IFAE 2025

Incontri di Fisica delle Alte Energie

Cagliari, 9-11 Aprile 2025

Osservazione del decadimento raro $\Sigma^+ \to p\mu^+\mu^-$ a LHCb

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a nome della collaborazione LHCb

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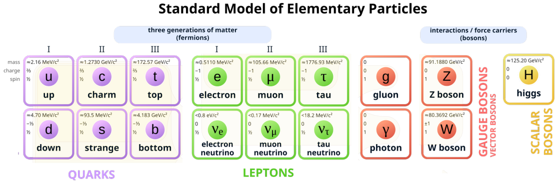
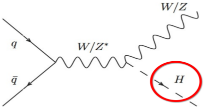
Introduction: rare and very rare decays

- The Standard Model (SM)
  - very successful, but... incomplete

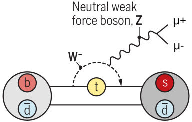


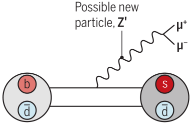
- New Physics (NP) beyond SM

– *direct searches* ⇒ observe new **real** particles created in high energy collisions



– *indirect searches* ⇒ test SM predictions to look for possible contributions from new **virtual** particles



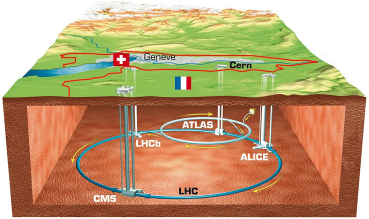


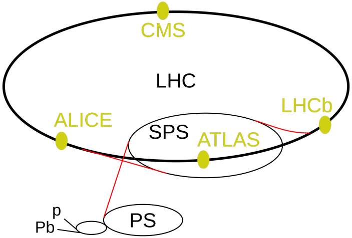
- Rare ($\mathcal{B} < 10^{-6}$) and very rare ($\mathcal{B} < 10^{-9}$) decays ⇒ sensitive tool to explore NP
  - Flavour Changing Neutral Currents (FCNC) → highly suppressed in SM, like $\Sigma^+ \to p\mu^+\mu^-$
  - Forbidden decays

LHCb: the experiment

Large Hadron Collider beauty (LHCb)

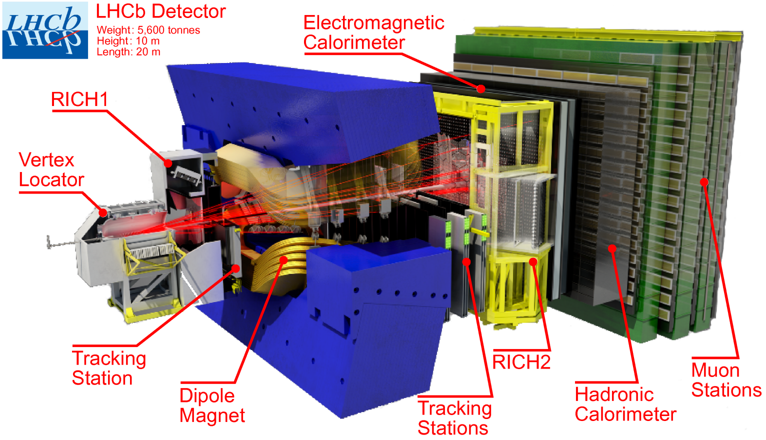
- Located at the LHC (CERN)
- Dedicated experiment for precision measurements on flavour physics (CP violation, rare decays, ...)
- pp collisions at
  $\sqrt{s} = 7/8$ TeV in Run 1
  $\sqrt{s} = 13$ TeV in Run 2
  $\sqrt{s} = 13.6$ TeV in Run 3





LHCb: the detector

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



- tracking system + particle identification system

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]

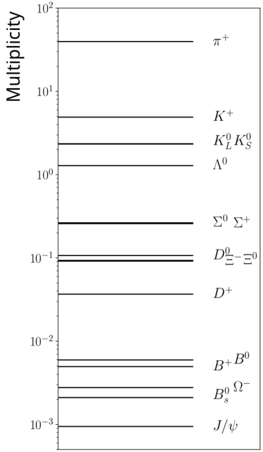


Figure: Multiplicity of particles produced in a single pp interaction

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

- $\Sigma^+ = uus$, $m_\Sigma = 1189.37$ MeV/c^2
- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare **FCNC**

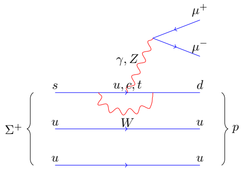
  $1.2 \times 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-)^{SM} < 7.8 \times 10^{-8}$

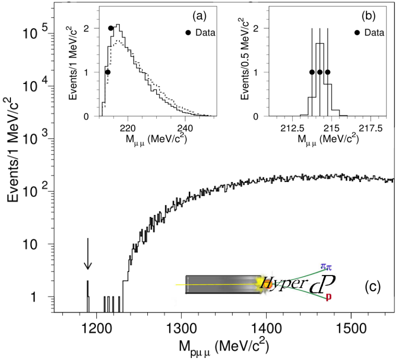
  [Phys. Rev. D72 (2005) 074003]

  [JHEP 1810 (2018) 040]

  [Phys. Rev. D111 (2025) 013003]

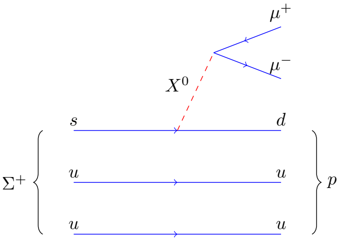
- First evidence found by **HyperCP**
  - 3 events in absence of background
  - Measured branching fraction $\mathcal{B} = (8.6^{+6.6}_{-5.4}) \times 10^{-8}$ [Phys. Rev. Lett. 94 (2005) 021801]
- The "**HyperCP anomaly**"
  - All the 3 signal events had the same dimuon invariant mass $m_{X_0} = 214.3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





$\Sigma^+ \to p\mu^+\mu^-$: beyond-SM hypothesis and search for X^0

- Many possible interpretations of the HyperCP anomaly:
  - "Sgoldstino interpretation of HyperCP events"
    [Phys. Rev. D73 (2006) 035002]
  - "On the possibility of a new boson X^0 (214 MeV) in $\Sigma^+ \to p\mu^+\mu^-$ "
    [Physics Letters B632 (2006) 212-214]
  - "Does the HyperCP Evidence for the Decay $\Sigma^+ \to p\mu^+\mu^-$ indicate a Light Pseudoscalar Higgs Boson?"
    [Phys. Rev. Lett. 98 (2007) 0818]
  - "U-boson and the HyperCP exotic events"
    [Physics Letters B663 (2008) 400-404]



- Many experimental attempts to search for X^0

BaBar: $\Upsilon(2S,3S) \to \gamma\mu^+\mu^-$ ✗ [Phys. Rev. Lett. 103 (2009) 081803]

Belle: $B^0 \to K^{*0}\mu^+\mu^-$, $B^0 \to \rho^0\mu^+\mu^-$ ✗ [Phys. Rev. Lett. 105 (2010) 091801]

LHCb: $B^0 \to \mu^+\mu^-\mu^+\mu^-$ ✗ [Phys. Rev. Lett. 110 (2013) 211801]; $B^0 \to K^{*0}\mu^+\mu^-$ ✗ [Phys. Rev. Lett. 115 (2015) 161802]

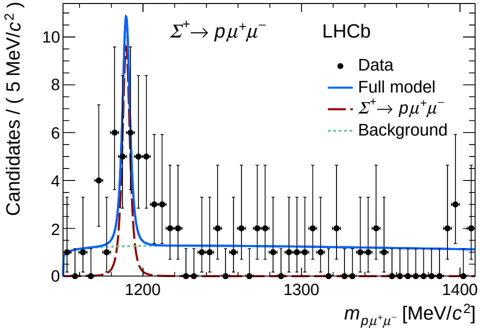
BESIII: $J/\psi \to \gamma\mu^+\mu^-$ ✗ [Phys. Rev. D 93 (2016) 052005]

- No other search in $\Sigma^+ \to p\mu^+\mu^-$ decays

$\Sigma^+ \to p\mu^+\mu^-$: Run 1 and Run 2 analysis

- **Analysis with Run 1 data** (2011–2012)
  - ~ 10 observed events
  - Stronger evidence with 4.1σ
  - Measured branching fraction $\mathcal{B} = (2.2\ ^{+0.9}_{-0.8}\ ^{+1.5}_{-1.1}) \times 10^{-8}$ consistent with SM prediction

    [Phys. Rev. Lett. 120 (2018) 221803]



- **Analysis with Run 2 data** (2016–2018)
  - Integrated luminosity of 5.4 fb^{-1}

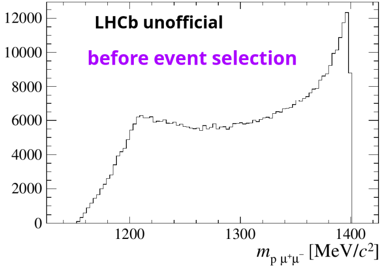
    $\Rightarrow$ paper "Observation of the $\Sigma^+ \to p\mu^+\mu^-$ very rare decay"

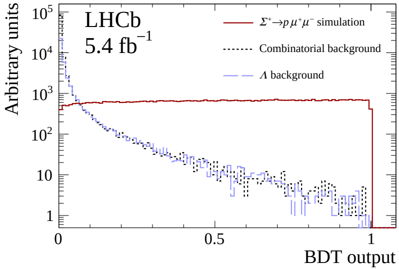
- **Improvements Run 2 w.r.t. Run 1**
  - Increase in statistics $\Rightarrow$ factor $\sim$ 4 larger
  - Increase in performances $\Rightarrow$ factor $\sim$ 13 larger

LHCb-PAPER-2025-002
PUBLISHED ON ARXIV
arXiv:2504.06096

$\Sigma^+ \to p\mu^+\mu^-$: Run 2 analysis   **NEW!** [LHCb-PAPER-2025-002]

- **Selection of events**
  $\Rightarrow$ Reject background and isolate signal
- **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. $\Sigma^+ \to p\pi^+\pi^-$ kinem. forbidden
- **Selection strategy**
  1. Preselection on kinematic/PID variables
  2. Multivariate selection (output=BDT)



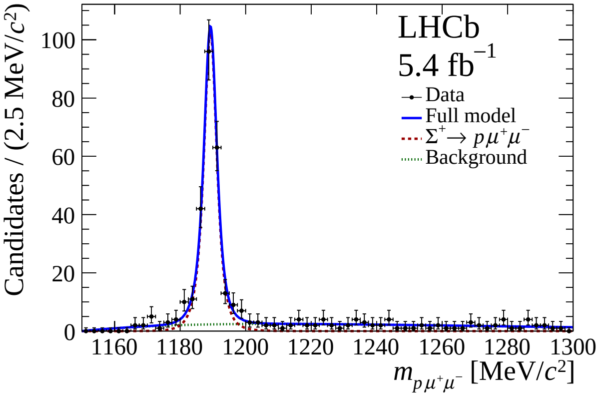


$\Sigma^+ \to p\mu^+\mu^-$: observation

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

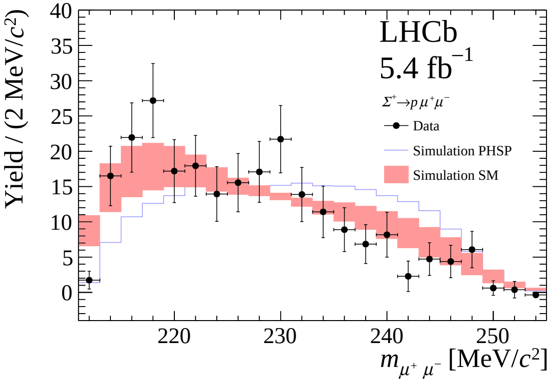
NEW!
LHCb-PAPER-2025-002
arXiv:2504.06096

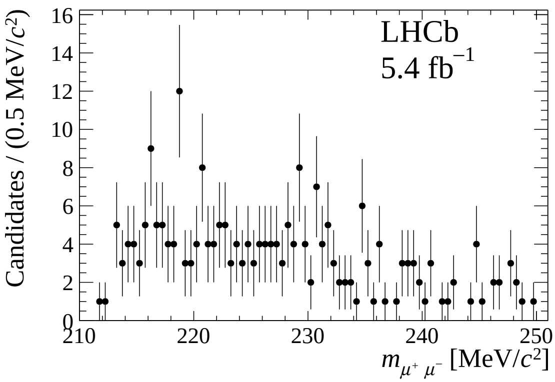


$\Sigma^+ \to p\mu^+\mu^-$: scan in the $\mu^+\mu^-$ invariant mass

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

NEW!
LHCb-PAPER-2025-002
arXiv:2504.06096





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

NEW!
LHCb-PAPER-2025-002
arXiv:2504.06096

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

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

The resulting branching fraction is:

RUN 2

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

RUN 1+2

$$\boxed{\mathcal{B}\left(\Sigma^+ \to p\mu^+\mu^-\right) = (1.09 \pm 0.17) \times 10^{-8}}$$

In agreement with SM predictions

THIS IS THE RAREST BARYON DECAY EVER OBSERVED

Conclusions and outlook

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

  $\Rightarrow$ First observation of the decay with overwhelming significance

- Investigated the dimuon spectrum for New Physics resonances
  - No significant peak structure
  - HyperCP anomaly excluded

- Branching fraction measurement using Run 2 pp collision data:

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

  $\Rightarrow$ Rarest baryon decay ever observed

- Future prospects (Run 2 but also Run 3) $\Rightarrow$ new accessible measurements
  - Charge-Parity symmetry violation
  - Forward-backward asymmetries

Grazie per l'attenzione!

Backup

LHCb acceptance

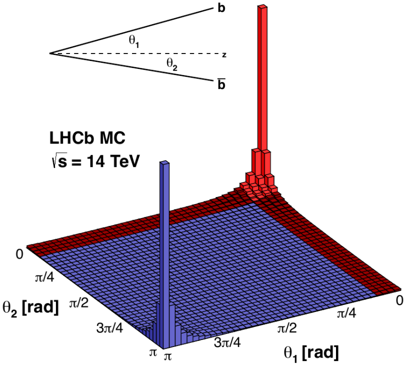


Figure 2.3: Production cross-section of $b\bar{b}$ pairs as a function of their polar angle with respect to the beam axis, for pp collisions simulated with PYTHIA at a center of mass energy of 14 TeV. The LHCb acceptance is displayed in red [41].

LHCb luminosity

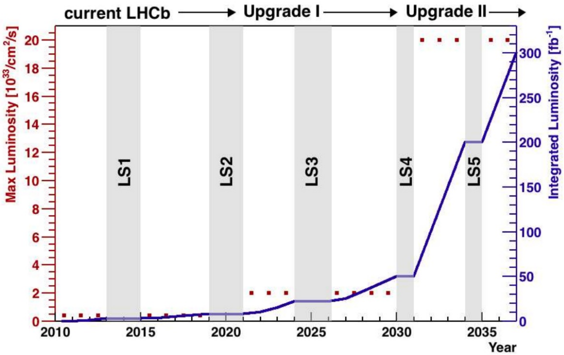


Figure 2.2: Luminosity projections for the original LHCb, Upgrade I, and Upgrade II experiments as a function of time. The red points and the left scale indicate the anticipated instantaneous luminosity during each period, with the blue line and right scale indicating the integrated luminosity accumulated.

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

- $\Sigma^+ = uus$, $m_\Sigma = 1189.37$ MeV/c^2
- $\Sigma^+ \to p\mu^+\mu^-$ 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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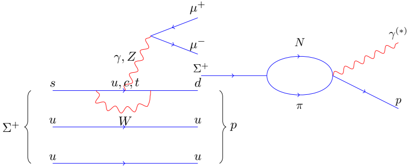
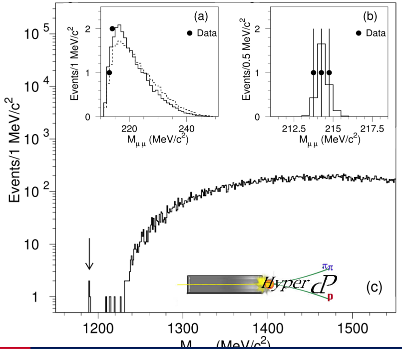




Additional theory interest

[Phys. Rev. D111 (2025) 013003]

III. SM LONG-DISTANCE CONTRIBUTIONS

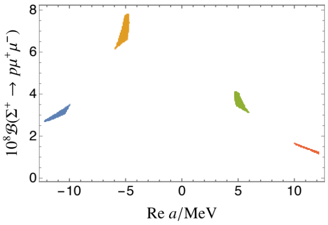
Lagrangian of $\Sigma^+ \to p\gamma$ depends on two form-factors $\mathcal{L} = \frac{eG_F}{2}\bar{u}_p[a + b\gamma_5]\sigma_{\mu\nu}q^\nu u_\Sigma \bar{u}_\mu \gamma^\mu v_{\bar{\mu}}$

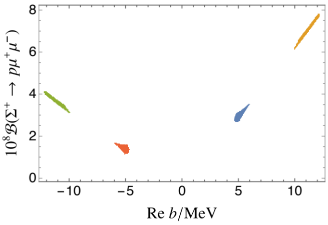
implying a partial width Γ_γ

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

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

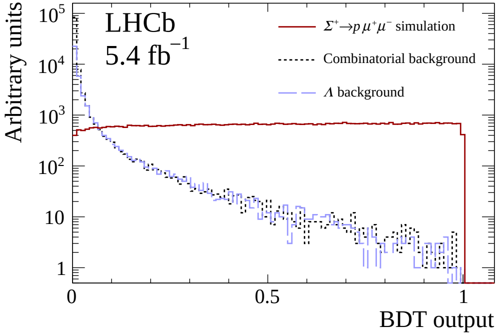
Re a (MeV)	Re b (MeV)	$10^8\,\mathcal{B}_{\mu\mu}$
-12.15 ± 0.24	4.78 ± 0.42	2.7 ± 0.2
-4.78 ± 0.42	12.15 ± 0.24	7.8 ± 0.3
4.78 ± 0.42	-12.15 ± 0.24	4.2 ± 0.2
12.15 ± 0.24	-4.78 ± 0.42	1.2 ± 0.1

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

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;



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)

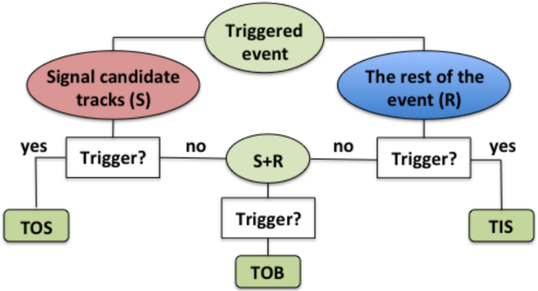
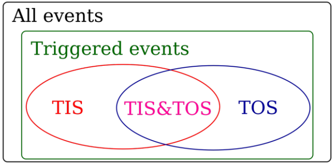


Figure 1: Diagram explaining the logic behind categorizing events into Trigger On Signal (TOS), Trigger Independent of Signal (TIS) and Trigger On Both (TOB) trigger categories. Note that an event can be both TIS and TOS simultaneously.



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

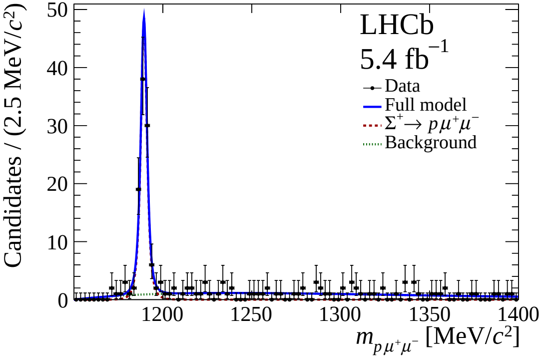


Figure: Distribution of the invariant mass of $\Sigma^+ \to p\mu^+\mu^-$ TOS candidates.

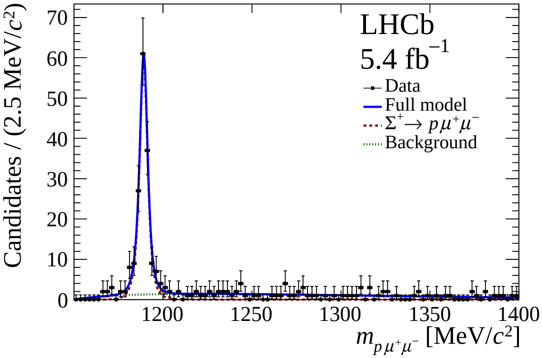


Figure: Distribution of the invariant mass of $\Sigma^+ \to p\mu^+\mu^-$ TIS candidates.

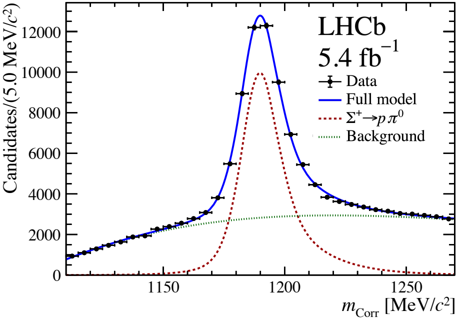
$\Sigma^+ \to p\mu^+\mu^-$: normalisation

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



Normalisation

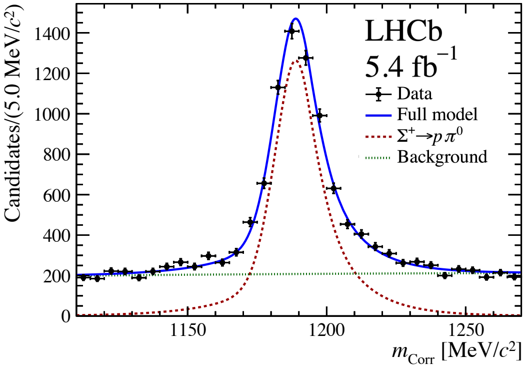


Figure: Distribution of the invariant mass of $p\pi^0$ TOS candidates.

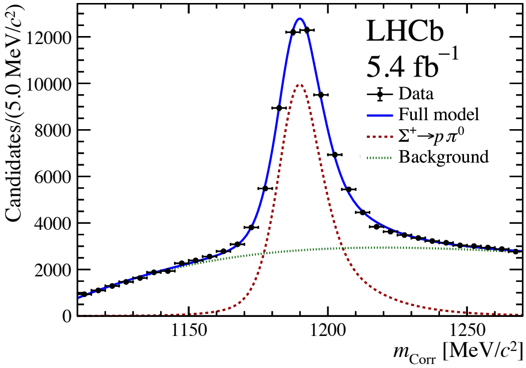


Figure: Distribution of the invariant mass of $p\pi^0$ TIS candidates.

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

NEW!
LHCb-PAPER-2025-002
arXiv:2504.06096

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

The resulting branching fraction is:

RUN 2

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

RUN 1+2

$$\boldsymbol{\mathcal{B}\left(\Sigma^+ \to p\mu^+\mu^-\right) = (1.09 \pm 0.17) \times 10^{-8}}$$

In agreement with SM predictions

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