Kaons at LHCb

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on behalf of the LHCb Collaboration

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University of Perugia (Italy)
LHCb experiment
• 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 \( \sqrt{s} = 7, 8(13) \) 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

[Int. J. Mod. Phys. A 30, 1530022 (2015)]
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 $\sim 10^{-3} B^0_s$ mesons)
- Reconstruction and trigger however bring this number down
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
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 $K^0_S \rightarrow \mu^+ \mu^-$ 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 (TIS)
Strange physics at LHCb with Run 1

Despite trigger and detector not designed for it

- World best limit on $K_S^0 \rightarrow \mu^+ \mu^-$ *EPJ.C*, 77 10(2017)678
  (See Miguel’s talk in “hot topics” session for the Run 2 update)
- Evidence for the $\Sigma^+ \rightarrow p\mu^+ \mu^-$ decay and measurement of the branching fraction, challenging to the HyperCP anomaly *PRL* 120, 221803
  (See my other talk for details)
LHCb Run 2 data-taking

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

450 kHz $h^\pm$
400 kHz $\mu/\mu\mu$
150 kHz $e/\gamma$

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

- Improved farm and algorithms: higher bandwidth
- Real time calibration between Hlt1 and Hlt2
- Factor 2 in cross-section from $\sqrt{s}$
- 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
- $\mathcal{L} = 2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$
  $\Rightarrow$ about 5 fb$^{-1}$ per year
- L0 hardware trigger is removed from Run 3
- Hlt1 run directly on collision data

Fundamental step forward for strange physics!
Sensitivity to $K_S^0 \to \pi^0 \mu^+ \mu^-$

- $K_L^0 \to \pi^0 \mu^+ \mu^-$ very sensitive to physics beyond the SM, e.g. extra-dimensions [M. Bauer et al. JHEP 09(2010)017]

- SM prediction with large uncertainty
  \[ \mathcal{B}_{SM}(K_L^0 \to \pi^0 \mu^+ \mu^-) = \{1.4 \pm 0.3, 0.9 \pm 0.2\} \times 10^{-11} \]

- Limited by knowledge of ChPT parameter $|a_S|$ extracted from $K_S^0 \to \pi^0 \mu^+ \mu^-$ branching fraction

- $\mathcal{B}(K_S^0 \to \pi^0 \mu^+ \mu^-) = (2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$ measured by NA48 Collaboration [J.R. Batley et al. PLB599 (2011) 197]
Sensitivity to $K^0_S \to \pi^0 \mu^+ \mu^-$

- Studied sensitivity of LHCb to this channel in Run 2 and Upgrade scenarios
- Difficult reconstruction due to soft $\pi^0$
- $\pi^0$ reconstruction non essential as constrained by very low $q$-value
- 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 $\mathcal{B}(K^0_S \to \pi^0 \mu^+ \mu^-)$ 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 $A(K^0_S \to \ell^+ \ell^- \ell^+ \ell^-)$ and $A(K^0_L \to \ell^+ \ell^- \ell^+ \ell^-)$ would give a measurement of the sign of $A(K^0_L \to \gamma \gamma)$ which is a stringent test of CKM
- $K^0_L \to \ell^+ \ell^- \ell^+ \ell^-$ studied by different experiments but no experimental constraints on $K^0_S$ modes
  
  \[ \mathcal{B}(K^0_S \to e^+e^-e^+e^-) \sim 10^{-10} \]
  
  \[ \mathcal{B}(K^0_S \to \mu^+\mu^-e^+e^-) \sim 10^{-11} \]
  
  \[ \mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) \sim 10^{-14} \]

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

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

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 $K^0_S \to \ell^+\ell^-\ell^+\ell^-$ 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

### Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>( R )</th>
<th>( \epsilon_L )</th>
<th>( \epsilon_D )</th>
<th>( \sigma_L (\text{MeV/c}^2) )</th>
<th>( \sigma_D (\text{MeV/c}^2) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_S^0 \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_S^0 \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_S^0 \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>
</tr>
<tr>
<td>( K_S^0 \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_S^0 \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_L^0 \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) ( \times 10^{-3} )</td>
<td>( \sim 1.0 )</td>
<td>( \sim 4.0 )</td>
</tr>
<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>
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<tr>
<td>( \Xi^- \to \Lambda\mu^-\nu_{\mu} )</td>
<td>( \sim 0.04 )</td>
<td>39 (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 (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 (6.7) ( \times 10^{-3} )</td>
<td>0.32 (0.10)</td>
<td>( \sim 7.0 )</td>
<td>( \sim 20 )</td>
</tr>
</tbody>
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<tr>
<td>( K_S^0 \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_S^0 \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 e^- 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 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>
</tr>
</tbody>
</table>

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</tr>
</thead>
<tbody>
<tr>
<td>( K_L^0 \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_S^0 \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]
Prospects for LFV modes

- Tests of lepton flavour violation are always important SM null tests
- Limits on kaon LFV are stringent but decades old

\[ \mathcal{B}(K_L \rightarrow e^\pm \mu^\mp) < 4.7 \times 10^{-12} \quad \mathcal{B}(K_L \rightarrow \pi^0 e^\pm \mu^\mp) < 7.6 \times 10^{-11} \]

[E871 PRL81,5734] [KTeV PRL100,131803]
\[ \mathcal{B}(K^+ \rightarrow \pi^+ e^- \mu^+) < 1.3 \times 10^{-11} \quad \mathcal{B}(K^+ \rightarrow \pi^+ e^+ \mu^-) < 5.2 \times 10^{-10} \]

[Sher et al. PRD 72, 012005] [Appel et al. PRL85, 2877]

- Using B-physics LFU constraints, branching fractions of order \(10^{-13}\) can be predicted for \(K_S\) LFV decays [Borsato et al. PRD 99, 055017 (2019)]
Prospects for LFV modes

- Electron reconstruction in LHCb is more difficult than muon due to bremsstrahlung and lower trigger efficiency
- LHCb could improve limits and maybe touch the $10^{-13}$ region with full Upgrade (2030s)
- Detailed full simulation studies are however not there yet

![Graph showing branching fractions for $B(K^+ \rightarrow \pi^+ \mu^+ e^-)$ and $B(K^+ \rightarrow \pi^+ \mu^+ e^-)$ as a function of LHCb integrated luminosity.]
A quick word on hyperons

LHCb can probe different hyperons and decays

- $\Sigma^+$: Besides the $\Sigma^+ \to p\mu^+\mu^-$, LHCb could improve the $\Sigma^+ \to p\gamma$ and try to access the $\Sigma^+ \to pe^+e^-$ decay

- $\Lambda$
  * LHCb could improve the $\Lambda \to p\pi\gamma$ branching fraction and try to access $\Lambda \to p\pi e^+e^-$
  * Large number of BNV / LFV decays constrained by the CLAS collaboration [CLAS PRD.92.072002] could be also tested and improved

- For higher $S$ number baryons LHCb could test $\Delta S = 2$ processes, such as $\Xi^0 \to p\pi$ and $\Omega \to \Lambda\pi$ improving limits by orders of magnitude

See also Alexandre’s talk in the “hyperon” session.
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
Bibliography

LHCb Collaboration

Papers

• Evidence for the rare decay $\Sigma^+ \rightarrow p\mu^+\mu^-$ [Phys. Rev. Lett. 120, 221803 (2018)] [LHCb-PAPER-2017-049] [hep-ex/1712.08606]

• Improved limit on the branching fraction of the rare decay $K_{S}^{0} \rightarrow \mu^{+}\mu^{-}$ [LHCb-PAPER-2017-009] [hep-ex/1706.00758] [Eur. Phys. J. C, 77 10 (2017) 678]

• Search for the CP-violating strong decays $\eta \rightarrow \pi^{+}\pi^{-}$ and $\eta' \rightarrow \pi^{+}\pi^{-}$ [LHCb-PAPER-2016-046] [hep-ex/1610.03666] [Physics Letters B 764 (2017) 233-240]

• Search for the rare decay $K_{S}^{0} \rightarrow \mu^{+}\mu^{-}$ [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 $\mathcal{B}(K_{S}^{0} \rightarrow \pi^{0}\mu^{+}\mu^{-})$ [LHCb-PUB-2016-017]

• Feasibility study of $K_{S}^{0} \rightarrow \pi^{+}\pi^{-}e^{+}e^{-}$ at LHCb [LHCb-PUB-2016-016]

Others

• Alves A. A. et al. “Prospects for Measurements with Strange Hadrons at LHCb” [JHEP05(2019)048]

Backup
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
  - $\mathcal{B}(\eta \rightarrow \pi^+\pi^-) < 1.3 \cdot 10^{-5}$ (KLOE $\phi \rightarrow \eta\gamma$ [PLB606 (2005) 276])
  - $\mathcal{B}(\eta' \rightarrow \pi^+\pi^-) < 5.5 \cdot 10^{-5}$ (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. $D_{(s)}^+ \to \pi^+\eta'$)
- MVA operator to reduce background
- Normalisation: $B(\eta' \to \pi^+\pi^-) = \frac{N_{\eta'}(r)}{N_{D_{(s)}^+ \to \pi^+\pi^-\pi^+}} \frac{1}{\varepsilon_{\eta'}(r)} \frac{B(D_{(s)}^+ \to \pi^+\pi^-\pi^+)}{B(D_{(s)}^+ \to \pi^+\eta')}$
- Constrained $D$ masses and origin vertex improves resolution significantly
- $\varepsilon_{\eta'}(r)$ small correction to efficiency versus $m_{\pi\pi}$
- 3 fb$^{-1}$ of Run 1 and 0.3 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 $\eta' \to \pi^+\pi^-$

- No excess on top of the background (signal phase space plus combinatorial)
- Upper limit on branching fractions with CLs method at 90% CL:
  \[ B(\eta \to \pi^+\pi^-) < 1.6 \times 10^{-5} \]
  \[ B(\eta' \to \pi^+\pi^-) < 1.8 \times 10^{-5} \]
- $\eta$ limit compatible with previous results, $\eta'$ limit improved by factor three
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/