Rare strange decays at LHCb

3 and 4 tracks decays

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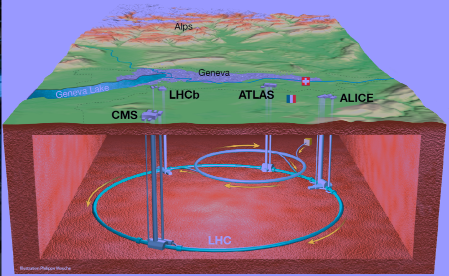
First forum on rare kaon decays - RKF 2018 - Edinburgh

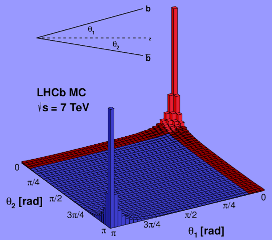
Introduction

- Strange physics at LHCb: why not?
- Two talks: this on 3/4 tracks and Miguel's on 2 tracks, split for convenience
- Concentrate on how and what we can do
- Already some results

LHCb experiment

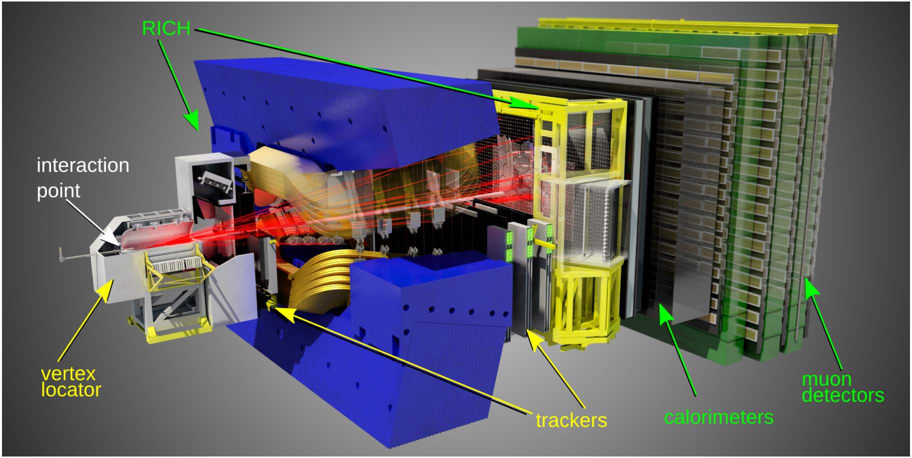
- 1150 members, from 69 institutes in 16 countries
- Dedicated experiment for precision measurements of CP violation and rare decays
- *Beautiful*, *charming*, *strange* physics program





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

LHCb detector



Excellent vertex and IP resolution

- $\sigma(IP) \simeq 24\mu\text{m}$ at $p_T = 2$ GeV/c
- $\sigma_{BV} \simeq 16\mu\text{m}$ in x, y

Very good momentum resolution

- $\sigma(p)/p = 0.4\% - 0.6\%$ for $p \in (0, 100)$ GeV/c
- $\sigma(m) \sim 24(4)$ MeV for two body $B(K_S)$ decays

Muon identification

- $\varepsilon_\mu = 98\%$, $\varepsilon_{\pi\to\mu} = 0.6\%$, $\varepsilon_{K\to\mu} = 0.3\%$, $\varepsilon_{p\to\mu} = 0.3\%$

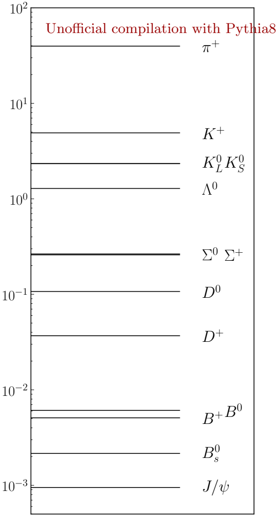
Trigger

- $\varepsilon_\mu = 90\%$ for B decays

Introduction: production

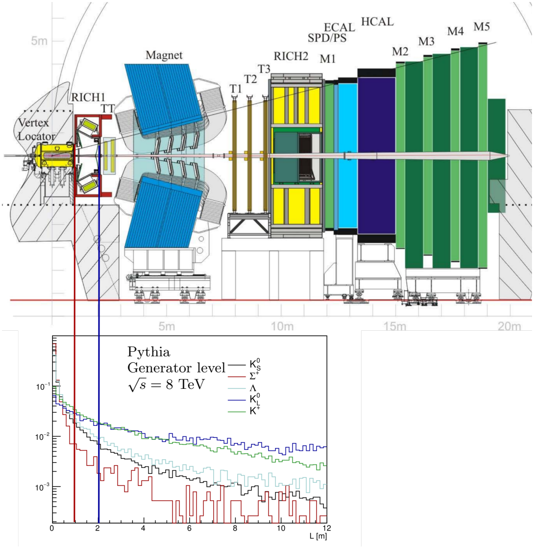
- Huge strange hadrons production cross-section at LHCb
- Production of particles in a minimum bias event within the geometric acceptance (400 mrad)
- About 1 strange hadron per event (compared to $\sim 10^{-3}$ B_s^0 mesons)
- Reconstruction and trigger however bring this number down

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

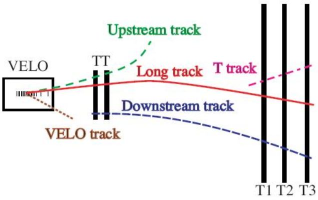


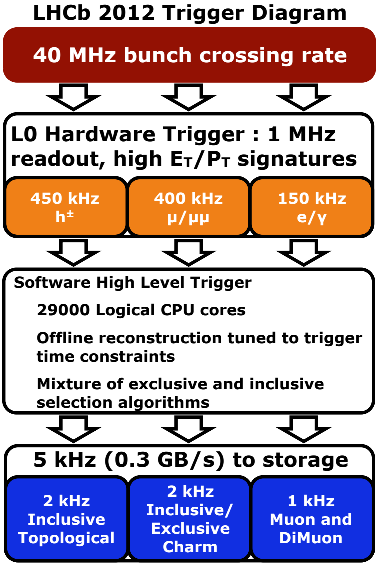
Introduction: setting the (long) stage

Reconstruction



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





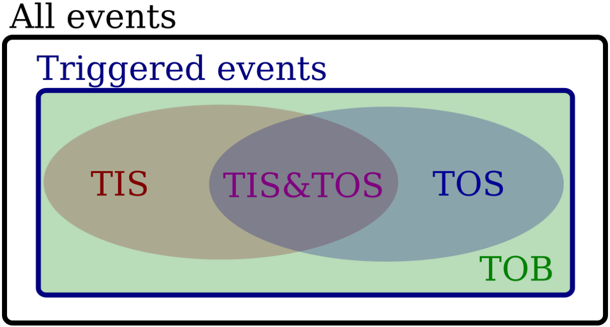
- LHCb trigger designed for heavy flavours
- Muon (hadron) L0 trigger require $p_{\mathrm{T}} > [1-5]GeV$
- **Too hard for primary strange hadrons**

- 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 I analyses mostly based on data triggered by the rest of the event

TIS events and the TISTOS method

- Triggered events can be
  - Triggered On the Signal (TOS) - the signal is sufficient to trigger
  - Triggered Independently of the Signal (TIS) - the signal is not necessary to trigger
  - Triggered on both (TOB=!TIS&!TOS)



- Events can be TIS and TOS
- Overlap can be used to measure trigger efficiencies

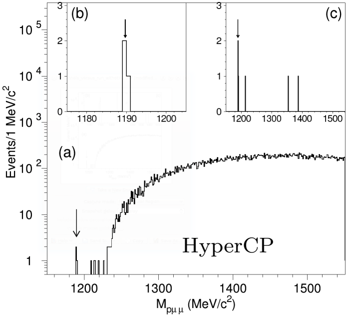
Tolk, S et al. LHCb-PUB-2014-039

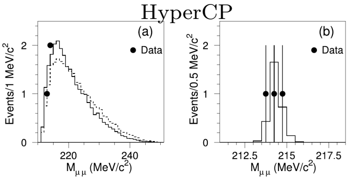
Strange physics at LHCb with Run I

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

The HyperCP anomaly

- $\Sigma^+ \to p\mu^+\mu^-$ is a very rare FCNC
- Short distance SM branching fraction is $O(10^{-12})$
- Dominated by long distance contributions: $1.6 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 9.0 \cdot 10^{-8}$ [He et al. - Phys.Rev. D72 (2005) 074003]
- An evidence for this decay was 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]
- This evidence attracted large attention since 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 $\mathcal{B}(\Sigma^+ \to pX^0(\to \mu\mu)) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8}$
- Large theoretical and experimental attention (see backup) but no other direct search for $\Sigma^+ \to p\mu^+\mu^-$





General analysis strategy

LHCb-PAPER-2017-049 - arXiv:1712.08606

1. Soft selection at stripping level
2. Cut on BDT and ProbNN to remove most of the background
3. Search for $\Sigma^+ \to p\mu^+\mu^-$ decays:
   - ⋆ Search around Σ mass window for SM signal
     $\to$ If peak is found, look at $\mu\mu$ invariant mass
   - ⋆ Search in Σ mass restricting to $m_{\mu\mu} \sim 214$
4. Normalize branching fraction to $\Sigma^+ \to p\pi^0$

Sample and selection:

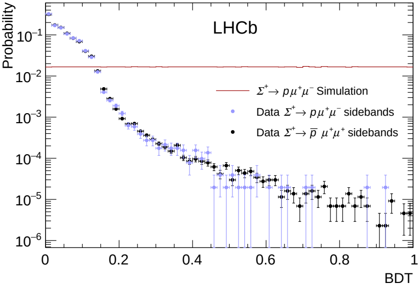
- Full 2011+2012 statistics, luminosity 3 fb^{-1}
- Decays reconstructed with long tracks (i.e. decays in VELO)
- Prompt decays (no displacement of the dimuon pair)
- Selections for final states: $\Sigma^+ \to p\mu^+\mu^-$, $\Sigma^+ \to \bar{p}\mu^+\mu^+$ (background), $\Sigma^+ \to p\pi^0$ (normalisation), $K^+ \to \pi^+\pi^-\pi^+$ (control)
- Signal channel accepts all events, normalisation TIS only

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

General analysis strategy

LHCb-PAPER-2017-049 - arXiv:1712.08606

- Soft pre-selection to reduce dataset
- Cut on BDT and PID to remove most of the background
- Explicit veto of $\Lambda \to p\pi$ background, no other peaking background contributes

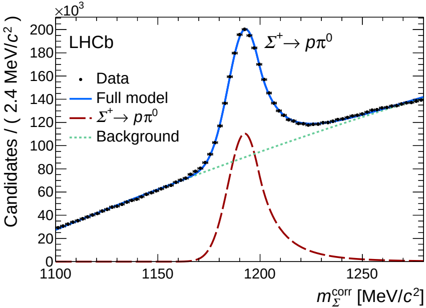


- No fully charged final state available in the Σ^+ to normalize
- Use high branching fraction $\Sigma^+ \to p\pi^0$ ($\mathcal{B} = (51.57 \pm 0.30)\%$)

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

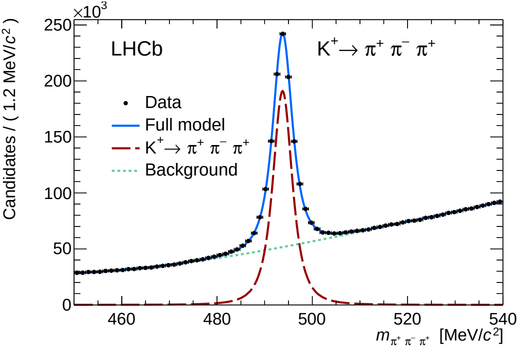
- Selection for $\Sigma^+ \to p\pi^0$ with $\pi^0 \to \gamma\gamma$ (resolved clusters) from calorimeter

For full Run I dataset, single event sensitivity $\alpha_{TIS} = (1.6 \pm 0.9) \times 10^{-9}$
(Correspondent to 31 ± 27 expected events with a SM BR)



LHCb-CONF-2016-013

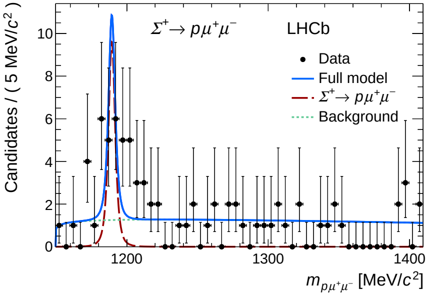
- Trigger efficiency estimated with dedicated simulations with all trigger configurations and calibrated on data with $\Sigma^+ \to p\pi^0$ with the TISTOS method
- Reconstruction of the π^0 calibrated with ratio of ratio of $B^+ \to J/\psi K^{*+}$ and $B^+ \to J/\psi K^+$ decays reconstructed in data.
- Particle identification calibrated with control channels in data ($\Lambda \to p\pi^-$ and J/ψ)
- BDT classifier calibrated with $K^+ \to \pi^+\pi^-\pi^+$ channel in data

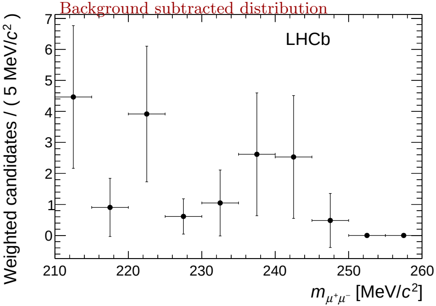


Systematic uncertainties

Selection efficiency	1%
BDT efficiency	6%
PID efficiency	28%
π^0 efficiency	10%
Trigger efficiency ratio	40%
Total	50%

Results





LHCb-PAPER-2017-049 - arXiv:1712.08606

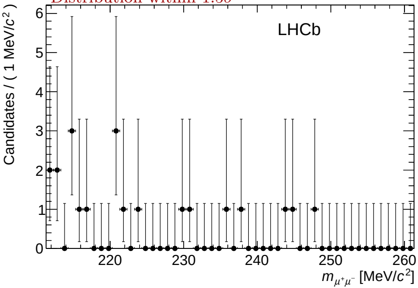
- Excess of events w.r.t. background with a significance of $4.0\,\sigma$
- Fitted signal yield: $12.9\,^{+\,5.1}_{-\,4.2}$
- Measured branching fraction $(2.1\,^{+\,0.8}_{-\,0.7}\,^{+\,1.4}_{-\,1.0}) \times 10^{-8}$

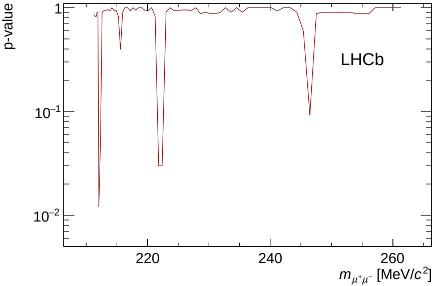
Results: analysis of the dimuon mass

LHCb-PAPER-2017-049 - arXiv:1712.08606

- Consider candidates within 1.5 σ from the Σ mass in the full selection
- Scan dimuon invariant mass for possible peaks:
  No significant peak found
- Repeated $m_{p\mu^+\mu^-}$ fit restricting to $m_{\mu^+\mu^-} \in [214.3 \pm 0.75 \text{MeV}/c^2]$):
  No significant peak found

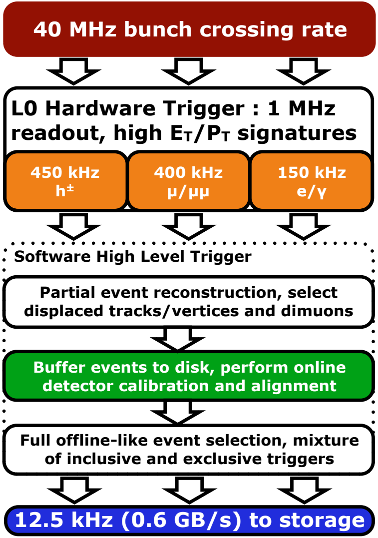
Distribution within 1.5σ





LHCb Run II and Upgrade

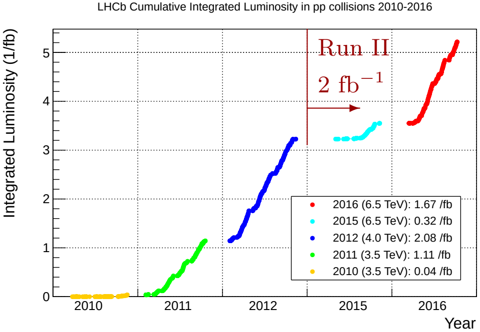
LHCb 2015 Trigger Diagram



- Higher bandwidth from improved farm and algorithms allows higher yields
- Real time calibration between Hlt1 and Hlt2
- **L0 trigger still limiting factor for strange hadrons**
- *Turbo* stream allows high rate channels to be stored: [Aaij et al. JCPC208(2016)35] important for non rare strange physics

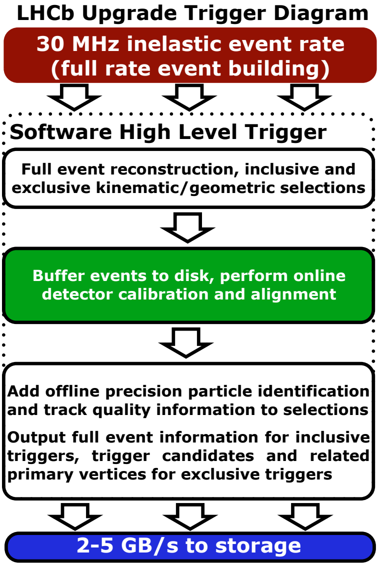
Software improvements for strange

- 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



Already 2 fb^{-1} on tape at $\sqrt{s} = 13$ TeV

- Analysis of $\Sigma^+ \to p\mu^+\mu^-$ with dedicated triggers
  - ⋆ Probable observation
  - ⋆ Precise branching fraction measurement
  - ⋆ Possible differential branching fraction and maybe other observables
- $K^0_S \to \mu^+\mu^-$ see Miguel's talk
- Different other rare hyperon decay searches possible ($\Sigma^+ \to pe^+e^-$, $\Lambda^0 \to p\pi^-e^+e^-$, LFV, etc)



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

Fundamental step forward for strange physics!

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

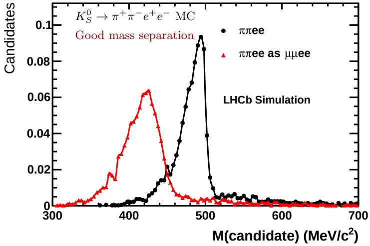
- $K^0 \to \ell^+\ell^-\ell^+\ell^-$ short distance sensitive to NP , dominated by the long distance contribution uncertainty
- Interference of $\mathcal{A}(K^0_S \to \ell^+\ell^-\ell^+\ell^-)$ and $\mathcal{A}(K^0_\mathrm{L} \to \ell^+\ell^-\ell^+\ell^-)$ would give a measurement of the sign of $\mathcal{A}(K^0_\mathrm{L}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

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

  $\mathcal{B}(K^0_S \to e^+e^-e^+e^-) \sim 10^{-10}$ $\mathcal{B}(K^0_S \to \mu^+\mu^-e^+e^-) \sim 10^{-11}$ $\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) \sim$
- 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 normalisation, control and background channel for $K^0_S \to \ell^+\ell^-\ell^+\ell^-$
- Sensitivity study at LHCb with MC simulations
- Both TIS and TOS trigger strategy devised: $\varepsilon \sim 0.2\%$, limited by L0 trigger
- $\mathcal{B}(K^0_S \to \pi^+\pi^-e^+e^-) = (4.79 \pm 0.15) \times 10^{-5}$ (PDG average)



LHCb-PUB-2016-016

With Run I 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 II, 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

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

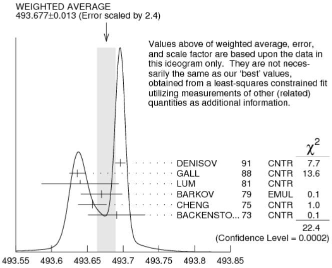
- Similar efficiencies are expected for the $K^0_S \to \ell^+\ell^-\ell^+\ell^-$ rare channels
- Single event sensitivities of order $9.6 \cdot 10^{-10}$ per each fb^{-1} in Upgrade conditions

Prospects for charged kaons

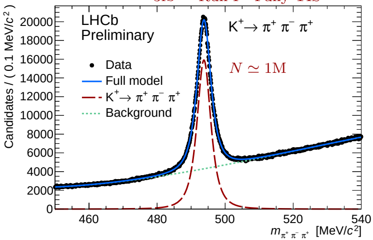
- Enormous K^+ production but small acceptance
- Run I has 1 M $K^+ \to \pi^+\pi^-\pi^+$ fully TIS
- Measurement of the charged kaon mass is under way to solve long standing disagreement
- With full software trigger $O(10^{-10})$ single event sensitivity per fb^{-1} obtainable
- $K^+ \to \pi^+\mu^-\mu^+$ and $K^+ \to \pi^+e^-e^+$ with $\mathcal{B} \sim 10^{-7}$ become accessible

Still possible improvements

- Use of downstream tracks increasing decay length acceptance
- Use of K^+ track in VELO to constrain partially reconstructed decays †

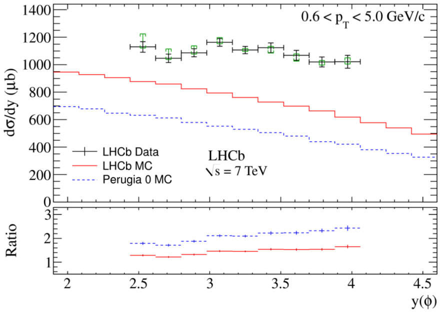


3fb^{-1} Run I - Fully TIS



† A. Contu LHCb-PUB-2014-032

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/

Rare'n'Strange workshops

- Bring together LHCb and the theoretical community on these new topics
- Goals:
  - boost theoretical interest on measurements in progress
  - explain LHCb capabilities
  - build up a shopping list
- 1st at CERN, 2nd at Santiago de Compostela with large attendence (https://indico.cern.ch/event/590880/)
- A third workshop will be organized soon

Summary and conclusions

- *LHCb expanding its physics reach towards strange physics complementary to the core program*
- Encouraging Run I 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 $K^0_{\rm L}$ and K^+ dedicated experiments
- Run II giving new results with improved trigger
- Upgrade trigger will allow unprecedented sensitivities on many channels

Backup

Bibliography

Papers

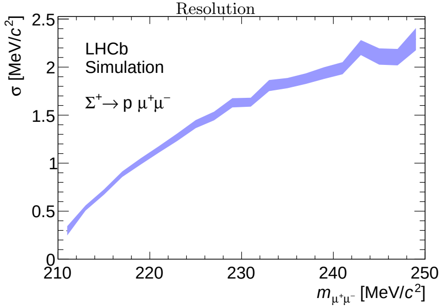
- Evidence for the rare decay $\Sigma^+ \to p\mu^+\mu^-$ [LHCb-PAPER-2017-049] [hep-ex/1712.08606]
- Improved limit on the branching fraction of the rare decay $K_S^0 \to \mu^+\mu^-$ [LHCb-PAPER-2017-009] [hep-ex/1706.00758] [Eur. Phys. J. C, 77 10 (2017) 678]
- Search for the CP-violating strong decays $\eta \to \pi^+\pi^-$ 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]

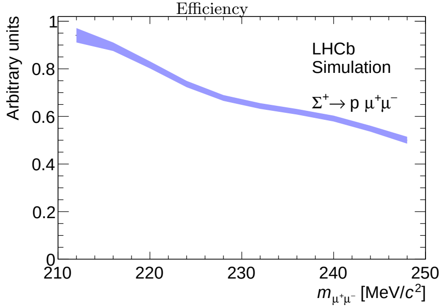
Public notes

- 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]

LHCb-CONF-2016-013

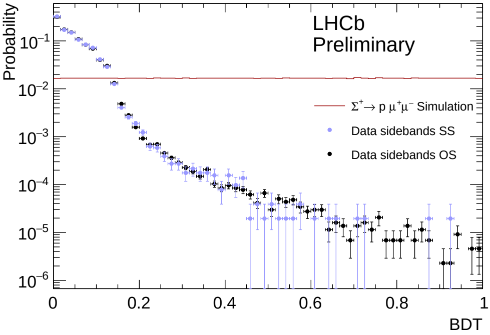
- Hyper-CP signal is consistent with $\Sigma^+ \to pX^0(\to \mu\mu)$, with $m_{X^0} = 214.3 \pm 0.5$ MeV
- Mass resolution in LHCb:
  - ⋆ Raises with $m_{\mu^+\mu^-}$ departing from threshold
- Study efficiency versus $m_{\mu^+\mu^-}$: higher efficiency at small mass due to higher minimum p_T





Multivariate selection: BDT

- BDT aiming at rejecting combinatorial background
- Training on signal MC sample and background from data same-sign sidebands ($\Sigma^+ \to \bar{p}\mu^+\mu^+$)
- Common geometric and kinematic variables: pointing, IP, p_{T} and isolations, ...



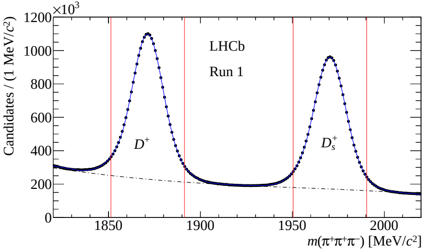
LHCb-PAPER-2016-046

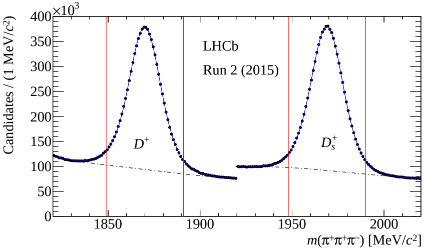
- QCD should violate CP symmetry (with a term $\mathcal{L}_\theta = -\frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}F_{\rho\sigma}$) but none is observed experimentally
- $\theta < 10^{-10}$ from neutron electric dipole moment (**strong CP problem**)
- $\eta^{(\prime)} \to \pi^+\pi^-$ would 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 I and 0.3 fb^{-1} of Run II data from Turbo stream
- Run II contribution enhanced by larger cross-section and trigger efficiency



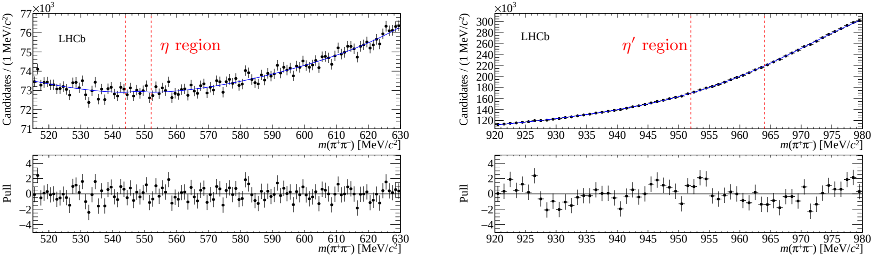


Search for CP violating strong decays $\eta' \to \pi^+\pi^-$

- 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



- Several interpretations were proposed
  - Light Higgs boson [He, Tandean, Valencia, PRL.98.081802 (2007)]
  - Sgoldstino [Gorbunov, Rubakov PRD 73 035002] [Demidov, Gorbunov PRD73(2006)035002]
  - Many others [He et al - PLB631 (2005) 100] [Geng, Hsiao - PLB632(2006) 215] [Deshpande et al - PLB632 (2006) 212] [Mangano, Nason - Mod. Phys. Lett. A22 (2007)] [Chen et al - PLB663 (2008) 400] [Xiangdong et al - EPJC55 (2008) 317] [Pospelov - PRD80 (2009) 095002]
  - In general pseudoscalar favoured over scalar and lifetime of order 10^{-14}s
- Many experimental searches for low mass resonances in dimuons:
  - CLEO, E391a, D0, BaBar, Belle, KTeV, BESIII
  - Searched also at LHCb in $B^0 \to \mu^+\mu^-\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$
  - Not confirmed nor disproved
- No other search in $\Sigma^+ \to p\mu^+\mu^-$ decays