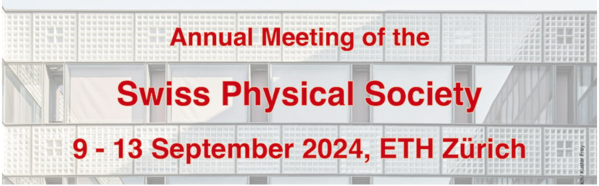
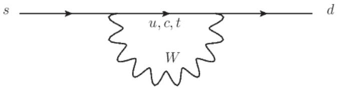
Search for $K^0_S \to \pi^+\pi^-\mu^+\mu^-$ decays at LHCb

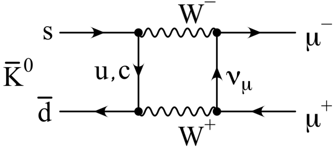
Luis Miguel Garcia Martin



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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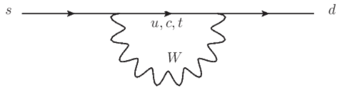
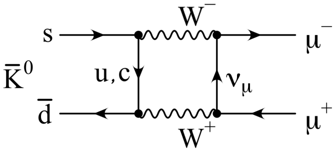


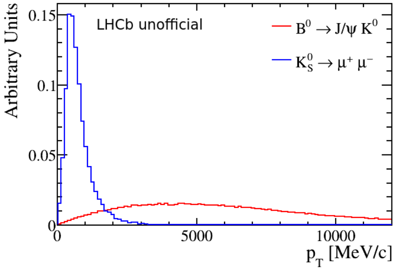


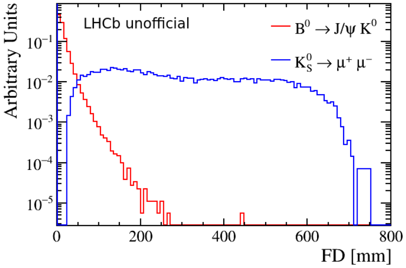
- Some exotic BSM scenarios can enhance it by 2 orders of magnitude [arXiV:2201.07805]
- LHCb already provided some world best measurements/limits:
  - $\mathcal{B}(K^0_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}$ @ 90% CL [PRL125(2020)231801]
  - $\mathcal{B}(K^0_{S(L)} \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}(2.3 \times 10^{-9})$ @ 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

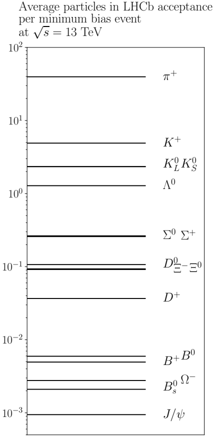




Challenges: Trigger

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

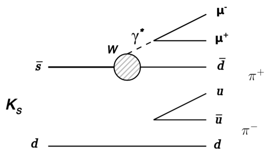
- Muon (hadron) L0 trigger $p_{\mathrm{T}} > 1\,\mathrm{GeV}/c$ (hardware)
- Hlt1 and Hlt2 are software and customizable
- L0 removed for Run 3 (2023 -)
- Huge strangeness production
  - About 1 strange hadron per event ($\sim 10^{-3}$ B_s^0)



[JHEP05(2019)048]

Motivation for $K^0_S \to \pi^+\pi^-\mu^-\mu^+$

- Very suppressed FCNC in the SM
  - $\mathcal{B}(K^0_S \to \pi^+\pi^-\mu^-\mu^+) = 4.69 \times 10^{-14}$ [arXiv:1712.10270]
  - Little PHSP: $m_{K^0_S} - 2m_\pi - 2m_\mu = 7.1\,\text{MeV}/c^2$
    - Extra suppression
    - Colinear decay products ($\varepsilon_{\text{reco.}} \sim 1\%$)
  - Possible enhancements from BSM
- No measurements yet (No SM prediction for $\mathcal{B}(K^0_L \to \pi^+\pi^-\mu^-\mu^+)$)



Analysis strategy

Following $K^0_S \to \mu^+\mu^-\mu^+\mu^-$ strategy [PRD108L031102]

- **Goal:** Measure/set a limit on $\mathcal{B}(K^0_S \to \pi^+\pi^-\mu^-\mu^+)$
  - If no signal: recompute limit for $\mathcal{B}(K^0_L \to \pi^+\pi^-\mu^-\mu^+)$
- **Data sample:** Run-II (2016-2018)
- **Blinded analysis:** excluding $m_{\pi\pi\mu\mu} \in [490, 510]$ MeV/c^2

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- **Data sample:** Run-II (2016-2018)
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- **Online selection (trigger):**
  - Looking for high-p_T muons from signal ($\varepsilon \sim 3\%$)
  - Also looking for high-p_T particles in the underlying event ($\varepsilon \sim 10\%$)
- **Offline selection:**
  - Preselection (Rectangular cuts)
  - BDT (Machine learning algorithm)

Normalization channel

- The branching ratio can be derived counting signal decays:

  $N(K^0_S \to \pi^+\pi^-\mu^-\mu^+) =$
  $2 \times \mathcal{L} \times \sigma_{s\bar{s}} \times f_{K^0_S} \times \mathcal{B}\,(K^0_S \to \pi^+\pi^-\mu^-\mu^+) \times \epsilon(K^0_S \to \pi^+\pi^-\mu^-\mu^+)$

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- Normalization channel: $K^0_S \to \pi^+\pi^-$ $(\mathcal{B} \sim 69\%)$

  $$\frac{N(K^0_S \to \pi^+\pi^-\mu^-\mu^+)}{N(K^0_S \to \pi^+\pi^-)} = \frac{\mathcal{B}(K^0_S \to \pi^+\pi^-\mu^-\mu^+)}{\mathcal{B}(K^0_S \to \pi^+\pi^-)} \frac{\epsilon(K^0_S \to \pi^+\pi^-\mu^-\mu^+)}{\epsilon(K^0_S \to \pi^+\pi^-)}$$

  - $\sigma_{s\bar{s}} \times f_{K^0_S} \times \mathcal{B}\left(K^0_S \to \pi^+\pi^-\right) \sim 1$ event/pp collision
  - No need to trigger (using Minimum bias with downscaling $\sim 10^{-6}$)

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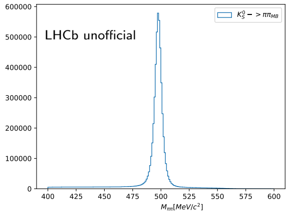
Needs to derive:

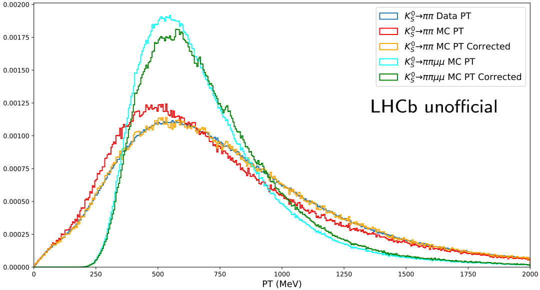
- Efficiency (ε): From Simulation
- Yields (N): From mass fits



Simulation corrections

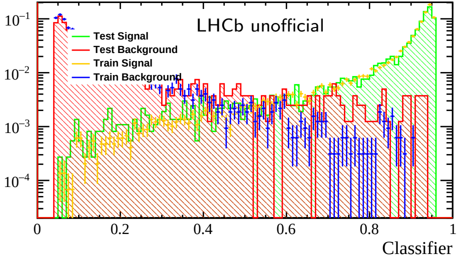
Need accurate simulation to train BDT, estimate eff. and mass shapes calibration:

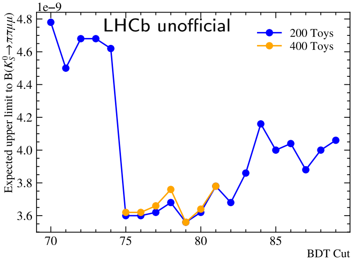
- Observed simulation mismodeling
- Corrected using Data/MC ratio in norm channel
- Corrected using centralized tools



Selection strategy: BDT

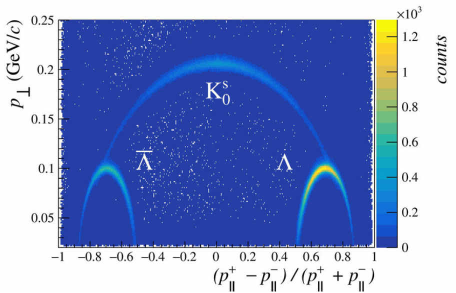
- Using Gradient Boosted Decision Trees (BDTG) to discriminate
  - Signal: Corrected simulation
  - Background: Data high-mass side-bands
- Using k-folding (k=6) to avoid overtraining
- BDT cut optimize: Toys to minimize $\mathcal{B}$ limit





Normalization channel:Armenteros Podoloski plot

Large contribution from $\Lambda \to p\pi^-$ decays in $K^0_S \to \pi^+\pi^-$ samples
Armenteros-Podolanski used to remove it:



$$\left| \left[\left(\left(\alpha \pm \frac{M_p^2 - M_\pi^2}{M_\Lambda^2} \right) \frac{M_\Lambda p_{K^0_S}}{2p^* \sqrt{p^2_{K^0_S} + M_\Lambda^2}} \right)^2 + \frac{p_T^2}{(p^*)^2} \right] - 1 \right| > 0.3$$

- $\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$
- $p^* \equiv \left[(M_\Lambda^2 - M_p^2 - M_\pi^2)^2 - 4M_p^2 M_\pi^2 \right] / (4M_\Lambda^2)$

Massfits

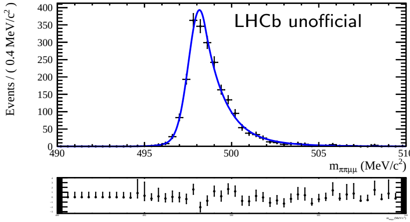
Signal described by two Crystal-balls

- All parameters must be fixed due to low expected yield

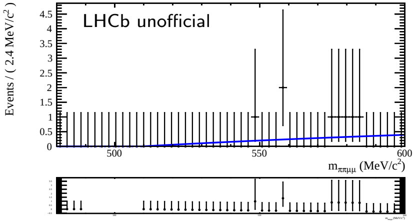
Comb. background modeled with a phase space function

- Accounts for $m(\pi^+\pi^-\mu^+\mu^-) \geq 2m(\pi) + 2m(\mu)$

Signal MC



Data Side-band (Bkg)



Systematics

Mainly limited by:

- MC Corrections: Searching ways to reduce systematic
- Trigger (L0, HLT) validation: Similar to previous K^0_S analyses

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	10.3
$K^0_S \to \pi^+\pi^-$ yield (fit)	≤ 1
Muon ID	2.2
Tracking	1.5
ε^{L0}	24 (TIS), 11 (xTOS)
$\varepsilon^{HLT\|L0}$	13
Total	$25 \lesssim$ %

Conclusions

Combining the results, the expected limit is:

$$\mathcal{B}(K^0_S \to \pi^+\pi^-\mu^+\mu^-)_{\text{expected}} < 3.54 \times 10^{-10}$$

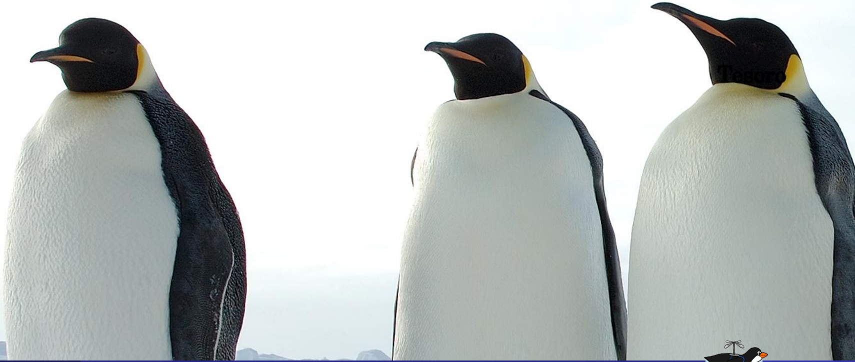
$$\mathcal{B}(K^0_L \to \pi^+\pi^-\mu^+\mu^-)_{\text{expected}} < 1.66 \times 10^{-7}$$

$\mathcal{B}(K^0_S \to \pi^+\pi^-\mu^-\mu^+)_{\text{SM}} = 4.69 \times 10^{-14}$ $\mathcal{B}(K^0_S \to \pi^+\pi^-\mu^-\mu^+)_{\text{no syst.}} = 3.72 \times 10^{-10}$

- LHCb big contributor for neutral kaon results:
  - NA48 already analyzed its full dataset
  - NA62 features a charged beam
- Aiming to provide results on $\mathcal{B}\ (K^0_S \to \pi^+\pi^-\mu^+\mu^-)$ by early next year

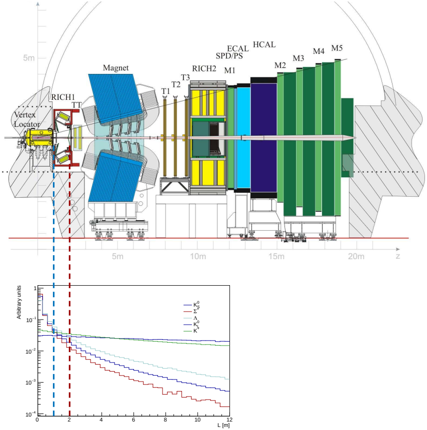
- Expect more precise results from the upcoming LHCb Run 3

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)

Normalization channel

- The branching ratio can be derived counting signal decays:

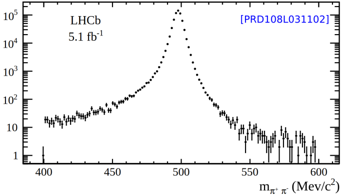
  $N(K^0_S \to \pi^+\pi^-\mu^-\mu^+) =$
  $2 \times \mathcal{L} \times \sigma_{s\bar{s}} \times f_{K^0_S} \times \mathcal{B}\ (K^0_S \to \pi^+\pi^-\mu^-\mu^+) \times \epsilon(K^0_S \to \pi^+\pi^-\mu^-\mu^+)$

  - 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])



Phase space model

The PHSP function is defined for a two-particle decay:

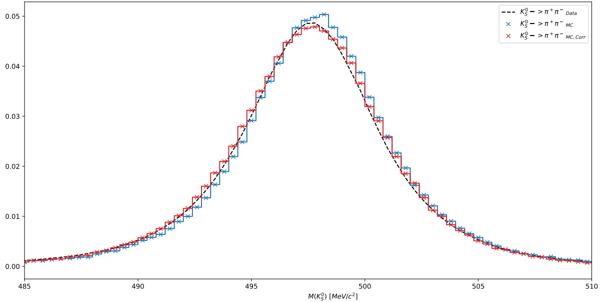
- Artificially doing $K^0_S \to AB$, with $A \to \mu^+\mu^-$ and $B \to \pi^+\pi^-$
- m_A and m_B are free parameters

$$Q(M, m_1, m_2) = \frac{M^4 - 2M^2(m_1^2 + m_2^2) + (m_1^4 + m_2^4) - 2m_1^2 m_2^2}{4M^2}$$

$$f(x, m_A, m_B) = \left(\frac{Q(x, m_A, m_B)}{x}\right)^2 \cdot \left(\frac{Q(m_A, m_\pi, m_\pi)}{m_A}\right)^2 \cdot \left(\frac{Q(m_B, m_\mu, m_\mu)}{m_B}\right)^2$$

$m(K^0_\mathrm{S})$ not perfectly described in simulation:

- Small downscale ($\simeq 0.99875$) in the daughters' momenta in simulation
- Corrected using $K^0_\mathrm{S} \to \pi^+\pi^-$
- Applied to signal and norm channels



The two trigger categories used in this analysis are defined by

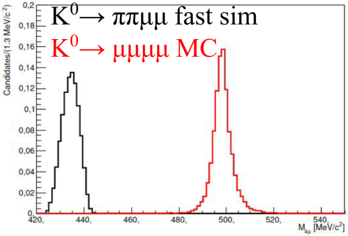
- TIS: `L0TIS&&HLTTOS`
- xTOS: `L0xTOS&&HLTTOS`

- L0TIS : `(L0Electron_TIS|L0Photon_TIS|L0Hadron_TIS|L0Muon_TIS|L0DiMuon_TIS)`
- L0TOS: `(L0Muon_TOS|L0DiMuon_TOS|L0Muon,lowMult_TOS)`
- L0xTOS: L0TOS + "&& !" + L0TIS
- HLTTOS: `((Hlt1DiMuonNoL0_TOS|Hlt1DiMuonLowMass_TOS)&&Hlt2DiMuonSoft_TOS)`

	TIS-TOS-TOS	xTOS-TOS-TOS
$\varepsilon^{L0\|stp}(\%)$ MC2017	11.409 ± 0.64	2.962 ± 0.024
$\varepsilon^{HLT1\|L0}(\%)$ MC2017	13.48 ± 0.14	23.18 ± 0.35
$\varepsilon^{HLT2\|HLT1}(\%)$ MC2017	69.32 ± 0.52	68.62 ± 0.80
$\varepsilon^{trig\|stp}(\%)$ MC2017	1.066 ± 0.014	0.4711 ± 0.0097

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 mm)
    - Will interpret our result in terms K^0_S and K^0_L

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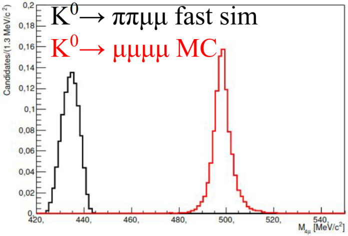

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  - $K^0_L \to \pi^+\pi^-\mu^-\mu^+$
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Main background expected to be combinatorial

Efficiency

Low signal ($K^0_S \to \pi^+\pi^-\mu^+\mu^-$) efficiency due to:

- Little PHSP $\implies$ Small opening angle / p_T

Efficiency (%)	$K^0_S \to \pi^+\pi^-\mu^+\mu^-$	$K^0_S \to \pi^+\pi^-$
Gen	26.7	-
Reco	1.13	1.53
Strip	16.4	50.4
L0	13.0	-
HLT1	19.3	-
HLT2	68.8	-
Add Cuts	60.5	96.1
Classifier	58.7	-
Total	3.04×10^{-4}	0.74

Normalization channels taken from MinBias (No trigger) sample:

- Gen. eff included in Reconstruction
- No trigger requirement (100% efficiency)

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