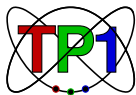


Flavour Physics 3

Flavor Beyond the Standard Model

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Theory Challenges for LHC Physics

Dubna, 20.07. - 30.07.2015

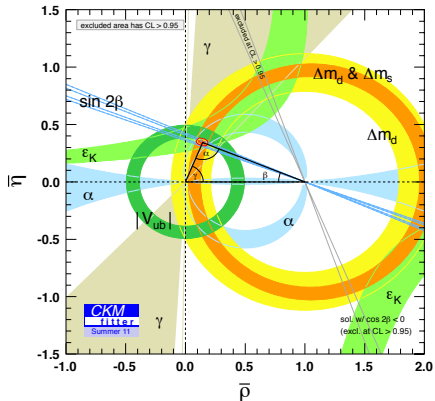
Contents

- 1 Why Study Flavour Physics?
 - Why do we believe in TeV Physics?
 - Hints from the leptonic sector
- 2 Minimal Flavour Violation
 - Quarks
 - Leptons
- 3 Flavor Models
 - Guesses for Mass Matrices

Why Study Flavour Physics?

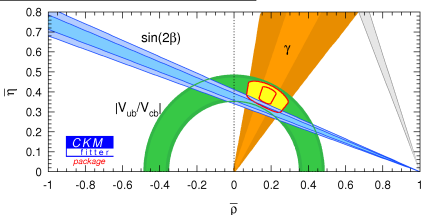
- The Standard Model passed all tests up to the 100 GeV Scale:
- LEP: test of the gauge Structure
- Flavour factories: test of the Flavour Sector

	Measurement	Fit	$ O^{\text{meas}} - O^{\text{fit}} /\sigma^{\text{meas}}$
$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759	0.1
m_Z [GeV]	91.1875 ± 0.0021	91.1874	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	0.1
σ_{had}^0 [nb]	41.540 ± 0.037	41.478	1.6
R_f	20.767 ± 0.025	20.742	0.2
$A_{\text{fb}}^{0,l}$	0.01714 ± 0.00095	0.01646	0.7
$A_f(P_f)$	0.1465 ± 0.0032	0.1482	0.5
R_b	0.21629 ± 0.00066	0.21579	0.1
R_c	0.1721 ± 0.0030	0.1722	0.0
$A_{\text{fb}}^{0,b}$	0.0992 ± 0.0016	0.1039	2.8
$A_{\text{fb}}^{0,c}$	0.0707 ± 0.0035	0.0743	1.0
A_b	0.923 ± 0.020	0.935	0.6
A_c	0.670 ± 0.027	0.668	0.1
$A_f(\text{SLD})$	0.1513 ± 0.0021	0.1482	1.4
$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$	0.2324 ± 0.0012	0.2314	0.8
m_W [GeV]	80.399 ± 0.023	80.378	0.9
Γ_W [GeV]	2.085 ± 0.042	2.092	0.2
m_t [GeV]	173.20 ± 0.90	173.27	0.1

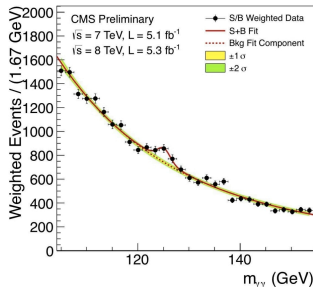
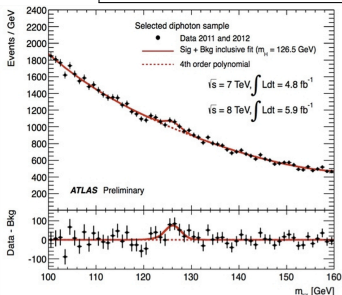


No significant deviation has been found (yet)!

... only a few “tensions”
(= Observables off by 2σ
or even less)

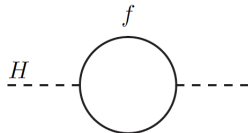


LHC will perform a direct test of the TeV Scale



Why do we believe in TeV Physics?

- **Theoretical argument:**
- Stabilization of the electroweak scale:

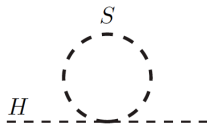
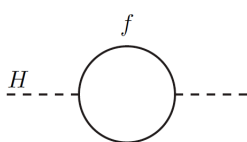


- Quadratic Dependence on the cut-off

$$\Delta m_H^2 = -\frac{\lambda_f^2}{8\pi^2} \Lambda_{UV}^2$$

- Drives the Higgs mass up to the UV cut off $\Lambda_{UV} \sim M_{PL}$

- Stabilization at the TeV scale: **e.g. through SUSY:**



- Only logarithmic divergence

$$\Delta m_H^2 = m_{\text{soft}}^2 \frac{\lambda}{16\pi^2} \ln \left(\frac{\Lambda_{\text{UV}}}{m_{\text{soft}}} \right)$$

- $m_{\text{soft}} \sim \mathcal{O}(\text{TeV})$:
 Splitting between particles and particles

- **How strong are these arguments?**
- Could there something be wrong with our understanding of
 - electroweak symmetry breaking?
 - scale and conformal invariance?
(c.f. Lee Wick Model)
 - ...
- **Does flavour tell us something about this?**
.... and what?

What can Flavour tell us?

- Effective field theory picture:
- Standard model (without right handed ν 's) is the (dim-4) starting point.
- Any new physics manifests itself as higher dimensional operators:

$$\mathcal{L} = \mathcal{L}_{\text{dim } 4}^{\text{SM}} + \mathcal{L}_{\text{dim } 5} + \mathcal{L}_{\text{dim } 6} + \dots$$

- $\mathcal{L}_{\text{dim } n}$ are suppressed by large mass scales

$$\mathcal{L}_{\text{dim } n} = \frac{1}{\Lambda^{n-4}} \sum_i c_n^{(i)} O_n^{(i)}$$

$O_n^{(i)}$: Operators of dimension n ,

$SU(3)_C \times SU(2)_W \times U(1)_Y$ gauge invariant

$c_n^{(i)}$: dimensionless couplings

Quark Flavour Physics

- For Quarks there is no contribution to $\mathcal{L}_{\text{dim } 5}$
- Some of the $O_j^{(n)}$ mediate $\Delta F = 2$ flavour transitions:

$$O_1^{(6)} = (\bar{s}_L \gamma_\mu d)(\bar{s}_L \gamma^\mu d) \quad (\text{Kaon Mixing})$$

$$O_2^{(6)} = (\bar{b}_L \gamma_\mu d)(\bar{b}_L \gamma^\mu d) \quad (B_d \text{ Mixing})$$

$$O_3^{(6)} = (\bar{b}_L \gamma_\mu 2)(\bar{b}_L \gamma^\mu s) \quad (B_s \text{ Mixing})$$

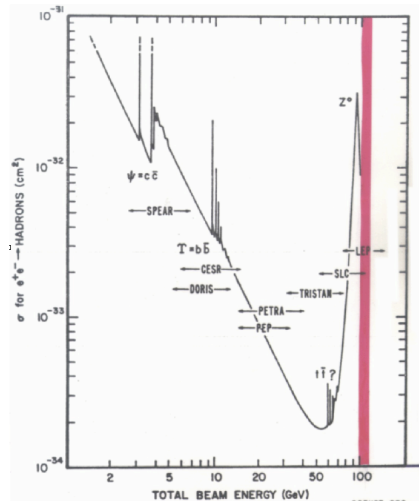
$$O_4^{(6)} = (\bar{c}_L \gamma_\mu u)(\bar{c}_L \gamma^\mu u) \quad (D \text{ Mixing})$$

- $\Lambda \sim 1000 \text{ TeV}$ from Kaon mixing ($C_i = 1$)
- $\Lambda \sim 1000 \text{ TeV}$ from D mixing
- $\Lambda \sim 400 \text{ TeV}$ from B_d mixing
- $\Lambda \sim 70 \text{ TeV}$ from B_s mixing

- “New physics” is around the corner??
- Are the flavour data a hint at a new physics scale well above the TeV scale?
- ... there are a few corners where $\mathcal{O}(1)$ flavour effects are still possible, c.f. Charm CPV
- Are there lessons from history?

The Top Quark Story

- First indirect hint to a heavy top quark:
 $B - \bar{B}$ Oscillation of ARGUS (1987)
- The world in 1987 (“PETRA Days”):
The top was believed to be at ~ 25 GeV
... based on good theoretical arguments
- **ARGUS could not have seen anything with a 25 GeV Top (within SM)**



- The consequences:
 - (-) No Toponium
 - (-) No Top quark discovery at LEP and SLC
 - (-) No “New Physics $\mathcal{O}(30 \text{ GeV})$ ” just around the corner
 - (+) CP violation in the B sector may become observable
 - (+) GIM is weak for bottom quarks
- This was actually good for Flavour Physics ...
- GIM suppressed decays as a probe for large scales
- From current data: TeV “New Physics” must have a flavour structure close to the one of the SM
- → Concept of “Minimal Flavour Violation” (MFV)

Hints from the leptonic sector

- $\mathcal{L}_{\text{dim } 4}^{\text{SM}}$ does not have a right handed neutrino
- ... thus no mixing for the leptons
- Discovery of Neutrino Oscillations:
Nontrivial Flavour Physics of Leptons
- Important observation: The combination

$$N_i = (H^{c,\dagger} L_i), \quad L_i = \begin{pmatrix} \nu_{L,i} \\ \ell_{L,i} \end{pmatrix}, \quad H^c = (i\tau^2)H^*, \quad H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

has no SM Quantum numbers

- This allows for a Unique dim -5 Operator:
Generates Majorana masses for the ν 's

$$\mathcal{L}_{\text{dim } 5} = \frac{1}{\Lambda_{\text{LNV}}} \sum_{ij} C_5^{ij} (\bar{L}_j H^c)^c (H^{c,\dagger} L_i)$$

- Generates a mixing matrix for the leptons (PMNS Matrix), analogous to the CKM Matrix
- This term is **Lepton Number Violating**, related to the scale Λ_{LNV}
- Small Neutrino masses: Λ_{LNV} must be high, almost as big as the GUT scale?
- **Hopefully Λ_{QFV} and Λ_{LFV} is not that high!**

Minimal Flavour Violation

- Flavour Violation of TeV “new physics” must be very close to one of the Standard Model
- **Concept of “minimal flavour violation”:**
All Flavour Violation (and CP violation) is CKM like
(D’Ambrosio et al. ’02, Ciuchini et al. ’98, Buras et al. ’00)
- More precise definition
D’Ambrosio et al., hep-ph/0207036
- **Leptonic Sector has also been considered as well**
Grinstein et al., hep-ph/0507001, hep-ph/0601111
- Standard Model is Minimally Flavour Violating per definition

- Most of the commonly used new physics models are constructed to solve any others but the flavor problems!
- .. but we hope to see something at LHC!
- So it has to be MFV!

Flavour Symmetry: Quarks

- Largest Quark Flavour Symmetry commuting with the Gauge Group of the Standard Model

$$G_F = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$

with

$$Q_L = \begin{pmatrix} U_L \\ D_L \end{pmatrix} \sim (3, 1, 1) \quad U_R \sim (1, 3, 1) \quad D_R \sim (1, 1, 3)$$

- G_F is *explicitly* broken by the Yukawa couplings

$$\mathcal{L}_{\text{Yuk}} = \bar{Q}_L H Y_D D_R + \bar{Q}_L \tilde{H} Y_U U_R$$

- Diagonalization of the Yukawa Couplings

$$Y_D^{\text{diag}} = V_{DL}^\dagger Y_D V_{DR} \quad Y_U^{\text{diag}} = V_{UL}^\dagger Y_U V_{UR}$$

- Leads after Spontaneous Symmetry Breaking to diagonal Mass Matrices for the Quarks
- Note that $V_{UR} \in SU(3)_{UR}$ and $V_{DR} \in SU(3)_{DR}$
- ... but both V_{UL} and V_{DL} should be $\in SU(3)_{QL}$
- this leads to a relative and observable mismatch and

$$V_{\text{CKM}} = V_{UL}^\dagger V_{DL}$$

- Using mass eigenstates, V_{CKM} appears as the matrix of charged current couplings.

Spurions

- Trick to parametrize explicit symmetry breaking:
Introduce “Spurions”
- **Spurion: Field with a well defined transformation under the symmetry to be explicitly broken.**
- **Write all terms that are allowed by the symmetry with a finite number of insertions of the spurion field(s)**
- **“Freeze” the spurion field(s) to a nonzero value: “vacuum expectation value”**
- Explicit Symmetry breaking = Spontaneous Symmetry Breaking without the Higgs degrees of freedom
- Small symmetry breaking: **Power counting** for the spurion insertions is needed.

Yukawa Couplings as Spurions

- Interpret the Yukawa couplings as spurion fields transforming as

$$Y_U \sim (3, \bar{3}, 1) \quad Y_D \sim (3, 1, \bar{3})$$

- In this way the Yukawa terms become formally invariant under G_F
- “Freezing” the Yukawa couplings to the observed values breaks G_F explicitly.
- **Minimal Flavour Violation:** The two spurions Y_U and Y_D are the only sources of flavour violation.

Example $B \rightarrow X_s \gamma$ in MFV

- The $b \rightarrow s \gamma$ decay is a $D_R \rightarrow D_L$ transition.
- $\bar{Q}_L D_R$ is not invariant under G_F
- $\bar{Q}_L Y_D D_R \rightarrow \bar{D}_L m_d^{\text{diag}} D_R$ is flavour diagonal.
- $\bar{Q}_L Y_U Y_U^\dagger Y_D D_R \rightarrow \bar{D}_L V_{\text{CKM}}^\dagger (m_u^{\text{diag}})^2 V_{\text{CKM}} m_d^{\text{diag}} D_R$
 minimal number of spurions for a flavour transition.
- Leading term in $b \rightarrow s \gamma$: $\bar{s}_L V_{ts}^* V_{tb} m_t^2 m_b b_R$
- Right handed helicities suppressed by a power of the quark mass
- FCNC require at least two CKM matrix elements, at least one of which is off diagonal
- GIM: no FCNC's in case of degenerate quark masses

Flavour Symmetry: Leptons

- “Minimal field content” (no right handed neutrino)

$$E_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad E_R = e_R$$

- Smaller flavour group for the leptons

$$\tilde{G}_F = SU(3)_{E_L} \times SU(3)_{E_R}$$

- Transformations under \tilde{G}_F :
 $E_L \sim (3, 1)$ and $E_R \sim (1, 3)$
- Yukawa term for the leptons

$$L_{\text{Yuk}} = \bar{E}_L H Y_E E_R$$

- Y_E can be diagonalized by a \tilde{G}_F transformation
No flavour mixing for leptons !

Lepton Flavour Violation: Higher Dimensional Operators

- Dim-5 operator leading to a ν Majorana Mass Term

$$\mathcal{L}_{\text{Maj}} = \frac{1}{2\Lambda_{\text{LN}}} (N^T g N)$$

$$\text{with } N = \left(T_3^{(R)} + \frac{1}{2} \right) H^\dagger L$$

$$\text{and } H = \frac{1}{\sqrt{2}} \begin{pmatrix} \nu + h_0 + i\chi_0 & \sqrt{2}\phi_+ \\ -\sqrt{2}\phi_- & \nu + h_0 - i\chi_0 \end{pmatrix}$$

- Λ_{LN} : Scale of lepton number violation
- g : New Spurion field transforming as $(\bar{6}, 1)$ under \tilde{G}_F
- Y_E, g can (in general) not be diagonal simultaneously

New Physics in MFV: Quarks

- Generic point of view: Consider the Standard model as an effective theory, valid at the electroweak scale
- “New Physics” enters below M_W through power suppressed operators with dimensions ≥ 6
- Assume that Y_U , Y_D (and Y_E) are still the only spurions explicitly breaking flavour
- The flavour transitions of the new-physics contributions are still suppressed by the same CKM factors and masses as in the Standard Model
- Focus first on quarks ...

Power Counting and Wolfenstein Parametrization

- Power Counting \sim “small” symmetry breaking
- Implemented by the Wolfenstein parametrization

$$V_{\text{CKM}} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \quad \lambda \sim 0.2$$

- Quark Masses (except top) are small compared to the electroweak scale
- **Additional spurion insertions yields more suppression** (except for $t \rightarrow b$ transitions, flavour diagonal)
- **Consider only minimal number of spurion insertions**
 - Up to four insertions for right \rightarrow right transitions

Effective Field Theory Picture of New Physics

- List the various quark transitions:

	U_L	U_R	D_L	D_R
\bar{U}_L	$V_{uL}^\dagger Y_D Y_D^\dagger V_{uL}$ $= V_{\text{CKM}}^\dagger \hat{m}_D^2 V_{\text{CKM}}$	$V_{uL}^\dagger Y_D Y_D^\dagger Y_U V_{uR}$ $= V_{\text{CKM}}^\dagger \hat{m}_D^2 V_{\text{CKM}}^\dagger \hat{m}_U$	$V_{uL}^\dagger V_{dL}$ $= V_{\text{CKM}}$	$V_{uL}^\dagger Y_D V_{dR}$ $= V_{\text{CKM}}^\dagger \hat{m}_D V_{\text{CKM}}$
\bar{U}_R	h.c.	$V_{uR}^\dagger Y_U^\dagger Y_D Y_D^\dagger Y_U V_{uR}$ $= \hat{m}_U V_{\text{CKM}}^\dagger \hat{m}_D^2 V_{\text{CKM}}^\dagger \hat{m}_U$	$V_{uR}^\dagger Y_U^\dagger V_{dL}$ $= \hat{m}_U V_{\text{CKM}}$	$V_{uR}^\dagger Y_U^\dagger Y_D V_{dR}$ $= \hat{m}_U V_{\text{CKM}}^\dagger \hat{m}_D V_{\text{CKM}}$
\bar{D}_L	h.c.	h.c.	$V_{dL}^\dagger Y_U Y_U^\dagger V_{dL}$ $= V_{\text{CKM}}^\dagger \hat{m}_U^2 V_{\text{CKM}}$	$V_{dL}^\dagger Y_U Y_U^\dagger Y_D V_{dR}$ $= V_{\text{CKM}}^\dagger \hat{m}_U^2 V_{\text{CKM}}^\dagger \hat{m}_D$
\bar{D}_R	h.c.	h.c.	h.c.	$V_{dR}^\dagger Y_D^\dagger Y_U Y_U^\dagger Y_D V_{dR}$ $= \hat{m}_D V_{\text{CKM}}^\dagger \hat{m}_U^2 V_{\text{CKM}}^\dagger \hat{m}_D$

- Loops may change the number of insertions:
 Suppressed by powers of Wolfenstein λ

New Physics in MFV: Leptons

- Majorana term is a “new physics” contribution
- Distinguish between the scale of lepton flavour violation and lepton number violation
- For dim-6 operators: Possible Spurion combinations

$$g^\dagger \times g \sim \bar{\mathbf{6}} \times \mathbf{6} = \mathbf{1} + \mathbf{8} + \mathbf{27}$$

- Bilinears (e.g. $\tau \rightarrow \mu\gamma$) are governed by $\Delta = (g^\dagger \times g)_8$
 \rightarrow predicts e.g. relations between $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow e\gamma$
- Four fermion operators for e.g. $\tau \rightarrow \mu\mu\mu$ can have a contribution of the 27-plet
- Even in MFV no relation between $\tau \rightarrow e\gamma$ and $\tau \rightarrow e\mu\mu$

Flavor Models

Top-down instead of bottom-up

- How to get an Idea about the mass matrices:
 - Guess some matrices with as few parameters as possible:
“Textures” as many zeros as possible
 - Use some symmetry to obtain (at least qualitatively) some insight into mass matrices
e.g. a simple horizontal $U(1)$
- „, or are the parameters “just so”?

Textures: Two Family Example

- Find two matrices \mathcal{M}_u and \mathcal{M}_d with less than five parameters
- \rightarrow **Relation(s) between m_u , m_c , m_d , m_s and Θ_C**
 Simplest guess: Diagonal \mathcal{M}_u and nondiagonal \mathcal{M}_d

$$\mathcal{M}_u = \begin{pmatrix} m_u & 0 \\ 0 & m_c \end{pmatrix} \quad \mathcal{M}_d = \begin{pmatrix} 0 & a \\ a & 2b \end{pmatrix}$$

- Matrix diagonalizing \mathcal{M}_d is already the CKM Matrix
- **Four Parameters \rightarrow One relation !**

- Model predicts $\tan \Theta_C = \sqrt{\frac{m_d}{m_s}}$ (which is not bad!)

- Has been done also for three families
- Guesses often supported by assuming (discrete) symmetries
- **Typical structure:** $\tan \theta_{ij} \sim \sqrt{m_i/m_j}$
- **Remains Guesswork**, until some deeper understanding of the guesses emerges.

Flavour Invariants

- Precise form of the mass matrices depend on the basis choice in Flavor space
- **Basis independent statements only as a relation between Invariants**
- For the two-family case these are e.g.

$$\begin{aligned}
 I_1 &= \text{Tr}(Y_U Y_U^\dagger) & I_2 &= \text{Tr}(Y_D Y_D^\dagger) \\
 I_3 &= \text{Tr}(Y_U Y_U^\dagger Y_U Y_U^\dagger) & I_4 &= \text{Tr}(Y_D Y_D^\dagger Y_D Y_D^\dagger) \\
 I_5 &= \text{Tr}(Y_D Y_D^\dagger Y_U Y_U^\dagger)
 \end{aligned}$$

- There are as many independent Invariants as there are physical parameters

Conclusion on New Physics in Flavor

- Unlike in the gauge sector we do not have a guiding principle to construct a theory of flavor
- CKM as well as MFV is just a parametrization of ignorance
- **No new physics model explaining flavor**
- ... maybe with the exception of some “Froggatt Nielsen like” models
- **can the parameters be “just so”?**

Overall Conclusions

- BaBar and Belle established the CKM picture of flavor
- LHCb is running, squeezing the SM further:
 - $B_s \rightarrow \mu\mu$
 - $B \rightarrow K^* \ell\ell$
 - V_{ub} measurements
- Belle 2 is upcoming:
 - Factor of 10 or 20 more data
 - Significant increase in precision
 - Look for rare and impossible decays
- At the end:
 - Possible a clear indirect hint to BSM physics?
- But how can we finally tell, if the scales are really very high?