Recent results and prospects of rare kaon decay measurements at LHCb

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on behalf of the LHCb collaboration

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Outline

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

- Published results: $K_s \to \mu\mu$.

- Prospects:
  - $K_s \to \mu\mu$
  - $K_s \to \pi^0\mu\mu$
  - $K_s \to 4\ell$
  - K^+ mass
  - $\Sigma^+ \to p\mu\mu$

Not covered in this talk:

- $K_S \to \pi\pi\mu\mu$
- K_L

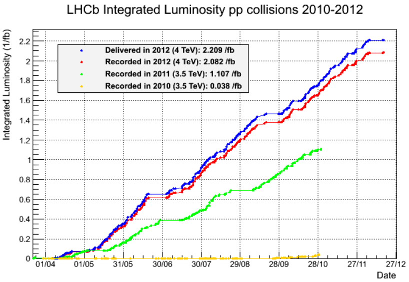
Motivation

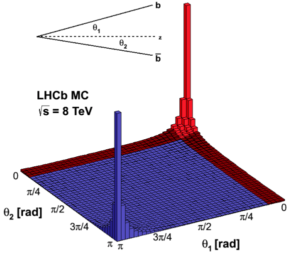
- Strange mesons have played a major role in the history of particle physics.
  - K^0 decays motivated the GIM mechanism and prediction of c quark.
  - Charge-parity violation (CPV) first observed in a strange decay.
- They can still teach us many things:
  - Precision measurements of CP violation.
  - 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:

- μ is kept low to ease secondary vertex reconstruction.
- Current data:
  - 2011: 1 fb^{-1} data.
  - 2012: 2 fb^{-1} data.

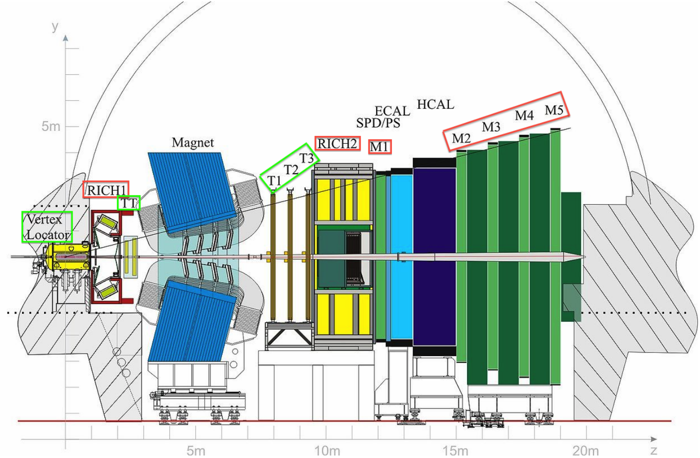




Detector shape:

- b quarks are produced very boosted.
- Single arm forward spectrometer.

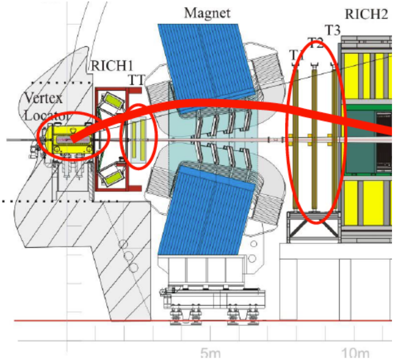
LHCb detector



- Excellent μ identification: μ ID $\sim 97\%$ for $1-3\%$ $\pi \to \mu$ 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: $\sim 10^{13}$ $\mathrm{K}_s/\mathrm{fb}^{-1}$ decay in LHCb acceptance.
But, it is not optimized for the study of these decays: lower m, larger τ.



	m (MeV)	τ (10^{-12}s)
B_d	5300	1.5
K_S	500	90
K_L	500	50000
$K^{\pm}$	490	10000
$\Sigma^{\pm}$	1190	80

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

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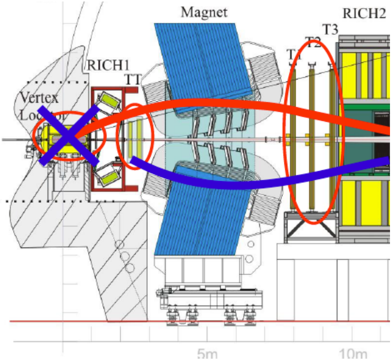

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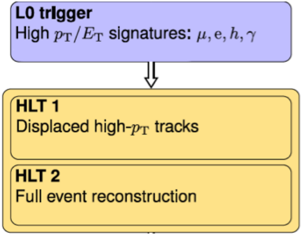
Long tracks: Vertex Locator (VELO) + TT + T. Few of the K_S decays.
Downstream: TT + T only. Sensitivity to larger flight distances but worse p resolution. Charged mothers ($K^\pm$, $\Sigma^\pm$) hits in the VELO can be matched to these tracks.

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 τ, lower p_T) $\Rightarrow$ they are selected as background in the underlying event!

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

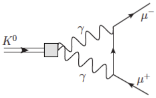
$$K_S \to \mu\mu$$

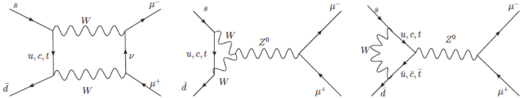
$K_s \to \mu\mu$ motivation

- 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)





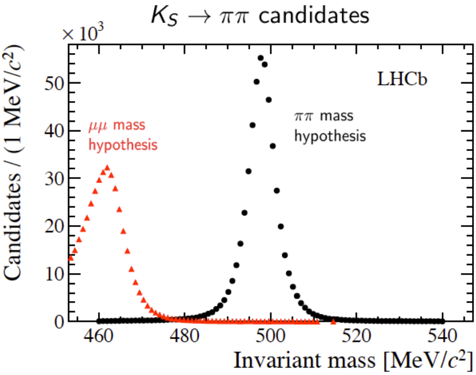
- $K_S \to \mu\mu$ allows to access easily the SD component (unlike K_L), which is related to the CPV part of $s \to d\ell\ell$.
  - Very sensitive to new physics.
  - Poorly constrained so far.

$\to$ In SM: $\text{BR}(K_S \to \mu\mu) = (5.1 \pm 0.2) \cdot 10^{-12}$ [Ecker and Pich, Nucl. Phys. B366 (1991) 189].

$\to$ Previous best measurement: $\text{BR}(K_S \to \mu\mu) < 3.1 \cdot 10^{-7}$ in 1973!! [CERN PS, Phys.Lett. B 44 (1973) 217–220]

$K_s \to \mu\mu$ analysis strategy [JHEP 01 (2013) 090]

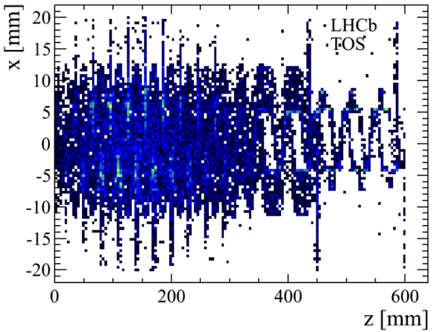
- Use 1 fb^{-1} data at 7 TeV.
- Select muon pairs from the same vertex using LHCb excellent μ identification and vertex and momentum resolution.
- Control channel $K_S \to \pi\pi$ could be a dangerous bkg. Exploit the $\sigma_m \sim 4\,\mathrm{MeV}$ to separate it from the signal.



$K_s \to \mu\mu$ 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, $K_S \to \pi\pi$ data for signal.
  - Samples are split in two: train on one, apply to the other.
  - Search is performed in 10 BDT bins.

Vertex position for mass side-bands

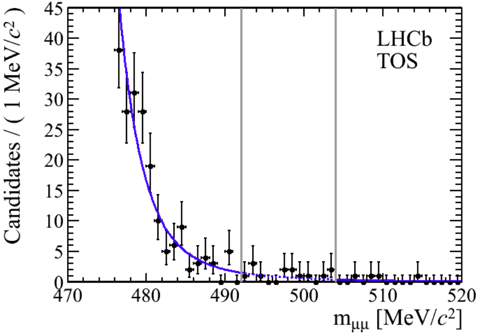


The structure in the plot corresponds to the material of the VELO

$K_s \to \mu\mu$ analysis strategy [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.

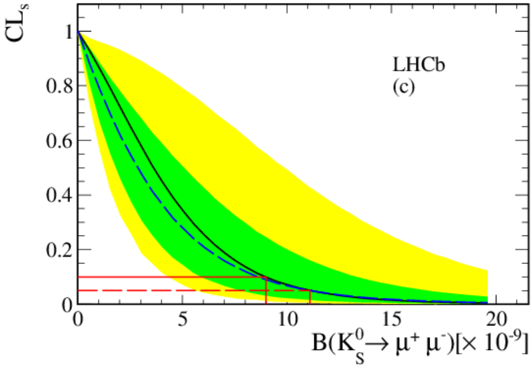
$K_S \to \mu\mu$ candidates



- Observed yield compatible with background expectation.

$K_s \to \mu\mu$ results [JHEP 01 (2013) 090]

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

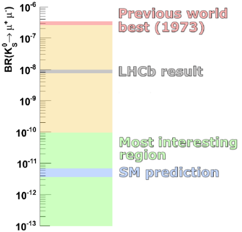


$$\text{BR } (K_s \to \mu\mu) < 9(11) \cdot 10^{-9} \text{ at } 90(95)\% \text{ CL}$$

30 times better than previous best!!

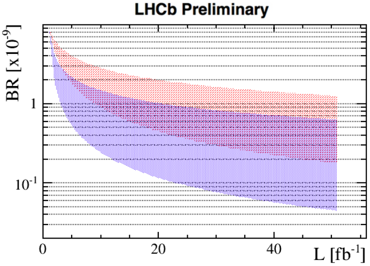
$K_s \to \mu\mu$ prospects

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



[X. Cid, *IV Jornadas CPAN*]

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

$K_S \to \pi^0\mu\mu$ prospects

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

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

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- π^0 reconstruction is challenging. Different options studied with MC:
  - $\pi^0 \to \gamma\gamma \to$ **Most feasible**.
  - $\pi^0 \to ee\gamma$
  - No π^0

- Ongoing sensitivity studies:
  - few events expected in 3 fb^{-1}.
  - could make a measurement in the upgrade (huge production of K_S).

$K_S \to 4\ell$ prospects

- Recent publication of SM and NP contributions to $K_{L,S} \to 4\ell$. [D'Ambrosio, Greynat and Vulvert, arXiv:1309.5736v3]
  - BRs in SM are up to:
    $$\begin{array}{ll} K_s \to eeee & \sim 10^{-10} \\ K_s \to ee\mu\mu & \sim 10^{-11} \\ K_s \to \mu\mu\mu\mu & \sim 10^{-14} \end{array}$$
- No experimental results so far $\Rightarrow$ worth looking at it!

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- No experimental results so far $\Rightarrow$ worth looking at it!
- LHCb prospects for $K_S \to 4\ell$ with electrons:
  - e reconstruction is also challenging. From MC studies:

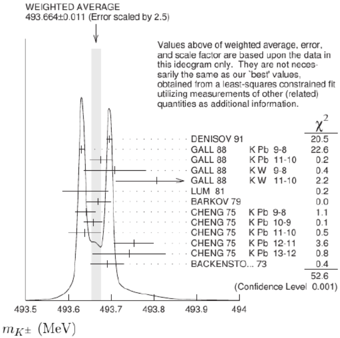
	Mass resolution	Single event sensitivity (3fb^{-1})
$K_s \to eeee$	~ 20 MeV	$\sim 10^{-6}$
$K_s \to ee\mu\mu$	~ 10 MeV	$\sim 10^{-7}$

  - Mass peak displacement due to e energy loss.
  - Both safe from main background: $K_S \to \pi\pi ee$.
- Ongoing work also with $K_S \to \mu\mu\mu\mu$.

K^+ mass prospects

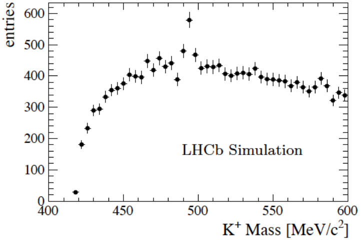
Disagreement between most precise K^+ mass measurements:

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



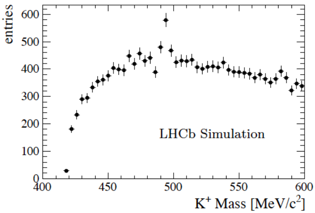
[J. Beringer et al. (PDG)]

LHCb approach:

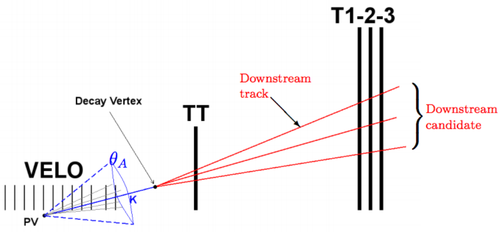


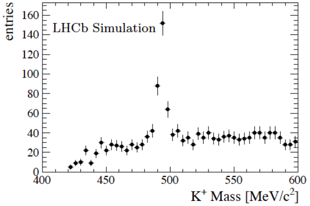
- Use long and downstream tracks.

K^+ mass prospects: VELO track matching



Without VELO track matching





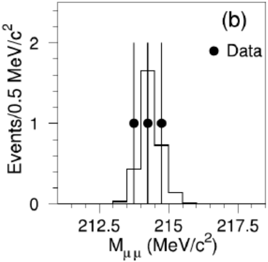
With VELO track matching

- 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]

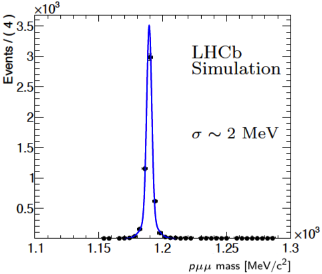
$\Sigma^+ \to p\mu\mu$ prospects

HyperCP (Tevatron) results [PRL 94 021801]:

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



[Hyper CP results]



LHCb approach:

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

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: $\mathrm{BR}(K_S \to \mu\mu) < 9.0 \cdot 10^{-9}$, 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

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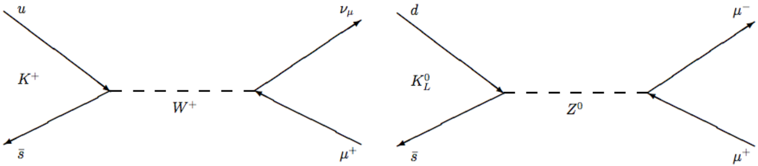
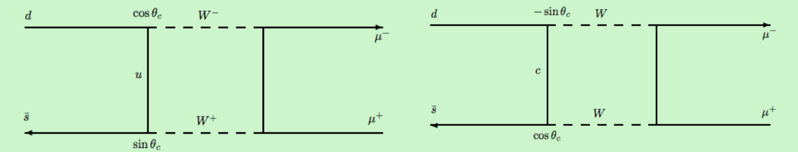
Stay tuned!!

THANK YOU!

BACK-UP

K^0 motivation for GIM mechanism and c quark





LHCb Trigger: TIS and TOS

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 $\rightarrow$ the signal is selected as background in this case. Signal and normalization channel have same efficiency.

$K_S \to \mu\mu$ contributions

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 $\to$ negligible.
- K_S: p-wave is CPC $\to$ 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($K_S \to \mu\mu$) $\to$ bounds on CPV phase of $s \to d\ell\ell$

$K_S \to \mu\mu$ expected events

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

$K_S \to \mu\mu$ systematics

- Bkg expectation: different fit models and different ranges. Different for each bin.
- Ratio of reconstruction, selection and μ-ID: different MC reweighting techniques and comparing to MC. $\sim 20\%$ for the ratios and $\sim 5\%$ for the μ-ID.
- $\mathrm{B}(K_S \to \pi^+\pi^-) = (69.20 \pm 0.05)\%$.
- 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.

$K_S \to \pi^0 \mu\mu$ backgrounds

- Combinatorial similar to $K_S \to \mu\mu \Rightarrow$ reasonably low.
  - Requiring 2 very detached muons, cleans a lot!
- $K_S \to \pi\pi$ with $\pi \to \mu$ misidentification $+ \pi^0$ from underlying event.
  - $\pi \to \mu$ moves the peak to the left.
  - Adding π^0 could move it back to the right!

  $BR(K_S \to \pi\pi) \times \epsilon(\pi \to \mu)^2 \sim 0.69 \times 0.01^2 \sim 7 \cdot 10^{-4}$
- Similar for $K_S \to \pi\mu\nu$.
  $BR(K_S \to \pi\mu\nu_\mu) \times \epsilon(\pi \to \mu) \sim 4.7 \cdot 10^{-4} \times 0.01 \sim 5 \cdot 10^{-6}$
- Selection should be tightened to fight them.
- This could diminish the signal efficiency.

$K_S \to 4\ell$: possible contamination

	$K_S \to \pi\pi ee$ separation
$K_s \to eeee$	~ 300 MeV
$K_s \to ee\mu\mu$	~ 70 MeV

$K_S \to 4\ell$: expected sensitivity

Normalization channel: $K_s \to e^+e^-\pi^+\pi^-$

Definition of single event sensitivity:

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

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

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

$$K_s \to e^+e^-e^+e^-:\ \alpha \sim 10^{-6}$$
$$K_s \to e^+e^-\mu^+\mu^-:\ \alpha \sim 10^{-7}$$

$K_S \to 4\ell$: expected $N_{K_s \to e^+e^-\pi^+\pi^-}$

$$N^{\text{TIS}}_{K_s \to e^+e^-\pi^+\pi^-} = N^{\text{TIS}}_{K_s \to \pi^+\pi^-, 1\text{fb}^{-1}} \cdot N_{\text{fb}^{-1}} \cdot \frac{\text{BR}(K_s \to e^+e^-\pi^+\pi^-)}{\text{BR}(K_s \to \pi^+\pi^-)} \cdot \frac{\epsilon_{K_s \to e^+e^-\pi^+\pi^-}}{\epsilon_{K_s \to \pi^+\pi^-}}$$

where:

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

K^+: expected mass precision

- Very rough estimate for systematic uncertainty: ~ 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.

$\Sigma^+ \to p\mu\mu$: 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 effciency.
- The ratio of $\epsilon_{reco,selec}$ is ~ 0.04 due to the diffcult 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 $N_{\Sigma^+\to p\pi^0(\to e^+e^-\gamma)} = 45\text{K}$ observed in 3 fb^{-1}:

$$\alpha_{\Sigma^+\to p\pi^0(\to e^+e^-\gamma)}: \sim 5 \cdot 10^{-9}$$

$K_S \to \pi\pi\mu\mu$ prospects

- Could allow precise measurement of K^0 mass.
  - Low Q: $m_{K_S} - (2 \cdot m_\pi + 2 \cdot m_\mu) \sim 10$ MeV$/c^2$.
  - Minimize systematics due to momentum scale uncertainty.
- SM prediction:
  - $\text{BR}(K_S \to \pi\pi\mu\mu) = 4 \cdot 10^{-14}$.
  - 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:

KS $\quad p(t) \sim e^{-(\beta+\Gamma_S)t} = e^{-\Gamma_{S,eff}t}$

KL $\quad p(t) \sim e^{-(\beta+\Gamma_L)t} = e^{-\Gamma_{L,eff}t}$

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

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