Flavour Seesaw and Phenomenological Consequences

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➔ **Sudip Jana, Sophie Klett, ML, PRD 105 (2022) 11, 115015 - arXiv: 2112.09155**

The Need for BSM Physics

Experimental facts:

- Dark Matter & Dark Energy exist!
- Neutrino masses have been detected!
- Baryon asymetry of the universe
  ←→ $m_\nu > 0$
- various 2-3σ indications / hints
  g-2, LHCb, low E_R-excess @XENON, ...
  ←→ BSM-implications

Theoretical arguments:

SM does not exist without cutoff
Higgs-doublett = only simplest extension
Gauge hierarchy problem
Which: particles (representations)
Many parameters (9+? masses, 4+? mixings)
Charge quantization, unification: GUTs, ...,
Gravity: ...
...

3 generations + apparent regularities!
➔does not require BSM, but is a hint!

How to solve these problems?
➔ pick some direction for an extension:

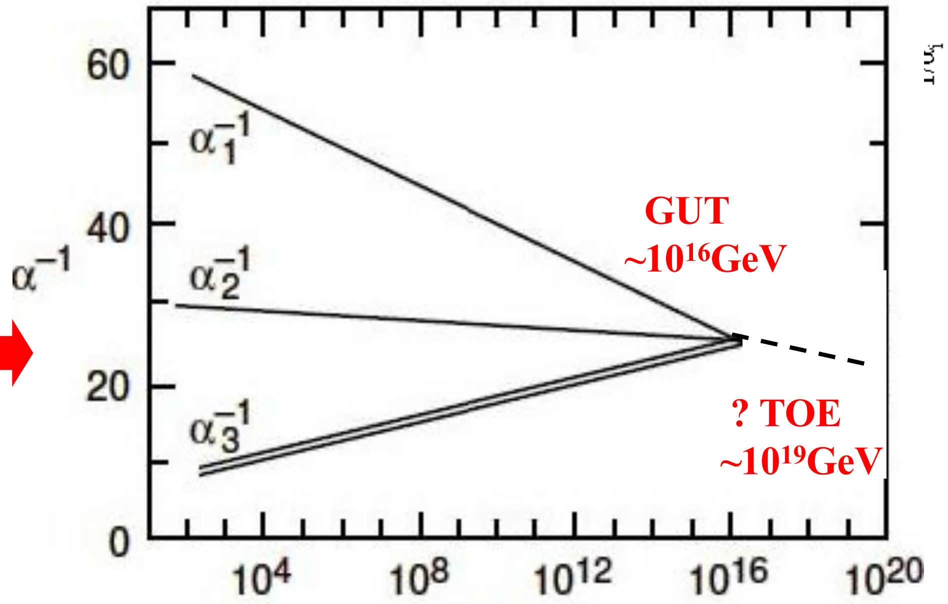
- **more represenations (particles)**
- **enlarged symmetries & breakings**
- **new concepts beyond 4d QFT**
- **combinations thereof**
- **more and more compexity...**

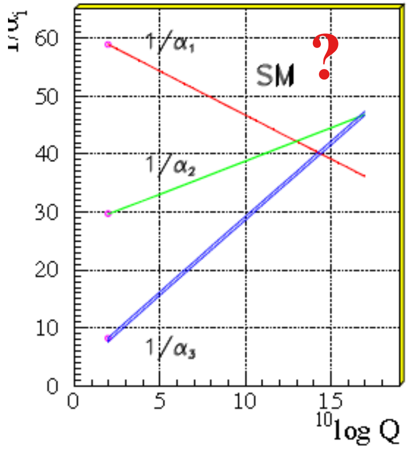
➔ Q: Are we on the right track or are we over-engineering problems?

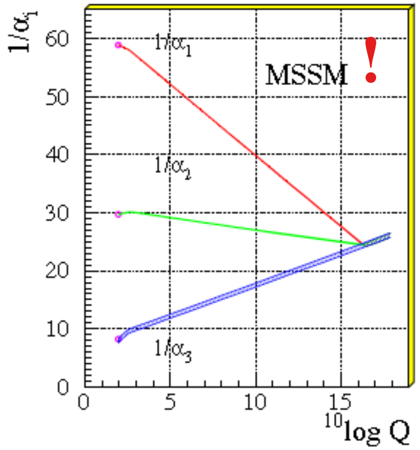
➔ Starting point: Some suggestive feature or interesting concept...

Indications pointing to SUSY + GUTs

gauge bosons







- SM particles fit nicely into GUT representations
- charge quantization

➔ evidence for some unification

SO(10): 16

SU(5): $\bar{5}$, 10

Higgs

gauge hierarchy problem:

$\delta m_H^2 \sim \Lambda^2$

➔**SUSY @ TeV ...?**

quarks leptons

flavour problem: 3 generations

many parameters (m_i ,mixings)

unification into GUTs

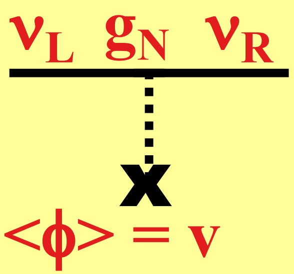
$\Lambda_{GUT} \leftarrow\rightarrow$ seesaw scale?

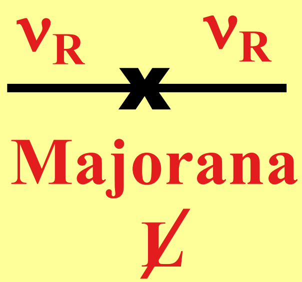
$m_\nu = (m^D)^T M_R^{-1} m_D$

supports „generations“

Flavour: Adding Neutrino Mass Terms

1) Simplest possibility: add 3 right handed neutrino fields





$$\rightarrow \quad \left(\bar{\nu}_L \quad \bar{\nu}_R^{\mathbf{c}}\right)\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \nu_L^{\mathbf{c}} \\ \nu_R \end{pmatrix}$$

like quarks and charged leptons → Dirac mass terms (including NMS mixing)

New ingredients:
1) Majorana mass (explicit)
2) lepton number violation

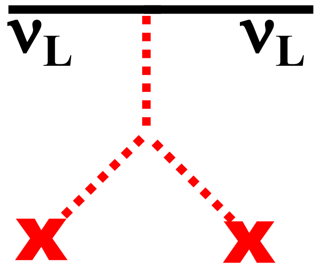
6x6 block mass matrix block diagonalization M_R heavy → 3 light ν's

NEW ingredients:
- SM=1-scale → multi-scale
- modified global symmetries (henn – egg)

→ SM+
- 9 parameters

Other Neutrino Mass Operators

2) new Higgs triplets Δ_L:

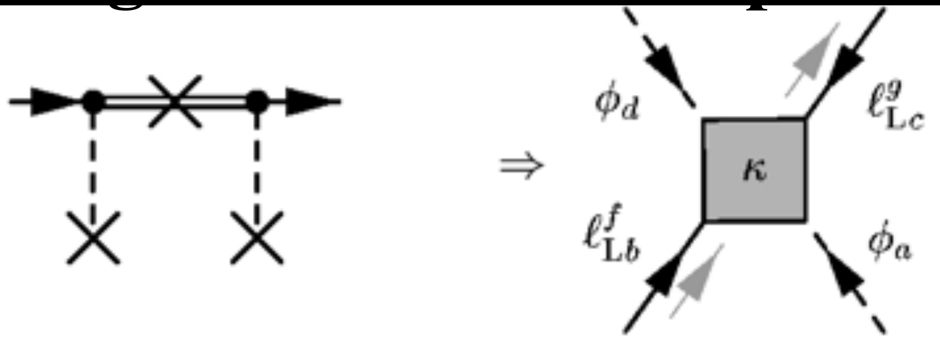


➔ left-handed Majorana mass term: ➔ $M_L \overline{L} L^c$

3) Both ν_R and new Higgs triplets Δ_L:

➔ see-saw type II $m_\nu = M_L - m_D M_R^{-1} m_D^T$

4) Higher dimensional operators: d=5, …



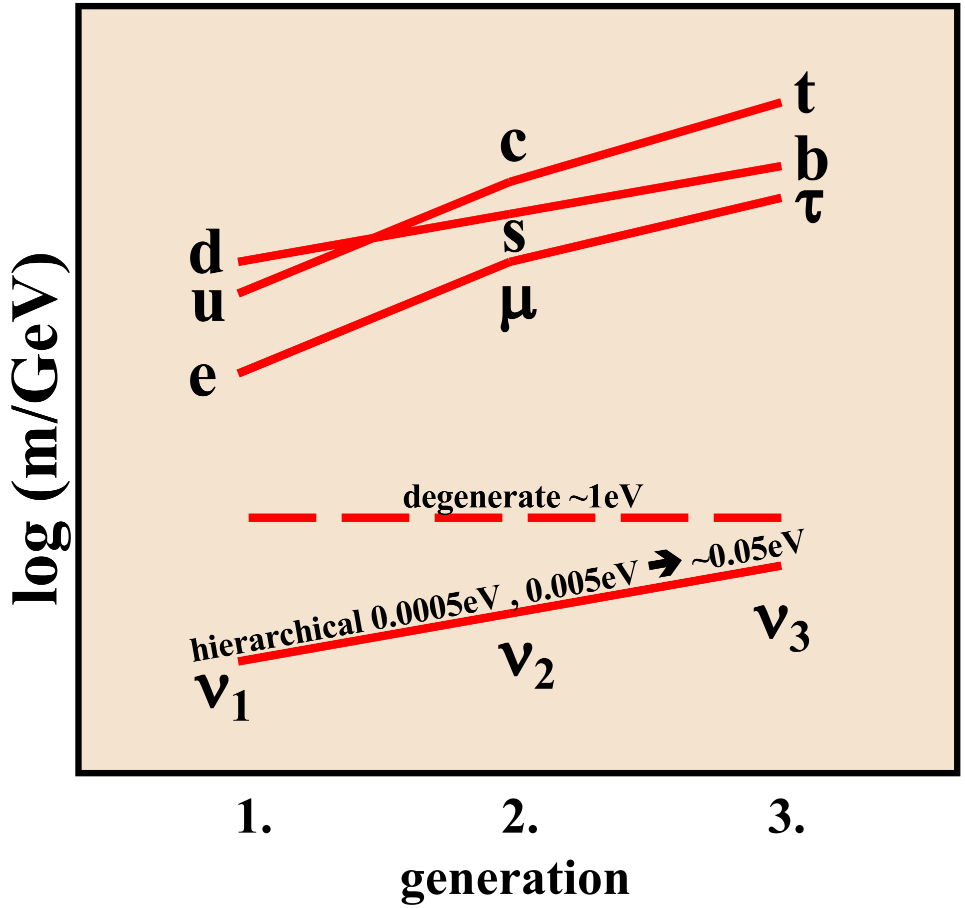
⇔ $\mathcal{L}_{mass} = \kappa \cdot \overline{\nu}^C_L \nu_L \Phi^T \Phi$

➔ $M_L \overline{L} L^c$

5-N) …

Empirical Regularities

Quarks & charged leptons ➔ mass hierarchy pattern ➔ neutrinos?



Quarks and charged leptons:

$m_D \sim H^n$; $n = 0,1,2$ ➔ $H \geq 20...200$

Neutrinos: $m_\nu \sim H^n$ ➔ $H \leq \sim 10$

See-saw:

$$m_\nu = -m_D^T \, M_R^{-1} \, m_D$$

	m_ν	m_D^T	M_R^{-1}	m_D
H	$\simeq 10$	≥ 20	?	≥ 20

- less hierarchy in m_D or correlated hierarchy in M_R ?
  ➔ theoretically connected?
- mixing patterns...

Obtaining aparent numerical Regularities

Quark and lepton masses as well as their mixings show apparent regularities

- moderate inter-generation scale hierarchies
- most mixings are either small or almost maximal

  ➔ how can this be understood?

Toolbox: Mechanisms to naturally explain moderate scale hierachies:

- scale ratios – e.g. two VEVs of two scalars (not too far apart... ←→ hierarchy...)
- small ratios from diagonalization in seesaw like structures
- loop suppression factors ~ $1/16\pi^2$
- group theory factors from flavour symmetries
- ...

One mechanism ←→ more than one mechanism at work?

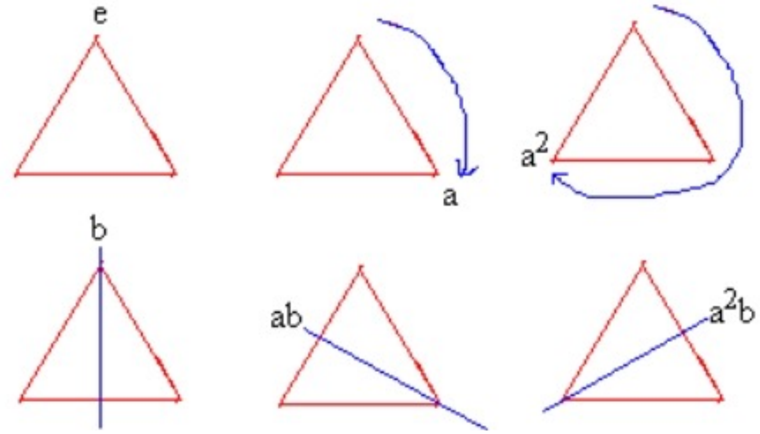
nicer? simpler?
one mechanism versus one new ingreident?
e.g. few fields, simpler groups, new flavour physics at moderate scales, ...

Flavour Symmetries

- **the basic idea:**
  horizontal symmetry (discrete, continuous)
- **broken at high scales**
- **by flavons**
  ➔ explain observed masses and mixings

e.g. dihedral groups D_n

geometric origin of D_3:



Many groups and breaking scenarious have been discussed
a phenomenologically promising example: D_5 **Hagedorn, ML, Plentinger**

task: search for mass terms which are for suitable Higges singlets under D_5

1) assign all fermions to representations $L = \{L_1, L_2, L_3\}$

2) write down any possible mass term using scalars ⇔ singlet under symmetry

➔ D_5 Allowed Mass Terms

Dirac mass terms: $\lambda_{ij} L_i^T (i\sigma_2) \phi L_j^c$

Majorana mass terms: $\lambda_{ij} L_i^T \Xi \phi L_j$

Scalars (flavons) ➔ D5 symmetry induced mass matrices:

$\Phi_1 \sim 1_1$
$\Phi_2 \sim 1_2$
$\Psi_1 \sim 2_1$

L	L^C	Mass Matrix
$(1_2, 1_1, 1_1)$	$(2_1, 1_1)$	$\begin{pmatrix} \kappa_1 \psi_2^1 & -\kappa_1 \psi_1^1 & \kappa_4 \phi^2 \\ \kappa_2 \psi_2^1 & \kappa_2 \psi_1^1 & \kappa_5 \phi^1 \\ \kappa_3 \psi_2^1 & \kappa_3 \psi_1^1 & \kappa_6 \phi^1 \end{pmatrix}$

➔ **check phenomenology** ➔ **... successful models + "predictions"**

BUT: Flavour models get more and more complex, often require an intricate selection / interplay special of symmetries, carefully choosen representations, several flavons and specific breakings

➔ **all very interesting, but is it the right track or is it overengineering?**

Flavor Seesaw Mechanism S. Jana, S. Klett, ML, 2112:09155

Assumed fermion sector structure: up- or down- sector (n=3) + vector fermions

$|h\rangle$ - n-element vector including Yukawa couplings

M_P - explicit mass of vector fermion(s)

v_{EW} - the electro-weak VEV

v_S - VEV of a suitable new scalar

➔ model details will follow

$$\begin{pmatrix} \mathbf{0} & v_{EW}|h\rangle \\ v_S\langle h| & M_P \end{pmatrix}$$

➔ **two non-zero and n – 1 zero mass-eigenvalues**

- assume seesaw limit: $M_P >> v_{EW}$, v_S

➔ non-zero eigenvalues: $\mathbf{m_t \simeq -(v_{EW*}v_S / M_P)\,\langle h|h\rangle}$

$\mathbf{m_P \simeq M_P}$

Notes:

- "0" will be a consequence of representations
- vector masses M_P can have without problems arbitrary values
- for n=3 →only 3rd generation masses ; two vanishing eigenvalues
- accidental symmetry of non-interacting theory @ tree level
- want: minimal set of extra scalars (avoid many "flavons")
- want: v_S as low as possible?

Step 1: ~universal seesaw ~ here not sucessful

Berezhiani, Chang and Mohapatra, Davidson and Wali

- loop effects create δM
- and corrections $|h\rangle \rightarrow |\alpha\rangle$

➔ final quark mass matrix:

$$M_T = \left(\begin{array}{c|c} \delta M & v_{EW}|\alpha\rangle \\ \hline v_S\langle\alpha| & M_P \end{array} \right)$$

$$\delta M|x\rangle + v_{EW}|\alpha\rangle x_{n+1} = 0$$

$$v_S\langle\alpha \mid x\rangle + M_P x_{n+1} = 0$$

➔ eliminate x_{n+1}

$$(\delta M + a_0|\alpha\rangle\langle\alpha|)\,|x\rangle \equiv M|x\rangle = 0$$

➔ $M = \delta M - (v_{EW} * v_S / M_P)\ |\alpha\rangle\langle\alpha|$

Outcome: If M has rank r

➔ $M_T\ M_T^\dagger$ possesses r + 1 nonzero eigenvalues

➔ r generations become massive

n=3: m_t generated by see-saw
2nd generation @ 1-loop
1st generation...

interplay of different mechanisms

Realizing the Flavor Seesaw

G ➔ G_{SM} × $U(1)_{B-L}$

➔ additional fields

j = 1,2,3 (will also cancel anomalies)

two generations of vector-like fermions:
T_k, B_k, E_k, N_k with k = 1, 2

SM singlet - will break **$U(1)_{B-L}$** ➔

Particle	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
$Q_{jL} = \begin{pmatrix} u_j \\ d_j \end{pmatrix}_L$	**3**	**2**	1/3	1/3
u_{jR}	**3**	**1**	4/3	1/3
d_{jR}	**3**	**1**	-2/3	1/3
$\Psi_{jL} = \begin{pmatrix} \nu_j \\ e_j \end{pmatrix}_L$	**1**	**2**	-1	-1
ν_{jR}	**1**	**1**	0	-1
e_{jR}	**1**	**1**	-2	-1
T_{kL}, T_{kR}	**3**	**1**	4/3	2/3
B_{kL}, B_{kR}	**3**	**1**	-2/3	0
N_{kL}, N_{kR}	**1**	**1**	0	-2/3
E_{kL}, E_{kR}	**1**	**1**	-2	-4/3
$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	**1**	**2**	1	1/3
η	**1**	**1**	0	1/3

important!
➔ "0"
➔ Dirac ν's

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu\,a} - \frac{1}{4}W^i_{\mu\nu}W^{\mu\nu\,i} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$

Scalar sector:

$$\mathcal{L}_{\text{scalar}} = (D_\mu \phi)^\dagger (D^\mu \phi) + (D_\mu \eta)^\dagger (D^\mu \eta) - V(\phi, \eta)$$

$$V(\phi, \eta) = -\mu_\phi^2 \phi^\dagger \phi + \frac{1}{2}\lambda_\phi (\phi^\dagger \phi)^2 - \mu_\eta^2 \eta^\dagger \eta + \frac{1}{2}\lambda_\eta (\eta^\dagger \eta)^2 + \lambda_{\phi\eta} (\phi^\dagger \phi)(\eta^\dagger \eta)$$

Symmetry breaking:

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ v_{EW}/\sqrt{2} \end{pmatrix} \qquad \langle \eta \rangle = \frac{v_S}{\sqrt{2}}$$

assume: $v_S \gg v_{EW}$

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \xrightarrow{\langle \eta \rangle} SU(3)_C \times SU(2)_L \times U(1)_Y$$
$$\xrightarrow{\langle \phi \rangle} SU(3)_C \times U(1)_{EM}$$

η is a weak singlet ➔ charged boson masses like in SM

$$M_{W^\pm}^2 = \frac{g^2 v_{EW}^2}{4} \, .$$

neutral gauge bosons ➔ (B,W$_3$,X) mass matrix (mixing by $U(1)_{B-L}$ charge of Φ

$$\mathcal{M}^2 = \frac{1}{4}\begin{pmatrix} g'^2 v_{EW}^2 & -gg'v_{EW}^2 & g'g_X q_\phi v_{EW}^2 \\ -gg'v_{EW}^2 & g^2 v_{EW}^2 & -g\, g_X q_\phi v_{EW}^2 \\ g'g_X q_\phi v_{EW}^2 & -g\, g_X q_\phi v_{EW}^2 & g_X^2\left(q_\phi^2 v_{EW}^2 + q_\eta^2 v_S^2\right) \end{pmatrix}$$

$$s_w \equiv \sin\theta_w = g'/\sqrt{g^2+g'^2}$$

$$\begin{pmatrix} A \\ Y \\ X \end{pmatrix} = \begin{pmatrix} c_w & s_w & 0 \\ -s_w & c_w & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} B \\ W^3 \\ X \end{pmatrix}$$

➔

$$M_{YY}^2 = \frac{v_{EW}^2\left[g^2 c_w^2(1+2s_w^2) + g'^2 s_w^2(1+2c_w^2)\right]}{4}$$

$$M_{XX}^2 = \frac{g_X^2(q_\phi^2 v_{EW}^2 + q_\eta^2 v_S^2)}{4}$$

$$M_{YX}^2 = -\frac{g_X q_\phi v_{EW}^2(g c_w + g' s_w)}{4}$$

$$\begin{pmatrix} Z \\ Z' \end{pmatrix} = \begin{pmatrix} c_\xi & s_\xi \\ -s_\xi & c_\xi \end{pmatrix}\begin{pmatrix} Y \\ X \end{pmatrix}$$

$$\tan 2\xi = \frac{2M_{YX}^2}{M_{YY}^2 - M_{XX}^2}$$

$$M_{Z,Z'}^2 = \frac{1}{2}\left(M_{YY}^2 + M_{XX}^2 \mp (M_{YY}^2 - M_{XX}^2)\sqrt{1+\tan^2 2\xi}\right)$$

Yukawa interactions: Only between quarks (leptons) and vector quarks (leptons)

$$\mathcal{L}_{\rm Yuk} = -y_a^q \overline{Q}_{jL} \tilde{\phi} T_{kR} - y_b^q \overline{T}_{kL} \eta\, u_{jR} - y_c^q \overline{Q}_{jL} \phi B_{kR} - y_d^q \overline{B}_{kL} \eta^\dagger\, d_{jR}$$
$$-y_a^\ell \overline{\Psi}_{jL} \tilde{\phi} N_{kR} - y_b^\ell \overline{N}_{kL} \eta\, \nu_{jR} - y_c^\ell \overline{\Psi}_{jL} \phi E_{kR} - y_d^\ell \overline{E}_{kL} \eta^\dagger\, e_{jR} + h.c.$$

Explicit masses for vector fermions:

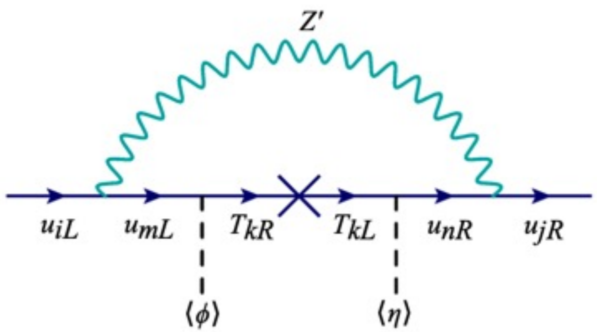
$$\mathcal{L}_{\rm explicit} = -\mathcal{M}_T \overline{T}_{kL} T_{kR} - \mathcal{M}_B \overline{B}_{kL} B_{kR} - \mathcal{M}_N \overline{N}_{kL} N_{kR} - \mathcal{M}_E \overline{E}_{kL} E_{kR} + h.c.$$

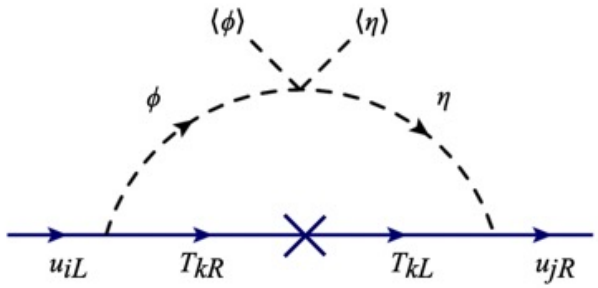
$$\mathcal{M}_T = \begin{pmatrix} M_{T1} & 0 \\ 0 & M_{T2} \end{pmatrix}$$

diagonal

Note: Neutrinos must be Dirac particles ←→ $U(1)_{B-L}$ charges

Radiative generation of further mass terms and mixings @ 1-loop:





Resulting up-type mass matrix:

$$\overline{\mathbf{u}}_L \mathcal{M}_u^{(1)} \mathbf{u}_R \equiv \begin{pmatrix} \overline{u}_{1L} & \overline{u}_{2L} & \overline{u}_{3L} & \overline{T}_{1L} & \overline{T}_{2L} \end{pmatrix} \left(\begin{array}{c|c} \delta\mathcal{M}^u & y_a^q \langle\phi\rangle \\ \hline (y_b^q)^T \langle\eta\rangle & \mathcal{M}_T \end{array}\right) \begin{pmatrix} u_{1R} \\ u_{2R} \\ u_{3R} \\ T_{1R} \\ T_{2R} \end{pmatrix}$$

@1-loop:

$$\begin{aligned} \delta M_{ij}^u &= \sum_{k=1}^{2} \sum_{m,n=1}^{3} i \frac{3 g_X^2 q_Q q_u [y_a^q]_{mk} [y_b^q]_{kn} v_{EW} v_S}{8} \int \frac{d^4 k}{(2\pi)^4} \frac{\gamma_\mu (\not{k} + M_{Tk}) \gamma_\nu g^{\mu\nu}}{k^2 \left(k^2 - M_{Tk}^2\right) \left((p-k)^2 - M_{Z'}^2\right)} \\ &= \sum_{k=1}^{2} \sum_{m,n=1}^{3} \frac{3 g_X^2 q_Q q_u [y_a^q]_{mk} [y_b^q]_{kn} v_{EW} v_S}{32\pi^2} \frac{M_{Tk}}{(M_{Z'}^2 - M_{Tk}^2)} \log \frac{M_{Z'}^2}{M_{Tk}^2} \, . \end{aligned}$$

Analogous for down-type, charged and neutral lepton mass matrices

…

➔ CKM and PMNS mixings including small unitarity violations from VF's

What did we win?

➔ moderate hierarchies from simple interplay of seesaw, two VEVs and loops

➔ no or less need to put hierarchies into SM Yukawas

➔ TeV-ish flavour physics?

Outcome: A mapping between SM Yukawas ←→ new Yukawas

It is highly non-trivial to obtain the known SM parameters!

➔ two benchmark points:

$\varepsilon_1 = 10^{-2}$, $\varepsilon_2 = 10^{-1} * \varepsilon_1^2$

$M_{Z'} = 300$ TeV

$M_{T1} = 8$ TeV ; $M_{T2} = 17.91$ TeV

$M_{B1} = 40$ TeV ; $M_{B2} = 65.69$ TeV

$M_{E1} = 50$ TeV ; $M_{E2} = 80$ TeV

$M_{N1} = 1.15 \times 10^6$ TeV ; $M_{N2} = 1.25 \times 10^6$ TeV

Mapped Yukawa couplings O(10⁻²) - O(1)
←→ hierarchies in SM Yukawas emerge mostly from seesaw, VEV ratio and loops

- Does not explain numbers
  ➔ parameter mapping
- But maybe easier to explain?!

Yukawa Couplings	Benchmark Points	
	BP1	BP2
y_a^q	$\begin{pmatrix} 0.625 & 0.513 \\ 0.186 \times e^{i0.05} & 0.159 \\ 0.401 & 0.327 \end{pmatrix}$	$\begin{pmatrix} 0.631 & 0.522 \\ 0.183 \times e^{i0.05} & 0.158 \\ 0.412 & 0.344 \end{pmatrix}$
y_b^q	$\begin{pmatrix} 0.332 & 0.229 \\ 0.340 & 0.224 \\ 0.294 & 0.232 \times e^{i0.05} \end{pmatrix}$	$\begin{pmatrix} 0.335 & 0.227 \\ 0.352 & 0.222 \\ 0.290 & 0.230 \times e^{i0.05} \end{pmatrix}$
y_c^q	$\begin{pmatrix} 1.539 & 1.287 \\ 0.195 & 0.538 \\ 1.060 & 0.754 \end{pmatrix} \epsilon_1$	$\begin{pmatrix} 1.501 & 1.341 \\ 0.205 & 0.600 \\ 1.061 & 0.795 \end{pmatrix} \epsilon_1$
y_d^q	$\begin{pmatrix} 1.110 & 0.332 \\ 0.850 & 1.506 \\ 13.969 & 12.405 \end{pmatrix} \epsilon_1$	$\begin{pmatrix} 1.129 & 0.331 \\ 0.811 & 1.624 \\ 14.076 & 13.236 \end{pmatrix} \epsilon_1$
y_a^ℓ	$\begin{pmatrix} 1.306 & 1.494 \\ 0.175 & 1.257 \\ 0.538 & 0.333 \end{pmatrix} \epsilon_1^2$	$\begin{pmatrix} 1.235 \times e^{i0.1} & 0.948 \\ 0.195 & 2.283 \\ 0.443 & 0.347 \end{pmatrix} \epsilon_2$
y_b^ℓ	$\begin{pmatrix} 0.319 & 1.048 \\ 0.285 & 0.668 \\ 0.967 & 0.328 \end{pmatrix} \epsilon_1^2$	$\begin{pmatrix} 0.101 & 1.210 \\ 2.871 & 0.947 \\ 0.243 & 1.589 \end{pmatrix} \epsilon_2$
y_c^ℓ	$\begin{pmatrix} 0.678 & 1.166 \\ 0.854 & 0.574 \\ 1.474 & 0.820 \end{pmatrix} \epsilon_1$	$\begin{pmatrix} 0.484 & 1.468 \\ 0.999 & 1.281 \\ 0.617 & 0.809 \end{pmatrix} \epsilon_1$
y_d^ℓ	$\begin{pmatrix} 1.398 & 0.960 \\ 0.740 & 0.780 \\ 0.747 & 1.445 \end{pmatrix} \epsilon_1$	$\begin{pmatrix} 1.555 & 0.479 \\ 1.355 & 1.381 \\ 0.858 & 0.982 \end{pmatrix} \epsilon_1$

Resulting SM observables for the two benchmark points

Quark Sector				Lepton Sector				
Observable (Masses in GeV)	3σ Exp. Range	Model Prediction BP1	Model Prediction BP2	Observable (Masses in GeV)	3σ Exp. Range (NH)	3σ Exp. Range (IH)	Model Prediction (NH) BP1	Model Prediction (IH) BP2
$m_u/10^{-3}$	$1.38 \to 3.63$	2.12	3.07	$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2}$	$6.82 \to 8.04$	$6.82 \to 8.04$	7.583	7.898
m_c	$1.21 \to 1.33$	1.29	1.25	$\frac{\Delta m^2_{3\ell}}{10^{-3}\,\mathrm{eV}^2}$	$2.421 \to 2.598$	$-2.583 \to -2.412$	2.567	-2.432
m_t	$171.7 \to 174.1$	172.3	174.1					
$m_d/10^{-3}$	$4.16 \to 6.11$	4.34	5.08	$m_e/10^{-3}$	$0.485 \to 0.537$		0.511	0.527
m_s	$0.078 \to 0.126$	0.122	0.109	m_μ	$0.100 \to 0.111$		0.109	0.109
m_b	$4.12 \to 4.27$	4.18	4.13	m_τ	$1.688 \to 1.866$		1.862	1.839
$\lvert V_{ud}\rvert$	$0.973 \to 0.974$	0.974	0.974					
$\lvert V_{us}\rvert$	$0.222 \to 0.227$	0.227	0.226	$\sin^2(\theta_{12})$	$0.269 \to 0.343$	$0.269 \to 0.343$	0.315	0.320
$\lvert V_{ub}\rvert/10^{-4}$	$31.0 \to 45.4$	38.4	44.8					
$\lvert V_{cd}\rvert$	$0.209 \to 0.233$	0.226	0.226					
$\lvert V_{cs}\rvert$	$0.954 \to 1.020$	0.973	0.973	$\sin^2(\theta_{23})$	$0.407 \to 0.618$	$0.411 \to 0.621$	0.444	0.413
$\lvert V_{cb}\rvert/10^{-3}$	$36.8 \to 45.2$	42.3	41.9					
$\lvert V_{td}\rvert/10^{-4}$	$71.0 \to 89.0$	84.0	78.7					
$\lvert V_{ts}\rvert/10^{-3}$	$35.5 \to 42.1$	41.6	41.4	$\sin^2(\theta_{13})$	$0.02034 \to 0.02430$	$0.02053 \to 0.02436$	0.02053	0.02300
$\lvert V_{tb}\rvert$	$0.923 \to 1.103$	0.999	0.999					
$\mathcal{J}/10^{-5}$	$2.73 \to 3.45$	3.12	3.40	$\delta_{cp}/^\circ$	$107 \to 403$	$192 \to 360$	0	250

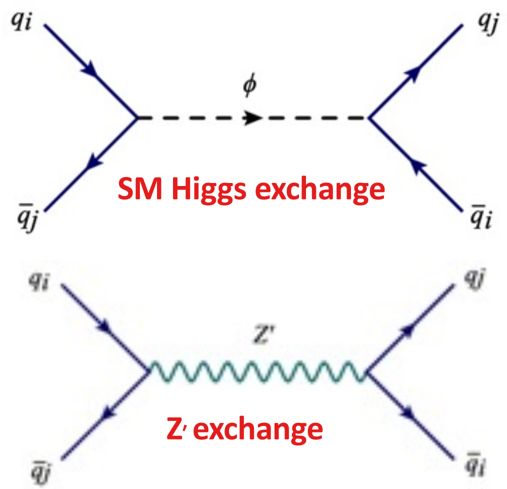
Notes:

- The two benchmark points are just two solutions of a numerical search
  → there may exist solutions with even lower scales
- Many other model realizations should exist

BSM Phenomenology

TeV-ish new physis...

- **FCNC's @ quark sector ➔ neutral meson mixing**
  estimate effects: $D^0 - \overline{D^0}$, $K^0 - \overline{K^0}$, $B_d^0 - \overline{B_d^0}$ and $B_s^0 - \overline{B_s^0}$
  dominating contributions: SM Higgs and Z' exchange
  ...
  ➔ new physics contributions



Observable (in GeV)	Model Prediction	
	BP1	BP2
$\Delta m_{B_d}^{NP}$	-1.402×10^{-13}	-1.495×10^{-14}
$\Delta m_{B_s}^{NP}$	2.663×10^{-14}	3.003×10^{-14}
Δm_{D}^{NP}	2.405×10^{-15}	2.036×10^{-15}
Δm_{K}^{NP}	0.504×10^{-15}	0.109×10^{-15}

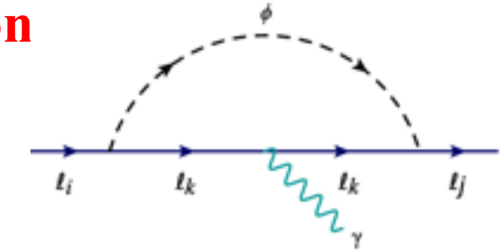
$$\Delta m_{B_d}^{\mathrm{exp}} - \Delta m_{B_d}^{\mathrm{SM}} = (-0.141 \pm 0.513) \times 10^{-13}\,\mathrm{GeV}$$

$$\Delta m_{B_s}^{\mathrm{exp}} - \Delta m_{B_s}^{\mathrm{SM}} = (-0.036 \pm 0.178) \times 10^{-11}\,\mathrm{GeV}$$

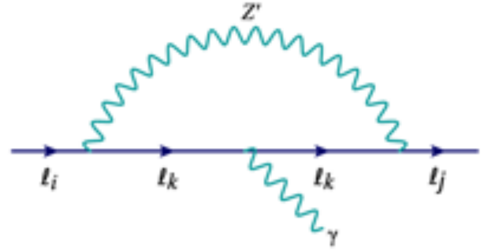
$$\Delta m_{K}^{\mathrm{exp}} - \Delta m_{K}^{\mathrm{SM}} = (0.410 \pm 0.922) \times 10^{-15}\,\mathrm{GeV}$$

the benchmark points are consistent with data

- **Charged Lepton Flavor Violation**
  1-loop contributions to $\ell_i \to \ell_j \gamma$

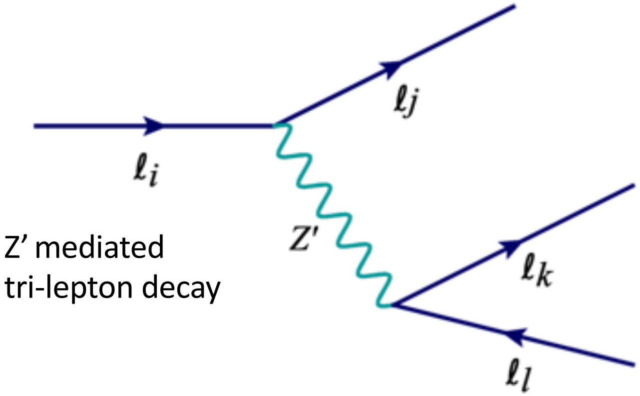


SM Higgs exchange



Z' exchange

tree level three lepton decay $\ell_i \to \bar{\ell}_j \ell_k \ell_l$



Z′ mediated
tri-lepton decay

Process	Experimental Limit	Model Prediction	
		BP1	BP2
$\mathrm{BR}(\mu^- \to e^- \gamma)$	$< 4.2 \times 10^{-13}$	1.8×10^{-14}	6.3×10^{-15}
$\mathrm{BR}(\tau^- \to e^- \gamma)$	$< 3.3 \times 10^{-8}$	2.2×10^{-14}	2.2×10^{-14}
$\mathrm{BR}(\tau^- \to \mu^- \gamma)$	$< 4.4 \times 10^{-8}$	6.8×10^{-15}	3.0×10^{-15}
$\mathrm{BR}(\mu^- \to e^- e^+ e^-)$	$< 1.0 \times 10^{-12}$	1.3×10^{-18}	3.9×10^{-19}
$\mathrm{BR}(\tau^- \to e^- e^+ e^-)$	$< 2.7 \times 10^{-8}$	2.2×10^{-17}	1.8×10^{-17}
$\mathrm{BR}(\tau^- \to \mu^- e^+ e^-)$	$< 1.8 \times 10^{-8}$	9.5×10^{-18}	4.1×10^{-18}

the benchmark points are consistent with data

- **Other implications**
  the presence of new TeV-ish physics can lead to various other effects
  not relevant for us – multi TeV-ish scales
  lower scale solutions may exists ➔ check which BSM signals...

Conclusions

- **Tremendous success of renomalizable QFTs: QED ➔ QCD ➔ SM**
- **Conceptual: 4d QFT ✚ symmetries ✚ representations ✚ numbers**
  ➔ type (q,l) and number (copies) of fermion representations is not understood
  ➔ generations appear special due to mass values and anomaly cancellation
- **Ideas to "understand" apparent regularities in fermion masses and mixings**
  ➔ flavour symmetries ✚ high scale breakings by flavons
  ➔ many models, become rather complex ←→ observed structures
- **Other routes?**
  ➔ flavour seesaw ←→ structure following from representaions
  ➔ moderate VEV ratio plus loops
  ➔ discussed a simple model realization with extra $U(1)_{B-L}$
  ➔ mapping of parameters to new patterns
  ➔ allows multi-TeV-ish flavour physics
  ➔ interesting phenomenological consequences: FCNC's , Dirac neutrinos, ...