Flavor physics

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Introduction

Flavor seems to be interesting

- Fermion masses are (mainly) small and hierarchical
- Quark mixing angles are small and hierarchical
- FCNCs are very small
- The charge current is universal

How flavor can help us in finding new physics?

Outline

- The flavor problems
  - The SM flavor problem
  - The EW hierarchy problem vs the SM flavor problem
  - The NP flavor problem
- Flavor data
  - Mesons (mainly B)
  - Leptons
  - Yes undiscovered particles (sfermions)

The flavor problems

The SM flavor problem

- In the SM there is no explanation for fermion masses and mixings
- Why most of the fermion masses are much smaller than the only scale in the theory, the weak scale?
- The absent of FCNCs and universality are explained

It seems that there is a structure in the fermion parameters

The SM flavor problem

Does the structure in the fermion parameters indicate NP?

Two options:

- No. The flavor parameters are just input parameters. They are just what they are
- Yes. There is an underlying structure that explained it (for example, broken flavor symmetries)

The EW hierarchy problems

- The “natural” scale of nature is the Planck scale. The hierarchy problem:

$$\text{Why} \quad m_W \ll m_{Pl}$$

- In additional, we know that radiative corrections generate a Higgs mass close to the high scale (at or below the Planck scale). The fine tuning problem:

$$\text{Why} \quad m_H^T - m_H^{loop} \ll m_H^T + m_H^{loop}$$

Hierarchy vs fine tuning problems

- The SM flavor problem is a hierarchy problem
- The EW sector has two problems, a hierarchy and a fine tuning problems
- It is often mentioned that fine tuning problems are "more severe"
- A term used for a hierarchy problem is "technically natural". That is to say that radiative corrections do not affect the smallness of the parameter
- Small m_u is technically natural, while small m_H is not

Scale separation

Another way to put it is as follows

- Small m_u requires a small parameter at one scale
- Small m_H requires connection between two scales. That is, physics at the high (say Planck) scale is relevant to the weak scale
- Scale separation is something we are so used to. Thus, we are saying that fine tuning problems are “more severe”
- Yet, I think that both problems provide strong indications for the presence of a more fundamental theory. Therefore, I do not think one is really more sever than the other

The new physics flavor problem

The SM flavor puzzle: why the masses and mixing angles exhibit hierarchy. This is not what we refer to here

The SM flavor structure is special

- Universality of the charged current interaction
- FCNCs are highly suppressed

Any NP model must reproduce these successful SM features

The new physics flavor scale

- K physics: ϵ_K

$$\frac{s\bar{d}s\bar{d}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^4 \text{ TeV}$$

- D physics: $D-\overline{D}$ mixing

$$\frac{c\bar{u}c\bar{u}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^3 \text{ TeV}$$

- B physics: $B-\overline{B}$ mixing and CPV

$$\frac{b\bar{d}b\bar{d}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^3 \text{ TeV}$$

There is no exact symmetry that can forbid such operators

Flavor and the hierarchy problem

There is tension:

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

Any TeV scale NP has to deal with the flavor bounds

$$\Downarrow$$

Such NP cannot have a generic flavor structure

Dealing with flavor

Any viable NP model has to deal with this tension

- The NP is flavor blind, MFV (GMSB; UED)
  - Small effects in flavor physics
- Flavor suppression mainly of first two generations (Heavy $\tilde{q}$; RS)
  - Large effects in the B and B_s systems
- Generic suppression (SUSY alignment; split fermions)
  - Can be tested with flavor physics
- Generic models
  - Huge effects in flavor physics: already ruled out

Probing new physics with mesons

While we have to wait to discover the new particles, we can still indirectly probe them

- Any new physics model has to deal with flavor
- In some cases we expect large effects in meson physics
- It is plausible that we can see such effects in rare processes
  - Meson mixing
  - Loop mediated decays
  - CKM suppressed amplitudes

The quark sector

New Physics

At present there is no significant deviation from the SM predictions in the flavor sector

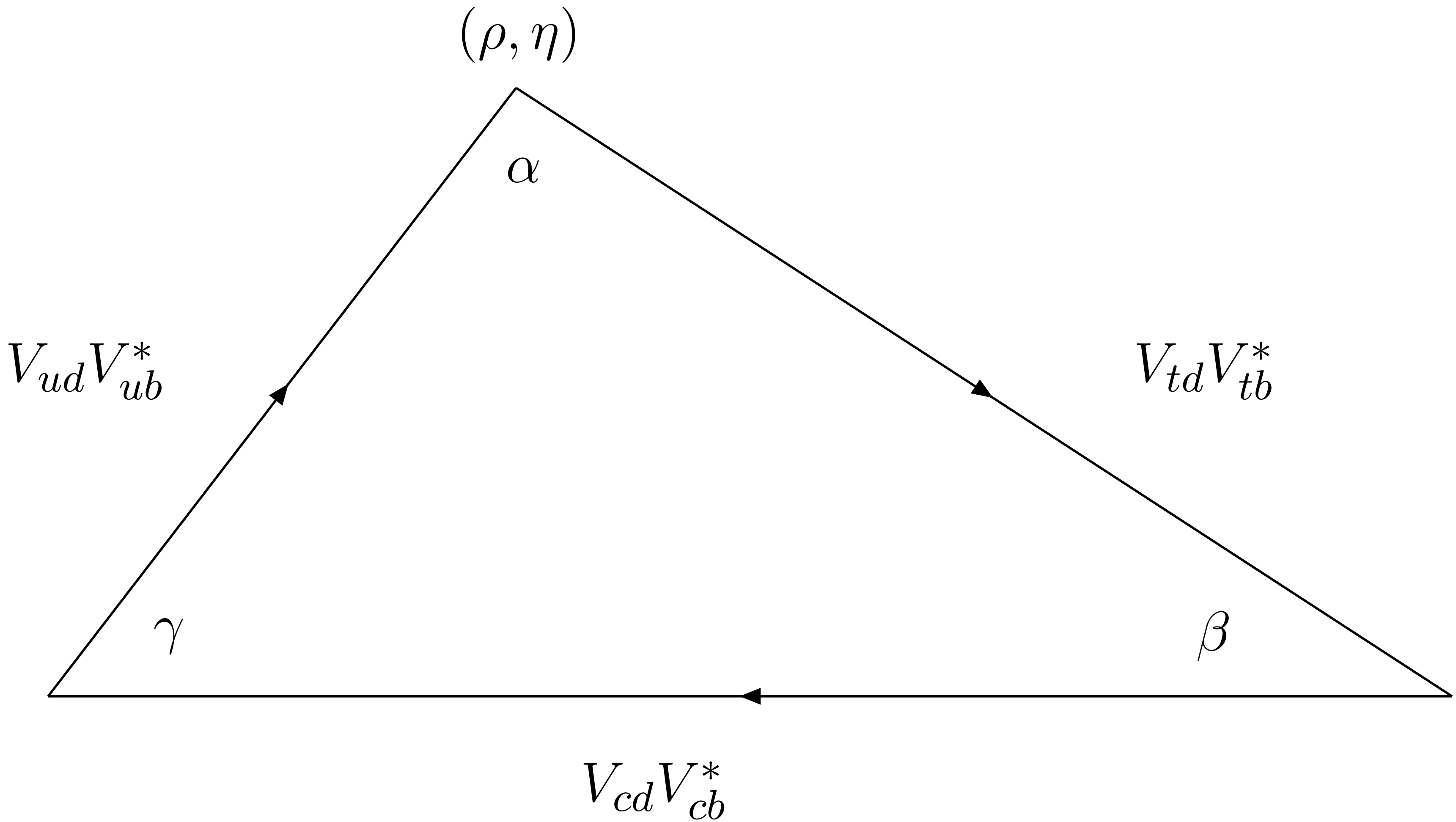
- Global fit

Yet, there are a few hints:

- $a_{\text{CP}}(B \to \psi K_S)$ vs $a_{\text{CP}}(b \to s\bar{s}s)$
- Polarization in $B \to VV$ decays
- and more...

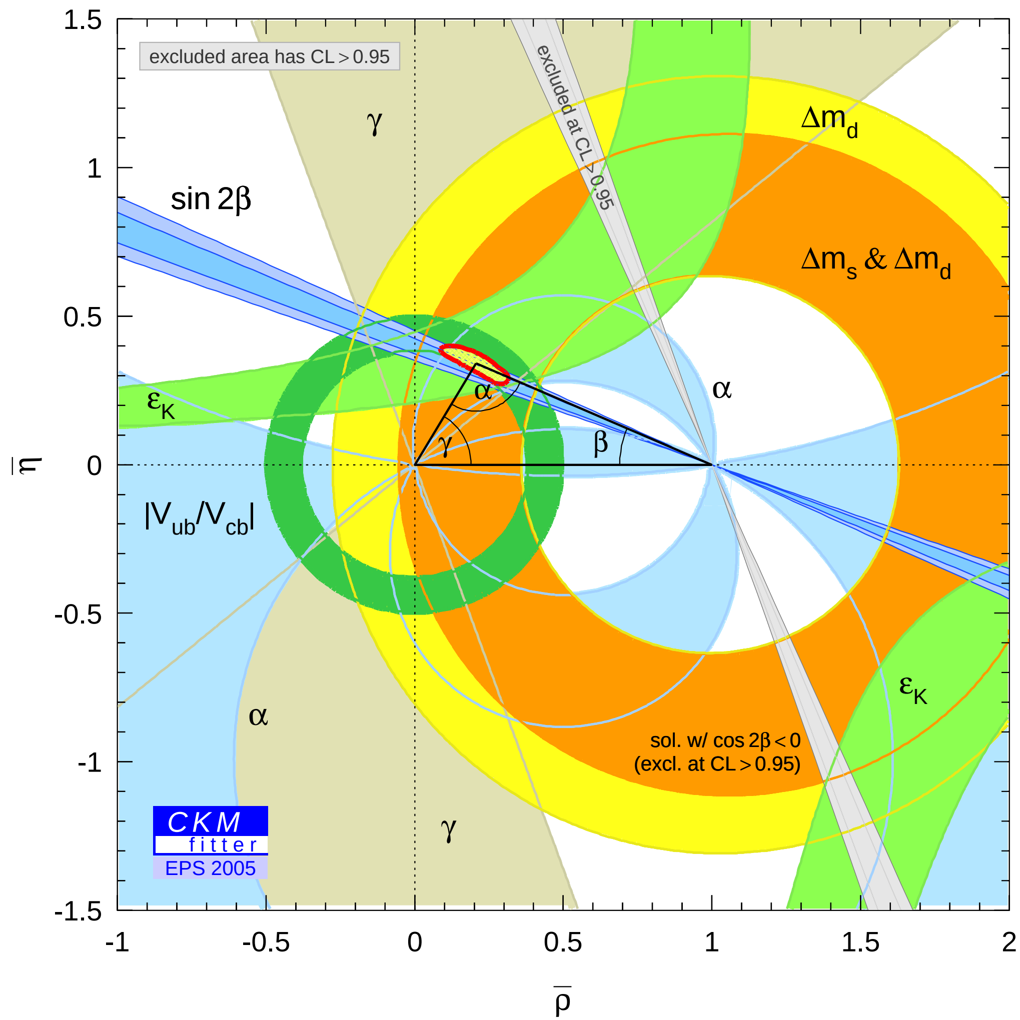
Global fit

Overconstraining the unitarity triangle



Current status of the global fit

V_{cb}, V_{ub}/V_{cb}, ε_K, B_d and B_s mixing, $a_{\rm CP}(B \to \psi K_S)$, α, γ



Hocker et al. (CKMfitter)

- Good agreement

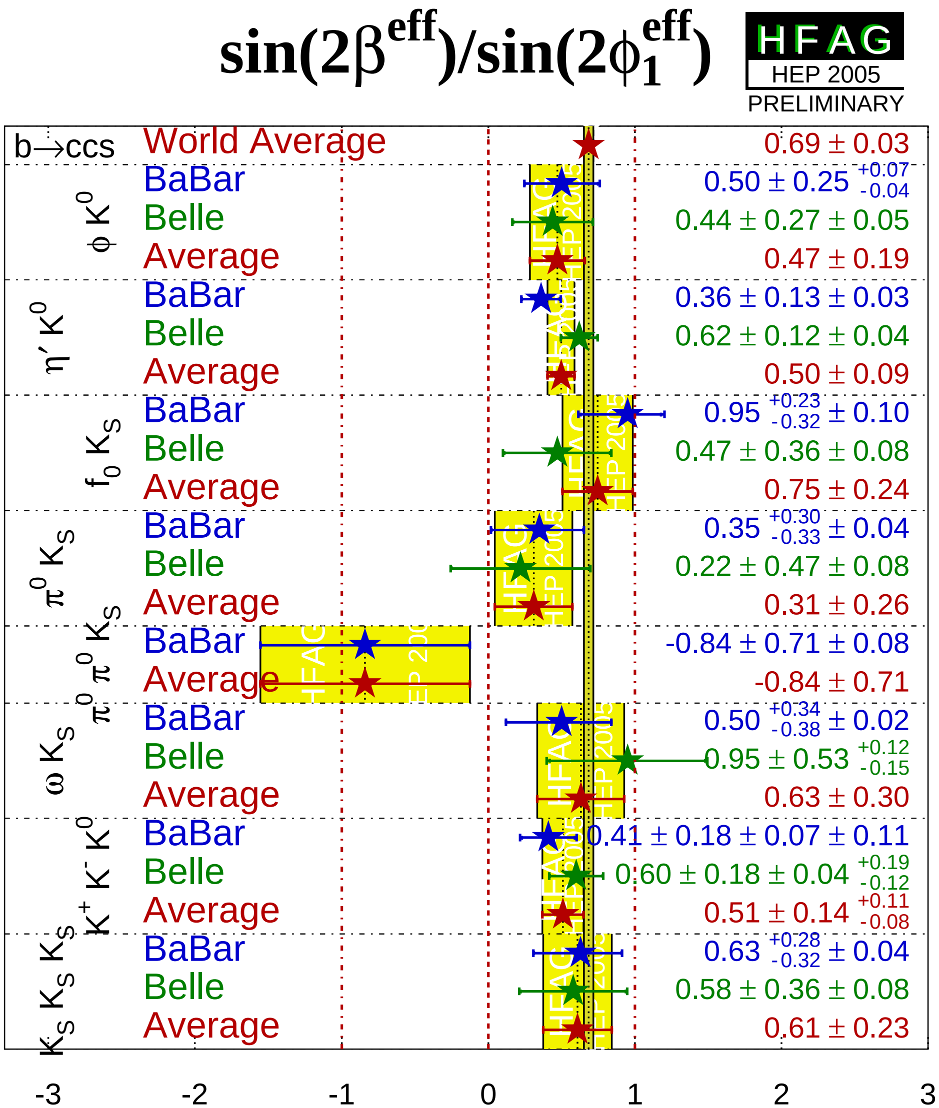
CP asymmetries in $b \to s\bar{s}s$ modes

- 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

$$a_{\rm CP}(B \to \psi K_S) = a_{\rm CP}(B \to \phi K_S) = \ldots$$

- The theoretical uncertainties, of $O(5\%)$ varies for diffrent modes

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



- Good agreement
- Naive averaging

$$S_T = 0.69 \pm 0.03$$
$$S_P = 0.50 \pm 0.06$$

- Not severe

$$S_T - S_P \gtrsim 2\sigma$$

Polarization in $B \to VV$ decays

Kagan

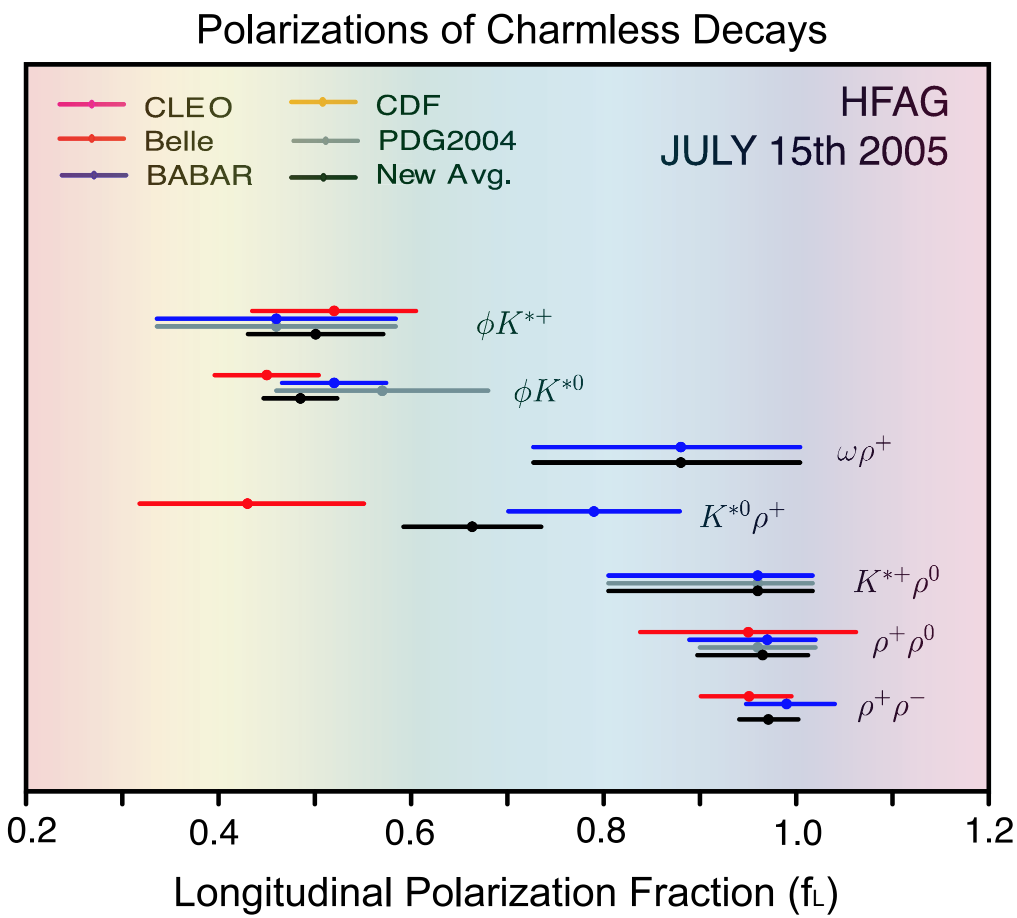
- Consider B decays into light vectors

$$B \to \rho\rho \qquad B \to \phi K^* \qquad B \to \rho K^*$$

- Due to the left handed nature of the weak interaction in the SM in the $m_B \to \infty$ limit we expect the final state to be longitudinal

$$\frac{f_T}{f_L} = O\left(\frac{1}{m_B}\right)$$

Polarization data



- Naive SM prediction:

$$f_L \sim 1$$

- Is there a problem with the penguin modes?

Explaining the polarization data

- The naive SM predictions do not hold in $B \to \phi K^*$
- This is a penguin $b \to s\bar{s}s$ decay
- SM explanation: the $1/m_B$ correction may be large for penguin amplitudes and small for tree amplitudes
- New physics explanation: right handed current operators can explain the polarization data

The lepton sector

Lepton flavor

We know much less. We are still trying to get the masses and mixing angles

- Charged lepton masses are known
- Neutrinos are massive (νSM)
- We do not know the masses (only Δm^2)
- We roughly know the value of two out of the three mixing angles, and have no idea about CPV
- It is not clear if the neutrinos parameters are hierarchical or not. We are not sure if we have a flavor problem here

leptons FCNCs

- While in the νSM neutrinos are massive, the only practical observable effect is neutrino oscillations
- leptonic GIM is very effective. In the νSM

$$\mathrm{BR}(\mu \to e\gamma) \sim 10^{-44}$$

- Searches for such processes are searches for NP

Flavor in the undiscovered sector

Flavor at the TeV

If we find NP at the TeV we may well be able to see new flavor structure. For example, low energy SUSY

- Many new types of flavors: squarks and sleptons
- There are many more flavor parameters
- Generic flavor structure is already ruled out. There must be some structure
  - The NP is flavor blind, for example, GMSB
  - New flavor physics, but there is a mechanism that suppresses it to an acceptable level

Example: SUSY

The effect on $B - \bar{B}$ mixing is of the order

$$\frac{\Delta m_{\rm SUSY}}{\Delta m_{\rm SM}} \sim 10^4 \left(\frac{100~{\rm GeV}}{m_{\tilde{Q}}}\right)^2 \left(\frac{\Delta m^2_{\tilde{Q}}}{m^2_{\tilde{Q}}}\right)^2 {\rm Re}\left[(K_L)_{13}(K_R)_{13}\right]$$

- Heavy squarks
- Degeneracy (GMSB)
- Alignment (Horizontal symmetry)

Example: SUSY effects on B

Different SUSY breaking scenarios give different flavor signals

- GMSB: Very small, $O(1\%)$, effect on $B-\bar{B}$ and $D-\bar{D}$ mixings
- Alignment: Small effect on $B-\bar{B}$ mixing and large $D-\bar{D}$ mixing
- Heavy squarks: $O(10\%)$ effect on B mixing and very small effect on $D-\bar{D}$ mixing

SUSY flavor at an ILC

Once SUSY is found, the next question is to understand SUSY breaking. Flavor can be very useful

- Not much work had been done about it
- Probably an ILC can do more about flavor than the LHC
- Lepton flavor and CPV can be probed with slepton oscillations
- It seems possible to measure squark flavor and CPV if one can measure squarks masses and decay rates

Conclusions

Conclusions

- The flavor problems are indications of new physics at a scale above the weak scale
- Searching for deviation from the SM in the flavor sector is a great way to indirectly look for new physics