Search for $K_{S}^{0} \rightarrow \mu^{+}\mu^{-}$ at LHCb

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on behalf of the LHCb collaboration

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Introduction

The $K_S^0 \rightarrow \mu^+\mu^-$ decay is:

- Flavour-changing neutral current (FCNC) transition.
- Dominated by long distance contributions through $K_{S/L}^0 \rightarrow \gamma\gamma$.
- In absence of CP violation the $K_L^0$ ($K_S^0$) mode could proceed only through S(P) wave.
- Notably new light scalars can affect $K_S^0$ exclusively.

Figure: (a): Long distance contribution. (b) Short distance contributions. [JHEP 01 (2004) 009]
Overall picture

While the branching fraction for the $K^0_L$ decay is within the SM prediction\(^1\): $B(K^0_L \rightarrow \mu^+\mu^-) = (6.84 \pm 0.11) \times 10^{-9}$, for the $K^0_S$ it can be enhanced by New Physics.

The LHCb opened the kaon physics program already in 2011 (1fb\(^{-1}\) of data).

Results so far (90\%CL)

- $B(K^0_S \rightarrow \mu^+\mu^-) < 3.1 \times 10^{-7}$ CERN PS\(^*\)
- $B(K^0_S \rightarrow \mu^+\mu^-) < 9 \times 10^{-9}$ LHCb Coll.\(^†\)

All distant from the SM prediction\(^‡\):

- $B(K^0_S \rightarrow \mu^+\mu^-) = (5.0 \pm 0.2) \times 10^{-12}$

\(^*\) CERN PS [PLB44 (1973) 217]

\(^†\) LHCb Coll. [JHEP 01 (2013) 090]


\(^1\) PDG [Chin. Phys. C, 38, 090001 (2014) and 2015 update]
The LHCb

Great Secondary Vertex (SV) and Impact Parameter (IP) resolution.

Very good p, p\_T and mass resolution.

Particle ID mostly done by two RICH detectors, complemented by other subdetectors.

Three different trigger levels
- Low level (L0)
- High level 1 (Hlt1)
- High level 2 (Hlt2)

Software (flexible)

Hardware

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[JINST3 (2008) S08005]
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Three different trigger levels

- Low level (L0) Hardware
- High level 1 (Hlt1) Software
- High level 2 (Hlt2) (flexible)

[JINST3 (2008) S08005]
Kaons at LHCb

- Lifetimes are much larger than for B mesons:
  - $\tau_{B^0} \sim 1.5 \times 10^{-12} \text{s}$
  - $\tau_{K^0_S} \sim 10^{-10} \text{s}$
  - $\tau_{K^0_L} \sim 5 \times 10^{-8} \text{s}$

- $K^0_S$ study is possible using long tracks.

- $K^0_L$ study is HARDLY possible.

Kaons at LHCb

For kaons...

- Largest limitation comes from the detector geometry.
- Second limitation comes from the trigger: $\varepsilon \sim 2.5 (1)\%$ for $K^0_S \rightarrow \mu^+\mu^-$ in 2012 (2011).
- Low $p_T \Rightarrow$ harder to distinguish from comb. bkg.

Studies on $K^0_S$, $K^\pm$ and $\Sigma^\pm$ are currently being performed at LHCb. Results obtained until now came from not dedicated triggers.

Large $K^0_S$ production cross-section inside the LHCb acceptance $10^{13}/\text{fb}^{-1}$. Efforts are being focused on adding new trigger lines and developing new low $p_T$ particle identification algorithms.

The use of downstream tracks for the analyses could increase the statistics. However, the resolution is much worse (VELO information not available).
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$K_S^0 \rightarrow \mu^+\mu^-$ at LHCb

Main features

- Very good mass resolution: $\sim 4\text{MeV}/c^2$.
- Great performance identifying muons.
- Luminosity recorded leads to $B_{exp}^{2012}(K_S^0 \rightarrow \mu^+\mu^-) \sim 10^{-9}$.
- Very clean decay $\Rightarrow$ few types of background contribute.

The main contamination sources are:

- $K_L^0 \rightarrow \mu^+\mu^-$ negligible: $B_{\text{eff.}} \sim 10^{-11}$.
- $K^{0}_{S/L} \rightarrow \pi^+\mu^-\bar{\nu}$ negligible.
- $\Lambda^0 \rightarrow p\pi^-$ removed by a cut in the Armenteros-Podolanski plot.
- $K^{*0} \rightarrow K^+\pi^-$ suppressed using the information from the RICH detectors.
- $\omega \rightarrow \pi^0\mu^+\mu^-$, $\eta \rightarrow \mu^+\mu^-\gamma$ are not expected to generate peaking structures.
- Combinatorial background is almost flat in the region $[400, 600] \text{MeV}/c^2$.
- Main source of background is $K^{0}_{S} \rightarrow \pi^+\pi^-$ double misID.
Analysis strategy

Main features

- Using 2012 data with 2fb$^{-1}$.
- Since it is a “search for” analysis, a blind strategy is done, avoiding the use of events in $m_{\mu\mu} \in [492, 504]$ MeV/c$^2$.
- Three different trigger selections have been used to exploit all the trigger capability.
- The $K_S^0 \rightarrow \pi^+\pi^-$ mode is used as a normalization channel.

Differences with respect to 2011 analysis

- Twice the luminosity.
- Trigger lines improved.
- New muon identification algorithm.
- Included function to describe the signal shape.
- Limit calculated directly from the $-\log L$ distribution.
- Taking into account the previous limit.
The new triggers and muonID algorithms in Run-I

**Triggers**
- Removed cuts on the di-muon mass.
- The $p_T$ cuts have been reduced.
- Trigger efficiency improved by a factor 2.5.

**Muon identification**
- Dedicated algorithm for low $p_T$ processes.
- $B^+ \rightarrow J/\psi K^+$ used for the muon calibration sample.
- Reduced dependence with the number of tracks.
- $\pi$ misID = 0.49% at 95% of signal efficiency.
Combinatorial background removal

To remove the combinatorial background events a MVA selection has been done:

- Different MVA algorithms have been studied: BDT, Neural Networks, ...
- Optimization has been done using the ROC curves.
- The proxies correspond to real data $K^0_S \rightarrow \pi^+\pi^-$ events (signal) and $K^0_S \rightarrow \mu^+\mu^-$ events from the far right sideband (background).

- One different MVA for each trigger category.
- Optimization lead to the same MVA algorithm (BDT) and the same set of variables.
- Analysis performed in bins of the BDT distribution.
- Bins selected after a loose cut and so the signal efficiency is the same in each of them.

[Graph showing distributions for signal and background]
Fit procedure

- A simultaneous Maximum Likelihood Fit to all the BDT bins and categories was performed.
- Fit performed in the region $m_{\mu^+\mu^-} \in [470, 600] \text{MeV/c}^2$.
- The previous result has been taken into account introducing a constraint on the branching fraction.

Contributions

- Right side of the $K^0_S \rightarrow \pi^+\pi^-$ double misID $\Rightarrow$ Power law
- Combinatorial background $\Rightarrow$ Exponential
- Signal peak $\Rightarrow$ Hypatia function*

* [NIM A, 764, 150 (2014)]
The results

The normalization is computed as:

\[ B(K^0_S \rightarrow \mu^+ \mu^-) = B(K^0_S \rightarrow \pi^+ \pi^-) \cdot \frac{\epsilon_{\pi\pi}}{\epsilon_{\mu\mu}} \cdot \frac{N_{\mu\mu}}{N_{\pi\pi}} \equiv \alpha N_{\mu\mu} \]

\[ \frac{\epsilon_{\pi\pi}}{\epsilon_{\mu\mu}} = \frac{\epsilon_{\pi\pi}^{sel}}{\epsilon_{\mu\mu}^{sel}} \times \frac{\epsilon_{\mu\mu}^{trig}}{\epsilon_{\mu\mu}^{BDT}} \times \frac{1}{\epsilon_{\mu\mu}^{ID}}. \]

Limit extracted integrating the posterior probability of the branching fraction.

\[ B(K^0_S \rightarrow \mu^+ \mu^-) < 6.9(5.8) \times 10^{-9} \text{ at } 95(90)\% \text{ CL} \]

This result improves the previous LHCb limit by a factor 1.6, becoming the new world best result.
Prospects for the Run-II (2015-2019) and the upgrade (2021-2023)

LHCb 2015 Trigger Diagram

- 40 MHz bunch crossing rate
- L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
- 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

LHCb Upgrade Trigger Diagram

- 30 MHz inelastic event rate (full rate event building)
- Software High Level Trigger
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- 2-5 GB/s to storage

Main limitation is still there.
• Improved both Hlt triggers
  - no $p_T$ cuts
• Real-time reconstruction and calibration.
• Similar online - offline reconstruction.
• Eff. on $K^0_S \rightarrow \mu^+ \mu^-$ $\sim 65\%$.
• L0 trigger removed.
• More similar online - offline reconstruction.
• Efficiencies up to $\sim 100\%$.

LHCb Upgrade TDR [CERN-LHCC-2014-016]
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Conclusions

• A preliminary result for $K_S^0 \rightarrow \mu^+ \mu^-$ analysis using the whole Run-I data has been shown.

• The limit has been measured to be

$$B(K_S^0 \rightarrow \mu^+ \mu^-) < 6.9(5.8) \times 10^{-9}$$

at 95(90)% CL

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• Most interesting results are expected to appear in Run-II data and after the upgrade.
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Stay tuned for the Run-II results!
BACKUP
Muon spectra

LHCb Simulation

$\mu$ Momentum (GeV/c)

$\mu$ Transverse Momentum (GeV/c)

[LHCb-CONF-2016-012]
From the PDG\(^2\):

\[
\mathcal{B} \left( K_L^0 \rightarrow \mu^+ \mu^- \right) = (6.84 \pm 0.11) \times 10^{-9}
\]

The effective branching fraction is computed as:

\[
\mathcal{B} \left( K_L^0 \rightarrow \mu^+ \mu^- \right)^{\text{eff.}} = \frac{\epsilon_{K_L^0}^L}{\epsilon_{K_S^0}^S} \mathcal{B} \left( K_L^0 \rightarrow \mu^+ \mu^- \right) \equiv s_{K_L^0 \rightarrow \mu^+ \mu^-} \mathcal{B} \left( K_L^0 \rightarrow \mu^+ \mu^- \right)
\]

The suppression \( s_{K_L^0 \rightarrow \mu^+ \mu^-} \) factor is obtained considering the time acceptance:

\[
A(t; a, n, t_0, \delta t) = \frac{[a(t - t_0)]^n}{1 + [a(t - t_0)]^n} e^{-\delta t}
\]

\( \delta t \) is calculated from a fit to \( K_S^0 \rightarrow \mu^+ \mu^- \) events. The suppression factor is the ratio between acceptance-corrected and theoretical proper time distributions, thus:

\[
\mathcal{B}_{\text{eff.}} \in [1.2, 1.7] \times 10^{-11}
\]

\(^2\)PDG [Chin. Phys. C, 38, 090001 (2014) and 2015 update]
MVA proxies
The Hypatia function is defined as follows:\(^3\):

\[
I(m, \mu, \sigma, \lambda, \zeta, \beta, a, n) \propto \begin{cases} 
( (m - \mu)^2 + A^2 \lambda (\zeta) \sigma^2 )^{\frac{1}{2} \lambda - \frac{1}{4}} e^{\beta(m-\mu)} K_{\lambda}^{-\frac{1}{2}} \left( \zeta \sqrt{1 + \left( \frac{m-\mu}{A \lambda (\zeta) \sigma} \right)^2} \right) 
& \text{, if } \frac{m-\mu}{\sigma} > -a \\
G(\mu - a \sigma, \mu, \sigma, \lambda, \zeta, \beta) 
& \text{, otherwise}
\end{cases}
\]

\(^3\)Diego Martínez Santos, Frederic Dupuis [NIM A, 764, 150 (2014)]
## Systematics

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<th>Source</th>
<th>TOS_µ-TOS_µ-TOS_µµ</th>
<th>TOS_µ-TOS_µµ-TOS_µµ</th>
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<td><strong>Uncertainties on signal yield</strong></td>
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<td><strong>Uncertainties on branching fraction</strong></td>
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<tr>
<td>Background shape</td>
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<td>$4 \times 10^{-11}$</td>
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</table>
Amoroso distribution to put a constraint on the $\mathcal{B}(K_S^0 \to \mu^+\mu^-)$ using the result from 2011.