Flavor physics

Yuval Grossman

Cornell
In Hebrew is may sound better

**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: $D - \bar{D}$ 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

$$L_{\text{eff}} = \frac{\mu e \nu \bar{\nu}}{\Lambda^2_W} \Rightarrow \Lambda_W \sim 100 \text{ GeV}$$

- The effective scale is roughly the masses of the new fields times unknown couplings
- Flavor bounds give $\Lambda \lesssim 10^4 \text{ TeV}$
Flavor and the hierarchy problem

There is tension:
- The hierarchy problem $\Rightarrow \Lambda \sim 1 \text{ TeV}$
- Flavor bounds $\Rightarrow \Lambda > 10^4 \text{ TeV}$

Any TeV scale NP has to deal with the flavor bounds

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
- $a_{\text{CP}}(B \rightarrow \psi K_S)$ vs $a_{\text{CP}}(B \rightarrow \phi K_S)$
- $B \rightarrow K\pi$
- Polarization in $B \rightarrow VV$
Current status of the global fit
Global fit: closer look

Very impressive 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
  
  $$\arg(A_{mix}) = 2\beta$$
  $$\arg(A_{b\to c\bar{c}s}) = 0 \text{ (Tree)} \quad B \to \psi K_S$$
  $$\arg(A_{b\to s\bar{s}s}) = 0 \text{ (Penguin)} \quad B \to \phi K_S, B \to \eta' K_S...$$

- To first approximation the SM predicts
  
  $$a_{CP}(B \to \psi K_S) = a_{CP}(B \to \phi K_S) = \sin 2\beta$$

- The theoretical uncertainties are small, roughly, $O(5\%)$
\( b \rightarrow s \bar{s}s \) data

\[
\sin(2\beta_{\text{eff}}) \equiv \sin(2\phi_1^\text{eff})
\]

**Combine (\(< 1 \sigma\))**

\[
S_P = 0.64 \pm 0.04 \\
S_T = 0.67 \pm 0.02
\]
Consider the four decays

\[ B^+ \rightarrow K^0 \pi^+ \quad b \rightarrow d \bar{d} s \]
\[ B^+ \rightarrow K^+ \pi^0 \quad b \rightarrow d \bar{d} s \quad \text{or} \quad b \rightarrow u \bar{u} s \]
\[ B^0 \rightarrow K^+ \pi^- \quad b \rightarrow u \bar{u} s \]
\[ B^0 \rightarrow K^0 \pi^0 \quad b \rightarrow d \bar{d} s \quad \text{or} \quad b \rightarrow u \bar{u} s \]

- There are many SM relations between the rates and CP asymmetries of 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
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 limited factor (not there yet).
New flavor results: $D - \bar{D}$ mixing
Not easy since the mixing is very small

\[ x \equiv \frac{\Delta m}{\Gamma} \quad y \equiv \frac{\Delta \Gamma}{2\Gamma} \]

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

\[ D \rightarrow K^+ K^- \quad D \rightarrow \pi^+ \pi^- \quad D \rightarrow K\pi\pi \quad D \rightarrow K\pi \]

- 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

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

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
$D - \bar{D}$ mixing predictions

\begin{itemize}
  \item $\bullet$: NP predictions for $x$
  \item $\triangle$: SM predictions for $x$
  \item $\square$: SM predictions for $y$
\end{itemize}

H. Nelson, hep-ex/9908021
SU(3) breaking

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

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

What is $\Lambda$?

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

Can we get better estimates?
## Inclusive vs exclusive calculations

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The data imply that

- The exclusive calculation has something in it
- The charm is probably too light for such an OPE
- The only robust test of the SM in the $D$ system is to look for CPV
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!
  - $B \rightarrow DK$
  - CPV in $D$ decays
  - $K_L \rightarrow \pi^0 \nu \bar{\nu}$
  - ...
Conclusions
Conclusions

- It is not easy to understand how come the SM describes flavor so good
- 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