Search for $K_S^0 \to \mu^+\mu^-$ at LHCb

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UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

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Introduction

The $K_S^0 \to \mu^+\mu^-$ decay is:

- Flavour-changing neutral current (FCNC) transition.
- Dominated by long distance contributions through $K_{S/L}^0 \to \gamma\gamma$.
- In absence of CP violation the K_L^0 (K_S^0) mode could proceed only through S(P) wave.
- Notably new light scalars can affect K_S^0 exclusively.

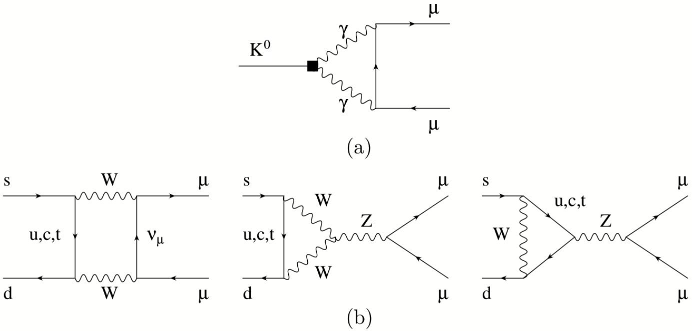


Figure: (a): Long distance contribution. (b) Short distance contributions. [JHEP 01 (2004) 009]

Overall picture

While the branching fraction for the K^0_L decay is within the SM prediction[1]: $\mathcal{B}\left(K^0_L \to \mu^+\mu^-\right) = (6.84 \pm 0.11) \times 10^{-9}$, for the K^0_S it can be enhanced by New Physics.

The LHCb opened the kaon physics program already in 2011 (1fb^{-1} of data).

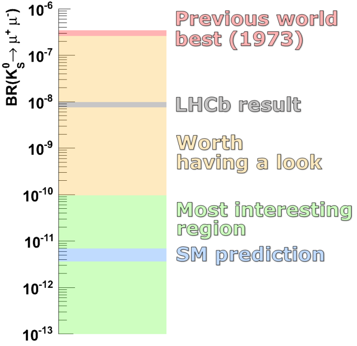
Results so far (90%CL)

- $\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) < 3.1 \times 10^{-7}$ CERN PS*
- $\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) < 9 \times 10^{-9}$ LHCb Coll.†

All distant from the SM prediction‡:

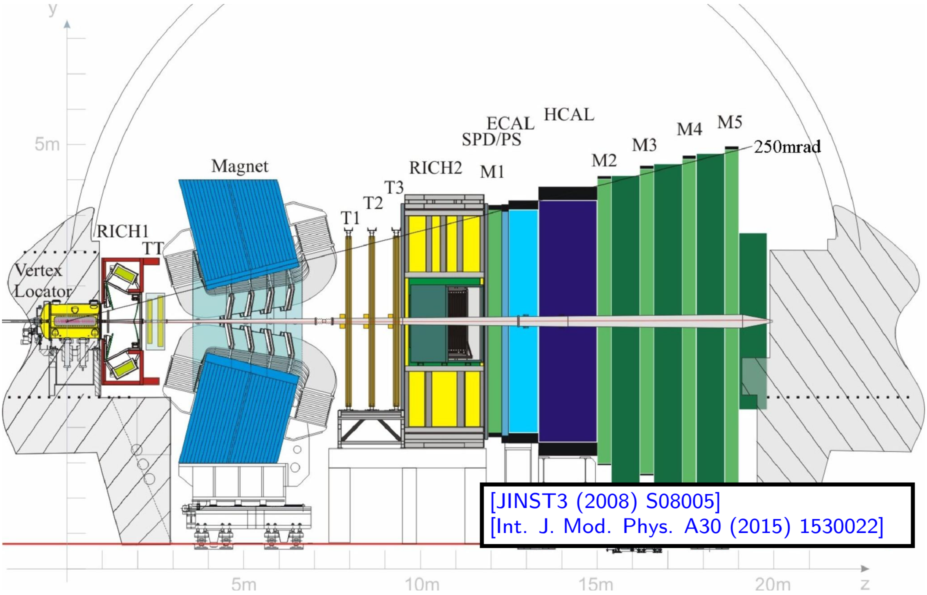
$$\mathcal{B}\left(K^0_S \to \mu^+\mu^-\right) = (5.0 \pm 0.2) \times 10^{-12}$$

*CERN PS [PLB44 (1973) 217]
†LHCb Coll. [JHEP 01 (2013) 090]
‡[NPB366 (1991) 189] , [JHEP 01 (2004) 009]



[1] PDG [Chin. Phys. C, 38, 090001 (2014) and 2015 update]

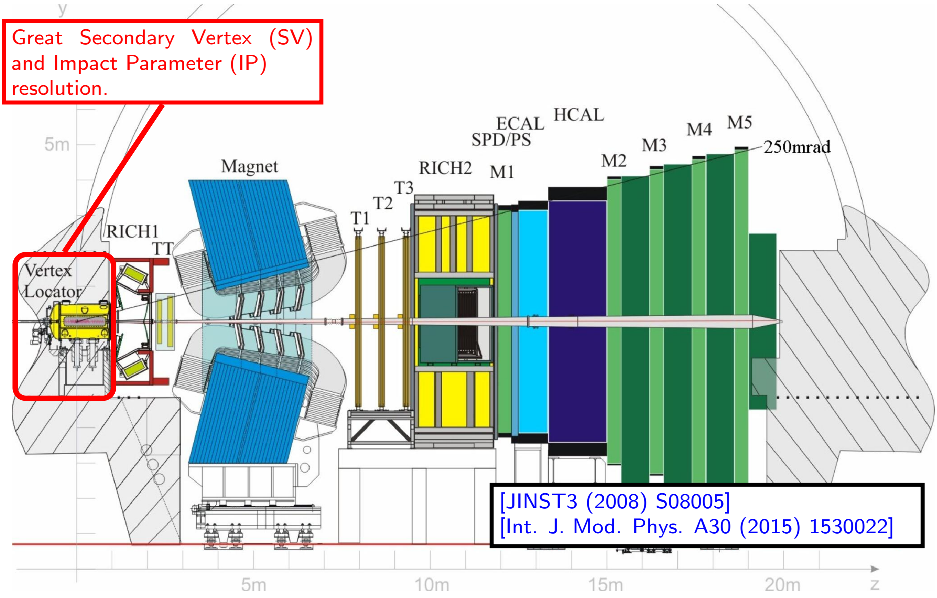
The LHCb



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

The LHCb

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



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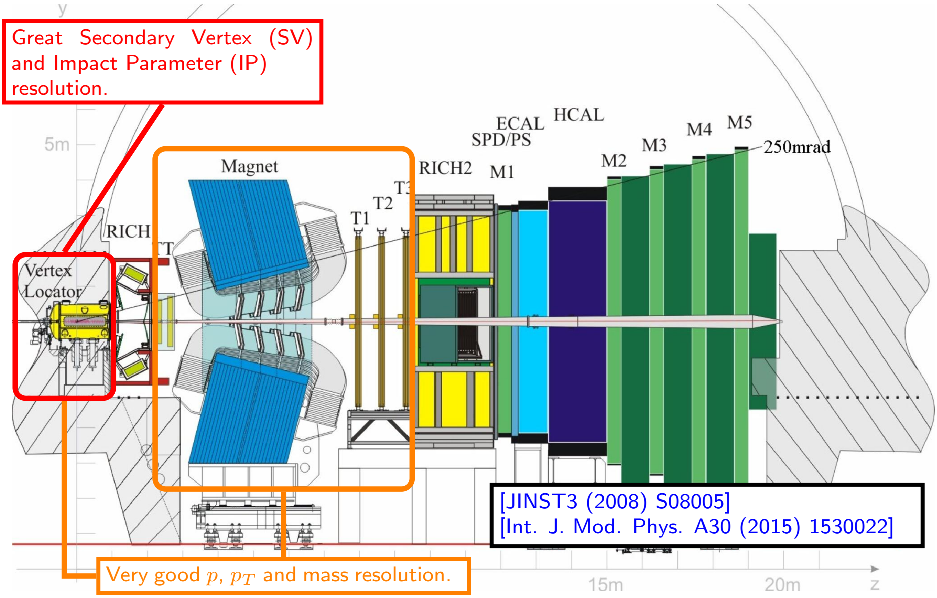
Great Secondary Vertex (SV) and Impact Parameter (IP) resolution.
Vertex Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
SPD/PS
ECAL
HCAL
M1
M2
M3
M4
M5
250mrad
5m
15m
20m
y
z
Very good p, p_T and mass resolution.
[JINST3 (2008) S08005]
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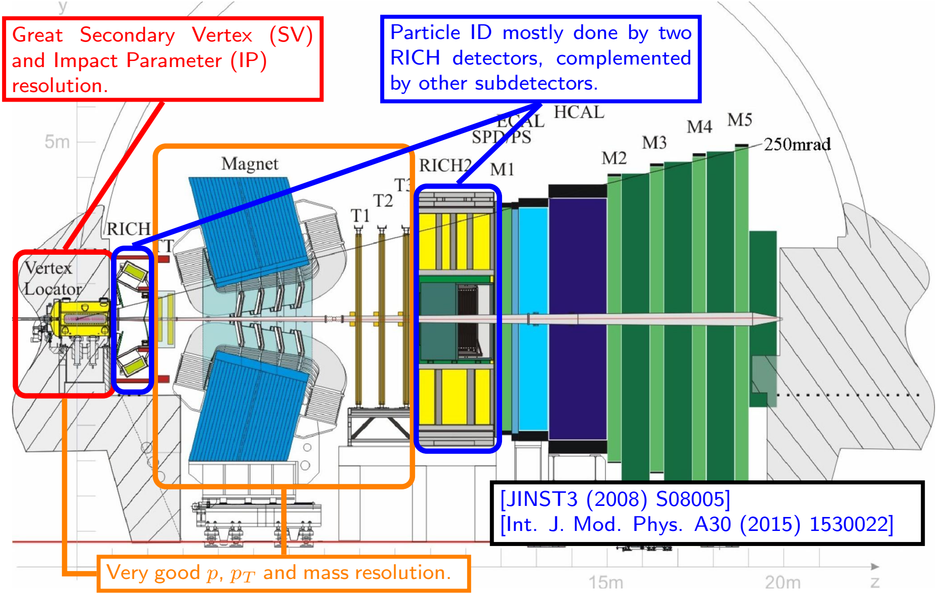
Particle ID mostly done by two RICH detectors, complemented by other subdetectors.



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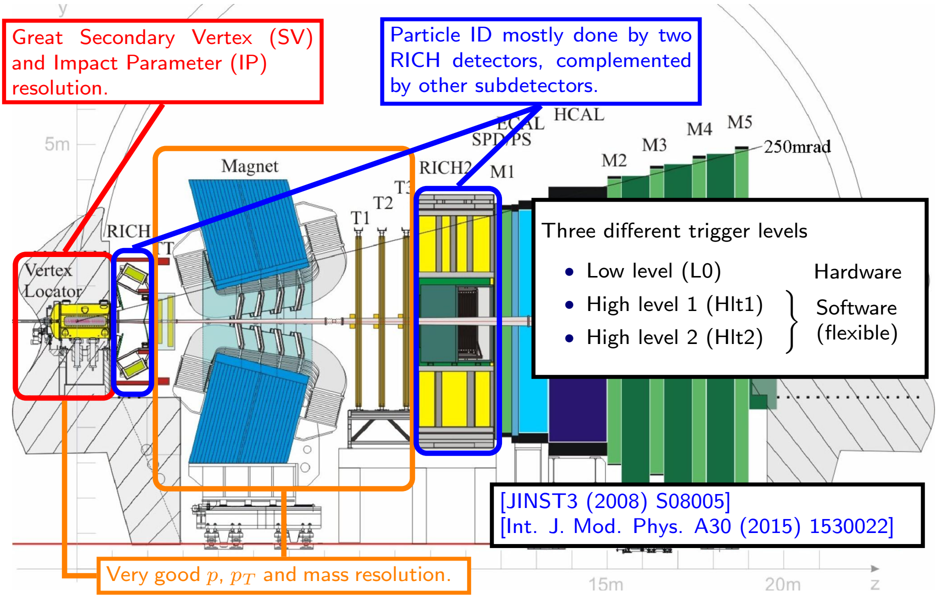

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Three different trigger levels

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

} Software (flexible)

Very good p, p_T and mass resolution.

[JINST3 (2008) S08005]
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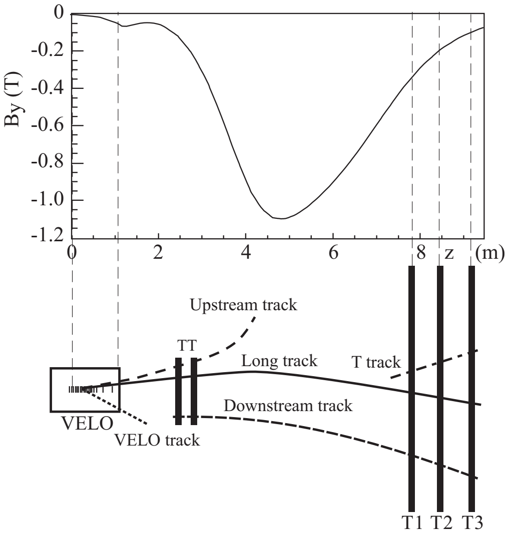
Kaons at LHCb

- Lifetimes are much larger than for B mesons:
  - $\tau_{B^0} \sim 1.5 \times 10^{-12} s$
  - $\tau_{K^0_S} \sim 10^{-10} s$
  - $\tau_{K^0_L} \sim 5 \times 10^{-8} s$
- K^0_S study is possible using long tracks.
- K^0_L study is HARDLY possible.

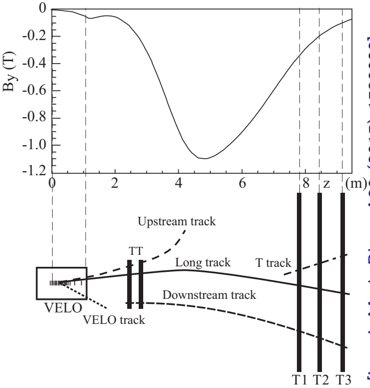


[Int. J. Mod. Phys. A30 (2015) 1530022]

Kaons at LHCb

For kaons...

- Largest limitation comes from the detector geometry.
- Second limitation comes from the trigger: $\varepsilon \sim 2.5\,(1)\,\%$ for $K^0_S \to \mu^+\mu^-$ in 2012 (2011).
- Low $p_T \Rightarrow$ harder to distinguish from comb. bkg.



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

Studies on K^0_S, $K^\pm$ and $\Sigma^\pm$ are currently being performed at LHCb. Results obtained until now came from not dedicated triggers.

Large K^0_S production cross-section inside the LHCb acceptance $10^{13}/\text{fb}^{-1}$. Efforts are being focused on adding new trigger lines and developing new low p_T particle identification algorithms.

The use of downstream tracks for the analyses could increase the statistics. However, the resolution is much worse (VELO information not available).

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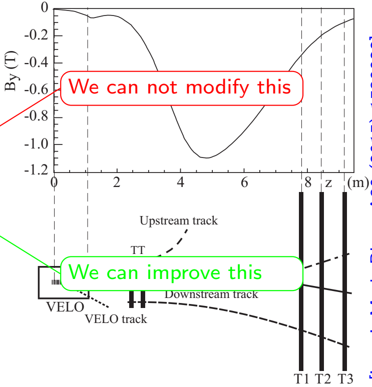

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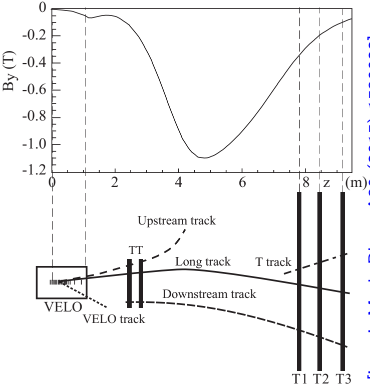

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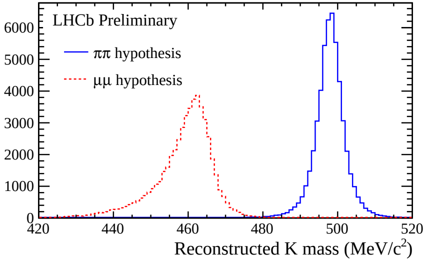
$K_S^0 \to \mu^+\mu^-$ at LHCb

Main features

- Very good mass resolution: ~ 4MeV/c^2.
- Great performance identifying muons.
- Luminosity recorded leads to $\mathcal{B}^{2012}_{exp.}\left(K_S^0 \to \mu^+\mu^-\right) \sim 10^{-9}$.
- Very clean decay $\Rightarrow$ few types of background contribute.



[LHCb-CONF-2016-012]

The main contamination sources are:

- $K_L^0 \to \mu^+\mu^-$ negligible: $\mathcal{B}_{\text{eff.}} \sim 10^{-11}$.
- $K^0_{S/L} \to \pi^+\mu^-\bar{\nu}$ negligible.
- $\Lambda^0 \to p\pi^-$ removed by a cut in the Armenteros-Podolanski plot.
- $K^{*0} \to K^+\pi^-$ suppressed using the information from the RICH detectors.
- $\omega \to \pi^0\mu^+\mu^-$, $\eta \to \mu^+\mu^-\gamma$ are not expected to generate peaking structures.
- Combinatorial background is almost flat in the region $[400, 600]$ MeV/c^2.
- Main source of background is $K_S^0 \to \pi^+\pi^-$ double misID.

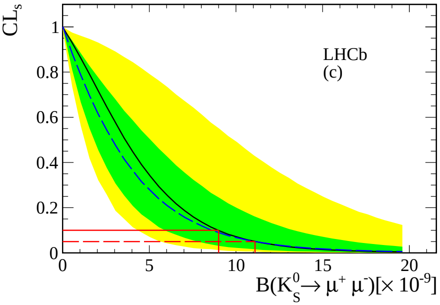
Analysis strategy

Main features

- Using 2012 data with 2fb^{-1}.
- Since it is a "search for" analysis, a blind strategy is done, avoiding the use of events in $m_{\mu\mu} \in [492, 504]$ MeV/c^2.
- Three different trigger selections have been used to exploit all the trigger capability.
- The $K_S^0 \to \pi^+\pi^-$ mode is used as a normalization channel.

Differences with respect to 2011 analysis

- Twice the luminosity.
- Trigger lines improved.
- New muon identification algorithm.
- Included function to describe the signal shape.
- Limit calculated directly from the $-\log\mathcal{L}$ distribution.
- Taking into account the previous limit.



LHCb [JHEP 01 (2013) 090]

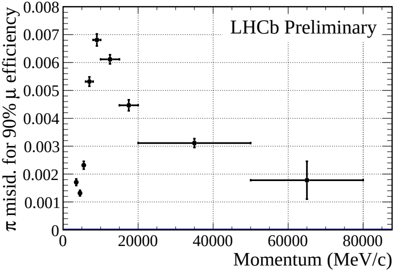
The new triggers and muonID algorithms in Run-I

Triggers

- Removed cuts on the di-muon mass.
- The p_T cuts have been reduced.
- Trigger efficiency improved by a factor 2.5.

Muon identification

- Dedicated algorithm for low p_T processes.
- $B^+ \to J/\psi K^+$ used for the muon calibration sample.
- Reduced dependence with the number of tracks.
- π misID $= 0.49\%$ at 95% of signal efficiency.



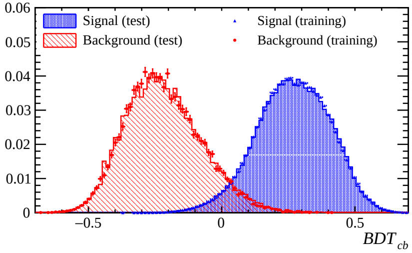
[LHCb-CONF-2016-012]

Combinatorial background removal

To remove the combinatorial background events a MVA selection has been done:

- Different MVA algorithms have been studied: BDT, Neural Networks, ...
- Optimization has been done using the ROC curves.
- The proxies correspond to real data $K_S^0 \to \pi^+\pi^-$ events (signal) and $K_S^0 \to \mu^+\mu^-$ events from the far right sideband (background).

- One different MVA for each trigger category.
- Optimization lead to the same MVA algorithm (**BDT**) and the same set of variables.
- Analysis performed in bins of the BDT distribution.
- Bins selected after a loose cut and so the signal efficiency is the same in each of them.



[LHCb-CONF-2016-012]

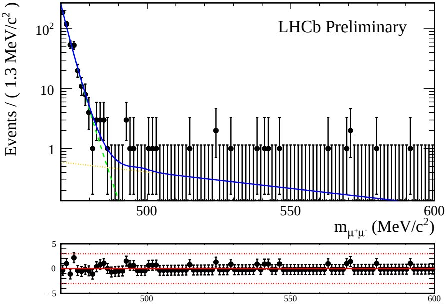
Fit procedure

- A simultaneous Maximum Likelihood Fit to all the BDT bins and categories was performed.
- Fit performed in the region $m_{\mu^+\mu^-} \in [470, 600]$ MeV/c^2.
- The previous result has been taken into account introducing a constraint on the branching fraction.

Contributions

- Right side of the $K_S^0 \to \pi^+\pi^-$ double misID $\Rightarrow$ Power law
- Combinatorial background $\Rightarrow$ Exponential
- Signal peak $\Rightarrow$ Hypatia function*

* [NIM A, 764, 150 (2014)]



[LHCb-CONF-2016-012]

The results

The normalization is computed as:

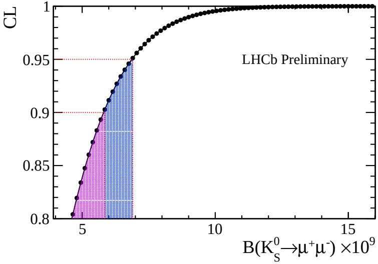
$$\mathcal{B}(K_S^0 \to \mu^+\mu^-) = \mathcal{B}(K_S^0 \to \pi^+\pi^-) \cdot \frac{\epsilon^{\pi\pi}}{\epsilon^{\mu\mu}} \cdot \frac{N^{\mu\mu}}{N^{\pi\pi}} \equiv \alpha N^{\mu\mu}$$

$$\frac{\epsilon^{\pi\pi}}{\epsilon^{\mu\mu}} = \frac{\epsilon_{sel}^{\pi\pi}}{\epsilon_{sel}^{\mu\mu}} \times \frac{\epsilon_{trig}^{\pi\pi}}{\epsilon_{trig}^{\mu\mu}} \times \frac{1}{\epsilon_{BDT}^{\mu\mu}} \times \frac{1}{\epsilon_{\mu\mathrm{ID}}}.$$

Limit extracted integrating the posterior probability of the branching fraction.

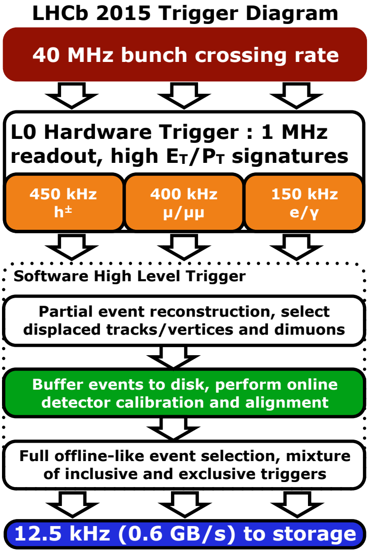
$\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right) < 6.9(5.8) \times 10^{-9}$ at $95(90)\%$ CL

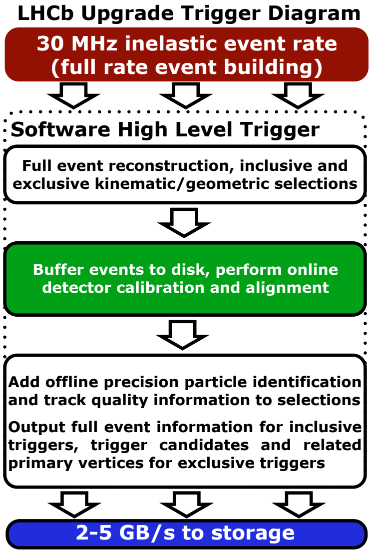
This result improves the previous LHCb limit by a factor 1.6, becoming the new world best result.



[LHCb-CONF-2016-012]

Prospects for the Run-II (2015-2019) and the upgrade (2021-2023)





LHCb Upgrade TDR [CERN-LHCC-2014-016]

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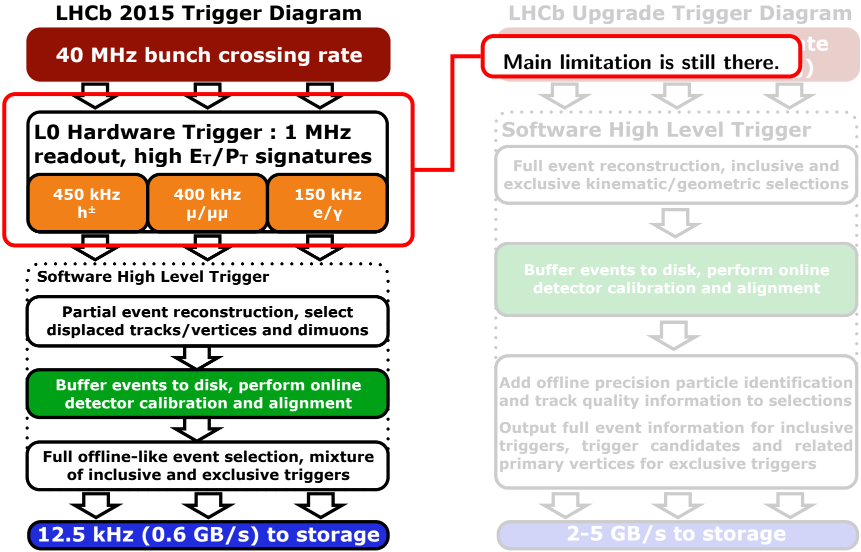

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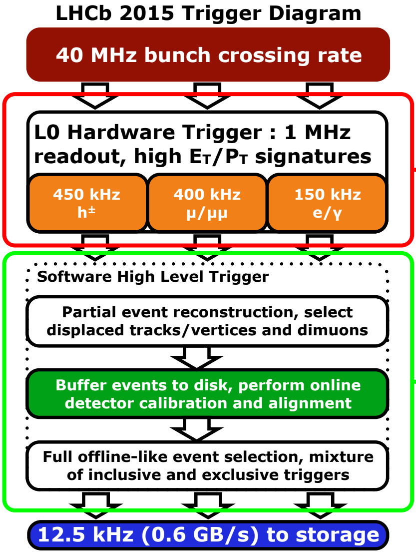

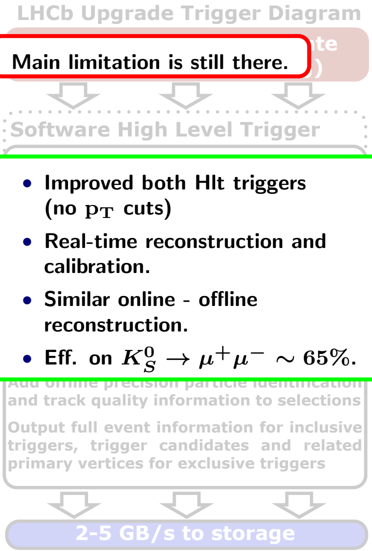

Main limitation is still there.

- Improved both Hlt triggers (no p_T cuts)
- Real-time reconstruction and calibration.
- Similar online - offline reconstruction.
- Eff. on $K^0_S \to \mu^+\mu^- \sim 65\%$.

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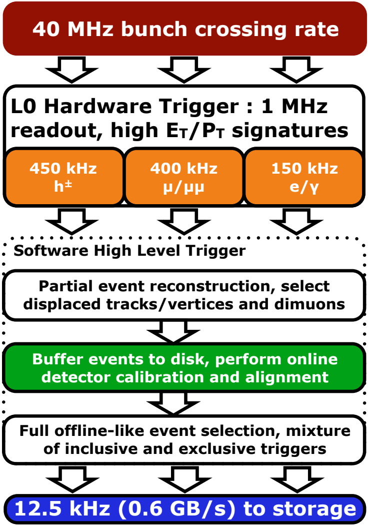
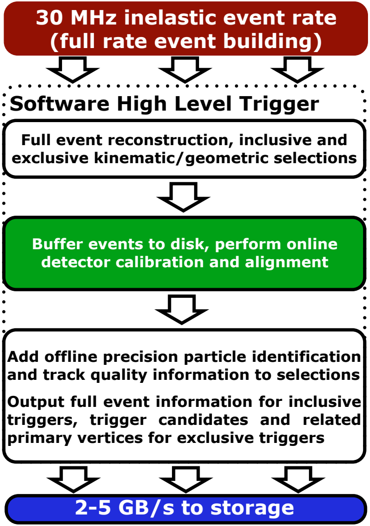
LHCb 2015 Trigger Diagram



LHCb Upgrade Trigger Diagram



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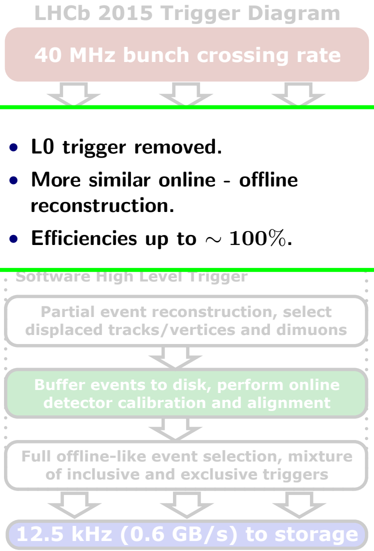
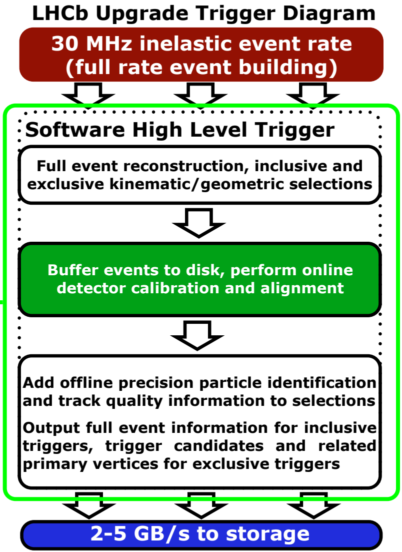


- L0 trigger removed.
- More similar online - offline reconstruction.
- Efficiencies up to $\sim 100\%$.



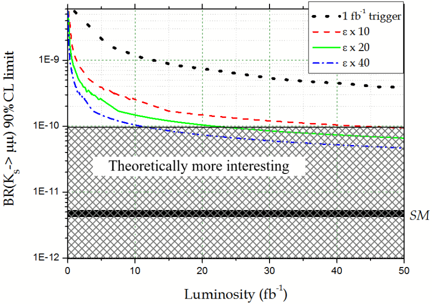
LHCb Upgrade TDR [CERN-LHCC-2014-016]

Conclusions

- A preliminary result for $K_S^0 \to \mu^+\mu^-$ analysis using the whole Run-I data has been shown.
- The limit has been measured to be

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

- Many efforts are being made to optimize the LHCb detector to study strange physics.
- Most interesting results are expected to appear in Run-II data and after the upgrade.



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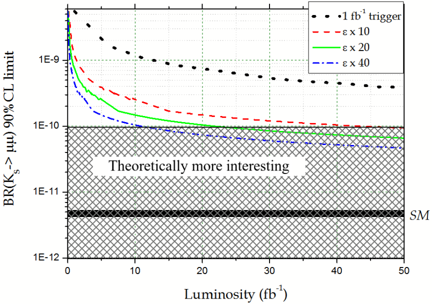
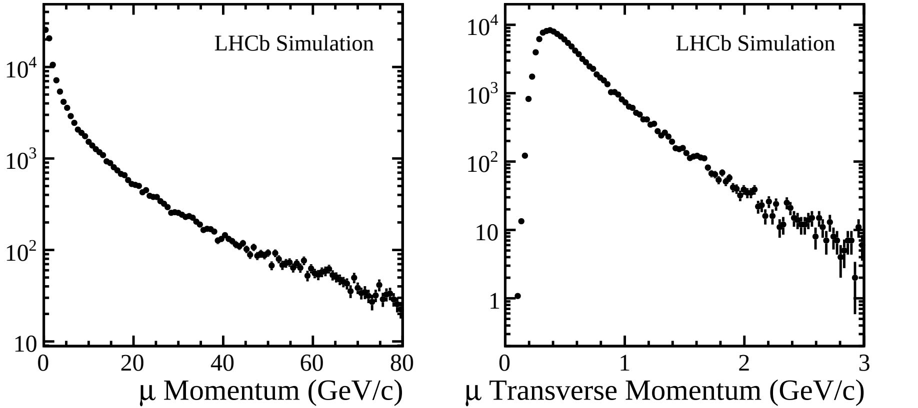


Stay tuned for the Run-II results!

BACKUP

Muon spectra



[LHCb-CONF-2016-012]

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

From the PDG[2]:

$$\mathcal{B}\left(K_L^0 \to \mu^+\mu^-\right) = (6.84 \pm 0.11) \times 10^{-9}$$

The effective branching fraction is computed as:

$$\mathcal{B}\left(K_L^0 \to \mu^+\mu^-\right)^{\text{eff.}} = \frac{\epsilon_{\mathsf{K}_L^0}}{\epsilon_{\mathsf{K}_S^0}} \mathcal{B}\left(K_L^0 \to \mu^+\mu^-\right) \equiv s_{K_L^0 \to \mu^+\mu^-} \mathcal{B}\left(K_L^0 \to \mu^+\mu^-\right)$$

The suppression $s_{K_L^0 \to \mu^+\mu^-}$ factor is obtained considering the time acceptance:

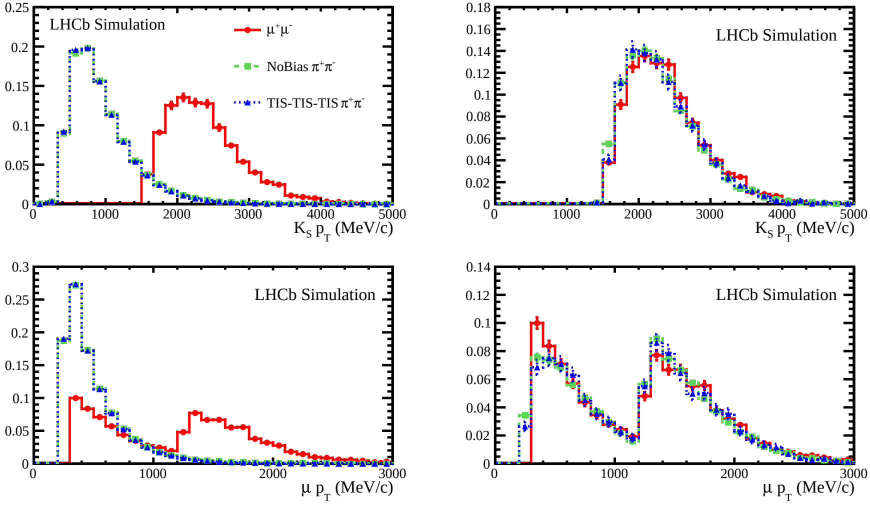
$$A(t; a, n, t_0, \delta t) = \frac{[a(t - t_0)]^n}{1 + [a(t - t_0)]^n} e^{-\delta t}$$

δt is calculated from a fit to $K_S^0 \to \mu^+\mu^-$ events. The suppression factor is the ratio between acceptance-corrected and theoretical proper time distributions, thus:

$$\mathcal{B}_{\text{eff.}} \in [1.2, 1.7] \times 10^{-11}$$

[2] PDG [Chin. Phys. C, 38, 090001 (2014) and 2015 update]

MVA proxies

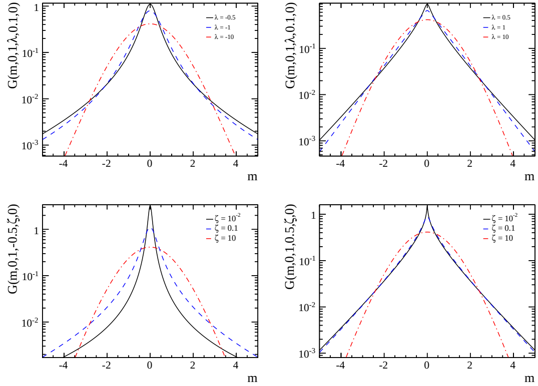


[LHCb-CONF-2016-012]

Signal shape

The Hypatia function is defined as follows[3]:

$$
I(m,\mu,\sigma,\lambda,\zeta,\beta,a,n) \propto
\begin{cases}
\left((m-\mu)^2 + A_\lambda^2(\zeta)\sigma^2\right)^{\frac{1}{2}\lambda-\frac{1}{4}} e^{\beta(m-\mu)} K_{\lambda-\frac{1}{2}}\left(\zeta\sqrt{1+\left(\frac{m-\mu}{A_\lambda(\zeta)\sigma}\right)^2}\right) & \text{, if } \frac{m-\mu}{\sigma} > -a \\
\frac{G(\mu-a\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{\left(1-m/\left(n\frac{G(\mu-a\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{G'(\mu-a\sigma,\mu,\sigma,\lambda,\zeta,\beta)}-a\sigma\right)\right)^n} & \text{, otherwise}
\end{cases}
$$



[3] Diego Martínez Santos, Frederic Dupertuis [NIM A, 764, 150 (2014)]

Systematics

Source	TOS$_\mu$-TOS$_\mu$-TOS$_{\mu\mu}$	TOS$_\mu$-TOS$_{\mu\mu}$-TOS$_{\mu\mu}$	TIS-TIS-TOS$_{\mu\mu}$
	Uncertainties on normalisation factor		
Tracking	0.4%	0.4%	0.4%
Selection	3.3%	3.9%	1.1%
Trigger	8%	11%	-
K spectrum	3.3%	3.3%	3.3%
Muon ID	0.2%	0.3%	0.8%
	Uncertainties on signal yield		
Signal mass shape	0.8%	0.8%	0.8%
	Uncertainties on branching fraction		
Background shape	4×10^{-11}		

Constraint using the prior result

Amoroso distribution to put a constraint on the $\mathcal{B}\left(K_S^0 \to \mu^+\mu^-\right)$ using the result from 2011.