Measurements and prospects for K_S^0 decays at LHCb

16th International Conference on Heavy Quarks and Leptons

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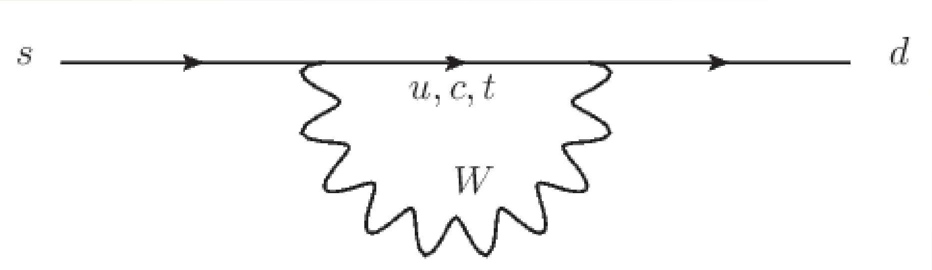
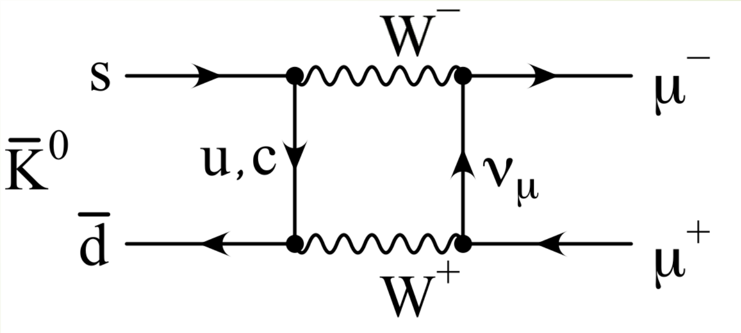
on behalf of the LHCb Collaboration

Introduction: Why Kaons?

- The $s \rightarrow d$ process is forbidden at tree level in the SM (suppressed)
- Some exotic BSM scenarios can enhance it by 2 orders of magnitude

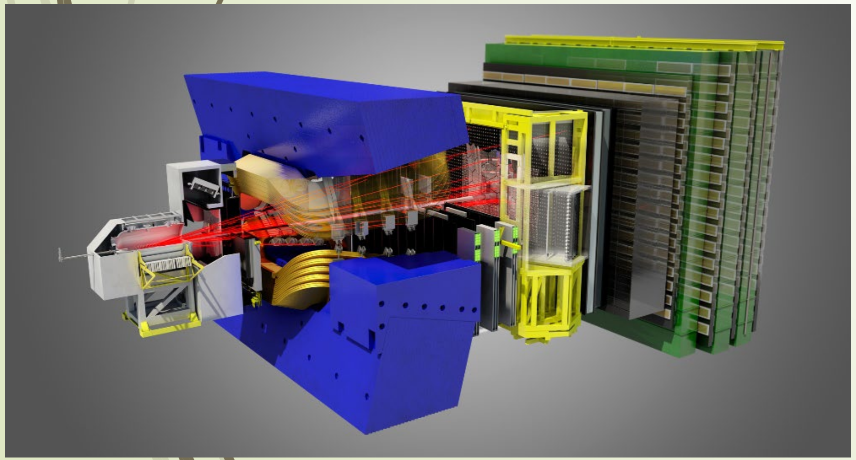
  arXiv:2201.07805



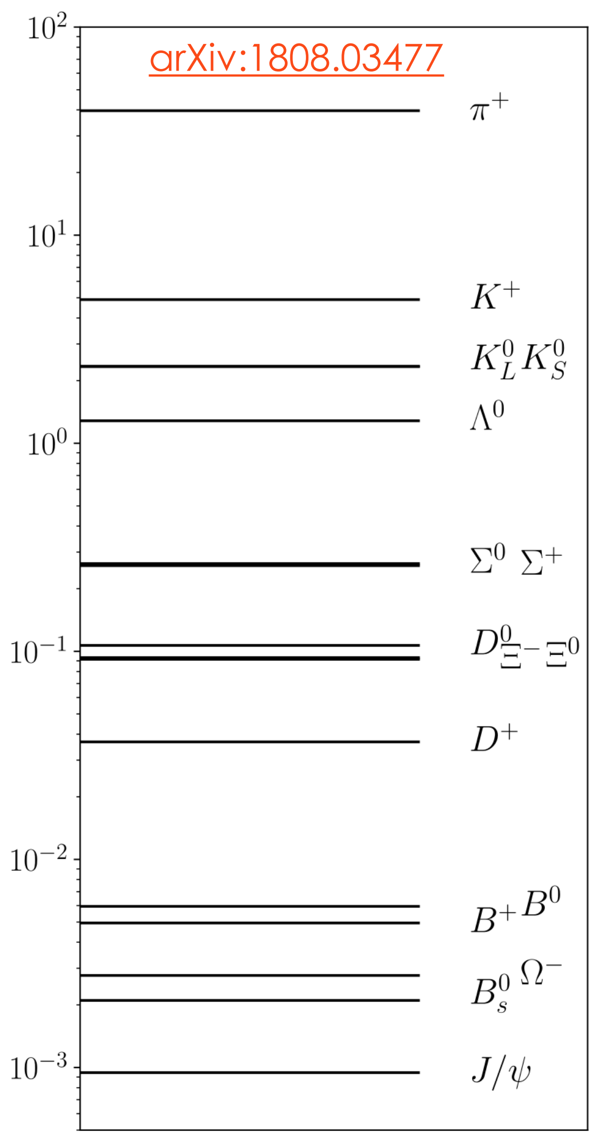


Introduction: LHCb

- Single-arm forward spectrometer
  - Optimized for b and c decays
  - Trigger efficiency close to zero for s decays
- Very large strangeness production at LHC
  - About 1 strange hadron per event (~1 B^0 in 500 events)
  - Also from b and c decays



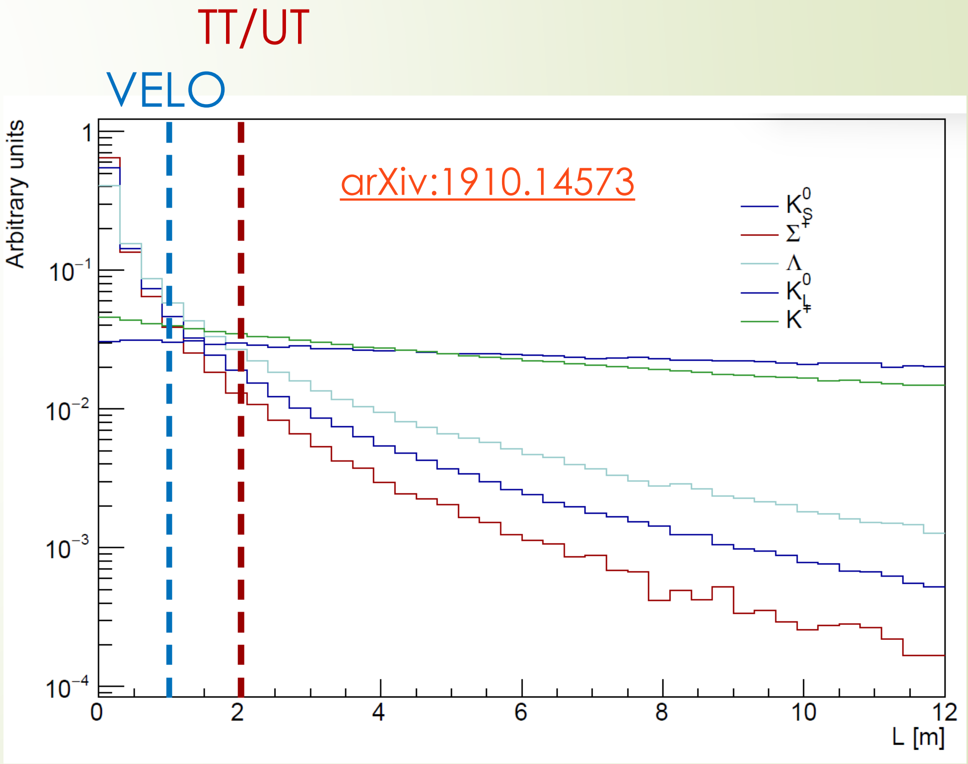
- Major trigger improvements for Run 2 (2016-2018)
- Two upgrades:
  - Upgrade 1 (2023-2030)
  - Upgrade 2 (2031-2035)



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



Challenges: Trigger

L0 (Hardware)

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

HLT1 (Software)

Not designed for K physics but **flexible**

HLT2 (Software)

Dedicated K triggers implemented in Run II

$\varepsilon_{trig}(\text{Run 1}) \sim 1-2\%$
$\varepsilon_{trig}(\text{Run 2}) \sim 18\%$ (dimuons)

- improved HLT
- Maximum allowed by L0 ~30%

JINST 14 (2019) P04013
LHCb-PUB-2017-023

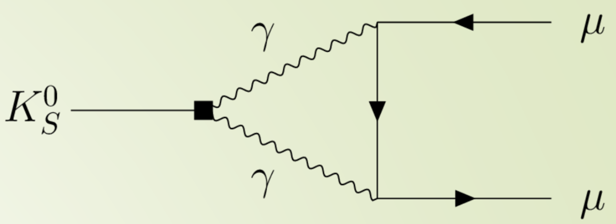
Upgrade(s)

HLT (Software)

LHCb upgrade(s):
$\varepsilon_{trig}(\textbf{2022}+) \sim \textbf{100\%}$

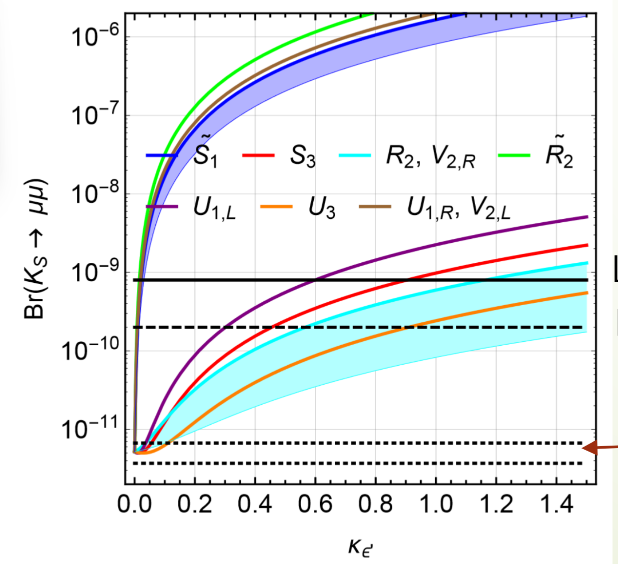
LHCB-TDR-021

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



- SM prediction: $\mathrm{BR}(K_S \to \mu^+\mu^-)_{SM} = (5.18 \pm 1.50_{\mathrm{LD}} \pm 0.02_{\mathrm{SD}}) \times 10^{-12}$
- Sensitive to different physics than $K_L \to \mu^+\mu^-$:
  - NP contributions can be an order of magnitude higher than the SM value
  - Can even saturate the current limits JHEP 03 (2022) 048

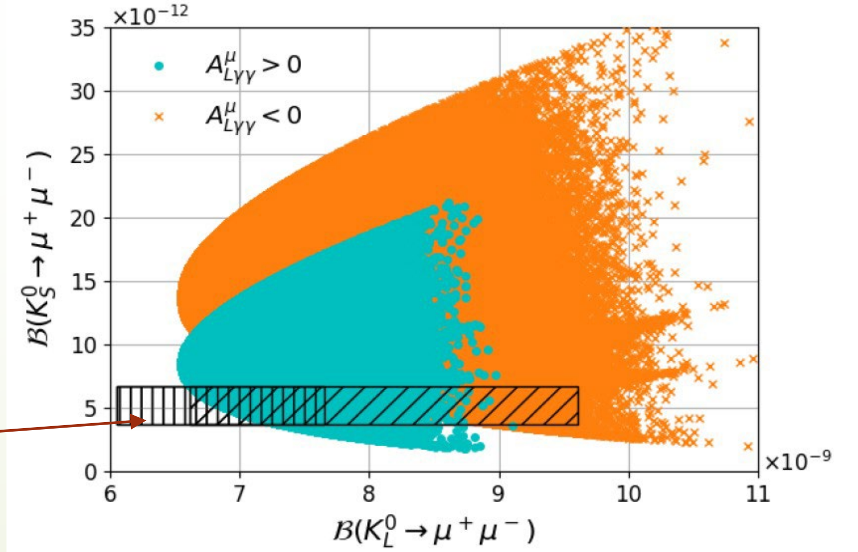
JHEP 05 (2018) 024 ,
JHEP 0401 (2004) 009,
NPB 366 (1991) 189



LHCb

LHCb prospects

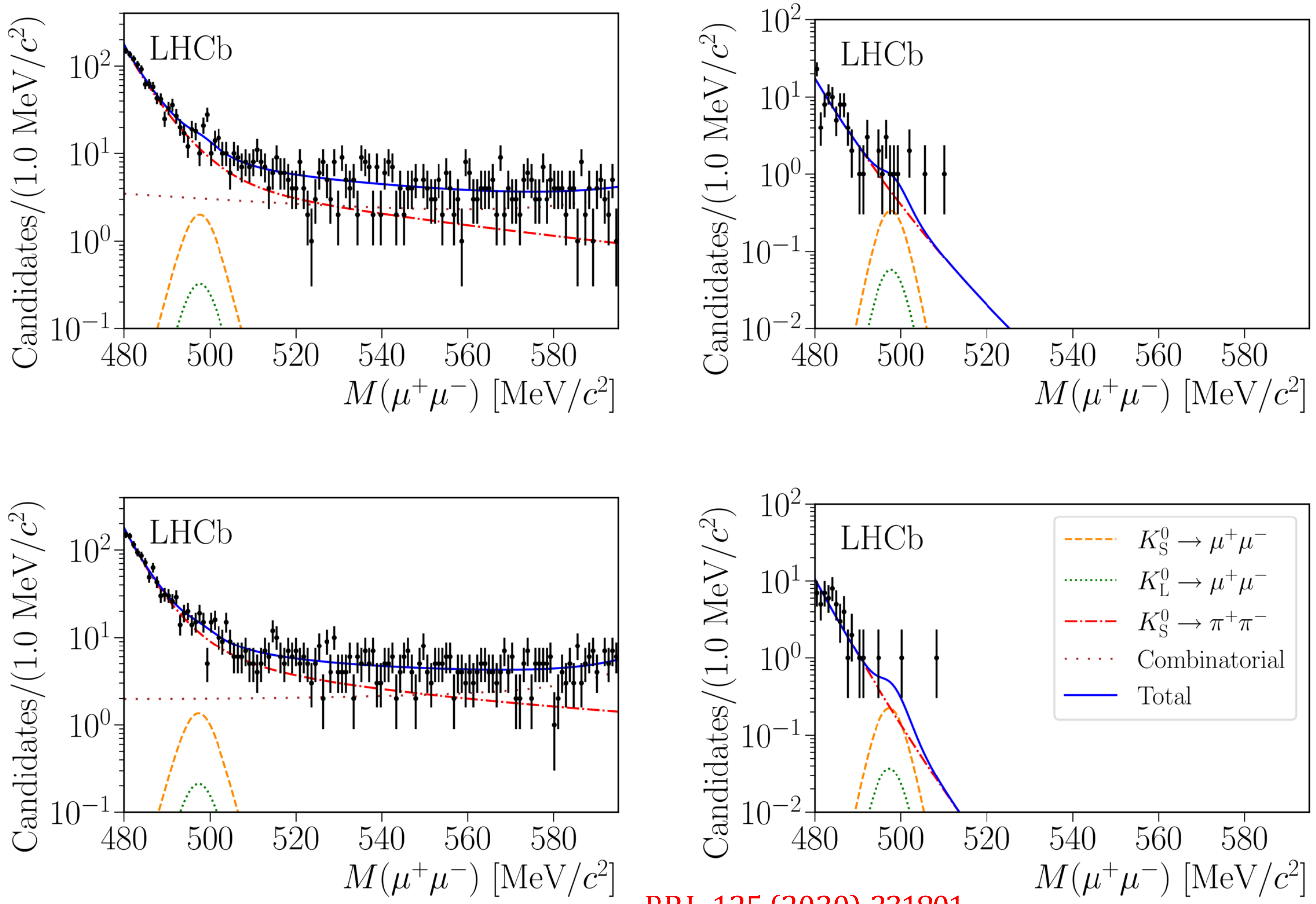
SM



Leptoquark scenarios JHEP 02 (2018) 101

SUSY scenario JHEP 05 (2018) 024

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



PRL 125 (2020) 231801

- Full Run 1 + 2 dataset (9 fb^{-1})
- Search performed in:
  - bins of the BDT output
  - trigger categories
- Normalization channel: $K_S \to \pi^+\pi^-$
- No evidence of signal (1.4 σ)

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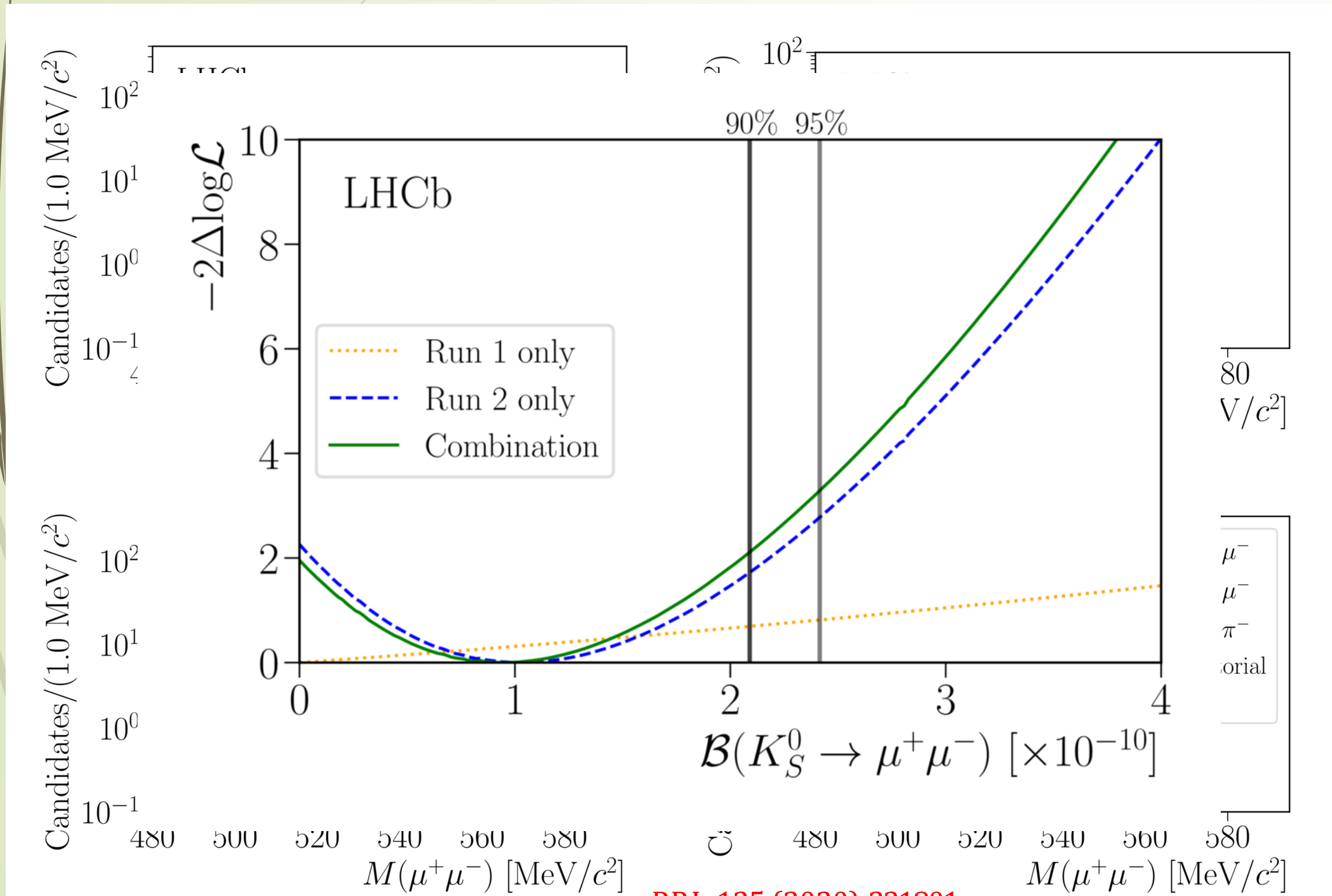

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$BR(K^0_S \to \mu^+\mu^-)_{theo} \sim 10^{-12}$

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

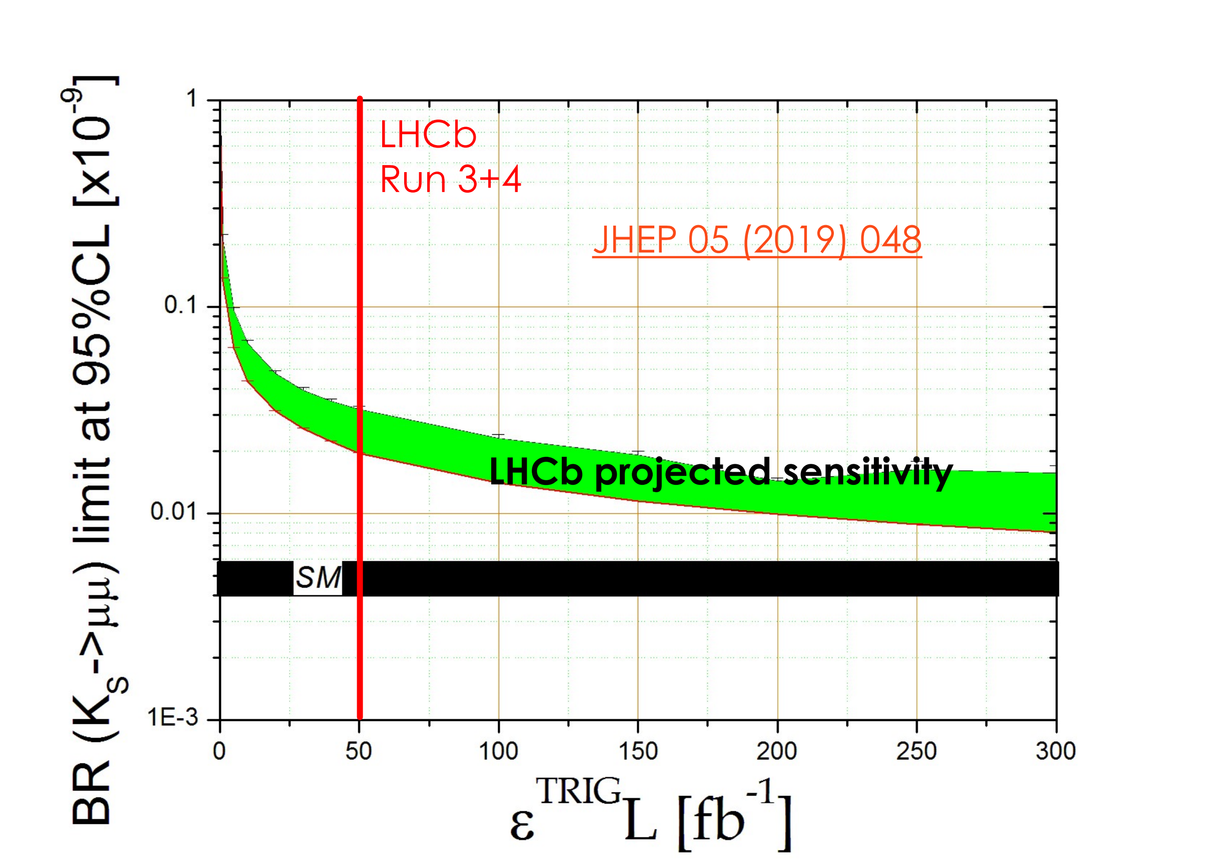
PRL 125 (2020) 231801

- Updates previous LHCb Run 1 result
  - $BR(K^0_S \to \mu^+\mu^-) < 0.8 \times 10^{-9}$ @ 90% CL

EPJC 77 (2017) 678

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

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



Phase II Upgrade → 300 fb^{-1}

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

- $K^0 \to l^+l^+l^-l^-$
  - 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
  - $\mathcal{A}(K_L^0 \to l^+l^+l^-l^-)$: Studied by other experiments
  - $\mathcal{A}(K_S^0 \to l^+l^+l^-l^-)$: No experimental constraint

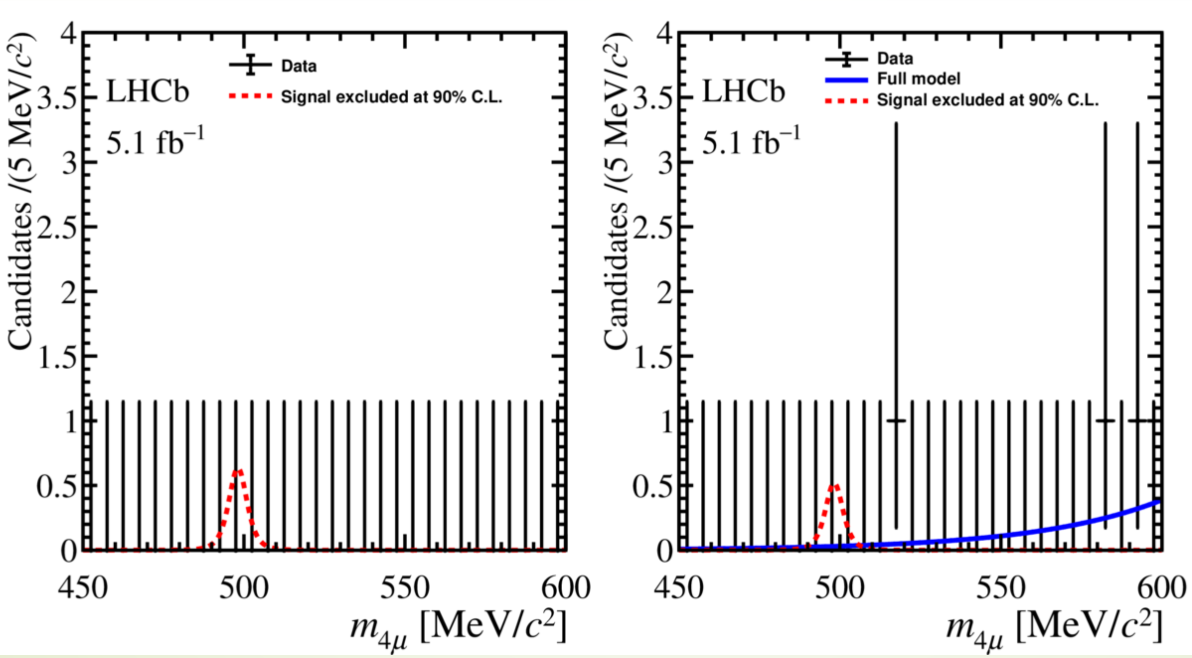
EPJC 73 (2013) 2678
JHEP 0401 (2004) 009

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

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

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

- SM prediction: $BR(K_S \to \mu^+\mu^-\mu^+\mu^-)_{SM} \sim O(10^{-14})$ EPJC 73 (2013) 2678
- Normalization channel: $K_S \to \pi^+\pi^-$
- Low background expected ($K_S \to \pi^+\pi^-$ supressed)
- No events found in signal region (Run 1 + 2)



PRD108 (2023) L031102

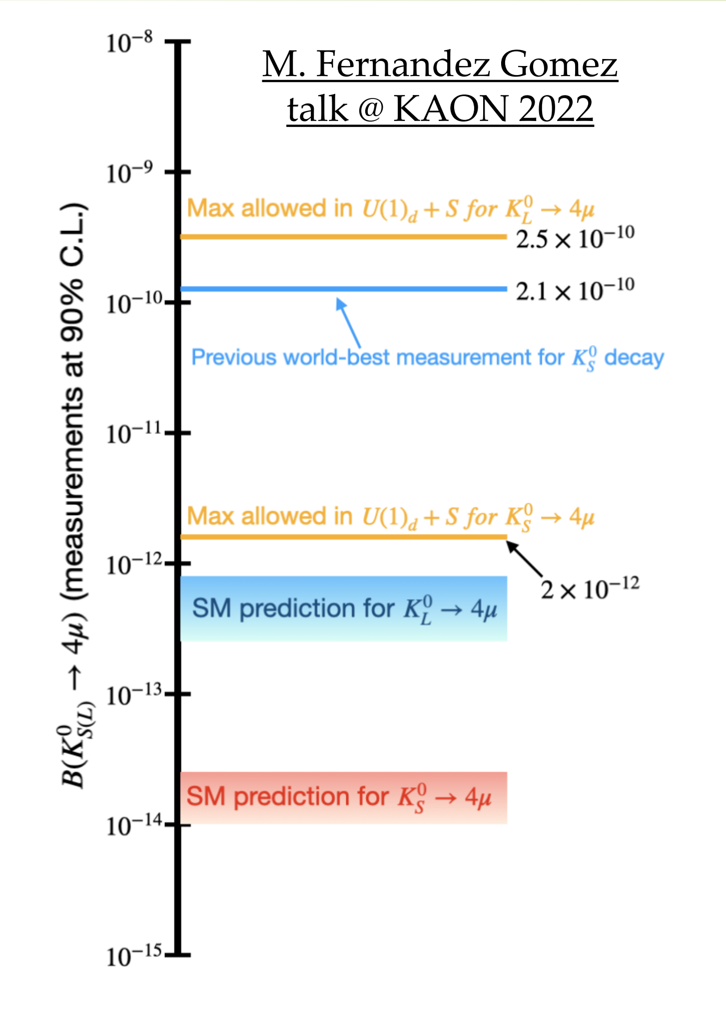
$K_S \to \mu^+\mu^-\mu^+\mu^-$: Results

- World's best (first) upper limit

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

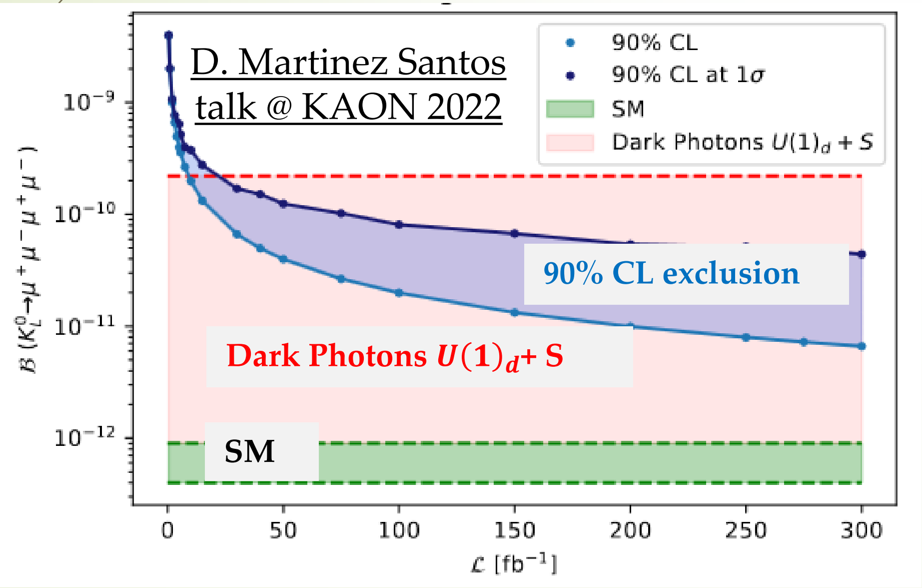
arXiv:2212.04977
PRD108 (2023) L031102

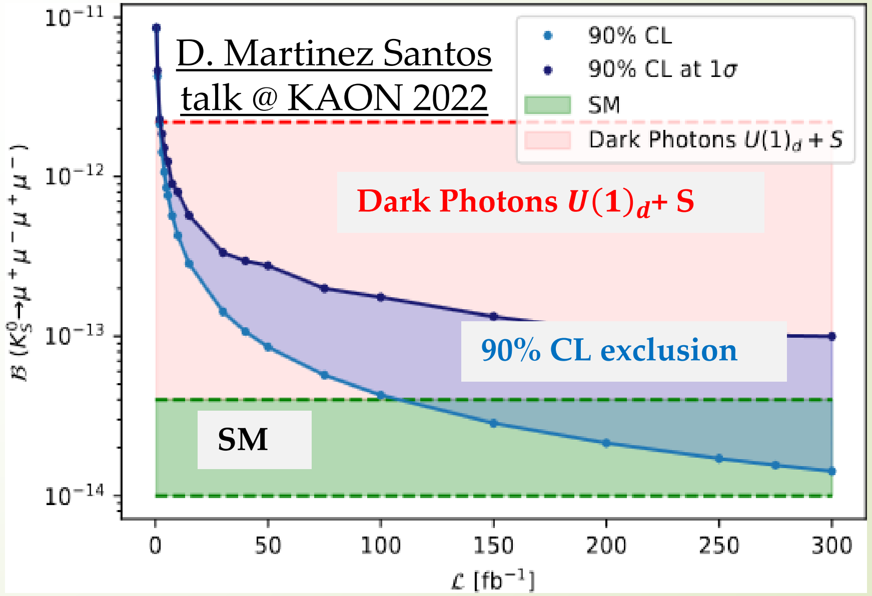
- First LHCb result with K_L^0!!
- Limits close to maximum allowed by the BSM



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





LHCb sensitivity to strange processes

arXiv:1808.03477

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	σ_L(MeV/c^2)	σ_D(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	σ_L(MeV/c^2)	σ_D(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	σ_L(MeV/c^2)	σ_D(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
ϵ – ratio of efficiencies

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

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

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

JHEP 08 (2006) 088

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

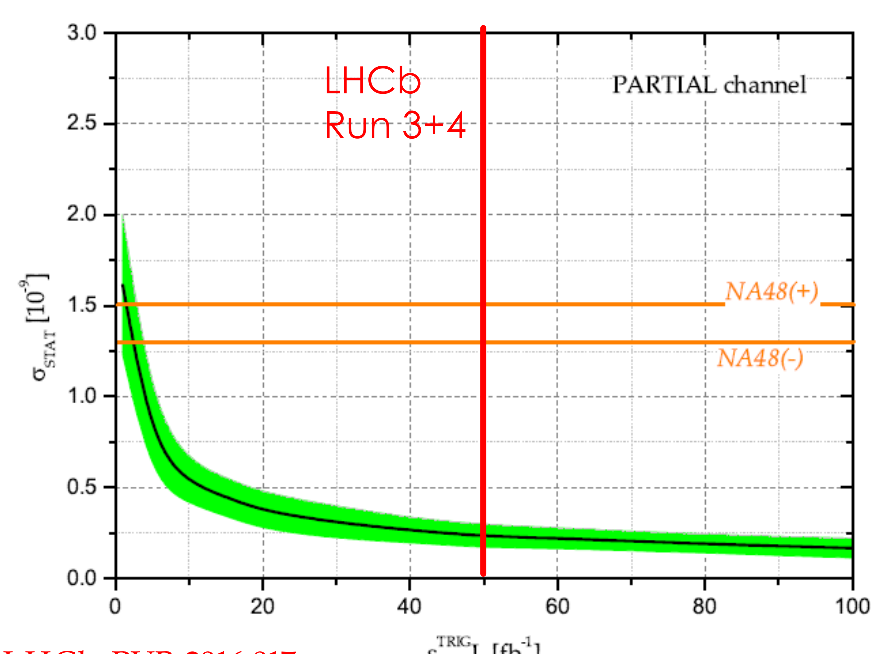
- $\mathrm{C^e_{dir}} = (4.62 \pm 0.24) \times \left(\mathrm{w}^2_{7V} + \mathrm{w}^2_{7A}\right)$
- $\mathrm{C^e_{int}} = (11.3 \pm 0.3) \times \mathrm{w}_{7V}$
- $\mathrm{C^e_{mix}} = 14.5 \pm 0.5$
- $\mathrm{C^e_{mix}} \approx 0$
- $\mathrm{C^\mu_{dir}} = (1.09 \pm 0.05) \times \left(\mathrm{w}^2_{7V}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

- 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
  - $\mathrm{BR}(K_S \to \pi^0\mu^+\mu^-) \sim 10^{-9}$
  - $\mathrm{BR}(K_S \to \mu^+\mu^-) \sim 10^{-12}$



LHCb-PUB-2016-017

Projected statistical uncertainties on a_S under various analysis conditions

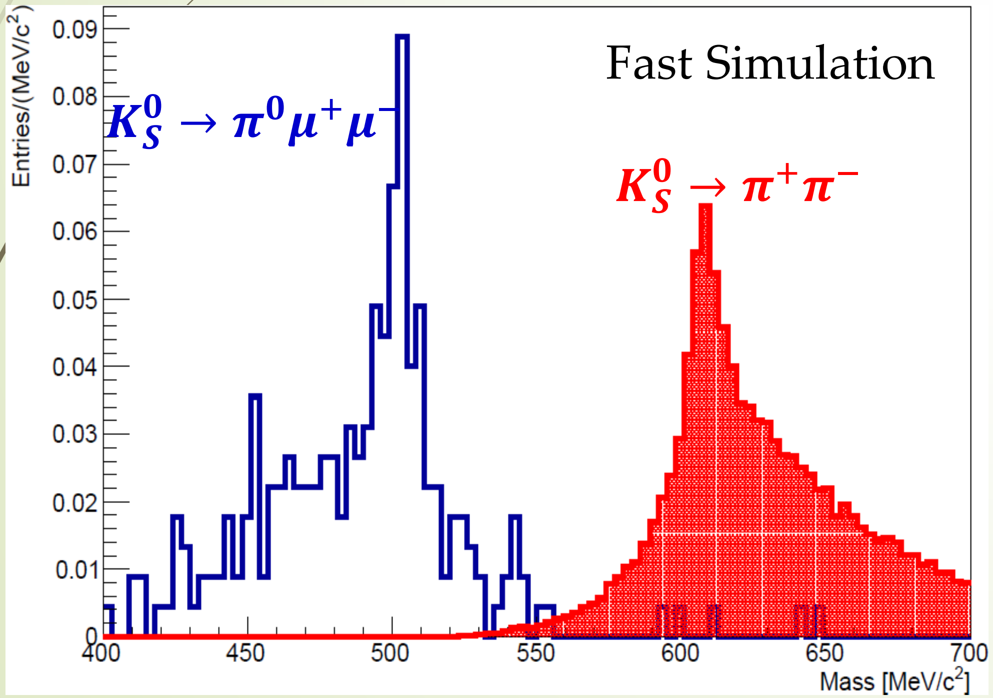
Configuration	Phase I	Phase II
BR & q^2 fit	0.25	0.10
BR & q^2 fit with NA48 constraint	0.19	0.10
BR & q^2 fit fixing b_S	0.06	0.024
a_S measurement from BR alone	0.06	0.024

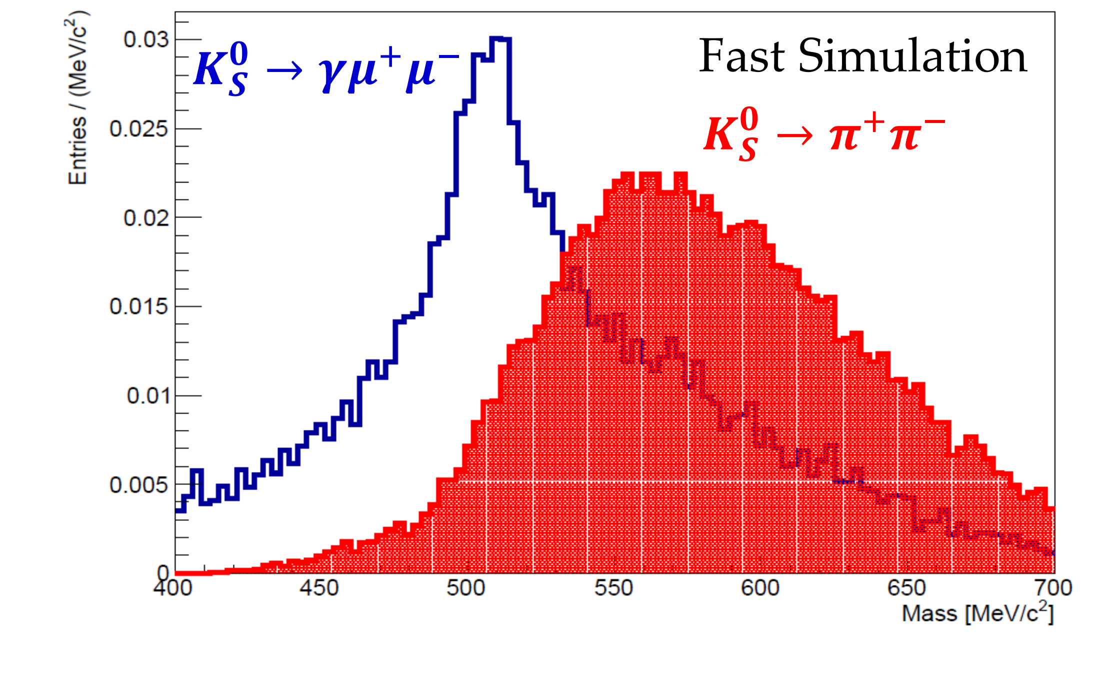
JHEP 05 (2019) 048

Phase II Upgrade → 300 fb^{-1}

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

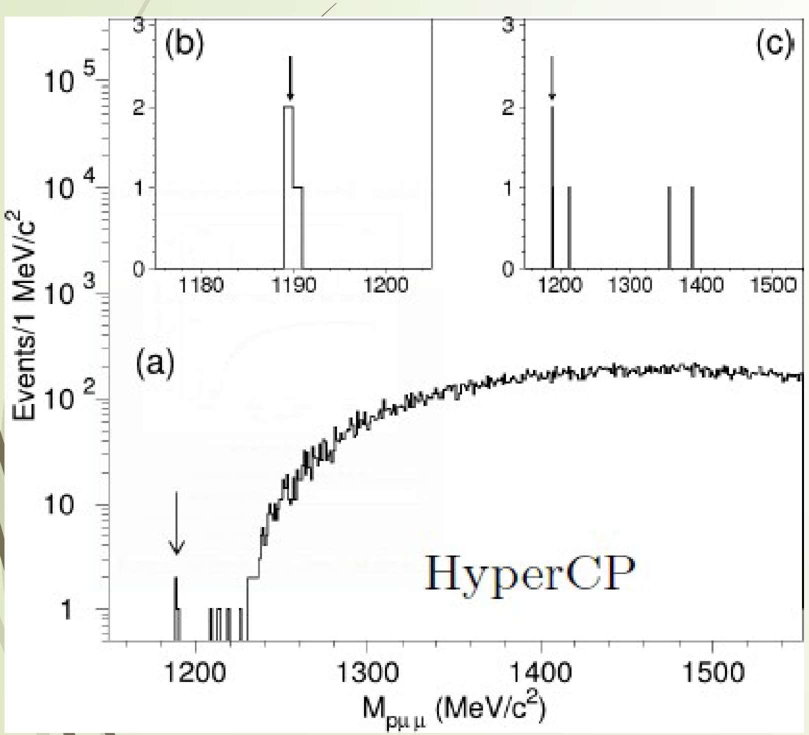


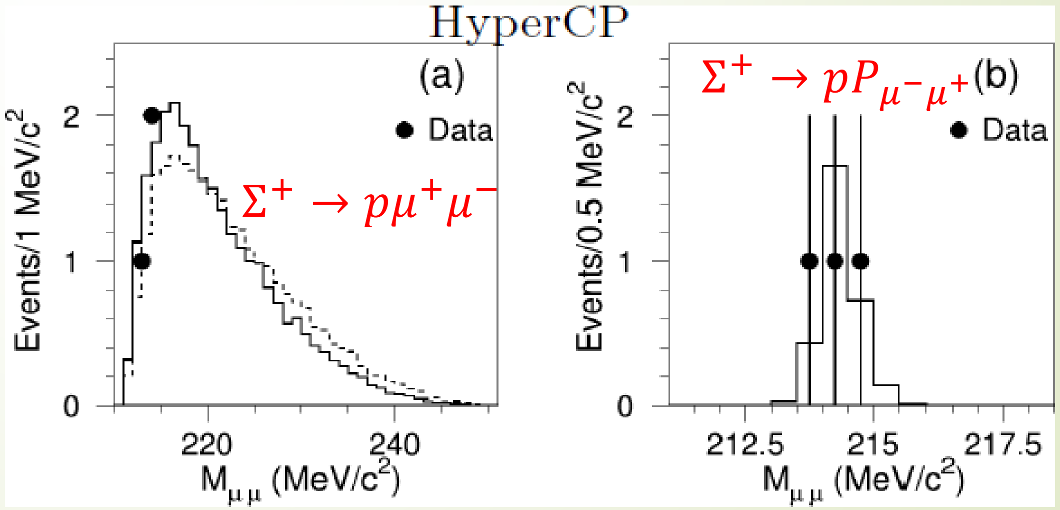


JHEP 05 (2019) 048

Beyond Kaons: $\Sigma^+ \rightarrow p\mu^+\mu^-$

- Evidence for the $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay (HyperCP)
  - $\boldsymbol{BR(\Sigma^+ \rightarrow p\mu^+\mu^-)_{\mathrm{HyperCP}} = \left(8.6^{+6.6}_{-5.4} \pm 5.5\right) \times 10^{-8}}$ PRL 94 (2005) 021801
  - $\boldsymbol{BR(\Sigma^+ \rightarrow p\mu^+\mu^-)_{SM} = [1.6,\ 9] \times 10^{-8}}$ PRD 72 (2005) 074003
- Existence of a new neutral particle at $m_{\mu\mu}$~214 MeV



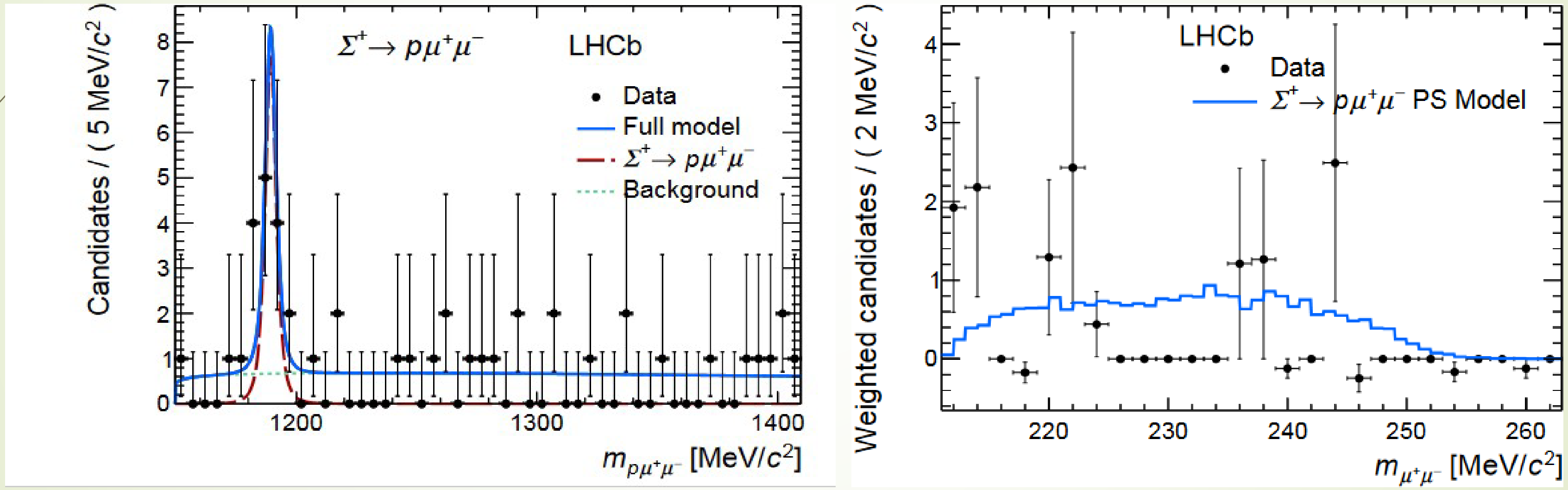


PRL 94 (2005) 021801

Considered impossible at LHCb 10 years ago

Beyond Kaons: $\Sigma^+ \to p\mu^+\mu^-$ at LHCb

- Using Run 1 (2011-2012) LHCb data PRL 120, 221803 (2018):
  - $\boldsymbol{BR(\Sigma^+ \to p\mu^+\mu^-) = \left(2.2^{+1.8}_{-1.3}\right) \times 10^{-8}}$ **with** $\boldsymbol{4.1\sigma}$
  - **No evidence of dilepton resonance**



- **New Run 2** (2016-2018) analysis ongoing (expected ~ 150 events)
  - If enough events, **Direct CP violation** measurement
- Goal for LHCb Upgrade(s): Measure differential branching ratio and A_{FB}

R. Marchevski
@FPCP

Beyond Kaons: Semileptonic hyperon decays

- SHD sensitive to suppressed helicity contributions:

$$R_{B_1 B_2} = \frac{\Gamma(B_1 \to B_2\, \mu^- \, \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2\, e^- \, \bar{\nu}_e)}$$

$$R^{\mathrm{NP}}_{B_1 B_2} \simeq \frac{\left(\epsilon_S^{s\mu} \frac{f_S(0)}{f_1(0)} + 12\, \epsilon_T^{s\mu} \frac{g_1(0)}{f_1(0)} \frac{f_T(0)}{f_1(0)}\right)}{(1 - \frac{3}{2}\delta)\left(1 + 3\frac{g_1(0)^2}{f_1(0)^2}\right)} \Pi(\Delta, m_\mu)$$

- High uncertainty in muonic modes (20-100%)
- High BR(~10^{-4}) – huge yields at LHCb
- Challenging peaking backgrounds
  - B1 → B2 μν → B1 → B2 π (misid rate O(1%))

Λ DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$p\pi^-$		(64.1 ±0.5) %	
Γ_2	$n\pi^0$		(35.9 ±0.5) %	
Γ_3	$n\gamma$		(8.3 ±0.7) × 10^{-4}	
Γ_4	$p\pi^-\gamma$	[a]	(8.5 ±1.4) × 10^{-4}	
Γ_5	$pe^-\bar{\nu}_e$		(8.34±0.14) × 10^{-4}	
Γ_6	$p\mu^-\bar{\nu}_\mu$		(1.51±0.19) × 10^{-4}	

Beyond Kaons: Semileptonic hyperon decays

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$$R_{B_1 B_2} = \frac{\Gamma(B_1 \to B_2\, \mu^- \,\bar{\nu}_\mu)}{\Gamma(B_1 \to B_2\, e^- \,\bar{\nu}_e)}$$

$$R^{\rm NP}_{B_1 B_2} \simeq \frac{\left(\epsilon_S^{s\mu} \frac{f_S(0)}{f_1(0)} + 12\, \epsilon_T^{s\mu} \frac{g_1(0)}{f_1(0)} \frac{f_T(0)}{f_1(0)}\right)}{(1-\frac{3}{2}\delta)\left(1+3\frac{g_1(0)^2}{f_1(0)^2}\right)} \Pi(\Delta, m_\mu)$$

- High uncertainty in muonic modes (10-100%)
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Γ_6	$p\mu^-\bar{\nu}_\mu$		$(1.51 \pm 0.19) \times 10^{-4}$	

- Mos recent $\mathcal{B}(\Lambda \to p\mu^-\nu_\mu)$ measurement by BES III
  - $\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu) = (1.48 \pm 0.21) \times 10^{-4}$ PRL 127, 121802 (2021)
  - LHCb aiming to improve it using Run 2 data

Other searches: Lepton Flavor Violation

- Lepton Flavor Violation is forbidden in the SM
  - Some BSM models predicts non-zero K → $(\pi)\mu e$ rate
  - K_L and K_S LFV model discriminator

[PRD 99 (2019) 055017]
[PRD 99 (2019) 055017]

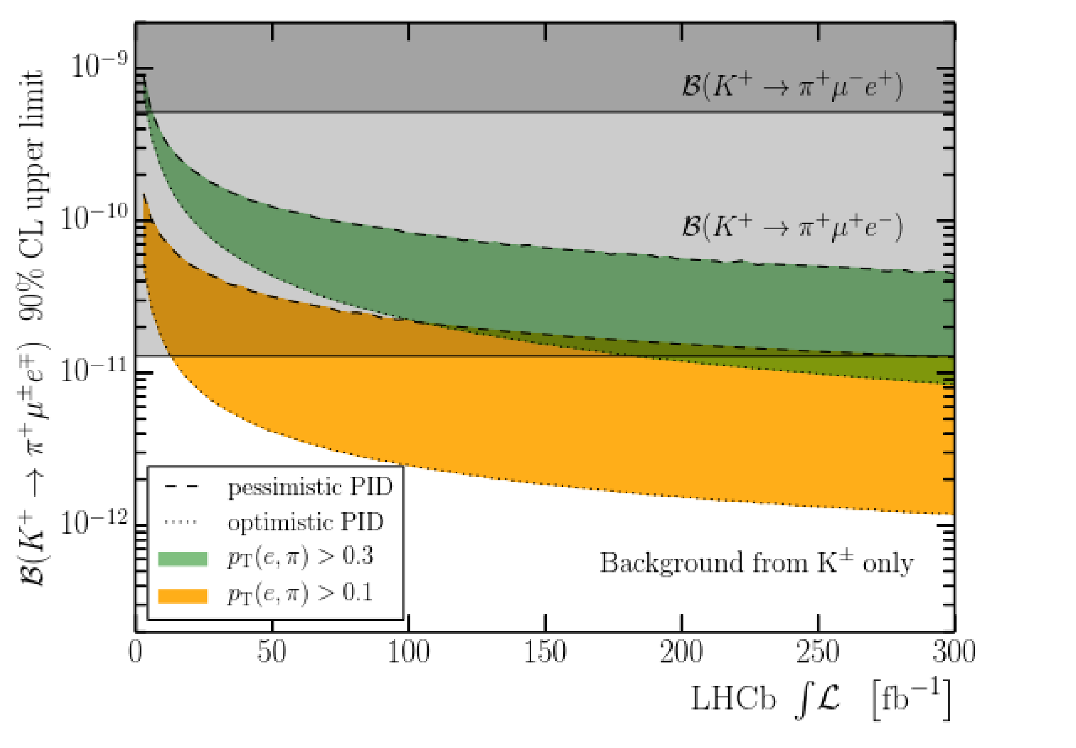
- Current status:

[PRL 81 (1998) 5734-5737]

  - $K_L \rightarrow e\mu < 4.7 \times 10^{-12}$ at BNL
  - $K_S \rightarrow e\mu$ no limit
  - $K^+ \rightarrow \pi^+\mu^-e^+ < 6.6 \times 10^{-11}$
  - $K^+ \rightarrow \pi^-\mu^+e^+ < 4.2 \times 10^{-11}$

PRL 127 (2021) 131802

- LHCb can contribute in these searches



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 $\Sigma^+ \to p\mu^+\mu^-, BR(K_S \to \mu^+\mu^-), K_{S(L)} \to \mu^+\mu^-\mu^+\mu^-$
- Published prospects for $K_S \to (\gamma/\pi^0)\mu^+\mu^-, K_S \to \pi^+\pi^-e^+e^-$
- Run II (2016-2018) data analyses ongoing: $\Sigma^+ \to p\mu^+\mu^-, K_S \to \pi^+\pi^-\mu^+\mu^-, \Lambda \to p\mu^-\nu$
- More channels in our TODO list (e.g. $K_S \to \mu\mu ee, K_S \to eeee$, other hyperon decays)

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


Thanks for your attention

Backup

Beyond Kaons: NP searches with Hyperons

Searches for NP using hyperons arXiv:2201.07805

- $\Xi^0 \to \pi^+\pi^- X$
  - Reach: few $\times 10^{-6}$ from statistics (systematics from backgrounds may be important)
- $\Xi^- \to \mu^+\mu^-\pi^- X$
  - Reach: few $\times 10^{-10} - 10^{-11}$from statistics, systematics from backgrounds expected to be small (peaking backgrounds $\Sigma \to p\mu\mu$ and $K \to \pi\mu\mu$ far away in mass)
  - Narrow peak near threshold, high trigger efficiency and low background due to the muons

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

Sensitive to BSM

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

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

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$$|a_S| = 1.20 \pm 0.20$$

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

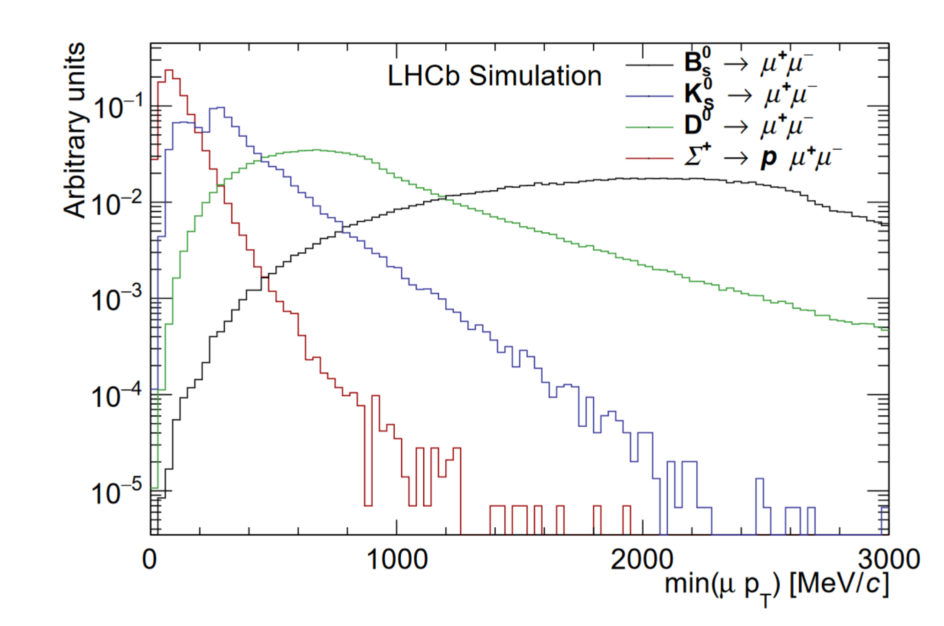
- $C^\mu_{dir} = (1.09 \pm 0.05) \times \left(w^2_{7V} + 2.32 \times w^2_{7A}\right)$
- $C^\mu_{int} = (2.63 \pm 0.06) \times w_{7V}$
- $C^\mu_{mix} = 3.36 \pm 0.20$
- $C^\mu_{mix} \approx 5.2 \pm 1.6$

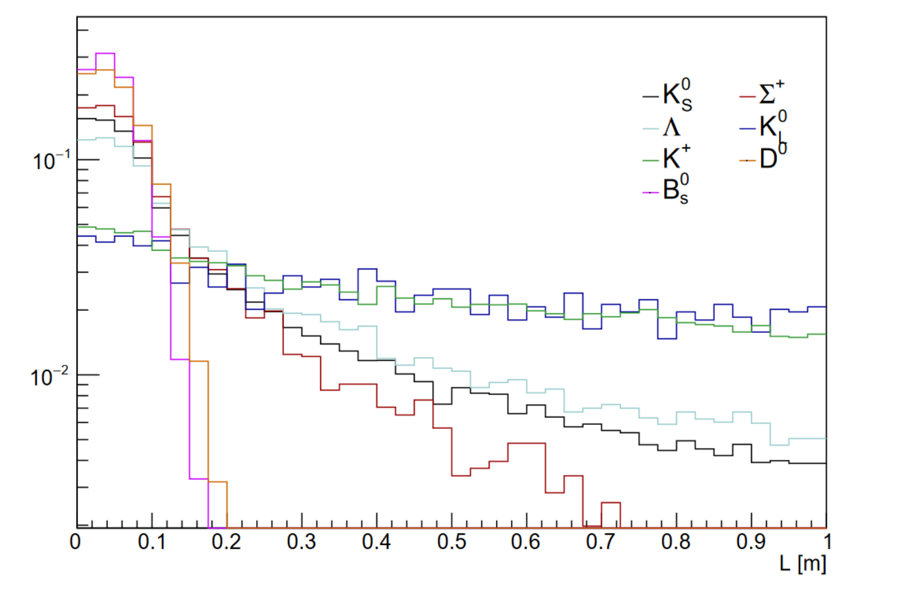
- $w_{7A,7V} = \frac{\mathrm{Im}(\lambda_t \times y_{7A,7V})}{\mathrm{Im}\lambda_t}$, $\quad y_{7V}(\mu \approx 1\mathrm{GeV}) = 0.73 \pm 0.04$, $\quad y_{7A}(M_W) = -0.68 \pm 0.03$
- $\mathrm{Im}\lambda_t = (1.407 \pm 0.098) \times 10^{-4}$

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





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