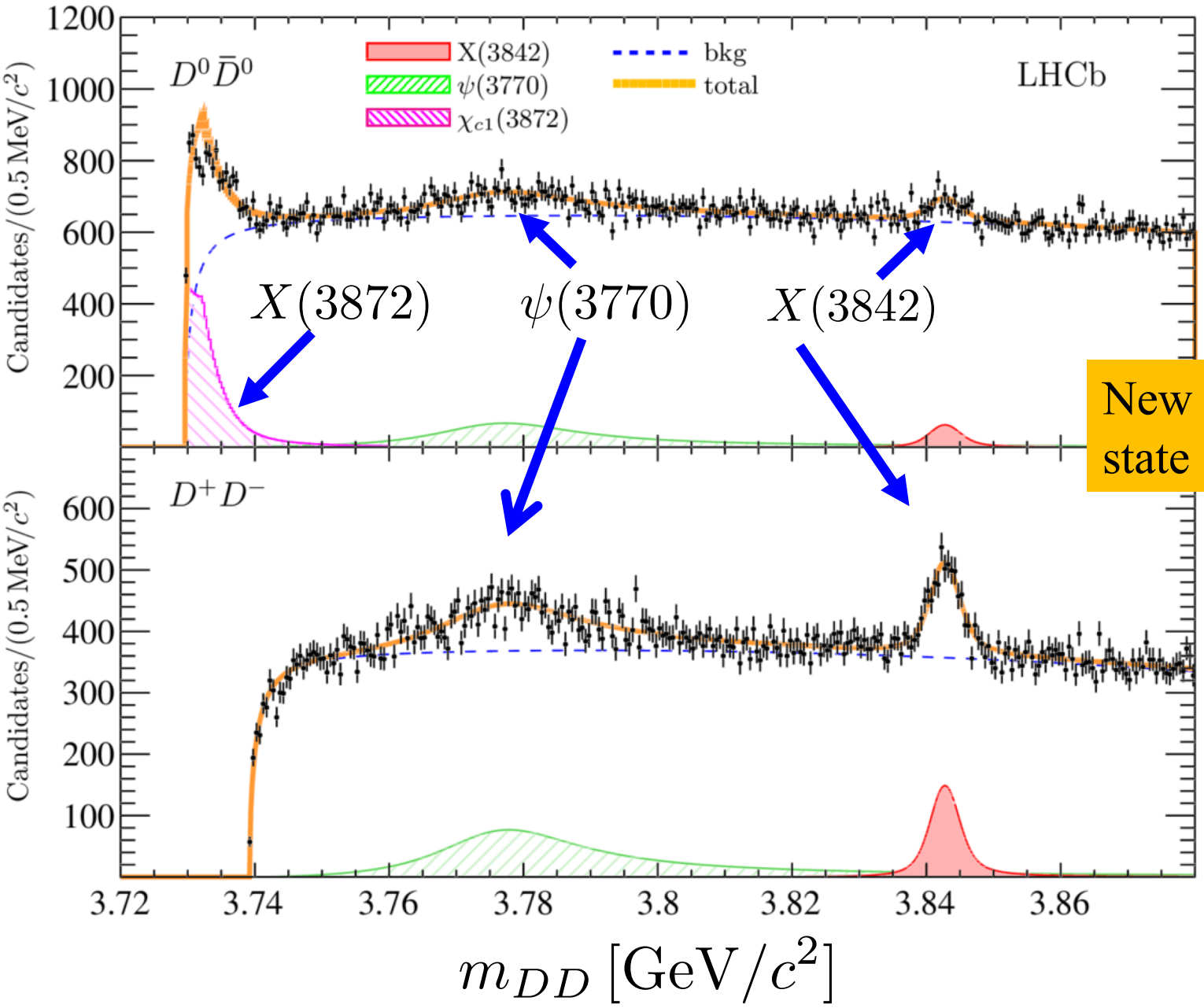




JHEP 07 (2019) 035

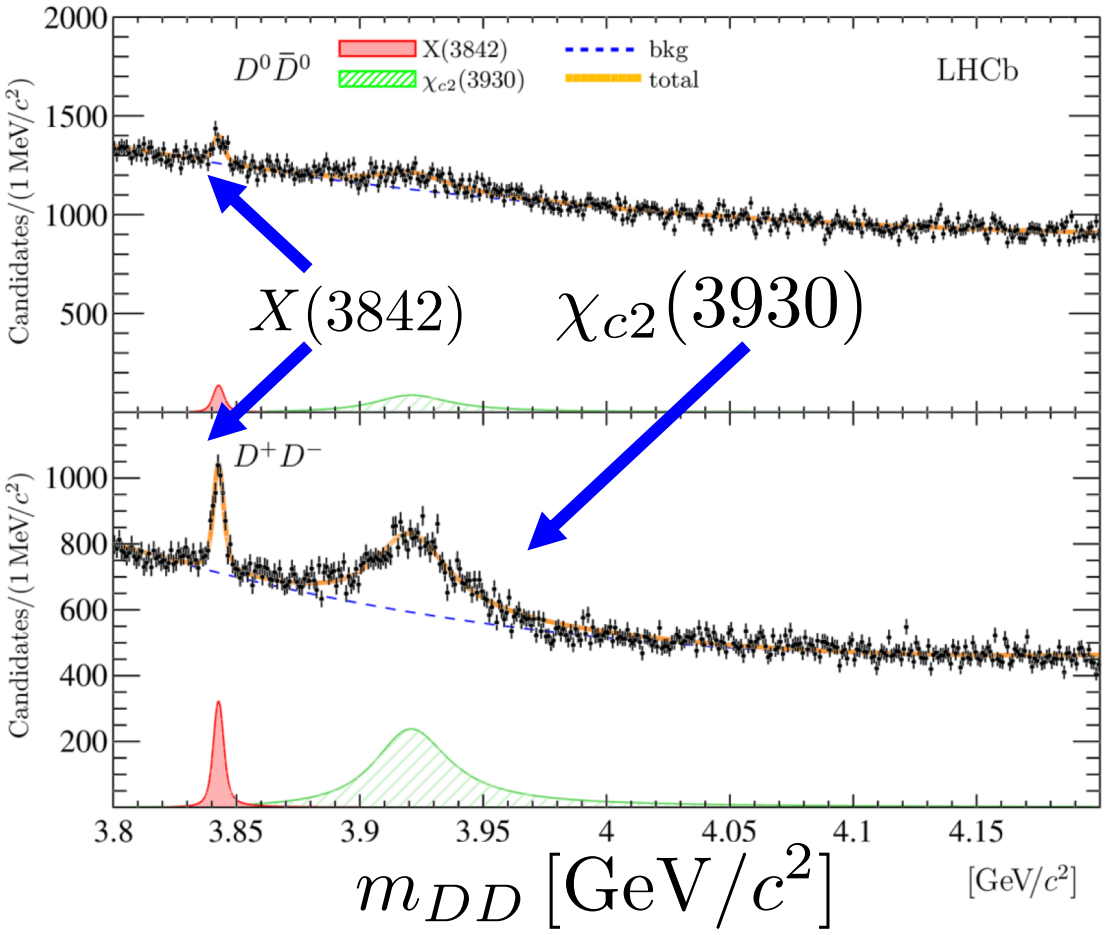
X(3842)

JHEP 07 (2019) 035



New narrow state

X(3842)



JHEP 07 (2019) 035

New narrow state

$$m_{X(3842)} = 3842.71 \pm 0.16 \pm 0.12\,\text{MeV}/c^2$$
$$\Gamma_{X(3842)} = 2.79 \pm 0.51 \pm 0.35\,\text{MeV}$$

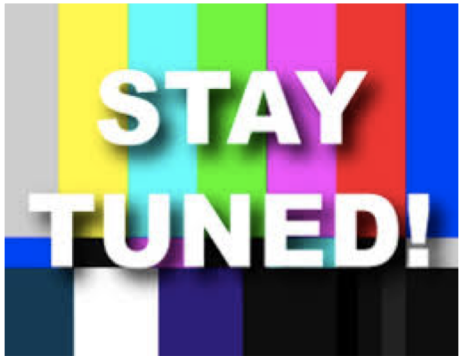
Properties consistent with $^3D_3$ state of charmonium system

Also measure:

$$m_{\psi(3770)} = 3778.1 \pm 0.7 \pm 0.6\,\text{MeV}/c^2$$
$$m_{\chi_{c2}(3930)} = 3921.9 \pm 0.6 \pm 0.2\,\text{MeV}/c^2$$
$$\Gamma_{\chi_{c2}(3930)} = 36.6 \pm 1.9 \pm 0.9\,\text{MeV}$$

Summary

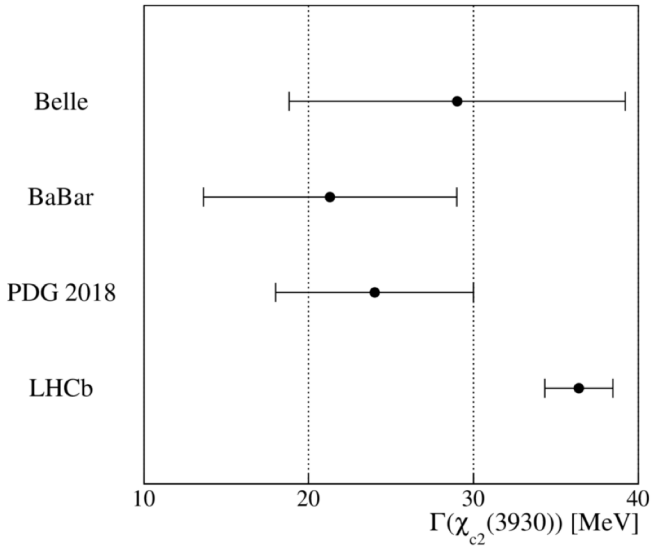
- Golden Era for spectroscopy
- Many results have already come out of LHCb
- Today focused on recent results on b-baryons, doubly charmed baryons and hidden charm
- Several analyses already exploit fully Run 1+2 dataset
  - A lot more to come in next years

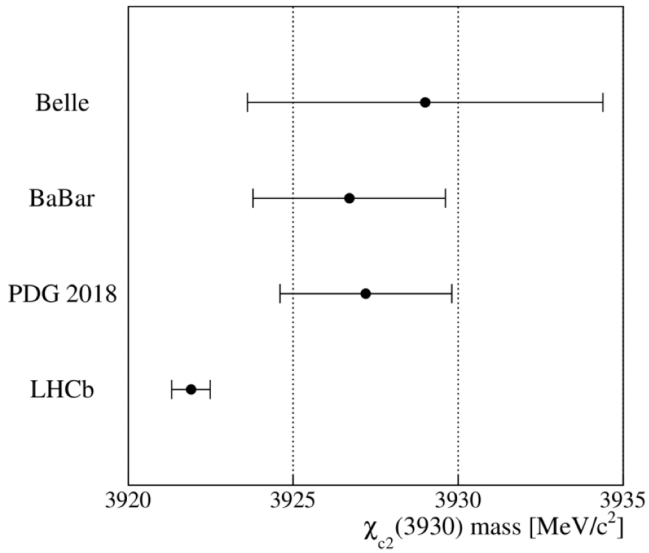


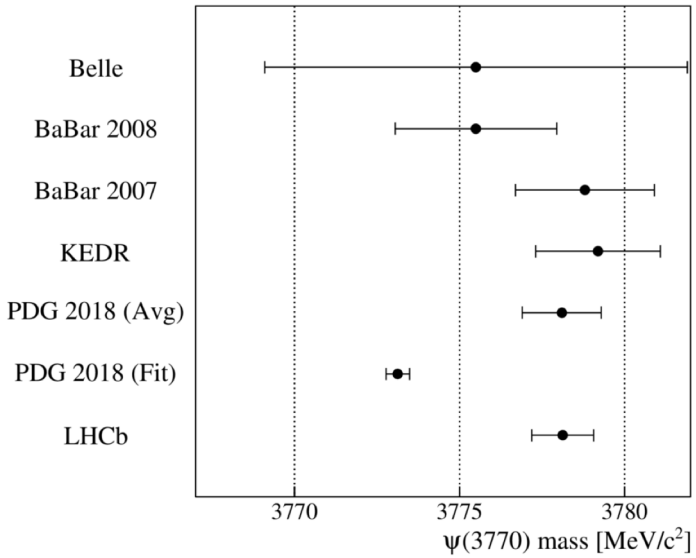
- Future: LHCb upgrade will increase dataset by factor 5-10 depending on mode

Backup

Near Threshold Charm Spectroscopy







The LHCb Detector