Strange decays at LHCb

Carla Marin Benito

XLII International Meeting on Fundamental Physics

Benasque, January 2014

Outline

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

- Public 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^+
  - $\Sigma^+ \to p\mu\mu$

Not covered in this talk:

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

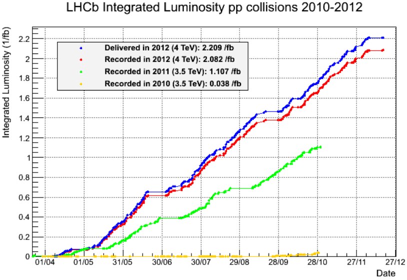
Motivation

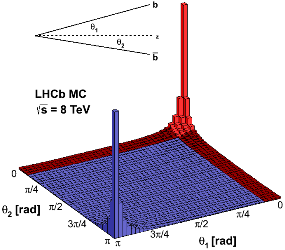
- Strange mesons have played a major role in the history of particle physics.
  - Long life of $K^0 \Rightarrow$ much better understanding of the weak interaction.
  - Charge-parity violation (CPV) first observed in a strange decay: $K_L \to \pi\pi$ [Brookhaven National Laboratory, 1964] It was completely unexpected at that moment!
- 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).
- Why strange?
  - Theoretically clean as few final states are allowed.
  - Relatively easy to produce.
  - Large CKM suppression ($V_{ts}V_{td} \sim 10^{-4}$)$\Rightarrow$ large sensitivity to NP.

LHCb detector

Luminosity

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



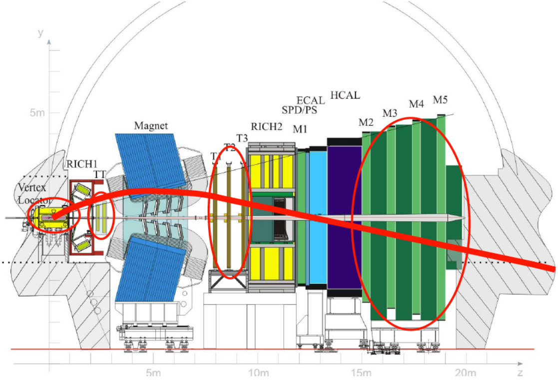


Detector shape

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

LHCb detector for strange decays

LHCb is not optimized for the study of strange mesons: lower m, larger τ.



	m (MeV)	$c\tau$ (cm)
B_d	5300	0.05
K_S	500	3
K_L	500	1500
$K^{\pm}$	490	400
Σ^{+}	1190	2

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

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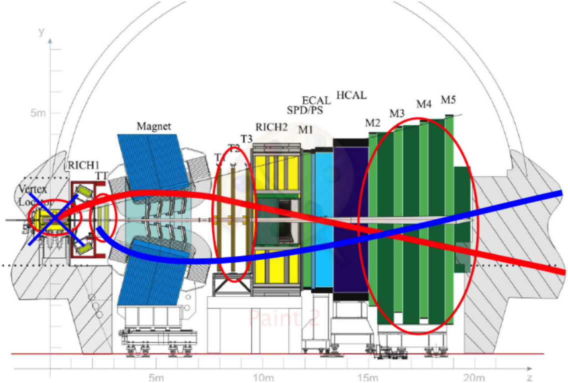

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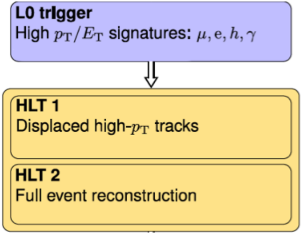
Long tracks(LL): $\sim 10^{13}\ K_s/fb^{-1}$ decay in LHCb acceptance.
Downstream (DD) tracks: more statistics but worse vertex and momentum resolution. VELO segment matching for charged mothers to improve it.

LHCb trigger for strange decays

Not designed to select strange decays ⇒ selected in the underlying event!

- They have larger τ and lower daugther's p_T.
- However, 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.
  - Current $m_{\mu\mu}$ range doesn't include m_{K_S}.
  - New line added in 2012⇒ x3 total efficiency ✓

- Only $\sim 1\%$ of the offline selected $K_S \to \mu\mu$ passed the whole trigger. The rest were selected in the underlying event.

- Run2: studying to include an exclusive di-μ line at Hlt1.

$K_S \to \mu\mu$

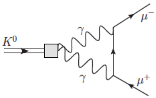
[JHEP 01 (2013) 090]

$K_s \to \mu\mu$ introduction

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

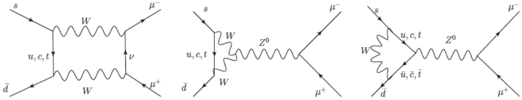
- 2 contributions to the amplitude:

Long-distance (LD)



Dominates $K_s \to \mu\mu$.

Short-distance (SD)

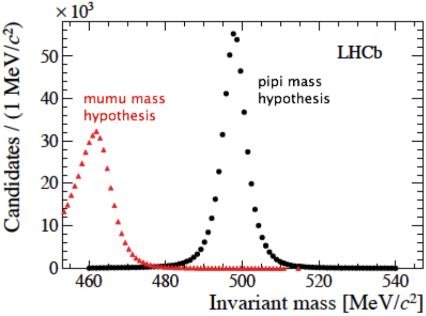


Dominates $K_L \to \mu\mu$.

- BR($K_L \to \mu\mu$)$= (6.84 \pm 0.11) \cdot 10^{-9}$ [J. Beringer et al. (PDG)], in agreement with SM.
- BR($K_S \to \mu\mu$) still can have NP contributions.
  - In SM: BR($K_S \to \mu\mu$) $= (5.1 \pm 0.2) \cdot 10^{-12}$ [Nucl.Phys.B366(1991)189].
  - Previous best measurement: BR($K_S \to \mu\mu$) $< 3.2 \cdot 10^{-7}$ in 1973!! [Phys.Lett. B 44 (1973) 217–220]

$K_s \to \mu\mu$ analysis: 1 fb^{-1} 2011 data at 7 TeV

- Reconstruct di-muon pairs.
- Boosted Decision Tree with geometrical and kinematical variables.
- Backgrounds: combinatorial and material interaction.
- Control channel: $K_S \to \pi\pi$, well separated from signal.

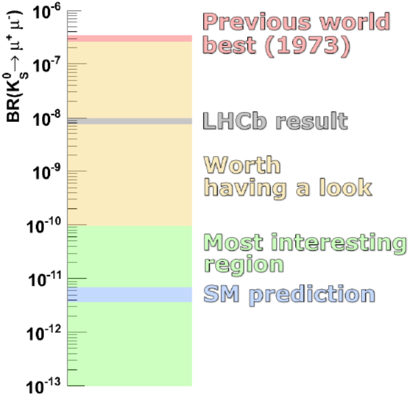


$K_s \to \mu\mu$ results with 1 fb^{-1} 2011 data

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

Previous best measurement: $\text{BR}(K_S \to \mu\mu) < 3.2 \cdot 10^{-7}$. 30 times better!!

- LHCb result greatly improves previous best measurement.
- Still 3 orders of magnitude to search for NP.
- Most interesting region is below 10^{-10}.
- Only 1/3 of the available data (1 fb^{-1}) has been analysed!

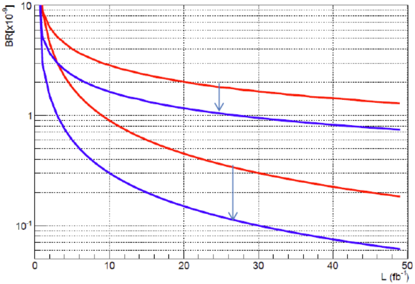


$K_s \to \mu\mu$ prospects

Main bottleneck for statistics is the trigger.

- Only $\sim 1\%$ of total efficiency in last analysis.
- Trigger already improved to $\sim 3\%$ efficiency. ✓
- Still much room for improvement.

Expected range sensitivity from last analysis and trigger improvement:



✓ Can go below 10^{-10} with the LHCb upgrade!

✓ Optimistically, extra gain $\sim 15\%$ using DD tracks.

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

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

- $K_L \to \pi^0 \mu\mu$ is a hot channel in Kaon physics as it is sensitive to NP.
- CP violating amplitude that enters BR($K_L \to \pi^0 \mu\mu$) could be constrained from $K_S \to \pi^0 \mu\mu$.
- Previous measurement from NA48 [Phys. Lett. B 599: 197-211, 2004]:
  BF($K_S \to \pi^0 \mu\mu$) $= (2.9^{+1.5}_{-1.2} \pm 0.2) \cdot 10^{-9}$ $\sim$ 50% uncertainty!
- Could LHCb improve this result?
  - LHCb is not designed for K_s decays.
  - π^0 makes it more challenging due to difficult reconstruction.

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

- Different options to reconstruct π^0 studied with MC:

	BR	Efficiency	Advantadge	Problems
$\pi^0 \to \gamma\gamma$	$\sim 99\%$	low	Most common	Combinatorial γ's
$\pi^0 \to ee$	$\ll 1\%$	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 or after the upgrade.
- Backgrounds:
  - Combinatorial, $K_S \to \pi\pi$ and $K_S \to \pi\mu\nu$.
  - Selection should be tightened to fight them.
  - This could diminish the signal efficiency.

$K_s \rightarrow 4\ell$ prospects

$K_S \to 4\ell$ prospects

- Growing interest after publication of $K_s \to \mu\mu$ paper.
- Recent publication of SM and NP contributions to $K_{L,S} \to 4\ell$. [arXiv:1309.5736v3]
  - BR in SM can reach: $K_s \to eeee \quad \sim 10^{-10}$
    $K_s \to ee\mu\mu \quad \sim 10^{-11}$
    $K_s \to \mu\mu\mu\mu \quad \sim 10^{-14}$
- No experimental results so far.

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- LHCb prospects for $K_S \to 4\ell$ with electrons:
  - challenging due to e's reconstruction.
  - From MC studies:

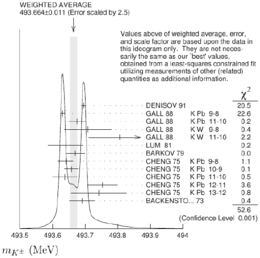
	Mass peak displacement	Mass resolution	$K_S \to \pi\pi ee$ separation	Expected BR limit
$K_s \to eeee$	$\sim$ 30 MeV	$\sim$ 20 MeV	$\sim$ 300 MeV	$\sim 10^{-6}$
$K_s \to ee\mu\mu$	$\sim$ 10 MeV	$\sim$ 10 MeV	$\sim$ 70 MeV	$\sim 10^{-7}$

K^+ prospects

K^+ prospects

- NA48 results [Phys. Lett. B 697 (2011) 107-115]:
  - 3k $K^+ \to \pi\mu\mu$ and 10^9k $K^+ \to \pi\pi\pi$ (for normalization) observed.
  - $\text{BR}(K^+ \to \pi\mu\mu) = (9.4 \pm 0.6) \cdot 10^{-8}$.
  - Also search for lepton-flavor violation with same sign μ.

- Disagreement between most precise K^+ mass measurements:
  - $K^+ \to \pi\pi\pi$ could give a competitive result

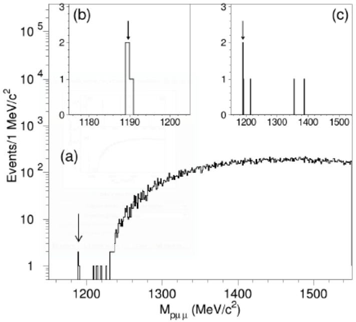


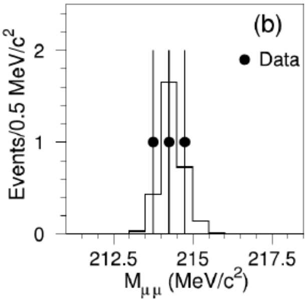
- LHCb approach:
  - Focus on $K^+ \to \pi\pi\pi$.
  - Use long tracks but also downstream with VELO matching.
  - 2011 data (1 fb^{-1}): $\sim$ 2k of $K^+ \to \pi\pi\pi$.

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

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

- HyperCP results [PRL 94 021801]:
  - 3 signal events observed with 0 background.
  - $BR(\Sigma^+ \to p\mu\mu) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$.
  - All 3 events have $m_{\mu\mu} \sim 214$ MeV $\Rightarrow$ possible new X^0 state!! $\Rightarrow$ $\Sigma^+ \to pX^0(\to \mu\mu)$.



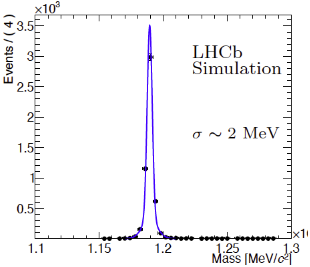


$\Sigma^+ \to p\mu\mu$ prospects

- LHCb approach:
  - Purpose: find evidence of the decay and study $m_{\mu\mu}$.
  - Forward production of many Σ at LHCb ($\sim 40\%$ events contain one).
  - Normalization channel: $\Sigma^+ \to p\pi^0(\to ee\gamma)$.
  - Use LL tracks but also DD with VELO matching.

- Preliminary results:

  - MC studies: very good mass resolution: $\sigma \sim 2$ MeV.
  - Full data (3 fb^{-1}): $\sim$ 45k of $\Sigma^+ \to p\pi^0(\to ee\gamma)$.
  - Expected BR limit: $\sim 5 \cdot 10^{-9}$.



Summary

Summary of rare strange prospects at LHCb

- LHCb is not designed for strange physics but can provide very competitive results.
- Public result: BR($K_S \to \mu\mu$) $< 9.0 \cdot 10^{-9}$, 30 times better than previous world best.
- Strange physics rising interest. Many prospects at LHCb:
  - $K_S \to \mu\mu$ update with 3 fb^{-1}.
  - $K_S \to \pi^0\mu\mu$: feasible after LS1 or upgrade.
  - $K_S \to 4\ell$: BR limit $\sim 10^{-7}$ (10^{-6}) for $K_S \to ee\mu\mu$ ($K_S \to eeee$).
  - K^+ decays: few in LHCb acceptance but worth to look at.
  - $\Sigma^+ \to p\mu\mu$: BR limit $\sim 5 \cdot 10^{-9}$.

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Stay tuned!!

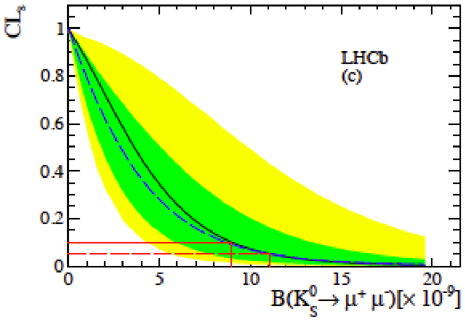
BACK-UP

LHCb Trigger for strange decays

- L0: high p_T signatures.
  - Only $\sim 16\%$ of μ in offline selected $K_S \to \mu\mu$ were responsible to fire the L0 trigger ($\sim 90\%$ for B decays).
- Hlt1: adds tracking and vertexing.
  - Only $\sim 20\%$ of L0 selected $K_S \to \mu\mu$ decays were responsible to fire the Hlt1 trigger ($> 40\%$ for other decays).
- Hlt2: performs full event reconstruction.
  - Current $m_{\mu\mu}$ range don't include m_{K_S}.
  - New line added in 2012 $\Rightarrow$ x3 total efficiency. ✓

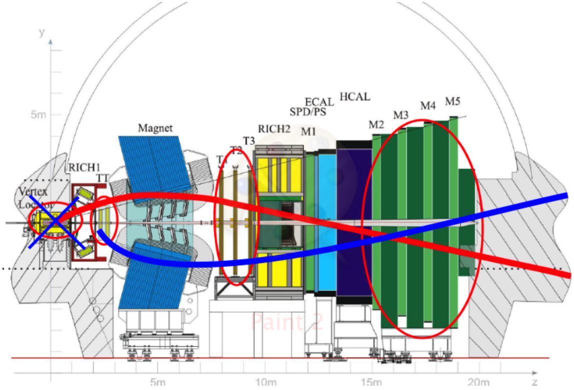
- No signal observed over background expectation.
- CLs method used to set a limit on the BR.

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



$K_s \to \mu\mu$ prospects

Long (LL) vs downstream (DD) tracks at LHCb.

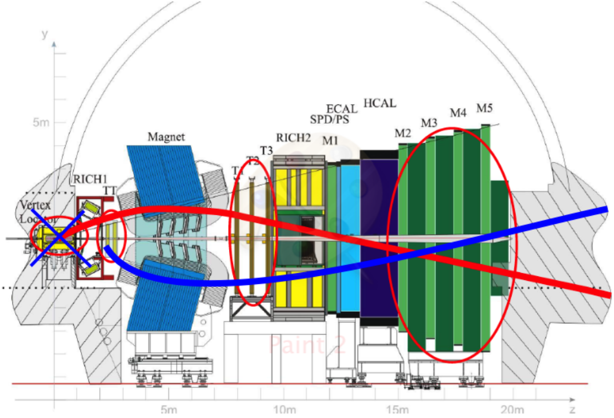


- Using DD tracks could improve statistics a lot (only LL in last paper).
- But DD tracks have worse momentum and vertex resolution.
- Optimistically, effective extra gain $\sim 15\%$ using DD tracks.

$K_S \to \pi\pi\mu\mu$ 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 uncertainity.
- SM prediction:
  - $\mathrm{BR}(K_S \to \pi\pi\mu\mu) = 4 \cdot 10^{-14}$.
  - Good probe for NP.
- Starting preliminar studies at LHCb.

K^+ prospects



- LL (DD) tracks are tipically reconstructed in the region $0 < z < 40$ cm ($40 < z < 250$ cm)
- K^+ with $p \sim 10$ GeV$/c$ decay in average at ~ 70 m.
- Use DD tracks with VELO segment matching. ✓

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.