Flavor and BSM physics

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Technion

$D-\overline{D}$ mixing

$D - \overline{D}$ mixing

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

Data show indications for finite y

$$y \sim 1\% \;\; (4\sigma) \qquad x \lesssim y \qquad \cancel{CP} \lesssim 1$$

- If $x \gg y$ or $\cancel{CP} \gg 10^{-3}$ we found NP!
- Assuming that $y \sim 1\%$, x is small and there is no $\cancel{CP}$, what can we learn?

WARNING!

$$4\sigma = 4\sigma$$

Calculation of x and y

- In the SM it is hard since both x and y are dominated by long distance contributions
- Still, there is one clean prediction: the SM is CP conserving to a very good approximation
- Why bother with x and y?
    - Is the charm “heavy” or “light”
    - The B is heavy: inclusive tools
    - Kaons are light: exclusive tools

Charm is light (sometimes...)

- Inclusive calculations suggest that $y \sim x \sim 10^{-3}$
- Exclusive calculations suggest that $x \lesssim y \sim 10^{-2}$

$$x, y \sim \sin^2 \theta_C \; \varepsilon_{SU(3)}^2$$

Exclusive calculations suggest that phase space effects give rise to

$$\varepsilon_{SU(3)} \sim \frac{m_s}{\text{phase space}} \sim 1 \qquad \Rightarrow \qquad y \sim 1\%$$

Even if the is no NP in $D - \overline{D}$ mixing, it still tells us

- about our ability to calculate for charm
- about the size of SU(3) breaking

Flavor and BSM physics

Introduction

Flavor is interesting

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

==> Flavor as input to new physics model building

==> How can flavor 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
- Dealing with the NP flavor problem
  - RS
  - SUSY
- Probing NP flavor
  - Low energy data (left to Buras)
  - quarks at the LHC
  - Some comments about leptons

The flavor problems

Flavor in the SM

The SM is doing great. The universal and the absence of FCNCs are explained. However,

- 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 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. Four example, broken flavor symmetries or split fermion is extra dimensions

The EW hierarchy problems

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

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

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

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

Hierarchy vs fine tuning problems

- The EW sector has two problems, a hierarchy and a fine tuning problems
- It is often stated 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
- The SM flavor problem is a hierarchy problem
- 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 indications for the presence of a more fundamental theory. The hierarchy problem is more severe since the number is smaller, and it points to the weak scale

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

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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

This tension is the NP flavor problem

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.
Basically, there are two options

- Trying to solve both the SM and NP flavor problems at once
- Solve only the NP flavor problem

Examples:

- Two birds: SUSY alignment, RS with split fermions
- Only NP: Gauge mediation SUSY breaking

Examples

Example: Randall-Sundrum

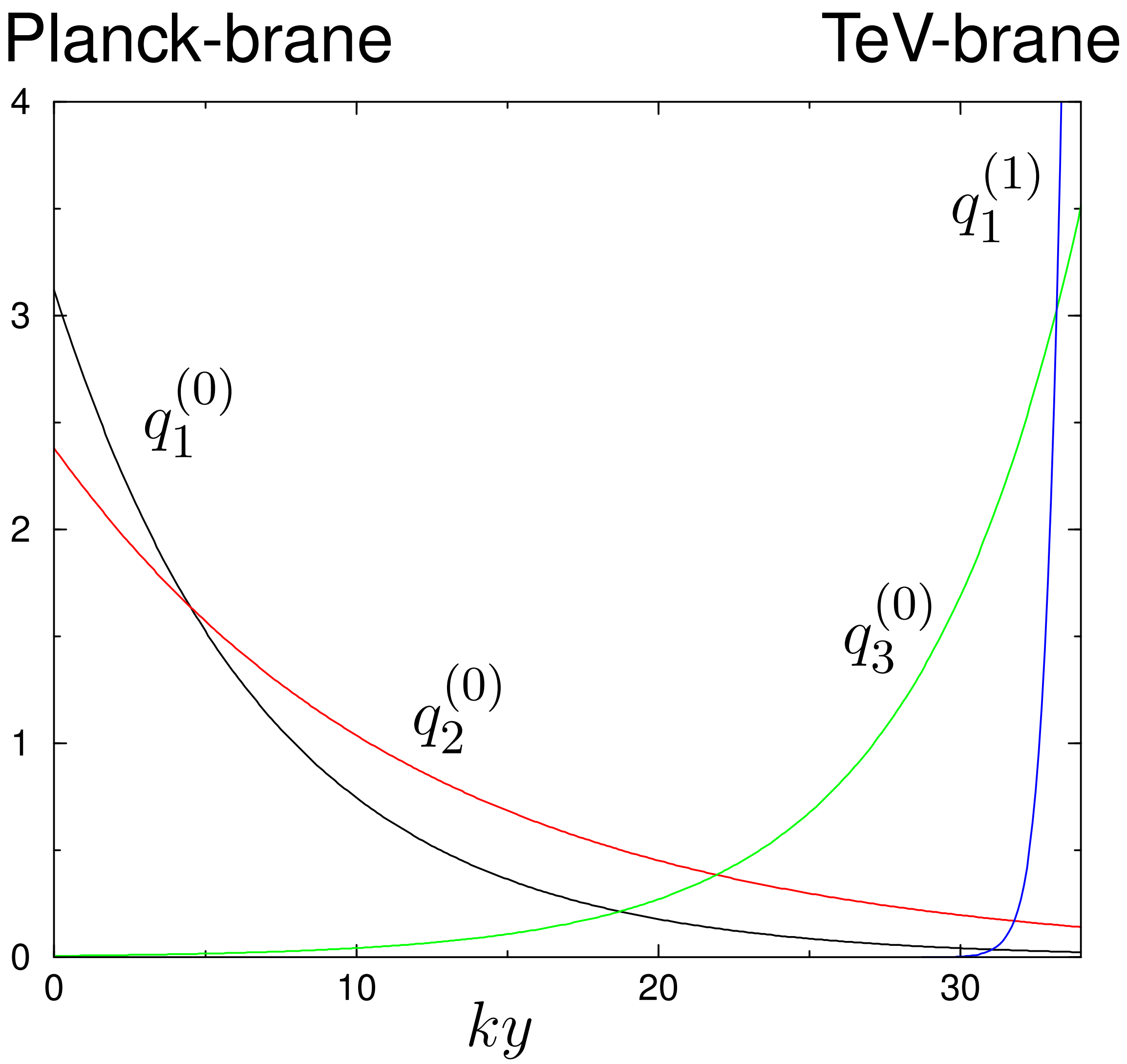
- The RS model solves the hierarchy problem with one extra non-factorizable dimension: $m = M_{\rm PL} \exp(-ky)$
- Solving the hierarchy problem requires a “TeV brane” at $ky \sim 40$, where the Higgs is localized
- Placing the fermions in the bulk can generate the observed flavor structure
- Generic new operators appear with scale of order

  $$\Lambda \sim M_{\rm PL} \exp(-ky^f)$$

  where y^f is the “localization” of the fermion f
- Heavy fermions have larger y^f and thus larger flavor violation effects

Fermions in Randall-Sundrum

Huber; Agashe et al.



- The effective NP scale is $\Lambda \sim M_{\rm PL}\exp(-ky)$
- Explain both the SM and NP problems with mild fine-tuning

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): All in one!

SUSY effects

- Each of these models give a different sparticle spectrum
- In general, once the SUSY spectrum is determined we can tell which (if at all) of these idea is at work
- The discrimination can also be done via low energy, by looking for B, D and K decays

Probing flavor

Low energy

- The new operators generated by the NP affect low energy observables
- The idea is to find observables that can be measured and have small theoretical uncertainties
- Buras will talk about it much more

Quarks at the LHC

- Once new, heavy particles are produced, their decays can teach us about flavor
- Not easy to look for flavor violating effects
- Only the top can be used (see WG1 talks)
- Very hard experimentally

Leptons

The situation with leptons may be a bit easier

- Also here, low energy and high energy are complementary
- Low energy: lepton flavor violating decays (like $\mu \to e\gamma$) and neutrino oscillation experiments
- High energy: slepton flavor oscillations and sneutrino oscillations

Conclusions

Conclusions

- The flavor problems are indications of new physics at a scale at or above the weak scale
- The flavor issue is very important in understanding the dynamics of the extension of the SM
- It seems that both low and high energy are needed in order to understand the flavor issues