Flavor physics

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Outline

- The new physics flavor problem
- Current status of the SM flavor sector
- Highlights of last year results and their implications
- 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 a scale as the denominator of an effective higher dimension operator. The weak scale is roughly

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

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

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

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 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

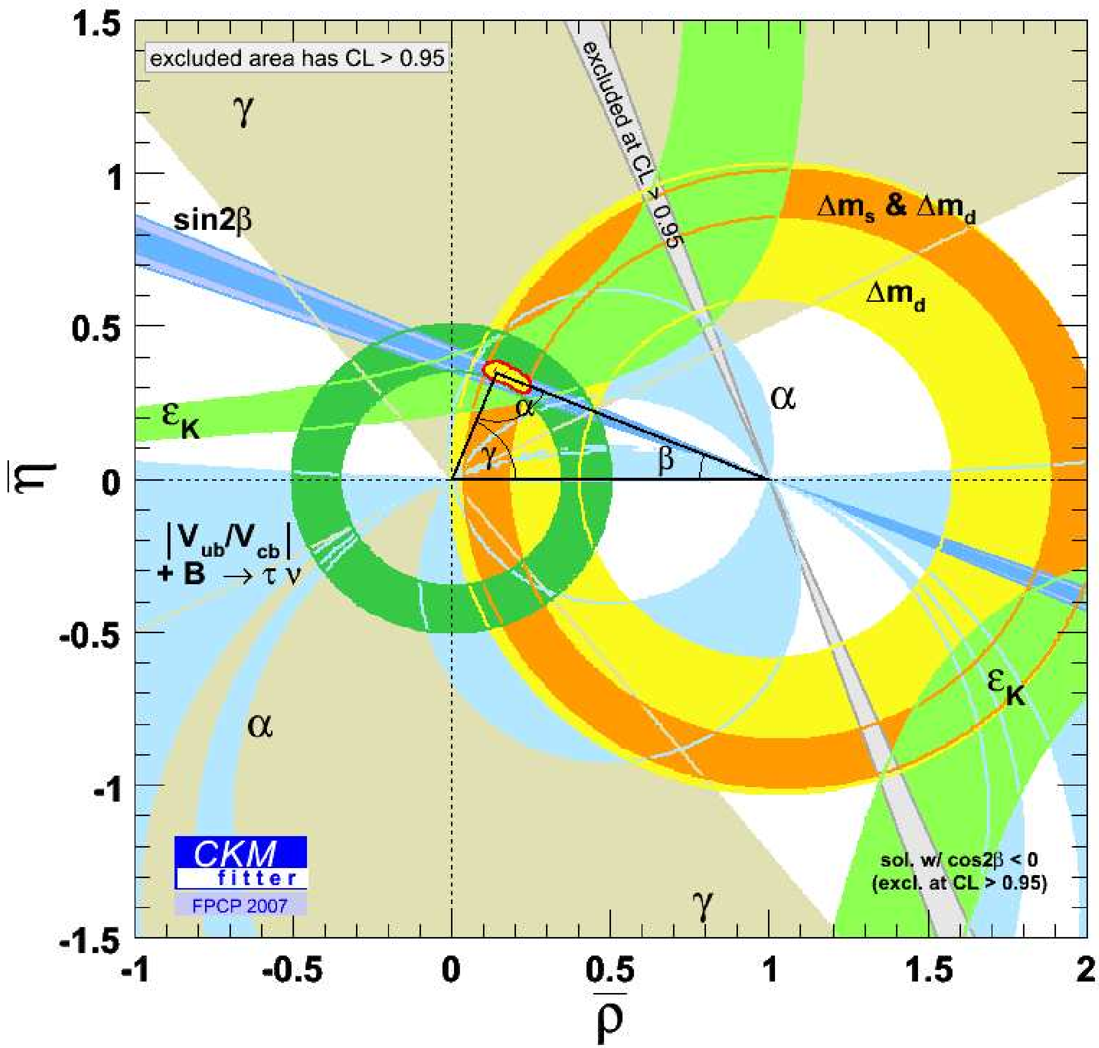
The SM flavor sector

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

There are some hints

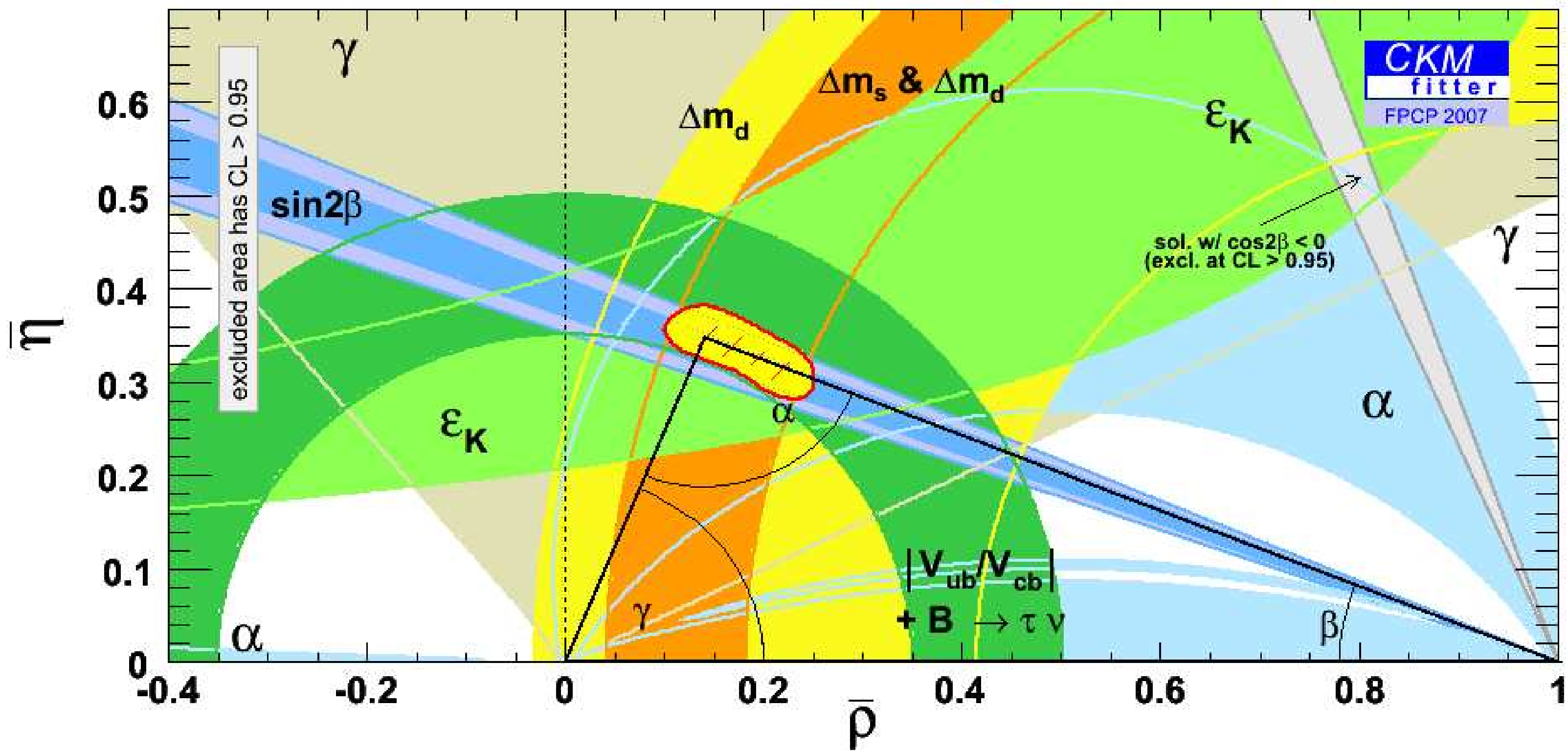
- Global fit
- $a_{\rm CP}(B \to \psi K_S)$ vs $a_{\rm CP}(B \to \phi K_S)$
- $B \to K\pi$

Global fit



excluded area has CL > 0.95
γ
sin2β
excluded at CL > 0.95
Δm_s & Δm_d
Δm_d
α
ε_K
β
|V_ub/V_cb|
+ B → τ ν
α
ε_K
CKM fitter
FPCP 2007
sol. w/ cos2β < 0
(excl. at CL > 0.95)
γ
η̄
ρ̄

Global fit (zoom in)



- Very impressive agreement

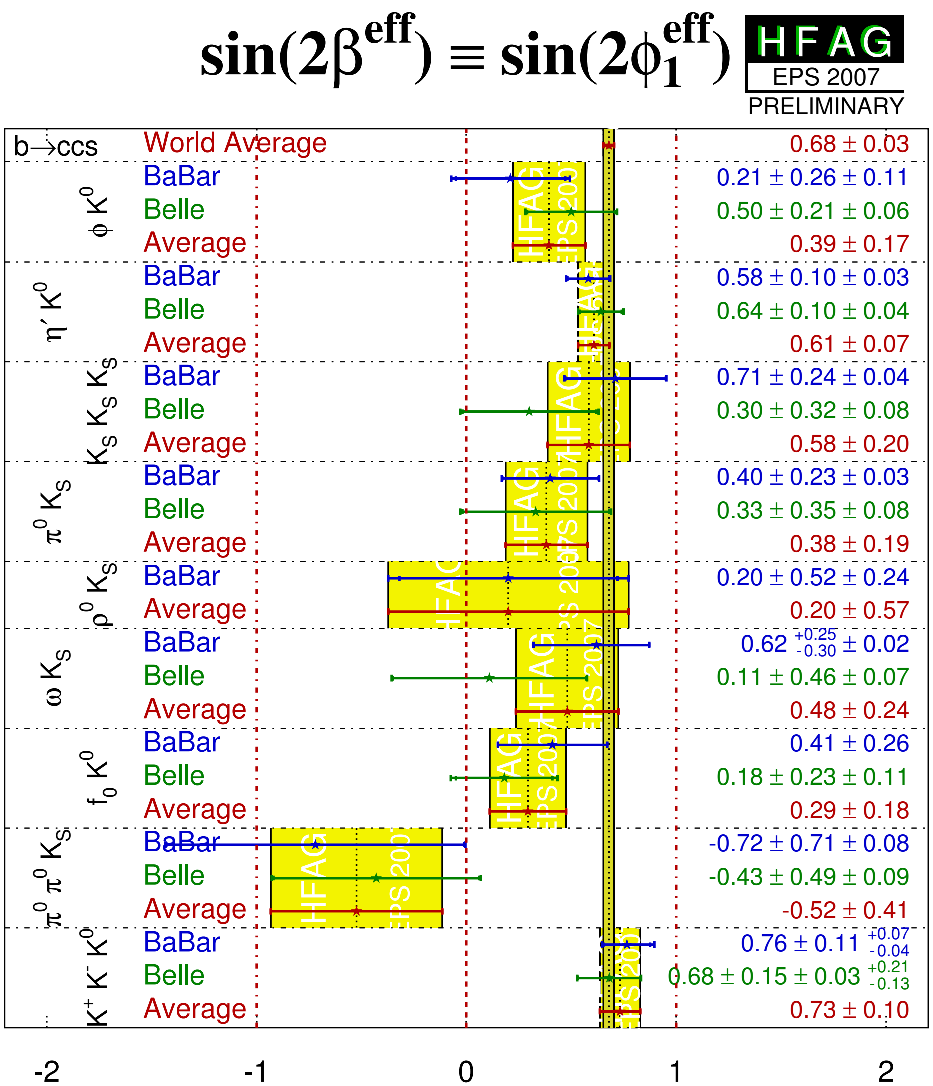
CP asymmetries in $b \to s\bar{s}s$ modes

- Time dependent CP asymmetries measure the phase between the mixing and twice the decay amplitudes
- In the SM
  - $\arg(A_{mix}) = 2\beta$
  - $\arg(A_{b\to c\bar{c}s}) = 0$ (Tree) $B \to \psi K_S$
  - $\arg(A_{b\to s\bar{s}s}) = 0$ (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. The question is how small. Roughly, $O(5\%)$

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



- Combine

$$S_P = 0.56 \pm 0.05$$
$$S_T = 0.68 \pm 0.03$$

About 2σ

- Theoretical uncertainties

$B \to K\pi$

Consider the four decays

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

- 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 $B \to K\pi$ data

- Data on rates agrees with the SM. For example

$$R_{\mathrm{L}} = \frac{2\Gamma(B^+ \to K^+\pi^0) + 2\Gamma(B^0 \to K^0\pi^0)}{\Gamma(B^+ \to K^0\pi^+) + \Gamma(B^0 \to K^+\pi^-)} = 1 + O(10^{-2})$$

- Experimentally, $R_{\mathrm{L}} = 1.07 \pm 0.09$
- The (direct) CP asymmetries are problematic. In the SM

$$a_{CP}(B \to K^+\pi^-) \approx a_{CP}(B \to K^+\pi^0)$$

The data, however

$$a_{CP}(B \to K^+\pi^-) = -0.10 \pm 0.01$$
$$a_{CP}(B \to K^+\pi^0) = 0.05 \pm 0.03$$

The status of the SM flavor sector

- Overall, the SM is very successful in describing flavor
- At present there are hints for NP
- We are not yet at the level that we can conclude either way
- Eventually, on these two examples, theory might be the limited factor (not yet)

Highlights of new flavor results

B_s mixing

Not easy since the mixing is very fast

- New results from D0 and CDF
- First observation of B_s oscillation ($> 5\sigma$)

$$\Delta M_s = 17.77 \pm 0.10 \pm 0.07 \text{ ps}^{-1}$$

- Progress in determining the mixing phase and $\Delta\Gamma$
- In the SM the calculation is rather precise. No surprises so far

$D-\bar{D}$ mixing

Not easy since the mixing is very small

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

- First indications for mixing from BaBar and Belle
- Found in several decay modes

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

- Roughly a 4σ signal for oscillation. Mainly in y
- No signal for CPV

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

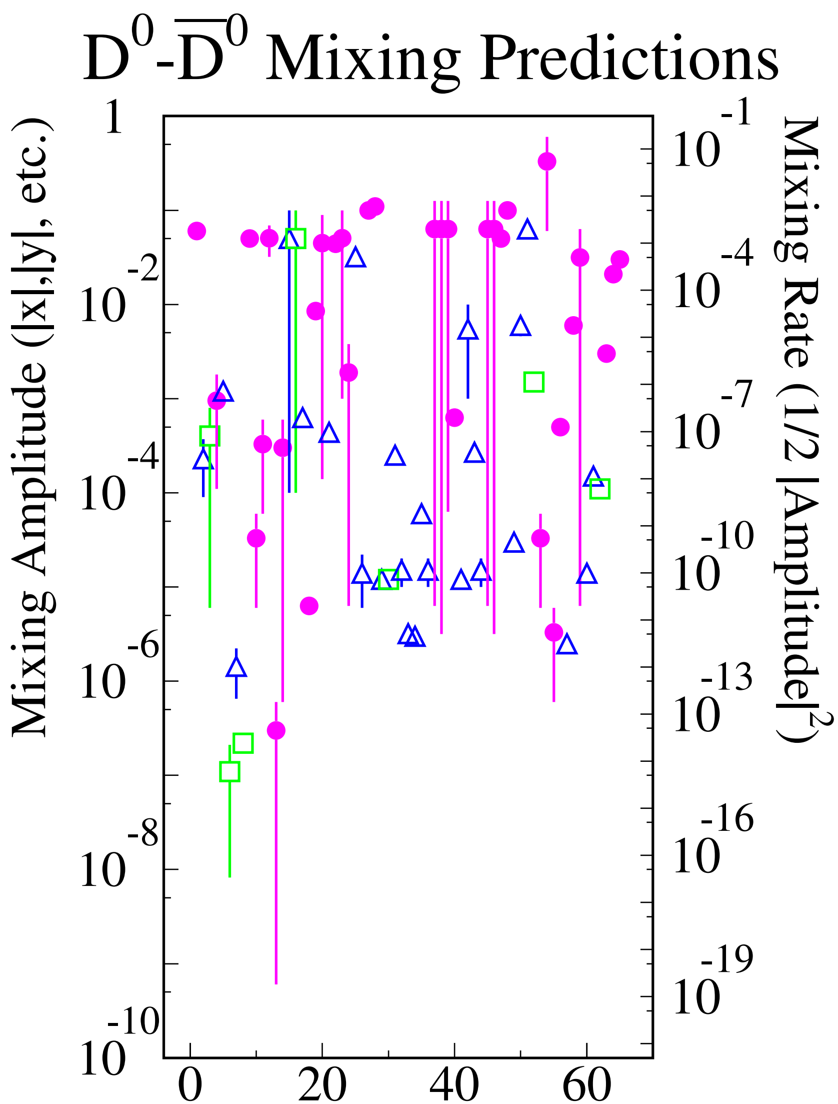
Two parameters

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

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)
- 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?

- $\Lambda \sim m_c \;\Rightarrow\; \varepsilon^2_{\mathrm{SU}(3)} \sim 10^{-2} \;\Rightarrow\; x,y \lesssim 10^{-3}$
- $\Lambda \sim Q < m_c \;\Rightarrow\; \varepsilon^2_{\mathrm{SU}(3)} \sim 10^{-1} \;\Rightarrow\; x,y \lesssim 10^{-2}$

Can we get better estimates?

Inclusive vs exclusive calculations

	inclusive	exclusive
Assumption	heavy charm	light charm
$\mathrm{SU}(3)$ breaking	amplitudes	phase space
Uncertainty	matrix elements	decay rates
Conclusion	$x, y \lesssim 10^{-3}$	$x, y \lesssim 10^{-2}$

If the indications for oscillation are confirmed

- The exclusive calculation seems to be right
- It might be that the charm is too light for this OPE
- No CPV implies no hints for NP

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 (Next talks)
- Theoretically? Yes!
  - $B \to DK$
  - CPV in D decays
  - $K_L \to \pi^0 \nu \bar{\nu}$
  - ...

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 deviations at or above the 1% level
- There are few modes that give superb theoretical predictions. We need to go after these modes in order to probe flavor at the 1% level

Backup slides

Inclusive calculation

Georgi; Bigi and Uraltsev

- Perform an OPE assuming $\Lambda/m_c \ll 1$ with $\Lambda \sim 1$ GeV
- The box diagram is the leading term (4 quark operators)
- Higher order terms have fewer powers of m_s and are more important

With some assumptions

$$x, y \lesssim 10^{-3}$$

Exclusive calculation

Falk et al.

- Using hadrons to calculate
- Assume that there are only small number of final states and sum their contributions to x and y
- Cannot really do it since we need very precise experimental data
- Phase space effects are a calculable source of $\mathrm{SU}(3)$ breaking
- They are important since large fraction of D decays is to final states close to threshold

With some assumptions

$$x, y \lesssim 1\%$$

Example: PP

Consider only the charged mesons U spin triplet

$$y_U = \sin^2\theta_C \times$$
$$\left[\Phi(\pi^+,\pi^-) + \Phi(K^+,K^-) - \Phi(K^+,\pi^-) - \Phi(K^-,\pi^+)\right]$$

- y_U is the “would-be" value of y, if D only decays to these four states
- We assume that $\mathrm{SU}(3)$ breaking enters only via the phase space function Φ
- The result is explicitly proportional to $\sin^2\theta_C$ and vanishes in $\mathrm{SU}(3)$ limit as m_s^2
- Similar calculations were done for other $\mathrm{SU}(3)$ multiplets

Two–body final states

Final state	$\varepsilon^2_{\mathrm{SU}(3)}$
(PP)s-wave	-0.011
(PV)p-wave	0.14
(VV)s-wave	-0.14
(VV)p-wave	-0.24
(VV)d-wave	1.1

- Only $\mathrm{SU}(3)$ breaking in phase space
- Contribution of PP is “anomalously" small
- Larger $\mathrm{SU}(3)$ breaking for heavier multiplets

Conclusions from this analysis

Fraction of the D width rounded to nearest 5%:

Final state	fraction	$\varepsilon^2_{\mathrm{SU(3)}}$
PP	5%	$O(10^{-2})$
PV	10%	$O(10^{-1})$
VV	10%	$O(1)$
$3P$	5%	$O(1)$
$4P$	10%	$O(1)$

- We expect $y \sim \sin^2\theta_C\, \varepsilon^2_{\mathrm{SU(3)}} \sim 1\%$
- Moral: It would require cancellations to suppress y much below $\sim 1\%$

The new physics scale

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

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

- Flavor and CP violating operators. From meson data (UTfit, arxiv:0707.0636)

$$\frac{QQQQ}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^{8}\ \mathrm{GeV}$$

- Electroweak data (Custodial symmetry violation)

$$\Lambda \gtrsim 1\ \mathrm{TeV}$$

Exact and broken symmetries

There is 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 protect the new operators

These two scales are associated with hierarchy problems

- The new physics flavor problem
- The little hierarchy problem

The NP flavor problem is stronger in terms of scales.

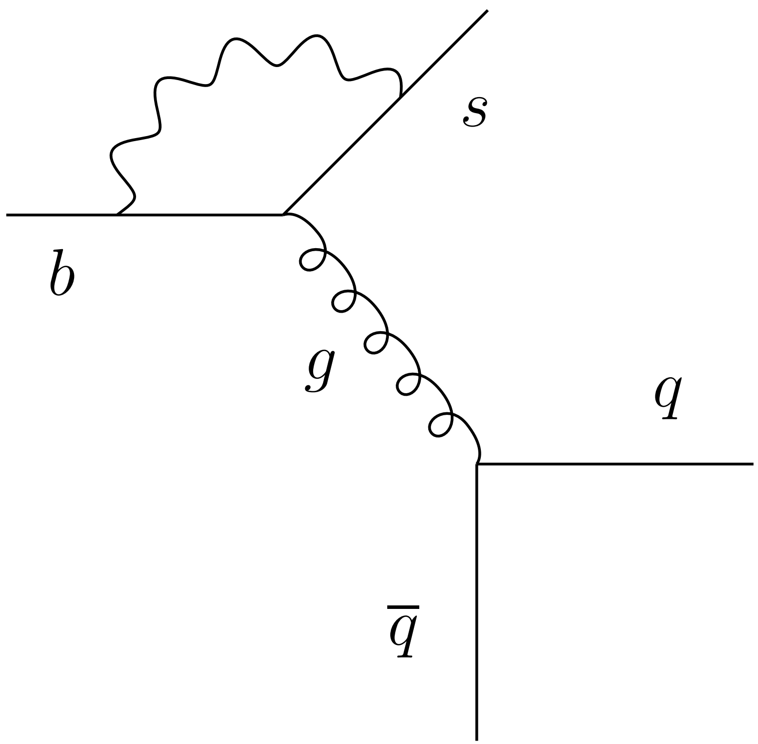
The NP scale

- Low energy observables put severe constraints on NP models
- Generally we have the most general operators
  - $\frac{QQQL}{\Lambda^2}$ $\Rightarrow$ proton decay $\Rightarrow$ $\Lambda \gtrsim 10^{16}$ GeV
  - $\frac{LLHH}{\Lambda}$ $\Rightarrow$ neutrino masses $\Rightarrow$ $\Lambda \sim 10^{15}$ GeV
- Proton decay and neutrino masses can be protected by conserve symmetries like $B-L$ or R-parity.

What about flavor bounds?

$B \to K\pi$ diagrams

(P) + (P_{EW}) $\qquad\qquad$ (T)



P is a loop amplitude, but due to CKM factors $P \gg T$