~~New Ideas in flavour~~

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Flavor physics: theory perspective

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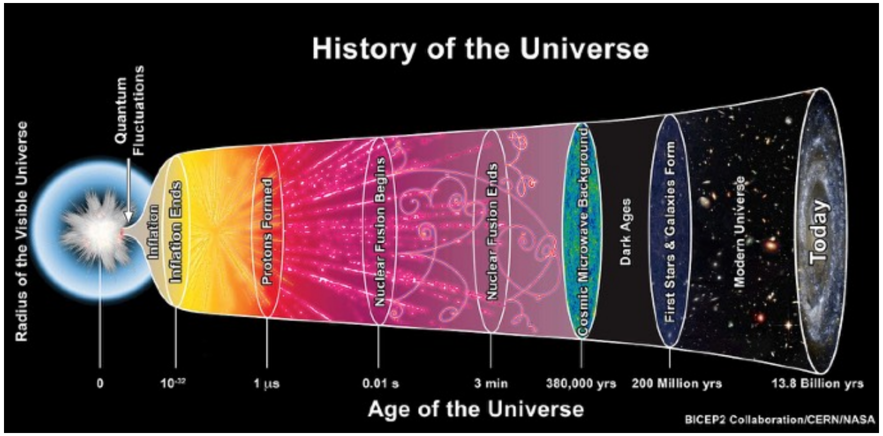
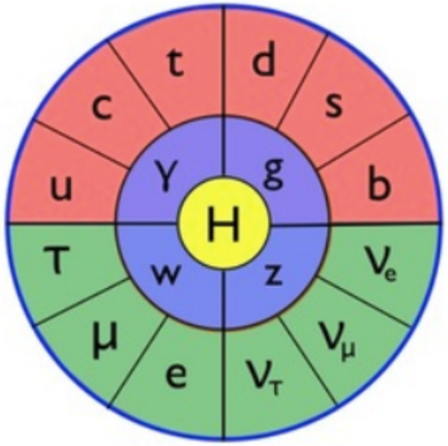
1. Introduction

★ Is it possible to build the Universe using the Standard Model as a tool?

- no, but maybe it can tell us where to look for new tools



BICEP2 Collaboration/CERN/NASA



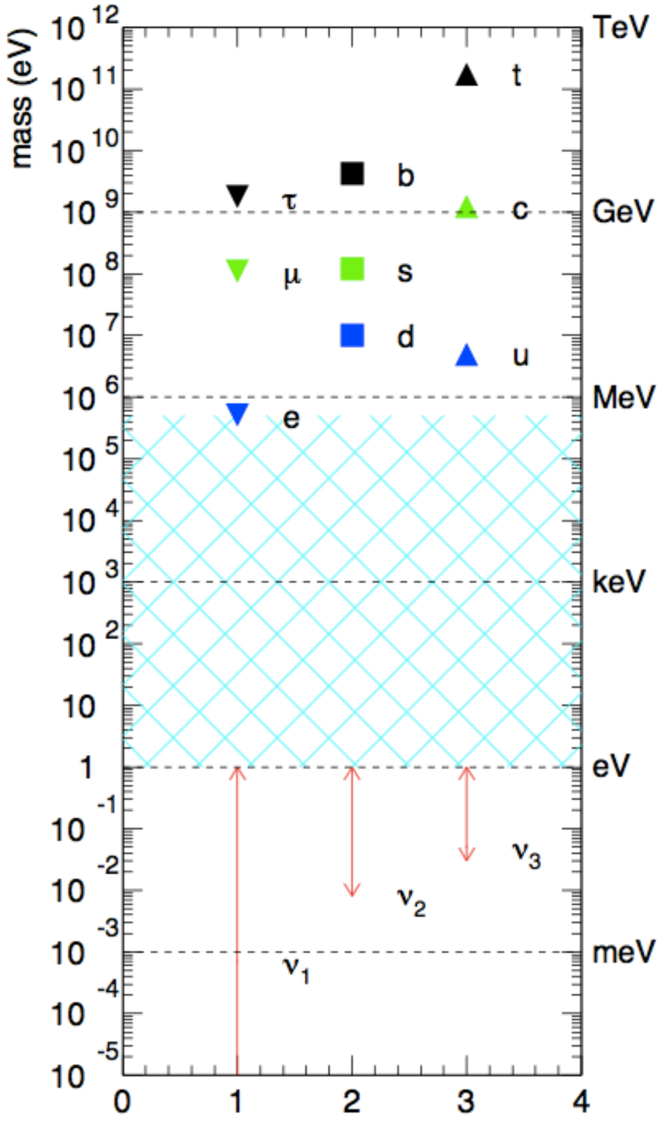
★ The era of "guaranteed discoveries" is over (top quark, electroweak breaking)

- new experiments designed to study rare decays or perform precision studies of various processes might point us in the right direction

★ What about New Physics?

- no new elementary particles so far at the LHC
- neutrinos oscillations: ν's have mass and so CLFV transitions are guaranteed
- use sphaleron mechanism: baryogenesis via leptogenesis   Fukugita, Yanagida
- new sources of CP-violation in the lepton sector

Fundamental physics: flavor problem



★ SM and BSM Flavor problem

★ Flavor problem: patterns of masses of particles

- quarks

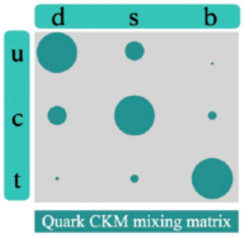
$$\frac{m_d}{m_u} \simeq 2\ , \quad \frac{m_s}{m_d} \simeq 21\ ,$$
$$\frac{m_t}{m_c} \simeq 267\ , \quad \frac{m_c}{m_u} \simeq 431\ , \quad \frac{m_t}{m_u} \simeq 1.2 \times 10^5\ .$$

- leptons

$$\frac{m_\tau}{m_\mu} \simeq 17\ , \quad \frac{m_\mu}{m_e} \simeq 207\ .$$

★ Flavor problem: pattern of fermion mixing

- why is the quark mixing matrix so different from the neutrino mixing matrix?



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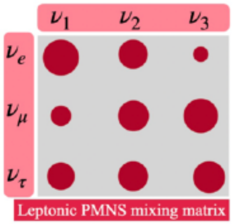


S. Cao, et al.

★ Flavor problem: nature of neutrino mass?

Is flavor "problem" actually a problem?

★ Yukawa couplings are protected by a chiral symmetry:

$$\frac{dy}{d\log\mu} \propto y \quad \Longrightarrow$$

Small couplings remain small:
"Technical Naturalness"

★ So, why is it a problem?

The reason there is a problem is that all these couplings appear to come from the same physics. Therefore they should all start at the same order of magnitude at some UV scale, and the hierarchy should come from RG effects. This is why gauge couplings are not considered hierarchal.

Now the above "technically natural" condition actually HURTS!

Fundamental physics: flavor problem

★ Flavor problem: flavor-changing neutral currents (FCNC)

- there is no term in the SM Lagrangian that leads to FCNC effects: quantum effects (one loop process)
- quarks: massive quarks and non-zero mixing parameters automatically lead to FCNC processes: $b \to s\gamma, c \to u\ell\bar{\ell}, B^0 - \bar{B}^0$-mixing, etc.
- leptons: massive neutrinos and non-zero mixing parameters automatically lead to FCNC processes: $\tau \to e\gamma, \tau \to eee, \mu A \to eA$, etc.

★ Flavor problem: patterns of masses of particles and neutrino mass: new symmetry?

- there could be a mechanism generating mass patterns (Froggatt-Nielsen, etc.)…

A. Blechman, AAP, G.K. Yeghiyan

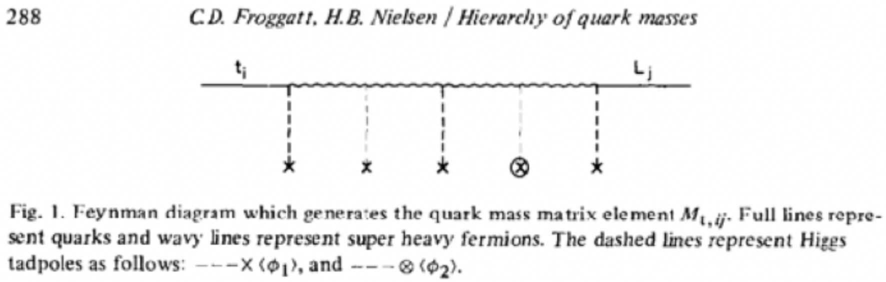
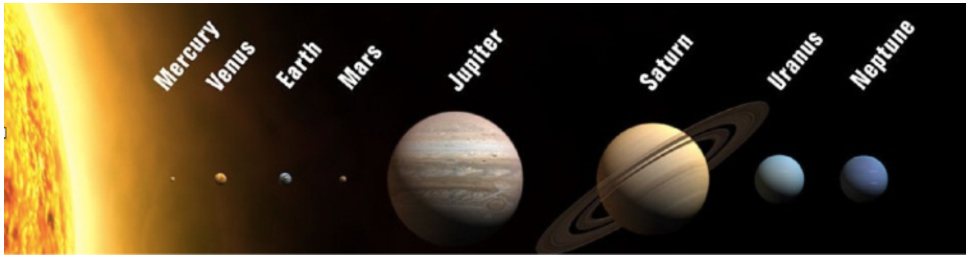

288 *C.D. Froggatt, H.B. Nielsen / Hierarchy of quark masses*

Fig. 1. Feynman diagram which generates the quark mass matrix element $M_{t,ij}$. Full lines represent quarks and wavy lines represent super heavy fermions. The dashed lines represent Higgs tadpoles as follows: $- - - \times \langle\phi_1\rangle$, and $- - - \otimes \langle\phi_2\rangle$.

- … or maybe not (a "just so" solution?)



2. Flavor in the Standard Model (quarks)

★ Flavor in the Standard Model: mass generation and CP-violation

- masses are generated through Yukawa terms (quarks)

$$-\mathcal{L}_Y = Y^d_{ij}\overline{Q^f_{Li}}HD^f_{Rj} + Y^u_{ij}\overline{Q^f_{Li}}\widetilde{H}U^f_{Rj} + h.c. \quad \text{with} \quad Q^f_{Li} = \begin{pmatrix} U^f_{Li} \\ D^f_{Li} \end{pmatrix}$$

- after spontaneous symmetry breaking $H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H^0 \end{pmatrix}$

$$-\mathcal{L}_M = (M_d)_{ij}\,\overline{D^f_{Li}}D^f_{Rj} + (M_u)_{ij}\,\overline{U^f_{Li}}U^f_{Rj} + h.c. \quad \text{with} \quad (M_q)_{ij} = \frac{v}{\sqrt{2}}(Y^q)_{ij}$$

- … but mass matrices above are NOT diagonal! For for both q = {u,d}:

$$V_{qL}M_qV^\dagger_{qR} = M^{\rm diag}_q \quad \text{with} \quad \begin{aligned} q_{Li} &= (V_{qL})_{ij}\, q^f_{Lj} \\ q_{Ri} &= (V_{qR})_{ij}\, q^f_{Rj} \end{aligned}$$

Some structure of the Yukawas that leads to the mass and CKM hierarchies? Leptons?

Flavor in the Standard Model

★ Charged current interactions: the only source of flavor violation in SM

- since left and right matrices are different: charge current part of $\mathcal{L}$:

$$-\mathcal{L}^q_{W^\pm} = \frac{g}{\sqrt{2}}\overline{u}_{Li}\gamma^\mu \left[\underbrace{V_{uL}V^\dagger_{qR}}\right]_{ij} d_{Lj}W^+_\mu + h.c.$$

$$V \equiv \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

(CKM matrix)

- Cabibbo-Kobayashi-Maskawa (CKM) matrix is unitary: $VV^\dagger = 1$ **(N^2 relations)**

2 generations: 1 angle and 0 phases; 3 generations: 3 angles and 1 phase!

(No CPV) **(CPV)**

★ In the Standard Model, CP-violation is part of the physics of flavor

CKM picture of CP-violation

★ There is a single phase of the CKM matrix for 3-generation SM

- Even though there are MULTIPLE ways to parameterize CKM matrix

$$V \equiv \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

(Wolfenstein)

- …there exists a parameterization-independent quantity,

$$Im\left[V_{ij}V_{kl}V_{il}^\dagger V_{kj}^\dagger\right] = J_{CKM} \sum_{m,n=1}^{3} \epsilon_{ilkm}\epsilon_{jlkm} \quad \text{with} \quad J_{CKM} \simeq \lambda^6 A^2 \eta$$

- Since CP-violation appears from imaginary parts of the Yukawas, there is a condition for CP-violation to be present in the SM:

(Jarlskog)

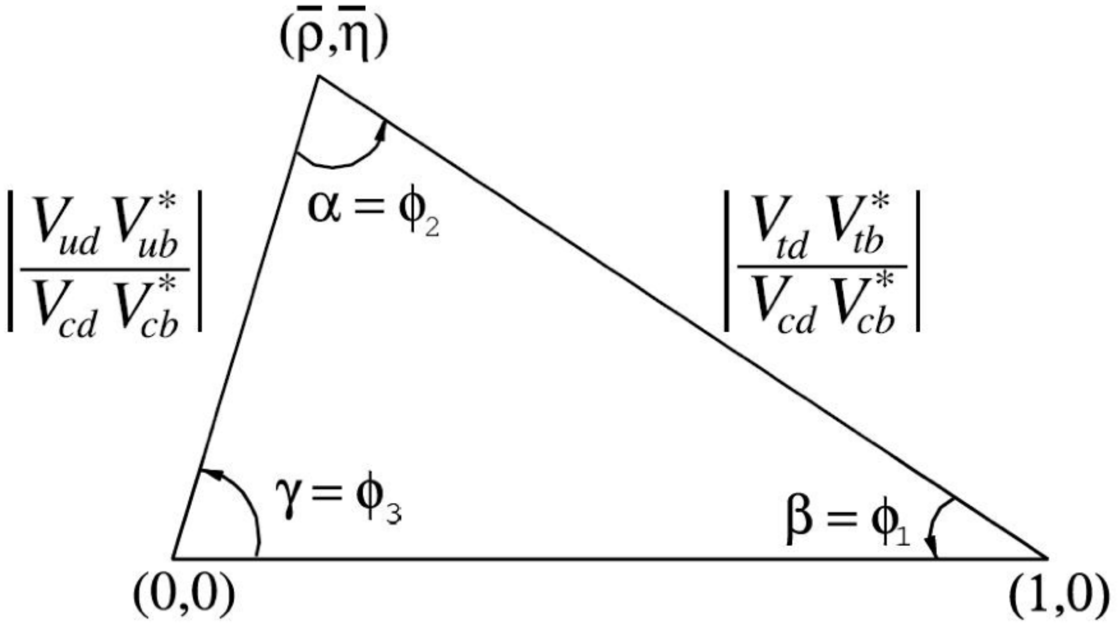
$$\Delta m_{tc}^2 \Delta m_{tu}^2 \Delta m_{cu}^2 \Delta m_{bs}^2 \Delta m_{bd}^2 \Delta m_{sd}^2 J_{CKM} \neq 0 \quad \text{with} \quad \Delta m_{ij}^2 = m_i^2 - m_j^2$$

i.e. no mass degeneracies or zero (or π) angles/phases

CKM picture of CP-violation

★ There is a single phase of the CKM matrix for 3-generation SM

- off-diagonal terms in unitarity relations $VV^\dagger = 1$ look like triangles in a complex plane (ρ,η), e.g. $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ Each term is $\mathcal{O}(\lambda^3)$



$$V \equiv \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- angles are

$$\phi_1(\beta) = arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$$ phase of V_{td} in Wolfenstein param

$$\phi_2(\alpha) = arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$$

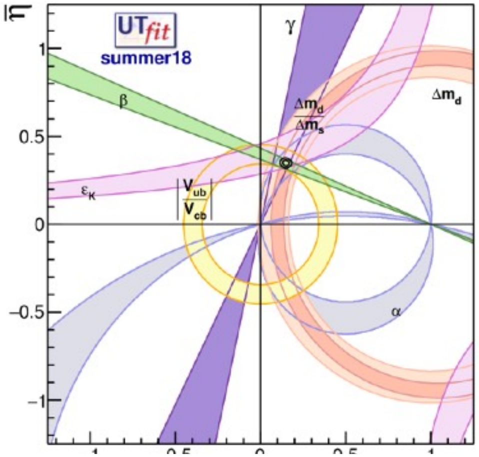
$$\phi_3(\gamma) = arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$$ phase of V_{ub} in Wolfenstein param

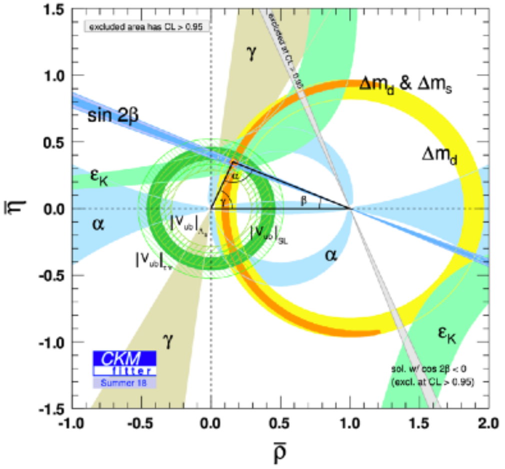
A recipe for searches for New Physics

★ Flavor can be used to search for NP, not just new flavor physics!

1. Measure as many processes that depend on CKM parameters independently
2. Interpret those measurements assuming there is no NP contribution and extract the CKM parameters
3. Build CKM triangles out of those CKM parameters. If a triangle does not close, then no-NP assumption was incorrect and there is a (possible) presence of New Physics

We are NOT checking if the CKM matrix is unitary!
We are searching for NP using the CKM matrix unitarity!

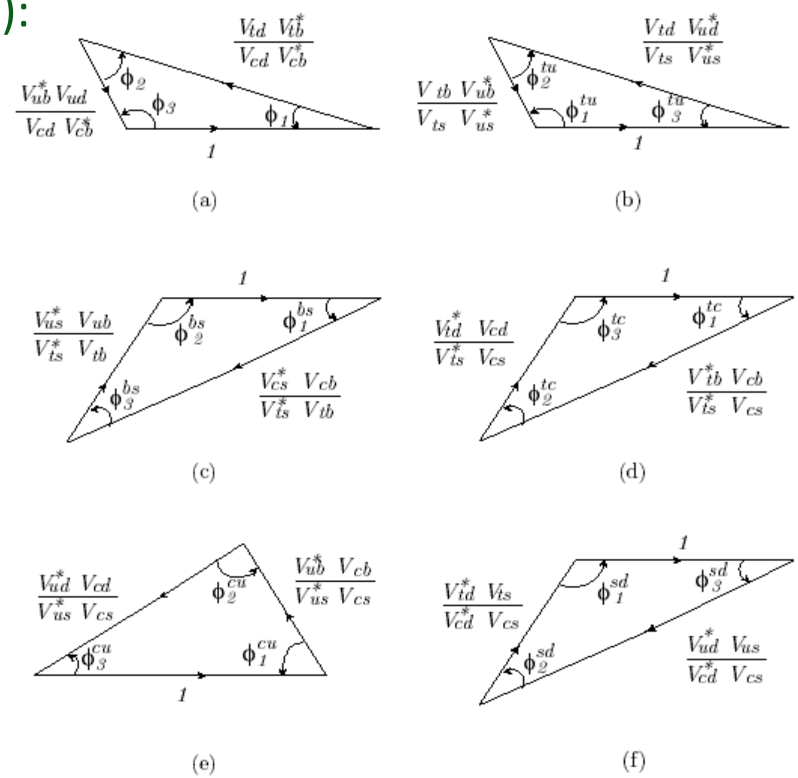




A recipe for searches for New Physics

★ There is a single phase of the CKM matrix for 3-generation SM

- off-diagonal terms in unitarity relations $VV^{+}=1$ look like triangles in a complex plane (ρ,η):

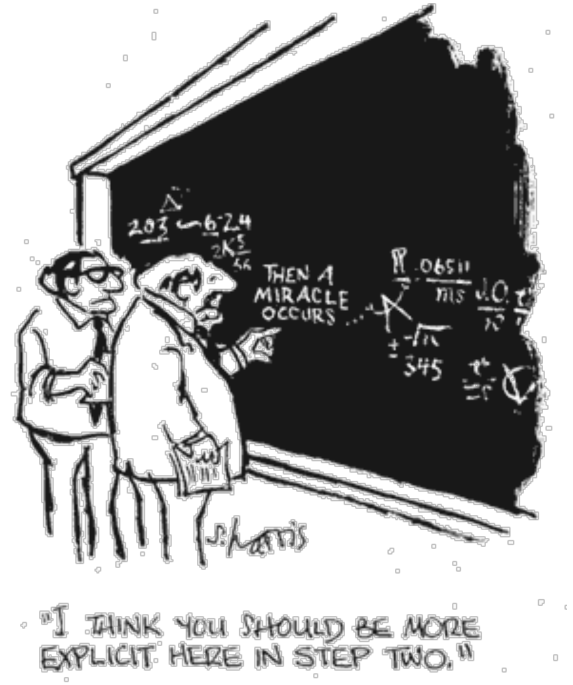


$$V \equiv \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- … but regardless of the lines/columns used all these triangles have the same area $A = J_{CKM}/2$ (useful cross-check for NP studies)!

3. NP: modify the SM solution

1. Why generations?
   - Why only 3?
   - Are there only 3?
2. Why hierarchies of masses and mixings?



S. Harris

$$\mathcal{L}_1 = -y_\psi \bar{\psi}_L \psi_R \phi + h.c. \to -\frac{y_\psi v}{\sqrt{2}} \left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \right),$$

$$m_\psi = y_\psi v / \sqrt{2}$$

No explanation of the hierarchy, but mass hierarchy is related to the hierarchy of Yukawa couplings

$$\begin{aligned} &y_u \sim 10^{-5}, \quad y_c \sim 10^{-2}, \quad y_t \sim 1, \\ &y_d \sim 10^{-5}, \quad y_s \sim 10^{-3}, \quad y_b \sim 10^{-2}, \\ &y_e \sim 10^{-6}, \quad y_\mu \sim 10^{-3}, \quad y_\tau \sim 10^{-2}. \end{aligned}$$

3. What about neutrino masses?

Flavor beyond the Standard Model (leptons)

★ There are two possible approaches: Dirac and Majorana

- Dirac masses: introduce a singlet (sterile) ν_R , so Dirac mass term
  - tiny relevant Yukawa couplings, $y_\nu \sim 10^{-12}$, so lepton flavor is an accidental symmetry broken by the Yukawa's
- Majorana masses: introduce Majorana mass
  - lepton flavor symmetry is broken by the mass term
  - easiest realization: a single operator in SMEFT (large NP scale)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} Q^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} Q_i^{(6)} + \dots$$ with

$$Q^{(5)} = \epsilon_{jk}\epsilon_{mn} H^j H^m \left(L_p^k\right)^T \mathcal{C} L_r^n$$ Weinberg operator

★ Consequence: CLFV decays are highly suppressed in the Standard Model:

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\mu i}^* U_{ei} \frac{m_{\nu_i}^2}{M_W^2} \right|^2 < 10^{-54}$$

Why are we still searching for the CLFV? Other mechanisms for CLFV

Mass generation $\neq$ flavor violation?

★ Example of the common origin of the neutrino masses and CLFV transitions

- consider a model with a triplet Higgs, e.g., a left-right model

$$-\mathcal{L}_{\text{Yukawa}} = \overline{\psi}'_{iL}\left(G_{ij}\phi + H_{ij}\tilde{\phi}\right)\psi'_{jR} + \frac{i}{2}F_{ij}\left(\psi'^T_{iL}C\tau_2\Delta_L\psi'_{jL} + \psi'^T_{iR}C\tau_2\Delta_R\psi'_{jR}\right) + \text{h.c.}$$

with $\psi'_{iL,R} = \begin{pmatrix} \nu'_{iL,R} \\ e'_{iL,R} \end{pmatrix}$ and $\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$

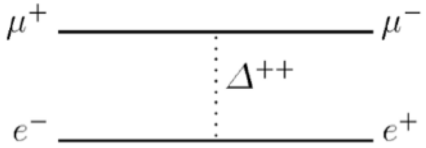
- this Lagrangian leads to the Majorana masses for the neutrinos

Pati, Salam; Mohapatra, Pati;
Senjanovic, et al, Schechter and Valle;
K. Kiers et al

$$-\mathcal{L}_{\text{Majorana}} = \frac{1}{2\sqrt{2}}\left(\overline{\nu'^c_L}Fv_L e^{i\theta_L}\nu'_L + \overline{\nu'^c_R}Fv_R\nu'_R\right) + \text{h.c.}$$

- … and both $\Delta L_\mu = 1$ (FCNC decays) and $\Delta L_\mu = 2$ (muonium oscillations) transitions

$$\mathcal{H}_\Delta = -\frac{g_{ee}g^*_{\mu\mu}}{8M_\Delta^2}(\overline{\mu}_L\gamma_\alpha e_L)(\overline{\mu}_L\gamma^\alpha e_L) + H.c.$$



Chang, Keung (89); Schwartz (89);
Conlin, AAP (21); Han, Tang, Zhang (21)

Effective Lagrangians: probing all NP models

★ Systematic approach: Standard Model Effective Field Theory (SMEFT)

- effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} Q^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} Q_i^{(6)} + \ldots$$

with the Weinberg operator $Q^{(5)}$

$$Q^{(5)} = \epsilon_{jk}\epsilon_{mn} H^j H^m \left(L_p^k\right)^T \mathcal{C} L_r^n$$

and lots (59+5) of $Q_i^{(6)}$ operators

- the strategy of identifying an NP model involves fitting C_i from experimental data and/or matching of $\mathscr{L}$ to UV-completed NP models

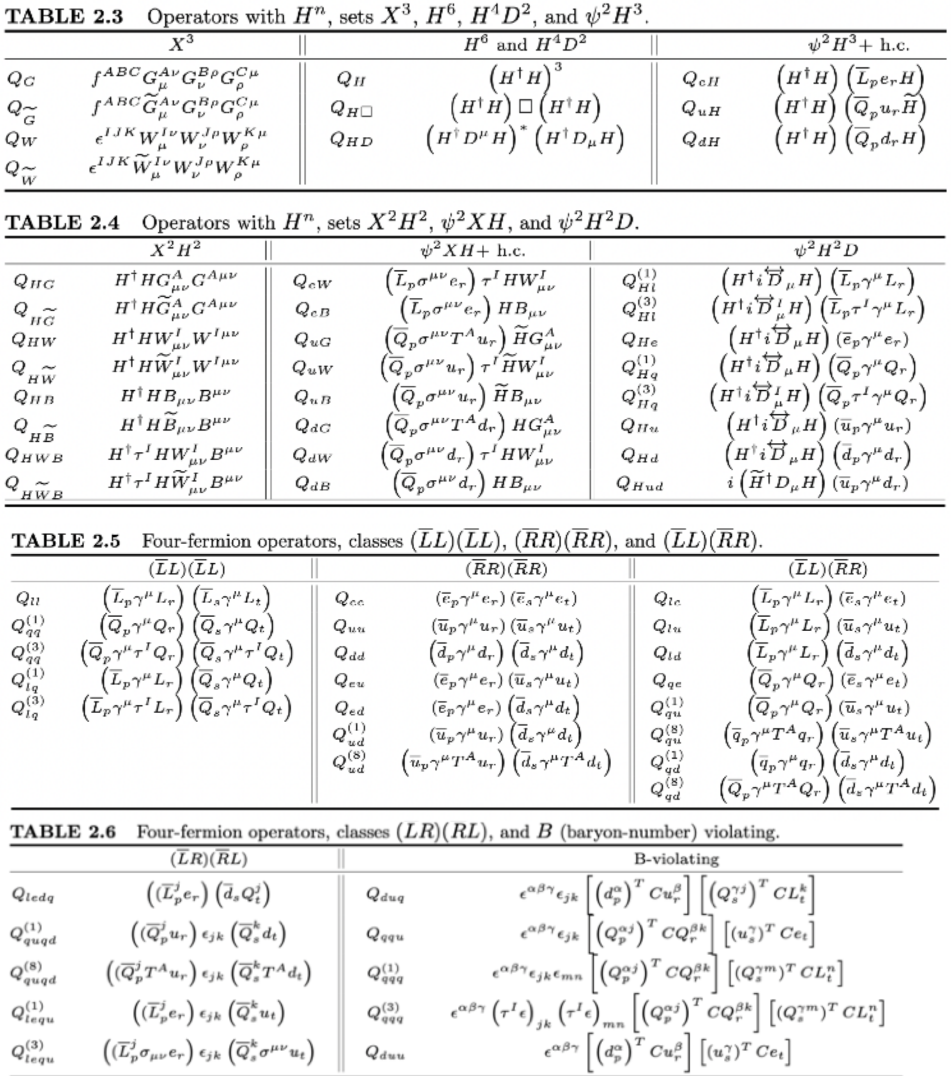


TABLE 2.3 Operators with H^n, sets X^3, H^6, H^4D^2, and ψ^2H^3.

X^3		H^6 and H^4D^2		ψ^2H^3+ h.c.	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$\left(H^\dagger H\right)^3$	Q_{eH}	$\left(H^\dagger H\right)\left(\overline{L}_p e_r H\right)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{H\Box}$	$\left(H^\dagger H\right)\Box\left(H^\dagger H\right)$	Q_{uH}	$\left(H^\dagger H\right)\left(\overline{Q}_p u_r \widetilde{H}\right)$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	Q_{HD}	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$	Q_{dH}	$\left(H^\dagger H\right)\left(\overline{Q}_p d_r H\right)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

TABLE 2.4 Operators with H^n, sets X^2H^2, ψ^2XH, and ψ^2H^2D.

X^2H^2		ψ^2XH+ h.c.		ψ^2H^2D	
Q_{HG}	$H^\dagger H G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$\left(\overline{L}_p\sigma^{\mu\nu}e_r\right)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\overline{L}_p\gamma^\mu L_r\right)$
$Q_{H\widetilde{G}}$	$H^\dagger H\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$\left(\overline{L}_p\sigma^{\mu\nu}e_r\right)HB_{\mu\nu}$	$Q_{Hl}^{(3)}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu^I H\right)\left(\overline{L}_p\tau^I\gamma^\mu L_r\right)$
Q_{HW}	$H^\dagger H W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$\left(\overline{Q}_p\sigma^{\mu\nu}T^A u_r\right)\widetilde{H}G_{\mu\nu}^A$	Q_{He}	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\overline{e}_p\gamma^\mu e_r\right)$
$Q_{H\widetilde{W}}$	$H^\dagger H\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$\left(\overline{Q}_p\sigma^{\mu\nu}u_r\right)\tau^I\widetilde{H}W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\overline{Q}_p\gamma^\mu Q_r\right)$
Q_{HB}	$H^\dagger H B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$\left(\overline{Q}_p\sigma^{\mu\nu}u_r\right)\widetilde{H}B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu^I H\right)\left(\overline{Q}_p\tau^I\gamma^\mu Q_r\right)$
$Q_{H\widetilde{B}}$	$H^\dagger H\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$\left(\overline{Q}_p\sigma^{\mu\nu}T^A d_r\right)HG_{\mu\nu}^A$	Q_{Hu}	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\overline{u}_p\gamma^\mu u_r\right)$
Q_{HWB}	$H^\dagger\tau^I H W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$\left(\overline{Q}_p\sigma^{\mu\nu}d_r\right)\tau^I H W_{\mu\nu}^I$	Q_{Hd}	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\overline{d}_p\gamma^\mu d_r\right)$
$Q_{H\widetilde{W}B}$	$H^\dagger\tau^I H\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$\left(\overline{Q}_p\sigma^{\mu\nu}d_r\right)HB_{\mu\nu}$	Q_{Hud}	$i\left(\widetilde{H}^\dagger D_\mu H\right)\left(\overline{u}_p\gamma^\mu d_r\right)$

TABLE 2.5 Four-fermion operators, classes $(\overline{L}L)(\overline{L}L)$, $(\overline{R}R)(\overline{R}R)$, and $(\overline{L}L)(\overline{R}R)$.

$(\overline{L}L)(\overline{L}L)$		$(\overline{R}R)(\overline{R}R)$		$(\overline{L}L)(\overline{R}R)$	
Q_{ll}	$\left(\overline{L}_p\gamma^\mu L_r\right)\left(\overline{L}_s\gamma^\mu L_t\right)$	Q_{ee}	$\left(\overline{e}_p\gamma^\mu e_r\right)\left(\overline{e}_s\gamma^\mu e_t\right)$	Q_{le}	$\left(\overline{L}_p\gamma^\mu L_r\right)\left(\overline{e}_s\gamma^\mu e_t\right)$
$Q_{qq}^{(1)}$	$\left(\overline{Q}_p\gamma^\mu Q_r\right)\left(\overline{Q}_s\gamma^\mu Q_t\right)$	Q_{uu}	$\left(\overline{u}_p\gamma^\mu u_r\right)\left(\overline{u}_s\gamma^\mu u_t\right)$	Q_{lu}	$\left(\overline{L}_p\gamma^\mu L_r\right)\left(\overline{u}_s\gamma^\mu u_t\right)$
$Q_{qq}^{(3)}$	$\left(\overline{Q}_p\gamma^\mu\tau^I Q_r\right)\left(\overline{Q}_s\gamma^\mu\tau^I Q_t\right)$	Q_{dd}	$\left(\overline{d}_p\gamma^\mu d_r\right)\left(\overline{d}_s\gamma^\mu d_t\right)$	Q_{ld}	$\left(\overline{L}_p\gamma^\mu L_r\right)\left(\overline{d}_s\gamma^\mu d_t\right)$
$Q_{lq}^{(1)}$	$\left(\overline{L}_p\gamma^\mu L_r\right)\left(\overline{Q}_s\gamma^\mu Q_t\right)$	Q_{eu}	$\left(\overline{e}_p\gamma^\mu e_r\right)\left(\overline{u}_s\gamma^\mu u_t\right)$	Q_{qe}	$\left(\overline{Q}_p\gamma^\mu Q_r\right)\left(\overline{e}_s\gamma^\mu e_t\right)$
$Q_{lq}^{(3)}$	$\left(\overline{L}_p\gamma^\mu\tau^I L_r\right)\left(\overline{Q}_s\gamma^\mu\tau^I Q_t\right)$	Q_{ed}	$\left(\overline{e}_p\gamma^\mu e_r\right)\left(\overline{d}_s\gamma^\mu d_t\right)$	$Q_{qu}^{(1)}$	$\left(\overline{Q}_p\gamma^\mu Q_r\right)\left(\overline{u}_s\gamma^\mu u_t\right)$
		$Q_{ud}^{(1)}$	$\left(\overline{u}_p\gamma^\mu u_r\right)\left(\overline{d}_s\gamma^\mu d_t\right)$	$Q_{qu}^{(8)}$	$\left(\overline{q}_p\gamma^\mu T^A q_r\right)\left(\overline{u}_s\gamma^\mu T^A u_t\right)$
		$Q_{ud}^{(8)}$	$\left(\overline{u}_p\gamma^\mu T^A u_r\right)\left(\overline{d}_s\gamma^\mu T^A d_t\right)$	$Q_{qd}^{(1)}$	$\left(\overline{q}_p\gamma^\mu q_r\right)\left(\overline{d}_s\gamma^\mu d_t\right)$
				$Q_{qd}^{(8)}$	$\left(\overline{Q}_p\gamma^\mu T^A Q_r\right)\left(\overline{d}_s\gamma^\mu T^A d_t\right)$

TABLE 2.6 Four-fermion operators, classes $(LR)(RL)$, and B (baryon-number) violating.

$(\overline{L}R)(\overline{R}L)$		B-violating	
Q_{ledq}	$\left((\overline{L}_p^j e_r\right)\left(\overline{d}_s Q_t^j\right)$	Q_{duq}	$\epsilon^{\alpha\beta\gamma}\epsilon_{jk}\left[\left(d_p^\alpha\right)^T C u_r^\beta\right]\left[\left(Q_s^{\gamma j}\right)^T C L_t^k\right]$
$Q_{quqd}^{(1)}$	$\left((\overline{Q}_p^j u_r\right)\epsilon_{jk}\left(\overline{Q}_s^k d_t\right)$	Q_{qqu}	$\epsilon^{\alpha\beta\gamma}\epsilon_{jk}\left[\left(Q_p^{\alpha j}\right)^T C Q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$\left((\overline{Q}_p^j T^A u_r\right)\epsilon_{jk}\left(\overline{Q}_s^k T^A d_t\right)$	$Q_{qqq}^{(1)}$	$\epsilon^{\alpha\beta\gamma}\epsilon_{jk}\epsilon_{mn}\left[\left(Q_p^{\alpha j}\right)^T C Q_r^{\beta k}\right]\left[(Q_s^{\gamma m})^T C L_t^n\right]$
$Q_{lequ}^{(1)}$	$\left((\overline{L}_p^j e_r\right)\epsilon_{jk}\left(\overline{Q}_s^k u_t\right)$	$Q_{qqq}^{(3)}$	$\epsilon^{\alpha\beta\gamma}\left(\tau^I\epsilon\right)_{jk}\left(\tau^I\epsilon\right)_{mn}\left[\left(Q_p^{\alpha j}\right)^T C Q_r^{\beta k}\right]\left[(Q_s^{\gamma m})^T C L_t^n\right]$
$Q_{lequ}^{(3)}$	$\left((\overline{L}_p^j\sigma_{\mu\nu}e_r\right)\epsilon_{jk}\left(\overline{Q}_s^k\sigma^{\mu\nu}u_t\right)$	Q_{duu}	$\epsilon^{\alpha\beta\gamma}\left[\left(d_p^\alpha\right)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Flavor hierarchies: NP flavor model building

- ★ GUT models: leptonic/quark Yukawas are related
- ★ Flavor symmetries

SM Lagrangian is $SU(3)^5$-invariant in the limit $y_i \to 0$

- Yukawas arise as a result of spontaneous breaking of a subgroup of $SU(3)^5$?

- continuous flavor symmetries
- discrete flavor symmetries
- accidental flavor symmetries

- numerology?

$$m_e + m_\mu + m_\tau = \frac{2}{3}(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2$$

Koide formula (also “works” for heavy quarks)

- ★ Dynamical approaches
- ★ Geometric approaches (localization in extra dimension)

Flavor hierarchies: NP flavor model building

Notice that an extra scalar boson can help to solve the flavor puzzle:

$$\mathcal{L}_2 = -y_\psi \bar{\psi}_L \psi_R \phi_1 - y_\chi \bar{\chi}_L \chi_R \phi_2 + \text{h.c.}$$

Then assuming $\tan\beta \gg 1$

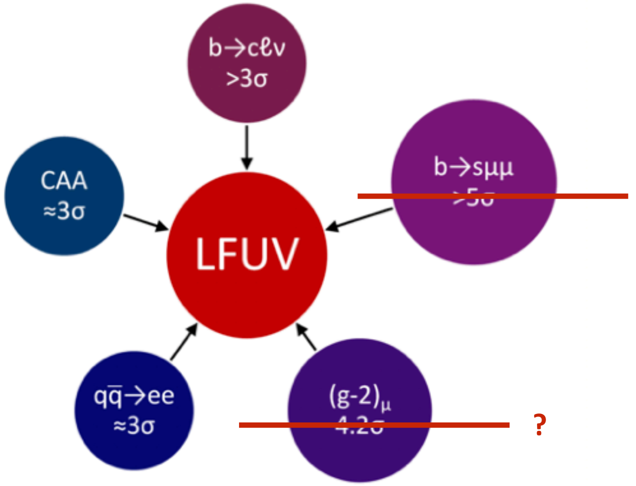
$$\frac{m_\chi}{m_\psi} = \frac{y_\chi}{y_\psi}\frac{v_2}{v_1} = \frac{y_\chi}{y_\psi}\tan\beta \gg 1$$

So it looks like we can solve the flavor puzzle by just having more scalar bosons, letting all Yukawa couplings be $\mathcal{O}(1)$ and $\tan\beta \gg 1$

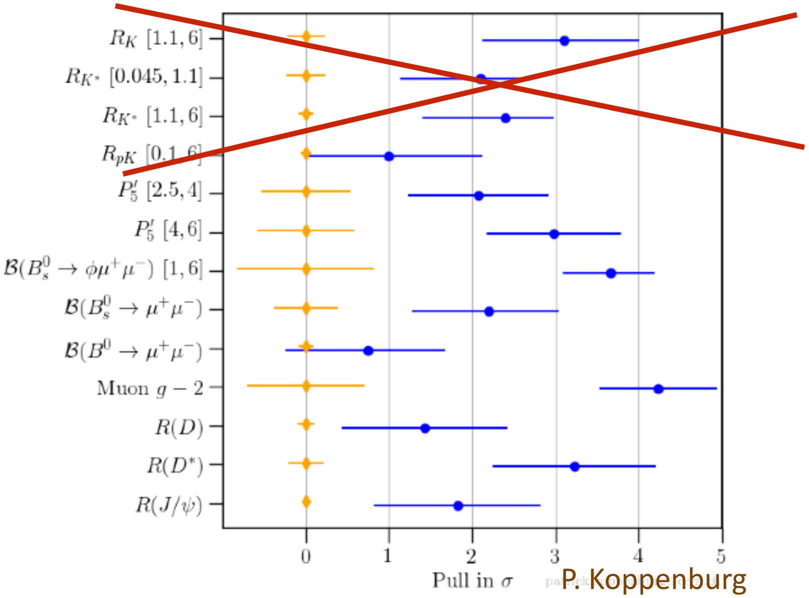
Top quark: Das, Kao, Phys. Lett. B 392 (1996) 106.
Xu, Phys. Rev. D44, R590 (1991).
Blechman, AAP, Yeghiyan, JHEP 1011 (2010) 075

Recent experimental anomalies: NP with leptons?

★ Several experimental anomalies involve interactions with muons and taus

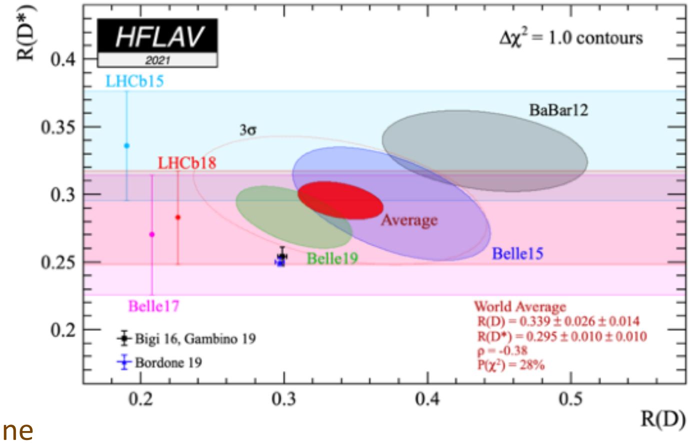


Crivellin, Hoferichter



P. Koppenburg

- other lepton-flavor conserving processes
  - magnetic properties: muon g-2
    - currently a discrepancy theory/exp
  - electric properties: muon EDM
    - probes CP-violation in leptons
  - muonic hydrogen
    - proton size/QED/New Physics



see talk by M.-H. Schune

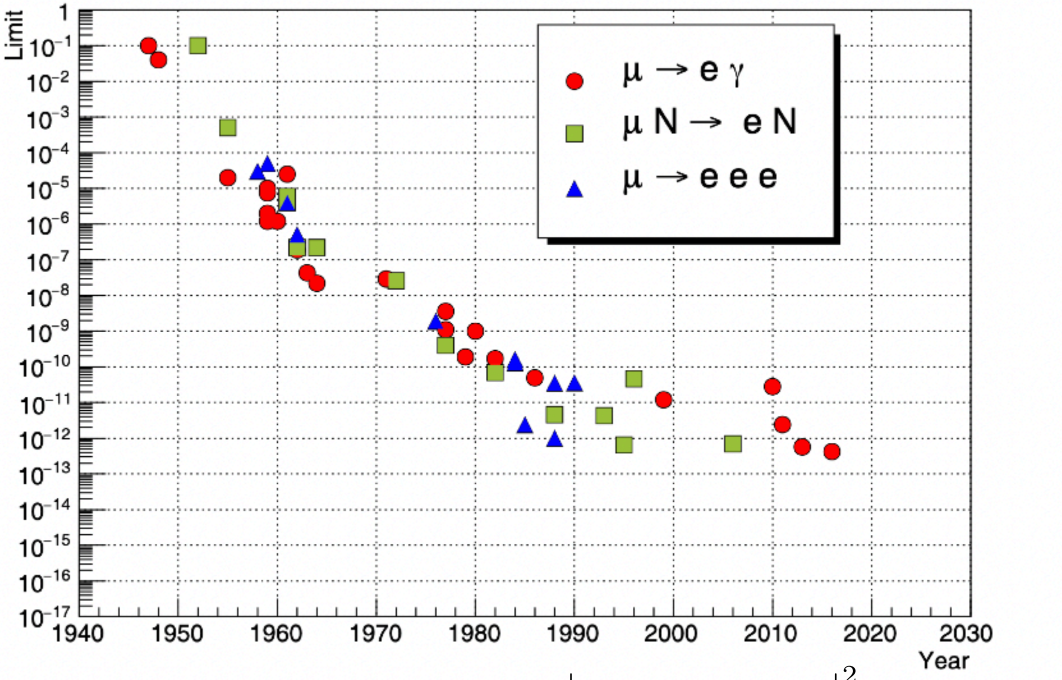
Lepton flavor violation

★ Leptons can help solve the most fundamental problems in particle physics! Flavor?

★ Possible experimental searches for Charged Lepton Flavor Violation (CLFV)

- lepton-flavor violating processes
  - $\mu \to e\gamma$, $\tau \to e\gamma$, etc.
  - $\mu \to eee$, $\tau \to \mu ee$, etc.
  - $\mu^+e^- \to e^-\mu^+$ (muonium oscillations)
  - $Z^0 \to \mu e$, τe, etc.
  - $H \to \mu e$, τe, etc.
  - K^0 (B^0, D^0, ...) $\to \mu e$, τe, etc.
  - $\mu^- + (A, Z) \to e^- + (A, Z)$
- lepton number and lepton-flavor violating processes
  - $(A, Z) \to (A, Z\pm2) + e^\mp e^\mp$
  - $\mu^- + (A, Z) \to e^+ + (A, Z-2)$

LORENZO CALIBBI and GIOVANNI SIGNORELLI



★ Decays are highly suppressed in the Standard Model:

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W}\right|^2 < 10^{-54}$$

★ But: no trivial FCNC vertices in the Standard Model: sensitive tests of New Physics!

Flavor violation and effective Lagrangians

★ Radiative FCNC decays of leptons $\ell_1 \to \ell_2 + \gamma$ (tau decays at Belle II)

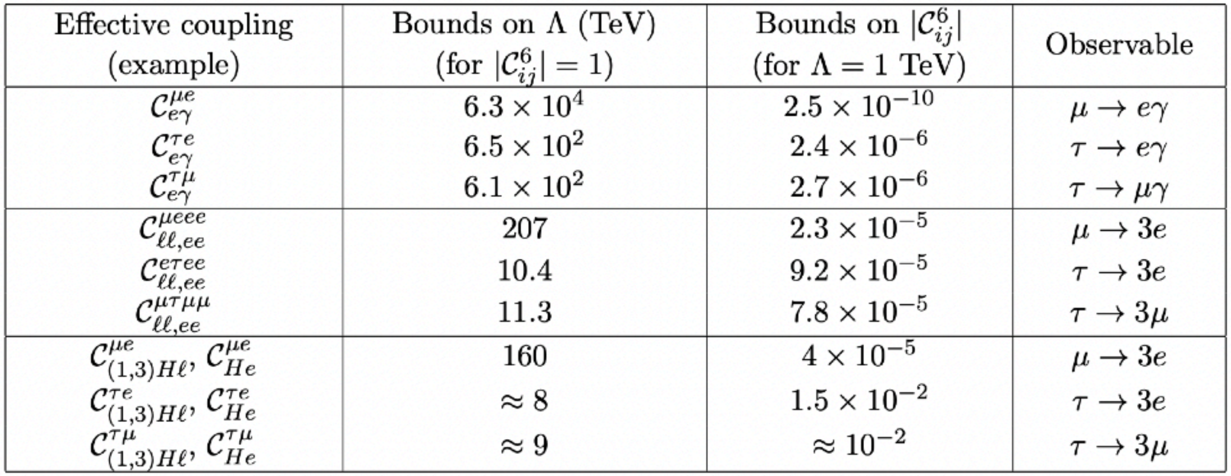
- the most general amplitude is

$$A_{\ell_1 \to \ell_2 \gamma}(p, p') = \frac{i}{m_{\ell_1}} \overline{u}_{\ell_2}(p') \left[A_L P_L + A_R P_R \right] \sigma_{\mu\nu} q^\nu u_{\ell_1}(p) \epsilon^{*\mu},$$

- which leads to the decay rate

$$\Gamma(\ell_1 \to \ell_2 \gamma) = \frac{m_{\ell_1}}{16\pi} \left(|A_L|^2 + |A_R|^2 \right)$$

with $A_R = A_L^* = \sqrt{2} \frac{v m_i^2}{\Lambda^2} \left(c_W C_{eB}^{fi} - s_W C_{eW}^{fi} \right) \equiv \sqrt{2} \frac{v m_i^2}{\Lambda^2} C_\gamma^{fi}$



Effective coupling (example)	Bounds on Λ (TeV) (for $\lvert\mathcal{C}_{ij}^6\rvert = 1$)	Bounds on $\lvert\mathcal{C}_{ij}^6\rvert$ (for $\Lambda = 1$ TeV)	Observable
$\mathcal{C}_{e\gamma}^{\mu e}$	6.3×10^4	2.5×10^{-10}	$\mu \to e\gamma$
$\mathcal{C}_{e\gamma}^{\tau e}$	6.5×10^2	2.4×10^{-6}	$\tau \to e\gamma$
$\mathcal{C}_{e\gamma}^{\tau\mu}$	6.1×10^2	2.7×10^{-6}	$\tau \to \mu\gamma$
$\mathcal{C}_{\ell\ell,ee}^{\mu eee}$	207	2.3×10^{-5}	$\mu \to 3e$
$\mathcal{C}_{\ell\ell,ee}^{e\tau ee}$	10.4	9.2×10^{-5}	$\tau \to 3e$
$\mathcal{C}_{\ell\ell,ee}^{\mu\tau\mu\mu}$	11.3	7.8×10^{-5}	$\tau \to 3\mu$
$\mathcal{C}_{(1,3)H\ell}^{\mu e}, \mathcal{C}_{He}^{\mu e}$	160	4×10^{-5}	$\mu \to 3e$
$\mathcal{C}_{(1,3)H\ell}^{\tau e}, \mathcal{C}_{He}^{\tau e}$	≈ 8	1.5×10^{-2}	$\tau \to 3e$
$\mathcal{C}_{(1,3)H\ell}^{\tau\mu}, \mathcal{C}_{He}^{\tau\mu}$	≈ 9	$\approx 10^{-2}$	$\tau \to 3\mu$

Teixeira; Feruglio, Paradisi, Pattori

Other interesting modes that probe similar couplings: $\ell_1 \to \ell_2\gamma\gamma$, $\ell_1 \to 3\ell_2$, and others

4. Flavor@Snowmass

Report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021)

Summary Chapter

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Nathaniel Craig[24], Csaba Csáki[25], Aida X. El-Khadra[9] (Theory), Laura Baudis[26],
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Fernanda Psihas[1], Sara M. Simon[1] (Early Career)

Editor: Michael E. Peskin[11]

J.N. Butler et. al.,
2301.06581 [hep-ex]


Marina Artuso (Syracuse U.)


Alexey Petrov (Wayne State U.)


Bob Bernstein (FNAL)

Flavor@Snowmass

Addressed by Frontier for Rare Processes and Precision Measurements (RPF)

Report: 2210.04765 [hep-ex]

Topical groups

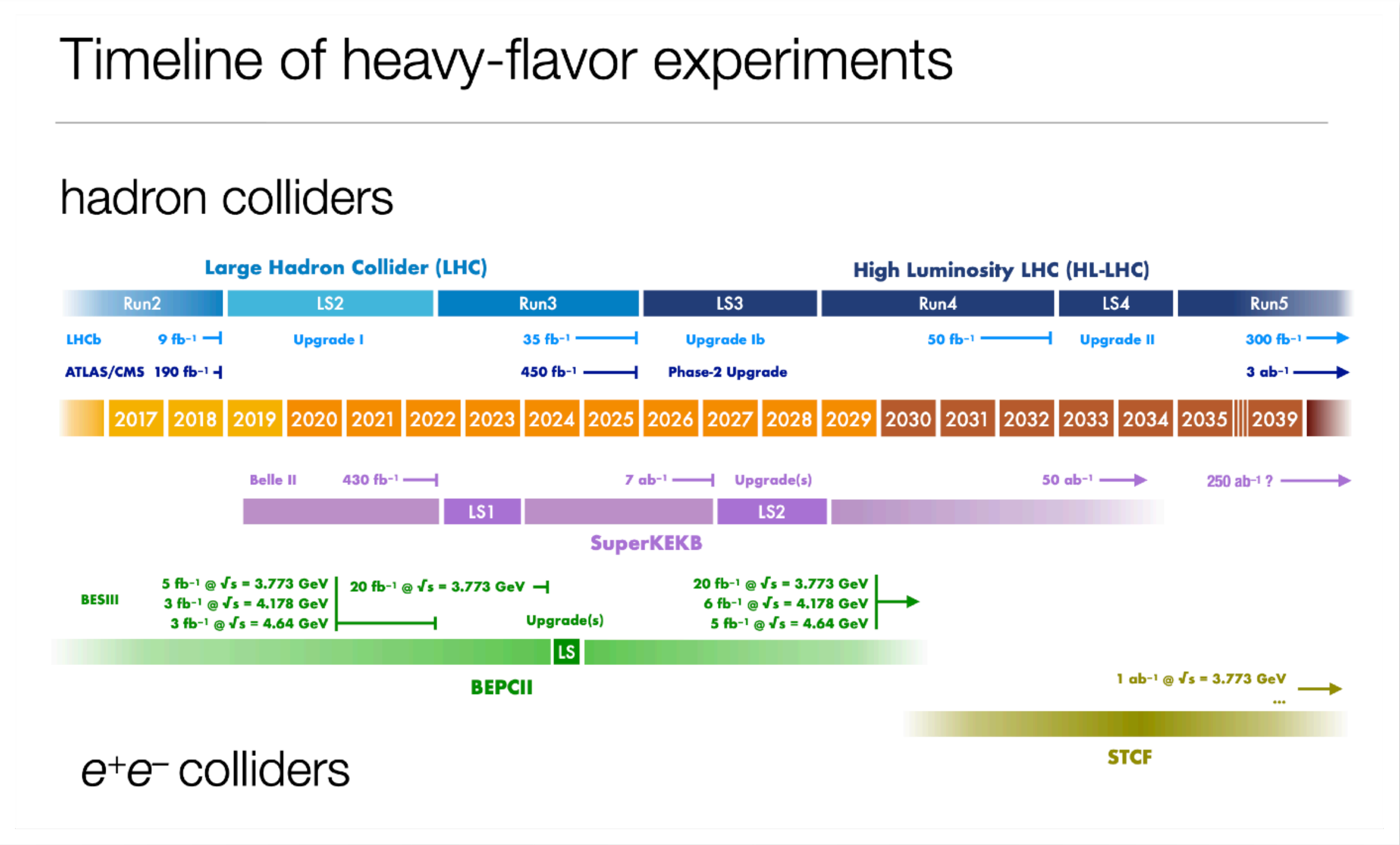
- RF1: Weak decays of b and c quarks (Angelo Di Canto/Stefan Meinel)
- RF2: Weak decays of strange and light quarks (Evgueni Goudzovski/Emilie Passemar)
- RF3: Fundamental Physics in Small Experiments (Tom Blum/Peter Winter)
- RF4: Baryon and Lepton Number Violating Processes (Pavel Fileviez Perez/Andrea Pocar)
- RF5: Charged Lepton Flavor Violation (electrons, muons and taus) (Bertrand Echenard/Sacha Davidson)
- RF6: Dark Sector Studies at High Intensities (Mike Williams/Stefania Gori)
- RF7: Hadron Spectroscopy (Tomasz Skwarnicki/Richard Lebed)

★ There are several fundamental physics questions addressed by RPF

- the origin of flavor, generations, and quark and lepton mass hierarchies
- the exploitation of flavor decays as precision probes of all the sectors of the Standard Model and windows to new physics
- the motivation underlying discrete SM symmetries and mechanisms for symmetry breaking
- the origin of baryon and lepton number violation and connections to the baryon asymmetry of the universe
- probe the physics of the dark sector available at high-intensity machines
- develop a deeper understanding of non-perturbative QCD using the rich landscape of conventional and exotic hadrons

★ Most of those questions are studied with small and medium-sized experiments

Flavor@Snowmass: heavy flavors (large scope)



Timeline of heavy-flavor experiments

hadron colliders

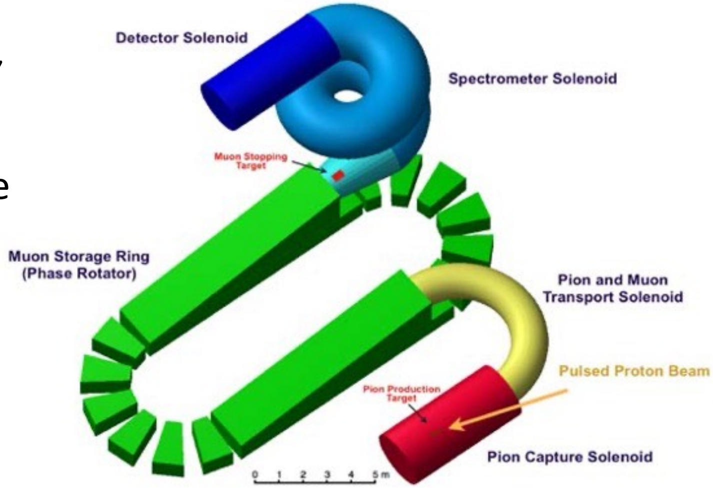
e^+e^- colliders

Flavor@Snowmass: charged leptons (large size)

★ The Advanced Muon Facility at Fermilab

★ The Advanced Muon Facility would employ PIP-II to enable

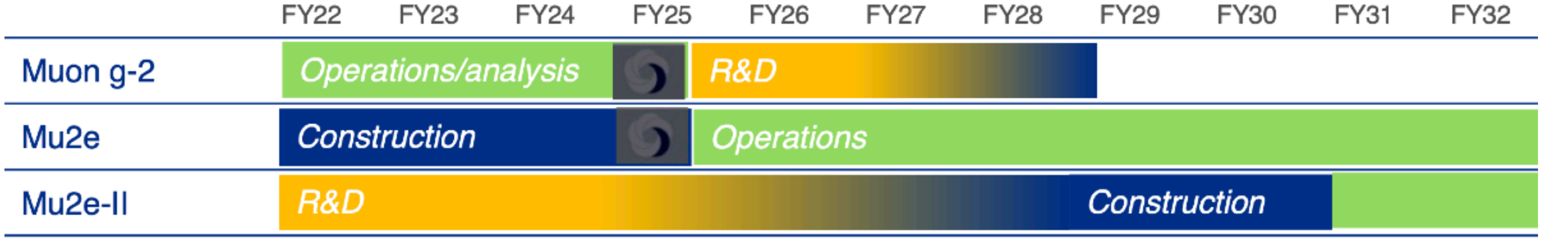
- CLFV in all three muon modes ($\mu N \to eN, \mu \to e\gamma, \mu \to 3e$): a world-leading facility
  - two new small rings for $\mu^- N \to e^- N$ and $\mu^- N \to e^+ N'$ at high-Z and additional x100 in rate
  - x100-1000 more beam for $\mu \to e\gamma$ and $\mu \to 3e$ than are possible at PSI
  - a possible DM experiment
- a possible muonium-antimuonium oscillation experiment
- a possible atomic physics studies with muonia
- a possible muon EDM experiment



see arXiv: 2203.08278 [hep-ex]

★ Technical challenges directly related to muon collider R&D

- PIP-II, compressor ring, fixed-field alternating gradient ring, experiments



	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31	FY32
Muon g-2	Operations/analysis			R&D							
Mu2e	Construction			Operations							
Mu2e-II	R&D							Construction			
AMF								R&D and construction: late 30's			

L. Merminga

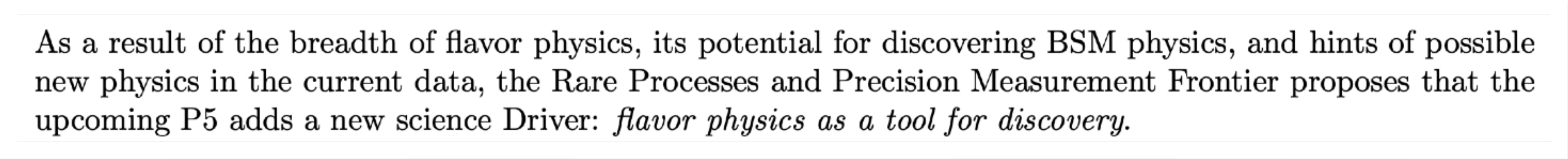
Flavor@Snowmass

★ RPF Community Consensus:

- The U.S. should support the LHCb Phase-II upgrades and Belle II
- We should select a portfolio of accelerator-based dark sector experiments that are well-motivated, unique, and affordable
- The U.S. should support a vigorous R&D program towards realization of experiments investigating charged lepton flavor violation and lepton number violation in the muon sector
- The theory efforts that guide and enable these investigations, while not a Project, should be vigorously supported by P5.
- A portfolio of experiments of different cost and time scales is an integral part of our physics program, including EDM experiments (a proton storage ring & AMO), rare light meson decays (JEF & REDTOP, as well as CERN and J-PARC experiments studying rare K decays), and the PIONEER experiment at PSI
- We call for a new science driver, *flavor as a tool for discovery*

We also stress that small and medium-sized multipurpose experiments allow early career researchers to gain experience in many stages of an experiment, from proposal writing to design and construction to publication.

★ Snowmass 2021 final report:



As a result of the breadth of flavor physics, its potential for discovering BSM physics, and hints of possible new physics in the current data, the Rare Processes and Precision Measurement Frontier proposes that the upcoming P5 adds a new science Driver: *flavor physics as a tool for discovery.*

Now we wait and see what P5 decides…

5. Conclusions and things to take home

- Flavor puzzle is still a big problem for particle physics
  - The reason(s) for generations and mass hierarchy are not known
  - Standard Models simply parameterizes the solution
  - New Physics models use flavor as input, not output
- Flavor-changing neutral current transitions provide great opportunities for studies of flavor in the SM and BSM
  - several anomalies in B physics might point to New Physics "around the corner"
  - studies of charmed transitions experience explosive growth
    - unique access to up-type quark sector
    - large available statistics/in many cases small SM background
    - large contributions from New Physics are possible, but not seen
- There is no indication from high energy studies where the NP show up
  - this makes indirect searches the most valuable source of information
- US Snowmass 2021 expressed full support to the international flavor program
  - New "flavor physics" driver: now wait for the input from P5
- Maybe flavor physics will be the first to see glimpses of New Physics