Heavy Quark Physics

Cracking the Standard Model?

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Lecture 1

- Flavor questions
- Beyond the Standard Model
- Precision measurements in the quark sector
- A bit of QCD …
1. Flavor Questions

Generations, Hierarchies, CP Violation, Baryogenesis
Problem of generations

🔹 Gauge forces in SM do not distinguish betw. fermions of different generations:
  - e,μ have same electrical charge
  - Quarks have same color charge
  - All equal, but not quite equal …

🔹 Why generations ?
🔹 Why 3 ?
🔹 A new quantum number ?
Hierarchies

Masses of quarks and leptons

Fermion masses and mixings constitute many of the parameters of the SM.

Neutrino masses may indicate the relevance of a very large mass scale (GUT, see-saw mechanism), or the existence of extra dimensions!
Fermions of different generations can communicate via flavor-changing weak interactions.

New parameters (mixing angles, phases)

\[ (d_L, s_L, b_L)_k \]

\[ (u_L, c_L, t_L)_i \]

Cabibbo-Kobayashi-Maskawa matrix element

\[ W^- \]
New hierarchies:

\[
V_{\text{CKM}} \approx \begin{pmatrix}
1 & \lambda & \lambda^3 \\
\lambda & 1 & \lambda^2 \\
\lambda^3 & \lambda^2 & 1
\end{pmatrix}, \quad U_{\text{MNS}} \approx \begin{pmatrix}
1 & 1 & \epsilon \\
1 & 1 & 1 \\
1 & 1 & 1
\end{pmatrix}
\]

Possible explanation of CP violation!

Properties of matter

Properties of antimatter

Needs \( \geq 3 \) generations!
The cosmic connection: Baryon asymmetry

Early Universe

Matter
10,000,000,000

Antimatter
10,000,000,000
Today:

Sakharov criteria:
- Baryon-number violation
- CP violation
- Non-equilibrium

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SM satisfies prerequisites for baryogenesis:

- Baryon-number violation at high temperatures ($\Delta B = \Delta L$)
- Non-equilibrium during phase transitions (symmetry breaking)
- CP violation in the quark and lepton sectors

However: CKM phase in the quark sector is not sufficient to account for the baryon asymmetry in the Universe

Need for additional CP-violating couplings!
2. Beyond the Standard Model

Complementarity of High Energy and High Luminosity
Exploring Nature

Colliders (Tevatron, LHC, ILC) + Factories (BaBar, Belle, BTeV, LHC-b, Super-B-Factories, Neutrinos, Kaons)

new particles
new flavors and CP-violating interactions
Future role of flavor physics

- Flavor physics can probe effects of New Physics at scales of 1-1000 TeV, far extending beyond the range of LHC and ILC.
- Many flavor- and CP-violating couplings can only be measured at highest luminosity.
Examples: top & neutrinos

Top-Quark:
- Direct production proves existence and gives mass and spin
- Mass predicted using electroweak precision measurements
- Couplings $|V_{ts}| \approx 0.04$ and $|V_{td}| \approx 0.01$ and CP-violating phase can only be measured in $B$- and $K$-physics

Neutrinos:
- Existence known since long, but only discovery of flavor-changing interactions (neutrino oscillations) brought far-reaching discoveries
- Possibility of CP violation in the lepton sector; leptogenesis
- Completely different hierarchy as in the quark
Empirical fact

- Data show no compelling evidence for Physics beyond the Standard Model:
  - Electroweak precision tests
  - Precision measurements in flavor physics

- **Either:**
  New Physics decouples very effectively:
  - SUSY, split SUSY

- **Or:**
  New Physics lives at scales of several TeV (apart from a few possibly lighter particles)
  - Extra dimensions, “little Higgs”, technicolor
Flavor/CP-violating couplings

- Generic properties:
  - Many new particles (SUSY partners, Kaluza-Klein partners, new gauge bosons, new fermions, etc.) at the TeV scale
  - Generation-changing couplings of new particles are *not diagonal* after field redefinitions of SM fields

- There *must* be effects in the flavor sector at some level of precision!
3. Precision Measurements in the Quark Sector

Wolfenstein parameterization and unitarity triangle

- CKM matrix can be parameterized in terms of 4 real quantities:

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3 (\rho - i\eta) \\
- \lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & - A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

- Complex couplings \(\Rightarrow\) CP violation!

\(\lambda = 0.22, A = 0.84\) well determined

\((\rho, \eta)\) are being determined at the B-factories
Experimental information on \((\rho, \eta)\) can be presented as a “unitarity triangle”:

\[
V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0
\]
The “standard analysis”
The “standard analysis”

- Determination of $|V_{ub}|$ in semileptonic $B$ decays
- Theoretical uncertainties due to hadronic binding effects
The “standard analysis”

- Determination of $|V_{td}|$ in $B^0$-$\overline{B}^0$ mixing
- Theoretical uncertainties due to hadronic binding effects
The “standard analysis”

- Determination of $\text{Im}(V_{td}^2)$ in $K^0$-$\bar{K}^0$ mixing
- Theoretical uncertainties due to hadronic binding effects
The “standard analysis”

- Determination of $\sin 2\beta$ in $B^0-\bar{B}^0$ mixing
- No theoretical uncertainties!
Measurement of $\sin 2\beta$

- CP-violating phases can only be probed via quantum-mechanical interference.
- Simplest case: Interference of $B$ decay and $B^0 - \bar{B}^0$ mixing for transitions into a CP eigenstate $f$.
- If decay amplitude $A$ has a single CP-violating phase $\phi_A$, then:

$$\Gamma(\overline{B}^0(t) \to f) \propto e^{-t/\tau_B} \left[ 1 \pm S(f) \sin(\Delta m_B t) \right]$$

with:

$$S(f) = \pm \sin 2(\beta - \phi_A)$$
How does this work?

- **Schrödinger equation for $B^0$, $\bar{B}^0$:**

  \[
i\frac{d}{dt}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M & \frac{1}{2}e^{-2i\beta}\Delta m \\ \frac{1}{2}e^{2i\beta}\Delta m & M \end{pmatrix} \begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}, \quad M_\pm = M \pm \frac{\Delta m}{2}
\]

- **Time evolution of a state $B^0$ at time $t=0$:**

  \[
  |\psi(t)\rangle = e^{-iMt} \left[ \cos\left(\frac{1}{2}\Delta mt\right) |B^0\rangle + ie^{2i\beta}\sin\left(\frac{1}{2}\Delta mt\right) |\bar{B}^0\rangle \right]
  \]

- **2 decay modes:** $B^0 \rightarrow f (A)$ and $\bar{B}^0 \rightarrow f (\bar{A})$
How does this work?

- Amplitude for decay of this state into final state $f$ after some time $t>0$:

$$A_{B^0}(t) = e^{-iMt} \left[ A \cos \left( \frac{1}{2} \Delta mt \right) + i \bar{A} e^{2i\beta} \sin \left( \frac{1}{2} \Delta mt \right) \right]$$

- Corresponding decay rate (assume $A \sim e^{i\varphi_A}$, $\bar{A} \sim e^{-i\varphi_A}$ single weak phase):

$$\Gamma_{B^0}(t) = |A|^2 \cos^2 \left( \frac{1}{2} \Delta mt \right) + |\bar{A}|^2 \sin^2 \left( \frac{1}{2} \Delta mt \right) + \text{Re}(iA^* \bar{A} e^{2i\beta}) \sin(\Delta mt)$$

$$|A| = |A^*| \equiv |A|^2 \left[ 1 - \sin 2(\beta - \varphi_A) \sin(\Delta mt) \right]$$
Time-dependent CP asymmetry:

\[ A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = S(f) \sin(\Delta m_B t) \]

Direct determination of CP-violating phases, even without knowledge of decay amplitudes!

"Golden" decay mode:

\[ B \to J/\psi K_S \]

Amplitude is real to an excellent approximation, i.e. \( \varphi_A = 0 \)

Direct determination on \( \sin 2\beta \), practically without theoretical uncertainties (~1%)
CP violation visible with the naked eye!

\[ \sin^2 \beta = 0.73 \pm 0.04 \]

**BaBar (2001)**

**Belle (2001)**

Combined: \( \sin 2\beta = 0.73 \pm 0.04 \)
Combination

- So far, all measurements are consistent with each other
- CKM mechanism established as the dominant contribution to flavor-changing interactions
- Confirmation of CP violation in the $t$ sector of the CKM matrix, i.e., $\text{Im}(V_{td}) \neq 0$
Future potential

- Probe of new Physics in $B_s - \bar{B}_s$ mixing at Tevatron (hopefully…) and/or LHC
  - Expect larger New Physics effects in $b \to s$ FCNC transitions as compared with $b \to d$
  - True for $\Delta B=2$ and $\Delta B=1$ (*2nd lecture*)
  - May become the most important measurement at the Tevatron!
Future potential

- Greater precision on $|V_{ub}|$:
  - Recent theoretical work using soft-collinear effective theory allows precision determination from inclusive $B \rightarrow X_u \ell \nu$ decay with theory errors at the 5% level
  - First measurements using this technology have just appeared (April-May 2005), with combined errors of about 10%
  - Comparison with $\beta$ will test SM with unprecedented precision

[Bosch, Lange, MN, Paz]
Impact of precise $|V_{ub}|$

- **Realistic:** $\delta|V_{ub}|: \pm 7\%$
4. A bit of QCD ...

Soft-Collinear Factorization in Inclusive B Decays
Basics

- Separation of scales ("factorization") is crucial to many applications of QCD
  \[ Q^2 \gg \Lambda_{QCD}^2 \]

- Wilsonian OPE: integrate out heavy particles or large virtualities (Fermi theory, HQET, correlators at large \( Q^2 \) …)

- Expansion in \( (\Lambda_{QCD}^2/Q^2)^n \) and \( \alpha_s(Q^2) \)
Basics

- Complication for jet-light physics: large energies and momenta, but small virtualities
  - $e^+e^-\rightarrow$ jets, $B\rightarrow$ light particles, ...

- Light-cone kinematics

How to integrate out short-distance physics in a situation where $p^\mu$ is large, but $p^2$ small?
Challenge

- Construct short-distance expansions for processes involving both soft and energetic light partons
  - Soft: $p_{\text{soft}} \sim \Lambda_{\text{QCD}}$
  - Collinear: $p_{\text{col}}^2 \ll E_{\text{col}}^2$
  - $p_{\text{soft}} \cdot p_{\text{col}} \sim E_{\text{col}} \Lambda$: semi-hard scale

- Technology: effective field theory, OPE, RG
Soft-collinear effective theory

- Effective Lagrangian for this kinematics
- Systematic power counting in $\lambda = \frac{\Lambda_{QCD}}{2E_{\text{jet}}}$
  - Operators classified in terms of their scaling with $\lambda$
- More complicated than previous heavy-quark expansions
  - Expansion in non-local string operators integrated over light-like field separation
  - Many degrees of freedom

[Bauer, Pirjol, Stewart]
Soft-collinear factorization

- Separation of short- and long-distance physics order by order in $1/m_b$:

\[ \Gamma = H J \otimes S + \frac{1}{m_b} H_i J_i' \otimes S_i' \]

[ Korchemsky, Sterman]
[ Lee, Stewart]
[ Bosch, MN, Paz]
Scale separation

- Master formula for inclusive decay

B-decay rates:

\[ \Gamma \sim H(\mu_h) \ast U(\mu_h, \mu_i) \ast J(\mu_i) \ast U(\mu_i, \mu_0) \ast S(\mu_0) \]

QCD → SCET → (RG evolution) → HQET → (RG evolution) → Shape Function

**Perturbation theory**

**Non-perturbative physics**

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Example: $B \rightarrow X_s \gamma$ decay

**Photon spectrum:**

\[
\frac{d\Gamma_s}{dE_\gamma} = \frac{G_F^2 \alpha}{2\pi^4} E_\gamma^3 |V_{tb}V_{ts}^*|^2 \frac{m_b^2(\mu_h)}{m_b^2(\mu_i)} |C^{\text{eff}}_{\gamma}(\mu_h)|^2 U(\mu_h, \mu_i) \mathcal{F}_\gamma(P_+)
\]

\[
\mathcal{F}^{(0)}(P_+) = |H_s(\mu_h)|^2 \int_0^{P_+} d\hat{\omega} \ m_b \ J(m_b(\hat{P}_+ - \hat{\omega}), \mu_i) \hat{S}(\hat{\omega}, \mu_i)
\]

**Jet function:**

\[
J(p^2, \mu) = \delta(p^2) \left[ 1 + \frac{C_F \alpha_s(\mu)}{4\pi} (7 - \pi^2) \right] + \frac{C_F \alpha_s(\mu)}{4\pi} \left[ \frac{1}{p^2} \left( 4 \ln \frac{p^2}{\mu^2} - 3 \right) \right] [\mu^2]
\]
Example: $B \rightarrow X_s \gamma$ decay


\[ H_s(\mu_h) = 1 + \frac{C_F \alpha_s(\mu_h)}{4\pi} \left( -2 \ln^2 \frac{m_b}{\mu_h} + 7 \ln \frac{m_b}{\mu_h} - 6 - \frac{\pi^2}{12} \right) + \varepsilon_{\text{ew}} \]

\[ + \frac{C_{1g}(\mu_h)}{C_{1\gamma}(\mu_h)} \frac{C_F \alpha_s(\mu_h)}{4\pi} \left( -\frac{8}{3} \ln \frac{m_b}{\mu_h} + \frac{11}{3} - \frac{2\pi^2}{9} + \frac{2\pi i}{3} \right) \]

\[ + \frac{C_1(\mu_h)}{C_{1\gamma}(\mu_h)} \frac{C_F \alpha_s(\mu_h)}{4\pi} \left( \frac{104}{27} \ln \frac{m_b}{\mu_h} + g(z) - \frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*} \left[ g(0) - g(z) \right] \right) \]
Nonperturbative input

- Shape function of B meson (usual parton distribution function) can be measured with good precision in $B \to X_s \gamma$ decay
- Use result to predict $B \to X_u \nu$ decay spectra
  - Extraction of $|V_{ub}|$
- Other applications:
  - Very precise determination of $m_b$ from moments of $B \to X_s \gamma$ photon spectrum:
    $$m_b^{SF} = (4.68 \pm 0.03_{th} \pm 0.07_{exp}) \text{GeV}$$
Lecture 2

• Rare hadronic B decays
• Departures from the Standard Model?
• Conclusions
1. Rare Hadronic B Decays

Determination of $\gamma$, Topological Amplitudes, Penguin Zoology
Rare exclusive B decays

- Precise determination of the phase $V_{ub} \sim e^{-iy}$ is difficult (→LHC-b, Super-B-factories)
  - clean measurement à la sin2$\beta$ possible at LHC (?)
- Independently, important information can be gained from rare hadronic $B \rightarrow M_1 M_2$ decays
- Theoretically challenging, since hadronic binding effects must be controlled
  - Much recent progress!
Flavor topologies

Tree:

Penguin:

Electroweak!
Beware of penguins ...
Amplitude interference

Rates for many charmless $B$ decays are characterized by significant interference of tree and penguin topologies:

**Amplitude:**
$$A = T e^{i\delta_1} e^{-i\gamma} + P e^{i\delta_2} + P_{EW} e^{i\delta_3}$$

**Rate:**
$$\Gamma(B \rightarrow f) + \Gamma(\overline{B} \rightarrow \overline{f}) \sim \cos \gamma \cos(\delta_i - \delta_j)$$

**Asymmetry:**
$$\Gamma(B \rightarrow f') - \Gamma(\overline{B} \rightarrow \overline{f'}) \sim \sin \gamma \sin(\delta_i - \delta_j)$$
Reality is far more complicated:

- Until few years ago such nonleptonic decays were believed to be theoretically intractable
- Recent developments:
  - Soft-Collinear Effective Theory
- Systematic treatment ($\Lambda_{QCD}/m_b$ expansion)
QCD factorization formula

First-principles calculation of decay amplitudes and their rescattering phases in heavy-quark limit
How well does it work?

- Compare theory predictions from 2003 (for fixed set of input parameters) with all available present experimental data
- Find good global agreement
- Heavy-quark limit appears to be a good first approximation to the intricate dynamics of these decays
$\mathcal{B}(B \rightarrow K\pi, \pi\pi, KK)$

Branching Ratio x $10^6$

HFAG
AUGUST 25th 2004
$\mathcal{B}(B \to K\pi, \pi\pi, KK)$

Branching Ratio x $10^6$

HFAG
AUGUST 25th 2004
\[ \mathcal{B}(B \rightarrow (\eta, \eta') (K^{(*)}, \pi, \rho)) \]

\[ \mathcal{B}(B \rightarrow (K^*, \rho, \omega, \phi)(\pi, K, \eta, \eta')) \]

HFAG
AUGUST 25th 2004
CP Asymmetry in Charmless B Decays

HFAG
AUGUST 25th 2004
CP Asymmetry in Charmless B Decays

HFAG
AUGUST 25th 2004
Extraction of $\gamma = \text{arg}(V_{ub}^*)$

- Decays $B \rightarrow \pi\pi$, $\pi\rho$ are dominated by tree topologies
- In limit where penguin amplitudes are neglected, decay amplitudes have phase $\varphi_A = -\gamma$, and hence time-dependent CP asymmetries measure $\sin 2(\beta + \gamma)$
- Use QCD factorization to estimate “penguin pollution”
Extraction of $\gamma$ in $B \to \pi \rho$ decay

[Beneke, MN]

- B$\to$PV modes have smaller penguin contributions than B$\to$PP modes
- Smaller theory uncertainties when $\gamma$ is extracted from time-dependent rates in B$\to\pi\rho$ decays
- Result:

$$\gamma = (62 \pm 8)^o$$
Impact of precise $\gamma$

- **Realistic**: $\delta\gamma: \pm 8^\circ$ (better at LHC-b?)
2. Departures from the Standard Model?

Quest for New Physics
Searching for the unknown

- So far, all measurements in the flavor sector are in agreement with the SM
- However, there are tantalizing hints of New Physics effects in some rare, penguin-dominated decays
- Not in contradiction with anything we know from other processes (e.g., $B \to X_s \gamma$)
- Experimental situation stabilizes, and theory is under good control
CP asymmetry in $B \rightarrow \Phi K_S$

- Interference of mixing and decay:
- Phase structure identical to the decay $B \rightarrow J/\psi K_S$
- Model-independent result:

\[
S(\Phi K_S) - S(J/\psi K_S) = 0.02 \pm 0.01
\]

[Beneke, MN]
It’s been a rollercoaster!
**Experimental situation:** (prior to LP 03)

- $S(\Phi K_S) = -0.18 \pm 0.51 \pm 0.07$  
  - BaBar
- $S(\Phi K_S) = -0.73 \pm 0.64 \pm 0.22$  
  - Belle

\[
S(\Phi K_S) - S(J/\psi K_S) = -1.11 \pm 0.41 \ (2.8\sigma)
\]
**Experimental situation:** (after LP 03)

- $S(\Phi K_S) = +0.45 \pm 0.43 \pm 0.07$ BaBar
- $S(\Phi K_S) = -0.96 \pm 0.50 \pm 0.10$ Belle

\[
S(\Phi K_S) - S(J/\psi K_S) = -0.88 \pm 0.33 \ (2.7\sigma)
\]
**Experimental situation:** (after ICHEP 04)

- $S(\Phi K_S) = +0.50\pm0.25\pm0.06$  
  BaBar
- $S(\Phi K_S) = +0.06\pm0.33\pm0.09$  
  Belle

\[
S(\Phi K_S) - S(J/\psi K_S) = -0.46\pm0.25 \text{ (1.8}\sigma)\]

**But, trends for deviations are also seen in other $b\rightarrow s$ penguin modes, e.g. a 3$\sigma$ effect for $\eta' K_S$ from BaBar!**
New Physics?

s-penguin average at 2.7σ different from sin2β[cc] (BABAR)

Similar difference at 2.4σ seen by Belle

[A. Hoecker, ICHEP 2004]
A year later ...
### 7 reasons for excitement!

<table>
<thead>
<tr>
<th>Charmonium</th>
<th>0.726 ± 0.037</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi K^0$</td>
<td>0.34 ± 0.20</td>
</tr>
<tr>
<td>$\eta' K_S^0$</td>
<td>0.43 ± 0.11</td>
</tr>
<tr>
<td>$f_0 K_S^0$</td>
<td>0.39 ± 0.26</td>
</tr>
<tr>
<td>$\pi^0 K_S^0$</td>
<td>0.34 ± 0.29</td>
</tr>
<tr>
<td>$\omega K_S^0$</td>
<td>0.55 ± 0.32</td>
</tr>
<tr>
<td>$K^+ K^- K_S^0$</td>
<td>0.53 ± 0.17</td>
</tr>
<tr>
<td>$K_S^0 K_S^0 K_S^0$</td>
<td>0.26 ± 0.34</td>
</tr>
<tr>
<td>Average (s-penguin)</td>
<td>0.43 ± 0.07</td>
</tr>
</tbody>
</table>

$$-\eta_f \times S_f \text{ Avg.: } 0.42 \pm 0.08$$
Measurements now consistent!

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\Delta S_f$ (Theory)</th>
<th>$\Delta S_f$ [Range]</th>
<th>Experiment [3] (BaBar/Belle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 K_S$</td>
<td>$0.07^{+0.05}_{-0.04}$</td>
<td>[+0.02, 0.15]</td>
<td>$-0.39^{+0.27}<em>{-0.29}$ ($-0.38^{+0.30}</em>{-0.33}$/$-0.43^{+0.60}_{-0.60}$)</td>
</tr>
<tr>
<td>$\rho^0 K_S$</td>
<td>$-0.08^{+0.08}_{-0.12}$</td>
<td>[−0.29, 0.02]</td>
<td>—</td>
</tr>
<tr>
<td>$\eta' K_S$</td>
<td>$0.01^{+0.01}_{-0.01}$</td>
<td>[+0.00, 0.03]</td>
<td>$-0.30^{+0.11}<em>{-0.11}$ ($-0.43^{+0.14}</em>{-0.14}$/$-0.07^{+0.18}_{-0.18}$)</td>
</tr>
<tr>
<td>$\eta K_S$</td>
<td>$0.10^{+0.11}_{-0.07}$</td>
<td>[−1.67, 0.27]</td>
<td>—</td>
</tr>
<tr>
<td>$\phi K_S$</td>
<td>$0.02^{+0.01}_{-0.01}$</td>
<td>[+0.01, 0.05]</td>
<td>$-0.39^{+0.20}<em>{-0.20}$ ($-0.23^{+0.26}</em>{-0.25}$/$-0.67^{+0.34}_{-0.34}$)</td>
</tr>
<tr>
<td>$\omega K_S$</td>
<td>$0.13^{+0.08}_{-0.08}$</td>
<td>[+0.01, 0.21]</td>
<td>$-0.18^{+0.30}<em>{-0.32}$ ($-0.23^{+0.34}</em>{-0.38}$/+0.02$^{+0.65}_{-0.66}$)</td>
</tr>
</tbody>
</table>

Deviation is 3.8σ !!!
In all cases ...

◉ Possible explanation in terms of new, CP-violating flavor-changing neutral currents (FCNC) of the type $b \rightarrow s \bar{q} q$, preferably with $(\bar{q}q)$ in flavor non-singlet configuration ("trojan penguins")

◉ Predicted in a variety of theories, e.g. SUSY (quark-squark-gluino couplings) and extra dimensions (Kaluza-Klein $Z'$)

Trojan Penguins

- In the SM, $b \rightarrow s\bar{q}q$ transitions with $q=d, s \neq u$ are mediated exclusively by electroweak penguins.
- Extensions of the SM can contain such processes without $\alpha_{EM}$ suppression.
- New Physics can easily compete with the SM!

Sensitivity to large scales:

$$M_{NP}^2 = \left(\frac{\alpha_s}{\alpha_{EM}}\right) M_W^2$$
3. Conclusions

Summary and Outlook
Summary

- Precision measurements in the flavor sector (quarks and leptons) complement the search for *New Physics* at high energy and are an indispensable part of the exploration of the TeV scale.
- The determination of the CKM matrix and tests of the CKM mechanism have reached a new quality:
  - Discovery of CP violation in both the $t$ and $b$ sectors of the CKM matrix
  - Precise determination of the unitarity triangle
CKM physics is only one of many ways to search for and explore *New Physics* effects

- Interesting hints exist for new, CP-violating FCNC interactions of the type $b \rightarrow s\bar{q}q$
  - Evidence for *New Physics* at the TeV scale (?)
  - Possible relevance for cosmology (baryogenesis)

- When will the SM collapse, and what lies beyond it?
  - The coming years will tell!