Strange physics at LHCb

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New physics in kaon and beam-dump experiments
3/12/2018 - Birmingham
• 1250 members, from 79 institutes in 18 countries
• Dedicated experiment for precision measurements of CP violation and rare decays
• Beautiful, charming, strange physics program

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

interaction point

vertex locator

RICH

trackers

calorimeters

muon detectors
Introduction: production

- Huge strange hadrons production cross-section at LHCb
- Production of particles in a minimum bias event within the geometric acceptance (400 mrad)
- About 1 strange hadron per event (compared to \( \sim 10^{-3} \ B_s^0 \) mesons)
- Reconstruction and trigger however bring this number down

Average particles in LHCb acceptance per minimum bias event at \( \sqrt{s} = 13 \text{ TeV} \)

- \( B_s^0 \)
- \( B_s^0 \pi^+ \)
- \( K^+ \)
- \( K^0_L K^0_S \)
- \( \Lambda^0 \)
- \( \Sigma^0 \Sigma^+ \)
- \( D^0 \)
- \( D^+ \)
- \( B^+ B^0 \)
- \( B_s^0 \)
- \( J/\psi \)

Alves et al. arXiv/1808.03477
Introduction: setting the (long) stage

Reconstruction

- Large lifetimes for LHCb...
  but the peak of an exponential is at zero!
- Different reconstruction methods for the daughter tracks

![Diagram of LHCb experiment](image)

![Graph showing decay lengths](graph)

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Strange physics at LHCb with Run 1
LHCb Run 1 data-taking

- LHCb trigger designed for heavy flavours
- Muon (hadron) L0 trigger require $p_T > [1 - 5]$ GeV
- Too hard for primary strange hadrons
- Hlt1 and Hlt2 are software and customizable
- No dedicated triggers in 2011, added a $K_S^0 \rightarrow \mu^+ \mu^-$ dedicated trigger in 2012
- Several generic (topological) triggers allowed good efficiencies
- Typical events contain more than one strange hadron
- $\Rightarrow$ Strange physics Run 1 analyses mostly based on data triggered by the rest of the event

**LHCb 2012 Trigger Diagram**

- 40 MHz bunch crossing rate
- L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
  - $450 \text{ kHz } h^\pm$
  - $400 \text{ kHz } \mu/\mu\mu$
  - $150 \text{ kHz } e/\gamma$
- Software High Level Trigger
  - 29000 Logical CPU cores
  - Offline reconstruction tuned to trigger time constraints
  - Mixture of exclusive and inclusive selection algorithms
- 5 kHz (0.3 GB/s) to storage
  - 2 kHz Inclusive Topological
  - 2 kHz Inclusive/Exclusive Charm
  - 1 kHz Muon and DiMuon

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3/12/2018 8/29
Search for $K_S^0 \rightarrow \mu^+ \mu^-$ decays

- $K_L^0 \rightarrow \mu^+ \mu^-$ is the “father” of flavour physics: charm quark and GIM mechanism
- $K_S^0 \rightarrow \mu^+ \mu^-$ in addition suppressed by CPV
- SM prediction $\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) = (5.18 \pm 1.50 \pm 0.02) \cdot 10^{-12}$ [Ecker, Pich - Nucl Phys B366 (1991)] [Isidori, Unter dorfer - JHEP 01 (2004) 009] [D’ambrosio, Kitahara - PRL 119(2018)02]

- Dominated by long distance contributions
- Sensitive to NP, e.g. light scalars with CP-violating Yukawa couplings
- Before LHCb: $\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) < 3.1 \cdot 10^{-7}$ at 90% CL at CERN PS in 1973 [S. Gjesdal et al. PLB44(1973)217]

- Recent theoretical interest following LHCb results: possibility to study the interference of $K_L^0$ and $K_S^0$ to two muons [D’ambrosio, Kitahara - PRL 119(2018)02]
Search for $K_S^0 \rightarrow \mu^+\mu^-$ decays

- **Search for $K_S^0 \rightarrow \mu^+\mu^-$ at LHCb with full Run 1 ($3 \, \text{fb}^{-1}$)**
- Common selection of $K_S^0 \rightarrow \mu^+\mu^-$ and $K_S^0 \rightarrow \pi^+\pi^-$, control and normalisation channel as well as main background
- Veto for $\Lambda \rightarrow p\pi^-$ and particle identification against $K^* \rightarrow K\pi$ and other backgrounds
- Two multivariate operators to fight different backgrounds:
  * Dedicated multivariate particle identification algorithm developed
  * BDT to fight combinatorial background

**Trigger strategy**

- Two categories based different trigger paths

![Invariant mass distribution](chart.png)
$K_S^0 \rightarrow \mu^+\mu^-$

Results

- $K_S^0 \rightarrow \mu^+\mu^-$ distribution fitted in the [470,600] MeV range
- Simultaneous maximum likelihood fit performed over the 30 bins
- Combinatorial and misID $K_S^0 \rightarrow \pi^+\pi^-$ background components included
- No excess of events is observed with respect to background expectations
$K_S^0 \rightarrow \mu^+\mu^-$

Results

- The upper limit of the previous search is reinterpreted as posterior on the branching fraction and included as prior in this search
- The new upper limit on the branching fraction is
  \[ \mathcal{B}(K_S^0 \rightarrow \mu^+\mu^-) < 0.8(1.0) \times 10^{-9} \text{ at } 90\% (95\%) \text{ CL} \]
- Factor 400 improvement with respect to the best limit before LHCb
Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ at LHCb

The HyperCP anomaly

- $\Sigma^+ \rightarrow p\mu^+\mu^-$ is a very rare FCNC
- Short distance SM $\mathcal{B} \sim O(10^{-12})$
- Dominated by long distance contributions: $1.6 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) < 9.0 \cdot 10^{-8}$
  [He et al. - Phys.Rev. D72 (2005) 074003]
- Evidence found by the HyperCP experiment with 3 events in absence of background
- Measured branching fraction is: $\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$
- All the 3 observed signal events have the same dimuon invariant mass: pointing towards a $\Sigma^+ \rightarrow pX^0(\rightarrow \mu\mu)$ decay with $m_{X^0} = 214.3 \pm 0.5$ MeV

$\mathcal{B}(\Sigma^+ \rightarrow pX^0(\rightarrow \mu\mu)) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8}$
Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ at LHCb

General analysis strategy

Sample and selection:
• Search with 3 fb$^{-1}$ (full Run 1)
• Prompt decays (no displacement of the dimuon pair)
• Soft pre-selection to reduce dataset
• Cut on BDT and PID to remove most of the background
• Explicit veto of $\Lambda \rightarrow p\pi$ background, no other peaking background contributes

![Graph showing probability distribution](attachment:image.png)
Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ at LHCb

Normalisation

- No fully charged final state available in the $\Sigma^+$ to normalize
- Use high branching fraction $\Sigma^+ \rightarrow p\pi^0$ ($\mathcal{B} = (51.57 \pm 0.30)\%$)

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

$$= \alpha N_{\Sigma^+ \rightarrow p\mu^+\mu^-}$$

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

For full Run 1 dataset, single event sensitivity $\alpha = (2.2 \pm 1.2) \times 10^{-9}$

Correspondent to $23 \pm 20$ expected events with a SM BR

![Graph showing data, full model, and background for $\Sigma^+ \rightarrow p\pi^0$]
Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ at LHCb

Results

- Excess of events w.r.t. background with a significance of $4.1 \sigma$
- Fitted signal yield: $10.2^{+3.9}_{-3.5}$
- Measured branching fraction $(2.2^{+0.9}_{-0.8} + 1.5_{-1.1}) \times 10^{-8}$
- No significant peak found in the dimuon mass: $\mathcal{B}(\Sigma^+ \rightarrow pX^0(\rightarrow \mu^+\mu^-)) < 1.4 \times 10^{-8}$ at 90%CL
LHCb Run 2 and Upgrade
LHCb 2015 Trigger Diagram

- Improved farm and algorithms: higher bandwidth
- Real time calibration between Hlt1 and Hlt2
- L0 still limiting factor for strange physics

Software improvements for strange
- Complement forward tracking for very soft muons implemented
- New Hlt1 inclusive lines developed with focus on strange physics
- Various novel Hlt2 inclusive and exclusive lines written, dedicated to strange

More than 6 fb$^{-1}$ on tape
LHCb Upgrade data-taking

- Upgraded detector for 40 MHz full readout
- $\mathcal{L} = 2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1} \Rightarrow \text{about} 5 \text{ fb}^{-1} \text{ per year}$
- L0 hardware trigger is removed in Upgrade
- Hlt1 run directly on collision data

Fundamental step forward for strange physics!
Future sensitivity to $K_S^0 \rightarrow \mu^+ \mu^-$

- Depends on real trigger efficiencies
- Approach interesting region in Run 2 and Upgrade
- Probe SM in Upgrade II
Sensitivity to $K^0_S \rightarrow \pi^0 \mu^+ \mu^-$

- $K^0_L \rightarrow \pi^0 \mu^+ \mu^-$ very sensitive to physics beyond the SM, e.g. extra-dimensions [M. Bauer et al. JHEP 09(2010)017]
- SM prediction with large uncertainty
  $\mathcal{B}_{SM}(K^0_L \rightarrow \pi^0 \mu^+ \mu^-) = \{1.4 \pm 0.3, 0.9 \pm 0.2\} \times 10^{-11}$
- Limited by knowledge of ChPT parameter $|a_S|$ extracted from $K^0_S \rightarrow \pi^0 \mu^+ \mu^-$ branching fraction
- $\mathcal{B}(K^0_S \rightarrow \pi^0 \mu^+ \mu^-) = (2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$ measured by NA48 Collaboration [J.R. Batley et al. PLB599 (2011) 197]
Sensitivity to $K^0_S \rightarrow \pi^0 \mu^+ \mu^-$

- Studied sensitivity of LHCb to this channel in Run 2 and Upgrade scenarios
- Difficult reconstruction due to soft $\pi^0$
- Double strategy: without $\pi^0$ (Partial) and with $\pi^0$ reconstructed from $\gamma$ pairs
- Combinatorial background estimated with real data TIS events
- Peaking backgrounds studied with MC: none found to contribute in LHCb
- Statistical uncertainty on $\mathcal{B}(K^0_S \rightarrow \pi^0 \mu^+ \mu^-)$ as a function of luminosity times trigger efficiency
- LHCb will be competitive with NA48 for trigger efficiencies of $\sim 50\%$ or larger
$K^0 \to \ell^+ \ell^- \ell^+ \ell^-$

- $K^0 \to \ell^+ \ell^- \ell^+ \ell^-$ short distance sensitive to NP, dominated by the long distance contribution uncertainty.
- Interference of $\mathcal{A}(K_S^0 \to \ell^+ \ell^- \ell^+ \ell^-)$ and $\mathcal{A}(K_L^0 \to \ell^+ \ell^- \ell^+ \ell^-)$ would give a measurement of the sign of $\mathcal{A}(K_L^0 \to \gamma \gamma)$ which is a stringent test of CKM.
  
  
  [D’Ambrosio et al - EPJC73(2013)2678]

- $K_L^0 \to \ell^+ \ell^- \ell^+ \ell^-$ studied by different experiments but no experimental constraints on $K_S^0$ modes

\[ \mathcal{B}(K_S^0 \to e^+e^-e^+e^-) \sim 10^{-10} \]
\[ \mathcal{B}(K_S^0 \to \mu^+\mu^-e^+e^-) \sim 10^{-11} \]
\[ \mathcal{B}(K_S^0 \to \mu^+\mu^-\mu^+\mu^-) \sim 10^{-14} \]

- Sensitive to NP at same order of SM.
Sensitivity to $K^0_S \rightarrow \pi^+\pi^-e^+e^-$

- $K^0_S \rightarrow \pi^+\pi^-e^+e^-$ is channel for $K^0_S \rightarrow \ell^+\ell^-\ell^+\ell^-$
- Sensitivity study at LHCb with MC
- $\varepsilon \sim 0.2\%$, limited by L0 trigger
- $\mathcal{B}(K^0_S \rightarrow \pi^+\pi^-e^+e^-) = (4.79 \pm 0.15) \times 10^{-5}$

With Run 1 conditions expected $N = 120^{+280}_{-100}$ events per fb$^{-1}$ of 8 TeV data on top of about $3 \cdot 10^3$ background events. No multivariate selection applied.

- Dedicated Hlt2 trigger line deployed in Run 2, still limited by Hlt1 and L0
- Upgrade trigger will improve the efficiency on this and related channels sensibly
- In the ideal scenario of $\sim 100\%$ w.r.t. offline selection

$$N_{exp} = 5 \cdot 10^4 \text{ per fb}^{-1}$$

- Similar efficiencies are expected for the $K^0_S \rightarrow \ell^+\ell^-\ell^+\ell^-$ rare channels
- Single event sensitivities of order $9.6 \cdot 10^{-10}$ per each fb$^{-1}$ in Upgrade conditions
A glimpse into LHCb possibilities

- Dedicated paper with some of us + theorists to explore future possibilities
- Approximate simulations (validated on published ones) to get sensitivities
- Countless channels to be probed

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\mathcal{R}$</th>
<th>$\epsilon_L$</th>
<th>$\epsilon_D$</th>
<th>$\sigma_L$(MeV/$c^2$)</th>
<th>$\sigma_D$(MeV/$c^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0_S \to \mu^+\mu^-$</td>
<td>1</td>
<td>1.0 (1.0)</td>
<td>1.8 (1.8)</td>
<td>$\sim 3.0$</td>
<td>$\sim 8.0$</td>
</tr>
<tr>
<td>$K^0_S \to \pi^+\pi^-$</td>
<td>1</td>
<td>1.1 (0.30)</td>
<td>1.9 (0.91)</td>
<td>$\sim 2.5$</td>
<td>$\sim 7.0$</td>
</tr>
<tr>
<td>$K^0_S \to \pi^0\mu^+\mu^-$</td>
<td>1</td>
<td>0.93 (0.93)</td>
<td>1.5 (1.5)</td>
<td>$\sim 35$</td>
<td>$\sim 45$</td>
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<tr>
<td>$K^0_S \to \gamma\mu^+\mu^-$</td>
<td>1</td>
<td>0.85 (0.85)</td>
<td>1.4 (1.4)</td>
<td>$\sim 60$</td>
<td>$\sim 60$</td>
</tr>
<tr>
<td>$K^0_S \to \mu^+\mu^-\mu^+\mu^-$</td>
<td>1</td>
<td>0.37 (0.37)</td>
<td>1.1 (1.1)</td>
<td>$\sim 1.0$</td>
<td>$\sim 6.0$</td>
</tr>
<tr>
<td>$K^0_L \to \mu^+\mu^-$</td>
<td>$\sim 1$</td>
<td>2.7 (2.7) $\times 10^{-3}$</td>
<td>0.014 (0.014)</td>
<td>$\sim 3.0$</td>
<td>$\sim 7.0$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi^+\pi^-$</td>
<td>$\sim 2$</td>
<td>9.0 (0.75) $\times 10^{-3}$</td>
<td>41.8 (6.6) $\times 10^{-3}$</td>
<td>$\sim 1.0$</td>
<td>$\sim 4.0$</td>
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<tr>
<td>$K^+ \to \pi^+\mu^+\mu^-$</td>
<td>$\sim 2$</td>
<td>6.3 (2.3) $\times 10^{-3}$</td>
<td>0.030 (0.014)</td>
<td>$\sim 1.5$</td>
<td>$\sim 4.5$</td>
</tr>
<tr>
<td>$\Sigma^+ \to p\mu^+\mu^-$</td>
<td>$\sim 0.13$</td>
<td>0.28 (0.28)</td>
<td>0.64 (0.64)</td>
<td>$\sim 1.0$</td>
<td>$\sim 3.0$</td>
</tr>
<tr>
<td>$\Lambda \to p\pi^-$</td>
<td>$\sim 0.45$</td>
<td>0.41 (0.075)</td>
<td>1.3 (0.39)</td>
<td>$\sim 1.5$</td>
<td>$\sim 5.0$</td>
</tr>
<tr>
<td>$\Lambda \to p\mu^-\nu_{\mu}$</td>
<td>$\sim 0.45$</td>
<td>0.32 (0.31)</td>
<td>0.88 (0.86)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\Xi^- \to \Lambda\mu^-\nu_{\mu}$</td>
<td>$\sim 0.04$</td>
<td>39.5 (5.7) $\times 10^{-3}$</td>
<td>0.27 (0.09)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\Xi^- \to \Sigma^0\mu^-\nu_{\mu}$</td>
<td>$\sim 0.03$</td>
<td>24.9 (4.9) $\times 10^{-3}$</td>
<td>0.21 (0.068)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$\Xi^- \to p\pi^-\pi^-$</td>
<td>$\sim 0.03$</td>
<td>0.41 (0.05)</td>
<td>0.94 (0.20)</td>
<td>$\sim 3.0$</td>
<td>$\sim 9.0$</td>
</tr>
<tr>
<td>$\Xi^0 \to p\pi^-$</td>
<td>$\sim 0.03$</td>
<td>1.0 (0.48)</td>
<td>2.0 (1.3)</td>
<td>$\sim 5.0$</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$\Omega^- \to \Lambda\pi^-$</td>
<td>$\sim 0.001$</td>
<td>95.6 (6.7) $\times 10^{-3}$</td>
<td>0.32 (0.10)</td>
<td>$\sim 7.0$</td>
<td>$\sim 20$</td>
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<td>$K^0_S \to \pi^+\pi^-e^+e^-$</td>
<td>1</td>
<td>1.0 (0.18)</td>
<td>2.83 (1.1)</td>
<td>$\sim 2.0$</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$K^0_S \to \mu^+\mu^-e^+e^-$</td>
<td>1</td>
<td>1.18 (0.48)</td>
<td>2.93 (1.4)</td>
<td>$\sim 2.0$</td>
<td>$\sim 11$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+e^-e^+$</td>
<td>$\sim 2$</td>
<td>0.04 (0.01)</td>
<td>0.17 (0.06)</td>
<td>$\sim 3.0$</td>
<td>$\sim 13$</td>
</tr>
<tr>
<td>$\Sigma^+ \to p\mu^+e^-$</td>
<td>$\sim 0.13$</td>
<td>1.76 (0.56)</td>
<td>3.2 (1.3)</td>
<td>$\sim 3.5$</td>
<td>$\sim 11$</td>
</tr>
<tr>
<td>$\Lambda \to p\pi^-e^+e^-$</td>
<td>$\sim 0.45$</td>
<td>$&lt; 2.2 \times 10^{-4}$</td>
<td>$\sim 17 (&lt; 2.2) \times 10^{-4}$</td>
<td>–</td>
<td>–</td>
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<tr>
<td>$K^0_S \to \mu^+e^-$</td>
<td>1</td>
<td>1.0 (0.84)</td>
<td>1.5 (1.3)</td>
<td>$\sim 3.0$</td>
<td>$\sim 8.0$</td>
</tr>
<tr>
<td>$K^0_L \to \mu^+e^-$</td>
<td>1</td>
<td>3.1 (2.6) $\times 10^{-3}$</td>
<td>13 (11) $\times 10^{-3}$</td>
<td>$\sim 3.0$</td>
<td>$\sim 7.0$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\mu^+e^-$</td>
<td>$\sim 2$</td>
<td>3.1 (1.1) $\times 10^{-3}$</td>
<td>16 (8.5) $\times 10^{-3}$</td>
<td>$\sim 2.0$</td>
<td>$\sim 8.0$</td>
</tr>
</tbody>
</table>
Prospects for charged kaons

- Enormous $K^+$ production but small acceptance
- Run 1 has 1 M $K^+ \rightarrow \pi^+ \pi^- \pi^+$ fully TIS
- Measurement of the charged kaon mass is under way to solve long standing disagreement
- With full software trigger $O(10^{-10})$ single event sensitivity per fb$^{-1}$ obtainable
- $K^+ \rightarrow \pi^+ \mu^- \mu^+$ and $K^+ \rightarrow \pi^+ e^- e^+$ become accessible

[Alves et al. arXiv/1808.03477]
Summary and conclusions

- **LHCb expanding its physics reach towards strange physics complementary to the core program**

- Encouraging Run 1 results on $K_S^0 \rightarrow \mu^+\mu^-$ and $\Sigma^+ \rightarrow p\mu^+\mu^-$

- Large samples available already on tape fully exploiting existing data

- **LHCb major player for $K_S^0$ and hyperons rare decays**

- Complementary to $K_L^0$ and $K^+$ dedicated experiments

- Run 2 giving new results with improved trigger

- Upgrade trigger will allow unprecedented sensitivities on many channels
LHCb Collaboration
Papers

• Evidence for the rare decay \( \Sigma^+ \to p\mu^+\mu^- \) [Phys. Rev. Lett. 120, 221803 (2018)] [LHCb-PAPER-2017-049] [hep-ex/1712.08606]
• Improved limit on the branching fraction of the rare decay \( K^0_S \to \mu^+\mu^- \) [LHCb-PAPER-2017-009] [hep-ex/1706.00758] [Eur. Phys. J. C, 77 10 (2017) 678]
• Search for the CP-violating strong decays \( \eta \to \pi^+\pi^- \) and \( \eta' \to \pi^+\pi^- \) [LHCb-PAPER-2016-046] [hep-ex/1610.03666] [Physics Letters B 764 (2017) 233-240]
• Search for the rare decay \( K^0_S \to \mu^+\mu^- \) [LHCb-PAPER-2012-023] [hep-ex/1209.4029] [JHEP 01 (2013) 090]

Public notes

• Physics case for an LHCb Upgrade II [LHCB-PUB-2018-009][arXiv/1808.08865]
• Low \( p_T \) dimuon triggers at LHCb in Run 2 [LHCb-PUB-2017-023]
• Sensitivity of LHCb and its upgrade in the measurement of \( B(K^0_S \to \pi^0\mu^+\mu^-) \) [LHCb-PUB-2016-017]
• Feasibility study of \( K^0_S \to \pi^+\pi^- e^+e^- \) at LHCb [LHCb-PUB-2016-016]

Others

• Alves A. A. et al. “Prospects for Measurements with Strange Hadrons at LHCb” [arXiv/1808.03477]
• Borsato et al. “The strange side of LHCb” [arXiv/1808.02006]
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](image1)

![Efficiency](image2)
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, …
Search for CP violating strong decays $\eta^{(')} \rightarrow \pi^+ \pi^-$

- QCD should violate CP symmetry (with a term $\mathcal{L}_\theta = -\frac{\theta}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$)
  but none is observed experimentally
- $\theta < 10^{-10}$ from neutron electric dipole moment (strong CP problem)
- $\eta^{(')} \rightarrow \pi^+ \pi^-$ would be strong CP violating decays
- nEDM limit constraints SM branching fractions to $< 3 \cdot 10^{-17}$
  any evidence higher than this would be NP
- Best limits at 90% CL
  \[ \mathcal{B}(\eta \rightarrow \pi^+ \pi^-) < 1.3 \cdot 10^{-5} \quad \text{(KLOE $\phi \rightarrow \eta \gamma$ [PLB606 (2005) 276])} \]
  \[ \mathcal{B}(\eta^{'} \rightarrow \pi^+ \pi^-) < 5.5 \cdot 10^{-5} \quad \text{(BESIII J/\psi \rightarrow \gamma \pi^+ \pi^- [PRD84(2011)032006])} \]
Search for CP violating strong decays $\eta' \to \pi^+\pi^-$

- LHCb strategy: look for peaks in $\pi \pi$ mass from $D^+_s \to \pi^+\pi^-\pi^+$ decays (i.e. $D^+_s \to \pi^+\eta'\eta'$)
- MVA operator to reduce background
- Normalisation: $B(\eta' \to \pi^+\pi^-) = \frac{N_{\eta'} \varepsilon_{\eta'}}{N_{D^+_s \to \pi^+\pi^-\pi^+}} \frac{B(D^+_s \to \pi^+\pi^-\pi^+)}{B(D^+_s \to \pi^+\eta'\eta')}$
- Constrained $D$ masses and origin vertex improves resolution significantly
- $\varepsilon_{\eta'}$ small correction to efficiency versus $m_{\pi\pi}$
- $3 \text{ fb}^{-1}$ of Run 1 and $0.3 \text{ fb}^{-1}$ of Run 2 data from Turbo stream
- Run 2 contribution enhanced by larger cross-section and trigger efficiency
Search for CP violating strong decays $\eta' \rightarrow \pi^+ \pi^-$

- No excess on top of the background (signal phase space plus combinatorial)
- Upper limit on branching fractions with CLs method at 90% CL:
  \[
  \mathcal{B}(\eta \rightarrow \pi^+ \pi^-) < 1.6 \cdot 10^{-5}
  \]
  \[
  \mathcal{B}(\eta' \rightarrow \pi^+ \pi^-) < 1.8 \cdot 10^{-5}
  \]
- $\eta$ limit compatible with previous results, $\eta'$ limit improved by factor three
\[ \Sigma^+ \rightarrow p\mu^+\mu^- : \text{theoretical interpretations and experimental status} \]

- Several interpretations were proposed
  - Light Higgs boson [He, Tandean, Valencia, PRL.98.081802 (2007)]
  - Sgoldstino [Gorbunov, Rubakov PRD 73 035002 ] [Demidov, Gorbunov PRD73(2006)035002]
  - 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 nor disproved

- No other search in \(\Sigma^+ \rightarrow p\mu^+\mu^-\) decays
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 (TOB=!TIS&!TOS)

All events

![Venn diagram showing TIS, TIS&TOS, TOS, and TOB]

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

Tolk, S et al. LHCb-PUB-2014-039

F. Dettori
Strange physics at LHCb

3/12/2018
Normalisation systematics

- Trigger efficiency estimated with dedicated simulations with all trigger configurations and calibrated on data with $\Sigma^+ \to p\pi^0$ with the TISTOS method.
- Reconstruction of the $\pi^0$ calibrated with ratio of ratio of $B^+ \to J/\psi K^{*+}$ and $B^+ \to J/\psi K^+$ decays reconstructed in data.
- Particle identification calibrated with control channels in data ($\Lambda \to p\pi^- \text{ and } J/\psi$)
- BDT classifier calibrated with $K^+ \to \pi^+\pi^-\pi^+$ channel in data

### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection efficiency</td>
<td>1%</td>
</tr>
<tr>
<td>BDT efficiency</td>
<td>6%</td>
</tr>
<tr>
<td>PID efficiency ratio</td>
<td>28%</td>
</tr>
<tr>
<td>$\pi^0$ efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>Trigger efficiency ratio</td>
<td>40%</td>
</tr>
<tr>
<td>Total</td>
<td>50%</td>
</tr>
</tbody>
</table>
Results: analysis of the dimuon mass

- Consider candidates within $1.5\sigma$ from the $\Sigma$ mass in the full selection
- Scan dimuon invariant mass for possible peaks:
  No significant peak found
- Repeated $m_{p\mu^+\mu^-}$ fit restricting to $m_{\mu^+\mu^-} \in [214.3 \pm 0.75\text{MeV/c}^2])$:
  No significant peak found

![Distribution within 1.5\sigma](image)

![p-value](image)
Kaon physics from $\phi$ decays

- Huge $\phi$ production at LHC
- Exploit $\phi \to K^+ K^-$ decays in which one of the kaons is fully reconstructed
- Study final state of second kaon, also partially reconstructed thanks to the $\phi$ constraint
- $O(10^{10})$ tagged $\phi \to KK$ decays per year in the upgrade *
- For example study $K^+ \to e\nu$ (tag also initial Kaon leg with RICH1)

*See talk by Vava Gligorov, Rare’n’Strange workshop https://indico.cern.ch/event/590880/