General Flavor Theory

”flavor 2019: (still) puzzling and great opportunity”

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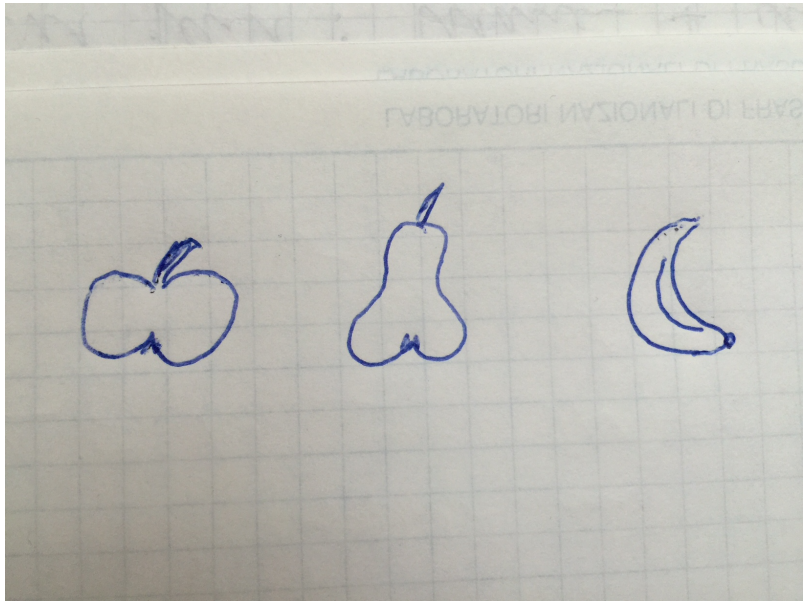
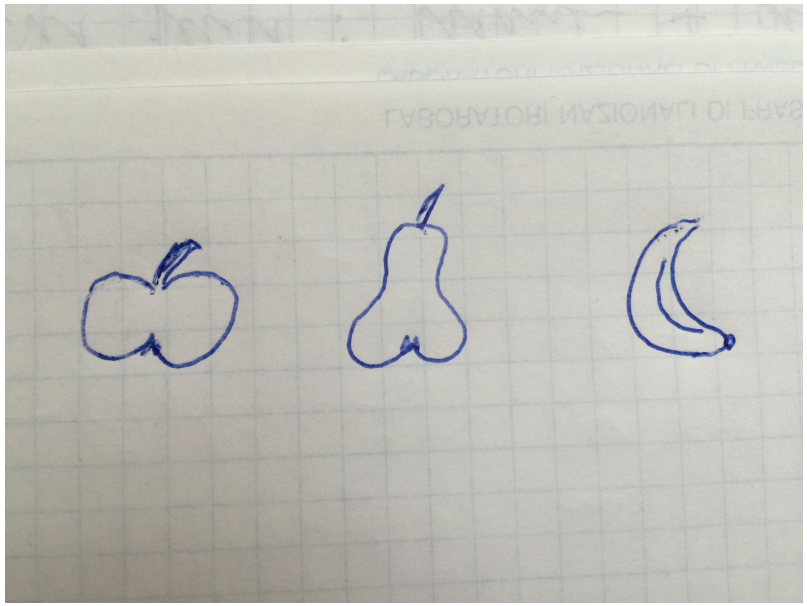




symmetry, and symmetry-breaking (the same yet not the same)

The Standard Model of Particle Physics

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

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

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

ψ: fermions (quarks and leptons)

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

Φ: Higgs doublet

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

Known fundamental matter comes in generations

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

subject to identical gauge transformations. ”universality”, hard-wired.

They are not the same

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

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 $SU(2)_L$

labelled with increasing mass, distinguished by 'flavor' (mass and mixing, i.e. CKM (quarks), PMNS (leptons)

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix}, U_R = u_R, c_R, t_R, \;\; D_R = d_R, s_R, b_R$$

$$L_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}, E_R = e_R, \mu_R, \tau_R$$

Flavor in the Standard Model

Flavor in the SM is sourced only by the Yukawa interactions:

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

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

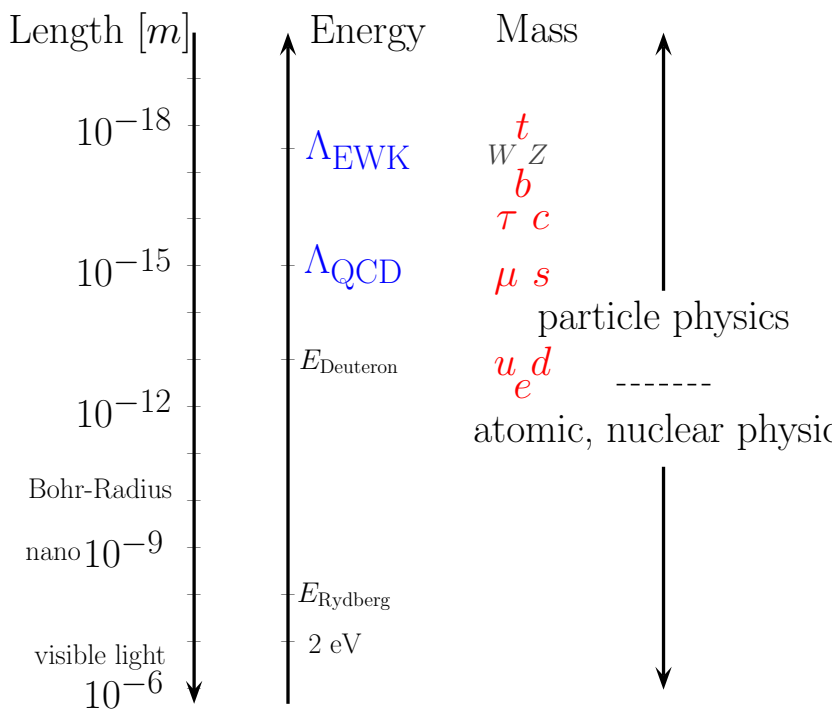
$$+\mathcal{L}_{higgs} + \mathcal{L}_{gauge}, \qquad \Phi^C = i\sigma^2 \Phi^*$$

$Y_{u,d,e}$: Yukawa matrices (3×3, complex)
different Yukawa $\rightarrow$ different mass from vev $\langle \Phi \rangle$ etc
off-diagonal entries open up possibility to mix generations

direct link with Higgs physics: $h \rightarrow \psi\bar{\psi}$ probes $Y_{u,d,e}$, flavor!

Program: determine flavor parameters (in SM)

Quark Spectrum



m_u (2 GeV)	m_d (2 GeV)	m_s (2 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

Spectrum spans five orders of magnitude.

Flavor puzzle

Experimentally (if rotated solely to up-sector)

$$
\begin{aligned}
Y_u &\sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix} \\
Y_d &\sim \mathrm{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \\
Y_e &\sim \mathrm{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right)
\end{aligned}
$$

diag (a,b)$= \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}$

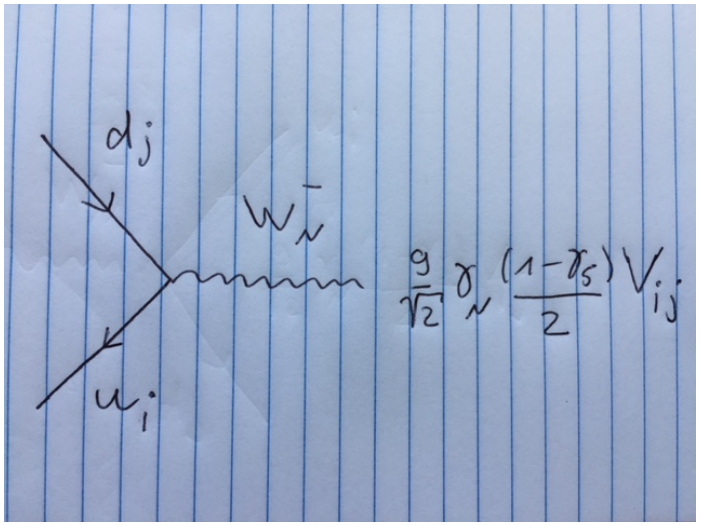
Quark mixing is hierarchal, as well as quark and charged lepton masses.

Why? ideas, no ”SM” nowhere near, needs BSM to progress

Flavor change

$\psi \to \psi_i, i = 1, 2, 3$ sounds simple but implies rich phenomenology: flavor change (within same and other generations), CP violation, meson mixing, ...

SM flavor change only through weak interaction among left-handed fermions:



$V_{ij} = (V_{CKM})_{ij}$. Product of up and down unitary matrices $V = V_u V_d^\dagger$, derived from $Y_{u,d}$ (diagonalization). Not physical each in SM.

Insert: Getting CKM from scratch

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

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

Want mass eigenstates rather than gauge eigenstates $QUDLE$:

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

$\tilde{q}_A(mass) = V_{A,q}\, q_A(gauge)$ with $V_{A,q} V_{A,q}^\dagger = 1, \quad A = L, R, q = u, d.$

The 4 unitary matrices $V_{A,q}$ are determined by

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

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

i.e., they diagonalize the Yukawas.

insert unit matrices

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

then rewrite term and split up

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

The tilde basis are mass eigenstates, down quarks analogously.

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

Lets look at the charged currents $W^\pm$:

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

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

Since quarks mix, $V_{L,u} \neq V_{L,d}$.

The charged current interaction gets a flavor structure by V

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

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

Via W exchange is the only way to change flavor in the SM. Since CKM is known (more or less precise, see talks), in SM every quark flavor changing process can be predicted! (TH uncertainties play an inportant role, see talks on hadronic matrix elements).
Overconstrain, fits (see talks!)

The Standard Model: CKM properties

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)

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

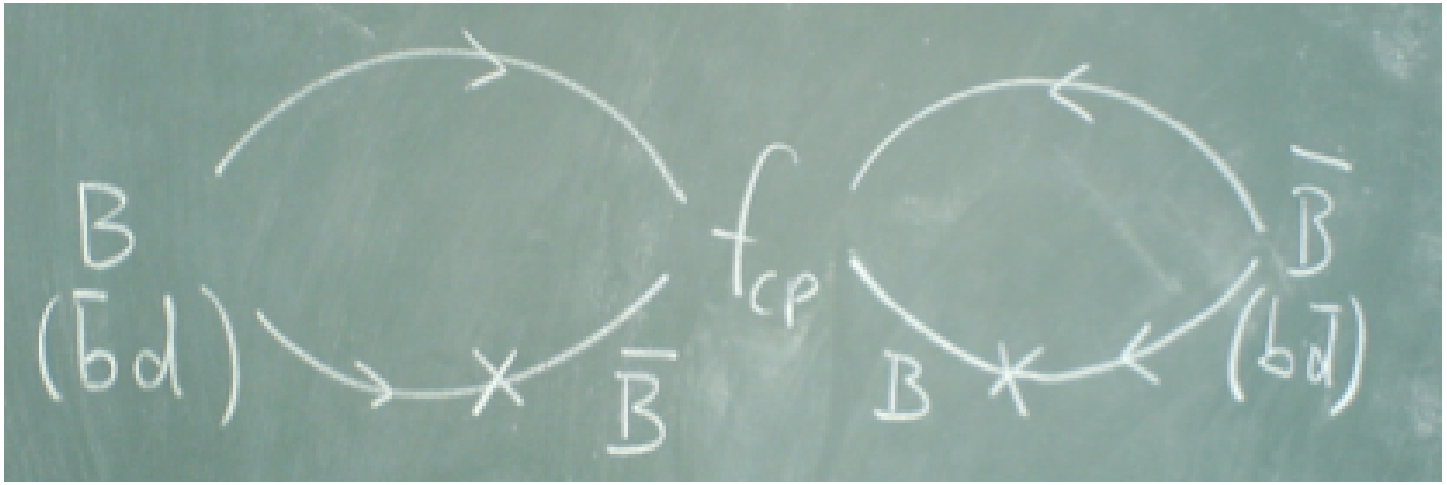
$s_{ij} \equiv \sin\Theta_{ij}$, $c_{ij} \equiv \cos\Theta_{ij}$. δ is the CP violating phase.
In Nature, $\delta \sim \mathcal{O}(1)$ and V is hierarchical $\Theta_{13} \ll \Theta_{23} \ll \Theta_{12} \ll 1$.
Very different – large mixing angles for leptons (PMNS-Matrix):

$\Theta_{23} \sim 45°$, $\Theta_{12} \sim 35°$, $\Theta_{13} \sim O(10°)$ 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

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

Results

NEW

LHCb-PAPER-2019-006

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

- Compatible with **previous** LHCb results and the **WA**
- **Combination** with LHCb Run 1 gives:

$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}}$$

CP violation observed at **5.3σ**!!

F. Betti - INFN Bologna, University of Bologna Moriond EW 2019 - 21/03/2019

Betti

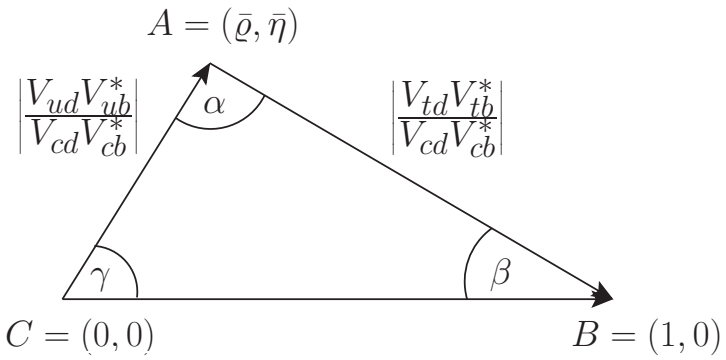
$$\Delta A_{\text{CP}} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

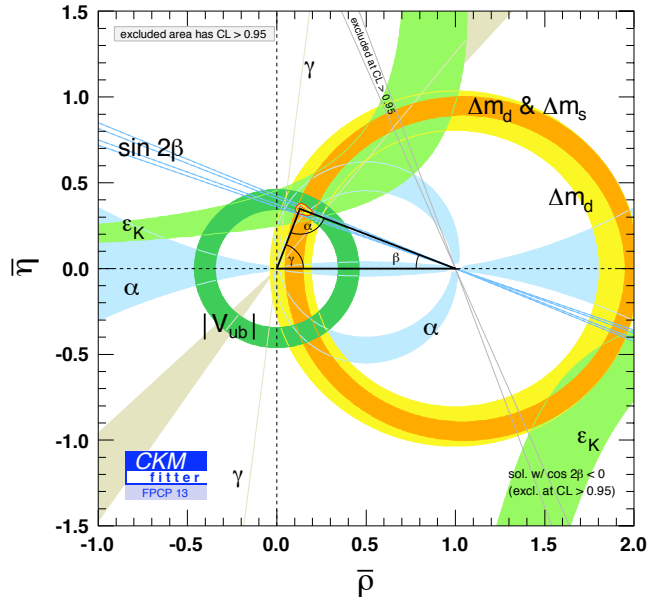
The CKM numerics you can memorize

V is hierarchical $\Theta_{13} \ll \Theta_{23} \ll \Theta_{12} \ll 1$. Wolfenstein parametrization: expansion in $\lambda = \sin\Theta_C \sim 0.2$, $A, \rho, \eta \sim \mathcal{O}(1)$

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

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





$$V_{CKM}V_{CKM}^\dagger = \mathbf{1}$$

Neutral Currents – a window beyond SM

Neutral current gauge interactions γ, Z, g remain unaffected by misalignement between gauge and mass bases in SM because of $\psi \to \psi_i$ (universality) since they involve the same fields, for instance:

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

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

Imagine a BSM $U(1)'$ with generation-dependent charges g_i:

$$\bar{U}_i \, g_i \gamma^\mu A_\mu U_i = \bar{\tilde{U}}_i \gamma^\mu A_\mu (V_u)_{ij} g_j (V^\dagger_u)_{jk} \tilde{U}_k$$

Consider 2 generations, V_u orthogonal with mixing angle ϑ_u between 1st and 2nd generation $V_u = \begin{pmatrix} \cos\vartheta_u & \sin\vartheta_u \\ -\sin\vartheta_u & \cos\vartheta_u \end{pmatrix}$

We obtain FCNC "flavor changing neutral current" amplitudes

$$\cos\vartheta_u \sin\vartheta_u (g_1 - g_2) \bar{\tilde{U}}_1 \gamma^\mu A_\mu \tilde{U}_2$$

Neutral Currents

FCNC "flavor changing neutral current" $U_2 \to U_1$ drop the tilde for mass eigenstates

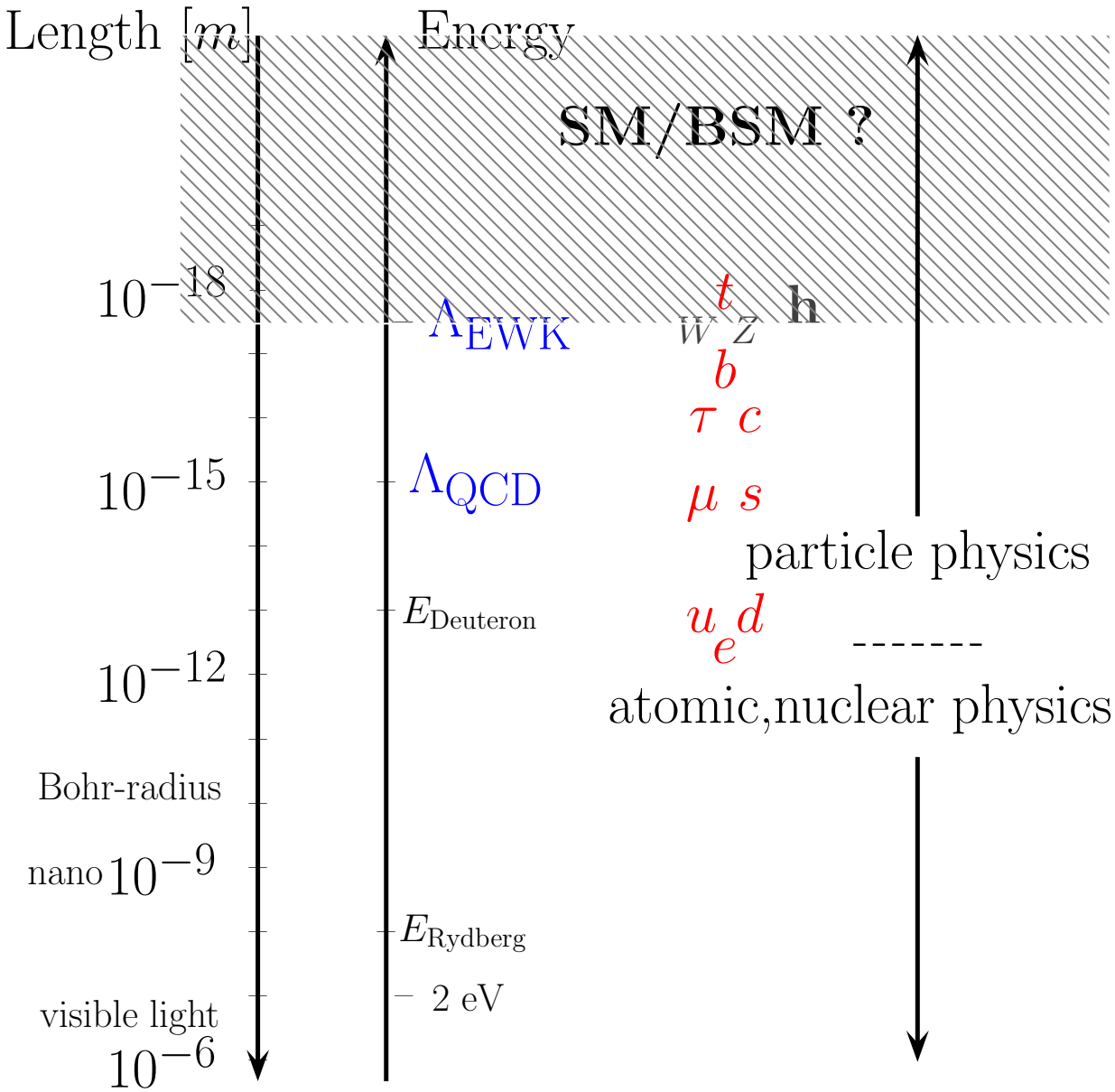
$$\cos\vartheta_u \sin\vartheta_u (g_1 - g_2)\bar{U}_1 \gamma^\mu A_\mu U_2$$

i) no tree-level FCNC in the SM or other models with universality, where $g_1 = g_2$ etc holds.

individual rotations ϑ_u, ϑ_d in SM not physical, only $V = V_{Lu} V_{Ld}^\dagger$, no contraint on V_{Ru}, V_{Rd}.

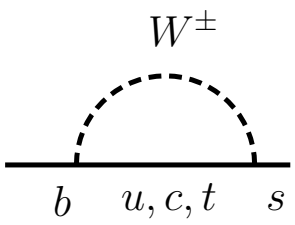
ii) FCNCs have sensitivity to a) BSM physics and b) origins of flavor (up versus down, it could be that mixing comes only from up-sector and $\vartheta_d = 0$)

Exploring Physics at Highest Energies

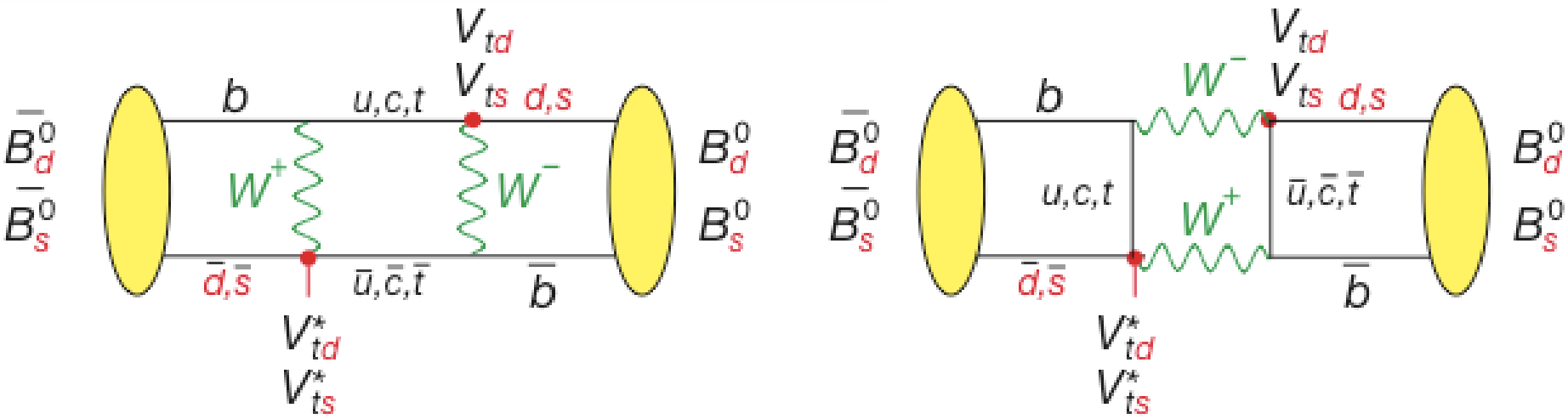


Testing the SM with flavor

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/couplings presently probed with FCNCs:

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

$c \to u$: $D^0 - \bar{D}^0$, ΔA_{CP}, $D \to \pi(\pi)\mu\mu$, $D \to \rho\gamma$

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

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

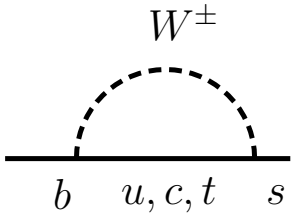
$t \to c, u$, $l \to l'$: not observed

in red: hot topics

”leaving no stone unturned” (see talks & lectures)

Flavor Changing Neutral Currents

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

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

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

$\mathcal{A}$ vanishes for trivial CKM matrix or if quarks in loop are degenerate.

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

amplitude is dominated by first term because of lesser CKM

Flavor Changing Neutral Currents

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, $O(\lambda^2)$.

Generic SM FCNC $c \to u$ amplitude

$\mathcal{A}(c \to u)_{\rm SM} = V_{cd}^* V_{ud} A_d + V_{cs}^* V_{us} A_s + V_{cb}^* V_{ub} A_b, \quad A_q = A(m_q^2/m_W^2).$

$\mathcal{A}(c \to u)_{\rm SM} = \underbrace{V_{cd}^* V_{ud}}_{-\lambda}(A_d - A_b) + \underbrace{V_{cs}^* V_{us}}_{+\lambda}(A_s - A_b)$ $\mathcal{A}$ is GIM-suppressed; CP violation is suppressed by $\frac{V_{cb}^* V_{ub}}{V_{cd}^* V_{ud}} \sim \lambda^4$. Very sensitive to corrections beyond the SM. How about $\Delta A_{CP}^{LHCb} \simeq -1.5 \cdot 10^{-3}$?

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

Lepton flavor violation (LFV) in SM arises through finite neutrino masses which is so small that LFV observables are "null tests".

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: (key in charm, useful in beauty)

– GIM $D \to \pi\pi\mu^+\mu^-$

– Isospin, or U-spin ΔA_{CP}

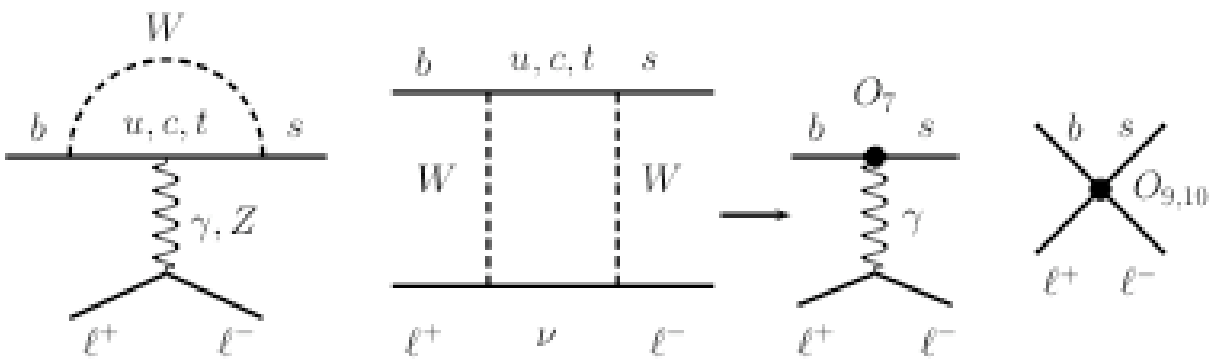
– CP ΔA_{CP}, B_s-mixing

– V-A , helicity P_5'

– LFV

– universality R_K, R_{K^*}

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



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

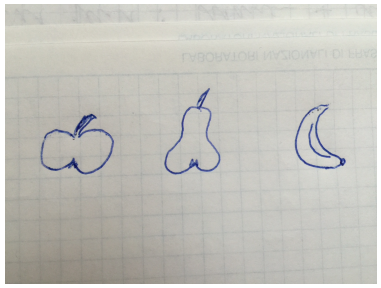
$$\mathcal{O}_P = [\bar{s}P_R b]\,[\bar{\ell}\gamma_5 \ell]\,, \quad \mathcal{O}_P' = [\bar{s}P_L b]\,[\bar{\ell}\gamma_5 \ell]$$

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

Lepton Non-universality?

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



Anomalies in semileptonic B-meson decays:

$R_K = \frac{\mathcal{B}(B \to K\mu\mu)}{\mathcal{B}(B \to Kee)}$ $\quad 2.6\sigma \quad$ (LHCb'14,19)

$R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu\mu)}{\mathcal{B}(B \to K^*ee)}$ $\quad 2.6\sigma \quad$ (LHCb'17)

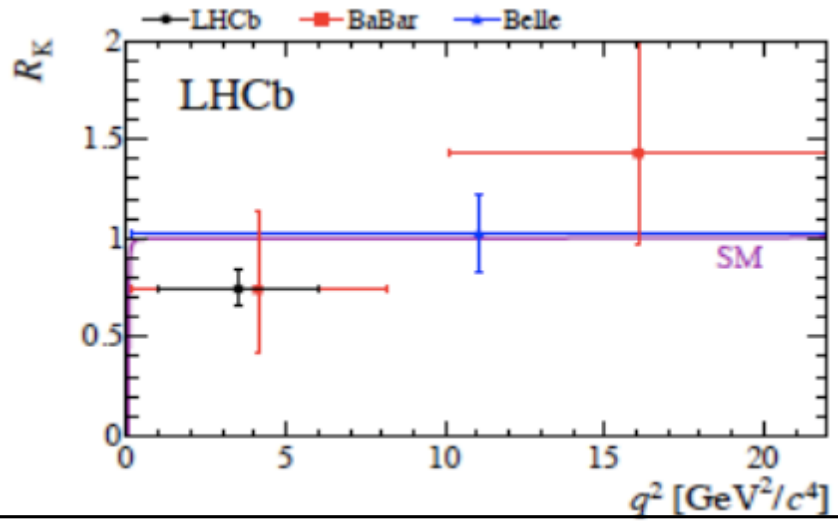
$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$ $\quad \sim 2.7\sigma\ (D^*), \sim 2\sigma\ (D)$

(LHCb'15,B-factories)

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

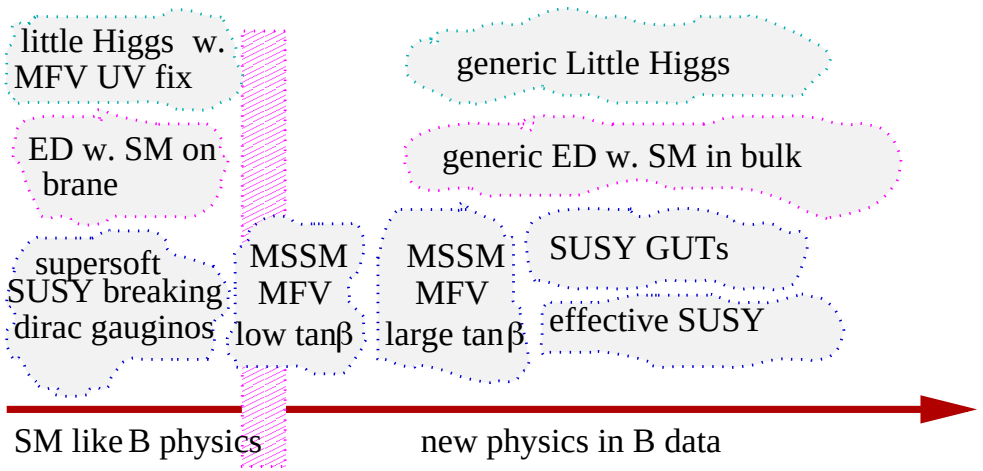
In models with lepton universality (incl. SM): $R_H = 1+$tiny GH, Krüger '03

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



Impact on model building

ψ_i may be more different than we thought



model space 2002

2002: top-down models plot from hep-ph/0207121

2018,19: $U(1)$-extensions, leptoquarks,...

theory activities how to get these from UV-models 1708.06450, 1708.06350, 1706.05033, 1808.00942 .. see talks during this school!

The situation

We are seeing $\sim 2.6\sigma$ hints of new physics in $b \to sll$, LNU between e's and μ's in both observables R_K and R_{K^*} LHCb '14, '17,

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

Lepton-universal models (incl. SM): $R_H = 1+$tiny GH, Krüger, hep-ph/0310219

How can we go on, consolidate and decipher this effect?

1. Which operators are responsible for the deviation? 1411.4773
2. BSM in electrons, or muons, or in both?
3. Side effects from flavor: LFV, τ's, or $SU(2)$: ν's 1411.0565 , 1412.7164, 1503.01084 Charm and Kaons
4. Collider implications (leptoquarks!)