Beyond the SM with B and K physics

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Technion

Outline

- New Physics and the flavor problem
  - The hierarchy problem
  - The new physics flavor problem
  - Types of new physics models and an example
- How can we probe the new physics?
  - Global fit
  - CP asymmetries in $b \to c\bar{c}s$ vs $b \to s\bar{s}s$
  - $B \to K\pi$
  - Polarization in $B \to VV$
  - $K \to \pi\nu\bar{\nu}$ vs B and B_s mixing

New Physics

Reasons Not to Believe the SM

1. The hierarchy problem
2. The strong CP problem
3. Baryogenesis
4. Gauge coupling unification
5. Neutrino masses
6. Gravity

- Very likely, there is new physics
- The hierarchy problem suggests

$$\Lambda \sim 4\pi m_W \sim 1\ \mathrm{TeV}$$

- We can directly probe new physics at such a 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

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

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- Generic models
  - Huge effects in flavor physics: already ruled out

Example: Randall-Sundrum

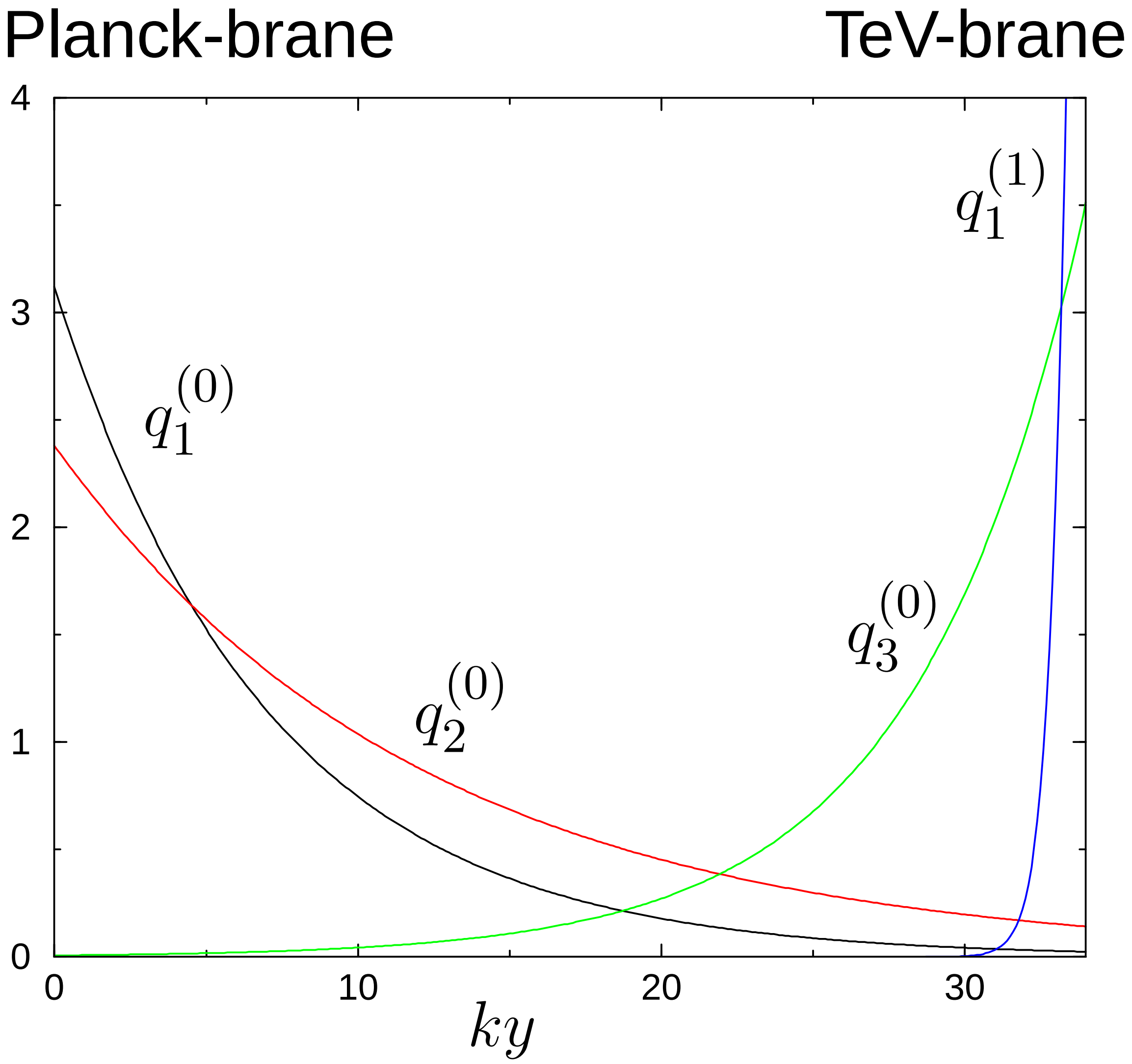
- The RS model solves the hierarchy problem with one extra non-factorizable dimension: $m = M_{\rm PL}\exp(-ky)$
- Solving the hierarchy problem requires a “TeV brane” at $ky \sim 40$, where the Higgs is localized
- Placing the fermions in the bulk can generate the observed flavor structure
- Generic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



The effective NP scale is
$\Lambda \sim M_{\rm PL}\exp(-ky)$

Probing new physics with mesons

Bottom line

- 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

Current hints for new physics

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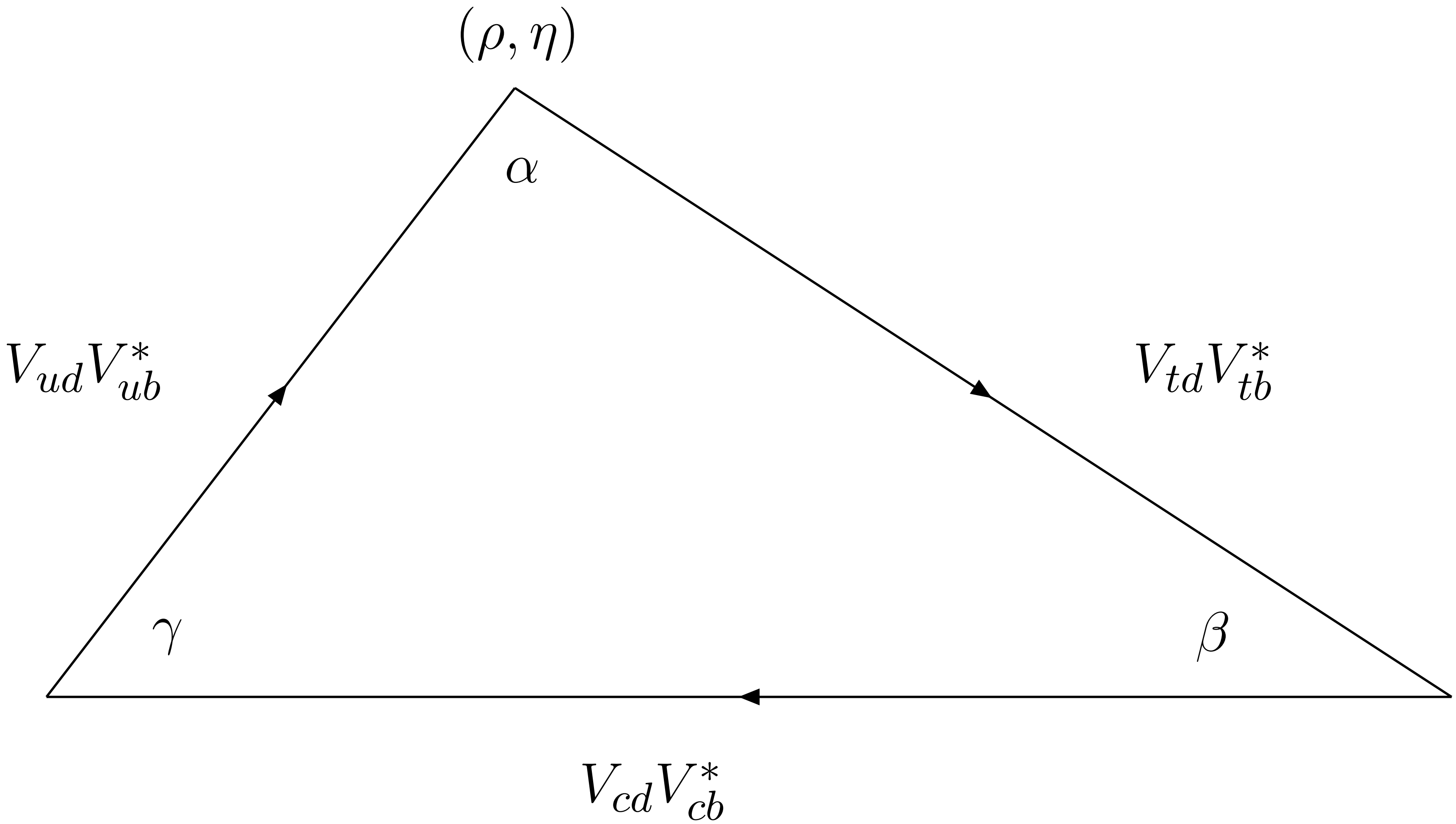
Yet, there are a few hints:

- $a_{\rm CP}(B \to \psi K_S)$ vs $a_{\rm CP}(B \to \phi K_S)$
- $B \to K\pi$
- Polarization in $B \to VV$ decays
- $K \to \pi\nu\bar{\nu}$ vs B and B_s mixing
- and more...

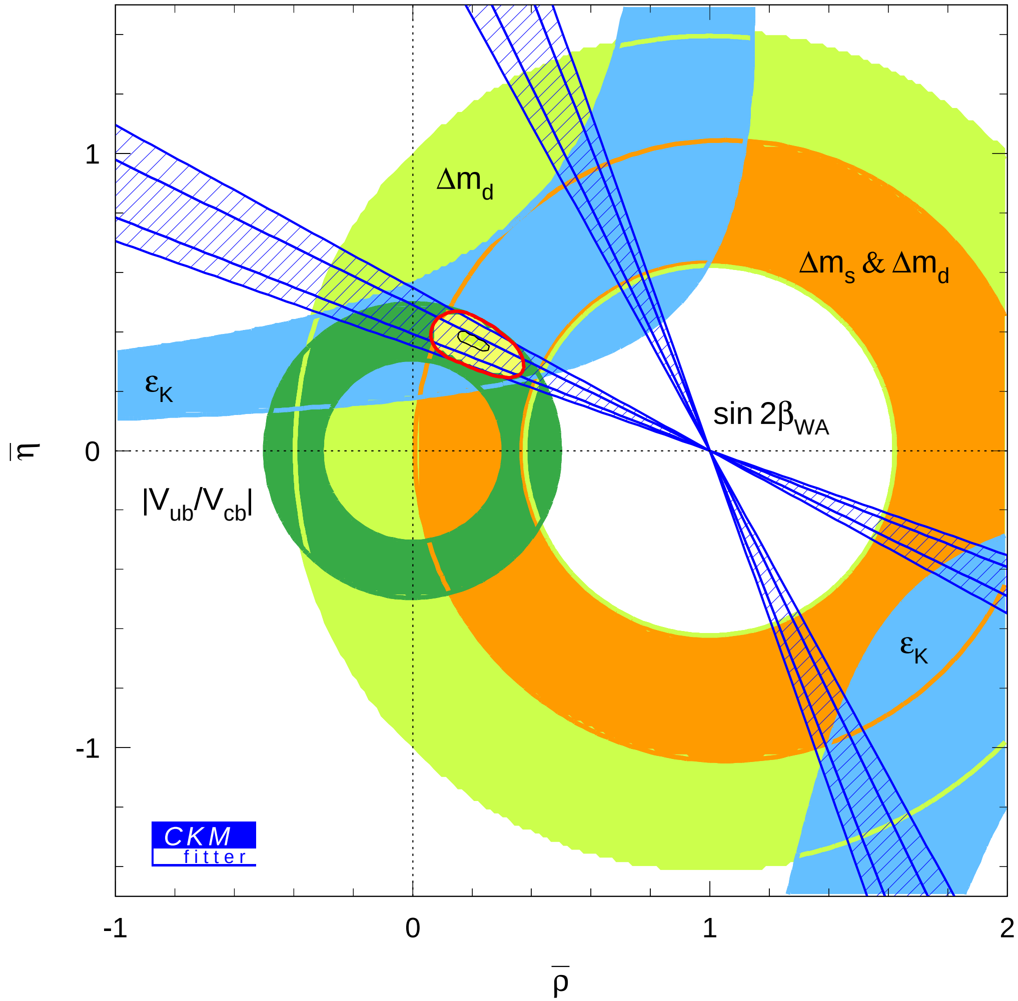
Global fit

Overconstraining the unitarity triangle



Current status of the global fit

V_{cb}, V_{ub}/V_{cb}, ε_K, $B-\overline{B}$ mixing, B_s mixing, $a_{\rm CP}(B\to\psi K_S)$



Hocker et al. (CKMfitter)

- Good agreement

(1) 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)
    $B \to \phi K_S$, $B \to \eta' K_S$, $B \to K^+K^-K_S$
- To first approximation the SM predicts

$$a_{\rm CP}(B \to \psi K_S) = a_{\rm CP}(B \to \phi K_S) =$$
$$a_{\rm CP}(B \to \eta' K_S) = -a_{\rm CP}(B \to K^+K^-K_S) = \sin 2\beta$$

- The theoretical uncertainties are less than $O(5\%)$ for the two body decays and $O(20\%)$ for the three body decay

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

$$S_{\psi K_S} = +0.73 \pm 0.05 \qquad S_{\eta' K_S} = +0.33 \pm 0.34$$

$$S_{\phi K_S} = -0.39 \pm 0.41 \qquad -S_{K^+K^-K_S} = +0.49 \pm 0.44^{+0.33}_{-0.00}$$

- To first approximation, these asymmetries are equal in the SM
- $S_{\phi K_S} - S_{\psi K_S} \neq 0$ at $2.7\,\sigma$
- $S_{K^+K^-K_S}$ is not as clean as the other modes

The anomaly: why $S_{\phi K_S} \neq S_{\psi K_S}$

Explanation of $S_{\psi K_S} \neq S_{\phi K_S} \neq S_{\eta' K_S}$

Long list of authors

- Since $B \to \eta' K_S$ and $B \to \phi K_S$ are one loop in the SM we expect large new physics effects
- Due to different hadronic matrix elements we expect the shift from $\sin 2\beta$ to be different in the two modes
- $B \to \psi K_S$ is a CKM favored tree level decay in the SM $\Rightarrow$ we expect small new physics effects

$$\Downarrow$$

New physics in $b \to s\bar{s}s$ generally gives $S_{\psi K_S} \neq S_{\phi K_S} \neq S_{\eta' K_S}$

(2) $B \to K\pi$

Consider the four decays

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

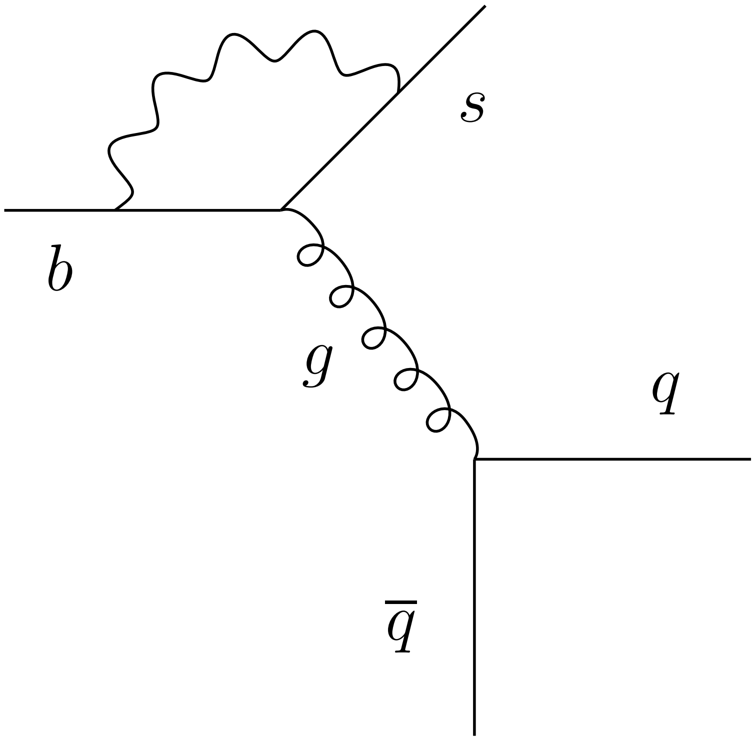
- In the SM these modes can be used to measure γ

  Fleischer, Gronau, Mannel, Neubert, Rosner

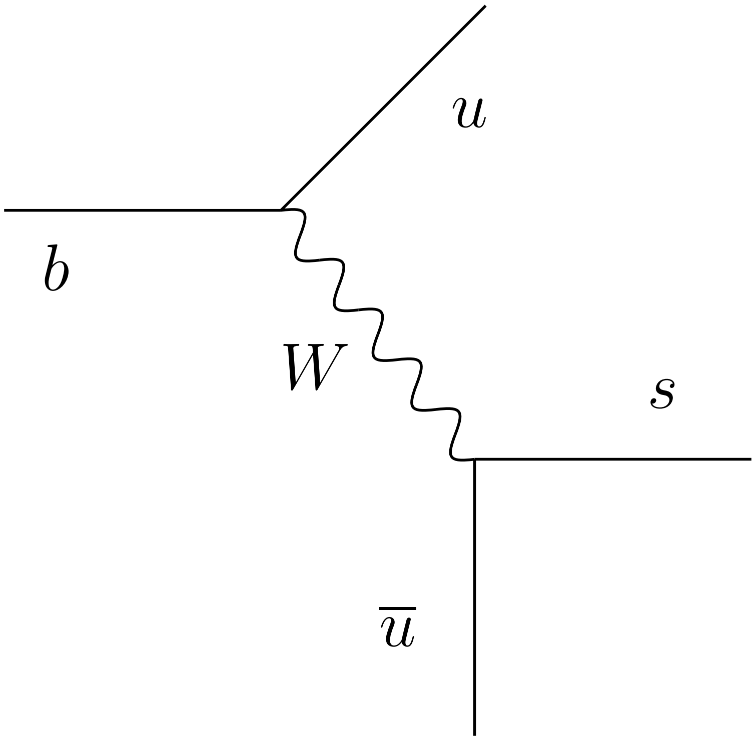
- There are many SM relations between these modes that can be used to look for new physics (Fleischer-Mannel, Neubert-Rosner, Lipkin sum rule)

$B \to K\pi$ diagrams

(P) + (P_{EW})



(T)



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

The Lipkin sum rule

- Using isospin only

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

$$= 1 + O\left(\frac{P_{EW} + T}{P}\right)^2$$

- Experimentally $R_{\rm L} = 1.24 \pm 0.10$
- Using $P_{EW}/P \sim T/P \sim 0.1$ we expect theoretically

$$R_L = 1 + O(10^{-2})$$

- The deviation of R_L from 1 is an $O(2\sigma)$ effect

Explanation of $R_L - 1 \gg 10^{-2}$

- Experimentally $R_{\rm L} = 1.24 \pm 0.10$
- New “Trojan penguins”, P_{NP}, which are isospin breaking ($\Delta I = 1$) amplitudes, modify the Lipkin sum rule

$$R_{\rm L} = 1 + O\left(\frac{P_{NP}}{P}\right)^2$$

Gronau and Rosner

- Need a large effect, $P_{NP} \approx P/2$
- In many models there are strong bounds from $b \to s\ell^+\ell^-$

Kagan, Neubert, YG

- Leptophobic Z' is a working example

(3) 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
  - $$\frac{R_T}{R_0} = O\left(\frac{1}{m_B}\right)$$
  - $$\frac{R_\perp}{R_\parallel} = 1 + O\left(\frac{1}{m_B}\right)$$

Polarization data

$$R_0(B \to \phi K^*) = 0.54 \pm 0.10 \quad \text{(BaBar and Belle)}$$
$$R_\perp(B \to \phi K^*) = 0.41 \pm 0.11 \quad \text{(Belle)}$$
$$R_0(B \to \rho K^*) = 0.96 \pm 0.16 \quad \text{(BaBar)}$$
$$R_0(B \to \rho\rho) = 0.96 \pm 0.06 \quad \text{(BaBar and Belle)}$$

$$R_0 + R_\perp + R_\parallel = 1 \quad \Rightarrow \quad R_\parallel(B \to \phi K^*) = 0.05 \pm 0.15$$

- SM prediction: $R_T/R_0 \ll 1$
  - $B \to \rho\rho,\ B \to K^*\rho:\ R_T/R_0 \ll 1$
  - $B \to \phi K^*:\ R_T/R_0 = O(1)$
- SM prediction: $R_\perp/R_\parallel \approx 1$
  - $B \to \phi K^*:\ R_\perp/R_\parallel \gg 1$

Explaining the polarization data

- The 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 penguins and small for tree amplitudes
- New physics explanation: right handed current operators can explain the polarization data
- Polarization measurements for other modes are important, e.g., the penguin mode $B \to K^{*0}\rho^+$

(4) $K \to \pi\nu\bar{\nu}$

Buras and Buchalla

$K \to \pi\nu\bar{\nu}$ is a very good probe of the unitarity triangle

- Dominated by $s \to d$ penguin with internal top $\Rightarrow$ sensitivity to $|V_{td}|$.
- Isospin and perturbative QCD can be used to eliminate almost all the hadronic uncertainties
- In many cases, new physics affects B and K differently

$K^+ \to \pi^+\nu\bar\nu$ data

Experimentally

$$\mathcal{B}(K^+ \to \pi^+\nu\bar\nu) = (15.7^{+17.5}_{-8.2}) \times 10^{-11}$$

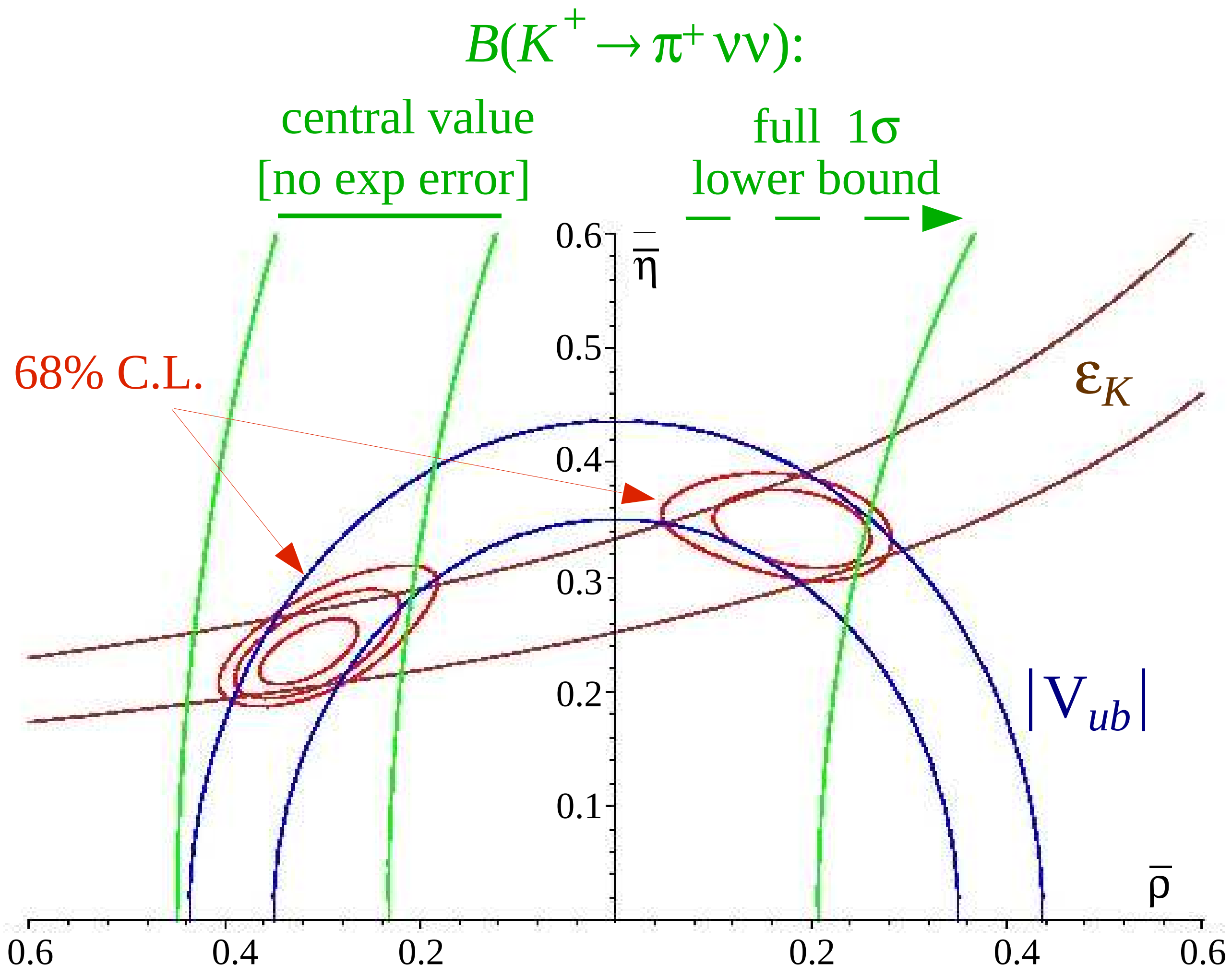
The SM predicts

$$\mathcal{B}(K^+ \to \pi^+\nu\bar\nu) = 4.4 \times 10^{-11} \times \left[\eta^2 + (1.4-\rho)^2\right]$$

- $|V_{ub}|$ tells us that $\eta \lesssim 0.4$
- B and B_s mixing tell us that $\rho > 0$
- To get the central value of $\mathcal{B}(K^+ \to \pi^+\nu\bar\nu)$ we need $\rho < 0$

B vs K unitarity triangle

Isidori



Explanation of $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$

Buras, D'Ambrosio, Isidori, Nir, Silvestrini, Worah

- New physics in B or B_s mixing: the K unitarity triangle is correct
- New physics in $s \to d$ penguin: the B unitarity triangle is correct
- Higher precision in $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ and a measurement of $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ are important

Conclusions

Conclusions

- It is likely that there is new physics at a TeV
- Such new physics can show up in K, D and B physics
- No signal yet, but there are intriguing results

Backup slides

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?

What NP can do?

Modify the low energy effective Hamiltonian

- New contributions to SM operators
- Generate new operators
- New CPV phases

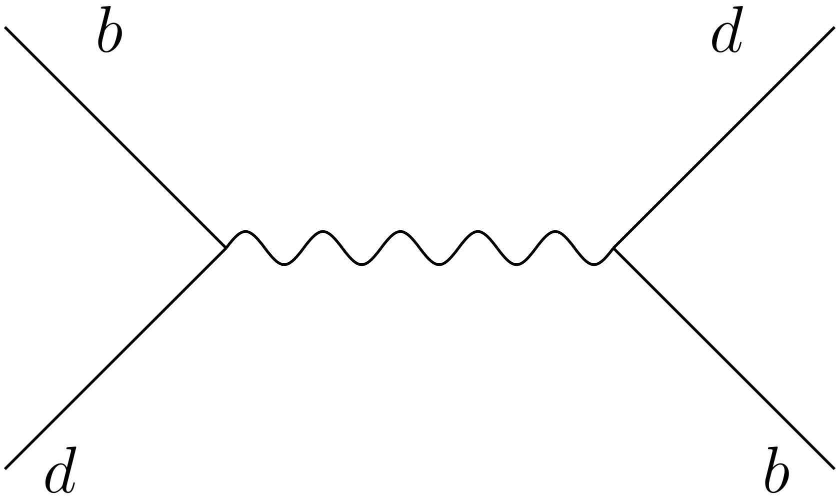
NP cannot do everything

- Cannot change things we “know”, like QCD
- Unlikely to compete with “large” SM contributions: $(b \to c\bar{u}d)$ is mainly SM

In general NP can affect observables that are suppressed in the SM: Meson mixing, loop mediated decays and CKM suppressed amplitudes

Example: Z' exchange

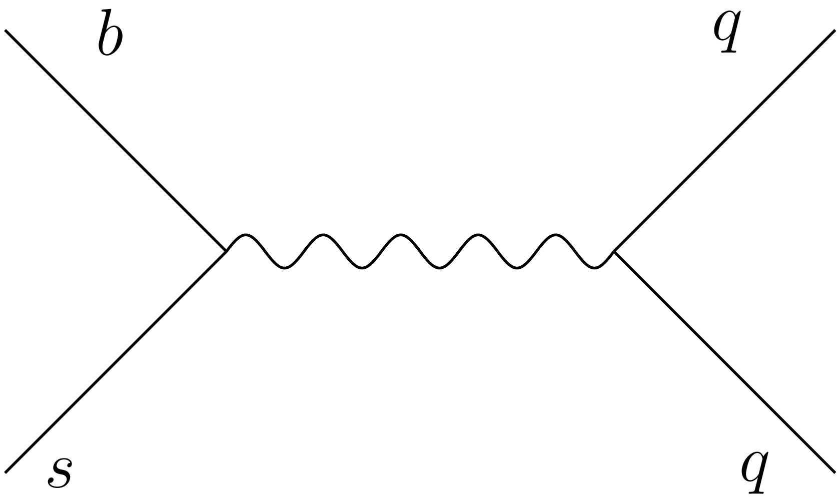
$B - \overline{B}$ mixing



$$\propto \quad \frac{\kappa_{bd}^{*}\kappa_{db}}{m_{Z'}^{2}}$$

Example: Z' exchange

$b \longrightarrow sq\overline{q}$



$$\propto \quad \frac{\kappa_{bs}^{*}\kappa_{qq}}{m_{Z'}^{2}}$$

Similar contributions exist in other NP models

Possible explanation

Can we get

$$S_{\phi K_S} \neq S_{\psi K_S} \;\; \text{with} \;\; S_{\eta' K_S} = S_{\psi K_S}$$

- $B \to \phi K_S$ is parity conserving while $B \to \eta' K_S$ is parity violating
- Parity conserving new physics in $b \to s$ penguins only affect $B \to \phi K_S$
- Generically, new physics models are not parity conserving
- Supersymmetric $SU(2)_L \times SU(R) \times \mathrm{Parity}$ models provide a framework for approximate parity conserving new physics

Kagan