K_S decays at LHCb

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on behalf of the LHCb collaboration

LES RENCONTRES DE PHYSIQUE DE LA VALLEE D'AOSTE

La Thuile, February 2014

Outline

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

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

- Future prospects:

  [All from *Rare'n'strange Workshop*, CERN, 06/12/13]

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

Not covered in this talk:

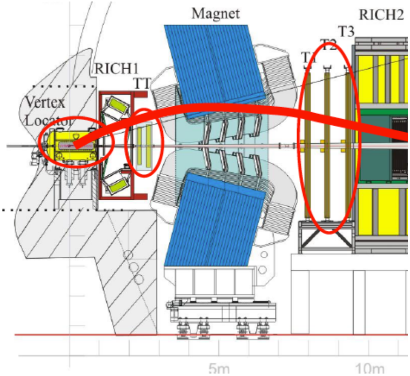
- $K_S \to \pi\pi\mu\mu$
- K_L

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 for strange decays

LHCb is not optimized for the study of strange mesons: 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 (LL): $\sim 10^{13}$ K_s/fb^{-1} decay in LHCb acceptance.

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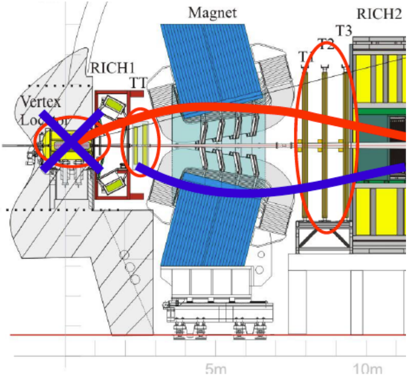

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Long tracks (LL): $\sim 10^{13}$ K_s/fb^{-1} decay in LHCb acceptance.

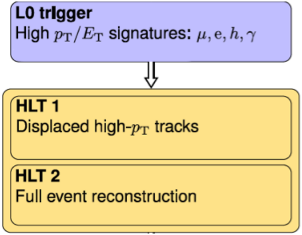
Downstream tracks (DD): more statistics but worse p resolution.

Charged mothers ($K^{\pm}$, $\Sigma^{\pm}$) leave hits in the VELO ⇒ use matching.

LHCb trigger for strange decays

Not designed to select strange decays ($\sim 1\%$ of offline selected $K_S \to \mu\mu$ candidates passed the whole trigger) $\Rightarrow$ selected in the underlying event!

- They have larger τ and lower daughter's p_T.
- In 2011, $1/3$ events contain a reconstructible $K_S \to \pi\pi$.



- L0: calorimeters and muon chambers.
- HLT1: adds tracking and vertexing.
- HLT2: performs full event reconstruction.
  - Old $m_{\mu\mu}$ range didn't include m_{K_S}.
  - Adjusted in 2012 trigger $\Rightarrow$ x3 total efficiency.

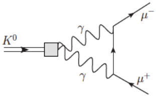
- Run2: studying to include an exclusive di-μ line at HLT1.

$K_s \to \mu\mu$ motivation

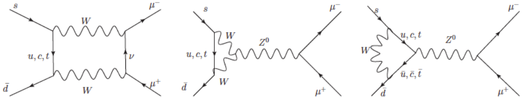
- No tree-level contribution in SM. FCNC sensitive to NP.

- 2 contributions to the amplitude: [Isidori and Unterdorfer, JHEP 01 (2004) 009]

Long-distance (LD)



Short-distance (SD)



- SD component of $K_S \to \mu\mu$ is dominated by CPV part of $s \to d\ell\ell$.
  - Very sensitive to new physics.
  - Poorly constrained so far.

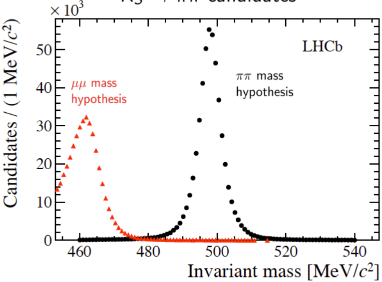
→ In SM: $\mathrm{BR}(K_S \to \mu\mu) = (5.1 \pm 0.2) \cdot 10^{-12}$ [Ecker and Pich, Nucl. Phys. B366 (1991) 189].

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

$K_s \to \mu\mu$: 1 fb^{-1} data at 7 TeV [JHEP 01 (2013) 090]

- Reconstruct di-muon pairs.
- Boosted Decision Tree to reject combinatorial and material interaction backgrounds.
- Control channel $K_S \to \pi\pi$ could be a dangerous bkg. It is well separated from the signal.

$K_S \to \pi\pi$ candidates



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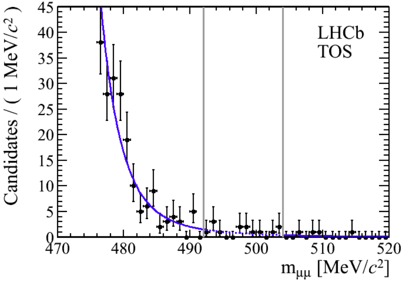
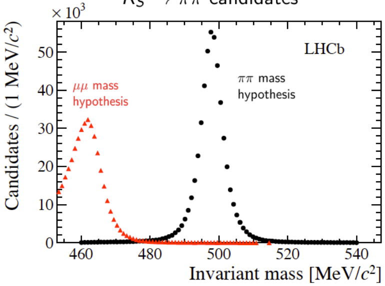


$K_S \to \pi\pi$ candidates



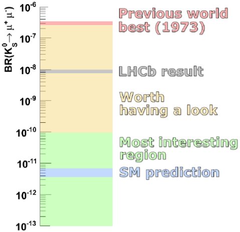
Results compatible with background only hypothesis. Set limit on BR:

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

30 times better than previous best!!

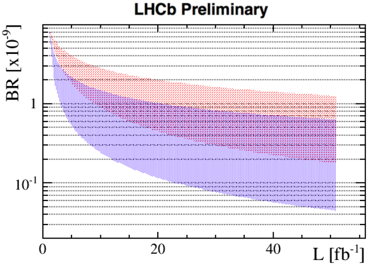
$K_s \rightarrow \mu\mu$ prospects

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



[X. Cid, *IV Jornadas CPAN*]

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



From last analysis

With trigger improvement

- Can go below 10^{-10} after the LHCb upgrade!
- Can have an extra gain using downstream tracks.

$K_S \to \pi^0\mu\mu$ 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]:
  $\mathrm{BF}(K_S \to \pi^0\mu\mu) = (2.9^{+1.5}_{-1.2} \pm 0.2) \cdot 10^{-9}$ $\sim$ 50% uncertainty!
- π^0 reconstruction is challenging. Different options studied with MC:

	BR	Efficiency	Advantage	Problems
$\pi^0 \to \gamma\gamma$	$\sim$ 99%	low	Most common	Combinatorial γ's
$\pi^0 \to ee\gamma$	$\sim$ 1%	very low	Allows vertexing	Too low efficiency
No π^0	-	high	Forget about π^0	Mass not peaking

- Most feasible is $\pi^0 \to \gamma\gamma$:
  - few events expected in 3 fb^{-1}.
  - may be observed after LS1 but surely after the upgrade.

$K_S \to 4\ell$ 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:
    $K_s \to eeee \quad \sim 10^{-10}$
    $K_s \to ee\mu\mu \quad \sim 10^{-11}$
    $K_s \to \mu\mu\mu\mu \quad \sim 10^{-14}$
- No experimental results so far ⇒ worth looking at it!

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$$\begin{array}{ll} K_s \to eeee & \sim 10^{-10} \\ K_s \to ee\mu\mu & \sim 10^{-11} \\ K_s \to \mu\mu\mu\mu & \sim 10^{-14} \end{array}$$

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

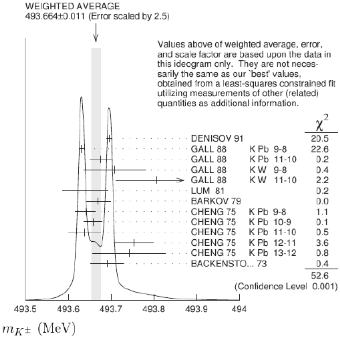
	Mass resolution	Single event sensitivity (3fb^{-1})
$K_s \to eeee$	~ 20 MeV	$\sim 10^{-6}$
$K_s \to ee\mu\mu$	~ 10 MeV	$\sim 10^{-7}$

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

K^+ mass prospects

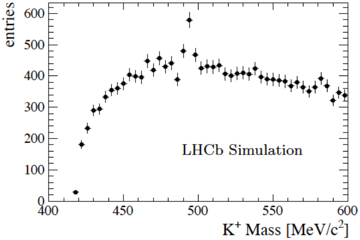
Disagreement between most precise K^+ mass measurements:

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



[J. Beringer et al. (PDG)]

LHCb approach:



- Use long tracks but also downstream. It cleans a lot matching to hits in the VELO from the K^+.

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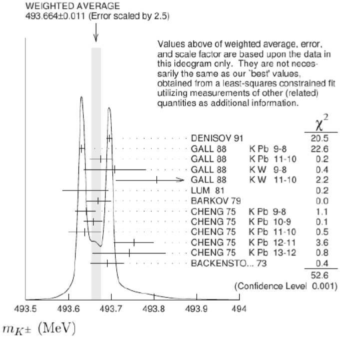
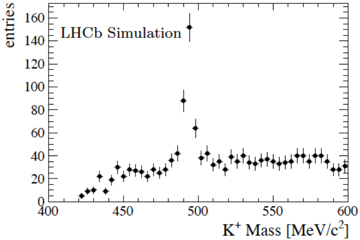


Values above of weighted average, error, and scale factor are based upon the data in this ideogram only. They are not necessarily the same as our 'best' values, obtained from a least-squares constrained fit utilizing measurements of other (related) quantities as additional information.

			χ^2
DENISOV 91			20.5
GALL 88	K Pb	9-8	22.6
GALL 88	K Pb	11-10	0.2
GALL 88	K W	9-8	0.4
GALL 88	K W	11-10	2.2
LUM 81			0.2
BARKOV 79			0.0
CHENG 75	K Pb	9-8	1.1
CHENG 75	K Pb	10-9	0.1
CHENG 75	K Pb	11-10	0.5
CHENG 75	K Pb	12-11	3.6
CHENG 75	K Pb	13-12	0.8
BACKENSTO... 73			0.4
			52.6
			(Confidence Level 0.001)

[J. Beringer et al. (PDG)]

LHCb approach:



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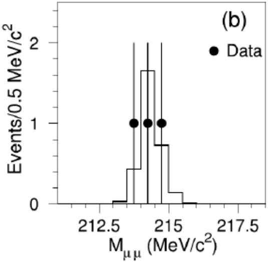
$\Sigma^+ \to p\mu\mu$ prospects

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??



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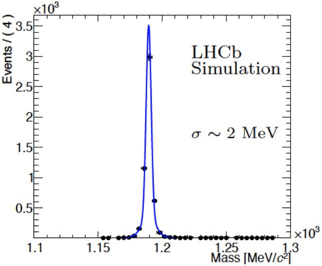

- Find evidence of the decay and study $m_{\mu\mu}$.
- Use long tracks but also downstream.
- MC studies: very good mass resolution.
- Single event sensitivity (3 fb^{-1}): $\sim 5 \cdot 10^{-9}$

Summary of rare strange prospects at LHCb

- LHCb is not designed for strange physics but can contribute a lot in this field.
- Published result: 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.

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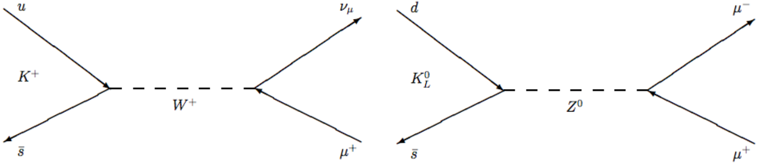
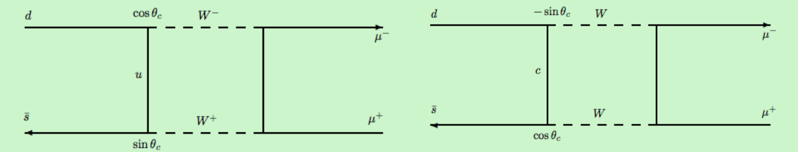
Stay tuned!!

THANK YOU!

BACK-UP

K^0 motivation for GIM mechanism and c quark

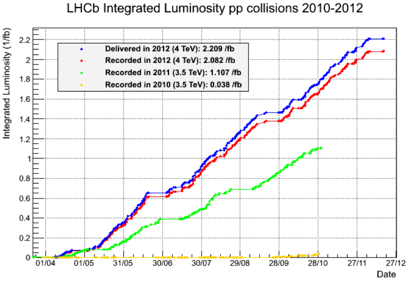


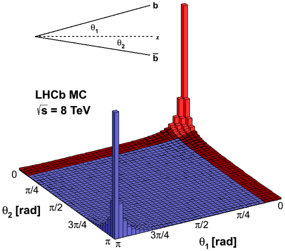


LHCb detector

Luminosity

- Low to ease secondary vertex reconstruction.
- Current data:
  - 2011: 1 fb^{-1} data.
  - 2012: 2 fb^{-1} data.

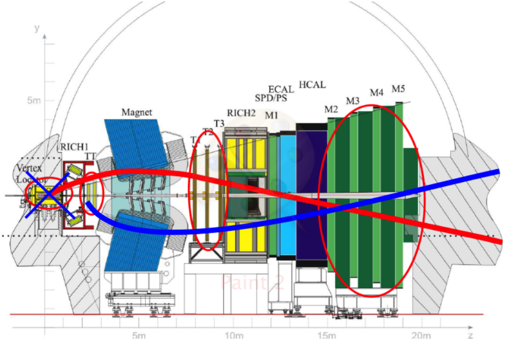




Detector shape

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

LHCb detector for strange decays

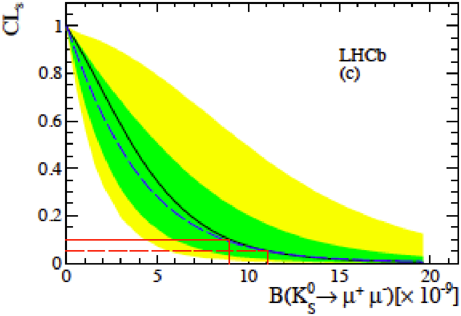


	m (MeV)	$< d >$ (m) at 100 GeV
B_d	5300	0.01
K_S	500	5
K_L	500	3000
$K^{\pm}$	490	600
$\Sigma^{\pm}$	1190	2

$K_s \to \mu\mu$ results

- No signal observed over background expectation.
- CLs method used to set a limit on the BR.

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



$K_S \to \pi^0\mu\mu$ 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 + π^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:

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

- ϵ^{accep} very similar for both channels.
- Assume $\epsilon^{sel|reco}$ and $\epsilon^{trig|sel}$ are the same.
- $\epsilon^{reco|accep}_e \approx 9\%$, $\epsilon^{reco|accep}_\mu \approx 20\%$ and $\epsilon^{reco|accep}_\pi \approx 6-9\%$.
- $\epsilon^{PID}_e \approx 50\%$ and $\epsilon^{PID}_\mu \approx 90\%$ (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}:

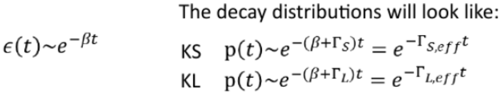
$$\alpha_{\Sigma^+\to p\pi^0(\to e^+e^-\gamma)}\text{: } \sim 5 \cdot 10^{-9}$$

$K_S \to \pi\pi\mu\mu$ 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:
  - 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 $\mathrm{p}(t) \sim e^{-(\beta+\Gamma_S)t} = e^{-\Gamma_{S,eff}t}$

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

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

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