Flavor Physics & BSM

1 lecture

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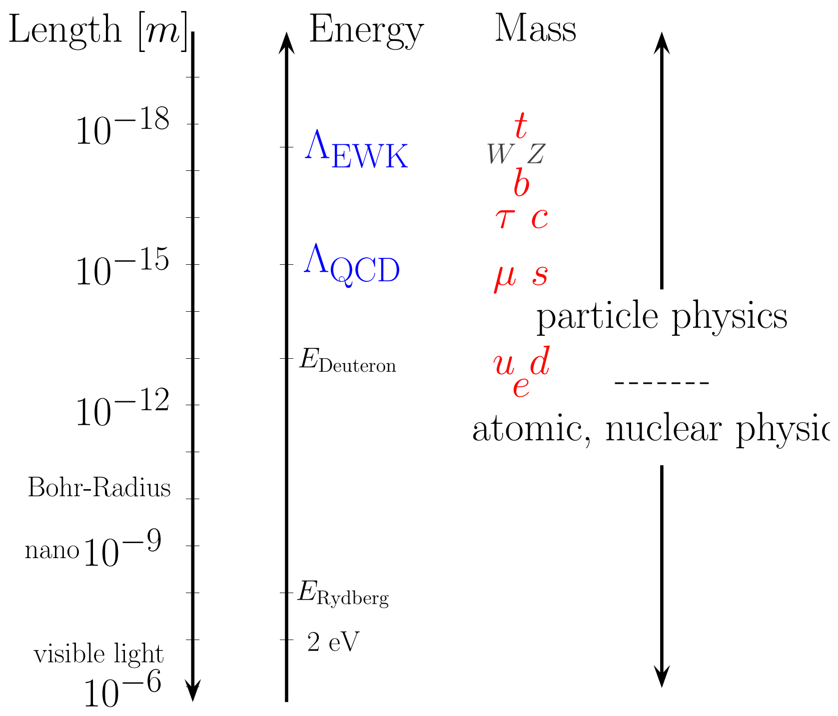
Matter comes in generations

$$\psi \to \psi_i, i = 1, 2, 3$$

commonly labelled with increasing mass, distinguished by 'flavor'.

quarks: $\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}$

leptons: $\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$



$m_u\,(2\text{ GeV})$	$m_d\,(2\text{ GeV})$	$m_s\,(2\text{ GeV})$
2.8 ± 0.6 MeV	5.0 ± 1.0 MeV	95 ± 15 MeV
$m_c\,(m_c)$	$m_b\,(m_b)$	$m_t\,(m_t)$
1.28 ± 0.05 GeV	4.22 ± 0.05 GeV	163 ± 3 GeV

hierarchical! Spectrum spans five orders of magnitude.

Matter comes in generations

$$\psi \to \psi_i, i = 1, 2, 3$$

commonly labelled with increasing mass, distinguished by 'flavor'.

Complex phenomenology: wide range in spectra, $m_u/m_t \sim 10^{-5}$, CP violation, mixing; Flavor physics intimately linked to the making of the Standard Model. New questions with new physics.

These lectures cover:

* Flavor at the TeV-scale (Standard Model and beyond)
* Flavor signals (LHC, Belle II, ...)

part 1: Flavor in the Standard Model

The Standard Model of Particle Physics

renormalizable QFT in 3+1 Minkowski space w. local symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{em}$$

$$\mathcal{L}_{\mathcal{SM}} = -\frac{1}{4}F^2 + \bar{\psi} i \not{D} \psi + \frac{1}{2}(D\Phi)^2 - \underbrace{\bar{\psi} Y \Phi \psi}_{Yukawa\, interact.} + \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$$

ψ: fermions (quarks and leptons)

$$D_\mu = \partial_\mu - ieA_\mu + \ldots$$

$F_{\mu\nu}$: gauge bosons $g^a, \gamma, Z^0, W^\pm$

Φ: Higgs doublet (1dof observation 2012 consistent with SM)

Known fundamental matter comes in generations $\psi \to \psi_i$, $i = 1, 2, 3$, subject to identical gauge transformations.

Flavor physics$=$ investigations on generational structure of fermions and BSM partners.

The Standard Model of Particle Physics: Flavor

fields in representations under the SM group $SU(3)_C \times SU(2)_L \times U(1)_Y$

Higgs: $\Phi(1,2,1/2)$ hypercharge $Y = Q - T^3$

quarks: $Q_L(3,2,1/6)_i$, $D_R(3,1,-1/3)_i$, $U_R(3,1,2/3)_i$

leptons: $L_L(1,2,-1/2)_i$, $E_R(1,1,-1)_i$ L: doublet, R:singlet under $SU(2)_L$

$$\mathcal{L}_{\mathcal{SM}} = \sum_{\psi=Q,U,D,L,E} \bar{\psi}_i i \not{D} \psi_i$$

$$-\bar{Q}_{L_i}(Y_u)_{ij}\Phi^C U_{R_j} - \bar{Q}_{L_i}(Y_d)_{ij}\Phi D_{R_j} - \bar{L}_{L_i}(Y_e)_{ij}\Phi E_{R_j}$$

$$+\mathcal{L}_{higgs} + \mathcal{L}_{gauge}, \qquad \Phi^C = i\sigma^2\Phi^*$$

$Y_{u,d,e}$: Yukawa matrices (3×3, complex), off diagonal entries mix generations; sole sources of flavor in SM. In hypothetical limit $Y_{u,d,e} \to 0$ SM gains large "flavor-symmetry"

$G_F = U(3)_{QL} \times U(3)_{UR} \times U(3)_{DR} \times U(3)_{LL} \times U(3)_{ER}$

The Standard Model of Particle Physics: Flavor

masses from spontaneous breaking of electroweak symmetry

$\Phi^T(x) \to 1/\sqrt{2}(0, v + h(x))$, Higgs vev $\langle\Phi\rangle = v/\sqrt{2} \simeq 174$ GeV

$$\mathcal{L}_{\mathcal{SM}}{}^{yukawa} = -\bar{Q}_L Y_u \Phi^C U_R - \bar{Q}_L Y_d \Phi D_R - \bar{L}_L Y_e \Phi E_R$$

Want mass eigenstates rather than the above gauge eigenstates:

perform unitary trafos on quark fields $Q_L = (U_L, D_L), U_R, D_R$

$q_A(gauge) \to \tilde{q}_A(mass) = V_{A,q} q_A$ with $V_{A,q} V_{A,q}^\dagger = 1$.

$$\mathcal{L}_{\mathcal{SM}}{}^{yukawa} = -\bar{U}_L \underbrace{V_{L,u}^\dagger V_{L,u}}_{=1} Y_u \Phi^C \underbrace{V_{R,u}^\dagger V_{R,u}}_{=1} U_R + \text{down quarks}$$

$$\mathrm{diag}(m_u, m_c, m_t) = \langle\Phi\rangle \cdot \mathrm{diag}(y_u, y_c, y_t) = \langle\Phi\rangle \cdot V_{L,u} Y_u V_{R,u}^\dagger$$

$$\mathrm{diag}(m_d, m_s, m_b) = \langle\Phi\rangle \cdot \mathrm{diag}(y_d, y_s, y_b) = \langle\Phi\rangle \cdot V_{L,d} Y_d V_{R,d}^\dagger$$

unitary trafos: $\tilde{q}_A = V_{A,q} q_A$ with $V_{A,q} V^\dagger_{A,q} = 1$.

$$\mathcal{L_{SM}}^{yukawa} = -\bar{U}_L \underbrace{V^\dagger_{L,u} V_{L,u}}_{=1} Y_u \Phi^C \underbrace{V^\dagger_{R,u} V_{R,u}}_{=1} U_R + \text{down quarks.}$$

$$\mathrm{diag}(m_u, m_c, m_t) = \langle \Phi \rangle \cdot V_{L,u} Y_u V^\dagger_{R,u}$$

$$\mathrm{diag}(m_d, m_s, m_b) = \langle \Phi \rangle \cdot V_{L,d} Y_d V^\dagger_{R,d}$$

$$\mathcal{L_{SM}}^{up-mass} = -\underbrace{\bar{U}_L V^\dagger_{L,u}}_{\bar{\tilde{U}}_L} \underbrace{V_{L,u} Y_u V^\dagger_{R,u}}_{diagonal} \Phi^C \underbrace{V_{R,u} U_R}_{\equiv \tilde{U}_R} = -\bar{\tilde{U}}_{Li} m_{ui} \Phi^C \tilde{U}_{Ri}.$$

The tilde basis are mass eigenstates, down quarks analogously.

What else happened under the basis change in $\mathcal{L}_{SM}$?

The Standard Model of Particle Physics: CKM

The SM higgs interactions are strictly flavor diagonal and neutral current gauge interactions γ, Z, g stay being flavor universal, since they dont mix the chiralities, for instance:

$$\bar{U}_L \gamma^\mu A_\mu U_L = \bar{U}_L \ \ (V_{L,u}^\dagger V_{L,u}) \ \ \gamma^\mu A_\mu \ \ (V_{L,u}^\dagger V_{L,u}) \ \ U_L$$

$$= \bar{\tilde{U}}_L \gamma^\mu A_\mu V_{L,u} V_{L,u}^\dagger \tilde{U}_L = \bar{\tilde{U}}_L \gamma^\mu A_\mu \tilde{U}_L \qquad \text{nothing has happend!}$$

However, lets look at the charged currents $W^\pm$:

$$\bar{U}_L \gamma^\mu W_\mu^+ D_L = \bar{U}_L \ \ (V_{L,u}^\dagger V_{L,u}) \ \ \gamma^\mu W_\mu^+ \ \ (V_{L,d}^\dagger V_{L,d}) \ \ D_L$$

$$= \bar{\tilde{U}}_L \gamma^\mu W_\mu^+ \ \ \underbrace{V_{L,u} V_{L,d}^\dagger}_{\equiv V_{CKM} = V \neq 1} \ \ \tilde{D}_L$$

Since Y_u and Y_d dont diagonalize (as observed!) under same unitary transformations, there is one important net effect related to flavor.

The Standard Model of Particle Physics: CKM

The charged current interaction gets a flavor structure, encoded in the Cabibbo Kobayashi Maskawa (CKM) matrix V.

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}}\left(\bar{\tilde{U}}_L \gamma^\mu W^+_\mu V \tilde{D}_L + \bar{\tilde{D}}_L \gamma^\mu W^-_\mu V^\dagger \tilde{U}_L\right).$$

V_{ij} connects left-handed up-type quark of the ith gen. to left-handed down-type quark of jth gen. Intuitive labelling by flavor:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \qquad V_{13} = V_{ub} \;\; etc$$

Via W exchange is the only way to change flavor in the SM.

V is unitary, is in general complex, and induces CP violation

V has 4 physical parameters, 3 angles and 1 phase.

"PDG" parametrization (exact, fully general)

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$s_{ij} \equiv \sin\Theta_{ij}$, $c_{ij} \equiv \cos\Theta_{ij}$. δ is the CP violating phase.

In Nature, $\delta \sim \mathcal{O}(1)$ and V is hierarchical $\Theta_{13} \ll \Theta_{23} \ll \Theta_{12} \ll 1$.

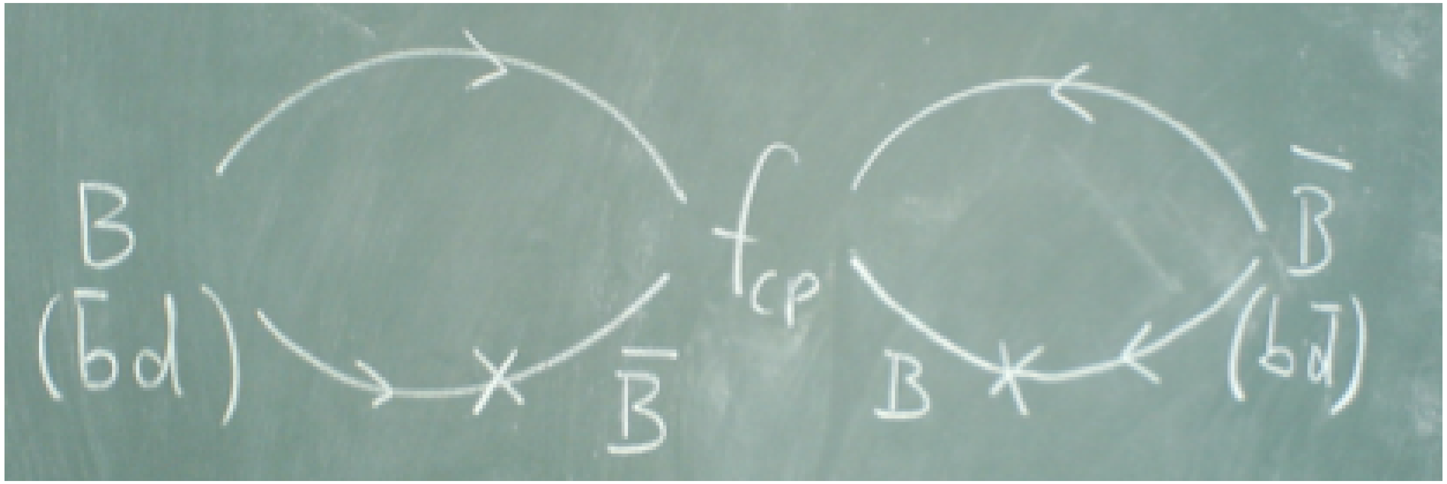
Very different – large mixing angles for leptons (PMNS-Matrix):

$\Theta_{23} \sim 45^\circ$, $\Theta_{12} \sim 35^\circ$, $\Theta_{13} \sim O(10^\circ)$ all O(1) – anarchy?

CP is violated!.. together with Quark Flavor

Quark mixing matrix has 1 physical CP violating phase δ_{CKM}.

Verified in $B\bar{B}$ mixing $\sin 2\beta = 0.672 \pm 0.023$ HFAG Aug 2010



δ_{CKM} is large, $O(1)$!

CPX also observed in B-decay $A_{CP}(B \to K^{\pm}\pi^{\mp}) = -0.098 \pm 0.013$

HFAG Aug 2010

$$\Gamma(B \to K^{+}\pi^{-}) \neq \Gamma(\bar{B} \to K^{-}\pi^{+})$$

The Standard Model: CKM properties

V in Nature is hierarchical $\Theta_{13} \ll \Theta_{23} \ll \Theta_{12} \ll 1$. Wolfenstein parametrization; expansion in $\lambda = \sin\Theta_C$, $A, \rho, \eta \sim \mathcal{O}(1)$

$$V = \begin{pmatrix} 1-\lambda^2/2 & +\lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & +A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

fits: $\lambda = 0.225, \quad A = 0.82, \quad \bar{\rho} = 0.13, \quad \bar{\eta} = 0.34$

beyond lowest order $\bar{\rho} = \rho(1-\lambda^2/2)$ and $\bar{\eta} = \eta(1-\lambda^2/2)$

$\eta \neq 0$ signals CP violation; third gen. quarks decoupled at order λ^2.

The Flavor of the Quarks u, d, s, c, b, t

There are in total 10 (known!) param. in quark flavor $\&$ CP sector:

6 masses, 3 angles and 1 phase in CKM-matrix

with accuracy: $|V_{us}| = 0.225$ (permille), $|V_{cb}| = 42 \cdot 10^{-3}$ (percent), $|V_{ub}| = 4 \cdot 10^{-3}$ (ten percent), $\sin 2\beta(\text{measured}) = 0.67$ (percent)

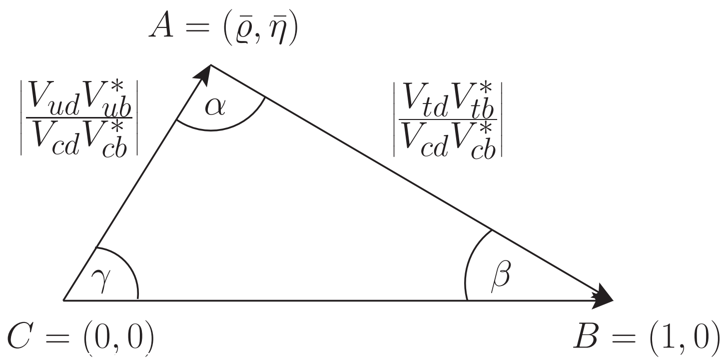
PS: enormous progress from B-factories over past decade. PPS: still improving precision.

All hadronic flavor violation, including decays, productions rates at colliders and meson mixing effects should be described by these 10 parameters alone, if SM is correct. Since all parameters are known, this statement is very predictive and subject to numerous tests.

V is unitary $VV^\dagger = 1$ or, $\sum_j V_{ij}V^*_{kj} = \delta_{ik}$.

the unitarity triangle

$V_{ub}V^*_{ud} + V_{cb}V^*_{cd} + V_{tb}V^*_{td} = 0$, all terms order λ^3.

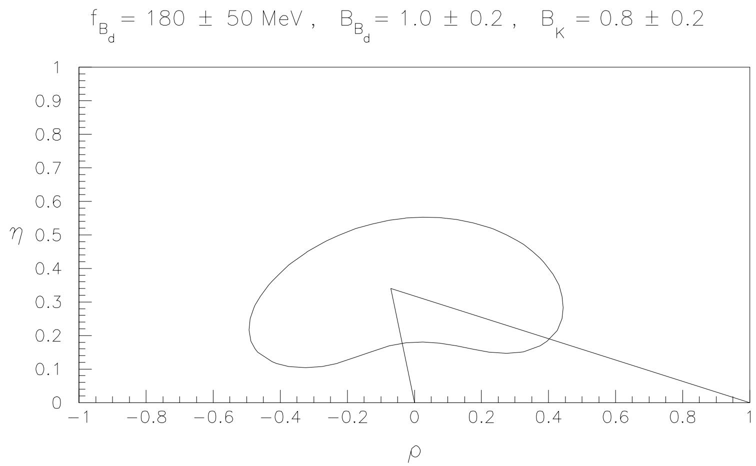


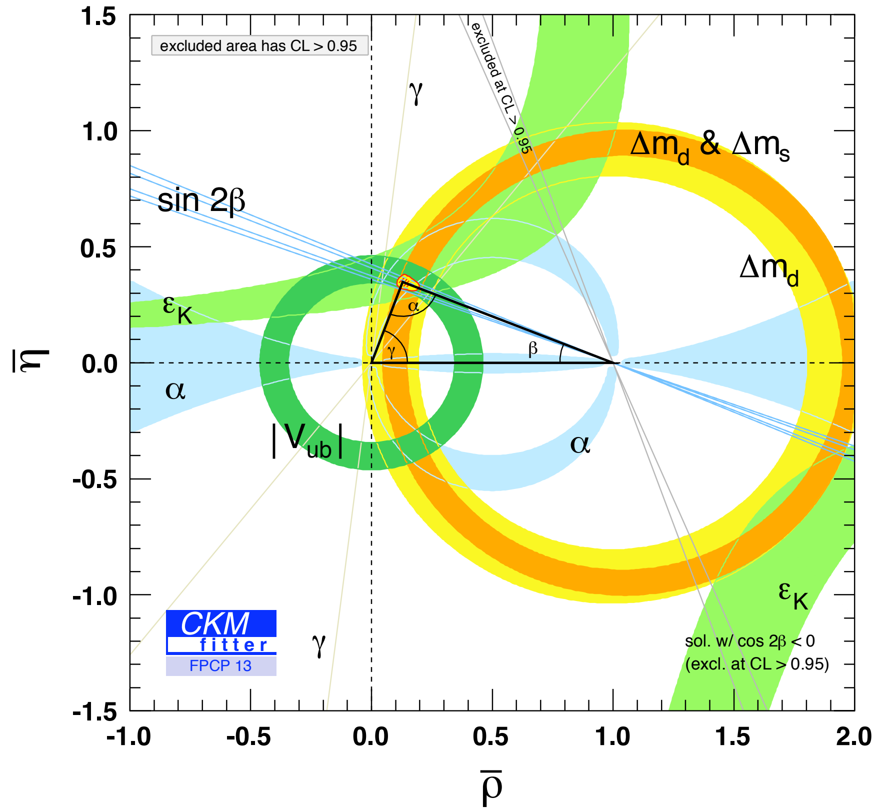
Its apex determines the Wolfenstein parameters $\bar\rho, \bar\eta$. In the absence of CP viol., the triangle would be squashed.

Information on the apex can come from various processes, measuring angles or sides.

SM tests with Quark flavor/CKM 1995 vs today

The CKM-picture of flavor and CP violation is currently consistent with all – and quite different – laboratory observations, although some tensions exist.





$$V_{CKM}V^{\dagger}_{CKM} = 1$$

The quarks spectrum and mixings are hierarchical, and stem from the Yukawa matrices.

Numerically, we determined them as

$$Y_u \sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix}$$

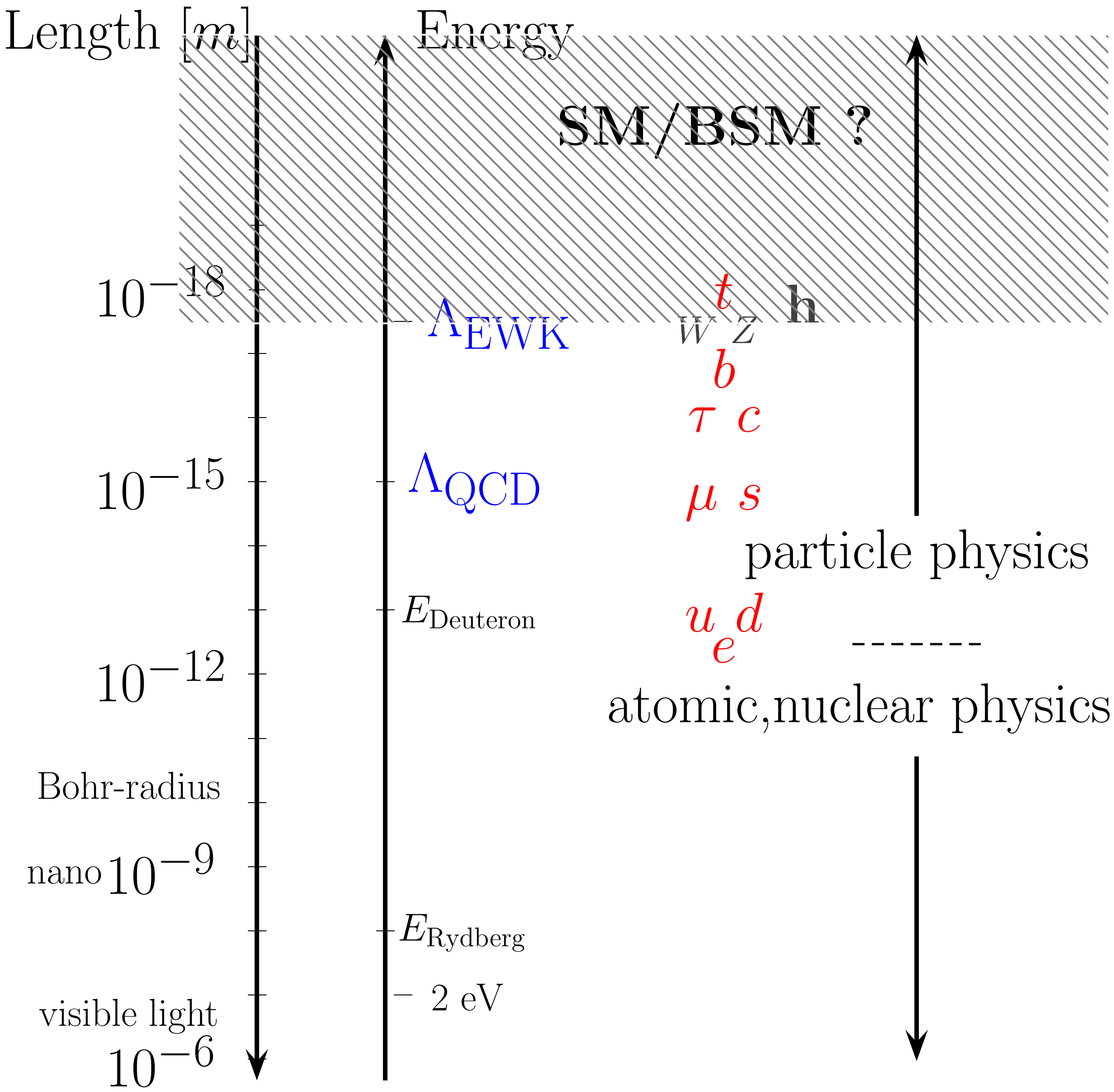
$$Y_d \sim \mathrm{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle})$$

$$Y_e \sim \mathrm{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle})$$

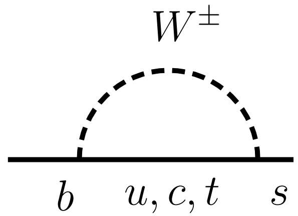
Very peculiar pattern. We dont know why it is this way.

part 2: Exploring the Borders of the SM with Flavor

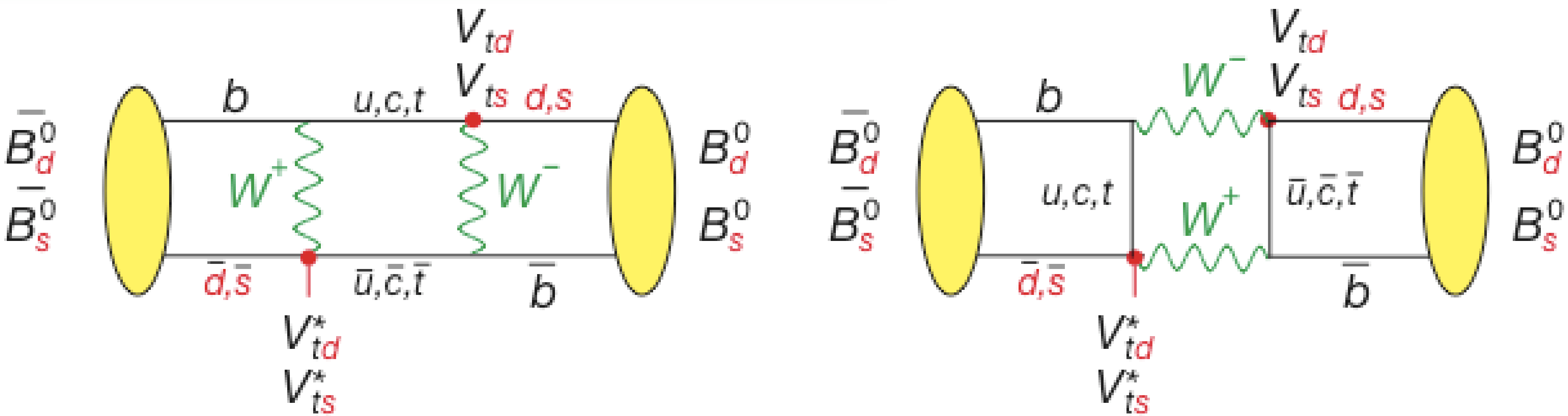
Exploring Physics at Highest Energies



In SM neutral currents conserve flavor. However, charged currents induce FCNCs through quantum loops.



The upper figure shows an FCNC with flavor number changing in units of one, $\Delta F = 1$, as in decays, meson mixing has $\Delta F = 2$.



Testing the SM with flavor

Different sectors and different couplings presently probed:

$s \to d$: $K^0 - \bar{K}^0$, $K \to \pi\nu\bar{\nu}$

$c \to u$: $D^0 - \bar{D}^0$, ΔA_{CP}

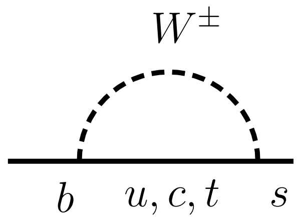
$b \to d$: $B^0 - \bar{B}^0$, $B \to \rho\gamma$, $b \to d\gamma$, $B \to \pi\mu\mu$

$b \to s$: $B_s - \bar{B}_s$, $b \to s\gamma$, $B \to K_s\pi^0\gamma$, $b \to sll$, $B \to K^{(*)}ll$ (precision, angular analysis), $B_s \to \mu\mu$

$t \to c, u$, $l \to l'$: not observed

in red: mentioned lated

Lets discuss a generic SM FCNC $b \to s$ amplitude



$$\mathcal{A}(b \to s)_{\rm SM} = V_{ub}V_{us}^{*}A_u + V_{cb}V_{cs}^{*}A_c + V_{tb}V_{ts}^{*}A_t$$

quantum loop effect induced by the weak interaction.

$A_q = A(m_q^2/m_W^2)$.

with CKM unitarity $VV^{\dagger} = 1$, specifically $\sum_i V_{ib}V_{is}^{*} = 0$:

$$\mathcal{A}(b \to s)_{\rm SM} = V_{tb}V_{ts}^{*}(A_t - A_c) + V_{ub}V_{us}^{*}(A_u - A_c)$$

$\mathcal{A}$ would vanish if *i* there wouldn't be a non-trivial CKM matrix, that is, one that allows for changes between different generations, and *ii* for identical up-type quark masses.

Flavor Changing Neutral Currents

$$\mathcal{A}(b \to s)_{\rm SM} = \underbrace{V_{tb}V_{ts}^*}_{\lambda^2}(A_t - A_c) + \underbrace{V_{ub}V_{us}^*}_{\lambda^4}(A_u - A_c)$$

amplitude is dominated by first term because of lesser CKM suppression and because the GIM (Glashow Iliopoulos Maiani) suppression inactive for tops $\frac{m_t^2 - m_c^2}{m_W^2} \sim \mathcal{O}(1)$, whereas $\frac{m_u^2 - m_c^2}{m_W^2} \ll 1$.

We probe top properties with rare b-decays despite of $m_t \gg m_b$.

CP violation requires interference between the two terms with different phases; for $b \to s$, this is small, $O(\lambda^2)$.

The general features hold for any FCNC in the SM:

Flavor Changing Neutral Currents in SM

i FCNCs are induced by the weak interaction thru loops.
ii FCNCs require $V \neq 1$.
iii FCNCs vanish for degenerate intermediate quarks. Since mass splitting among up-quarks is larger than for down quarks, GIM suppression is larger with external up-type than down-type quarks.

$\mathcal{B}(b \to s\gamma) = 3 \cdot 10^{-4}$ $(E_\gamma > 1.6$ GeV$)$

$\mathcal{B}(b \to s l^+ l^-) = 4 \cdot 10^{-6}$ $(m_{ll}^2 > 0.04$ GeV$^2)$

SM: $\mathcal{B}(t \to cg) \sim 10^{-10}$, $\mathcal{B}(t \to c\gamma) \sim 10^{-12}$, $\mathcal{B}(t \to cZ) \sim 10^{-13}$, $\mathcal{B}(t \to ch) \lesssim 10^{-13}$ Eilam, Hewett, Soni '91/99

Flavor Changing Neutral Currents in SM

We see that 3 mechanisms suppress FCNCs in SM: CKM, GIM and absence at tree level. New physics, which doesnt need to share these features, competes with small SM background!

FCNCs feel physics in the loops from energies much higher than the ones actually involved in the real process.

They are very useful to look for new physics, in fact, we already now a lot about new physics from FCNCs!

	$K^0\bar{K}^0$	$D^0\bar{D}^0$	$B_d^0\bar{B}_d^0$	$B_s^0\bar{B}_s^0$
$\Lambda_{\rm NP}$ [TeV]	$2 \cdot 10^5$	$5 \cdot 10^3$	$2 \cdot 10^3$	$3 \cdot 10^2$

Table 1: The lower bounds on the scale of new physics from FCNC mixing data in TeV for arbitrary new physics at 95 % C.L.

Sensitivity, Reach, Strategy

Besides statistics, BSM reach is limited by theoretical uncertainties, dominated by hadronic physics.

Use approximate symmetries of SM to improve here:

– CP

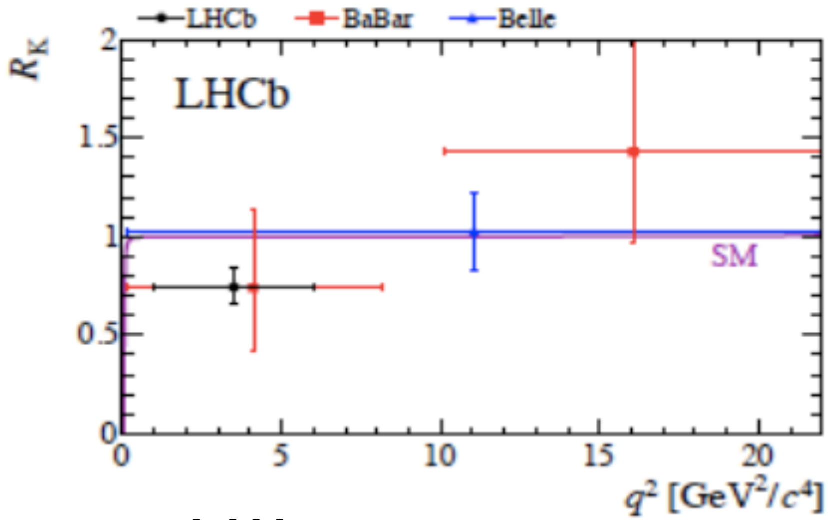
– V-A

– flavor symmetries (MFV)

– lepton-universality of gauge interactions

$$R_H = \frac{\mathcal{B}(\bar{B}\to\bar{H}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{H}ee)}, \quad H = K, K^*, X_s, ...$$

Lepton-universal models (SM): $R_H = 1+$tiny, GH, Krüger '03



LHCb 2014: $R_K = 0.745 \pm^{0.090}_{0.074} \pm 0.036 < 1$ at 2.6 σ

http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.151601, arXiv:1406.6482 [hep-ex]

physics highlight: http://physics.aps.org/articles/v7/102

apriori too few muons, or too many electrons, or combination thereof.

situation for numerator $\mu\mu$ and denominator ee of R_K separately:

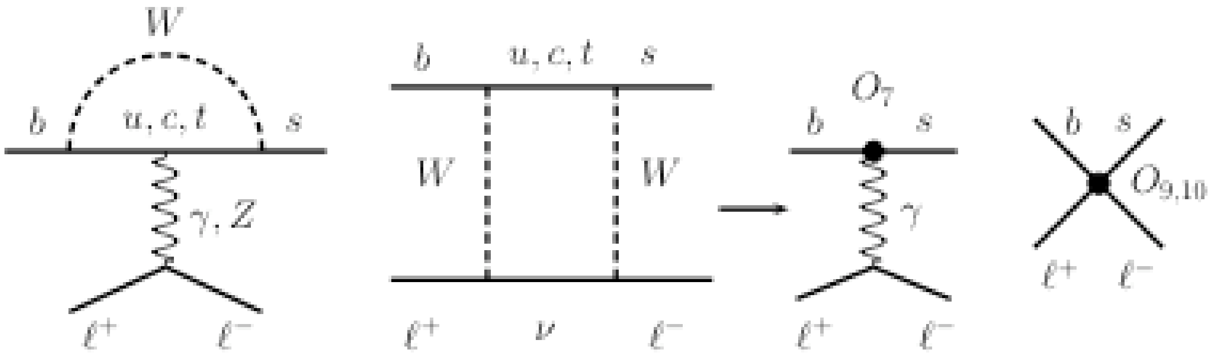
	LHCb[a]	SM[b]
$\mathcal{B}(B \to K\mu\mu)_{[1,6]}$	$(1.21 \pm 0.09 \pm 0.07) \cdot 10^{-7}$	$(1.75^{+0.60}_{-0.29}) \cdot 10^{-7}$
$\mathcal{B}(B \to Kee)_{[1,6]}$	$(1.56^{+0.19+0.06}_{-0.15-0.04}) \cdot 10^{-7}$	same
$R_K\|_{[1,6]}$	$0.745 \pm^{0.090}_{0.074} \pm 0.036$	$\simeq 1$

[a] 1209.4284 (μ) and 1406.6482 (e) [b] Bobeth, GH, van Dyk '12, form factors from 1006.4945

Individual branching ratios make presently no case for new physics, although muons are a bit below SM. The ratio R_K is much cleaner.

PS: There is another anomaly pointing hat LNU: $R_{D^{(*)}}$.

$b \to s\ell\ell$ FCNCs model-independently



Construct EFT $\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i C_i(\mu)O_i(\mu)$ at dim 6

V,A operators $\mathcal{O}_9 = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \ell]\,, \quad \mathcal{O}_9' = [\bar{s}\gamma_\mu P_R b]\,[\bar{\ell}\gamma^\mu \ell]$

$$\mathcal{O}_{10} = [\bar{s}\gamma_\mu P_L b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]\,, \quad \mathcal{O}_{10}' = [\bar{s}\gamma_\mu P_R b]\,[\bar{\ell}\gamma^\mu \gamma_5 \ell]$$

S,P operators $\mathcal{O}_S = [\bar{s}P_R b]\,[\bar{\ell}\ell]\,, \quad \mathcal{O}_S' = [\bar{s}P_L b]\,[\bar{\ell}\ell]\,,$ ONLY O_9, O_{10} are SM, all other BSM

$$\mathcal{O}_P = [\bar{s}P_R b]\,[\bar{\ell}\gamma_5 \ell]\,, \quad \mathcal{O}_P' = [\bar{s}P_L b]\,[\bar{\ell}\gamma_5 \ell]$$

and tensors $\mathcal{O}_T = [\bar{s}\sigma_{\mu\nu} b]\,[\bar{\ell}\sigma^{\mu\nu} \ell]\,, \quad \mathcal{O}_{T5} = [\bar{s}\sigma_{\mu\nu} b]\,[\bar{\ell}\sigma^{\mu\nu}\gamma_5 \ell]$

lepton specific $C_iO_i \to C_i^\ell O_i^\ell$, $\ell = e, \mu, \tau$

Model-independent interpretations with V,A operators: Das et al 1406.

$$0.7 \lesssim \mathrm{Re}[X^e - X^\mu] \lesssim 1.5\,,$$

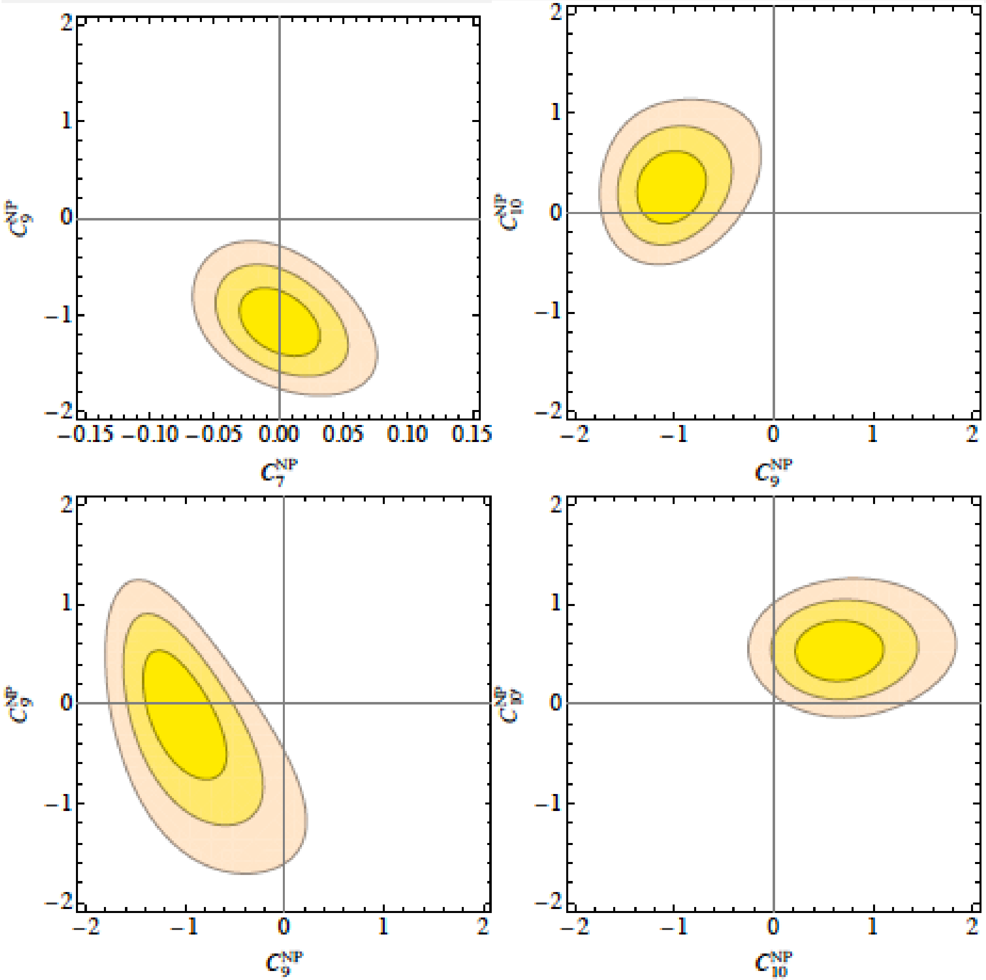
$$X^\ell = C_9^{\mathrm{NP}\ell} + C_9'^\ell - (C_{10}^{\mathrm{NP}\ell} + C_{10}'^\ell)$$

The required NP is sizeable since $C_9^{\mathrm{SM}} \simeq -C_{10}^{\mathrm{SM}} \simeq 4.2$.

$X^e \simeq 0$ and $X^\mu \simeq C_9^{\mu NP} \simeq -1$ is consistent with global fit to existing $b \to s$ data!

Descotes-Genon et al

Global fits: 2D hypotheses



Hyp.	Best-fit pt	Pull
(C_7^{NP}, C_9^{NP})	(0.0, -1.1)	4.2
(C_9^{NP}, C_{10}^{NP})	(-1.1, 0.2)	4.2
$(C_9^{NP}, C_{9'})$	(-1.0, -0.1)	4.2
$(C_{10}^{NP}, C_{10'})$	(0.5, 0.6)	3.4

$\to$ Main effect from C_9

Explanations ?

- Z' boson
- Leptoquarks
- Composite models
- Difficult with susy (?)

[Almannshoffer, Straub, Haisch, Gauld, Peczak, Buras, De Fazio, Girrbach, Hiller, Schmaltz, Varzielas, Crivellin. . .]

S. Descotes-Genon (LPT-Orsay) | $b \to s\ell\ell$ 2015 & NP | 12/06/15 | 18

$b \to s$ fits: lepton flavor structure

Why are muons different from electrons?

Splitting electrons from muons:

Z'- $U(1)_{\tau-\mu}$ (BSM in $b \to s\mu\mu$, not in $b \to see$).

Altmannshofer, Crivellin, Fuentes, Vicente, .. et al

Links with $h \to \tau\mu$ with extras Higgses Crivellin et al, Heeck et al

new particle exchanged at tree level, including leptoquarks, MSSM with R-Parity violation amended with Froggatt-Nielsen flavor symmetry (both $\mu\mu$ and/or ee possible) Schmaltz, Gripaios, Varzielas, .. et al

This naturally provides a link for LFV decays Guadagnoli, Kane, Varzielas which however is not strict Alonso et al, Fuentes et al

pl see original refs for complete list of contributions to this effort

Leptoquark model $\mathcal{L} = -\lambda_{d\ell}\, \varphi\, (\bar{d} P_L \ell)$ with scalar leptoquark $\varphi(3,2)_{1/6}$ with mass M; includes R-parity violating MSSM)

$\mathcal{H}_{\text{eff}} = -\frac{|\lambda_{d\ell}|^2}{M^2}(\bar{d} P_L \ell)\,(\bar{\ell} P_R d) = \frac{|\lambda_{d\ell}|^2}{2M^2}[\bar{d}\gamma^\mu P_R d]\,[\bar{\ell}\gamma_\mu P_L \ell]$
from tree level φ exchange and fierzing.

In terms of the usual Wilson coefficients:

$$C_{10}^{\prime e} = -C_9^{\prime e} = \frac{\lambda_{se}\lambda_{be}^*}{V_{tb}V_{ts}^*}\frac{\pi}{\alpha_e}\frac{\sqrt{2}}{4M^2 G_F} = -\frac{\lambda_{se}\lambda_{be}^*}{2M^2}(24\text{TeV})^2$$

R_K-data implies $\quad\lambda_{se}\lambda_{be}^*/M^2 \simeq 1/(24\text{TeV})^2$

Viable parameters of the (scalar) leptoquarks read

$$1\,\text{TeV} \lesssim M \lesssim 48\,\text{TeV}$$
$$2 \cdot 10^{-3} \lesssim |\lambda_{se}\lambda_{be}^*| \lesssim 4$$

The upper limit on M arises from correlation with B_s mixing, which constrains $(\lambda_{se}\lambda_{be}^*)^2/M^2$.

Decay modes of φ-dublet: $\varphi^{2/3} \to b\, e^+ \;, \quad \varphi^{-1/3} \to b\, \nu$

If triplet model:

$$\begin{aligned} \varphi^{2/3} &\to t\,\nu \\ \varphi^{-1/3} &\to b\,\nu\,,\; t\,\mu^- \\ \varphi^{-4/3} &\to b\,\mu^- \end{aligned}$$

Summary

- We discussed flavor in the SM. Its parameters are known, and to date – modulo anomalies – all observed flavor and CP violation is consistent with them. – Very predictive
- There are strong flavor constraints for model building: In the absence of O(1) New Physics observations in FCNC-processes implies that physics at theTeV-scale has non-generic flavor properties, and suppression mechanisms of similar power as the SM ones need to be at work.
- Several avenues exist to improve reach: employing fits and correlations, and using observables designed to have small SM backgrounds.

Summary

- Current anomalies – LNU in quark decays – inspired new bottom-up model building Leptoquarks, $U(1)\prime$, multi-Higgses.
- Great prospects to link with direct searches.
- Linking lepton to quark physics may provide opportunities towards the understanding of flavor.