Prospects for the search of $K^0_S \to \pi^+\pi^-e^+e^-$ at LHCb

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on behalf of the LHCb collaboration

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Motivation

- LHCb has proved to be very competitive in strange physics.
  - Up to 5 talks with results and prospects in this conference!

- Recent interest in $K^0_S \to \ell^+\ell^-\ell^+\ell^-$ decays: [Eur. Phys. J. C73 (2013) no. 12 2678]

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

  - Any enhancement is a sign of NP!
  - Interference between $K^0_S \to \ell^+\ell^-\ell^+\ell^-$ and $K^0_L \to \ell^+\ell^-\ell^+\ell^-$ would allow CKM stringent constraints.
  - No experimental results in the literature [PDG].

Electron modes

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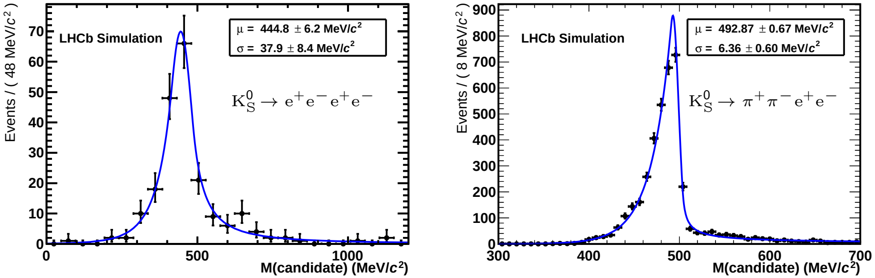
- Electron reconstruction is the main issue:
  - Low momenta + loss by Bremsstrahlung.

- Preliminary studies with MC:
  - Mass resolution good with two $\mathrm{e}^{\pm}$, worse with four.
  - Peak displacement in both cases, larger with four $\mathrm{e}^{\pm}$.



Electron modes

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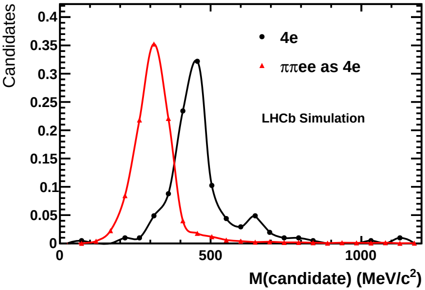
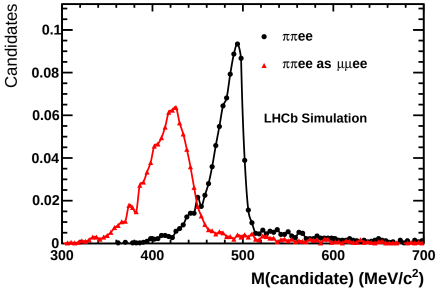
- Dangerous background: $K^0_S \to \pi^+\pi^-e^+e^-$
- Study separation with two misidentified pions:





$K^0_S \to \pi^+\pi^- e^+ e^-$

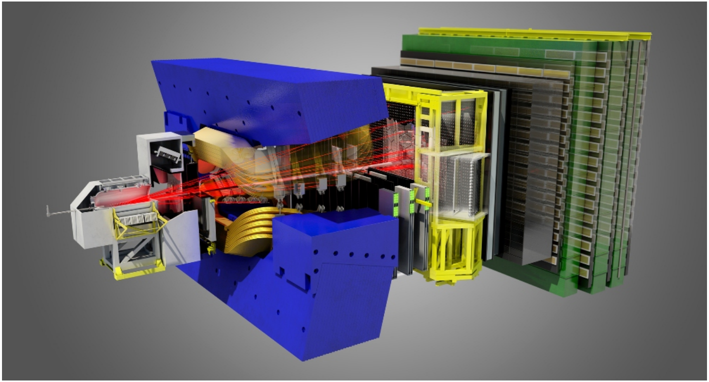
- Dangerous background for $K^0_S \to \ell^+\ell^-\ell^+\ell^-$.
- Good candidate for normalisation channel.
- Interesting itself: light dark matter states decaying to e^+e^-.
  - Search for peaks in e^+e^- invariant mass following [PRD 92 (2015) no. 11 115017].
- Relatively large $\mathcal{B}$ [PDG]:

$$\mathcal{B}(K^0_S \to \pi^+\pi^- e^+ e^-) = (4.79 \pm 0.15) \times 10^{-5}$$

Study feasibility of observing $K^0_S \to \pi^+\pi^- e^+ e^-$ at LHCb

LHCb detector

JINST3 (2008) S08005

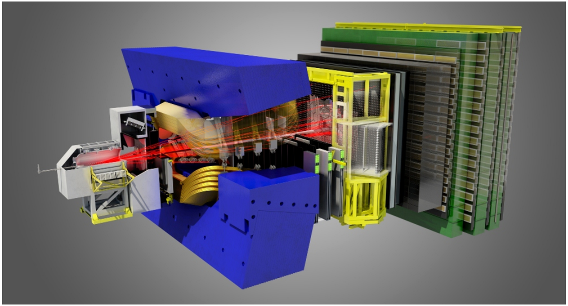


- e identification: e ID ~ 90 % for ~ 5 % e $\rightarrow$ h mis-id probability.
- p resolution: $\Delta p/p \sim 0.4$ % at 5 GeV/c to 0.6 % at 100 GeV/c
  $\rightarrow$ Excelent mass resolution: ~ 4 MeV/c^2 for $\mathrm{K^0_S} \rightarrow \mu^+\mu^-$.

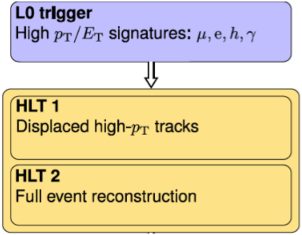
LHCb detector for K^0_S decays

LHCb is a kaon factory: $\sim 10^{13}\ K^0_S/\ fb^{-1}$ decay in LHCb acceptance.
But, it is not optimised for the study of these decays:

	m (MeV)	τ (10^{-12} s)
B_d	5300	1.5
K_S	500	90



LHCb Run I trigger for K^0_S decays



Flexible trigger

- L0: calorimeters and muon chambers.
- HLT1: adds tracking and vertexing.
- HLT2: exclusive and inclusive full selections.

LHCb trigger was not designed to select K^0_S decays:

- They have larger τ and lower daughter's p_T.
- No dedicated trigger selection for $K^0_S \to \pi^+\pi^-e^+e^-$ in Run I.
- They may pass the trigger as background.

Analysis strategy

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- Study based on MC and data in 2012 conditions: 2 fb^{-1} at 8 TeV.
- Obtain reconstruction, selection and trigger efficiency in LHCb Run I.
  - Extract expected signal yield.
  - Estimate background level.
- Study trigger improvements for Run II and upgrade data-taking.
  - Extract expected signal yields.
- Asses observation feasibility.

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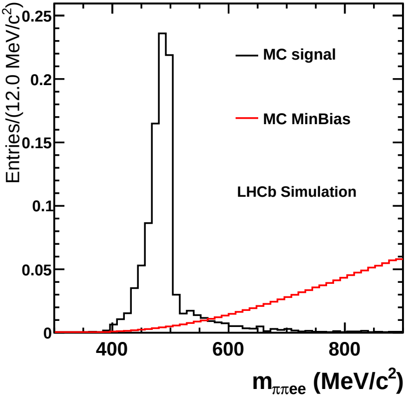
- Evaluated matching reconstructed particles to MC ones.

$$\epsilon_{reco}^{sig} = (0.134 \pm 0.002)\ \%$$



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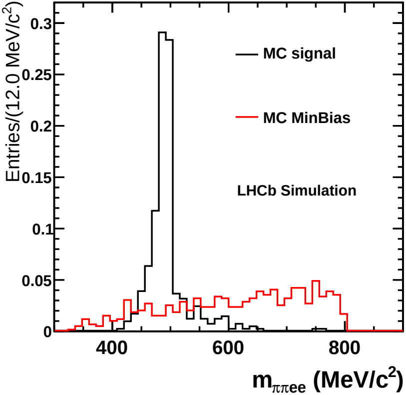
- Offline selection based on linear cuts (details in slide 21):
  - Loose p_T but tight flight distance requirements.

$$\epsilon^{sig}_{sel} = (10.1 \pm 0.5)\ \%$$



$K^0_S \to \pi^+\pi^-e^+e^-$ trigger

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- No dedicated selection in Run I.
  - Scan all available physics selections [LHCb-PUB-2014-046].
- One MC signal candidate selected:

$$\epsilon_{trig}^{sig} = (0.24^{+0.56}_{-0.20})\ \%$$

- No MC background candidates pass the same trigger requirement:

$$\epsilon_{trig}^{bkg} < 0.51\ \%$$

at 90 % CL.

Expected yields in Run I

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- Define signal region: $450 < M < 520$ MeV
- Expected signal yield per fb^{-1} of Run I data:

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

$$N_{exp}^{sig} = 120^{+280}_{-100}$$

- Expected background yield per fb^{-1} of Run I data:

$$N_{exp}^{bkg} = \sigma_{tot} \cdot \epsilon^{bkg}$$

$$N_{exp}^{bkg} < 6.1 \times 10^5 \text{ at } 90\ \%\ \text{CL.}$$

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- Apply same selection & trigger to 2012 data (2 fb^{-1} at 8 TeV):

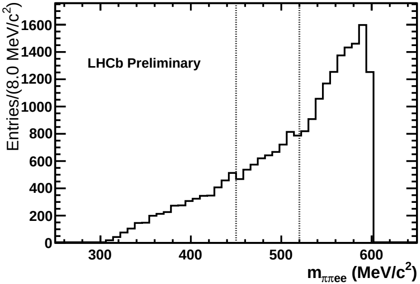

Figure: $\pi^+\pi^-e^+e^-$ invariant mass distribution for reconstructed and selected 2012 data candidates.

$$N_{obs}^{bkg} \sim 6 \times 10^3$$

- Observed background compatible with limit obtained from MC.

Expected yields in Run II and beyond

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- New dedicated HLT2 selection included for 2016 data-taking:
  - Based on linear cuts following the offline selection.
  - Inclusive selection for K^0_S decays with e^+e^- in the final state.
  - Efficiency estimated on 2012 MC (no 2016 MC available yet):

$$\epsilon^{sig}_{trig} = (0.24^{+0.56}_{-0.20})\ \%$$

  - Other differences in Run II neglected:
    - Increase in K^0_S cross-section: much smaller than linear.
    - More K^0_S decaying outside VeLo: small effect.
    - Possible reconstruction and selection improvements.
  - Signal yield per fb^{-1} in Run II with these assumptions:

$$N^{sig}_{exp} = 120^{+280}_{-100}$$

Expected yields in Run II and beyond

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- New dedicated HLT2 selection included for 2016 data-taking:
  - Run I trigger selection exploited a complementary approach.
  - Could also benefit from dedicated HLT1 selection.
    $\rightarrow$ Room for improvement!

- Trigger fully based on software after the LHCb upgrade ($\sim$2021).
  - See Miguel Ramos talk for details.
  - A 100 % trigger efficiency can be achieved.
  - Expected signal yield per fb^{-1} during the upgrade:

$$N_{exp}^{sig} = (5.0 \pm 0.3) \times 10^4$$

Observation feasibility with Run I data

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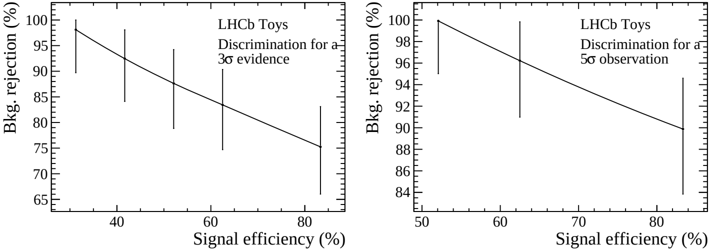
- Estimate feasibility of an evidence or observation from pseudoexperiments.
- Signal efficiency vs background rejection curves to achieve 3 and 5σ significance.



- Well within the usual discrimination of MVA selections.

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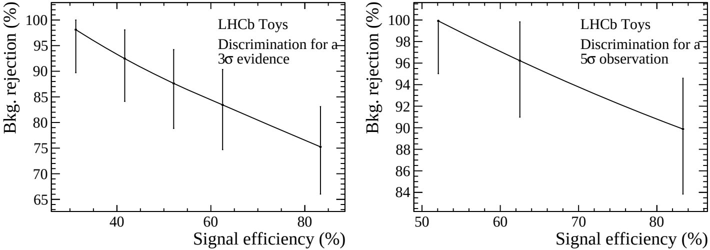

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An evidence or observation is feasible with the LHCb Run I dataset!

Summary & Conclusions

- LHCb has proved to be competitive in the search for strage decays.

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LHCb-PUB-2016-016

- Feasibility study of observing $K_S^0 \to \pi^+\pi^-e^+e^-$ at LHCb:
  - Expected signal and observed background yield obtained for Run I.
  - Dedicated trigger selection included for 2016 data-taking.
    - Still room for improvement in the trigger.
  - Large signal yield expected in the upgrade phase.
  - Pseudoexperiments to asses the observation feasibility with Run I data.

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- Feasibility study of observing $K^0_S \to \pi^+\pi^-e^+e^-$ at LHCb:
  - Expected signal and observed background yield obtained for Run I.
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    - ★ Still room for improvement in the trigger.
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  - Pseudoexperiments to asses the observation feasibility with Run I data.

An evidence or observation is feasible with the LHCb Run I dataset

- Observation of $K^0_S \to \pi^+\pi^-e^+e^-$ would allow to:
  - Test the SM predictions for $K^0_S \to \ell^+\ell^-\ell^+\ell^-$.
  - Search for light dark matter states decaying to e^+e^-.

THANK YOU

BACK-UP

LHCb Trigger: TIS and TOS

Different trigger categories:

- TOS (Trigger On Signal): the event is selected because the signal triggers it.
- TIS (Trigger Independent of Signal): the event is selected because some other particles in the event (not the signal ones) trigger it.

Offline selection

Selection	Units	
track $\chi^2/ndof$		< 3
track ghost probability		< 0.5
track IP χ^2		> 16
e $\mathrm{DLL}_{\mathrm{e}\pi}$		> -4
e p_{T}	MeV/c	> 100
π $\mathrm{DLL}_{\mathrm{K}\pi}$		< 5
π p_{T}	MeV/c	> 250
$\mathrm{e}^+\mathrm{e}^-$ DOCA	mm	> 10
$\mathrm{e}^+\mathrm{e}^-$ invariant mass	MeV/c^2	> 250
$\mathrm{e}^+\mathrm{e}^-$ p_{T}	MeV/c	> 250
$\pi^+\pi^-\mathrm{e}^+\mathrm{e}^-$ max DOCA	mm	< 1.0
$\pi^+\pi^-\mathrm{e}^+\mathrm{e}^-$ invariant mass	MeV/c^2	< 800
K^0_S IP	mm	< 1
K^0_S τ	ns	> 0.08953

Trigger efficiencies

Trigger Selection	$K^0_S \to \pi^+\pi^-e^+e^-$ MC Efficiency (%)	MinBias MC Efficiency (%)
L0 & Hlt1 & Hlt2		
TIS TIS TIS	< 0.73	$0.85^{+0.38}_{-0.38}$
TIS TIS TOS	< 0.73	$0.51^{+0.49}_{-0.28}$
TOS TOS TOS	$0.24^{+0.56}_{-0.20}$	< 0.51

Other efficiencies

- Offline selection efficiency on Minimum Bias MC:

$$\epsilon_{sel}^{bkg} = (2.95 \pm 0.12) \times 10^{-5}$$

- Signal region cut efficiency on $K_S^0 \to \pi^+\pi^-e^+e^-$ MC:

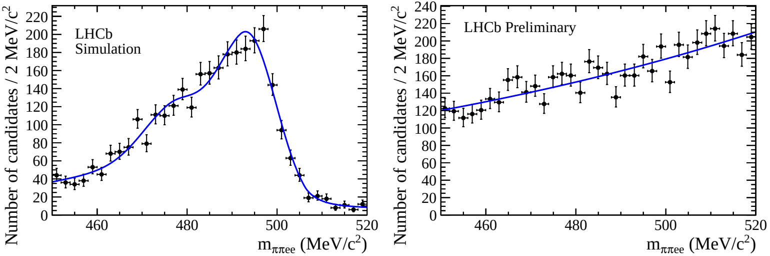
$$\epsilon_{M}^{sig} = (76.9 \pm 1.8)\%$$

- Signal region cut efficiency on Minimum Bias MC:

$$\epsilon_{M}^{bkg} = (4.33 \pm 0.02)\%$$

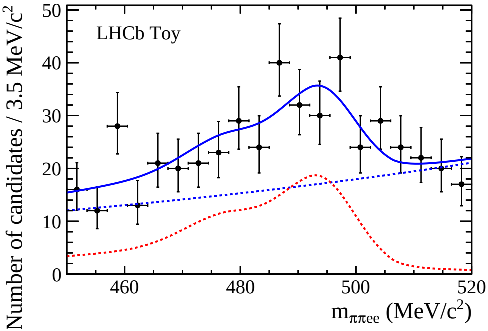
Pseudoexperiments in detail

- Fit signal MC and data to extract signal and background PDFs.



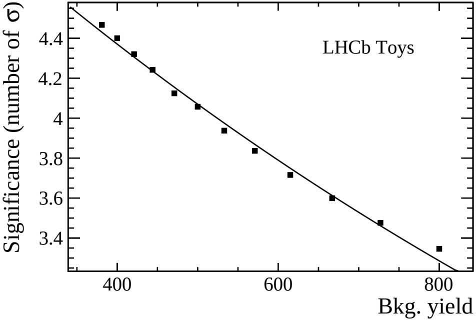
Pseudoexperiments in detail

- Build list of signal and background yields. For each pair:
  - Generate 10k toys: distributions floated according to errors obtained in previous step.
  - Fit generated distribution w/ and w/o signal components $\rightarrow$ obtain significance.



Pseudoexperiments in detail

- Fit significance vs background yield curves for each signal yield with an exponential.



- Obtain background yield at 3 and 5σ from fitted curve.

Pseudoexperiments in detail

- Build signal efficiency vs background rejection curves at 3 and 5σ.
  - Efficiency (rejection) wrt expected signal (observed background) yield in signal region.