Flavor Theory 2017 plus

a primer

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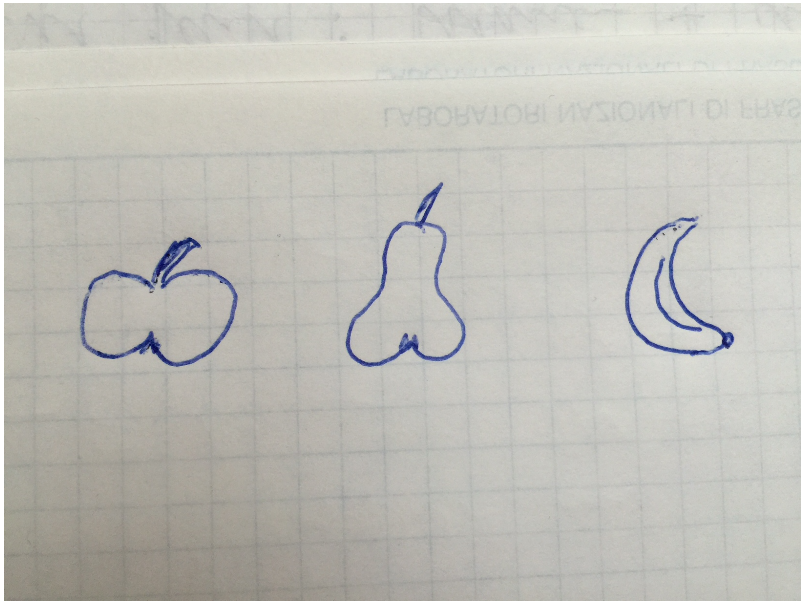


the same yet not the same

symmetry, and symmetry-breaking

Matter comes in 3 generations $\psi \to \psi_i$, $i = 1, 2, 3$.

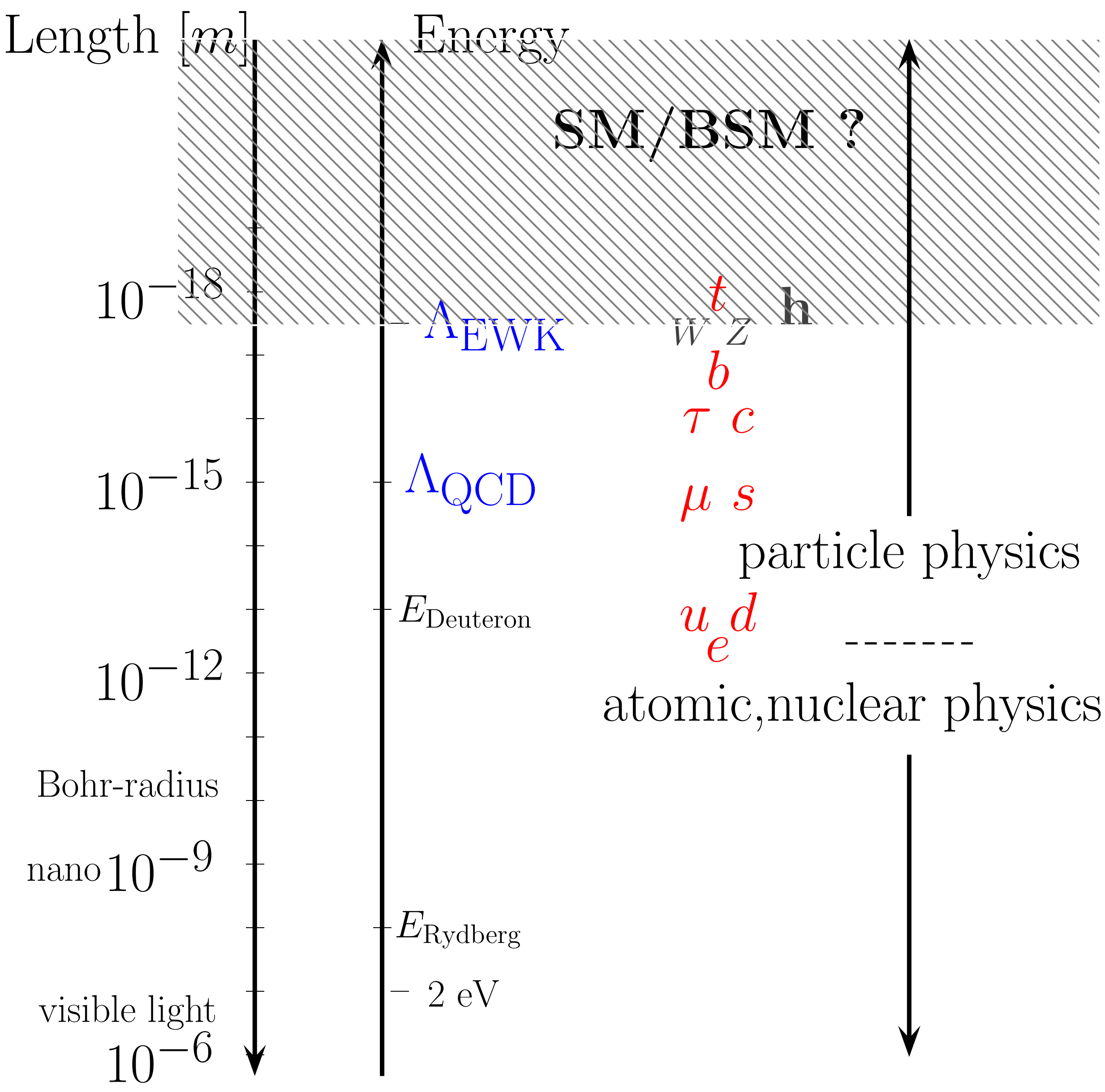
$$\text{quarks: } \begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \begin{pmatrix} t \\ b \end{pmatrix} \text{ leptons: } \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Fermions mix, change ”flavor” in weak processes and violate CP!

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

Strength of couplings, forces: $\alpha_s, \alpha_w, \alpha_e$:	3
Electroweak scale, e.g., m_Z:	1
Scalar potential, e.g., m_h:	1
Fermions:	13

18 parameters (minimal, without neutrino masses and strong phase)
flavor most uneconomical part of SM, masses and mixing puzzling


Length [m]
Energy
SM/BSM ?
10^{-18}
$\Lambda_{\rm EWK}$
t
W Z
h
b
τ c
10^{-15}
$\Lambda_{\rm QCD}$
μ s
particle physics
$E_{\rm Deuteron}$
u d
e

10^{-12}
atomic,nuclear physics
Bohr-radius
nano 10^{-9}
$E_{\rm Rydberg}$
2 eV
visible light
10^{-6}

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 $SU(2)_L$

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

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

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

$Y_{u,d,e}$: 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"

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

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 $V_{A,q} V^\dagger_{A,q} = 1$.

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

$$\mathrm{diag}(m_u, m_c, m_t) = \langle\Phi\rangle \cdot \mathrm{diag}(y_u, y_c, y_t) = \langle\Phi\rangle \cdot V_{L,u} Y_u V^\dagger_{R,u}$$
$$\mathrm{diag}(m_d, m_s, m_b) = \langle\Phi\rangle \cdot \mathrm{diag}(y_d, y_s, y_b) = \langle\Phi\rangle \cdot V_{L,d} Y_d V^\dagger_{R,d}$$

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

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

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

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

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

The tilde basis are mass eigenstates, down quarks analogously.

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

The 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:

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

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)

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

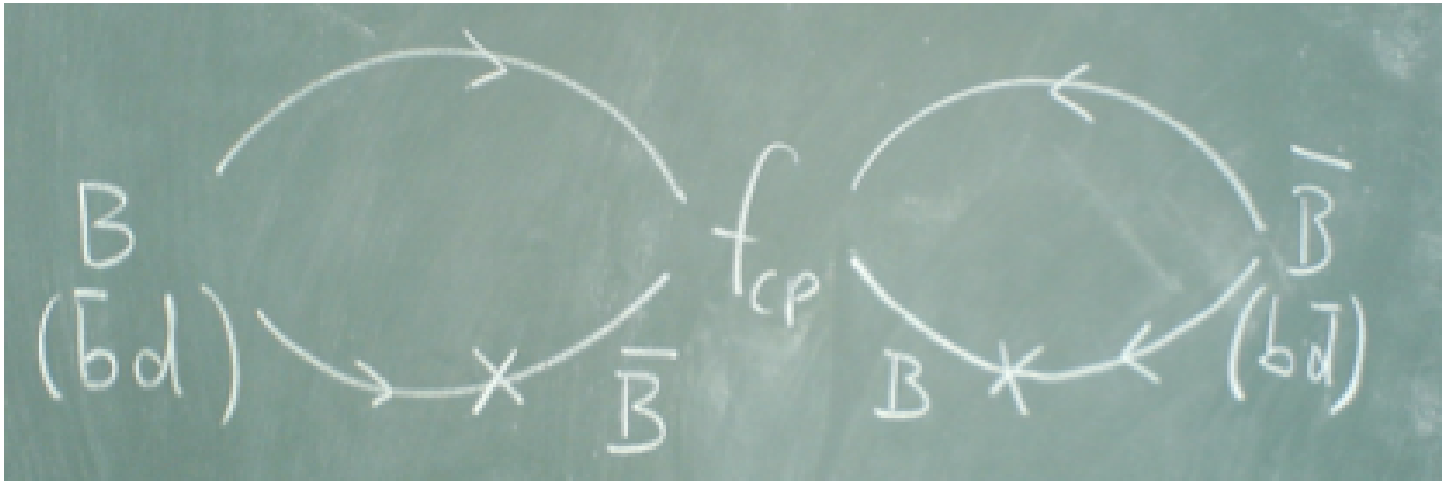
$s_{ij} \equiv \sin\Theta_{ij}$, $c_{ij} \equiv \cos\Theta_{ij}$. δ is the CP violating phase.
In Nature, $\delta \sim \mathcal{O}(1)$ and V is hierarchical $\Theta_{13} \ll \Theta_{23} \ll \Theta_{12} \ll 1$.
Very different – large mixing angles for leptons (PMNS-Matrix):

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

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

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)

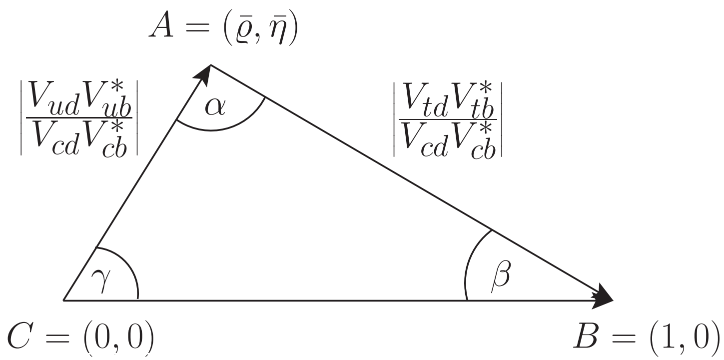
PS: enormous progress from B-factories over past decade. PPS: still improving precision.

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.

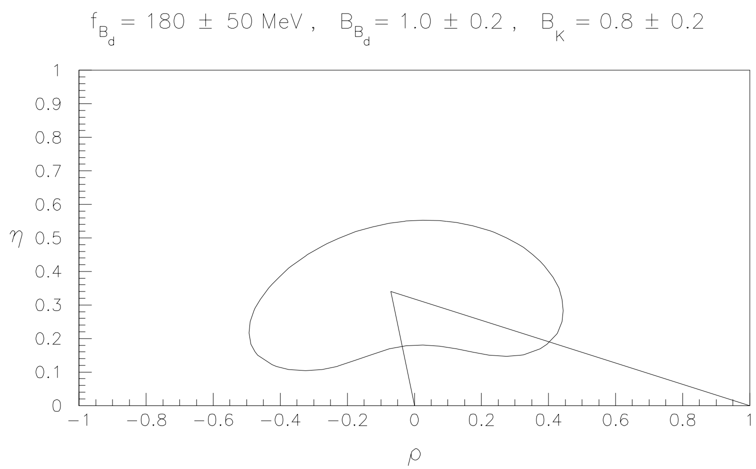


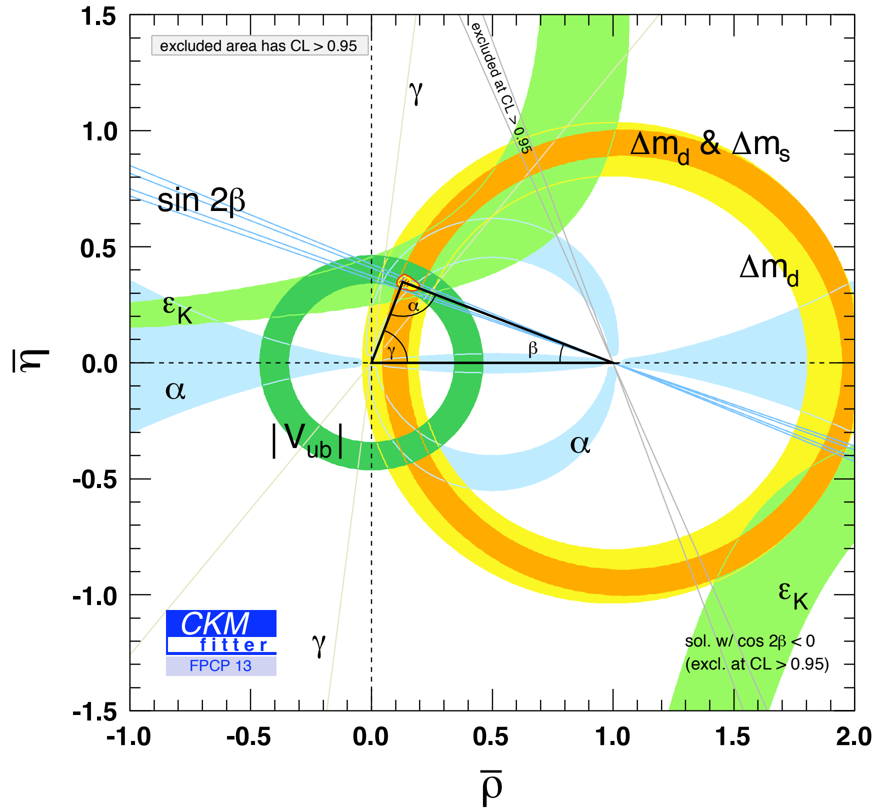
Its apex determines the Wolfenstein parameters $\bar\rho, \bar\eta$. In the absence of CP viol., the triangle would be squashed.

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.





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

the Yukawa coupling Y in $\mathcal{L}_{SM} = -\bar{\psi} Y \psi \Phi + ...$ is a 3×3 matrix.

Experimentally:

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

very peculiar structure

quark mixing is hierarchal, lepton mixing anarchical $O(1)$ entries

Flavor tests of the SM

Generational structure & mixing is a feature of the SM and many beyond-SM particles. VIRTUES:

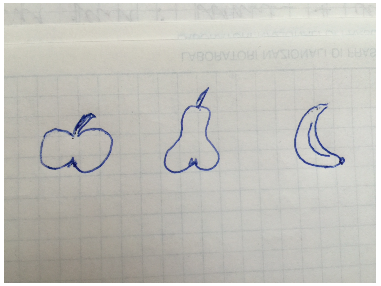
i) high sensitivity to BSM in flavor violation; predictive, and suppressed in SM therefore ideal to look for New Physics in,e.g., $b \to s\ell\ell, \mu \to e\gamma, ..$

ii) flavorful processes are intrinsically linked to the "flavor puzzle": masses, i.e., Yukawa matrices in $\mathcal{L}_{SM} = -\bar{Q}Y_u H^C U - \bar{Q}Y_d H D + ...$ do not appear to be random but rather structured - from where? with a BSM-signal, we may be able to progress here

iii) plenty of modes $s \to d$, $c \to u$, $b \to s, d$, $t \to c, u$, $\mu \to e$, $\tau \to \mu, e$ plus charged ones and $h \to f\bar{f}'$; ongoing & future experiments, too. we may identify $\mathcal{L}_{BSM}$; complementary to direct searches

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)

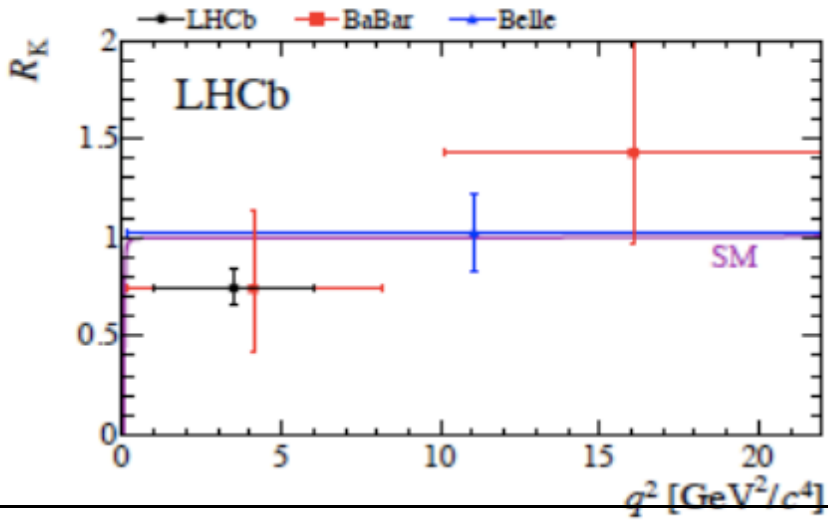
$R_{K^*} = \frac{\mathcal{B}(B\to K^*\mu\mu)}{\mathcal{B}(B\to K^*ee)}$ $\quad 2.6\sigma \quad$ (LHCb'17)

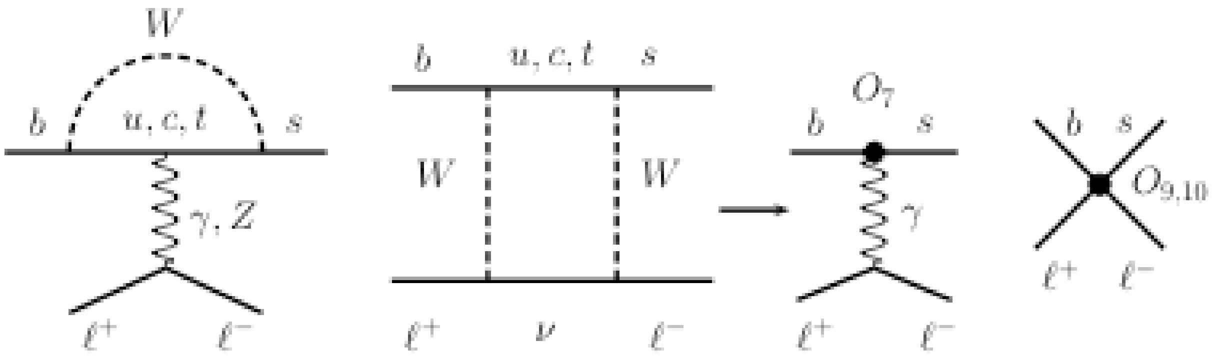
$R_{D^{(*)}} = \frac{\mathcal{B}(B\to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B\to D^{(*)}\ell\nu_\ell)}$ $\quad 3.4.\sigma$ (D^*), 2.1σ (D) $\quad$ (LHCb'15,B-factories)

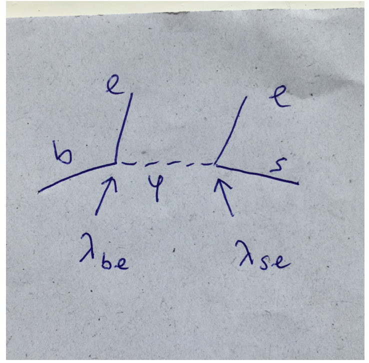
$$R_H = \frac{\mathcal{B}(B \to H\mu\mu)}{\mathcal{B}(B \to Hee)}, \quad H = K, K^*, X_s, \Phi, \ldots$$

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
$R_K\vert_{[1,6]}$	$0.745 \pm^{0.090}_{0.074} \pm 0.036$	$\simeq 1$





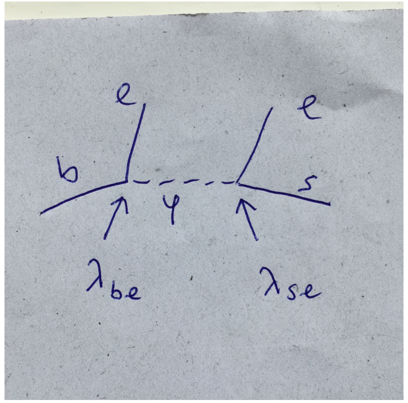


R_K, R_{K^*} tells us at face value $C_9^\mu = -C_{10}^\mu \simeq -0.6$ vs $C_9^{\rm SM} \simeq -C_{10}^{\rm SM} \simeq 4$

about 20 % BSM contribution to $O_{LL} = \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L$.

This actually is "according to plan": FCNCs are suppressed (GIM,CKM,loop) in SM and BSM physics can show up without big competition.

$R_{K^{(*)}} \neq 1$ would not only be a (loud) breakdown of the SM, it tells us something about flavor $\rightarrow$ possibly learn something about flavor

Tree level explanations: 

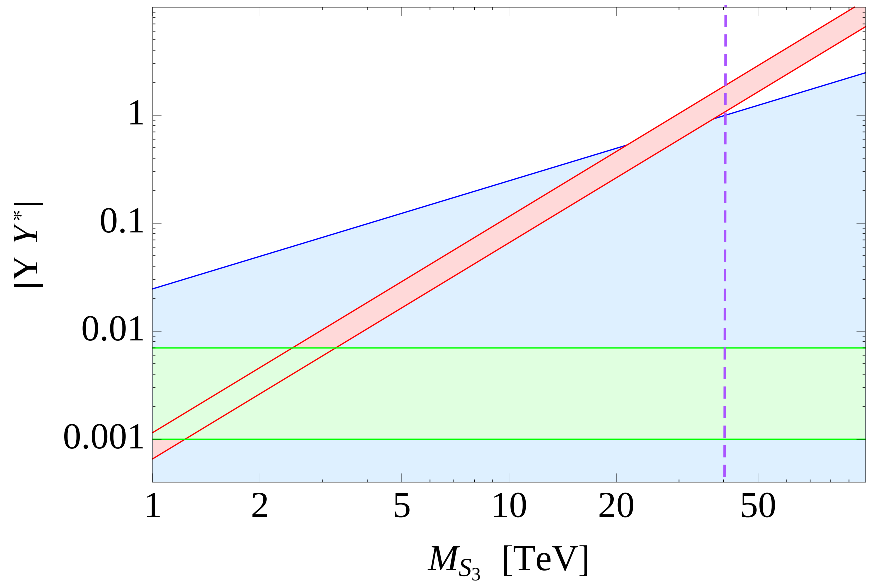
$$\frac{\lambda^2}{M^2} \sim \frac{1}{5}\frac{g^4}{m_W^2}\frac{1}{16\pi^2}V_{tb}V_{ts}^* \sim \frac{1}{(30\text{TeV})^2}$$

for order one couplings this points to a collider-mass scale.

With (minimal) flavor violating BSM $\frac{\lambda^2}{M^2} \sim \frac{1}{5}\frac{g^4}{m_W^2}\frac{1}{16\pi^2} \sim \frac{1}{(6\text{TeV})^2}$ this is within reach of the LHC.

In flavor models that explain quark, lepton masses, CKM, PMNS the BSM couplings can be further suppressed $\rightarrow$ TeV-ish BSM mass.

R_{K,K^*}: $\frac{Y_{b\mu}Y^*_{s\mu} - Y_{be}Y^*_{se}}{M^2} \simeq \frac{1.1}{(35\,\text{TeV})^2}$, (S_3) LQ scalar triplet GH, Nisandzic, 1704.05444



red: explains R_K, R_{K^*}, blue: allowed by $B_s - \bar{B}_s$-mixing, green: flavor model prediction

$Y_{q_3\ell} \sim c_l\,, \quad Y_{q_2\ell} \sim c_l\lambda^2\,, \quad q_3 = b, t, \;\; q_2 = s, c, \;\; \lambda, c_l \lesssim 0.2$ points to TeV-ish mass M!

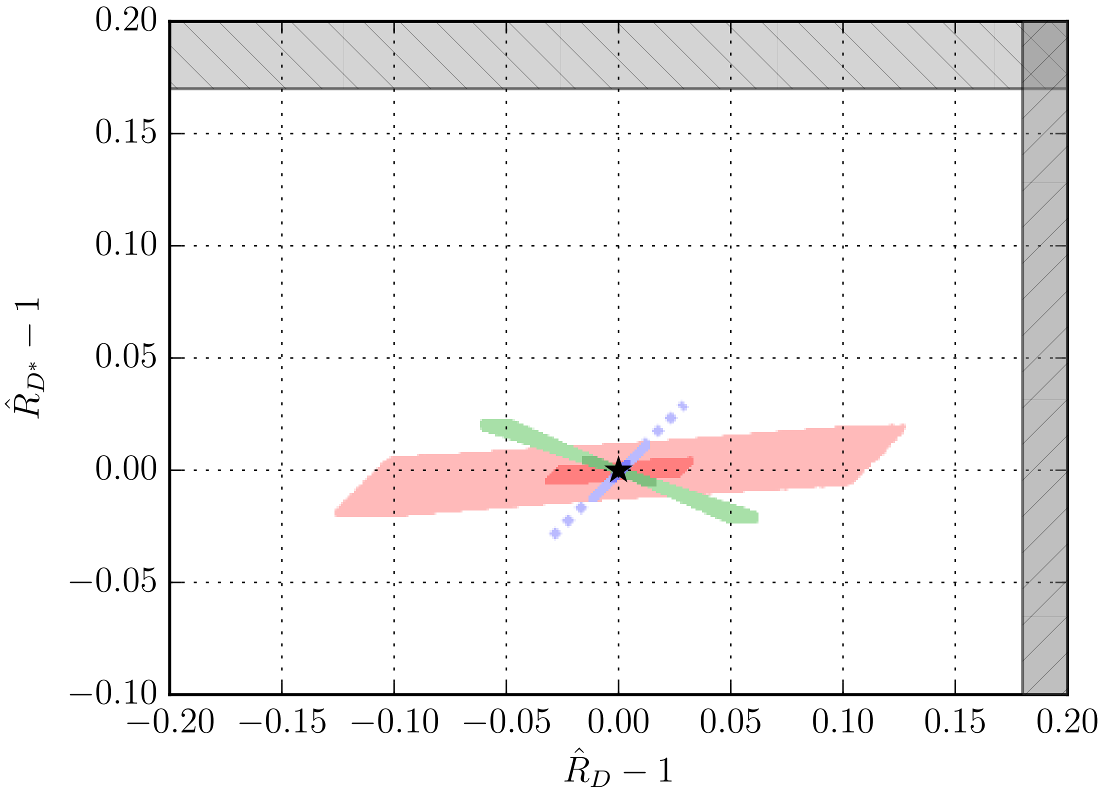
Model-independent upper limit by B_s-mixing $\propto \lambda^4/M^2$ at 40 TeV.

Expected mass scale M depends on flavor couplings λ^2/M^2 fixed

The size of the effect – current hints for SM deviation – in $R_{K^{(*)}}$ is ”natural”, in the core of parameter space. How about $R_{D^{(*)}}$?
Tree-level in SM, similar order of anomalous data as $R_{K^{(*)}}$ implies large couplings and very low BSM:

flavor	generic	minimal	PMNS/CKM
$R_{K^{(*)}}$ tree	30 TeV	6 TeV	few TeV
$R_{K^{(*)}}$ loop	few TeV	0.5 TeV	expected similar to $R_{D^{(*)}}$
$R_{D^{(*)}}$ tree	$\sim$ a TeV	0.3 TeV	not viable 1609.08895

Linking the anomalies is intriuging however not straightforward, lower deviation in $R_{D^{(*)}}$, in particular R_{D*} more ”natural”.

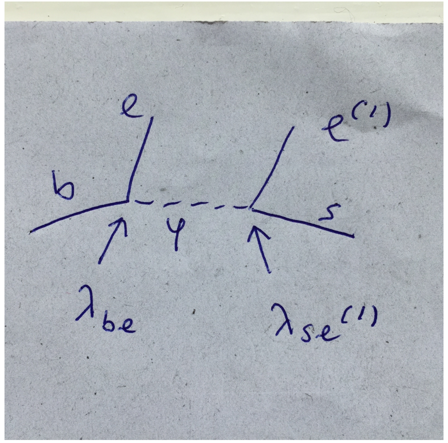


$\hat{R}_{D^{(*)}} = R_{D^{(*)}}/R^{\mathrm{SM}}_{D^{(*)}}$; star: SM, grey: exp 1σ band (too far away from SM to fit the plot); red:V_1, blue V_3, green S_2. LQs with flavor patterns, constraints: rare K decays, $\mu - e$ conversion, $B \to K\nu\nu$, perturbativity 1609.08895 — Ignoring the flavor model ones, only model V_1 can avoid exp constraints. All models S_3, V_1, V_3 can explain $R_{K^{(*)}}$.

$R_{K^{(*)}}$

- triggered new type of BSM model-building: Z', leptoquarks
- its plausible (OK order of magnitude)
- its an opportunity (highly informative clash with SM)
- how to consolidate? rule out?
- if this really stays, decipher

$\rightarrow$ 4 points



Leptoquark coupling matrix: $\lambda_{ql} \equiv \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix}$

columns=leptons

rows=quarks

mixed structures, not present in standard model!

columns=leptons, discrete non-abelian flavor symmteries (sub-groups of $SU(3)$), e.g. A_4 Altarelli, Feruglio) "zeros and ones"

Rows=quarks, hierarchical, $U(1)$-Froggatt-Nielsen-Symmetry
$1 \gg \rho \gg \rho_d$ "hierarchies"

We can use these symmetries to explain quark and lepton properties. Then predict leptoquark textures, for instance,

$$\lambda_{ql} \sim \begin{pmatrix} \rho_d & \rho_d & \rho_d \\ \rho & \rho & \rho \\ 1 & 1 & 1 \end{pmatrix}, \quad \begin{pmatrix} 0 & \rho_d & 0 \\ 0 & \rho & 0 \\ 0 & 1 & 0 \end{pmatrix}, \ldots$$

second matrix can explain R_K – leptoquark couples to muons only.

Very general ansatz 1503.01084

LQ coupling matrix: $\lambda_{ql} \equiv \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix} \sim \begin{pmatrix} \rho_d \kappa & \rho_d & \rho_d \\ \rho \kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}$

rows $=$quarks, columns$=$ leptons

data:

$$\rho_d \lesssim 0.02\,, \quad \kappa \lesssim 0.5\,, \quad 10^{-4} \lesssim \rho \lesssim 1\,, \quad \kappa/\rho \lesssim 0.5\,, \quad \rho_d/\rho \lesssim 1.6\,.$$

Froggatt-Nielsen: $\rho \sim \epsilon^2$, $\rho_d \sim \epsilon^3$ or ϵ^4 , (Q_L) with $\epsilon \sim 0.2$.

Ready to use for correlations for B, charm, lepton and collider prczesses

1. Study more LNU ratios and do this more precisely including the high q^2 bins

$$R_H = \frac{\mathcal{B}(\bar{B}\to\bar{H}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{H}ee)}, \quad H = K, K^*, X_s, ...$$ GH, Krüger '03

At linear approximation it suffices to measure 2 different (by spin parity of final hadron) R_H ratios and then all others serve as consistency checks 1411.4773

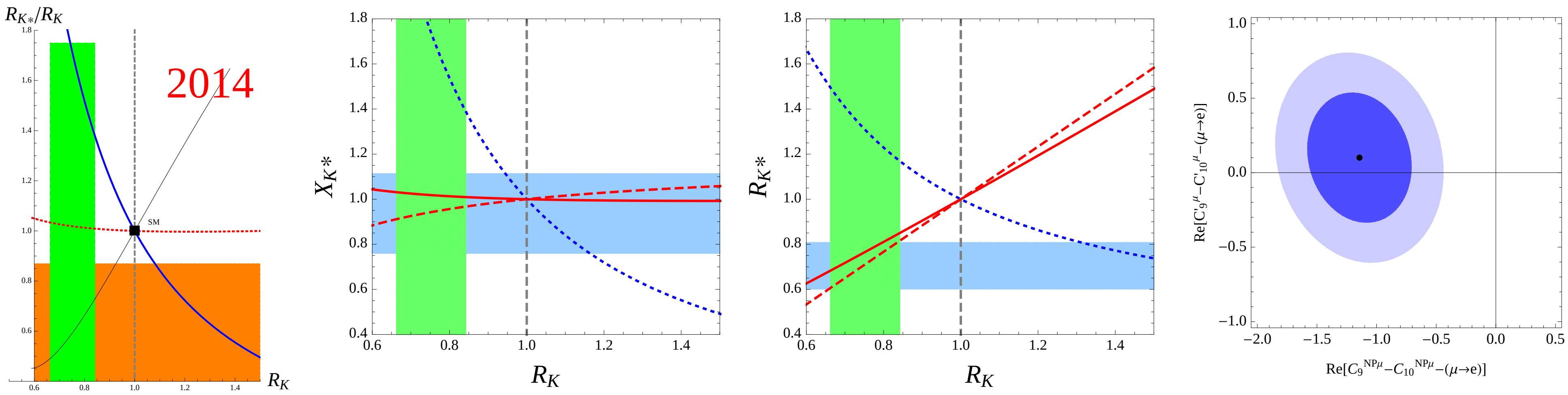
Wilson coefficients C: V-A, C': V+A currents

$$C + C' : \quad K, K^*_\perp, \ldots$$
$$C - C' : \quad K_0(1430), K^*_{0,\|}, \ldots$$

and $K^*_\perp$ subleading at both high and low q^2 windows. Predictions: $R_K \simeq R_\eta$, $R_{K^*} \simeq R_\Phi \simeq R_{K_0(1430)}$ and all R_H equal if no V+A currents.

The measurement of R_K and R_{K^*} does this diagnozing job. SM-like chirality operators are the dominant source behind the anomalies.

Prediction: $R_{X_s} \simeq 0.73 \pm 0.07$ inclusive decays, Belle II



Green band: R_K 1σ LHCb, blue band R_{K^*} 1σ LHCb. Different BSM scenarios are red dashed: pure C_{LL} (LQ triplet). Black solid: $C_{LL} = -2C_{RL}$. Blue: C_{RL} (LQ doublet)/disfavored as dominant source of LNU. Orange: data from $B \to X_s \ell\ell$. $R_{X_s}^{\mathrm{Belle}'09} = 0.42 \pm 0.25\,, \quad R_{X_s}^{\mathrm{BaBar}'13} = 0.58 \pm 0.19\,.$

$R_H < 1$: too few muons, or too many electrons, or combination thereof.

2. To disentangle this lepton specific modes are required.

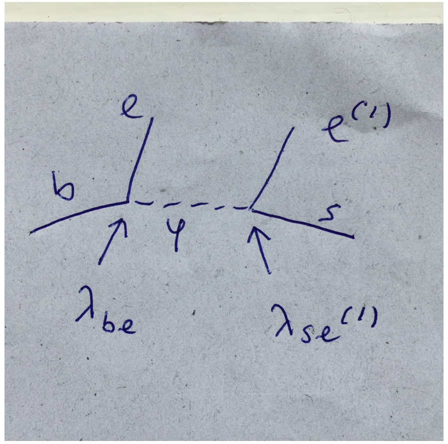
$B \to Hee$ and $B \to H\mu\mu$ studies; global fits Bobeth, van Dyk, Mahmoudi, Matias,Virto,Straub,Camalich,Altmannshofer, Hurth, Hofer,Jäger

It is interesting that also $B \to K, K^* \mu\mu$ has presently an anomaly, that even can point to the same direction as R_{K,K^*}.

LNU in explicit models can be arranged by gauging lepton flavor (Z') Altmannshofer, Straub, Fuentes, Bishara, Quiros, Panico LQs can be charged under flavor group Varzielas, GH, Loose, Schönwald

From a flavor perspective, LNU quite generically implies LFV

Guadagnoli, Lane



3. Search for LFV

in B-decays, in charm decays, and with charged leptons (μ -e conversion, rare decays), at colliders

observable	current 90 % CL limit	constraint	future sens.
$\mathcal{B}(\mu \to e\gamma)$	$5.7 \cdot 10^{-13}$ MEG	$\lvert\lambda_{qe}\lambda^*_{q\mu}\rvert \lesssim \frac{M^2}{(34\text{TeV})^2}$	$6 \cdot 10^{-14}$ MEG
$\mathcal{B}(\tau \to e\gamma)$	$1.2 \cdot 10^{-8}$ Belle	$\lvert\lambda_{qe}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(1\text{TeV})^2}$	
$\mathcal{B}(\tau \to \mu\gamma)$	$4.4 \cdot 10^{-8}$ Babar	$\lvert\lambda_{q\mu}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(0.7\,\text{TeV})^2}$	$5 \cdot 10^{-9}$ $[B2]$
$\mathcal{B}(\tau \to \mu\eta)$	$6.5 \cdot 10^{-8}$ Belle	$\lvert\lambda_{s\mu}\lambda^*_{s\tau}\rvert \lesssim \frac{M^2}{(3.7\,\text{TeV})^2}$	$2 \cdot 10^{-9}$ $[B2]$
$\mathcal{B}(B \to K\mu^\pm e^\mp)$	$3.8 \cdot 10^{-8}$ BaBar	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(19.4\,\text{TeV})^2}$	
$\mathcal{B}(B \to K\tau^\pm e^\mp)$	$3.0 \cdot 10^{-5}$ PDG	$\sqrt{\lvert\lambda_{s\tau}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\tau}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(3.3\,\text{TeV})^2}$	
$\mathcal{B}(B \to K\mu^\pm \tau^\mp)$	$4.8 \cdot 10^{-5}$ PDG	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{b\tau}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{s\tau}\rvert^2} \lesssim \frac{M^2}{(2.9\,\text{TeV})^2}$	$\lesssim 10^{-6}$ K.Petridis
$\mathcal{B}(B \to \pi\mu^\pm e^\mp)$	$9.2 \cdot 10^{-8}$ BaBar	$\sqrt{\lvert\lambda_{d\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{de}\rvert^2} \lesssim \frac{M^2}{(15.6\,\text{TeV})^2}$	

Table 1: Selected LFV data, constraints and future sensitivities. Here, $q = d, s, b$. The Belle II projections $[B2]$ are for $50\ ab^{-1}$.

For the constraint from $\mathcal{B}(\tau \to \mu\eta)$ we ignored the possibility of cancellations with $\lambda_{d\mu}\lambda^*_{d\tau}$. We ignore tuning between leading order diagrams in the $\ell \to \ell'\gamma$ amplitudes. R_K: $0.7 \lesssim \text{Re}[\lambda_{se}\lambda^*_{be} - \lambda_{s\mu}\lambda^*_{b\mu}]\frac{(24\text{TeV})^2}{M^2} \lesssim 1.5$, K-decays $\lvert\lambda_{d\mu}\lambda^*_{s\mu}\rvert \lesssim \frac{M^2}{(183\text{TeV})^2}$.

Next round of μ-e conversion experiments reaching 10^{-16} sensitive to the R_{K,K^*} parameter space!

predictions semileptonic B-decays:

$$\mathcal{B}(B \to K\mu^\pm e^\mp) \simeq 3 \cdot 10^{-8}\,\kappa^2 \left(\frac{1-R_K}{0.23}\right)^2 , \tag{1}$$

$$\mathcal{B}(B \to K e^\pm \tau^\mp) \simeq 2 \cdot 10^{-8}\,\kappa^2 \left(\frac{1-R_K}{0.23}\right)^2 , \tag{2}$$

$$\mathcal{B}(B \to K\mu^\pm \tau^\mp) \simeq 2 \cdot 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2 , \tag{3}$$

predictions μ and τ decays:

$$\mathcal{B}(\mu \to e\gamma) \simeq 2 \cdot 10^{-12} \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{4}$$

$$\mathcal{B}(\tau \to e\gamma) \simeq 4 \cdot 10^{-14} \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{5}$$

$$\mathcal{B}(\tau \to \mu\gamma) \simeq 3 \cdot 10^{-14} \frac{1}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{6}$$

$$\mathcal{B}(\tau \to \mu\eta) \simeq 4 \cdot 10^{-11} \rho^2 \left(\frac{1 - R_K}{0.23} \right)^2 . \tag{7}$$

predictions purely leptonic decays (asymmetric branching ratios):

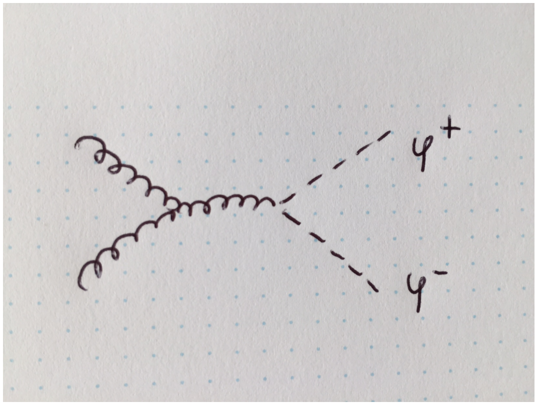
$$\frac{\mathcal{B}(B_s \to \ell^+ \ell'^-)}{\mathcal{B}(B_s \to \ell^- \ell'^+)} \simeq \frac{m_\ell^2}{m_{\ell'}^2} \qquad \text{assuming left-handed leptons only} \tag{8}$$

$$\frac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\rm SM}} \simeq 0.01\,\kappa^2 \cdot \left(\frac{1-R_K}{0.23}\right)^2 , \tag{9}$$

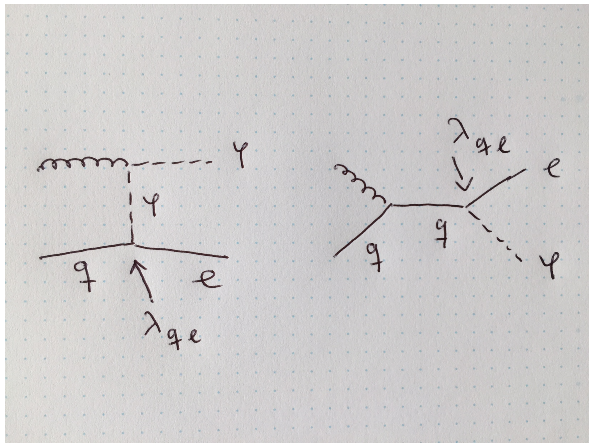
$$\frac{\mathcal{B}(B_s \to \tau^+ e^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\rm SM}} \simeq 4\,\kappa^2 \cdot \left(\frac{1-R_K}{0.23}\right)^2 , \tag{10}$$

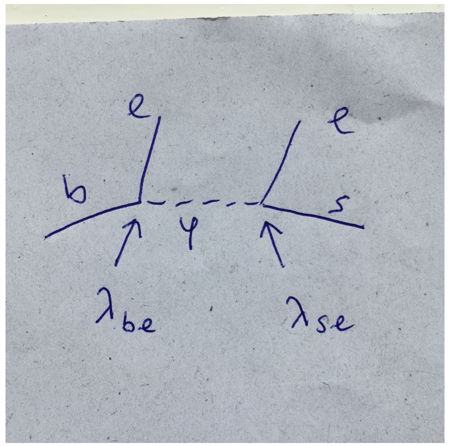
$$\frac{\mathcal{B}(B_s \to \tau^+ \mu^-)}{\mathcal{B}(B_s \to \mu^+ \mu^-)_{\rm SM}} \simeq 4 \cdot \left(\frac{1-R_K}{0.23}\right)^2 , \tag{11}$$

Pair production, e.g. recent works Bastian Diaz, Martin Schmaltz, Yi-Ming Zhong 1706.05033 $\sigma(pp \to \varphi^+\varphi^-) \propto \alpha_s^2$



Single LQ production from b-anomalies GH, Dennis Loose, Ivan Nisandzic, DO-TH 17/27, in preparation in association with a lepton $\sigma(pp \to \varphi\ell) \propto |\lambda_{q\ell}|^2\alpha_s$ depends on flavor





- 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.

- Current anomalies – LNU in quark decays – inspired new bottom-up model building Leptoquarks, Z'
- Understanding LNU anomalies involves measurements at LHCb, B-Factories, Belle II and direct searches, ATLAS, CMS.
- Great prospects to link with direct searches. $\rightarrow$ see talk on leptoquarks at the LHC by Dennis Loose in Exotics session
- Linking lepton to quark physics may provide opportunities towards the understanding of flavor.