Status and future prospects for rare kaon decay measurements at LHCb

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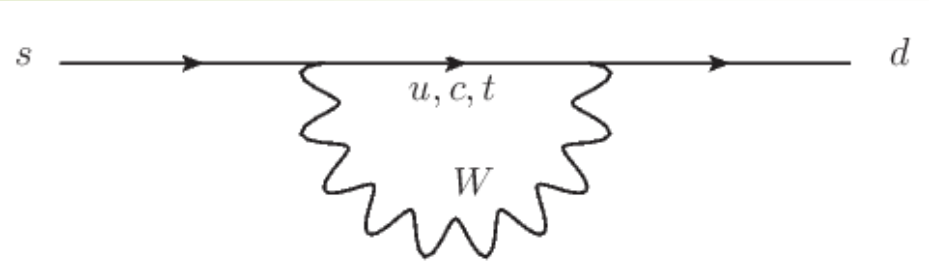
on behalf of the LHCb Collaboration

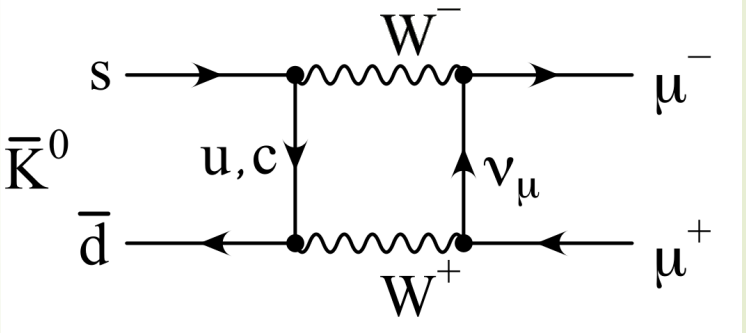
17/09/2025

Introduction: Why Kaons?

- The $s \to d\ell\ell$ process is forbidden at tree level in the SM (suppressed)
  - Several golden-plated observables: theoretically clean
- Some exotic BSM scenarios can enhance it by 2 orders of magnitude

arXiv:2201.07805

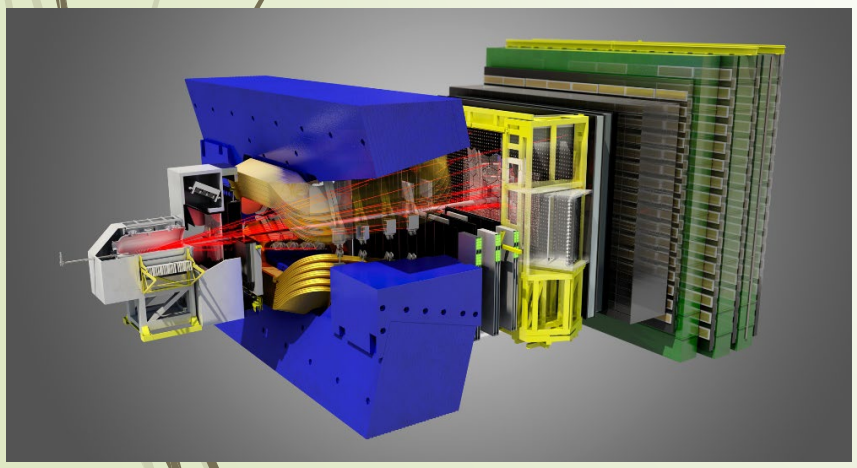




Introduction: LHCb

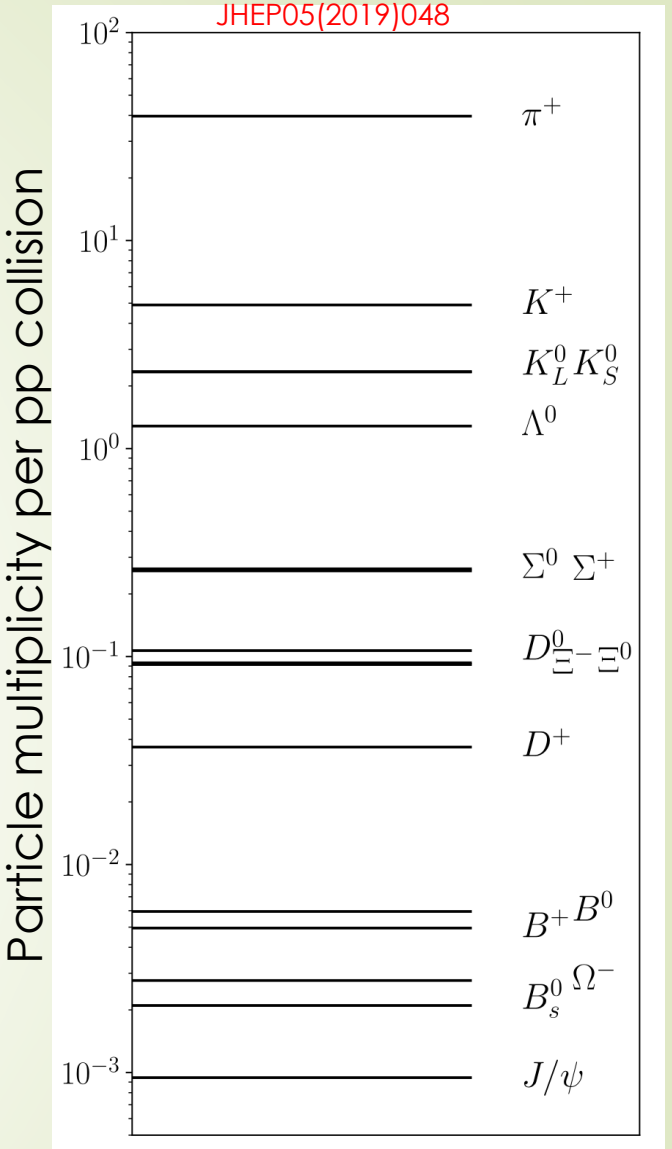
- Very large strangeness production at LHC
  - About 10 strange hadron per event
  - ~10^{14} collisions per fb^{-1} JHEP 06 (2018) 100
- Single-arm forward spectrometer
  - Optimized for b and c decays
  - Trigger efficiency close to zero for s decays

JINST8023(2008)S08005
JINST19(2024)P05065



- Major trigger improvements for:
  - Run 2 (2016-2018)
  - Run 3 (2023-2026) + Run 3 (2030-2033)
- Planned upgrade:
  - Upgrade 2 (2034-2035)

JHEP05(2019)048



Challenges: Trigger

L0 (Hardware)

HLT1 (Software)

HLT2 (Software)

Main bottleneck for K physics: p_T > O(GeV)

Not designed for K physics but **flexible**

Dedicated K triggers implemented in Run II

Upgrade(s)

HLT (Software)

$\varepsilon_{trig}(\text{Run 1}) \sim 1-2\%$

$\varepsilon_{trig}(\text{Run 2}) \sim 18\%$ (dimuons)

- improved HLT
- Maximum allowed by L0 ~30%

LHCb upgrade(s):

$\varepsilon_{trig}(\mathbf{2024+}) \sim \mathbf{100\%}$

JINST 14 (2019) P04013

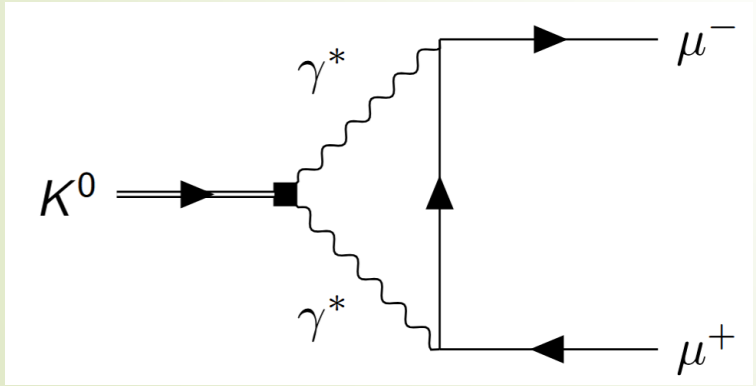
LHCb-PUB-2017-023

LHCB-TDR-021

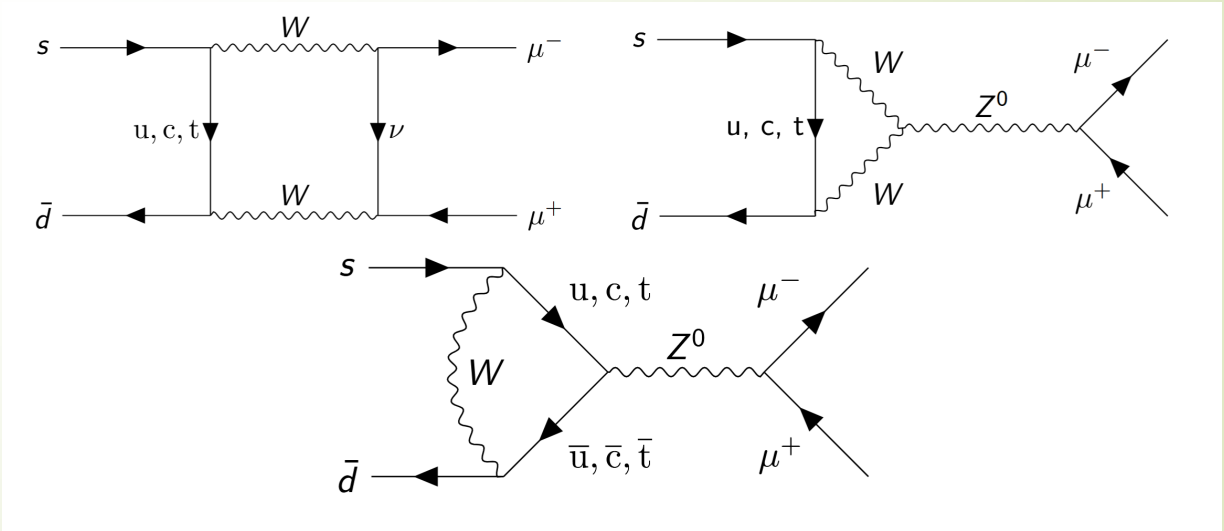
$K^0 \to \mu^+\mu^-$: Motivation

- Dominated by Long Distance (LD) contribution:
  - $A^{\mu}_{L\gamma\gamma}$ unkown
- Short Distance (SD) contributions theoretically clean
  - SD can be saturated by exotic BSM JHEP 03 (2022) 048

LD



SD



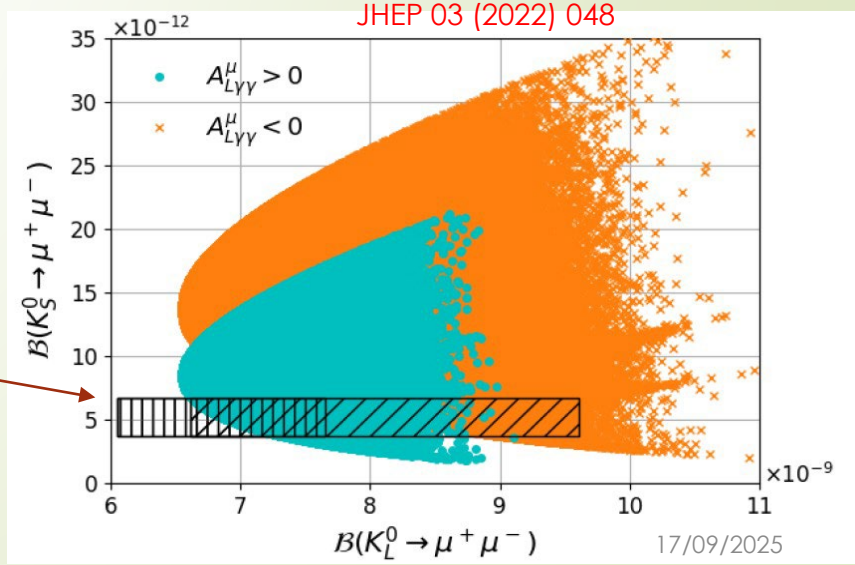
$K_S \to \mu^+\mu^-$: Motivation

- $\mathrm{BR}(K_L \to \mu^+\mu^-)_{PDG} = (6.84 \pm 0.11) \times 10^{-9}$
  - Provides $|A^{\mu}_{L\gamma\gamma}|$
  - Limited sensitivity to BSM without $A^{\mu}_{L\gamma\gamma}$ sign
    - Existing arguments for negative sign JHEP01(2004)009

- $\mathrm{BR}(K_S \to \mu^+\mu^-)_{SM} = (5.18 \pm 1.50_{\mathrm{LD}} \pm 0.02_{\mathrm{SD}}) \times 10^{-12}$
  - SD dominated by the CP-violating $s \to d\ell\ell$
  - Could be enhanced up to 2 orders of magnitude by BSM
  - Model-independent bounds on the CP-violating $s \to d\ell\ell$ phase

JHEP 05 (2018) 024 ,
JHEP 0401 (2004) 009,
NPB 366 (1991) 189

JHEP 03 (2022) 048

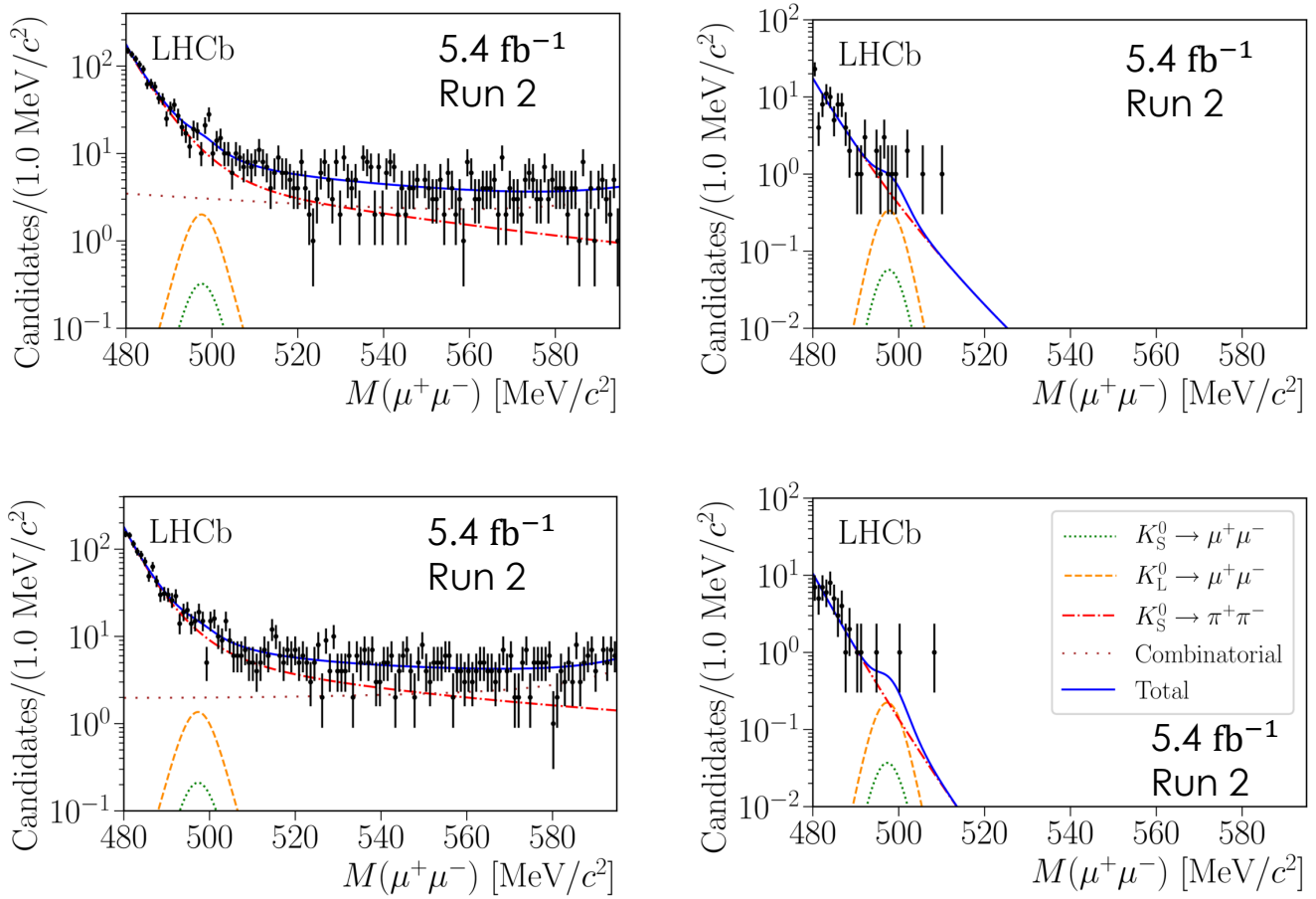


SM

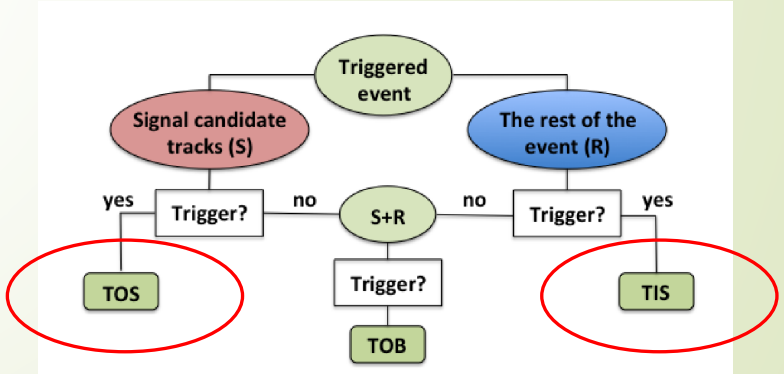
PRL119 (2017) 2018
JHEP 0401 (2004) 00902
JHEP 03 (2022) 048

$K_S \to \mu^+\mu^-$: Results

PRL 125 (2020) 231801

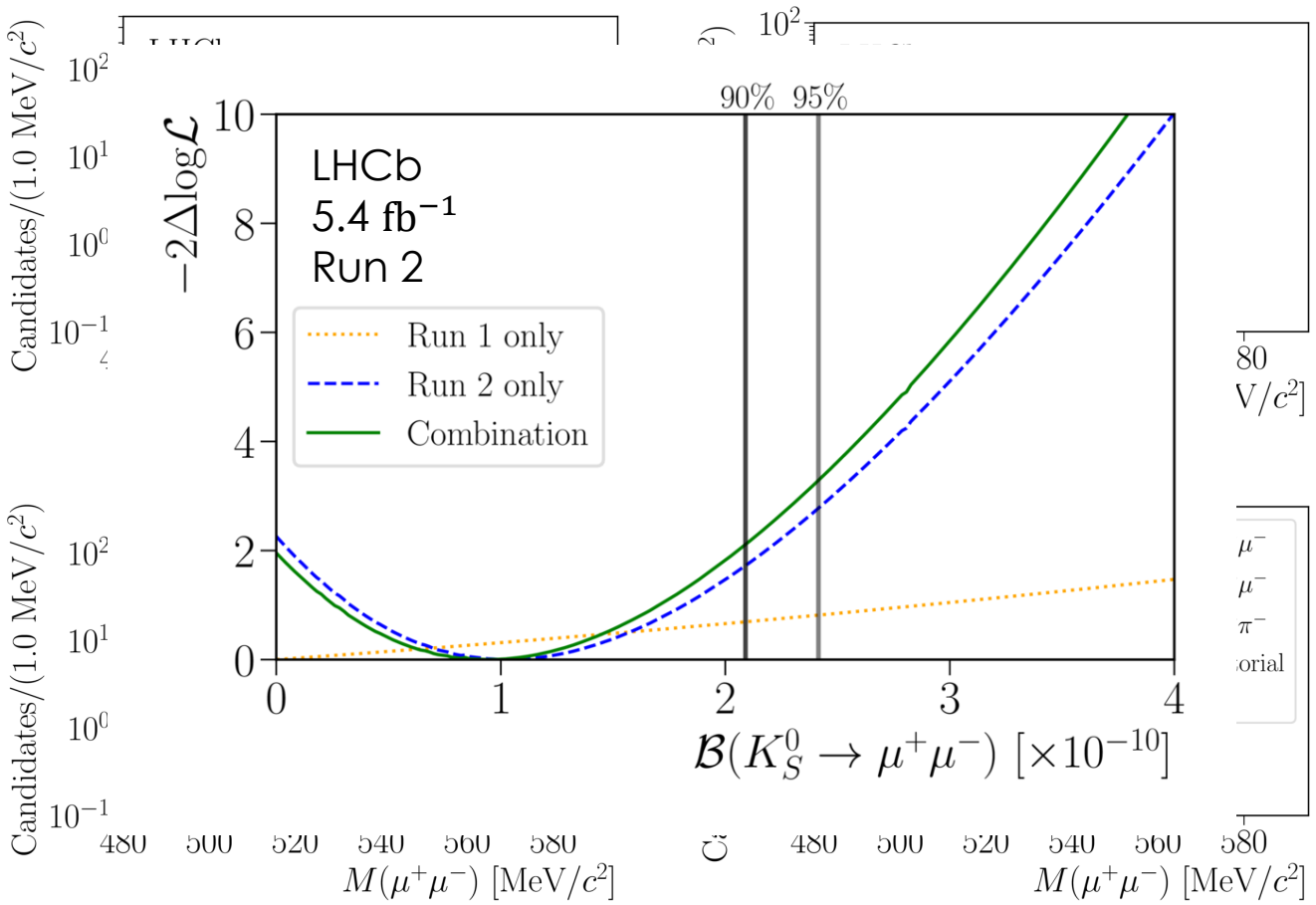


- Search performed in:
  - bins of the BDT output
  - trigger categories
- Normalization channel: $K_S \to \pi^+\pi^-$
- No evidence of signal



$K_S \to \mu^+\mu^-$: Results

PRL 125 (2020) 231801



- Search performed in:
  - bins of the BDT output
  - trigger categories
- Normalization channel: $K_S \to \pi^+\pi^-$
- No evidence of signal (1.4 σ)
- Combined with Run 1 result

$BR(K_S^0 \to \mu^+\mu^-)_{theo} \sim 10^{-12}$

$BR(K_S^0 \to \mu^+\mu^-) < 2.2 \times 10^{-10}$ @ 90% CL

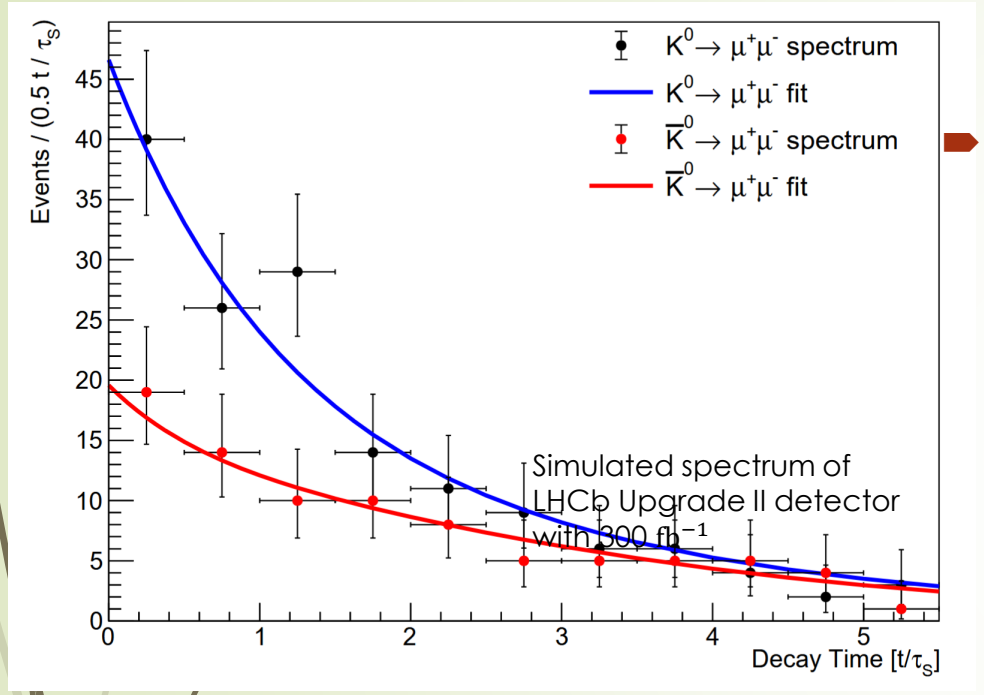
PRL 125 (2020) 231801

- prospects to reach $O(10^{-11})$ sensitivity with Run 3 data (analysis ongoing)

JHEP 05 (2019) 048

$K_S \to \mu^+\mu^-$: Prospects

arXiv:2507.13445



- $K^0 \to \mu^+\mu^-$ interference grants access to SD

Time-dependent rate

$$\frac{1}{\mathcal{N}}\frac{d\Gamma(\overline{(K)}^0 \to \mu^+\mu^-)}{dt} = C_L\, e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t} \pm 2\, C_{\text{Int.}} \cos(\Delta M_K t - \varphi_0) e^{-\Gamma t}$$

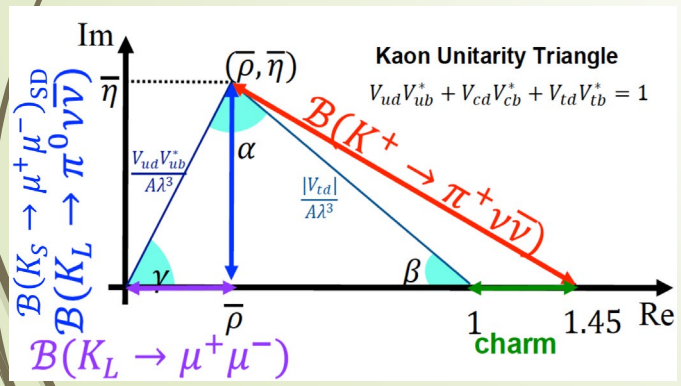
$$C_L = |A(K_L)_{\ell=0}|^2,$$

$$C_S = |A(K_S)_{\ell=0}|^2 + \beta_\mu^2 |A(K_S)_{\ell=1}|^2,$$

$$C_{\text{Int.}} = |A(K_S)_{\ell=0}|\,|A(K_L)_{\ell=0}|$$

Short-distance CPV contribution

- Also grants access to CKM η
- Time-dependence and Tagging required
- Benefit from extending acceptance (Downstream tracks)

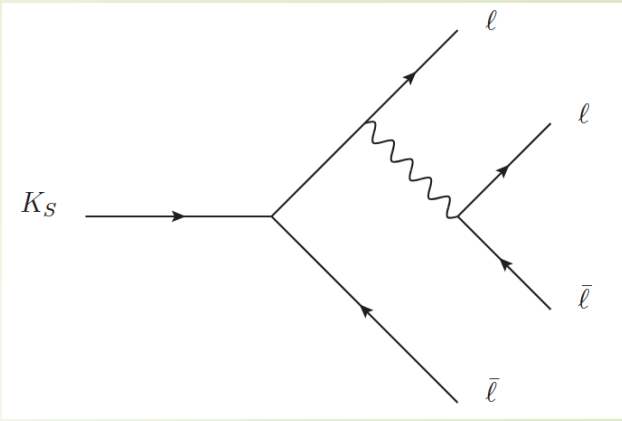


LHCb Upgrade II might be able to achieve:

- $\delta\eta/\eta$ ~35%
- Sign of $A_{L\gamma\gamma}^{\mu}$ with at least 3σ

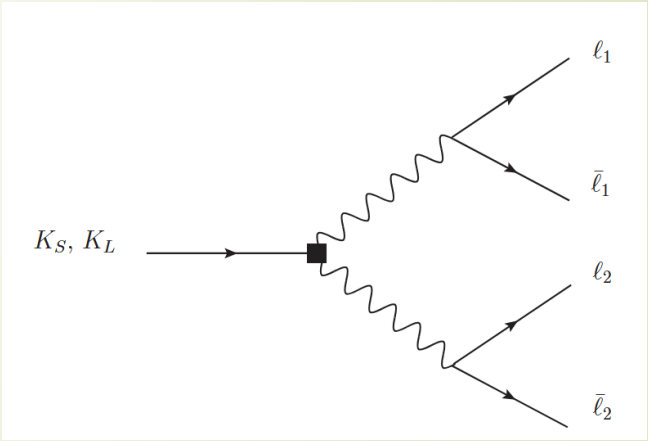
$K_S \to \mu^+\mu^-\mu^+\mu^-$: Motivation

- $K^0 \to \ell^+\ell^+\ell^-\ell^-$
  - SD component sensitive to NP
  - Dominated by LD uncertainties



- Sign of $\mathcal{A}(K_L^0 \to \gamma\gamma)$ can be derived from interference between
  - $\mathcal{A}(K_L^0 \to \ell^+\ell^+\ell^-\ell^-)$: No experimental constraint
  - $\mathcal{A}(K_S^0 \to \ell^+\ell^+\ell^-\ell^-)$: No experimental constraint

EPJC 73 (2013) 2678
JHEP 0401 (2004) 009



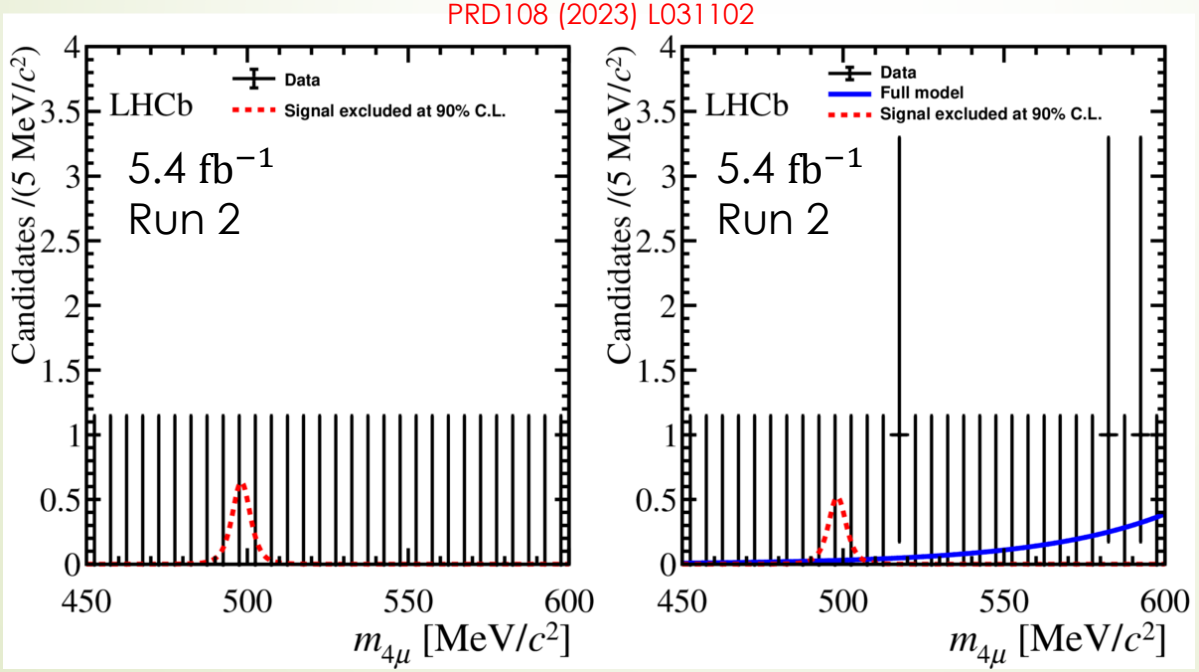
$$BR(K_S^0 \to e^+e^-e^+e^-) \sim 10^{-10}$$
$$BR(K_S^0 \to \mu^+\mu^-e^+e^-) \sim 10^{-11}$$
$$BR(K_S^0 \to \mu^+\mu^-\mu^+\mu^-) \sim 10^{-14}$$

Sensitive to New Physics at the same order as the SM contribution

$K_S \to \mu^+\mu^-\mu^+\mu^-$

- Normalization channel: $K_S \to \pi^+\pi^-$
- Low background expected
- Search performed in trigger categories
- No events found in signal region

PRD108 (2023) L031102



$K_S \to \mu^+\mu^-\mu^+\mu^-$: Results

- World's best (first) upper limit

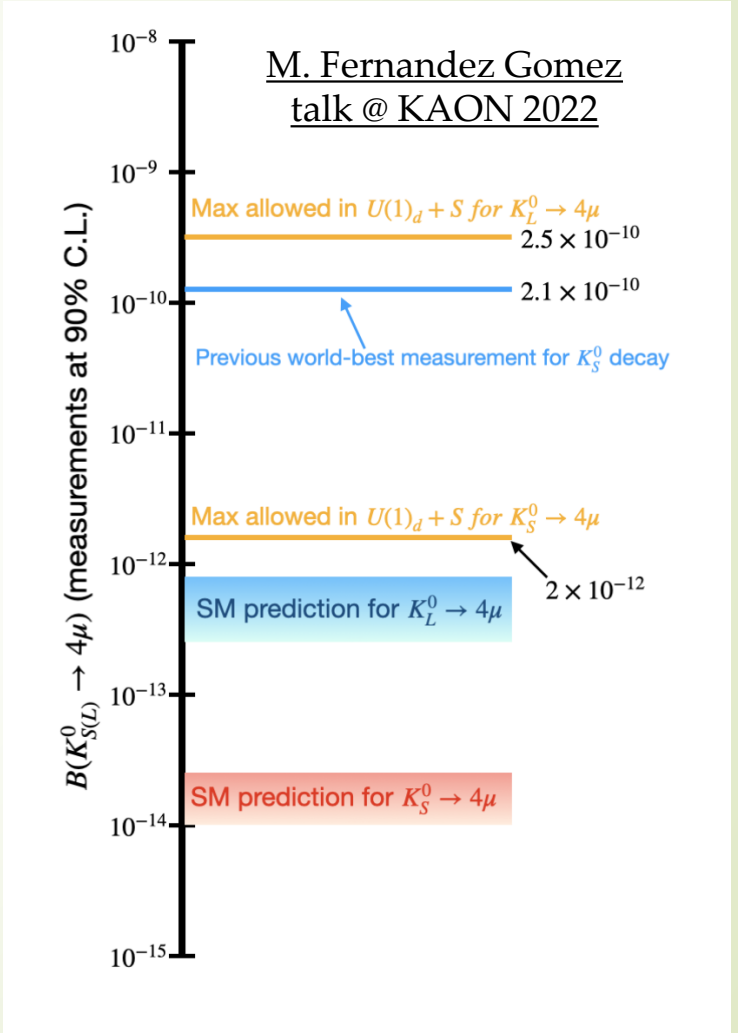
$$BR(K_S^0 \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$$
$$BR(K_L^0 \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$$
@ 90% CL

PRD108 (2023) L031102

- Stringiest upper limit for a K_S^0 so far
- First LHC result with K_L^0!!
- Limits close to maximum allowed by the BSM

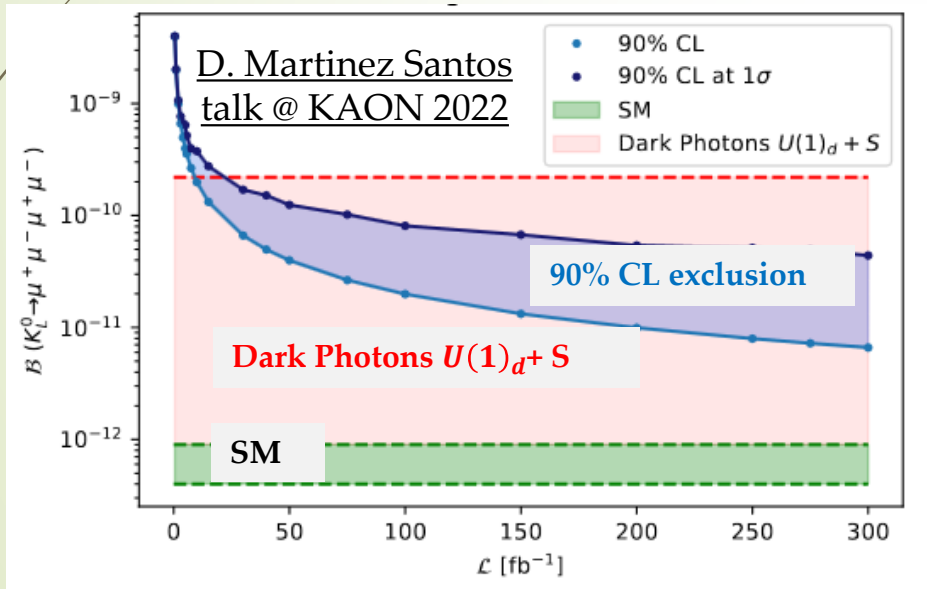
$$\frac{\epsilon_{K_L^0}}{\epsilon_{K_S^0}} = \frac{\Gamma_L \int_{0.1\tau_S}^{1.45\tau_S} e^{-t(\Gamma_S+\beta)}dt}{\Gamma_S \int_{0.1\tau_S}^{1.45\tau_S} e^{-t(\Gamma_L+\beta)}dt} \approx 2.2 \times 10^{-3}$$

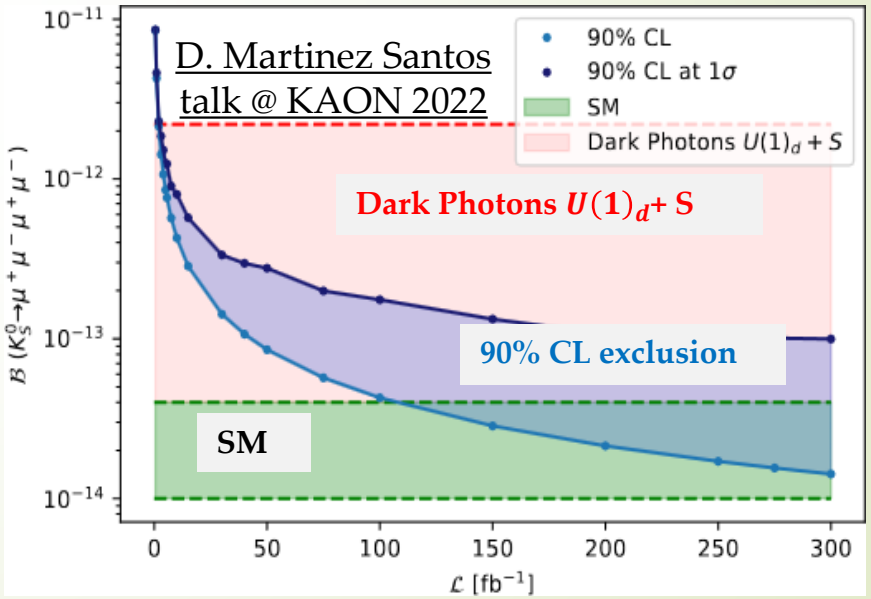
JHEP05(2019)048



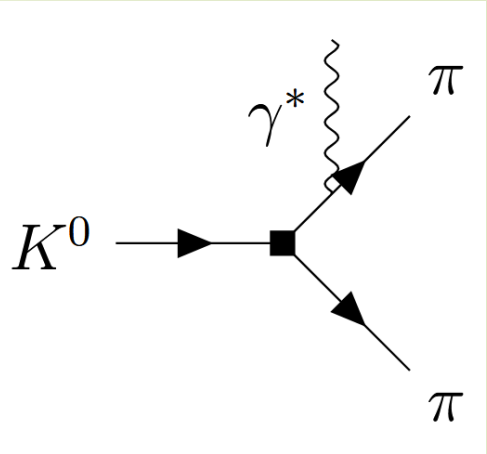
$K_S \to \mu^+\mu^-\mu^+\mu^-$: Prospects

- Excellent prospects for Upgrade(s)
- Most of the allowed BSM range explored (e.g. Dark Photons)
- If no signal is found, getting closer to SM values





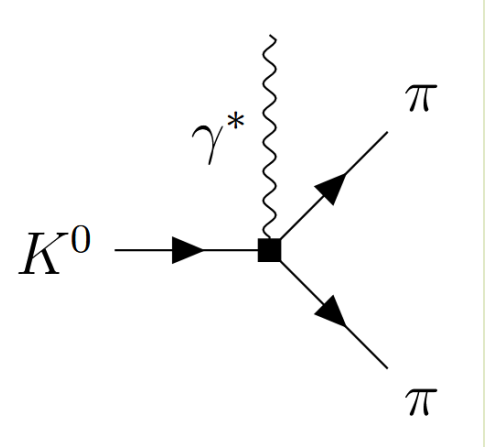
$K^0_{S(L)} \to \pi^+\pi^-\mu^+\mu^-$: Motivation



- $K^0 \to \pi^+\pi^-\gamma^*$:
  - $K^0_S \to \pi^+\pi^-\gamma^*$: LD chiral terms
  - $K^0_L \to \pi^+\pi^-\gamma^*$: CP violation
- Electron mode measured by NA48:

$$\boldsymbol{BR\left(K^0_S \to \pi^+\pi^- e^+ e^-\right) = (4.8 \pm 0.2) \times 10^{-5}}$$
$$\boldsymbol{BR\left(K^0_L \to \pi^+\pi^- e^+ e^-\right) = (3.1 \pm 0.2) \times 10^{-7}}$$

EPJC30(2003)33
PLB694(2011)301



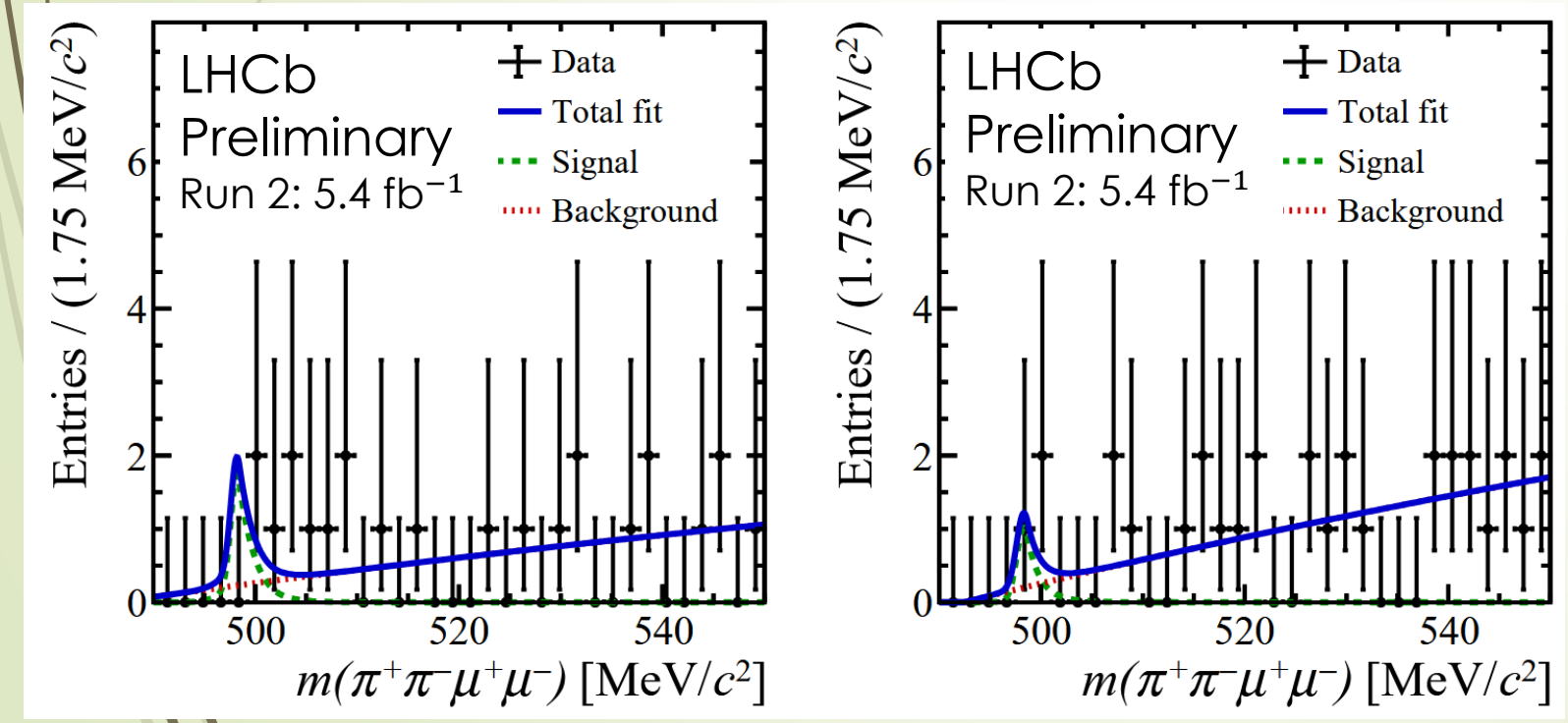
- Muon mode probes higher q^2 regions:
  - Complementary test for form-factor shapes and chiral counterterms
  - Direct emission relatively larger
  - More suppression (only 7MeV)

$$\boldsymbol{BR\left(K^0_S \to \pi^+\pi^-\mu^+\mu^-\right)_{SM} \sim 10^{-14}}$$

EPJC78(2018)275

$K^0_{S(L)} \to \pi^+\pi^-\mu^+\mu^-$

- Normalization channel: $K_S \to \pi^+\pi^-$
- Bkg model challenging (close to kinematic limit)
- Search performed in trigger categories
- No evidence of signal



$$BR(K^0_S \to \pi^+\pi^-\mu^+\mu^-) < 1.4 \times 10^{-9}$$
$$BR(K^0_L \to \pi^+\pi^-\mu^+\mu^-) < 6.6 \times 10^{-7}$$
@ 90% CL

LHCb-PAPER-2025-045
in preparation

$K_S \to \pi^0\mu^+\mu^-$: Motivation

$$\mathrm{BR}(\mathrm{K_L} \to \pi^0\mu^+\mu^-)_{\mathrm{SM}} = \{1.4 \pm 0.3, 1.0 \pm 0.2\} \times 10^{-11}$$

→ Sensitive to BSM

$$BR(K_L \to \pi^0 l^+ l^-)_{SM} = \left(\mathrm{C}^l_{\mathrm{dir}} \pm \mathrm{C}^l_{\mathrm{int}} \times |\mathrm{a_S}| + \mathrm{C}^l_{\mathrm{mix}} \times |\mathrm{a_S}|^2 + \mathrm{C}^l_{\gamma\gamma}\right) \times 10^{-12}$$

JHEP 08 (2006) 088

$|\mathrm{a_S}| = 1.20 \pm 0.20$ PLB 576 (2003) 43-54, PLB 599 (2004) 197-201

- $\mathrm{C}^{\mathrm{e}}_{\mathrm{dir}} = (4.62 \pm 0.24) \times \left(\mathrm{w}^2_{7\mathrm{V}} + \mathrm{w}^2_{7\mathrm{A}}\right)$
- $\mathrm{C}^{\mathrm{e}}_{\mathrm{int}} = (11.3 \pm 0.3) \times \mathrm{w}_{7\mathrm{V}}$
- $\mathrm{C}^{\mathrm{e}}_{\mathrm{mix}} = 14.5 \pm 0.5$
- $\mathrm{C}^{\mathrm{e}}_{\mathrm{mix}} \approx 0$
- $\mathrm{C}^{\mu}_{\mathrm{dir}} = (1.09 \pm 0.05) \times \left(\mathrm{w}^2_{7\mathrm{V}} + 2.32 \times \mathrm{w}^2_{7\mathrm{A}}\right)$
- $\mathrm{C}^{\mu}_{\mathrm{int}} = (2.63 \pm 0.06) \times \mathrm{w}_{7\mathrm{V}}$
- $\mathrm{C}^{\mu}_{\mathrm{mix}} = 3.36 \pm 0.20$
- $\mathrm{C}^{\mu}_{\mathrm{mix}} \approx 5.2 \pm 1.6$

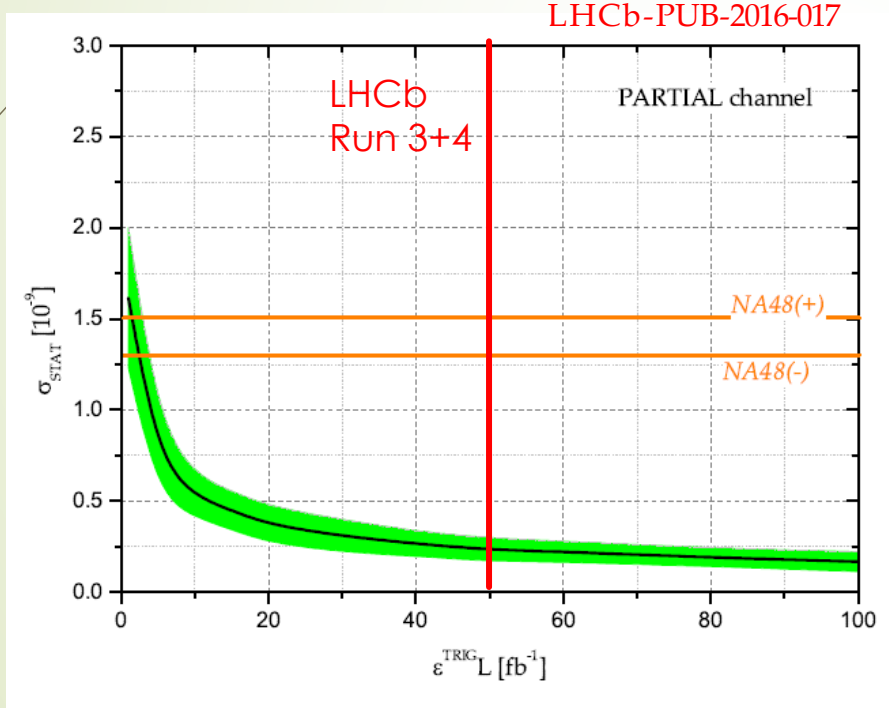
- Significant $|a_S|$ uncertainty coming from $\mathrm{BR}(K_S \to \pi^0 l^+ l^-)$
  - $\mathrm{BR}(K_S \to \pi^0\mu^+\mu^-)_{NA48} = \left(2.9^{+1.5}_{-1.2}\right) \times 10^{-9}$ PLB 599 (2004) 197-201
  - $\mathrm{BR}(K_S \to \pi^0 e^+ e^-)_{NA48} = \left(3.0^{+1.5}_{-1.2}\right) \times 10^{-9}$ PLB 576 (2003) 43-54
- Hard BSM interpretation of $\mathrm{BR}(\mathrm{K_L} \to \pi^0\mu^+\mu^-)$

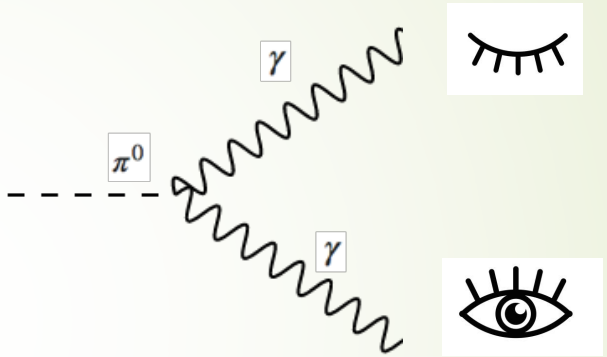
Improved measurement of $K_S \to \pi^0\mu^+\mu^-$ will translate into improved BSM constraints from $K_L \to \pi^0\mu^+\mu^-$

$K_S \to \pi^0\mu^+\mu^-$: Sensitivity study

- More background than $K_S \to \mu^+\mu^-$ but ~ 1000 times more signal
  - BR($K_S \to \pi^0\mu^+\mu^-$)~ 10^{-9}
  - BR($K_S \to \mu^+\mu^-$)~ 10^{-12}

LHCb-PUB-2016-017





Δa_s

Configuration	Phase I	Phase II
BR & q^2 fit	0.25	0.10
BR & q^2 fit with NA48 constraint	0.19	0.10
BR & q^2 fit fixing b_S	0.06	0.024
a_S measurement from BR alone	0.06	0.024

JHEP 05 (2019) 048

Phase II Upgrade → 300 fb^{-1}

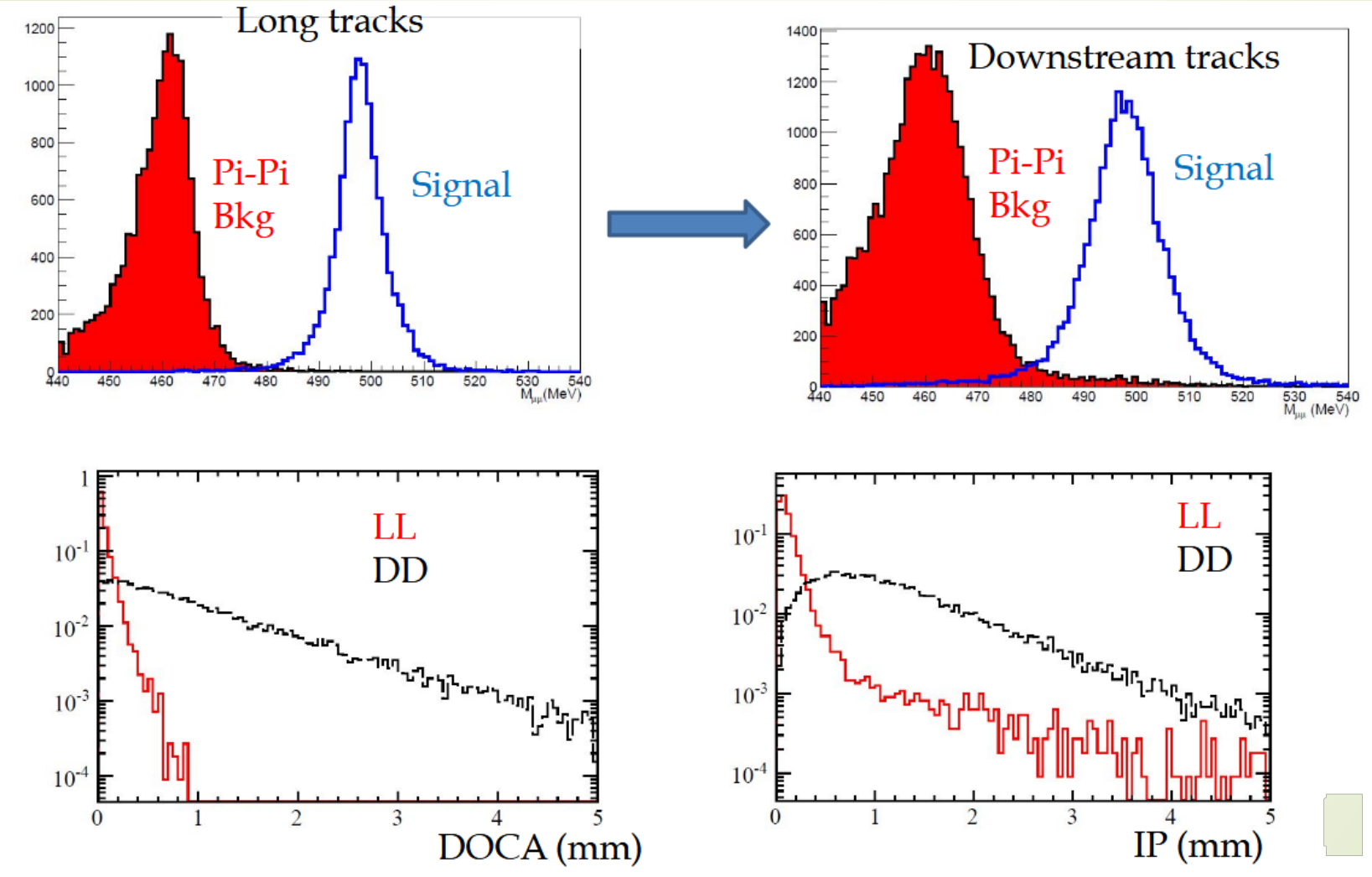
Summary

- There is a **s**trange physics community at LHC**b**
  - Constant trigger improvements
  - Run III: Expected to reach efficiencies for **s** as high as for b's
- Available measurement for $K_S \to \mu^+\mu^-, K_{S(L)} \to \mu^+\mu^-\mu^+\mu^-, K_{S(L)} \to \pi^+\pi^-\mu^+\mu^-$
- Published prospects for $K_S \to (\gamma/\pi^0)\mu^+\mu^-, K_S \to \pi^+\pi^-e^+e^-$ JHEP05(2019)048
- More channels in our TODO list (e.g. $K_S \to \mu\mu ee, K_S \to eeee$)

LHCb Upgrades offer an unique opportunity to study rare kaon decays!

Thanks for your attention

$K_S \to \mu^+\mu^-$: Downstream tracks



D. Martinez, **Kaons@J-PARC 2024**

$K_S \to \pi^0\mu^+\mu^-$: Sensitivity study

Sensitive to BSM

$$BR(K_L \to \pi^0 l^+ l^-)_{SM} = \left(C^l_{\mathrm{dir}} \pm C^l_{\mathrm{int}} \times |a_S| + C^l_{\mathrm{mix}} \times |a_S|^2 + C^l_{\gamma\gamma}\right) \times 10^{-12}$$

$$BR(K_L \to \pi^0 \mu^+ \mu^-)_{SM} = \{1.4 \pm 0.3, 1.0 \pm 0.2\} \times 10^{-11}$$

JHEP 08 (2006) 088

$|a_S| = 1.20 \pm 0.20$

PLB 576 (2003) 43-54
PLB 599 (2004) 197-201

- $C^e_{\mathrm{dir}} = (4.62 \pm 0.24) \times \left(w^2_{7V} + w^2_{7A}\right)$
- $C^e_{\mathrm{int}} = (11.3 \pm 0.3) \times w_{7V}$
- $C^e_{\mathrm{mix}} = 14.5 \pm 0.5$
- $C^e_{\mathrm{mix}} \approx 0$

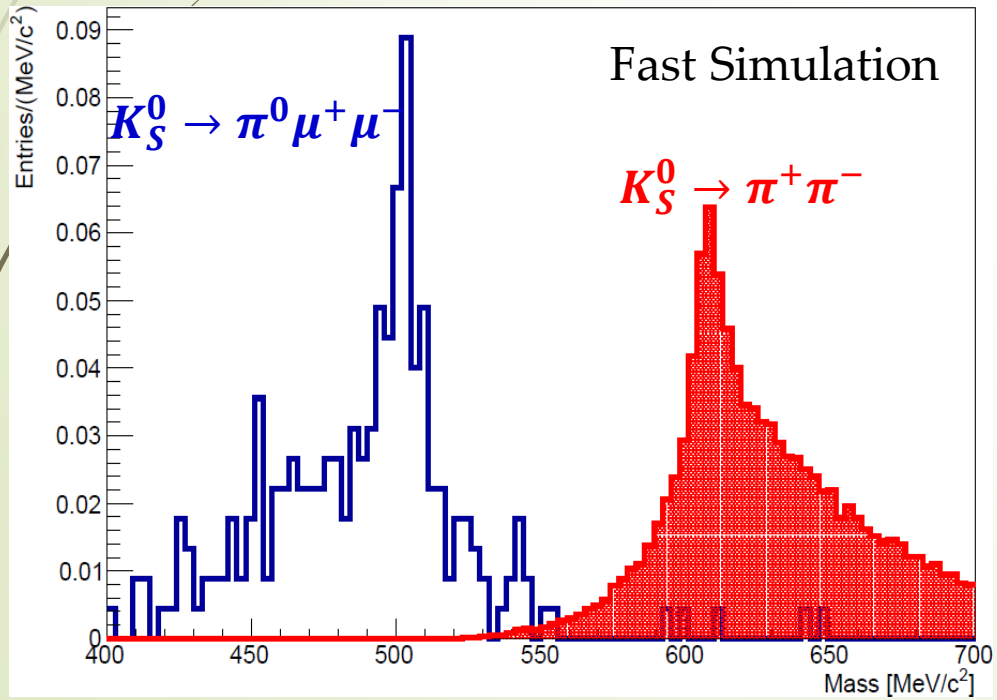
- $C^\mu_{\mathrm{dir}} = (1.09 \pm 0.05) \times \left(w^2_{7V} + 2.32 \times w^2_{7A}\right)$
- $C^\mu_{\mathrm{int}} = (2.63 \pm 0.06) \times w_{7V}$
- $C^\mu_{\mathrm{mix}} = 3.36 \pm 0.20$
- $C^\mu_{\mathrm{mix}} \approx 5.2 \pm 1.6$

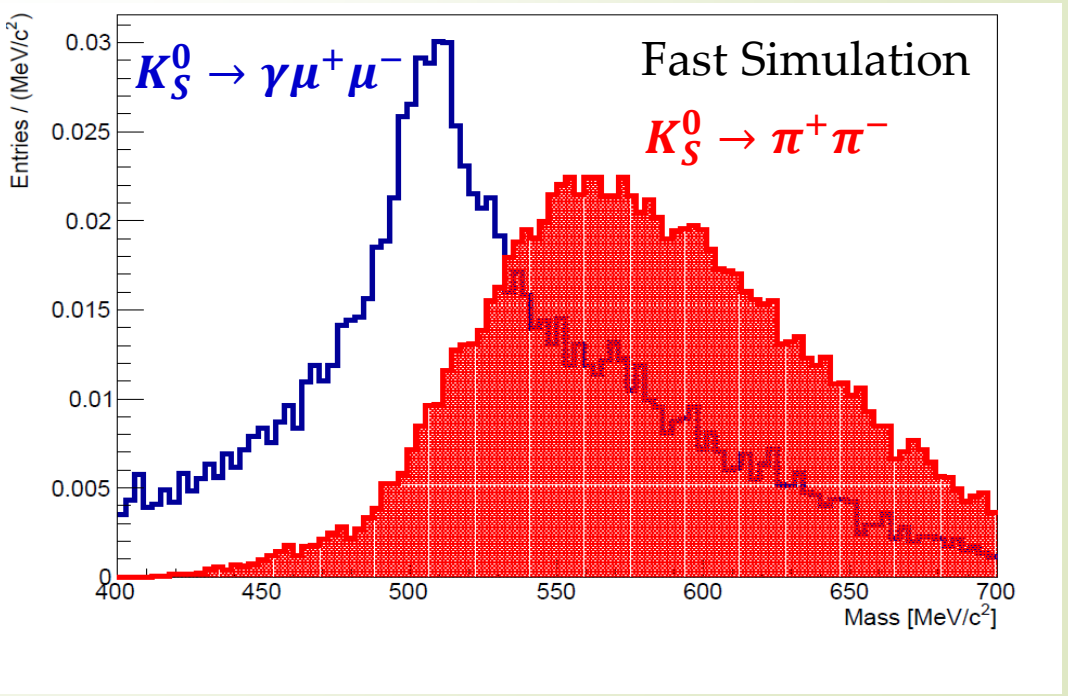
- $w_{7A,7V} = \frac{\mathrm{Im}(\lambda_t \times y_{7A,7V})}{\mathrm{Im}\lambda_t}$, $\quad y_{7V}(\mu \approx 1\mathrm{GeV}) = 0.73 \pm 0.04$, $\quad y_{7A}(M_W) = -0.68 \pm 0.03$
- $\mathrm{Im}\lambda_t = (1.407 \pm 0.098) \times 10^{-4}$

$K_S \to \pi^0\mu^+\mu^-$: Extension to $K_S \to X^0\mu^+\mu^-$

- $K_S \to \pi^0\mu^+\mu^-$ can be extended to any other neutral (X^0), or $X^0\pi\mu$
  - Better resolution for massive X^0
  - More restrictive case: $X^0 = \gamma$ (massless)
- Main background from $K_S^0 \to \pi^+\pi^-$

JHEP 05 (2019) 048



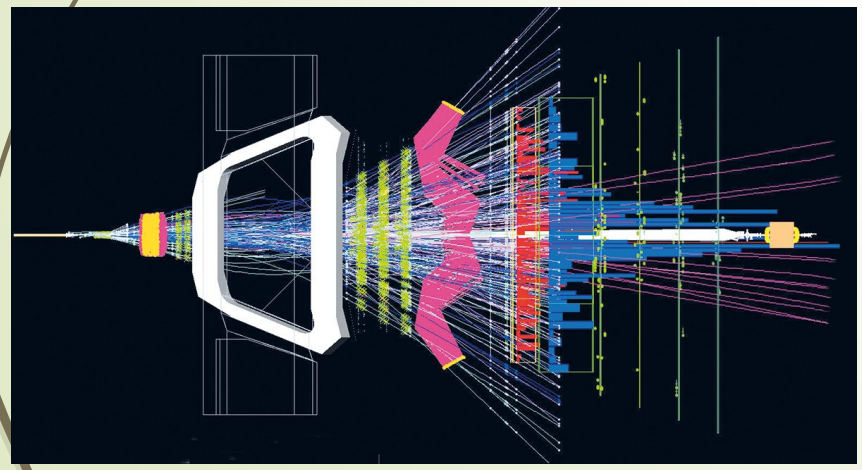


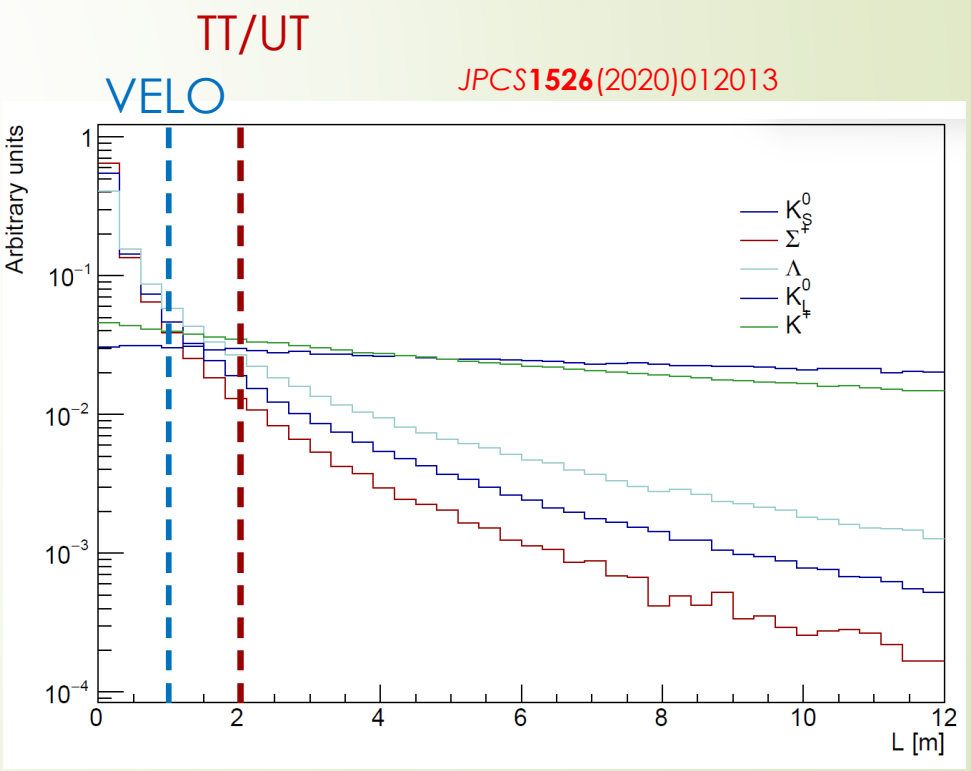
Challenges: Transverse momentum

Transverse momentum (p_T) standard handle for signal-bkg separation at LHCb

- Not usable for s decays due to their low energy
  - B physics: p_T ~ 1-2 GeV/c
  - s physics: p_T ~ 0.08 GeV/c
- Compensated requiring large flight distance (FD)
  - B physics: FD~ 1-2 cm
  - s physics: FD ~ O(70) cm

CERN Courier – May/22





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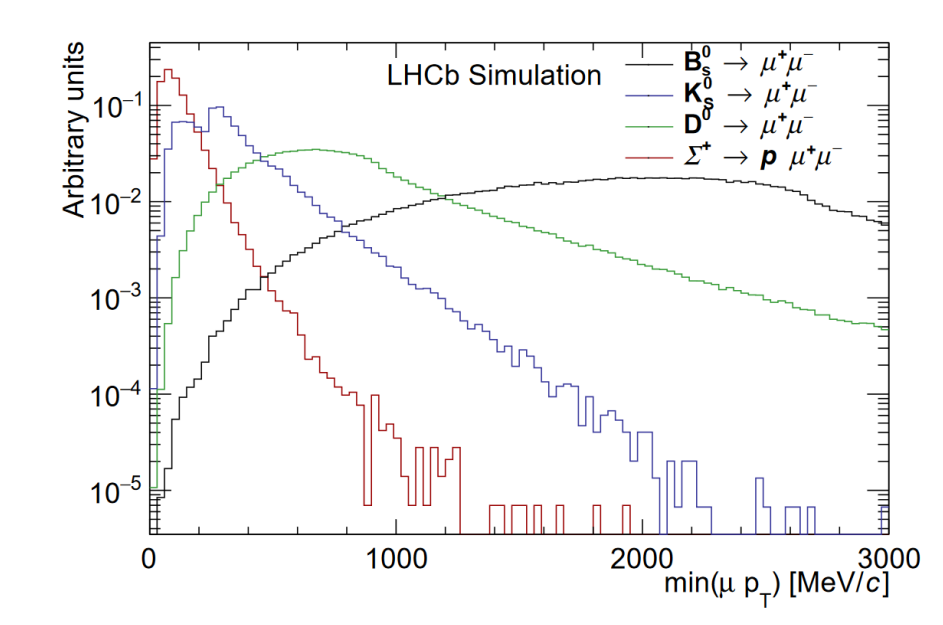
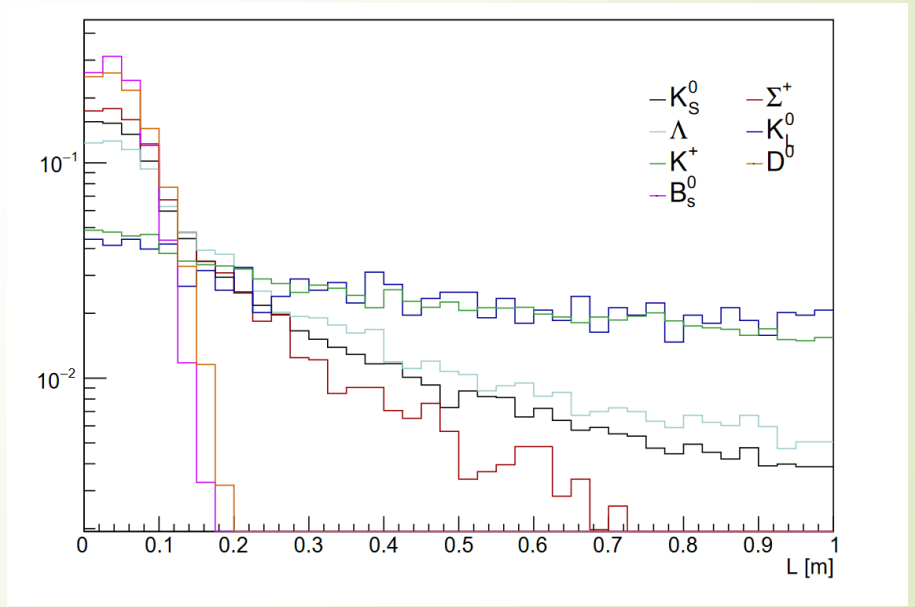




LHCb-PUB-2017-023

LHCb sensitivity to strange processes

JHEP05(2019)048

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K_S^0 \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K_S^0 \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K_S^0 \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K_S^0 \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K_L^0 \to \mu^+\mu^-$	~ 1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~ 3.0	~ 7.0
$K^+ \to \pi^+\pi^+\pi^-$	~ 2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~ 1.0	~ 4.0
$K^+ \to \pi^+\mu^+\mu^-$	~ 2	6.3 (2.3) $\times 10^{-3}$	0.030 (0.014)	~ 1.5	~ 4.5
$\Sigma^+ \to p\mu^+\mu^-$	~ 0.13	0.28 (0.28)	0.64 (0.64)	~ 1.0	~ 3.0
$\Lambda \to p\pi^-$	~ 0.45	0.41 (0.075)	1.3 (0.39)	~ 1.5	~ 5.0
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~ 0.45	0.32 (0.31)	0.88 (0.86)	–	–
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~ 0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	–	–
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~ 0.03	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	–	–
$\Xi^- \to p\pi^-\pi^-$	~ 0.03	0.41(0.05)	0.94 (0.20)	~ 3.0	~ 9.0
$\Xi^0 \to p\pi^-$	~ 0.03	1.0 (0.48)	2.0 (1.3)	~ 5.0	~ 10
$\Omega^- \to \Lambda\pi^-$	~ 0.001	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~ 7.0	~ 20

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \pi^+\pi^-e^+e^-$	1	1.0 (0.18)	2.83 (1.1)	~ 2.0	~ 10
$K_S^0 \to \mu^+\mu^-e^+e^-$	1	1.18 (0.48)	2.93 (1.4)	~ 2.0	~ 11
$K^+ \to \pi^+e^+e^-$	~ 2	0.04 (0.01)	0.17 (0.06)	~ 3.0	~ 13
$\Sigma^+ \to pe^+e^-$	~ 0.13	1.76 (0.56)	3.2 (1.3)	~ 3.5	~ 11
$\Lambda \to p\pi^-e^+e^-$	~ 0.45	$< 2.2 \times 10^{-4}$	~ 17 (< 2.2) $\times 10^{-4}$	–	–

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	$\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K_S^0 \to \mu^+e^-$	1	1.0 (0.84)	1.5 (1.3)	~ 3.0	~ 8.0
$K_L^0 \to \mu^+e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	~ 3.0	~ 7.0
$K^+ \to \pi^+\mu^+e^-$	~ 2	3.1 (1.1) $\times 10^{-3}$	16 (8.5) $\times 10^{-3}$	~ 2.0	~ 8.0

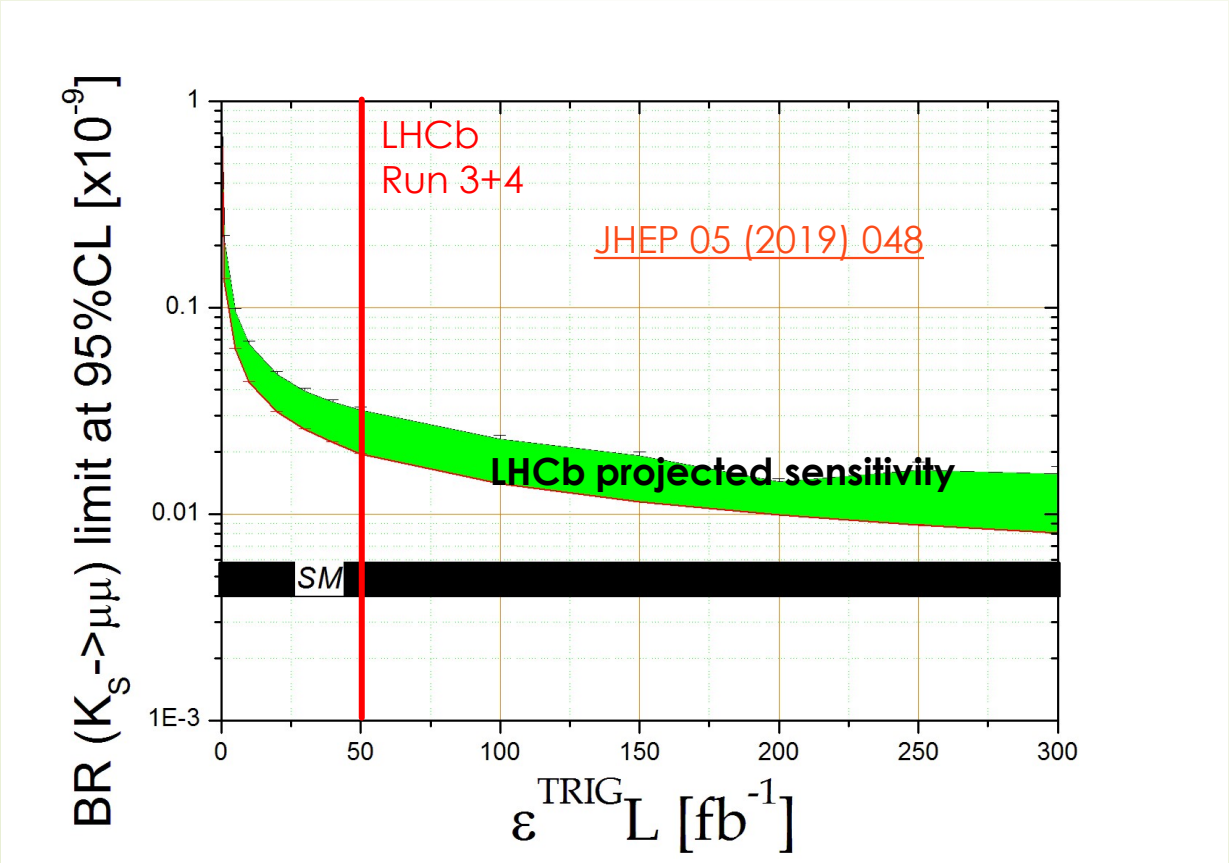
$\mathcal{R}$ – ratio of production w.r.t. K_S^0

ϵ – ratio of efficiencies w.r.t. $K_S^0 \to \mu^+\mu^-$

- Approximate simulations (validated with published ones) to get sensitivities
- Many channels to be probed

$K_S \to \mu^+\mu^-$: Prospects

- Expected to reach sensitivity close to the SM prediction with the Upgrade II



Phase II Upgrade → 300 fb^{-1}