Flavor Theory
Flavor as a portal beyond the Standard Model

Matthias Neubert
Johannes Gutenberg University Mainz

International Europhysics Conference on High-Energy Physics
Grenoble, France, 21-27 July 2011
Introduction - Flavor as a portal beyond the SM

• Besides the **hierarchy problem** (mechanism of EWSB) and the **dark-matter puzzle**, the **origin of flavor** is one of the big, unsolved mysteries of fundamental physics
  ‣ connected to deep questions such as the **matter-antimatter asymmetry** in the Universe, the **origin of fermion generations**, and the reason for the **striking hierarchies** observed in the spectrum of fermion masses and mixing angles
  ‣ in SM, **flavor physics is connected to EWSB** via the Higgs Yukawa interactions

• Flavor physics is an issue for any extension of the SM ("flavor problem")
Introduction - Flavor as a portal beyond the SM

- For almost two decades, when SUSY was the most popular extension of the SM, flavor physics was largely ignored and considered irrelevant to high-energy discovery physics.
- The reason was that SUSY has little to say about the origin of flavor -- and worse, that flavor is potentially problematic for many (generic) SUSY models.
- Fortunately, in recent years the situation has changed significantly.
- Flavor is now generally viewed as a key ingredient of any BSM theory, which may help to discover New Physics (even beyond the direct LHC reach) and decipher its nature.
Introduction - Flavor as a portal beyond the SM

Intriguing example: Anomalous top-quark forward-backward asymmetry at the Tevatron

- New Physics contribution from s- or t-channel exchange of a new heavy particle, interfering with SM tree-level contribution
- In all but one model,*) the existence of new heavy particles with non-trivial flavor structure is required!

\[ \cos \theta \text{ term } \propto -g_{Aq} g_{At}, \text{ and hence these couplings must have opposite sign } (g_{Aq} \neq g_{At}) \]

requires flavor off-diagonal couplings of top to light quarks

*) Tavarez, Schmalz (2011): light axigluon model

see e.g.: Grinstein, Kagan, Trott, Zupan (2011); Blum, Hochberg, Nir (2011); Haisch, Westhoff (2011)
Westhoff @ EPS11
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 ...
Complementary of direct and indirect searches

- Production of **new particles** at high-energy colliders probes directly the structure of matter and its interactions

- But quite different scenarios of New Physics can lead to very similar signatures and hence to experimental signals that are difficult to disentangle

- Low-energy precision measurements study quantum corrections from **virtual particles**, offering indirect insights into the structure of matter and its interactions

- In the history of physics, this has often provided **first clues** about a new layer of reality (e.g. weak interactions, charm and top quarks, Higgs boson, ...), since it provides sensitivity to higher energy scales
Legacy of the B factories (BaBar, Belle, CDF, D0)

- Spectacular confirmation of the CKM model as the **dominant source of flavor and CP violation**
- 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**

\[
V \approx \begin{pmatrix}
1 & \lambda & \lambda^3 \\
-\lambda & 1 & \lambda^2 \\
-\lambda^3 & -\lambda^2 & 1
\end{pmatrix}
\]

\(\lambda \approx 0.22: \) Cabibbo angle

2008 Nobel Prize to Kobayashi, Maskawa

\footnote{EPS HEPP Prize 2011 to Glashow, Iliopoulos, Maiani}
Legacy of the B factories (BaBar, Belle, CDF, D0)

• Spectacular confirmation of the CKM model as the **dominant source of flavor and CP violation**

• 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**

M. Kobayashi
N. Cabibbo
T. Maskawa

2008 Nobel Prize to Kobayashi, Maskawa

*) EPS HEPP Prize 2011 to Glashow, Iliopolous, Maiani

\[
\begin{align*}
q_i & \quad \delta_{ij} & \quad q_j \\
\delta: \text{ unit matrix} & \quad V: \text{ CKM matrix}
\end{align*}
\]

Niess @ EPS11; see also: Bona @ EPS11
In extensions of the SM, additional flavor and CP violation can arise from exchange of new scalar ($H^+$, $\tilde{q}$, ...), fermionic ($\tilde{g}$, $t'$, ...), or gauge ($Z'$, $W'$, ...) 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 very heavy: $\tilde{m}_i >> 1$ TeV
  - their masses are degenerate: $\Delta\tilde{m}_{ij} << \tilde{m}_i$
  - or mixing angles are very small: $U_{ij} << 1$

The absence of dominant New Physics signals in FCNCs implies strong constraints on the flavor structure of TeV-scale physics!
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 a flavor symmetry
Introduction - Flavor as a portal beyond the SM

A more refined look indeed hints at some tensions with the SM in several areas of flavor physics:

**B_d-meson system**
- Tensions in UT fit
- $V_{ub}$ crisis
- sin2$\beta$ tree vs. penguin

**B_s-meson system**
- CPV in $B_s$-meson mixing
- Anomalous like-sign dimuon production
- Rare decay $B_s \to \mu^+\mu^-$

At present, some of the most tantalizing hints (not more) of BSM physics -- besides $(g-2)_\mu$ and the top-quark forward-backward asymmetry at the Tevatron -- come from the flavor sector!

We live in exciting times, since many of these hints will very soon be cross-checked and perhaps corroborated at LHC!
Outline

• Recent developments in flavor theory
• Hints for New Physics in B-meson mixing
• Hints for New Physics in B-meson decays
• Outlook

Unfortunately no time for:
• Production of heavy flavors
• Spectroscopy and exotic states
• Detailed discussion of hadronic B-meson decays
• Detailed discussion of improved CKM measurements
• Charm decays and D-meson mixing ...
Recent developments in flavor theory
Recent developments in flavor theory

• Intense theory effort of hard-core QFT calculations for flavor observables (~1990-2010) based on heavy-quark expansions, effective field theories and lattice QCD has been a triumph of particle phenomenology

• Many important conceptual developments (HQET, NRQCD, QCDF, SCET, LCSR, ...)

• In several cases, irreducible theoretical uncertainties have been reached

• Compared to a few years ago, there have been relatively few new theoretical calculations with a direct impact on phenomenology
  ‣ discuss three examples

Blossier @ EPS11; Tantalo @ EPW11

Khodjamirian @ EPS11; Melikhov @ EPS11
Inclusive semileptonic B-decay spectra

- Extraction of $|V_{cb}|, |V_{ub}|, m_b, m_c$, heavy-quark parameters

- Two-loop QCD corrections ($\sim \alpha_s^2$) to differential $B \to X_q l \nu$ (for $q=c,u$) have been calculated
  
  Melnikov (2008); Pak, Czarnecki (2008); Biswas, Melnikov (2009); Bonciani, Ferroglia (2008); Asatrian, Greub, Pecjak (2008); Beneke, Huber, Li (2008); Bell (2008)

- Their effects on moments have been computed

- Higher-order power corrections $\sim 1/m_b^{4,5}$ have been estimated
  
  Mannel, Turczyk, Uraltsev (2010)

- One-loop QCD corrections to the leading power-suppressed corrections have still only been calculated for the kinetic operator ($\sim \alpha_s \cdot \mu_{\pi}^2/m_b^2$)
  
  Becher, Boos, Lunghi (2007)

- Resummation of Sudakov logarithms in the shape-function region has been completed at NNLO ($\sim N^3LL$)
  
  Greub, MN, Pecjak (2009)
QCD factorization for hadronic B decays

Calculation of BBNS kernels $T_{ij}^{I,II}$ at NNLO:

- One-loop corrections to hard spectator scattering (tree and penguin topologies)  

- Imaginary parts of two-loop vertex corrections  
  Bell (2007)

- Two-loop vertex corrections to topological tree amplitudes  
  Beneke, Huber, Li (2009); Bell 2009

- 2-loop penguin topologies in progress  
  Bell, Beneke, Huber, Li
Non-local power corrections in $B \rightarrow X_s \gamma$ decay

$$\mathcal{B}(B \rightarrow X_s \gamma)_{\text{SM}}^{E_\gamma > 1.6 \text{ GeV}} = \mathcal{B}(B \rightarrow X_c e \bar{\nu})_{\text{exp}} \left[ \frac{\Gamma(b \rightarrow s \gamma)}{\Gamma(b \rightarrow c e \bar{\nu})} \right]_{\text{LO}}$$

$$\times \left\{ 1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha) + \mathcal{O}(\alpha_s^2) + \mathcal{O}\left( \frac{\Lambda_{\text{QCD}}^2}{m_b^2} \right) + \mathcal{O}\left( \frac{\Lambda_{\text{QCD}}^2}{m_c^2} \right) + \mathcal{O}\left( \frac{\Lambda_{\text{QCD}}}{m_b^2} \right) \right\}$$

Misiak et al. (2006)


relative size of corrections compared to leading-order (LO) branching ratio
Non-local power corrections in $B \to X_s \gamma$ decay

Systematic analysis of non-local $\Lambda_{QCD}/m_b$ corrections based on novell factorization theorem derived using soft-collinear effective theory:

- Estimate irreducible theoretical uncertainty in the calculation of the $B \to X_s \gamma$ branching ratio of about $\pm 5\%$ (relative error)
- Show that non-local power corrections give the formally leading contribution to the direct CP asymmetry in the Standard Model:

$$A_{X_s \gamma}^{SM} \approx \left( 1.11 \times \frac{\tilde{\Lambda}_{17}^u - \tilde{\Lambda}_{17}^c}{300 \text{ MeV}} + 0.69 \right) \%$$

Recent developments in flavor theory

• **Important:** Some of the theoretical tools originally developed for flavor physics have found important applications in other fields, e.g.:
  
  ‣ Renormalon calculus for estimating power corrections for non-Euclidean observables (1990s)
  ‣ SCET applications to collider physics: an effective field theory approach to **factorization**, **Sudakov resummation**, and **jet physics**
  ‣ SCET applications to heavy-ion physics
Flavor phenomenology in extensions of the SM

• Much recent activity on a variety of models, including:
  ‣ SUSY models (MSSM, CMSSM, BMSSM, ...)
  e.g.: Buras, Nagai, Paradisi (2010); Girrbach et al. (2011)
  Girrbach @ EPS11
  Crivellin @ EPS11; Straub @ EPS11; Jones=Perez @ EPS11
  ‣ (SUSY-) GUTs
  e.g.: Buras, Carlucci, Gori, Isidori (2010); Blankenburg, Isidori (2011)
  Girrbach @ EPS11
  e.g.: Buras et al. (2010); Rohrwild et al. (2009, 2010, 2011)
  Soni @ EPS11; Xu @ EPS11
  ‣ models with extra dimensions (UED, RS, ...)
  e.g.: Buras, Carlucci, Gori, Isidori (2010); Blankenburg, Isidori (2011)
  Girrbach et al. (2011)
  e.g.: Buras et al. (2010); Rohrwild et al. (2009, 2010, 2011)
  Soni @ EPS11; Xu @ EPS11
  ‣ models with extended Higgs sectors
  ‣ models with a 4th generation
  ‣ models with new gauge bosons W’, Z’

• Models featuring a warped extra dimension (Randall-Sundrum) offer a simultaneous, geometrical solution to the hierarchy and flavor problems
  ‣ very different from SUSY
  Csaki, Falkowski, Weiler (2008);
  Casagrande, Goertz, Haisch, MN, Pfoh (2008);
  Blanke, Buras, Duling, Gori, Weiler (2008);
  Blanke, Buras, Duling, Gemmler, Gori (2008);
  Bauer, Casagrande, Haisch, MN (2009)
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 so many orders of magnitude?
- Why is the mixing between different generations governed by small mixing angles?
- Why is the CP-violating phase of the CKM matrix unsuppressed?
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
Localization of fermions in extra dimension depends exponentially on $O(1)$ parameters related to the five-dimensional bulk masses. 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.

Hierarchies of quark masses and CKM angles

SM mass matrices can be written as:  

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

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

• In analogy to seesaw mechanism, matrices of this form give rise to hierarchical mass eigenvalues and mixing matrices
• Hierarchies can be adjusted by \( O(1) \) variations of bulk mass parameters
• Yet the CKM phase is predicted to be \( O(1) \)

Warped-space Froggatt-Nielsen mechanism!

Casagrande et al. (2008); Blanke et al. (2008)
Flavor structure in RS models

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

Davoudiasl, Hewett, Rizzo (1999); Pomarol (1999)
RS-GIM protection of FCNCs

Quark FCNCs are induced at tree-level through virtual exchange of KK gauge bosons (including KK gluons!)

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)

This mechanism suffices to suppress all but one of the dangerous FCNC couplings!
RS-GIM Protection of FCNCs

- RS-GIM protection with KK masses of order few TeV
- Requires fine-tuning of O(1%) or a good idea

Csaki, Falkowski, Weiler (2008); Blanke et al. (2008); Bauer et al. (2008, 2009)
Hints for New Physics in B-meson mixing
Basic formulae

Schrödinger equation:

\[
i \frac{d}{dt} \left( \begin{align*}
|B_q(t)\rangle \\
|\bar{B}_q(t)\rangle
\end{align*} \right) &= \left( M^q - \frac{i}{2} \Gamma^q \right) \left( \begin{align*}
|B_q(t)\rangle \\
|\bar{B}_q(t)\rangle
\end{align*} \right)
\]

Three observables:

\[
\phi_q = \text{arg}\left( -\frac{M^q_{12}}{\Gamma^q_{12}} \right)
\]

\[
\Delta M_q = M^q_H - M^q_L = 2 |M^q_{12}|
\]

\[
\Delta \Gamma_q = \Gamma^q_L - \Gamma^q_H = 2 |\Gamma^q_{12}| \cos \phi_q
\]

Flavor-specific (e.g. semileptonic) asymmetries, assuming no CPV in the decay amplitudes:

\[
a^q_{fs} = a^q_{SL} = \text{Im} \frac{\Gamma^q_{12}}{M^q_{12}} = \frac{|\Gamma^q_{12}|}{|M^q_{12}|} \sin \phi_q = \frac{\Delta \Gamma_q}{\Delta M_q} \tan \phi_q
\]

Parametrisation of New Physics effects (assuming NP only in $M^q_{12}$):

\[
\frac{M^q_{12}}{M^q_{12,SM}} = \Delta_q = |\Delta_q| e^{i\phi_q^\Delta} = 1 + h_q e^{i2\sigma_q}
\]
**CP-violating observables**

Mixing-induced, time-dependent CP asymmetries in decays to CP eigenstates:

\[
S_{\psi K} = \sin(2\beta + \phi_d) \quad S_{\psi\phi} = \sin(2\beta_s - \phi_s^\Delta)
\]

Semileptonic asymmetry measured at B factories:

\[a_{SL}^d\]

Flavor-specific asymmetry in tree-level \(B_s^0\rightarrow\mu^+D_s^-X\) decays (D0):

\[a_{fs}^s = a_{SL}^s\]

Like-sign dimuon charge asymmetry (D0):

\[
A_{sl}^b = \frac{N_{b}^{+-} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}} = C_d a_{SL}^d + (1 - C_d) a_{SL}^s; \quad C_d = 0.594 \pm 0.022
\]

\* No need to use the theoretical prediction for \(\Delta \Gamma_s\)!
**Tevatron data**

Like-sign dimuon charge asymmetry (D0):
- not an easy measurement
- if taken at face value, a rather compelling hint of New Physics!

Mixing-induced CP asymmetry (B_s):

**Preliminary**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DØ Run II, 8 fb⁻¹</td>
<td>ΔM = 17.77 ± 0.12 ps⁻¹</td>
<td>SM p-value = 29.8%</td>
</tr>
</tbody>
</table>

**CDF Run II Preliminary**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>95% CL</td>
<td>68% CL</td>
<td>SM prediction</td>
</tr>
</tbody>
</table>

**Figure 9:** Cumulative likelihood ratio distribution for the two-dimensional profile likelihood with the likelihood ratios for the standard model point. 3.9 σ!
Theoretical analyses (prior to D0 update)

Constraints on New Physics parameters \( (h_d, \sigma_d) \) and \( (h_s, \sigma_s) \): Ligeti, Papucci, Perez, Zupan (2010)

- SM \( (h_d=h_s=0) \) disfavored at \(<3\sigma\) in \( B_s \) mixing and \(<2\sigma\) in \( B_d \) mixing
- case \( h_d=h_s \) and \( \sigma_d=\sigma_s \) (e.g., minimal flavor violation models) strongly disfavored
Theoretical analyses (prior to D0 update)

Constraints on New Physics parameters $\Delta_d$ and $\Delta_s$:

- SM ($\Delta_d=\Delta_s=1$) disfavored at $3.6\sigma$ ($\approx 4.2\sigma$ after D0 update)
- no indication of New Physics in $K$-$\bar{K}$ mixing
- minimal flavor violation ($\Delta_d=\Delta_s$ real) disfavored at $3.7\sigma$ (generalized MVF is still ok)
Theoretical analyses without CPV in $B_s$ mixing

Much of this is driven by the anomalous like-sign dimuon asymmetry seen at D0, but there is also tension in the standard unitarity-triangle fit if the Tevatron results on CP violating in $B_s$ mixing are left out:

Lenz, Nierste + CKMfitter (2010)
Theoretical analyses without CPV in $B_s$ mixing

Unitarity-triangle fit with different inputs:

- input: $V_{cb}$, $\varepsilon_K$, $\gamma$, $\Delta M_{d,s}$, $B \rightarrow \tau \nu$
- output: $\sin 2\beta$, $f_B$, $|V_{ub}|$

→ obtain excellent fit, hinting at New Physics in $B_d$ mixing

- input: same as above, but without use of semileptonic decays ($V_{cb}$)

- input: same as above, but without use of $K$-$\bar{K}$ mixing

Lunghi, Soni (2010)
Theoretical analyses without CPV in $B_s$ mixing

лин

### Inputs:

<table>
<thead>
<tr>
<th>Input</th>
<th>$\sin(2\beta)$</th>
<th>$f_B$(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_K, \Delta M_q,</td>
<td>V_{cb}</td>
<td>, \gamma, B \to \tau\nu$</td>
</tr>
<tr>
<td>$\epsilon_K, \Delta M_q,</td>
<td>V_{cb}</td>
<td>$</td>
</tr>
<tr>
<td>$\epsilon_K, \Delta M_q, \gamma, B \to \tau\nu$</td>
<td>0.891±0.052 (2.8σ)</td>
<td>201±9</td>
</tr>
<tr>
<td>$\Delta M_{B_q},</td>
<td>V_{cb}</td>
<td>, \gamma, B \to \tau\nu$</td>
</tr>
<tr>
<td>$\epsilon_K, \Delta M_q,</td>
<td>V_{cb}</td>
<td>, \gamma, B \to \tau\nu$</td>
</tr>
<tr>
<td>$\epsilon_K, \Delta M_q,</td>
<td>V_{cb}</td>
<td>, \gamma,</td>
</tr>
<tr>
<td>$\epsilon_K, \Delta M_q,</td>
<td>V_{cb}</td>
<td>, \gamma$</td>
</tr>
<tr>
<td>$[\epsilon_K, \Delta M_q,</td>
<td>V_{cb}</td>
<td>, \gamma, B \to \tau\nu]^{**}$</td>
</tr>
<tr>
<td>$[\epsilon_K, \Delta M_q,</td>
<td>V_{cb}</td>
<td>, \gamma, B \to \tau\nu]^{**}$</td>
</tr>
<tr>
<td>$[\epsilon_K, \Delta M_q,</td>
<td>V_{cb}</td>
<td>, \gamma, B \to \tau\nu]^{**}$</td>
</tr>
</tbody>
</table>

| $B \to ccs$ tree | 0.668±0.023 |
| $\phi K^0$ | 0.56±0.16 |
| $\eta K^0$ | 0.59±0.07 |
| $(\phi, \eta')K$ | 0.58±0.065 |

- consistent determination of $\sin 2\beta$ much larger than direct measurement!
- direct measurement from mixing-induced CP violation in tree-level decays
- direct measurement from mixing-induced CP violation in penguin modes (interpreted as a hint for New Physics in penguin-induced FCNC processes)

Lunghi, Soni (2010)

*** lattice errors increased by 50%
+++ adding hadronic uncertainty $\delta \Delta S_{\gamma K} = 0.021$
Hints for New Physics in B-meson decays
Three intriguing observations

• Several measurements of rare $B_{u,d}$ and $B_s$ decays suggest the existence of New Physics contributions in the decay amplitudes, not related to $B$-meson mixing:

  ‣ discrepancies in the determinations of $V_{ub}$ from inclusive semileptonic decays $B \rightarrow X_u \ell \nu$, exclusive semileptonic decays $B \rightarrow \pi \ell \nu$, and leptonic decay $B \rightarrow \tau \nu$ ("$V_{ub}$ crisis")

  ‣ large difference of $(14.4 \pm 2.9)\%$ in the direct CP asymmetries measured in $B^0 \rightarrow K^+\pi^-$ vs. $B^+ \rightarrow K^+\pi^0$ decays, which is in conflict with the prediction of $(2.2 \pm 2.4)\%$ from QCD factorization ("$B \rightarrow K\pi$ puzzle")

  ‣ enhanced $B_s \rightarrow \mu^+\mu^-$ branching ratio observed by CDF (but not by LHCb and CMS 😞)
The “$V_{ub}$ crisis”

For many years, there has been a persistent discrepancy between determinations of $|V_{ub}|$ from inclusive and exclusive semileptonic decays of B mesons ($B \to X_u \nu$ vs. $B \to \pi \nu$). HFAG quotes:

$$|V_{ub}|_{incl} = (4.32 \pm 0.16 \pm 0.22) \cdot 10^{-3}$$

$$|V_{ub}|_{excl} = (3.51 \pm 0.10 \pm 0.46) \cdot 10^{-3}$$

Measurement of the purely leptonic decay $B \to \tau \nu$ sharpen the discrepancy further:

(not most up-to-date values!)

Lunghi, Soni (2010)
The “$V_{ub}$ crisis”

A very elegant solution is offered by the addition of a **right-handed weak current** with coupling $V_{ub}^R$, which enters as $|V_{ub}^{L}+V_{ub}^{R}|^2$ in $B\to\pi l\nu$, $|V_{ub}^{L}-V_{ub}^{R}|^2$ in $B\to\tau\nu$, and $|V_{ub}^{L}|^2+|V_{ub}^{R}|^2$ in $B\to X_u l\nu$:

- a small admixture of approx. -15% of right-handed current (i.e. from gluino-squark loops in MSSM) brings all three measurements in agreement with each other!

---

| $|V_{ub}|\times10^3$ |
|------------------|
| 7               |
| 6               |
| 5               |
| 4               |
| 3               |
| 2               |
| 1               |
| 0               |

-15% admixture of a right-handed current

---

**Crivellin (2009);**
see also: **Buras, Gemmler (2011)**
Rare decays $B_{d,s} \rightarrow \mu^+ \mu^-$

* interesting rare decays, which can be much enhanced in models with a warped extra dimension or SUSY models with large $\tan \beta$

Excess in $B_s$ mode reported by CDF:

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (1.8^{+1.1}_{-0.9}) \cdot 10^{-8}$$

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) < 6.0 \cdot 10^{-9}$$

SM: $(3.2 \pm 0.2) \cdot 10^{-9}$

SM: $(1.0 \pm 0.1) \cdot 10^{-10}$

Unfortunately no excess seen at LHCb (CMS):

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 1.5 (1.9) \cdot 10^{-8}$$

(at 95% CL)

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) < 5.2 (4.6) \cdot 10^{-9}$$

These bounds to not rule out the CDF result, but without refined LHC measurements the situation is inconclusive!
Theoretical predictions: Randall-Sundrum model

Both rare modes $B_{d,s} \rightarrow \mu^+ \mu^-$ can be significantly enhanced over their SM values:

Bauer, Casagrande, Haisch, MN (2009); see also: Blanke et al. (2008)
Theoretical predictions: Randall-Sundrum model

Both rare modes $B_{d,s} \rightarrow \mu^+\mu^-$ can be significantly enhanced over their SM values:

- New results on $B_s \rightarrow \mu^+\mu^-$ begin cutting into the interesting parameter space
- Expected effects in $B_s$ mixing are unlikely to reproduce the central values of the data
Theoretical predictions: BMSSM

A generalized SUSY model with additional CP phases in the Higgs sector from higher-dimensional operators can give rise to interesting effects in the $B_s$ system:

- New upper bound on $B_s \to \mu^+ \mu^-$ implies an interesting upper limit on the magnitude of the New Physics contributions to CP violation in $B_d$ and $B_s$ mixing
Forward-backward asymmetry in $B \rightarrow K^{*}\mu^{+}\mu^{-}$

A lesson how quickly tentative hints can disappear with improved measurements (in a closely related rare decay mode):

- B-factory data prior to EPS11 hinted at a positive asymmetry for all $q^{2}$
- CDF update for EPS11 is already closer to the SM...
- ... and new LHCb data provide a textbook confirmation of the SM prediction!

see also:
Bobeth @ EPS11;
Descotes-Genon @ EPS11
Outlook
Flavor as a portal beyond the Standard Model

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

Existing hints about New Physics flavor signature suggest that only the synergy of LHC and high-precision experiments will give us the key to solving the puzzles of the Terascale