Search for $K^0_S \rightarrow \mu^+ \mu^-$ at LHCb

Miguel Ramos Pernas
on behalf of the LHCb collaboration

Universidade de Santiago de Compostela

miguel.ramos.pernas@cern.ch

KAON 2019
September 10, 2019
• Strongly suppressed Flavour-changing Neutral Current (FCNC) transition

• Dominated by long distance contributions through $K^0 \rightarrow \gamma \gamma$.

• $\mathcal{B}(K^0_L \rightarrow \mu^+ \mu^-)$ in agreement with the SM.

• Allows to set model-independent bounds on the CP-violating phase of the $s \rightarrow dl^+ l^-$ amplitude.

• SM prediction: $\mathcal{B}(K^0_S \rightarrow \mu^+ \mu^-) = (5.18 \pm 1.50_{\text{LD}} \pm 0.02_{\text{SD}}) \times 10^{-12}$ [JHEP 05 (2018) 024], [JHEP 01 (2004) 009], [NPB 366 (1991) 189].
A global look at the limits

Need for a huge production of $K^0_S$ and a good muon identification in order to study this decay.

• First measurement from the 70s
  [PLB44 (1973) 217].

• No activity from the experimental side till the LHCb operation started.

• First measurement with data from 2011 [JHEP 01 (2013) 090].

• Combination with full Run-I made in 2016 [EPJ-C (2017) 77:678].

• Full Run-II data sample studied and presented here [LHCB-CONF-2019-002].

Still far from the SM prediction, but current bounds can help to discriminate among many BSM scenarios.
BSM in $K_S^0 \rightarrow \mu^+ \mu^-$

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]
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 (flexible)

Hardware

[JINST3 (2008) S08005]
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]
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 (flexible)

Hardware

[JINST3 (2008) S08005]
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) Hardware
- High level 1 (HLT1) Software (flexible)
- High level 2 (HLT2)

[JINST3 (2008) S08005]
The LHCb detector to study $K_{S}^{0} \rightarrow \mu^{+} \mu^{-}$

- The LHCb detector has been designed for the study of hadrons containing the $b$ and $c$ quarks.
- Huge production of strange hadrons at the LHC.
- About 22% of the generated $K_{S}^{0}$ decay inside the VELO.
- Translated into $\mathcal{O} \left(10^{13}\right) K_{S}^{0}/fb^{-1}$. 

LHCb MC $\sqrt{s} = 14$ TeV
The LHCb detector to study $K_S^0 \rightarrow \mu^+ \mu^-$

- The LHCb detector has been designed for the study of hadrons containing the $b$ and $c$ quarks.
- Huge production of strange hadrons at the LHC.
- About 22% of the generated $K_S^0$ decay inside the VELO.
- Translated into $O\left(10^{13}\right) K_S^0/\text{fb}^{-1}$.

Use tracks with the information from the whole detector.

- VELO decay volume

*VELO decay volume*
The LHCb detector to study $K_S^0 \rightarrow \mu^+ \mu^-$

Use tracks with the information from the whole detector.

- The LHCb detector has been designed for the study of hadrons containing the $b$ and $c$ quarks.
- Huge production of strange hadrons at the LHC.
- About 22% of the generated $K_S^0$ decay inside the VELO.
- Translated into $\mathcal{O} \left(10^{13}\right) K_S^0/fb^{-1}$.

Not included in Run-I and Run-II analyses: no dedicated reconstruction and trigger, worse resolution...

VeLO decay volume
Extended tracking for very low-$p_T$ particles

Muon tracks from strange decays have a very low transverse momentum ($p_T$) at the LHC energies $\mathcal{O}(250)$ MeV/c.

- Number of tracks (and combinations) to be processed per event drastically increases when $p_T$ decreases.
- Profit from small occupancy in muon detectors to do a prompt muon identification.
- Implemented for 2016-2018 at HLT1.
- Constitutes one of the mayor differences with respect to Run-I.

Include information from the muon chambers early in the reconstruction chain:
Changes in the trigger with respect to Run-I

Categories defined by the $K^0_S \rightarrow \mu^+ \mu^-$ candidate, depending whether it satisfies the trigger requirements or not:

- **TIS**: Triggered Independent of Signal.
- **TOS**: Triggered On Signal.

- New tracking allowed to improve the Run-II LHCb software trigger to cover strange decays.
- L0 (hardware) could not be changed, but HLT1 and HLT2 were optimized.
- Analysis was done using two different trigger selections depending on the L0 requirements:
  - **TIS**: any candidate from an event surviving the L0 selections and satisfying the trigger requirements at the HLT.
  - **xTOS**: candidates from events surviving specific muonic trigger selections at all levels and not belonging to the TIS category.
- Candidates are required to satisfy the same HLT requirements for both categories (TOS at HLT).
$K_S^0 \rightarrow \pi^+\pi^-$ as control mode

- Large abundance at the LHC, cross-section of $K_S^0 \sim 0.6$ barn [JHEP 05 (2019) 048].
- Very low L0 and HLT1 efficiencies.
- To simplify the normalization, trigger-unbiased events were used.
- Similar selection to that of $K_S^0 \rightarrow \mu^+\mu^-$. 
- Only trigger and particle identification requirements are different.

Most of the systematic effects cancel in the ratio of efficiencies:

$$B (K_S^0 \rightarrow \mu^+\mu^-) = \frac{N_{\mu}^{\text{observed}}}{N_{\pi}^{\text{observed}}} \times \frac{\varepsilon_{\pi \text{ selection}}}{\varepsilon_{\mu \text{ selection}}} \times \frac{\varepsilon_{\pi \text{ trigger}}}{\varepsilon_{\mu \text{ trigger}}} \times \frac{1}{\varepsilon_{\text{muon-ID}}} \times B (K_S^0 \rightarrow \pi^+\pi^-)$$

From fits to data

Similar for both

Only $K_S^0 \rightarrow \mu^+\mu^-$

Diferent
\( \pi \rightarrow \mu \) misidentification

- Main background comes from misidentification of pions as muons.
- \( K^0_S \rightarrow \pi^+\pi^- \) dominates and is the most dangerous background.
- Residual contribution from \( K^0_S \rightarrow \pi\mu\nu \), indistinguishable from \( K^0_S \rightarrow \pi^+\pi^- \).
$\pi \rightarrow \mu$ misidentification

Decays in flight

- Main background comes from misidentification of pions as muons.
- $K_S^0 \rightarrow \pi^+\pi^-$ dominates and is the most dangerous background.
- Residual contribution from $K_S^0 \rightarrow \pi\mu\nu$, indistinguishable from $K_S^0 \rightarrow \pi^+\pi^-$. 
\[ \pi \rightarrow \mu \text{ misidentification} \]

- Main background comes from misidentification of pions as muons.
- \( K_S^0 \rightarrow \pi^+\pi^- \) dominates and is the most dangerous background.
- Residual contribution from \( K_S^0 \rightarrow \pi\mu\nu \), indistinguishable from \( K_S^0 \rightarrow \pi^+\pi^- \).
$\pi \rightarrow \mu$ misidentification

- Main background comes from misidentification of pions as muons.
- $K_S^0 \rightarrow \pi^+\pi^-$ dominates and is the most dangerous background.
- Mass shifted to the left by $\sim 40 \text{ MeV}/c^2$ ($10 \times$ the resolution!).
- Residual contribution from $K_S^0 \rightarrow \pi\mu\nu$, indistinguishable from $K_S^0 \rightarrow \pi^+\pi^-$. 
- Profit from muon-identification tools already present in Run-I for strange decays.

From Run-I [JHEP 01 (2013) 090] (similar in Run-II)
Inelastic interactions with the detector material

- Remaining background comes from inelastic material interactions with the VELO material.
- New description of the VELO material and RF foil [JINST 13 P06008] allows to discriminate better our signal against this type of background.
- Probability of a candidate to come from a material interaction given by the uncertainty-weighted distance to the material:

\[
D = \sqrt{\left(\frac{x - SV_x}{\sigma_x}\right)^2 + \left(\frac{y - SV_y}{\sigma_y}\right)^2 + \left(\frac{z - SV_z}{\sigma_z}\right)^2}
\]
MVA discriminator

- Random combination of muon tracks lead to a background almost-flat in the di-muon invariant mass.
- Most of it reduced using an Adaptive-Boosted Decision Tree (BDT) from the XGBoost package \[\text{arXiv:1603.02754}\].
- Trained using candidates from the right sideband as a proxy for background and MC for signal.
- Two algorithms trained for each of the trigger categories.
- Topological variables were used, making $K^0_S \rightarrow \mu^+\mu^-$ and $K^0_S \rightarrow \pi^+\pi^-$ (control mode) selections as close as possible.
- Material-veto \[\text{JINST 13 P06008}\] from previous slide also included.
- Analysis done in 10 bins of the classifier for each trigger category (20 bins in total).

Credit to TomaszGolan@github.com
Backgrounds from other strange decays

- Irreducible background.
- $B_{\text{eff.}} (K^0_L \rightarrow \mu^+\mu^-) \sim 10^{-11}$.
- 5 SM candidates expected in the final dataset.
- Considered in the di-muon mass fit.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0_L \rightarrow \mu^+\mu^-$</td>
<td>$(6.84 \pm 0.11) \times 10^{-9}$</td>
</tr>
<tr>
<td>$K^0 \rightarrow \mu^+\mu^-\gamma$</td>
<td>——</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\mu^+\mu^-$</td>
<td>$(9.4 \pm 0.6) \times 10^{-8}$</td>
</tr>
<tr>
<td>$\Sigma^+ \rightarrow p\mu^+\mu^-$</td>
<td>$2.2^{+1.8}_{-1.3} \times 10^{-8}$</td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow p\pi$</td>
<td>$(63.9 \pm 0.5)$ %</td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow p\mu\nu$</td>
<td>$(1.57 \pm 0.35) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Values from [PDG]
### Backgrounds from other strange decays

- Irreducible background.
- $\mathcal{B}_{\text{eff.}}(K^0_L \rightarrow \mu^+\mu^-) \sim 10^{-11}$.
- 5 SM candidates expected in the final dataset.
- Considered in the di-muon mass fit.

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0_L \rightarrow \mu^+\mu^-$</td>
<td>$(6.84 \pm 0.11) \times 10^{-9}$</td>
</tr>
<tr>
<td>$K^0 \rightarrow \mu^+\mu^-\gamma$</td>
<td>———</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\mu^+\mu^-$</td>
<td>$(9.4 \pm 0.6) \times 10^{-8}$</td>
</tr>
<tr>
<td>$\Sigma^+ \rightarrow p\mu^+\mu^-$</td>
<td>$2.2^{+1.8}_{-1.3} \times 10^{-8}$</td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow p\pi$</td>
<td>$(63.9 \pm 0.5)%$</td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow p\mu\nu$</td>
<td>$(1.57 \pm 0.35) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Values from [PDG]

- $\mathcal{B}_{\text{SM}}(K_S^0 \rightarrow \mu^+\mu^-\gamma) = (1.45 \pm 0.27) \times 10^{-9}$
- $\mathcal{B}(K^0_L \rightarrow \mu^+\mu^-\gamma) = (3.59 \pm 0.11) \times 10^{-7}$
- Di-muon spectrum displaced to the left, no candidates in the fit region.
- $K^0_S \rightarrow \mu^+\mu^-\gamma\gamma$ even more suppressed.

• Irreducible background.
• $\mathcal{B}_{\text{eff.}}(K^0_L \rightarrow \mu^+\mu^-) \sim 10^{-11}$.
• 5 SM candidates expected in the final dataset.
• Considered in the di-muon mass fit.
Backgrounds from other strange decays

- Irreducible background.
- \( \mathcal{B}_{\text{eff.}} (K_L^0 \to \mu^+\mu^-) \sim 10^{-11} \).
- 5 SM candidates expected in the final dataset.
- Considered in the di-muon mass fit.

- Very rare decays.
- Di-muon mass below the thresholds.

\[ \begin{array}{|c|c|}
\hline
\text{Decay} & \text{Branching fraction} \\
\hline
K_L^0 \to \mu^+\mu^- & (6.84 \pm 0.11) \times 10^{-9} \\
K^0 \to \mu^+\mu^- & \\
K^+ \to \pi^+\mu^+\mu^- & (9.4 \pm 0.6) \times 10^{-8} \\
\Sigma^+ \to p\mu^+\mu^- & 2.2^{+1.8}_{-1.3} \times 10^{-8} \\
\Lambda^0 \to p\pi & (63.9 \pm 0.5) \% \\
\Lambda^0 \to p\mu\nu & (1.57 \pm 0.35) \times 10^{-4} \\
\hline
\end{array} \]

Values from [PDG]
Backgrounds from other strange decays

- Irreducible background.
- $\mathcal{B}_{\text{eff.}}\left(K_L^0 \rightarrow \mu^+\mu^-\right) \sim 10^{-11}$.
- 5 SM candidates expected in the final dataset.
- Considered in the di-muon mass fit.

- Very rare decays.
- Di-muon mass below the thresholds.

- For $K_S^0 \rightarrow \mu^+\mu^-$ no candidates overpass the mass threshold.
- For $K_S^0 \rightarrow \pi^+\pi^-$, applied a veto using the Armenteros-Podolanski plane [Phil. Mag. 45 (1954) 13].

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L^0 \rightarrow \mu^+\mu^-$</td>
<td>$(6.84 \pm 0.11) \times 10^{-9}$</td>
</tr>
<tr>
<td>$K^0 \rightarrow \mu^+\mu^-\gamma$</td>
<td>$(9.4 \pm 0.6) \times 10^{-8}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\mu^+\mu^-$</td>
<td>$2.2^{+1.8}_{-1.3} \times 10^{-8}$</td>
</tr>
<tr>
<td>$\Sigma^+ \rightarrow p\mu^+\mu^-$</td>
<td>$(63.9 \pm 0.5)%$</td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow p\pi$</td>
<td>$(1.57 \pm 0.35) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow p\mu\nu$</td>
<td>Values from [PDG]</td>
</tr>
</tbody>
</table>
Backgrounds from resonances

Decays from resonances have been considered as possible backgrounds [PDG]:

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega (782) \rightarrow \pi^0 \mu^+ \mu^-$</td>
<td>$(1.34 \pm 0.18) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\eta \rightarrow \mu^+ \mu^- \gamma$</td>
<td>$(3.1 \pm 0.4) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\omega (782) \rightarrow \pi^0 \pi^+ \pi^-$</td>
<td>$(89.3 \pm 0.6) %$</td>
</tr>
<tr>
<td>$\eta \rightarrow \pi^+ \pi^- \gamma$</td>
<td>$(4.22 \pm 0.08) %$</td>
</tr>
</tbody>
</table>

- These resonances decay promptly.
- Only those coming from $c$ and $b$ hadron decays could survive the trigger and selection requirements.
- Decays in the pionic mode are not visible in the $K_S^0 \rightarrow \pi^+ \pi^-$ selection.
- MC studies showed that none of them is expected to appear in the final selection.

Miguel Ramos Pernas

Search for $K_S^0 \rightarrow \mu^+ \mu^-$ at LHCb

(KAON 2019, September 10, 2019)
Systematic uncertainties

Biggest systematic comes from the determination of the trigger efficiency:

- Hardware trigger (L0): 11%
- Software trigger (HLT): 13%

Other sources of systematic uncertainties are:

- Efficiency of the muon-identification, cross-checked using \( J/\psi \rightarrow \mu^+ \mu^- \) real and simulated data. Low statistics for low-\( p_T \) muons, so also need to use \( K_S^0 \rightarrow \pi \mu \nu \) to cross-check.
- Systematic on the correction for data-simulation differences.
- Efficiency ratio between \( K_S^0 \rightarrow \mu^+ \mu^- \) and \( K_S^0 \rightarrow \pi^+ \pi^- \).
- BDT response across the years.
- Determination of the no-bias trigger rates.

Total systematic varies between 19% and 23%, depending on the trigger category and BDT bin. Lowest values are in the TIS category and higher BDT bins.
Summary of the analysis strategy

Analysis using data from 2016, 2017 and 2018 using:

- Two trigger categories defined by the hardware trigger (L0):
  - TIS: candidates from triggered events where the signal decay ($K^0_S \rightarrow \mu^+\mu^-$) could (or not) have satisfied the trigger requirements.
  - xT0S: candidates from events exclusively triggered due to the presence of the signal decay.

- HLT selection common for both trigger categories.

- Topological selections, followed by cuts in the Armenteros-Podolanski plane [Phil. Mag. 45 (1954) 13] to reduce contamination from $\Lambda^0$ decays.

- One BDT classifier trained for each trigger category (common across the years).

- Analysis done in 20 bins of the BDT classifiers.

- Use muon-identification optimized for strange decays.

- Normalization channel is $K^0_S \rightarrow \pi^+\pi^-$, taken from trigger-unbiased events.

- Fit to the di-muon invariant mass, calculating the limit on the branching fraction from the posterior probability.
Fit to the di-muon invariant mass spectrum

TIS (BDT bin 8)

TOS (BDT bin 8)

TIS (BDT bin 9)

TOS (BDT bin 9)

Search for $K^0_S \rightarrow \mu^+ \mu^-$ at LHCb

(KAON 2019, September 10, 2019)
New world-best limit!

Preliminary result obtained from the posterior probability of the branching fraction in the fit [LHCB-CONF-2019-002].

Using Run-II data only:
\[ \mathcal{B} \left( K^0_S \rightarrow \mu^+ \mu^- \right) < 2.2(2.6) \times 10^{-10} \text{ at } 90(95)\% \text{ CL} \]
Minimum: \[ \mathcal{B} \left( K^0_S \rightarrow \mu^+ \mu^- \right) = 1.03^{+0.76}_{-0.68} \times 10^{-10} \]

Combining with Run-I [JHEP 01 (2013) 090]:
\[ \mathcal{B} \left( K^0_S \rightarrow \mu^+ \mu^- \right) < 2.1(2.4) \times 10^{-10} \text{ at } 90(95)\% \text{ CL} \]
Minimum: \[ \mathcal{B} \left( K^0_S \rightarrow \mu^+ \mu^- \right) = 0.94^{+0.72}_{-0.64} \times 10^{-10} \]
Improvements for the Upgrade

Run-II conditions 2015-2018

**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

Upgrade conditions (ongoing)

**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
- Buffer events to disk, perform online detector calibration and alignment
- 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

2-5 GB/s to storage

Miguel Ramos Pernas

Search for \( K^0_S \rightarrow \mu^+\mu^- \) at LHCb

(KAON 2019, September 10, 2019)
The LHCb trigger in the Upgrade

- Implementation of a full software trigger with two levels.
- Needs to work at 30 MHz.
- Luminosity increases by a factor of 5: $4 \times 10^{32} \rightarrow 2 \times 10^{33} \text{ (cm}^{-2}\text{s}^{-1})$.
- Huge amount of work done in order to run the reconstruction at this rate.
- Port the improvements in Run-II tracking to the Upgrade.
- Efficiencies for $K_S^0 \rightarrow \mu^+\mu^-$ could be similar to the current offline selections (without trigger requirements).
Prospects for the Upgrade and beyond

- Drastically improved tracking detectors.
- Some work done to do the trigger in GPUs and part of the reconstruction using FPGAs (nothing decisive yet).
- Need not only to boost the reconstruction and trigger, but also simulation.
- Profit from software improvements and new simulation techniques [EPJ-C (2018) 78:1009].

Run-II (9 fb$^{-1}$) — Run-IV (Upgrade) (50 fb$^{-1}$) — Upgrade Phase II (300 fb$^{-1}$)
Conclusions

- No significant signal observed so far.

- New best world limit [LHCB-CONF-2019-002]:
  \[ \mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10} \text{ at } 90\% \text{ CL} \]

- Maintaining the current detector performance for the Upgrade is possible.

- Expect to enter into a very interesting region
  \[ \mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) \sim 10^{-11} \]

  Excellents prospects for the Upgrade!