



Status and prospects for strange physics at LHCb

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On behalf of the LHCb collaboration

CERN European Organization for Nuclear Research



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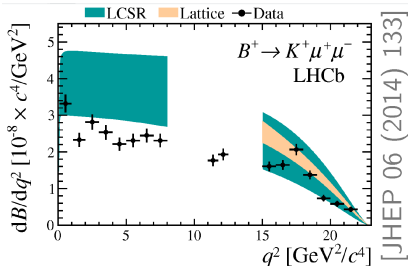
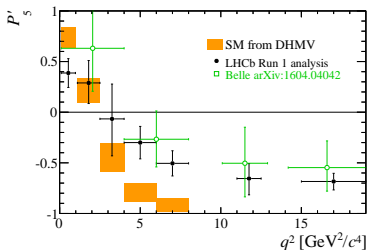
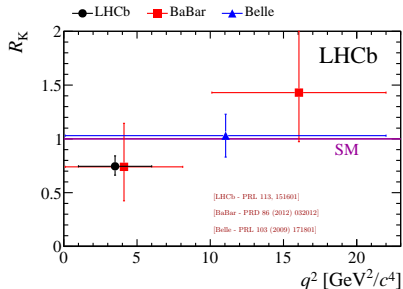
Outline

- Flavour anomalies and strange physics
- Searches for rare strange hadron decays at LHCb
 - * $\Sigma^+ \rightarrow p\mu^+\mu^-$
 - * $K_S^0 \rightarrow \mu^+\mu^-$
 - * $\eta^{(\prime)} \rightarrow \pi^+\pi^-$
- Prospect for selected channels
 - * Run II
 - * Upgrade
- Conclusions

Status of flavour physics anomalies (1)

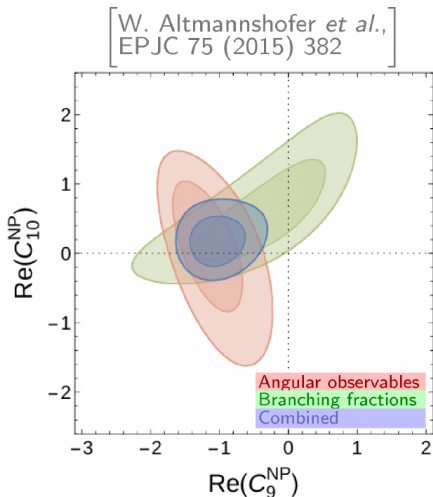
Several measurements showing discrepancies with respect to SM

- $B_d^0 \rightarrow K^* \mu^+ \mu^-$ angular distributions
- Low $b \rightarrow s \mu^+ \mu^-$ branching fractions
- Hints of **lepton non-universality** in $B \rightarrow K \ell \ell$ and $B \rightarrow D \ell \nu$ decays
- Ratio of $B^0 \rightarrow \mu^+ \mu^- / B_s^0 \rightarrow \mu^+ \mu^-$ branching fractions



Status of flavour physics anomalies (2)

- All points to the presence of an additional interaction
- Several global fits to Wilson coefficients agree [Buttazzo et al - 1604.03940]
 - [Bauer et al - PRL116,141802(2016)]
 - [Crivellin et al - PRL114,151801(2015)]
 - [Altmannshofer et al - PRD89(2014)095033]...
- Possible underestimated contributions from $c\bar{c}$ loops
 - [Lyon et al - 1406.0566] [Altmannshofer et al -1503.06199]
 - [Ciuchini et al - JHEP06(2016)116]
- Possible explanation is new high mass boson (Z')
- Can be **out of reach for direct production at LHC**
- Fundamental to be confirmed with Run II data

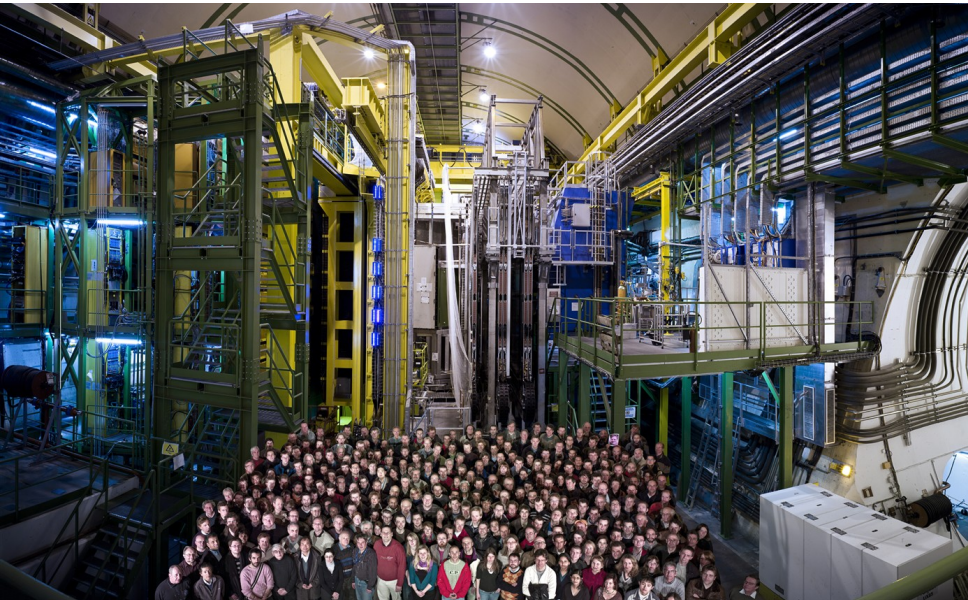


Importance of strange physics

- LHC confirmed SM even more:
a light Higgs boson and nothing else up to TeV energies
- Motivations for NP are still there but no clear indication of possible NP directions
- Need to search for NP in a broad spectrum
- Unique role of strange physics
 - ★ Unique probe of fundamental SM parameters
 - ★ Extremely suppressed FCNC $A(s \rightarrow d) \sim \lambda^5 \sim 5 \cdot 10^{-4}$
 - ★ Largest sensitivity to non-MFV dynamics
 - ★ Useful probe of very light (weakly coupled) NP dynamics

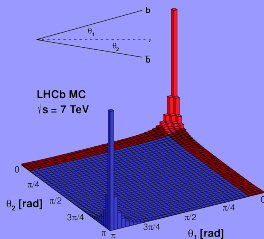
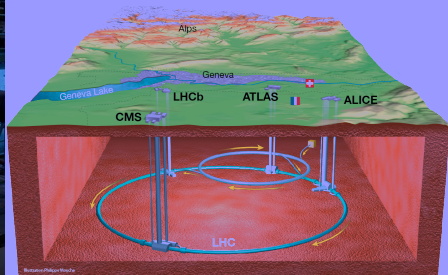
	d	s	b
u	$1 - \lambda^2/2$	λ	$A\lambda^3(\rho - i\eta)$
c	$-\lambda$	$1 - \lambda^2/2$	$A\lambda^2$
t	$A\lambda^3(1 - \rho - i\eta)$	$-A\lambda^2$	1

See G. Isidori at KAON 2016 [talk]



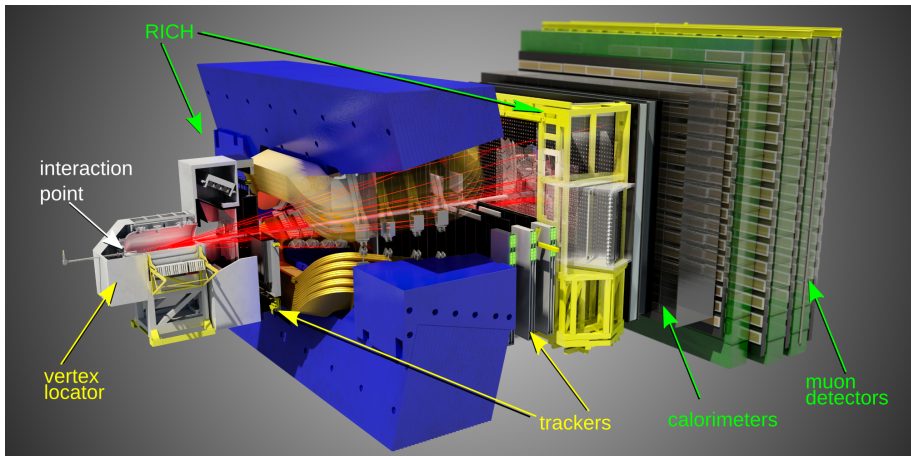
LHCb experiment

- 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 $4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

LHCb detector



Excellent vertex and IP resolution

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

Very good momentum resolution

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

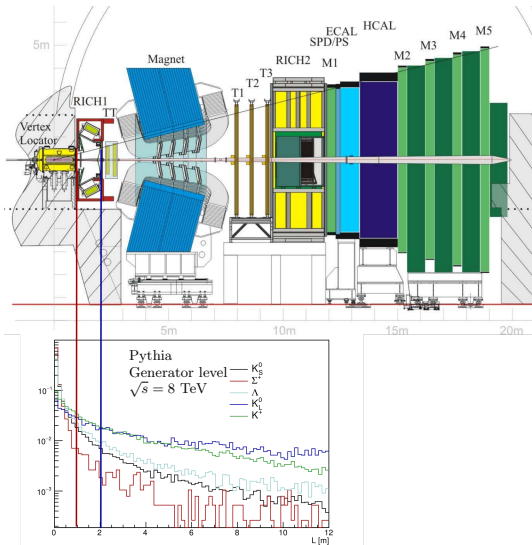
Muon identification

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

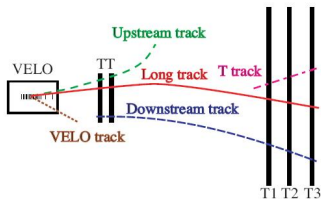
Trigger

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

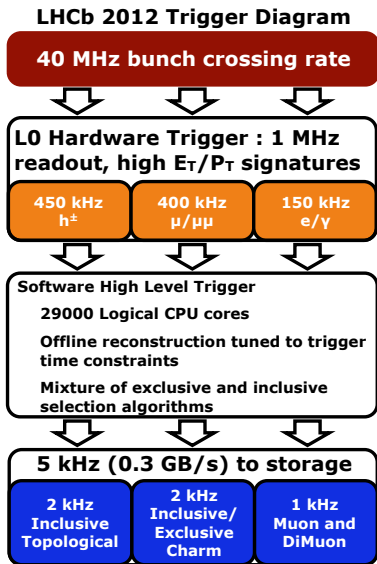
Setting the (long) stage



- Huge strange hadrons production cross-section at LHCb:
O(1) strange hadron per minbias event
- Large lifetimes for LHCb...
but the peak of an exponential is at zero!



LHCb Run I data-taking

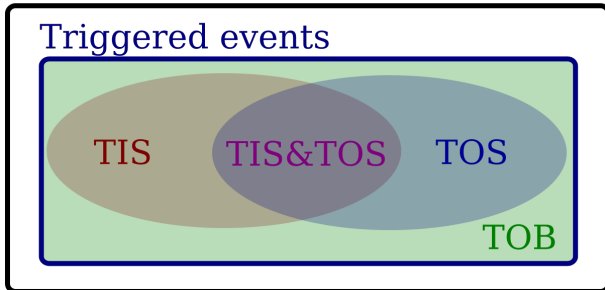


- LHCb trigger designed for heavy flavours
- Muon (hadron) L0 trigger require $p_T > [1 - 5] GeV$
- **Too hard for primary strange hadrons**
- Hlt1 and Hlt2 are software and customizable
- No dedicated triggers in 2011, added a $K_S^0 \rightarrow \mu^+ \mu^-$ dedicated trigger in 2012
- Several generic (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= $\text{TIS} \& \text{TOS}$)

All events



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

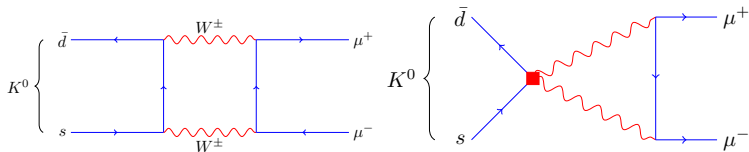
Tolk, S et al. [LHCb-PUB-2014-039](#)



Strange physics at LHCb with Run I

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

- $K_L^0 \rightarrow \mu^+ \mu^-$ is the “father” of flavour physics motivating the need for charm quark and GIM mechanism
- $K_S^0 \rightarrow \mu^+ \mu^-$ in addition suppressed by CPV
- SM prediction $\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) = (5.1 \pm 1.5) \cdot 10^{-12}$
[Ecker, Pich - Nucl Phys B366 (1991)] [Isidori, Unterdorfer - JHEP 01 (2004) 009]
- Dominated by long distance contributions
- Sensitive to NP, e.g. light scalars with CP-violating Yukawa couplings





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

- Best limit before LHCb was $\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) < 3.1 \cdot 10^{-7}$ at 90% CL at CERN PS in 1973 [S. Gjesdal et al. PLB44(1973)217]
- In Run I about 10^{13} K_S^0 in LHCb acceptance per fb^{-1} of luminosity 40% of which decaying inside the VELO
- Limit obtained by LHCb with 1fb^{-1} at 7 TeV: $\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) < 9 \cdot 10^{-9}$ at 90% CL
- Updated analysis with 2fb^{-1} 8 TeV and combined with the first one

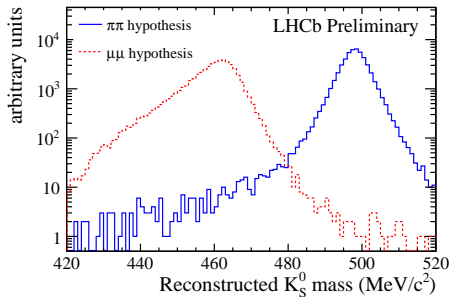
Search for $K_S^0 \rightarrow \mu^+ \mu^-$ decays

Selection strategy

- Search for $K_S^0 \rightarrow \mu^+ \mu^-$ from two well identified muons
- Common selection of $K_S^0 \rightarrow \mu^+ \mu^-$ and $K_S^0 \rightarrow \pi^+ \pi^-$, control and normalisation channel as well as main background
- Armenteros-Podolanski veto for $\Lambda \rightarrow p\pi^-$ and particle identification against $K^* \rightarrow K\pi$ and other backgrounds

Trigger strategy

- Three categories based on TIS / TOS information at the different levels



$$K_S^0 \rightarrow \mu^+ \mu^-$$

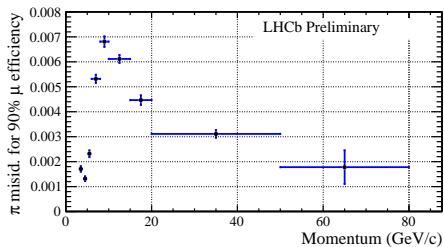
Two multivariate operators to fight different backgrounds

Dedicated multivariate particle identification algorithm developed

- Trained on $K_S^0 \rightarrow \pi^+ \pi^-$ and $B^+ \rightarrow J/\psi K^+$ reweighted to match kinematics
- 21 variables using Muon detector information and 14 variables related to RICH information
- Fourfold improvement in misID with respect to previous analysis

BDT to fight combinatorial background

- Trained on $K_S^0 \rightarrow \pi^+ \pi^-$ data proxy for signal and right data sideband for background
- Geometric and kinematic variables as input
- Trained separately per trigger category



$$K_S^0 \rightarrow \mu^+ \mu^-$$

Normalisation

- Search performed in bins of BDT and trigger category

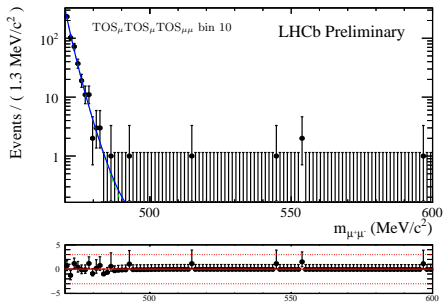
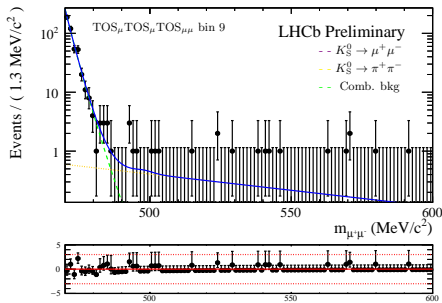
$$\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) = \mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-) \cdot \frac{\varepsilon^{\pi\pi}}{\varepsilon_i^{\mu\mu}} \cdot \frac{N_i^{\mu\mu}}{N^{\pi\pi}} = \alpha_i N_i^{\mu\mu}$$

- NoBias trigger used for $K_S^0 \rightarrow \pi^+ \pi^-$ (of known prescale of $\sim 3 \cdot 10^{-7}$)
- Efficiencies from MC but calibrated with data corrections
- Total systematic uncertainty of 4 – 5% on the normalisation depending on the bin
- Final fit performed with different background shapes for an absolute uncertainty of 4×10^{-11}

$$K_S^0 \rightarrow \mu^+ \mu^-$$

Results

- $K_S^0 \rightarrow \mu^+ \mu^-$ distribution fitted in the [470,600] MeV range
- Simultaneous maximum likelihood fit performed over the 30 bins
- Combinatorial and misID $K_S^0 \rightarrow \pi^+ \pi^-$ background components included
- **No excess of events is observed with respect to background expectations**



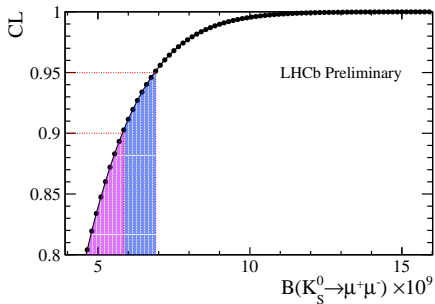
$$K_S^0 \rightarrow \mu^+ \mu^-$$

Results

- The upper limit of the previous search is reinterpreted as posterior on the branching fraction and included as prior in this search
- The new upper limit on the branching fraction is

$$\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^-) < 5.8(6.9) \times 10^{-9} \text{ at 90 (95\%) CL}$$

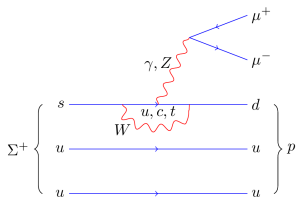
- Factor 50 improvement with respect to the best limit before LHCb



Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays

Standard Model

- $\Sigma^+ \rightarrow p\mu^+\mu^-$ is a very rare FCNC
- Short distance SM branching fraction is $O(10^{-12})$
- Dominated by long distance contributions:
 $1.6 \cdot 10^{-8} < \mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) < 9.0 \cdot 10^{-8}$ [He et al. - Phys.Rev. D72 (2005) 074003]

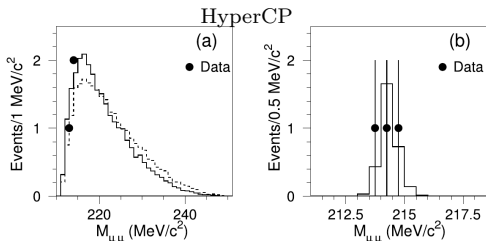
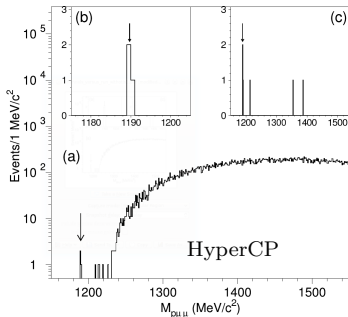


The HyperCP evidence

- An evidence for this decay was found by the HyperCP experiment with 3 events in absence of background
- Measured branching fraction is:

$$\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$$
[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 $\Sigma^+ \rightarrow pX^0(\rightarrow \mu\mu)$ decay with $m_X^0 = 214.3 \pm 0.5$ MeV

$$\mathcal{B}(\Sigma^+ \rightarrow pX^0(\rightarrow \mu\mu)) = (3.1^{+2.4}_{-1.9} \pm 5.5) \cdot 10^{-8}$$





Theoretical interpretations and experimental status

- 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 $B^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ and $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
 - ★ Not confirmed nor disproved
- No other search in $\Sigma^+ \rightarrow p \mu^+ \mu^-$ decays



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

General analysis strategy

Sample and selection:

- Full 2011+2012 statistics, luminosity $3 fb^{-1}$
- Selections for final states: $\Sigma^+ \rightarrow p\mu^+\mu^-$, $\Sigma^+ \rightarrow \bar{p}\mu^+\mu^+$, $\Sigma^+ \rightarrow p\pi^0$, $K^+ \rightarrow \pi^+\pi^-\pi^+$
- Decays reconstructed with long tracks (i.e. decays in VELO)
- Prompt decays

Datasets strategy

- Very soft signal to be triggered
- Two trigger strategies:
 1. Full - all events are retained, for search purposes, no normalisation
 2. TIS - for normalization purposes (sub sample)



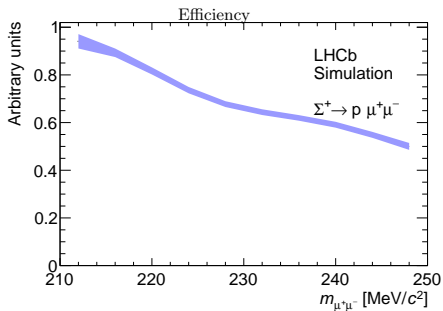
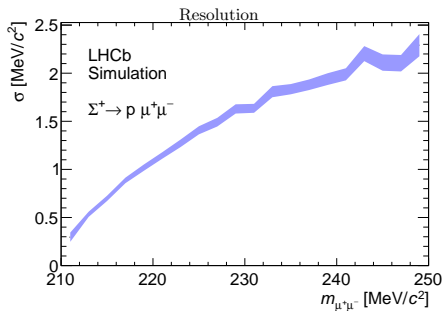
$\Sigma^+ \rightarrow p\mu^+\mu^-$ at LHCb

General analysis strategy

1. Soft pre-selection to reduce dataset
2. Cut on BDT and PID to remove most of the background
3. Explicit veto of $\Lambda \rightarrow p\pi$ background, no other peaking background contributes
4. Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$ decays:
 - * Search around Σ mass window for signal
 - If peak is found, look at $\mu\mu$ invariant mass
5. Normalize branching fraction to $\Sigma^+ \rightarrow p\pi^0$ decays

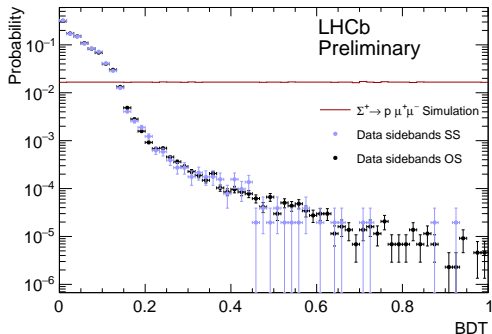
Search for an Hyper-CP like signal

- Hyper-CP signal is consistent with $\Sigma^+ \rightarrow p X^0 (\rightarrow \mu\mu)$, 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 ($\Sigma^+ \rightarrow \bar{p}\mu^+\mu^+$)
- Common geometric and kinematic variables: pointing, IP, p_T and isolations, ...



Normalisation

- No fully charged final state available in the Σ^+ to normalize the branching fraction
- Use high branching fraction $\Sigma^+ \rightarrow p\pi^0$

$$\begin{aligned}
 \mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) &= \frac{\varepsilon_{\Sigma^+ \rightarrow p\pi^0}}{\varepsilon_{\Sigma^+ \rightarrow p\mu^+\mu^-}} \frac{\mathcal{B}(\Sigma^+ \rightarrow p\pi^0)}{N_{\Sigma^+ \rightarrow p\pi^0}} N_{\Sigma^+ \rightarrow p\mu^+\mu^-} \\
 &= \alpha N_{\Sigma^+ \rightarrow p\mu^+\mu^-}
 \end{aligned}$$

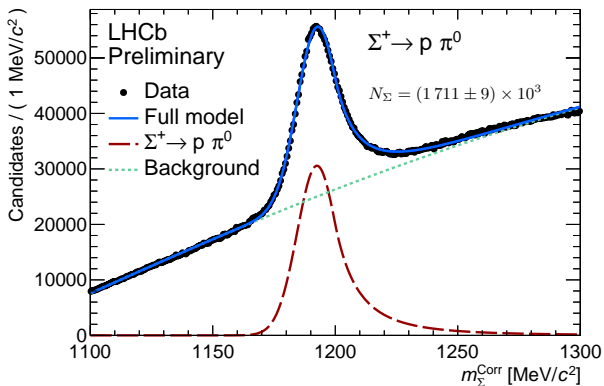
- Selection for $\Sigma^+ \rightarrow p\pi^0$ with $\pi^0 \rightarrow \gamma\gamma$ (resolved clusters) from calorimeter
- Branching fraction $\mathcal{B} = (51.57 \pm 0.30)\%$

For full Run I dataset, only TIS:

- Single event sensitivity $\alpha_{TIS} = (1.1 \pm 0.6) \times 10^{-8}$
- Correspondent to 4.6 ± 4.2 expected events in the TIS sample with a SM branching fraction

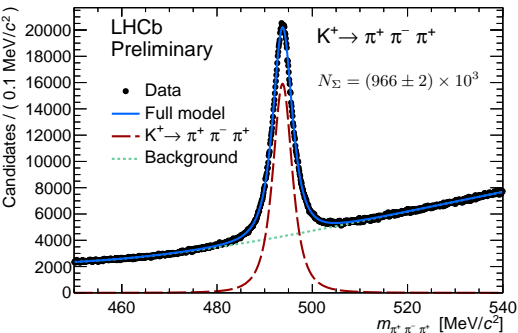
Normalisation with $\Sigma^+ \rightarrow p\pi^0$

- Fit to corrected mass: $m_\Sigma - m_{\pi^0} + m_{\pi^0}^{PDG}$
- Single Crystal-Ball pdf with right tail for the signal
- Modified ARGUS function for the background



Normalisation systematics

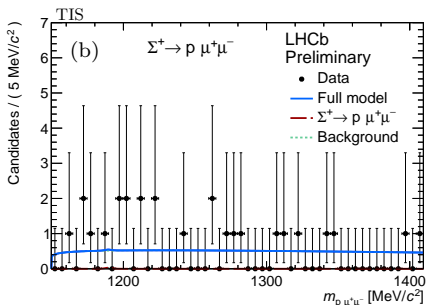
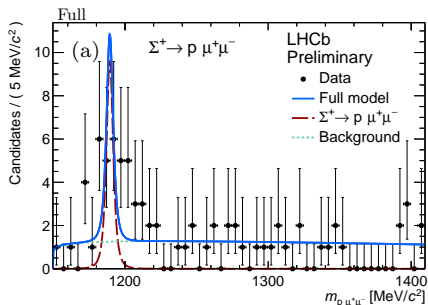
- TIS Trigger efficiency calibrated with large $K^+ \rightarrow \pi^+ \pi^- \pi^+$ sample and TISTOS method
- Reconstruction of the π^0 calibrated with ratio of ratio of $B^+ \rightarrow J/\psi K^{*+} (\rightarrow K^+ \pi^0)$ and $B^+ \rightarrow J/\psi K^+$ decays reconstructed in data.
- Particle identification calibrated with control channels in data ($\Lambda \rightarrow p \pi^-$ and J/ψ)
- BDT classifier calibrated with $K^+ \rightarrow \pi^+ \pi^- \pi^+$ channel in data



Systematic uncertainties

Selection Data-MC differences	1.4%
Calibration of BDT efficiency	6.4%
Calibration of PID efficiency	20%
Calibration of the π^0 efficiency	10%
Calibration of the TIS efficiency	30%
Total	43%

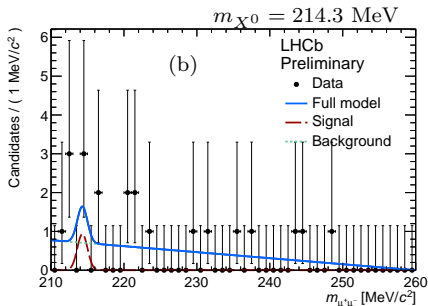
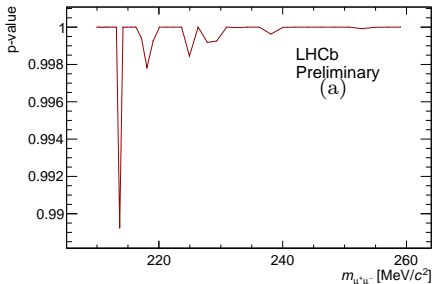
Results



- Excess of events w.r.t. background with a significance of 4.0σ
- Fitted signal yield: $12.9^{+5.1}_{-4.2}$
- No excess of events in the TIS sub-sample for which normalisation is performed
- Upper limit with CLs method: $\mathcal{B}(\Sigma^+ \rightarrow p\mu^+\mu^-) < 6.3 \times 10^{-8}$ at 95% CL

Results: analysis of the dimuon mass

- Consider candidates within 2σ from the Σ mass in the full selection
- Scan dimuon invariant mass for possible peaks
- Fit with gaussian of known mass and resolution
- No significant peak found
- Most pronounced at 213.7 MeV (but not significant)
- Fit at $m_{X^0} = 214.3$ MeV yields 1.6 ± 1.9 events corresponding to a fraction 0.078 ± 0.092 of the total seen signal





Discussion of the results

- Found signal only in the full sample:
most of the seen events have only one of the three trigger layers not being TIS
- Full detailed study of $\Sigma^+ \rightarrow p\mu^+\mu^-$ trigger efficiency is under way
- The main conclusions are anyway independent of absolute normalisation:
 1. Evidence of $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay
 2. SM-like distribution of the dimuon invariant mass
 3. Contribution from putative X^0 particle consistent with zero



LHCb Run II and Upgrade

LHCb Run II data-taking

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz

h^\pm

400 kHz

$\mu/\mu\mu$

150 kHz

e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

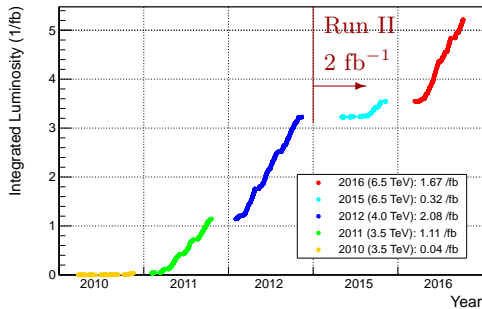
- Higher bandwidth from improved farm and algorithms allows higher yields
- Real time calibration between Hlt1 and Hlt2
- L0 trigger still limiting factor for strange hadrons
- *Turbo* stream allows high rate channels to be stored: [Aaij et al. JCP208(2016)35] important for non rare strange physics

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

Prospects for strange physics with Run II data

LHCb Cumulative Integrated Luminosity in pp collisions 2010-2016



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

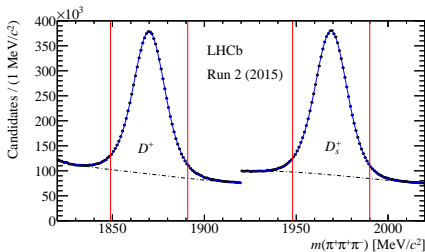
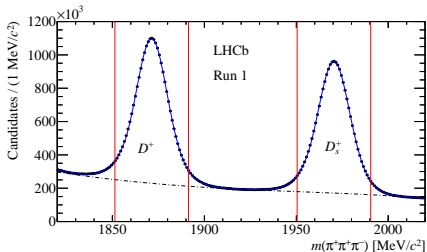
- Analysis of $\Sigma^+ \rightarrow p\mu^+\mu^-$ with dedicated triggers
 - * Probable observation
 - * Precise branching fraction measurement
 - * Possible differential branching fraction
- $K_S^0 \rightarrow \mu^+\mu^-$ see later
- Different other rare hyperon decay searches possible ($\Sigma^+ \rightarrow pe^+e^-$, $\Lambda^0 \rightarrow p\pi^-e^+e^-$, LFV, etc)

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

- 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**)
- $\eta^{(\prime)} \rightarrow \pi^+ \pi^-$ 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
 $\mathcal{B}(\eta \rightarrow \pi^+ \pi^-) < 1.3 \cdot 10^{-5}$ (KLOE $\phi \rightarrow \eta\gamma$ [PLB606 (2005) 276])
 $\mathcal{B}(\eta' \rightarrow \pi^+ \pi^-) < 5.5 \cdot 10^{-5}$ (BESIII $J/\psi \rightarrow \gamma\pi^+ \pi^-$ [PRD84(2011)032006])

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

- LHCb strategy:
look for peaks in $\pi\pi$ mass from $D_{(s)}^+ \rightarrow \pi^+ \pi^- \pi^+$ decays (*i.e.* $D_{(s)}^+ \rightarrow \pi^+ \eta^{(\prime)}$)
- MVA operator to reduce background
- Normalisation: $\mathcal{B}(\eta^{(\prime)} \rightarrow \pi^+ \pi^-) = \frac{N_{\eta^{(\prime)}}}{N_{D_{(s)}^+ \rightarrow \pi^+ \pi^- \pi^+}} \frac{1}{\varepsilon_{\eta^{(\prime)}}} \frac{\mathcal{B}(D_{(s)}^+ \rightarrow \pi^+ \pi^- \pi^+)}{\mathcal{B}(D_{(s)}^+ \rightarrow \pi^+ \eta^{(\prime)})}$
- 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



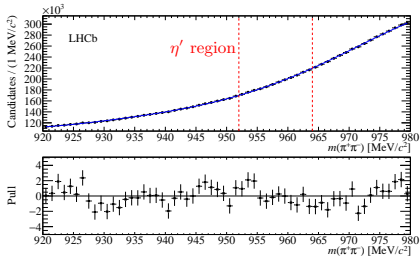
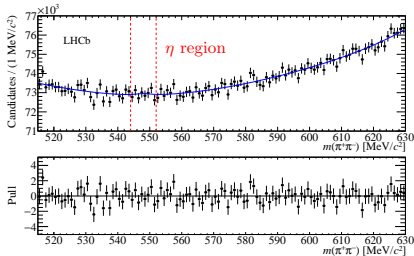
Search for CP violating strong decays $\eta' \rightarrow \pi^+ \pi^-$

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

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

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

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



LHCb Upgrade data-taking

LHCb Upgrade Trigger Diagram

**30 MHz inelastic event rate
(full rate event building)**

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

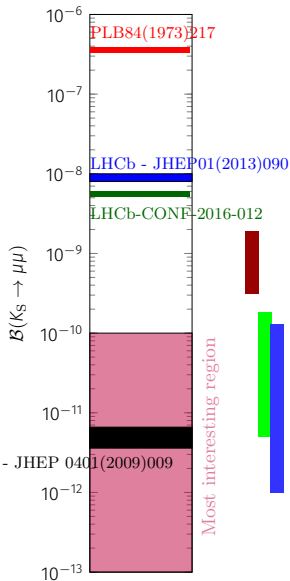
Add offline precision particle identification and track quality information to selections
Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

- Upgraded detector for 40 MHz full readout
- $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \Rightarrow$ 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!

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



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

- 8 fb⁻¹ Run II - [4 · 10⁻¹⁰, 2 · 10⁻⁹]
- 23 fb⁻¹ - [4 · 10⁻¹², 2 · 10⁻¹⁰]
- 100 fb⁻¹ - [10⁻¹², 10⁻¹⁰]

- Possible change towards higher value of SM expectation
- Approach interesting region in Run II
- Probe SM in Upgrade

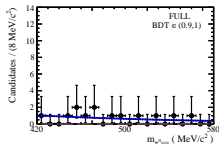
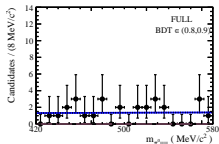
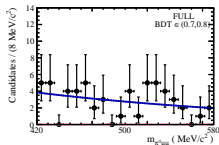
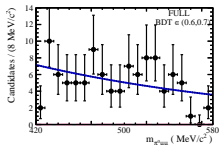
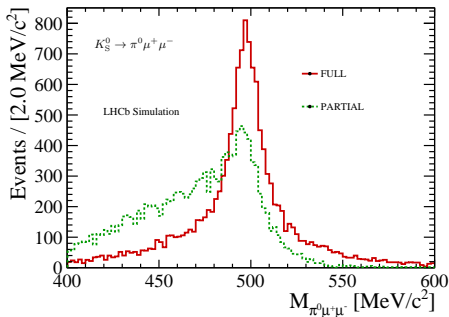
Sensitivity to $K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$

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

[J.R. Batley et al. PLB599 (2011) 197]

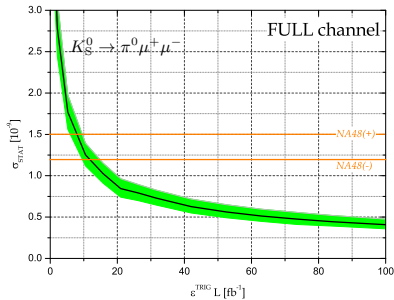
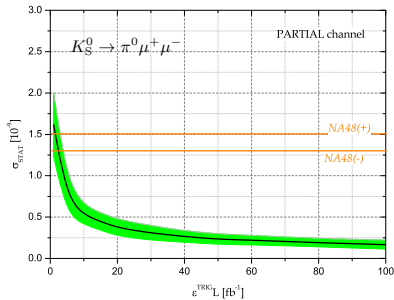
Sensitivity to $K_S^0 \rightarrow \pi^0 \mu^+ \mu^-$

- Studied sensitivity of LHCb to this channel in Run II and Upgrade scenarios
- Difficult reconstruction due to soft π^0
- 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



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

- Statistical uncertainty on $\mathcal{B}(K_S^0 \rightarrow \pi^0 \mu^+ \mu^-)$ as a function of luminosity times trigger efficiency
- LHCb will be competitive with NA48 for trigger efficiencies of $\sim 50\%$ or larger



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

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

[D'Ambrosio et al - EPJC73(2013)2678]

- $K_L^0 \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ studied by different experiments
- No experimental constraints on K_S^0 modes
- K_S^0 four lepton decays very suppressed in SM

$$\mathcal{B}(K_S^0 \rightarrow e^+ e^- e^+ e^-) \sim 10^{-10}$$

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

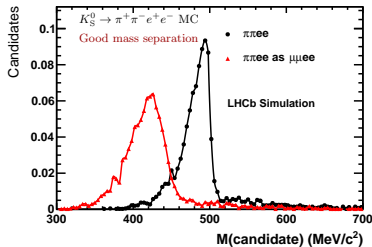
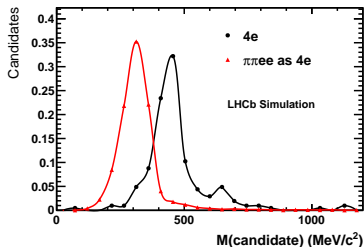
$$\mathcal{B}(K_S^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) \sim 10^{-14}$$

- Sensitive to NP at same order of SM

Sensitivity to $K_S^0 \rightarrow \pi^+\pi^-\ell^+\ell^-$

- $K_S^0 \rightarrow \pi^+\pi^-\ell^+\ell^-$ is normalisation, control and background channel for $K_S^0 \rightarrow \ell^+\ell^-\ell^+\ell^-$
- Sensitivity study at LHCb with MC simulations
- Standard selection with four displaced good quality tracks
- Particle identification and geometry requirements to suppress the background
- Both TIS and TOS trigger strategy devised: $\varepsilon \sim 0.2\%$, limited by L0 trigger
- $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-\ell^+\ell^-) = (4.79 \pm 0.15) \times 10^{-5}$ (PDG average)

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





Sensitivity to $K_S^0 \rightarrow \pi^+ \pi^- e^+ e^-$

- 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

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

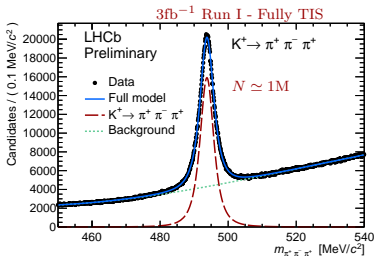
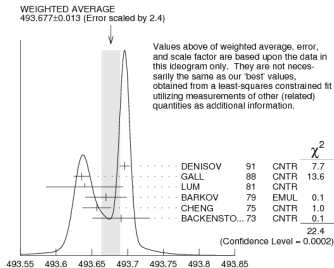
- Similar efficiencies are expected for the $K_S^0 \rightarrow \ell^+ \ell^- \ell^+ \ell^-$ rare channels
- Single event sensitivities of order $9.6 \cdot 10^{-10}$ per each fb^{-1} in Upgrade conditions

Prospects for charged kaons

- Enormous K^+ production but small acceptance
- Run I has 1 M $K^+ \rightarrow \pi^+ \pi^- \pi^+$ 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
- $K^+ \rightarrow \pi^+ \mu^- \mu^+$ and $K^+ \rightarrow \pi^+ e^- e^+$ 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 [†]



[†]A. Contu LHCb-PUB-2014-032



Summary and conclusions

- *LHCb expanding its physics reach towards strange physics complementary to the core program*
- Encouraging Run I results on $K_S^0 \rightarrow \mu^+ \mu^-$, $\Sigma^+ \rightarrow p \mu^+ \mu^-$ and $\eta^{(\prime)} \rightarrow \pi^+ \pi^-$
- 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 II giving new results with improved trigger
- Upgrade trigger will allow unprecedented sensitivities on many channels



Fit to the invariant mass distribution

- Signal shape described as Hypatia function used with fixed parameters (only mean and resolution floating)*
 - * Resolution and mean calibrated with $K^+ \rightarrow \pi^+ \pi^- \pi^+$ Data/MC ratio
 - * Signal resolution left free to vary in the fit with gaussian constraint in final fits
- Background described as modified ARGUS function

$$f(m, m_0, p, c) = m \left(\frac{m^2}{m_0^2} - 1 \right)^p e^{-c \frac{m}{m_0}} \quad (1)$$

where m_0 is the threshold mass typically of the order of the sum of the daughters masses; p and c are free parameters.

*D. Martinez Santos, F. Dupertuis, *Nucl.Instrum.Meth.* A764 (2014) 150-155