Strange physics at LHCb

FPCP 2023, May 29th– June 2nd, Lyon, France

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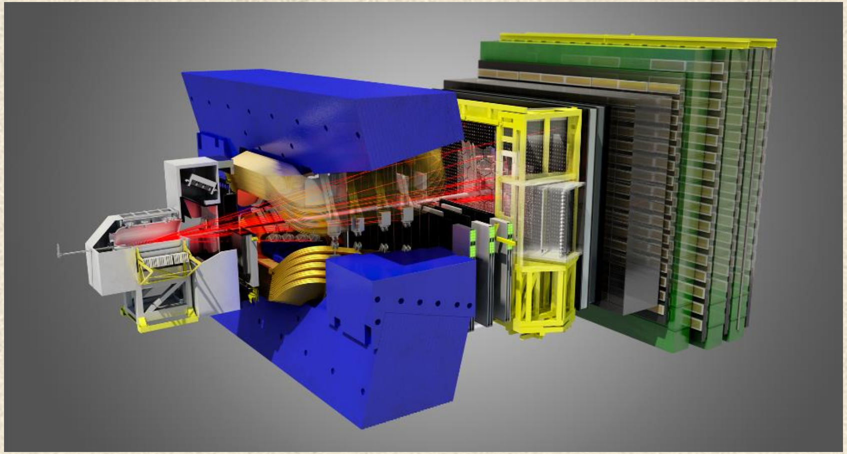
On behalf of the LHCb collaboration

Introduction



- LHCb experiment at the LHC
  - designed mostly to study **b** and **c** decays
  - trigger efficiency close to zero for **s** decays
- Very large strangeness production at the LHC ($\sigma_K^{prod} \sim \mathbf{1.2\ barn}$)
- World – best results on $K_S \to \mu^+\mu^-$(Run I + II) and $\Sigma^+ \to p\,\mu^+\mu^-$ (Run I)
- Major improvements in the trigger for **s** decays in Run-II (2016-18) and beyond
- Two upgrade phases
  - Phase I (2022 – 2030): Data taking has already started
  - Phase II (2031 – 2035): Framework TDR published (CERN-LHCC-2021-012)

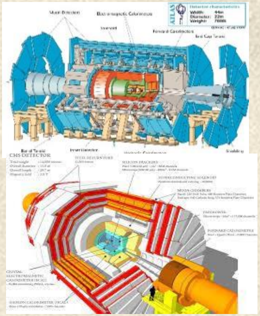
Exciting prospects for s physics at LHCb

Strange physics at the LHC

- Transverse momentum is a standard handle at the LHC to separate signal from generic pp collisions

- Doesn`t work for strange decays due to very low pT decay products

- Can be compensated by requiring large separation between the pp collision and the kaon decay point

	Typical pT
	**30 – 40 GeV**
***B* physics**	**~ 1 – 2 GeV**
***s* physics**	**0.08 GeV**

Trigger system – status and prospects

Run I + II

L0
(Hardware)

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

HLT1
(Software)

Not designed
for K physics
but flexible

HLT2
(Software)

Dedicated K
triggers
implemented in
Run II

Upgrade(s)

HLT
(Software)

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

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

- improved HLT
- Maximum allowed by L0 ~30%

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

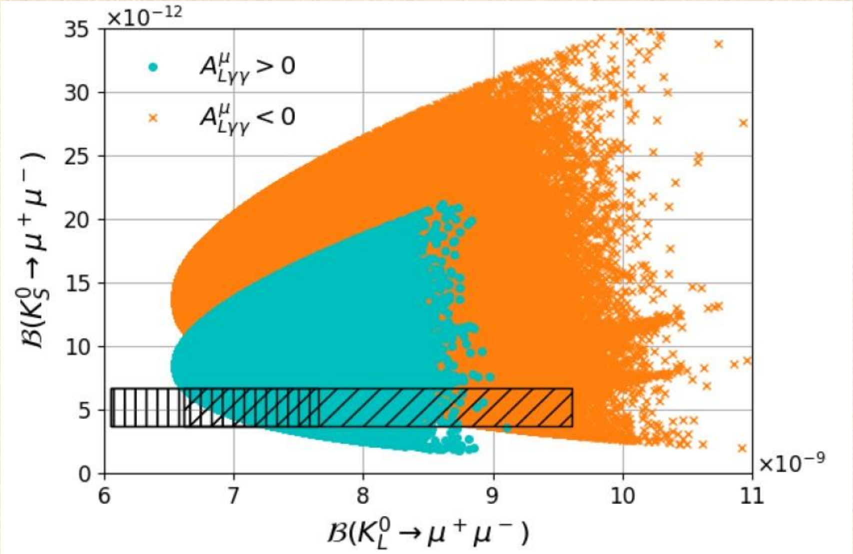
Recent strangeness measurements at LHCb

[PRL 125, 231801 (2020)], [PRL 120, 221803 (2018)], [arXiv:2212.04977v4]

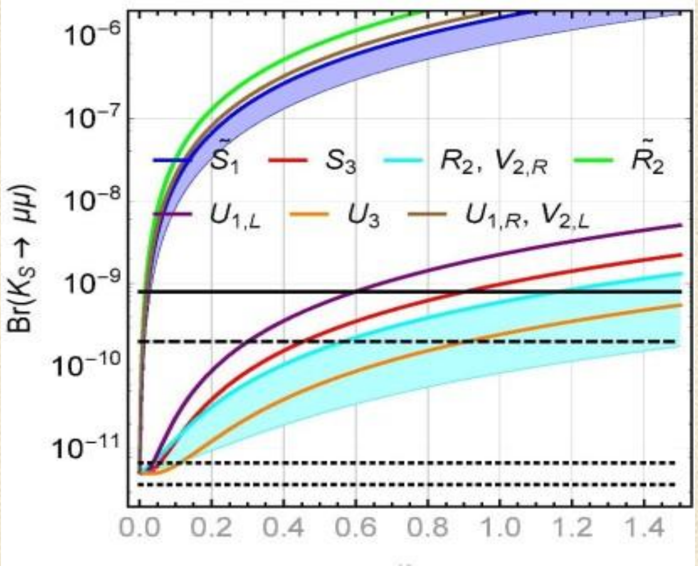
$K_S \to \mu^+\mu^-$: motivation

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

- 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 and can even saturate [JHEP03(2022)048] the current limits



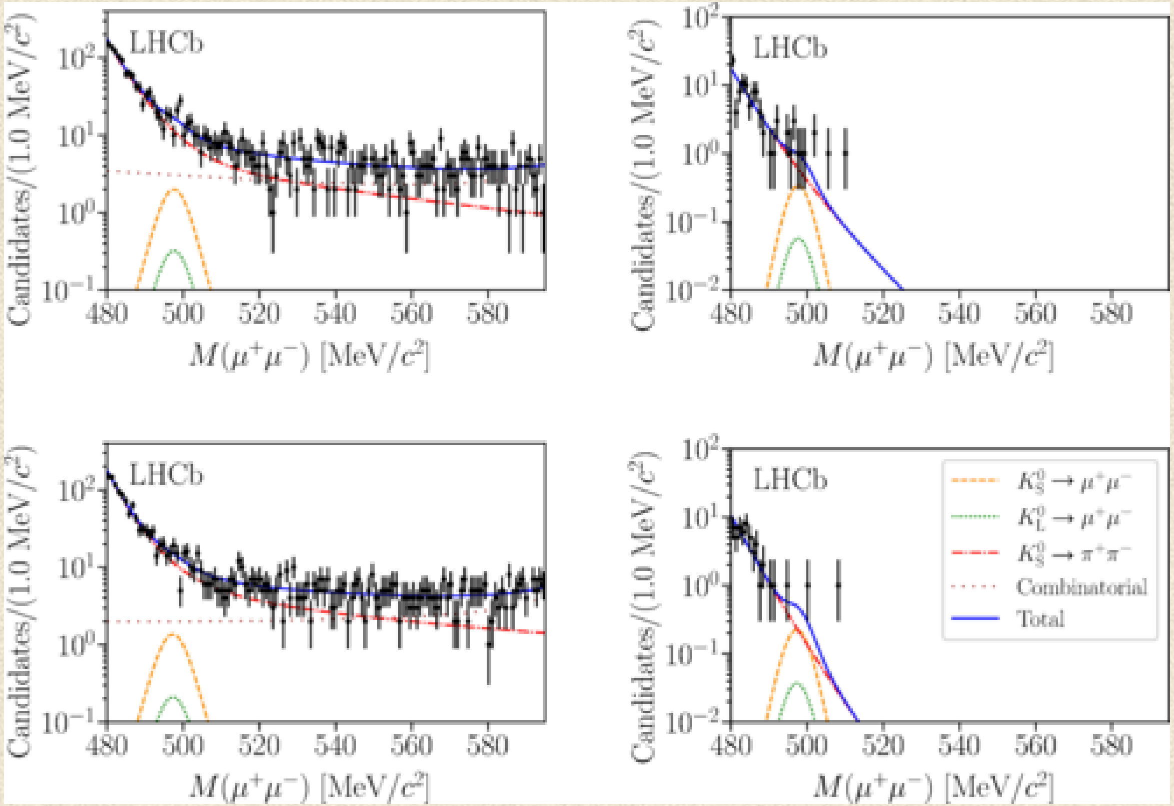
Example of a SUSY scenario JHEP 05 (2018) 024



Leptoquark scenarios from JHEP 02 (2018) 101

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

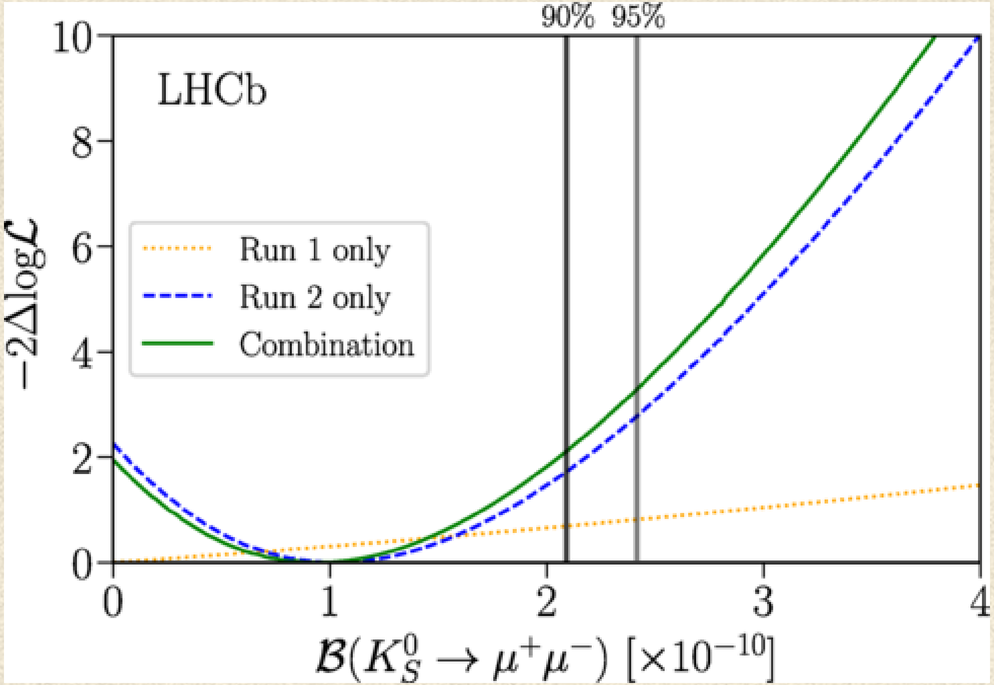
LHCb-PAPER-2019-038
arXiv: 2001.10354
PRL 125, 231801 (2020)



- Full Run I + II dataset (9 fb^{-1})
- No evidence of signal (1.4 σ)
- Search performed in bins of the BDT output for different trigger categories

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

LHCb-PAPER-2019-038
arXiv: 2001.10354
PRL 125, 231801 (2020)



- Full Run I + II dataset (9 fb^{-1}) analyzed
- No evidence of signal (1.4 σ)

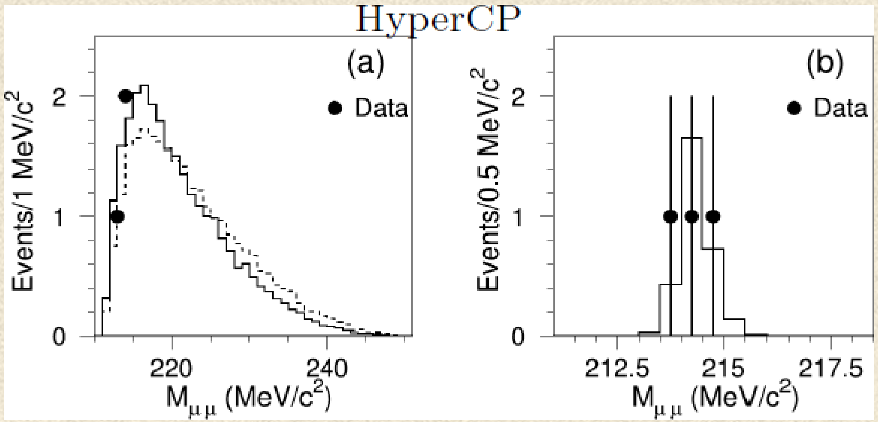
$$BR(K_S \to \mu^+\mu^-) < 2.1 \times 10^{-10} \text{ @ } 90\% \text{ CL}$$

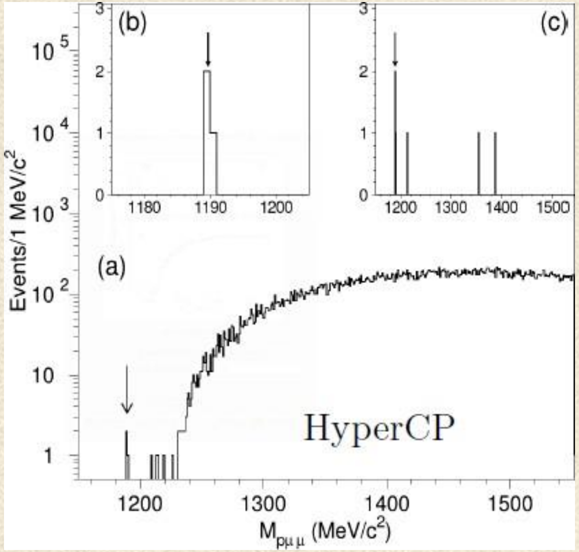
Expected to reach sensitivity close to the SM prediction with the Phase II upgrade

At 1σ: $BR(K_S \to \mu^+\mu^-) = 0.9^{+0.7}_{-0.6} \times 10^{-10}$

The $\Sigma^+ \to p\mu^+\mu^-$ decay: the HyperCP evidence

- The HyperCP collaboration (E871) at Fermilab found evidence for the $\Sigma^+ \to p\mu^+\mu^-$ decay
  - $BR(\Sigma^+ \to p\mu^+\mu^-) = \left(8.6^{+6.6}_{-5.4} \pm 5.5\right) \times 10^{-8}$ PRL 94 021801 (2005)
- Consistent with the SM expectation
  - $1.6 < BR(\Sigma^+ \to p\mu^+\mu^-)_{SM}\left[\times 10^{-8}\right] < 9$ PRD 72 074003 (2005)
- All three observed events had the same dimuon mass (214 MeV)
- Existence of a new neutral particle at that mass suggested

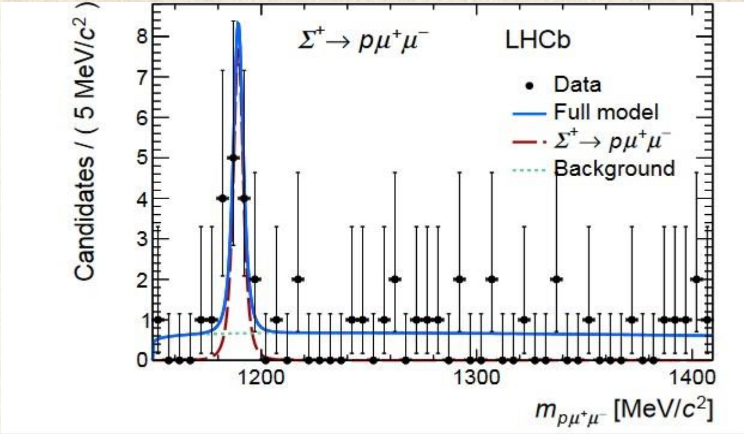


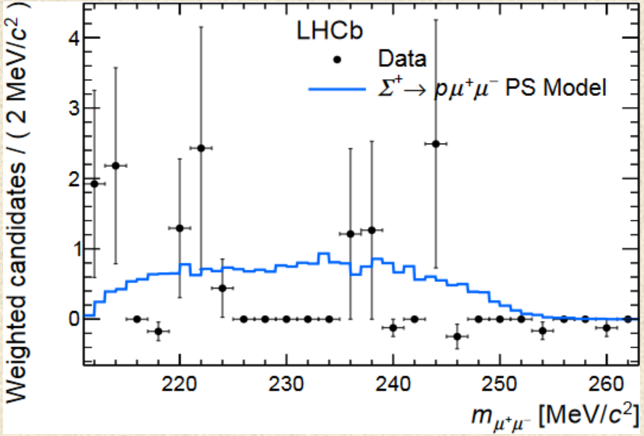


$\Sigma^+ \to p\mu^+\mu^-$ at LHCb

LHCb-PAPER-2017-049
arXiv:1712.08606
PRL 120, 221803 (2018)

- $\mathbf{4.1\sigma}$ evidence using Run I data ($3fb^{-1}$): $\boldsymbol{BR(\Sigma^+ \to p\mu^+\mu^-) = \left(2.2^{+1.8}_{-1.3}\right) \times 10^{-8}}$
- No evidence of resonant intermediate dilepton state
- Run II data: ~ 150 events expected allowing us to measure A_{FB} (analysis ongoing)
- Upgrade(s): differential decay rate measurement

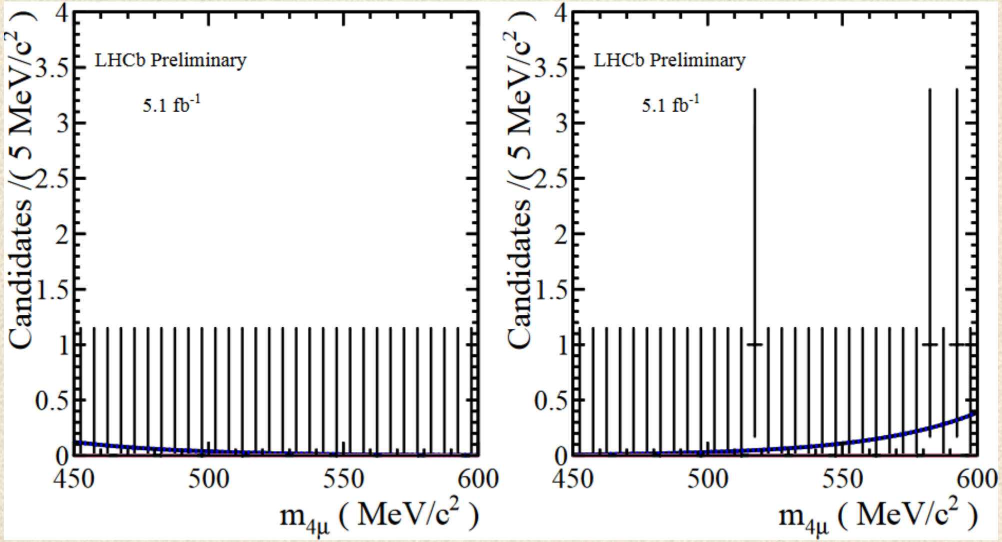




10 years ago this channel was considered impossible at LHCb. Now we are considering amplitude analysis

$K^0 \to \mu^+\mu^-\mu^+\mu^-$ at LHCb

- Search for $K_{S(L)} \to \mu\mu\mu\mu$ decays, heavily suppressed in the SM: $10^{-13}(K_L), 10^{-14}(K_S)$)
- No events found in signal region (Run I + II): world's best (first) upper limits on these decays

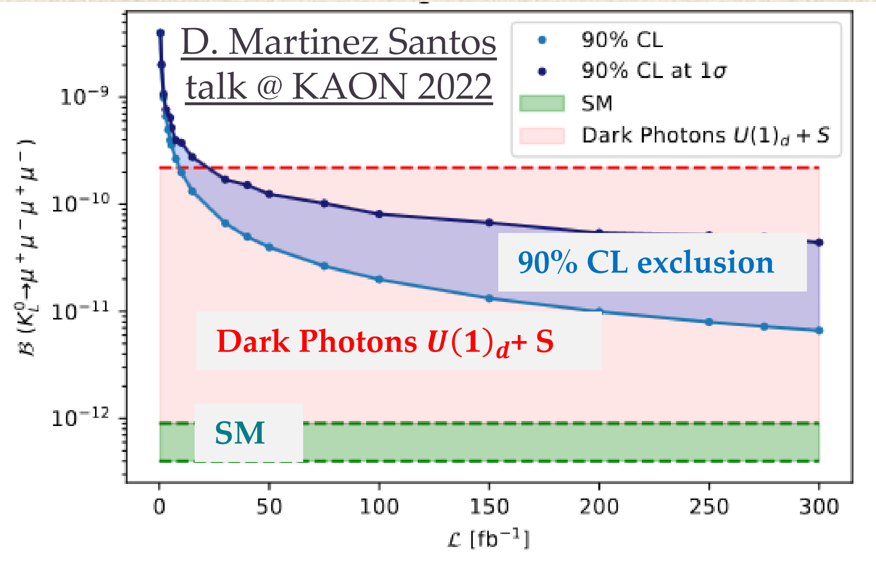


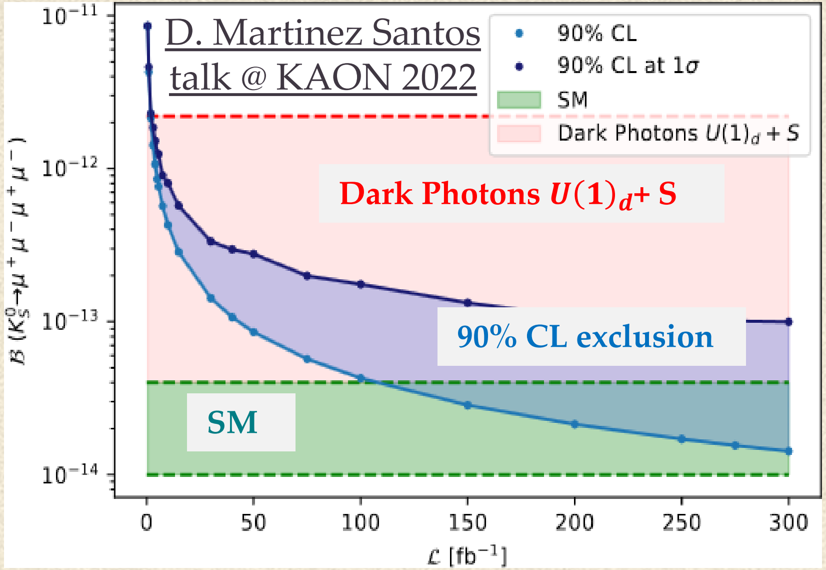
$$BR(K_S^0 \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$$
$$BR(K_L^0 \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$$

arXiv:2212.04977v4
(approved by PRD)

$K^0 \to \mu^+\mu^-\mu^+\mu^-$ at LHCb: Prospects

- Prospects for the next LHCb Upgrade(s) are excellent
- Scan most of the allowed range in BSM models (e.g. dark photons)
- Get close to the SM sensitivity if no signal is found





Prospects for other strangeness decays at LHCb

[JHEP 05 (2019) 048], [LHCb-PUB-2016-017], [LHCb-PUB-2016-016]

$K_S \to \pi^0\mu^+\mu^-$ at LHCb: Sensitive study

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

Sensitive to BSM

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

JHEP 08 (2006) 088

$|a_S| = 1.20 \pm 0.20$

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

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

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

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

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

Sensitive to BSM

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

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

JHEP 08 (2006) 088

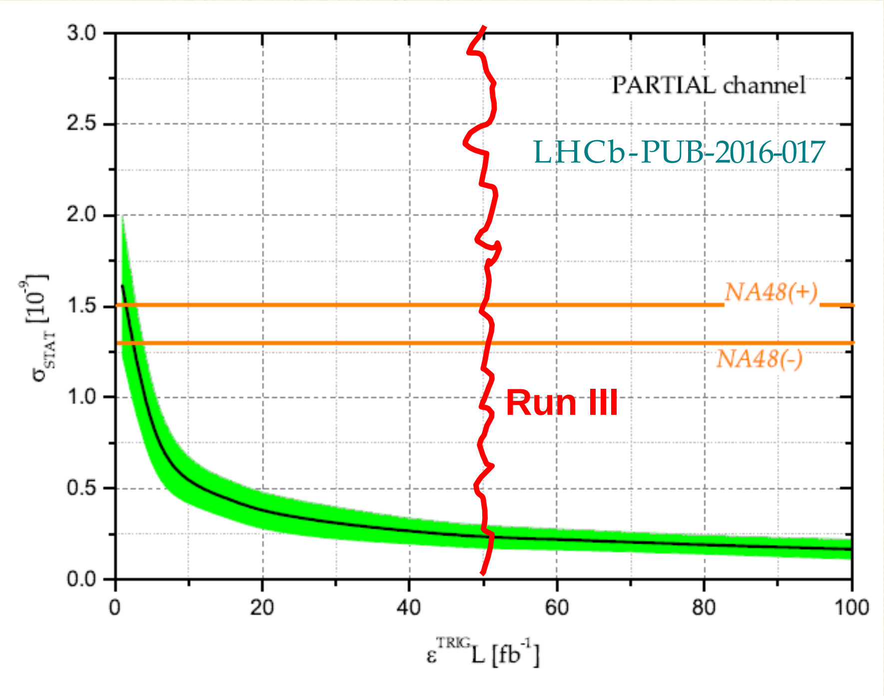
$|\mathrm{a_S}| = 1.20 \pm 0.20$ PLB 576 (2003) 43-54
PLB 599 (2004) 197-201

- Significant $|a_S|$ uncertainty that makes BSM interpretations of $K_L \to \pi^0\mu^+\mu^-$ difficult
- Comes from the experimental uncertainty on $\mathrm{BR}(K_S \to \pi^0 l^+ l^-)$
  - $\mathrm{BR}(K_S \to \pi^0\mu^+\mu^-)_{NA48} = \left(2.9^{+1.5}_{-1.2}\right) \times 10^{-9}$ 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

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

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

- Much more background but **~ 1000 times more signal**



Phase II Upgrade → 300 fb^{-1}

$|a_S| = 1.20 \pm 0.20$, fixing b_s from VMD models

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

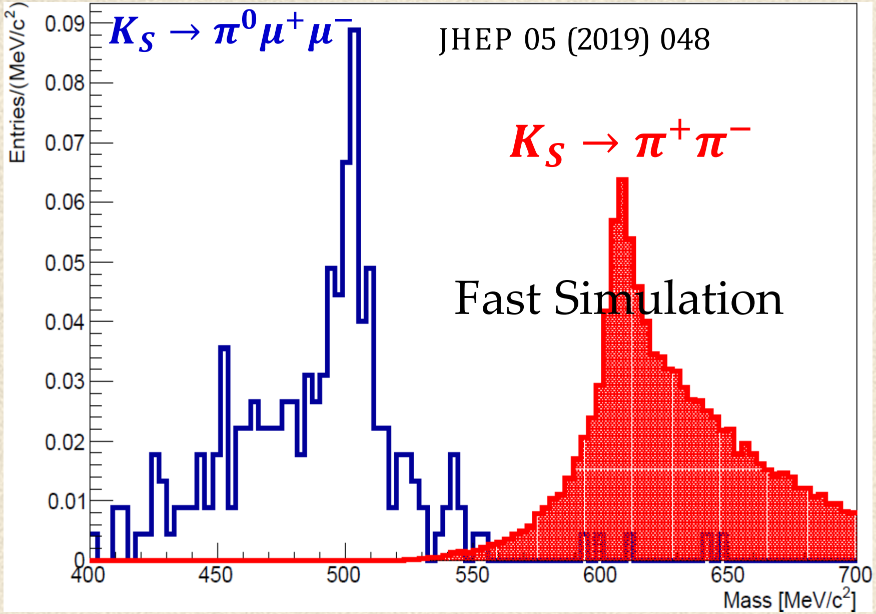
Projected statistical uncertainties on a_S under various analysis conditions

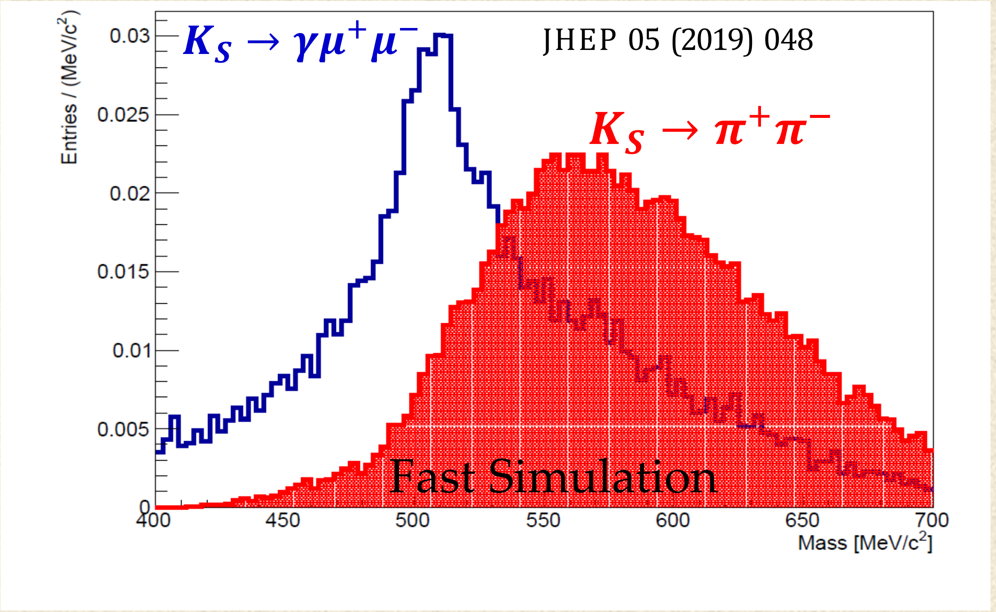
Configuration	Phase I	Phase II
BR & q^2 fit	0.25	0.10
BR & q^2 fit with NA48 constraint	0.19	0.10
BR & q^2 fit fixing b_S	0.06	0.024
a_S measurement from BR alone	0.06	0.024

JHEP 05 (2019) 048

What about $K_S \to \gamma\mu^+\mu^-, K_S \to X\mu^+\mu^-, K_S \to X\pi\mu$?

- $K_S \to \pi^0\mu^+\mu^-$ analysis can be extended to other neutrals (e.g. $K_S \to \gamma\mu^+\mu^-$)
- Harder to separate from $K_S \to \pi^+\pi^-$ ($m_\gamma < m_{\pi^0}$): a cut on the energy could be used





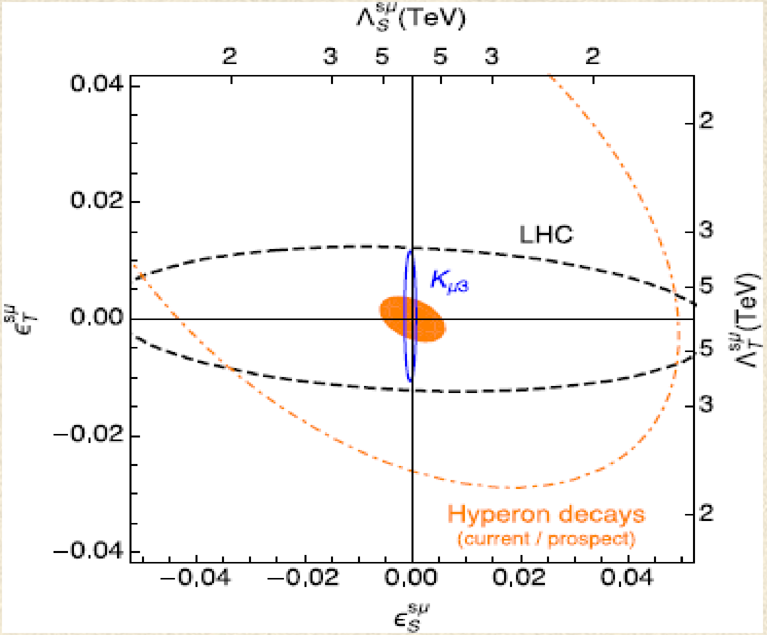
Semileptonic Hyperon Decays (SHD)

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

- Many muonic modes have still poor precision (20%-100%)
  - **Pro:** High BR($\sim 10^{-4}$) – huge yields at LHCb

- Sensitivity to helicity suppressed contributions $\epsilon_S^{S\mu}$ and $\epsilon_T^{S\mu}$

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

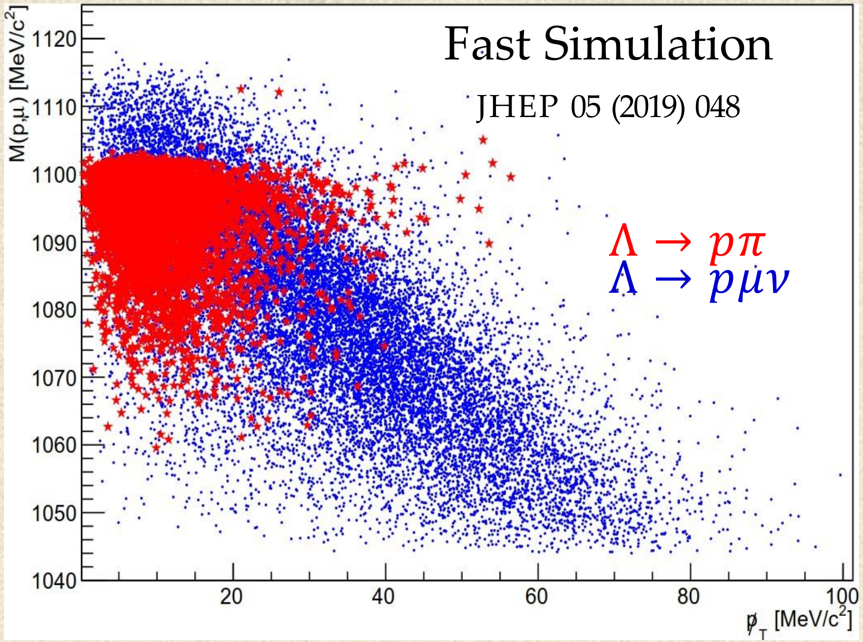


(extrapolations from 1412.8484)
Rare'N'Strange Workshop, 2017

Semileptonic Hyperon Decays (SHD)

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

- Many muonic modes have still poor precision (20%-100%)
  - **Pro:** High BR($\sim 10^{-4}$) – huge yields at LHCb
  - Con: Challenging peaking backgrounds



For each B1 → B2 μν there is always a B1 → B2 π (misid rate O(1%))

Conclusions

- There is a **s**trange physics community at LHC**b**
  - constant trigger improvements
  - with Run III we should 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 not covered in this talk (e.g. $K_S \to \mu\mu ee, K_S \to eeee,$ etc ...)