Rare and very rare decays of hyperons and heavy baryons at LHCb

Gabriele Martelli
Università degli Studi di Perugia and INFN Perugia
On behalf of the LHCb collaborartion

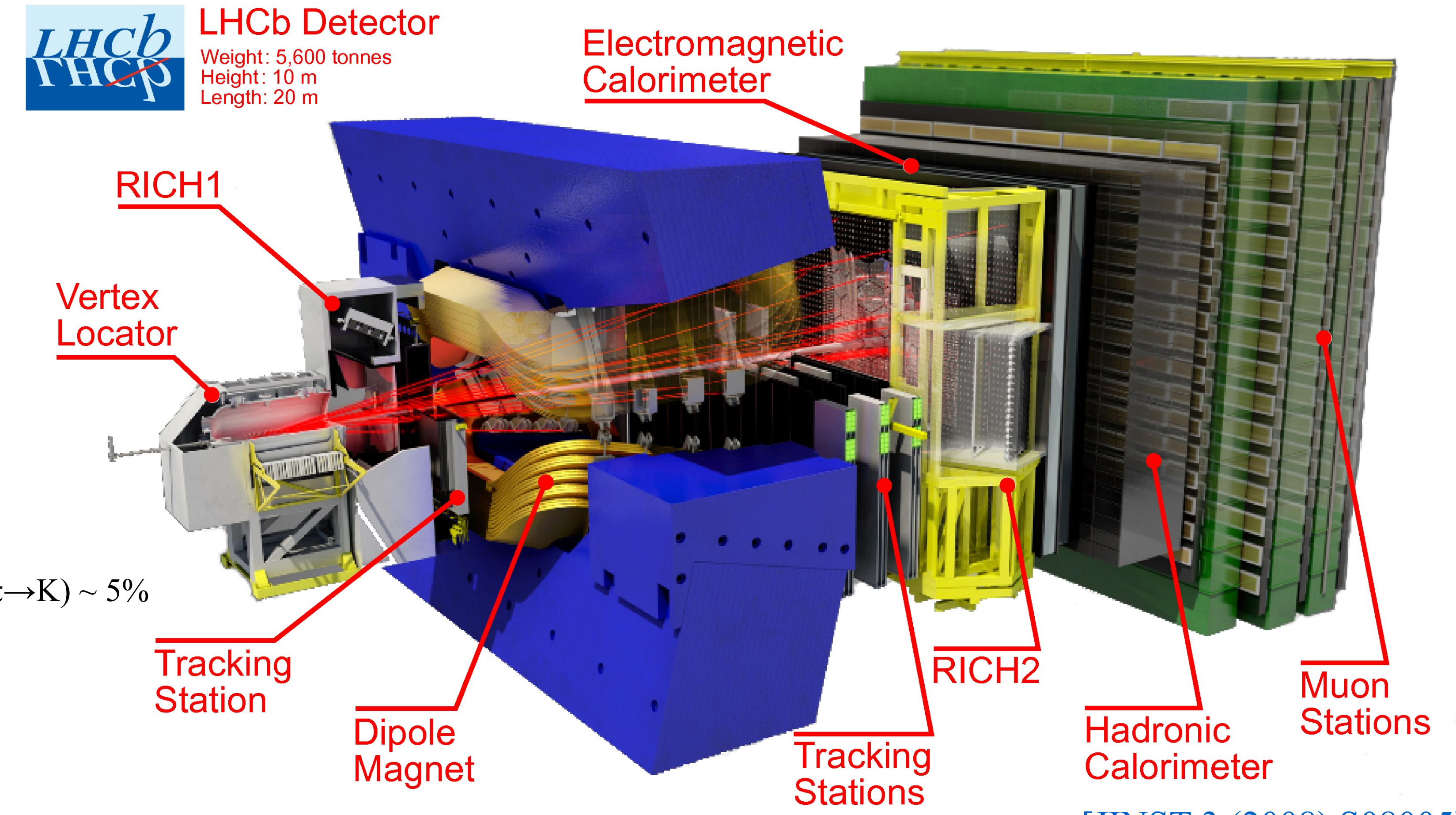
La Thuile, 5 – 11 March 2023
Les Rencontres de Physique de la Vallée d'Aoste

Outline

- First observation and branching fraction measurement of the $\Lambda_b^0 \to D_s^- p$ decay
  - First observation of the decay
  - Submitted on December 23, 2022
  - [arXiv:2212.12574] **Submitted to JHEP**
- Observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$
  - Observation of a new decay mode
  - Submitted on February 11, 2022
  - [JHEP. 2022, 38 (2022)]
- Evidence for the Rare Decay $\Sigma^+ \to p\mu^+\mu^-$
  - Search for the rare decay
  - Submitted on December 22, 2017
  - [Phys. Rev. Lett. 120, 221803]
  - **Prospects for the ongoing Run2 analysis**

The LHCb experiment

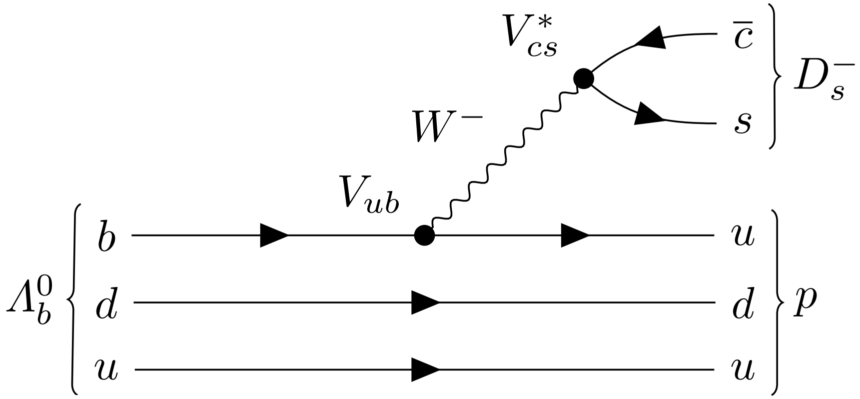
- Single arm forward spectrometer
- Fully instrumented in $2 < \eta < 5$
- Vertex Locator
  - Reconstruct vertices
  - Decay time resolution: 45 fs
  - IP resolution: 20 μm
- Dipole Magnet
  - Bending power: 4 Tm
- Tracking stattions TT and OT
  - Momentum resolution $\Delta p/p = 0.5\% - 1.0\%$ (5 GeV/c – 100 GeV/c)
- RICH detectors
  - K/π/p separation $\varepsilon(K \to K) \sim 95\%$, mis-ID $\varepsilon(\pi \to K) \sim 5\%$
- Calorimeters (ECAL, HCAL)
  - Energy measurement e/γ identification
  - $\Delta E/E = 1\ \% \oplus 10\ \%/\sqrt{E}$ (GeV)
- Muon stations
  - μ identification $\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID $\varepsilon(\pi \to \mu) \sim$ 1-3%

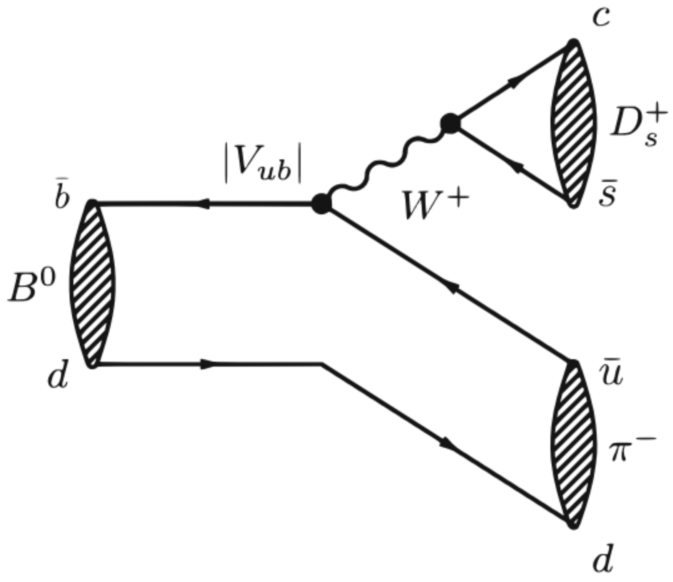


[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

The $\Lambda_b^0 \to D_s^- p$ decay

- $\Lambda_b^0 \to D_s^- p$ is a weak hadronic decay
  - Proceeding through a $b \to u$ transition
  - Described by a single leading-order diagram
- $\mathcal{B}(\Lambda_b^0 \to D_s^- p) \propto |V_{ub}|^2 |V_{cs}|^2 f_{D_s}^2 |a_{NF}|^2 |F_{\Lambda_b^0 \to p}(m_{D_s}^2)|^2$
  - $|V_{ij}|$ – CKM matrix elements describing $i \to j$ quark transitions
  - f_{D_s} – Decay constant for D_s^-
  - $F_{\Lambda_b^0 \to p}$ – Form factor describing the $\Lambda_b^0 \to p$ transition
  - a_{NF} – Non-factorizable parameter describing the gluon interactions between D_s^- and p
- Motivations:
  - V_{ub} is the CKM matrix element with the most poorly determined magnitude
    - ✓ Better knowledge on $|V_{ub}|$ would check the SM consistency [Phys. Rev. D 91, 073007]
  - $\mathcal{B}(\Lambda_b^0 \to D_s^- p)$ very similar to $\mathcal{B}(B^0 \to D_s^+ \pi^-)$ having the same tree-level transition
    - ✓ $\Lambda_b^0 \to D_s^- p$ would provide another measure of the breaking factorisation hypothesis [Eur. Phys. J. C81 (2021) 314]



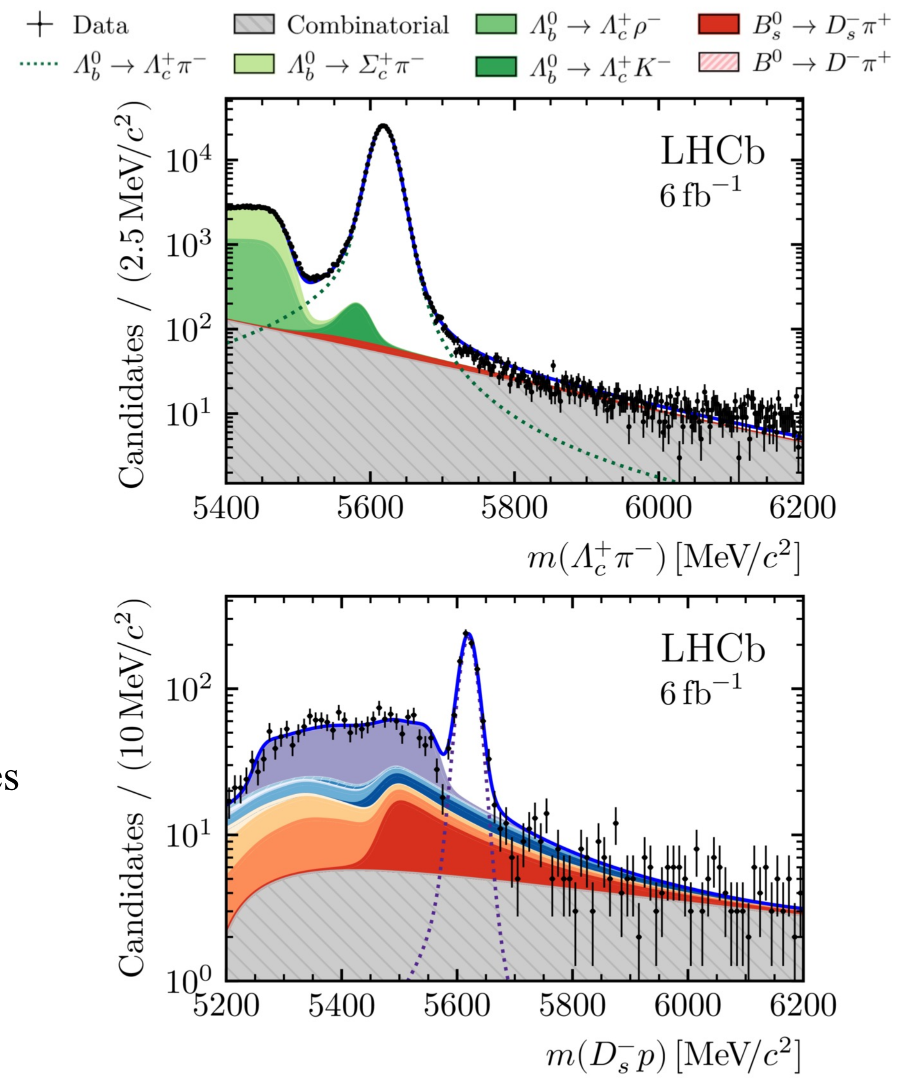


Analysis strategy for the $\Lambda_b^0 \to D_s^- p$ decay

- **First observation and branching fraction measurement of the $\Lambda_b^0 \to D_s^- p$ decay Submitted to JHEP**
  - Search perfomed with pp collision data recorded during Run2
  - $\sqrt{s} = 13$ TeV, $\mathcal{L} = 6$ fb^{-1}
- Analysis strategy:
  - $\Lambda_b^0 \to \Lambda_c^+ \pi^- (\Lambda_c^+ \to p K^- \pi^+)$ used as normalisation channel
  - D_s^- reconstructed as $D_s^- \to K^- K^+ \pi^-$

$$\mathcal{B}(\Lambda_b^0 \to D_s^- p) = \mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) \frac{N_{\Lambda_b^0 \to D_s^- p}}{N_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}} \frac{\epsilon_{\Lambda_b^0 \to \Lambda_c^+ \pi^-}}{\epsilon_{\Lambda_b^0 \to D_s^- p}} \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{\mathcal{B}(D_s^- \to K^- K^+ \pi^-)}$$

  - Efficiencies ϵ_X evaluated using simulated candidates and calibration data samples
- Yields N_X determined with using unbinned maximum-likehood fits on invariant masses
  - Signal parameterised by double-sided Hypatia function + Johnson S_U function
  - Different parameterizations for background sources:
    - ✓ Residual combinatorial
    - ✓ Partially reconstructed
    - ✓ Misidentificated background



$\Lambda_b^0 \to D_s^- p$: Results and conclusions

- $\mathcal{B}(\Lambda_b^0 \to D_s^- p)$ can be determined using measured efficiencies and yields
  - Additional inputs:
    - ✓ $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.28 \pm 0.32)\times 10^{-2}$
    - ✓ $\mathcal{B}(D_s^- \to K^-K^+\pi^-) = (5.38 \pm 0.10)\times 10^{-2}$

      [Prog. Theor. Exp. Phys. 2022 (2022) 083C01]
- The branching fraction ratio of $\Lambda_b^0 \to D_s^- p$ and $\Lambda_b^0 \to \Lambda_c^+\pi^-$ is found to be

$$\frac{\mathcal{B}(\Lambda_b^0 \to D_s^- p)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} = (2.56 \pm 0.10_{stat.} \pm 0.05_{syst.} \pm 0.14_{ext.})\times 10^{-3}$$

- The obtained $\Lambda_b^0 \to D_s^- p$ branching fraction is

$$\mathcal{B}(\Lambda_b^0 \to D_s^- p) = (12.6 \pm 0.5_{stat.} \pm 0.3_{syst.} \pm 1.2_{ext.})\times 10^{-6}$$

- This measurement will serve as input for future studies in hadronic Λ_b^0 decays

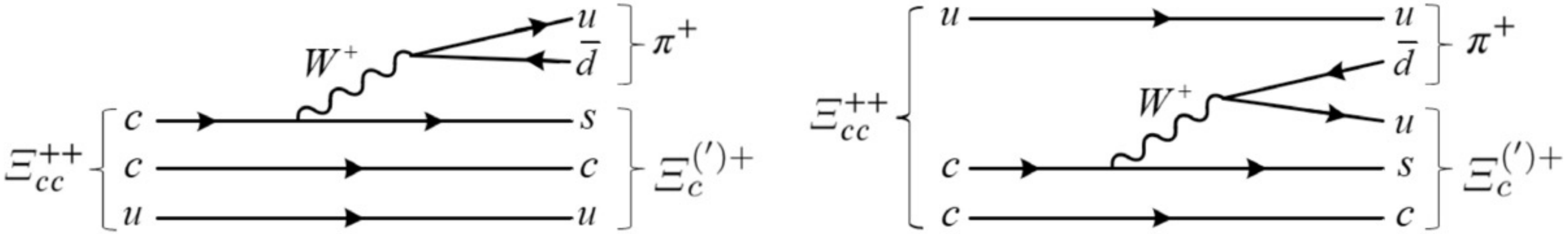
Source	Relative uncertainty (%)
Invariant-mass fits:	
$m(D_s^- p)$ fit:	
Signal parametrisation	0.54
Combinatorial background parametrisation	0.73
Constrained/fixed yields	0.71
Specific background parametrisation	0.89
$m(\Lambda_c^+\pi^-)$ fit:	
Signal parametrisation	0.27
Combinatorial background parametrisation	0.04
Constrained/fixed yields	0.03
Specific background parametrisation	0.01
Efficiencies:	
PID efficiency	0.49
hardware trigger efficiency	1.15
Reconstruction efficiency	0.50
Total	2.01

	$\Lambda_b^0 \to D_s^- p$	$\Lambda_b^0 \to \Lambda_c^+\pi^-$
Yield	831 ± 32	$(4.047 \pm 0.007) \times 10^5$
Efficiency	$(0.1819 \pm 0.0013)\%$	$(0.1947 \pm 0.0012)\%$
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)$	$(4.9 \pm 0.4) \times 10^{-3}$	
$\mathcal{B}(D_s^- \to K^-K^+\pi^-)$	$(5.38 \pm 0.10) \times 10^{-2}$	
$\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$	$(6.28 \pm 0.32) \times 10^{-2}$	

[arXiv:2212.12574]

The $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$ decay

- Doubly charmed baryons existence is predicted by the quark model [Phys. Lett. 8 (1964) 214]
  - Two charm quarks and a light quark $(\mathrm{u}, \mathrm{d}, \mathrm{s})$
  - Ideal systems to test QCD effective theories
- $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$:
  - Heavy doubly charmed baryon with a light quark u
  - Decay amplitude contributed by external and internal W-emission



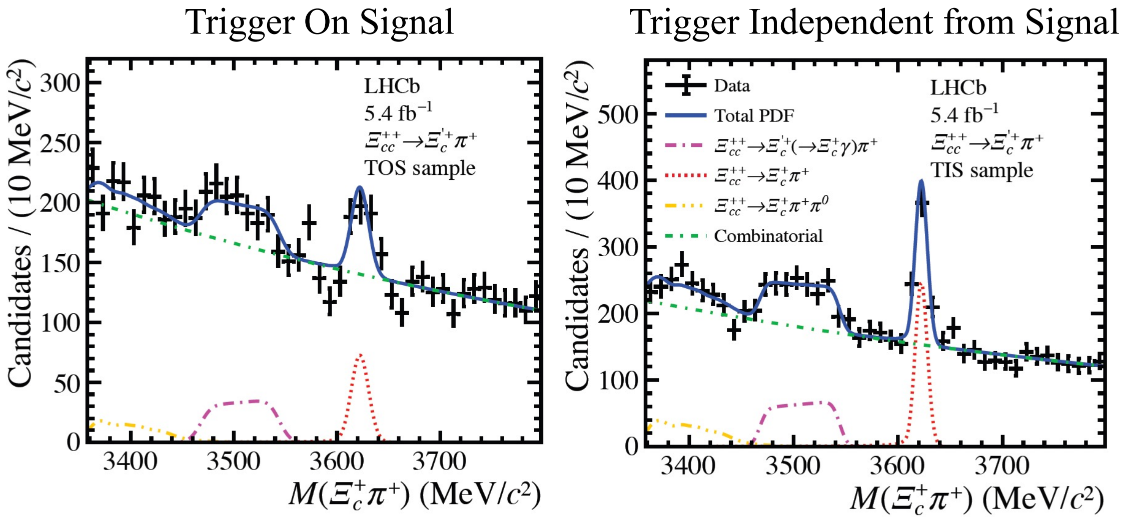
- Recent results on Ξ_{cc}^{++} by LHCb:
  - First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Lambda_c K^- \pi^+ \pi^-$ [Phys. Rev. Lett. 119, 112001]
  - First observation of the boubly charmed daryon Decay $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$ [Phys. Rev. Lett. 121, 162002]
  - Measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++} [Phys. Rev. Lett. 121, 052002]
  - Measurement of Ξ_{cc}^{++} production in pp collisions at $\sqrt{s} = 13$ TeV [Chin. Phys. C44 (2020) 022001]
  - A search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decays [JHEP10 (2019) 124]
  - Precision measurement of the Ξ_{cc}^{++} mass [JHEP02 (2020) 049]

Analysis strategy for the $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$ decay

- **Observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$** [JHEP. 2022, 38 (2022)]
  - Search perfomed with pp collision data recorded during Run2
  - $\sqrt{s} = 13$ TeV, $\mathcal{L} = 5.4\ \text{fb}^{-1}$
- Analysis strategy:
  - $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$ used as normalisation channel
  - Signal partially reconstructed with missing photon from $\Xi_c'^{+} \to \Xi_c^{+}\gamma$
  - Ξ_c^{+} baryon reconstructed with $\Xi_c^{+} \to pK^{-}\pi^{+}$ decay

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+})} = \frac{N_{\Xi_c'^{+}}}{N_{\Xi_c^{+}}} \times \frac{\epsilon_{\Xi_c^{+}}}{\epsilon_{\Xi_c'^{+}}}$$

- Yield evaluated by fitting the $\Xi_c^{+}\pi^{+}$ invariant mass distribution
  - Unbinned maximum-likelihood fit:
    - ✓ $\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$ described by a Crystal Ball function
    - ✓ $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$ by limited linear function convoluted with Gaussian
    - ✓ Combinatorial background described by an exponential function
- Fully simulated samples used to evaluate relative efficiencies



Category	$\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$	$\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$	$N_{\Xi_c'^{+}}/N_{\Xi_c^{+}}$
TOS	262 ± 53	159 ± 32	1.64 ± 0.39
TIS	494 ± 63	379 ± 32	1.30 ± 0.18

$\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$: Results and conclusions

- The relative branching fraction measurement has systematic uncertainties
  - Arising from measurements of relative signal yields and efficiencies
- Including all systematic uncertainties, the measured relative branching fraction are:
  - $1.81 \pm 0.43_{\text{stat.}} \pm 0.25_{\text{syst.}}$ for TOS sample
  - $1.34 \pm 0.19_{\text{stat.}} \pm 0.11_{\text{syst.}}$ for TIS sample
- Combination of the two measurements performed using the best linear unbiased estimator [Nucl. Instrum. Meth. A270 (1988) 110]

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+})} = 1.41 \pm 0.17_{stat.} \pm 0.10_{syst.}$$

- The result is not consistent with current theoretical predictions [Phys. Rev. D 96, 113006]
  - It will provide inputs for future calculations

Source	TOS [%]	TIS [%]
Signal model	4.9	0.8
normalisation model	3.7	3.8
Combinatorial background	0.6	3.1
Partially reconstructed background	3.7	1.5
Mass window	11.0	3.9
Simulated sample size	4.5	3.6
Lifetime and kinematic corrections	0.5	1.8
Hardware trigger	0.0	1.6
Particle identification	0.5	0.7
Sum in quadrature	13.9	7.9

[JHEP. 2022, 38 (2022)]

The $\Sigma^+ \to p\mu^+\mu^-$ decay

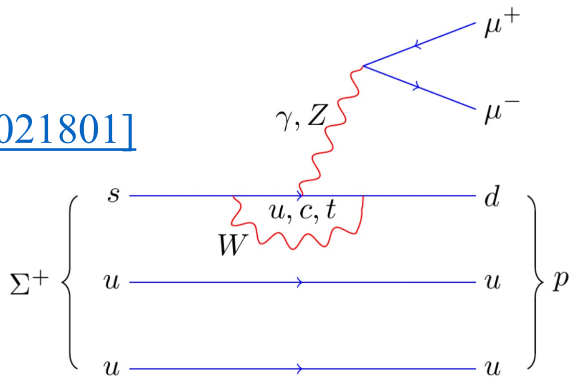
- The $\Sigma^+ \to p\mu^+\mu^-$ decay is an $s \to d$ quark-FCNC process
  - Allowed only at loop level in the SM
  - Dominated by long-distance contributions:
    $1.6 \times 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 9.0 \times 10^{-8}$
    [Phys. Rev. D 72, 074003]
- Evidence reported by the HyperCP experiment [Phys. Rev. Lett. 94 (2005) 021801]
  - Measured branching fraction, compatible with SM prediction:

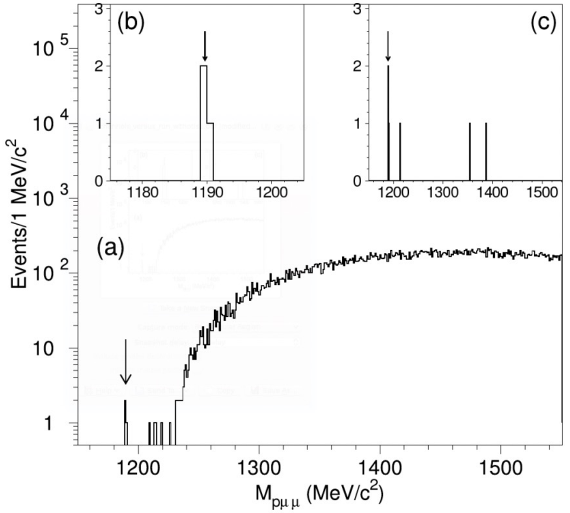
$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(8.6^{+6.6}_{-5.4} \pm 5.5\right) \times 10^{-8}$$

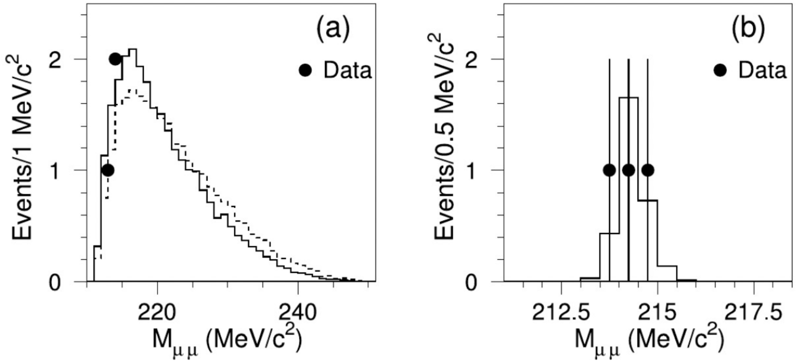
  - Three candidates observed:

$$m_{X^0} = 214.3 \pm 0.5 \text{ MeV}$$

  - Possible $\Sigma^+ \to pX^0(\to \mu^+\mu^-)$ decay with evidence for physics BSM
- Various BSM theories have been proposed to explain the HyperCP result:
  - Light pseudoscalar Higgs boson [Phys. Rev. Lett. 98, 081802 (2007)]
  - Sgoldstino [Phys. Rev. D 73, 035002 (2006)]
  - In general pseudoscalar particle with $\tau \sim s^{-14}$ estimated





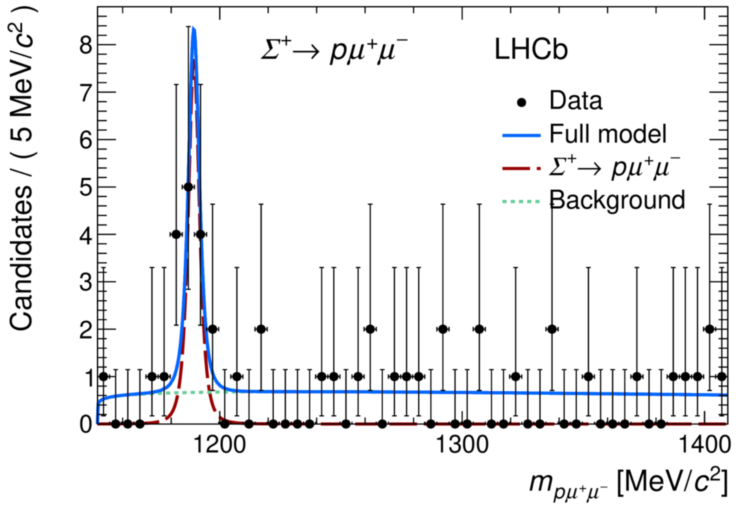


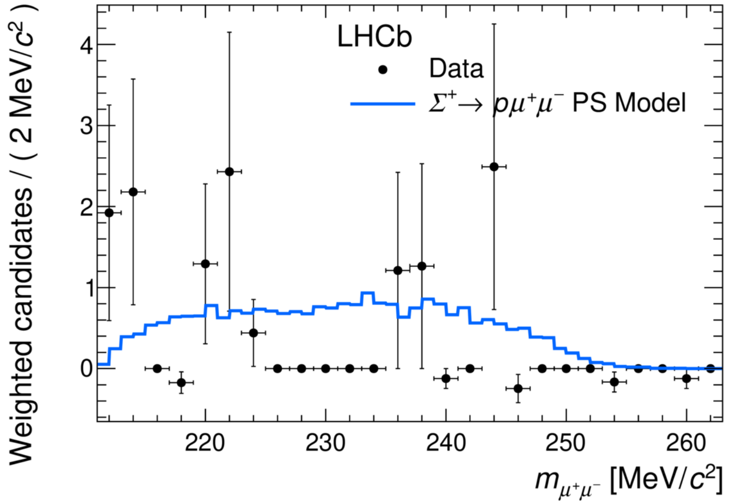
Search for $\Sigma^+ \to p\mu^+\mu^-$: Run1

- **Evidence for the Rare Decay $\Sigma^+ \to p\mu^+\mu^-$** [Phys. Rev. Lett. 120, 221803]
  - Search perfomed with pp collision data recorded during Run1
  - $\sqrt{s} = 7-8$ TeV, $\mathcal{L} = 3$ fb^{-1}
- Observed candidates for the normalisation channel $\Sigma^+ \to p\pi^0$ obtained from a binned extended maximum likehood fit to m_Σ^{corr}

$$m_\Sigma^{corr} = m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}^{PDG}$$

  - $N_{\Sigma^+\to p\pi^0} = (1171 \pm 9)\times 10^3$
- Observed $\Sigma^+ \to p\mu^+\mu^-$ candidates evaluated by fitting $m_{p\mu^+\mu^-}$
  - $N_{\Sigma^+\to p\mu^+\mu^-} = \left(10.2^{+3.9}_{-3.5}\right)$
  - Measured $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \left(2.2^{+0.9+1.5}_{-0.8-1.1}\right)\times 10^{-8}$
- No significant peak found in the dimuon invariant mass distribution
  - $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4\times 10^{-8}$ at 90% CL
  - HyperCP result excluded





$\Sigma^+ \to p\mu^+\mu^-$ ongoing analysis for Run2

- Use 2016-2018 pp collision data recorded
  - $\sqrt{s} = 13$ TeV, $\mathcal{L} = 5.6\ \text{fb}^{-1}$
  - Increase in statistics of a factor $\sim$4 from luminosity and cross-section
- Dedicated triggers implemented in Run2 since 2016
  - Good gain expected (near a factor $\sim$10) in efficiency
- **Observables in Run2**:
  - Observation of the channel
  - Repeat search for dimuon resonances in the decay spectrum
  - More precise measurement of its branching fraction
  - "Direct" CP violation measurement:

$$\mathcal{A}_{CP} = \frac{\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) - \mathcal{B}(\bar{\Sigma}^+ \to \bar{p}\mu^+\mu^-)}{\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) + \mathcal{B}(\bar{\Sigma}^+ \to \bar{p}\mu^+\mu^-)}$$

  - Differential branching fraction vs dimuon mass
  - Forward-backward asymmetry in the decay
- For the moment focus on the first three observables
  - Building the analysis ready to perform the "direct" CP violation measurement

$\Sigma^+ \to p\mu^+\mu^-$ analysis strategy for Run2

- Analysis strategy:
  - Loose preselection based on geometric and kinematic variables
  - Hard selection based on BDT and PID variables
  - Search for the observation of the channel minimizing the background
  - Develope analysis without introducing bias in $m_{p\mu^+\mu^-}$ or $m_{\mu^+\mu^-}$
  - Convertion of the signal yield into a branching fraction:

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \frac{\varepsilon_{\Sigma^+\to p\pi^0}}{\varepsilon_{\Sigma^+\to p\mu^+\mu^-}} \frac{\mathcal{B}(\Sigma^+ \to p\pi^0)}{N_{\Sigma^+\to p\pi^0}} N_{\Sigma^+\to p\mu^+\mu^-}$$

- No fully charged final state available in the Σ^+ to normalize:
  - Use high branching fraction $\Sigma^+ \to p\pi^0$
  - $\mathcal{B}(\Sigma^+ \to p\pi^0) = (51.77 \pm 0.30)\%$
  - $\Sigma^+ \to p\pi^0(\to \gamma\gamma)$ reconstructed as a charged track plus two well separated photon clusters in the calorimeter

- Analysis in final stage
  - Final result expected by the end of the year

Summary and conclusions

- Presented recent results and ongoing analysis for rare and very rare decays of hyperons and heavy baryons at LHCb:
  - $\Lambda_b^0 \to D_s^- p$ observed for the first time with measured branching fraction

$$\mathcal{B}(\Lambda_b^0 \to D_s^- p) = (12.6 \pm 0.5_{stat.} \pm 0.3_{syst.} \pm 1.2_{ext.})\times 10^{-6}$$

  - Branching fraction ratio of $\mathcal{B}(\Lambda_b^0 \to D_s^- p)$ and $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)$ determined

$$\frac{\mathcal{B}(\Lambda_b^0 \to D_s^- p)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} = (2.56 \pm 0.10_{stat.} \pm 0.05_{syst.} \pm 0.14_{ext.})\times 10^{-3}$$

  - Observed $\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+$, new decay mode for the doubly charmed baryon Ξ_{cc}^{++}
  - Branching fraction relative to that of the $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ decay measured

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+} \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+} \pi^+)} = 1.41 \pm 0.17_{stat.} \pm 0.10_{syst.}$$

  - Result not consistent with current theoretical predictions

  - $\Sigma^+ \to p\mu^+\mu^-$ searched with an excess of events observed with respect to the background expectation: $N_{\Sigma^+ \to p\mu^+\mu^-} = (10.2^{+3.9}_{-3.5})$
  - No significant structure observed in the dimuon invariant mass distribution, in contrast with the previous result from HyperCP
  - Measured branching fraction: $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+0.9+1.5}_{-0.8-1.1})\times 10^{-8}$
  - **Run2 analysis ongoing and results are expected soon**

On behalf of the LHCb collaboration thank you for your attention