Prospects for the search of $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ at LHCb

Carla Marin Benito
on behalf of the LHCb collaboration

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Birmingham, 14-17 September 2016
Motivation

- LHCb has proved to be very competitive in strange physics.
  - Up to 5 talks with results and prospects in this conference!

- Recent interest in $K^0_S \to \ell^+\ell^-\ell^+\ell^-$ decays: [Eur. Phys. J. C73 (2013) no. 12 2678]

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

  - Any enhancement is a sign of NP!
  - Interference between $K^0_S \to \ell^+\ell^-\ell^+\ell^-$ and $K^0_L \to \ell^+\ell^-\ell^+\ell^-$ would allow CKM stringent constraints.
  - No experimental results in the literature [PDG].
Electron modes

- Electron reconstruction is the main issue:
  - Low momenta + loss by Bremsstrahlung.

- Preliminary studies with MC:
  - Mass resolution good with two $e^\pm$, worse with four.
  - Peak displacement in both cases, larger with four $e^\pm$.

![Graphs showing mass distribution and peak displacement for $K_S^0 \rightarrow e^+e^- e^+e^-$ and $K_S^0 \rightarrow \pi^+\pi^- e^+e^-$ channels.](image)
Electron modes

- Dangerous background: $K_S^0 \to \pi^+ \pi^- e^+ e^-$

- Study separation with two misidentified pions:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Graphs showing candidates distribution for different combinations of particles.}
\end{figure}
$K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$

- Dangerous **background** for $K_S^0 \rightarrow \ell^+ \ell^- \ell^+ \ell^-$. 

- Good candidate for **normalisation channel**.

- Interesting itself: light dark matter states decaying to $e^+ e^-$. 
  - Search for peaks in $e^+ e^-$ invariant mass following [PRD 92 (2015) no. 11 115017].

- Relatively large $\mathcal{B}$ [PDG]:

\[
\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-) = (4.79 \pm 0.15) \times 10^{-5}
\]

- Study feasibility of observing $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ at LHCb
- **e identification**: $e$ ID $\sim 90\%$ for $\sim 5\% e \rightarrow h$ mis-id probability.
- **p resolution**: $\Delta p/p \sim 0.4\%$ at 5 GeV/c to 0.6\% at 100 GeV/c
- **Excellent mass resolution**: $\sim 4$ MeV/$c^2$ for $K^0_S \rightarrow \mu^+ \mu^-$.
LHCb detector for $K^0_S$ decays

LHCb is a kaon factory: $\sim 10^{13} \, K^0_S/\text{fb}^{-1}$ decay in LHCb acceptance. But, it is not optimised for the study of these decays:

<table>
<thead>
<tr>
<th></th>
<th>$m$ (MeV)</th>
<th>$\tau$ ($10^{-12}$ s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d$</td>
<td>5300</td>
<td>1.5</td>
</tr>
<tr>
<td>$K_S$</td>
<td>500</td>
<td>90</td>
</tr>
</tbody>
</table>

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LHCb Run I trigger for $K_S^0$ decays

Flexible trigger

- L0: calorimeters and muon chambers.
- HLT1: adds tracking and vertexing.
- HLT2: exclusive and inclusive full selections.

LHCb trigger was not designed to select $K_S^0$ decays:

- They have larger $\tau$ and lower daughter’s $p_T$.
- No dedicated trigger selection for $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ in Run I.
- They may pass the trigger as background.
Analysis strategy

- Study based on MC and data in 2012 conditions: 2 fb\(^{-1}\) at 8 TeV.

- Obtain reconstruction, selection and trigger efficiency in LHCb Run I.
  - Extract expected signal yield.
  - Estimate background level.

- Study trigger improvements for Run II and upgrade data-taking.
  - Extract expected signal yields.

- Assess observation feasibility.
$K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$ reconstruction

- Evaluated matching reconstructed particles to MC ones.

$$\epsilon_{\text{reco}}^{\text{sig}} = (0.134 \pm 0.002) \%$$
\( K_S^0 \rightarrow \pi^+ \pi^- e^+ e^- \) selection

- Offline selection based on linear cuts (details in slide 21):
  - Loose \( p_T \) but tight flight distance requirements.
  - \( \epsilon_{\text{sel}}^{\text{sig}} = (10.1 \pm 0.5) \% \)
\[ K_S^0 \rightarrow \pi^+ \pi^- e^+ e^- \text{ trigger} \]

- **No dedicated selection in Run I.**
  - Scan all available physics selections [LHCb-PUB-2014-046].

- **One MC signal candidate selected:**
  \[ \epsilon_{\text{sig}}^{\text{trig}} = (0.24^{+0.56}_{-0.20}) \% \]

- **No MC background candidates** pass the same trigger requirement:
  \[ \epsilon_{\text{bkg}}^{\text{trig}} < 0.51 \% \]
  at 90 \% CL.
Expected yields in Run I

- Define signal region: \( 450 < M < 520 \) MeV

- Expected signal yield per \( \text{fb}^{-1} \) of Run I data:

\[
N_{\text{exp}}^{\text{sig}} = N(K^0_S/\text{fb}^{-1}) \cdot B(K^0_S \to \pi^+\pi^-e^+e^-) \cdot \epsilon^{\text{sig}}
\]

\[
N_{\text{exp}}^{\text{sig}} = 120^{+280}_{-100}
\]

- Expected background yield per \( \text{fb}^{-1} \) of Run I data:

\[
N_{\text{exp}}^{\text{bkg}} = \sigma_{\text{tot}} \cdot \epsilon^{\text{bkg}}
\]

\[
N_{\text{exp}}^{\text{bkg}} < 6.1 \times 10^5 \text{ at } 90\% \text{ CL.}
\]
Apply same selection & trigger to 2012 data (2 \( fb^{-1} \) at 8 \( TeV \)):

\[
N_{obs}^{bkg} \sim 6 \times 10^3
\]

Observed background compatible with limit obtained from MC.

Figure: \( \pi^+ \pi^- e^+ e^- \) invariant mass distribution for reconstructed and selected 2012 data candidates.
New dedicated HLT2 selection included for 2016 data-taking:

- Based on linear cuts following the offline selection.
- Inclusive selection for $K^0_S$ decays with $e^+e^-$ in the final state.
- Efficiency estimated on 2012 MC (no 2016 MC available yet):

$$\epsilon_{\text{trig}}^{\text{sig}} = (0.24^{+0.56}_{-0.20})\%$$

- Other differences in Run II neglected:
  - Increase in $K^0_S$ cross-section: much smaller than linear.
  - More $K^0_S$ decaying outside VeLo: small effect.
  - Possible reconstruction and selection improvements.

- Signal yield per $fb^{-1}$ in Run II with these assumptions:

$$N_{\exp}^{\text{sig}} = 120^{+280}_{-100}$$
Expected yields in Run II and beyond

LHCb-PUB-2016-016

- New dedicated HLT2 selection included for 2016 data-taking:
  - Run I trigger selection exploited a complementary approach.
  - Could also benefit from dedicated HLT1 selection.
  - Room for improvement!

- Trigger fully based on software after the LHCb upgrade (∼2021).
  - See Miguel Ramos talk for details.
  - A 100 % trigger efficiency can be achieved.
  - Expected signal yield per fb⁻¹ during the upgrade:

\[ N_{\text{exp}}^{\text{sig}} = (5.0 \pm 0.3) \times 10^4 \]
Observation feasibility with Run I data

- Estimate feasibility of an evidence or observation from pseudoexperiments.
- **Signal efficiency vs background rejection curves** to achieve 3 and 5\(\sigma\) significance.

Well within the usual discrimination of MVA selections.
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- **Signal efficiency vs background rejection curves** to achieve 3 and 5σ significance.

Well within the usual discrimination of MVA selections.

An evidence or observation is feasible with the LHCb Run I dataset!
LHCb has proved to be competitive in the search for strange decays.

- Expected signal and observed background yield obtained for Run I.
- Dedicated trigger selection included for 2016 data-taking.
- Still room for improvement in the trigger.
- Large signal yield expected in the upgrade phase.
- Pseudoexperiments to assess the observation feasibility with Run I data.

An evidence or observation is feasible with the LHCb Run I dataset.

Observation of $\mathcal{K}_S^0 \rightarrow \pi^+\pi^-e^+e^-$ would allow to:

- Test the SM predictions for $\mathcal{K}_S^0 \rightarrow \ell^+\ell^-\ell^+\ell^-$. 
- Search for light dark matter states decaying to $e^+e^-$. 

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Summary & Conclusions

- LHCb has proved to be competitive in the search for strange decays.

LHCb-PUB-2016-016

- Feasibility study of observing $K_0^S \rightarrow \pi^+\pi^-e^+e^-$ at LHCb:
  - Expected signal and observed background yield obtained for Run I.
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Summary & Conclusions

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THANK YOU
BACK-UP
Different trigger categories:

- **TOS (Trigger On Signal):** the event is selected because the signal triggers it.

- **TIS (Trigger Independent of Signal):** the event is selected because some other particles in the event (not the signal ones) trigger it.
## Offline selection

<table>
<thead>
<tr>
<th>Selection</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>track $\chi^2 / ndof$</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>track ghost probability</td>
<td>&lt; 0.5</td>
</tr>
<tr>
<td>track IP $\chi^2$</td>
<td>&gt; 16</td>
</tr>
<tr>
<td>$e$ DLL$_{e\pi}$</td>
<td>&gt; −4</td>
</tr>
<tr>
<td>$e$ $p_T$</td>
<td>MeV/c</td>
</tr>
<tr>
<td>$\pi$ DLL$_{K\pi}$</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>$\pi$ $p_T$</td>
<td>MeV/c</td>
</tr>
<tr>
<td>$e^+e^−$ DOCA</td>
<td>mm</td>
</tr>
<tr>
<td>$e^+e^−$ invariant mass</td>
<td>MeV/c$^2$</td>
</tr>
<tr>
<td>$e^+e^−$ $p_T$</td>
<td>MeV/c</td>
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<tr>
<td>$\pi^+\pi^-e^+e^−$ max DOCA</td>
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<tr>
<td>$\pi^+\pi^-e^+e^−$ invariant mass</td>
<td>MeV/c$^2$</td>
</tr>
<tr>
<td>$K^0_S$ IP</td>
<td>mm</td>
</tr>
<tr>
<td>$K^0_S$ $\tau$</td>
<td>ns</td>
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</table>
# Trigger efficiencies

**Search for $K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ at LHCb**

<table>
<thead>
<tr>
<th>Trigger Selection</th>
<th>$K_S^0 \rightarrow \pi^+\pi^-e^+e^-$ Efficiency (%)</th>
<th>MinBias MC Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0 &amp; Hlt1 &amp; Hlt2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TIS TIS TIS</td>
<td>$&lt; 0.73$</td>
<td>$0.85^{+0.38}_{-0.38}$</td>
</tr>
<tr>
<td>TIS TIS TOS</td>
<td>$&lt; 0.73$</td>
<td>$0.51^{+0.49}_{-0.28}$</td>
</tr>
<tr>
<td>TOS TOS TOS TOS</td>
<td>$0.24^{+0.56}_{-0.20}$</td>
<td>$&lt; 0.51$</td>
</tr>
</tbody>
</table>
Other efficiencies

- Offline selection efficiency on Minimum Bias MC:
  \[ \epsilon_{sel}^{bkg} = (2.95 \pm 0.12) \times 10^{-5} \]

- Signal region cut efficiency on \( K^0_S \rightarrow \pi^+ \pi^- e^+ e^- \) MC:
  \[ \epsilon_{M}^{sig} = (76.9 \pm 1.8)\% \]

- Signal region cut efficiency on Minimum Bias MC:
  \[ \epsilon_{M}^{bkg} = (4.33 \pm 0.02)\% \]
Pseudoexperiments in detail

- Fit signal MC and data to extract signal and background PDFs.

[Graph showing the number of candidates over m_{\pi\pi e e} (MeV/c^2)]
Pseudoexperiments in detail

- Build list of signal and background yields. For each pair:
  - Generate 10k toys: distributions floated according to errors obtained in previous step.
  - Fit generated distribution w/ and w/o signal components → obtain significance.
Pseudoexperiments in detail

- Fit significance vs background yield curves for each signal yield with an exponential.

- Obtain background yield at 3 and 5σ from fitted curve.
Pseudoexperiments in detail

- Build signal efficiency vs background rejection curves at 3 and 5\(\sigma\).
  - Efficiency (rejection) wrt expected signal (observed background) yield in signal region.

![Graph showing signal efficiency vs background rejection for 3 and 5\(\sigma\) discrimination.](image)