Flavor physics

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Flavor at a junction

Every end is a new beginning

- End: The Nobel to KM is a “formal declaration” that the CKM picture of flavor is correct
- Beginning: Looking for corrections to the SM picture of flavor

Outline

- The new physics flavor problem
- Current status of the SM flavor sector
- The highlight of recent results: $D-\overline{D}$ mixing
- The new goal of flavor physics: going beyond the SM

The new physics flavor problem

The SM is not perfect...

- We know the SM does not describe gravity
- At what scale it breaks down?

We parametrize the NP scale as the denominator of an effective higher dimension operator. The weak scale is roughly

$$\mathcal{L}_{\rm eff} = \frac{\mu\, e \nu \bar\nu}{\Lambda_W^2} \Rightarrow \Lambda_W \sim 100 \text{ GeV}$$

- The effective scale is roughly the masses of the new fields times unknown couplings
- Flavor bounds give $\Lambda \gtrsim 10^4$ TeV

The flavor bounds

Q: Why the flavor bounds are so tight, $\Lambda \gtrsim 10^4~\mathrm{TeV}$?

A: Because in the SM there are many suppression factors (and the data agree with the SM)

$$\frac{m_c^2}{m_W^2}\,\frac{1}{16\pi^2}\,\alpha_W^2\,V_{us}^2\,\arg(V_{us}) \sim 10^{-10}$$

- The naive scale of the operator that generate ϵ_K is $\Lambda \sim 10^4~\mathrm{TeV}$
- In the SM there is a suppression of 10^{-10}, so the mass scale is five order of magnitudes smaller, $100~\mathrm{GeV}$

Flavor and the hierarchy problem

There is tension:

- The hierarchy problem $\Rightarrow \Lambda \sim 1$ TeV
- Flavor bounds $\Rightarrow \Lambda \gtrsim 10^4$ TeV

Any TeV scale NP has to deal with the flavor bounds

$$\Downarrow$$

Such NP cannot have a generic flavor structure

Flavor is mainly an input to model building, not an output

Dealing with flavor

Any viable NP model has to deal with this tension. Thus, the NP at the TeV must not be generic

- At what level we expect to see deviations from the SM predictions?
- There is no simple answer. Naively, we should have seen it already
- One class of models can accommodate "large" flavor violations. That is, as large as current bounds
- The other is Minimal Flavor Violation (MFV): The NP at the TeV has minimal impact on flavor
- Roughly, even in MFV we expect $O(1\%)$ effects. Clearly the exact numbers and modes are important

The goal of flavor physics

Flavor physics must look for problems with the SM in order to see the nature of the NP

- “Past”: Confirmation that the SM explain flavor physics at leading order
- “Future”: Looking for small deviations from the SM predictions. As a rough guideline aiming at the 1% level
- The main issue is theoretical uncertainties, that is, QCD. The name of the game is to try to overcome QCD and get to the fundamental physics

Current status of the SM flavor sector

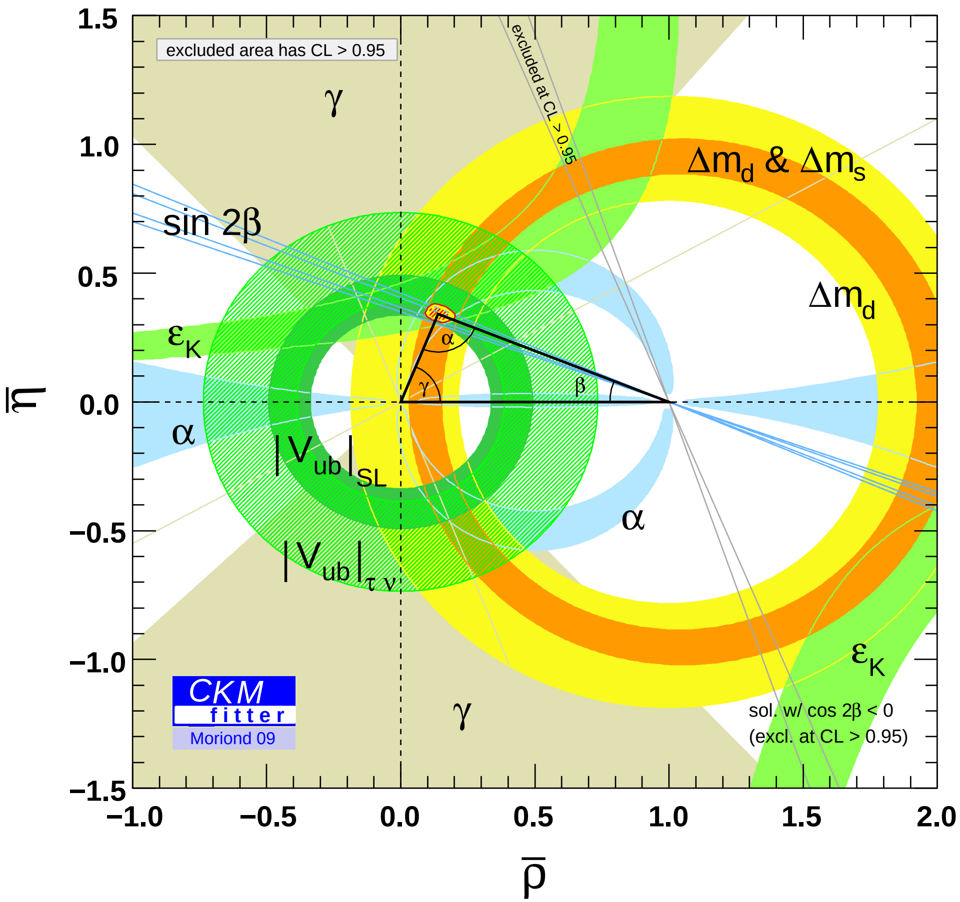
The SM flavor sector

At present there are no significant deviations from the SM predictions in the flavor sector

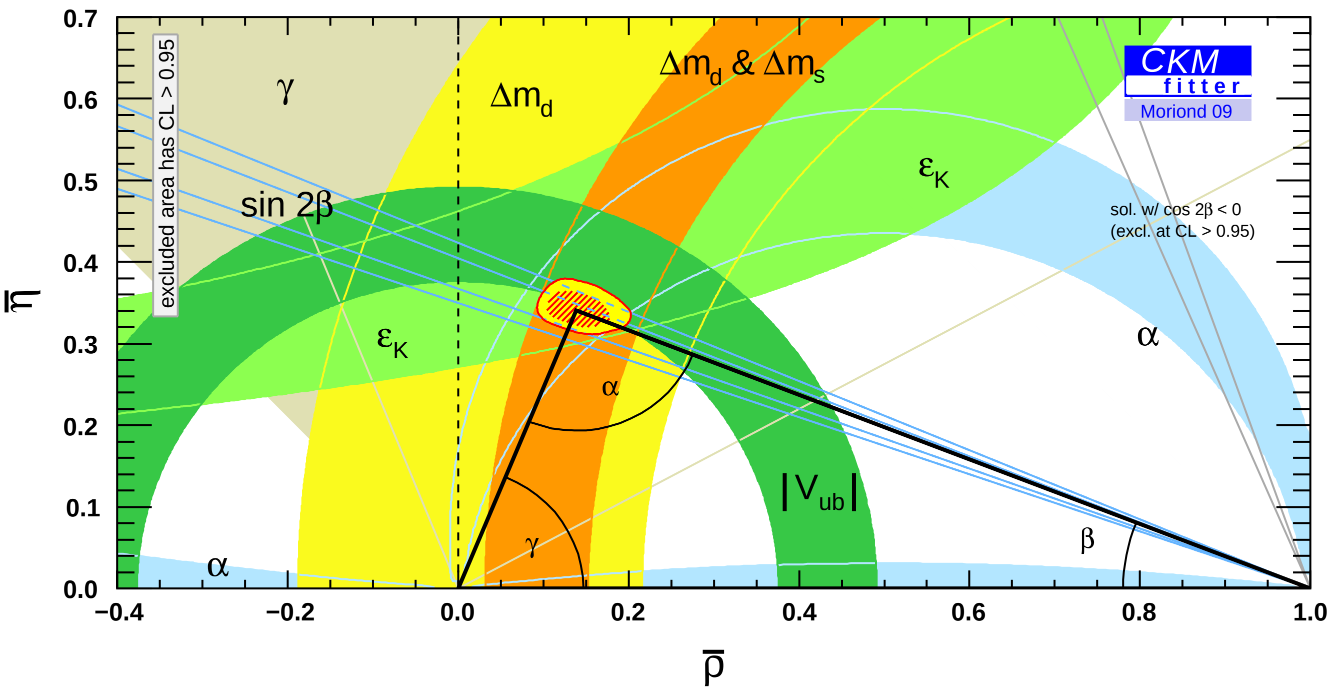
Even the hints we had in the last few years are now weaker

- Global fit
- $a_{\rm CP}(B \to \psi K_S)$ vs $a_{\rm CP}(B \to \phi K_S)$
- $B \to K\pi$
- Polarization in $B \to VV$

Current status of the global fit



Global fit: closer look



- Very impressive agreement
- One "small" problem: The rate of $B \to \tau\nu$

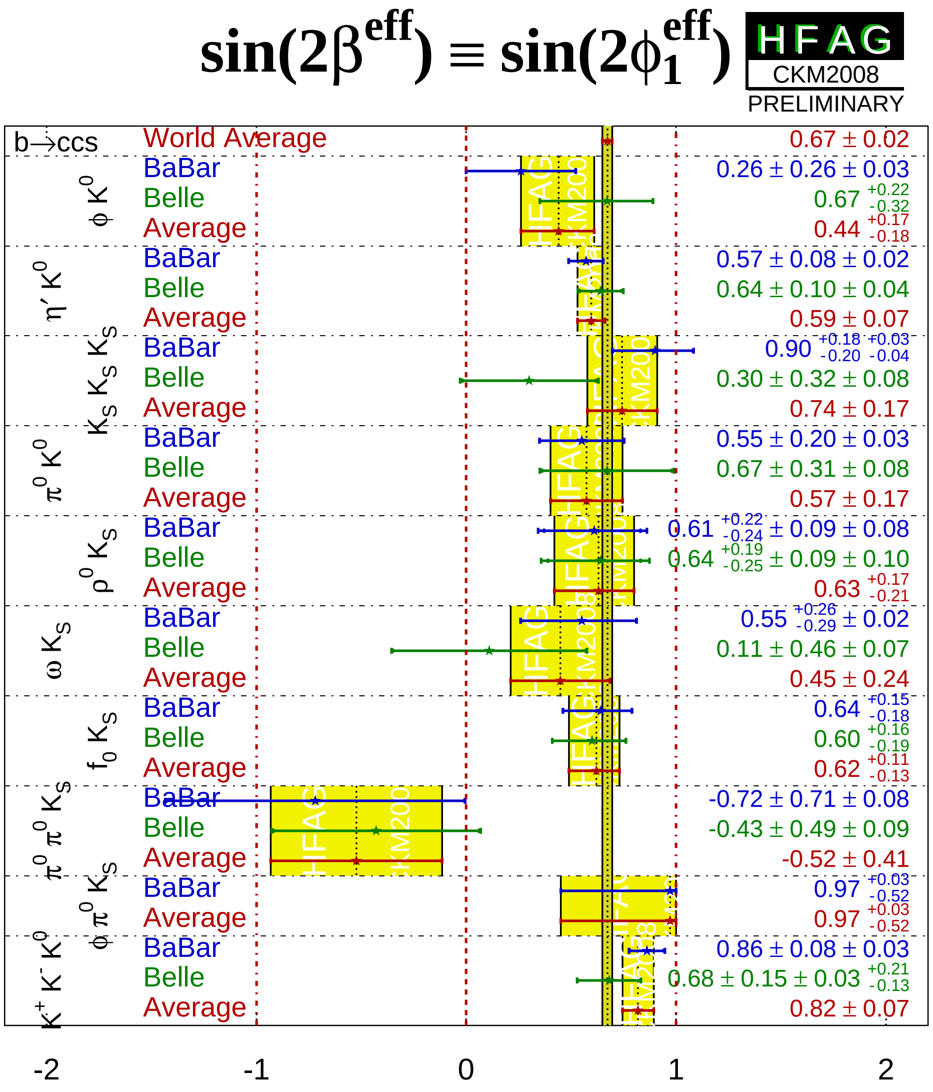
CP asymmetries in $b \to s\bar{s}s$ modes

- Time dependent CP asymmetries measure the phase between the mixing and twice the decay amplitudes
- In the SM
  - $\arg(A_{mix}) = 2\beta$
  - $\arg(A_{b\to c\bar{c}s}) = 0$ (Tree) $\quad B \to \psi K_S$
  - $\arg(A_{b\to s\bar{s}s}) = 0$ (Penguin)
    $B \to \phi K_S$, $B \to \eta' K_S$...
- To first approximation the SM predicts

$$a_{\rm CP}(B \to \psi K_S) = a_{\rm CP}(B \to \phi K_S) = \sin 2\beta$$

- The theoretical uncertainties are small, roughly, $O(5\%)$

$b \to s\bar{s}s$ data



- Combine ($< 1\,\sigma$)

$$S_P = 0.64 \pm 0.04$$

$$S_T = 0.67 \pm 0.02$$

$B \to K\pi$

Consider the four decays

$$
\begin{array}{lll}
B^+ \to K^0\pi^+ & b \to d\bar{d}s & \\
B^+ \to K^+\pi^0 & b \to d\bar{d}s \quad \text{or} & b \to u\bar{u}s \\
B^0 \to K^+\pi^- & b \to u\bar{u}s & \\
B^0 \to K^0\pi^0 & b \to d\bar{d}s \quad \text{or} & b \to u\bar{u}s
\end{array}
$$

- There are many SM relations between these modes
- To first approximation, all the rates are equal since the penguin diagram dominate
- The data used to be “problematic”, but not any more
- One problem is $A_{K^+\pi^0} - A_{K^+\pi^-} = 0.15 \pm 0.03$

The status of the SM flavor sector

- Overall, the SM is very successful in describing flavor
- At present there are no real hints for NP at the flavor sector
- We did not really expect deviation at that level. Need to go to the next level
- Eventually, theory will be the limiting factor (not there yet)

New flavor results: $D - \bar{D}$ mixing

$D - \bar{D}$ mixing

Not easy since the mixing is very small

$$x \equiv \frac{\Delta m}{\Gamma} \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

- First observation of the mixing
- It was found by combining several decay modes

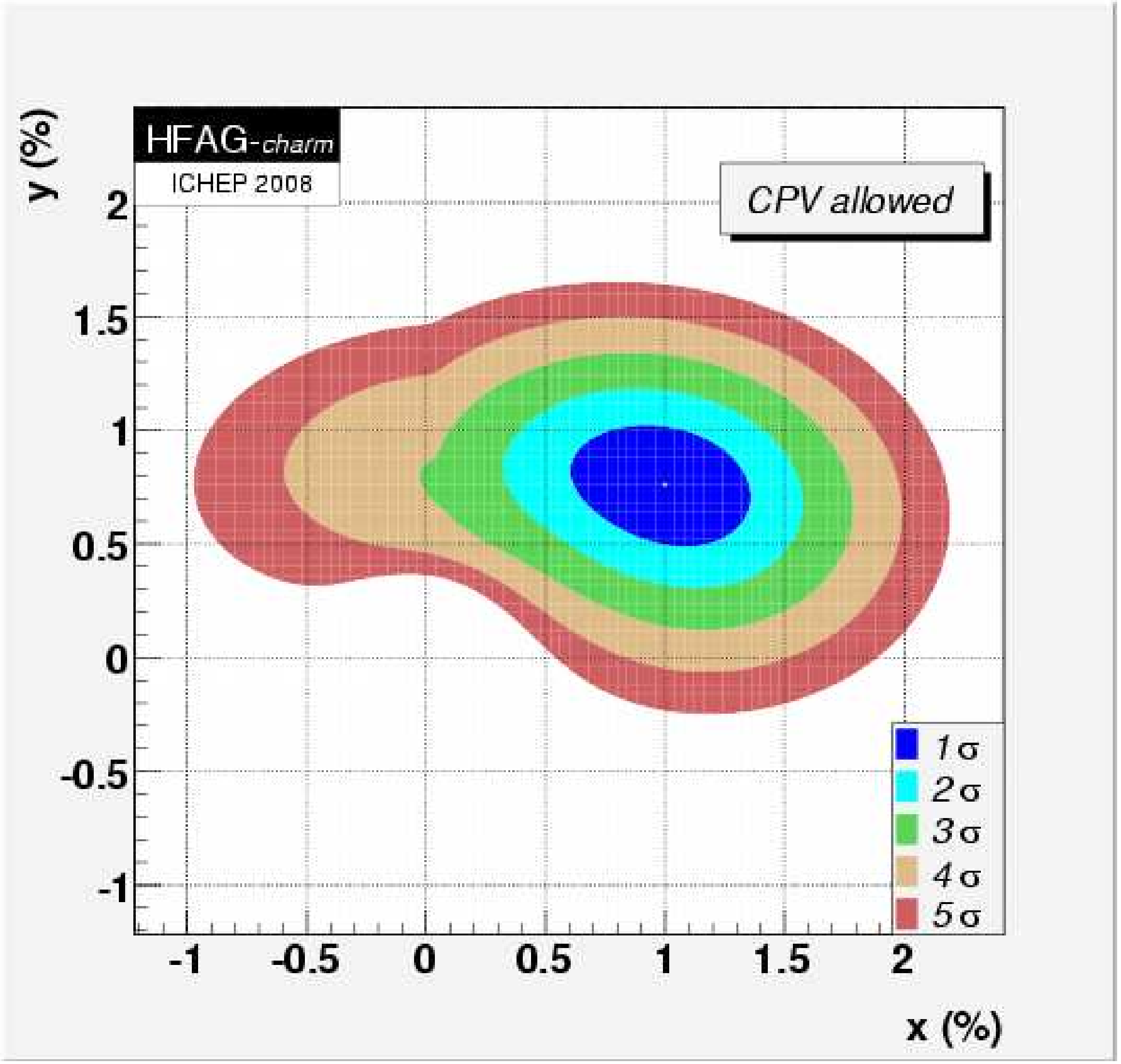
$$D \to K^+K^- \quad D \to \pi^+\pi^- \quad D \to K\pi\pi \quad D \to K\pi$$

- More than 5σ signal for oscillation in the combined fit

$$x \sim y \sim 1\%$$

- No signal for CPV

$D - \bar{D}$ mixing: data



$D - \bar{D}$ mixing: Theory

Two parameters

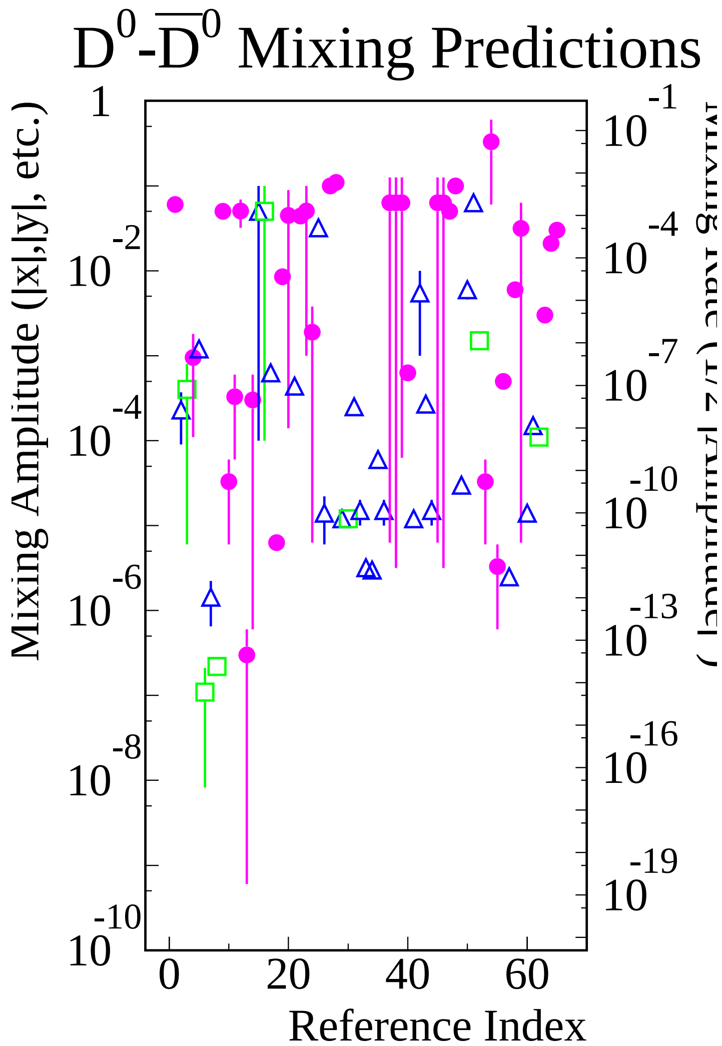
$$x \equiv \frac{\Delta m}{\Gamma} \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

Can we calculate them in the SM?

- Very hard to calculate. The charm is not really heavy and not really light
- The only robust SM prediction is that there is no CPV

$D - \overline{D}$ mixing predictions

H. Nelson,hep-ex/9908021



● : NP predictions for x

△ : SM predictions for x

□ : SM predictions for y

$\mathrm{SU}(3)$ breaking

- The contribution form the third generation is negligible
- $D-\overline{D}$ mixing vanishes in the flavor $\mathrm{SU}(3)$ limit (GIM mechanism)
- It arises only at second order in $\mathrm{SU}(3)$ breaking

$$x, y \sim \sin^2\theta_C\, \varepsilon^2_{\mathrm{SU}(3)} \qquad \varepsilon_{\mathrm{SU}(3)} \sim \frac{m_s}{\Lambda}$$

What is Λ?

- $\Lambda \sim m_c \;\Rightarrow\; x, y \lesssim 10^{-3}$
- $\Lambda \sim Q \ll m_c \;\Rightarrow\; x, y \lesssim 10^{-2}$

The larger value is preferred

Still, we can learn a lot

- Any signal of CPV is a signal on NP
- Already now, the combination of K and D bounds put significant bounds on NP models. TeV scale NP must have some amount of universality
- The pattern of CPV can teach us about the NP. For example, if the NP is only significant in the mixing we have

$$yA_{CP}(D \to K\pi) = xA_{SL}$$

The future of flavor physics

What next for flavor physics?

- We need to aim at the 1% level to find deviations from the SM
- Can we go below the 1% level?
- Experimentally. Yes (but I am not going to talk about it)
- Theoretically. Yes!
  - $B \to DK$
  - $B_s \to \psi\phi$
  - CPV in D decays
  - $K_L \to \pi^0 \nu\bar{\nu}$
  - ...

Conclusions

Conclusions

- It is not easy to understand why the SM describes flavor so well
- A very rough prediction is that we will see deviation at or above the 1% level
- There are few modes that give superb theoretical predictions, and we can go and probe flavor below the 1% level