Observation of the $\Sigma^+ \rightarrow \rho \mu^+ \mu^-$ rare decay at LHCb

Gabriele Martelli
Istituto Nazionale di Fisica Nucleare - Sezione di Perugia
On behalf of the LHCb collaboration

Charleston, 3-7 June 2024
BEACH 2024: XV International Conference on Beauty, Charm, Hyperons in Hadronic Interactions
Large Hadron Collider (LHC)
- Located at CERN
- World largest particle collider
  - 26.7 km long, 100 m underground
- Proton/heavy ion beams collide in **four points**
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- Investigate the quark flavour sector
  - CP violation
  - Rare decays with possible New Physics (NP) hints
- Positioned in the forward region relative to the collision point
- Large production $b\bar{b}$ and $c\bar{c}$ cross sections within its acceptance
  - 72(144) µb and 1.4(2.6) mb at $\sqrt{s} = 7(13)$ TeV
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22 countries are involved in the collaboration
- About 1700 scientists, engineers and technicians
- More than 700 articles published up-to-date
[https://lhcb.web.cern.ch/]

Observation of the $\Sigma^{+}\rightarrow p\mu\mu$ rare decay at LHCb - G. Martelli
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\[ \sigma_{ip} = \left[ 15 + \frac{29}{p_T(GeV)} \right] \mu m \]
\[ \Sigma^+ \to p \mu^+ \mu^- \] - The decay

\[ \Sigma^+ \to p \mu^+ \mu^- \] is a FCNC process allowed only at loop level

- Short distance SM \( \mathcal{B} \sim \mathcal{O}(10^{-12}) \)
- Dominated by long distance contributions from \( \Sigma^+ \to (N \pi)^+ \) decays

\[ 1.6 \times 10^{-8} < \mathcal{B}(\Sigma^+ \to p \mu^+ \mu^-) < 9.1 \times 10^{-8} \]

[JHEP 1810 (2018) 040]
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- First evidence from the HyperCP experiment
  - Three candidates observed in absence of background
  - Measured branching fraction:
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- The Anomaly
  - Same dimuon invariant mass for the observed candidates
  - Possible $\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+\mu^-)$ decay
    $m_{X^0} = 214.3 \pm 0.5$ MeV
    $B(\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+\mu^-)) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$
Many BSM hypotheses

“Sgoldstino interpretation of HyperCP events”

“On the possibility of a new boson $X^0$ (214MeV) in $\Sigma^+ \rightarrow p\mu^+\mu^-$”

“Does the HyperCP Evidence for the Decay $\Sigma^+ \rightarrow p\mu^+\mu^-$ Indicate a Light Pseudoscalar Higgs Boson?”

“$U$-boson and the HyperCP exotic events”
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New searches for low dimuon mass resonances

$\Upsilon(2S, 3S) \to \gamma\mu^+\mu^-$

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“Evidence for the rare decay $\Sigma^+ \rightarrow p\mu^+\mu^-$”
- Run 1 dataset
  $\sqrt{s} = 7.8$ TeV, $\mathcal{L} = 3.0$ fb$^{-1}$

Stronger evidence by LHCb
- Excess of signal candidates w.r.t. background
  $N_{\Sigma^+ \rightarrow p\mu^+\mu^-} = (10.2^{+3.9}_{-3.5})$
- Measured branching fraction:
  $\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (2.2^{+0.9+1.5}_{-0.8-1.1}) \times 10^{-8}$
- Consistent with SM prediction

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Search for the $X^0$ resonance

- No significant peak found in the $m_{\mu^+\mu^-}$ distribution
- Upper limit at 90% C.L.
  $\mathcal{B}(\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+\mu^-)) < 1.4 \times 10^{-8}$
- HyperCP result central value excluded
New $\Sigma^+ \rightarrow p\mu^+\mu^-$ results by BESIII [Phys. Rev. Lett. 130 (2023) 211901]

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Chiral perturbation theory ($\chi$PT)
- Relativistic and heavy baryon approaches
- Four-fold degeneracy in each method [arXiv:2404.15268]

Experiments should be able to solve it

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LHCb-CONF-2024-002

Shown for the first time ever!
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General overview
- New improvements w.r.t. Run 1
- Analysis strategy

Search for the $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay
- Selection
- Fit and signal evaluation

Search for the HyperCP-like resonance
- Confirm/exclude the Anomaly

Shown for the first time ever!
New improvements

➤ **Increase in statistics**
   - Run 1 $\rightarrow \sqrt{s} = 7, 8$ TeV, $\mathcal{L} = 3.0$ fb$^{-1}$
   - Run 2 $\rightarrow \sqrt{s} = 13$ TeV, $\mathcal{L} = 5.4$ fb$^{-1}$
     ✓ Factor $\sim 4$ larger w.r.t. previous analysis
   - Larger MC samples

➤ **Increase in performances**
   - Run 1 $\rightarrow$ Highly prescaled minimum bias data
   - Run 2 $\rightarrow$ Dedicated trigger lines
     ✓ Gain of a factor $\sim 13$ in signal efficiency
   - Improved PID performance on protons and muons
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New accessible measurements
- Differential branching fraction vs dimuon mass
- Forward-backward asymmetry in the decay
- $\Sigma^+$ and $\Sigma^-$ polarisations
- “Direct” CP violation measurement

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

8 June 2024
Dedicated trigger

Run 1: “take what is there”
- Analyse data already collected with very small efficiency

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

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| Total       | 0.0083 ± 0.0013 | 0.111 ± 0.004 |

Increase in trigger efficiency from HLT
Analysis strategy

➤ Blind analysis technique
  • Avoid introduction of biases
  • Blinded $m_{p\mu^+\mu^-}$ region: $1173 < m_{p\mu^+\mu^-} < 1205$ MeV/$c^2$

**Selection**: Reject most of the background sources and isolate the signal candidates
  • Loose preselection on kinematic variables
  • Tight selection with PID variables
  • Multivariate operator and optimisation

**Fit**: Estimate the signal candidates
  • Unblinding and fit to the full $m_{p\mu^+\mu^-}$ distribution

**Dimuon spectrum**: Look for a resonant structure
  • Background subtraction with the *sPlot* method
  • Scan in the $m_{\mu^+\mu^-}$ invariant mass
Selection

$$\tau_{\Sigma^+} = (8.018 \pm 0.026) \times 10^{-11} \text{ s}$$

Decay products may be reconstructed with
- Long tracks
- Downstream tracks

Loose preselection
- Kinematic variables
- Reduce the dataset size
Tight selection
- PID variables

Only long tracks today
Selection

\[ \tau_{\Sigma^+} = (8.018 \pm 0.026) \times 10^{-11} \text{ s} \]

Decay products may be reconstructed with
- Long tracks
- Downstream tracks

Residual background sources
- Combinatorial
- \( \Lambda \rightarrow p\pi^- \) decays with misID \( \pi^- \rightarrow \mu^- \) with accidental \( \mu^+ \)

Small q-value
- Few modes can mimic the signal final state
  \[ (m_{\Sigma^+} - m_p - 2m_\mu) = 39.78 \text{ MeV}/c^2 \]
- \( K^+ \rightarrow \pi^+\pi^-\pi^+ \) and \( K^+ \rightarrow \pi^+\mu^+\mu^- \) decays
  - Mass peak shifter higher w.r.t. the signal

Loose preselection
- Kinematic variables
- Reduce the dataset size
Tight selection
- PID variables

No other baryon decays with a final state proton
- Larger reconstructed mass w.r.t. the signal
Final selection with a multivariate operator
- BDT built in TMVA
- Trained to reject combinatorial on:
  - MC signal sample
  - Sidebands in data sample

Discriminating variables (backup slides for description)
- \( \log(1 - \Sigma^+\text{DIRA}) \)
- \( \Sigma^+\text{IP}\chi^2, \text{DOCA}, \text{FD}\chi^2, Vtx\chi^2 \)
- \( p\text{IP}\chi^2, p_T \)
- \( \text{min(}\mu\text{IP}\chi^2), \text{min(}\mu p_T) \)

Data divided in a \( \Lambda \) veto sample and a complementary one
- Very similar distribution at high BDT values
- A BDT requirement will reject both background sources
Optimisation

- Optimisation for the best chances of observation
  - Performed on:
    - MC and data samples
  - Optimal point chosen as the largest significance

\[ S = \frac{N_S}{\sqrt{N_S + (N_C + N_\Lambda)}} \]

- \( N_S \) = Expected signal yield
- \( N_C \) = Expected combinatorial
- \( N_\Lambda \) = Expected \( \Lambda \) background

- Four dimensions
  - BDT
  - PID variables
  - \( \Lambda \) vetos \( \Rightarrow |m_{p\pi^-} - m^{PDG}_\Lambda| > 6, 8, 10 \text{ MeV}/c^2 \)

LHCb Preliminary

- 5.4 fb\(^{-1}\)

Bijective transformation to the BDT output

BDT > 0.35
Extended maximum likelihood fit

- $\Sigma^+ \rightarrow p\mu^+\mu^-$ parametrized by an *Hypatia* function
  
  $N_{\Sigma^+\rightarrow p\mu^+\mu^-} = 279 \pm 19$

- Background by a modified *Argus* function

\[ N = 2.5 \text{ MeV} / (2.5 \text{ MeV} / c^2) \]

\[ \text{Candidates} / (5.4 \text{ fb}^{-1}) \]
Extended maximum likelihood fit

- $\Sigma^+ \rightarrow p\mu^+\mu^-$ parametrized by an Hypatia function
- $N_{\Sigma^+\rightarrow p\mu^+\mu^-} = 279 \pm 19$
- Background by a modified Argus function

First observation with overwhelming significance
Observation of the $\Sigma \rightarrow p \mu^+ \mu^-$ rare decay at LHCb - G. Martelli

- **Background subtraction**
  - *sPlot* method using $m_{\mu^+\mu^-}$ as discriminant variable
    - Event-by-event signal re-weight

- No significant peaking structure is visible
  - Data compared with simulated phase space
    - Simulation re-weighted according to SM amplitude
  - Good agreement found in the full $m_{\mu^+\mu^-}$ distribution

---

**Yield / (2 MeV/c^2) vs. $m_{\mu^+\mu^-}$ [MeV/c^2]**

LHCb Preliminary

- $5.4 \text{ fb}^{-1}$
- Same distribution in 88 bins

- **Data**
- Simulation PHSP
- Simulation SM
Scan in the $m_{\mu^+\mu^-}$ invariant mass
- $\pm 2\sigma_{\mu^+\mu^-}$ around the $\Sigma^+$ mass with sidebands $[1.5 - 4.0]\sigma_{\mu^+\mu^-}$
- Steps of $\pm 0.5\sigma_{\mu^+\mu^-}$ in signal windows of $\pm 1.5\sigma_{\mu^+\mu^-}$

No significant structure is found and considering a putative candidate with $m_{X^0} = 214.3$ MeV/c$^2$:
- The fractional contribution to all the candidates in the mass window is $3.7\%$
- The difference w.r.t. to the expected background from the $m_{\mu^+\mu^-}$ sidebands is $-4$ events
Conclusions and outlook

“Observation of the $\Sigma^+ \to p\mu^+\mu^-$ rare decay at LHCb”

- First observation of the decay with significance greater than $5\sigma$
- Investigated the dimuon spectrum for NP resonances
  - No significant structure is found
  - HyperCP Anomaly excluded
LHCb-CONF-2024-002

Near future (Run 2)
- Integrated branching fraction measurement with the $\Sigma^+ \to p\pi^0$ decay

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

Far future (Run 2 and Run 3)
- Large signal yield $\rightarrow$ new accessible measurements
  - Charge-parity symmetry violation
  - Forward-backward asymmetries
On behalf of the LHCb collaboration thank you for your attention
Backup slides
Summary

- $IP\chi^2$ - The difference in the vertex-fit $\chi^2$ of a given PV reconstructed with and without the particle being considered;
- $DOCA$ - The maximum distance of closest approach between any pair of the three daughter tracks;
- $FD\chi^2$ - The flight distance of the mother particle from the primary vertex divided by its uncertainty;
- $DIRA$ - The angle between the mother particle momentum and the lines joining the primary and the decay vertex;
- $Vtx\chi^2$ - The $\chi^2$ of the vertex fit.