Rare strange decays at LHCb

Miguel Ramos Pernas

on behalf of the LHCb collaboration

Universidade de Santiago de Compostela

miguel.ramos.pernas@cern.ch

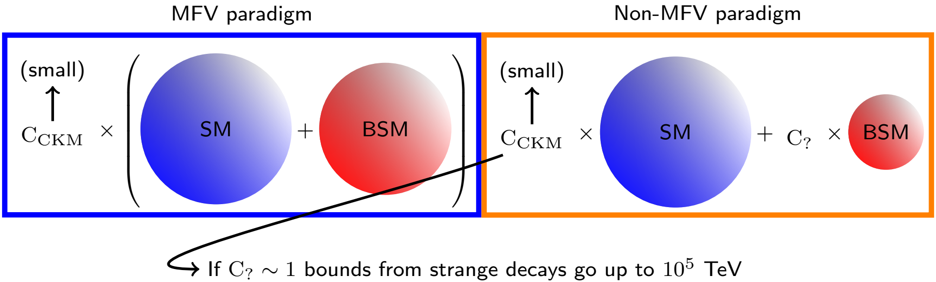
EPS-HEP

Venice, July 8, 2017

Introduction

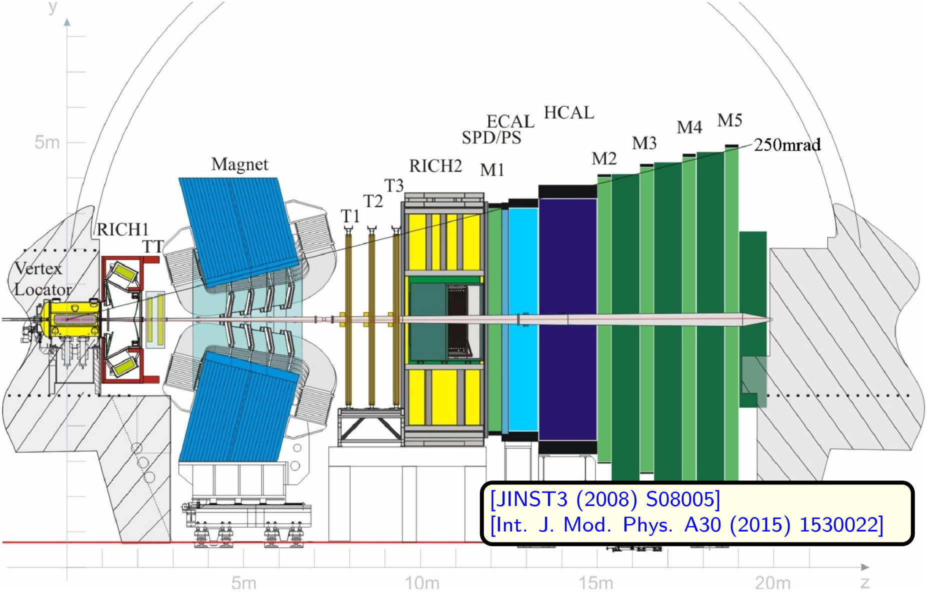
Strange decays play a major role in particle physics:

- For BSM at $\mathcal{O}(\text{TeV})$, it can only be seen if there are new sources of flavour violation
- $s \to d$ transitions have the strongest suppression in the SM: $V_{td}V_{ts}^{*} \sim 10^{-4}$
- In a Non-Mininimal-Flavour-Violating (Non-MFV) paradigm, they have the highest sensitivity



If $C_{?} \sim 1$ bounds from strange decays go up to 10^{5} TeV

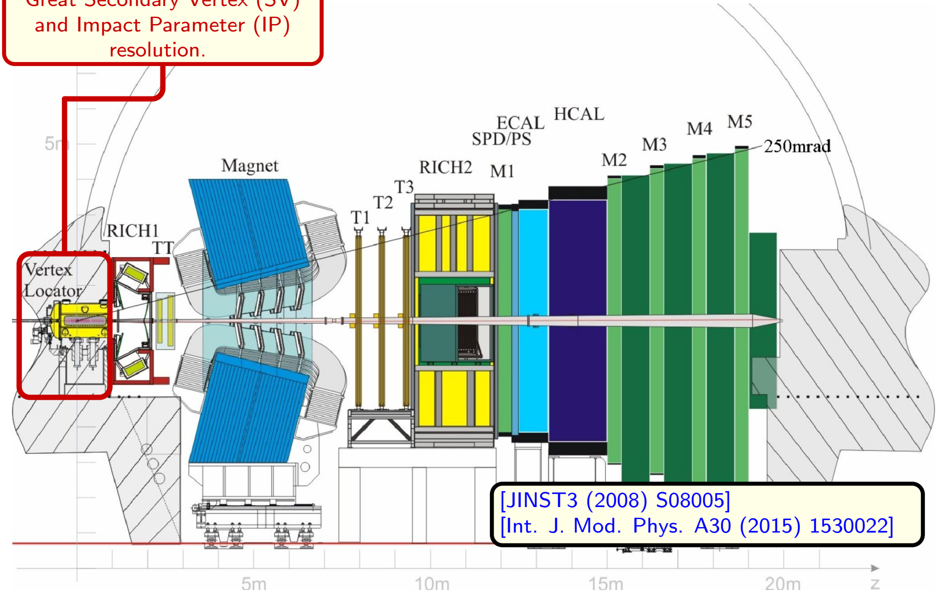
The LHCb detector



[JINST3 (2008) S08005]
[Int. J. Mod. Phys. A30 (2015) 1530022]

The LHCb detector

Great Secondary Vertex (SV) and Impact Parameter (IP) resolution.

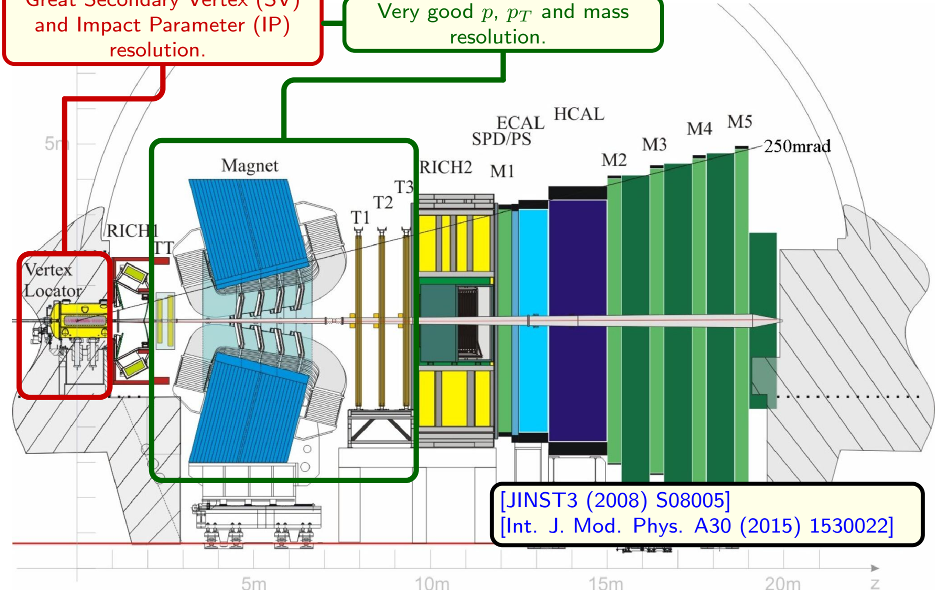


[JINST3 (2008) S08005]
[Int. J. Mod. Phys. A30 (2015) 1530022]

The LHCb detector

Great Secondary Vertex (SV) and Impact Parameter (IP) resolution.

Very good p, p_T and mass resolution.



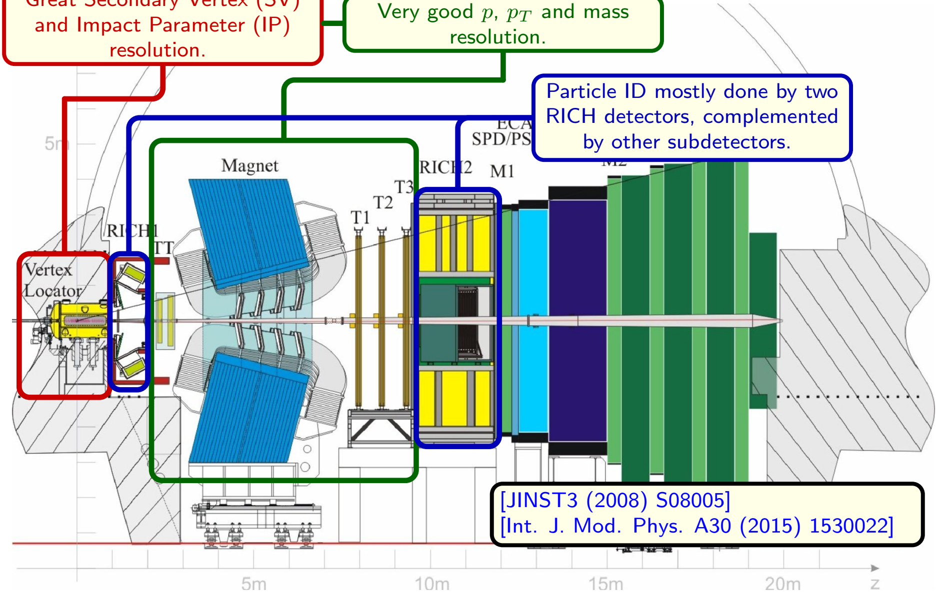
[JINST3 (2008) S08005]
[Int. J. Mod. Phys. A30 (2015) 1530022]

The LHCb detector

Great Secondary Vertex (SV) and Impact Parameter (IP) resolution.

Very good p, p_T and mass resolution.

Particle ID mostly done by two RICH detectors, complemented by other subdetectors.



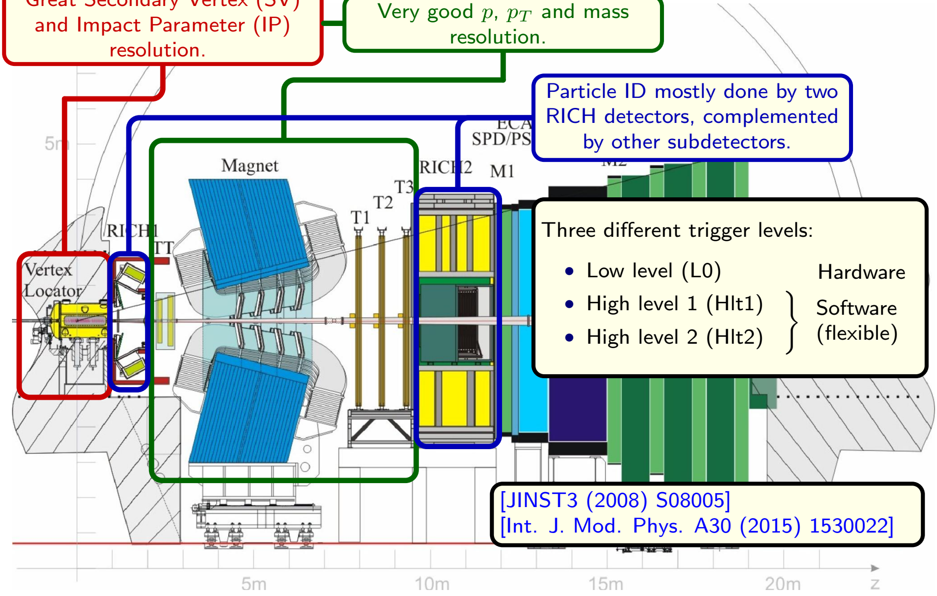
[JINST3 (2008) S08005]
[Int. J. Mod. Phys. A30 (2015) 1530022]

The LHCb detector

Great Secondary Vertex (SV) and Impact Parameter (IP) resolution.

Very good p, p_T and mass resolution.

Particle ID mostly done by two RICH detectors, complemented by other subdetectors.



Three different trigger levels:

- Low level (L0) — Hardware
- High level 1 (Hlt1) — Software (flexible)
- High level 2 (Hlt2) — Software (flexible)

[JINST3 (2008) S08005]
[Int. J. Mod. Phys. A30 (2015) 1530022]

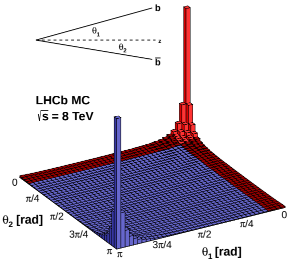
Strange decays at LHCb

The main purpose

- Study of b and c hadron decays.
- Good vertexing
- Good particle identification
- Very good mass resolution

However, much more can be done...

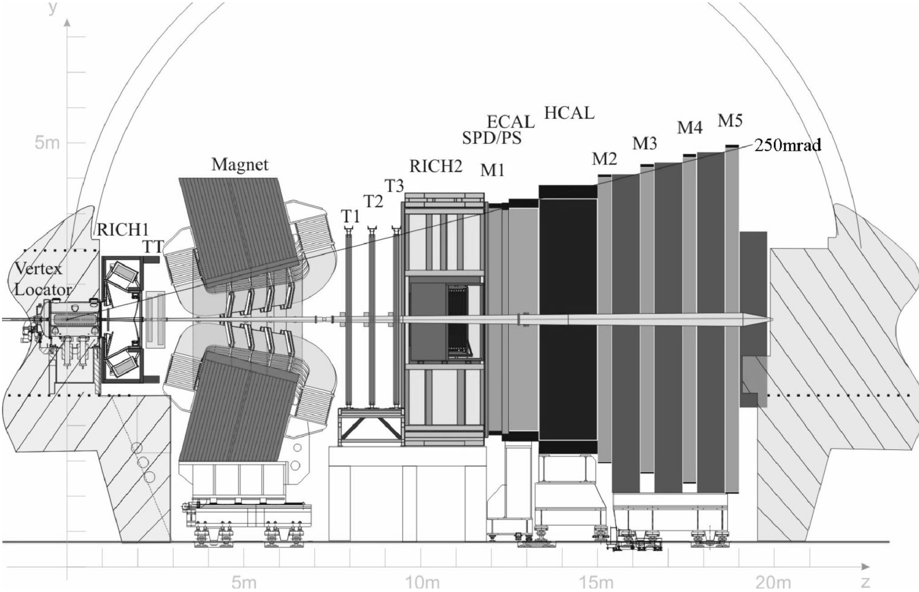
- Direct searches for new physics: dark photons, A_1^0, ...
- QCD at high pseudorapidity: p-Pb, p-He, p-Ar, ...
- Exotic particles: Pentaquarks, ...

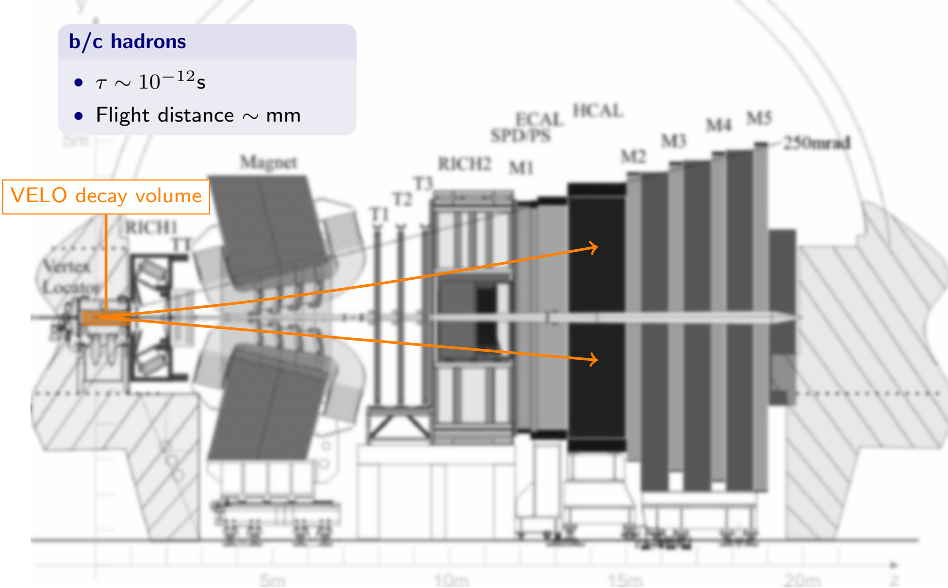


The LHCb Rare and Strange program

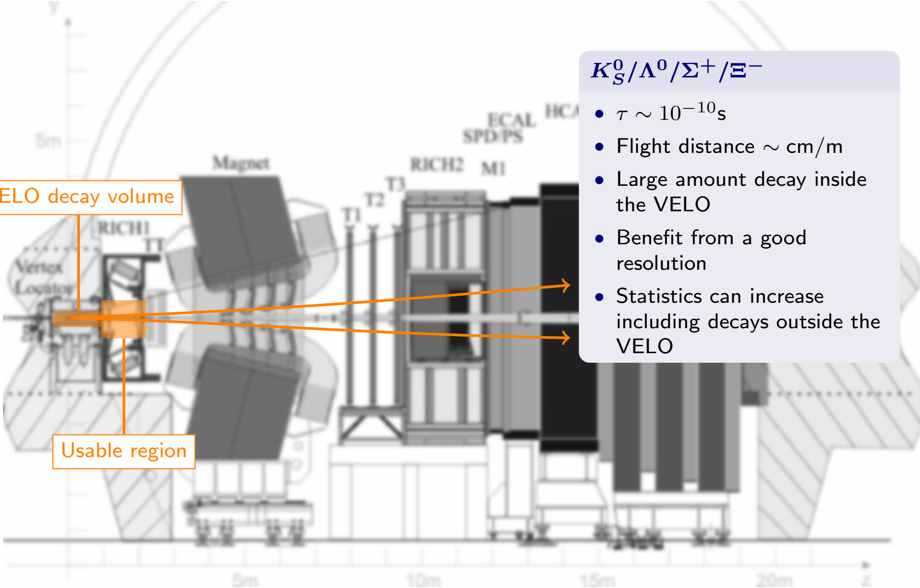
- Strange sector still largely unexplored
- First studies at LHCb in 2011
- $K_S^0 \to \mu^+\mu^-$ analysis has been the main benchmark

Strange decays at LHCb




b/c hadrons
• $\tau \sim 10^{-12}$s
• Flight distance ∼ mm
VELO decay volume
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
250mrad
5m
10m
15m
20m

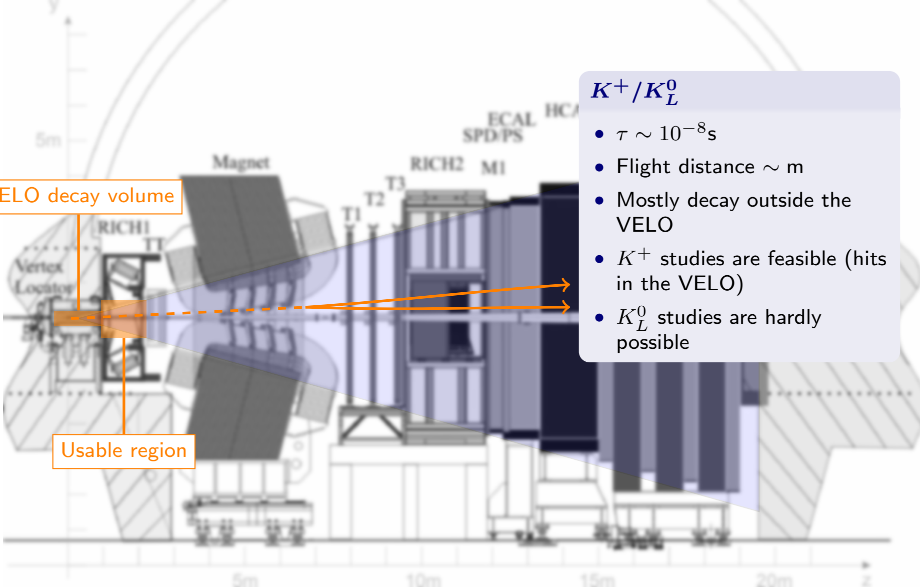
Strange decays at LHCb



$K_S^0/\Lambda^0/\Sigma^+/\Xi^-$

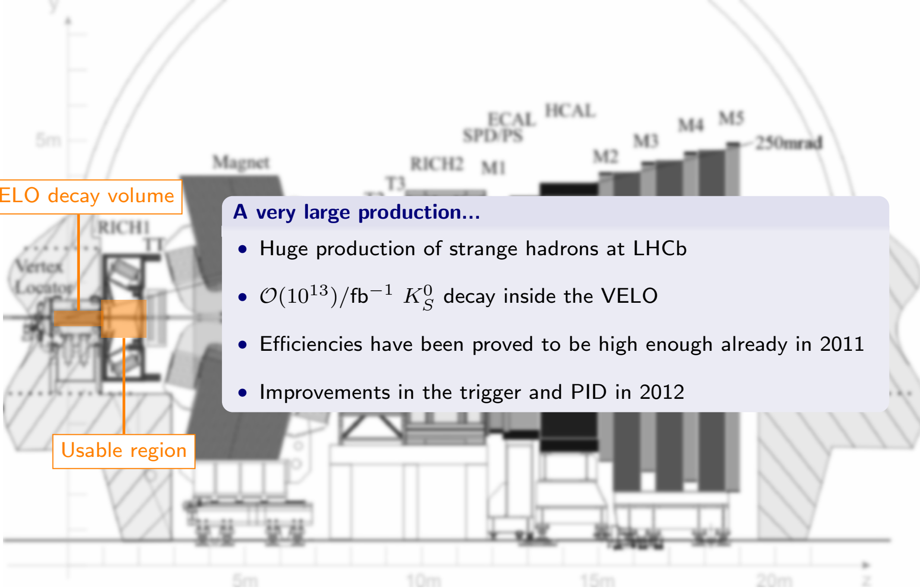
- $\tau \sim 10^{-10}$s
- Flight distance $\sim$ cm/m
- Large amount decay inside the VELO
- Benefit from a good resolution
- Statistics can increase including decays outside the VELO

Strange decays at LHCb



K^+/K^0_L

- $\tau \sim 10^{-8}$s
- Flight distance $\sim$ m
- Mostly decay outside the VELO
- K^+ studies are feasible (hits in the VELO)
- K^0_L studies are hardly possible



A very large production...

- Huge production of strange hadrons at LHCb
- $\mathcal{O}(10^{13})/\text{fb}^{-1}$ K_S^0 decay inside the VELO
- Efficiencies have been proved to be high enough already in 2011
- Improvements in the trigger and PID in 2012

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

- Flavour-changing neutral current (FCNC) transition
- Dominated by long distance contributions through $K_{S/L}^0 \to \gamma\gamma$
- Notably new light scalars can affect K_S^0 exclusively
- Model-independent bounds on the CP-violating phase of the $s \to dl^+l^-$ amplitude
- SM prediction: $\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) = (5.0 \pm 1.5) \times 10^{-12}$ [Nucl. Phys. B366 (1991) 189][JHEP 01 (2004) 009]

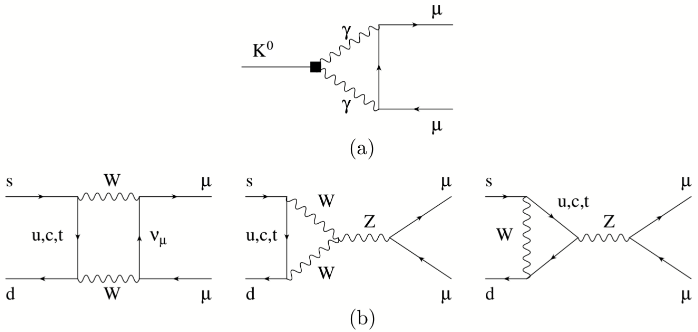
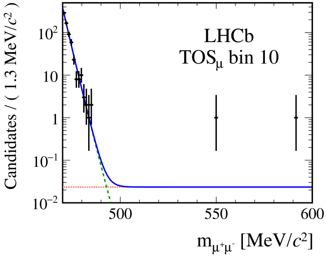


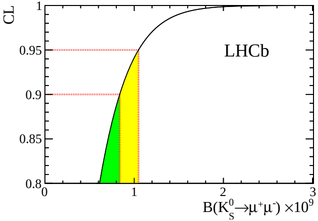
Figure: (a): Long distance contribution. (b) Short distance contributions. [JHEP 01 (2004) 009]

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

Analysis features

- Analysis using MC and data in 2012 conditions: $2\ \text{fb}^{-1}$ at 8 TeV
- Improvements on background rejection, μ_{ID} and trigger
- Normalized to $K_S^0 \to \pi^+\pi^-$ (most dangerous background)
- Negligible contributions from $K_L^0 \to \mu^+\mu^-$, $K^0 \to \pi^+\mu^-\bar{\nu}$, $\eta \to \mu^+\mu^-\gamma$, ...
- Fit done in bins of two MVA discriminants for two different trigger selections
- Result from 2011 is included as a prior [JHEP 01 (2013) 090]

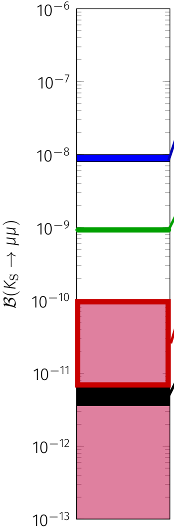




[arXiv:1706.00758] submitted to EPJ C

New world best limit!

$\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) < 0.8(1.0) \times 10^{-9}$ at $90(95)\%$ of CL

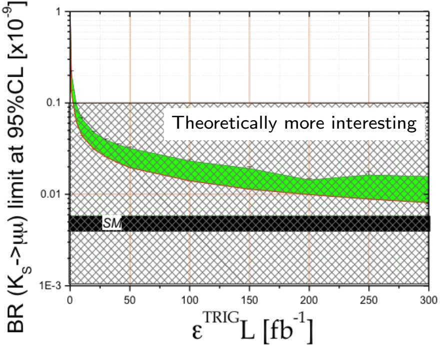


Old LHCb limit
$\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) < 9(11) \times 10^{-9}$ at 90(95)% of CL
[JHEP 01 (2013) 090]

New limit!
$\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) < 0.8(1.0) \times 10^{-9}$ at 90(95)% of CL
[arXiv:1706.00758] submitted to EPJ C

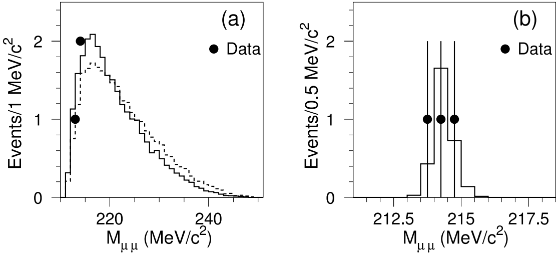
Theoretically more interesting region

Standard Model prediction

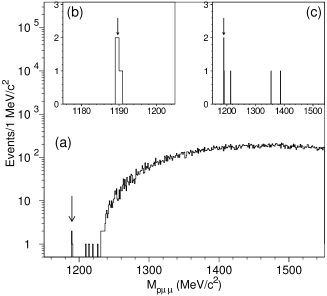


$\Sigma^+ \to p^+\mu^+\mu^-$

- Evidence for this decay was found by the HyperCP experiment with 3 events in absence of background
- $\mathcal{B}\left(\Sigma^+ \to p^+\mu^+\mu^-\right) = \left(8.6^{+6.6}_{-5.4} \pm 5.5\right) \times 10^{-8}$
- The three events had the same dimuon invariant mass, thus pointing towards a $\Sigma^+ \to p^+ X^0\,(\to \mu\mu)$ decay
- $\mathcal{B}\left(\Sigma^+ \to p^+ X^0\,(\to \mu\mu)\right) = \left(3.1^{+2.4}_{-1.9} \pm 5.5\right) \times 10^{-8}$



[Phys. Rev. Lett. 94]

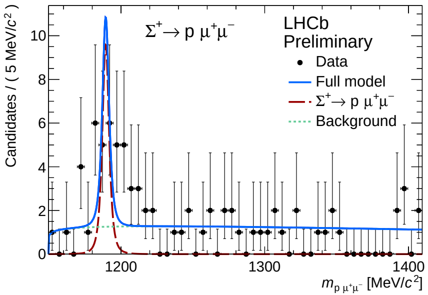


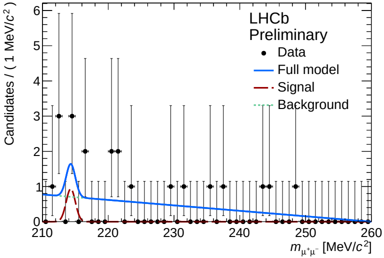
$\Sigma^+ \to p^+\mu^+\mu^-$

[LHCb-CONF-2016-013]

Analysis strategy

- Using full Run-I statistics: 3fb^{-1}
- Search using prompt decays
- Two different trigger strategies were adopted
  - FULL - all events are retained. No normalization.
  - TIS - candidates are taken independetly of any trigger decision. Normalization to $\Sigma^+ \to p^+\pi^0$.





SM once again

- 4σ evidence of $\Sigma^+ \to p^+\mu^+\mu^-$ in the FULL sample: $12.9^{+5.1}_{-4.2}$ fitted events
- No signal in the TIS sample
- $\mathcal{B}\left(\Sigma^+ \to p^+\mu^+\mu^-\right) < 6.3 \times 10^{-8}$ at 95% CL
- No significant peaks have been seen in the dimuon mass
- Branching fraction measurement ongoing

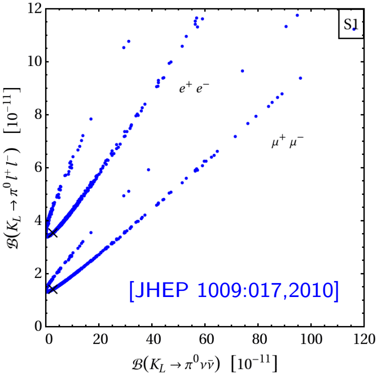
$K_S^0 \to \pi^0\mu^+\mu^-$

Randall-Sundrum model

$\mathcal{B}\left(K_L^0 \to \pi^0\mu^+\mu^-\right)$ has a variation of ~ 1 order of magnitude in models with extra dimensions.

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

$|a_S| = 1.2 \pm 0.2$ dominates the theoretical uncertainty. Comes from the measurements of $\mathcal{B}\left(K_S^0 \to \pi^0 l^+ l^-\right)$.



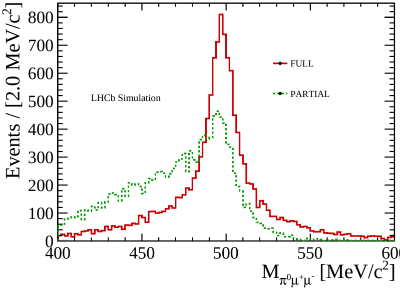
- Large uncertainties on $\mathcal{B}\left(K_S^0 \to \pi^0\mu^+\mu^-\right) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$ (NA48) [Phys. Lett. B599 (2004) 197]
- Current kaon experiments do not expect to improve such measurement
- A sensitivity study has been done at LHCb

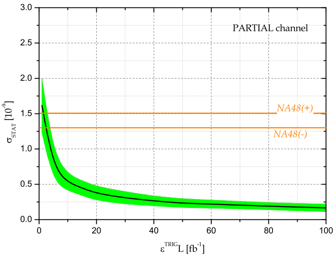
$K_S^0 \to \pi^0 \mu^+ \mu^-$

Analysis strategy

- Low reconstruction efficiency of $\pi^0 \to \gamma\gamma$ at LHCb
- The K_S^0 mass does not depend too much on the information from the π^0
- Two different strategies adopted:
  - FULL: Include the information from the π^0, Run-I 3 fb^{-1}
  - PARTIAL: Add a virtual particle with $p \sim 10$ GeV/c (provides the best $M_{\pi^0\mu^+\mu^-}$ resolution), Run-II 0.3 fb^{-1}

[CERN-LHCb-PUB-2016-017]





Clean and very promising decay

- No peaking backgrounds from other decays: $K_S^0 \to \pi^+\pi^-$, $X^0 \to \pi^+\pi^-\pi^0$, $K^0 \to \mu^+\mu^-\gamma$, ...
- Main source of background is combinatorial
- Best sensitivity without reconstructing the π^0
- A precision measurement will be possible in the Upgrade!

$K_S^0 \to l^+l^-l^+l^-$

Many interest on the study of $K_S^0 \to l^+l^-l^+l^-$ decays. Very supressed in the SM [Eur. Phys. J. C73 (2013) no. 12 2678]:

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

Interesting physics behind this

- Interference between $K_S^0 \to l^+l^-l^+l^-$ and $K_L^0 \to l^+l^-l^+l^-$ decays would allow CKM stringent constraints.
- Highly suppressed, sensitive to NP

No experimental results in the literature so far [PDG].

Electron modes are challenging

- Need to study $K_S^0 \to \pi^+\pi^-e^+e^-$ to be used as normalization/control channel.
- Branching fraction measured by the NA48 collaboration [PLB vol. 694 pages 301-309].

Current world average [PDG].
$\mathcal{B}\left(K_S^0 \to \pi^+\pi^-e^+e^-\right) = 4.79 \pm 0.15 \times 10^{-5}$

Study the feasibility of observing $K_S^0 \to \pi^+\pi^-e^+e^-$ at LHCb

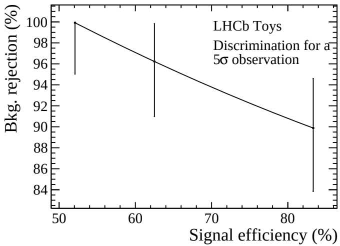
$K_S^0 \to l^+l^-l^+l^-$

Analysis goals

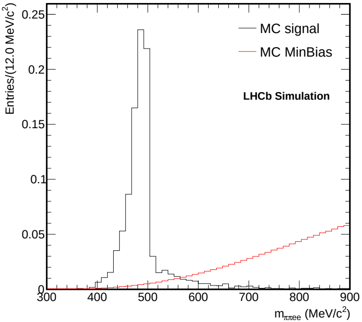
- Study based on MC and data in 2012 conditions 2 fb^{-1} at 8 TeV
- Calculate expected signal yields for Run-II and upgrade

Dealing with electrons

- Low p_T + energy loss by Bremsstrahlung
- Mass resolution is better in $K_S^0 \to \pi^+\pi^- e^+e^-$ than in $K_S^0 \to e^+e^-e^+e^-$



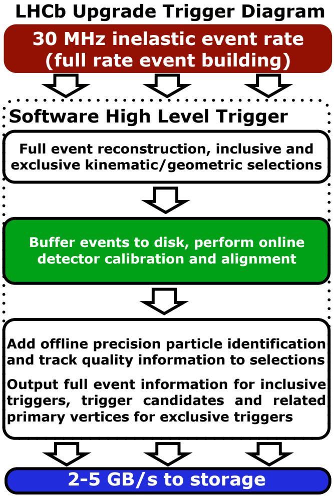
[LHCb-PUB-2016-016]



Very good prospects

- Evidence or observation possible in Run-I
- $\mathrm{N}^{\mathrm{exp}}_{\mathrm{Run\text{-}II}} = 120^{+280}_{-100}/\mathrm{fb}^{-1}$
- Assuming $\mathrm{eff}_{\mathrm{trigg.}} \sim 100\%$ for the upgrade $\mathrm{N}^{\mathrm{exp}}_{\mathrm{up}} = (5.0 \pm 0.3) \times 10^4/\mathrm{fb}^{-1}$

Prospects



Many improvements on strange decays

- Removal of p_T cuts at the trigger level allows to reach much higher efficiencies
- Study of (rare)strange decays can benefit a lot from a full software trigger
- More efficient particle identification and reconstruction algorithms at low-p_T

Many other incoming ideas on strange decays:

- Study of semileptonic hyperon decays $\Lambda^0 \to p^+ \mu^- \bar{\nu}$, $\Xi^- \to \Lambda^0 \mu^- \bar{\nu}$
- Semileptonic kaon decays $K^0_S \to \pi^+ \mu^- \bar{\nu}$, $K^+ \to \pi^+ \pi^- \mu^+ \nu$
- LHCb as a ϕ factory
- ...

Conclusions

- Strange decays can still provide a lot of information about flavour physics
- Reaching unprecedented values on branching fractions for SM processes
- The rare and strange program at LHCb keeps growing: ~ 20 people working on this field
- A full software trigger is crucial to study these decays at LHCb
- Many improvements have been/are being developed for the Run-II and the upgrade
- Feedback from the theoretical side. Your contribution is very appreciated!
- Many interesting results to come!

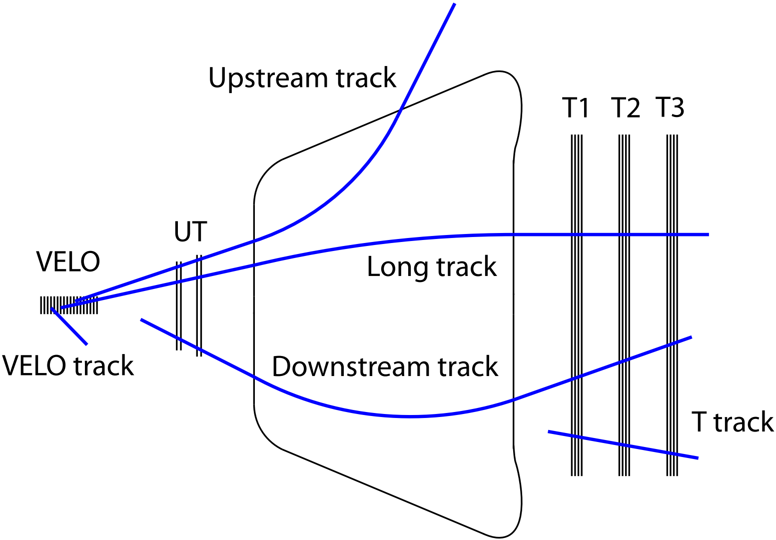
Conclusions

- Strange decays can still provide a lot of information about flavour physics
- Reaching unprecedented values on branching fractions for SM processes
- The rare and strange program at LHCb keeps growing: ~ 20 people working on this field
- A full software trigger is crucial to study these decays at LHCb
- Many improvements have been/are being developed for the Run-II and the upgrade
- Feedback from the theoretical side. Your contribution is very appreciated!
- Many interesting results to come!

selcouth (from Middle/Old English)
(adj.) rare, strange, marvelous

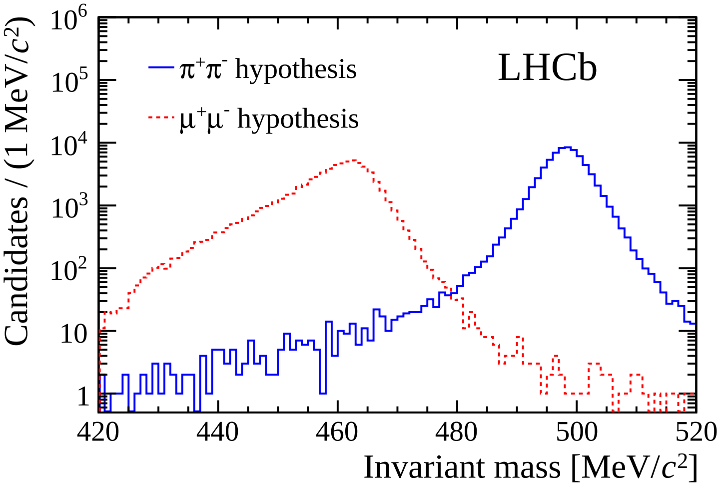
BACKUP

Track types at LHCb



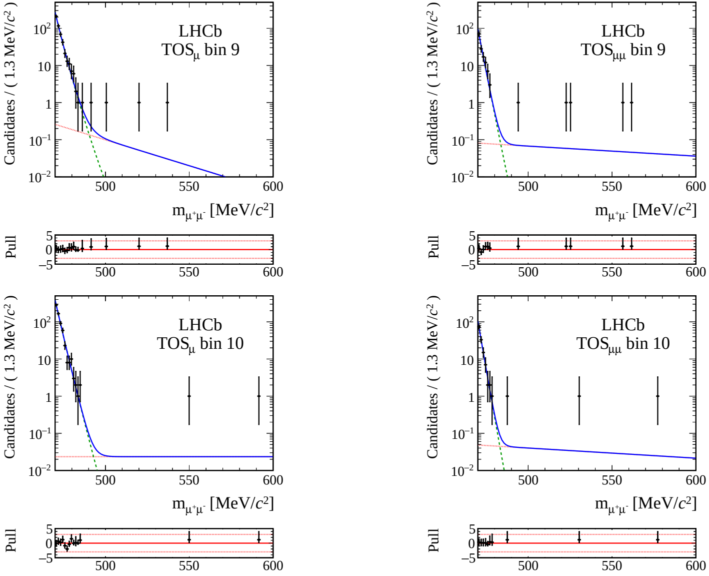
$K_S^0 \to \mu^+\mu^-$ mass resolution

$K_S^0 \to \pi^+\pi^-$ candidates



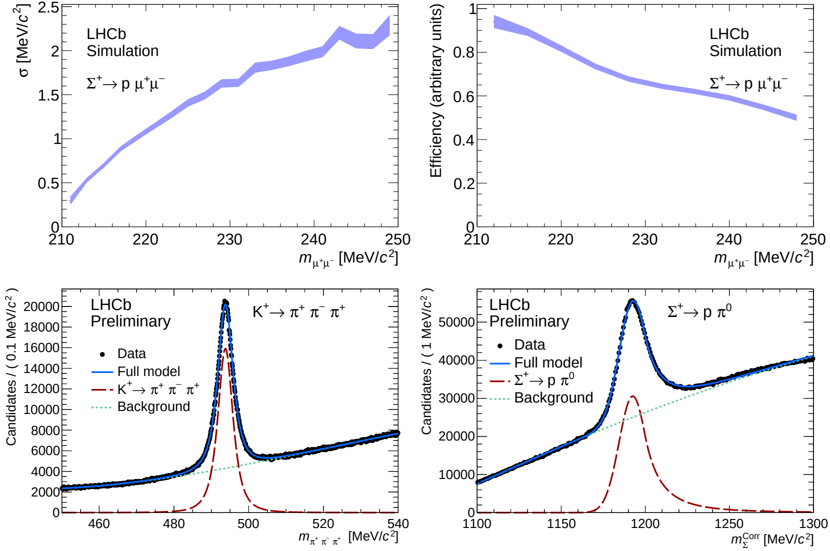
[arXiv:1706.00758] submitted to EPJ C

$K_S^0 \to \mu^+\mu^-$ mass plots



[arXiv:1706.00758] submitted to EPJ C

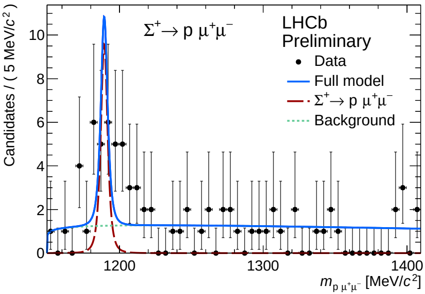
$\Sigma^+ \to p^+\mu^+\mu^-$



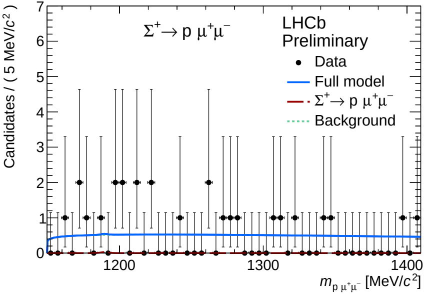
[LHCb-CONF-2016-013]

$\Sigma^+ \to p^+\mu^+\mu^-$ mass plots

FULL (no normalization)

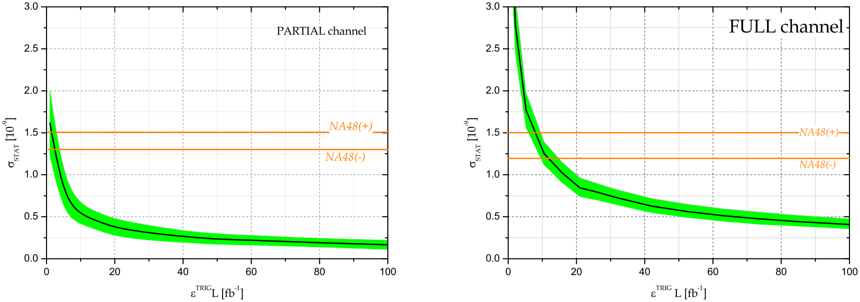


TIS (normalization possible)



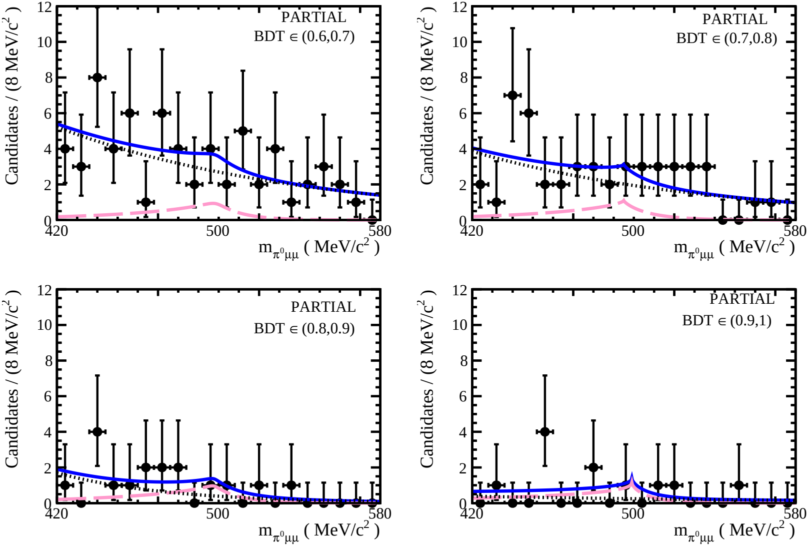
[LHCb-CONF-2016-013]

$K_S^0 \to \pi^0\mu^+\mu^-$ PARTIAL vs FULL



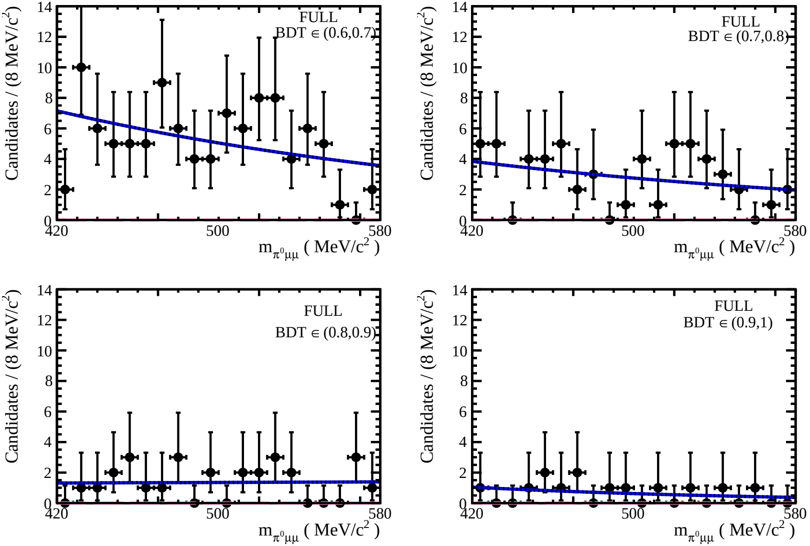
[CERN-LHCb-PUB-2016-017]

$K_S^0 \to \pi^0\mu^+\mu^-$ mass plots PARTIAL



[CERN-LHCb-PUB-2016-017]

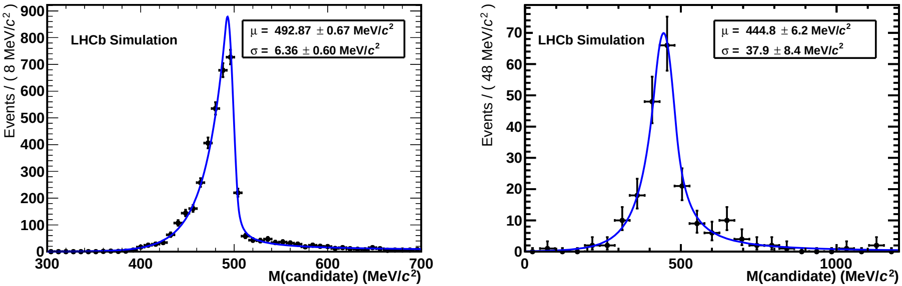
$K_S^0 \to \pi^0\mu^+\mu^-$ mass plots FULL



[CERN-LHCb-PUB-2016-017]

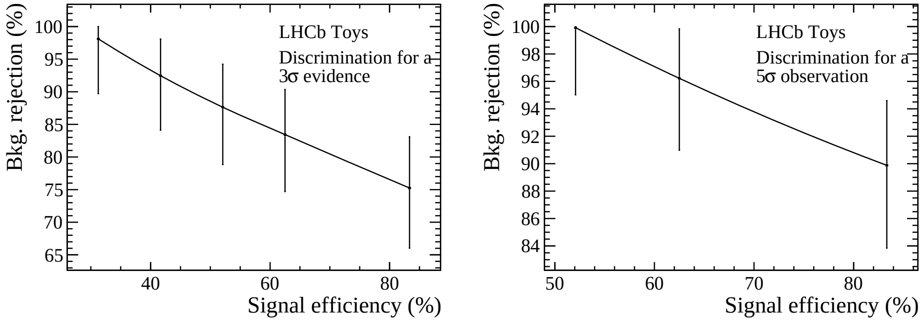
$K_S^0 \to \pi^+\pi^-e^+e^-$

$K_S^0 \to \pi^+\pi^-e^+e^-$ $\qquad\qquad$ $K_S^0 \to e^+e^-e^+e^-$



[LHCb-PUB-2016-016]

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



[LHCb-PUB-2016-016]

Comparison of trigger diagrams