Evidence for the rare decay $\Sigma^+ \rightarrow p\mu^+\mu^-$ at LHCb

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Introduction

$\Sigma^+ \rightarrow p\mu^+\mu^-$ in the Standard Model

- $\Sigma^+ \rightarrow p\mu^+\mu^-$ is a very rare FCNC
- Short distance SM branching fraction is $O(10^{-12})$
- Dominated by long distance contributions:
  \[1.6 \cdot 10^{-8} < B(\Sigma^+ \rightarrow p\mu^+\mu^-) < 9.0 \cdot 10^{-8}\]
  [He et al. - Phys.Rev. D72 (2005) 074003]
The HyperCP evidence

- An evidence for this decay was found by the HyperCP experiment with 3 events in absence of background.
- Measured branching fraction is:
  \[ B(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8} \]
- This evidence had wide relevance since all the 3 observed signal events have the same dimuon invariant mass: pointing towards a \( \Sigma^+ \to p X^0 \rightarrow \mu\mu \) decay
  \[ B(\Sigma^+ \to p X^0 \rightarrow \mu\mu) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8} \]
Theoretical interpretations and experimental status

- Several interpretations were proposed
  - Light Higgs boson [He, Tandean Valencia, PRL.98.081802 (2007)]
  - Sgoldstino [Gorbunov, Rubakov PRD 73 035002 ]
  - Many others
  - In general pseudoscalar favoured over scalar and lifetime of order $10^{-14}$s

- Many experimental searches for low mass resonances in dimuons:
  - CLEO, E391a, D0, BaBar, Belle, KTeV, BESIII
  - Searched also at LHCb in $B^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$ and $B^0 \rightarrow K^{*0}\mu^+\mu^-$
  - Not confirmed

- No other search in $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays
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LHCb experiment

- 1075 members, from 68 institutes in 17 countries (September 2014)
- Dedicated experiment for precision measurements of CP violation and rare decays
- Beautiful, charming, strange physics program

- $pp$ collisions at $\sqrt{s} = 7, 8(13)$ TeV in RunI (RunII)
- $b\bar{b}$ quark pairs produced correlated in the forward region
- Luminosity of $4 \times 10^{32} cm^{-2} s^{-1}$

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LHCb detector

Excellent vertex and IP resolution
- $\sigma(IP) \approx 24\mu m$ at $p_T = 2$ GeV/c
- $\sigma_{BV} \approx 16\mu m$ in $x, y$

Very good momentum resolution
- $\sigma(p)/p = 0.4\% - 0.6\%$ for $p \in (0, 100)$ GeV/c
- $\sigma(m_B) \sim 24$ MeV for two body decays

Muon identification
- $\epsilon_\mu = 98\%$, $\epsilon_{\pi \rightarrow \mu} = 0.6\%$, $\epsilon_{K \rightarrow \mu} = 0.3\%$
- $\epsilon_{p \rightarrow \mu} = 0.3\%$

Trigger
- $\epsilon_\mu = 90\%$

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Setting the (long) stage

- Huge strange hadrons production cross-section at LHCb
- Large lifetimes for LHCb... but the peak of an exponential is at zero!
General analysis strategy

1. Soft pre-selection to reduce dataset
2. Cut on BDT and PID to remove most of the background
3. Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays:
   * Search around $\Sigma$ mass window for SM signal
   * If peak is found, look at $\mu\mu$ invariant mass
4. Normalize branching fraction to $\Sigma^+ \rightarrow p\pi^0$ decays

Sample and selection:

- Full 2011+2012 statistics, luminosity 3 $fb^{-1}$
- Selections for final states: $\Sigma^+ \rightarrow p\mu^+\mu^-$, $\Sigma^+ \rightarrow \bar{p}\mu^+\mu^+$, $\Sigma^+ \rightarrow p\pi^0$, $K^+ \rightarrow \pi^+\pi^-\pi^+$
- Decays reconstructed with long tracks (i.e. decays in VELO)
- Prompt decays

Datasets strategy

- Very soft signal to be triggered
- Two trigger strategies:
  1. Full - all events are retained, for search purposes, no normalisation
  2. TIS - for normalization purposes (sub sample)
TIS events and the TISTOS method

- 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)

- Events can be TIS and TOS
- Overall can be used to measure trigger efficiencies

Tolk, S et al. LHCb-PUB-2014-039
Evidence for the rare decay $\Sigma^+ \rightarrow p\mu^+\mu^-$ at LHCb
Search for an Hyper-CP like signal

- Hyper-CP signal is consistent with $\Sigma^+ \rightarrow pX^0(\rightarrow \mu\mu)$, with $m_{X^0} = 214.3 \pm 0.5$ MeV
- Mass resolution in LHCb:
  * Raises with $m_{\mu^+\mu^-}$ departing from threshold
- Study efficiency versus $m_{\mu^+\mu^-}$: higher efficiency at small mass due to higher minimum $p_T$

![Resolution and Efficiency Plots](image-url)
Multivariate selection: BDT

- BDT aiming at rejecting combinatorial background
- Training on signal MC sample and background from data same-sign sidebands ($\Sigma^+ \rightarrow \bar{p}\mu^+\mu^+$)
- Common geometric and kinematic variables: pointing, IP, $p_T$ and isolations, ...
Fit to the invariant mass distribution

- Signal shape described as Hypatia function used with fixed parameters (only mean and resolution floating)*
  
  * Resolution and mean calibrated with $K^+ \rightarrow \pi^+\pi^-\pi^+$ Data/MC ratio
  
  * Signal resolution left free to vary in the fit with gaussian constraint in final fits

- Background described as modified ARGUS function

$$f(m, m_0, p, c) = m \left( \frac{m^2}{m_0^2} - 1 \right)^p e^{c \frac{m}{m_0}}$$

where $m_0$ is the threshold mass typically of the order of the sum of the daughters masses; $p$ and $c$ are free parameters.

Normalisation

• No fully charged final state available in the $\Sigma^+$ to normalize the branching fraction

• Use high branching fraction $\Sigma^+ \rightarrow p\pi^0$

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

• Selection for $\Sigma^+ \rightarrow p\pi^0$ with $\pi^0 \rightarrow \gamma\gamma$ (resolved clusters) from calorimeter

• Branching fraction $\mathcal{B} = (51.57 \pm 0.30)\%$

For full RunI dataset, only TIS:

• Single event sensitivity $\alpha_{TIS} = (1.1 \pm 0.6) \times 10^{-8}$

• Correspondent to $4.6 \pm 4.2$ expected events in the TIS sample with a SM branching fraction
Normalisation with $\Sigma^+ \rightarrow p\pi^0$

- Fit to corrected mass: $m_\Sigma - m_{\pi^0} + m_{\pi^0}^{PDG}$
- Single Crystal-Ball pdf with right tail for the signal
- Modified Argus (with threshold on the left) for the background

![Graph showing the decay $\Sigma^+ \rightarrow p\pi^0$]

- $N_\Sigma = (11711 \pm 9) \times 10^3$
Normalisation systematics

- TIS Trigger efficiency calibrated with large $K^+ \rightarrow \pi^+\pi^-\pi^+$ sample and TISTOS method
- Reconstruction of the $\pi^0$ calibrated with ratio of ratio of $B^+ \rightarrow J/\psi K^{*+}(\rightarrow K^+\pi^0)$ and $B^+ \rightarrow J/\psi K^+$ decays reconstructed in data.
- Particle identification calibrated with control channels in data ($\Lambda \rightarrow p\pi^-$ and $J/\psi$)
- BDT operator calibrated with $K^+ \rightarrow \pi^+\pi^-\pi^+$ channel in data

<table>
<thead>
<tr>
<th>Selection Data-MC differences</th>
<th>1.4%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration of BDT efficiency</td>
<td>6.4%</td>
</tr>
<tr>
<td>Calibration of PID efficiency</td>
<td>20%</td>
</tr>
<tr>
<td>Calibration of the $\pi^0$ efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>Calibration of the TIS efficiency</td>
<td>30%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>43%</strong></td>
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</tbody>
</table>
Excess of events w.r.t. background with a significance of 4.0σ
Fitted signal yield: 12.9^{+5.1}_{-4.2}
No excess of events in the TIS sub-sample
Upper limit with CLS method: \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 6.3 \times 10^{-8} at 95\% CL
Results: analysis of the dimuon mass

- Consider candidates within $2\sigma$ from the $\Sigma$ mass in the full selection
- Scan dimuon invariant mass for possible peaks
- Fit with gaussian of known mass and resolution
- No significant peak found
- Most significant at 213.7 MeV (but not significant)
- Fit at $m_{X^0} = 214.3$ MeV yields $1.6 \pm 1.9$ events corresponding to a fraction $0.078 \pm 0.092$ of the total seen signal

\[ m_{X^0} = 214.3 \text{ MeV} \]
Discussion of the results

- Found signal only in the full sample:
  most of the seen events have only one of the three trigger stage not being TIS
- Full detailed study of $\Sigma^+ \rightarrow p\mu^+\mu^-$ trigger efficiency is under way
- The main conclusions are anyway independent of absolute normalisation:
  * Evidence of $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay
  * SM-like distribution of the dimuon invariant mass
  * Limit on the possible contribution of an additional particle
Summary and conclusions

- Search for the $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay fundamental to cross-check HyperCP evidence
- First study of rare strange baryon at LHC
- Sensitivity in the $10^{-8}$ range
- Clear evidence of the $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay
- Upper limits on branching fractions from TIS events
- No peaks in the dimuon invariant mass: SM once again
- Run II will fortunately not have these problems thanks to new dedicated trigger lines
- Conference Note LHCb-CONF-2016-013 will be public in few days
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