Strange-hadrons results from LHCb

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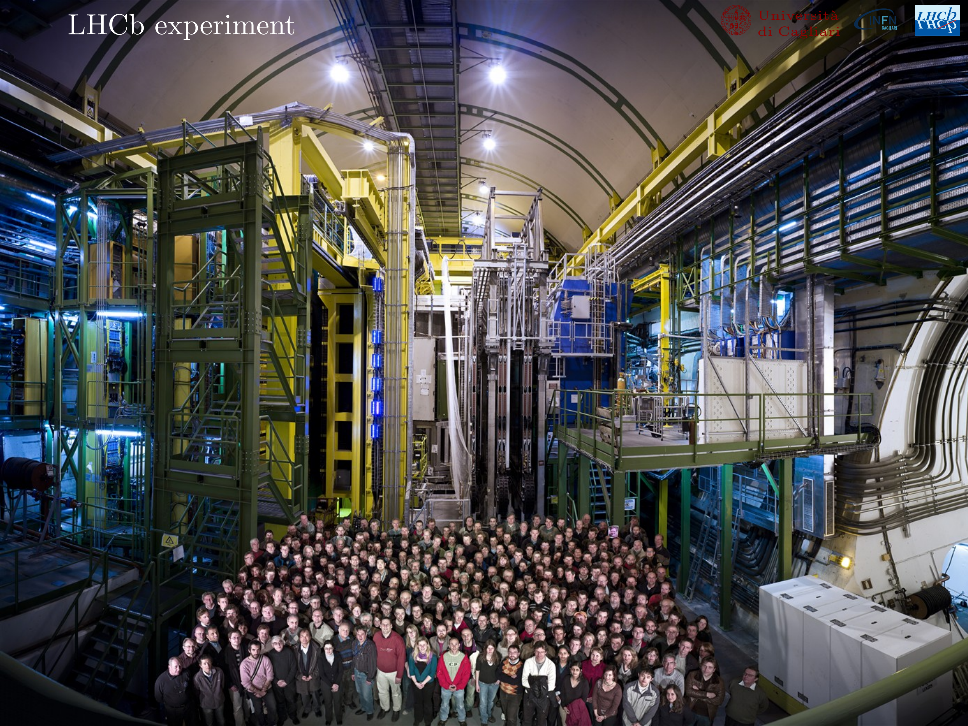
on behalf of the LHCb Collaboration

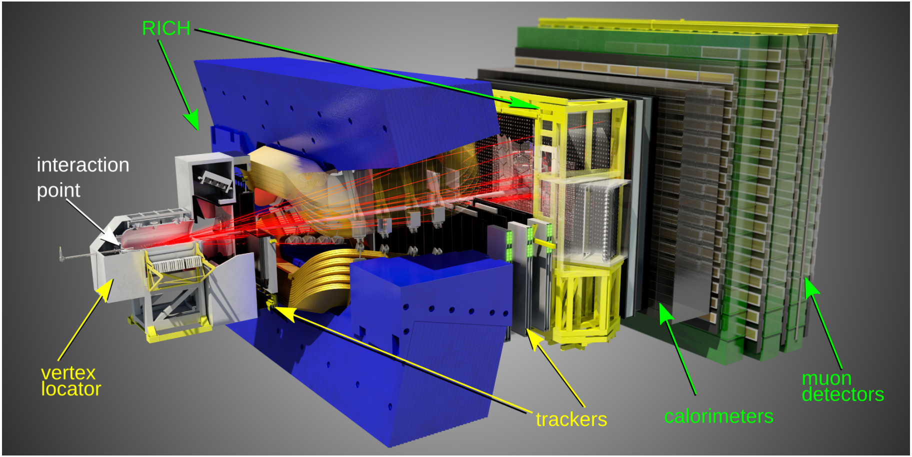
Università degli Studi di Cagliari and INFN Cagliari

Conference on Flavour Physics and CP Violation - FPCP 2020
A Toxa, Galicia - Online

LHCb experiment



LHCb detector

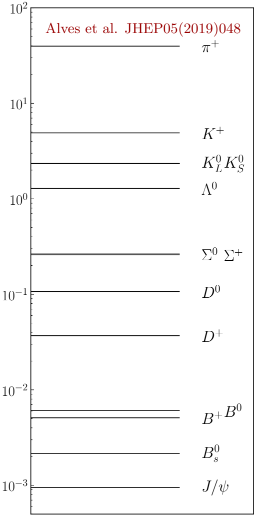


[Int. J. Mod. Phys. A 30, 1530022 (2015)]

Introduction: production

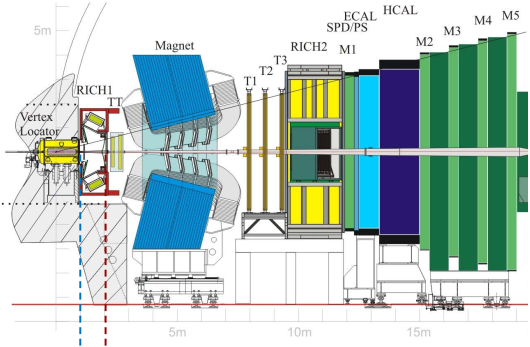
- Huge strange hadrons production cross-section at LHCb
- Production of particles in a minimum bias event within the geometric acceptance (400 mrad)
- About 1 strange hadron per event (compared to $\sim 10^{-3}$ B_s^0 mesons)
- Reconstruction and trigger however bring this number down

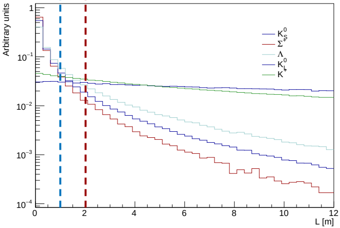
Average particles in LHCb acceptance per minimum bias event at $\sqrt{s} = 13$ TeV



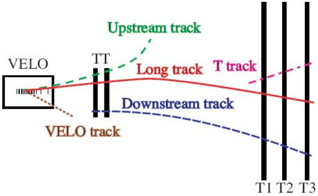
Introduction: setting the (long) stage

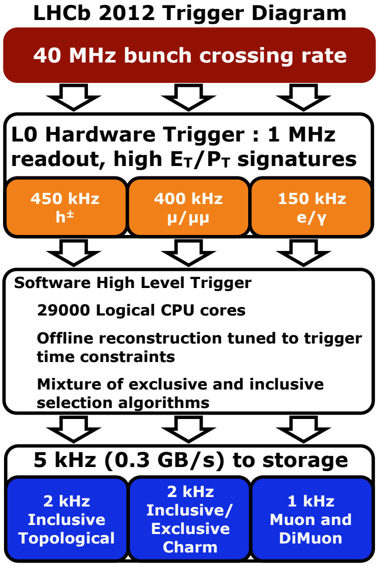
Reconstruction





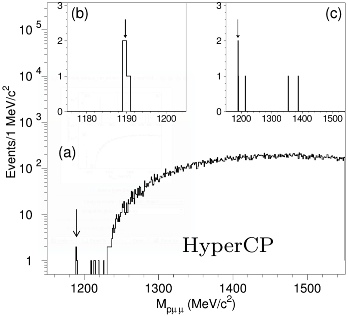
- Large lifetimes for LHCb... but the peak of an exponential is at zero!
- Different reconstruction methods for the daughter tracks

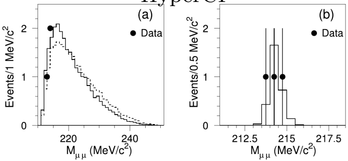




- LHCb trigger designed for heavy flavours
- Muon (hadron) L0 trigger require $p_{\mathrm{T}} > [1-5]\mathrm{GeV}$
- **Too hard for primary strange hadrons**
- Hlt1 and Hlt2 are software and customizable
- No dedicated triggers in 2011, added a $K^0_S \to \mu^+\mu^-$ dedicated trigger in 2012
- Several generic (topological) triggers allowed good efficiencies
- Typical events contain more than one strange hadron
- $\Rightarrow$ Strange physics Run 1 analyses mostly based on data triggered by the rest of the event (TIS)

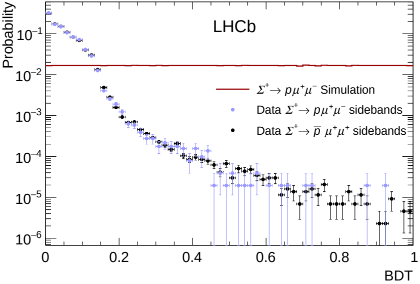
- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare FCNC
- Short distance SM $\mathcal{B} \sim O(10^{-12})$
- Dominated by long distance contributions:
  $1.2 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 10.2 \cdot 10^{-8}$
  [Xiao-Gang He et al. - Phys.Rev. D72 (2005) 074003]
  [Xiao-Gang He et al. - JHEP 1810 (2018) 040]
- Evidence found by the HyperCP experiment with 3 events in absence of background
- Measured branching fraction is:
  $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$
  [Phys.Rev.Lett. 94 (2005) 021801]
- All the **3** observed signal events have the same dimuon invariant mass: pointing towards a $\Sigma^+ \to pX^0(\to \mu\mu)$ decay
  with $m_X^0 = 214.3 \pm 0.5$ MeV
  $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu\mu)) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8}$

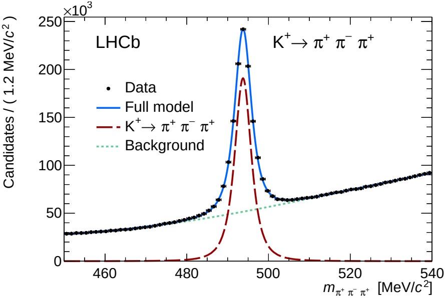




Sample and selection:

- Search with 3 fb^{-1} (full Run 1)
- Prompt decays (no displacement of the dimuon pair)
- Soft pre-selection + cut on BDT and PID to remove most of the background
- Explicit veto of $\Lambda \to p\pi$ background, no other peaking background contributes
- Calibrate BDT shape with $K^+ \to \pi^+\pi^-\pi^+$ decays in data



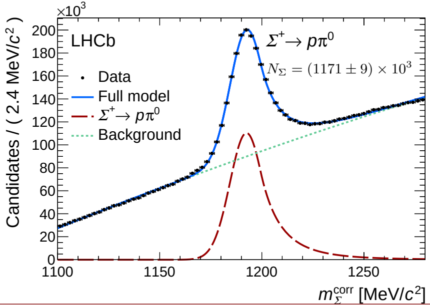


- No fully charged final state available in the Σ^+ to normalize
- Use high branching fraction $\Sigma^+ \to p\pi^0$ ($\mathcal{B} = (51.57 \pm 0.30)\%$)

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \frac{\varepsilon_{\Sigma^+\to p\pi^0}}{\varepsilon_{\Sigma^+\to p\mu^+\mu^-}} \frac{\mathcal{B}(\Sigma^+ \to p\pi^0)}{N_{\Sigma^+\to p\pi^0}} N_{\Sigma^+\to p\mu^+\mu^-} = \alpha \times N_{\Sigma^+\to p\mu^+\mu^-}$$

- Selection for $\Sigma^+ \to p\pi^0$ with $\pi^0 \to \gamma\gamma$ (resolved clusters) from calorimeter

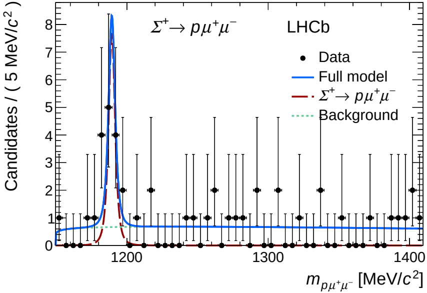
For full Run 1 dataset, single event sensitivity $\alpha = (2.2 \pm 1.2) \times 10^{-9}$
Correspondent to 23 ± 20 expected events with a SM BR



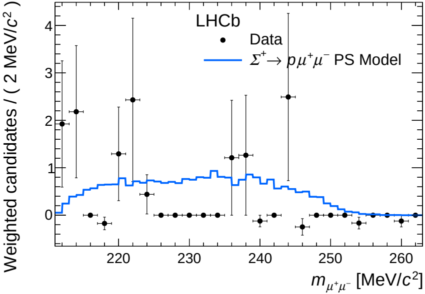
PRL 120, 221803 - arXiv:1712.08606

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

Results



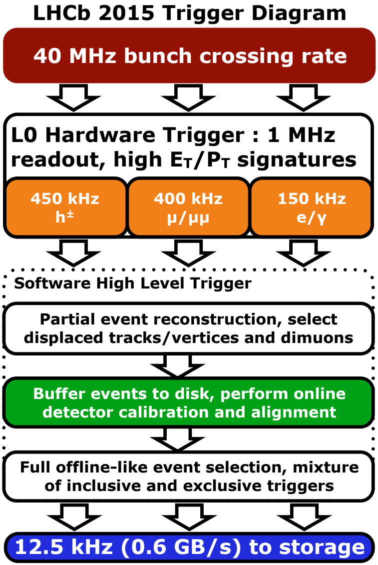
Background subtracted distribution



PRL 120, 221803 - arXiv:1712.08606

- Excess of events w.r.t. background with a significance of $4.1\,\sigma$
- Fitted signal yield: $10.2\,^{+\,3.9}_{-\,3.5}$
- Measured branching fraction $(2.2\,^{+\,0.9}_{-\,0.8}\,^{+\,1.5}_{-\,1.1}) \times 10^{-8}$
- No significant peak found in the dimuon mass: $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu^+\mu^-)) < 1.4 \times 10^{-8}$ at 90%CL excluding the HyperCP result

LHCb Run 2 data-taking

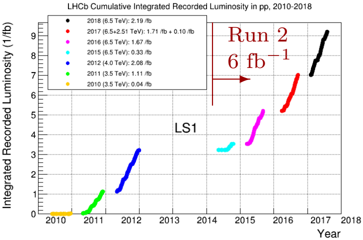


- Improved farm and algorithms: higher bandwidth
- Real time calibration between Hlt1 and Hlt2
- Factor 2 in cross-section from $\sqrt{s}$
- **L0 still limiting factor for strange physics**

Software improvements for strange

- Complement forward tracking for very soft muons implemented
- New Hlt1 inclusive lines developed with focus on strange physics
- Various novel Hlt2 inclusive and exclusive lines written, dedicated to strange

More than 6 fb^{-1} on tape

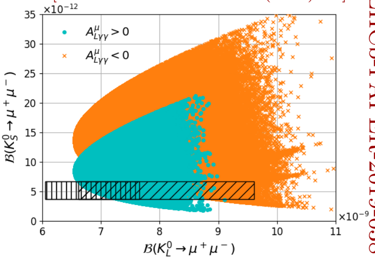


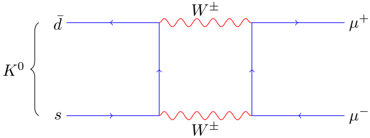
LHCb-PUB-2017-023

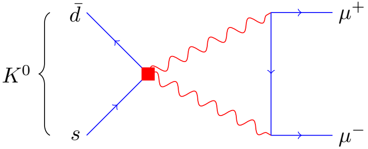
Search for $K_S^0 \to \mu^+\mu^-$ decays

- $K_L^0 \to \mu^+\mu^-$ is the "father" of flavour physics: charm quark and GIM mechanism
- $K_S^0 \to \mu^+\mu^-$ in addition suppressed by CPV
- SM prediction $\mathcal{B}(K_S^0 \to \mu^+\mu^-) = (5.18 \pm 1.50 \pm 0.02) \cdot 10^{-12}$
  [Ecker, Pich - Nucl Phys B366 (1991)]
  [Isidori, Unterdorfer - JHEP 01 (2004) 009]
  [D'ambrosio, Kitahara - PRL 119(2018)02]
- Dominated by long distance contributions
- Sensitive to NP, e.g. MSSM, leptoquarks
  [Chobanova et al. JHEP05(2018)024] [Dorsner et al. JHEP11(2011)002] [Bobeth, Buras - JHEP02(2018)101]
- Before LHCb: $\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 3.1 \cdot 10^{-7}$ at 90% CL at CERN PS in 1973
  [S. Gjesdal et al. PLB44(1973)217]
- Recent theoretical interest following LHCb results: possibility to study the interference of K_L^0 and K_S^0 to two muons
  [D'ambrosio, Kitahara - PRL 119(2018)02]

[Chobanova et al. JHEP05(2018)024]



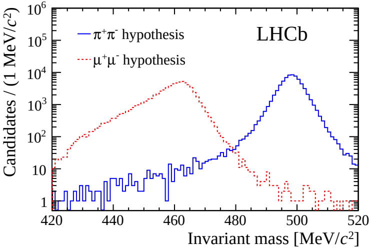


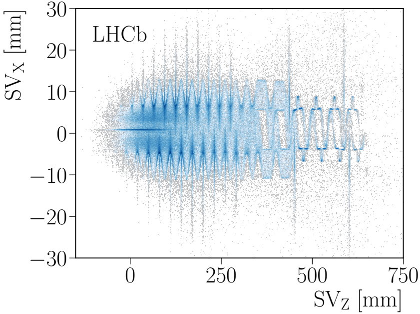


LHCb-PAPER-2019-038 - Submitted to PRL

LHCb Run 2 analysis

- 5.6 fb^{-1} from 2016-2018
- Dedicated software trigger used: efficiency improved by about 1 order of magnitude [LHCb-PUB-2017-023]
- Backgrounds: $K^0_S \to \pi^+\pi^-$ misID, combinatorial background, material interactions
- Dedicated multivariate muon ID developed (0.4% $\pi \to \mu$ misID at $\varepsilon = 90\%$)
- Specific veto for candidates close to VELO material
- $K^0_\mathrm{L} \to \mu^+\mu^-$ background suppressed by a factor 1.3×10^{-3} due to lifetime efficiency





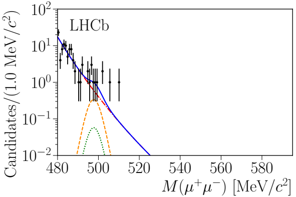
LHCb-PAPER-2019-038 - Submitted to PRL

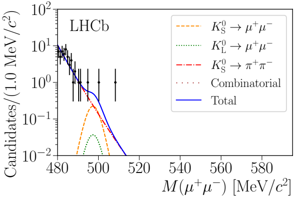
Analysis performed in

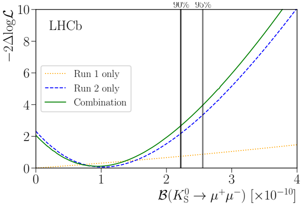
- Two trigger categories: xTOS and TIS
- Ten BDT bins for each trigger category
- $K^0_L \to \mu^+\mu^-$ component constrained to expectation from measured branching fraction
- Final upper limit (Run 1+2) at 90 (95) CL

$$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 2.1(2.4) \times 10^{-10}$$

- $\mathcal{B}(K^0_S \to \mu^+\mu^-) = 0.9^{+0.7}_{-0.6} \times 10^{-10}$
- Compatible at 1.4σ with background only and 1.3σ with SM
- Improved previous LHCb result by a factor 4 and and three orders of magnitude w.r.t. previous experiments







LHCb-PAPER-2019-038 - Submitted to PRL

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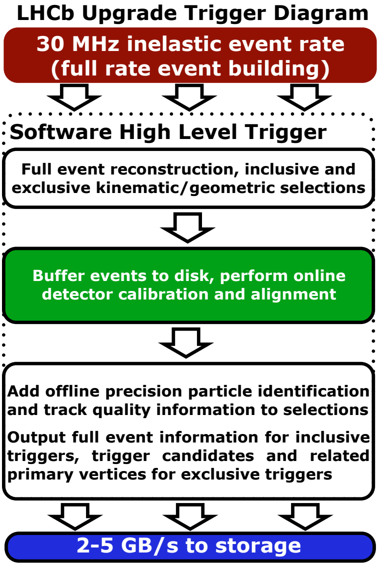
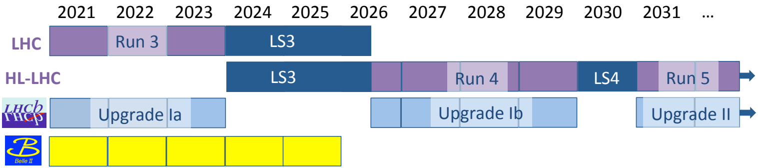
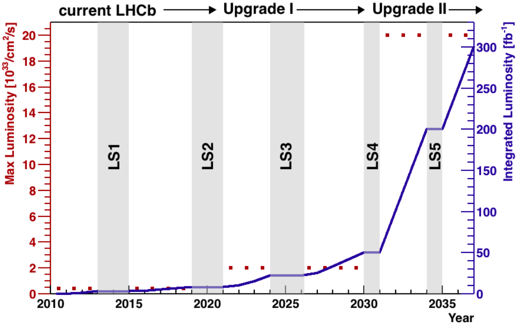


- Upgraded detector for 40 MHz full readout
- $\mathcal{L} = 2 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  $\Rightarrow$ about 5 fb^{-1} per year
- L0 hardware trigger is removed from Run 3
- Hlt1 run directly on collision data

Fundamental step forward for strange physics!

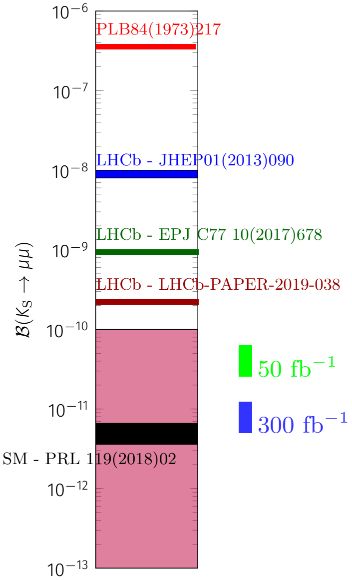
Future Upgrades

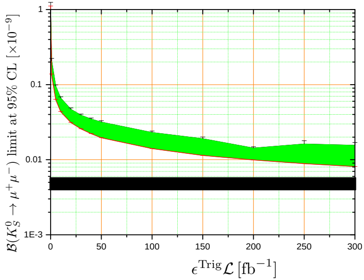




LHCB-PUB-2018-009

$K_S^0 \to \mu^+\mu^-$ prospects





LHCB-PUB-2018-009

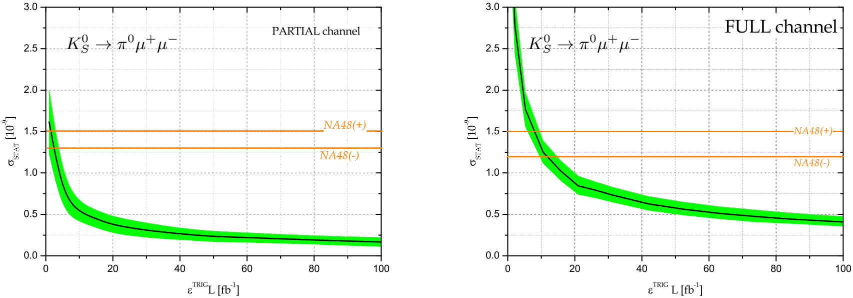
Future sensitivity to $K_S^0 \to \mu^+\mu^-$

- Depends on real trigger efficiencies
- Approach interesting region in Run 2 and Upgrade
- Probe SM in Upgrade II

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

LHCb-PUB-2016-017

- $K_L^0 \to \pi^0\mu^+\mu^-$ very sensitive to physics beyond the SM, e.g. extra-dimensions [M. Bauer et al. JHEP 09(2010)017]
- SM prediction with large uncertainty $\mathcal{B}_{SM}(K_L^0 \to \pi^0\mu^+\mu^-) = \{1.4 \pm 0.3, 0.9 \pm 0.2\} \times 10^{-11}$
- Limited by knowledge of ChPT parameter $|a_S|$ extracted from $K_S^0 \to \pi^0\mu^+\mu^-$ branching fraction
- $\mathcal{B}(K_S^0 \to \pi^0\mu^+\mu^-) = (2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$ measured by NA48 Collaboration [J.R. Batley et al. PLB599 (2011) 197]
- Studied sensitivity of LHCb to this channel in Run 2 and Upgrade scenarios
- LHCb will be competitive with NA48 for trigger efficiencies of $\sim 50\%$ or larger



Sensitivity to $K^0_S \to \pi^+\pi^-e^+e^-$

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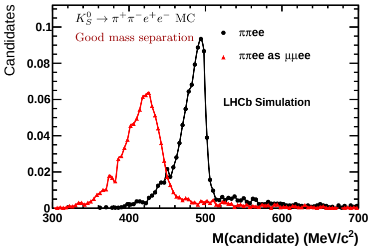
- $K^0_S \to \pi^+\pi^-e^+e^-$ is a proxy channel for $K^0_S \to \ell^+\ell^-\ell^+\ell^-$
- Sensitivity study at LHCb with MC
- $\varepsilon \sim 0.2\%$, limited by L0 trigger
- $\mathcal{B}(K^0_S \to \pi^+\pi^-e^+e^-) = (4.79 \pm 0.15) \times 10^{-5}$



LHCb-PUB-2016-016

With Run 1 conditions expected $N = 120^{+280}_{-100}$ events per fb^{-1} of 8 TeV data on top of about $3 \cdot 10^3$ background events. No multivariate selection applied.

- Dedicated Hlt2 trigger line deployed in Run 2, still limited by Hlt1 and L0
- Upgrade trigger will improve the efficiency on this and related channels sensibly
- In the ideal scenario of $\sim 100\%$ w.r.t. offline selection

$$N_{exp} = 5 \cdot 10^4 \text{ per fb}^{-1}$$

- Similar efficiencies are expected for the $K^0_S \to \ell^+\ell^-\ell^+\ell^-$ rare channels
- Single event sensitivities of order $9.6 \cdot 10^{-10}$ per each fb^{-1} in Upgrade conditions

A glimpse into LHCb possibilities

- Dedicated paper with some of us + theorists to explore future possibilities
- Approximate simulations (validated on published ones) to get sensitivities
- Countless channels to be probed

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	σ_L(MeV/c^2)	σ_D(MeV/c^2)
$K^0_S \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K^0_S \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K^0_S \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K^0_S \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K^0_S \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K^0_L \to \mu^+\mu^-$	~ 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)
$K^0_S \to \pi^+\pi^-e^+e^-$	1	1.0 (0.18)	2.83 (1.1)	~ 2.0	~ 10
$K^0_S \to \mu^+\mu^-e^+e^-$	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) $\times 10^{-4}$	–	–

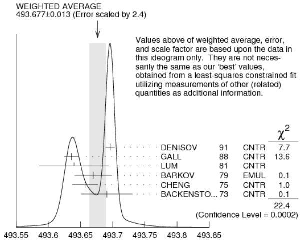
Channel	$\mathcal{R}$	ϵ_L	ϵ_D	σ_L(MeV/c^2)	σ_D(MeV/c^2)
$K^0_S \to \mu^+e^-$	1	1.0 (0.84)	1.5 (1.3)	~ 3.0	~ 8.0
$K^0_L \to \mu^+e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	~ 3.0	~ 7.0
$K^+ \to \pi^+\mu^+e^-$	~ 2	3.1 (1.1) $\times 10^{-3}$	16 (8.5)$\times 10^{-3}$	~ 2.0	~ 8.0

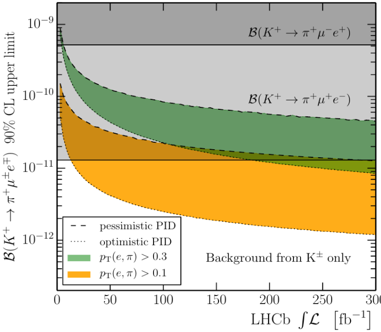
R = ratio of production
ϵ = ratio of efficiencies

Alves et al. JHEP05(2019)048

Prospects for charged kaons

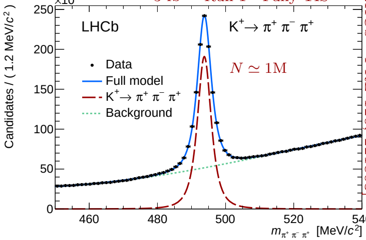
- Enormous K^+ production but small acceptance
- Run 1 has 1 M $K^+ \to \pi^+\pi^-\pi^+$ fully TIS
- Measurement of the charged kaon mass is under way to solve long standing disagreement: currently limiting D masses uncertainties
- With full software trigger $O(10^{-10})$ single event sensitivity per fb^{-1} obtainable
- Possibility to probe LFV channels





[Borsato et al. PRD 99, 055017 (2019)]

3 fb^{-1} Run 1 - Fully TIS



[LHCb - PRL 120, 221803]

- *LHCb expanding its physics reach towards strange physics complementary to the core program*
- Encouraging Run 1-2 results on $K^0_S \to \mu^+\mu^-$ and $\Sigma^+ \to p\mu^+\mu^-$
- Large samples available already on tape
  fully exploiting existing data
- **LHCb major player for K^0_S and hyperons rare decays**
- Complementary to K^0_{L} and K^+ dedicated experiments
- Run 2 giving new results with improved trigger
- Upgrade trigger will allow unprecedented sensitivities on many channels

Bibliography

LHCb Collaboration

Papers

- Strong constraints on the $K_S^0 \to \mu^+\mu^-$ branching fraction [LHCb-PAPER-2019-038 - Submitted to PRL] [hep-ex/2001.10354]
- Evidence for the rare decay $\Sigma^+ \to p\mu^+\mu^-$ [Phys. Rev. Lett. 120, 221803 (2018)] [LHCb-PAPER-2017-049] [hep-ex/1712.08606]
- Improved limit on the branching fraction of the rare decay $K_S^0 \to \mu^+\mu^-$ [LHCb-PAPER-2017-009] [hep-ex/1706.00758] [Eur. Phys. J. C, 77 10 (2017) 678]
- Search for the CP-violating strong decays $\eta \to \pi^+\pi^-$ and $\eta' \to \pi^+\pi^-$ [LHCb-PAPER-2016-046] [hep-ex/1610.03666] [Physics Letters B 764 (2017) 233-240]
- Search for the rare decay $K_S^0 \to \mu^+\mu^-$ [LHCb-PAPER-2012-023] [hep-ex/1209.4029] [JHEP 01 (2013) 090]

Public notes

- Physics case for an LHCb Upgrade II [LHCB-PUB-2018-009][arXiv/1808.08865]
- Low p_T dimuon triggers at LHCb in Run 2 [LHCb-PUB-2017-023]
- Sensitivity of LHCb and its upgrade in the measurement of $\mathcal{B}(K_S^0 \to \pi^0\mu^+\mu^-)$ [LHCb-PUB-2016-017]
- Feasibility study of $K_S^0 \to \pi^+\pi^-e^+e^-$ at LHCb [LHCb-PUB-2016-016]

Others

- Alves A. A. et al. “Prospects for Measurements with Strange Hadrons at LHCb” [JHEP05(2019)048]
- Borsato et al. “The strange side of LHCb” [Phys. Rev. D 99, 055017 (2019)]

Search for $K_S^0 \to \mu^+\mu^-$ decays

Università di Cagliari

LHCb-PAPER-2019-038 - Submitted to PRL

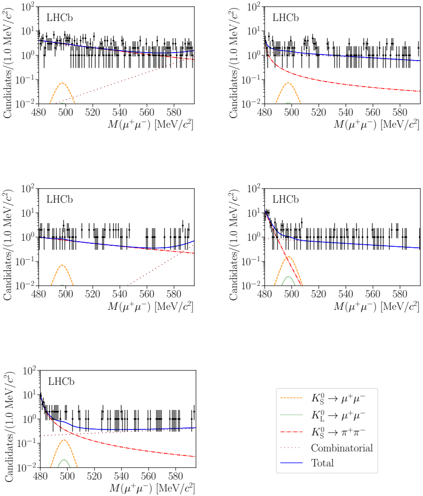


Figure: TIS Bins 1-5

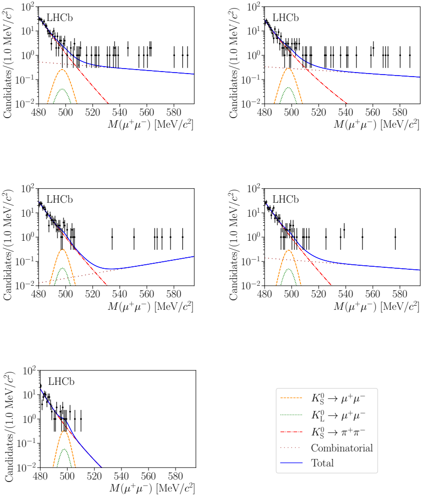


Figure: TIS Bins 6-10

Search for $K_S^0 \to \mu^+\mu^-$ decays

LHCb-PAPER-2019-038 - Submitted to PRL

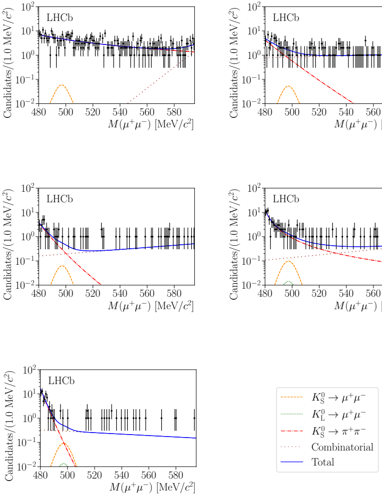


Figure: TOS Bins 1-5

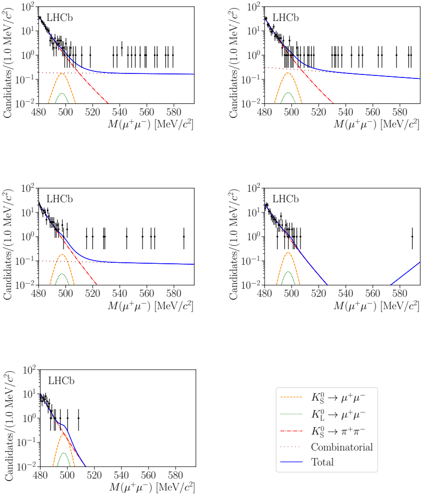


Figure: TOS Bins 6-10

A quick word on hyperons

Alves et al. JHEP05(2019)048

LHCb can probe different hyperons and decays

- Σ^+: Besides the $\Sigma^+ \to p\mu^+\mu^-$, LHCb could improve the $\Sigma^+ \to p\gamma$ and try to access the $\Sigma^+ \to pe^+e^-$ decay
- Λ
  - LHCb could improve the $\Lambda \to p\pi\gamma$ branching fraction and try to access $\Lambda \to p\pi e^+e^-$
  - Large number of BNV / LFV decays constrained by the CLAS collaboration [CLAS PRD.92.072002] could be also tested and improved
- For higher S number baryons LHCb could test $\Delta S = 2$ processes, such as $\Xi^0 \to p\pi$ and $\Omega \to \Lambda\pi$ improving limits by orders of magnitude

- $K^0 \to \ell^+\ell^-\ell^+\ell^-$ short distance sensitive to NP , dominated by the long distance contribution uncertainty
- Interference of $\mathcal{A}(K^0_S \to \ell^+\ell^-\ell^+\ell^-)$ and $\mathcal{A}(K^0_\mathrm{L} \to \ell^+\ell^-\ell^+\ell^-)$ would give a measurement of the sign of $\mathcal{A}(K^0_\mathrm{L} \to \gamma\gamma)$ which is a stringent test of CKM

  [D'Ambrosio et al - EPJC73(2013)2678] [Isidori, Unterdorfer - JHEP 0401 (2004) 009]
- $K^0_\mathrm{L} \to \ell^+\ell^-\ell^+\ell^-$ studied by different experiments but no experimental constraints on K^0_S modes

$$\mathcal{B}(K^0_S \to e^+e^-e^+e^-) \sim 10^{-10}$$
$$\mathcal{B}(K^0_S \to \mu^+\mu^-e^+e^-) \sim 10^{-11}$$
$$\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) \sim 10^{-14}$$

- Sensitive to NP at same order of SM

Prospects for LFV modes

- Tests of lepton flavour violation are always important SM null tests
- Limits on kaon LFV are stringent but decades old

$$\mathcal{B}(K_L \to e^{\pm}\mu^{\mp}) < 4.7 \times 10^{-12} \quad \mathcal{B}(K_L \to \pi^0 e^{\pm}\mu^{\mp}) < 7.6 \times 10^{-11}$$

[E871 PRL81,5734] [KTeV PRL100,131803]

$$\mathcal{B}(K^+ \to \pi^+ e^- \mu^+) < 1.3 \times 10^{-11} \quad \mathcal{B}(K^+ \to \pi^+ e^+ \mu^-) < 5.2 \times 10^{-10} \ ,$$

[Sher et al. PRD 72, 012005] [Appel et al. PRL85, 2877]

- Using B-physics LFU constraints, branching fractions of order 10^{-13} can be predicted for K_S LFV decays [Borsato et al. PRD 99, 055017 (2019)]