Latest results from kaon and hyperon decays at LHCb

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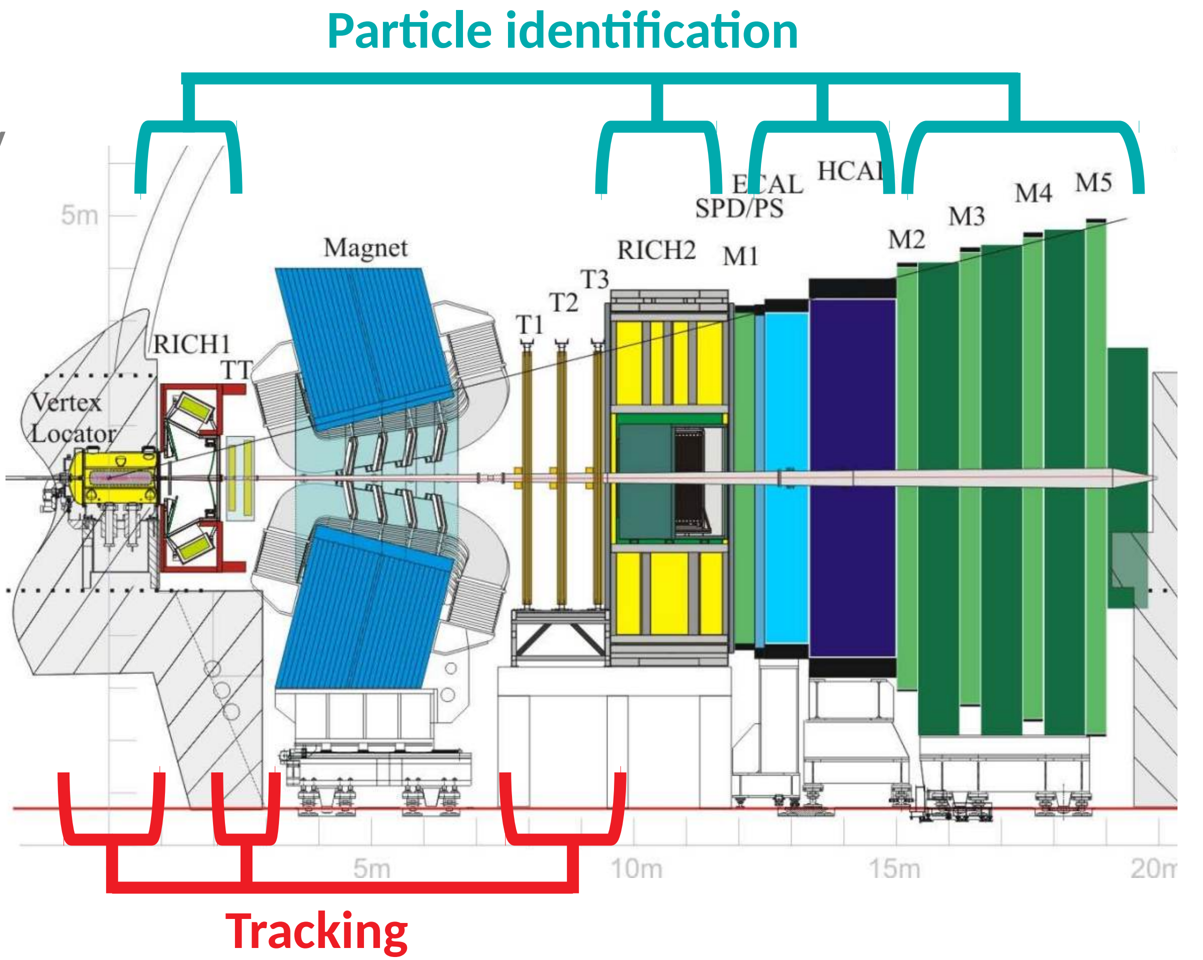
The LHCb experiment

- 2011: $1fb^{-1}$ at $\sqrt{s}$ = 7TeV
- 2012: $2fb^{-1}$ at $\sqrt{s}$ =8TeV
- 2016-2018: $5b^{-1}$ at $\sqrt{s}$ =13TeV
- Momentum resolution: 1%
- K_S mass resolution for tracks starting in the VELO: 4MeV
- π^0 mass resolution: ~10MeV
- Muon ID ~ 97 % for 1-3 % $\pi \to \mu$ mis-id probability



LHCb for strange physics

- Forward geometry optimized for b-physics
- Length of VELO optimized for b-hadron decay length
- Trigger optimized for b-physics → trigger thresholds too high for strange physics

L0 Hardware
High E_T, p_T thresholds

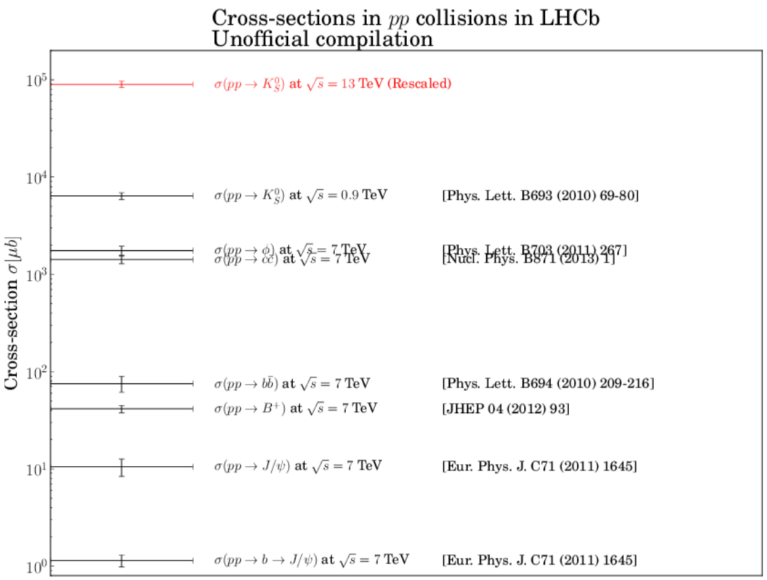
HLT1 Software
Partial event reco

HLT2 Software
Full event reco.

\+ **Large strange production cross-section: O(10^{13}) K_S per fb^{-1} in LHCb acceptance**

\+ **LHCb designed for precision measurements and rare decays**

→ **world best result on $K_S \to \mu^+\mu^-$ in 2011**
LHCb can do strange physics!



Strange physics at LHCb

- **Branching ratio limit on** $K_s \rightarrow \mu^+\mu^-$
- **Search for new physics in** $\Sigma^+ \rightarrow p\mu^+\mu^-$
- **Sensitivity study of branching ratio of** $K_s \rightarrow \pi^0\mu^+\mu^-$
- **Feasibility study of** $K_s \rightarrow \pi^+\pi^- e^+ e^-$ **evidence / observation**

Limit on branching ratio of $K_S \to \mu^+\mu^-$

[EPJC, 77 10 (2017) 678]

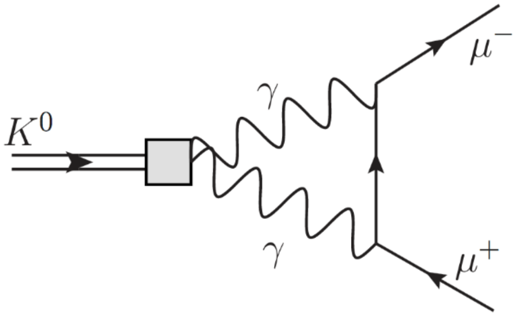
$K_S \to \mu^+\mu^-$

- FCNC = suppressed in the SM

- SM prediction: **BR($K_S \to \mu^+\mu^-$) = (5.18 ± 1.50$_{LD}$ ± 0.02$_{SD}$) · 10^{-12}**
  [JHEP05(2018) 024 , JHEP 0401 (2004) 009, NPB 366 (1991) 189]

- **New physics** could lead to contributions of **one order of magnitude above SM predictions** + be compatible with current measurements from other FCNC processes

- Dominated by long distance contributions as $K_L \to \mu^+\mu^-$ but s-***wave* component is *CP*-violating for** $K_S \to \mu^+\mu^-$



- Previous BR limit from LHCb (1fb^{-1} 2011 data): BR($K_S \to \mu^+\mu^-$) < 9 · 10^{-9} (90%CL)
  → **much space for physics beyond the SM**

Updated measurement with 2fb^{-1} of data collected by LHCb in 2012 + trigger efficiency increased by ~2.5!

Analysis strategy

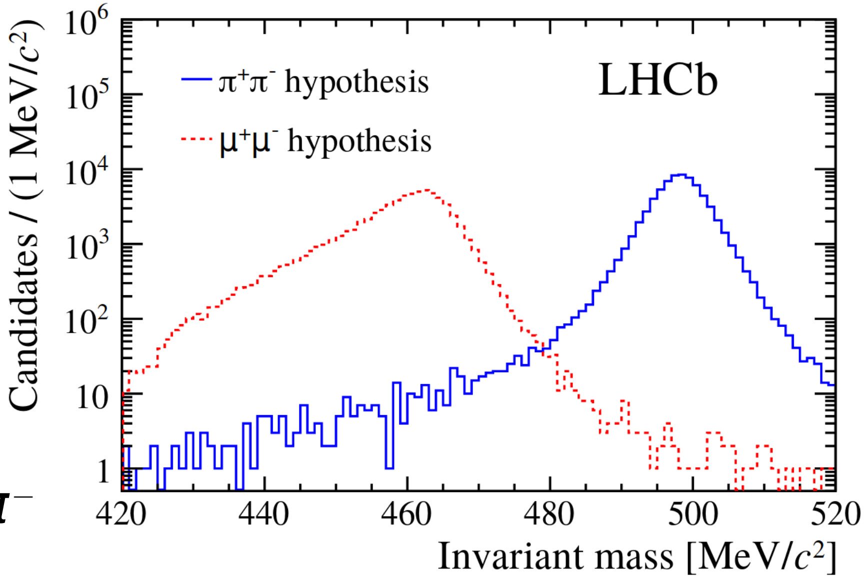
1. Event selection:

a) <u>Trigger:</u> trigger on μ and $\mu^+\mu^-$ of $K_S \to \mu^+\mu^-$

b) <u>Selection / background rejection:</u>

- Cut based pre-selection
- BDT_{cb} against **combinatorial bkg**
- BDT_{μ} focused on muon-ID

  against $K_S \to \pi^+\pi^-$
- Vetoes against $\Lambda \to p\pi^-$ and $K^{*0} \to K^+\pi^-$



2. Division of data sample:

- Trigger categories → BDT_{cb} trained for each trigger category
- BDT_{cb} bins → cut on BDT_{μ} optimized for each BDT_{cb} bin

Analysis strategy

3. Extraction of $K_S \to \mu^+\mu^-$ signal yields in each bin with maximum likelihood fit

4. Translation of signal yields into branching ratio

$$\mathcal{B}(K^0_S \to \mu^+\mu^-) = \mathcal{B}(K^0_S \to \pi^+\pi^-) \cdot \frac{\epsilon^{\pi\pi}}{\epsilon^{\mu\mu}_{ij}} \cdot \frac{N^{\mu\mu}_{ij}}{N^{\pi\pi}}$$

- $K_S \to \pi^+\pi^-$ decay as normalization
- Ratio of efficiencies from simulation or other decay channels

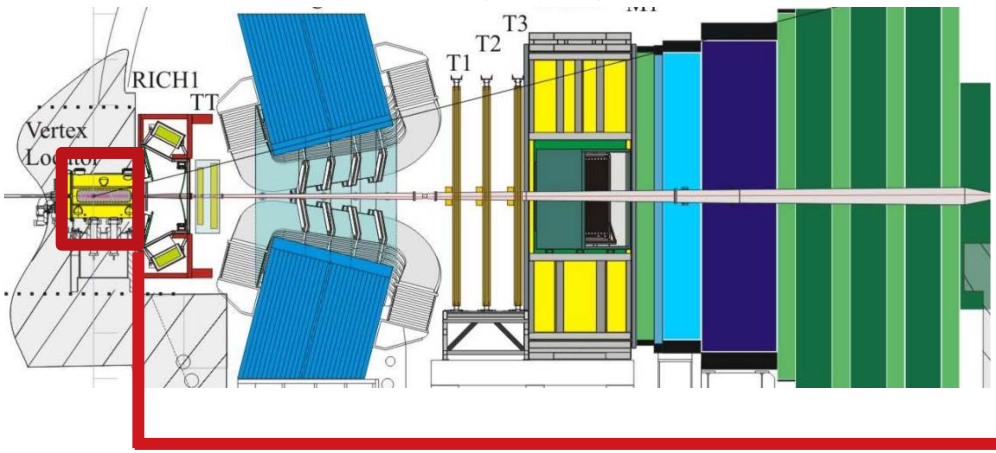
$$\frac{\epsilon^{\pi\pi}}{\epsilon^{\mu\mu}_{ij}} = \frac{\epsilon^{\pi\pi}_{\rm sel}}{\epsilon^{\mu\mu}_{\rm sel}} \times \frac{\epsilon^{\pi\pi}_{\rm trig}}{\epsilon^{\mu\mu}_{{\rm trig};j}} \times \frac{1}{\epsilon^{\mu\mu}_{{\rm BDT};ij}} \times \frac{1}{\epsilon_{\mu{\rm ID};ij}}$$

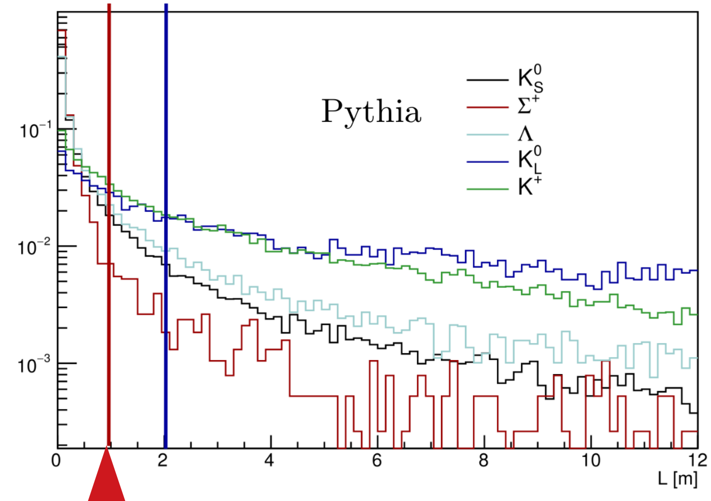
5. Branching ratio limit

Limitations to efficiency

K_S **required to decay in VertexLocator:**

~1.5 m long → **only ~1/3 of K_S decay in Velo**



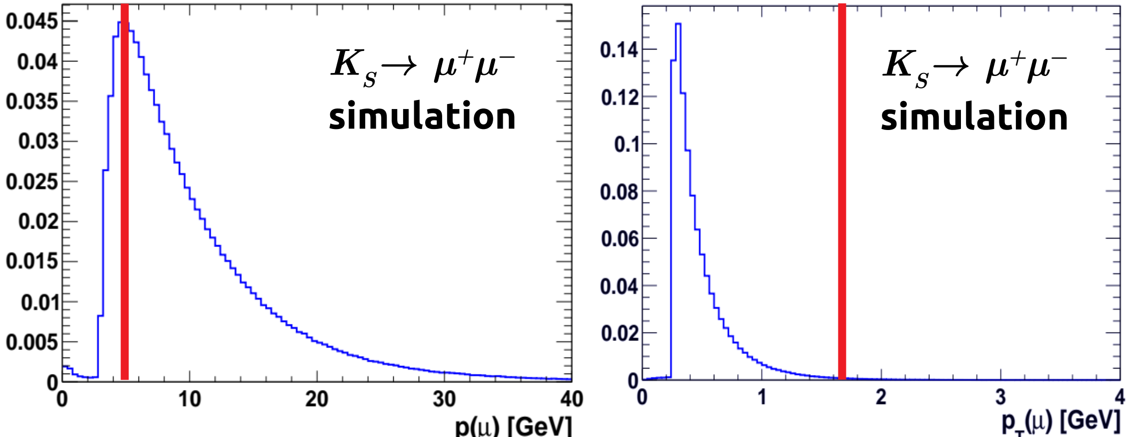


Low hardware (L0) trigger efficiency:

~ p(μ) > 5GeV

&& $p_T(\mu)$>1.76GeV

→ **~1-2% trigger efficiency**



Greatest uncertainties

Ratio of trigger efficiencies:

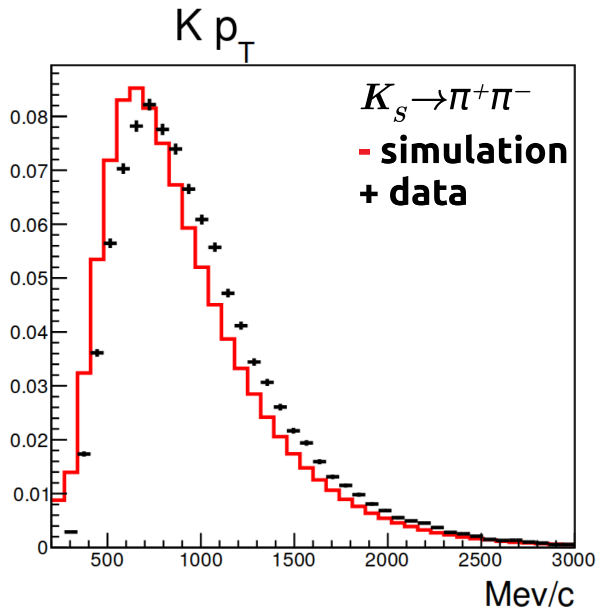
- Trigger efficiencies taken from simulation → trigger response not perfectly described in simulation
- **Use proxy with high signal yield to determine trigger efficiency in data:** $B^{\pm} \to J/\psi(\to \mu^+\mu^-)K^{\pm}$

→ **~10 % uncertainty on normalization**

Kaon p_T spectrum in not well modeled in simulation:

- $K_S \to \pi^+\pi^-$ data used to obtain correct p_T spectrum
- All efficiencies obtained from $K_S \to \mu^+\mu^-$ simulation are reweighted

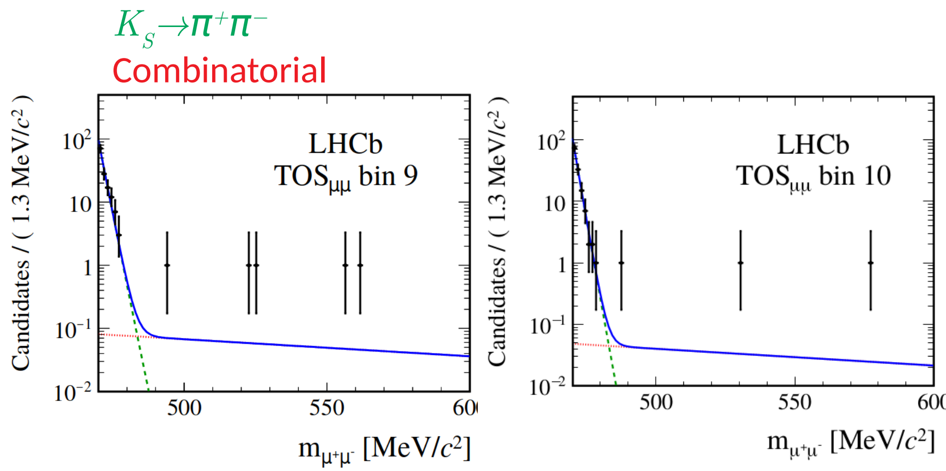
→ **4.3 % uncertainty on normalization**



Results

Previous result:

$BR(K_S \to \mu^+\mu^-) < 9 \cdot 10^{-9}$ (90%CL)



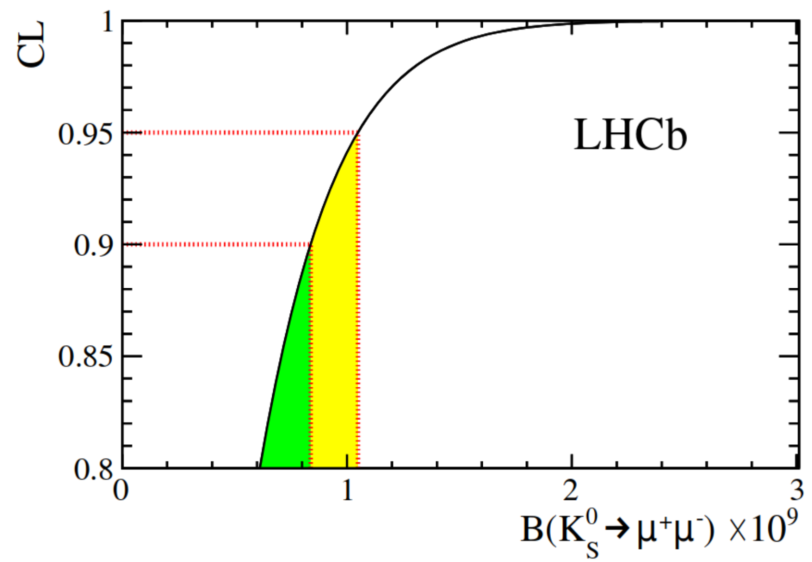
New result:

$BR(K_S \to \mu^+\mu^-) < 0.8 \cdot 10^{-9}$ **(90%CL)**

$BR(K_S \to \mu^+\mu^-) < 1.0 \cdot 10^{-9}$ **(95%CL)**

→ **Worlds best upper limit on BR($K_S \to \mu^+\mu^-$)**

→ Orders of magnitude away from SM, still room for physics beyond the SM.

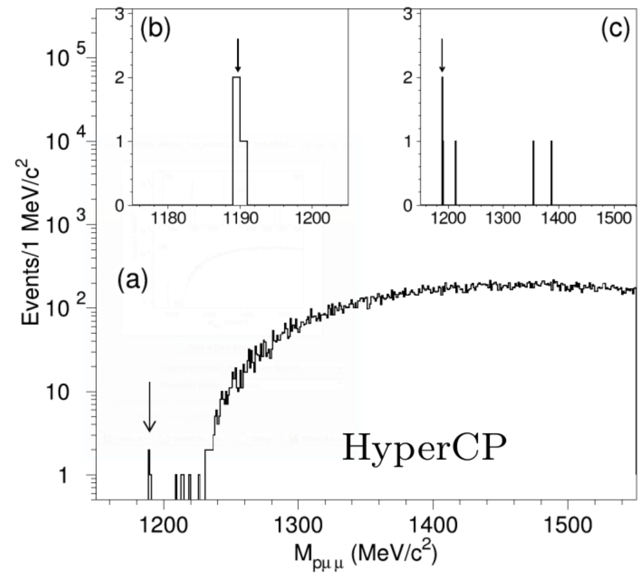


Search for new physics in $\Sigma^+ \rightarrow p\mu^+\mu^-$

[Phys. Rev. Lett. 120, 221803 (2018)]

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

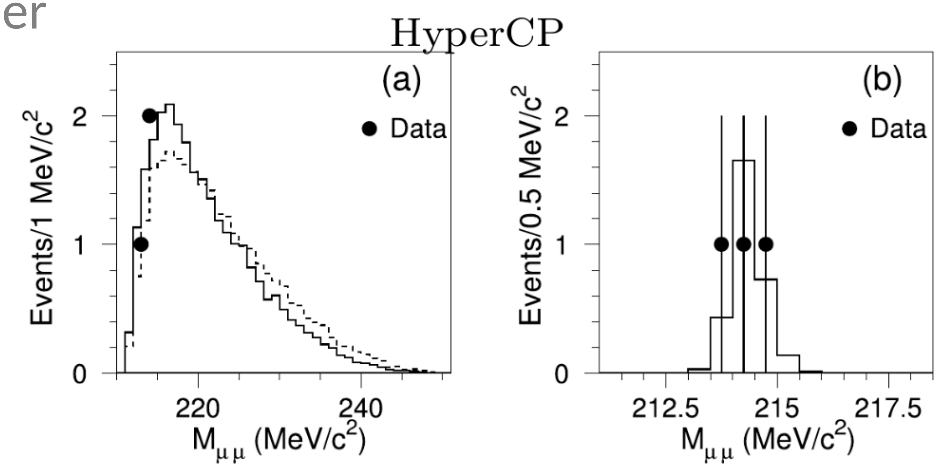
- Evidence for $\Sigma^+ \to p\mu^+\mu^-$ **found by HyperCP collaboration:** BR = $(8.6\,^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$



- Consistent with SM: $1.6 \cdot 10^{-8} < \text{BR} < 9.0 \cdot 10^{-8}$
  [X G He et al, PRD 72 (2005) 074003]

- All three observed events had the same dimuon invariant mass $M_{inv}(\mu^+\mu^-)$ = 214 MeV
  → **possible new particle X^0 with $X^0 \to \mu^+\mu^-$?**

- No such dimuon resonance found in other decays ($B_{(s)} \to \mu^+\mu^-\mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^+\mu^+\mu^-$).



Search for $\Sigma^+ \to p\mu^+\mu^-$ at LHCb in 3fb^{-1} collected in 2011 + 2012.

Analysis strategy

1. Event selection:

a) <u>Trigger:</u> triggered by $\Sigma^+ \to p\mu^+\mu^-$ and independently of it

b) Selection / background rejection:

- Cut based pre-selection
- BDT_{cb} against **combinatorial bkg**
- Vetoes against $\Lambda \to p\pi^-$

2. Extraction of $\Sigma^+ \to p\mu^+\mu^-$ signal yields with maximum likelihood fit

3. Translation of signal yields into branching ratio:

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

- $\Sigma^+ \to p\pi^0$ decay as normalization
- Ratio of efficiencies from simulation or other decay channels

4. Scan of dimuon invariant mass for possible resonances

Greatest uncertainties

Ratio of trigger efficiencies (similar to $K_S \to \mu^+\mu^-$):

- Trigger efficiencies taken from simulation → trigger response not perfectly described in simulation
- **Uncertainty: difference between trigger efficiency from data and simulation**
- **Use proxy to estimate uncertainty: $\Sigma^+ \to p\pi^0$**

→ **~40 % uncertainty on the normalization**

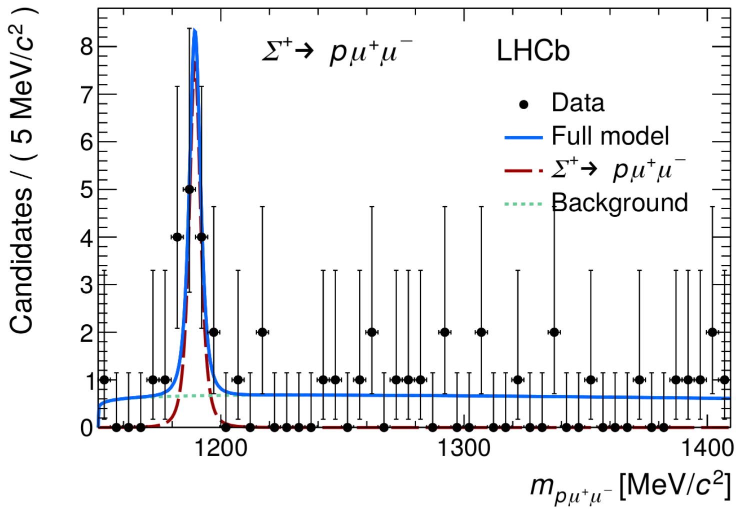
Efficiency of particle identification:

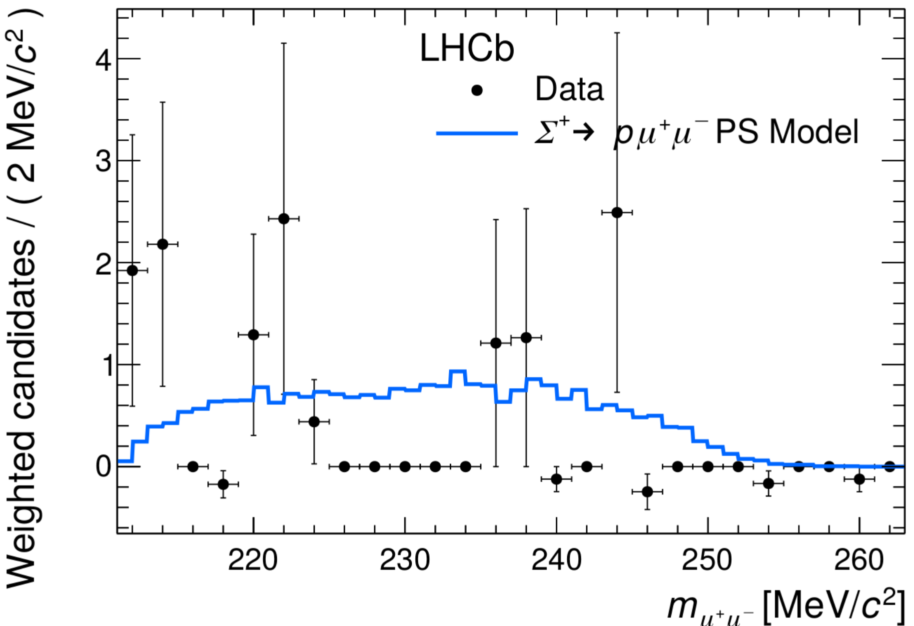
- Calculated using simulation and calibrated using dedicated LHCb data samples
- Small size of calibration sample for p introduces big uncertainty

→ **28% uncertainty on the normalization**

Results

- HyperCP: BR = ($8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$
- **$10.2^{+3.9}_{-3.5}$ $\Sigma^+ \to p\mu^+\mu^-$ events observed**
- Improved branching ratio measurement:
  BR($\Sigma^+ \to p\mu^+\mu^-$) = $(2.2^{+1.8}_{-1.9}) \cdot 10^{-8}$
- **No evidence of new particle at 124 MeV**





Sensitivity study

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

[CERN-LHCb-PUB-2016-017]

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

- Search for physics beyond the SM:
  - $s \to d$ quark transitions have strongest CKM suppression factor and are particularly sensitive to new sources of flavour violation
  - $K_L \to \pi^0\mu^+\mu^-$ is very sensitive but SM prediction has large uncertainty on BR = {1.4 ± 0.3; 0.9 ± 0.2} 10^{-11}

    → **Improved measurement on $K_S \to \pi^0\mu^+\mu^-$ will reduce uncertainty from SM**
- Previous NA48 measurement: BR($K_S \to \pi^0\mu^+\mu^-$) = $(2.9^{+1.5}_{-1.2} \pm 0.2)\ 10^{-9}$

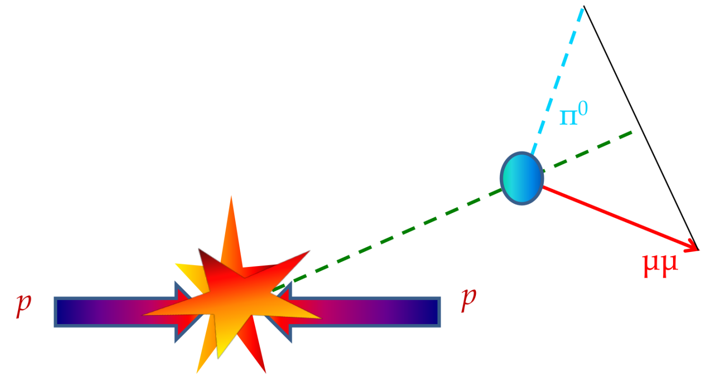
➡ **Use data collected by LHCb to evaluate the sensitivity on BR expected after the LHCb upgrade.**

Strategy

1. $K_S \rightarrow \pi^0 \mu^+ \mu^-$ reconstruction:

a) Fully reconstructed

b) Partially reconstructed: π^0 not reconstructed, π^0 momentum constrained

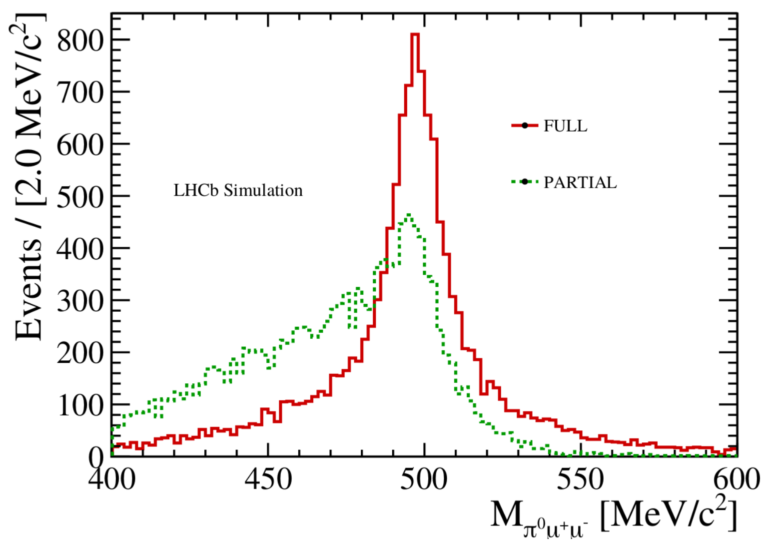


2. Pseudo-experiments for expected lumi:

a) Background yield in $3fb^{-1}$ LHCb data extrapolated

b) Signal yields extrapolated from $K_S \rightarrow \pi\pi$ signal yield in $3fb^{-1}$ LHCb

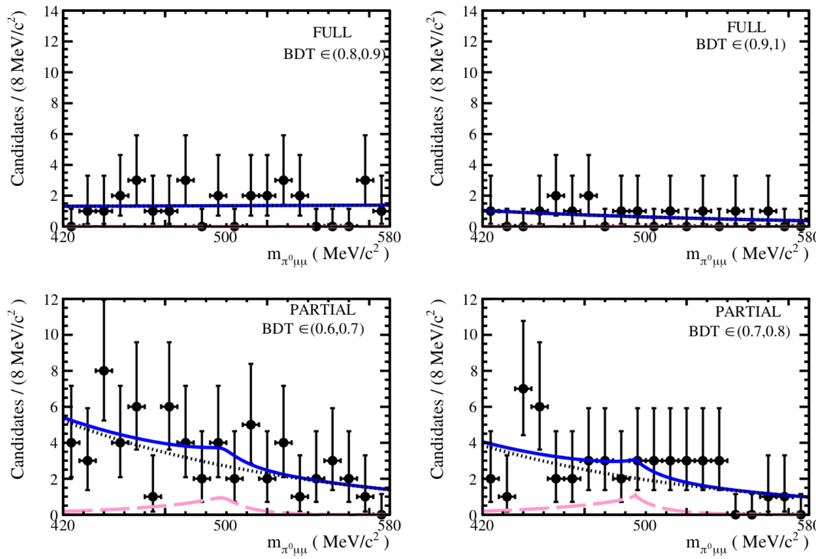
$$N_{sig} = \frac{\mathcal{B}(K^0_S \rightarrow \pi^0 \mu^+ \mu^-)}{\mathcal{B}(K^0_S \rightarrow \pi^+ \pi^-)} \frac{\epsilon_{K^0_S \rightarrow \pi^0 \mu^+ \mu^-}}{\epsilon_{K^0_S \rightarrow \pi^+ \pi^-}} N(K^0_S \rightarrow \pi^+ \pi^-) \times \frac{L_{fut}}{L_{curr}}$$



3. Fit to the pseudo-experiments to obtain statistical uncertainty

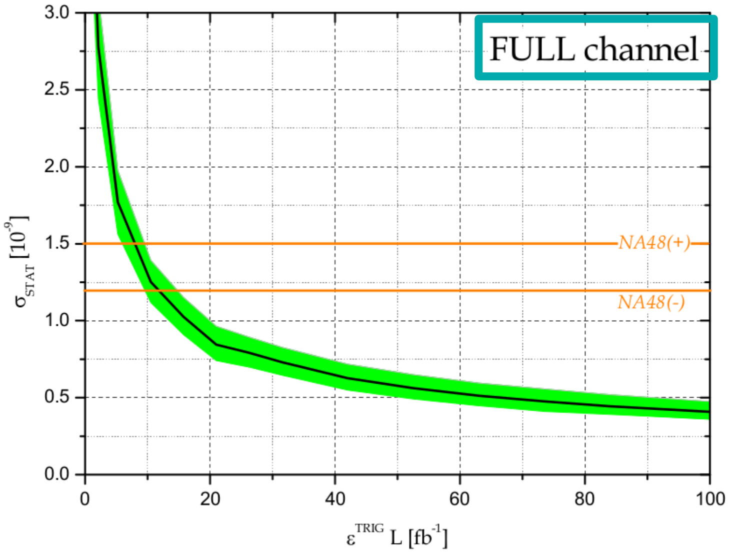
Results

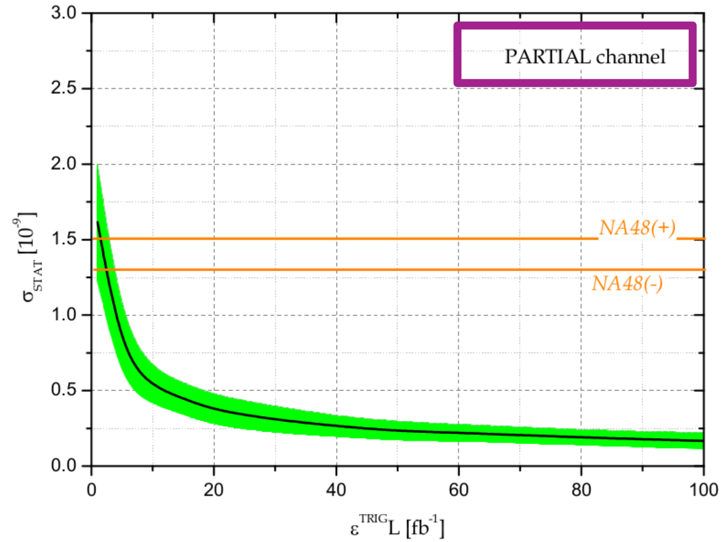
- No evidence of $K_S \to \pi^0\mu^+\mu^-$ found in 3fb^{-1} 2011 + 2012 LHCb data



- 100fb^{-1} and 50% ε_{trig}: σ_{stat} = 0.6 / 0.25 · 10^{-9}
- 50fb^{-1} and 50% ε_{trig}: σ_{stat} = 0.7 / 0.3 · 10^{-9}

- **With ε_{trig} > 50% LHCb can supersede NA48 branching ratio measurement.**





Feasibility study

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

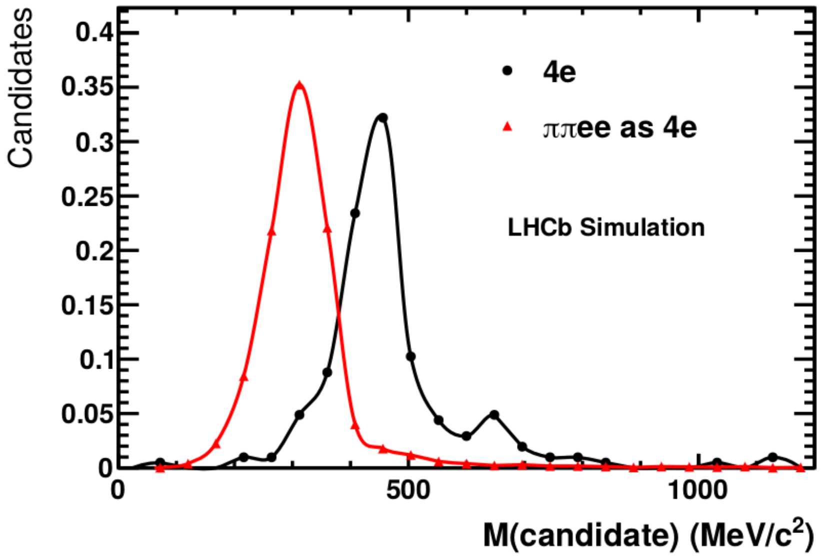
[LHCb-PUB-2016-016]

$K_s \to \pi^+\pi^- e^+ e^-$

- Search for light dark-matter states decaying into dileptons

- $$\begin{aligned}\mathcal{B}(K^0_S \to e^+e^-e^+e^-) &\sim 10^{-10}\\ \mathcal{B}(K^0_S \to \mu^+\mu^-e^+e^-) &\sim 10^{-11}\\ \mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) &\sim 10^{-14}\end{aligned}$$

→ never observed, sensitive to physics beyond the SM



- $K_s \to \pi^+\pi^- e^+ e^-$ is important background
- $K_s \to \pi^+\pi^- e^+ e^-$ could be used as normalization

→ **Need to understand $K_s \to \pi^+\pi^- e^+ e^-$ first!**

Study of feasibility of observing $K_s \to \pi^+\pi^- e^+ e^-$ decays at LHCb.

Strategy

1. Data samples:

- $K_S \to \pi^+\pi^- e^+ e^-$ simulated sample
- $2fb^{-1}$ LHCb data recorded in 2012

2. Selection:

a) Trigger
b) Simple offline pre-selection

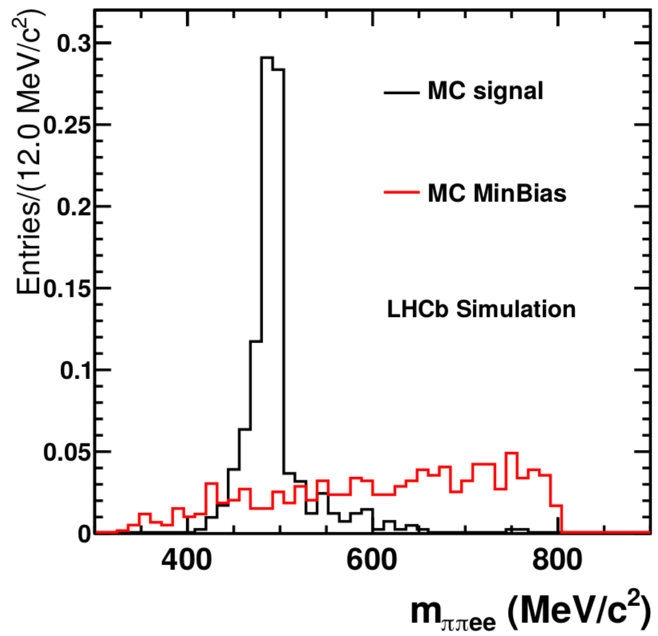
3. Expected yields after simple selection:

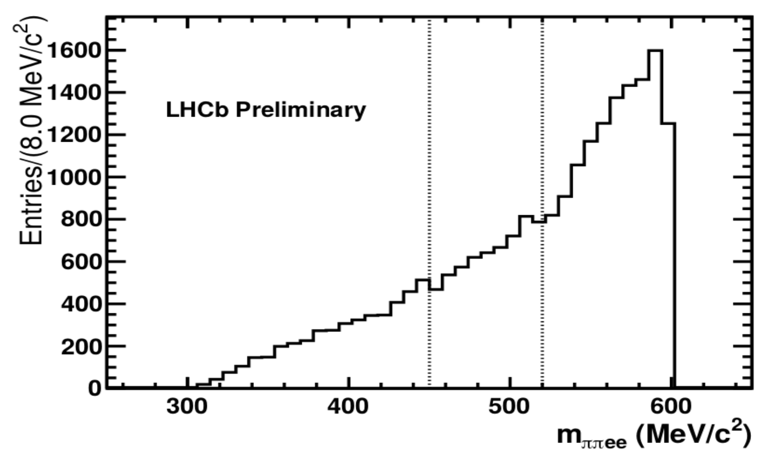
- Efficiencies for $K_S \to \pi^+\pi^- e^+ e^-$ taken from simulation

$$N_{sig}^{exp} = N(K_S^0/\text{fb}^{-1}) \cdot \mathcal{B}(K_S^0 \to \pi^+\pi^- e^+ e^-) \cdot \epsilon^{sig}$$

→ $K_S \to \pi^+\pi^- e^+ e^-$: 120^{+280}_{-100} / fb^{-1}

- Background yield estimated from data
→ Background: ~ 2800 / fb^{-1}



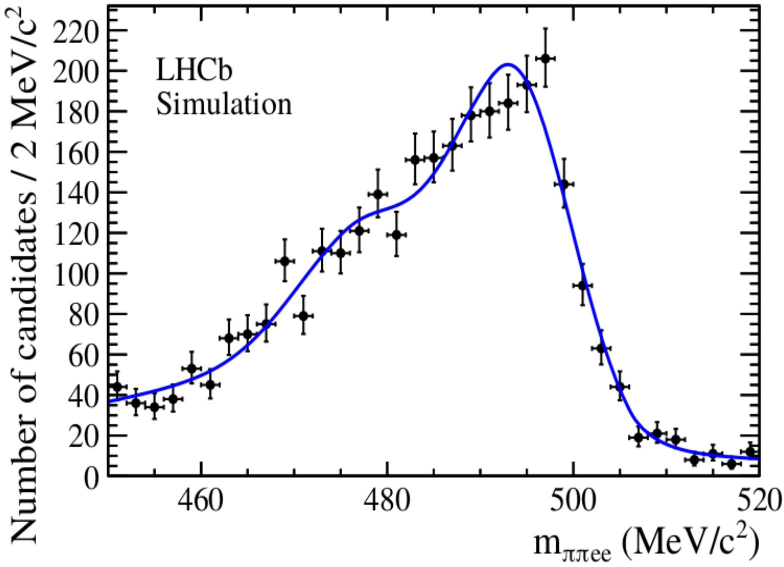


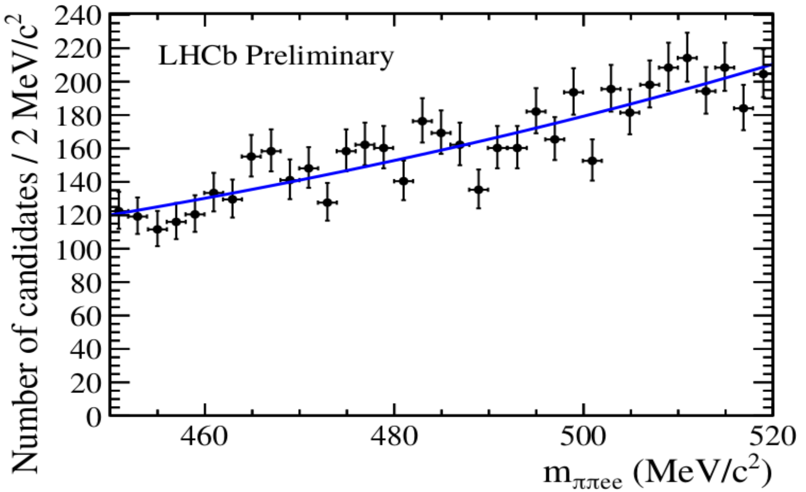
Strategy

4. Pseudo-experiments:

- Further offline selection needed
- Data-sets created for different combinations of signal selection efficiency and background rejection efficiency

5. Signal significance determined for each combination



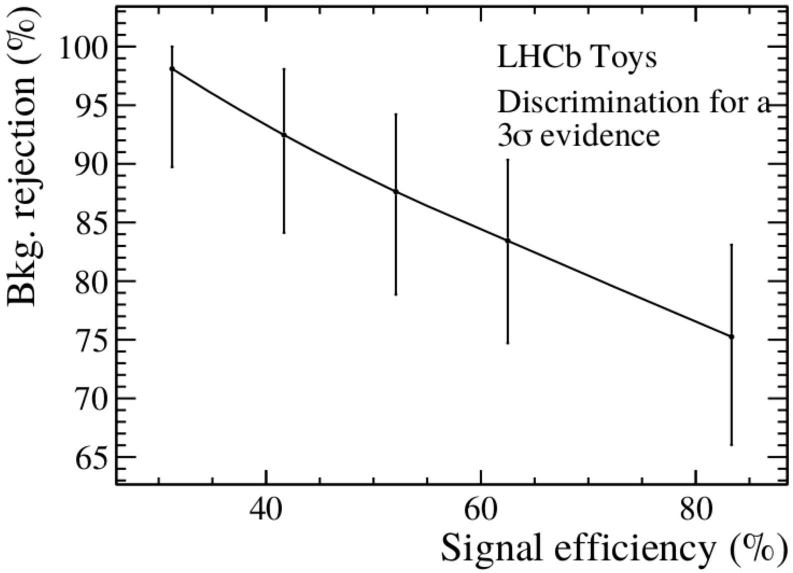


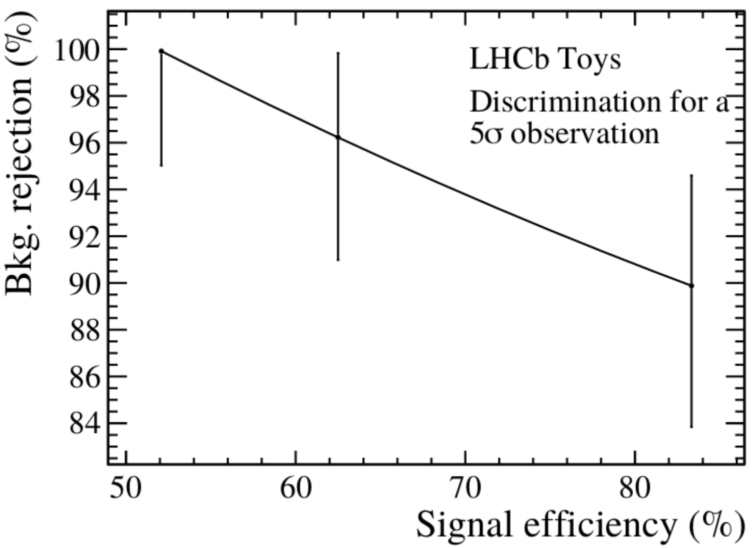
Results

- Signal efficiency vs. background rejection curves for 3σ evidence and 5σ observation

- Both curves achievable with standard MVA selections

→ $K_s \to \pi^+\pi^- e^+e^-$ **evidence or observation possible with only 2011 + 2012 LHCb data!**





Summary

Summary

- LHCb was build for b-physics
  - Trigger thresholds too high for strange physics

- Huge strange production cross-section + good particle identification + good resolution on mass / vertex / impact parameter etc

- Best limits on $K_S \to \mu^+\mu^-$ branching ratio with 2011 + 2012 data

- Improved BR measurement for $\Sigma^+ \to p\mu^+\mu^-$ with 2011 + 2012 data
  + No evidence of dimuon resonance (e.g. physics beyond the SM) found

- Sensitivity study on branching ratio measurement for $K_S \to \pi^0\mu^+\mu^-$ shows that LHCb improve on NA48 measurement after the upgrade.

- Feasibility study shows that $K_S \to \pi^+\pi^- e^+ e^-$ should be observable with data recorded by LHCb in 2011 + 2012.

Thank you!

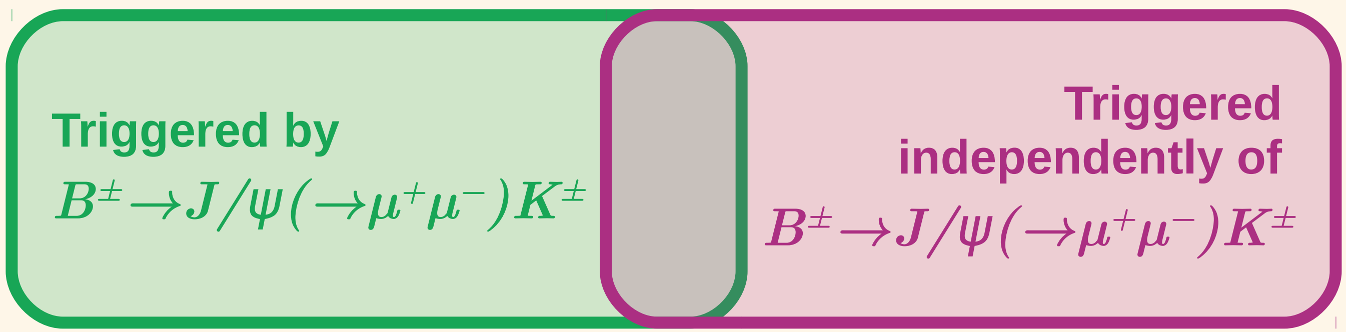
Backup

Greatest uncertainties

<u>Ratio of trigger efficiencies:</u>

- Trigger efficiencies taken from simulation
- Trigger response not perfectly described in simulation
- **Uncertainty: difference between trigger efficiency from data and simulation**
- **Use proxy to estimate uncertainty:** $B^{\pm} \to J/\psi(\to \mu^{+}\mu^{-})K^{\pm}$

<u>Trigger efficiency from data:</u> Overlap between trigger categories



- Correct for different momentum distribution

→ **~10 % uncertainty on normalization**

Greatest uncertainties

Kaon p_T spectrum in not well modeled in simulation:

- $K_S \to \pi^+\pi^-$ data used to obtain correct p_T spectrum
- All efficiencies obtained from $K_S \to \mu^+\mu^-$ simulation are reweighted
- Systematic uncertainty estimated by using a **different binning in the reweighting** and evaluating the difference

→ **4.3 % uncertainty on normalization**