Rencontres du Vietnam

Flavour Physics Conference

17-23 aug 2025

Quy Nhon

Rare (and very rare) decays at LHCb

Daniele Provenzano

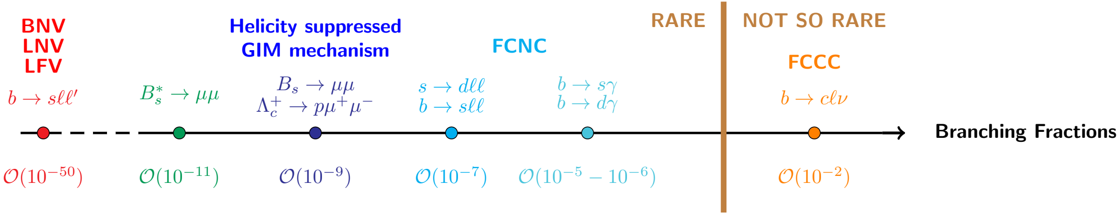
on behalf of the LHCb Collaboration

CERN, University and INFN Cagliari

Introduction: rare and very rare decays

- New Physics (NP) beyond SM $\Rightarrow$ *indirect searches*: test SM predictions to look for possible contributions from new **virtual** particles
- Rare ($\mathcal{B} < 10^{-5}$) and very rare ($\mathcal{B} < 10^{-8}$) decays $\Rightarrow$ sensitive tool to explore NP
- How would NP manifest? What to measure?
  1) Modification of the **decay rates** ($\uparrow$ or $\downarrow$) $\rightarrow$ **Branching Fractions** ($\mathcal{B}$)
  2) Modification of the **angular distributions**
  3) New sources of **CP violation**

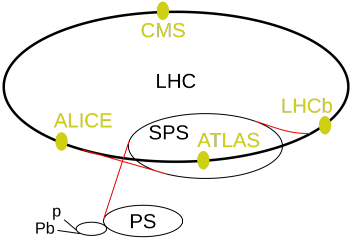
  $\rightarrow$ **CP asymmetries and angular observables**
- Why rare?



LHCb: the experiment

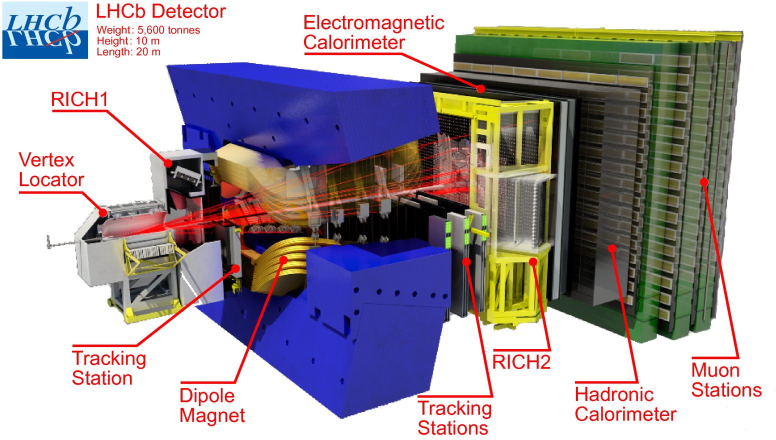
Large Hadron Collider beauty (LHCb)

- Located at the LHC (CERN)
- $\sim$ 1200 authors, from 120 institutes in 26 countries
- Dedicated experiment for precision measurements on flavour physics (CP violation, rare decays, ...)
- pp collisions at
  $\sqrt{s} = 7/8$ TeV in Run 1
  $\sqrt{s} = 13$ TeV in Run 2
  $\sqrt{s} = 13.6$ TeV in Run 3



LHCb: the detector

- single-arm forward spectrometer
- pseudorapidity $2 < \eta < 5$



- tracking system + particle identification system

Selected results:

1)	$\Sigma^+ \to p\mu^+\mu^-$	$\Rightarrow$	**FCNC**	**STRANGE**	PRL 135, 051801 (2025)
2)	$B^0 \to K^{*0}\tau^\pm e^\mp$	$\Rightarrow$	**LFV**	**BEAUTY**	arXiv 2506.15347 Sub. to JHEP
3)	$\Lambda_c^+ \to p\mu^+\mu^-$	$\Rightarrow$	**FCNC + GIM**	**CHARM**	PRD 110 (2024) 052007 PRD 111 (2025) L091102

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PHYSICAL REVIEW LETTERS **135,** 051801 (2025)

Observation of the very rare $\Sigma^+ \to p\mu^+\mu^-$ decay

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 9 April 2025; accepted 2 June 2025; published 29 July 2025)

The first observation of the $\Sigma^+ \to p\mu^+\mu^-$ decay is reported with high significance using proton-proton collision data, corresponding to an integrated luminosity of 5.4 fb^{-1}, collected with the LHCb detector at a center-of-mass energy of 13 TeV. A yield of 237 ± 16 $\Sigma^+ \to p\mu^+\mu^-$ decays is obtained, where the uncertainty is statistical only. A branching fraction of $(1.08 \pm 0.17) \times 10^{-8}$ is measured, where the uncertainty includes statistical and systematic sources. No evidence of resonant structures is found in the dimuon invariant-mass distribution. All results are compatible with standard model expectations. This represents the rarest decay of a baryon ever observed.

LHCb-PAPER-2025-002

Published in PRL on 29th July
PRL 135, 051801 (2025)

LHCb: strange hadrons production

- Huge strange-hadrons production
  (kaons and hyperons Λ^0/Σ)
- About one strange-hadron per event
  (compared to one B meson every 1000 events)
- Statistics necessary for
  $\rightarrow$ precision measurements of strange decays
  $\rightarrow$ searches for rare strange decays

[JHEP 05 (2019) 048]

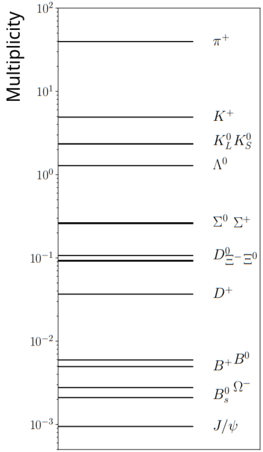
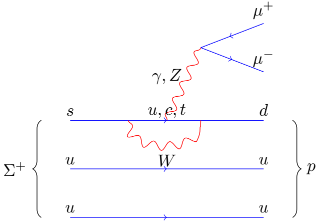
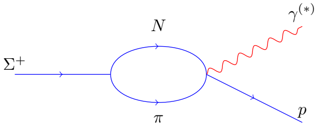


Figure: Multiplicity of particles produced in a single pp interaction

$\Sigma^+ \to p\mu^+\mu^-$: motivation

- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare **FCNC**
  - Short-distance contribution (penguin/box diagrams) $\mathcal{B} \sim O(10^{-12})$
  - Long-distance contribution (from the decay $\Sigma^+ \to p\gamma^*$)
    $1.2 \times 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-)^{SM} < 7.8 \times 10^{-8}$
    [Phys. Rev. D72 (2005) 074003]
    [JHEP 1810 (2018) 040]
    [Phys. Rev. D111 (2025) 013003]





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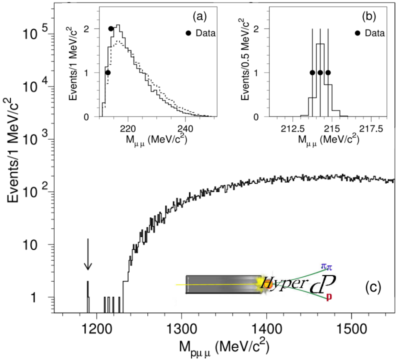
    [Phys. Rev. D72 (2005) 074003]
    [JHEP 1810 (2018) 040]
    [Phys. Rev. D111 (2025) 013003]
- First evidence found by **HyperCP** (2005)
  - 3 events in absence of background
  - Measured branching fraction $\mathcal{B} = (8.6^{+6.6}_{-5.4}) \times 10^{-8}$
    [Phys. Rev. Lett. 94 (2005) 021801]
- The "**HyperCP anomaly**"
  - All the 3 signal events had the same dimuon invariant mass
    $m_{X_0} = 214.3 \pm 0.5$ MeV/c^2
  - Possible $\Sigma^+ \to pX^0(\to \mu^+\mu^-)$ decay

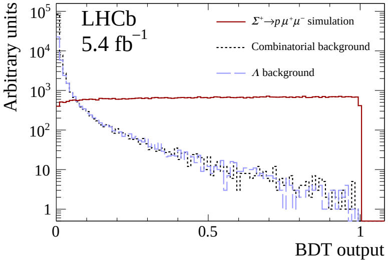


$\Sigma^+ \to p\mu^+\mu^-$: analysis

- **Analysis with Run 1 data** (2011–2012) $\Rightarrow \mathcal{L} = 3$ fb^{-1}, evidence with 4.1σ [PRL 120 (2018) 221803]
- **Analysis with Run 2 data** (2016–2018) $\Rightarrow \mathcal{L} = 5.4$ fb^{-1} **[PRL 135, 051801 (2025)]**
- **Improvements Run 2 w.r.t. Run 1**
  - Increase in statistics
  - Increase in performances $\Rightarrow$ factor $\sim$ 13 larger

Run 2 analysis

- **Background sources**
  - Combinatorial (random associations)
  - $\Lambda^0 \to p\pi^-$ decays where misID $\pi \to \mu$ with accidental μ
- **No other background sources**
  - small q-value (~ 40 MeV/c^2), e.g. $\Sigma^+ \to p\pi^+\pi^-$ forbidden
  - misID decays with higher mass peak, e.g. $K^+ \to \pi\pi\pi$ excluded
- **Selection strategy**
  1. Preselection on kinematic/PID variables
  2. Multivariate selection (output=BDT)

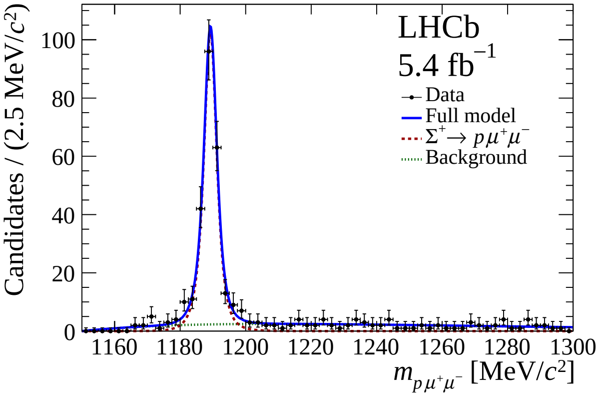


$\Sigma^+ \to p\mu^+\mu^-$: observation

Fit to the $p\mu^+\mu^-$ invariant mass distribution $\Rightarrow$ fitted yield $N_{\Sigma^+\to p\mu^+\mu^-} = 237 \pm 16$

FIRST OBSERVATION WITH OVERWHELMING SIGNIFICANCE

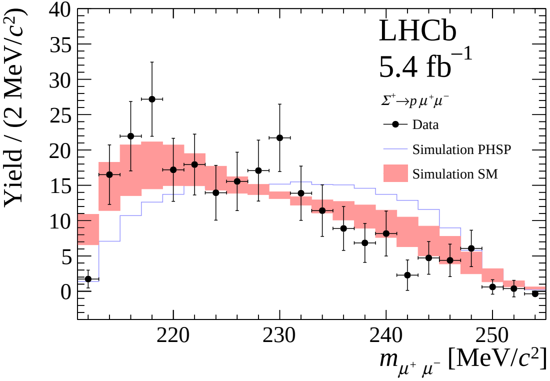
PRL 135, 051801 (2025)



$\Sigma^+ \to p\mu^+\mu^-$: scan in the $\mu^+\mu^-$ invariant mass

- Search for resonances in the dimuon invariant mass distribution
- No evidence of resonant structures found $\Rightarrow$ HyperCP anomaly excluded
- Distribution compatible with SM prediction

PRL 135, 051801 (2025)



Distribution of background-subtracted dimuon invariant mass for $\Sigma^+ \to p\mu^+\mu^-$ candidates in data compared with simulation (PHSP blue line, SM amplitude red band).

$\Sigma^+ \to p\mu^+\mu^-$: branching fraction

Number of signal candidates converted into a branching fraction through a normalisation to the $\mathbf{\Sigma^+ \to p\pi^0}$ **decay**

PRL 135, 051801 (2025)

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

The resulting branching fraction is:

RUN 2

$$\boxed{\boldsymbol{\mathcal{B}\left(\Sigma^+ \to p\mu^+\mu^-\right) = (1.08 \pm 0.17) \times 10^{-8}}}$$

In agreement with SM predictions

THIS IS THE RAREST BARYON DECAY EVER OBSERVED

Selected results:

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CERN-EP-2025-107
LHCb-PAPER-2025-005
June 18, 2025

Search for the lepton-flavour-violating decays $B^0 \to K^{*0}\tau^\pm e^\mp$

LHCb collaboration[†]

Abstract

A first search for the lepton-flavour-violating decays $B^0 \to K^{*0}\tau^\pm e^\mp$ is presented. The analysis is performed using a sample of proton-proton collision data, collected with the LHCb detector at a centre-of-mass energy of 13 TeV between 2016 and 2018, corresponding to an integrated luminosity of 5.4 fb^{-1}. No significant signal is observed, and upper limits on the branching fractions are determined to be $\mathcal{B}(B^0 \to K^{*0}\tau^- e^+) < 5.9\ (7.1) \times 10^{-6}$ and $\mathcal{B}(B^0 \to K^{*0}\tau^+ e^-) < 4.9\ (5.9) \times 10^{-6}$ at the 90% (95%) confidence level.

Submitted to JHEP

LFV searches at LHCb

- Neutrino oscillations lead to charged-LFV
- cLFV highly suppressed $(m_\nu/m_W)^4 \sim \mathcal{O}(10^{-50})$ and their observation will constitute an unambiguous **sign of NP**
- Some **NP models** (LQ, SUSY, ...) predicts $\mathcal{B}$ close to current experimental limit
- **B factories and LHCb** set stringent LFV bounds
- LHCb has carried out several searches for cLFV decays with $e\mu$ and $\tau\mu$ final states
- Till now, τe coupling has only been tested by `BaBar` and `Belle`

Leptons	Decay	Limit (90% C.L.)	Integrated luminosity	Experiment
$e\mu$	$B^0 \to e^\mp\mu^\pm$	1.0×10^{-9} [84]	$3fb^{-1}$	LHCb
	$B^0_s \to e^\mp\mu^\pm$	5.4×10^{-9} [84]	$3fb^{-1}$	LHCb
	$B^0 \to \pi^0 e^\mp\mu^\pm$	1.4×10^{-7} [85]	472M BB ($426fb^{-1}$)	BaBar
	$B^+ \to \pi^+ e^\mp\mu^\pm$	1.7×10^{-7} [85]	472M BB ($426fb^{-1}$)	BaBar
	$B^0 \to K^0 e^\mp\mu^\pm$	3.8×10^{-8} [86]	772M BB ($771fb^{-1}$)	Belle
	$B^0 \to K^{*0} e^\mp\mu^\pm$	10.1×10^{-9} [87]	$9fb^{-1}$	LHCb
	$B^0 \to K^{*0} e^-\mu^+$	5.7×10^{-9} [87]	$9fb^{-1}$	LHCb
	$B^0 \to K^{*0} e^+\mu^-$	6.8×10^{-9} [87]	$9fb^{-1}$	LHCb
	$B^+ \to K^+ e^+\mu^-$	7.0×10^{-9} [88]	$3fb^{-1}$	LHCb
	$B^+ \to K^+ e^-\mu^+$	6.4×10^{-9} [88]	$3fb^{-1}$	LHCb
	$B^+ \to K^{*+} e^-\mu^+$	9.9×10^{-7} [89]	472M BB ($426fb^{-1}$)	BaBar
	$B^+ \to K^{*+} e^+\mu^-$	1.3×10^{-6} [89]	472M BB ($426fb^{-1}$)	BaBar
	$B^+ \to D^- e^+\mu^+$	1.8×10^{-6} [90]	772M BB ($771fb^{-1}$)	Belle
	$B^0_s \to \phi e^\pm\mu^\mp$	1.6×10^{-8} [87]	$9fb^{-1}$	LHCb
$\tau\mu$	$B^0 \to \tau^\mp\mu^\pm$	1.4×10^{-5} [91]	$3fb^{-1}$	LHCb
	$B^0_s \to \tau^\mp\mu^\pm$	4.2×10^{-5} [91]	$3fb^{-1}$	LHCb
	$B^+ \to \pi^+\tau^+\mu^-$	4.5×10^{-5} [85]	472M BB ($426fb^{-1}$)	BaBar
	$B^+ \to \pi^+\tau^-\mu^+$	2.45×10^{-5} [85]	472M BB ($426fb^{-1}$)	BaBar
	$B^0 \to K^{*0}\tau^+\mu^-$	1.0×10^{-5} [92]	$9fb^{-1}$	LHCb
	$B^0 \to K^{*0}\tau^-\mu^+$	9.8×10^{-6} [92]	$9fb^{-1}$	LHCb
	$B^+ \to K^+\tau^+\mu^-$	5.9×10^{-6} [93]	772M BB ($771fb^{-1}$)	Belle
	$B^+ \to K^+\tau^-\mu^+$	2.45×10^{-5} [93]	772M BB ($771fb^{-1}$)	Belle
	$B^0_s \to \phi\tau^\pm\mu^\mp$	1.0×10^{-5} [94]	$9fb^{-1}$	LHCb
τe	$B^0 \to e^\mp\tau^\pm$	1.6×10^{-5} [95]	772M BB ($771fb^{-1}$)	Belle
	$B^0_s \to e^\mp\tau^\pm$	1.4×10^{-3} [96]	772M BB ($771fb^{-1}$)	Belle
	$B^+ \to K^+ e^+\tau^-$	1.53×10^{-5} [97]	772M BB ($771fb^{-1}$)	Belle
	$B^+ \to K^+ e^-\tau^+$	1.51×10^{-5} [97]	772M BB ($771fb^{-1}$)	Belle
	$B^+ \to \pi^+ e^+\tau^-$	7.4×10^{-5} [98]	472M BB ($426fb^{-1}$)	BaBar
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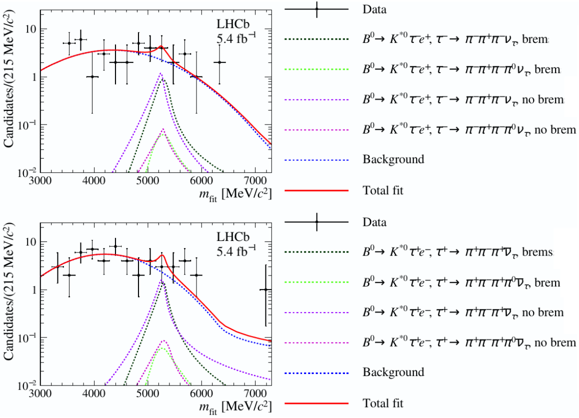
Table 1.2.1: Searches for LFV B decays, classified by the presence of $e\mu$, $\tau\mu$ or τe in the final state.

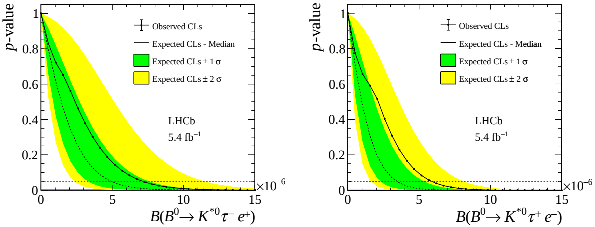
PhD Thesis Tommaso Fulghesu

$B^0 \to K^{*0}\tau^{\pm}e^{\mp}$

[arXiv 2506.15347]

- First search in LHCb for τe (Run 2)
- τ^+e^- and τ^-e^+ treated independently
- $\tau \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau$





The expected and observed p-values derived with the CL$_s$ method as a function of the BR. The red line corresponds to the 95% CL.

$$\mathcal{B}(B^0 \to K^{*0}\tau^- e^+) < 5.9\ (7.1) \times 10^{-6}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^+ e^-) < 4.9\ (5.9) \times 10^{-6}$$
at 90% (95%) CL

No significant signal contribution

Most stringent limit on $b \to s\tau l$ so far!

Selected results:

1)	$\Sigma^+ \to p\mu^+\mu^-$	$\Rightarrow$	**FCNC**	**STRANGE**	PRL 135, 051801 (2025)
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3) $\Lambda_c^+ \to p\mu^+\mu^-$ $\Rightarrow$ **FCNC + GIM** **CHARM** PRD 110 (2024) 052007, PRD 111 (2025) L091102

PHYSICAL REVIEW D **110,** 052007 (2024)

Search for the rare decay of charmed baryon Λ_c^+ into the $p\mu^+\mu^-$ final state

R. Aaij *et al.**
(LHCb Collaboration)

(Received 22 July 2024; accepted 27 August 2024; published 24 September 2024)

A search for the nonresonant $\Lambda_c^+ \to p\mu^+\mu^-$ decay is performed using proton-proton collision data recorded at a center-of-mass energy of 13 TeV by the LHCb experiment, corresponding to an integrated luminosity of 5.4 fb^{-1}. No evidence for the decay is found in the dimuon invariant-mass regions where the expected contributions of resonances is subdominant. The upper limit on the branching fraction of the $\Lambda_c^+ \to p\mu^+\mu^-$ decay is determined to be $2.9(3.2) \times 10^{-8}$ at 90%(95%) confidence level. The branching fractions in the dimuon invariant-mass regions dominated by the η, ρ and ω resonances are also determined.

LHCb-PAPER-2024-005

PHYSICAL REVIEW D **111,** L091102 (2025)

Search for resonance-enhanced *CP* and angular asymmetries in the $\Lambda_c^+ \to p\mu^+\mu^-$ decay at LHCb

R. Aaij *et al.**
(LHCb Collaboration)

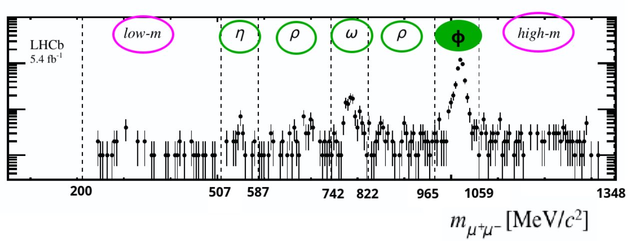
(Received 10 February 2025; accepted 16 March 2025; published 12 May 2025)

The first measurement of the *CP* asymmetry of the decay rate (A_{CP}) and the *CP* average (ΣA_{FB}) and *CP* asymmetry (ΔA_{FB}) of the forward-backward asymmetry in the muon system of $\Lambda_c^+ \to p\mu^+\mu^-$ decays is reported. The measurement is performed using a data sample of proton-proton collisions, recorded by the LHCb experiment from 2016 to 2018 at a center-of-mass energy of 13 TeV, which corresponds to an integrated luminosity of 5.4 fb^{-1}. The asymmetries are measured in two regions of dimuon mass near the ϕ-meson mass peak. The dimuon-mass integrated results are $A_{CP} = (-1.1 \pm 4.0 \pm 0.5)\%$, $\Sigma A_{\text{FB}} = (3.9 \pm 4.0 \pm 0.6)\%$, $\Delta A_{\text{FB}} = (3.1 \pm 4.0 \pm 0.4)\%$, where the first uncertainty is statistical and the second systematic. The results are consistent with the conservation of *CP* symmetry and the Standard Model expectations.

LHCb-PAPER-2024-051

$\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 110 (2024) 052007]

- $\Lambda_c^+ \to p\mu^+\mu^-$ is a very rare **FCNC + GIM mechanism**
- Short-distance contribution $\mathcal{B} \sim \mathcal{O}(10^{-8})$
- Long-distance contribution $\mathcal{B} \sim \mathcal{O}(10^{-6})$ from $\Lambda_c^+ \to pX(\to \mu^+\mu^-)$ where $X = \eta, \rho, \omega, \phi$
- LHCb data from **Run 2** ($\mathcal{L} = 5.4$ fb^{-1})
- $\mathcal{B}$ in six regions of dimuon mass: **resonant** $(\eta, \rho, \omega, \phi)$ and **non-resonant** (low and high mass)



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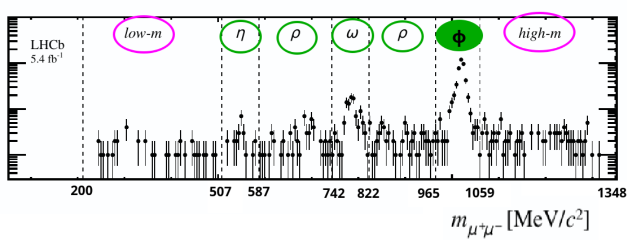
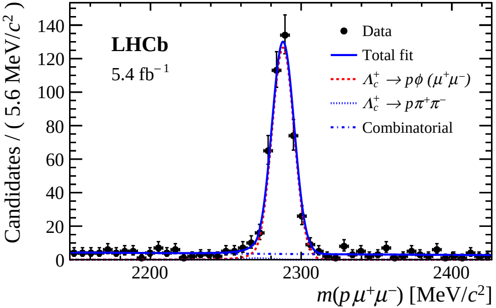
- LHCb data from **Run 2** ($\mathcal{L} = 5.4$ fb^{-1})
- $\mathcal{B}$ in six regions of dimuon mass: **resonant** (η, ρ, ω, ϕ) and **non-resonant** (low and high mass)
- Normalised to ϕ resonant region: $\Lambda_c^+ \to p\phi(\to \mu\mu)$

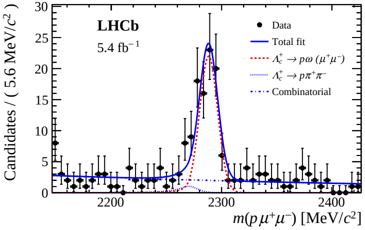


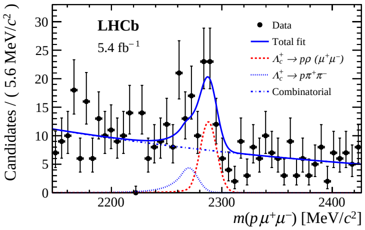


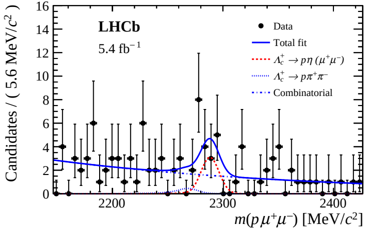
$\Lambda_c^+ \to p\mu^+\mu^-$: resonant regions

[PRD 110 (2024) 052007]

$\Lambda_c^+ \to p\omega(\to \mu\mu)$	$\Lambda_c^+ \to p\rho(\to \mu\mu)$	$\Lambda_c^+ \to p\eta(\to \mu\mu)$
significance $> 7\sigma$	significance $> 5.6\sigma$	significance $> 3.0\sigma$





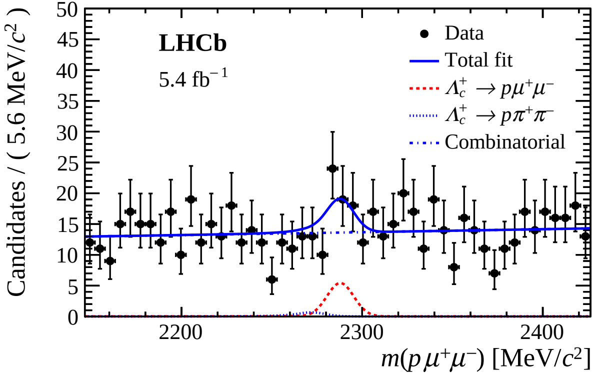


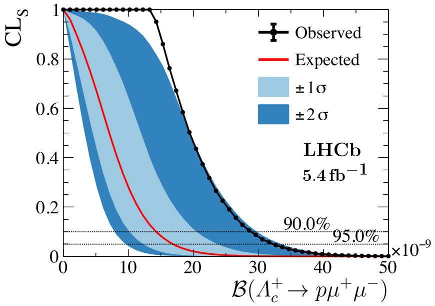
$$\mathcal{B}(\Lambda_c^+ \to p\omega) = (9.82 \pm 1.23\ (\text{stat.}) \pm 0.73\ (\text{syst.}) \pm 2.79\ (\text{ext.})) \times 10^{-4},$$

$$\mathcal{B}(\Lambda_c^+ \to p\rho) = (1.52 \pm 0.34\ (\text{stat.}) \pm 0.14\ (\text{syst.}) \pm 0.24\ (\text{ext.})) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to p\eta) = (1.67 \pm 0.69\ (\text{stat.}) \pm 0.23\ (\text{syst.}) \pm 0.34\ (\text{ext.})) \times 10^{-3},$$

No evidence for $\Lambda_c^+ \to p\mu^+\mu^-$ decays in the non-resonant regions





$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 2.9\ (3.2) \times 10^{-8} \quad \text{at} \quad 90\%\ (95\%)\ \text{CL.}$$

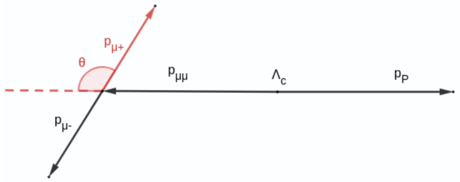
most stringent limit to date

Study of CP asymmetry of the decay rate (A_{CP}) and the CP average (ΣA_{FB}) and CP asymmetry (ΔA_{FB}) of the Forward-Backward asymmetry

$$A_{CP} \equiv \frac{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) - \Gamma(\overline{\Lambda}_c^- \to \overline{p}\mu^+\mu^-)}{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) + \Gamma(\overline{\Lambda}_c^- \to \overline{p}\mu^+\mu^-)}$$

$$A_{\mathrm{FB}} \equiv \frac{\Gamma(\cos\theta > 0) - \Gamma(\cos\theta < 0)}{\Gamma(\cos\theta > 0) + \Gamma(\cos\theta < 0)}$$

$$\Sigma A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} + A_{FB}^{\overline{\Lambda}_c^-}\right) \quad \Delta A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} - A_{FB}^{\overline{\Lambda}_c^-}\right)$$



$\Lambda_c^+ \to p\mu^+\mu^-$: CP and angular asymmetries [PRD 111 (2025) L091102]

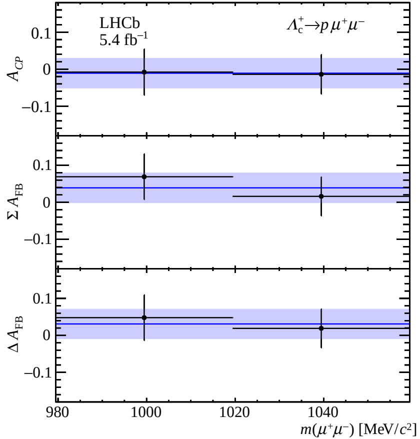
Study of CP asymmetry of the decay rate (A_{CP}) and the CP average (ΣA_{FB}) and CP asymmetry (ΔA_{FB}) of the Forward-Backward asymmetry

$$A_{CP} \equiv \frac{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) - \Gamma(\bar{\Lambda}_c^- \to \bar{p}\mu^+\mu^-)}{\Gamma(\Lambda_c^+ \to p\mu^+\mu^-) + \Gamma(\bar{\Lambda}_c^- \to \bar{p}\mu^+\mu^-)}$$

$$A_{\mathrm{FB}} \equiv \frac{\Gamma(\cos\theta > 0) - \Gamma(\cos\theta < 0)}{\Gamma(\cos\theta > 0) + \Gamma(\cos\theta < 0)}$$

$$\Sigma A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} + A_{FB}^{\bar{\Lambda}_c^-}\right) \qquad \Delta A_{FB} = \frac{1}{2}\left(A_{FB}^{\Lambda_c^+} - A_{FB}^{\bar{\Lambda}_c^-}\right)$$

$$\boxed{\begin{aligned} A_{CP} &= (-1.1 \pm 4.0 \pm 0.5)\%, \\ \Sigma A_{\mathrm{FB}} &= (\ \ 3.9 \pm 4.0 \pm 0.6)\%, \\ \Delta A_{\mathrm{FB}} &= (\ \ 3.1 \pm 4.0 \pm 0.4)\%, \end{aligned}}$$



No significant deviation from the SM are observed

Conclusions and outlook

- **(Very) Rare and forbidden decays** constitute a unique environment to look for NP
- Many LHCb measurements are world's best: **beauty**, **charm** and **strange** sectors
- LHCb is giving a major contribution:
  - $\Sigma^+ \to p\mu^+\mu^-$: **first observation and rarest baryon decay ever observed**, compatible with SM
  - $B^0 \to K^{*0}\tau^\pm e^\mp$: **most stringent limit in $b \to s\tau l$ so far**, no significant signal contribution
  - $\Lambda_c^+ \to p\mu^+\mu^-$: **most stringent limit to date**, all results compatible with SM
- **Prospects:**
  - 9.5 fb^{-1} data collected in 2024, and Run 3 still ongoing
  - exploit the larger Run 3 dataset with improved efficiency from the fully software trigger to achieve unprecedented precision in these measurements
  - new searches, new observations and new more stringent limits increasingly closer to the ranges of interest for NP

Thank you for your attention!

Backup

LHCb acceptance

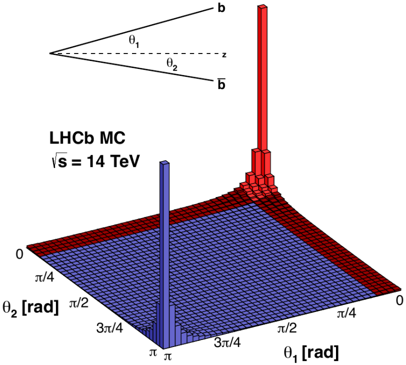


Figure 2.3: Production cross-section of $b\bar{b}$ pairs as a function of their polar angle with respect to the beam axis, for pp collisions simulated with PYTHIA at a center of mass energy of 14 TeV. The LHCb acceptance is displayed in red [41].

LHCb luminosity

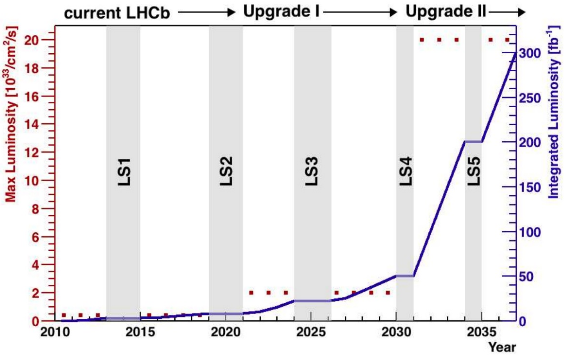


Figure 2.2: Luminosity projections for the original LHCb, Upgrade I, and Upgrade II experiments as a function of time. The red points and the left scale indicate the anticipated instantaneous luminosity during each period, with the blue line and right scale indicating the integrated luminosity accumulated.

Experimental observables

from M.Atzeni's talk at LHCP 2025 "Rare decays and lepton flavour studies at the LHC"

Experimental observables in $b \to s\ell^+\ell^-$

Branching fractions

Theory:

Large hadronic uncertainties (local and non-local)

Exception: Leptonic decays, e.g. $B^0_{(s)} \to \mu^+\mu^-$

Angular observables

Theory:

Reduced form-factor uncertainties

$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

LFU tests

Theory:

Cancellation of hadronic uncertainties

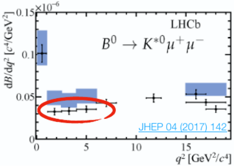
Larger theory uncertainty

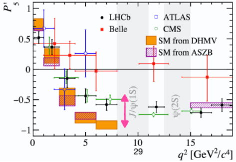
Smaller theory uncertainty

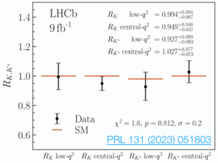
Tensions in BR SM higher than data

Tensions in angular observables

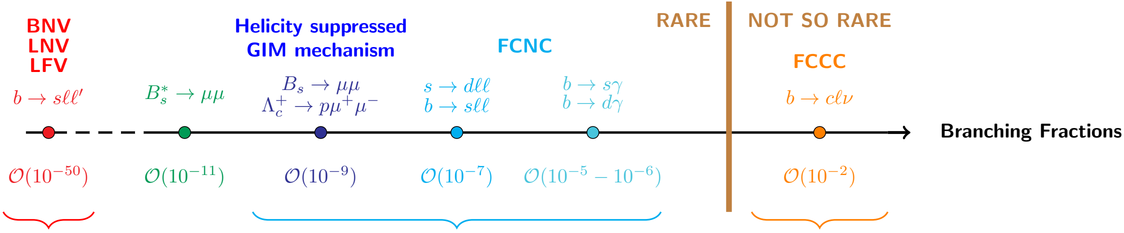
Tests compatible with LFU







Why rare?



- Lepton Flavour Violating
- Lepton Number Violating
- Baryon Number Violating
- Not allowed in SM
- Beyond-SM theories could predict BR up to $\mathcal{O}(10^{-7})$

Flavour-Changing Neutral Currents

- Loop-level in the SM
- Sensitive to effects of NP in the loops
- FCNC can be further suppressed for helicity and GIM mechanism

Flavour-Changing Charged Currents

- Tree-level in the SM

$\Sigma^+ \to p\mu^+\mu^-$: Additional theory interest [Phys. Rev. D111 (2025) 013003]

III. SM LONG-DISTANCE CONTRIBUTIONS

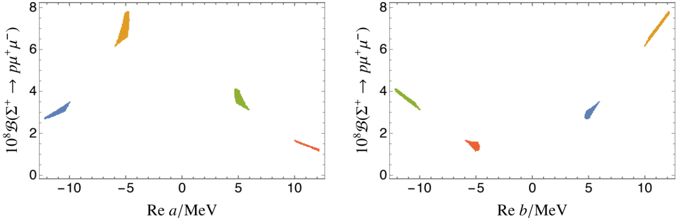
Lagrangian of $\Sigma^+ \to p\gamma$ depends on two form-factors $\mathcal{L} = \frac{eG_F}{2}\bar{u}_p[a + b\gamma_5]\sigma_{\mu\nu}q^\nu u_\Sigma \bar{u}_\mu \gamma^\mu v_{\bar{\mu}}$

implying a partial width Γ_γ

$$\Gamma = \frac{G_F^2 e^2}{\pi}(a^2 + b^2)E_\gamma^3 \qquad \alpha = \frac{2\Re[ab^*]}{a^2 + b^2}$$

4-fold ambiguity on the a and b form-factors needed as input for $\Sigma^+ \to p\mu^+\mu^-$

where E_γ denotes the photon's energy in the rest frame of the Σ^+ and ϑ is the angle between its polarization and the proton's three-momentum in this frame.



possible branching fractions

Relativistic baryon

Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$
-12.15 ± 0.24	4.78 ± 0.42	2.7 ± 0.2
-4.78 ± 0.42	12.15 ± 0.24	7.8 ± 0.3
4.78 ± 0.42	-12.15 ± 0.24	4.2 ± 0.2
12.15 ± 0.24	-4.78 ± 0.42	1.2 ± 0.1

Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$
-9.74 ± 0.54	6.17 ± 0.74	3.7 ± 0.5
-6.17 ± 0.74	9.74 ± 0.54	6.1 ± 0.5
6.17 ± 0.74	-9.74 ± 0.54	3.2 ± 0.3
9.74 ± 0.54	-6.17 ± 0.74	1.9 ± 0.2

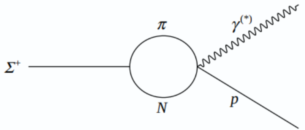
Heavy baryon

$\Sigma^+ \to p\mu^+\mu^-$: Additional theory interest

from F.Dettori's talk at EPS 2025 "Rare strange decays at LHCb"

Amplitude

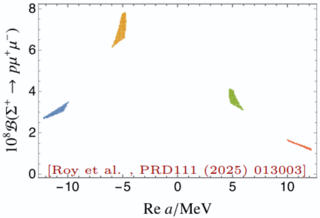
$$A^{\mathrm{LD}}_{\Sigma^+\to p\mu^+\mu^-} = \{-iq_\alpha \bar{u}_p[a(q^2) + \gamma_5 b(q^2)]\sigma^{\alpha\beta}u_\Sigma - \bar{u}_p\gamma^\beta[c(q^2) + \gamma_5 d(q^2)]u_\Sigma\}\bar{u}_\mu\gamma_\beta v_{\bar{\mu}}$$



- Dominated by long distance contributions $\Sigma \to N\pi \to p\gamma^*$
- With some assumptions a and b can be taken from $\Sigma^+ \to p\gamma$ experimental data [BESIII - Phys. Rev. Lett. 130, 211901 (2023)]
- Four-fold theoretical ambiguity
- Relativistic-baryon and heavy-baryon χPT approaches do not agree

Hence final prediction has large uncertainty:

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) \in [1.8, 5.8] \times 10^{-8}$$



Experiment can help solve the ambiguity

$\Sigma^+ \to p\mu^+\mu^-$: Additional theory interest

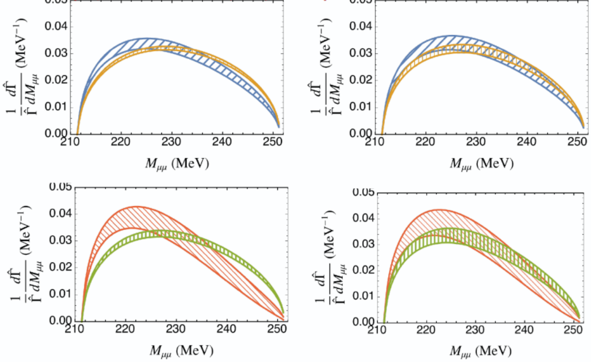
from F.Dettori's talk at EPS 2025 "Rare strange decays at LHCb"

Dimuon mass distribution

- Different predictions for the different approaches and parameter values

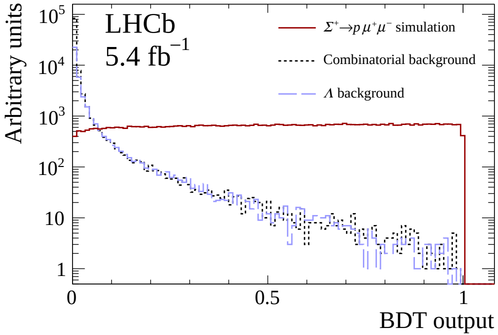
Additional observables: forward-backward asymmetry, CP violation

[Roy et al. , PRD111 (2025) 013003]



$\Sigma^+ \to p\mu^+\mu^-$: BDT

- Variables
  - the impact parameter χ^2 of the Σ^+ and of the final-state particles tracks with respect to the best PV;
  - the maximum distance of closest approach between any pair of the three daughter tracks;
  - the flight distance of the Σ^+ from the PV divided by its uncertainty;
  - the angle between the Σ^+ momentum and the lines joining the PV and the SV;
  - the χ^2 of the Σ^+ vertex fit;
  - the transverse momentum of the final-state particles tracks;



$\Sigma^+ \to p\mu^+\mu^-$: Optimisation

The final selection is based on the BDT output, the muon and proton particle- identification variables, and the width of the Λ veto window. Criteria on these four variables are optimised, on a four-dimensional grid, to have the largest significance, defined as

$$S = \frac{N_s}{\sqrt{N_s + N_B}} \tag{1}$$

where N_S is the expected signal and N_B the expected background yield.

$\Sigma^+ \to p\mu^+\mu^-$: Run 2 trigger

Since 2016, two inclusive dimuon trigger selections have been added at the two software trigger stages specifically designed to retain low transverse-momentum pT combinations whilst remaining within the strict time constraints imposed for the software trigger. In addition, an exclusive trigger selection has been introduced for the $\Sigma^+ \to p\mu^+\mu^-$ decay channel.

- Run 2 improvements for strange physics [LHCb-PUB-2017-023]:
  - HLT1: Complementary forward tracking lowered down to 80 MeV for muon tracks
    Generic **Hlt1DiMuonNoL0** for soft dimuons **not** requiring only **L0Muon** or **L0Dimuon** triggered events in input
  - HLT2: Generic **Hlt2DiMuonSoft** for soft dimuons
    Dedicated **Hlt2RareStrangeSigmaPMuMu** for $\Sigma^+ \to p\mu^+\mu^-$ decays

Efficiency	$\Sigma \to p\mu^+\mu^-$	
L0	0.269 ± 0.006	
	Run 1	Run 2
`Hlt1Global` | `L0`	0.191 ± 0.011	0.459 ± 0.014
`Hlt1DiMuonNoL0` | `L0`	-	0.325 ± 0.013
`Hlt2Global` | `Hlt1Global`	0.162 ± 0.023	0.901 ± 0.012
`Hlt2DiMuonSoft` | `Hlt1Global`	-	0.804 ± 0.016
`Hlt2SigmaPMuMu` | `Hlt1Global`	-	0.485 ± 0.020
Total	0.0083 ± 0.0013	0.111 ± 0.004

TISTOS method [S. Tolk et al. LHCb-PUB-2014-039]

Triggered events can be Triggered On the Signal (TOS) (the signal is sufficient to trigger), Triggered Independently of the Signal (TIS) (the signal is not necessary to trigger), Triggered on both (TIS&TOS)

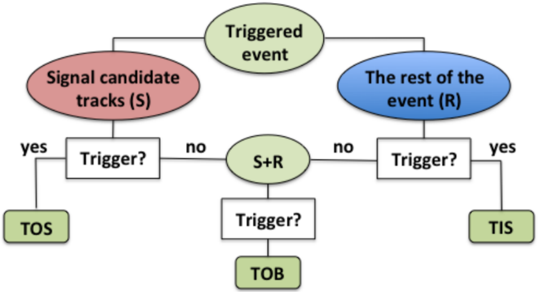
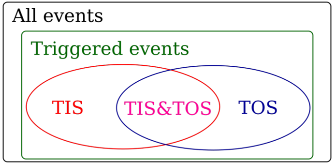


Figure 1: Diagram explaining the logic behind categorizing events into Trigger On Signal (TOS), Trigger Independent of Signal (TIS) and Trigger On Both (TOB) trigger categories. Note that an event can be both TIS and TOS simultaneously.



$\Sigma^+ \to p\mu^+\mu^-$: signal fit

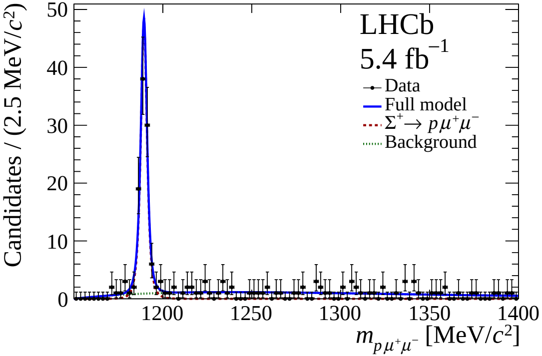


Figure: Distribution of the invariant mass of $\Sigma^+ \to p\mu^+\mu^-$ TOS candidates.

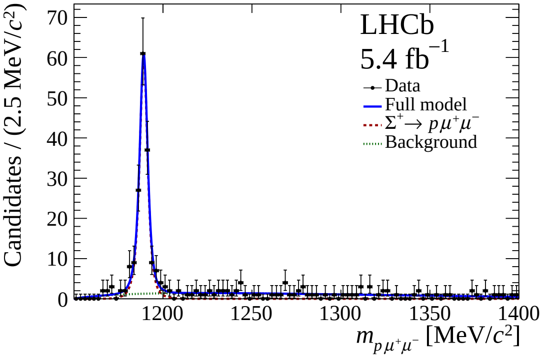


Figure: Distribution of the invariant mass of $\Sigma^+ \to p\mu^+\mu^-$ TIS candidates.

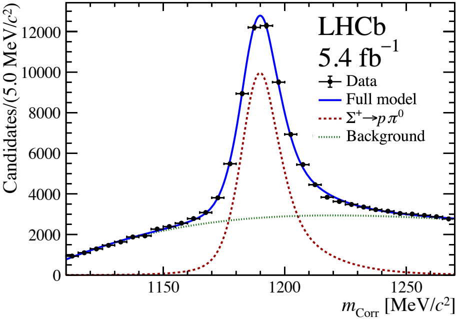
$\Sigma^+ \to p\mu^+\mu^-$: normalisation

NEW!
LHCb-PAPER-2025-002

Number of signal candidates converted into a branching fraction through a normalisation to the $\boldsymbol{\Sigma^+ \to p\pi^0}$ **decay**

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

- not trivial as no fully charged final states of the Σ^+ are available
- $\boldsymbol{\Sigma^+ \to p\pi^0}$ highest branching fraction $\mathcal{B} \sim 52\%$
- Fit to corrected mass $m_{corr} = m_{p\gamma\gamma} - m_{\gamma\gamma} + m_{\pi^0}^{PDG}$



$\Sigma^+ \to p\mu^+\mu^-$: Normalisation

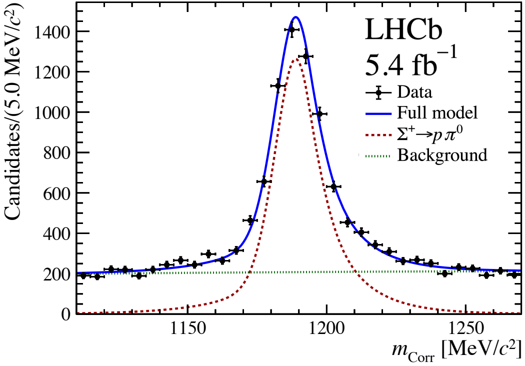


Figure: Distribution of the invariant mass of $p\pi^0$ TOS candidates.

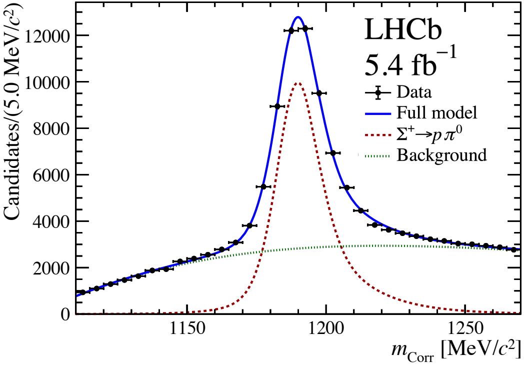


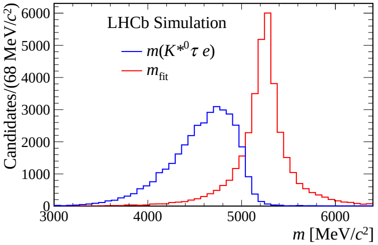
Figure: Distribution of the invariant mass of $p\pi^0$ TIS candidates.

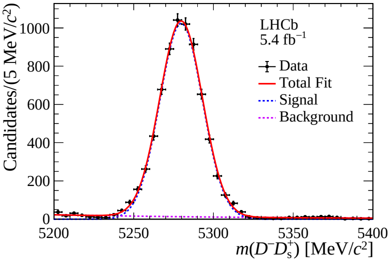
$B^0 \to K^{*0}\tau^{\pm}e^{\mp}$

- First search in LHCb for $\boldsymbol{\tau e}$ **coupling**
- LHCb data from Run 2 ($\boldsymbol{\mathcal{L} = 5.4}$ fb$^{\boldsymbol{-1}}$)

- **Analysis strategy:**
  - $\boldsymbol{\tau^+ e^-}$ and $\boldsymbol{\tau^- e^+}$ final states treated independently: different sensitivity and experimental backgrounds
  - Signal model including hadronic $\boldsymbol{\tau \to \pi^+\pi^-\pi^+(\pi^0)\overline{\nu}_\tau}$
  - $\boldsymbol{B^0 \to D^-(K^+\pi^-\pi^-)D_s^+(K^+K^-\pi^+)}$ as a normalisation channel (abundant and similar topology)

- **Analysis challenges:**
  - Missing neutrinos: mass refitted including missing neutrino momentum and kinematic constraints
  - Electrons: bremsstrahlung photon recover (when possible)





Test the Lepton Flavour Universality at LHCb

Relative rates of $b \to s\mu^+\mu^-$ and $b \to se^+e^-$:

$$R_X = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathscr{B}(B \to X\mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\mathscr{B}(B \to Xe^+e^-)}{d^2}\, dq^2}$$

- clean: QCD uncertainties cancels out in the ratio
- predicted by the SM with very high precision

- $B^0 \to K^0_S \ell^+\ell^-$, $B^0_s \to \phi\, \ell^+\ell^-$
- $B^+ \to K^{(*)+}\ell^+\ell^-$, $B^0 \to K^{*0}\ell^+\ell^-$
- $B^+ \to K^+\pi^+\pi^-\ell^+\ell^-$
- $\Lambda^0_b \to pK^-\ell^+\ell^-$