Probing the TeV scale (and above) with Flavor Physics

Maurizio Pierini
CERN-PH UTfit Collaboration


www.utfit.org
The UTfit in the Standard Model

\[ \bar{\rho} = 0.164 \pm 0.029 \]
\[ [0.107, 0.222] @ 95\% \text{ Prob.} \]

\[ \bar{\eta} = 0.340 \pm 0.017 \]
\[ [0.307, 0.373] @ 95\% \text{ Prob.} \]

everything is consistent but...
NP effects should be there

The SM works beautifully up to a few hundred GeV's, but if it is an effective theory valid up to a scale $\Lambda < M_{\text{planck}}$

$$\mathcal{L}(M_W) = \Lambda^2 H^\dagger H + \lambda (H^\dagger H)^2 + \mathcal{L}_{\text{gauge}}^{\text{SM}} + \mathcal{L}_{\text{Yukawa}}^{\text{SM}} + \mathcal{L}_5 / \Lambda + \mathcal{L}_6 / \Lambda^2$$

Gauge hierarchy problem: $\Lambda \sim \text{TeV}$

In general, without deviations from SM in B physics: $\Lambda \sim 100-1000 \text{ TeV}$

With the present experimental situation on B-physics side and the expectations of discovery at LHC, there is a “tension” between the NP scales
New Physics and flavor

New Physics scenarios can be classified according to their flavor structure

Generic flavor structure: NP introduces additional complex couplings among quarks (e.g. off-diagonal elements in squark mixing matrix)

Minimal Flavor Violation: CKM is the only source of flavor mixing even beyond SM

- single Higgs doublet or low tanβ: NP enters as a universal correction to K and B_q mixing
- large tanβ: NP enters differently in K and B_q mixing
- very large tanβ: only relevant contribution to B_s mixing

Next-to-Minimal Flavor Violation: NP introduces additional complex couplings among quarks, having the same hierarchy than CKM (same powers of sinθ_c) but arbitrary phase

Using this classification, we will translate the UT bounds into useful information for direct search at LHC
Model independent NP parameters

Consider for example $B_d$ mixing process. Given the SM amplitude, we can define

$$C_{B_d} e^{-2i \phi_{B_d}} = \frac{\langle B^0 | H_{\text{eff}}^{\text{SM}} + H_{\text{eff}}^{\text{NP}} | B^0 \rangle}{\langle \bar{B}^0 | H_{\text{eff}}^{\text{SM}} | B^0 \rangle} = 1 + \frac{A_{\text{NP}} e^{-2i \phi_{\text{NP}}}}{A_{\text{SM}} e^{-2i \beta}}$$

All NP effects can be parameterized in terms of one complex parameter for each meson mixing, to be determined in a simultaneous fit with the CKM parameters (now there are enough experimental constraints to do so). For Kaons we use Re and Im, since the two exp. constraints $\varepsilon_K$ and $\Delta m_K$ are directly related to them (with different theoretical issues)
How the bounds are modified

<table>
<thead>
<tr>
<th>Model independent assumptions</th>
<th>( \rho, \eta )</th>
<th>( C_{B_d}, \phi_{B_d} )</th>
<th>( C_{\varepsilon_K} )</th>
<th>( C_{B_s}, \phi_{B_s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{ub}/V_{cb} )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( \gamma ) (DK)</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( \varepsilon_K )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( \sin 2\beta )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( \Delta m_d )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( \alpha (\rho \rho, \rho \pi, \pi \pi) )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( A_{SL} B_d )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( \Delta \Gamma_d/\Gamma_d )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( \Delta \Gamma_s/\Gamma_s )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( \Delta m_s )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
<tr>
<td>( A_{CH} )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
<td>( \times )</td>
</tr>
</tbody>
</table>

\[ SM \]

- \( (V_{ub}/V_{cb})^{SM} \)
- \( \gamma^{SM} \)

\[ SM+NP \]

- \( (V_{ub}/V_{cb})^{SM+NP} \)
- \( \gamma^{SM+NP} \)

\[ Bd Mixing \]

- \( \beta^{SM} \)
- \( \alpha^{SM} \)
- \( \Delta m_d \)
- \( \beta^{SM+\phi_{B_d}} \)
- \( \alpha^{SM-\phi_{B_d}} \)
- \( C_{B_d}\Delta m_d \)

\[ Bs Mixing \]

- \( \Delta m_s^{SM} \)
- \( \beta_s^{SM} \)
- \( C_{B_s}\Delta m_s^{SM} \)
- \( \beta_s^{SM+\phi_{B_s}} \)

\[ K Mixing \]

- \( \varepsilon_K^{SM} \)
- \( \Delta m_K^{SM} \)
- \( C_{\Delta m_K}\Delta m_K^{SM} \)

References:
- N. G. Deshpande et al. hep-ph/9608231
- J. P. Silva and L. Wolfenstein, hep-ph/9610208
Experimental Inputs

For Bd and K sector:
- same as the SM inputs (see www.utfit.org)
- Added $A_{SL}^d$

For D sector:
- use the analysis of Ciuchini et al. hep-ph/0703204

For Bs sector:
- $\Delta m_s$ from CDF
- $L(\Delta \Gamma_s, \Gamma_s, \beta_s)$ from D0 (4 ambiguities)
- $\tau(B_s)$ from flavor specific decays
- $A_{CH}$ from D0
- $A_{SL}^s$ from D0

HFAG averages used
The UTfit allowing New Physics

\[ \bar{\rho} = 0.167 \pm 0.051 \]
\[ [0.069, 0.290] \at\ 95\%\ Prob. \]

\[ \bar{\eta} = 0.386 \pm 0.035 \]
\[ [0.306, 0.459] \at\ 95\%\ Prob. \]
New Physics in the K sector

\[ C_{\Delta mK} = 0.93 \pm 0.32 \]

\[ [0.51, 2.07] @ 95\% \text{ Prob.} \]

\[ C_{\varepsilon K} = 0.88 \pm 0.14 \]

\[ [0.63, 1.26] @ 95\% \text{ Prob.} \]
New Physics in the $B_d$ sector

$C_{Bd} = 1.04 \pm 0.34$

$[0.52, 2.07] \text{ @ 95\% Prob.}$

$\phi_{Bd} = (-4.1 \pm 2.1)^\circ$

$[-8.6^\circ, 0.4^\circ] \text{ @ 95\% Prob.}$

$~2\sigma$ effect induced by $\sin2\beta$

vs Vub tension Bona et al.

New Physics in the $B_s$ sector

$C_{B_s} = 1.04 \pm 0.29$

$[0.60, 1.93] \text{ at } 95\% \text{ Prob.}$

$\phi_{B_s} = (-75 \pm 14)^\circ U (-18 \pm 12)^\circ U (7 \pm 11)^\circ$

$[-90^\circ, 55^\circ] U [-39^\circ, 30^\circ] U [55^\circ, 90^\circ] \text{ at } 95\% \text{ Prob.}$

$X \text{ SM expectation}$
New Physics in the D sector

\[ A_{NP} \tau_D < 0.0072 \text{ @ 95% Prob.} \]

\[ \phi_{NP} = (15 \pm 41)^\circ \cup (165 \pm 41)^\circ \]

\([-68^\circ, 248^\circ]\) @ 95% Prob.

X SM expectation
How NP effects are induced

At the High scale
new physics enters according its specific features (i.e model)

At the Low scale
We can use OPE to write the most general effective Hamiltonian
The operators have different chiralities that the SM
NP effects are in the Wilson Coefficients $C$

NP effects are enhanced
- up to a factor 10 by the values of the matrix elements (especially for transitions among quarks of different chiralities)
- up to a factor 8 by the RGE that

\[
\mathcal{H}_{\text{eff}}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}
\]

\[
Q_1^{q_i q_j} = \bar{q}_j^\alpha \gamma_\mu q_i^\alpha \bar{q}_j^\beta \gamma_\mu q_i^\beta ,
\]

\[
Q_2^{q_i q_j} = \bar{q}_j^\alpha q_i^\alpha \bar{q}_j^\beta q_i^\beta ,
\]

\[
Q_3^{q_i q_j} = \bar{q}_j^\alpha q_i^\beta \bar{q}_j^\beta q_i^\alpha ,
\]

\[
Q_4^{q_i q_j} = \bar{q}_j^\alpha q_i^\alpha \bar{q}_j^\beta q_i^\beta ,
\]

\[
Q_5^{q_i q_j} = \bar{q}_j^\alpha q_i^\beta \bar{q}_j^\beta q_i^\alpha .
\]
From Wilson Coeff. to NP Scale (I)

"magic numbers" (see paper) \( \eta = \alpha_s (\Lambda)/\alpha_s (m_t) \),

\[
\langle \bar{B}_q | \mathcal{H}_{\text{eff}}^{\Delta B=2} | B_q \rangle_i = \sum_{j=1}^{5} \sum_{r=1}^{5} \left( b_j^{(r,i)} \right) + \eta C_j^{(r,i)} \eta^\alpha C_i(\Lambda) \langle \bar{B}_q | Q^b_{r} | B_q \rangle
\]

The dependence of the \( C \) on \( L \) changes according to flavor structure:

**Generic**: \( C(\Lambda) = a/\Lambda^2 \) with arbitrary phase

**NMFV**: \( C(\Lambda) = a \times |F_{SM}|/\Lambda^2 \) with arbitrary phase

**MFV**: \( C(\Lambda) = a \times F_{SM}/\Lambda^2 \) (i.e. with SM phase)

\( a \) is the coupling among NP and SM:

\( a \sim 1 \) for strongly coupled NP

\( a \sim \alpha_W (\alpha_s) \) in case of loop coupling through weak (strong) interactions

\( F_{SM} \) is the combination of CKM factors for the considered process

More detailed strategy according to tan\( \beta \) value
From Wilson Coeff. to NP Scale (II)

Generic Flavor Structure
From Wilson Coeff. to NP Scale (II)

NMFV
From Wilson Coeff. to NP Scale (III)

Scale in TeV for different scenarios and different couplings

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\alpha_s$ loop</th>
<th>$\alpha_W$ loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMFV</td>
<td>6.2</td>
<td>2</td>
</tr>
<tr>
<td>General</td>
<td>24000</td>
<td>2400</td>
</tr>
</tbody>
</table>

Cannot explain NP (if) seen at LHC

Not a first year physics (small couplings means small production rates)
Minimal Flavor Violation (I)

All tree-level and CP violating processes are constrained to their SM value. A more precise determination of CKM matrix is possible, common to MFV and SM

\[ \bar{\rho} = 0.156 \pm 0.039 \]

[0.084, 0.235] @ 95% Prob.

\[ \bar{\eta} = 0.340 \pm 0.019 \]

[0.303, 0.376] @ 95% Prob.

NP is a shift in the Inami-Lim functions

\[ S_0(x_t) \rightarrow S_0(x_t) + \delta S_0(x_t) \]

\[ \delta S_0(x_t) = 4a \left( \frac{\Lambda_0}{\Lambda} \right)^2 \]

D'Ambrosio et al.

hep-ph/0207036
single Higgs doublet or small $\tan \beta$:
the shift of the Inami-Lim function
induced by NP is universal.
$\Lambda > 5.5 \, @95\% \text{ prob.}$

large $\tan \beta$:
Yukawa of the $b$ plays a role
Different shifts for $K$ and
$Bq$ mixing amplitudes
$\Lambda > 5.1 \, @95\% \text{ prob.}$
additional contributions to $C_4$ ($\Lambda$) can be generated by Higgs exchange

$$C_4(\Lambda) = \frac{(a_0 + a_1)(a_0 + a_2)}{\Lambda^2} \lambda_b \lambda_q F_{SM}$$

where $l$ are the Yukawa couplings, the $a$'s are tan$b$-enhanced loop factors and $F_{SM}$ is the combination of CKM factors for the considered process. Here $\Lambda$ is the scale of the non-standard Higgs.

We can then translate the bound on $C$ into a bound on the Higgs Mass

$$M_H > 5 \sqrt{(a_0 + a_1)(a_0 + a_2)} \left(\frac{\tan \beta}{50}\right) \text{TeV}$$
Conclusions

The abundance of information from flavor physics allows to determine
the CKM matrix even in presence of NP effects.

The result is close to the SM one, favoring MFV scenarios for NP.

If this information is used to bounds NP, NP scale is pushed beyond LHC
energy range, except in some cases for which small couplings (i.e. small
production rates) make the LHC discovery difficult but not impossible.

For MFV, the allowed energy is accessible to LHC.

These bounds represent the stringent bounds for flavor violating NP
and are competitive to the EW constraints from LEP/SLD.