Kaons at LHCb

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on behalf of the LHCb Collaboration

Università degli Studi di Cagliari and INFN Cagliari

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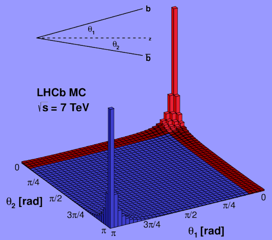
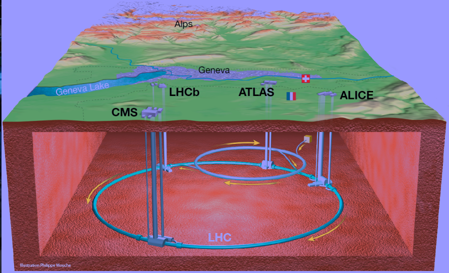
LHCb experiment

LHCb experiment

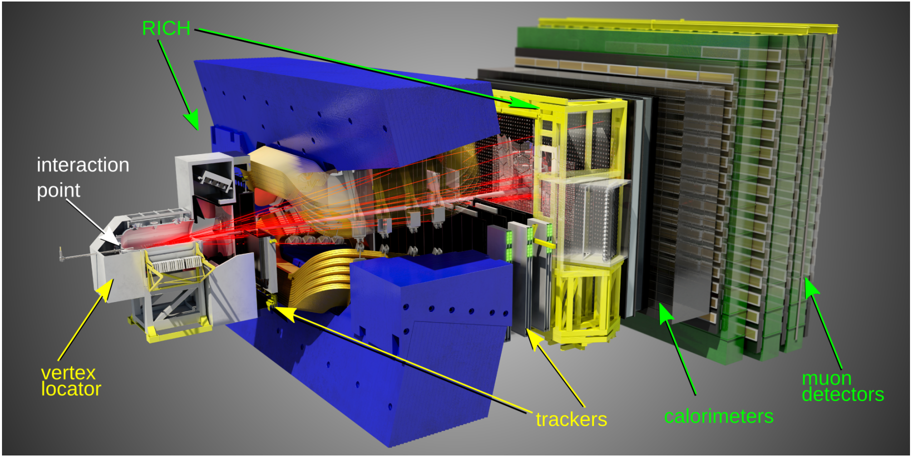
- 1250 members, from 79 institutes in 18 countries
- Dedicated experiment for precision measurements of CP violation and rare decays
- *Beautiful*, *charming*, *strange* physics program





- pp collisions at $\sqrt{s} = 7, 8(13)$ TeV in Run 1 (Run 2)
- $b\bar{b}$ quark pairs produced correlated in the forward region
- Luminosity leveled at $4 \times 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

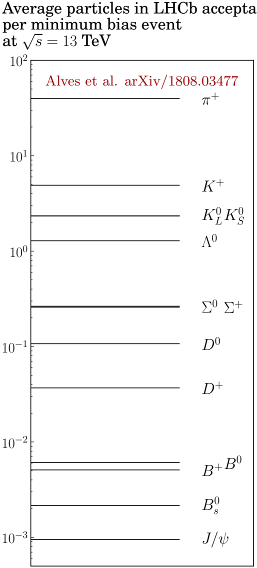
LHCb detector



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

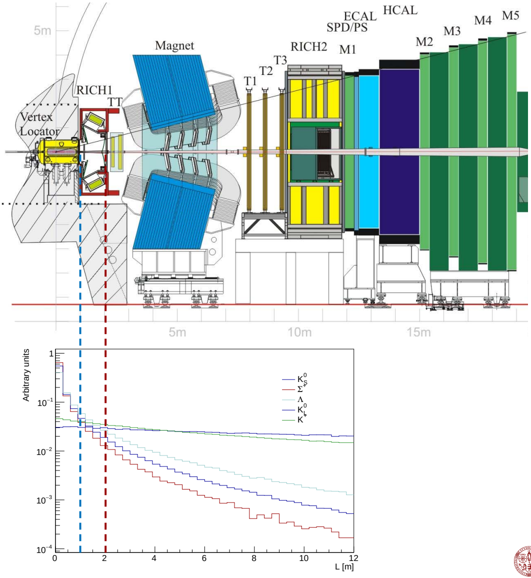
Introduction: production

- 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

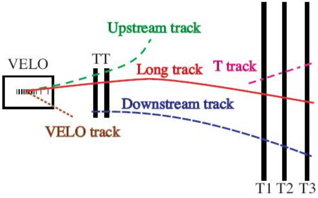


Introduction: setting the (long) stage

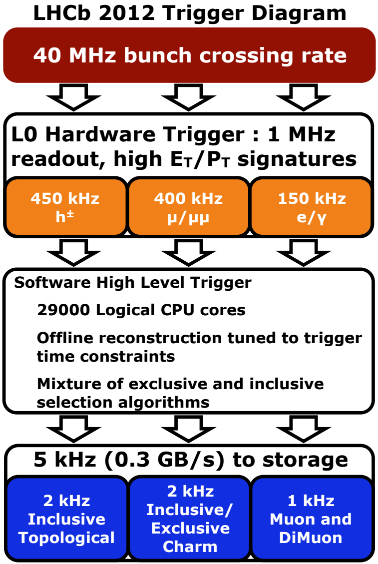
Reconstruction



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



LHCb Run 1 data-taking



- 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 $K_S^0 \to \mu^+\mu^-$ dedicated trigger in 2012
- Several generic (topological) triggers allowed good efficiencies
- Typical events contain more than one strange hadron
- ⇒ Strange physics Run 1 analyses mostly based on data triggered by the rest of the event (TIS)

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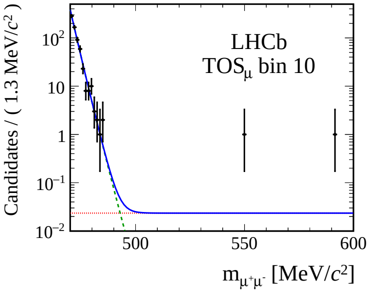
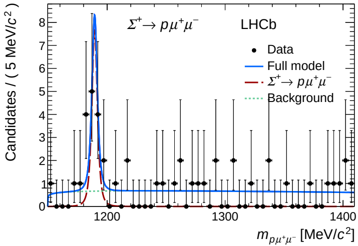
Strange physics at LHCb with Run 1

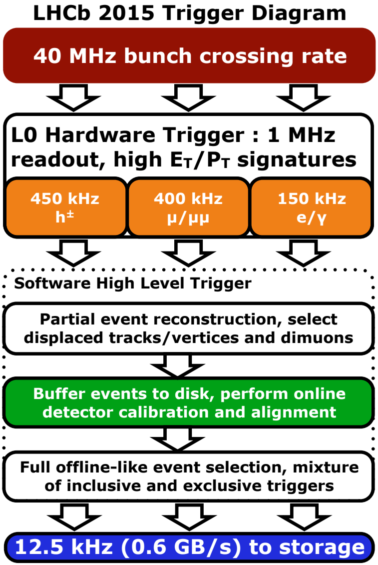
Despite trigger and detector not designed for it

- World best limit on $K^0_S \to \mu^+\mu^-$- EPJ.C, 77 10(2017)678
  (See Miguel's talk in "hot topics" session for the Run 2 update)
- Evidence for the $\Sigma^+ \to p\mu^+\mu^-$ decay and measurement of the branching fraction, challenging to the HyperCP anomaly
  PRL 120, 221803
  (See my other talk for details)





LHCb Run 2 data-taking

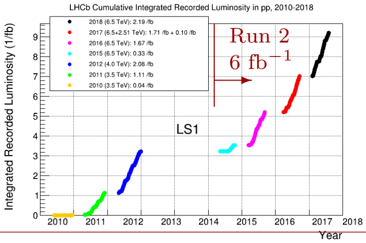


- Improved farm and algorithms: higher bandwidth
- Real time calibration between Hlt1 and Hlt2
- Factor 2 in cross-section from $\sqrt{s}$
- **L0 still limiting factor for strange physics**

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

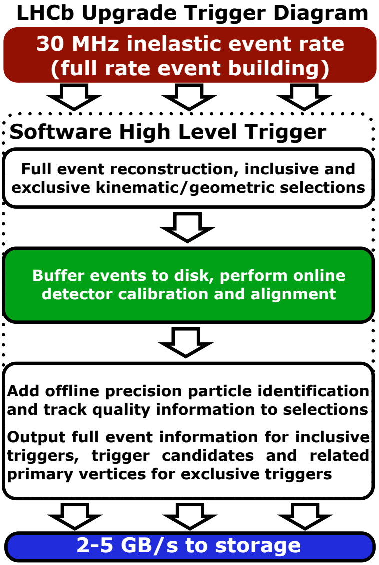
More than 6 fb^{-1} on tape



LHCb-PUB-2017-023

Cagliari

LHCb Upgrade data-taking

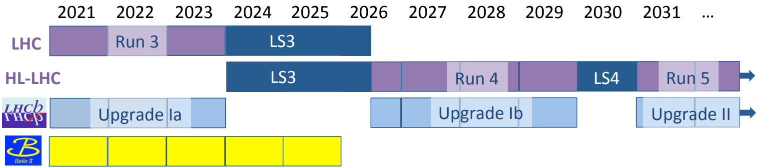


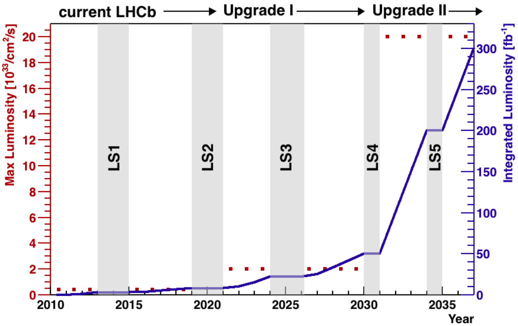
- Upgraded detector for 40 MHz full readout
- $\mathcal{L} = 2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$
  $\Rightarrow$ about 5 fb^{-1} per year

- 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

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

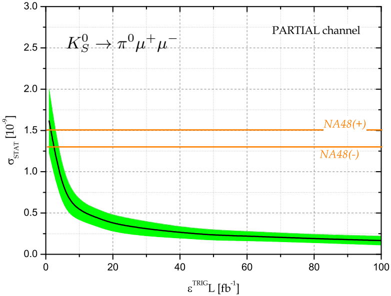
LHCb-PUB-2016-017

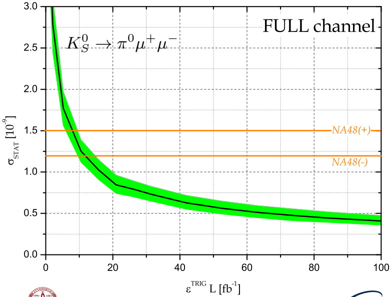
- $K^0_{\mathrm{L}} \to \pi^0\mu^+\mu^-$ very sensitive to physics beyond the SM, e.g. extra-dimensions [M. Bauer et al. JHEP 09(2010)017]
- SM prediction with large uncertainty $\mathcal{B}_{SM}(K^0_{\mathrm{L}} \to \pi^0\mu^+\mu^-) = \{1.4 \pm 0.3, 0.9 \pm 0.2\} \times 10^{-11}$
- Limited by knowledge of ChPT parameter $|a_S|$ extracted from $K^0_S \to \pi^0\mu^+\mu^-$ branching fraction
- $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-) = (2.9^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$ measured by NA48 Collaboration [J.R. Batley et al. PLB599 (2011) 197]

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

LHCb-PUB-2016-017

- Studied sensitivity of LHCb to this channel in Run 2 and Upgrade scenarios
- Difficult reconstruction due to soft π^0
- π^0 reconstruction non essential as constrained by very low q-value
- Double strategy: without π^0 (Partial) and with π^0 reconstructed from γ pairs
- Combinatorial background estimated with real data TIS events
- Peaking backgrounds studied with MC: none found to contribute in LHCb
- Statistical uncertainty on $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ as a function of luminosity times trigger efficiency
- LHCb will be competitive with NA48 for trigger efficiencies of $\sim 50\%$ or larger





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$K^0 \to \ell^+\ell^-\ell^+\ell^-$

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

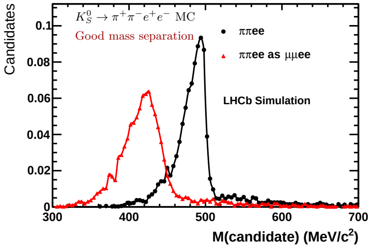
  [D'Ambrosio et al - EPJC73(2013)2678] [Isidori, Unterdorfer - JHEP 0401 (2004) 009]
- $K_L^0 \to \ell^+\ell^-\ell^+\ell^-$ studied by different experiments but no experimental constraints on K_S^0 modes

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

- Sensitive to NP at same order of SM

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

- $K^0_S \to \pi^+\pi^-e^+e^-$ 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) $\times 10^{-4}$	–	–

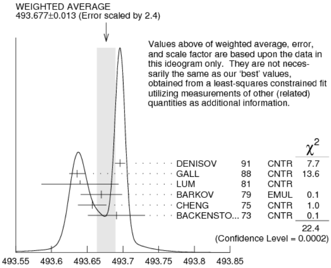
Channel	$\mathcal{R}$	ϵ_L	ϵ_D	σ_L(MeV/c^2)	σ_D(MeV/c^2)
$K^0_S \to \mu^+e^-$	1	1.0 (0.84)	1.5 (1.3)	~ 3.0	~ 8.0
$K^0_L \to \mu^+e^-$	1	3.1 (2.6) $\times 10^{-3}$	13 (11) $\times 10^{-3}$	~ 3.0	~ 7.0
$K^+ \to \pi^+\mu^+e^-$	~ 2	3.1 (1.1) $\times 10^{-3}$	16 (8.5)$\times 10^{-3}$	~ 2.0	~ 8.0

R = ratio of production
ϵ = ratio of efficiencies

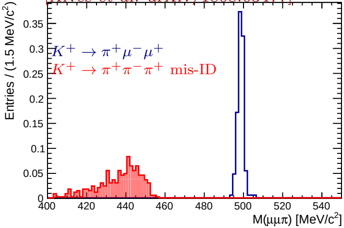
Alves et al. arXiv/1808.03477

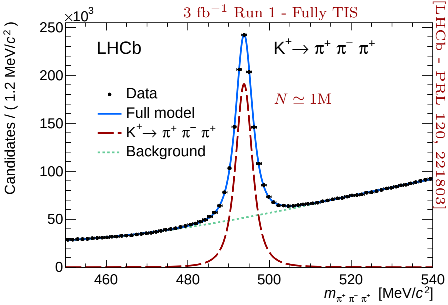
Prospects for charged kaons

- 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
- With full software trigger $O(10^{-10})$ single event sensitivity per fb^{-1} obtainable
- $K^+ \to \pi^+\mu^-\mu^+$ and $K^+ \to \pi^+e^-e^+$ become accessible



[Alves et al. arXiv/1808.03477]





Prospects for LFV modes

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

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

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

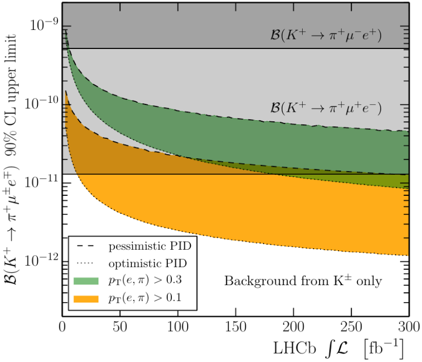
$$\mathcal{B}(K^+ \to \pi^+ e^- \mu^+) < 1.3 \times 10^{-11} \quad \mathcal{B}(K^+ \to \pi^+ e^+ \mu^-) < 5.2 \times 10^{-10} \ ,$$

[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)]

Prospects for LFV modes

- Electron reconstruction in LHCb is more difficult than muon due to bremsstrahlung and lower trigger efficiency
- Preliminary estimates of prospects [Borsato et al. PRD 99, 055017 (2019)] [Alves et al. JHEP05(2019)048]
- LHCb could improve limits and maybe touch the 10^{-13} region with full Upgrade (2030s)
- Detailed full simulation studies are however not there yet



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A quick word on hyperons

Alves et al. arXiv/1808.03477

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

See also Alexandre's talk in the "hyperon" session.

Summary and conclusions

- *LHCb expanding its physics reach towards strange physics complementary to the core program*
- Encouraging Run 1 results on $K_S^0 \to \mu^+\mu^-$ and $\Sigma^+ \to p\mu^+\mu^-$
- Large samples available already on tape
  fully exploiting existing data
- **LHCb major player for K_S^0 and hyperons rare decays**
- Complementary to K_L^0 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

- 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 $K^0_S \to \mu^+\mu^-$ [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 $K^0_S \to \mu^+\mu^-$ [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 $\mathcal{B}(K^0_S \to \pi^0\mu^+\mu^-)$ [LHCb-PUB-2016-017]
- Feasibility study of $K^0_S \to \pi^+\pi^-e^+e^-$ 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)]

Backup

Search for CP violating strong decays $\eta^{(\prime)} \to \pi^+\pi^-$

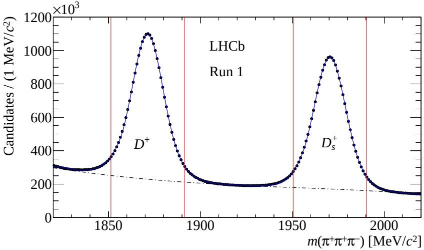
LHCb-PAPER-2016-046

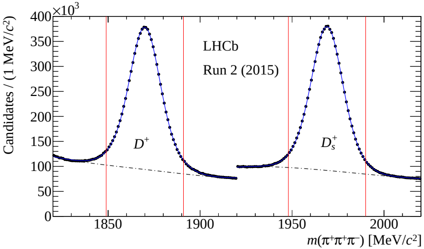
- QCD should violate CP symmetry (with a term $\mathcal{L}_\theta = -\frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$) but none is observed experimentally
- $\theta < 10^{-10}$ from neutron electric dipole moment (**strong CP problem**)
- $\eta^{(\prime)} \to \pi^+\pi^-$ would be strong CP violating decays
- nEDM limit constraints SM branching fractions to $< 3 \cdot 10^{-17}$ any evidence higher than this would be NP
- Best limits at 90% CL
  $\mathcal{B}(\eta \to \pi^+\pi^-) < 1.3 \cdot 10^{-5}$ (KLOE $\phi \to \eta\gamma$ [PLB606 (2005) 276])
  $\mathcal{B}(\eta' \to \pi^+\pi^-) < 5.5 \cdot 10^{-5}$ (BESIII $J/\psi \to \gamma\pi^+\pi^-$ [PRD84(2011)032006])

Search for CP violating strong decays $\eta' \to \pi^+\pi^-$

LHCb-PAPER-2016-046

- LHCb strategy:
  look for peaks in $\pi\pi$ mass from $D^+_{(s)} \to \pi^+\pi^-\pi^+$ decays (i.e. $D^+_{(s)} \to \pi^+\eta^{(\prime)}$)
- MVA operator to reduce background
- Normalisation: $\mathcal{B}(\eta^{(\prime)} \to \pi^+\pi^-) = \frac{N_{\eta^{(\prime)}}}{N_{D^+_{(s)}\to\pi^+\pi^-\pi^+}} \frac{1}{\varepsilon_{\eta^{(\prime)}}} \frac{\mathcal{B}(D^+_{(s)}\to\pi^+\pi^-\pi^+)}{\mathcal{B}(D^+_{(s)}\to\pi^+\eta^{(\prime)})}$
- Constrained D masses and origin vertex improves resolution significantly
- $\varepsilon_{\eta^{(\prime)}}$ small correction to efficiency versus $m_{\pi\pi}$
- 3 fb^{-1} of Run 1 and 0.3 fb^{-1} of Run 2 data from Turbo stream
- Run 2 contribution enhanced by larger cross-section and trigger efficiency





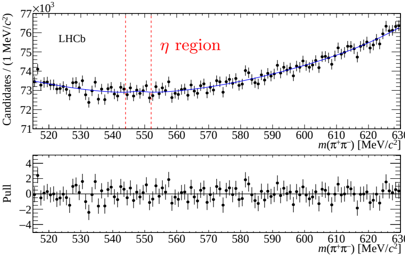
Search for CP violating strong decays $\eta' \to \pi^+\pi^-$

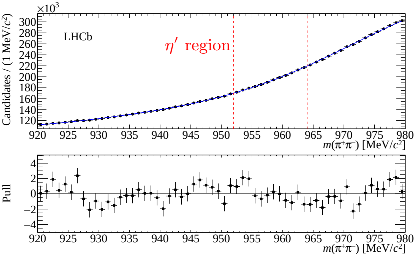
LHCb-PAPER-2016-046

- No excess on top of the background (signal phase space plus combinatorial)
- Upper limit on branching fractions with CLs method at 90% CL:

$$\mathcal{B}(\eta \to \pi^+\pi^-) < 1.6 \cdot 10^{-5}$$
$$\mathcal{B}(\eta' \to \pi^+\pi^-) < 1.8 \cdot 10^{-5}$$

- η limit compatible with previous results, η' limit improved by factor three





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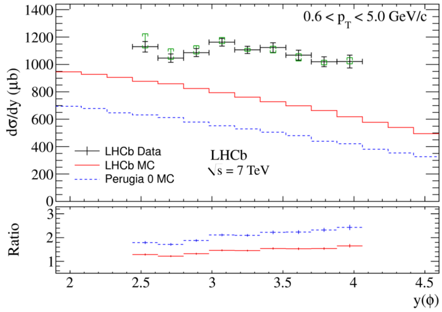
Kaon physics from ϕ decays



- Huge ϕ production at LHC
- Exploit $\phi \to K^+K^-$ decays in which one of the kaons is fully reconstructed
- Study final state of second kaon, also partially reconstructed thanks to the ϕ constraint
- $O(10^{10})$ tagged $\phi \to KK$ decays per year in the upgrade *
- For example study $K^+ \to e\nu$ (tag also initial Kaon leg with RICH1)

*See talk by Vava Gligorov, Rare'n'Strange workshop https://indico.cern.ch/event/590880/