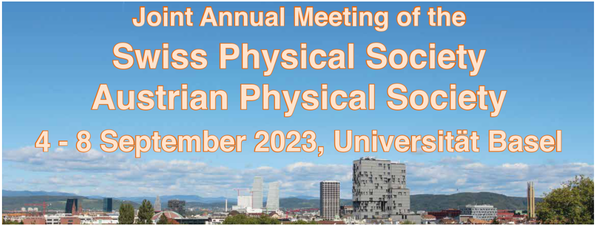
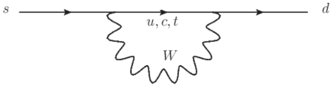
Search for the $K^0_S \to \pi^+\pi^-\mu^+\mu^-$ decay using the LHCb Run II data

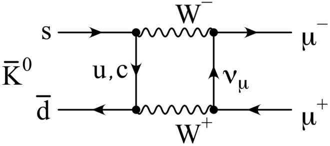
Luis Miguel Garcia Martin



Introduction: Why Kaons?

- The $s \to d$ process is forbidden at tree level in the SM (suppressed)





- Some exotic BSM scenarios can enhance it by 2 orders of magnitude [arXiV:2201.07805]

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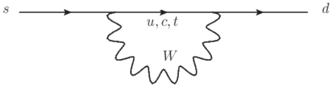
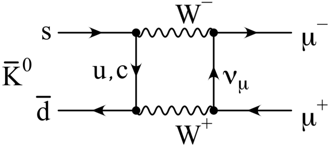


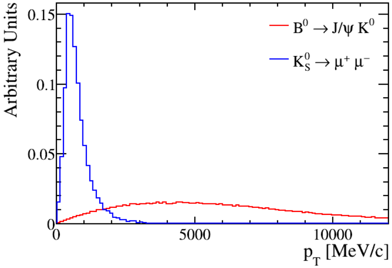


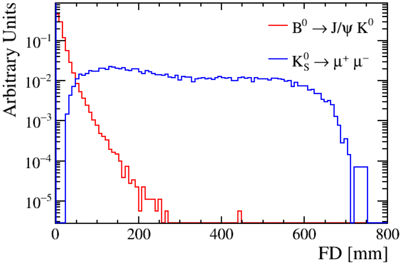
- Some exotic BSM scenarios can enhance it by 2 orders of magnitude [arXiV:2201.07805]
- LHCb already provided some world best measurements/limits:
  - $\mathcal{B}(K^0_{\mathrm{S}} \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ @ 90% CL [PRL125(2020)231801]
  - $\mathcal{B}(K^0_{\mathrm{S(L)}} \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12} (2.3 \times 10^{-9})$ @ 90% CL [PRD108(2023)L031102]
    - **First LHCb result with K^0_{L}**
  - $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = 2.2^{+1.8}_{-1.3} \times 10^{-8}$ (4.1σ) [PRL120(2018)221803]

Challenges: Transverse momentum

Transverse momentum standard handle for signal-bkg separation at LHCb

- Not usable for *s* decays due to their low energy
- Compensated requiring large flight distance
- B-physics: $p_{\mathrm{T}} \sim$ 1-2 GeV/c, FD $\sim$ 1-2 cm
- *s*-physics: $p_{\mathrm{T}} \sim$ 0.08 GeV/c, FD $\sim \mathcal{O}(70)$ cm

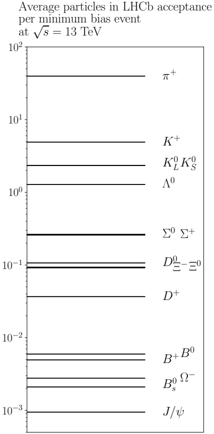




Challenges: Trigger

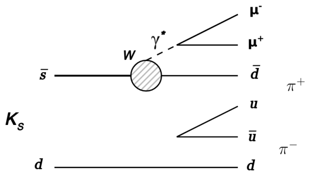
Designed mostly for b and c decays (very low efficiency otherwise)

- Muon (hadron) L0 trigger
  $p_{\mathrm{T}} > 1\,\mathrm{GeV}/c$ (hardware)
- Hlt1 and Hlt2 are software and customizable
- L0 removed for Upgrade (2022 -)
- Huge strangeness production
  - Also from b and c decays
  - About 1 strange hadron per event ($\sim 10^{-3}$ B_s^0)



Motivation

- Very suppressed FCNC in the SM
  - $\mathcal{B}(K^0_S \to \pi^+\pi^-\mu^-\mu^+) = 4.69 \times 10^{-14}$ [arXiv:1712.10270]
  - Possible enhancements from BSM
  - Little PHSP: $m(K^0_S) - 2m(\pi) - 2m(\mu) = 7.1\,\text{MeV}/c^2$
    - Extra suppression
    - Colinear decay products
- No measurements yet
- Could give some insights on $K^0_S \to \pi^+\pi^-\gamma^*$
- In collaboration with analysts from $K^0_S \to \mu^+\mu^-\mu^+\mu^-$ [PRD108L031102]
  - Same topology (can benefit from expertise and framework)



Selection strategy

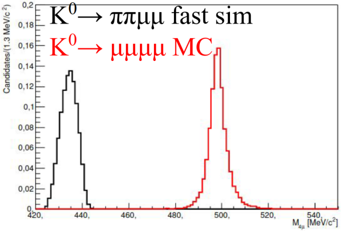
- **Data sample:** Run-II (2016-2018)
- **Trigger:**
  - Looking for high-p_{T} muons from signal
  - Increasing statistics by also looking for high-p_{T} particles in the underlying event
  - Refining the search imposing both muons to share a common vertex
- **Offline selection:**
  - Preselection (Rectangular cuts)
  - BDT (Machine learning algorithm)

Disclaimer: Analysis is early state. Preliminary results or from $K_{\mathrm{S}}^{0} \to \mu^{+}\mu^{-}\mu^{+}\mu^{-}$

[PRD108L031102]

Selection strategy: Backgrounds

- Potential physical backgrounds:
  - $K^0_S \to \mu^+\mu^-\mu^+\mu^-$ with double $\mu \to \pi$ misID
    - Negligible: Peak is 16 sigma away from signal and low $\mathcal{B}$



  - $K^0_S \to \pi^+\pi^-e^+e^-$ with double $e \to \mu$ misID
    - Higher $\mathcal{B}$ but $\Delta m(e \to \mu) >> \Delta m(\mu \to \pi)$
  - $K^0_L \to \pi^+\pi^-\mu^-\mu^+$
    - Small contribution for LHCb (FD $< 800\,\text{mm}$)
    - Will interpret our result in terms K^0_S and K^0_L

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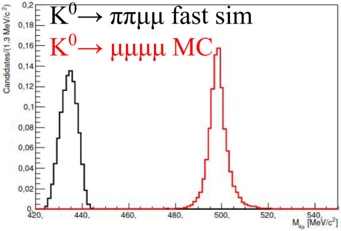

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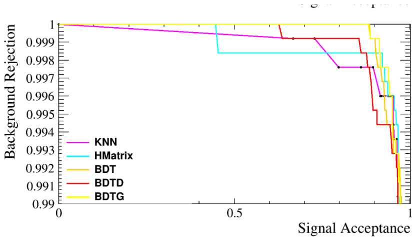
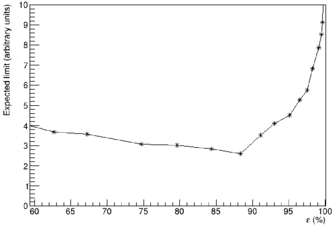
Main background expected to be combinatorial

Selection strategy: BDT

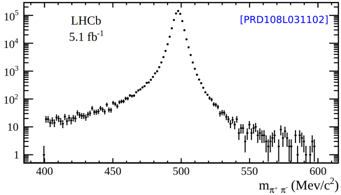
- Using MVA (Multivariate analysis) to discriminate sgl and comb. bkg.
- Testing several methods
  - Done in $K^0_S \to \mu^+\mu^-\mu^+\mu^-$ analysis
  - Gradient Boosted Decision Trees (BDTG) found to be the optimal one
- BDT cut optimize by minimizing the expected $\mathrm{CL_s}$ limit
  - Also tested with Punzi with similar results





Normalization channel

- The branching ratio can be derived counting signal decays:
  $N(K^0_S \to \pi^+\pi^-\mu^-\mu^+) =$
  $2 \times \mathcal{L} \times \sigma_{s\bar{s}} \times f_{K^0_S} \times \mathcal{B}\left(K^0_S \to \pi^+\pi^-\mu^-\mu^+\right) \times \epsilon(K^0_S \to \pi^+\pi^-\mu^-\mu^+)$
  - High uncertainty on some terms
- Using a known (normalization) channel: $K^0_S \to \pi^+\pi^-$
  $$\frac{N(K^0_S\to\pi^+\pi^-\mu^-\mu^+)}{N(K^0_S\to\pi^+\pi^-)} = \frac{\mathcal{B}(K^0_S\to\pi^+\pi^-\mu^-\mu^+)}{\mathcal{B}(K^0_S\to\pi^+\pi^-)}\frac{\epsilon(K^0_S\to\pi^+\pi^-\mu^-\mu^+)}{\epsilon(K^0_S\to\pi^+\pi^-)}$$
  - Very abundant at LHCb ($\mathcal{B}(K^0_S \to \pi^+\pi^-) \sim 69\%$ [PDG])



Efficiency

Preliminary study of the expected efficiency

Efficiency (%)	$K_S^0 \to \pi^+\pi^-\mu^+\mu^-$	$K_S^0 \to \mu^+\mu^-\mu^+\mu^-$
Reconstruction	1	5.2
Stripping	16	35
L0	13	29
HLT1	16	78
HLT2	69	92
Offline selection	TBD	10

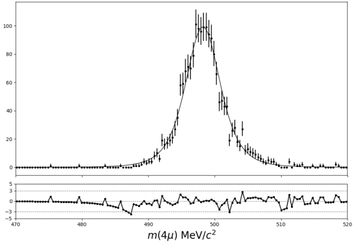
Lower efficiency than $K_S^0 \to \mu^+\mu^-\mu^+\mu^-$:

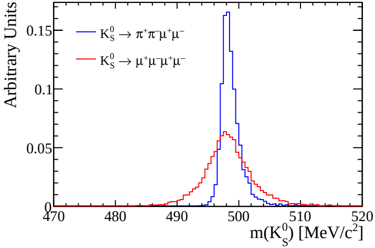
- Less PHSP (Smaller opening angle / p_T)
- Only one $\mu^+\mu^-$ pair

Massfits

Hypatia used to describe the mass peak

- All parameters must be fixed due to low expected yield
- Seen MC-Data discrepancies in peak position and width
  - Corrected using $K^0_S \to \pi^+\pi^-$
- Expected better mass resolution due to limited PHSP
  - $\sim$ 1.2 vs $\sim$ 3.6 MeV/c^2





Systematics

Assuming similar systematics to $K^0_S \to \mu^+\mu^-\mu^+\mu^-$ analysis [PRD108L031102]

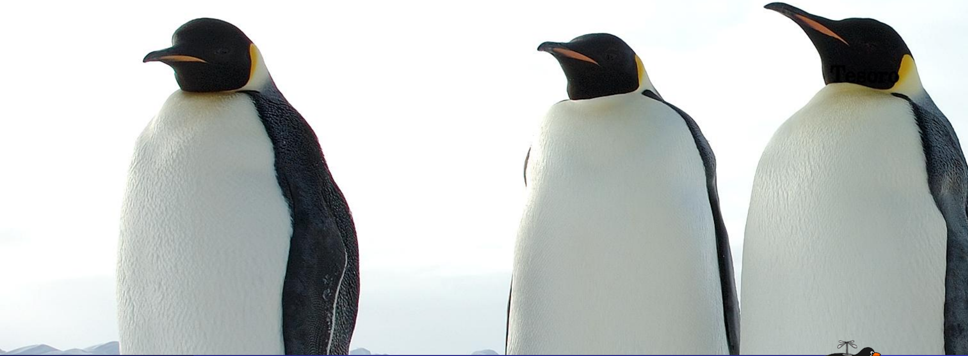
Source	Relative effect (%)
$\mathcal{B}(K^0_S \to \pi^+\pi^-)$	0.07
sMB	$\lesssim 0.3$
R_ε	1
Rec/Sel/Stp/MVA MC corrections	4.4
$K^0_S \to \pi^+\pi^-$ yield (fit)	≤ 1
Muon ID	3.3
Tracking	1.2
ε^{L0}	10 (TIS), 21 (xTOS)
$\varepsilon^{HLT\|L0}$	11
Mass model (signal)	negligible
Mass model (background)	negligible
Total	$\lesssim 24\%$ (limited by trigger validation)

Conclusions

- LHCb big contributor for neutral kaon results:
  - NA48 already analyzed its full dataset
  - NA62 features a charged beam
- Aiming to provide results on $\mathcal{B}\left(K_S^0 \to \pi^+\pi^-\mu^+\mu^-\right)$ by early next year
- Using expertise and framework from $K_S^0 \to \mu^+\mu^-\mu^+\mu^-$ analysis

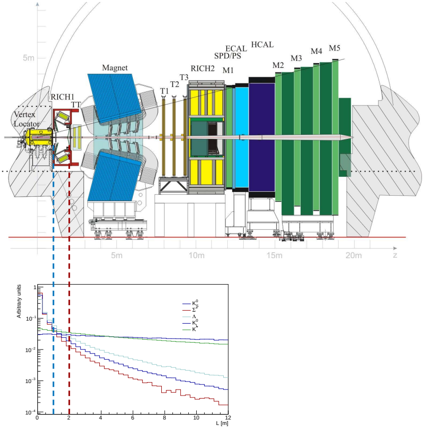
- Expect more precise results from the upcoming LHCb Run 3
  - Plan to specialize in Kaon physics ($K_S^0 \to \pi^+\pi^- e^+e^-$, $K_S^0 \to \pi^0\mu^+\mu^-$,...)

Thanks for your attention



Prospects

The measurement can be improved in Run III (2023-2025):



- More luminosity: Expected factor 2-3 w.r.t Run II
- L0 removed: Expected factor 3 improvement in trigger efficiency
- Using decays after Velo (Downstream) and Magnet (T-Tracks)

Introduction: Why Kaons?

- Very strong GIM suppression of top contribution
  - $\lambda^5 \sim 0.0005$ (kaons) vs. $\lambda^3 \sim 0.01$ (B mesons)
- Generically large QCD enhancements
- Sensitivity to high-scale (non-MFV) dynamics