BSM with kaons

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At the dentist

The dentist, kaons, and the fundamental laws of nature

The big picture

- The SM is amazing
- We really understand how nature works

What next?

- What extends the SM
- Understanding QCD

Kaon physics helps in both

How to get to these goals?

- What extends the SM
  - Fishing expeditions for new particles
  - Precise measurements
- Understanding QCD
  - Using the weak interaction as input to QCD

Kaon physics helps in all

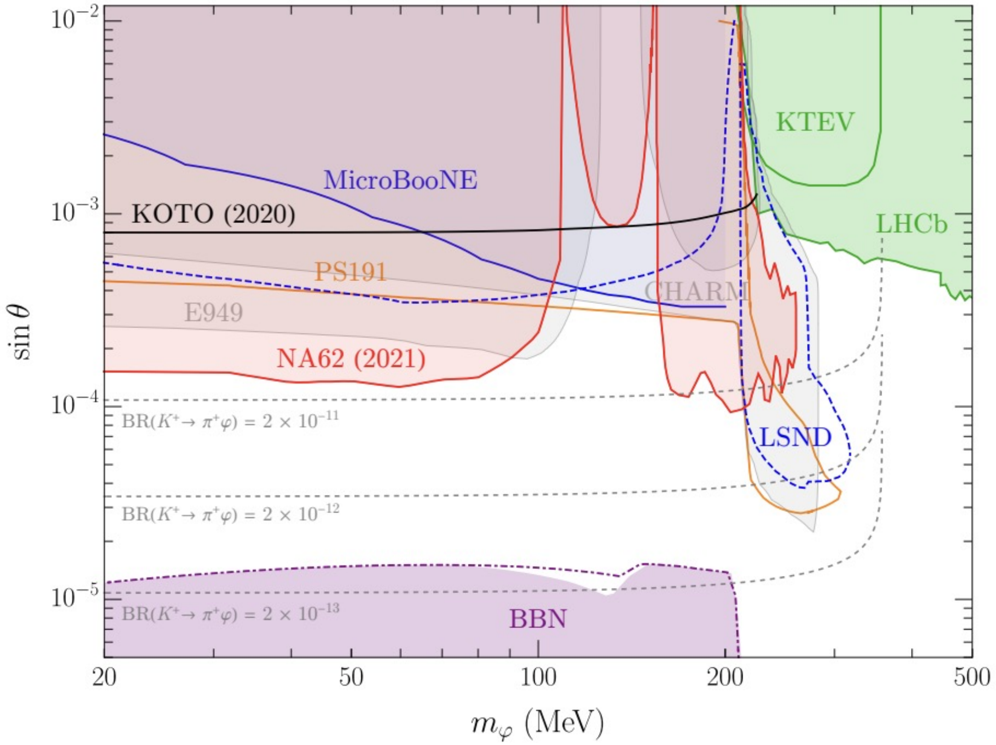
Kaons to the rescue

- We need a "kaon factory". Multi purpose experiment like the B-factories. A lot of different analyses
  - New particles: very weakly interactive with mass of order m_K
  - Precise measurements: Get the CKM from kaons alone
  - QCD: kaon decay rates and spectra

Kaons and new particles

Kaon decays to new light particles

- The big review: arxiv:2201.07805.
- Probing a scalar mixing with the Higgs



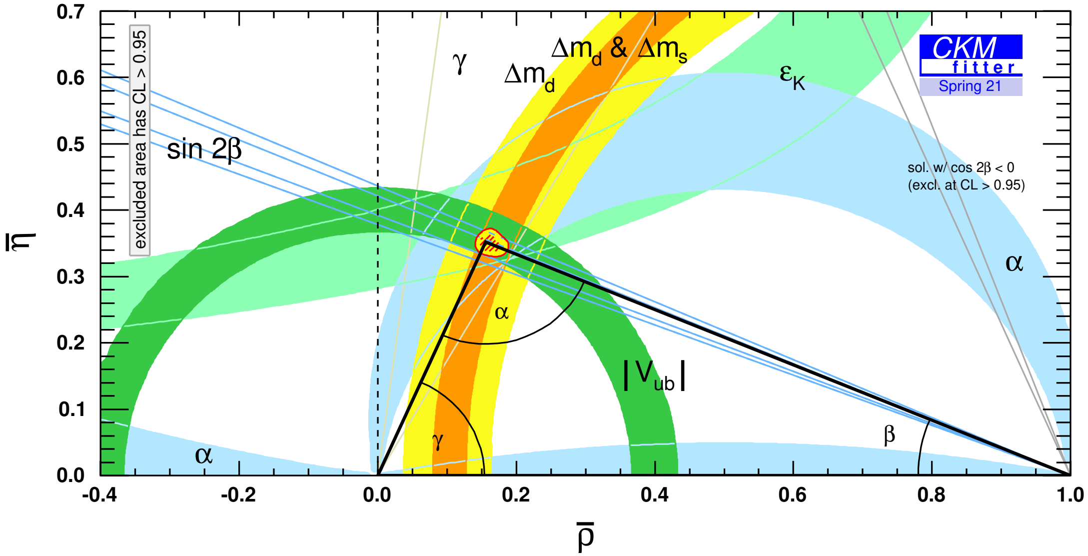
Why kaons?

- We can use both Kaons
- You generate a lot of them
- They have a very narrow width, so we can probe very small couplings
- They probe a unique mass range
- No need to "assume" flavor violation. Only if we are unlucky and it is small we cannot probe it

Kaon factories are unique in our search for light particles

Kaons and flavor

Why is that?



- Almost everything in the plot is from B
- We would love to get it from kaons
  - Diferent experimental issues
  - Different theoretical issues
  - Different sensitivty to BSM physics

The golden modes $K \to \pi\nu\bar{\nu}$

We have a very nice program with $K \to \pi\nu\bar{\nu}$

- It is very hard experimentally
- But it is very clean theoretically
- We can get (roughly)
  - $|V_{td}V_{ts}|$ from $K^+ \to \pi^+\nu\bar{\nu}$
  - $Im(V_{td}V_{ts}^*)$ (or η) from $K_L \to \pi^0\nu\bar{\nu}$

“Theoretically clean, experimentally hard”

The third golden mode: $K \to \mu^+\mu^-$

I am excited about $K \to \mu^+\mu^-$

D'Ambrosio, Kitahara, 1707.06999

Dery, Ghosh, YG, Schacht, 2104.06427

Dery, Ghosh, 2112.05801

Brod, Stamou, 2209.07445

Dery, Ghosh, YG, Kitahara, Schacht, 2211.03804

The bottom line:

We can very cleanly measure $Im(V_{td}^* V_{ts}) \sim \eta$ from $K \to \mu^+\mu^-$

- It is hard to find theoretical clean observables
- It seems that it can be done
- Complamantary to $K_L \to \pi\nu\bar{\nu}$

What about $K \to \mu^+\mu^-$?

- It is considered to be
  "theoretically not-clean, experimentally not-hard"
- Using the interference terms we can make it
  "theoretically clean, experimentally hard"
- We can get sensitivity to the same CKM combination as we have in $K_L \to \pi^0 \nu\bar{\nu}$ (that is η)
- The only hadronic uncertainty lies in f_K. Thus, it is very clean theoretically
- Experimentally, it is not simple to measure the interference terms, but a study is needed

The physics of $K \to \mu^+\mu^-$

The problem

How to get around QCD?

- There are Long Distance (LD) effects that we cannot calculate cleanly
- We have estimates of these effects, but with large uncertainties $> 10\%$
- We need to get to the level of 1% to be “clean”
- We know how to calculate the Short Distance (SD) physics cleanly
- How can we measure the SD physics?

The basics of $K \to \mu^+\mu^-$

Before we start: We neglect ϵ_K everywhere

Angular momentum conservation implies that we have only $\ell = 0$ and $\ell = 1$ final states

- CP conservation decays

$$K_L \to (\mu\mu)_{\ell=0}, \qquad K_S \to (\mu\mu)_{\ell=1}$$

- CP violating decays

$$K_S \to (\mu\mu)_{\ell=0}, \qquad K_L \to (\mu\mu)_{\ell=1}$$

$K \to \mu^+\mu^-$ in the SM

In the SM (to a good approximation)

- The LD effects are CP conserving
  - The CP violating amplitudes are purely SD
- We have CP violation only in the $\ell = 0$ decay
  - $A(K_L \to (\mu\mu)_{\ell=1}) = 0$ since it is CP violating

We conclude

- We can cleanly calculate $K_S \to (\mu\mu)_{\ell=0}$ in the SM
- In fact we can do it in many BSM models as well

The prediction

The calculation gives

Brod, Stamou, 2209.07445

$$\mathcal{B}(K_S \to (\mu\mu)_{\ell=0}) = 1.70 \times 10^{-13} \times \left(\frac{A^2\lambda^5\eta}{1.3 \times 10^{-4}}\right)$$

- Hadronic uncertainties from f_K are less than 1%
- The numerical value is known from SD calculations
- Blue is theoretically clean
- We have a theoretically clean determination of η

How to measure the SD physics?

The problem: We cannot separate $\ell = 0$ from $\ell = 1$

The solution: Look at the time dependence

A generic time dependence for K decay $[\Gamma = (\Gamma_S + \Gamma_L)/2]$

$$\left(\frac{d\Gamma}{dt}\right) \propto C_L e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t}$$
$$+2\left[C_{sin}\sin(\Delta m t) + C_{cos}\cos(\Delta m t)\right] e^{-\Gamma t}$$

- The C's are observables
- They depend on the final state, and they are calculated theoretically from the decay amplitudes

All those Cs

$$\left(\frac{d\Gamma}{dt}\right) \propto C_L e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t}$$
$$+2\left[C_{sin}\sin(\Delta m t) + C_{cos}\cos(\Delta m t)\right] e^{-\Gamma t}$$

- C_L is related to K_L decay rate
- C_S is related to K_S decay rate
- C_{sin} and C_{cos} are due to interference
- For a $\overline{K}$ beam the sign of C_{sin} and C_{cos} is flipped
- CP conservation implies $C_{sin} = C_{cos} = 0$

In the SM

$$\left(\frac{d\Gamma}{dt}\right) \propto C_L e^{-\Gamma_L t} + C_S\, e^{-\Gamma_S t}$$
$$+2\left[C_{sin}\sin(\Delta m t) + C_{cos}\cos(\Delta m t)\right] e^{-\Gamma t}$$

$$\begin{aligned} C_L &= |A(K_L)_{\ell=0}|^2 \\ C_S &= |A(K_S)_{\ell=0}|^2 + |A(K_S)_{\ell=1}|^2 \\ C_{cos} &= Re[A(K_S)_{\ell=0} \times A^*(K_L)_{\ell=0}] \\ C_{sin} &= Im[A(K_S)_{\ell=0} \times A^*(K_L)_{\ell=0}] \end{aligned}$$

Then, we can get the clean amplitude

$$|A(K_S)_{\ell=0}|^2 = \frac{C_{cos}^2 + C_{sin}^2}{C_L}$$

The clean information

We can write it as

$$\mathcal{B}(K_S \to (\mu^+\mu^-)_{\ell=0}) = \mathcal{B}(K_L \to \mu^+\mu^-) \times \frac{\tau_S}{\tau_L} \times \frac{C_{cos}^2 + C_{sin}^2}{C_L^2}$$

- Most of what we need is already measured
- We still need the interference terms

We know how to cleanly extract η

Experimental considerations

How to get the interference?

The problem: the interference terms in K and $\overline{K}$ have opposite signs

- We need an asymmetric (in K vs $\overline{K}$) beam
- How can we do it?
  - QCD production with a K vs $\overline{K}$ asymmetry (NA48 reported about 30% asymmetry)
  - Regeneration in K_L beams
  - Charge exchange target in order to generate a pure K beam from a K^+ beam
  - Flavor tagging in high energy production

It seems the first option is the best

A K_S beam

- We need a K_S beam
- We need asymmetrical production of K vs $\bar{K}$
- We need a lot of kaons

A very preliminary study: with 10^5 $K \to \mu\mu$ events, in the SM

Jacinto, Marchevski

$$\frac{\Delta\eta}{\eta} \approx 23\%$$

$K \to \mu\mu$ beyond the SM

BSM

Dery, Ghosh, 2112.05801

- Can have large effects. There is no GN-type bound on that case
- The best bound comes from LHCb bound on the rate of $K_S \to \mu\mu$
- "It is easy" to generate an $O(10)$ effect
- A preliminary study finds that with 10^5 $K \to \mu\mu$ it will be a very clear signal of BSM physics

Jacinto, Marchevski

Conclusions

Why kaons?

- Kaons can be used to address the two biggest open question in HEP
- They have unique probing power
- $K \to \mu^+\mu^-$ gives the same information as $K_L \to \pi^0\nu\bar{\nu}$, and I hope it will be studied