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 $b \rightarrow c\bar{c}s$ vs $b \rightarrow s\bar{s}s$
  - $B \rightarrow K\pi$
  - Polarization in $B \rightarrow VV$
  - $K \rightarrow \pi\nu\bar{\nu}$ 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

\[ \Lambda \sim 4\pi m_W \sim 1 \text{ TeV} \]

- 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.

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**: $\epsilon_K$

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

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

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

- **$B$ physics**: $B - \bar{B}$ mixing and CPV

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

There is no exact symmetry that can forbid such operators.
Flavor and the hierarchy problem

There is tension:

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

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

- The NP is flavor blind, MFV (GMSB; UED)
- Small effects in flavor physics
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  - Large effects in the $B$ and $B_s$ systems
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- Generic suppression (SUSY alignment; split fermions)
  - Can be tested with flavor physics
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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: \( m = M_{PL} \exp(-k y) \)

- Solving the hierarchy problem requires a “TeV brane” at \( k y \sim 40 \), 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

  \[
  \Lambda \sim M_{PL} \exp(-k y^f)
  \]

  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

The effective NP scale is
\[ \Lambda \sim M_{PL} \exp(-k y) \]
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
At present there is no significant deviation from the SM predictions in the flavor sector
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Global fit
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- Global fit

Yet, there are a few hints:

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

\[ (\rho, \eta) \]

\[ V_{ud}V_{ub}^* \quad \alpha \quad V_{td}V_{tb}^* \]

\[ \gamma \quad V_{cd}V_{cb}^* \quad \beta \]
Current status of the global fit

$V_{cb}, V_{ub}/V_{cb}, \varepsilon_K, B - \bar{B} \text{ mixing}, B_s \text{ mixing}, a_{CP}(B \rightarrow \psi K_S)$

Hocker et al. (CKMfitter)

Good agreement
(1) CP asymmetries in $b \rightarrow s\bar{s}s$ modes

- Time dependent CP asymmetries measure the phase between the mixing and twice the decay amplitudes

- In the SM
  - $\arg(A_{mix}) = 2\beta$
  - $\arg(A_{b\rightarrow c\bar{s}s}) = 0$ (Tree) $B \rightarrow \psi K_S$
  - $\arg(A_{b\rightarrow s\bar{s}s}) = 0$ (Penguin) $B \rightarrow \phi K_S, B \rightarrow \eta' K_S, B \rightarrow K^+ K^- K_S$

- To first approximation the SM predicts
  \[
  a_{CP}(B \rightarrow \psi K_S) = a_{CP}(B \rightarrow \phi K_S) = 0
  \]
  \[
  a_{CP}(B \rightarrow \eta' K_S) = -a_{CP}(B \rightarrow K^+ K^- K_S) = \sin 2\beta
  \]

- The theoretical uncertainties are less than $O(5\%)$ for the two body decays and $O(20\%)$ for the three body decay
To first approximation, these asymmetries are equal in the SM

- $S_{\phi K_S} - S_{\psi K_S} \neq 0$ at 2.7σ
- $S_{K^+K^- K_S}$ is not as clean as the other modes

The anomaly: why $S_{\phi K_S} \neq S_{\psi K_S}$
Explanation of $S_{\psi K_S} \neq S_{\phi K_S} \neq S_{\eta' K_S}$

Since $B \rightarrow \eta' K_S$ and $B \rightarrow \phi K_S$ 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.

$B \rightarrow \psi K_S$ is a CKM favored tree level decay in the SM

⇒ we expect small new physics effects

↓

New physics in $b \rightarrow s\bar{s}s$ generally gives $S_{\psi K_S} \neq S_{\phi K_S} \neq S_{\eta' K_S}$
(2) $B \rightarrow K\pi$

Consider the four decays

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

- In the SM these modes can be used to measure $\gamma$ (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)
\( B \rightarrow K\pi \) 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

\[ R_L = \frac{2\Gamma(B^+ \rightarrow K^+\pi^0) + 2\Gamma(B^0 \rightarrow K^0\pi^0)}{\Gamma(B^+ \rightarrow K^0\pi^+) + \Gamma(B^0 \rightarrow K^+\pi^-)} \]

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

Experimentally \( R_L = 1.24 \pm 0.10 \)

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

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

- Need a large effect, $P_{NP} \approx P/2$
- In many models there are strong bounds from $b \rightarrow s\ell^+\ell^-$
- Leptophobic $Z'$ is a working example

Gronau and Rosner

Kagan, Neubert, YG
(3) Polarization in $B \rightarrow VV$ decays

- Consider $B$ decays into light vectors
  \[ B \rightarrow \rho \rho \quad B \rightarrow \phi K^* \quad B \rightarrow \rho K^* \]

- Due to the left handed nature of the weak interaction in the SM in the $m_B \rightarrow \infty$ 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

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

\[ R_0 + R_\perp + R_{||} = 1 \implies R_{||}(B \to \phi K^*) = 0.05 \pm 0.15 \]

- **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:** \( R_\perp/R_{||} \approx 1 \)
  - \( B \to \phi K^* : R_\perp/R_{||} \gg 1 \)
Explaining the polarization data

- The SM predictions do not hold in $B \rightarrow \phi K^*$
- This is a penguin $b \rightarrow s\bar{s}s$ 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 $B \rightarrow K^{*0} \rho^+$
\( (4) \ K \rightarrow \pi \nu \bar{\nu} \)

\( K \rightarrow \pi \nu \bar{\nu} \) is a very good probe of the unitarity triangle

- Dominated by \( s \rightarrow d \) 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
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ data

Experimentally

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

The SM predicts

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

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

$B(K^+ \rightarrow \pi^+ \nu \nu)$:

- Central value (no exp error)
- Full $1\sigma$ lower bound

68% C.L.
Explanation of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

- New physics in $B$ or $B_s$ mixing: the $K$ unitarity triangle is correct
- New physics in $s \rightarrow d$ penguin: the $B$ unitarity triangle is correct
- Higher precision in $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and a measurement of $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ 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
  \[ \frac{QQQL}{\Lambda^2} \Rightarrow \text{proton decay} \Rightarrow \Lambda \gtrsim 10^{16} \text{ GeV} \]
  \[ \frac{LLHH}{\Lambda} \Rightarrow \text{neutrino masses} \Rightarrow \Lambda \sim 10^{15} \text{ GeV} \]
- 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: 
  \( (b \rightarrow c\bar{u}d) \) 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

$B - \bar{B}$ mixing

\[ \propto \frac{k_{bd}^* k_{db}}{m_{Z'}^2} \]
Example: $Z'$ exchange

\[ b \rightarrow s\bar{q}q \]

\[ \propto \frac{\kappa_{bs}^* \kappa_{qq}}{m_{Z'}^2} \]

Similar contributions exist in other NP models.
Possible explanation

Can we get

\[ S_{\phi K_S} \neq S_{\psi K_S} \text{ with } S_{\eta^I K_S} = S_{\psi K_S} \]

- \( B \to \phi K_S \) is parity conserving while \( B \to \eta^I K_S \) 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 \( SU(2)_L \times SU(R) \times \text{Parity models} \) provide a framework for approximate parity conserving new physics

Kagan