Beyond the Standard Model, including Neutrinos

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Outline

- General considerations on physics Beyond the SM (BSM)
    - The SM challenge to New Physics
    - Why Beyond
    - The SM as an effective theory
- Neutrino masses and BSM
    - High scale origin of neutrino masses
    - Low scale origin of neutrino masses
    - Neutrino properties and their implications for model building

The SM challenge to New Physics

but first, a boring preliminary: L and R fermions

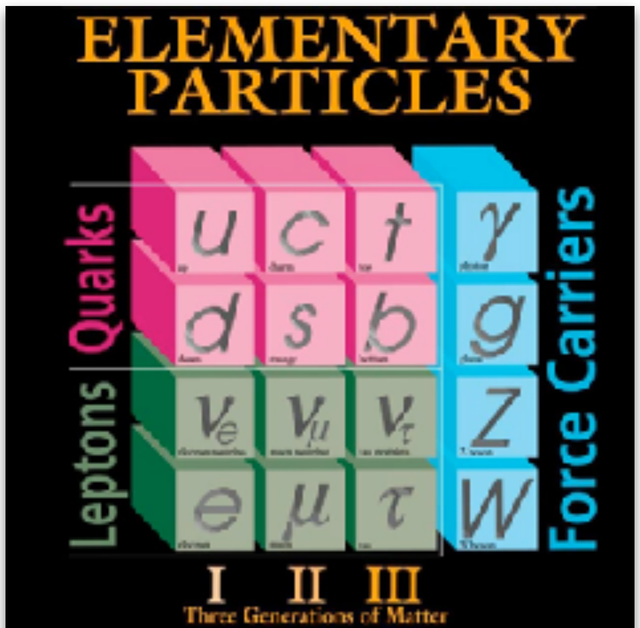
A Dirac spinor is not “elementary”

$$\Psi(x) = \begin{pmatrix} \Psi_1(x) \\ \Psi_2(x) \\ \Psi_3(x) \\ \Psi_4(x) \end{pmatrix} \to \left(\begin{array}{c|c} L^{\dagger -1} & \\ \hline & L \end{array}\right) \begin{pmatrix} \Psi_1(x) \\ \Psi_2(x) \\ \Psi_3(x) \\ \Psi_4(x) \end{pmatrix} \qquad (\det L = 1)$$

$$\Psi_R(x) = \begin{pmatrix} \Psi_1(x) \\ \Psi_2(x) \\ 0 \\ 0 \end{pmatrix} \qquad \Psi_L(x) = \begin{pmatrix} 0 \\ 0 \\ \Psi_3(x) \\ \Psi_4(x) \end{pmatrix} \qquad \Psi = \Psi_L + \Psi_R$$

inequivalent, conjugated representations of SO(3,1)

Left- and Right-handed



u_{iL} d_{iL} v_{iL} e_{iL} L

u_{iR} d_{iR} e_{iR} R

$\overline{u_{iL}}$ $\overline{d_{iL}}$ $\overline{v_{iL}}$ $\overline{e_{iL}}$ R

$\overline{u_{iR}}$ $\overline{d_{iR}}$ $\overline{e_{iR}}$ L

Most general gauge transformation can mix all L

The SM fermions in a BSM perspective

- $d_{iL} \quad u_{iL} \quad e_{iL} \quad \nu_{e_i L} \quad \overline{d_{iR}} \quad \overline{u_{iR}} \quad \overline{e_{iR}} \quad + \ \text{h.c.}$

- We will also denote the L-handed dofs as follows
  - $\psi_L \rightarrow \psi$ (L-handed)
  - $\overline{\psi_R} \rightarrow \psi^c$ (L-handed)

- $d_i \quad u_i \quad e_i \quad \nu_{e_i} \quad d_i^c \quad u_i^c \quad e_i^c \quad + \ \text{h.c.}$

$$\Psi = \begin{pmatrix} \epsilon\,\psi_c^* \\ \psi \end{pmatrix} \qquad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \qquad \Psi_L \leftrightarrow \psi$$

$$\overline{\Psi_R} \leftrightarrow \psi^c$$

- $\Psi_L = \begin{pmatrix} 0 \\ \psi \end{pmatrix}, \overline{\Psi_R} = \begin{pmatrix} 0 \\ \epsilon\,\psi_c \end{pmatrix}$

- $\Psi_L \to \begin{pmatrix} 0 & \\ & L \end{pmatrix} \Psi_L \qquad \psi \to L\psi$

  $\overline{\Psi_R} \to \begin{pmatrix} 0 & \\ & L^{T-1} \end{pmatrix} \overline{\Psi_R} \qquad \psi^c \to L\psi^c$

$$\underbrace{\Psi_L, \overline{\Psi_R}}_{\text{left}} + \underbrace{\overline{\Psi_L}, \Psi_R}_{\text{right}} \leftrightarrow \underbrace{\psi, \psi_c}_{\text{left}} + \underbrace{\psi^*, \psi_c^*}_{\text{right}}$$

- There exists a unique way of combining two elementary fermions in a Lorentz invariant way

$$\psi_1\psi_2 = \psi_2\psi_1 = \psi_1^\alpha \epsilon_{\alpha\beta} \psi_2^\beta$$

- Most general (Lorentz) mass term and Yukawa with $\psi_1,\ldots,\psi_n$

$$\frac{m_{ij}}{2}\psi_i\psi_j + \text{h.c.}$$

$$\frac{\lambda_{ij}}{2}\psi_i\psi_j\phi^{(*)} + \text{h.c.}$$

(only terms allowed by gauge invariance)

The SM challenge to New Physics

The SM challenge to New Physics

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{l} \bar\Psi_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \\ +\lambda_{ij}\Psi_i\Psi_j H + \text{h.c.} \\ +|D_\mu H|^2 - V(H) \end{array}$$

$\bar\Psi_i i\gamma^\mu D_\mu \Psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$	gauge	few ‰
$+\lambda_{ij}\Psi_i\Psi_j H + \text{h.c.}$	flavor	few %
$+\lvert D_\mu H\rvert^2 - V(H)$	symmetry breaking	few 10%

Notable features

- Gauge sector
  - chirality
  - anomaly cancellation
  - electroweak precision tests
- Flavour sector
  - $U(3)^5$ and accidental symmetries
  - no tree level FCNC
  - anomalous suppression of loop FCNC
- Higgs sector
  - electric charge conserved
  - custodial symmetry
  - perturbative extrapolation

Gauge sector

$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$$Q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix} \qquad L_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}$$

	SU(3)	SU(2)	U(1)
L_i	1	2	-1/2
e^c_i	1	1	1
Q_i	3	2	1/6
u^c_i	3^*	1	-2/3
d^c_i	3^*	1	1/3
			Y

L-handed spinors

i = 1,2,3

A nice property

- The fermion content is “chiral”: no L and R with same G_{SM} quantum numbers

- Equivalently: r irrep on L ⇒ r* is not

- Equivalently: no explicit (G_{SM} symmetric) fermion mass term is allowed

- Extra heavy fermions ($M \gg \langle H \rangle$) should be “vectorlike”

- A puzzle, a blessing, or what expected?

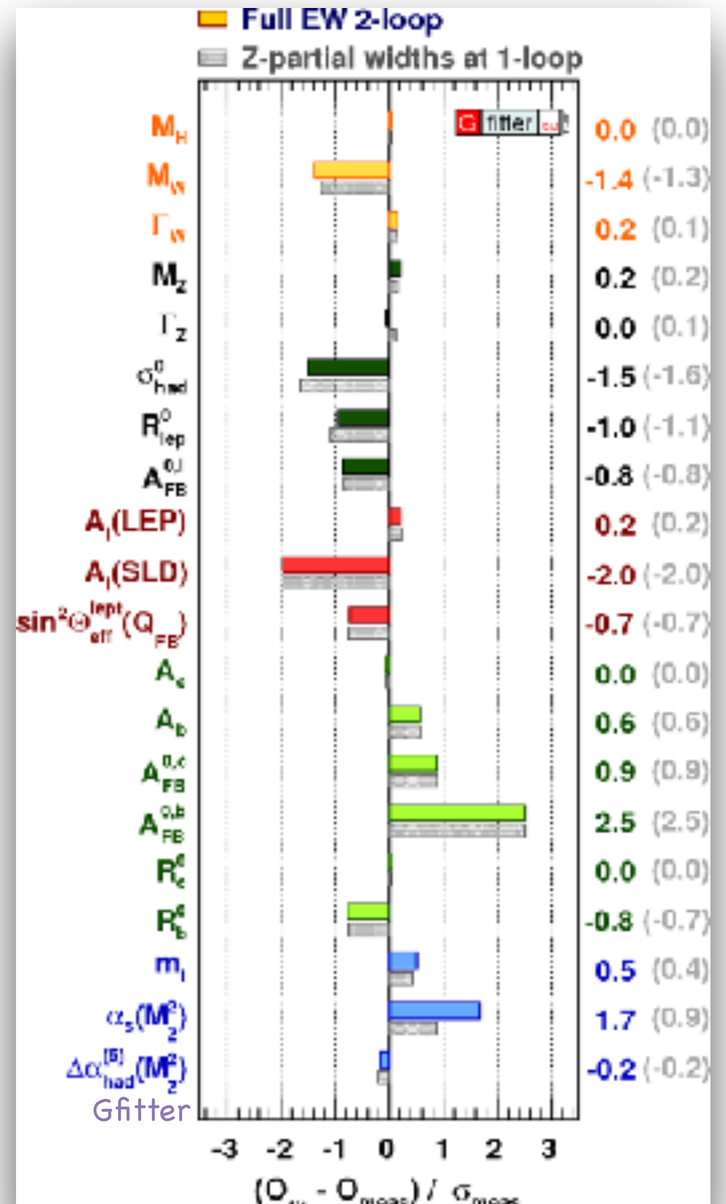
Another nice property

- Anomaly cancellation
- Is $T_{ijk} \equiv \mathrm{Tr}\,(\tau_i\,\{\tau_j, \tau_k\}) = 0$? $\tau_i = T_A, T_a, Y$

$SU(3)^3$	vectorlike
$SU(3)^2 \times SU(2)$	$\mathrm{Tr}(\sigma_a) = 0$
$SU(3)^2 \times U(1)$	$2\,Y_q + Y_{u^c} + Y_{d^c} = 0$
$SU(3) \times (\text{not } SU(3))^2$	$\mathrm{Tr}(\lambda_A) = 0$
$SU(2)^2 \times U(1)$	$Y_l + 3Y_q$
$U(1)^3$	$2Y_l^3 + 6Y_q^3 + 3Y_{u^c}^3 + 3Y_{d^c}^3 + Y_{e^c}^3 = 0$
grav. anomaly	$2Y_l + 6Y_q + 3Y_{u^c} + 3Y_{d^c} + Y_{e^c} = 0$

(nice, but why??)

Electroweak precision tests (EWPT)



- Accuracy up to the ‰ level → sensitivity to 1-loop corrections, which involve
  - g, g’, v
  - m_t , $\alpha_s(MZ)$, $\Delta\alpha_{had}(MZ)$
  - m_h
- and bring together
  - the gauge sector: $g^2/(4\pi)^2$, $g'^2/(4\pi)^2$
  - the flavour sector: $\lambda^2/(4\pi)^2$
  - the EW-breaking sector: $g^2/(4\pi)^2 \log(m_h/M_W)$
- The agreement works because of the relatively low value of m_h

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  - electric charge conserved
  - custodial symmetry
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The flavour sector

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{ll} \psi_i^\dagger i\sigma^\mu D_\mu \psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} & \text{gauge} \\ +\lambda_{ij}\psi_i\psi_j H + \text{h.c.} & \text{flavor} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \end{array}$$

family number (horizontal) not understood

	1	2	3
l	l_1	l_2	l_3
e^c	$(e^c)_1$	$(e^c)_2$	$(e^c)_3$
q	q_1	q_2	q_3
u^c	$(u^c)_1$	$(u^c)_2$	$(u^c)_3$
d^c	$(d^c)_1$	$(d^c)_2$	$(d^c)_3$

gauge irreps (vertical) well understood

The flavour sector allows to tell the three families: gauge interactions are $U(3)^5$ symmetric

U(3)⁵ x U(1)$_H$

$$\mathcal{L}_{\text{SM}}^{\text{ren}} = \begin{array}{ll} \psi_i^\dagger i\sigma^\mu D_\mu \psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} & \text{gauge} \\ +\lambda_{ij}\psi_i\psi_j H + \text{h.c.} & \text{flavor} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \end{array}$$

Family replication ↔ the gauge lagrangian cannot tell families ↔ is U(3)⁵ invariant:

$$U(3)^5: \begin{array}{l} L_i \to U^L_{ij} L_j \\ e^c_i \to U^{e^c}_{ij} e^c_j \\ Q_i \to U^Q_{ij} Q_j \Rightarrow \mathcal{L}_{\text{SM}}^{\text{gauge}} \to \mathcal{L}_{\text{SM}}^{\text{gauge}} \\ u^c_i \to U^{u^c}_{ij} u^c_j \\ d^c_i \to U^{d^c}_{ij} d^c_j \end{array}$$

also $U(1): H \to e^{i\alpha} H \Rightarrow \mathcal{L}_{\text{SM}}^{\text{EWSB}} \to \mathcal{L}_{\text{SM}}^{\text{EWSB}}$

U(3)^5

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{ll} \psi_i^\dagger i\sigma^\mu D_\mu \psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} & \text{gauge} \\ +\lambda_{ij}\psi_i\psi_j H + \text{h.c.} & \text{flavor} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \end{array}$$

The flavour (Yukawa) lagrangian is is not U(3)^5 invariant (unless $\lambda_{ij}=0$)

$$U(3)^5: \begin{array}{l} l_i \to U^l_{ij} l_j \\ e^c_i \to U^{e^c}_{ij} e^c_j \\ q_i \to U^q_{ij} q_j \\ u^c_i \to U^{u^c}_{ij} u^c_j \\ d^c_i \to U^{d^c}_{ij} d^c_j \end{array} \Rightarrow \begin{array}{l} \lambda_E \to U^T_{e^c} \lambda_E U_L \\ \lambda_D \to U^T_{d^c} \lambda_D U_Q \\ \lambda_U \to U^T_{u^c} \lambda_U U_Q \end{array} \quad \begin{array}{l} \mathcal{L}^{\rm gauge}_{\rm SM} \to \mathcal{L}^{\rm gauge}_{\rm SM} \\ \mathcal{L}^{\rm SB}_{\rm SM} \to \mathcal{L}^{\rm SB}_{\rm SM} \\ \langle h \rangle \to \langle h \rangle \end{array}$$

$$\mathcal{L}^{\rm flavor}_{\rm SM} = \lambda^E_{ij} e^c_i l_j H^\dagger + \lambda^D_{ij} d^c_i q_j H^\dagger + \lambda^U_{ij} u^c_i q_j H + \text{h.c.}$$

Accidental symmetries (ren lagrangian)

- The flavour lagrangian breaks $U(3)^5 \times U(1)_H$ to $U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_B \times U(1)_Y$

$$\lambda^E_{ij} e^c_i L_j H^\dagger \longrightarrow \lambda_{e_i} e^{c\prime}_i L^\prime_i H^\dagger$$
$$\lambda^D_{ij} d^c_i Q_j H^\dagger \longrightarrow \lambda_{d_i} d^{c\prime}_i Q^\prime_i H^\dagger$$
$$\lambda^U_{ij} u^c_i Q_j H \longrightarrow \lambda_{u_i} V_{ij} u^{c\prime}_i Q^\prime_i H$$

- L_e L_μ L_τ individual lepton numbers (also $L = L_e + L_\mu + L_\tau$ total)
  B Baryon number

- Welcome that they arise as accidental symmetries
  - prediction of the SM, not by hand
  - broken by non perturbative effects
  - allows SM extensions in which they are broken (e.g. GUTs, see-saw) (effects can be parameterised by non-renormalisable operators)
  - allows such extensions to be tested (e.g. nu masses, proton decay)
  - property not necessarily shared by SM extensions

No tree level FCNC

- Fermion masses: $H = \begin{pmatrix} 0 \\ v + \frac{h}{\sqrt{2}} \end{pmatrix}$ (unitarity gauge)

$$\begin{aligned}\mathcal{L}_{\rm SM}^{\rm flavor} &= \lambda^E_{ij} e^c_i L_j H^\dagger + \lambda^D_{ij} d^c_i Q_j H^\dagger + \lambda^U_{ij} u^c_i Q_j H + \text{h.c.} \\ &= m^E_{ij} e^c_i e_j \quad + m^D_{ij} d^c_i d_j \quad + m^U_{ij} u^c_i u_j \quad + \text{h.c.} + \ldots\end{aligned}$$

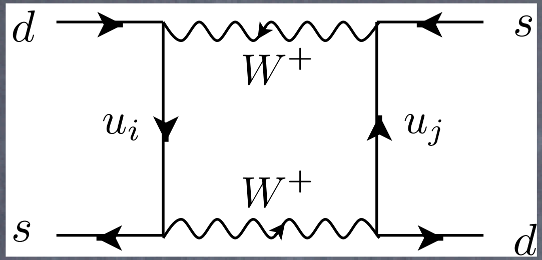
- In terms of mass eigenstates:

$$\begin{aligned} j^\mu_{\rm c,had} &= \overline{u}_i \sigma^\mu d_i = V_{ij} \overline{u}'_i \sigma^\mu d'_j \\ j^\mu_{\rm n,had} &= (j^\mu_{\rm n,had})' \\ j^\mu_{\rm em,had} &= (j^\mu_{\rm em,had})' \end{aligned}$$

$V = U_u U_d^\dagger$ Cabibbo Kobayashi Maskawa (CKM) matrix

Anomalously small loop-induced FCNC

- Expect:



$$\sim \quad \frac{1}{M_W^2} \times \frac{g^4}{(4\pi)^2}$$

K^0 - $\overline{K}^0$ oscillations

- Instead: 10^6 smaller

- Because of peculiar flavour structure of the SM, or approximate $U(2)^5$ symmetry of SM lagrangian

- Challenge for new physics at TeV scale

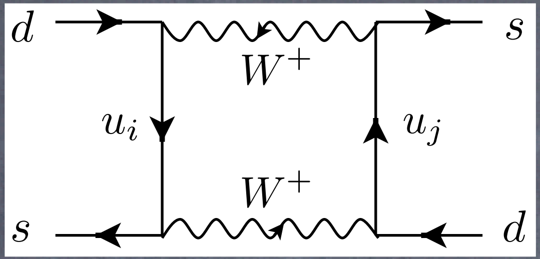
Approximate flavour symmetry

- The flavour lagrangian is approximately $U(2)^5$ flavour symmetric (exactly symmetric in the limit $\lambda = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda_{33} \end{pmatrix}$ which also implies $V = 1_3$)

- This (or equivalently the smallness of $\lambda_{1,2}$ and V_{ij} $i \neq j$) is the origin of the anomalously small FCNC processes in the SM (and the origin of the flavour problem)

Anomalously small loop-induced FCNC

- Because of the approximate $U(2)^5$



K^0 - $\overline{K}^0$ oscillations

$$\sim \quad \frac{1}{M_W^2} \times \frac{g^4}{(4\pi)^2} \times \epsilon$$

$\epsilon = 0 \quad$ in the $U(2)^5$ limit

$\epsilon \sim 10^{-6} \quad$ experiment

- $\left(\epsilon = (V^\dagger_{su_i} V_{u_i d})(V^\dagger_{su_j} V_{u_j d}) f\left(\frac{m^2_{u_i}}{M_W^2}, \frac{m^2_{u_j}}{M_W^2}\right)\right.$

  i = 3: $f = O(1)$, $|V_{td}V_{ts}| \ll 1$

  i = 1,2: $|V_{id}V_{is}| = O(1)$, $f \ll 1$)

Challenge for new physics at TeV

- Same for CP-violating effects

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  - perturbative extrapolation

The Higgs sector

- Most general gauge invariant ren. lagrangian for H:

$$\mathcal{L}_H = (D_\mu H)^\dagger (D^\mu H) - V(H^\dagger H)$$
$$V(H^\dagger H) = \mu^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$

- $\lambda_H > 0$
- $\mu^2 < 0 \Rightarrow \langle H \rangle \neq 0 \Rightarrow$ electroweak symmetry breaking
- ($\mu^2 > 0 \Rightarrow$ still electroweak symmetry breaking, but at $\Lambda \approx m_\pi$)

QED unbroken

- Fix the Higgs quantum numbers from fermion masses. Then the electric charge is automatically conserved

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}, \; v > 0, \; v^2 = \frac{|\mu^2|}{2\lambda_H} \approx (174\,\mathrm{GeV})^2 \qquad m_H^2 = 4\,\lambda_H(v^2)\,v^2$$

$$T = aY + b_a T_a, \; a, b_a \text{ real}, \; T_a = \frac{\sigma}{2}, \; Y = \frac{\mathbf{1}}{2}$$

$$0 = T\,\langle H \rangle = \frac{v}{2} \begin{pmatrix} b_1 - i b_2 \\ a - b_3 \end{pmatrix} \Rightarrow T \propto Q$$

- 3 broken generators $\leftrightarrow$ 3 massive vectors $\leftrightarrow$ 3 unphysical Goldstone bosons $\leftrightarrow$ 1 real physical Higgs particle

Custodial symmetry

- $\rho \equiv \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 \text{ (tree level)}$
  - Not guaranteed by gauge invariance or breaking pattern
  - Peculiar of EW breaking by a doublet
    (dominant contribution from triplets ruled out)
  - Exact in the limit $g' = 0$, $\lambda_U = \lambda_D$

$\rho \approx 1 \leftrightarrow$ (approximate) custodial SU(2)

- $\rho = 1$ if in the $g' = 0$ limit $W^{1,2,3}$ have equal mass

- I.e. if a SO(3) ≈ SU(2) symmetry rotates the real fields $W^{1,2,3}$

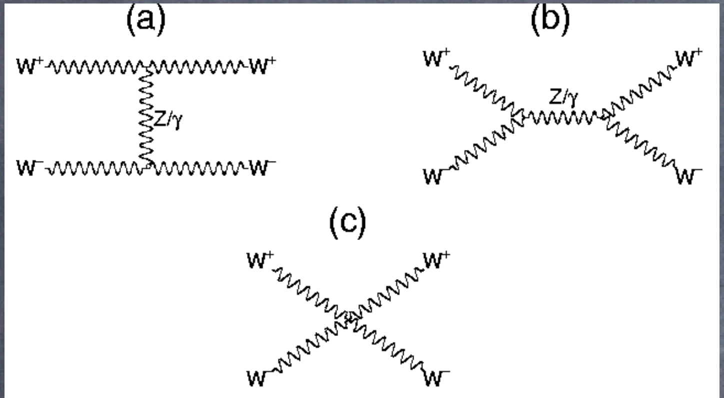
- The custodial symmetry in the Higgs sector: the Higgs lagrangian is accidentally SO(4) symmetric, as
$$|H|^2 = h_{1R}^2 + h_{1I}^2 + h_{2R}^2 + h_{2I}^2$$
SO(4) is spontaneously broken to SO(3) by $\langle h_{2R} \rangle \neq 0$

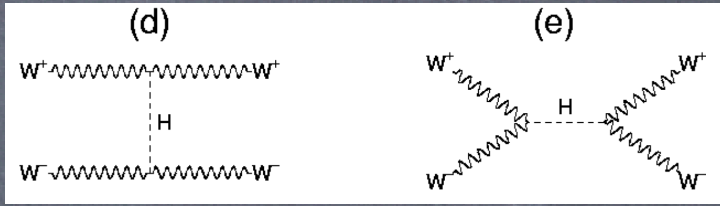
- The custodial symmetry in the fermion sector: SO(4) ≈ $SU(2)_L \times SU(2)_R$, where $SU(2)_R$ acts on the right-handed fields

- The symmetry is exact in the limit $g' = 0$, $\lambda_U = \lambda_D \rightarrow$ loop corrections to $\rho = 1$

Light Higgs + SM couplings = perturbativity

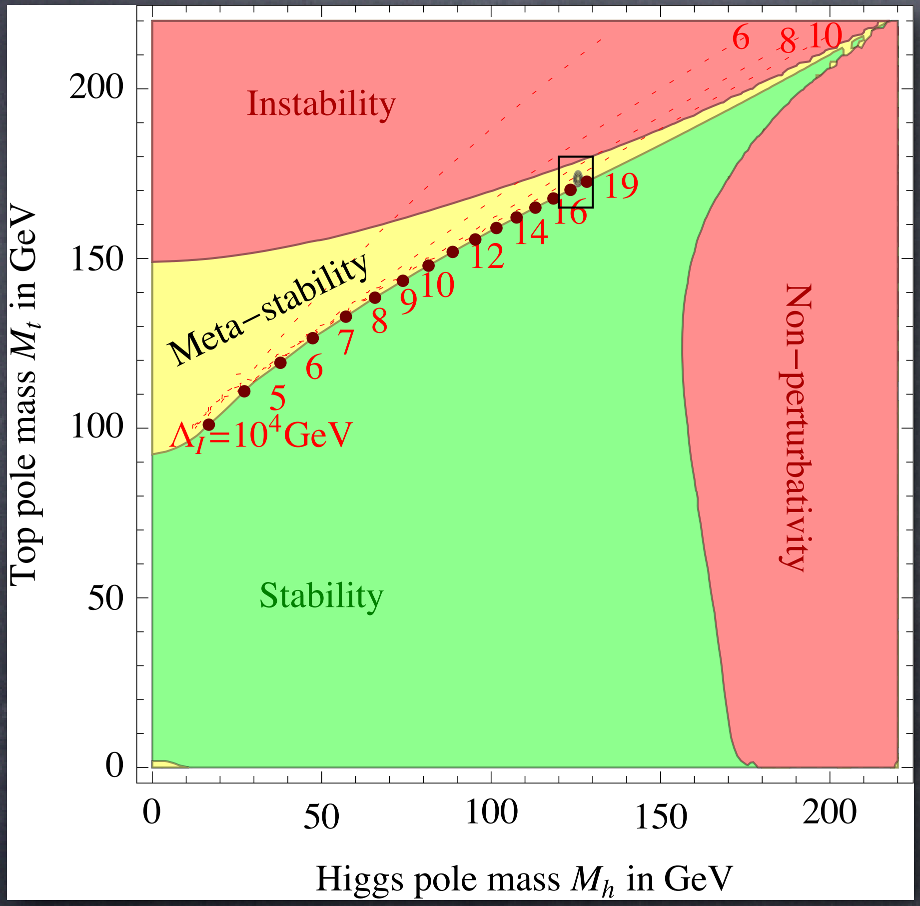
- $A(W_L W_L \to W_L W_L) = \Sigma_l\, a_l\, A_l$, a_l = partial wave amplitude
- Unitarity bound: $|a_0| \leq 1$
- Tree level, no Higgs: $a_0 \sim \frac{s}{16\pi v^2}$, $s = (p_1+p_2)^2$, $v \approx 174$ GeV

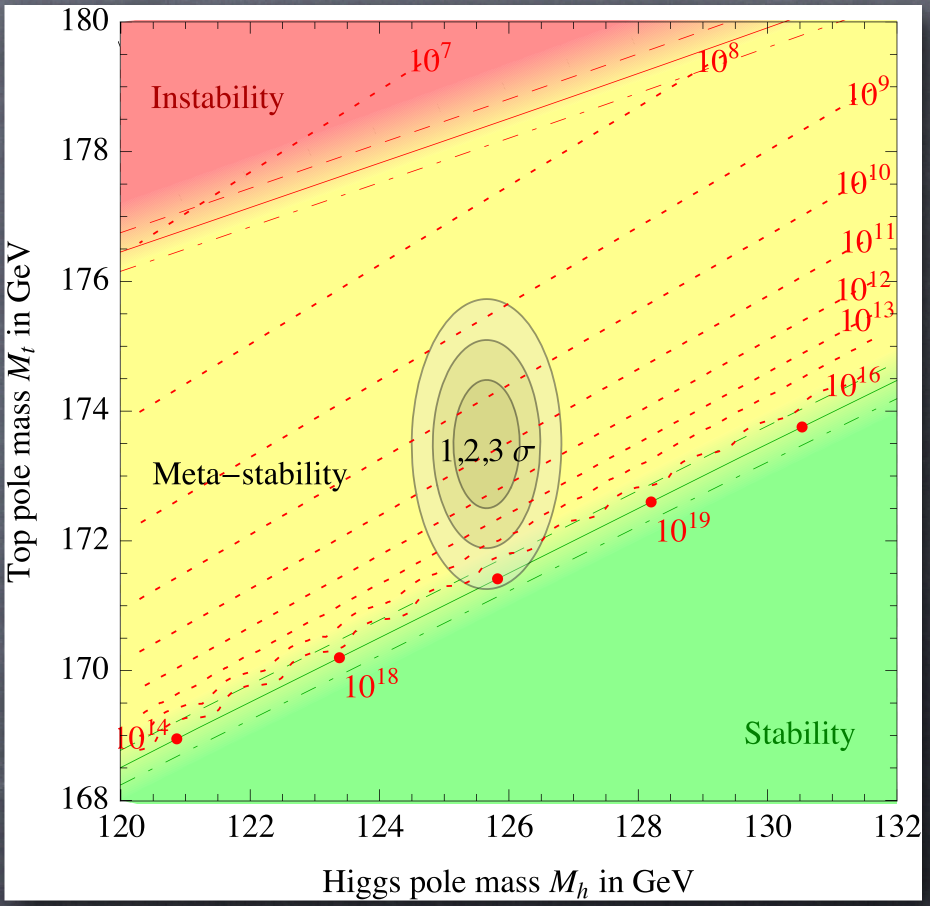




- Unitarity bound saturated at $s \approx (1.2\ \text{TeV})^2$
- Bad behaviour of a_0 due to the longitudinal part of the W propagator ~ $p_\mu p_\nu/(M_W)^2$, cancelled by Higgs exchange

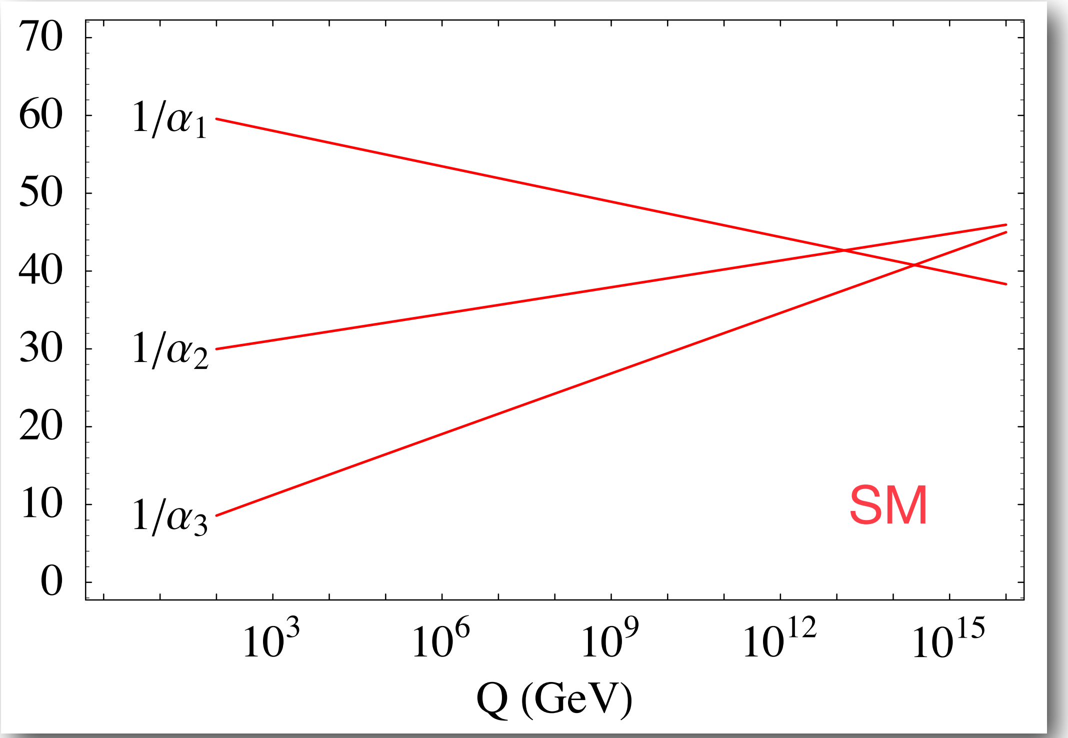
(perturbative extrapolation possible up to M_{Pl})





Buttazzo et al

(perturbative extrapolation possible up to M_{Pl})



Why Beyond?

Some reasons to go beyond the SM

- Experimental "problems" of the SM
    - Gravity
    - Dark matter
    - Baryon asymmetry
    - Neutrino masses
- Experimental "hints" of physics beyond the SM
    - Quantum number unification
- Theoretical puzzles of the SM
    - $\langle H \rangle \ll M_{Pl}$
    - Family replication
    - Small Yukawa couplings, pattern of masses and mixings
    - Gauge group, no anomaly, charge quantization, quantum numbers
- Theoretical problems of the SM
    - Higgs mass naturalness problem
    - Cosmological constant problem
    - Strong CP problem
    - Landau poles

Experimental “problems” of the SM

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Experimental “hints” of physics beyond the SM

- Quantum number unification

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Q_i	3	2	1/6
u^c_i	3^*	1	-2/3
d^c_i	3^*	1	1/3
			Y

⇒

SO(10)
16

p-decay bounds: $M \gg m_H$

an accident?

Theoretical puzzles of the SM

- $\langle H \rangle \ll M_{Pl}$
- Family replication
- Small Yukawa couplings, masses and mixings

Theoretical problems of the SM

- Landau poles
- Strong CP problem $\theta\, G_{\mu\nu}\tilde{G}^{\mu\nu}$ $D=4$
- Naturalness problem $\alpha\, Q^2_{\max} H^\dagger H$ $D=2$
- Cosmological constant problem $\beta\, Q^4_{\max}\sqrt{g}$ $D=0$

General approach to physics beyond the EW scale:

The SM as an effective theory

Reminder

- $S = \int d^4x\, \mathcal{L}(x)$ basic object, $[\mathcal{L}] = 4,\ \mathcal{L}(x) = \sum_i c_i \mathcal{O}_i(x)$

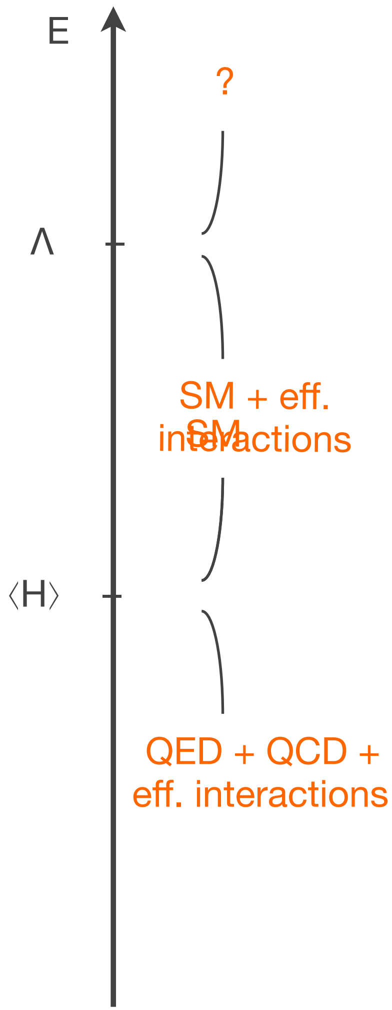
- Dimension D of O(x):
  - D = 0 constant terms, not physical without gravity
  - D = 1 linear terms, reabsorbed by shifting fields (SSB)
  - D = 2,3 "relevant" operators $[c] = M^2, M$
  - D = 4 "marginal operators" $[c] = g$
  - D ≥ 5 "irrelevant operators" $[c] = 1/M^{D-4}$

renormalizable theory (D = 0 to D = 4)

effective theory (D = 0 to D ≥ 5)

- Irrelevant operators: effect suppressed by $(E/M)^{D-4}$ at $E \ll M$
  - finite number of counter-terms order by order in D-expansion
  - any theory looks renormalizable at sufficiently low scales

The SM as an effective theory



Analogously..

$$\mathcal{L}^{\text{eff}}_{E \ll \Lambda} = \mathcal{L}^{\text{ren}}_{\text{SM}} + \mathcal{L}^{\text{NR}}_{\text{SM}}$$

(in the limit $\Lambda \gg M_Z$)

Effective theories

- $\mathcal{L}(\phi, \Phi) \qquad \phi \text{ light, } \Phi \text{ heavy}$

- At scales E « Λ ~ mass of Φ

from eqs of motion of Φ

- $\mathcal{L}_{\text{eff}}(\phi) = \mathcal{L}(\phi, \Phi(\phi)) = \mathcal{L}_{\text{ren}}(\phi) + \sum_n \frac{c_n}{\Lambda^n} \mathcal{O}_{4+n}(\phi)$

- Only depends on light dofs

The SM as a effective theory

$$\mathcal{L}^{\text{eff}}_{E\ll\Lambda} = \mathcal{L}^{\text{ren}}_{\text{SM}} + \sum_n \frac{c_n}{\Lambda^n}\,\mathcal{O}_{4+n}$$

- Consistent renormalisation at each order in (E/Λ)
- Low E effects suppressed by $(E/\Lambda)^n$
- Allows a general parameterisation of the low scale indirect effects of any heavy new physics in terms of light fields only
- The identification of O_{4+n} would provide a crucial handle on the underlying physics (example: from Fermi theory to SM)
- No clear hint of O_{4+n} from the TeV scale (but hints from higher scales)

- The best chance for indirect NP effects to emerge is if they violate the "accidental symmetries" symmetries of $\mathcal{L}_{\mathrm{SM}}^{\mathrm{ren}}$, also called: L_e, L_μ, L_τ B
- NP effects can also emerge if suppressed in $\mathcal{L}_{\mathrm{SM}}^{\mathrm{ren}}$, e.g. if they contribute to
  - Flavour Changing Neutral Current (FCNC) processes
  - CP-violating (CPV) processes
  - Electroweak precision tests (EWPT)

Lepton number violating operators

The SM effective lagrangian contains only a single dimension 5 operator, which happens to violate lepton number: the “Weinberg operator”

$$\mathcal{L}^{\text{eff}}_{E\ll\Lambda} = \mathcal{L}^{\text{ren}}_{\text{SM}} + \frac{c_{ij}}{2\Lambda}(h\,l_i)(h\,l_j) + \ldots$$

$$(h\,l) \equiv \epsilon_{rs} h_r l_s$$

Neutrino masses from the Weinberg operator

$$\mathcal{L}^{\text{eff}}_{E \ll \Lambda} = \mathcal{L}^{\text{ren}}_{\text{SM}} + \frac{c_{ij}}{2\Lambda}(h\, l_i)(h\, l_j) + \ldots$$

$$m^{E,D,U}_{ij} = \lambda^{E,D,U}_{ij} v \qquad m^{\nu}_{ij} = c_{ij} v \times \frac{v}{\Lambda}$$ (Majorana)

$$\Lambda \sim 0.5 \times 10^{15}\,\text{GeV}\, c \left(\frac{0.05\,\text{eV}}{m_\nu}\right)$$

Baryon number violating operators

- Arise at the D=6 level (SUSY: D=5)
- With one family, only 4 possible operators:

$$G_1\, qqql + G_2\, d^c d^c u^c e^c + G_3\, u^c e^c q^* q^* + G_4\, d^c u^c q^* l^*$$

- They all (accidentally) conserve B-L (B-breaking L-conserving at D=9)
- Induce p-decay
- $\Gamma(p \to e\pi) = f(G_1, G_2, G_3, G_4)$
- $|G_i| \lesssim (10^{15}\ \text{GeV})^{-2}$

Bounds on NR terms

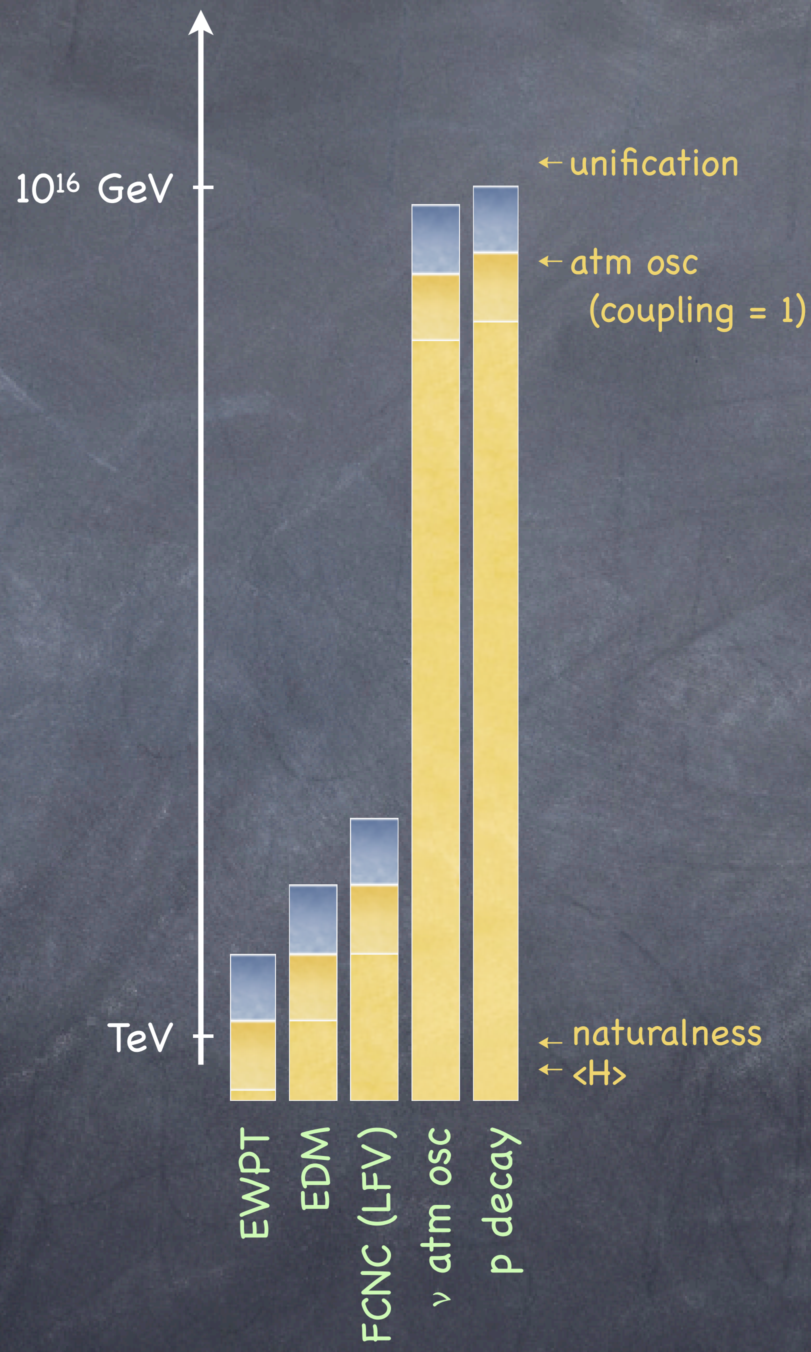
- B number e.g. $\frac{c}{\Lambda^2} qqql$ (proton decay) $\Lambda > c^{1/2}\, 10^{15}$ GeV
- L number e.g. $\frac{c}{\Lambda} llhh$ (neutrino masses) $\Lambda \approx c\; 0.5\; 10^{15}$ GeV
- L_i numbers e.g. $\frac{c}{\Lambda^2} \mu^c \sigma^{\mu\nu} l_e F_{\mu\nu} h$ ($\mu \to e\gamma$) $\Lambda > c^{1/2}\, 10^3$ TeV

SM accidental symmetries

- Quark FCNC, CP e.g. $\frac{c}{\Lambda^2} \bar{s}\sigma^\mu d\, \bar{s}\sigma_\mu d$ (ε_K, Δm_K) $\Lambda > c^{1/2}$ 500 TeV

$c_{SM} \approx 10^{-8}$
(loop + $U(2)^5$)

- $\frac{c}{\Lambda^2} |h^\dagger D_\mu h|^2$, $\frac{c}{\Lambda^2} \bar{e}\sigma^\mu e\, \bar{e}_i \sigma_\mu e_i$ (EWPTs) $\Lambda > c^{1/2}$ 5 TeV



10^{16} GeV
TeV
← unification
← atm osc
(coupling = 1)
← naturalness
← <H>
EWPT
EDM
FCNC (LFV)
ν atm osc
p decay