A strange program for the LHC

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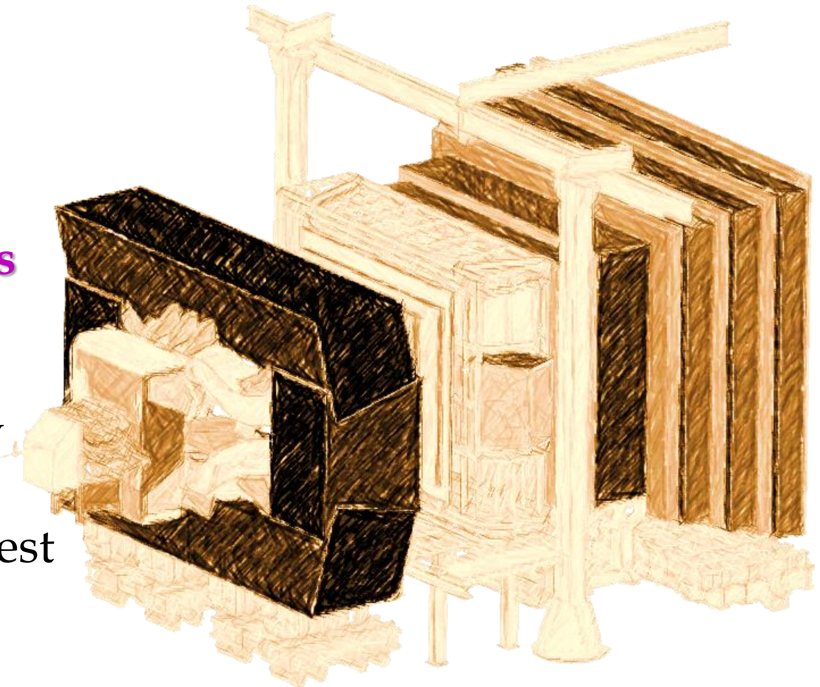
GAIN
(on behalf of the LHCb Collaboration)

Introduction

- LHCb experiment at LHC
  - Designed mostly for **b** and **c** decays
    → low trigger efficiency otherwise
  - But there is also an ~infinite **strangeness** production at LHC (kaon xs ~ 1.2 **barn**)
  - Infinite production times zero efficiency requires L'Hopital
    - In 2011 we managed to get world best result in $K_S \to \mu\mu$
  - Major improvements in the trigger for **s** decays done for Run-II (2016-2018), and ongoing for Upgrade (>=2021)

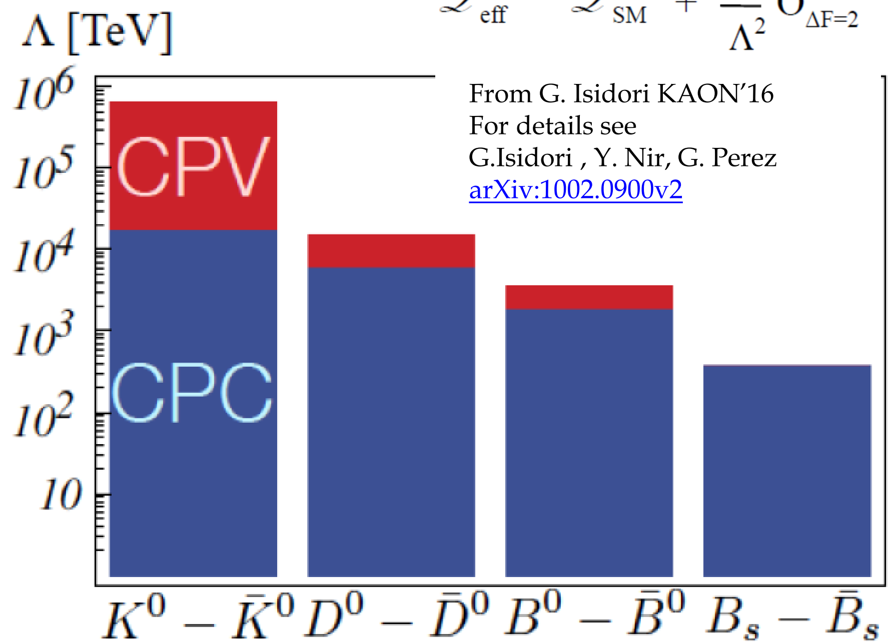


Strangeness decays

- So far a kaons provided showed great success on indirect searches: *c*, *b*, *t* , CKM …

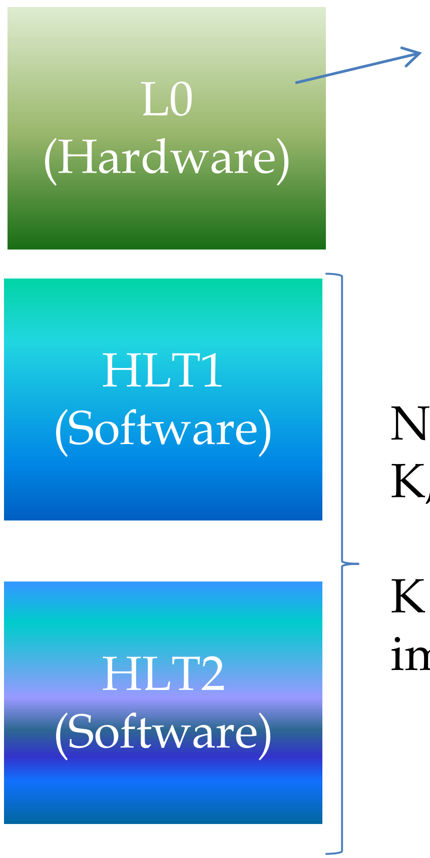
- High theoretical interest, most notably to test departures from MFV paradigm (eg, flavor generic)

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda^2} O_{\Delta F=2}$$



- Useful to understand "Hints" for BSM in b sector
  - Eg: deviations in b→sμμ: are they replicated in s → dμμ?
    - Y ➔ interesting
    - N ➔ interesting
- Potentially immense samples : high(est) ultimate experimental precision

Trigger system: status and prospects



Main bottleneck for K. Can't be changed

Not designed for K, but flexible.

K triggers being implemented

Trigger system: status and prospects

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ε(2011-2012) ~ 1-2%
ε(Run-II) improved HLT1,2 ~ 18%
Maximum possible ~30% (L0 won’t allow more)

Trigger system: status and prospects

L0
(Hardware)

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HLT1
(Software)

HLT2
(Software)

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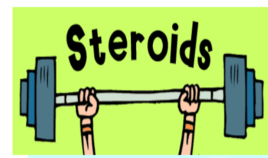
LHCb Upgrade



(Note: This logo may not be official)

HLT
(Software)

Trigger system: status and prospects

L0 (Hardware)

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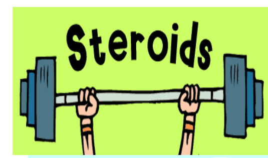
LHCb Upgrade



(Note: This logo may not be official)

HLT (Software)

ε(Upgrade) ~ 80-100%?
Simulation studies show that rate would be under control

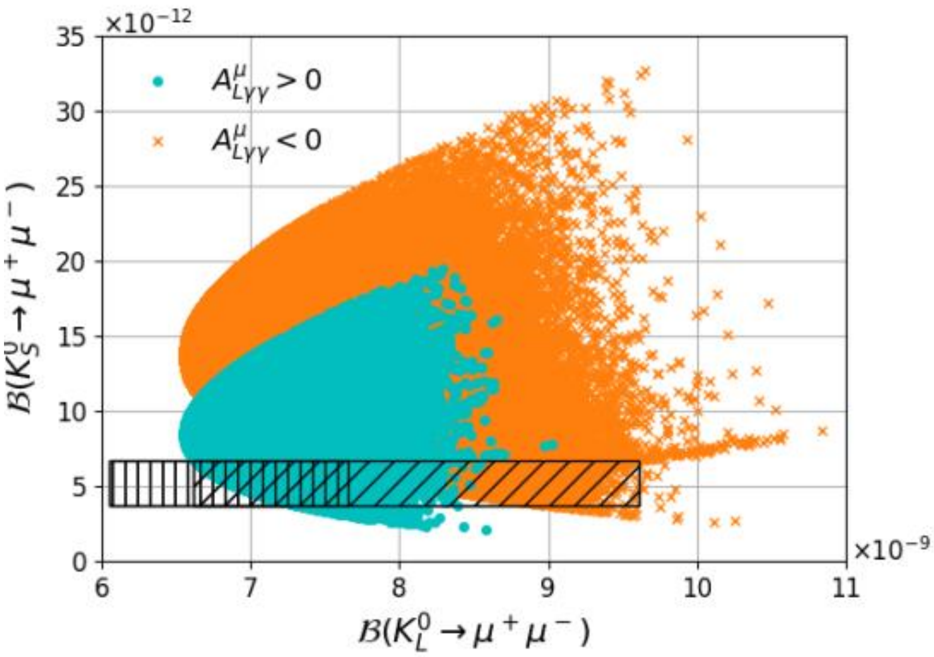
V. Chobanova et al, CERN-LHCb-PUB-2016-017

$K_S \rightarrow \mu\mu$ full Run-I analysis

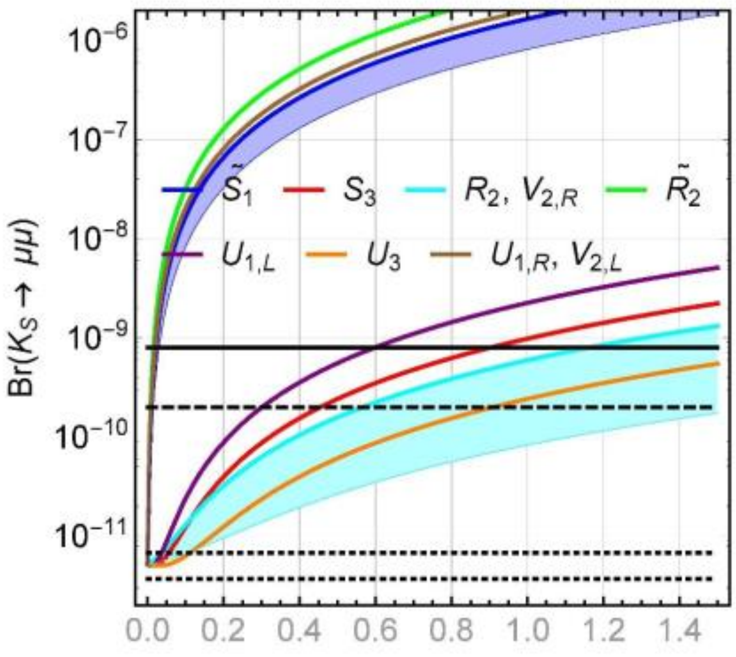
EPJC, 77 10 (2017) 678

$K_S \to \mu\mu$: motivation

- SM prediction: $BR(K_S \to \mu\mu) = (5.18 \pm 1.50_{LD} \pm 0.02_{SD})\times 10^{-12}$
  JHEP05(2018) 024 , JHEP 0401 (2004) 009, NPB 366 (1991) 189
- $K_S \to \mu\mu$ sensitive to different physics than $K_L \to \mu\mu$, NP can be bigger than SM by ~1 order of magnitude or even more



Example of a SUSY scenario from V.Chobanova et al., JHEP05(2018) 024

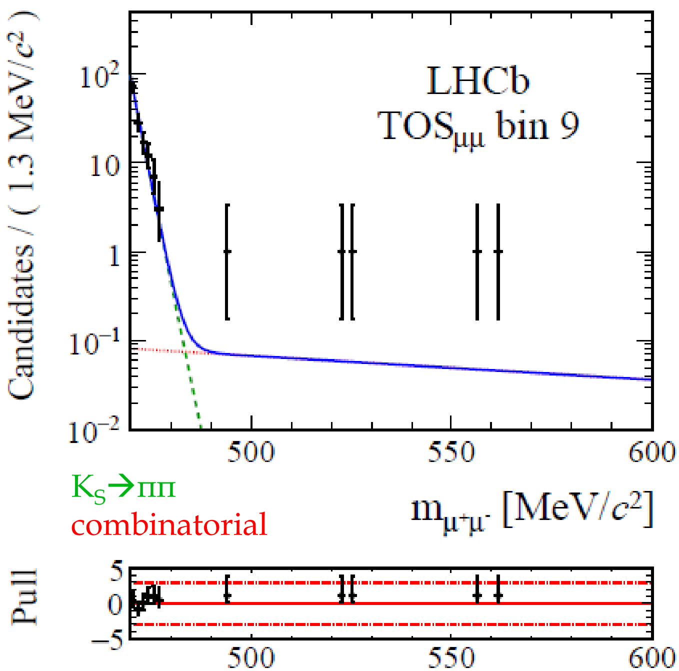


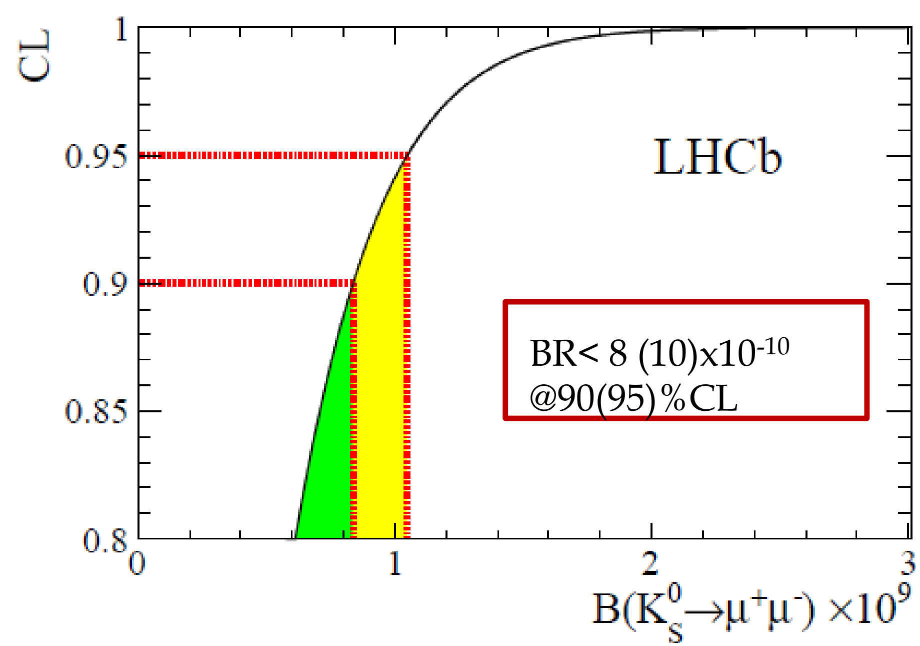
Leptoquark scenarios from Bobeth & Buras, JHEP02(2018)101

$K_S \to \mu\mu$ full Run-I analysis

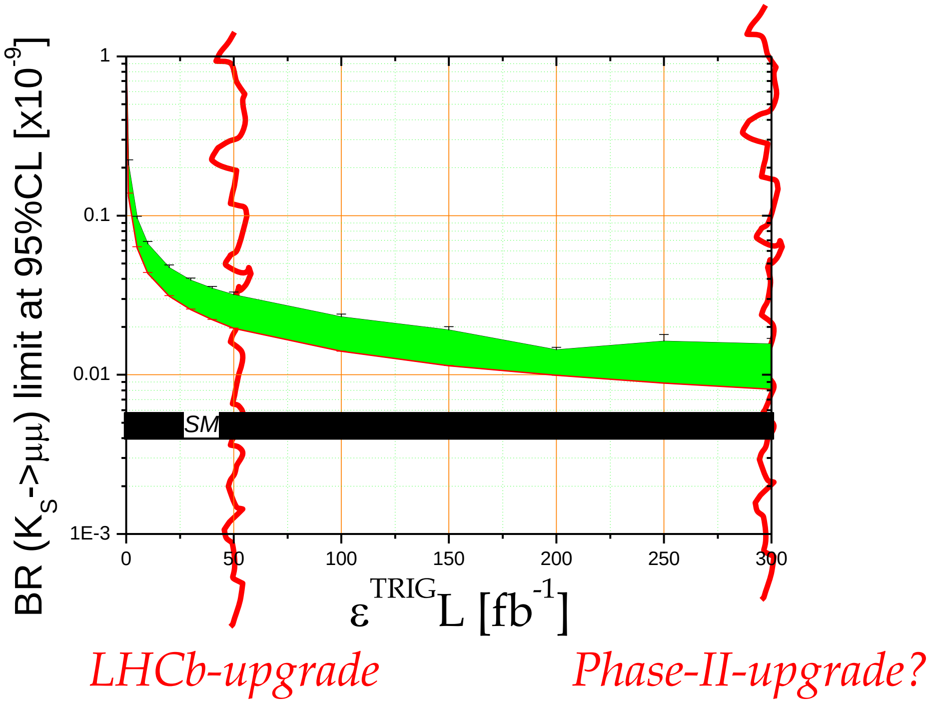
EPJC, 77 10 (2017) 678

- Event yield extracted from a maximum likelihood fit in BDT categories
- Yield translated to BR via normalization to $K_S \to \pi\pi$ decays
- $K_S \to \pi\pi$ is also the main background: muon identification BDT trained against it
- Upper limit obtained integrating the posterior probability, combined 2011+2012





$K_S \rightarrow \mu\mu$ prospects



- Extrapolating from Run-I result
- Full Run-II analysis ongoing: expected to improve by a **factor 3 to 10** Run-I's sensitivity
- Future: start to investigate tagged decays, which would allow to access NP in the K_S-K_L interference
  [D'Ambrosio&Kitahara PRL 119, 201802 (2017)]

Very high ultimate precision: could well become the strongest limit on a BR by an LHC experiment

$\Sigma \to p\mu\mu$ full Run-I analysis

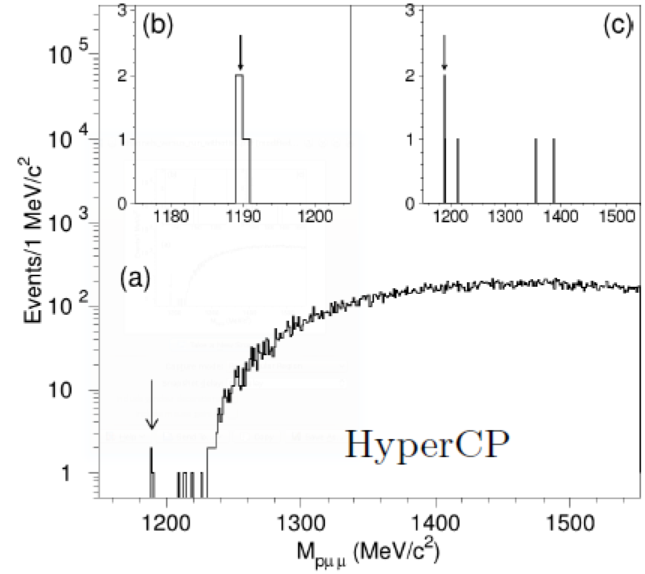
LHCb-PAPER-2017-049
Phys. Rev. Lett. 120,
221803 (2018)

The HyperCP evidence

- The HyperCP collaboration found evidence for $\Sigma \to p\mu\mu$ decays, and provided a BR:

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$$

[Phys.Rev.Lett. 94 (2005) 021801]

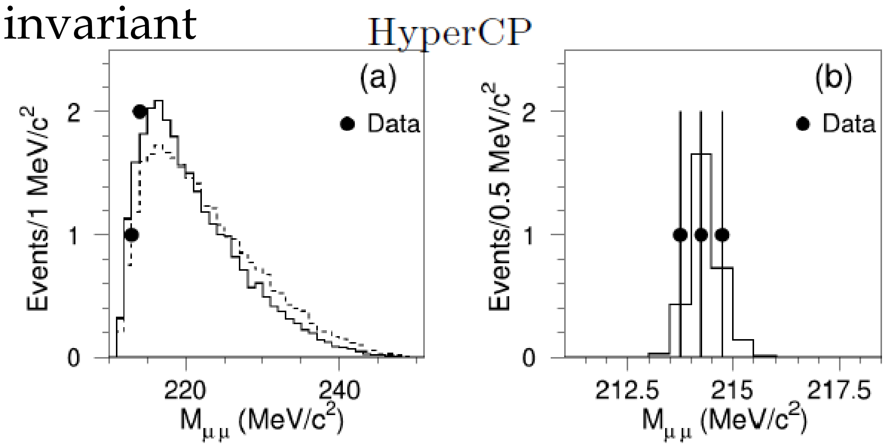


- Consistent w/ SM: $1.6 < \mathrm{BR}[\mathrm{x}10^{-8}] < 9$

X G He et al, PRD 72 (2005) 074003

- This evidence had wide relevance since all 3 observed events had the same dimuon invariant mass (214 MeV)

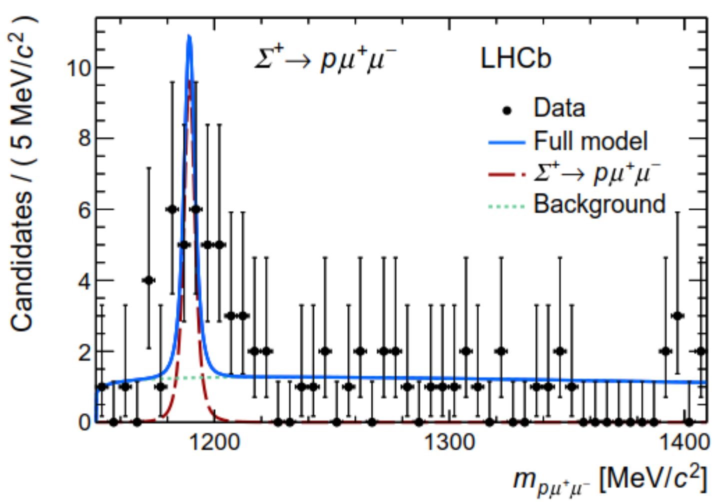
- Suggested the existence of a new neutral particle at that mass

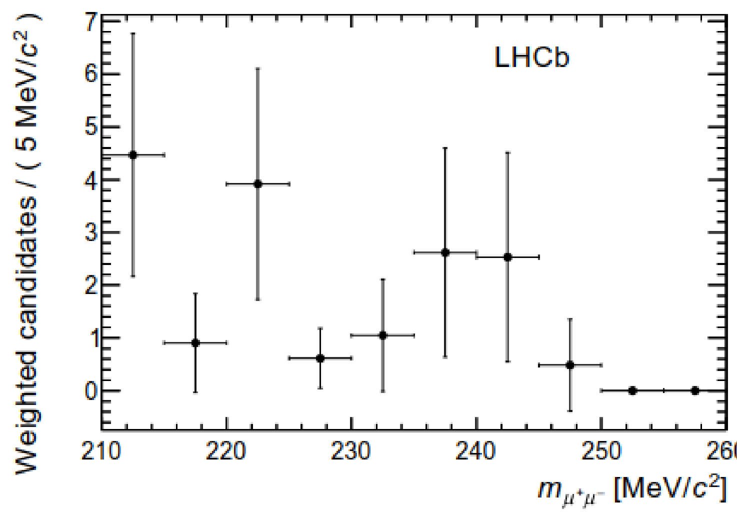


$\Sigma \to p\mu\mu$ full Run-I analysis

LHCb-PAPER-2017-049
arXiv:1712.08606

- $\Sigma \to p\mu\mu$: Found 4σ evidence
- BR($\Sigma \to p\mu\mu$) : $2.1^{+1.6}_{-1.2} \times 10^{-8}$
- $X \to \mu\mu$: Found no evidence for the 214 MeV particle. Upper limit for the resonant channel: 1.2×10^{-8} @95% CL





10y ago we thought this channel was ~impossible and instead now we are even thinking on an amplitude analysis….

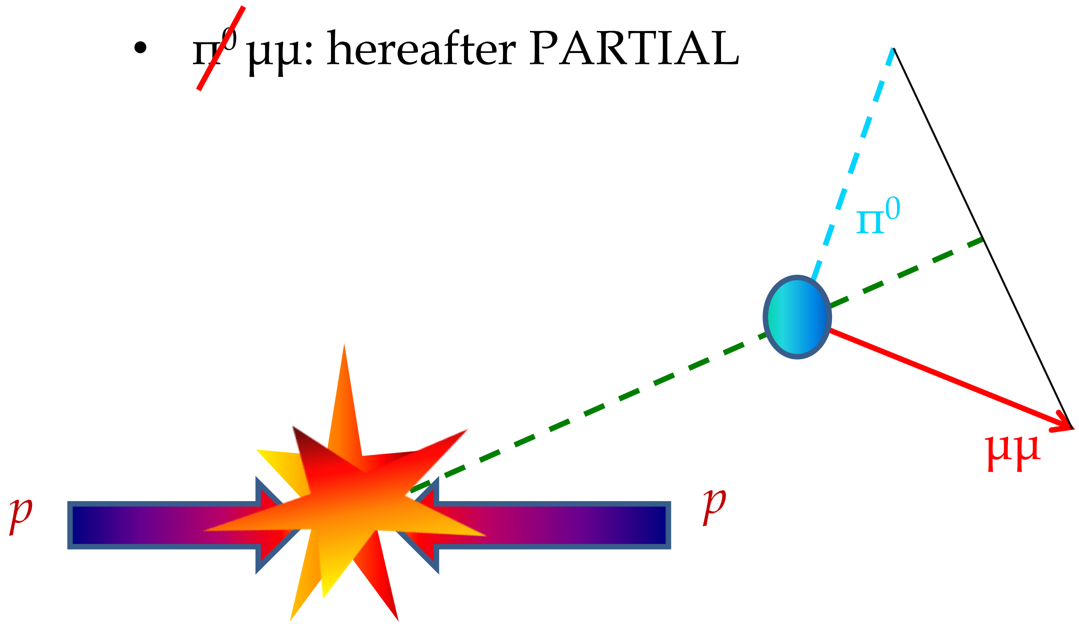
$K_S \to \pi^0 \mu\mu$ sensitivity study

CERN-LHCb-PUB-2016-017

$K_S \to \pi^0\mu\mu$ sensitivity study

V. Chobanova et al, LHCb-PUB-2016-017

- $K_S \to \pi^0\mu\mu$ is searched for in two channels:
  - π^0 ($\to \gamma\gamma$) $\mu\mu$: hereafter FULL (low eff.)
  - ~~π^0~~ $\mu\mu$: hereafter PARTIAL

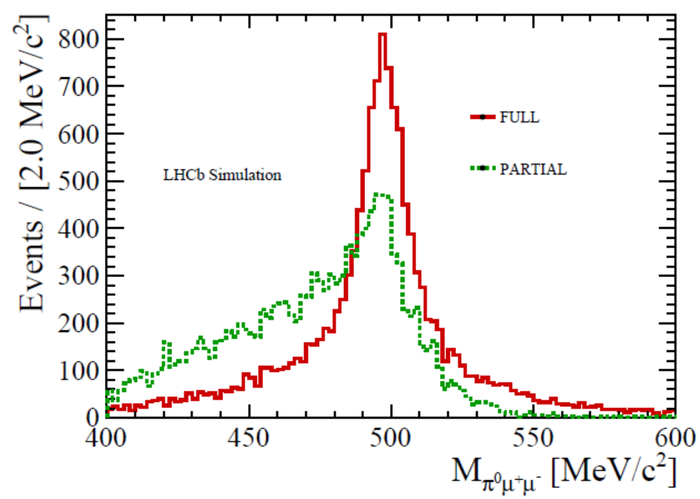


Much more bkg than Ks→μμ, but also 1000x more signal

In order to reconstruct the kaon mass for PARTIAL:

- π^0 mass → PDG
- $p_T^{\pi} = -p_T^{\mu\mu}$

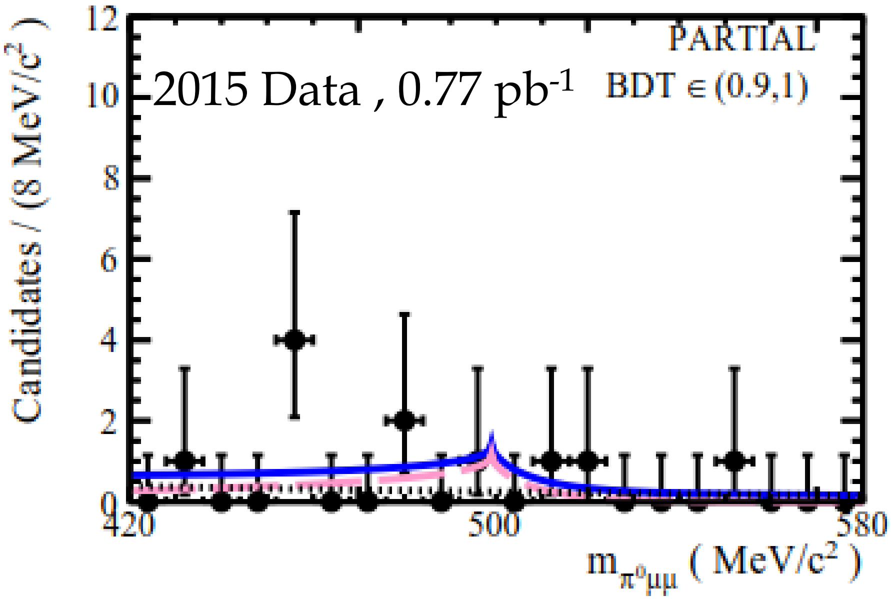
The only unknown is p_L^{π}.
But statistically is ≈10GeV

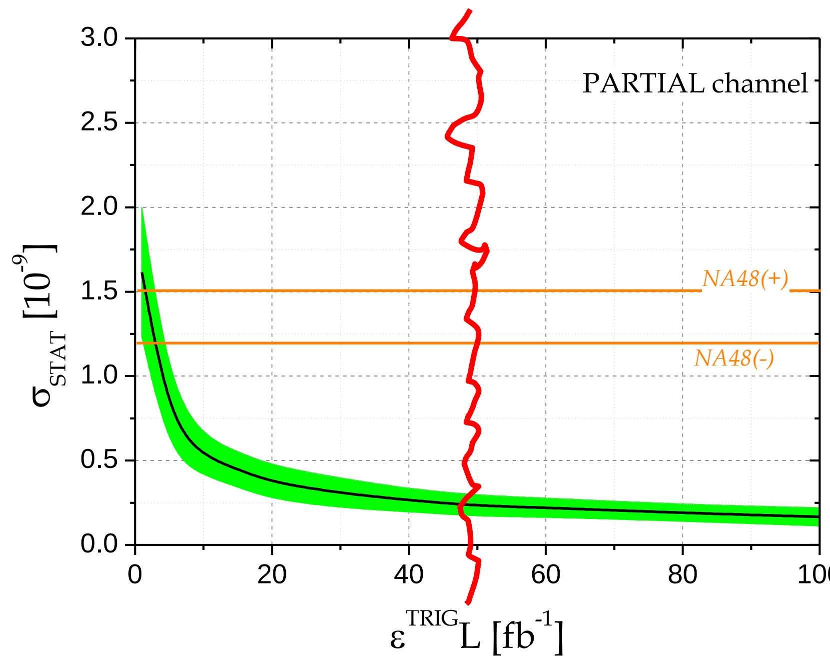


$K_S \to \pi^0\mu\mu$ sensitivity study

V. Chobanova et al,
LHCb-PUB-2016-017

Normalize yields to $K_S \to \pi\pi$ → sensitivity to BR





LHCb-upgrade

Phase-II-upgrade? →

Much more bkg than $K_S \to \mu\mu$,
but also 1000x more signal

Ongoing/future studies

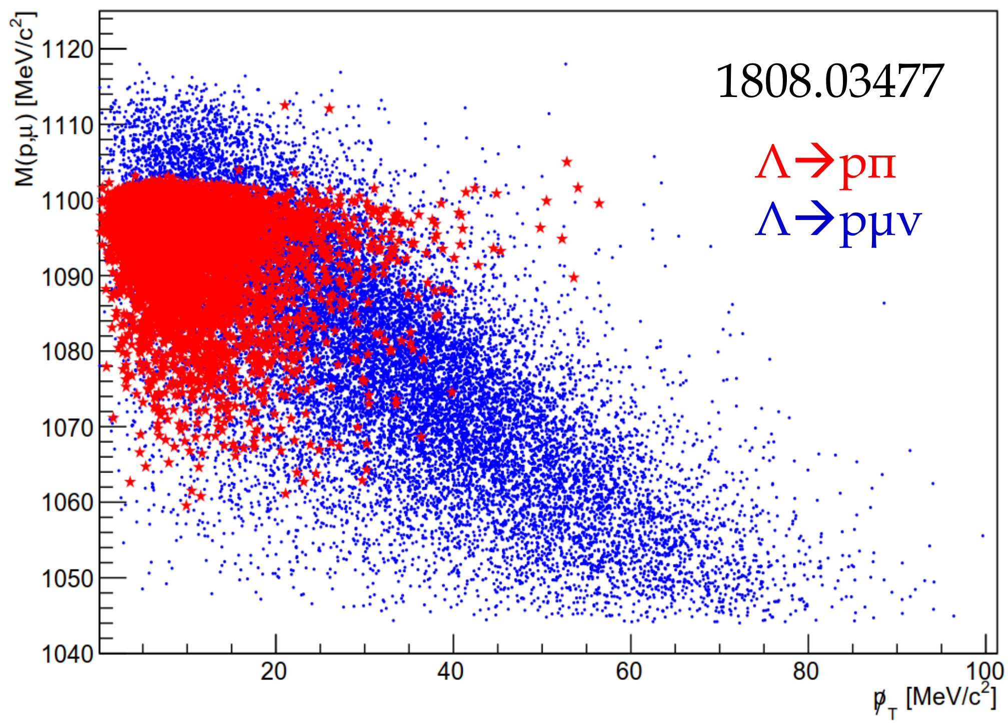
arXiv:1808.03477 [hep-ex]

- Semileptonic Hyperon Decays (SHD)

Very interesting in view of LUV hints in semileptonic B decays

Many muonic modes have still very poor precision (20%, 100%)

- ☺ High BR (10^{-4}): Massive yields in LHCb acceptance
- ☹ Challenging peaking backgrounds:



For each
B1 → B2 μν there is always a
B1 → B2π (inc. →B2μν)

☺ Can be separated in search planes

Ongoing/future studies

arXiv:1808.02006 [hep-ex]

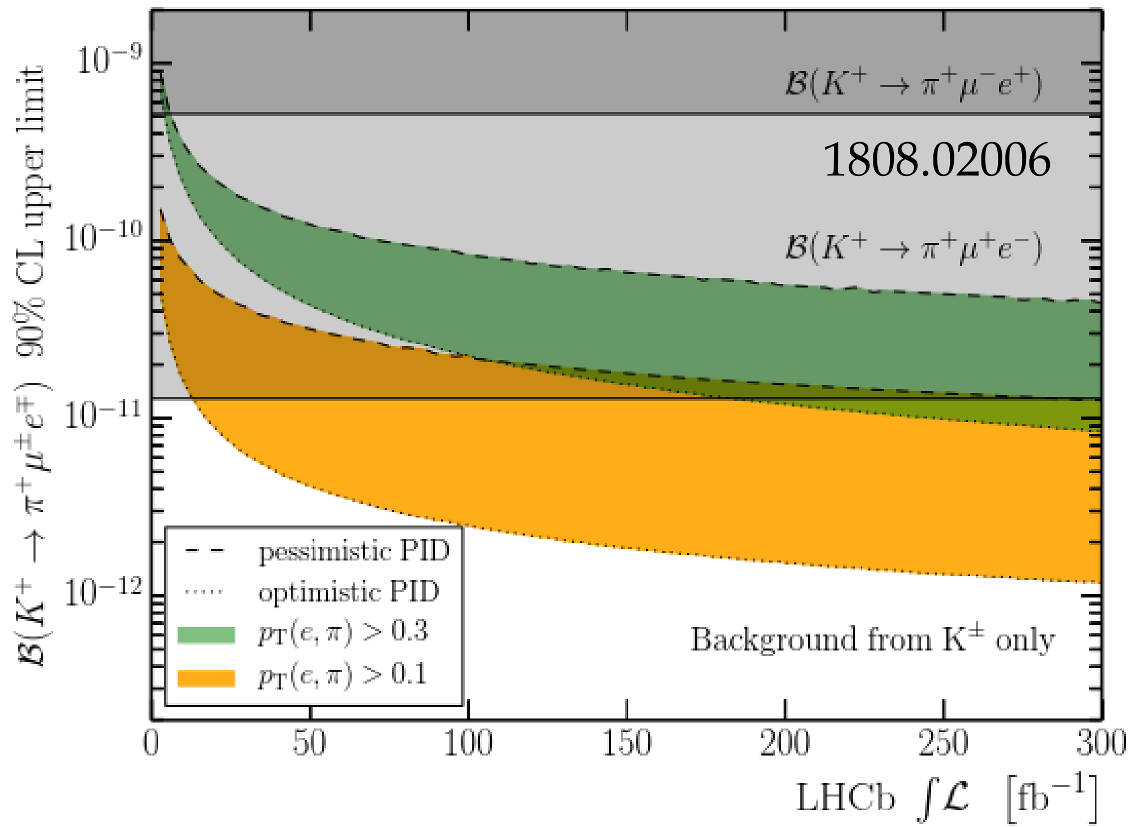
- Semileptonic Hyperon Decays (SHD)

- LFV

LHCb can do:

$K_S \to e\mu$
$K^+ \to \pi^+\mu^-e^+$
Maybe $K^+ \to \pi^+\mu^+e^-$

Competition w/ NA62 to be clarified



Ongoing/future studies

- Semileptonic Hyperon Decays (SHD)
- LFV
- Tagged kaons
- K^+ mass in $K \rightarrow 3\pi$ (ongoing) *(Also under study sensit. $K^+ \rightarrow \pi^+\mu\mu$ vs NA62)*
- $K_S \rightarrow X^0\mu\mu$, (X whatever neutral system: eg γ) (ongoing)

Ongoing/future studies

- Semileptonic Hyperon Decays (SHD)
- LFV
- Tagged kaons
- K^+ mass in $K \to 3\pi$
- $K_S \to X^0\mu\mu$, (X whatever neutral system: eg γ)
- $K_S \to X^0\pi\mu$ (X whatever neutral system: eg sterile neutrino)
- $\Delta S = 2$
- Workshop in 2013 and 2017 to discuss with TH community
  https://indico.cern.ch/event/280883/overview
  https://indico.cern.ch/event/590880/timetable/#20170426

Ongoing/future studies

* More details in: arXiv:1808.03477 [hep-ex]

Channel	$Xs/Xs(K_S)$	$eff/eff(K_S)$	$eff/eff(K_S)$ w/ Downstream tracks	Mass resolution $\sigma_L(\mathrm{MeV}/c^2)$	$\sigma_D(\mathrm{MeV}/c^2)$
$K^0_S \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~ 3.0	~ 8.0
$K^0_S \to \pi^+\pi^-$	1	1.1 (0.30)	1.9 (0.91)	~ 2.5	~ 7.0
$K^0_S \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~ 35	~ 45
$K^0_S \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~ 60	~ 60
$K^0_S \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~ 1.0	~ 6.0
$K^0_L \to \mu^+\mu^-$	~ 1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~ 3.0	~ 7.0
$K^+ \to \pi^+\pi^+\pi^-$	~ 2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~ 1.0	~ 4.0
$K^+ \to \pi^+\mu^+\mu^-$	~ 2	6.3 (2.3) $\times 10^{-3}$	0.030 (0.014)	~ 1.5	~ 4.5
$\Sigma^+ \to p\mu^+\mu^-$	~ 0.13	0.28 (0.28)	0.64 (0.64)	~ 1.0	~ 3.0
$\Lambda \to p\pi^-$	~ 0.45	0.41 (0.075)	1.3 (0.39)	~ 1.5	~ 5.0
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~ 0.45	0.32 (0.31)	0.88 (0.86)	–	–
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~ 0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	–	–
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~ 0.03	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	–	–
$\Xi^- \to p\pi^-\pi^-$	~ 0.03	0.41(0.05)	0.94 (0.20)	~ 3.0	~ 9.0
$\Xi^0 \to p\pi^-$	~ 0.03	1.0 (0.48)	2.0 (1.3)	~ 5.0	~ 10
$\Omega^- \to \Lambda\pi^-$	~ 0.001	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~ 7.0	~ 20

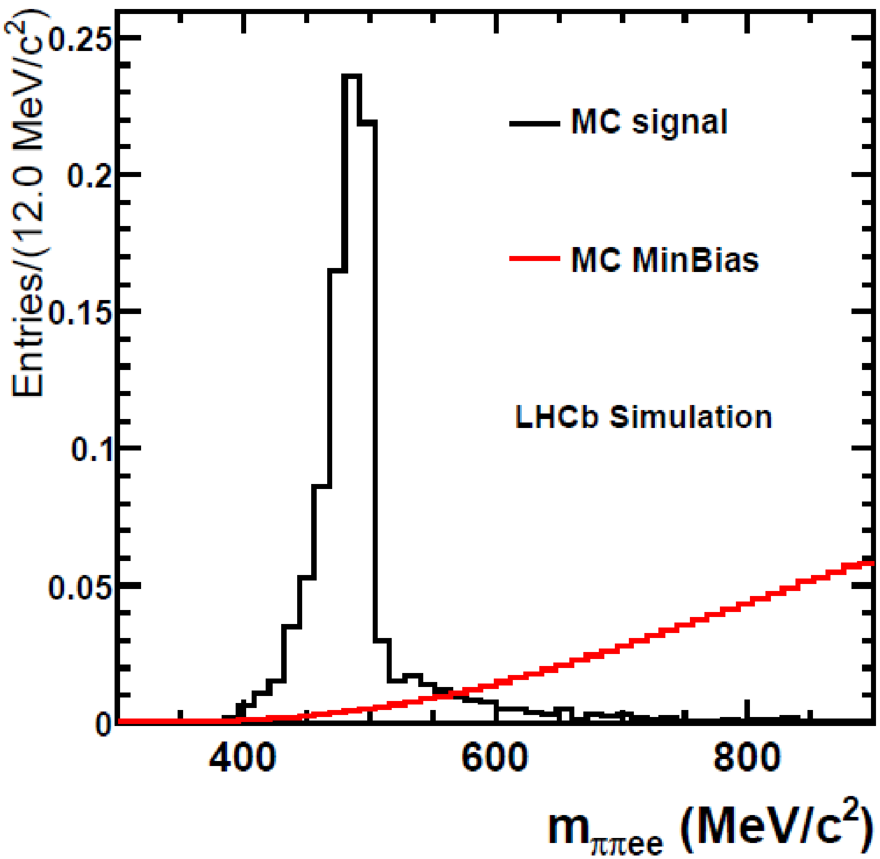
Conclusions

- s decays are awesome
  - High interest for BSM
  - Ultimate experimental precision ~ 10^{-11} - 10^{-12}
- There is an LHCs community in the LHCb village
  - Trigger is constantly improving
  - We aim for LHCb upgrade to reach efficiencies s as high as for b's
- Available measurements for: $\Sigma \to p\mu\mu$, BR($K_S \to \mu\mu$)
- Published prospects for $K_S \to \pi^0\mu\mu$, $K_S \to \pi^+\pi^- ee$
- Run-II (2016-2018) data analysis ongoing $\Sigma \to p\mu\mu$, $K_S \to \mu\mu$, $K_S \to (\gamma/\pi^0)\mu\mu$...
- Some more channels in our TODO list
- Workshops to discuss with the TH community

Backup

$K_S \rightarrow \pi^+\pi^- ee$ sensitivity study

C.Marin et al,
LHCb-PUB-2016-016



Based on simulation:

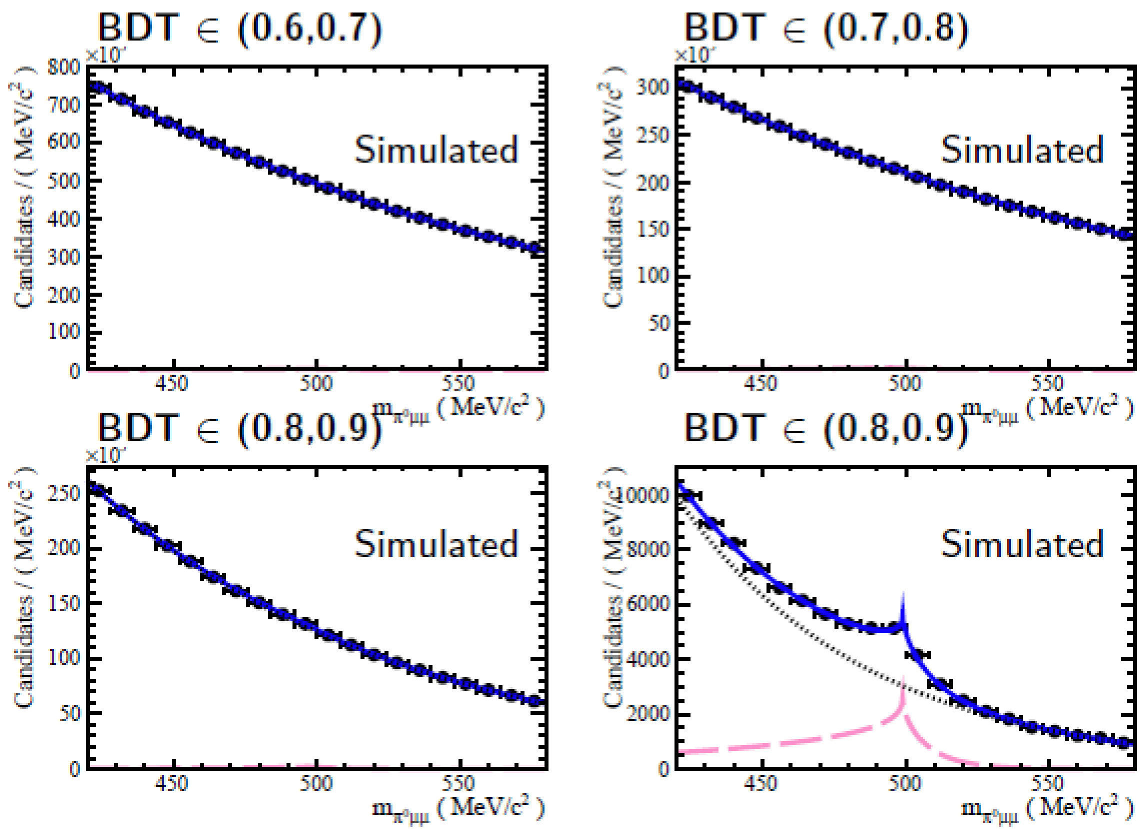
Expected a signal yield of

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

For the full Run-I dataset

Expected background yield is not well known yet

Toy MC for 50fb^{-1}



Lifetime acceptance and $K_L \to \mu\mu$ background

K_L and K_S are distinguishable only by the decaytime…
… and that is in theory. In practice, LHCb decaytime acceptance is not great for kaons

$\epsilon(t) \sim e^{-\beta t}$ With $\beta \gtrsim 5 \text{x} \Gamma_s$ ($>> \Gamma_L$).

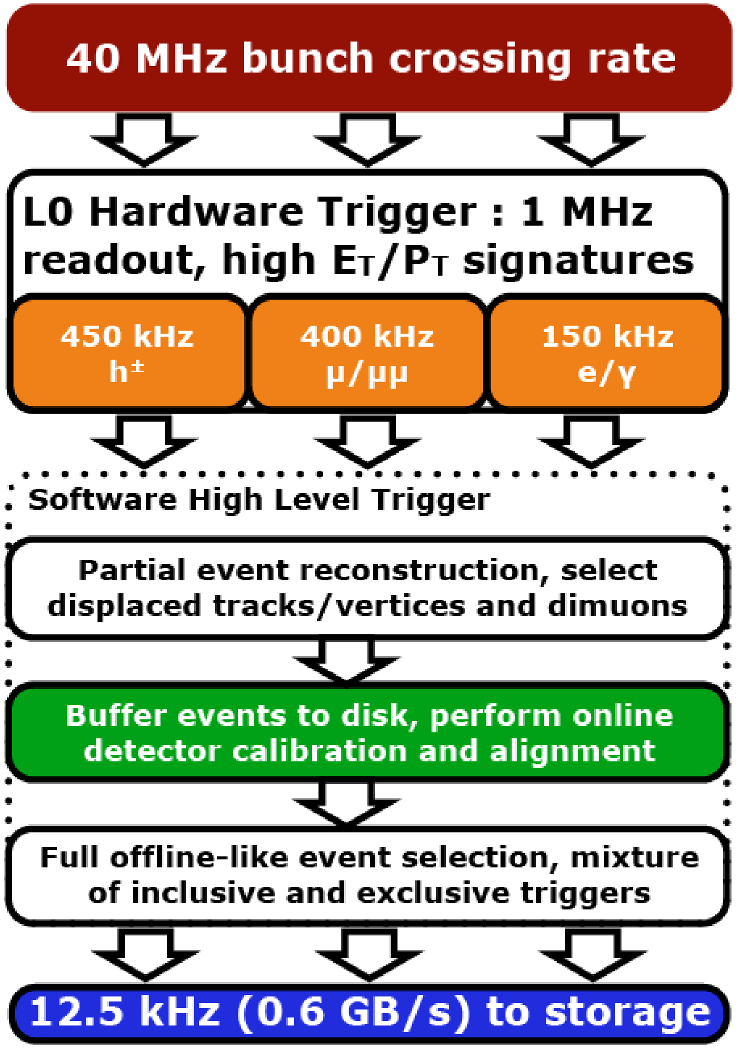
This makes the two lifetime distributions to look similar

But the overall efficiency ratio is of course different

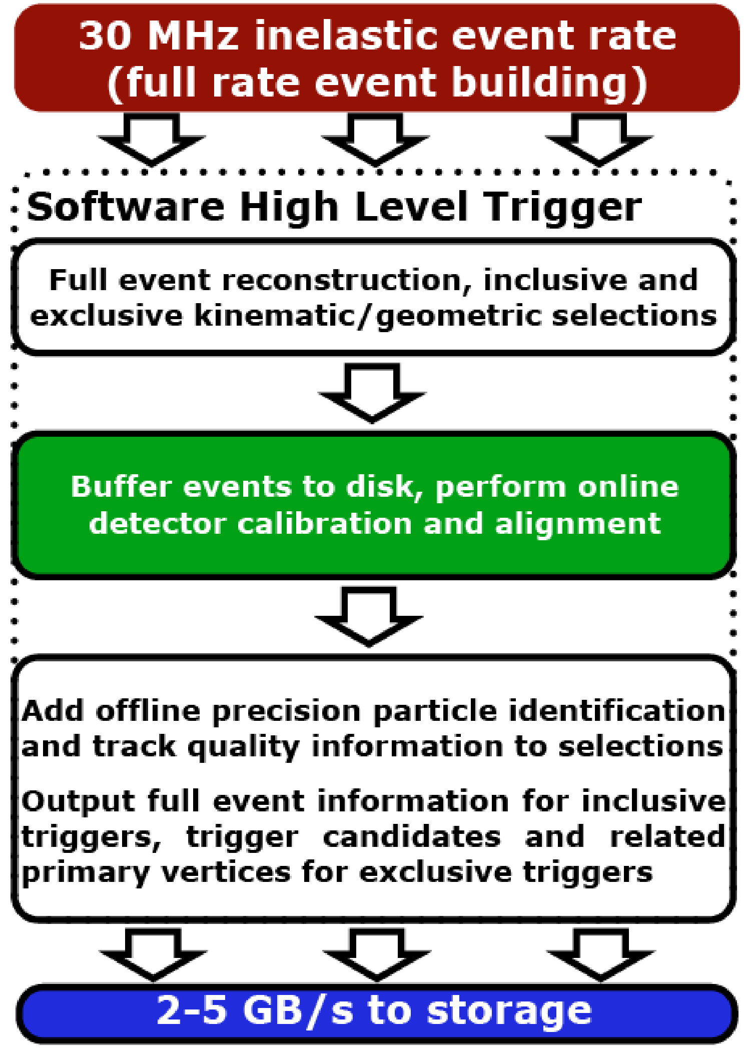
$$\frac{\epsilon_{K^0_L \to \mu^+\mu^-}}{\epsilon_{K^0_S \to \mu^+\mu^-}} = \frac{\dfrac{\int_0^\infty Acc(t) e^{-\Gamma_L t} dt}{\int_0^\infty e^{-\Gamma_L t} dt}}{\dfrac{\int_0^\infty Acc(t) e^{-\Gamma_S t} dt}{\int_0^\infty e^{-\Gamma_S t} dt}} = O(10^{-3})$$

And makes $K_L \to \mu\mu$ to become a negligible background for the current level of precision
But can be relevant when we approach the 10^{-11} level

LHCb 2015 Trigger Diagram



LHCb Upgrade Trigger Diagram



Normalization of event yield

Converting a signal yield into a branching ratio

K_s^0 production crossection

Absolute efficiency

$$\mathrm{N}(K_s^0 \to \pi\mu\mu) = \sigma(K_s^0)\mathrm{B}R(K_s^0 \to \pi\mu\mu)\boldsymbol{\varepsilon}L$$

Integrated luminosity

How? (normalization of event yield)

European Research Council

Converting a signal yield into a branching ratio

K_s^0 production crossection

Absolute efficiency

$$\mathrm{N}(K_s^0 \to \pi\mu\mu) = \sigma(K_s^0)\mathrm{B}R(K_s^0 \to \pi\mu\mu)\boldsymbol{\varepsilon}L$$

Integrated luminosity

$$\frac{\mathrm{N}(K_s^0 \to \pi\mu\mu)}{\mathrm{N}(K_s^0 \to \pi\pi)} = \frac{\sigma(K_s^0)\mathrm{B}R(K_s^0 \to \pi\mu\mu)\boldsymbol{\varepsilon}L}{\sigma(K_s^0)\mathrm{B}R(K_s^0 \to \pi\pi)\boldsymbol{\varepsilon}'L}$$

Introduce in the ntuples a $K_s^0 \to \pi\pi$ decays counter

Very well known (69.20±0.05)%

Dilepton mass distribution

Take formulae from hep-ph/9808289

$$\frac{d\Gamma}{dz} = \frac{\alpha^2 M_K}{12\pi(4\pi)^4}\,\lambda^{3/2}(1,z,r_\pi^2)\sqrt{1-4\frac{r_\ell^2}{z}}\left(1+2\frac{r_\ell^2}{z}\right)|W(z)|^2\,, \qquad (3)$$

z= m^2 ➔ dΓ/dm = 2m dΓ/dz

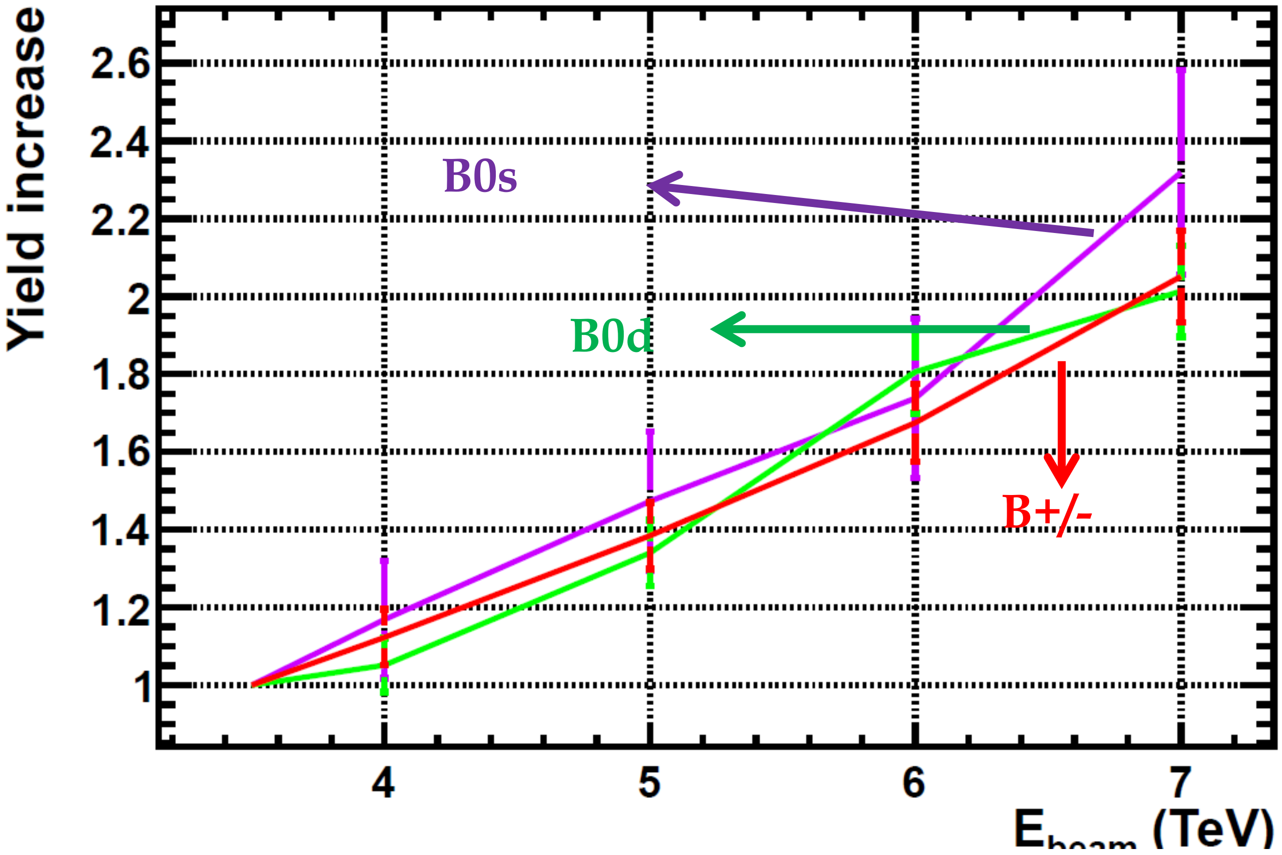
$$W_i(z) = G_F M_K^2(a_i + b_i z) + W_i^{\pi\pi}(z)\,, \qquad (11)$$

$$W_i^{\pi\pi}(z) = \frac{1}{r_\pi^2}\left[\alpha_i + \beta_i \frac{z - z_0}{r_\pi^2}\right] F(z)\ \chi(z)\ ,$$

Remind of Bmm sensitivity

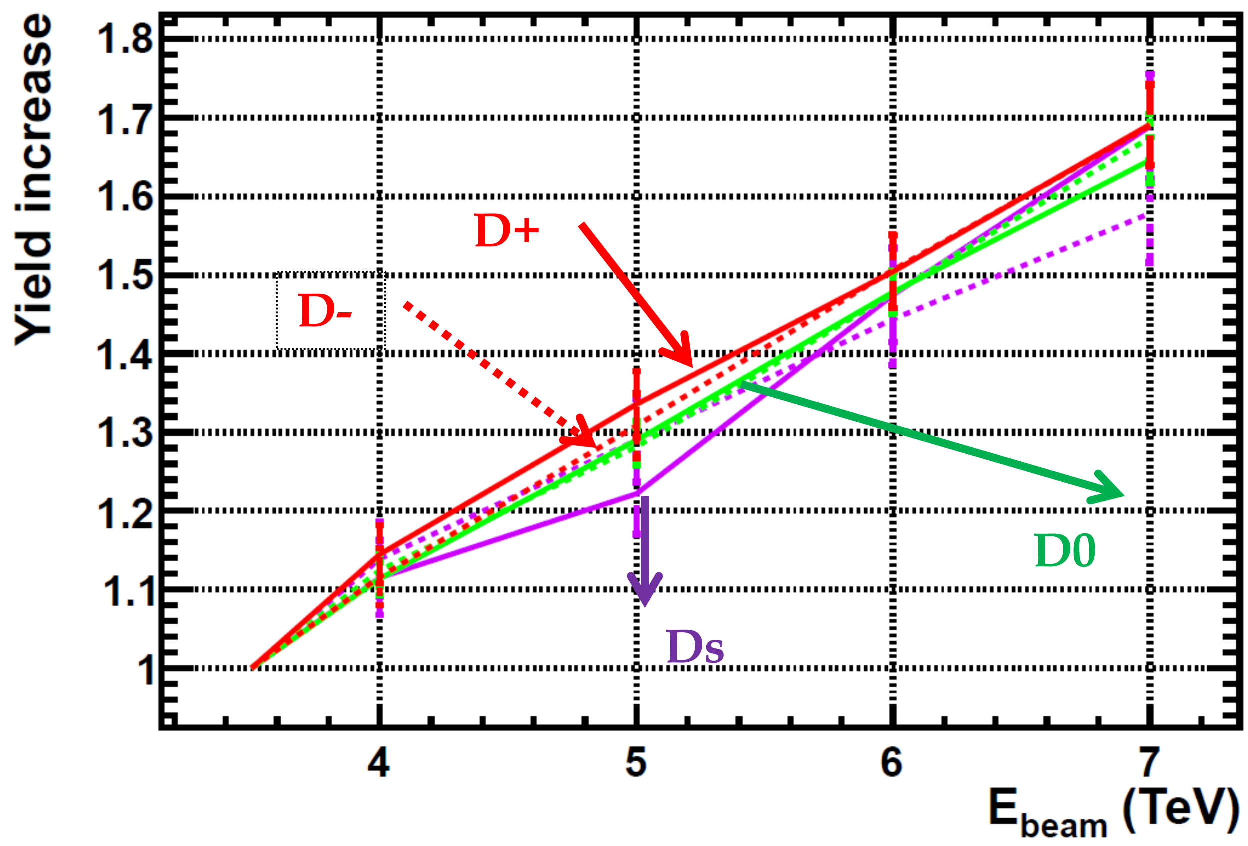
B mesons

We check that we get right the expected increase of B meson yields (i.e, a factor ~2)



D mesons

For D mesons the increase is slightly smaller (~1.6- 1.7)

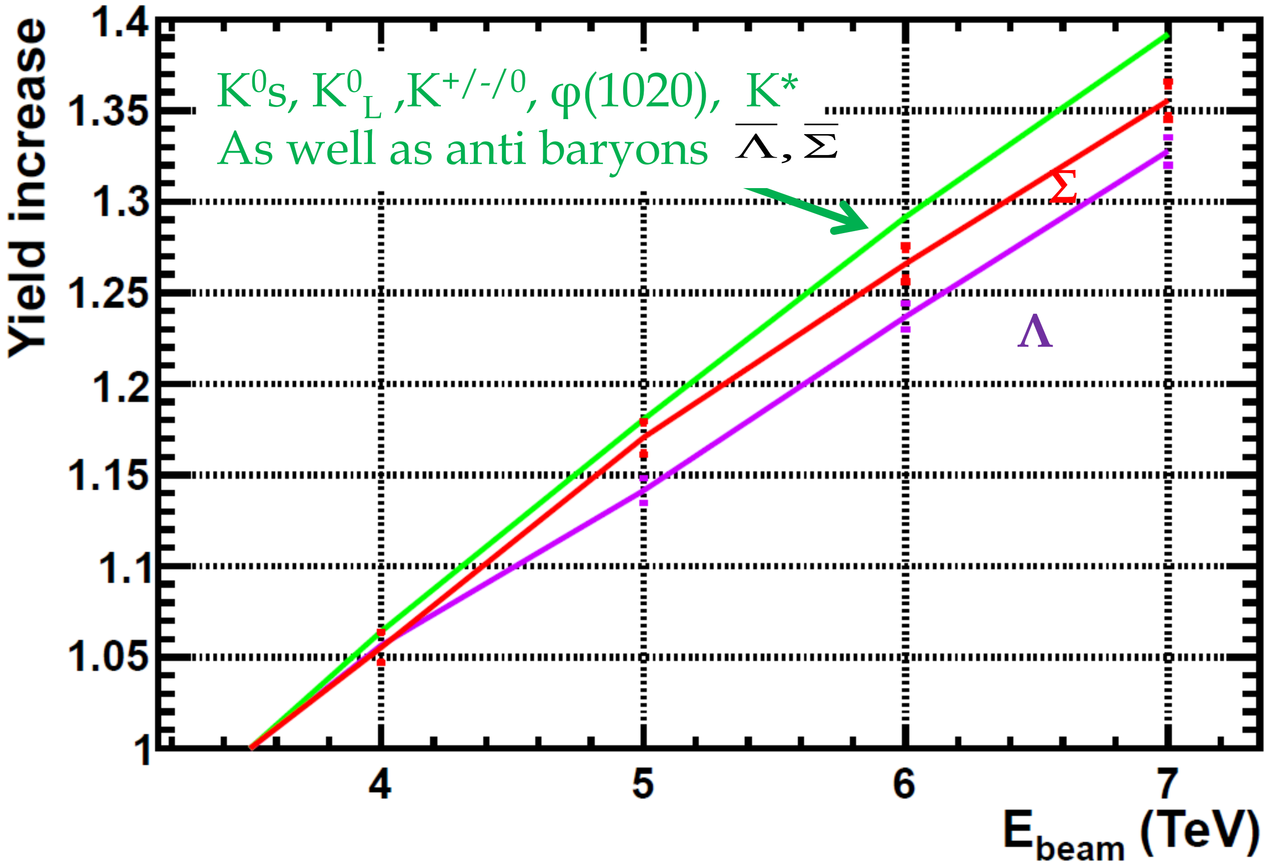


Strange particles

Increase for most of them is ~40%

A bit less for baryons (note: baryons, not anti-baryons)

However, the momentum is also different w.r.t 7 TeV.

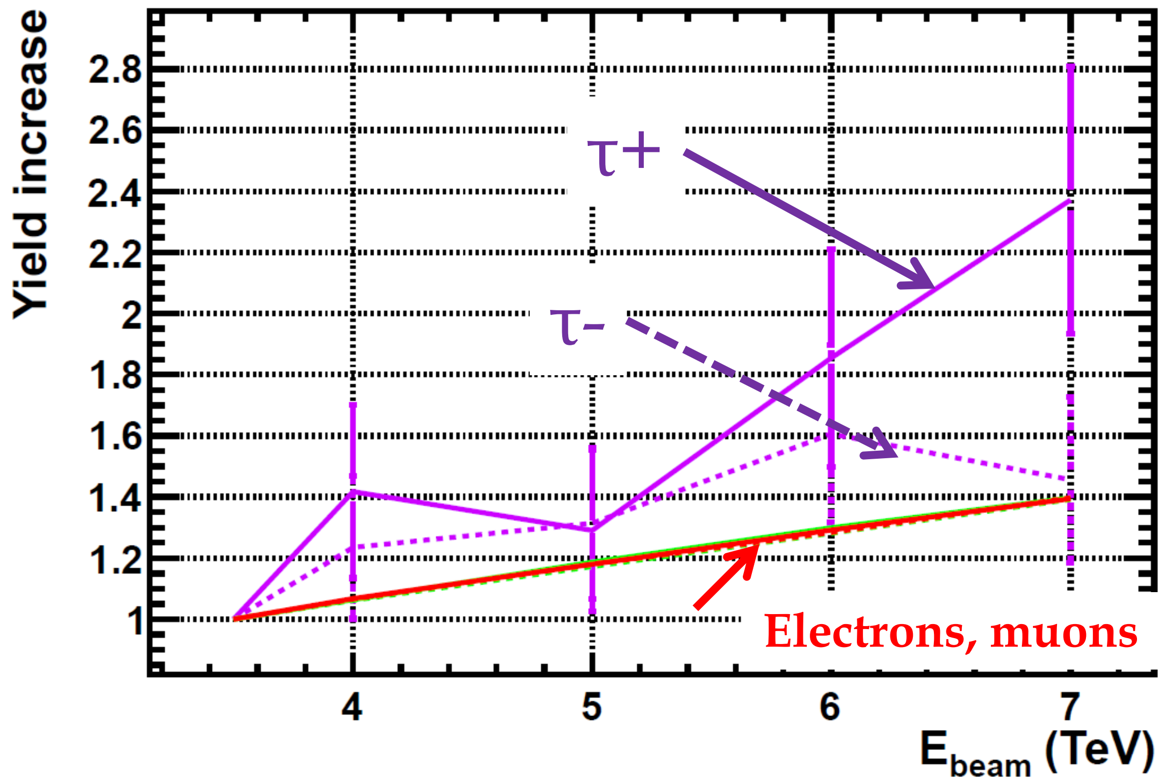


In particular, for the K0s decaying in the VELO the increase is "only" ~30% → This is the number we really care for Ks → μμ studies

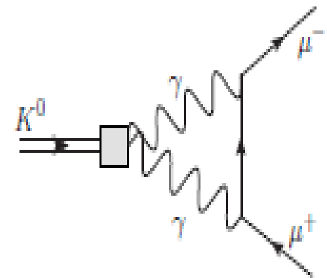
Leptons

Increase in tau yiled consistent with ~ 2 , expected by the fact that most of them come from b's and c's

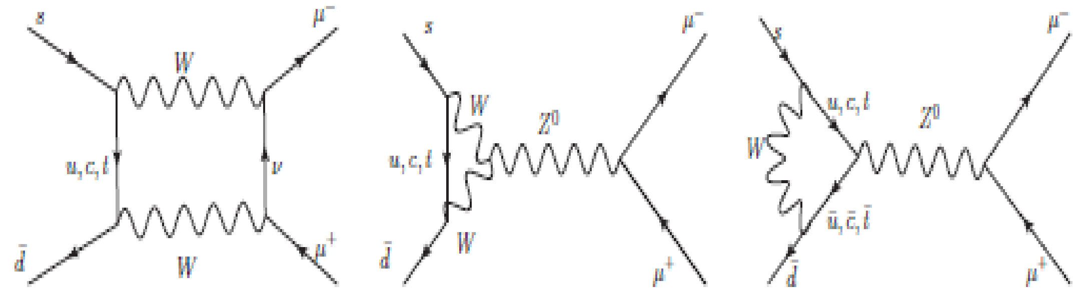
Check with more stats if the asymmetry +/- is still there

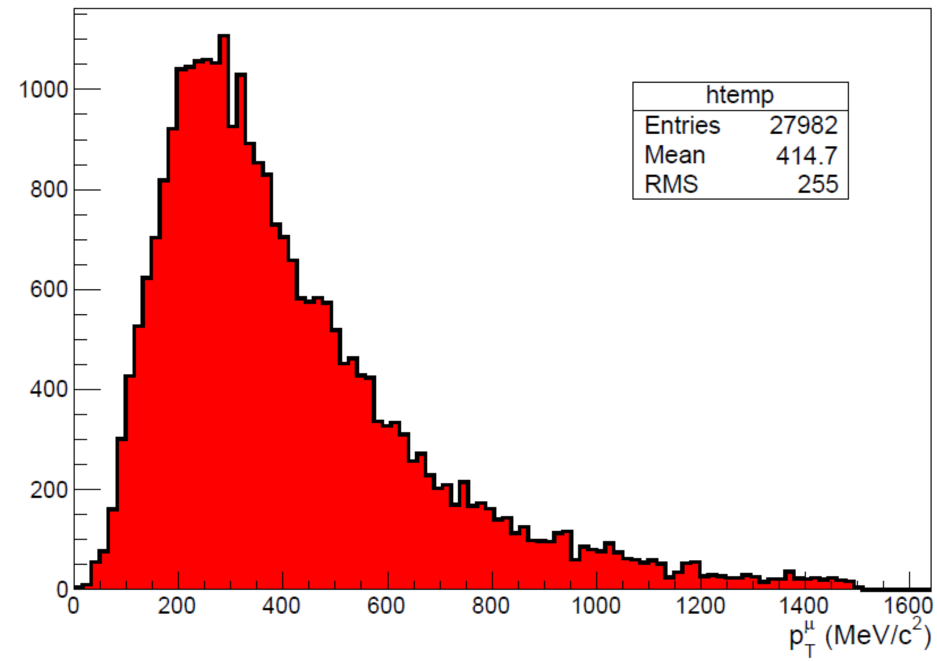


→ the long-distance (LD) contributions:



→ the short-distance (SD) contributions:

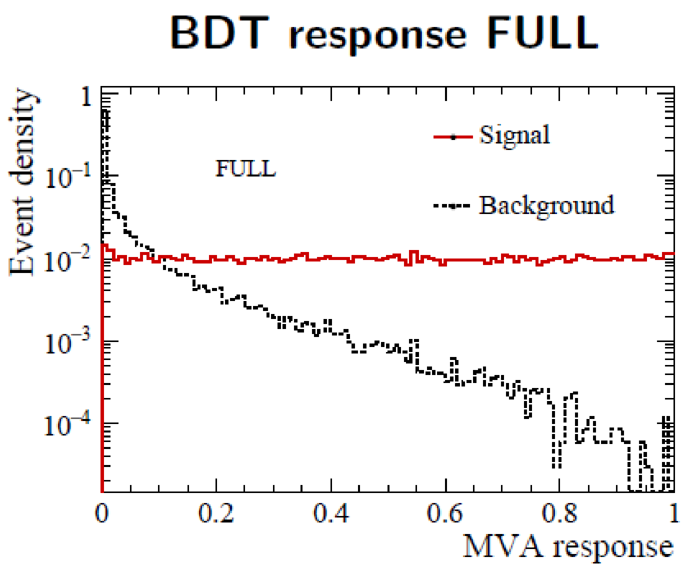


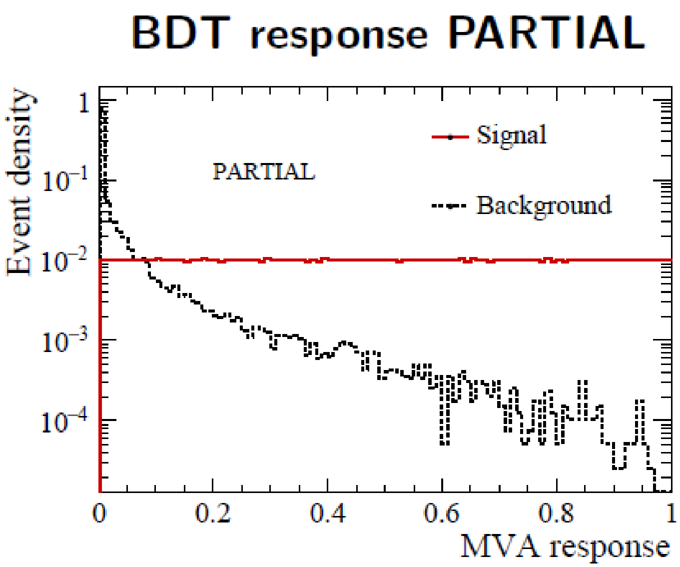

htemp
Entries 27982
Mean 414.7
RMS 255
0
200
400
600
800
1000
0
200
400
600
800
1000
1200
1400
1600
p_T^μ (MeV/c^2)

$K_S \to \pi^0 \mu\mu$ sensitivity study

The background discrimination

V. Chobanova et al,
CERN-LHCb-PUB-2016-017





- As usual: BDT trained against combinatorial background
- Specific backgrounds: $K_S \to \pi\pi$, $K_L \to \pi\pi\pi$, $K_{S/L} \to \mu\mu\gamma\gamma$ (negligible)

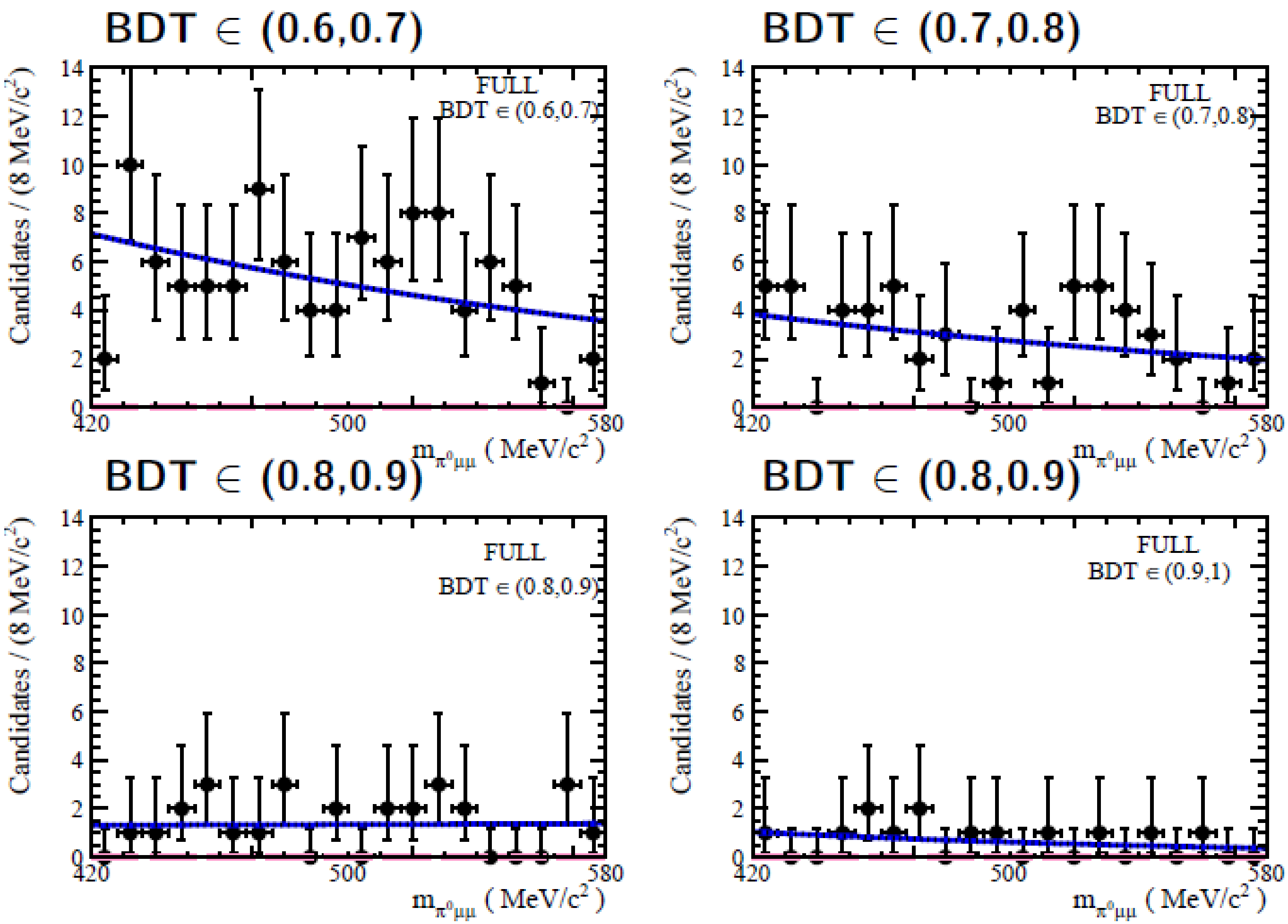
Don't affect the sensitivity estimate

$K_S \rightarrow \pi^0\mu\mu$ sensitivity study

European Research Council

Fit, FULL

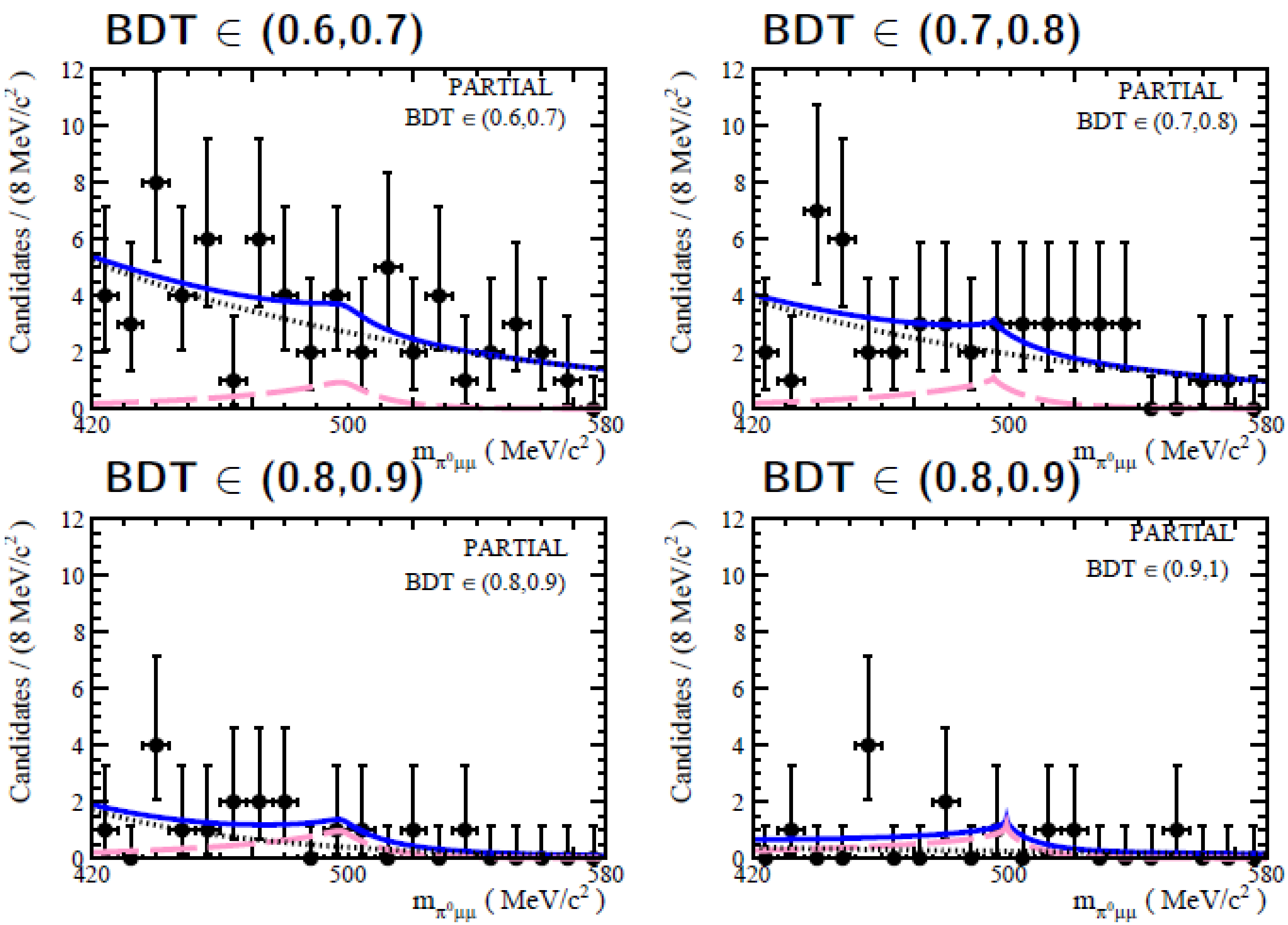
V. Chobanova et al,
CERN-LHCb-PUB-2016-017



$K_S \to \pi^0 \mu\mu$ sensitivity study

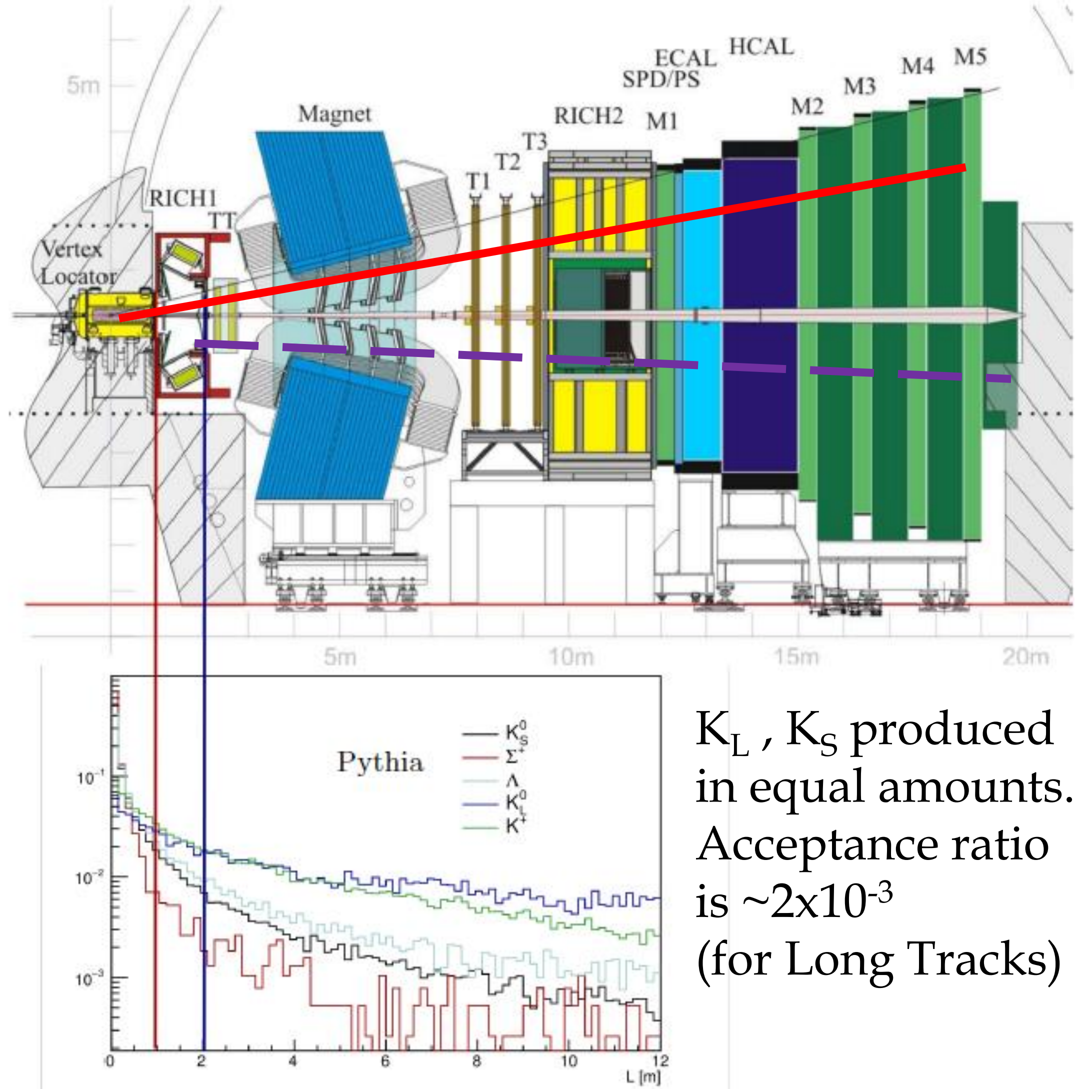
Fit, PARTIAL

V. Chobanova et al,
CERN-LHCb-PUB-2016-017



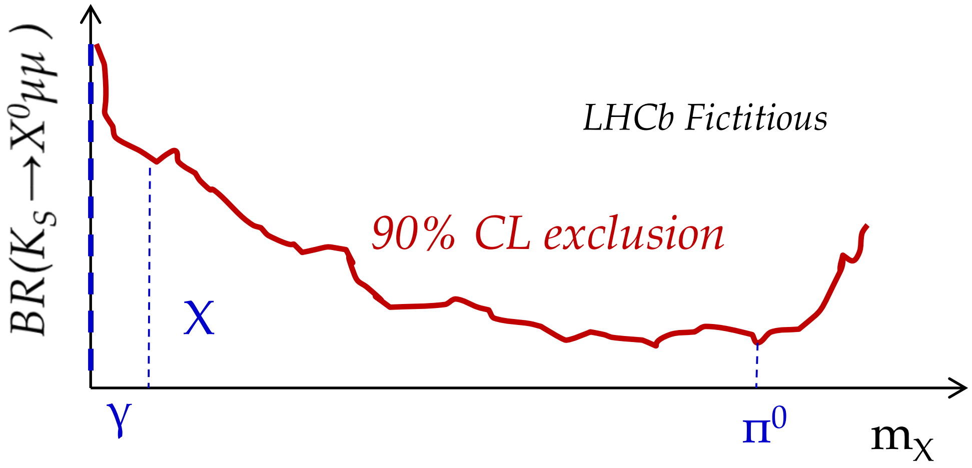
Strangeness production/detection at LHCb

- The pp collisions @ LHC produce a 'kaon flux' of 10^{13} K_S per fb^{-1} of luminosity in the LHCb acceptance
- Charged decay products can be reconstructed using Long Tracks or Downstream Tracks
- We use Long Tracks for RnS
- Downstream will be investigated (extra yield, but worse reconstruction quality)

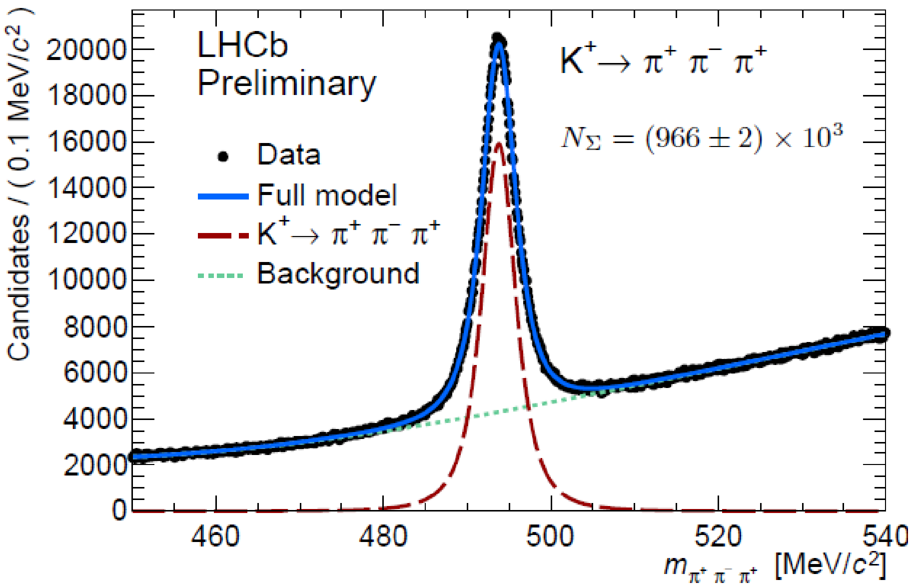


K_L, K_S produced in equal amounts. Acceptance ratio is ~$2x10^{-3}$ (for Long Tracks)

Ongoing stuff



K^+ studies



Large samples of charged kaon decays are available

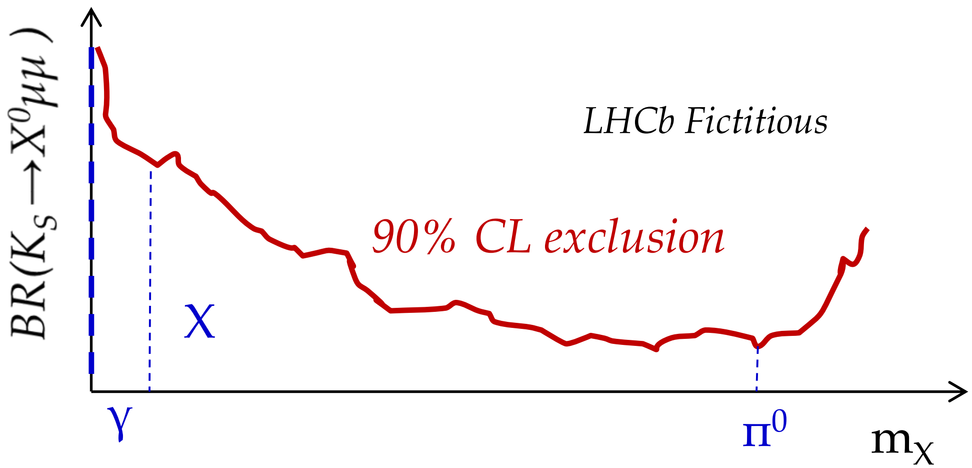
K^+ mass is not very well known

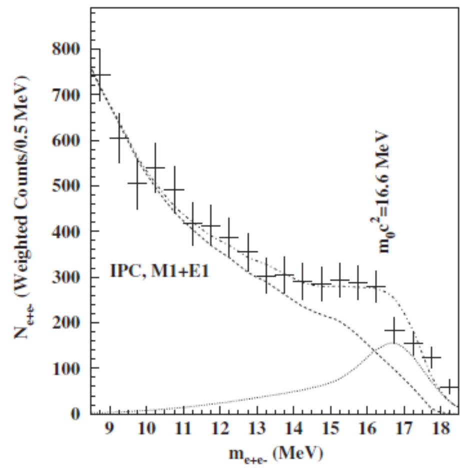
$K^+ \rightarrow \pi\mu\mu$?

$K_S \to X^0\mu\mu$

- The $K_S \to \pi^0\mu\mu$ PARTIAL analysis can be recasted for general/inclusive $K_S \to X^0\mu\mu$. With X being whatever neutral system:
  - $K_S \to \gamma\mu\mu$. Can also be completed with photon reconstruction
  - $K_S \to (l^+l^-)\mu\mu$. Some of them are also being searched for explicitly
  - Some exotic, eg, 17 MeV neutral boson of Phys. Rev. Lett. 116, 042501 (2016)

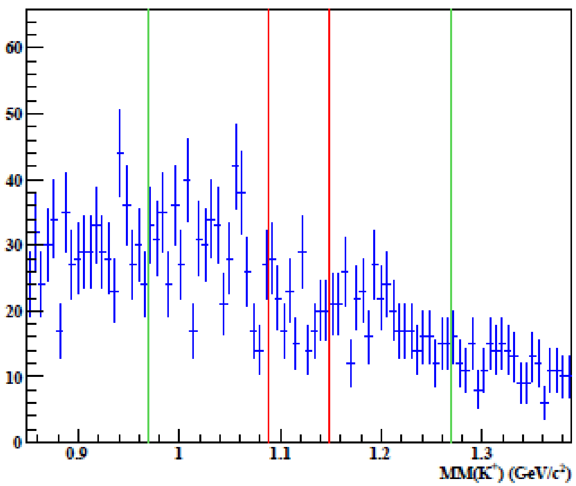
Limits can be provided as a function of X^0 mass





B and L violation (very low priority)

CLAS collaboration (Jefferson Lab):
Limits on B and L violation



Reaction	$\mathcal{B}_{\rm UL}$
$\Lambda \to K^+ e^-$	2×10^{-6}
$\Lambda \to K^+ \mu^-$	3×10^{-6}
$\Lambda \to K^- e^+$	2×10^{-6}
$\Lambda \to K^- \mu^+$	3×10^{-6}
$\Lambda \to \pi^+ e^-$	6×10^{-7}
$\Lambda \to \pi^+ \mu^-$	6×10^{-7}
$\Lambda \to \pi^- e^+$	4×10^{-7}
$\Lambda \to \pi^- \mu^+$	6×10^{-7}
$\Lambda \to \bar{p}\pi^+$	9×10^{-7}
$\Lambda \to K^0_S \nu$	2×10^{-5}

arXiv:1507.03859 [hep-ex]

We can easily do many of CLAS' decays

…as well as others:

- $\Sigma \rightarrow 3\mu$
- $\Lambda \rightarrow \pi 3\mu$

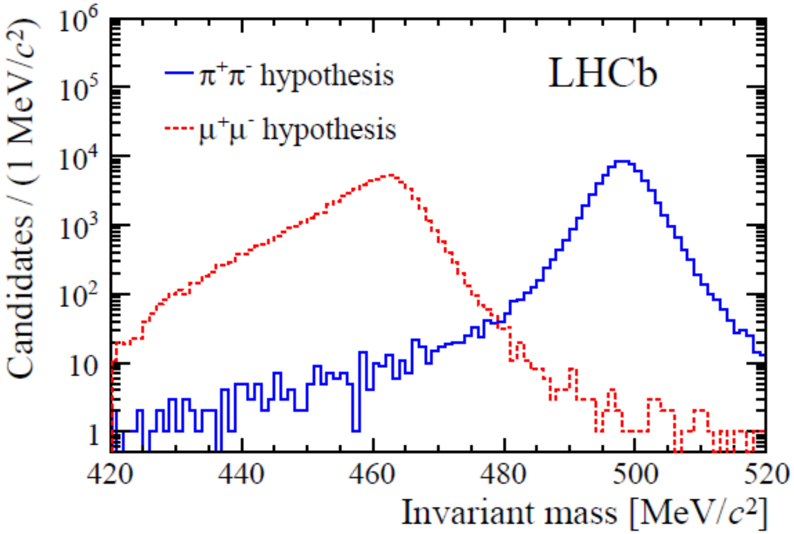
…and many other crazy (J conserving) combinations.

Currently very low priority, since we assume that BSM contributions can only be as much as BR ~10^{-56}

$K_S \rightarrow \mu\mu$ full Run-I analysis

arXiv:1706.00758 [hep-ex]

- Analysed full Run-I (2011-2012) data
- Events classified using a BDT trained against combinatorial background
- Dedicated muon identification algorithm trained against $K_S \rightarrow \pi\pi$
- Mass resolution 4 MeV



Background

$K_L \rightarrow \mu\mu$ negligible: (down to 10^{-11} precision)

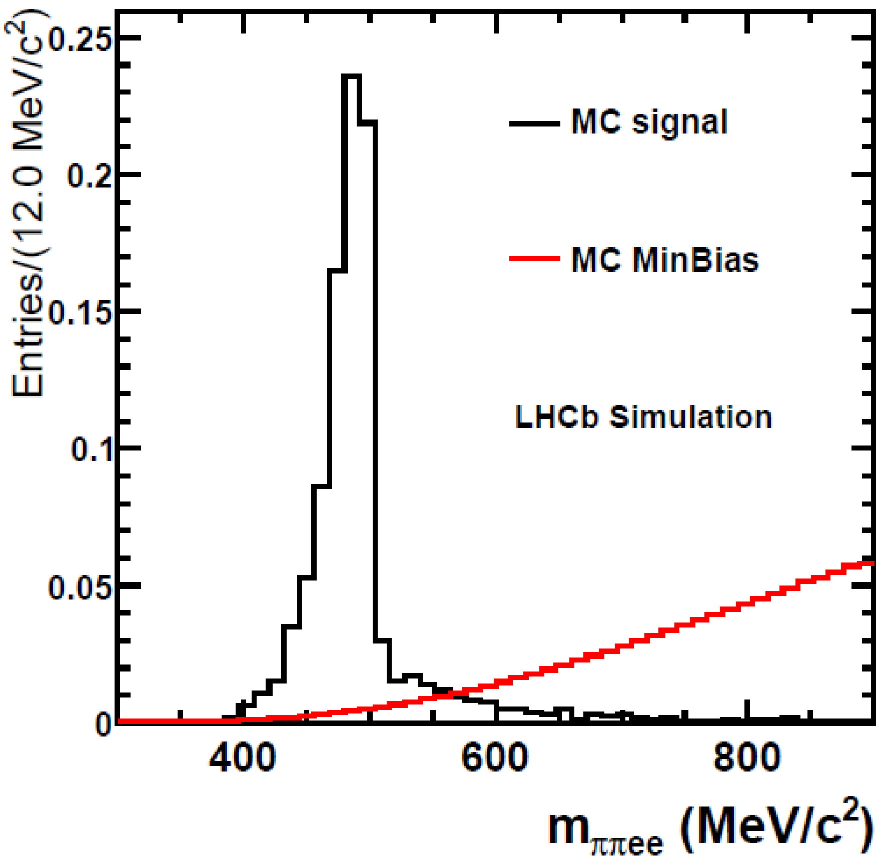
$K \rightarrow \pi\mu\nu$: negligible

$\Lambda \rightarrow p\pi$ removed by a cut in the Armenteros-Podolanski plot.

- **Combinatorial background**
- **$K_S \rightarrow \pi\pi$ double misid**

$K_S \rightarrow \pi^+\pi^- ee$ sensitivity study

C.Marin et al,
CERN-LHCb-PUB-2016-016



Based on simulation:

Expected a signal yield of

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

For the full Run-I dataset

Expected background yield is not well known yet

Why? ($K_S \to \pi^0\mu\mu$ and SM errors on $K_L \to \pi^0\mu\mu$)

$$\mathcal{B}(K_L \to \pi^0\mu^+\mu^-)_{\rm SM} = \{1.4 \pm 0.3, 0.9 \pm 0.2\} \cdot 10^{-11}$$

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

$$|a_S| = 1.20 \pm 0.20$$

Dominant uncertainty, that makes difficult potential BSM interpretation of $K_L \to \pi^0\mu\mu$

$$C^e_{\rm dir} = (4.62 \pm 0.24)\left[({\rm Im}\,Y_A)^2 + ({\rm Im}\,Y_V)^2\right],$$
$$C^e_{\rm int} = (11.3 \pm 0.3)\,{\rm Im}\,Y_V\,,$$
$$C^e_{\rm mix} = 14.5 \pm 0.5\,,$$
$$C^e_{\gamma\gamma} \approx C^e_S \approx 0\,,$$
$$C^\mu_{\rm dir} = (1.09 \pm 0.05)\left[2.32\,({\rm Im}\,Y_A)^2 + ({\rm Im}\,Y_V)^2\right]$$
$$C^\mu_{\rm int} = (2.63 \pm 0.06)\,{\rm Im}\,Y_V\,,$$
$$C^\mu_{\rm mix} = 3.36 \pm 0.20\,,$$
$$C^\mu_{\gamma\gamma} = 5.2 \pm 1.6\,,$$
$$C^\mu_S = (0.04 \pm 0.01)\,{\rm Re}\,Y_S + 0.0041\,({\rm Re}\,Y_S)^2\,.$$

It comes from the **experimental uncertainty** on BR($K_S \to \pi^0\mu\mu$) measured by NA48

$K^0_S \to \pi^0\mu^+\mu^-$	NA48	$(2.9\,^{+1.5}_{-1.2}) \times 10^{-9}$

~50% relative error

Improved measurements of BR($K_S \to \pi^0\mu\mu$) will translate into improved BSM constraints from $K_L \to \pi^0\mu\mu$