Flavor Physics in the New Decade

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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

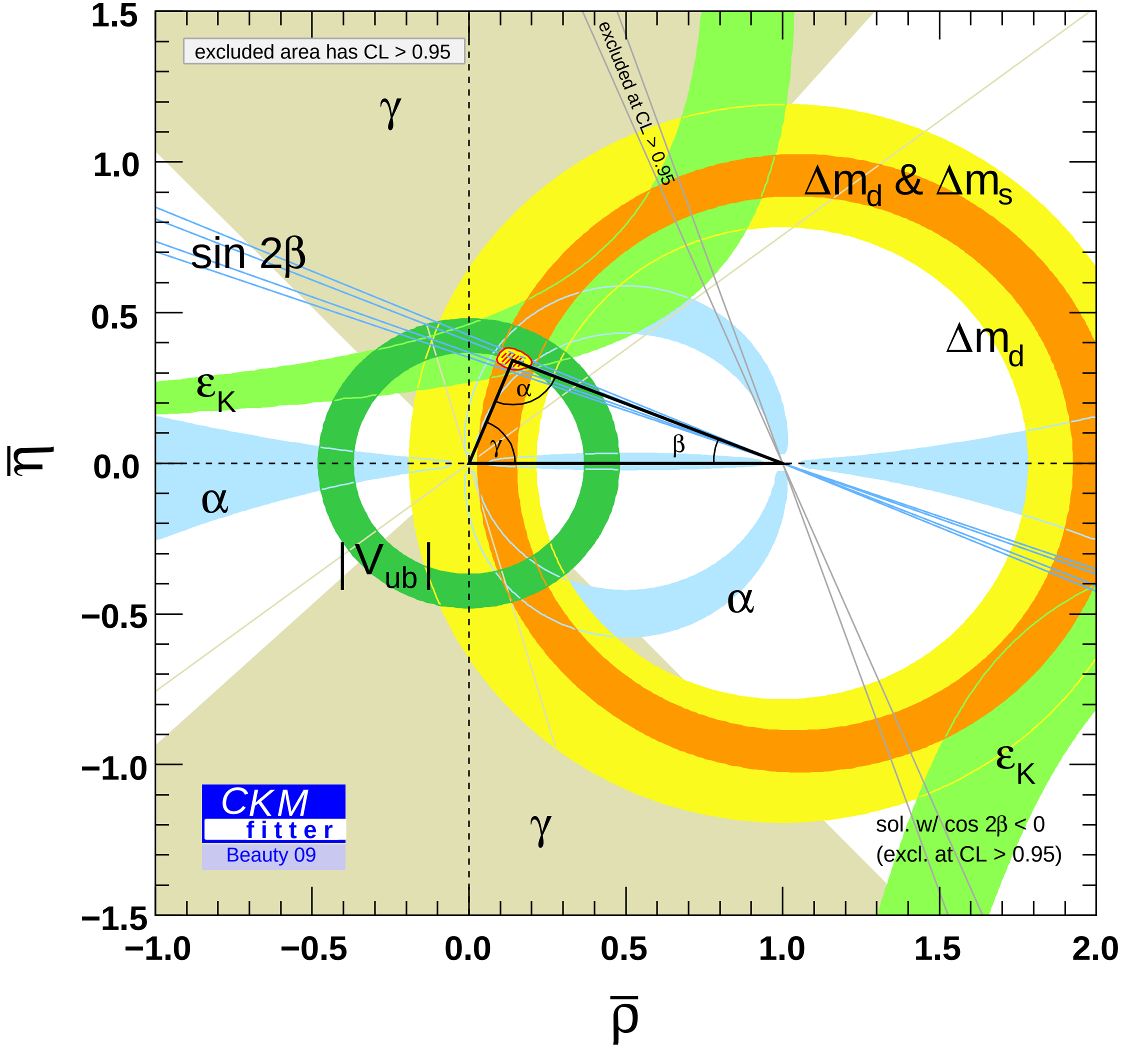
- Current status of the SM flavor sector
- The new physics flavor problem
- The new goal of flavor physics: going beyond the SM
- Some possible future analysis: $B \to DK$ and $K \to \pi\nu\bar{\nu}$
- Conclusion

Current status of the SM flavor sector

The SM flavor sector

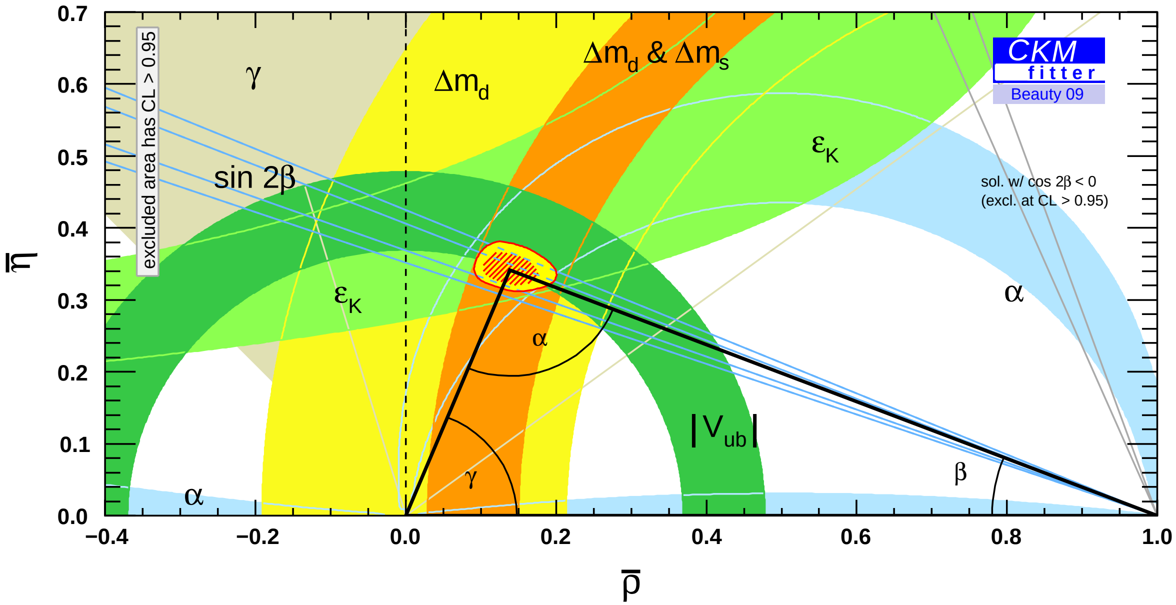
At present there are no significant deviations from the SM predictions in the flavor sector

Global fit



excluded area has CL > 0.95
γ
excluded at CL > 0.95
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
$|V_{ub}|$
α
ε_K
γ
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
CKM fitter
Beauty 09
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$

Global fit: closer look



- Very impressive agreement

The flavor problem

Problems are good

The SM is not perfect...

- We all know the SM has its issues
- 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

The new physics scale

- Baryon and lepton number violating operators. From proton decay data

$$\frac{QQQL}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{16}\ \text{GeV}$$

- Flavor and CP violating operators

$$\frac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{7}\ \text{GeV}$$

- Electroweak data

$$\Lambda \gtrsim 10^{3}\ \text{GeV}$$

Exact and broken symmetries

There is a fundamental difference between the first and the last two

- Baryon and lepton numbers may be exact symmetries. Thus, the new operators may be small due to the high scale or due to a symmetry.
- Flavor symmetry and custodial symmetry are known to be broken by the SM. There cannot be an exact symmetry that protects the new operators

These two scales are associated with hierarchy problems

- The new physics flavor problem
- The little hierarchy problem

The flavor bounds

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

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

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

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

The new physics flavor 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

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, 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 future of flavor physics

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”:
  - If we are lucky we will be able to look for “new flavor”, for example with squarks
  - More traditionally, we will look for small deviations from the SM predictions. As a rough guideline aiming at the 1% level
  - We talk about “measuring CKM parameters,” but we are looking for new physics

High energy flavor

Q: Say we find new physics at the LHC. Can we look for its flavor structure directly?

- Not easy...
- Still we can hope to measure some flavor decay rates
- In some case we can predict some properties of the spectrum

Experimental future

There are several upgraded and new experiments

- LHCb
- CDF, D0, Atlas and CMS
- Super-Belle
- tau-charm machine at China, BES-3
- More future machines (project-X, Italian super-flavor machine)

Future of low energy flavor

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

- More precise measurements of things we already did
- New measurements, in particular with D and B_s
  - $B \to DK$
  - $K \to \pi\nu\bar{\nu}$
  - D Mixing and rare charm decay
  - B_s decays
  - Rare and CPV in B
  - ...

$$B \to DK$$

The basic of $B \to DK$

Very clean way to measure γ

$$B^+ \to DK^+ \to f_D K^+ \quad \text{and} \quad B^+ \to \overline{D} K^+ \to f_D K^+$$

- f_D can be a state common to D and $\overline{D}$
- In terms of quarks

$$b \to c\bar{u}s \qquad b \to u\bar{c}s$$

- The phase between the two amplitudes is γ
- The size of the two amplitudes is roughly the same
- Theory uncertainties at a level below 10^{-4}

Factorization and interference

They are both needed

- Interference: We need it in order to get CP violation
  - $B \to K\pi$: Penguin and tree
  - $B \to \psi K_S$: Mixing and decay
- Factorization: It help us calculating

$$A(B \to \psi K_S \to (\mu^+\mu^-)_\psi(\pi^+\pi^-)_{K_S}) =$$
$$A(B \to \psi K_S)A(\psi \to \mu^+\mu^-)A(K_S \to \pi^+\pi^-)$$

Usually, these two do not come together

$B \to DK$: both

$B \to DK$ is clean: we have factorization and interference

- $B \to DK$ and $D \to f_D$ amplitudes factorized
- $B \to DK$ and $B \to \overline{D}K$ interfere
- Look for n different f_D states
- Look for k different $B \to DKX$ decays
- $n + k$ amplitudes and $n \times k$ observables

All hadronic parameters can be measured

$$\Downarrow$$

No hadronic uncertainties

$$K \to \pi\nu\bar{\nu}$$

Basic of $K \to \pi\nu\bar{\nu}$

- Purely weak interaction (Z penguin)
- Dominate by internal top quark
- In the CP limit $\Gamma(K_L \to \pi^0\nu\bar{\nu}) = 0$
- Both the K^+ and K_L decays are very sensitive to CKM parameters
- Almost no hadronic uncertainties due to isospin

The future of $K \to \pi\nu\bar{\nu}$

There are several proposals to measure these decays

- Very hard. Basically, a pion with nothing
- Very small rate, of order 10^{-10}
- Very good for testing the SM. Different NP sensitivity compared to the B case

Conclusions

Conclusions

- It is not easy to understand why the SM describes flavor so well
- There are few modes that give superb theoretical predictions, and we can go and probe flavor below the 1% level