Baryon spectroscopy at LHCb

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on behalf of the LHCb collaboration

18th International Conference on Hadron Spectroscopy and Structure

16-21 August 2019, Guilin, China

Introduction

- Hadron spectrum is the primary observable of QCD
- LHCb has been providing propellants for heavy flavour spectroscopy
- Focus on very recent results of baryon spectroscopy
  - Beautiful baryons
    - ▸ Observation of new excited $\Sigma_b^{\pm}$ states
    - ▸ Observation of new excited Λ_b states (NEW)
    - ▸ Observation of a new excited Ξ_b state
  - Doubly charmed baryons
    - ▸ Observation of $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$
    - ▸ A search for $\Xi_{cc}^{++} \to D^{+}pK^{-}\pi^{+}$ (NEW)

The LHCb detector

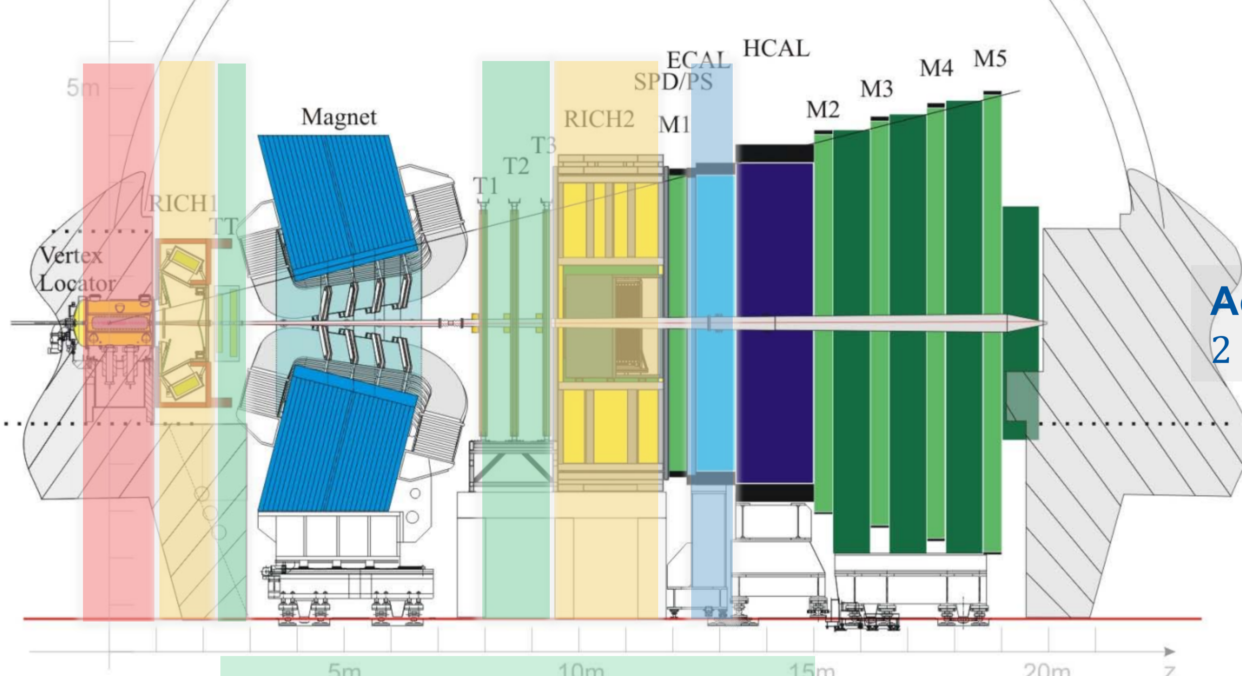
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

- A single-arm forward spectrometer at LHC

Vertex Locator
$\sigma_{\text{IP}} = 20\ \mu\text{m}$
$\sigma_{\tau} = 45\ \text{fs}$

RICHs
$\epsilon(K \to K) \sim 95\%$
mis-ID $\epsilon(\pi \to K) \sim 5\%$

ECAL
$\sigma_E/E = \frac{10\%}{\sqrt{E}} \oplus 1\%$

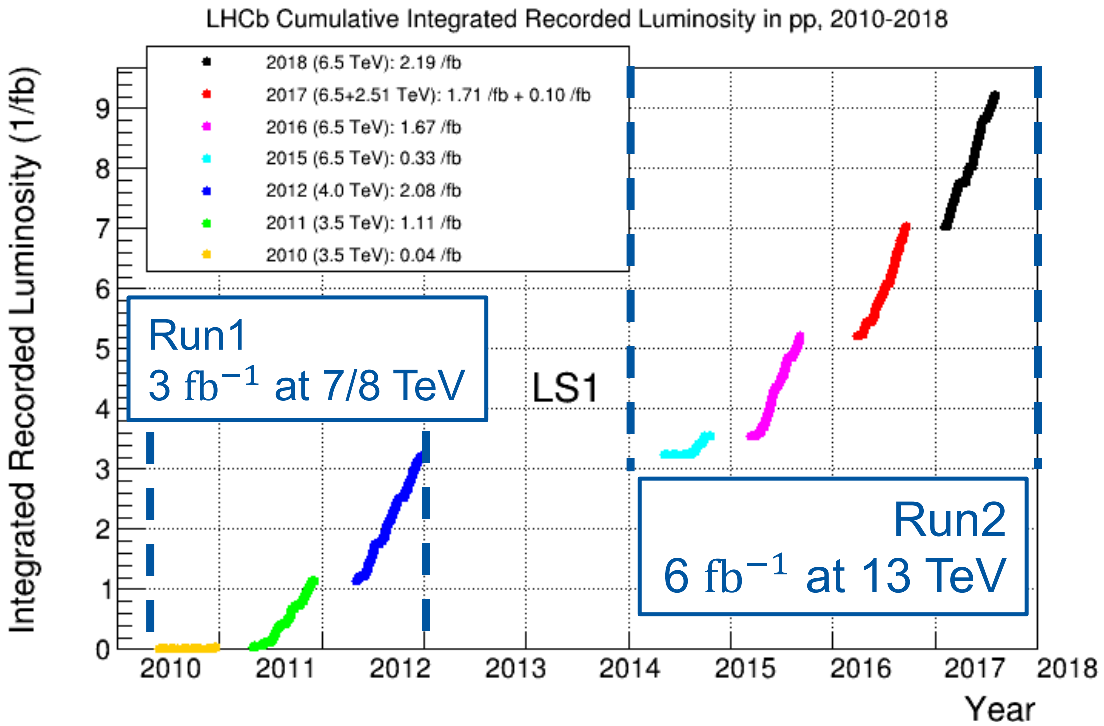


Acceptance
$2 < \eta < 5$

Tracking stations
$\epsilon_{\text{tracking}} \sim 96\%$
$\sigma_p/p \sim 0.5\% - 1\% (5 - 200\ \text{GeV})$

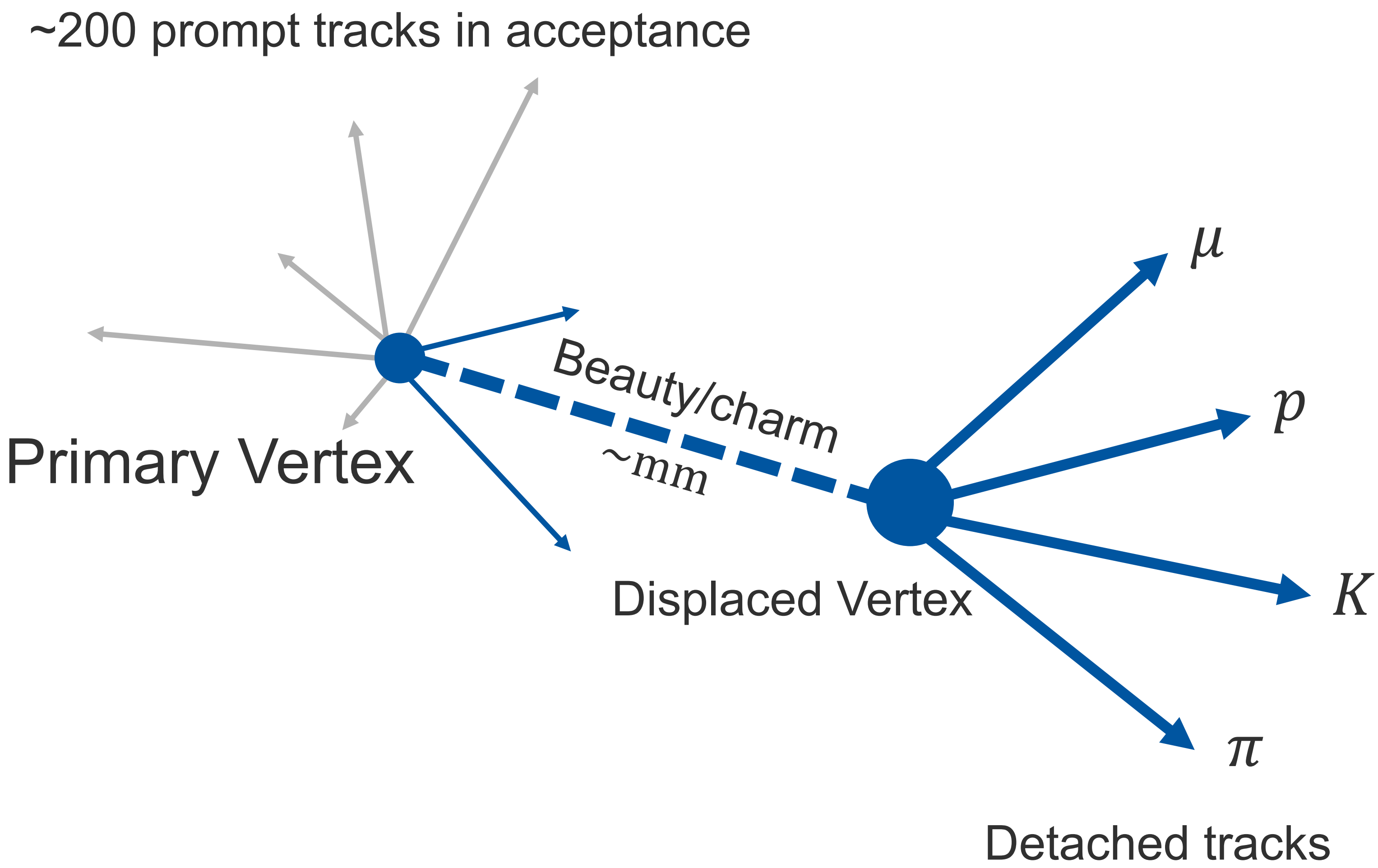
LHCb data taking

- A huge amount of $b\bar{b}$ and $c\bar{c}$ have been produced
  - About 10^{12} $b\bar{b}$ and 10^{13} $c\bar{c}$
- High b-baryon production fraction
  - $B: B_s: \Lambda_b \approx 4: 1: 2$



About 9 fb^{-1} accumulated in Run1+Run2

Reconstruct heavy flavour decays at LHCb



Beautiful Baryons

$$\Lambda_b^0 = udb$$

$$\Sigma_b^+ = uub \quad \Sigma_b^0 = udb \quad \Sigma_b^- = ddb$$

$$\Xi_b^0 = usb \quad \Xi_b^- = dsb$$

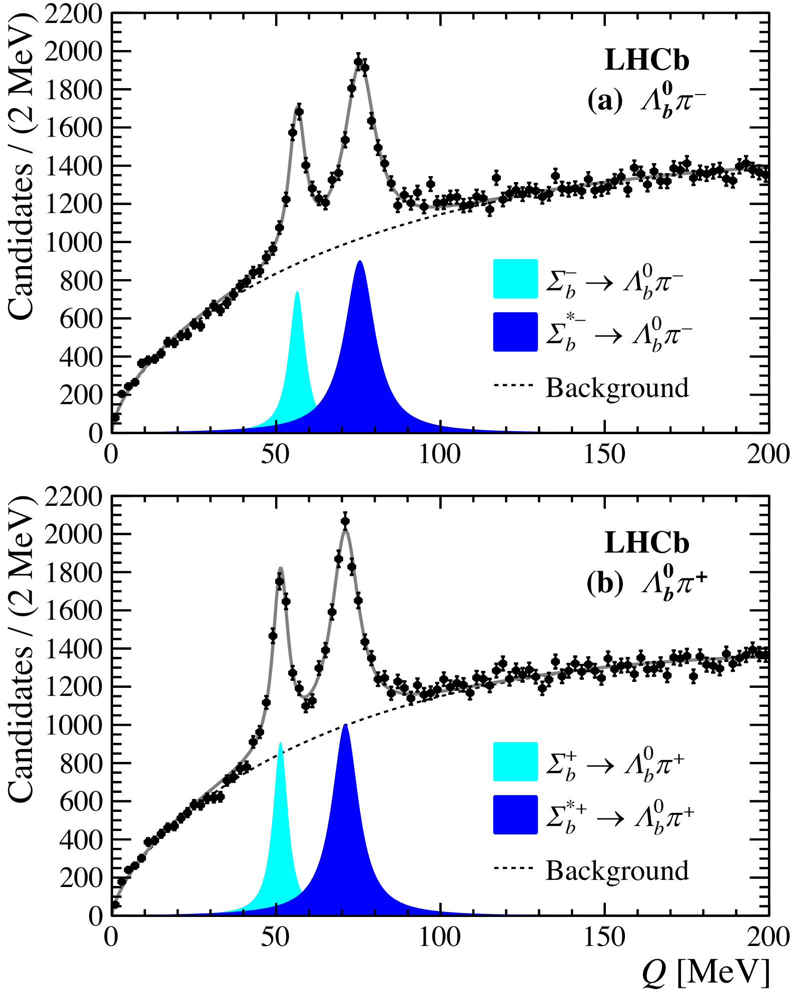
$$\Omega_b^- = ssb$$

Σ_b and Σ_b^* at LHCb

PRL 122 (2019) 012001

- Study $\Lambda_b^0\pi^\pm$ mass spectra
- With $\Lambda_b^0 \to \pi^-\Lambda_c^+(\to pK^-\pi^+)$
- 230k Λ_b^0 candidates in 3 fb^{-1}
- Measure mass and width
  - Agree with CDF measurement
  - Improved by a factor of 5

Quantity	Value [MeV]
$m(\Sigma_b^-)$	$5815.64 \pm 0.14 \pm 0.24$
$m(\Sigma_b^{*-})$	$5834.73 \pm 0.17 \pm 0.25$
$m(\Sigma_b^+)$	$5810.55 \pm 0.11 \pm 0.23$
$m(\Sigma_b^{*+})$	$5830.28 \pm 0.14 \pm 0.24$
$\Gamma(\Sigma_b^-)$	$5.33 \pm 0.42 \pm 0.37$
$\Gamma(\Sigma_b^{*-})$	$10.68 \pm 0.60 \pm 0.33$
$\Gamma(\Sigma_b^+)$	$4.83 \pm 0.31 \pm 0.37$
$\Gamma(\Sigma_b^{*+})$	$9.34 \pm 0.47 \pm 0.26$



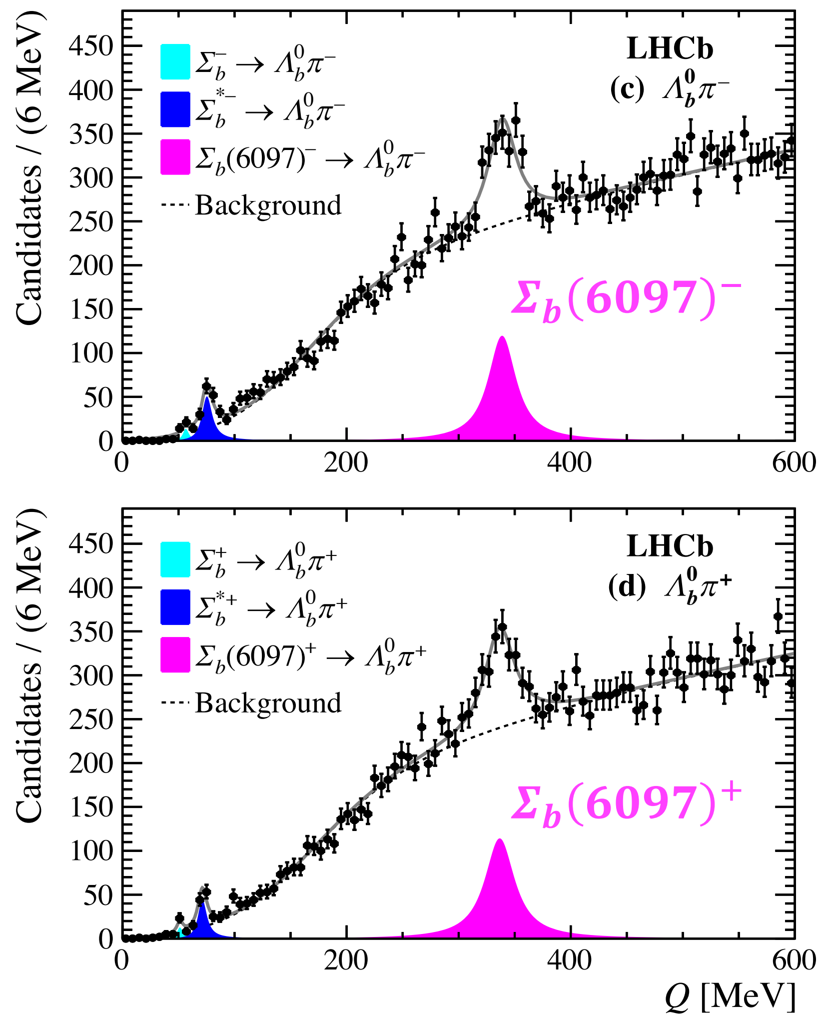
$$Q \equiv m(\Lambda_b^0\pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm)$$

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

PRL 122 (2019) 012001

- Extend to higher mass region
  - With tighter $p_{\mathrm{T}}(\pi_s)$ requirement
- Fit the Q-value distributions
- Compatible with $\Sigma_b(1P)$ states
  - Expected in heavy-quark limit
  - Might be a superposition of several resonances

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

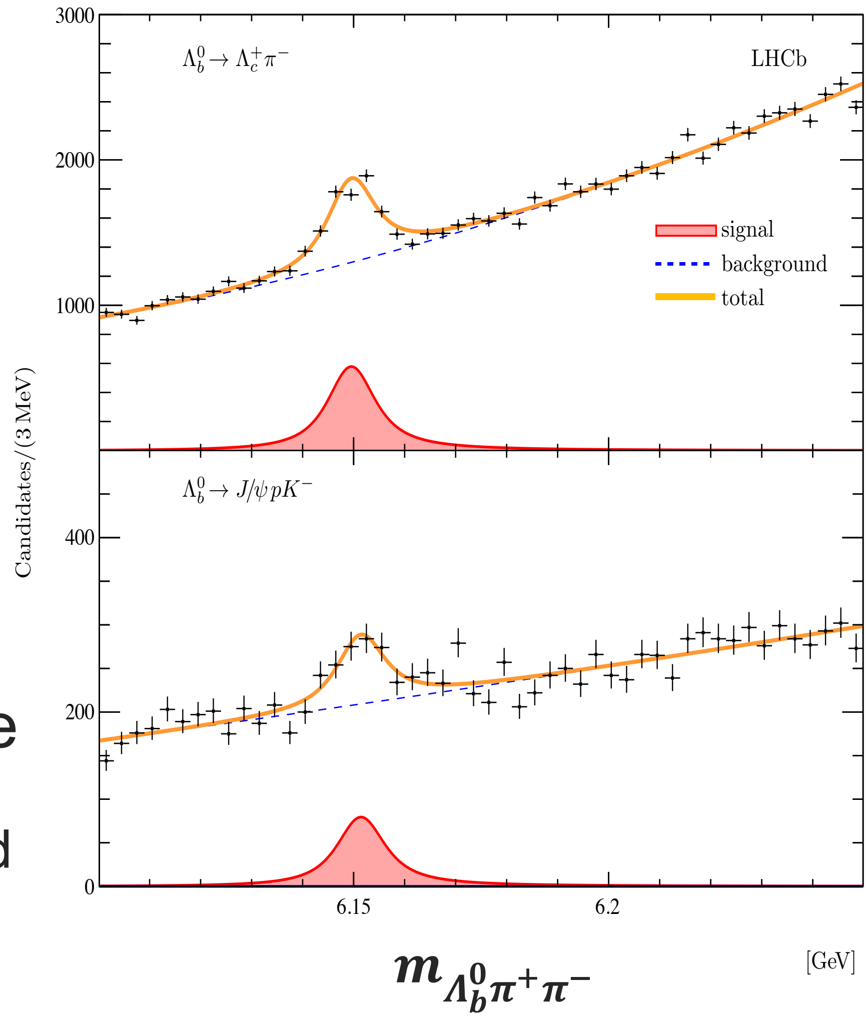


$$Q \equiv m(\Lambda_b^0\pi^{\pm}) - m(\Lambda_b^0) - m(\pi^{\pm})$$

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

arXiv:1907.13598

- Study $\Lambda_b^0\pi^+\pi^-$ spectra
- With $\Lambda_b^0 \to \pi^-\Lambda_c^+(\to pK^-\pi^+)$
- 900k Λ_b^0 candidates in 9 fb^{-1}
- Structure around 6.15 GeV
- Cross-check with
  - $\Lambda_b^0 \to pK^-J/\psi\ (\to \mu^+\mu^-)$
- Investigate decay substructure
  - Mass above the $\Sigma_b^{(*)\mp}\pi^\pm$ threshold

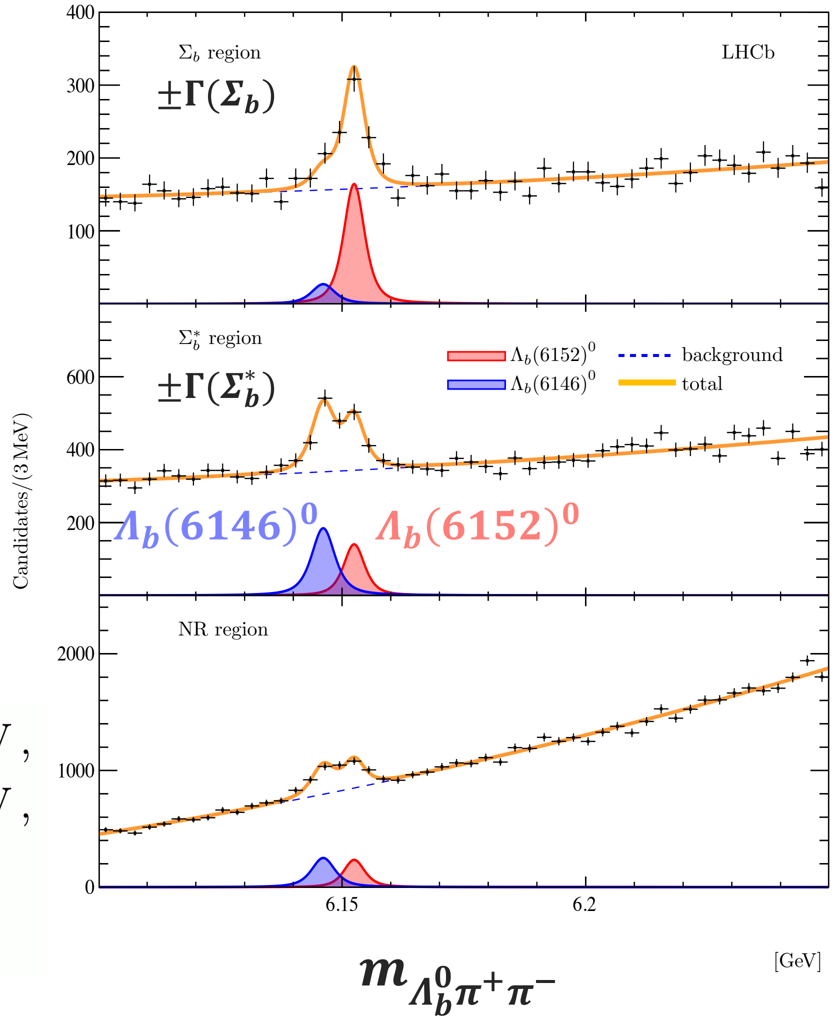


Λ_b^0 excitations in $\Lambda_b^0\pi^+\pi^-$

arXiv:1907.13598

- Split by $\Lambda_b^0\pi^\pm$ invariant mass
  - Σ_b region
  - Σ_b^* region
  - Nonresonant (NR) region
- A simultaneous fit
  - Two-signal hypothesis with 7σ
- Almost degenerate narrow states

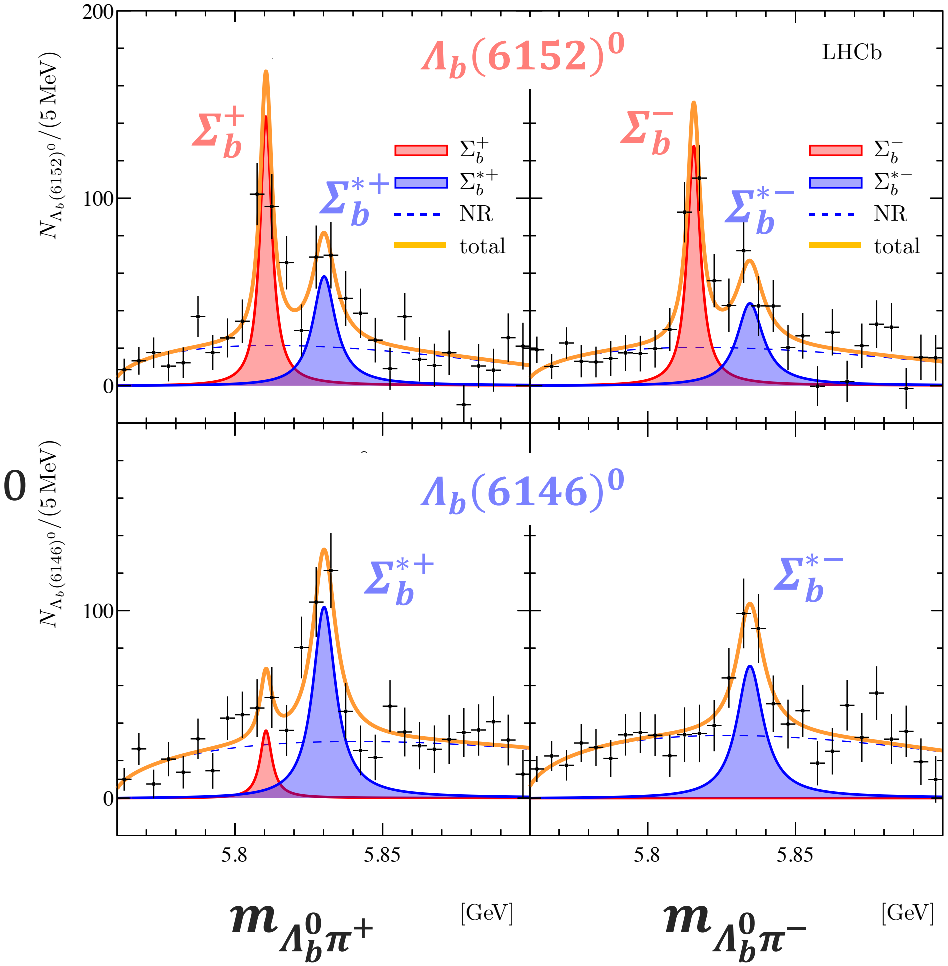
$$
\begin{aligned}
m_{\Lambda_b(6146)^0} &= 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\,\text{MeV}\,,\\
m_{\Lambda_b(6152)^0} &= 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\,\text{MeV}\,,\\
\Gamma_{\Lambda_b(6146)^0} &= 2.9 \pm 1.3 \pm 0.3\ \text{MeV}\,,\\
\Gamma_{\Lambda_b(6152)^0} &= 2.1 \pm 0.8 \pm 0.3\ \text{MeV}\,,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



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

arXiv:1907.13598

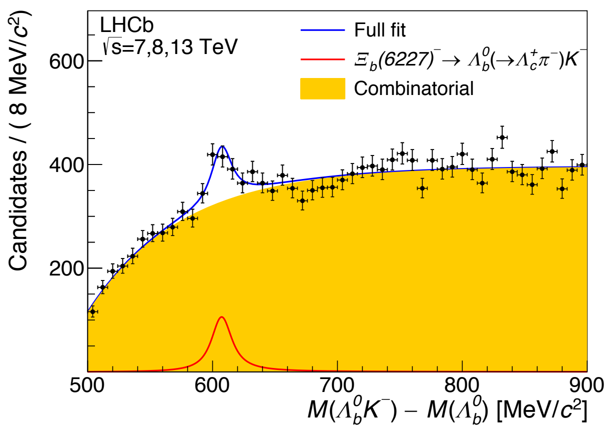
- Study $\Lambda_b^0\pi^\pm$ spectra
  - sPlot technique
- Different couplings
  - $\Lambda_b(6152)^0$ to both Σ_b and Σ_b^*
  - $\Lambda_b(6146)^0$ primarily to Σ_b^*
- Consistent with the $\Lambda_b(1D)^0$ doublet of $J^P = \frac{3}{2}^+$ and $\frac{5}{2}^+$
  - Observed mass
  - Measured natural width
  - Observed decay pattern



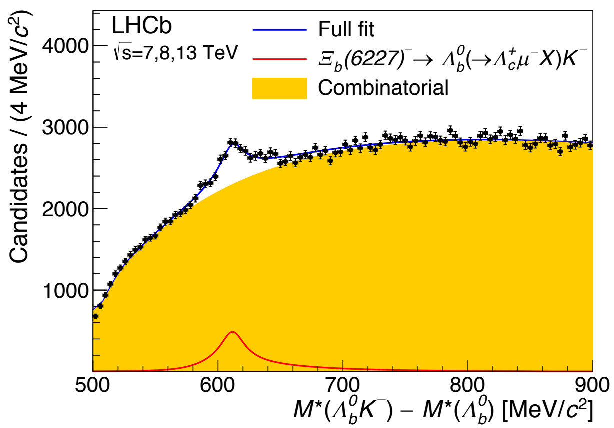
Observation of $\Xi_b(6227)^-$

PRL 121 (2018) 072002

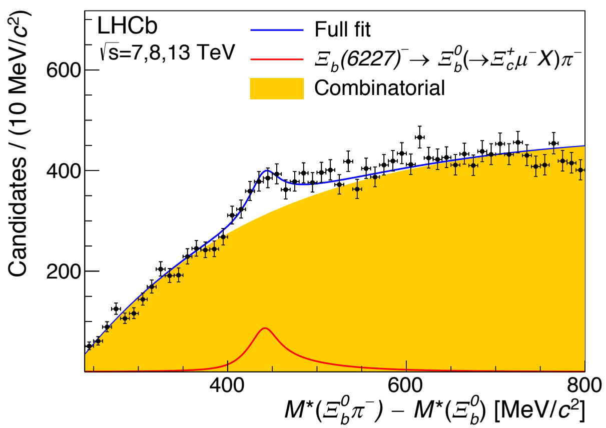
- Study the $\Lambda_b^0 K^-$ and $\Xi_b^0 \pi^-$ spectra in 4.5 fb^{-1}
- The most massive baryon observed so far
  - $m_{\Xi_b(6227)^-} = 6226.9 \pm 2.0 \pm 0.3 \pm 0.2$ MeV
  - $\Gamma_{\Xi_b(6227)^-} = 18.1 \pm 5.4 \pm 1.8$ MeV



$\Xi_b(6227)^- \to \Lambda_b^0(\to \Lambda_c^+\pi^-)K^-$



$\Xi_b(6227)^- \to \Lambda_b^0(\to \Lambda_c^+\mu^- X)K^-$



$\Xi_b(6227)^- \to \Xi_b^0(\to \Xi_c^+\mu^- X)\pi^-$

Observation of $\Xi_b(6227)^-$

PRL 121 (2018) 072002

- Production ratios

$$R(\Lambda_b^0 K^-) \equiv \frac{f_{\Xi_b(6227)^-}}{f_{\Lambda_b^0}} \mathcal{B}(\Xi_b(6227)^- \to \Lambda_b^0 K^-)$$

$$R(\Xi_b^0 \pi^-) \equiv \frac{f_{\Xi_b(6227)^-}}{f_{\Xi_b^0}} \mathcal{B}(\Xi_b(6227)^- \to \Xi_b^0 \pi^-)$$

Quantity $[10^{-3}]$	7 , 8 TeV	13 TeV
$R(\Lambda_b^0 K^-)$	$3.0 \pm 0.3 \pm 0.4$	$3.4 \pm 0.3 \pm 0.4$
$R(\Xi_b \pi^-)$	$47 \pm 10 \pm 7$	$22 \pm 6 \pm 3$

- Assuming $f_{\Xi_b^0} \approx 0.1 f_{\Lambda_b^0}$

$$\mathcal{B}(\Xi_b(6227)^- \to \Lambda_b^0 K^-)/\mathcal{B}(\Xi_b(6227)^- \to \Xi_b^0 \pi^-) \approx 1$$

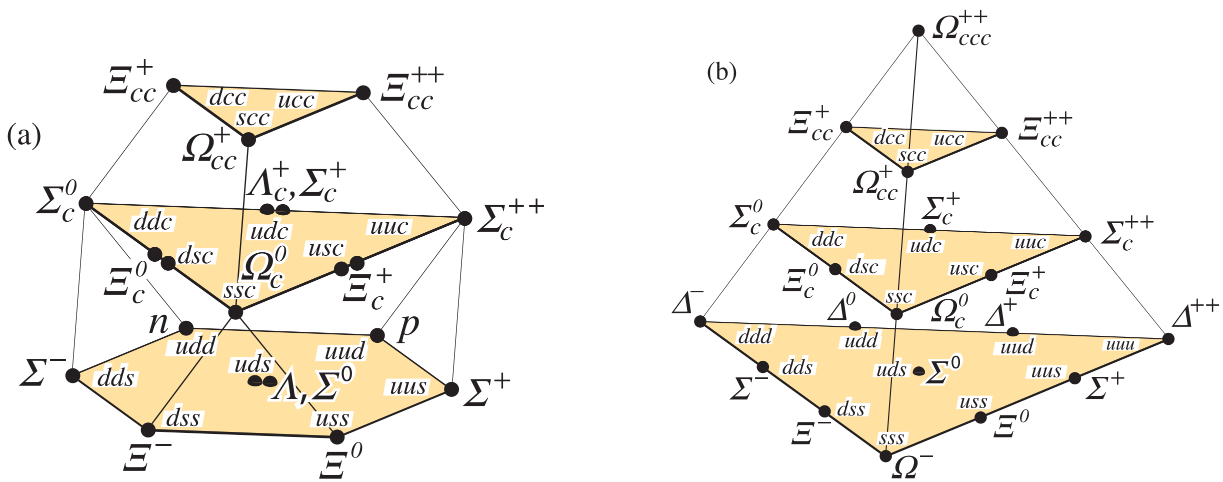
- Candidate of $\Xi_b(1P)^-$ or $\Xi_b(2S)^-$ or the admixture?

DOUBLY CHARMED BARYONS

The doubly charmed baryons

- Two SU(4) 20-plets containing SU(3) triplets
  - $\Xi_{cc}^{+} = ccd,\ \Xi_{cc}^{++} = ccu,\ \Omega_{cc}^{+} = ccs$

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



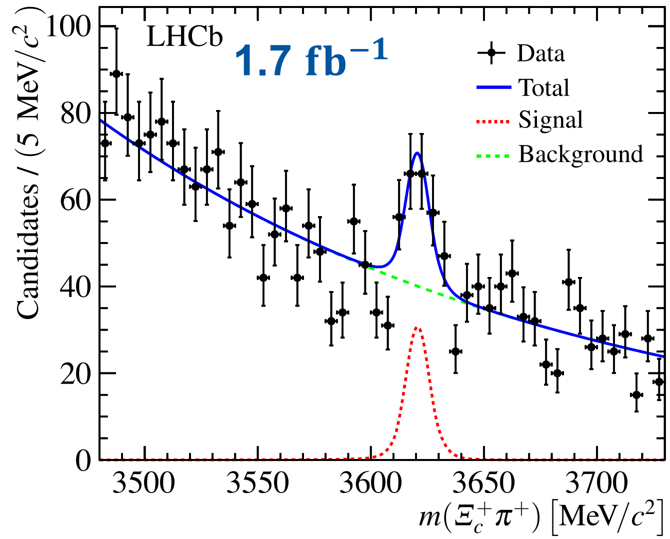
$J^P = \frac{3}{2}^+$

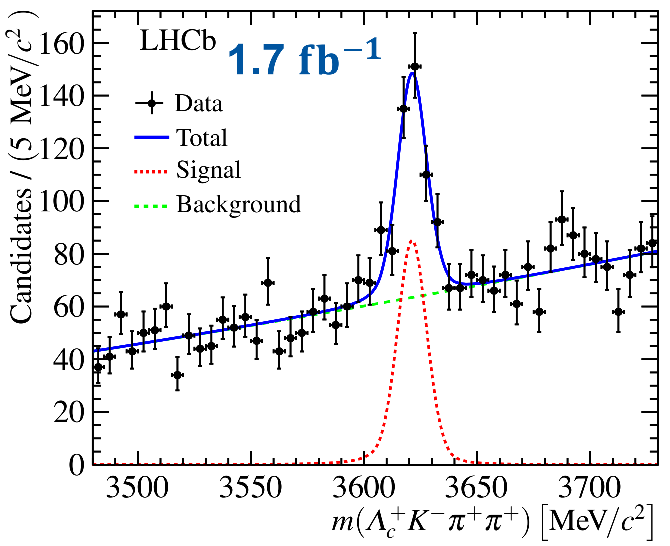
- Ξ_{cc}^{++} was observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ final state in 2017
  - $m_{\Xi_{cc}^{++}} = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14$ MeV — PRL 119 (2017) 112001
  - $\tau_{\Xi_{cc}^{++}} = 0.256^{+0.024}_{-0.022} \pm 0.014$ ps — PRL 121 (2018) 052002

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

PRL 121 (2018) 162002

- Study $\Xi_c^+(\to pK^-\pi^+)\pi^+$ spectrum
- Significance of 5.9σ
- Weighted average
  - $m_{\Xi_{cc}^{++}} = 3621.24 \pm 0.65 \pm 0.31$ MeV
- $\mathcal{R} \equiv \dfrac{\mathcal{B}(\Xi_{cc}^{++}\to\Xi_c^+\pi^+;\Xi_c^+\to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^+;\Lambda_c^+\to pK^-\pi^+)}$
  - $\mathcal{R} = (3.5 \pm 0.9 \pm 0.3)\times 10^{-2}$
  - $\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$ [Belle, Phys.Rev. D100 031101]
  - $\dfrac{\mathcal{B}(\Xi_{cc}^{++}\to\Xi_c^+\pi^+)}{\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^+)} \approx 0.5$

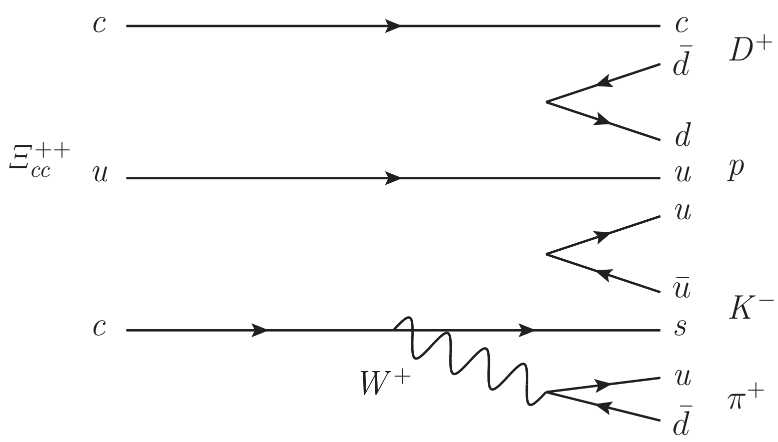




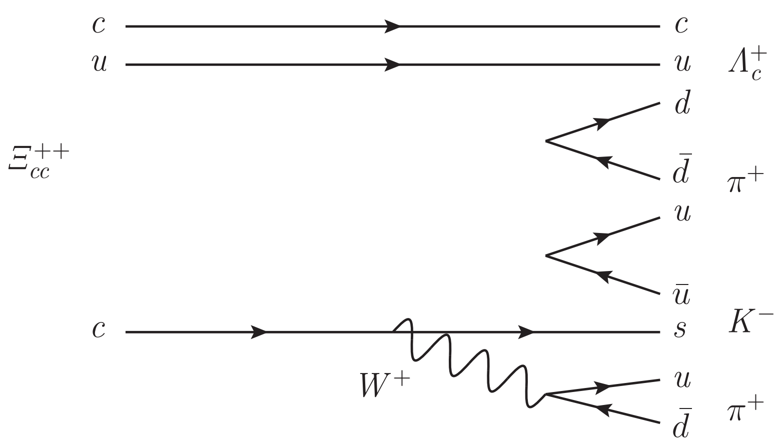
A search for $\Xi_{cc}^{++} \to D^{+} p K^{-} \pi^{+}$

arXiv:1905.02421

- Helpful to further understand the dynamics of Ξ_{cc}^{++}
- Efficient D^{+} trigger at LHCb
- Low branching fraction due to small phase space



$Q = 180$ MeV

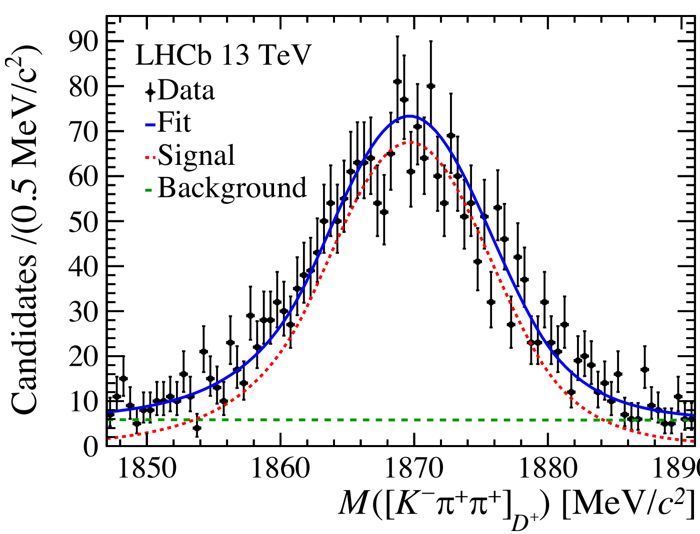


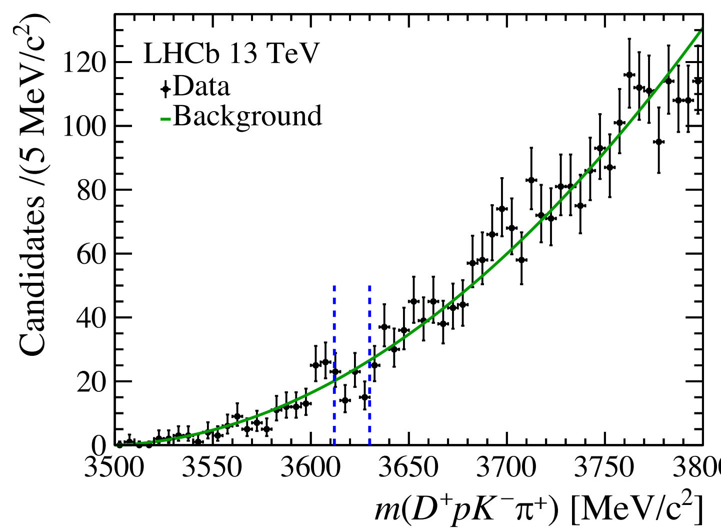
$Q = 320$ MeV

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

arXiv:1905.02421

- Study the $D^+pK^-\pi^+$ spectrum with 2016 data of 1.7 fb^{-1}
- With $D^+ \to K^-\pi^+\pi^+$
- No significant signal is observed
- Upper limit on $\mathcal{R} \equiv \frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+)}$
  - $\mathcal{R} < 2.1 \times 10^{-2}$ at 95% CL

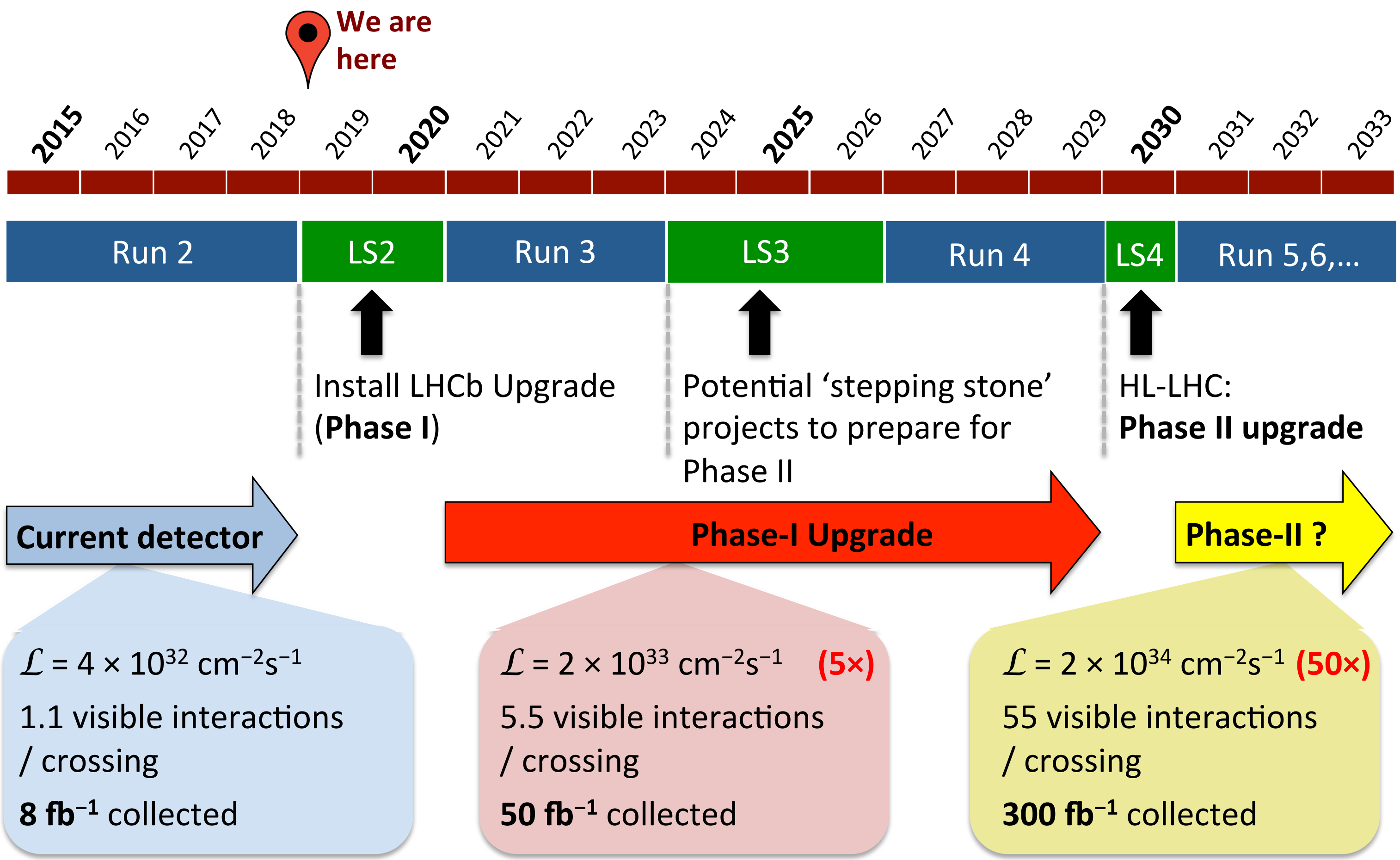




Prospects

CERN-LHCC-2011-001
CERN-LHCC-2017-003

- LHCb Upgrade I: installation ongoing
- LHCb Upgrade II: investigation started



Courtesy of Mark Williams

Projection of the yield

CERN-LHCC-2018-027

- LHCb data sample will be boosted
  - Observation of new states
  - Precise measurement of the observed states

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

[*] Updated according to the latest measurement

Summary

- LHCb has been and will continue providing propellants for heavy flavour spectroscopy
  - Observation of several beautifully excited baryons
  - Progress in the sector of doubly charmed baryons
  - The full Run1+Run2 data are being exploited
  - The ongoing upgrade will increase the instantaneous luminosity by a factor of 5 with fully software trigger

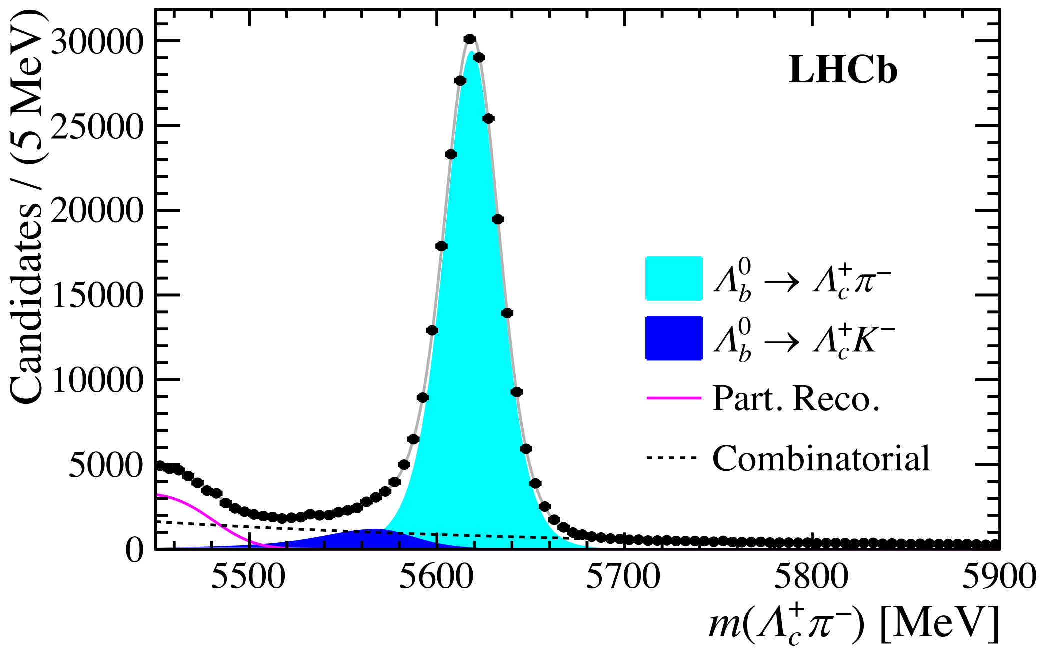
Stay Tuned

Backup slides

Σ_b and Σ_b^* at LHCb

PRL 122 (2019) 012001

- Study $\Lambda_b^0\pi^\pm$ spectra
- With $\Lambda_b^0 \to \pi^-\Lambda_c^+(\to pK^-\pi^+)$
- 230k Λ_b^0 candidates in 3 fb^{-1}



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

arXiv:1907.13598

- $\Lambda_b^0\pi^+\pi^-$ spectra
- With $\Lambda_b^0 \to \pi^-\Lambda_c^+(\to pK^-\pi^+)$ and $\Lambda_b^0 \to pK^-J/\psi\,(\to \mu^+\mu^-)$