Rare Kaons Decays at LHCb

Marc-Olivier Bettler

All credits to: Diego Martinez Santos, Xabier Cid Vidal, Victor Renaudin, Carla Marin Benito, Mar Barrio Luna, Ricardo Vazquez Gomez, Andrea Contu, Adam Davis, Mike Sokoloff, T. Gialopsos, Francesco Dettori, Antonio Di Domenico, Thomas Ruf.

For contact, conveners of the rare decays working group:
Gaia Lanfranchi and Thomas Blake

Why study Kaon decays at LHCb?

LHCb was not designed to study Kaon decays: The overall length of the detector is several times too short …

The trigger is mainly designed to anti-select them.

'Enough' kaons decay in LHCb, 10^{13} K_S^0 per fb^{-1}.

For most of the studies, we don't need trigger. We have kaon decays in the events that were triggered because they contain another interesting feature (TIS).

No other experiment can study K_S^0 and hyperon decays.
NA62 will focus on charged Kaons for at least 5 years.

LHCb can produce world-best results for Kaon physics, as attests the search for $K_S^0 \to \mu\mu$

We have a unique opportunity to try and exploit.

[JHEP 01 (2013) 090]

[Nucl.Phys.B366 (1991) 189]
[JHEP0401(2004) 009]

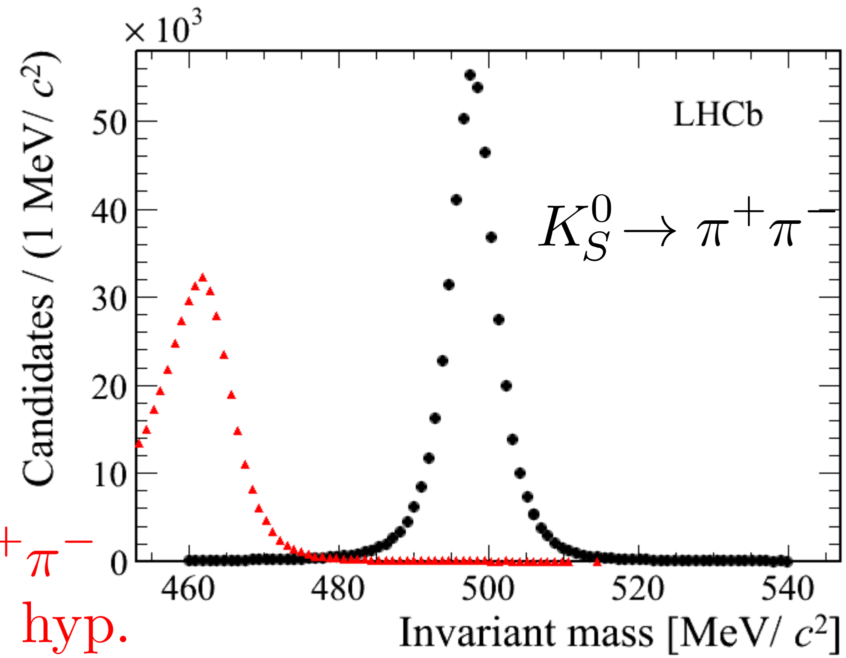
Yet unobserved FCNC decay with $\mathcal{B}_{\rm SM} = (5.0 \pm 1.5) \times 10^{-12}$

$K_L^0 \to \mu^+\mu^-$ and $K_S^0 \to \mu^+\mu^-$ receive different contributions, complementary interest. Enhancement up to 10^{-10} is possible.

Previous experimental limit dates from 1973 [Phys.Lett.B44(1973)217]

Background from $K_S^0 \to \pi^+\pi^-$ with double mis-ID.

Good mass resolution helps to containing it.

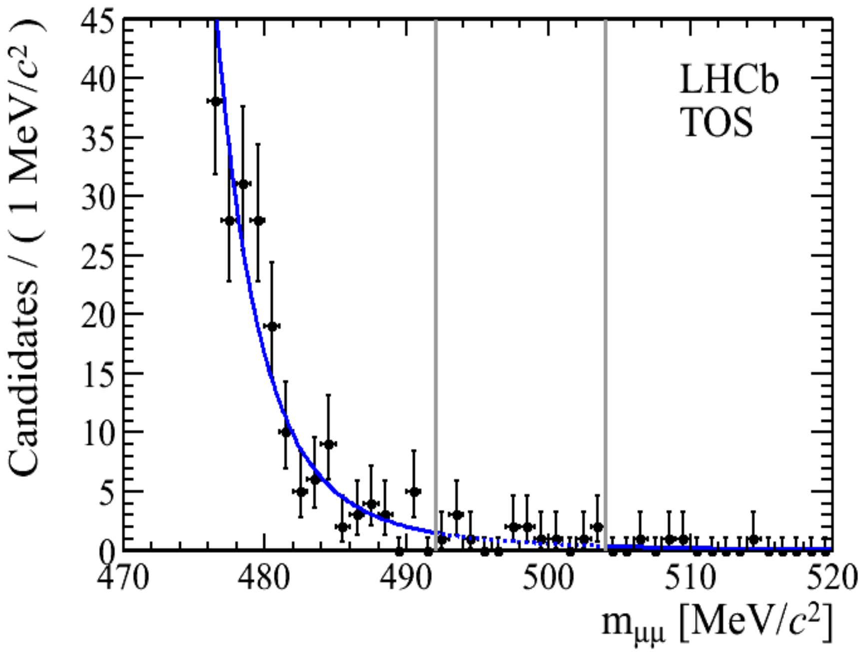


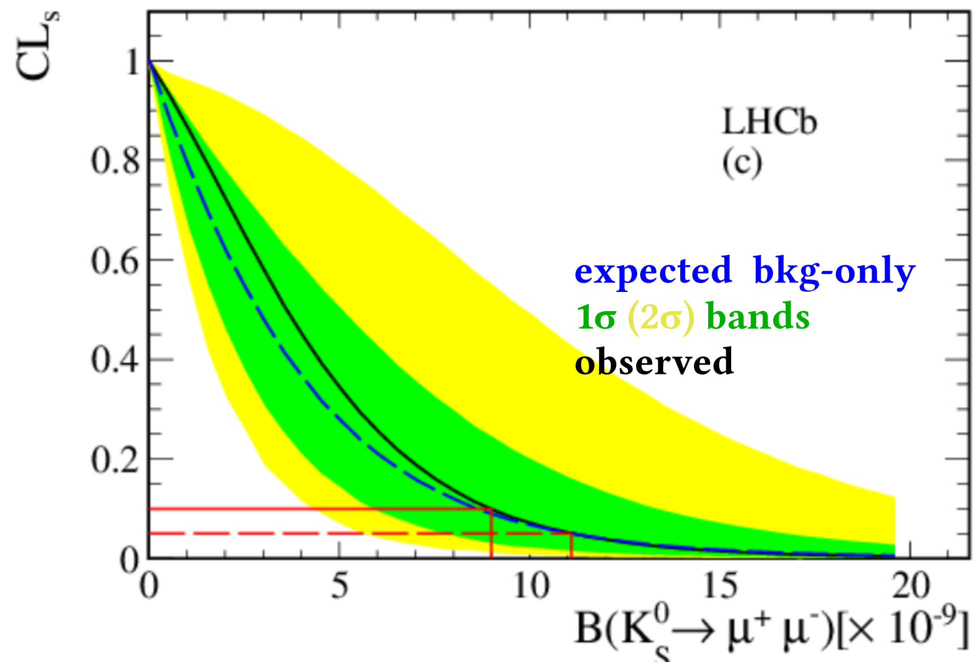
$K_S^0 \to \pi^+\pi^-$
$\mu\mu$ mass hyp.

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

[JHEP 01 (2013) 090]

Observed yield compatible with background expectation



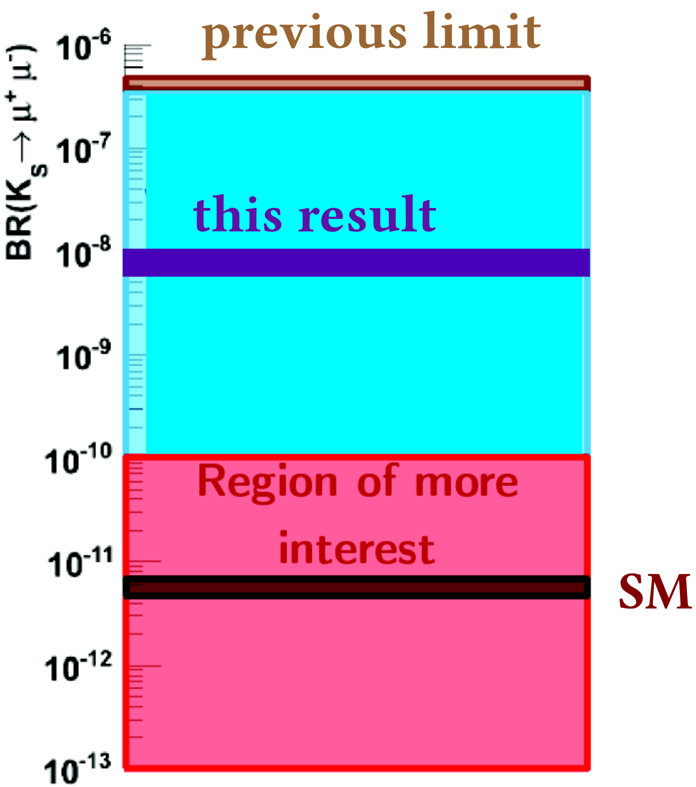


CLs method used to set a limit

$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 11 \times 10^{-9}$ at 95% CL

World best limit, a factor 35 lower than the previous result.

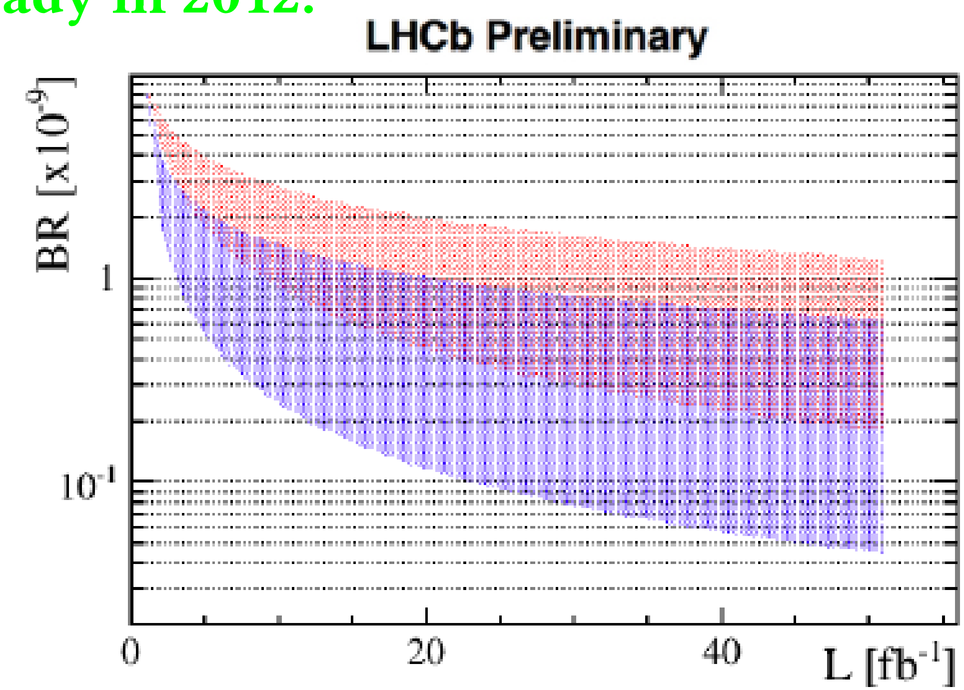
$K_S^0 \to \mu\mu$ prospects



Only a third of the data have been analysed.

Can improve using Down-Down tracks as well.

Efficiency of the trigger has improved already in 2012.



Sensitivity with current trigger could reach below 10^{-10} with upgrade

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

- $K_L \to \pi^0 \mu^+ \mu^-$ is one of the hot channels in rare kaon decays (BF could be sensitive to new physics!)
  - K_S equivalent decay very useful to constraint the CP violating amplitude that enters in this BF
  - Current experimental measurement from NA48:

$$BF(K_S \to \pi^0 \mu^+ \mu^-) = [2.9^{+1.5}_{-1.2} \pm 0.2] \times 10^{-9}$$

~50% error **Based on 6 events, 0.22+0.18-0.11 bkg**

Challenging reconstruction of the neutral pion via $\gamma\gamma$
But encouraging studies indicate manageable expected background.

Estimated yield before selection: on tape: ~7 evts
after run II: ~30 evts

Interesting at longer term!

$K_S^0 \to eeee$ and $K_S^0 \to ee\mu\mu$

Our purpose: study the feasibility of $K_s \to e^+e^-e^+e^-(\mu^+\mu^-)$ in LHCb.

- Taking into account new predictions
  BR are up to:
  - $\to$ $BR(K_s \to e^+e^-e^+e^-) \sim 10^{-10}$
  - $\to$ $BR(K_s \to \mu^+\mu^-e^+e^-) \sim 10^{-11}$
- Challenge:
  - $\to$ Very low BR
  - $\to$ electrons are experimentally complicated (energy loss by Bremsstrahlung).

$K_S^0 \to \pi\pi ee$ **(with BF = 4.8 10^{-5}) is both the main background (double misID) and the normalisation channel.**

sensitivity is dominated by mass resolution and mass shift wrt main background: $K^0_S \to \pi\pi ee$

$K^0_S \to eeee$ σ_m**~22 MeV**

easily distinguishable

$\Delta_m(\pi\pi \to ee)$ **-278 MeV**

$K^0_S \to \pi\pi ee$ σ_m**~10 MeV**

$\Delta_m(\pi\pi \to \mu\mu)$ **-68 MeV**

also distinguishable

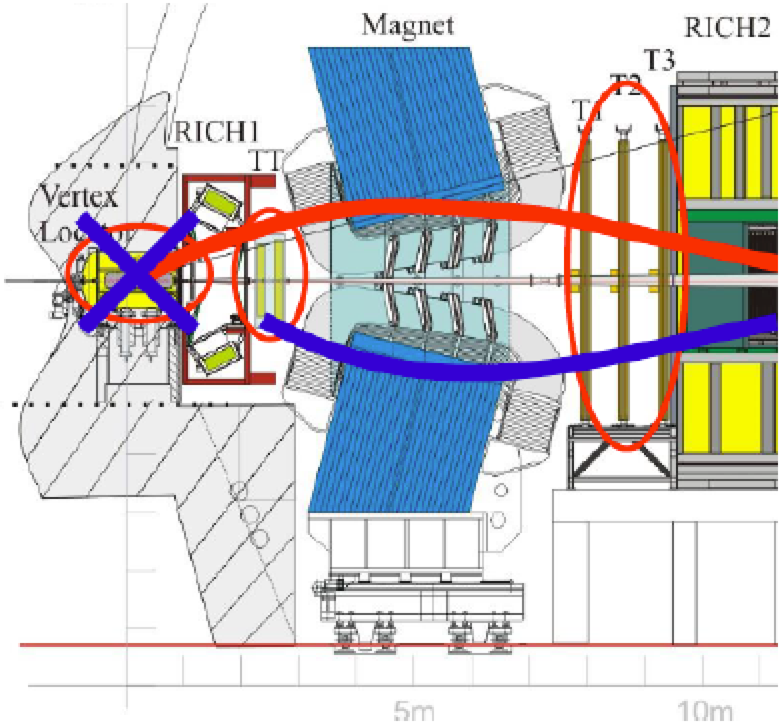
$K^0_S \to ee\mu\mu$ σ_m**~10 MeV**

single event sensitivity for 3fb^{-1} with TIS events

$$K_s \to e^+e^-e^+e^-:\ \alpha \sim 10^{-6}$$
$$K_s \to e^+e^-\mu^+\mu^-:\ \alpha \sim 10^{-7}$$

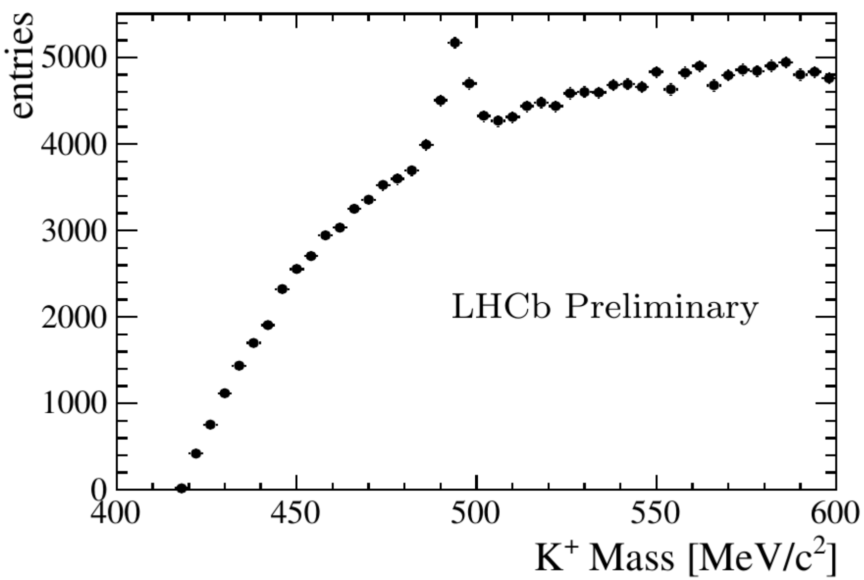
$K^0_S \to \mu\mu\mu\mu$ **also under study.**

Strange particle fly a long way!
We can reconstruct some of those that decay outside the VeLo (D tracks), increase statistics by using Down tracks.



Long Track
Down Track

$K^+ \to 3\pi$, **1 fb^{-1} of TIS data vertexing Down pions**

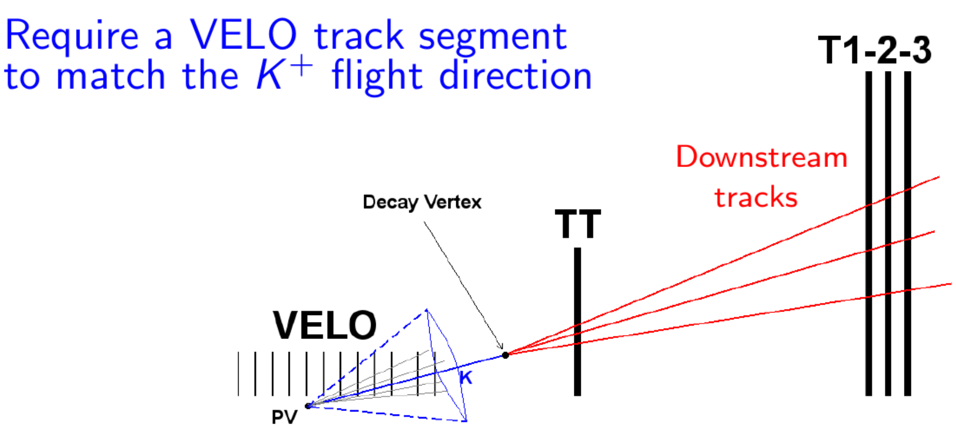


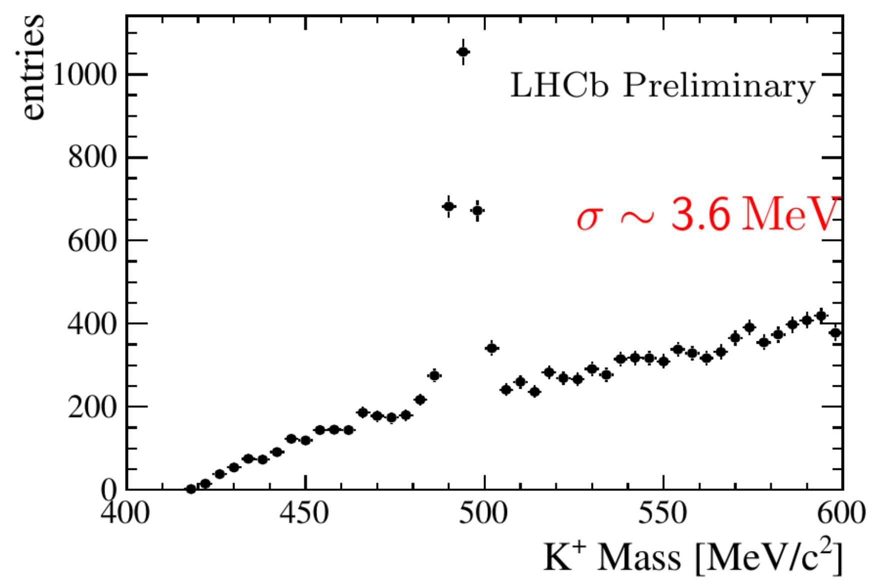
[A. Contu, CERN-LHCb-PUB-2014-032]

Strange particle fly a long way!
We can reconstruct some of those that decay outside the VELO (D tracks), increase statistics by using Down tracks.

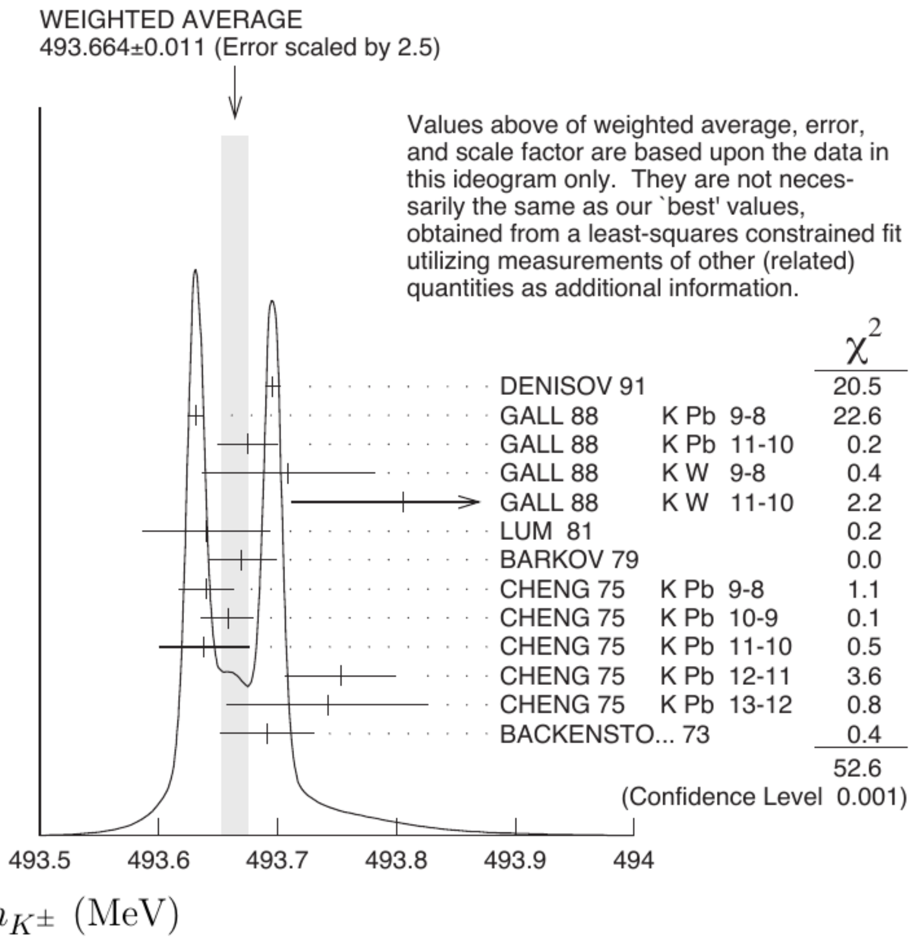
Trick: to require a VELO track to match the reconstructed K+
=> large background reduction

$K^+ \to 3\pi$, **1 fb^{-1} of TIS data vertexing Down pions**
requiring a VELO match





Charged Kaon mass is an input to loads of HEP measurement
serious experimental discrepancies!



LHCb can contribute:

1. $K^+ \to \pi^+\pi^-\pi^+$

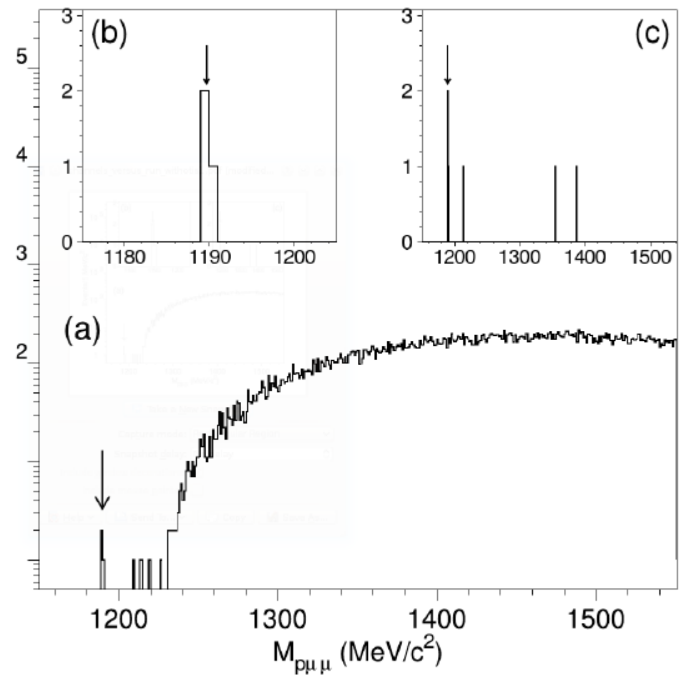
not impossible to reach interesting resolution with current data set.

2. $\Omega^- \to \Lambda K^-$
   $\Omega^- \to \Xi^-\pi^+\pi^-$

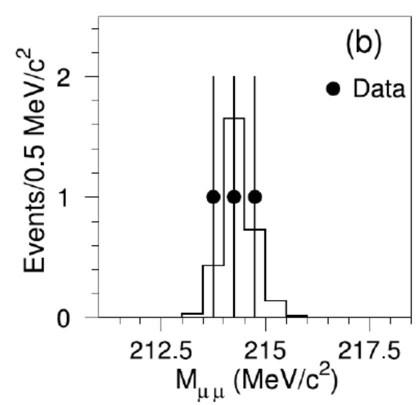
smartly using kinematics to reduce uncertainties. Will benefit from better hyperon trigger in run II

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

- An evidence for this decay was found by the HyperCP experiment with 3 events in absence of background
- Measured branching fraction is:
  $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \cdot 10^{-8}$
  [Phys.Rev.Lett. 94 (2005) 021801]
- This evidence had wide relevance since all the **3** observed signal events have the same dimuon invariant mass: pointing towards a $\Sigma^+ \to pX^0(\to \mu\mu)$ decay



This X^0 searched for in a variety of channels at CLEO, KTeV, E391a, Babar, Belle, D0 and LHCb (with Bs->4mu analysis) without success.



Look in $\Sigma^+ \to p\mu^+\mu^-$ directly!

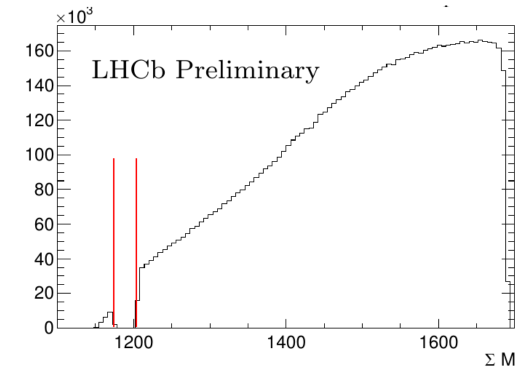
Analysis will be performed on TIS events.

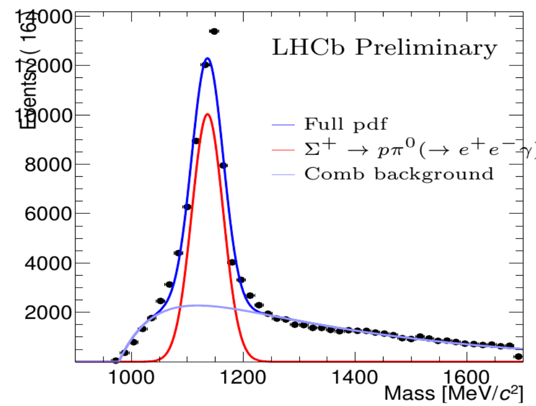
Using Long tracks at the moment, ideal candidate for the Down+Velo trick!

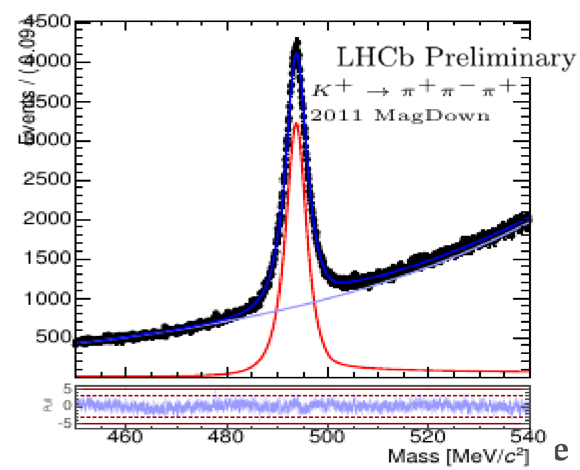
Normalisation with two separate channels: $K^+ \to \pi\pi\pi$ (1.2M in run I) and $\Sigma^+ \to p\pi^0(\to e^+e^-\gamma)$ (45k)

A single-event sensitivity of O(10^{-9}) for 3fb^{-1} can be reached.

Sensibility to the BF measured by HyperCP







Conclusion

LHCb is not designed to study strange decays, but can bring surprising contributions.

Copious production of strange hadrons at the LHC
Exploit the possibility to analyse decays that have not been triggered on, dedicated trigger can only help!

The search for $K^0_S \to \mu\mu$ is a show-case. World best limit.

No other experiment is looking at K^0_S and hyperon.

In the search for subtle NP effect, the kaon sector is complementary to the B sector in many aspects.
(see Giancarlo's talk)

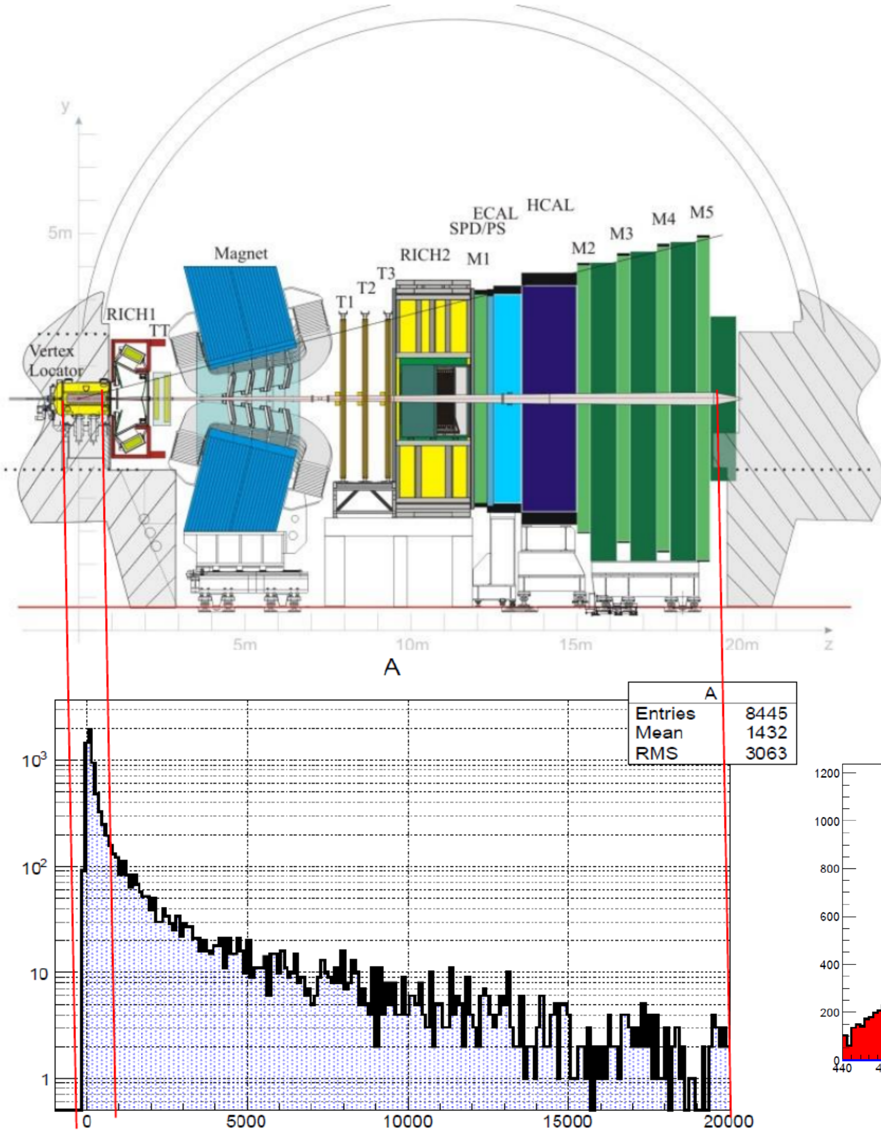
Backup

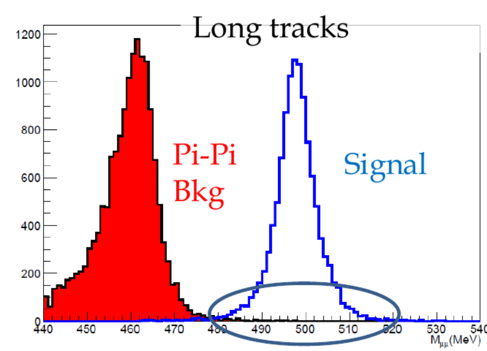
Marc-Olivier Bettler

Adding decays in DD final states we gain **176%**, but

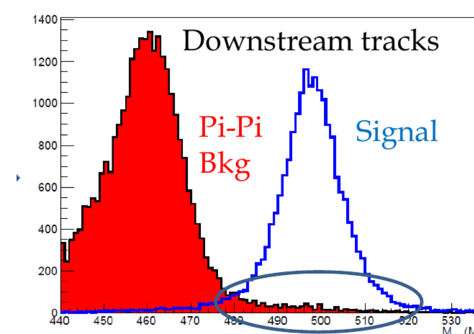
- worse mass resolution, increase of peaking background
- lack of dedicated trigger

Optimistically, gain of **15%** in effective luminosity is possible.



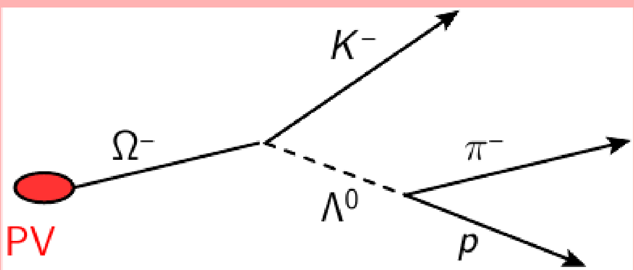


resolution ~6 MeV



resolution ~9 MeV

$\Omega^- \to \Lambda K^-$

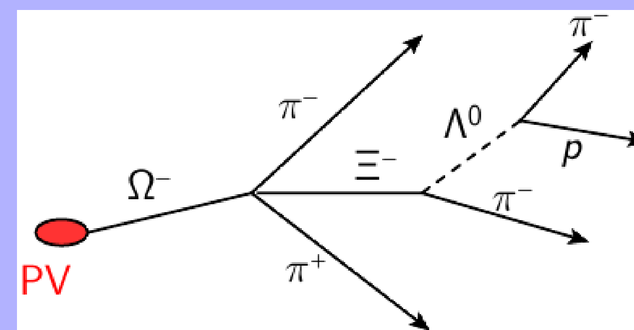


$B(\Omega^- \to \Lambda K^-) = 0.678 \pm 0.007$

$Q = 63.1$ MeV

$\Omega^- \to \Xi^- \pi^+ \pi^-$

$\searrow \Lambda \pi^-$



$B(\Omega^- \to \Xi^- \pi^+ \pi^-) = (3.7^{+0.7}_{-0.6}) \times 10^{-4}$

$Q = 71.6$ MeV

$$m^2(\Lambda K^-) - m^2(\Xi^- \pi^+ \pi^-) = 0 = m^2(K) - 2m^2(\pi^\pm) + \mathcal{F}[p(\Lambda), p(K), p(\Xi), p(\pi^+), p(\pi^-)]$$

Ratio of cross-section

- $\frac{\sigma_{\Sigma^+}}{\sigma_{K^+}}$ not measured in LHCb
- We measured $\frac{\sigma_{\bar{\Lambda}^0}}{\sigma_{K^0_S}}$ and $\frac{\sigma_{\bar{\Lambda}^0}}{\sigma_{\Lambda^0}}$ at 7 TeV *
- K^+ and K^0 hadronisations are expected to be equal be equal

$$\Rightarrow \frac{\sigma_{K_S}}{\sigma_{K^+} + \sigma_{K^-}} \simeq \frac{1}{2}$$

- Hadronisation of Λ and Σ should be similar provided isospin is taken into account

$$\Rightarrow \frac{\sigma_{\Sigma^+}}{\sigma_{\Lambda}} \sim \frac{1}{3} \text{ to } \frac{1}{4}$$

measured as far-from-threshold limit of many experiments

- Plan to use:

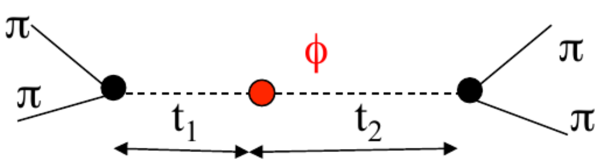
$$\boxed{\frac{\sigma_{\Sigma^+} + \sigma_{\bar{\Sigma}^-}}{\sigma_{K^+} + \sigma_{K^-}} = c_1 \frac{\sigma_{\bar{\Lambda}^0}}{\sigma_{K^0_S}} (1 + c_2 \frac{1}{\sigma_{\bar{\Lambda}^0}/\sigma_{\Lambda^0}})}$$

where c_1 and c_2 take into account data/MC and other differences

Testing the quantum coherence of entangled pairs

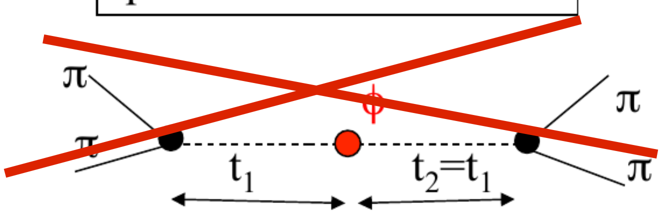
$$|i\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle|\overline{K}^0\rangle - |\overline{K}^0\rangle|K^0\rangle\right]$$

$$\Delta t = |t_1 - t_2|$$

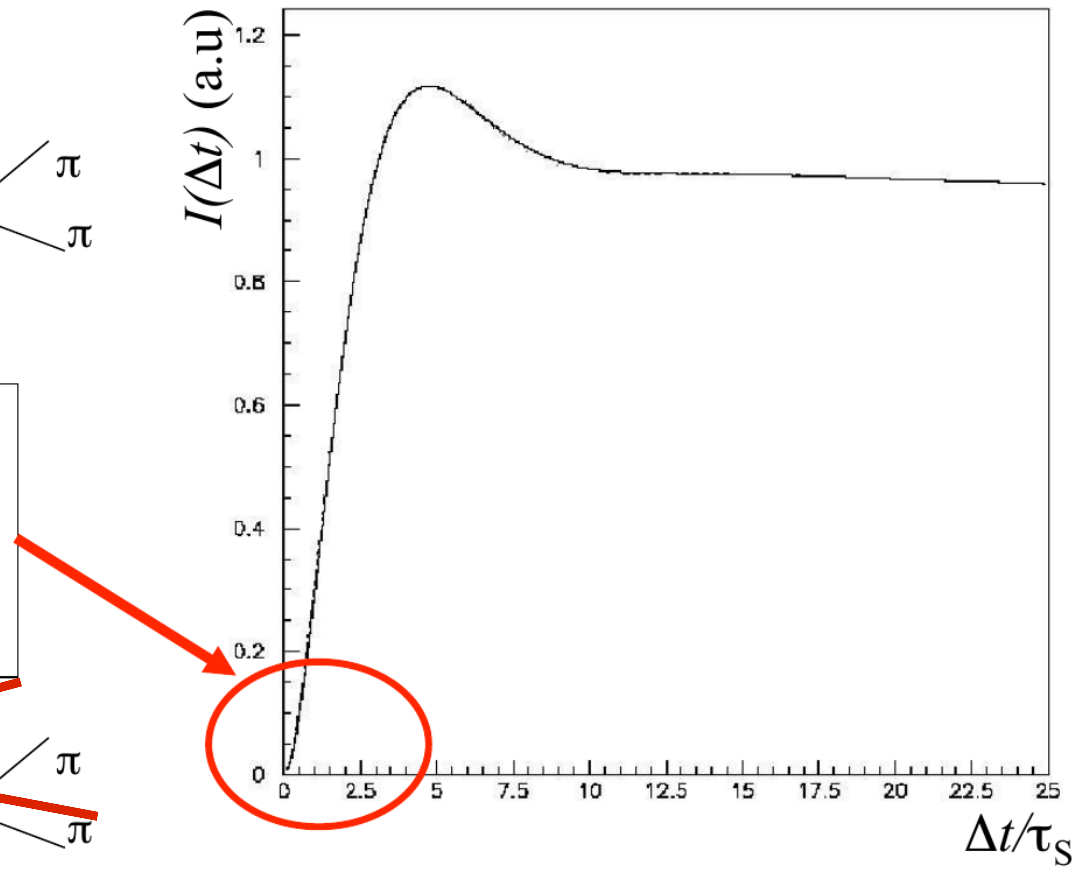


EPR correlation:

no simultaneous decays ($\Delta t=0$) in the same final state due to the destructive quantum interference



Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$



Testing QM and CPT in $\Phi \to K^0 \overline{K^0}$

Testing the quantum coherence of entangled pairs

- Decoherence parameter:

$$\zeta_{0\bar{0}} = 0 \quad \to \quad \text{QM}$$

$$\zeta_{0\bar{0}} = 1 \quad \to \quad \text{total decoherence}$$

KLOE result: PLB 642(2006) 315; Found. Phys. 40 (2010) 852

$$\zeta_{0\bar{0}} = \left(1.4 \pm 9.5_{STAT} \pm 3.8_{SYST}\right) \times 10^{-7}$$

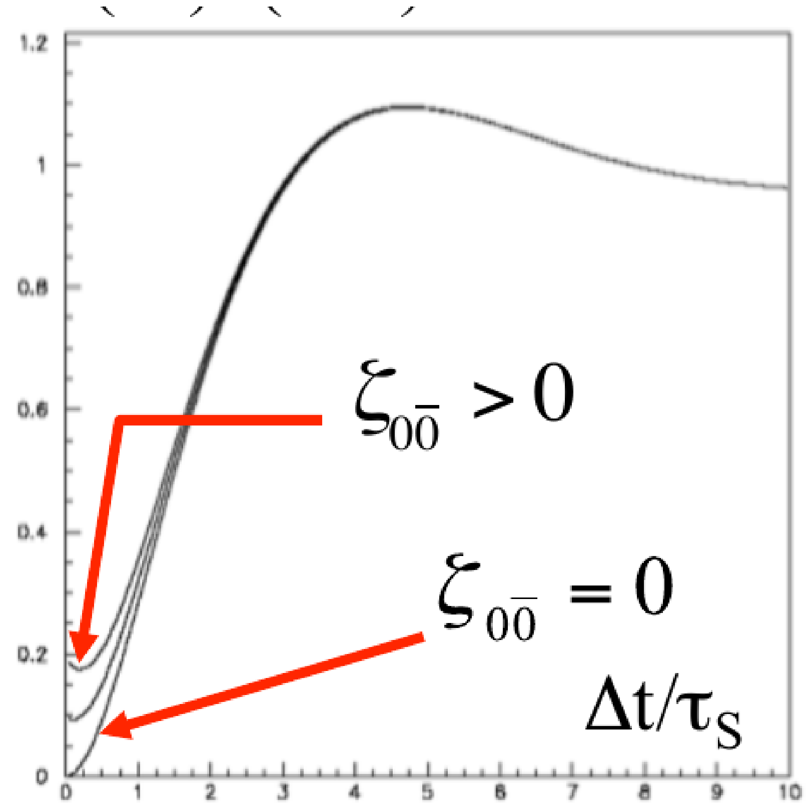
as CP viol. $O(|\varepsilon|^2) \sim 10^{-6}$ =>
high sensitivity to $\zeta_{0\bar{0}}$

From CPLEAR data, Bertlmann et al. (PR D60 (1999) 114032) obtain:

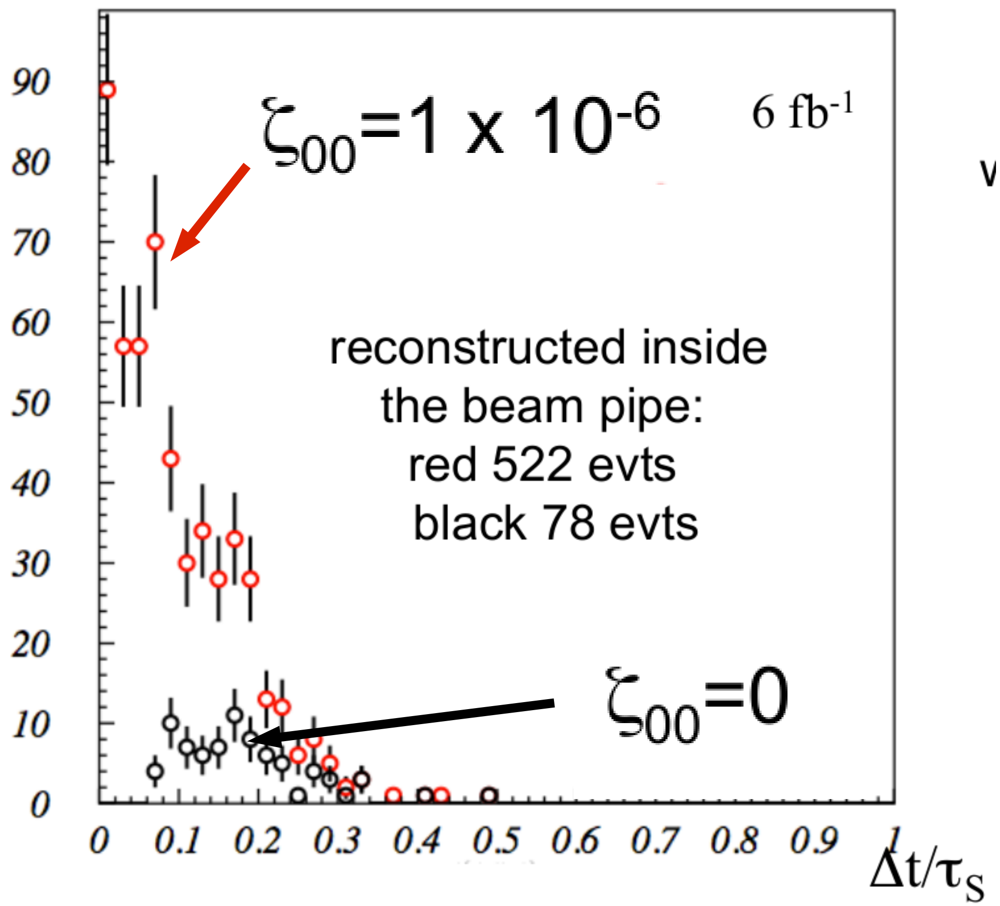
$$\zeta_{0\bar{0}} = 0.4 \pm 0.7$$

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

$$\zeta^{B}_{0\bar{0}} = 0.029 \pm 0.057$$



acceptance limitation is not a problem as the VELO covers the interesting region.
vertex resolution is crucial as well



Challenges are the background and the need for a trigger.

Gino Isidori

Rate decomposition of neutral K decays into a lepton pair:

$$\Gamma(K_{L,S} \to \ell^+\ell^-) = \frac{m_K \beta_\ell}{8\pi}\left(|A|^2 + \beta_\ell^2 |B|^2\right)$$

$$\beta_\ell = \left(1 - \frac{4m_\ell^2}{m_K^2}\right)^{1/2}$$

S-wave ($|A|^2$):

Long-distance (2γ)
+
Short-distance (↔ NP)

K_S=CPV K_L=CPC

P-wave ($|B|^2$):

Long-distance (2γ) dominated

K_S=CPC K_L=CPV

Theory considerations II

Rate decomposition of neutral K decays into a lepton pair:

Gino Isidori

$$\Gamma(K_S \to \ell^+\ell^-) = \frac{m_K \beta_\ell}{8\pi}\left(|A|^2 + \beta_\ell^2 |B|^2\right)$$

$$\beta_\ell = \left(1 - \frac{4m_\ell^2}{m_K^2}\right)^{1/2}$$

S-wave (↑ $|A|^2$)

~~Long-distance (2γ)~~

\+

CPV Short-distance (↔ NP)

- *Sub-leading within the SM*
- *Not directly bounded by* $K_L \to \mu\mu$

Ecker, Pich, '91
G.I, Unterdorfer, '04

P-wave (↑ $|B|^2$)

Long-distance (2γ) dominated

- *Calculable with good accuracy*
- *Not interfering with short-distance*
- *Leads to tiny SM rates:*

$BR(K_S \to \mu\mu)_{SM} \sim 5\times10^{-12}$
$BR(K_S \to ee)_{SM} \sim 2\times10^{-14}$

Gino Isidori

- On the other hand, having not seen anything so far, we can relax pessimistic assumptions about flavor mixing beyond the SM (such as MFV) → flavor physics remains an essential ingredient in the (*difficult*...) search for physics beyond the SM → worth to look in all possible channels without too strong theoretical prejudices...

- Worth to extend the kaon physics program of LHCb, even if only focused on discovering/constraining exotic NP models

My interpretation: please keep surprising us.