Two-tracks strange decays at LHCb

Miguel Ramos Pernas

Universidade de Santiago de Compostela

miguel.ramos.pernas@cern.ch

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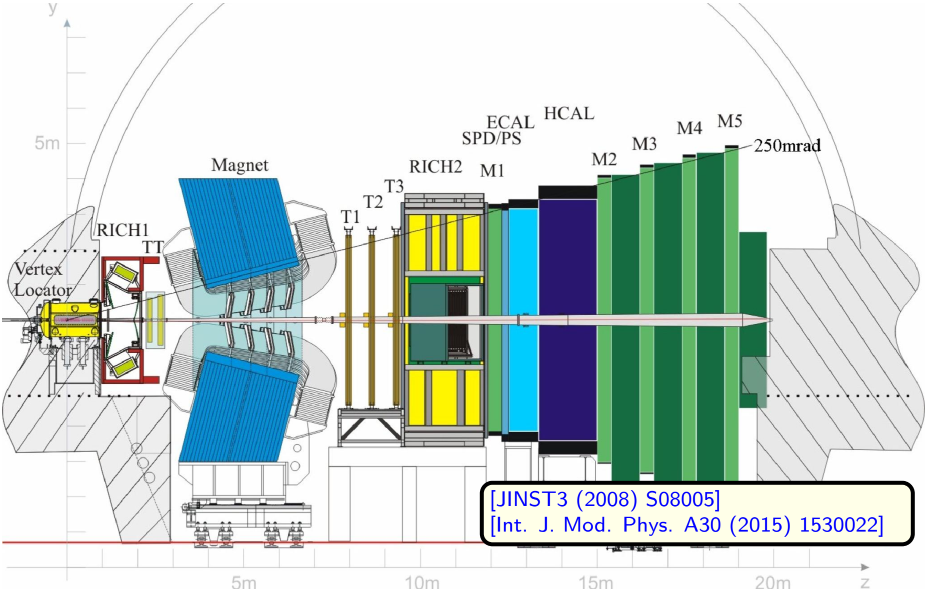
Outline

1. **The LHCb detector**
2. **Strange decays at LHCb**
3. **Decays**
   - $K_S^0 \to \mu^+\mu^-$
   - $K_S^0 \to \pi^0\mu^+\mu^-$
   - Semileptonic hyperon decays and $K_S^0 \to \pi^+\mu^-\bar{\nu}$
4. **Prospects for the upgrade**
5. **Conclusions**

For more about strange decays at LHCb see Francesco's talk.

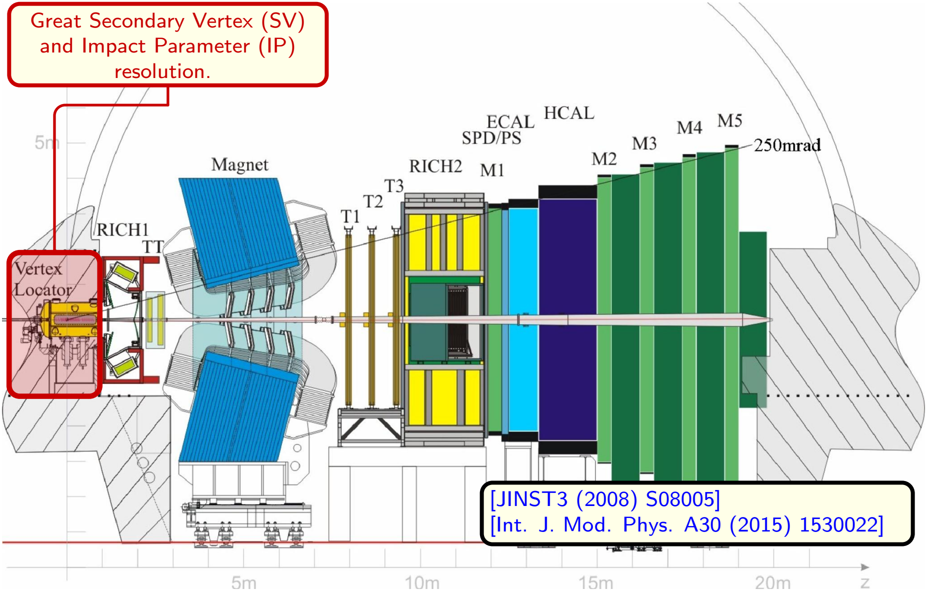
The LHCb detector



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

The LHCb detector

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



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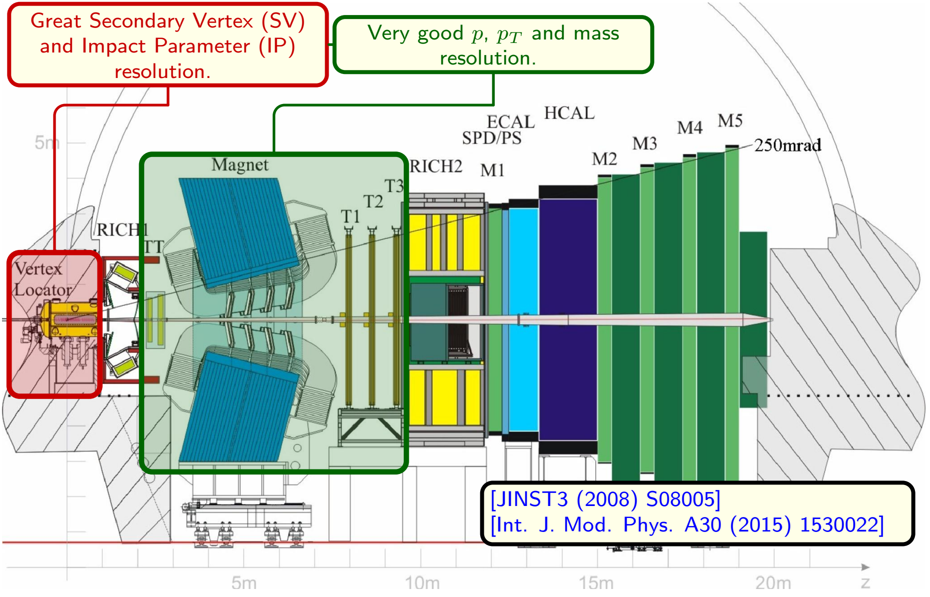
The LHCb detector



[JINST3 (2008) S08005]
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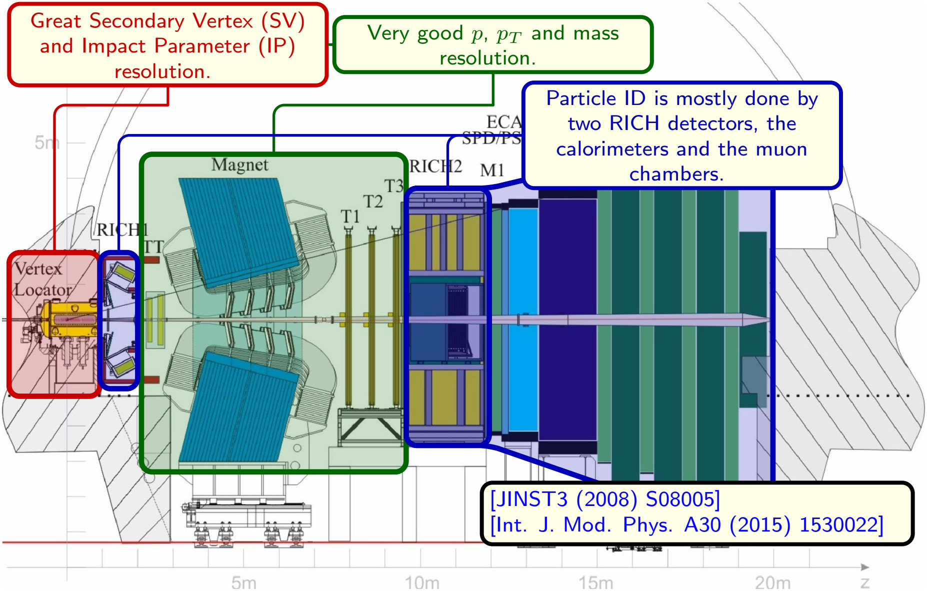
The LHCb detector

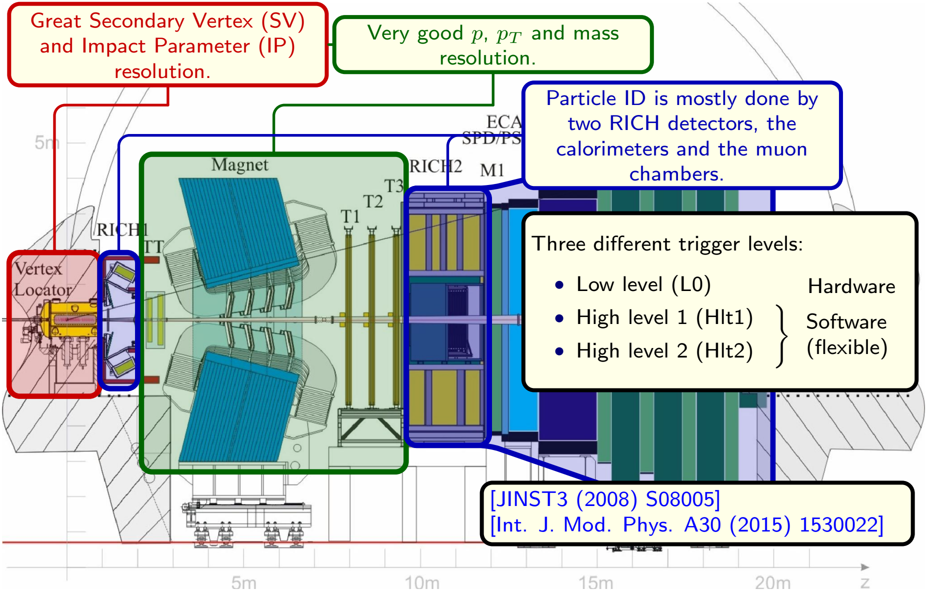


The LHCb detector

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

Very good p, p_T and mass resolution.

Particle ID is mostly done by two RICH detectors, the calorimeters and the muon chambers.



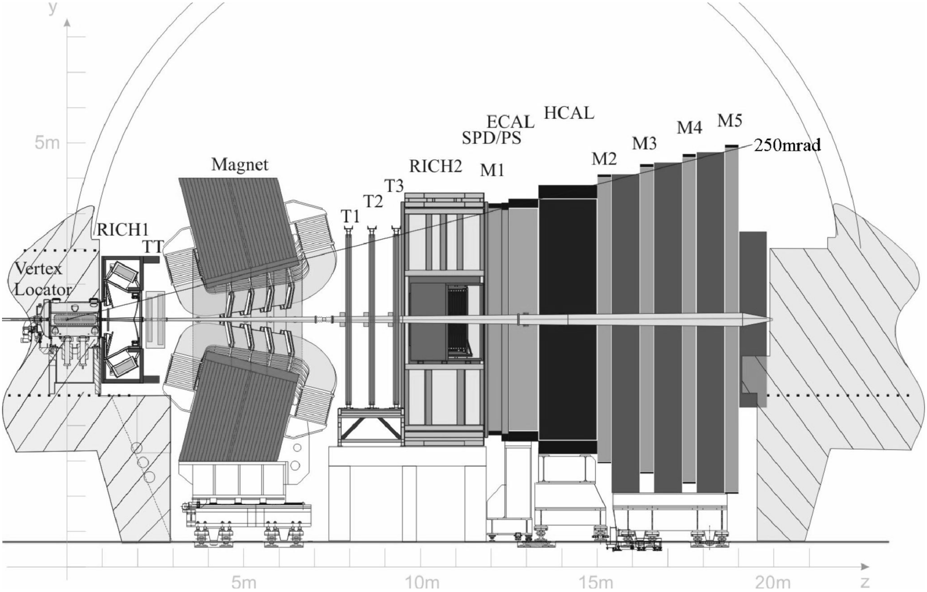
Three different trigger levels:

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

} Software (flexible)

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

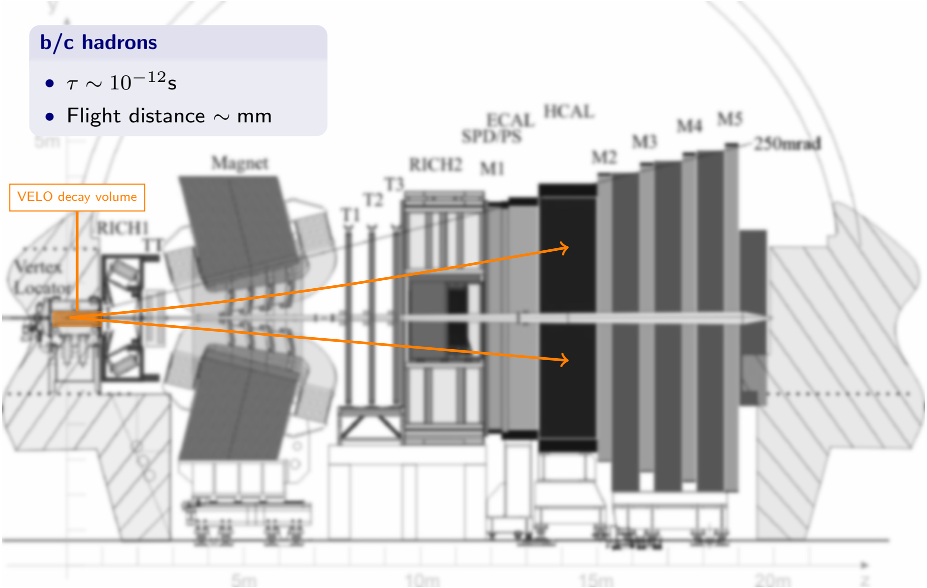
Strange decays at LHCb



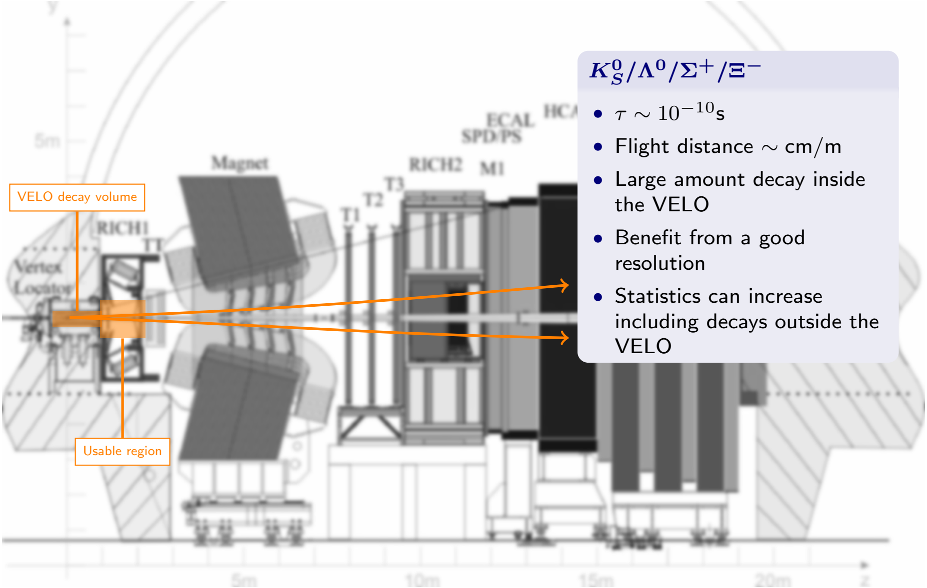
Strange decays at LHCb

b/c hadrons

- $\tau \sim 10^{-12}$s
- Flight distance $\sim$ mm



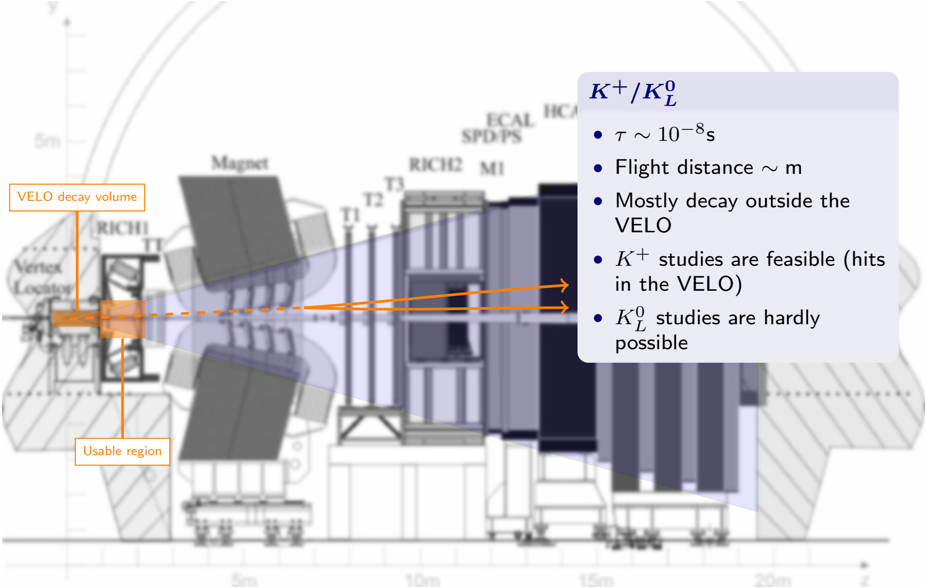
Strange decays at LHCb



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

- $\tau \sim 10^{-10}$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

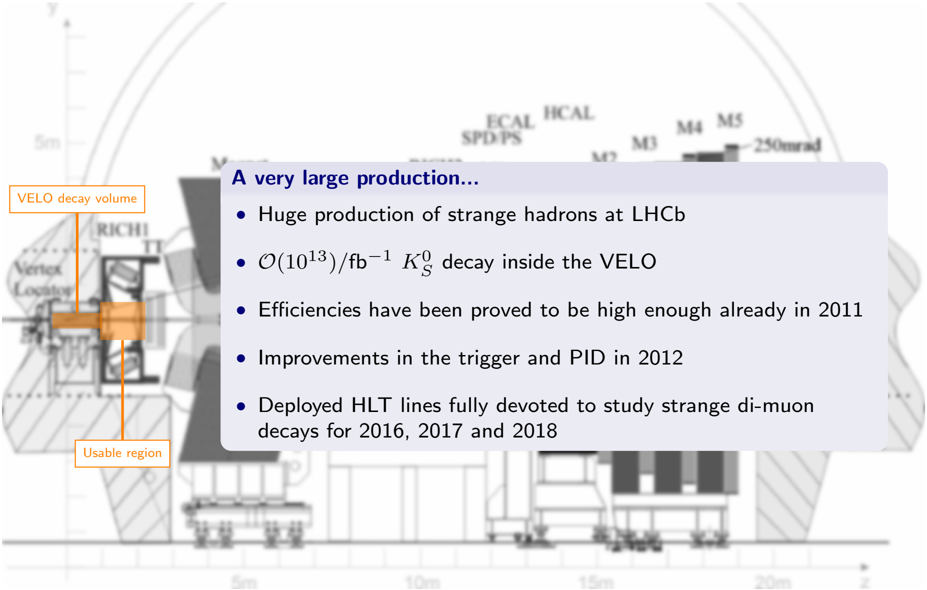
Strange decays at LHCb



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

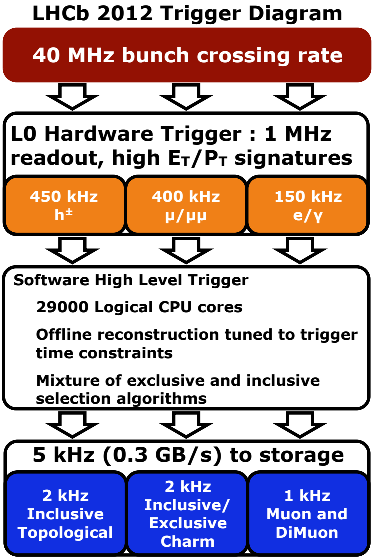
Strange decays at LHCb



A very large production...

- Huge production of strange hadrons at LHCb
- $\mathcal{O}(10^{13})/\text{fb}^{-1}$ K^0_S decay inside the VELO
- Efficiencies have been proved to be high enough already in 2011
- Improvements in the trigger and PID in 2012
- Deployed HLT lines fully devoted to study strange di-muon decays for 2016, 2017 and 2018

The LHCb conditions for Run-I



- LHCb is optimized to study heavy flavour decays
- L0 trigger requires high p_T tracks (very inefficient to study strange decays)
- No dedicated trigger lines to study strange hadrons
- Trigger selections mainly based on topological inclusive lines and data triggered by the rest of the event (e.g. $K_S^0 \to \mu^+\mu^-$ analysis from 2011)
- Some HLT lines tuned to increase the efficiency for 2012

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

- Flavour-changing neutral current (FCNC) transition
- Dominated by long distance contributions through $K^0_{S/L} \to \gamma\gamma$
- SM prediction: $\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$ [Nucl. Phys. B366 (1991) 189] [JHEP 01 (2004) 009] [Phys. Rev. Lett. 119, 201802 (2017)]

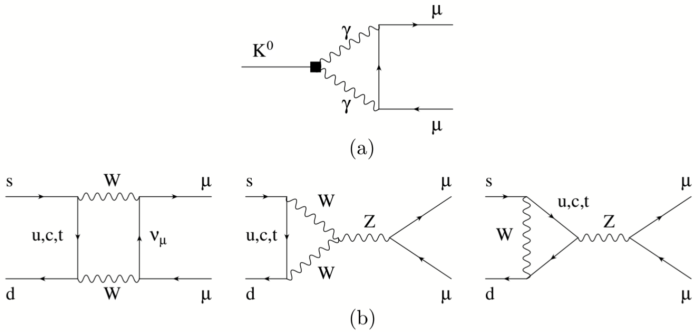


Figure: (a): Long distance contribution. (b) Short distance contributions. [JHEP 01 (2004) 009]

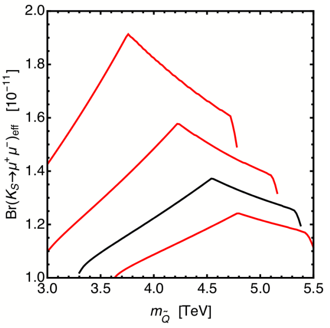
$K_S^0 \to \mu^+\mu^-$ in BSM

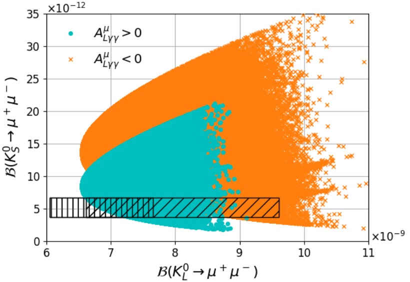
$\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right)$ helps to kill models with leptoquarks [arXiv:1712.01295], or supersymmetric contributions [arXiv:1711.11030], [arXiv:1712.04959].

Study of the interference between $K_L^0 \to \mu^+\mu^-$ and $K_S^0 \to \mu^+\mu^-$ allows to determine sign$(A^\mu_{L\gamma\gamma})$.

$$\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) = (5.18 \pm 1.50 \pm 0.02) \times 10^{-12}$$

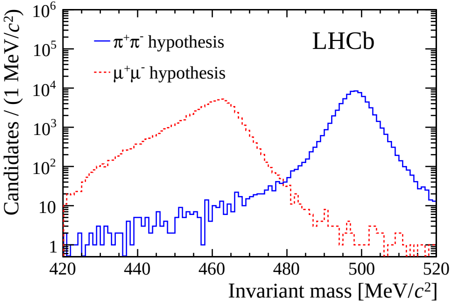
$$\mathcal{B}\left(K_L^0 \to \mu^+\mu^-\right) = \begin{cases} (6.85 \pm 0.80 \pm 0.06) \times 10^{-9} & \text{if } A^\mu_{L\gamma\gamma} > 0 \\ (8.11 \pm 1.49 \pm 0.13) \times 10^{-9} & \text{if } A^\mu_{L\gamma\gamma} < 0 \end{cases} \qquad A^\mu_{L\gamma\gamma} = \text{sign}\left(\frac{\mathcal{A}(K_L^0 \to \gamma\gamma)}{\mathcal{A}(K_L^0 \to (\pi^0)^* \to \gamma\gamma)}\right)$$





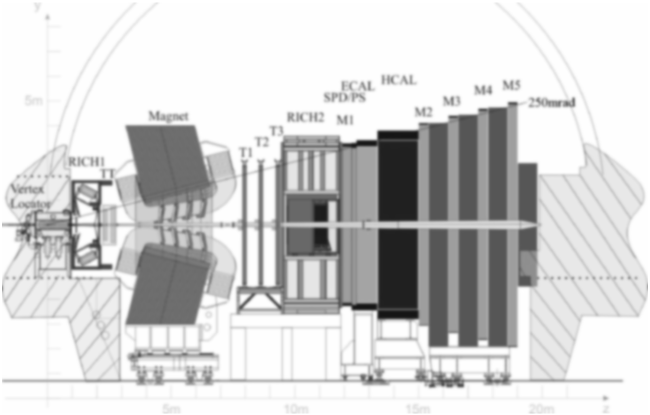
$K_S^0 \to \mu^+\mu^-$ backgrounds

- Very good resolution around the K_S^0 mass (~ 4MeV/c^2).
- Low soft-QCD background level at LHCb.
- For the moment, the only significant contribution is $K_S^0 \to \pi^+\pi^-$ where the two pions are misidentified as muons.



- $K_L^0 \to \mu^+\mu^-$: effective branching fraction $\sim 2 \times 10^{-11}$, below the current sensitivity
- $\Lambda^0 \to p\pi^-$: removed with cuts in the Armenteros-Podolanski plane.
- $K^0 \to \pi^+\mu^-\bar{\nu}$: no candidate survives the trigger selection. Even in the hypothesis $\varepsilon^{\text{trig}}_{K^0\to\pi^+\mu^-\bar{\nu}} = \varepsilon^{\text{trig}}_{K_S^0\to\mu^+\mu^-}$, the expected yields are negligible.
- $\eta \to \mu^+\mu^-\gamma$ and $\omega \to \pi^0\mu^+\mu^-$: prompt decays can be removed with a cut on the flight distance. Detached production from charm decays is negligible.

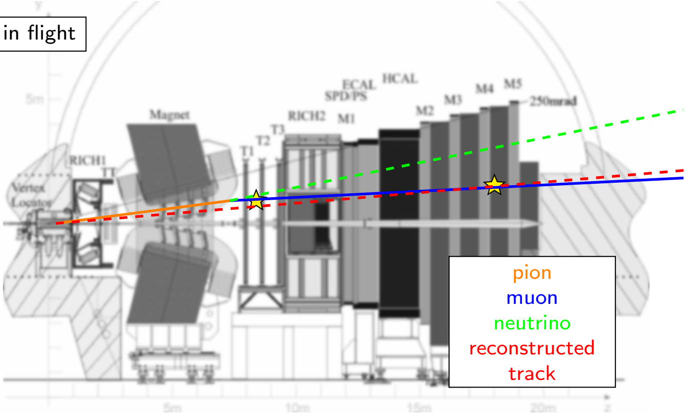
$K_S^0 \to \pi^+\pi^-$ as $K_S^0 \to \mu^+\mu^-$



- $K_S^0 \to \pi^+\pi^-$ is the most dangerous background to study $K_S^0 \to \mu^+\mu^-$ at LHCb.
- Background produced by doubly-misidentifying of the two pions.
- Two different sources: decays in flight and incorrect assignment of clusters in the muon chambers.

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

Decays in flight



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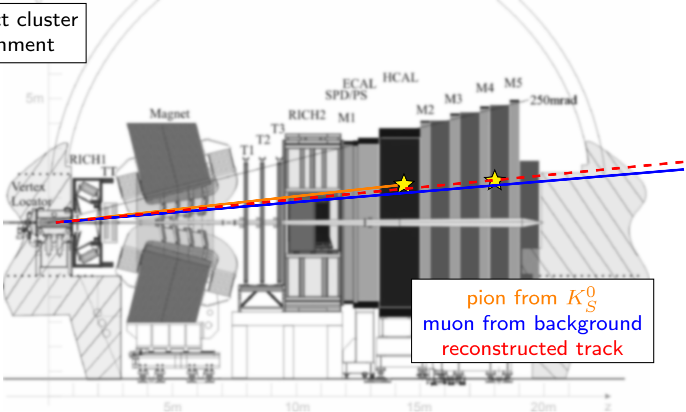
$K_S^0 \to \pi^+\pi^-$ as $K_S^0 \to \mu^+\mu^-$

Incorrect cluster assignment

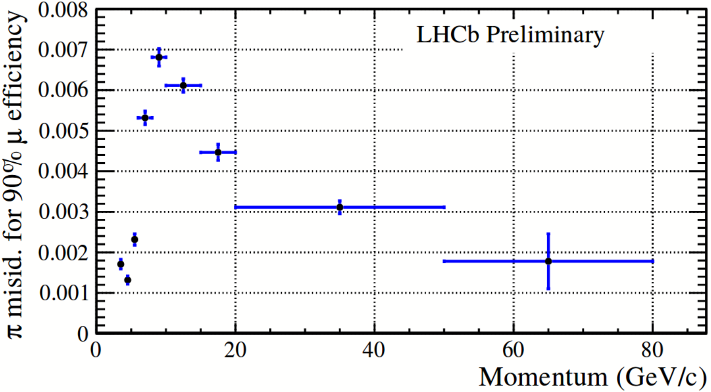


pion from K_S^0
muon from background
reconstructed track

- $K_S^0 \to \pi^+\pi^-$ is the most dangerous background to study $K_S^0 \to \mu^+\mu^-$ at LHCb.
- Background produced by doubly-misidentifying of the two pions.
- Two different sources: decays in flight and incorrect assignment of clusters in the muon chambers.

New muon identification algorithm for 2012 and beyond

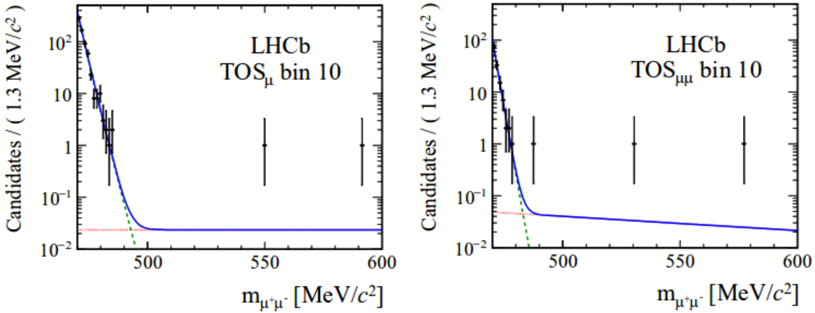
- Muon ID algorithms at LHCb were optimized for heavy flavour decays
- In 2012, an algorithm was designed to increase the efficiencies on strange decays



[LHCb-CONF-2016-012]

$K_S^0 \to \mu^+\mu^-$ in Run-I

- Last analysis includes data in 2012 conditions: $2\ \text{fb}^{-1}$ at 8 TeV
- Follows the previous study from 2011 [JHEP 01 (2013) 090]
- Normalized to $K_S^0 \to \pi^+\pi^-$
- Fit done in bins of two MVA discriminants for two different trigger selections (20 bins in total)
- Result from 2011 (as a posterior probability) is considered as a prior in the $\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right)$



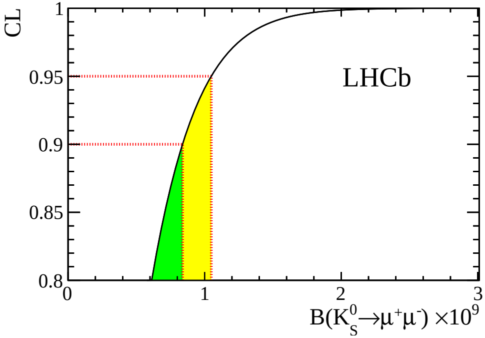
[Eur. Phys. J. C (2017) 77: 678]

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

- Limit set from the $\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right)$ likelihood profile
- New world best limit:

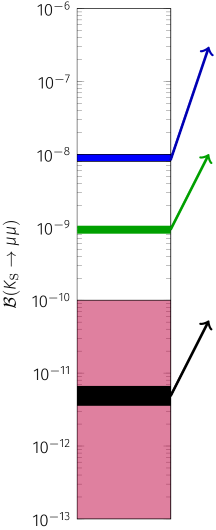
  $$\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) < 0.8(1.0) \times 10^{-9} \text{ at } 90(95)\% \text{ of CL}$$

- Factor of ~ 400 of improvement with respect to the best limit before LHCb [PLB44 (1973) 217], and ~ 10 with respect to the previous LHCb measurement [JHEP 01 (2013) 090]



[Eur. Phys. J. C (2017) 77: 678]

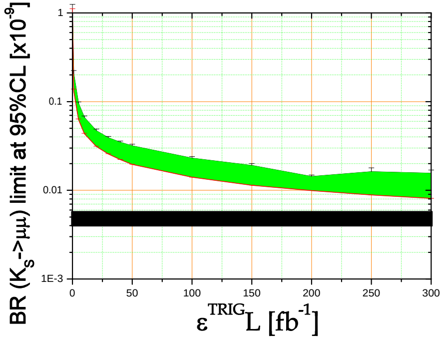
$K_S^0 \to \mu^+\mu^-$ in a nutshell



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
[Eur. Phys. J. C (2017) 77: 678]

Standard Model prediction



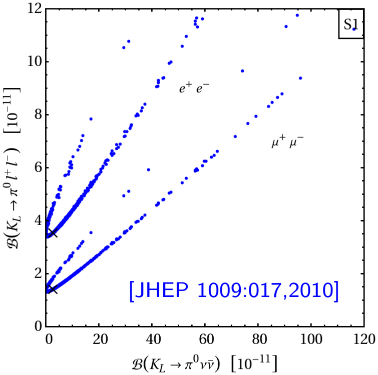
$K_S^0 \to \pi^0\mu^+\mu^-$

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 $\mathcal{B}\left(K_S^0 \to \pi^0 l^+ l^-\right)$.

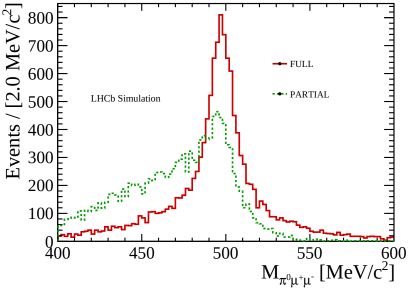


- Large uncertainties on $\mathcal{B}\left(K_S^0 \to \pi^0\mu^+\mu^-\right) = 2.9^{+1.5}_{-1.2} \times 10^{-9}$ (NA48) [Phys. Lett. B599 (2004) 197]
- Current kaon experiments do not expect to improve such measurement
- Last year, a sensitivity study was done at LHCb

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

[CERN-LHCb-PUB-2016-017]

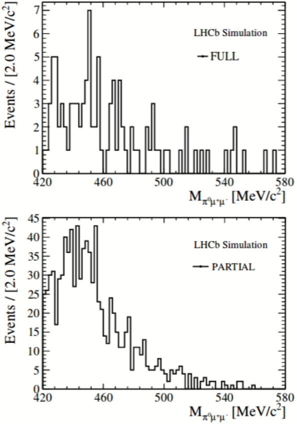


Two different strategies adopted:

- 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}

Clean and very promising decay

- $K_S^0 \to \pi^+\pi^-$: both pions are misidentified as muons. No evidence is seen in the fit.
- $K^0 \to \mu^+\mu^-\gamma\gamma$: in the K_L^0 case, the effective branching fraction turns $\mathcal{O}(10^{-11})$. No measurement of the K_S^0 mode has been done, expected to be $\sim 4.8 \times 10^{-11}$.
- $K_L^0 \to \pi^0\pi^+\pi^-$: No resonant structure is seen on data. Sensitivity does not change if this component is included.
- Main source of background is purely combinatorial.



[CERN-LHCb-PUB-2016-017]

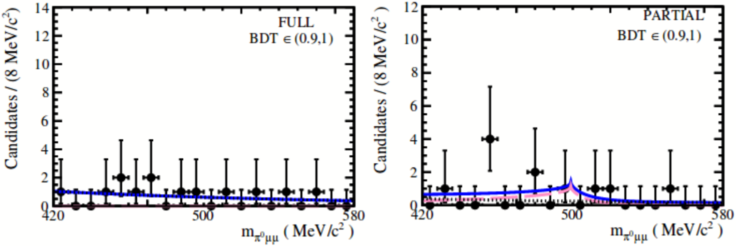
Simulated $K^0 \to \pi^0\pi^+\pi^-$ decays, reconstructed as $K^0 \to \pi^0\mu^+\mu^-$

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

- Analysis done taking into account events triggered independently on the signal decay
- This ensures an almost trigger-unbiased sample
- Uncertainty obtained from fits to pseudo-experiments
- Expected signal is calculated from the NA48 measurement [Phys. Lett. B599 (2004) 197]

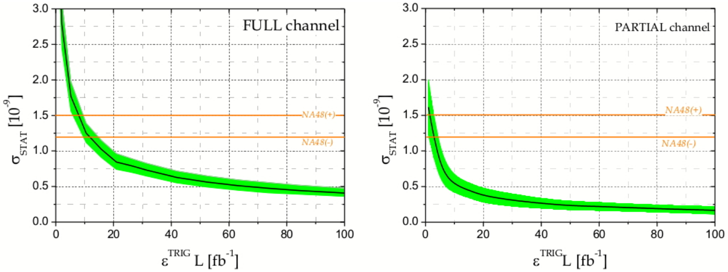
$$N_{\text{sig}} = \frac{\mathcal{B}\left(K_S^0 \to \pi^0\mu^+\mu^-\right)}{\mathcal{B}\left(K_S^0 \to \pi^+\pi^-\right)} \frac{\epsilon_{K_S^0 \to \pi^0\mu^+\mu^-}}{\epsilon_{K_S^0 \to \pi^+\pi^-}} N(K_S^0 \to \pi^+\pi^-) \frac{\mathcal{L}_{\text{fut}}}{\mathcal{L}_{\text{curr}}}$$

- Background yields are extrapolated for a desired luminosity and trigger efficiency



[CERN-LHCb-PUB-2016-017]

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



[CERN-LHCb-PUB-2016-017]

- The PARTIAL strategy seems the way to go
- Beating the NA48 measurement [Phys. Lett. B599 (2004) 197] is possible in the upgrade $\mathcal{L}_{\text{eff}} > 5$ fb^{-1}

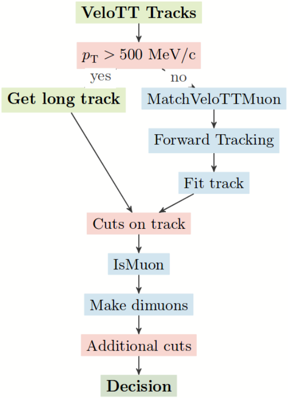
The di-muon triggers for the Run-II

Efficiency	$K_S^0 \to \mu^+\mu^-$	$K_S^0 \to \pi^0\mu^+\mu^-$
L0	0.361 ± 0.004	0.344 ± 0.009
HLT1/L0	0.699 ± 0.007	0.705 ± 0.015
HLT1/L0 (old)	0.274 ± 0.006	0.299 ± 0.015
HLT2/HLT1	0.9898 ± 0.0017	0.983 ± 0.005
HLT2/HLT1 (old)	0.293 ± 0.013	0.26 ± 0.03
global	0.250 ± 0.004	0.238 ± 0.008
global (old)	0.0290 ± 0.0015	0.026 ± 0.003

green: trigger with new lines

red: trigger without new lines

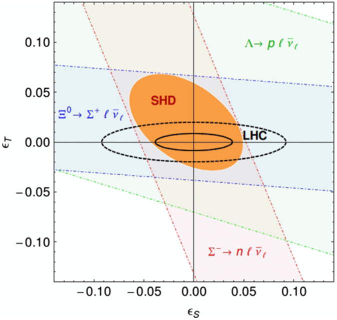
- Big increase on the efficiencies: a factor ~ 2.4 for HLT1 and ~ 3.5 for HLT2
- Total efficiency increased by a factor ~ 10



[CERN-LHCb-PUB-2017-023]

Prospects on semileptonic hyperon decays

- Semileptonic hyperon decays can be probes of TeV scales complementary to kaons
- Vast room of improvement on many decays (specially the muonic modes $\delta\mathcal{B}/\mathcal{B} \sim [10, 100]\%$)
- Rare hyperon decays... still unexplored
- Possibilities to study
  - $\Lambda^0 \to p\mu^-\bar{\nu}$
  - $\Xi^- \to \Lambda^0\mu^-\bar{\nu}$
- No dedicated trigger lines ($\mathcal{B} \sim 10^{-4}$)



[Chang et al. PRL114(2015)16,161802]

$$\epsilon_S^{S\mu} = 0.003(40) \qquad \epsilon_T^{S\mu} = 0.017(34)$$

Nothing published so far, but some benchmarks have been set for Run-II

Prospects on $K_S^0 \to \pi^+\mu^-\bar{\nu}$

No measurement of $K_S^0 \to \pi^+\mu^-\bar{\nu}$ at present!

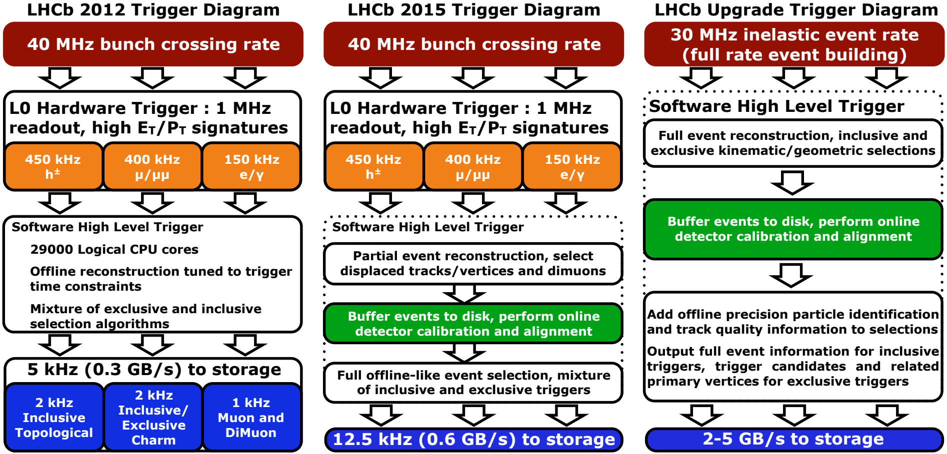
δ	CPT violation in mixing
y	CPT violation in decay with $\Delta S = \Delta Q$
x_-	$\Delta S \neq \Delta Q$ with CPT violation
A_S	$\frac{\mathcal{B}(K_S^0 \to \pi^-\mu^+\nu_\mu) - \mathcal{B}(K_S^0 \to \pi^+\mu^-\bar{\nu}_\mu)}{\mathcal{B}(K_S^0 \to \pi^-\mu^+\nu_\mu) + \mathcal{B}(K_S^0 \to \pi^+\mu^-\bar{\nu}_\mu)}$

	Goal	Implications
V_{us} and $\Delta S = \Delta Q$	$\delta\mathcal{B} < 0.4\%$	Reduce error on V_{us}
CPT	$A_S \sim 0.1\%$	Reduce uncertainty on $\mathcal{R}(x_-)$ and $\mathcal{R}(y)$, and push down $\mathcal{R}(\delta)$
LFU	$\delta\mathcal{B} \sim 0.5\%$	Competitive with K_L^0 measurements

Main issues at LHCb are:

- Irreducible background from $K_L^0 \to \pi^+\mu^-\bar{\nu}$
- Also expect a huge background from $K_S^0 \to \pi^+\pi^-$
- No dedicated trigger lines ($\mathcal{B} \sim 10^{-4}$)

The LHCb trigger in the upgrade



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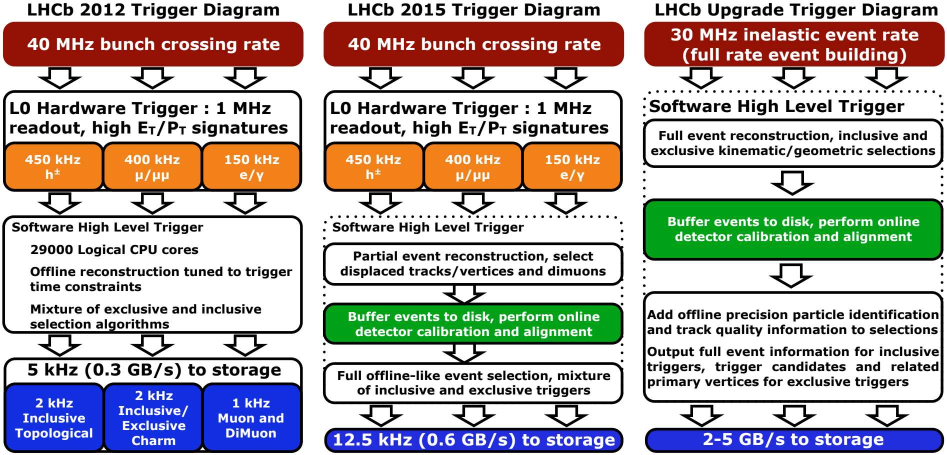
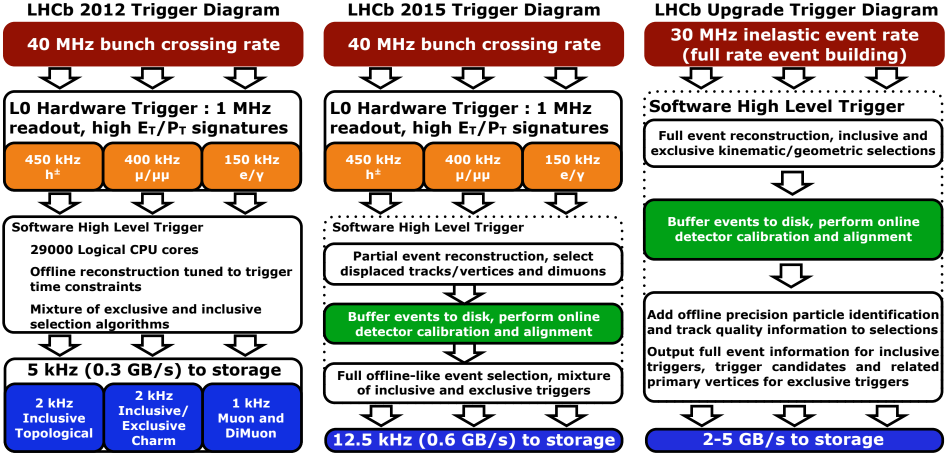


- Non-dedicated trigger lines, use standard di-muon lines

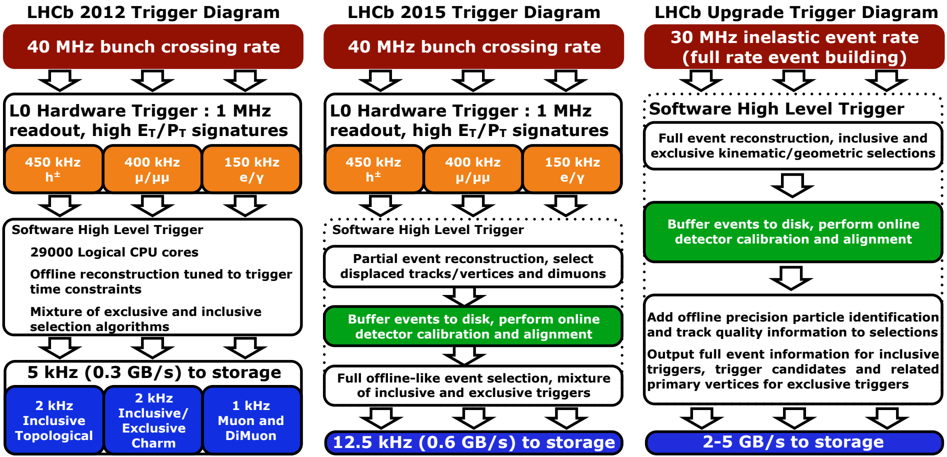
The LHCb trigger in the upgrade



- Non-dedicated trigger lines, use standard di-muon lines

- Dedicated HLT di-muon lines
- Improve low-p_T muon track reconstruction at HLT

The LHCb trigger in the upgrade

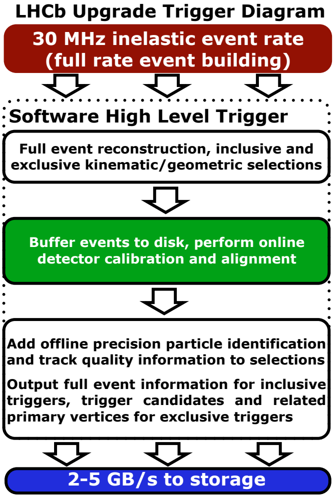


- Non-dedicated trigger lines, use standard di-muon lines

- Dedicated HLT di-muon lines
- Improve low-p_T muon track reconstruction at HLT

- There is no L0 bottleneck
- Dedicated di-muon lines
- Current offline low-p_T muon identification algorithm in the trigger
- Efficiencies $> 90\%$ possible

Strange decays in the new trigger

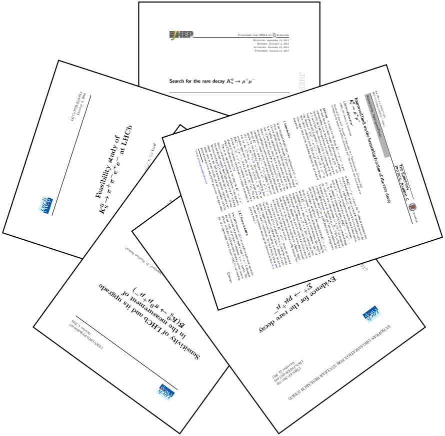


The upgrade trigger benefits a lot the strange program

- Replacement of inclusive triggers (general) by exclusive (focused on each decay)
- Only the requested information from the event is saved
- Removal of p_T cuts at the trigger level allows to reach much higher efficiencies
- More efficient particle identification and reconstruction algorithms at low-p_T

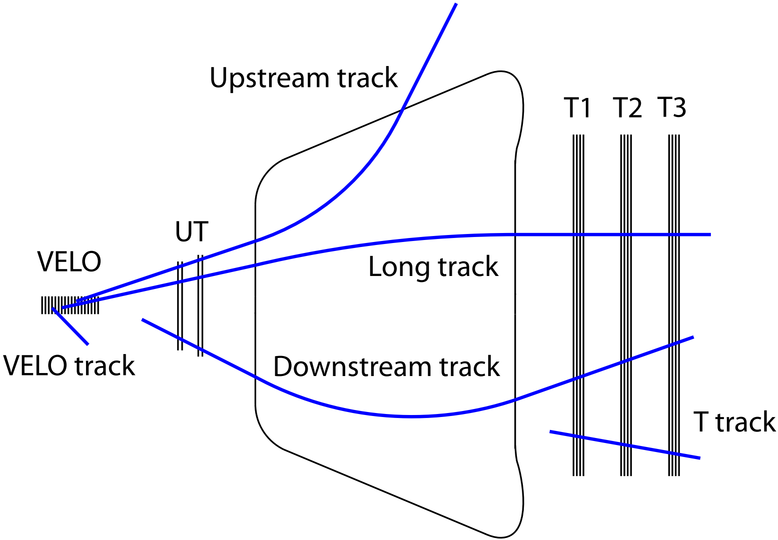
Conclusions

- The LHCb has produced a large number of publications in two years on this topic
- Some studies using Run-II data currently ongoing
- The Run-II trigger allows to improve the efficiencies on $K_S^0 \to \mu^+\mu^-$ and $K_S^0 \to \pi^0\mu^+\mu^-$
- Benchmark set for the study of semileptonic hyperon decays as well as for $K_S^0 \to \pi^+\mu^-\bar{\nu}$
- A full software trigger will benefit a lot the study of strange decays at LHCb

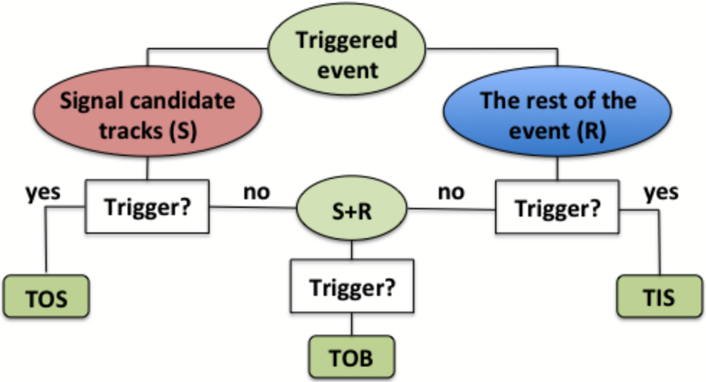


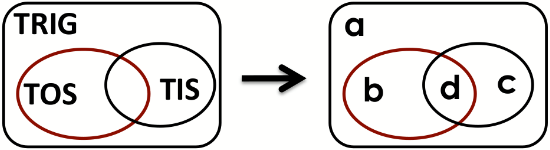
BACKUP

Track types at LHCb



Trigger definitions





Where:

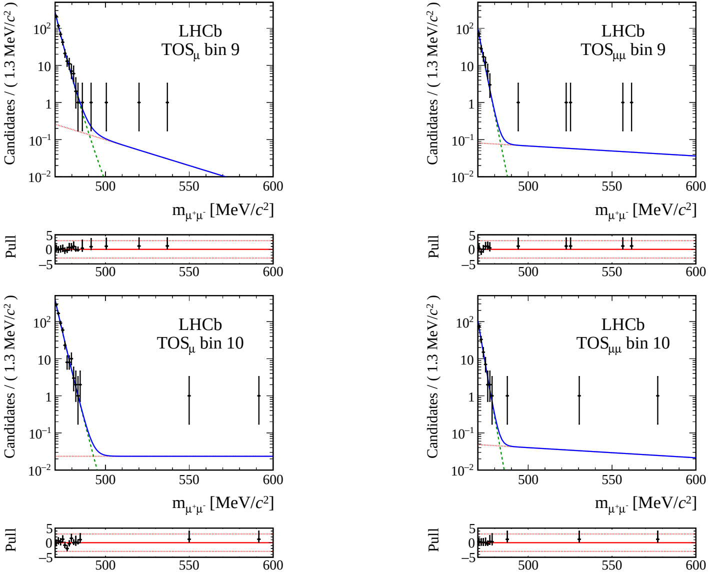
$a = N^{TRIG} - N^{TIS} - N^{TOS} + N^{TISTOS}$

$b = N^{TOS} - N^{TISTOS}$

$c = N^{TIS} - N^{TISTOS}$

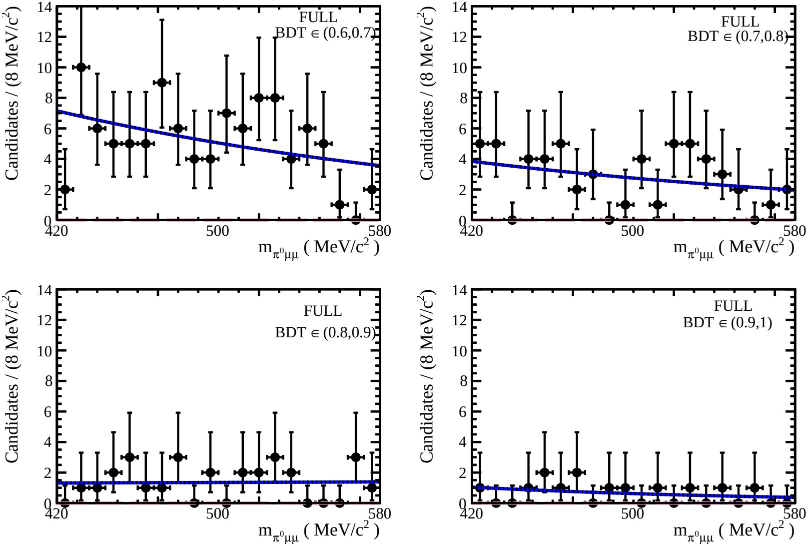
$d = N^{TISTOS}$

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



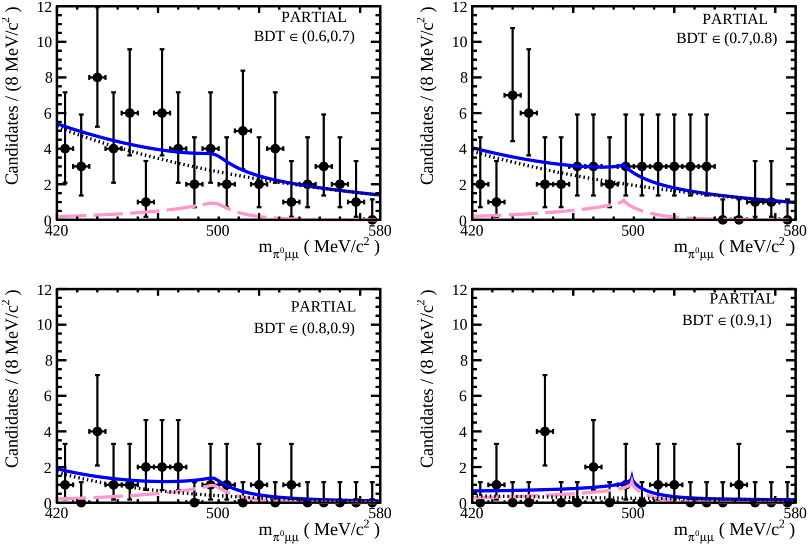
[Eur. Phys. J. C (2017) 77: 678]

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



[CERN-LHCb-PUB-2016-017]

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



[CERN-LHCb-PUB-2016-017]