Recent results and prospects of rare kaon decay measurements at LHCb

Carla Marin Benito
on behalf of the LHCb collaboration

XIIth International Conference on Heavy Quarks and Leptons

Schloss Waldthausen, Mainz, Germany, 25-29 August 2014
Introduction.

- Motivation
- LHCb detector for strange decays.
- LHCb trigger for strange decays.

Published results: $K_s \rightarrow \mu\mu$.

Prospects:

- $K_s \rightarrow \mu\mu$
- $K_s \rightarrow \pi^0\mu\mu$
- $K_s \rightarrow 4\ell$
- $K^+ \text{ mass}$
- $\Sigma^+ \rightarrow p\mu\mu$

Not covered in this talk:

- $K_s \rightarrow \pi\pi\mu\mu$
- $K_L$
Motivation

Strange mesons have played a major role in the history of particle physics.
- $K^0$ decays motivated the GIM mechanism and prediction of $c$ quark.
- Charge-parity violation (CPV) first observed in a strange decay.

They can still teach us many things:
- Precision measurements of CP violation.
- Search for new physics (NP) in rare strange decays: lepton-flavour violation (LFV) searches.

Why strange?
- Theoretically clean as few final states are allowed.
- Copious production at LHC.
- Large CKM suppression ($V_{ts}V_{td} \sim 10^{-4}$) $\Rightarrow$ large sensitivity to NP.
LHCb detector

Luminosity:
- $\mu$ is kept low to ease secondary vertex reconstruction.
- Current data:
  - 2011: $1 \text{ fb}^{-1}$ data.
  - 2012: $2 \text{ fb}^{-1}$ data.

Detector shape:
- $b$ quarks are produced very boosted.
- Single arm forward spectrometer.

![Graph of LHCb Integrated Luminosity pp collisions 2010-2012](image)
- **Excellent \( \mu \) identification**: \( \mu \) ID \( \sim 97\% \) for 1 – 3\% \( \pi \rightarrow \mu \) mis-ID.
- **Good momentum resolution**: \( \Delta p/p \sim 0.4\% \) at 5 GeV/c to 0.6\% at 100 GeV/c.
LHCb detector for strange decays

LHCb is a kaon factory: \( \sim 10^{13} \frac{K_s}{fb^{-1}} \) decay in LHCb acceptance. But, it is not optimized for the study of these decays: lower \( m \), larger \( \tau \).

<table>
<thead>
<tr>
<th>( m ) (MeV)</th>
<th>( \tau ) (10^{-12}s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_d )</td>
<td>5300</td>
</tr>
<tr>
<td>( K_S )</td>
<td>500</td>
</tr>
<tr>
<td>( K_L )</td>
<td>500</td>
</tr>
<tr>
<td>( K^\pm )</td>
<td>490</td>
</tr>
<tr>
<td>( \Sigma^\pm )</td>
<td>1190</td>
</tr>
</tbody>
</table>

**Long tracks:** Vertex Locator (VELO) + TT + T. Few of the \( K_S \) decays.
LHCb detector for strange decays

LHCb is a kaon factory: $\sim 10^{13}$ $K_s/\text{fb}^{-1}$ decay in LHCb acceptance. But, it is not optimized for the study of these decays: lower $m$, larger $\tau$.

<table>
<thead>
<tr>
<th></th>
<th>$m$ (MeV)</th>
<th>$\tau$ ($10^{-12}\text{s}$)</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>
<tr>
<td>$K_L$</td>
<td>500</td>
<td>50000</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>490</td>
<td>10000</td>
</tr>
<tr>
<td>$\Sigma^\pm$</td>
<td>1190</td>
<td>80</td>
</tr>
</tbody>
</table>

**Long tracks:** Vertex Locator (VELO) + TT + T. Few of the $K_S$ decays.

**Downstream:** TT + T only. Sensitivity to larger flight distances but worse $p$ resolution. Charged mothers ($K^\pm$, $\Sigma^\pm$) hits in the VELO can be matched to these tracks.

Carla Marin (carla.marin.benito@cern.ch) - Rare kaon decays at LHCb
LHCb trigger for strange decays

L0: calorimeters and muon chambers.
HLT1: adds tracking and vertexing.
HLT2: performs full event reconstruction.

LHCb trigger is not designed to select strange decays (larger $\tau$, lower $p_T$) $\Rightarrow$ they are selected as background in the underlying event!

- In 2011, 1/3 events contain a reconstructible $K_S \rightarrow \pi\pi$.
- In 2012, $m_{\mu\mu}$ range at HLT1 was extended to include $m_{K_S}$ $\Rightarrow$ x3 total efficiency.
- For Run2: studying improvements for $K_S \rightarrow \mu\mu$ reconstruction in the trigger.
$K_s \rightarrow \mu\mu$
**$K_S \rightarrow \mu\mu$ motivation**

- No tree-level contribution in SM. FCNC sensitive to NP.
- 2 contributions to the amplitude: [Isidori and Unterdorfer, JHEP 01 (2004) 009]
- **Long-distance (LD)**
- **Short-distance (SD)**

$K_S \rightarrow \mu\mu$ allows to access easily the SD component (unlike $K_L$), which is related to the CPV part of $s \rightarrow d\ell\ell$.
  - Very sensitive to new physics.
  - Poorly constrained so far.

→ In SM: $\text{BR}(K_S \rightarrow \mu\mu) = (5.1 \pm 0.2) \cdot 10^{-12}$ [Ecker and Pich, Nucl. Phys. B366 (1991) 189].
→ Previous best measurement: $\text{BR}(K_S \rightarrow \mu\mu) < 3.1 \cdot 10^{-7}$ in 1973!! [CERN PS, Phys.Lett. B 44 (1973) 217–220]
$K_S \rightarrow \mu\mu$ analysis strategy [JHEP 01 (2013) 090]

- Use 1 fb$^{-1}$ data at 7 TeV.
- Select muon pairs from the same vertex using LHCb excellent $\mu$ identification and vertex and momentum resolution.
- Control channel $K_S \rightarrow \pi\pi$ could be a dangerous bkg. Exploit the $\sigma_m \sim 4$ MeV to separate it from the signal.

![Graph showing $K_S \rightarrow \pi\pi$ candidates](image)
$K_S \rightarrow \mu\mu$ analysis strategy [JHEP 01 (2013) 090]

- Boosted Decision Tree to reject combinatorial bkg.
  - Decay vertex position to reject material interaction bkg.
  - Train on data: side-bands for bkg, $K_S \rightarrow \pi\pi$ data for signal.
  - Samples are split in two: train on one, apply to the other.
  - Search is performed in 10 BDT bins.

The structure in the plot corresponds to the material of the VELO
$K_S \to \mu\mu$ analysis strategy \cite{JHEP 01 (2013) 090}

- Background is interpolated to the signal region from the side-bands.
  - Exponential component for combinatorial.
  - Empirical function (checked with MC) for the $K_S \to \pi\pi$ tails.
  - Other peaking bkg found to be negligible.

- Observed yield compatible with background expectation.
$K_s \rightarrow \mu\mu$ results [JHEP 01 (2013) 090]

- CLs method used to set an upper limit on the BR.

$$\text{BR} (K_s \rightarrow \mu\mu) < 9(11) \cdot 10^{-9} \text{ at } 90(95)\% \text{ CL}$$

30 times better than previous best!!
$K_s \rightarrow \mu\mu$ prospects

- Most interesting region is below $10^{-10}$.
- Only 1/3 of the available data ($1 \text{ fb}^{-1}$) has been analyzed so far!

Expected sensitivity: the range takes into account the background estimation uncertainty.

Direct extrapolation from last analysis
Assuming 3 times trigger improvement

- Could reach the $10^{-10}$ level with the LHCb upgrade.
- Could have an extra gain using downstream tracks.
LHCb prospects for other rare strange decays
$K_S \rightarrow \pi^0 \mu\mu$ prospects

- **Motivation**
  - $K_S \rightarrow \pi^0 \mu\mu$ measures the indirect CPV contribution of $K_L \rightarrow \pi^0 \mu\mu \Rightarrow$ extract the direct CPV component which is sensitive to CKM.
  - Study structure of $K \rightarrow \pi\gamma^*$ form factor.

- **Previous measurement from NA48** [Phys. Lett. B 599: 197-211, 2004]:
  $\text{BR}(K_S \rightarrow \pi^0 \mu\mu) = (2.9^{+1.5}_{-1.2} \pm 0.2) \cdot 10^{-9} \sim 50\%$ uncertainty!
**Motivation**

- $K_S \rightarrow \pi^0 \mu\mu$ measures the indirect CPV contribution of $K_L \rightarrow \pi^0 \mu\mu$ to extract the direct CPV component which is sensitive to CKM.
- Study structure of $K \rightarrow \pi\gamma^*$ form factor.

**Previous measurement from NA48** [Phys. Lett. B 599: 197-211, 2004]:

\[
\text{BR}(K_S \rightarrow \pi^0 \mu\mu) = (2.9^{+1.5}_{-1.2} \pm 0.2) \cdot 10^{-9} \sim 50\% \text{ uncertainty!}
\]

**$\pi^0$ reconstruction is challenging. Different options studied with MC:**

- $\pi^0 \rightarrow \gamma\gamma$ → **Most feasible**.
- $\pi^0 \rightarrow ee\gamma$
- No $\pi^0$

**Ongoing sensitivity studies:**

- Few events expected in 3 fb$^{-1}$.
- Could make a measurement in the upgrade (huge production of $K_S$).
$K_S \rightarrow 4\ell$ prospects

- Recent publication of SM and NP contributions to $K_{L,S} \rightarrow 4\ell$.
  [D’Ambrosio, Greynat and Vulvert, arXiv:1309.5736v3]
  - BRs in SM are up to:
    $K_S \rightarrow eeee \sim 10^{-10}$
    $K_S \rightarrow ee\mu\mu \sim 10^{-11}$
    $K_S \rightarrow \mu\mu\mu\mu \sim 10^{-14}$

- No experimental results so far ⇒ worth looking at it!
$K_S \rightarrow 4\ell$ prospects

- Recent publication of SM and NP contributions to $K_{L,S} \rightarrow 4\ell$.
  [D'Ambrosio, Greynat and Vulvert, arXiv:1309.5736v3]
  - BRs in SM are up to:
    \[ K_S \rightarrow eeee \approx 10^{-10} \]
    \[ K_S \rightarrow ee\mu\mu \approx 10^{-11} \]
    \[ K_S \rightarrow \mu\mu\mu\mu \approx 10^{-14} \]
  - No experimental results so far \( \Rightarrow \) worth looking at it!
  - LHCb prospects for $K_S \rightarrow 4\ell$ with electrons:
    - $e$ reconstruction is also challenging. From MC studies:
      \begin{center}
      \begin{tabular}{l|cc}
        & Mass resolution & Single event sensitivity (3fb$^{-1}$) \\
        \hline
        $K_S \rightarrow eeee$ & \( \sim 20\) MeV & \( \sim 10^{-6} \) \\
        $K_S \rightarrow ee\mu\mu$ & \( \sim 10\) MeV & \( \sim 10^{-7} \)
      \end{tabular}
      \end{center}
    - Mass peak displacement due to $e$ energy loss.
    - Both safe from main background: $K_S \rightarrow \pi\pi ee$.
  - Ongoing work also with $K_S \rightarrow \mu\mu\mu\mu$. 

Carla Marin (carla.marin.benito@cern.ch)

Rare kaon decays at LHCb

HQL 2014 16 / 21
Disagreement between most precise $K^+$ mass measurements:

- $K^+ \rightarrow \pi\pi\pi$ could give a competitive result.

LHCb approach:

- Use long and downstream tracks.
Matching the downstream tracks to $K^+$ hits in the VELO cleans a lot of background with high signal efficiency. [A. Contu, CERN-LHCb-PUB-2014-032]
HyperCP (Tevatron) results [PRL 94 021801]:

- 3 signal events observed with 0 background.
- \( \text{BR}(\Sigma^+ \rightarrow p\mu\mu) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8} \)
- All 3 events have \( m_{\mu\mu} \sim 214 \text{ MeV} \) \( \Rightarrow \) \( \Sigma^+ \rightarrow pX^0 (\rightarrow \mu\mu) \) with new \( X^0 \) state?

LHCb approach:

- Find evidence of the decay and study \( m_{\mu\mu} \).
- Use long and downstream tracks.
- From MC studies:
  - very good mass resolution: \( \sim 2 \text{ MeV} \).
  - single event sensitivity (3 fb\(^{-1}\)): \( O(10^{-9} \sim 10^{-8}) \)

Carla Marin (carla.marin.benito@cern.ch)
LHCb is not designed for strange physics but can contribute a lot in this field.
- Copious production of strange hadrons at the LHC.
- Exploit the possibility of analysing data that was triggered as background.

Published result: $\text{BR}(K_S \rightarrow \mu\mu) < 9.0 \cdot 10^{-9}$, 30 times better than previous world best!

Strange physics is a new area of interest for LHCb.
- No other experiment will be looking at $K^0$ decays in the near future!
Summary

- LHCb is not designed for strange physics but can contribute a lot in this field.
  - Copious production of strange hadrons at the LHC.
  - Exploit the possibility of analysing data that was triggered as background.

- Published result: \( \text{BR}(K_S \rightarrow \mu \mu) < 9.0 \cdot 10^{-9} \), 30 times better than previous world best!

- Strange physics is a new area of interest for LHCb.
  - No other experiment will be looking at \( K^0 \) decays in the near future!

Stay tuned!!
THANK YOU!
BACK-UP
$K^0$ motivation for GIM mechanism and c quark

\[\begin{align*}
K^+ & \rightarrow W^+ u \rightarrow \ell^+ v_{\ell} \\
K^0_L & \rightarrow Z^0 d \rightarrow \mu^+ \bar{\nu}_{\mu} \\
& \rightarrow W^+ c \rightarrow \mu^+ \bar{\nu}_{\mu}
\end{align*}\]
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) triggered it → the signal is selected as background in this case. Signal and normalization channel have same efficiency.
Two amplitude components:

- **s-wave**: CPC for $K_L$, CPV for $K_S$. Both LD and SD contribute.
- **p-wave**: CPV for $K_L$, CPC for $K_S$. Only LD contributes in SM.

Consequently:

- $K_L$: p-wave is CPV $\rightarrow$ negligible.
- $K_S$: p-wave is CPC $\rightarrow$ relevant. s-wave is CPV but has contribution from SD.

Moreover:

- LD contribution to $K_S$ can be determined from chiral expansion $\sim 5 \cdot 10^{-12}$.
- Bounds of $10^{-11}$ on $B(K_S \rightarrow \mu\mu) \rightarrow$ bounds on CPV phase of $s \rightarrow d\ell\ell$
### $K_S \rightarrow \mu\mu$ expected events

<table>
<thead>
<tr>
<th>sample</th>
<th>bin</th>
<th>base model</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>bin 1</td>
<td>2.05$^{+1.31}_{-0.91}$</td>
</tr>
<tr>
<td>A</td>
<td>bin 2</td>
<td>0.86$^{+0.73}_{-0.39}$</td>
</tr>
<tr>
<td>A</td>
<td>bin 3</td>
<td>0.23$^{+0.4}_{-0.23}$</td>
</tr>
<tr>
<td>A</td>
<td>bin 4</td>
<td>0.23$^{+0.5}_{-0.23}$</td>
</tr>
<tr>
<td>A</td>
<td>bin 5</td>
<td>0.35$^{+0.53}_{-0.35}$</td>
</tr>
<tr>
<td>A</td>
<td>bin 6</td>
<td>0.28$^{+0.45}_{-0.28}$</td>
</tr>
<tr>
<td>A</td>
<td>bin 7</td>
<td>0.21$^{+0.36}_{-0.14}$</td>
</tr>
<tr>
<td>A</td>
<td>bin 8</td>
<td>0.59$^{+0.8}_{-0.59}$</td>
</tr>
<tr>
<td>A</td>
<td>bin 9</td>
<td>0.00268$^{+0.00045}_{-0.00198}$</td>
</tr>
<tr>
<td>A</td>
<td>bin 10</td>
<td>0.68$^{+0.69}_{-0.43}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 1</td>
<td>1.66$^{+1.1}_{-0.78}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 2</td>
<td>1.51$^{+1.14}_{-0.75}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 3</td>
<td>0.39$^{+0.8}_{-0.39}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 4</td>
<td>0.46$^{+0.55}_{-0.21}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 5</td>
<td>0.3$^{+0.45}_{-0.2}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 6</td>
<td>0.018$^{+0.029}_{-0.012}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 7</td>
<td>0.027$^{+0.264}_{-0.018}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 8</td>
<td>1.36$^{+0.88}_{-0.7}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 9</td>
<td>0.0133$^{+0.0034}_{-0.009}$</td>
</tr>
<tr>
<td>B</td>
<td>bin 10</td>
<td>0.14$^{+0.37}_{-0.14}$</td>
</tr>
</tbody>
</table>
**$K_S \to \mu\mu$ systematics**

- Bkg expectation: different fit models and different ranges. Different for each bin.
- Ratio of reconstruction, selection and $\mu$-ID: different MC reweighting techniques and comparing to MC. $\sim 20\%$ for the ratios and $\sim 5\%$ for the $\mu$-ID.
- $\mathcal{B}(K_S \to \pi^+\pi^-) = (69.20 \pm 0.05)\%$.
- Absolute TOS efficiency: comparison to MC. $\sim 15\%$ depending on the bin.
- Prescale factor of the MB sample: difference between the factor in the trigger system and the one measured in data. $s^{MB} = (2.70 \pm 0.76) \times 10^{-6}$.

Leading ones: TOS efficiency and $s^{MB}$ for TOS and ratio of reconstruction and selection for TIS.
$K_S \rightarrow \pi^0\mu\mu$ backgrounds

- Combinatorial similar to $K_S \rightarrow \mu\mu \Rightarrow$ reasonably low.
  - Requiring 2 very detached muons, cleans a lot!

- $K_S \rightarrow \pi\pi$ with $\pi \rightarrow \mu$ misidentification + $\pi^0$ from underlying event.
  - $\pi \rightarrow \mu$ moves the peak to the left.
  - Adding $\pi^0$ could move it back to the right!
  
  \[ BR(K_S \rightarrow \pi\pi) \times \epsilon(\pi \rightarrow \mu)^2 \sim 0.69 \times 0.01^2 \sim 7 \cdot 10^{-4} \]

- Similar for $K_S \rightarrow \pi\mu\nu$.
  \[ BR(K_S \rightarrow \pi\mu\nu\mu) \times \epsilon(\pi \rightarrow \mu) \sim 4.7 \cdot 10^{-4} \times 0.01 \sim 5 \cdot 10^{-6} \]

- Selection should be tightened to fight them.
- This could diminish the signal efficiency.
**$K_S \rightarrow 4\ell$: possible contamination**

<table>
<thead>
<tr>
<th></th>
<th>$K_S \rightarrow \pi\pi ee$ separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_S \rightarrow eeee$</td>
<td>$\sim 300$ MeV</td>
</tr>
<tr>
<td>$K_S \rightarrow ee\mu\mu$</td>
<td>$\sim 70$ MeV</td>
</tr>
</tbody>
</table>
**$K_S \rightarrow 4\ell$: expected sensitivity**

Normalization channel: $K_S \rightarrow e^+ e^- \pi^+ \pi^-$

Definition of single event sensitivity:

$$\alpha = \frac{\epsilon_{\text{norm}}^{\text{accep}}}{\epsilon_{\text{phys}}^{\text{accep}}} \cdot \frac{\epsilon_{\text{norm}}^{\text{reco|accep}}}{\epsilon_{\text{phys}}^{\text{reco|accep}}} \cdot \frac{\epsilon_{\text{norm}}^{\text{sel|reco}}}{\epsilon_{\text{phys}}^{\text{sel|reco}}} \cdot \frac{1}{(\epsilon_{\text{PID}})^2} \cdot \frac{\epsilon_{\text{norm}}^{\text{trig|sel}}}{\epsilon_{\text{phys}}^{\text{trig|sel}}} \cdot \frac{\text{BR}_{\text{norm}}}{N_{\text{norm}}},$$

- $\epsilon_{\text{accep}}$ very similar for both channels.
- Assume $\epsilon_{\text{sel|reco}}$ and $\epsilon_{\text{trig|sel}}$ are the same.
- $\epsilon_{e}^{\text{reco|accep}} \approx 9\%$, $\epsilon_{\mu}^{\text{reco|accep}} \approx 20\%$ and $\epsilon_{\pi}^{\text{reco|accep}} \approx 6 - 9\%$.
- $\epsilon_{e}^{\text{PID}} \approx 50\%$ and $\epsilon_{\mu}^{\text{PID}} \approx 90\%$ (from $B \rightarrow e\mu$ and $K_S \rightarrow \mu^+ \mu^-$ analysis).
- $\text{BR}(K_S \rightarrow e^+ e^- \pi^+ \pi^-) = 4.79 \cdot 10^{-5}$ from PDG.

Assuming $N_{K_S \rightarrow e^+ e^- \pi^+ \pi^-} \sim 50$ (very conservative!)

- $K_S \rightarrow e^+ e^- e^+ e^-: \alpha \sim 10^{-6}$
- $K_S \rightarrow e^+ e^- \mu^+ \mu^-: \alpha \sim 10^{-7}$
$K_S \rightarrow 4\ell$: expected $N_{K_s\rightarrow e^+ e^- \pi^+ \pi^-}$

\[
N_{K_s\rightarrow e^+ e^- \pi^+ \pi^-}^{TIS} = N_{K_s\rightarrow \pi^+ \pi^-}^{TIS} \cdot 1\text{fb}^{-1} \cdot N_{fb}^{-1} \cdot \frac{BR(K_s \rightarrow e^+ e^- \pi^+ \pi^-)}{BR(K_s \rightarrow \pi^+ \pi^-)} \cdot \frac{\epsilon_{K_s\rightarrow e^+ e^- \pi^+ \pi^-}}{\epsilon_{K_s\rightarrow \pi^+ \pi^-}}
\]

where:

- $N_{K_s\rightarrow \pi^+ \pi^-}^{TIS} \sim 10^8$ from $K_s \rightarrow \mu\mu$ analysis.
- We have in tape $N_{fb}^{-1} = 3$.
- $BR(K_s \rightarrow e^+ e^- \pi^+ \pi^-) = 4.79 \cdot 10^{-5}$ and $BR(K_s \rightarrow \pi^+ \pi^-) = 6.9 \cdot 10^{-1}$, from PDG.
- $\frac{\epsilon_{K_s\rightarrow e^+ e^- \pi^+ \pi^-}}{\epsilon_{K_s\rightarrow \pi^+ \pi^-}} \sim \frac{\epsilon_{PIDe}^2 \cdot \epsilon_{reco}^2}{\epsilon_{reco}^2 \cdot \epsilon_{reco}^2 \cdot \epsilon_{PIDe}^2}$ is the ratio of efficiencies, computed with the values given in previous slide.
$K^+$: expected mass precision

- Very rough estimate for systematic uncertainty: $\sim 0.02$ MeV/c$^2$.
  - Could be improved with some effort.

- To have a similar statistical error $\sim 200K$ events are needed.
  - In 1 fb$^{-1}$ we observe $\sim 2K$ events.
  - Dedicated selection $\sim \times 10$ statistics.
  - Dedicated trigger line could have a similar result, but only available from Run2.
\[ \Sigma^+ \to p\mu\mu: \text{expected sensitivity} \]

Normalization channel: \( \Sigma^+ \to p\pi^0(\to e^+e^-\gamma) \)

Definition of single event sensitivity:

\[
\alpha = \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{phys}}} \cdot \frac{\text{BR}_{\text{norm}}}{N_{\text{norm}}}
\]

- Assuming same trigger efficiency.
- The ratio of \( \epsilon_{\text{reco,select}} \) is \( \sim 0.04 \) due to the difficult reconstruction of very soft electrons.
- \( \text{BR}(\Sigma^+ \to p\pi^0(\to e^+e^-\gamma)) = 51.57\% \times 1.174\% \sim 6 \cdot 10^{-3} \) from PDG.
- Without optimisation of final selection.

With \( N_{\Sigma^+\to p\pi^0(\to e^+e^-\gamma)} = 45K \) observed in 3 fb\(^{-1}\):

\[
\alpha_{\Sigma^+\to p\pi^0(\to e^+e^-\gamma)}: \sim 5 \cdot 10^{-9}
\]
Could allow precise measurement of $K^0$ mass.
- Low Q: $m_{K_S} - (2 \cdot m_\pi + 2 \cdot m_\mu) \sim 10 \text{ MeV}/c^2$.
- Minimize systematics due to momentum scale uncertainty.

SM prediction:
- $\text{BR}(K_S \rightarrow \pi\pi\mu\mu) = 4 \cdot 10^{-14}$.
- Good probe for NP.

Starting preliminary studies at LHCb.
$K_L$ prospects

- $K_L$ and $K_S$ distinguishable by the decay time. But in LHCb acceptance:

$$\epsilon(t) \sim e^{-\beta t}$$

The decay distributions will look like:

\[
\begin{align*}
K_S & \quad p(t) \sim e^{-(\beta + \Gamma_S)t} = e^{-\Gamma_{S,\text{eff}}t} \\
K_L & \quad p(t) \sim e^{-(\beta + \Gamma_L)t} = e^{-\Gamma_{L,\text{eff}}t}
\end{align*}
\]

Using DD tracks, $\sim 50\%$ separation can be reached.

- The overall reconstruction efficiency is $\sim 1000$ times smaller than for the corresponding $K_S$ decay.