A strange program for the LHC

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GAIN
(on behalf of the LHCb Collaboration)
Introduction

• LHCb experiment at LHC
  • Designed mostly for $b$ and $c$ decays → low trigger efficiency otherwise
  • But there is also an ~infinite strangeness production at LHC (kaon $\times s \sim 1.2$ barn)
  • Infinite production times zero efficiency requires L’Hopital
    • In 2011 we managed to get world best result in $K_S \rightarrow \mu\mu$
  • Major improvements in the trigger for $s$ decays done for Run-II (2016-2018), and ongoing for Upgrade ($\geq 2021$)
Strangeness decays

- So far kaons provided showed great success on indirect searches: c, b, t, CKM …

- High theoretical interest, most notably to test departures from MFV paradigm (eg, flavor generic)

- Useful to understand “Hints” for BSM in b sector
  - Eg: deviations in $b \rightarrow s \mu \mu$: are they replicated in $s \rightarrow d \mu \mu$?

- Potentially immense samples: high(est) ultimate experimental precision

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} O_{\Delta F=2} \]

From G. Isidori KAON’16
For details see
G. Isidori, Y. Nir, G. Perez
arXiv:1002.0900v2
Trigger system: status and prospects

- **L0 (Hardware)**
  - Main bottleneck for K. Can’t be changed

- **HLT1 (Software)**
  - Not designed for K, but flexible.

- **HLT2 (Software)**
  - K triggers being implemented
Trigger system: status and prospects

- **L0 (Hardware)**: Main bottleneck for K. Can’t be changed.
- **HLT1 (Software)**: Not designed for K, but flexible.
- **HLT2 (Software)**: K triggers being implemented.

\[\varepsilon(2011-2012) \approx 1-2\%\]
\[\varepsilon(\text{Run-II}) \text{ improved HLT1,2} \approx 18\%\]
Maximum possible \~30\% (L0 won’t allow more)
Trigger system: status and prospects

- **L0** (Hardware)
- **HLT1** (Software)
- **HLT2** (Software)

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- **HLT1**: Software (K triggers being implemented)
- **HLT2**: Software

ε(2011-2012) ~ 1-2%
ε(Run-II) improved HLT1,2 ~ 18%
Maximum possible ~30% (L0 won’t allow more)

ε(Upgrade) ~ 80-100%?
Simulation studies show that rate would be under control
V. Chobanova et al, CERN-LHCb-PUB-2016-017
$K_S \rightarrow \mu\mu$ full Run-I analysis
EPJC, 77 10 (2017) 678
**K_S \rightarrow \mu\mu: motivation**

- **SM prediction:** \( \text{BR}(K_S \rightarrow \mu\mu) = (5.18 \pm 1.50_{\text{LD}} \pm 0.02_{\text{SD}}) \times 10^{-12} \)
  

- **K_S \rightarrow \mu\mu** sensitive to different physics than \( K_L \rightarrow \mu\mu \), NP can be bigger than SM by \( \sim 1 \) order of magnitude or even more

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**Example of a SUSY scenario from**

V.Chobanova et al., JHEP05(2018) 024

**Leptoquark scenarios from Bobeth & Buras,**

JHEP02(2018)101
KS→μμ full Run-I analysis

- Event yield extracted from a maximum likelihood fit in BDT categories
- Yield translated to BR via normalization to KS→ππ decays
- KS→ππ is also the main background: muon identification BDT trained against it
- Upper limit obtained integrating the posterior probability, combined 2011+2012
**K_s → μμ prospects**

- Extrapolating from Run-I result
- Full Run-II analysis ongoing: expected to improve by a factor 3 to 10 Run-I’s sensitivity
- Future: start to investigate tagged decays, which would allow to access NP in the K_s-K_L interference

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**Very high ultimate precision:** could well become the strongest limit on a BR by an LHC experiment
Σ→μμμ full Run-I analysis

LHCb-PAPER-2017-049
The HyperCP evidence

- The HyperCP collaboration found evidence for $\Sigma \rightarrow p \mu^+ \mu^-$ decays, and provided a BR:

$$B(\Sigma^+ \rightarrow p \mu^+ \mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$$


- Consistent w/ SM: $1.6 < BR[x10^{-8}] < 9$

  X G He et al, PRD 72 (2005) 074003

- This evidence had wide relevance since all 3 observed events had the same dimuon invariant mass (214 MeV)

- Suggested the existence of a new neutral particle at that mass
$\Sigma \rightarrow \rho \mu \mu$ full Run-I analysis

- $\Sigma \rightarrow \rho \mu \mu$ : Found 4$\sigma$ evidence
- BR($\Sigma \rightarrow \rho \mu \mu$) : $2.1^{+1.6}_{-1.2} \times 10^{-8}$

- $X \rightarrow \mu \mu$ : Found no evidence for the 214 MeV particle. Upper limit for the resonant channel: $1.2 \times 10^{-8}$ @95% CL

10y ago we thought this channel was ~impossible and instead now we are even thinking on an amplitude analysis....
$K_S \rightarrow \pi^0 \mu \mu$ sensitivity study

CERN-LHCB-PUB-2016-017
**K_S → π^0 μμ sensitivity study**

- **K_S → π^0 μμ** is searched for in two channels:
  - π^0 (→ γγ) μμ: hereafter FULL (low eff.)
  - π^0 μμ: hereafter PARTIAL

In order to reconstruct the kaon mass for PARTIAL:

- π^0 mass → PDG
- \( p_T^{\pi} = -p_T^{\mu\mu} \)

The only unknown is \( p_L^{\pi} \).
But statistically is ≈10GeV

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Much more bkg than Ks→μμ, but also 1000x more signal
$K_S \rightarrow \pi^0 \mu\mu$ sensitivity study

Normalize yields to $K_S \rightarrow \pi\pi \rightarrow$ sensitivity to BR

2015 Data, 0.77 pb$^{-1}$

2015 Data, 0.77 pb$^{-1}$

BDT ∈ (0.9, 1)

$\sigma_{\text{STAT}} [10^{-9}]$

$\epsilon_{\text{TRIG}} [\text{fb}^{-1}]$

$\mu^0_{\pi\mu\mu}$ (MeV/c$^2$)

Candidates / (8 MeV/c$^2$)

Much more bkg than $K_S \rightarrow \mu\mu$, but also 1000x more signal

LHCb-upgrade

Phase-II-upgrade?
Ongoing/future studies

• Semileptonic Hyperon Decays (SHD)

Very interesting in view of LUV hints in semileptonic B decays

Many muonic modes have still very poor precision (20%, 100%)

• ☺ High BR ($10^{-4}$): Massive yields in LHCb acceptance

• ☹ Challenging peaking backgrounds:

For each $B_1 \rightarrow B_2 \mu \nu$ there is always a $B_1 \rightarrow B_2 \pi$ (inc. $\rightarrow B_2 \mu \nu$)

☺ Can be separated in search planes
Ongoing/future studies

- Semileptonic Hyperon Decays (SHD)
- LFV

LHCb can do:

\( K_S \rightarrow e\mu \)
\( K^+ \rightarrow \pi^+\mu^-e^+ \)
Maybe \( K^+ \rightarrow \pi^+\mu^+e^- \)

Competition w/ NA62 to be clarified
Ongoing/future studies

• Semileptonic Hyperon Decays (SHD)

• LFV

• Tagged kaons

• $K^+$ mass in $K \rightarrow 3\pi$ (ongoing) (Also under study sensitz. $K^+ \rightarrow \pi^+\mu\mu$ vs NA62)

• $K_S \rightarrow \chi^0\mu\mu$, ($\chi$ whatever neutral system: eg $\gamma$) (ongoing)
Ongoing/future studies

• Semileptonic Hyperon Decays (SHD)

• LFV

• Tagged kaons

• $K^+$ mass in $K \rightarrow 3\pi$

• $K_S \rightarrow X^0\mu\mu$, ($X$ whatever neutral system: eg $\gamma$)

• $K_S \rightarrow X^0\pi\mu$ ($X$ whatever neutral system: eg sterile neutrino)

• $\Delta S = 2$

• Workshop in 2013 and 2017 to discuss with TH community
  
  [Link to event 2013](https://indico.cern.ch/event/280883/overview)
  [Link to event 2017](https://indico.cern.ch/event/590880/timetable/#20170426)
Ongoing/future studies


<table>
<thead>
<tr>
<th>Channel</th>
<th>Xs/Xs(K_S)</th>
<th>eff/eff(K_S)</th>
<th>eff/eff(K_S)</th>
<th>Mass resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>w/ Downstream tracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^0_S \to \mu^+\mu^-$</td>
<td>1</td>
<td>1.0 (1.0)</td>
<td>1.8 (1.8)</td>
<td>$\sim 3.0$</td>
</tr>
<tr>
<td>$K^0 \to \pi^+\pi^-$</td>
<td>1</td>
<td>1.1 (0.30)</td>
<td>1.9 (0.91)</td>
<td>$\sim 2.5$</td>
</tr>
<tr>
<td>$K^0 \to \pi^0\mu^+\mu^-$</td>
<td>1</td>
<td>0.93 (0.93)</td>
<td>1.5 (1.5)</td>
<td>$\sim 35$</td>
</tr>
<tr>
<td>$K^0 \to \gamma\mu^+\mu^-$</td>
<td>1</td>
<td>0.85 (0.85)</td>
<td>1.4 (1.4)</td>
<td>$\sim 60$</td>
</tr>
<tr>
<td>$K^0 \to \mu^+\mu^-\mu^+\mu^-$</td>
<td>1</td>
<td>0.37 (0.37)</td>
<td>1.1 (1.1)</td>
<td>$\sim 1.0$</td>
</tr>
<tr>
<td>$K^0_L \to \mu^+\mu^-$</td>
<td>$\sim 1$</td>
<td>2.7 (2.7) $\times 10^{-3}$</td>
<td>0.014 (0.014)</td>
<td>$\sim 3.0$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\pi^+\pi^-$</td>
<td>$\sim 2$</td>
<td>9.0 (0.75) $\times 10^{-3}$</td>
<td>41 (8.6) $\times 10^{-3}$</td>
<td>$\sim 1.0$</td>
</tr>
<tr>
<td>$K^+ \to \pi^+\mu^+\mu^-$</td>
<td>$\sim 2$</td>
<td>6.3 (2.3) $\times 10^{-3}$</td>
<td>0.030 (0.014)</td>
<td>$\sim 1.5$</td>
</tr>
<tr>
<td>$\Sigma^+ \to p\mu^+\mu^-$</td>
<td>$\sim 0.13$</td>
<td>0.28 (0.28)</td>
<td>0.64 (0.64)</td>
<td>$\sim 1.0$</td>
</tr>
<tr>
<td>$\Lambda \to p\pi^-$</td>
<td>$\sim 0.45$</td>
<td>0.41 (0.075)</td>
<td>1.3 (0.39)</td>
<td>$\sim 1.5$</td>
</tr>
<tr>
<td>$\Lambda \to p\mu^-\bar{\nu}_\mu$</td>
<td>$\sim 0.45$</td>
<td>0.32 (0.31)</td>
<td>0.88 (0.86)</td>
<td>--</td>
</tr>
<tr>
<td>$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$</td>
<td>$\sim 0.04$</td>
<td>39 (5.7) $\times 10^{-3}$</td>
<td>0.27 (0.09)</td>
<td>--</td>
</tr>
<tr>
<td>$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$</td>
<td>$\sim 0.03$</td>
<td>24 (4.9) $\times 10^{-3}$</td>
<td>0.21 (0.068)</td>
<td>--</td>
</tr>
<tr>
<td>$\Xi^- \to p\pi^-\pi^-$</td>
<td>$\sim 0.03$</td>
<td>0.41 (0.05)</td>
<td>0.94 (0.20)</td>
<td>$\sim 3.0$</td>
</tr>
<tr>
<td>$\Xi^0 \to p\pi^-$</td>
<td>$\sim 0.03$</td>
<td>1.0 (0.48)</td>
<td>2.0 (1.3)</td>
<td>$\sim 5.0$</td>
</tr>
<tr>
<td>$\Omega^- \to \Lambda\pi^-$</td>
<td>$\sim 0.001$</td>
<td>95 (6.7) $\times 10^{-3}$</td>
<td>0.32 (0.10)</td>
<td>$\sim 7.0$</td>
</tr>
</tbody>
</table>
Conclusions

• s decays are awesome
  • High interest for BSM
  • Ultimate experimental precision \(\sim 10^{-11}-10^{-12}\)

• There is an LHCs community in the LHCb village
  • Trigger is constantly improving
  • We aim for LHCb upgrade to reach efficiencies s as high as for b’s

• Available measurements for: \(\Sigma \rightarrow \rho \mu \mu\), \(\text{BR}(K_S \rightarrow \mu \mu)\)

• Published prospects for \(K_S \rightarrow \pi^0 \mu \mu\), \(K_S \rightarrow \pi^+ \pi^- e e\)

• Run-II (2016-2018) data analysis ongoing \(\Sigma \rightarrow \rho \mu \mu\), \(K_S \rightarrow \mu \mu\), \(K_S \rightarrow (\gamma/\pi^0) \mu \mu\)...

• Some more channels in our TODO list

• Workshops to discuss with the TH community
Backup
The sensitivity study of $K_S \rightarrow \pi^+\pi^-ee$ is discussed, based on simulation.

Expected a signal yield of

$$N = 120^{+280}_{-100}$$

For the full Run-I dataset.

Expected background yield is not well known yet.
Toy MC for $50 \text{fb}^{-1}$

- **BDT $\in (0.6, 0.7)$**
  - Simulated

- **BDT $\in (0.7, 0.8)$**
  - Simulated

- **BDT $\in (0.8, 0.9)$**
  - Simulated

- **BDT $\in (0.8, 0.9)$**
  - Simulated
**Lifetime acceptance and \( K_L \rightarrow \mu\mu \) background**

\( K_L \) and \( K_S \) are distinguishable only by the decaytime...

... and that is in theory. In practice, LHCb decaytime acceptance is not great for kaons

\[
\epsilon(t) \sim e^{-\beta t} \quad \text{With } \beta \gtrsim 5 \times \Gamma_s (\gg \Gamma_L).
\]

This makes the two lifetime distributions to look similar

But the overall efficiency ratio is of course different

\[
\frac{\epsilon_{K_L^0 \rightarrow \mu^+\mu^-}}{\epsilon_{K_S^0 \rightarrow \mu^-\mu^+}} = \frac{\int_0^\infty \text{Acc}(t) e^{-\Gamma_L t} dt}{\int_0^\infty \int_0^\infty e^{-\Gamma_L t} dt} = \text{O}(10^{-3})
\]

And makes \( K_L \rightarrow \mu\mu \) to become a negligible background for the current level of precision

But can be relevant when we approach the \( 10^{-11} \) level
LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^+$
- 400 kHz $\mu/\mu\mu$
- 150 kHz $e/\gamma$

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- Buffer events to disk, perform online detector calibration and alignment
- Add offline precision particle identification and track quality information to selections
- Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage
Normalization of event yield

Converting a signal yield into a branching ratio

\[ N(K_S^0 \rightarrow \pi\mu\mu) = \sigma(K_S^0)BR(K_S^0 \rightarrow \pi\mu\mu)\epsilon L \]

- \( K_S^0 \) production crosssection
- Absolute efficiency
- Integrated luminosity
How? (normalization of event yield)

Converting a signal yield into a branching ratio

\[ N(K_s^0 \rightarrow \pi\mu\mu) = \sigma(K_s^0) BR(K_s^0 \rightarrow \pi\mu\mu) \epsilon_L \]

\[ \frac{N(K_s^0 \rightarrow \pi\mu\mu)}{N(K_s^0 \rightarrow \pi\pi)} = \frac{\sigma(K_s^0) BR(K_s^0 \rightarrow \pi\mu\mu) \epsilon_L}{\sigma(K_s^0) BR(K_s^0 \rightarrow \pi\pi) \epsilon'_L} \]

Introduce in the ntuples a \( K_s^0 \rightarrow \pi\pi \) decays counter

Very well known (69.20±0.05)\%
Dilepton mass distribution

Take formulae from hep-ph/9808289

\[
\frac{d\Gamma}{dz} = \frac{\alpha^2 M_K}{12\pi (4\pi)^4} \lambda^{3/2}(1, z, r_\pi^2) \sqrt{1 - 4 \frac{r_\ell^2}{z}} \left(1 + 2 \frac{r_\ell^2}{z}\right) |W(z)|^2, \tag{3}
\]

\(z = m^2 \Rightarrow d\Gamma/dm = 2m \, d\Gamma/dz\)

\[
W_i(z) = G_F M_K^2 (a_i + b_i z) + W_i^{\pi\pi}(z), \tag{11}
\]

\[
W_i^{\pi\pi}(z) = \frac{1}{r_\pi^2} \left[\alpha_i + \beta_i \frac{z - z_0}{r_\pi^2}\right] F(z) \chi(z),
\]
Remind of Bmm sensitivity
B mesons

We check that we get right the expected increase of B meson yields (i.e., a factor ~2)
D mesons

For D mesons the increase is slightly smaller (~1.6 - 1.7)
Strange particles

Increase for most of them is ~40%

A bit less for baryons (note: baryons, not anti-baryons)

However, the momentum is also different w.r.t 7 TeV.

In particular, for the K0s decaying in the VELO the increase is “only” ~30% →
This is the number we really care for Ks → μμ studies
Leptons

Increase in tau yield consistent with ~ 2, expected by the fact that most of them come from b’s and c’s

Check with more stats if the asymmetry +/- is still there
→ the long-distance (LD) contributions:

→ the short-distance (SD) contributions:
$K_S \rightarrow \pi^0 \mu \mu$ sensitivity study

The background discrimination

- As usual: BDT trained against combinatorial background
- Specific backgrounds: $K_S \rightarrow \pi \pi$, $K_L \rightarrow \pi \pi \pi$, $K_{S/L} \rightarrow \mu \gamma \gamma$ (negligible)

Don’t affect the sensitivity estimate
$K_S \rightarrow \pi^0 \mu \mu$ sensitivity study

Fit, FULL

V. Chobanova et al,
CERN-LHCb-PUB-2016-017
$K_S \rightarrow \pi^0 \mu\mu$ sensitivity study

Fit, PARTIAL

V. Chobanova et al, CERN-LHCb-PUB-2016-017
Strangeness production/detection at LHCb

- The pp collisions @ LHC produce a ‘kaon flux’ of $10^{13} K_S$ per fb$^{-1}$ of luminosity in the LHCb acceptance.

- Charged decay products can be reconstructed using Long Tracks or Downstream Tracks.

- We use Long Tracks for RnS.

- Downstream will be investigated (extra yield, but worse reconstruction quality).

$K_L, K_S$ produced in equal amounts. Acceptance ratio is $\sim 2 \times 10^{-3}$ (for Long Tracks).
Ongoing stuff

\[ BR(K_S \rightarrow X^0 \mu\mu) \]

\( X \)

\( Y \)

\( \pi^0 \)

\( m_X \)

LHCb Fictitious

90% CL exclusion
**K^+ studies**

Large samples of charged kaon decays are available

K^+ mass is not very well known

K^+ → πμμ ?
$K_S \rightarrow X^0 \mu\mu$

- The $K_S \rightarrow \pi^0 \mu\mu$ PARTIAL analysis can be recasted for general/inclusive $K_S \rightarrow X^0 \mu\mu$. With $X$ being whatever neutral system:
  - $K_S \rightarrow \gamma \mu\mu$. Can also be completed with photon reconstruction
  - $K_S \rightarrow (l+l-)\mu\mu$. Some of them are also being searched for explicitly

Limits can be provided as a function of $X^0$ mass

![Graph showing BR($K_S \rightarrow X^0 \mu\mu$) as a function of $m_X$. There is a 90% CL exclusion region.](image)
B and L violation (very low priority)

**CLAS collaboration (Jefferson Lab):**
Limits on B and L violation

We can easily do many of CLAS’ decays

...as well as others:

- $\Sigma \rightarrow 3\mu$
- $\Lambda \rightarrow \pi 3\mu$

...and many other crazy (J conserving) combinations.

Currently very low priority, since we assume that BSM contributions can only be as much as BR $\sim 10^{-56}$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$B_{UL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda \rightarrow K^+ e^-$</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow K^+ \mu^-$</td>
<td>$3 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow K^- e^+$</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow K^- \mu^+$</td>
<td>$3 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow \pi^+ e^-$</td>
<td>$6 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow \pi^+ \mu^-$</td>
<td>$6 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow \pi^- e^+$</td>
<td>$4 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow \pi^- \mu^+$</td>
<td>$6 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow \bar{p} \pi^+$</td>
<td>$9 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\Lambda \rightarrow K^0 \nu$</td>
<td>$2 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

**K_S→μμ full Run-I analysis**

- Analysed full Run-I (2011-2012) data
- Events classified using a BDT trained against combinatorial background
- Dedicated muon identification algorithm trained against K_S→ππ
- Mass resolution 4 MeV

### Background

K_L→μμ negligible: (down to 10^{-11} precision)

K→πμν : negligible

Λ→ππ removed by a cut in the Armenteros-Podolanski plot.

- **Combinatorial background**
- **K_S→ππ double misid**
Based on simulation:

Expected a signal yield of

\[ N = 120^{+280}_{-100} \]

For the full Run-I dataset

Expected background yield is not well known yet
Dominant uncertainty, that makes difficult potential BSM interpretation of $K_L \rightarrow \pi^0\mu\mu$

It comes from the experimental uncertainty on $\text{BR}(K_S \rightarrow \pi^0\mu\mu)$ measured by NA48

$K^0_S \rightarrow \pi^0\mu^+\mu^-$ NA48

$\approx 50\%$ relative error

Improved measurements of $\text{BR}(K_S \rightarrow \pi^0\mu\mu)$ will translate into improved BSM constraints from $K_L \rightarrow \pi^0\mu\mu$