Footprints of New Physics in the B System

Yuval Grossman

Outline

- New Physics and the flavor problem
  - The hierarchy problem
  - The new physics flavor problem
  - Types of new physics models
- Searching new physics
  - CP asymmetries in $b \to c\bar{c}s$ vs $b \to s\bar{s}s$
  - $B \to K\pi$
  - Polarization in $B \to VV$

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

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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

- The NP is flavor blind, MFV (GMSB; UED)
  - Small effects in flavor physics
- Flavor suppression mainly of first two generations (Heavy $\tilde{q}$; RS)
  - Large effects in the B and B_s systems
- Generic suppression (SUSY alignment; split fermions)
  - Can be tested with flavor physics
- Generic models
  - Huge effects in flavor physics: already ruled out

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

New Physics

At present there is no significant deviation from the SM predictions in the flavor sector

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Yet, there are a few hints:

- $a_{\rm CP}(B \to \psi K_S)$ vs $a_{\rm CP}(b \to s q\bar{q})$
- $B \to K\pi$
- Polarization in $B \to VV$ decays
- and more...

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

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

- To good approximation both the tree $b \to c\bar{c}s$ and penguin $b \to q\bar{q}$ decay amplitudes are real
- To first approximation the SM predicts

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

- The theoretical uncertainties are between $O(1\%)$ to $O(20\%)$

The problem with $b \to sq\bar{q}$ decays

$$A = \underbrace{\overset{[\lambda^2]}{V_{cb}V_{cs}^*}}\, P + \underbrace{\overset{[\lambda^4]}{V_{ub}V_{us}^*}}\, T$$

dominant contribution   suppressed by λ^2

$$\xi_f \equiv \frac{V_{ub}^* V_{us}}{V_{cb}^* V_{cs}} \frac{T}{P}\,, \qquad \left|\frac{V_{ub}^* V_{us}}{V_{cb}^* V_{cs}}\right| = \mathcal{O}(\lambda^2)\,, \qquad \delta_f = \arg \frac{a_f^u}{a_f^c}$$

- $S_f - \sin 2\beta \approx 2\cos 2\beta\, \sin\gamma\, \cos\delta_f\, |\xi_f|$
- $C_f \approx -2 \sin\gamma\, \sin\delta_f\, |\xi_f|$

How large are the subleading effects in the SM?

SU(3) relations

YG, Isidori, Worah; YG, Ligeti, Nir, Quinn; Gronau, Rosner

- For $b \to q\bar{q}s$ transitions

$$A_f = V_{cb}^* V_{cs}\, P_f + V_{ub}^* V_{us}\, T_f = V_{cb}^* V_{cs}\, P_f\, (1 + \xi_f)$$

- For $b \to q\bar{q}d$ transitions

$$A_{f'} = V_{cb}^* V_{cd}\, P_f' + V_{ub}^* V_{ud}\, T_f' = V_{ub}^* V_{ud}\, T_f'\, (1 + \lambda^2 \xi_{f'}^{-1})$$

SU(3) gives relations among T_f and T_f'

$$T = \sum_{f'} x_{f'} T_f' \quad \Rightarrow \quad \xi_f \lesssim \lambda \sum_{f'} |x_{f'}| \sqrt{\frac{\mathcal{B}(f')}{\mathcal{B}(f)}}$$

Example: $B \to \pi^0 K_S$

- SU(3) relation

$$A(\pi^0 K^0) = A(\pi^0 \pi^0) + A(K^+ K^-)/\sqrt{2}$$

- Data: $\mathcal{B}(B^0 \to \pi^0 K^0) = (11.92 \pm 1.44) \times 10^{-6}$

$$\mathcal{B}(B^0 \to \pi^0 \pi^0) = (1.89 \pm 0.46) \times 10^{-6}$$

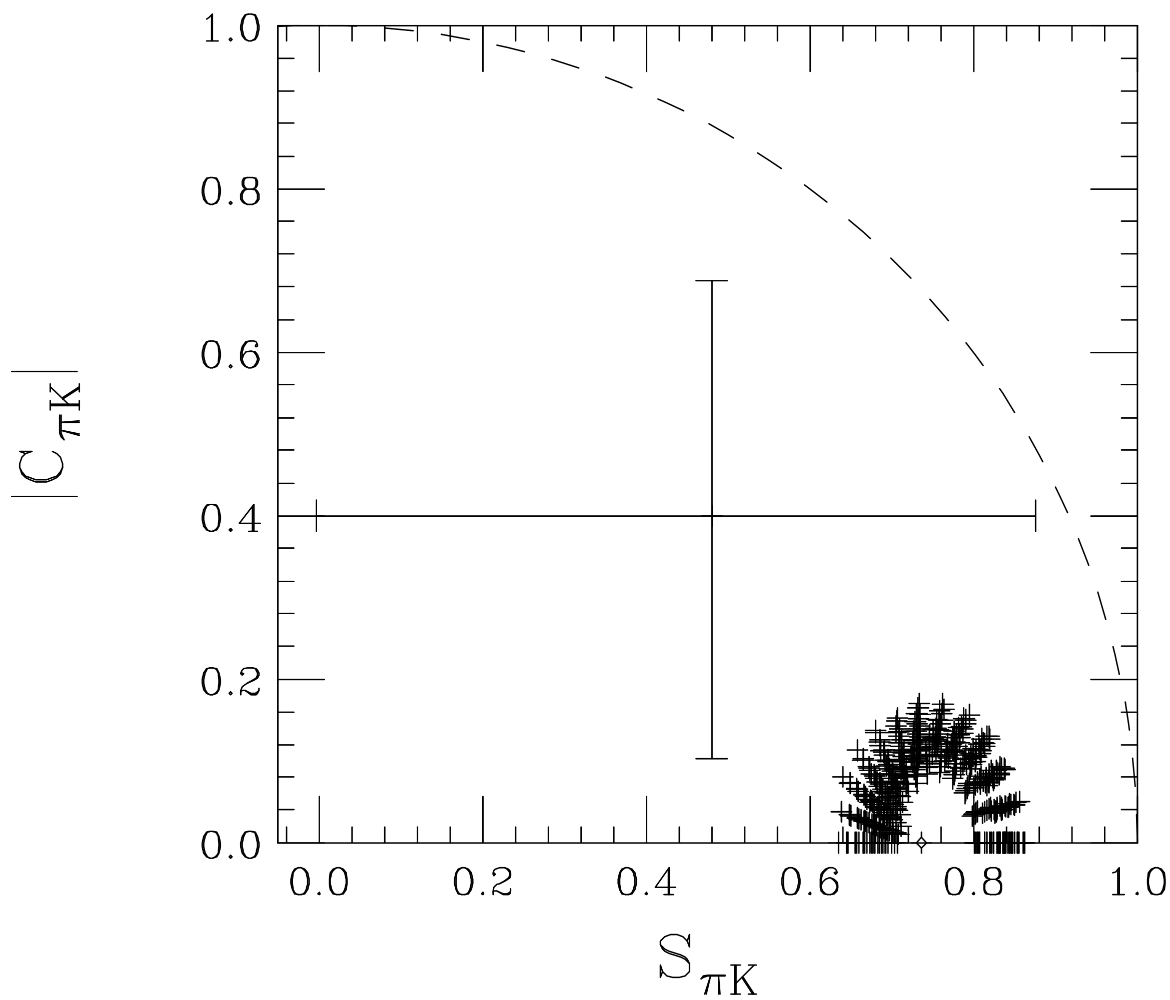
$$\mathcal{B}(B^0 \to K^+ K^-) < 0.6 \times 10^{-6}$$

- We get

$$\xi \leq 0.13, \quad |S_{\pi K} - \sin 2\beta| < 0.19, \quad |C_{\pi K}| < 0.26$$

- We expect $\mathcal{B}(B^0 \to K^+ K^-)$ to be very small. Neglecting it we get stronger bounds

$B \to \pi^0 K_S$



- Neglecting $B^0 \to K^+K^-$

Comments on SU(3)

- Similar analysis for other modes
- SU(3) relations are most useful for simple relations
- SU(3) and U spin are the same
- Since we use SU(3) there are large, $O(30\%)$, corrections. They can be larger or smaller in specific cases
- Bottom line: Large deviations from the SU(3) bounds are signals for new physics

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

$$S_{\psi K_S} = +0.73 \pm 0.05$$

$$S_{\pi K_S} = +0.48^{+0.38}_{-0.47} \pm 0.11 \qquad S_{\eta' K_S} = +0.27 \pm 0.21$$

$$S_{\phi K_S} = -0.15 \pm 0.70 \qquad -S_{K^+K^-K_S} = +0.49 \pm 0.44^{+0.33}_{-0.00}$$

- To first approximation, these asymmetries are equal in the SM
- For $S_{\phi K_S}$ the experimental situation is not clear

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

$$\Downarrow$$

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

Getting a shift only in $B \to \phi K_S$

Kagan

While no indication, still we ask: Can we get

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

- $B \to \phi K_S$ 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 $SU(2)_L \times SU(2)_R \times \text{Parity}$ is an example of an approximate parity conserving new physics model

Opposite chirality

- NP models often include opposite chirality operators

$$Q_3 = (\bar{s}b)_{V-A}\,(\bar{q}q)_{V-A} \quad \to \quad \tilde{Q}_5 = (\bar{s}b)_{V+A}\,(\bar{q}q)_{V+A}$$

- Effective Hamiltonian: $\mathcal{H}_{\rm eff} \propto \sum_i C_i Q_i + \tilde{C}_i \tilde{Q}_i$

- Under Parity, $Qi \leftrightarrow \tilde{Q}_i \;\Rightarrow$ final state, f, with parity P_f

$$\langle f|Q_i|B\rangle = (-1)^{P_B}(-1)^{P_f}\langle f|\tilde{Q}_i|B\rangle$$
$$\Rightarrow\; A_i(B\to f) \propto C_i - (-1)^{P_f}\tilde{C}_i$$

- In the SM $\tilde{C}=0 \;\Rightarrow\; A_i^{\rm NP}(B\to f) \propto C_i^{\rm NP} - (-1)^{P_f}\tilde{C}_i^{\rm NP}$
- For P-invariant NP $A_i^{\rm NP}=0$ for all P_f even states

Examples

- P-even: $\eta' K$, $K\pi$, Ka_1, $K_1\pi$, $(\phi K^*)_{0,\|}$, $(K^*\rho)_{0,\|}$,...
- P-odd: ϕK, $K^{*0}\pi$, $f_0 K$, $(\phi K^*)_{\perp}$, $(\phi K_1)_{0,\|}$,...

P-invariant new physics affects only the P-odd final states

- $S(f) - S(\psi K_S) \neq 0$
- Possible to get $C(f) \neq 0$
- The effect is in general different in each of the P-odd modes
- Hard to see the effect on rates. Too large theoretical uncertainties

Left right symmetric new physics

It is not easy to naturally get $C_i = \tilde{C}_i$

- The SM is maximally parity violating
- Any model without a parity symmetry needs fine tuning
- Parity at the high scale must be broken
- Need to arrange that symmetry breaking effects are large for the SM sector and small for the NP sector
- Example: SUSY LRS model
  - SM: $m(W_L) \ll m(W_R)$
  - NP: $m(\tilde{q}_L) \approx m(\tilde{q}_R)$. Parity breaking via RGE only

$$B \to K\pi$$

$B \to K\pi$

Consider the four decays

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

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

The Lipkin sum rule

Lipkin; Gronau, Rosner

- 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 $b \to s\ell^+\ell^-$
- Leptophobic Z' is a working example

Kagan, Neubert, YG; Leroux, London

Polarization in $B \to VV$ decays

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
  - $$\frac{R_T}{R_0} = O\left(\frac{1}{m_B^2}\right)$$
  - $$\frac{R_\perp}{R_\parallel} = 1 + O\left(\frac{1}{m_B}\right)$$

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 $B \to K^{*0}\rho^+$

Conclusions

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