Flavor Physics in a Warped Extra Dimension

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Standard Model and Beyond

Fundamental laws derived from few, basic guiding principles:

- **Symmetries** (gauge theories)
- **Simplicity** and beauty (few parameters)
- **Naturalness** (avoid fine-tuning)
- **Anarchy** (everything is allowed)

But many questions remain unanswered:

- Origin of generations and structure of Yukawa interactions?
- Matter-antimatter asymmetry?
- Unification of forces? Neutrino masses?
- Dark matter and dark energy?

Strong prejudice that there must be “New Physics”
What is the “New Physics” and how to find it?
**Standard Model and Beyond**

- **4th generation**
- **extended Higgs sectors**
- **extended technicolor**
- **left-right symmetry**
- **leptoquarks**
- **universal extra dimensions**
- **large extra dimensions**
- **warped extra dimensions**
- **gauge-Higgs unification**
- **Higgsless models**
- **MSSM**
- **CMSSM**
- **NMSSM**
- **vMSSM**
- **SUSY GUTs**
- **unparticles**
- **Little Higgs**
- **hidden valleys**
- **not yet thought of ...**
Searches for New Physics: Interplay

Complementarity and synergy:

Answering the open questions of elementary particle physics requires a joint effort:

- **Theory**: precision calculations in the SM, studies of New Physics, model-building, ...
- **High-energy experiments**: Tevatron, LHC, ILC (?), CLIC (?), Muon Collider (?), ...
- **Low-energy experiments**: BaBar, Belle, Super-B, NA62, J-PARC, Project X, neutrino physics, EDMs, (g-2)\(\mu\), ...

Quark flavor physics is a crucial component in this program, which provides surgical probes of subtle corrections to fundamental interactions.
Flavor Structure in the SM and Beyond

**Flavor physics** means phenomena related to Yukawa couplings and generation-changing interactions in the fermion sector.

**In SM:**

- all flavor-violating interactions encoded in Yukawa couplings to Higgs boson
- suppression of flavor-changing neutral currents (FCNCs) and CP violation in quark sector due to unitarity of CKM matrix, small mixing angles, and GIM mechanism

\[
\sum_{i,j} \lambda_i \lambda_j f(m_i, m_j) \approx \lambda_b^2 \frac{m_b^2 - m_d^2}{M_W^2} + \lambda_s^2 \frac{m_s^2 - m_d^2}{M_W^2} \approx \lambda_b^2 \frac{m_b^2}{M_W^2}, \quad \lambda_i \equiv V_{ui} V_{ci}
\]
In extensions of SM, additional flavor and CP violation can arise from exchange of new scalar ($H^+, \tilde{q}, ...$), fermionic ($\tilde{g}, t', t^{(1)}, ...$), or gauge ($Z', g^{(1)}, ...$) degrees of freedom

- new flavor-violating terms in general not aligned with SM Yukawa couplings $Y_u, Y_d$
- can lead to excessive FCNCs, unless:
  - new particles are heavy: $\tilde{m}_i >> 1$ TeV
  - masses are degenerate: $\Delta \tilde{m}_{ij} << \tilde{m}_i$
  - mixing angles are very small: $U_{ij} << 1$

Absence of clear New Physics signals in FCNCs implies strong constraints on flavor structure of TeV-scale physics (if it exists)
Flavor Structure in the SM and Beyond

\[ \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{UV}}^2} (\bar{Q}_i Q_j)(\bar{Q}_i Q_j) \]

Generic bounds without flavor symmetry
Hierarchies from geometry
What is the Dynamics of Flavor?

While SM describes flavor physics very accurately, it does not explain its mysteries:

- Why are there three generations in nature?
- Why does the spectrum of fermion masses cover many orders of magnitude (1st hierarchy)?
What is the Dynamics of Flavor?

While SM describes flavor physics very accurately, it does not explain its mysteries:

• Why are there three generations in nature?
• Why does the spectrum of fermion masses cover many orders of magnitude (1st hierarchy)?
• Why is the mixing between different generation governed by small mixing angles (2nd hierarchy)?
• Why is the CP-violating phase of the CKM matrix unsuppressed?

Answers to these questions necessarily require going beyond the SM -- an interesting approach is offered by Randall-Sundrum models with warped extra dimensions.
Flavor Structure in RS Models

\[ ds^2 = \left( \frac{R}{z} \right)^2 \left( \eta_{\mu\nu} dx^\mu dx^\nu - dz^2 \right) \]

- Solution to gauge hierarchy problem via gravitational redshift
- AdS/CFT calculable strong electroweak-symmetry breaking: holographic technicolor, composite Higgs
- Unification possible due to logarithmic running of couplings

Randall, Sundrum (1999)
Flavor Structure in RS Models

Localization of fermions in extra dimension depends exponentially on O(1) parameters: five-dimensional bulk masses parameters $c_q$

Flavor Structure in RS Models

Overlaps $F(Q_L), F(q_R)$ with IR-localized Higgs sector and Yukawa couplings are exponentially small for light quarks, while O(1) for top quark

Flavor Structure in RS Models

Kaluza-Klein (KK) excitations of SM particles live close to IR brane

Davoudiasl, Hewett, Rizzo (1999); Pomarol (1999)
Flavor Structure in RS Models

Since light quarks live in UV, their couplings to $W$ and $Z$ bosons, as well as to KK gauge bosons, are almost flavor-independent.

Gherghetta, Pomarol (2000)
Hierarchies of Quark Masses and CKM Angles

- SM mass matrices can be written as

$$m_q^{SM} = \frac{v}{\sqrt{2}} \text{diag}[F(Q_i)] Y_q \text{diag}[F(q_i)] = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \boxed{\cdot} \end{pmatrix}$$

where $Y_q$ with $q = u, d$ are structureless, complex Yukawa matrices with $O(1)$ entries, and $F(Q_i) \ll F(Q_j), F(q_i) \ll F(q_j)$ for $i < j$

- In analogy to seesaw mechanism for neutrinos, matrices of this form give rise to hierarchical mass eigenvalues and mixing matrices

Warped-space Froggatt-Nielsen mechanism!

Froggatt, Nielsen (1979); Casagrande et al. (2008); Blanke et al. (2008)
Hierarchies of Quark Masses and CKM Angles

- Thus:

\[ m_q \sim \frac{v}{\sqrt{2}} \text{diag} [F(Q_i)F(q_i)] = \begin{pmatrix} & \cdot & \cdot \\ & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{pmatrix} \]

\[ (V_{CKM})_{ij} \sim \begin{cases} 
\frac{F(Q_i)}{F(Q_j)}, & i \leq j \\
\frac{F(Q_j)}{F(Q_i)}, & i > j 
\end{cases} = \begin{pmatrix} & \cdot & \cdot & \cdot \\ & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot \end{pmatrix} \]

- Hierarchies predicted and readily adjusted by O(1) variations of bulk masses
- CP violating phase is predicted to be unsuppressed! [Casagrande et al. (2008); Blanke et al. (2008)]
RS-GIM Protection of FCNCs

- Quark FCNCs are induced at tree-level through virtual exchange of KK gauge bosons (including KK gluons!)  
  \[ F(Q_{1L}) \xrightarrow{d} g_s \sqrt{L} \quad g^{(1)} \quad g_s \sqrt{L} \xrightarrow{s} F(s_R) \]

- Resulting FCNC couplings depend on same exponentially small overlaps \( F(Q_L), F(q_R) \) that generate fermion masses

- FCNCs involving quarks other than top are strongly suppressed!  
  (true for all induced FCNC couplings)  
  \[ F(Q_{2L}) \xrightarrow{s} g_s \sqrt{L} \quad g_s \sqrt{L} \xrightarrow{d} F(d_R) \]

This mechanism suffices to suppress all but one of the dangerous FCNC couplings!

Huber (2003); Burdman (2003); Agashe et al. (2004); Casagrande et al. (2008)

Agashe et al. (2004)
RS-GIM Protection of FCNCs

RS-GIM protection with KK masses of order few TeV
RS-GIM Protection of FCNCs

RS-GIM protection with KK masses of order few TeV

\[ \Delta \text{uv [TeV]} \]

\[ \begin{align*}
\Delta m_K, \epsilon_K & \quad \Delta m_d, \sin 2\beta & \quad \Delta m_s, A_{SL}^s & \quad D - \bar{D} \\
(\text{large effects}) & \quad \text{small effects} & \quad \text{large effects} & \quad \text{large effects} \\
\text{requires fine-tuning of } O(10^{-2}) & \\
\text{Csaki, Falkowski, Weiler (2008); Blanke et al. (2008); Bauer et al. (2008, 2009)}
\end{align*} \]
Golden Modes: Rare Kaon Decays

- Spectacular corrections are possible in very clean $K \rightarrow \pi\nu\bar{\nu}$ decays, even saturating the Grossman-Nir bound, $\mathcal{B}(K_L \rightarrow \pi^0\nu\bar{\nu}) < 4.4 \mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$.

Blanke et al. (2008); Bauer et al. (2009)

- SM: $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) \approx 8.3 \cdot 10^{-11}$,
  $\mathcal{B}(K_L \rightarrow \pi^0\nu\bar{\nu}) \approx 2.7 \cdot 10^{-11}$

- Central value and 68% CL limit
  $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = (17.3_{-10.5}^{+11.5}) \cdot 10^{-11}$
  from E949

- Consistent with quark masses, CKM parameters, and 95% CL limit
  $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$
Golden Modes: Rare B Decays

- Factor ~10 enhancements possible in rare $B_{d,s} \rightarrow \mu^+\mu^-$ modes without violation of $Z \rightarrow b\bar{b}$ constraints; effects largely uncorrelated with $|\epsilon_K|$

$\star$ SM: $\mathcal{B}(B_d \rightarrow \mu^+\mu^-) \approx 1.2 \cdot 10^{-10}$,
$\mathcal{B}(B_s \rightarrow \mu^+\mu^-) \approx 3.9 \cdot 10^{-9}$

- minimum of $5.5 \cdot 10^{-9}$ for 5$\sigma$ discovery by LHCb, 2 fb$^{-1}$

- 95% CL upper limit from CDF:
$\mathcal{B}(B_s \rightarrow \mu^+\mu^-) < 5.8 \cdot 10^{-8}$

- consistent with quark masses, CKM parameters, $Z \rightarrow b\bar{b}$, and 95% CL limit $|\epsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

Blanke et al. (2008); Bauer et al. (2009)
New Physics in $B_s - \bar{B}_s$ mixing?

- Tantalizing hints for new physics phase in $B_s - \bar{B}_s$ mixing from flavor-tagged analysis of mixing-induced CP violation in $B_s \rightarrow J/\psi \phi$ by CDF and DØ, and more recently from anomalous like-sign di-muon charge asymmetry at DØ

Discrepancy of $\phi_s = 2|\beta_s| - 2\phi_{B_s}$ with respect to SM value $\phi_s \approx 2^\circ$ at around 2-3σ level
New Physics in $B_s$-$\bar{B}_s$ mixing?

- Constraint from $|\varepsilon_K|$ does not exclude $O(1)$ effects in width difference $\Delta \Gamma_s/\Gamma_s$ of $B_s$ system, but difficult to account for central values of data.

- SM: $\Delta \Gamma_s/\Gamma_s \approx 0.13$, $S_{\psi\phi} \approx 0.04$

- preferred experimental range

- consistent with quark masses, CKM parameters, $Z\rightarrow bb$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$

Blanke et al. (2008); Bauer et al. (2009)
New Physics in $B_d$-$\bar{B}_d$ mixing?

- Constraint from $|\varepsilon_K|$ does not exclude significant modifications of the CP asymmetry in $B \rightarrow \psi K_S$, which could relax the $|V_{ub}|$ - sin2$\beta$ tension

\[ \phi_{B_d} = \phi_{B_d}^{SM} \pm \sigma \]

consistent with quark masses, CKM parameters, $Z \rightarrow b\bar{b}$, and 95% CL limit $|\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3}$
**D-\bar{D} Mixing**

- Very large effects possible, including large CP violation; predictions might be testable at LHCb

- Consistent with quark masses, CKM parameters, \( Z \rightarrow b\bar{b} \), and 95% CL limit \( |\varepsilon_K| \in [1.3, 3.3] \cdot 10^{-3} \)

Bauer et al. (2009)
Correlations with Higgs physics

- Properties of the Higgs boson offer alternative ways to probe, via modifications of SM couplings and virtual effects from heavy KK states, the structure of warped extra-dimension models.

- Recently, we have performed the first complete one-loop analysis of Higgs production and decays in the RS model with custodial symmetry.

Casagrande, Goertz, Haisch, MN, Pföh (2010)
Higgs production cross sections

- Find possibly spectacular effects on Higgs production via gluon fusion, even for high KK masses ($m_{G^{(1)}_{KK}} \approx 2.45 M_{KK}$):

![Graphs showing Higgs production cross sections at Tevatron and LHC for different center-of-mass energies and KK masses.](image)
Higgs decay branching fractions

- Correspondingly, find possibly significant impact on $h \rightarrow gg$ and $h \rightarrow \gamma\gamma$ branching ratios:
Puzzles in the Flavor Sector: Facts or Fiction?

Several observables don’t look quite right ... (~2σ effects)
Puzzles in the Flavor Sector: **Facts or Fiction?**

Perhaps, one of these hints will solidify and point us the way beyond the SM!

Several observables don’t look quite right ... (~2σ effects)
Summary and Outlook

The first collisions at the LHC mark the beginning of a fantastic era for particle physics, which holds promise of ground-breaking discoveries.

ATLAS and CMS discoveries alone are unlikely to provide a complete understanding of the observed phenomena.

Flavor physics (more generally, low-energy precision physics) will play a key role in unravelling what lies beyond the Standard Model, providing access to energy scales and couplings unaccessible at the energy frontier.

Only the synergy of LHC and high-precision experiments may give us the key to solving the puzzles of fundamental physics.