Two-track strange decays at LHCb

Miguel Ramos Pernas
Universidade de Santiago de Compostela
miguel.ramos.pernas@cern.ch

First forum on kaon decays
Edinburgh, February 22, 2018
The LHCb detector

Strange decays at LHCb

Decays

\[ K_S^0 \to \mu^+ \mu^- \]
\[ K_S^0 \to \pi^0 \mu^+ \mu^- \]
Semileptonic hyperon decays and \( K_S^0 \to \pi^+ \mu^- \bar{\nu} \)

Prospects for the upgrade

Conclusions

For more about strange decays at LHCb see Francesco’s talk.
The LHCb detector

Great Secondary Vertex (SV) and Impact Parameter (IP) resolution. Very good $p$, $p_T$ and mass resolution. Particle ID is mostly done by two RICH detectors, the calorimeters and the muon chambers.

Three different trigger levels:

- Low level (L0)
- High level 1 (Hlt1)
- High level 2 (Hlt2)

Software

Hardware

[JINST3 (2008) S08005]
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Part of the diagram:

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Software (flexible)

Hardware

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[INST3 (2008) S08005]
Strange decays at LHCb

Huge production of strange hadrons at LHCb

$O(10^{13})$ fb$^{-1}

Efficiencies have been proved to be high enough already in 2011

Improvements in the trigger and PID in 2012

Deployed HLT lines fully devoted to study strange di-muon decays for 2016, 2017 and 2018

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Strange decays at LHCb

b/c hadrons
- $\tau \sim 10^{-12}$s
- Flight distance $\sim$ mm

VELO decay volume

A very large production...
- Huge production of strange hadrons at LHCb
- $O(10^{13})/fb$
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Strange decays at LHCb

- \( K^0_S/\Lambda^0/\Sigma^+/\Xi^- \)
  - \( \tau \sim 10^{-10} \) s
  - Flight distance \( \sim \) cm/m
  - Large amount decay inside the VELO
  - Benefit from a good resolution
  - Statistics can increase including decays outside the VELO

Huge production of strange hadrons at LHCb
- \( \mathcal{O}(10^{13})/\) fb

H0 decay inside the VELO
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Strange decays at LHCb

**VELO decay volume**

- Usable region

**K^+ / K_L^0**

- $\tau \sim 10^{-8}$ s
- Flight distance $\sim$ m
- Mostly decay outside the VELO
- $K^+$ studies are feasible (hits in the VELO)
- $K_L^0$ studies are hardly possible

A very large production...

- Huge production of strange hadrons at LHCb
- $O(10^{13}) / fb$
- $K_0^S$ decay inside the VELO
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- Huge production of strange hadrons at LHCb
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- Deployed HLT lines fully devoted to study strange di-muon decays for 2016, 2017 and 2018
LHCb is optimized to study heavy flavour decays

L0 trigger requires high $p_T$ tracks (very inefficient to study strange decays)

No dedicated trigger lines to study strange hadrons

Trigger selections mainly based on topological inclusive lines and data triggered by the rest of the event (e.g. $K^0_S \rightarrow \mu^+ \mu^-$ analysis from 2011)

Some HLT lines tuned to increase the efficiency for 2012
$K_S^0 \rightarrow \mu^+ \mu^-$

- Flavour-changing neutral current (FCNC) transition
- Dominated by long distance contributions through $K_{S/L}^0 \rightarrow \gamma \gamma$
- SM prediction: $\mathcal{B} \left( K_S^0 \rightarrow \mu^+ \mu^- \right) = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$

\[ \text{[Nucl. Phys. B366 (1991) 189]} \]
\[ \text{[JHEP 01 (2004) 009]} \]
\[ \text{[Phys. Rev. Lett. 119, 201802 (2017)]} \]

**Figure:** (a): Long distance contribution. (b) Short distance contributions. \[ \text{[JHEP 01 (2004) 009]} \]
\( K_S^0 \rightarrow \mu^+ \mu^- \) in BSM

\( \mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) \) helps to kill models with leptoquarks [arXiv:1712.01295], or supersymmetric contributions [arXiv:1711.11030], [arXiv:1712.04959].

Study of the interference between \( K_L^0 \rightarrow \mu^+ \mu^- \) and \( K_S^0 \rightarrow \mu^+ \mu^- \) allows to determine sign(\( A_{\mu L \gamma \gamma} \)).

\[
\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}
\]

\[
\mathcal{B}(K_L^0 \rightarrow \mu^+ \mu^-) = \begin{cases} 
(6.85 \pm 0.80 \pm 0.06) \times 10^{-9} & \text{if } A_{\mu L \gamma \gamma} > 0 \\
(8.11 \pm 1.49 \pm 0.13) \times 10^{-9} & \text{if } A_{\mu L \gamma \gamma} < 0
\end{cases}
\]

\( A_{\mu L \gamma \gamma} = \text{sign} \left( \frac{A(K_L^0 \rightarrow \gamma \gamma)}{A(K_L^0 \rightarrow (\pi^0)^* \rightarrow \gamma \gamma)} \right) \)
\( K_{S}^{0} \rightarrow \mu^{+}\mu^{-} \) backgrounds

- Very good resolution around the \( K_{S}^{0} \) mass (\( \sim 4\text{MeV}/c^2 \)).
- Low soft-QCD background level at LHCb.
- For the moment, the only significant contribution is \( K_{S}^{0} \rightarrow \pi^{+}\pi^{-} \) where the two pions are misidentified as muons.

- \( K_{L}^{0} \rightarrow \mu^{+}\mu^{-} \): effective branching fraction \( \sim 2 \times 10^{-11} \), below the current sensitivity
- \( \Lambda^{0} \rightarrow p\pi^{−} \): removed with cuts in the Armenteros-Podolanski plane.
- \( K^{0} \rightarrow \pi^{+}\mu^{−}\bar{\nu} \): no candidate survives the trigger selection. Even in the hypothesis \( \varepsilon_{\text{trig}}^{K_{S}^{0} \rightarrow \mu^{+}\mu^{-}} = \varepsilon_{\text{trig}}^{K_{S}^{0} \rightarrow \mu^{+}\mu^{-}} \), the expected yields are negligible.
- \( \eta \rightarrow \mu^{+}\mu^{-}\gamma \) and \( \omega \rightarrow \pi^{0}\mu^{+}\mu^{-} \): prompt decays can be removed with a cut on the flight distance. Detached production from charm decays is negligible.
$K_S^0 \rightarrow \pi^+\pi^-$ as $K_S^0 \rightarrow \mu^+\mu^-$

- $K_S^0 \rightarrow \pi^+\pi^-$ is the most dangerous background to study $K_S^0 \rightarrow \mu^+\mu^-$ at LHCb.
- Background produced by doubly-misidentifying of the two pions.
- Two different sources: decays in flight and incorrect assignment of clusters in the muon chambers.
$K_S^0 \rightarrow \pi^+ \pi^-$ as $K_S^0 \rightarrow \mu^+ \mu^-$

- $K_S^0 \rightarrow \pi^+ \pi^-$ is the most dangerous background to study $K_S^0 \rightarrow \mu^+ \mu^-$ at LHCb.
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- Two different sources: decays in flight and incorrect assignment of clusters in the muon chambers.
\[ K_S^0 \rightarrow \pi^+\pi^- \quad \text{as} \quad K_S^0 \rightarrow \mu^+\mu^- \]

- Incorrect cluster assignment

- \( K_S^0 \rightarrow \pi^+\pi^- \) is the most dangerous background to study \( K_S^0 \rightarrow \mu^+\mu^- \) at LHCb.
- Background produced by doubly-misidentifying of the two pions.
- Two different sources: decays in flight and incorrect assignment of clusters in the muon chambers.
New muon identification algorithm for 2012 and beyond

- Muon ID algorithms at LHCb were optimized for heavy flavour decays
- In 2012, an algorithm was designed to increase the efficiencies on strange decays

![Graph showing π misid. for 90% μ efficiency vs. Momentum (GeV/c)]
$K_S^0 \rightarrow \mu^+ \mu^-$ in Run-I

- Last analysis includes data in 2012 conditions: 2 fb$^{-1}$ at 8 TeV
- Follows the previous study from 2011 [JHEP 01 (2013) 090]
- Normalized to $K_S^0 \rightarrow \pi^+ \pi^-$
- Fit done in bins of two MVA discriminants for two different trigger selections (20 bins in total)
- Result from 2011 (as a posterior probability) is considered as a prior in the $\mathcal{B} (K_S^0 \rightarrow \mu^+ \mu^-)$

![Graphs showing candidates distribution](image_url)
$K^0_S \rightarrow \mu^+ \mu^-$ new limit

- Limit set from the $\mathcal{B}(K^0_S \rightarrow \mu^+ \mu^-)$ likelihood profile

- New world best limit:
  $$\mathcal{B}(K^0_S \rightarrow \mu^+ \mu^-) < 0.8(1.0) \times 10^{-9} \text{ at } 90(95)\% \text{ of CL}$$

- Factor of $\sim 400$ of improvement with respect to the best limit before LHCb [PLB44 (1973) 217], and $\sim 10$ with respect to the previous LHCb measurement [JHEP 01 (2013) 090]
$K^0_{S} \rightarrow \mu^+ \mu^-$ in a nutshell

Old LHCb limit

$\mathcal{B} \left( K^0_{S} \rightarrow \mu^+ \mu^- \right) < 9(11) \times 10^{-9}$ at 90(95)% of CL

[JHEP 01 (2013) 090]

New limit!

$\mathcal{B} \left( K^0_{S} \rightarrow \mu^+ \mu^- \right) < 0.8(1.0) \times 10^{-9}$ at 90(95)% of CL


Standard Model prediction

$\mathcal{B} \left( K^0_{S} \rightarrow \mu^+ \mu^- \right) < 10^{-13}$
$K^0_S \rightarrow \pi^0 \mu^+ \mu^-$

$\mathcal{B} \left( K^0_L \rightarrow \pi^0 \mu^+ \mu^- \right)$ has a variation of $\sim 1$ order of magnitude in models with extra dimensions.

$\mathcal{B} \left( K^0_L \rightarrow \pi^0 l^+ l^- \right)_{SM} = \left( C^l_{\text{dir}} \pm C^l_{\text{int}} |a_S| + C^l_{\text{mix}} |a_S|^2 + C^l_{\gamma \gamma} + C^l_{S} \right) \times 10^{-12}$

$|a_S| = 1.2 \pm 0.2$ dominates the theoretical uncertainty. Comes from the measurements of $\mathcal{B} \left( K^0_S \rightarrow \pi^0 l^+ l^- \right)$.

- Large uncertainties on $\mathcal{B} \left( K^0_S \rightarrow \pi^0 \mu^+ \mu^- \right) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$ (NA48) [Phys. Lett. B599 (2004) 197]
- Current kaon experiments do not expect to improve such measurement
- Last year, a sensitivity study was done at LHCb
Two different strategies adopted:

- **FULL**: Include the information from the $\pi^0$, Run-I $3 \text{ fb}^{-1}$
- **PARTIAL**: Add a virtual particle with $p \sim 10 \text{ GeV/c}$ (provides the best $M_{\pi^0\mu^+\mu^-}$ resolution), Run-II $0.3 \text{ fb}^{-1}$
$K^0_S \rightarrow \pi^0 \mu^+ \mu^-$ backgrounds

Clean and very promising decay

- $K^0_S \rightarrow \pi^+ \pi^-$: both pions are misidentified as muons. No evidence is seen in the fit.

- $K^0 \rightarrow \mu^+ \mu^- \gamma \gamma$: in the $K^0_L$ case, the effective branching fraction turns $\mathcal{O}(10^{-11})$. No measurement of the $K^0_S$ mode has been done, expected to be $\sim 4.8 \times 10^{-11}$.

- $K^0_L \rightarrow \pi^0 \pi^+ \pi^-$: No resonant structure is seen on data. Sensitivity does not change if this component is included.

- Main source of background is purely combinatorial.

Simulated $K^0 \rightarrow \pi^0 \pi^+ \pi^-$ decays, reconstructed as $K^0 \rightarrow \pi^0 \mu^+ \mu^-$
\[ K^0_S \rightarrow \pi^0 \mu^+ \mu^- \text{ analysis} \]

- Analysis done taking into account events triggered independently on the signal decay
- This ensures an almost trigger-unbiased sample
- Uncertainty obtained from fits to pseudo-experiments

\[
N_{\text{sig}} = \frac{B(K^0_S \rightarrow \pi^0 \mu^+ \mu^-)}{B(K^0_S \rightarrow \pi^+ \pi^-)} \frac{\epsilon_{K^0_S \rightarrow \pi^0 \mu^+ \mu^-}}{\epsilon_{K^0_S \rightarrow \pi^+ \pi^-}} N(K^0_S \rightarrow \pi^+ \pi^-) \frac{\mathcal{L}_{\text{fut}}}{\mathcal{L}_{\text{curr}}}
\]

- Background yields are extrapolated for a desired luminosity and trigger efficiency
$K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$ prospects

- The PARTIAL strategy seems the way to go

- Beating the NA48 measurement [Phys. Lett. B599 (2004) 197] is possible in the upgrade $L_{\text{eff}} > 5 \text{ fb}^{-1}$
The di-muon triggers for the Run-II

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>$K_S^0 \rightarrow \mu^+\mu^-$</th>
<th>$K_S^0 \rightarrow \pi^0\mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0</td>
<td>0.361 ± 0.004</td>
<td>0.344 ± 0.009</td>
</tr>
<tr>
<td>HLT1/L0</td>
<td>0.699 ± 0.007</td>
<td>0.705 ± 0.015</td>
</tr>
<tr>
<td>HLT1/L0 (old)</td>
<td>0.274 ± 0.006</td>
<td>0.299 ± 0.015</td>
</tr>
<tr>
<td>HLT2/HLT1</td>
<td>0.9898 ± 0.0017</td>
<td>0.983 ± 0.005</td>
</tr>
<tr>
<td>HLT2/HLT1 (old)</td>
<td>0.293 ± 0.013</td>
<td>0.26 ± 0.03</td>
</tr>
<tr>
<td>global</td>
<td>0.250 ± 0.004</td>
<td>0.238 ± 0.008</td>
</tr>
<tr>
<td>global (old)</td>
<td>0.0290 ± 0.0015</td>
<td>0.026 ± 0.003</td>
</tr>
</tbody>
</table>

**green:** trigger with new lines

**red:** trigger without new lines

- Big increase on the efficiencies: a factor $\sim 2.4$ for HLT1 and $\sim 3.5$ for HLT2
- Total efficiency increased by a factor $\sim 10$
Prospects on semileptonic hyperon decays

- Semileptonic hyperon decays can be probes of TeV scales complementary to kaons

- Vast room of improvement on many decays (specially the muonic modes $\delta B/B \sim [10, 100]\%$)

- Rare hyperon decays... still unexplored

- Possibilities to study
  - $\Lambda^0 \to p \mu^- \bar{\nu}$
  - $\Xi^- \to \Lambda^0 \mu^- \bar{\nu}$

- No dedicated trigger lines ($B \sim 10^{-4}$)

Nothing published so far, but some benchmarks have been set for Run-II
Prospects on $K^0_S \rightarrow \pi^+ \mu^- \bar{\nu}$

No measurement of $K^0_S \rightarrow \pi^+ \mu^- \bar{\nu}$ at present!

$\delta$ CPT violation in mixing
$y$ CPT violation in decay with $\Delta S = \Delta Q$
$x_-$ $\Delta S \neq \Delta Q$ with CPT violation
$A_S \frac{B(K^0_S \rightarrow \pi^- \mu^+ \nu_\mu) - B(K^0_S \rightarrow \pi^+ \mu^- \bar{\nu}_\mu)}{B(K^0_S \rightarrow \pi^- \mu^+ \nu_\mu) + B(K^0_S \rightarrow \pi^+ \mu^- \bar{\nu}_\mu)}$

Goal Implications

<table>
<thead>
<tr>
<th>$V_{us}$ and $\Delta S = \Delta Q$</th>
<th>$\delta B &lt; 0.4%$</th>
<th>Reduce error on $V_{us}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPT $A_S \sim 0.1%$</td>
<td></td>
<td>Reduce uncertainty on $R(x_-)$ and $R(y)$, and push down $R(\delta)$</td>
</tr>
<tr>
<td>LFU $\delta B \sim 0.5%$</td>
<td></td>
<td>Competitive with $K^0_L$ measurements</td>
</tr>
</tbody>
</table>

Main issues at LHCb are:

- Irreducible background from $K^0_L \rightarrow \pi^+ \mu^- \bar{\nu}$
- Also expect a huge background from $K^0_S \rightarrow \pi^+ \pi^-$
- No dedicated trigger lines ($B \sim 10^{-4}$)
The LHCb trigger in the upgrade

- **LHCb 2012 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**
    - 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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    - Partial event reconstruction, select displaced tracks/vertices and dimuons
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  - **12.5 kHz (0.6 GB/s) to storage**
  - **Full offline-like event selection**, mixture of inclusive and exclusive triggers

- **LHCb Upgrade Trigger Diagram**
  - **30 MHz inelastic event rate**
    - **Software High Level Trigger**
      - Add offline precision particle identification and track quality information to selections
      - Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers
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LHCb Upgrade Trigger Diagram

- 30 MHz inelastic event rate (full rate event building)

Software High Level Trigger
- Full event reconstruction, inclusive and exclusive kinematic/geometric selections

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- Non-dedicated trigger lines, use standard di-muon lines

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### LHCb Upgrade Trigger Diagram

- **30 MHz inelastic event rate (full rate event building)**
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### Notes
- **Non-dedicated trigger lines, use standard di-muon lines**
- **Dedicated HLT di-muon lines**
- **Improve low-$p_T$ muon track reconstruction at HLT**

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The LHCb trigger in the upgrade

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- **2-5 GB/s to storage**

- • Non-dedicated trigger lines, use standard di-muon lines
  - • Dedicated HLT di-muon lines
  - • Improve low-$p_T$ muon track reconstruction at HLT

- There is no L0 bottleneck
  - • Dedicated di-muon lines
  - • Current offline low-$p_T$ muon identification algorithm in the trigger
  - • Efficiencies $>90\%$ possible

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Strange decays in the new trigger

The upgrade trigger benefits a lot the strange program

- Replacement of inclusive triggers (general) by exclusive (focused on each decay)
- Only the requested information from the event is saved
- Removal of $p_T$ cuts at the trigger level allows to reach much higher efficiencies
- More efficient particle identification and reconstruction algorithms at low-$p_T$
Conclusions

- The LHCb has produced a large number of publications in two years on this topic
- Some studies using Run-II data currently ongoing
- The Run-II trigger allows to improve the efficiencies on $K_S^0 \rightarrow \mu^+ \mu^-$ and $K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$
- Benchmark set for the study of semileptonic hyperon decays as well as for $K_S^0 \rightarrow \pi^+ \mu^- \bar{\nu}$
- A full software trigger will benefit a lot the study of strange decays at LHCb
BACKUP
Track types at LHCb

- VELO track
- Downstream track
- Long track
- Upstream track
- T track

VELO

UT

T1 T2 T3

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Two-track strange decays at LHCb

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Trigger definitions

Where:
- \(a = N^{TRIG} - N^{TIS} - N^{TOS} + N^{TISTOS}\)
- \(b = N^{TOS} - N^{TISTOS}\)
- \(c = N^{TIS} - N^{TISTOS}\)
- \(d = N^{TISTOS}\)
$K_S^0 \rightarrow \mu^+ \mu^-$ mass plots
$K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$ mass plots FULL

[CERN-LHCb-PUB-2016-017]
$K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$ mass plots PARTIAL

[PARTIAL]

BDT  $\in$ (0.6,0.7)

BDT  $\in$ (0.7,0.8)

BDT  $\in$ (0.8,0.9)

BDT  $\in$ (0.9,1)

[CERN-LHCb-PUB-2016-017]

Miguel Ramos Pernas
Two-track strange decays at LHCb
(First forum on kaon decays, Edinburgh, February 22, 2018)