Anomaly free Froggatt-Nielsen model of flavor

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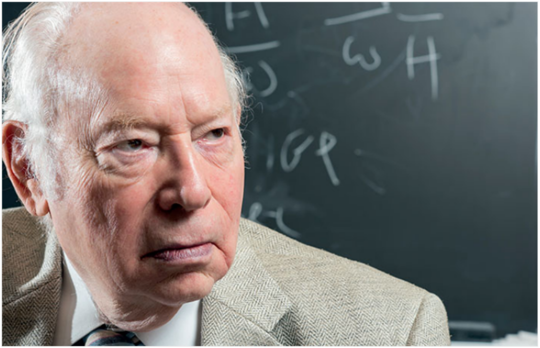
FEATURE

Model physicist

13 October 2017

Steven Weinberg talks to *CERN Courier* about his seminal 1967 work and discusses where next for particle physics following the discovery of the Higgs boson.



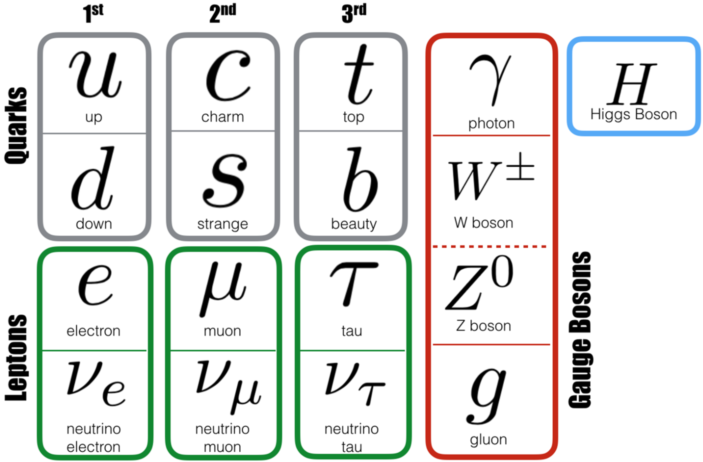
Steven Weinberg

Asked what single mystery, if he could choose, he would like to see solved in his lifetime, Weinberg doesn't have to think for long: he wants to be able to explain the observed pattern of quark and lepton masses. In the summer of 1972, when the SM was coming together, he set himself the task of figuring it out but couldn't come up with anything. "It was the worst summer of my life! I mean, obviously there are broader questions such as: why is there something rather than nothing? But if you ask for a very specific question, that's the one. And I'm no closer now to answering it than I was in the summer of 1972," he says, still audibly irritated. He also doesn't want to die without knowing what dark matter is. There are all kinds of frustrations, he says. "But how could it be otherwise? I am enjoying what I am doing and I have had a good run, and I have a few more years. We're having a total eclipse here in April 2024 and I look forward to seeing that."

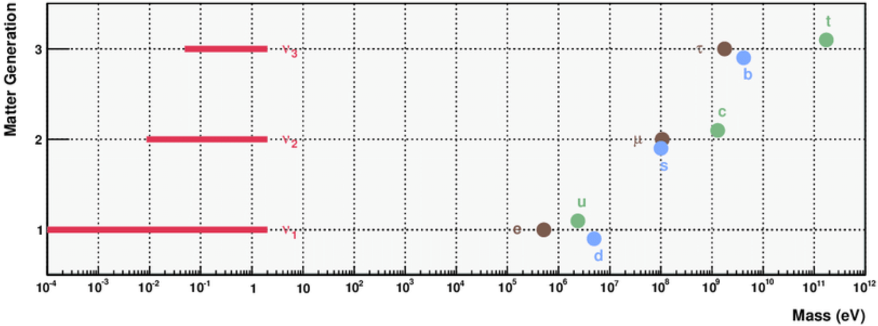
I think we should make Steven happy.

A mandatory slide

The Standard Model!



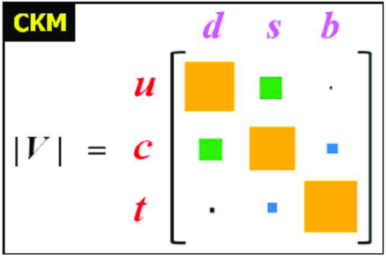
Mass hierarchy

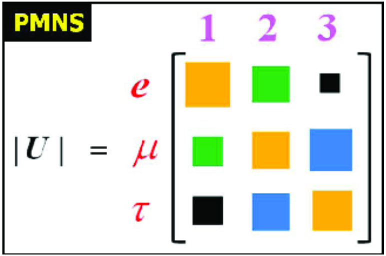


Fermion masses show a huge hierarchy!

Neutrino: $m_\nu \lesssim \text{eV}$, Electron: $m_e \sim \text{MeV}$, Top: $m_t \sim 100\,\text{GeV}$.

Mixing structure





CKM matrix is mostly diagonal.

PMNS is ”anarchic”.

How can we explain these structures?

New Physics!

Can we generate exponential hierarchies between scales?

Not in the SM. Need New Physics!

- Extra dimensions [RS: 99, 0107190, 1903.08359 and many others];
- Two (or more) Higgs Doublets Models [1512.03458, 1704.04869 and many others];
- Clockwork [1807.09792];
- Extra abelian gauge group [Froggatt, Nielsen: 79, many others and now also A. Smolkovic, MT, J. Zupan: 1907.xxxx].

Froggatt - Nielsen

Introduce an extra abelian gauge group $U(1)_H$ [Froggatt, Nielsen: 79]. Chiral SM fermion fields are charged under this new group.

Need to introduce one new scalar field ϕ (flavon) and a set of massive vector-like fermions.

Symmetry breaking through $\langle\phi\rangle$ generates an exponential suppression of fermion masses.

But, without additional matter content, this model is anomalous.

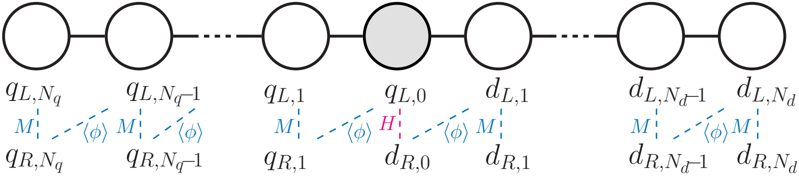
A different "construction" of this model can be realized and be anomaly-free.

Outline

- Anomaly-free FN model;
- Extension to leptons;
- Z' phenomenology;
- Conclusions.

One generation example

- Gauge group: $G_{FN} = U(1)$;
- Flavon: $[\phi] = 1$;
- Chiral fermions: $[d_{R,0}] = [q_{L,0}] = 0$;
- Higgs: $[H] = 0$;
- Vector-like fermions $[d_{R/L,n}] = +n$, $[q_{R/L,n}] = -n$.



$$\mathcal{L}_1 = \mathcal{L}_{kin} + \mathcal{L}_q + \mathcal{L}_d + \left(Y_0^d \bar{q}_{L,0} d_{R,0} H + \text{h.c.}\right),$$

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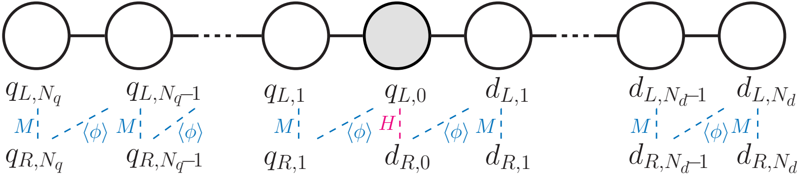

$$\mathcal{L}_1 = \mathcal{L}_{kin} + \mathcal{L}_q + \mathcal{L}_d + \underline{\left(Y_0^d \bar{q}_{L,0} d_{R,0} H + \text{h.c.}\right)}$$

Higgs only couples with chiral fermions on the zero-th node!

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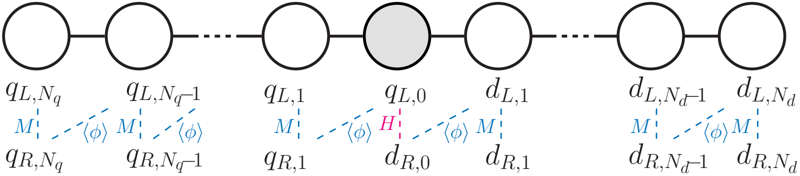

$$\mathcal{L}_1 = \underline{\mathcal{L}_{kin}} + \mathcal{L}_q + \mathcal{L}_d + \left(Y_0^d \bar{q}_{L,0} d_{R,0} H + \text{h.c.}\right)$$

$$\mathcal{L}_{kin} = i\sum_{n=1}^{N_q} \bar{q}_{R,n} \not{D} q_{R,n} + i\sum_{n=0}^{N_q} \bar{q}_{L,n} \not{D} q_{L,n} + i\sum_{n=0}^{N_d} \bar{d}_{R,n} \not{D} d_{R,n} + i\sum_{n=1}^{N_d} \bar{d}_{L,n} \not{D} d_{L,n}$$

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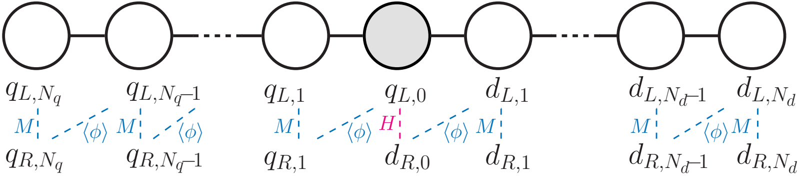

$$\mathcal{L}_1 = \mathcal{L}_{kin} + \underline{\mathcal{L}_q} + \mathcal{L}_d + \left(Y_0^d \bar{q}_{L,0} d_{R,0} H + \text{h.c.}\right)$$

$$\mathcal{L}_q = -\sum_{n=1}^{N_q} \left(M_n^q \bar{q}_{L,n} q_{R,n} - Y_n^q \phi \bar{q}_{L,n-1} q_{R,n} + \text{h.c.}\right)$$

M_n vector-like fermion mass, Y_n fermion-flavon Yukawa coupling

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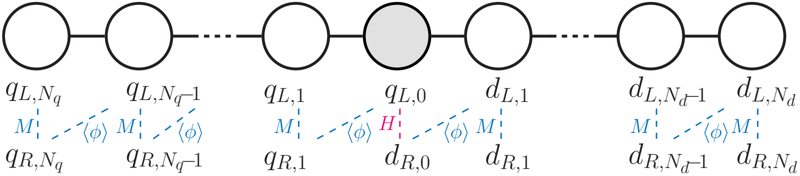

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M_n vector-like fermion mass, Y_n fermion-flavon Yukawa coupling

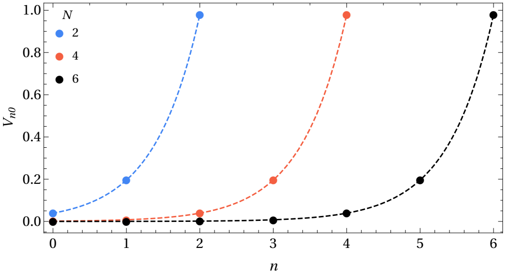
- Flavon vev $\langle\phi\rangle$ spontaneously breaks G_{FN},
- $N_q \times (N_q+1)$ mass matrix for q and $(N_d+1)\times N_d$ for d,
- $N_q + N_d$ massive eigenstates and two massless eigenstates (zero modes)

$$q'_{L,0} = \sum_{n=0}^{N_q} V_{n0}^{q_L} q_{L,n}, \qquad d'_{R,0} = \sum_{n=0}^{N_d} V_{n0}^{d_R} d_{R,n}.$$

Overlap of the zero modes with the n-th node ($Y_n^d = Y_n^q = 1$, $M_n^d = M_n^q = M$)

$$V_{n0}^{q_L} = \mathcal{N}_0^{q_L}\left(\frac{M}{\langle\phi\rangle}\right)^{N_q-n}, \qquad V_{n0}^{d_R} = \mathcal{N}_0^{d_R}\left(\frac{M}{\langle\phi\rangle}\right)^{N_d-n},$$

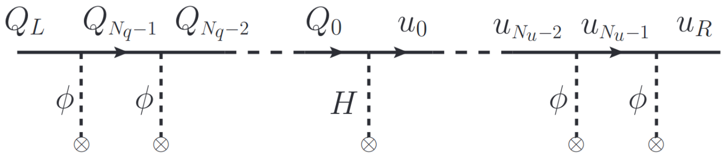
- for $\langle\phi\rangle \gg M$ and large $N_{q(d)}$, the zero mode - zero node overlap is exponentially suppressed



New vs Old FN

Chain setting:

N: Vector — Chiral — Vector
O: Chiral — Vector — Chiral

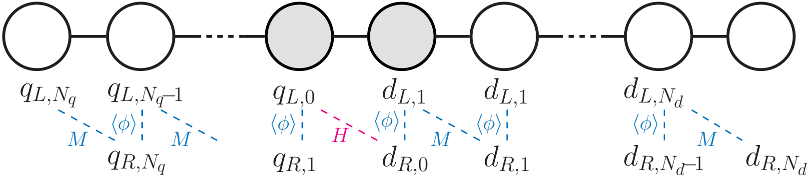


Expansion parameter: N: $\lambda = M/\langle\phi\rangle$ O: $\lambda = \langle\phi\rangle/M$.

Anomalies: N: free O: anomalous $U(1)$.

After G_{FN} broken, $\mathcal{L}$ shows an approximate $U(1)_{app}$ explicitly broken by M.

Treat M as a spurion with $[M] = +1$, the fermion mass matrix is formally invariant under $U(1)_{app}$.



Diagonalize the matrix, the $U(1)_{app}$ invariant term is

$$\mathcal{L}_{\rm SM} \sim Y_0^d \left(\frac{M}{\langle\phi\rangle}\right)^{N_q+N_d} \bar{q}_{L,N_q} d_{R,N_d} H,$$

The zero modes acquire mass once Higgs acquires a vev

$$m_d \simeq V_{00}^{q_L} V_{00}^{d_R} \frac{Y_0^d v}{\sqrt{2}} \simeq \frac{Y_0^d v}{\sqrt{2}} \left(\frac{M}{\langle\phi\rangle} \right)^{N_q+N_d} .$$

The quark mass is exponentially suppressed!

$$\frac{M}{\langle\phi\rangle} \simeq \lambda = \sin\theta_C \sim 0.2, \quad m_d \sim \lambda^7 \quad \Rightarrow \quad N_q = 3, N_d = 4.$$

If we have the up-quarks too

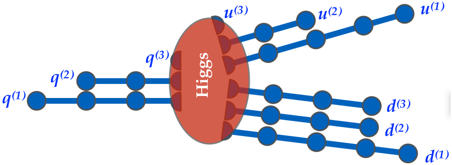
$$m_u \sim \lambda^7 \,, \quad V_{CKM}^{ij} \sim \frac{V_{00}^{q_L^i}}{V_{00}^{q_L^j}} \,, \quad |V_{ud}| \sim 1 \,, \quad |V_{us}| \sim \lambda$$

$$N_{q(1)} = 3 \,, \quad N_{u(1)} = N_{d(1)} = 4 \,, \quad N_{q(2)} = 2$$

How can we extend this model to three quark generations?

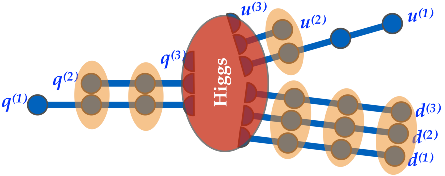
- "Decoupled chains": $G_{FN} = U(1)^3$ (one per generation);
- "Coupled chains": $G_{FN} = U(1)$.

Decoupled chains



$$
\begin{aligned}
N_{q(1)} &= 3, & N_{q(2)} &= 2, & N_{q(3)} &= 0, \\
N_{u(1)} &= 4, & N_{u(2)} &= 2, & N_{u(3)} &= 0, \\
N_{d(1)} &= 4, & N_{d(2)} &= 3, & N_{d(3)} &= 3.
\end{aligned}
$$

Coupled chains

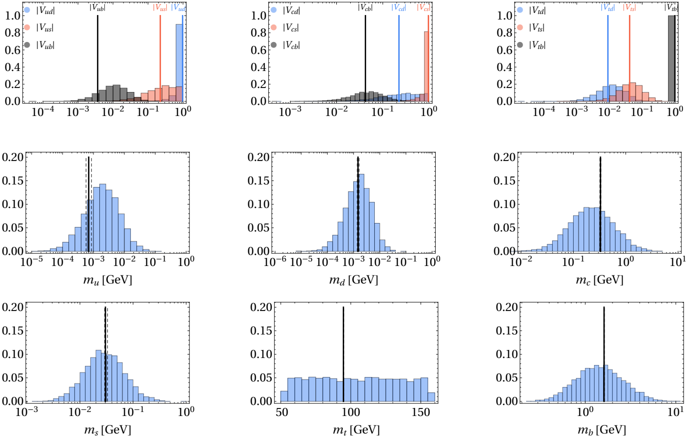


$$
\begin{aligned}
N_{q(1)} &= 3, & N_{q(2)} &= 2, & N_{q(3)} &= 0, \\
N_{u(1)} &= 3, & N_{u(2)} &= 1, & N_{u(3)} &= 0, \\
N_{d(1)} &= 3, & N_{d(2)} &= 3, & N_{d(3)} &= 3.
\end{aligned}
$$

$$\frac{M_1}{\langle\phi_1\rangle} = \frac{M_2}{\langle\phi_2\rangle} = \frac{M_3}{\langle\phi_3\rangle} = \frac{1}{q} \simeq \lambda = 0.2, \qquad \frac{\langle\phi\rangle}{q} \sim 10^7\,\mathrm{GeV}$$

Generate random complex Yukawas and $M_n^f = r_a e^{i\varphi_a}\langle\phi\rangle/q,\ r_a \in [0.3, 0.9],\ \varphi \in [0, 2\pi)$

Decoupled FN Chains, $G_{\mathrm{FN}} = U(1)^3$



$$\frac{M}{\langle\phi\rangle} = \frac{1}{q} \simeq \lambda = 0.2, \quad \frac{\langle\phi\rangle}{q} \sim 10^7\text{GeV}$$

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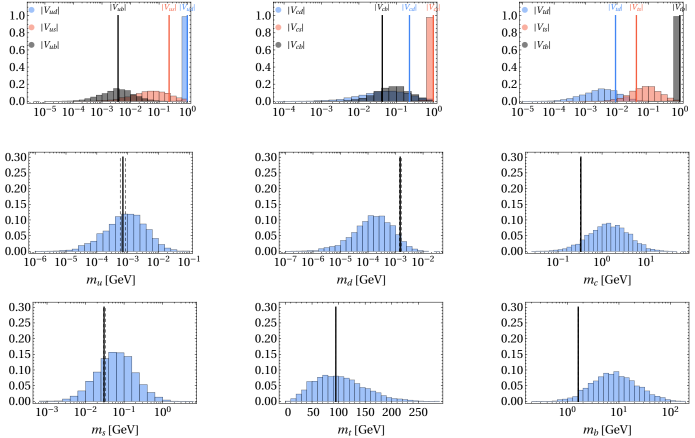


Extension to leptons

Need some assumptions:

- neutrino have Majorana masses from dim 5 Weinberg operator

$$\mathcal{L}_{\dim 5} \supset \frac{c_{ij}}{\Lambda_{\rm LN}}(L_i H)(L_j H), \qquad m^{\nu}_{ij} \simeq c_{ij}\frac{v^2}{\Lambda_{\rm LN}}\left(\frac{M^L}{\langle\phi\rangle}\right)^{N_{L(i)}+N_{L(j)}},$$

  Pick $\Lambda_{\rm LN} \sim 10^{11}\,\mathrm{GeV}$ to saturate the cosmology bound $\sum_i m_{\nu_i} \lesssim 0.15$ eV

- PMNS mixing angles "anarchic", all of $\mathcal{O}(1) \Rightarrow$ left-handed leptons must have same chain length

$$N_{L(1)} = N_{L(2)} = N_{L(3)}.$$

Decoupled chains:

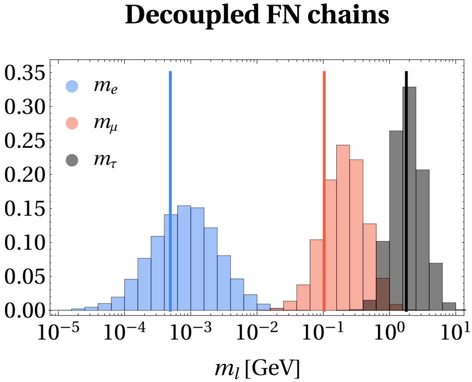
$$m_{ij}^e \sim v\left(\frac{M}{\langle\phi\rangle}\right)^{N_{L(i)}+N_{e(j)}}.$$

The observed hierarchy between $m_e : m_\mu : m_\tau$ is obtained for

$$N_{e(1)} = N_{e(2)} + 3 = N_{e(3)} + 4.$$

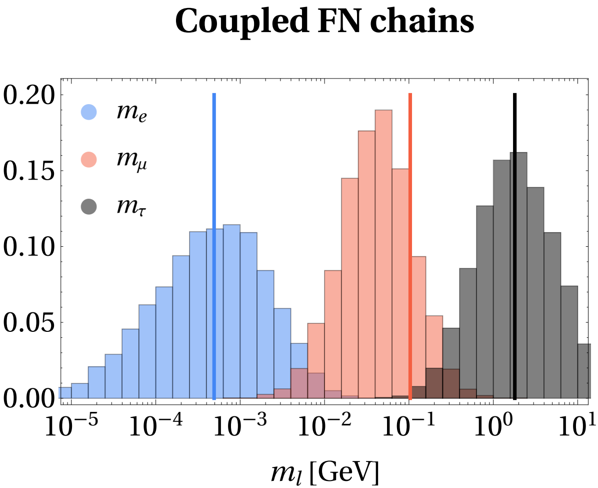
In this benchmark

$$N_{L(1)} = N_{L(2)} = N_{L(3)} = 3, \qquad N_{e(1)} = 4, \qquad N_{e(2)} = 1, \qquad N_{e(3)} = 0,$$

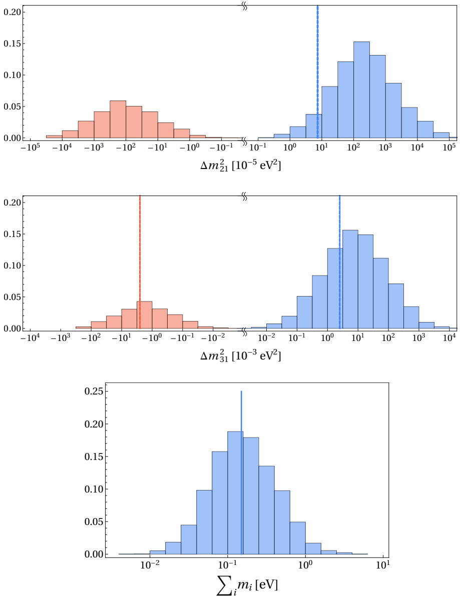


Coupled chains: products of random matrices have hierarchical eigenvalues [von Gersdorff: 1705.05430]. Pick completely anarchic charge assignment

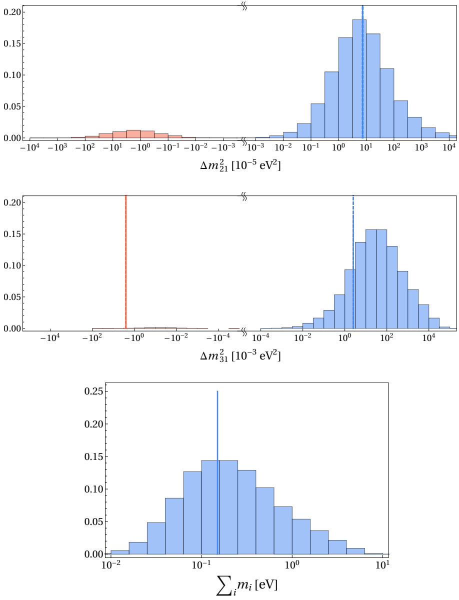
$$N_{L(i)} = N_L = 2, \qquad N_{e(i)} = N_e = 3.$$



Decoupled FN Chains, $G_{\mathbf{FN}} = U(1)^3$ - neutrinos



Coupled FN Chains, $G_{\mathbf{FN}} = U(1)$ - neutrinos



Z' phenomenology

Coupled chains model: $G_{FN} = U(1)$, one extra gauge boson with gauge coupling g'.

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + B_\mu J^\mu_Y + W^a_\mu J^\mu_{W^a} - \frac{\epsilon}{2}B_{\mu\nu}Z'^{\mu\nu} + Z'_\mu J^\mu_{\rm FN}\,,$$

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Gauge boson kinetic terms.

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Electroweak currents

Coupled chains model: $G_{FN} = U(1)$, one extra gauge boson with gauge coupling g'.

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Kinetic mixing, allowed with new abelian gauge group.

Field redefinition: $B_\mu \to B_\mu - \epsilon Z'_\mu$, kin. mix. can be traded for $\epsilon Z'_\mu J^\mu_Y$ and $Z - Z'$ mixing by a field redefinition.

We consider $\epsilon \to 0$ scenario, phenomenology dictated by g'.

Coupled chains model: $G_{FN} = U(1)$, one extra gauge boson with gauge coupling g'.

$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + B_\mu J^\mu_Y + W^a_\mu J^\mu_{W^a} - \frac{\epsilon}{2}B_{\mu\nu}Z'^{\mu\nu} + \underline{Z'_\mu J^\mu_{\text{FN}}}\,,$$

New gauge current:

$$\begin{aligned} J^\mu_{\text{FN}} = g' &\sum_{n=1}^{N_{d(1)}} \sum_{i=1}^{\hat{N}_d|_n} n\big(\bar{d}^{(i)}_{L,n}\gamma^\mu d^{(i)}_{L,n} + \bar{d}^{(i)}_{R,n}\gamma^\mu d^{(i)}_{R,n}\big) + \cdots \\ + g' &\sum_{n=1}^{N_{q(1)}} \sum_{i=1}^{\hat{N}_q|_n} n\big(-\bar{q}^{(i)}_{L,n}\gamma^\mu q^{(i)}_{L,n} - \bar{q}^{(i)}_{R,n}\gamma^\mu q^{(i)}_{R,n}\big) + \cdots \end{aligned}$$

Unitary transformation to mass basis

$$J_Y^\mu = \sum_{f,i,j} \left[g' c^{ij}_{f_L} \left(\bar{f}_L^{(i)} \gamma^\mu f_L^{(j)} \right) + g' c^{ij}_{f_R} \left(\bar{f}_R^{(i)} \gamma^\mu f_R^{(j)} \right) \right],$$

Couplings get rotated too

$$c^{ij}_{u_L} = \left(V^\dagger_{u_L} c'^{q_L} V_{u_L} \right)_{ij}$$

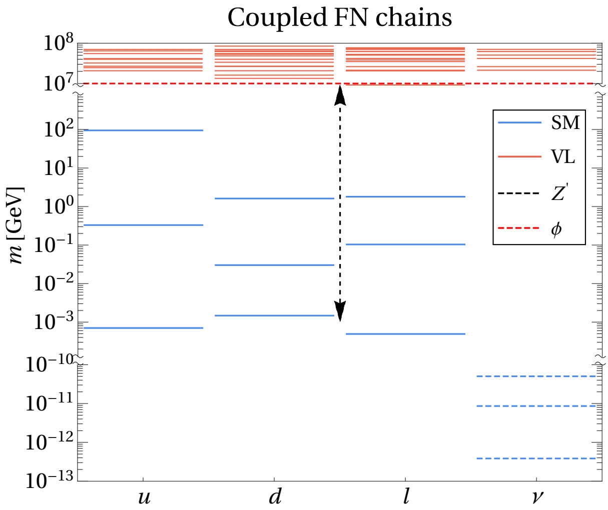
Both diagonal and off-diagonal entries!

$$c^{ij}_{u_L} = \begin{pmatrix} -2.722 & -0.411 + 0.102i & 0.004 + 0.013i \\ -0.411 - 0.102i & -2.228 & 0.025 + 0.058i \\ 0.004 - 0.013i & 0.025 - 0.058i & -0.002 \end{pmatrix}$$

$$c^{ij}_{u_R} = \begin{pmatrix} 2.932 & 0.058 + 0.155i & 0.004 + 0.005i \\ 0.058 - 0.155i & 0.992 & 0.078 - 0.049i \\ 0.004 - 0.005i & 0.078 + 0.049i & 0.009 \end{pmatrix}$$

- Magnitude of couplings depends on chain length;
- Mostly axial couplings (q - negative charges, u/d - positive charges);

Benchmark



Can ignore VL fermions and flavon in flavor observables because $m_F \sim m_\phi \sim \mathcal{O}(\langle\phi\rangle)$

Rich collection of processes to look at!

Flavor diagonal

- Direct Z' production
- Atomic Parity Violation
- Neutrino trident
- $(g-2)$/EDM
- SN1987A
- White dwarf cooling

Flavor off-diagonal

- Meson mixing
  $(K^0 - \bar{K}^0,\ B_q - \bar{B}_q,\ D^0 - \bar{D}^0)$
- $\mu \to e$ conversion
- Decay to three leptons
  $(\tau \to 3\mu,\ \tau \to 3e,\ \mu \to 3e)$
- Radiative decays
  $(\tau \to e\gamma,\ \tau \to \mu\gamma,\ \mu \to e\gamma)$
- Rare meson decays $(K^+ \to \pi^+ \mu^+ e^-)$

Direct production

Production of Z' at colliders dominated by diagonal couplings.

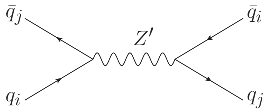
- $e^+e^- \to Z'\gamma$, $Z' \to e^+e^-, \mu^+\mu^-, inv$ (BaBar, KLOE);
- $eZ \to eZZ'$, $Z' \to e^+e^-$ (APEX, E137, E141, E774, Orsay, KEK, NA64);
- $pZ \to pZZ'$, $Z' \to e^+e^-$ (ν-CAL I);
- $\bar{q}_i q_i \to Z'$, $Z' \to \mu^+\mu^-$ (LHCb) for $m_{Z'} > 1$ GeV.

Can recast dark photon searches by $\epsilon e Q_f \to g' \left[(c^{11}_{fV})^2 + (c^{11}_{fA})^2\right]^{1/2}$ with `Darkcast`
[Ilten et al. : 1801.04847]

Meson mixing

Tree level process. Involves two off-diagonal couplings.

Match into EFT to constraint Wilson coefficients

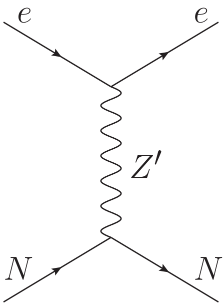


- $K^0 - \bar{K}^0$: $s\bar{d} \to d\bar{s}$;
- $B_q - \bar{B}_q$: $b\bar{q} \to q\bar{b}\,, \quad q = s, d$;
- $D^0 - \bar{D}^0$: $c\bar{u} \to u\bar{c}$.

Use UTFiT results to constrain the paramenter space

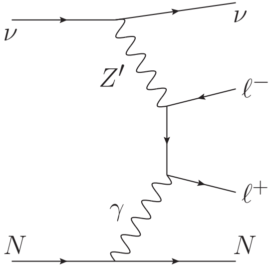
WC	Current	Projected
$\mathrm{Im}C_K^5$	$[-5.2, 2.8] \cdot 10^{-17}$	$[-1.16, 3.2] \cdot 10^{-17}$
$\lvert C_{B_s}^4\rvert$	$< 1.16 \cdot 10^{-11}$	$< 1.7 \cdot 10^{-13}$
$\lvert C_{B_s}^5\rvert$	$< 4.5 \cdot 10^{-11}$	$< 4.8 \cdot 10^{-13}$
$\lvert C_{B_d}^4\rvert$	$< 2.1 \cdot 10^{-13}$	$< 1.6 \cdot 10^{-14}$
$\lvert C_{B_d}^5\rvert$	$< 6.0 \cdot 10^{-13}$	$< 4.5 \cdot 10^{-14}$
C_D^4	$\lvert C_D^4\rvert < 4.8 \cdot 10^{-14}$	$\mathrm{Im}C_D^4 \in [-5.5, 5.5] \cdot 10^{-17}$
C_D^5	$\lvert C_D^5\rvert < 4.8 \cdot 10^{-13}$	$\mathrm{Im}C_D^5 \in [-6.6, 6.6] \cdot 10^{-16}$

Atomic Parity Violation



Bounds from $g'^2|c^{11}_{\ell A} c^V_N|$ in Cs $6s - 7s$ transitions
[Dzuba et al.: 1709.10009]

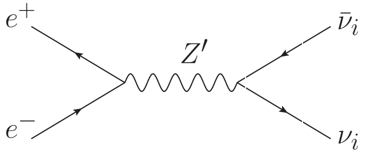
Neutrino trident



For small g', SM - NP interference dominates: bounds from

$g' \left[c^{22}_{\nu_L} \left((-\frac{1}{4} + s^2_W) c^{22}_{\ell_L} + s^2_W c^{22}_{\ell_R} \right) / (-\frac{1}{4} + 2 s^2_W) \right]^{1/2}$
[Altmannshofer et al.: 1902.06765]

White dwarf cooling

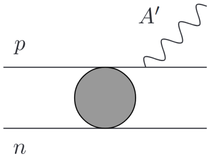


Temperature inside WD is $\mathcal{O}$(few) keV, use EFT to bound Wilson coefficients

$$\frac{1.12 \cdot 10^{-5}}{\mathrm{GeV}^{-2}} < \frac{g'^2 c^{\mathrm{eff}}_{\nu L} |c^{11}_{\ell A}|}{m^2_{Z'}} < \frac{4.50 \cdot 10^{-3}}{\mathrm{GeV}^{-2}} .$$

[Bauer et al.: 1803.05466]

SN1987A

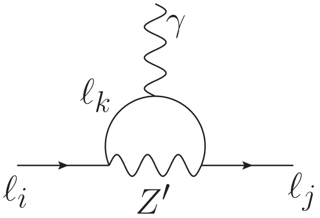


Restrict analysis to $m_{Z'} > 10$ MeV:

- corrections from coupling with electron plasma are negligible;
- main production channel is bremsstrahlung in neutron–proton scattering $pn \to pnZ'$.

Can rescale bounds from [Chang et al. : 1611.03864] by the replacement $\epsilon' \sim 3g'^2 c^2_{pA}$

One loop



Anomalous magnetic moment:

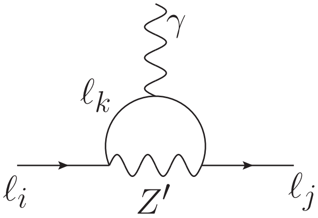
$$\delta a_\ell \propto (g' c^{ii}_{\ell A})^2 \frac{m_\ell^2}{m_{Z'}^2} L\,.$$

Chirality flip from τ in the loop is suppressed by two off-diagonal couplings.

Limits

$$\delta a_e \lesssim 10^{-12}\,, \quad \delta a_\mu \lesssim 2.7 \cdot 10^{-9}\,,$$

One loop



Electric dipole moment:

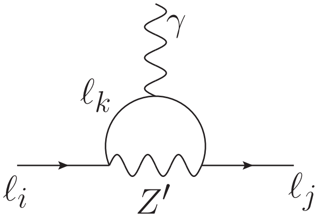
$$\frac{d_{f_i}}{e} \propto m_{f_k} \mathrm{Im}\left(c_{fV}^{ik} c_{fA}^{ik\,*} - c_{fA}^{ik} c_{fV}^{ik\,*}\right) L' \,.$$

Vanishes for diagonal couplings.

Limits

$$|d_e| < 1.1 \cdot 10^{-29} e\,\mathrm{cm}, \quad |d_n| < 2.9 \cdot 10^{-26} e\,\mathrm{cm}.$$

One loop



Radiative decays:

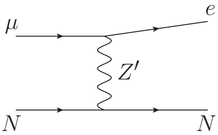
$$\Gamma(\ell_i \to \ell_j \gamma) \propto \frac{\alpha g'^4 m_i^5}{4\pi m_{Z'}^4} \left(|c_L^\gamma|^2 + |c_R^\gamma|^2\right) L'',$$

Largest contribution from τ in the loop.

$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8}, \quad \mathrm{Br}(\tau \to e\gamma) < 3.3 \cdot 10^{-8}, \quad \mathrm{Br}(\mu \to e\gamma) < 4.2 \cdot 10^{-13}.$$

Belle-II (for τ) and MEG-II (for μ) will improve these bounds.[Altmannshofer et al.: 1808.10567; Baldini et al.: 1801.04688]

$\mu \to e$ conversion



Stopped muons ($q^2 \simeq -m_\mu^2$) coherently scattering with heavy nuclei

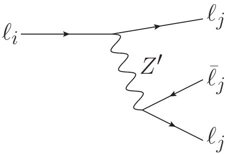
$$\mathrm{Br}(\mu \to e) \propto \left(\frac{(g')^2 c_{fV}^{11} c_{\ell V}^{12}}{m_\mu^2 + m_{Z'}^2} \right)^2 \frac{1}{\Gamma_{\mathrm{capt}}}$$

Axial part induces spin-dependent interactions which are relevant for $m_{Z'} < 1 - 10$ MeV.

$$\mathrm{Br}(\mu \to e) = \frac{\Gamma(\mu^- \mathrm{Au} \to e^- \mathrm{Au})}{\Gamma_{\mathrm{capt}}(\mu^- \mathrm{Au})} < 7 \cdot 10^{-13}.$$

Future improvements from Mu2e. [Bertl et al.: Eur. Phys. J, 337 (2006); Bernstein et al.: 1901.11099]

Three lepton decays



$$\Gamma(\ell_i \to 3\ell_j) \propto \frac{g'^4 m_{\ell_i}^5}{m_{Z'}^4} |c_{\ell A}^{jj}|^2 \left(|c_{\ell V}^{ij}|^2 + |c_{\ell A}^{ij}|^2 \right)$$

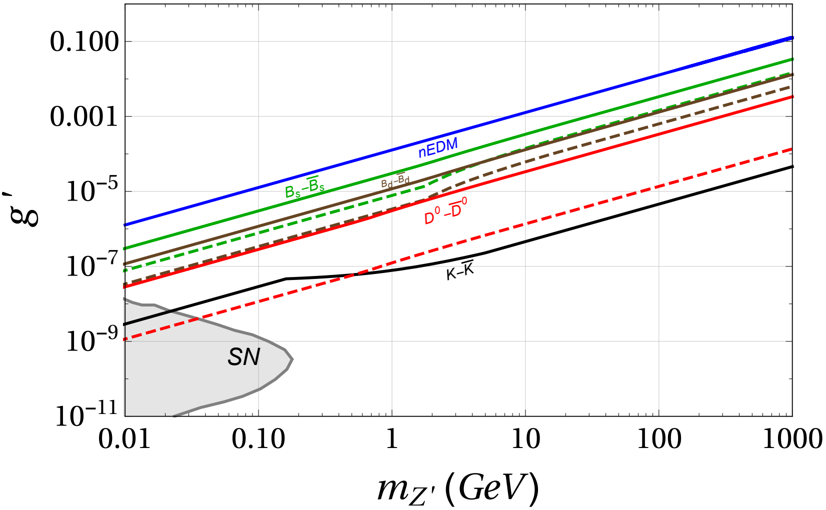
Longitudinal part of the propagator gives $1/m_{Z'}^2$ also for very light Z'.
Most stringent [Bellgardt et al.: Nucl. Phys. B299, 1 (1988); Bernstein et al.: 1901.11099. For $\tau \to 3\ell$ Hayasaka et al.: 1001.3221]

$$\mathrm{Br}(\mu \to 3e) < 1.0 \cdot 10^{-12}.$$

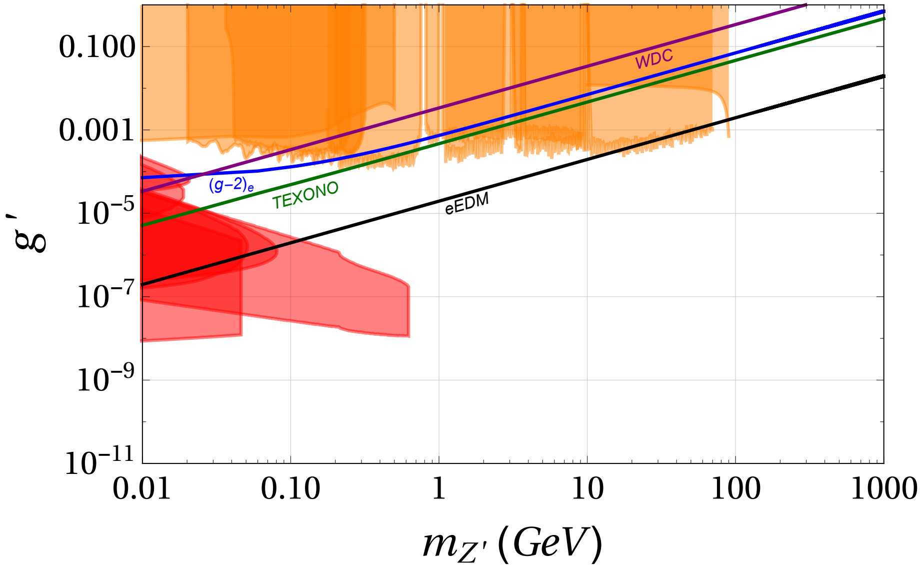
Projections from Belle-II and Mu3e [Perrevoort et al.: 1812.00741]

Preliminary!

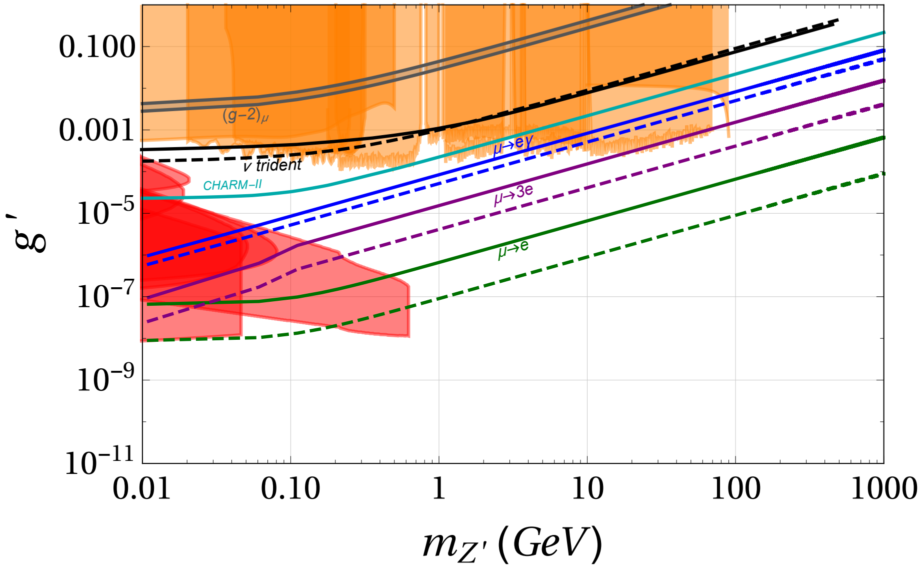
Switch on only quark interactions



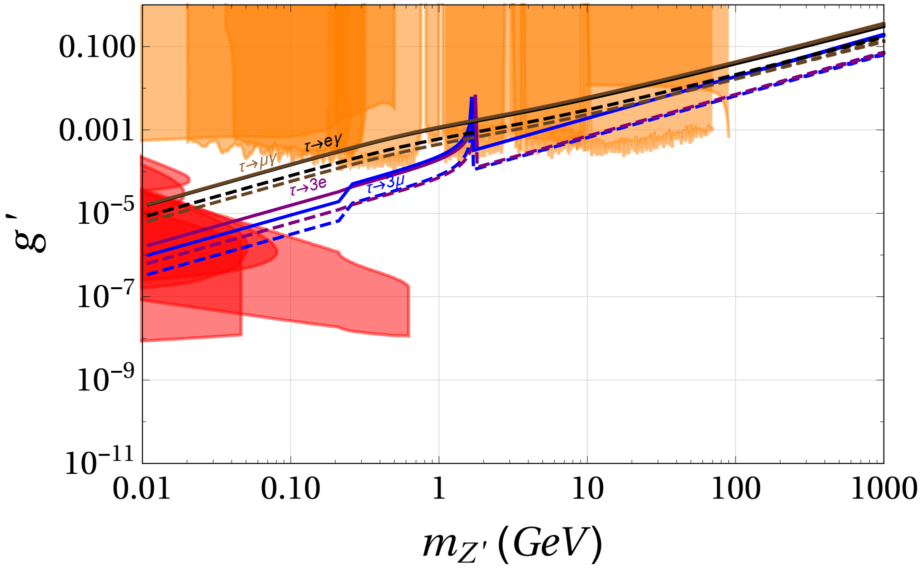
Only electrons



Only muons


0.100
0.001
10^{-5}
10^{-7}
10^{-9}
10^{-11}
g'
0.01
0.10
1
10
100
1000
$m_{Z'}\,(GeV)$
$(g-2)_\mu$
ν trident
CHARM–II
μ→eγ
μ→3e
μ→e

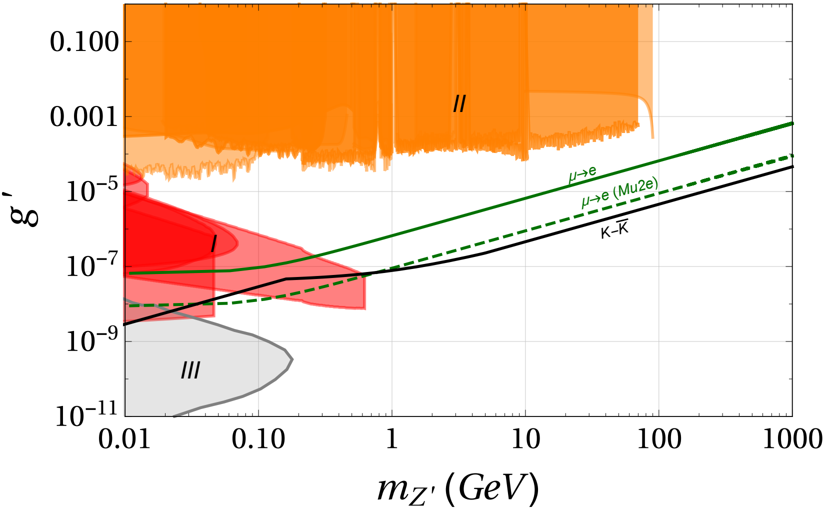
Only taus



0.100
0.001
10^{-5}
10^{-7}
10^{-9}
10^{-11}
g'
0.01
0.10
1
10
100
1000
$m_{Z'}\,(GeV)$
$\tau\to e\gamma$
$\tau\to\mu\gamma$
$\tau\to 3e$
$\tau\to 3\mu$

Preliminary!

Strongest bounds on parameter space



Summary and Conclusions

- we identified a simple anomaly free twist of FN models of flavor;
- expansion in $M/\langle\phi\rangle \sim \lambda$ can reproduce fermion mass spectrum;
- can be gauged;
- rich phenomenology for Z';
- Z' can be light.

Thanks!

Backup slides

Before electroweak symmetry breaking: $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{fermion} \supset i \sum_f \bar{f} \not{D} f - \sum_{j=1}^{3} Y_j^{\ell} \bar{L}_L H \ell_R - \sum_{j=1}^{3} \left(Y_j^d \bar{q}_L H d_R + Y_j^u \bar{q}_L \tilde{H} u_R \right) + \text{h.c.}$$

Fermion mass

Before electroweak symmetry breaking: $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{fermion} \supset i \sum_f \bar{f} \not{D} f - \sum_{j=1}^{3} Y_j^\ell \bar{L}_L H \ell_R - \sum_{j=1}^{3} \left(Y_j^d \bar{q}_L H d_R + Y_j^u \bar{q}_L \tilde{H} u_R \right) + \text{h.c.}$$

Yukawa couplings Y_j are free parameters of the theory.

No symmetry or other mechanism preventing them to be all of $\mathcal{O}(1)$.

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Yukawa couplings Y_j are free parameters of the theory.

No symmetry or other mechanism preventing them to be all of $\mathcal{O}(1)$.

Higgs acquires a vev $v = 246$ GeV ⇒ EWSB: $SU(3)_C \times U(1)_{em}$

$$\mathcal{L}_{fermion} \supset -\sum_f \left(\frac{Y_f v}{\sqrt{2}} \bar{f}_L f_R + \text{h.c.} \right), \qquad m_f = \frac{Y_f v}{\sqrt{2}},$$

The Yukawa determines the fermion mass.

If all of $\mathcal{O}(1)$, all fermions have similar masses, but...

Fermion mixing

The covariant derivative contains the gauge boson fields

$$\mathcal{L}_{fermion} \supset i\sum_f \bar{f}\not{D}f - \sum_{j=1}^{3} Y_j^\ell \bar{L}_L H \ell_R - \sum_{j=1}^{3}\left(Y_j^d \bar{Q}_L H d_R + Y_j^u \bar{Q}_L \tilde{H} u_R\right) + \text{h.c.}$$

Charged currents mediated by W_μ boson

$$\mathcal{L}_{CC} \propto W_\mu^\dagger \left(\bar{u}\gamma^\mu(1-\gamma_5)d + \bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\ell + \text{h.c.}\right)$$

Rotate from interaction basis to mass basis

$$f' = V_f f\,, \quad V_f^\dagger V_f = 1$$

$$\mathcal{L}_{CC} \propto W_\mu^\dagger \left(\bar{u}' \underbrace{V_u^\dagger V_d}_{CKM} \gamma^\mu(1-\gamma_5)d' + \bar{\nu}'_\ell \underbrace{V_\nu^\dagger V_\ell}_{PMNS} \gamma^\mu(1-\gamma_5)\ell' + \text{h.c.}\right)$$

$K^0 - \bar{K}^0$

- light Z': use ChPT with Z' as external field. Leading order is axial

$$(\bar{s}\gamma^\mu\gamma_5 d) \to -f_K \partial^\mu K^0 + \cdots$$

Vector part comes at 1-loop.

$$M_{12}^{Z'} = \langle K^0|\mathcal{H}_{\rm eff}^{Z'}|\bar{K}^0\rangle = -g'^2 (c_{dA}^{12})^2 f_K^2 \frac{m_K^2}{m_{Z'}^2},$$

$1/m_{Z'}^2$ behavior from longitudinal component of propagator.

- heavy Z': integrate out the Z' at scale $\mu \simeq m_{Z'}$. Match onto effective hamiltonian $H_{\rm eff} = \sum_a C_a Q_a$.

$$Q_1^{sd} = (\bar{d}\gamma^\mu s_L)^2, \tilde{Q}_1^{sd} = (\bar{d}\gamma^\mu s_R)^2, Q_5^{sd} = (\bar{d}^\alpha s_R^\beta)(\bar{d}^\beta s_L^\alpha).$$

With coefficients

$$C_1^{sd} = \frac{g'^2}{m_{Z'}^2}(c_{d_L}^{12})^2, \quad \tilde{C}_1^{sd} = \frac{g'^2}{m_{Z'}^2}(c_{d_R}^{12})^2, \quad C_5^{sd} = -4\frac{g'^2}{m_{Z'}^2} c_{d_L}^{12} c_{d_R}^{12},$$

Run these from $\mu \simeq m_{Z'}$ to $\mu \simeq 2$ GeV.

$B_q - \bar{B}_q$

- light Z': Operator Product Expansion at $\mu \simeq m_b$.

$$Q_2^{qb} = (\bar{b}_R q_L)^2, \tilde{Q}_2^{qb} = (\bar{b}_L q_R)^2, Q_4^{qb} = (\bar{b}_R q_L)(\bar{b}_L q_R).$$

With coefficients

$$C_2^{qb} = -\frac{g'^2}{m_{Z'}^2}(c_{d_L}^{i3})^2, \quad \tilde{C}_2^{qb} = -\frac{g'^2}{m_{Z'}^2}(c_{d_R}^{i3})^2, \quad C_4^{qb} = -2\frac{g'^2}{m_{Z'}^2} c_{d_L}^{i3} c_{d_R}^{i3}$$

- heavy Z': integrate out the Z' at scale $\mu \simeq m_{Z'}$. Match onto effective hamiltonian $H_{\text{eff}} = \sum_a C_a Q_a$.

$$Q_1^{qb} = (\bar{b}\gamma^\mu q_L)^2, \tilde{Q}_1^{qb} = (\bar{b}\gamma^\mu q_R)^2, Q_5^{qb} = (\bar{b}^\alpha q_R^\beta)(\bar{b}^\beta q_L^\alpha).$$

With coefficients

$$C_1^{qb} = \frac{g'^2}{m_{Z'}^2}(c_{d_L}^{i3})^2, \quad \tilde{C}_1^{qb} = \frac{g'^2}{m_{Z'}^2}(c_{d_R}^{i3})^2, \quad C_5^{qb} = -4\frac{g'^2}{m_{Z'}^2} c_{d_L}^{i3} c_{d_R}^{i3},$$

Run these from $\mu \simeq m_{Z'}$ to $\mu \simeq m_b$.