Beyond the SM

Many reasons to go beyond the SM

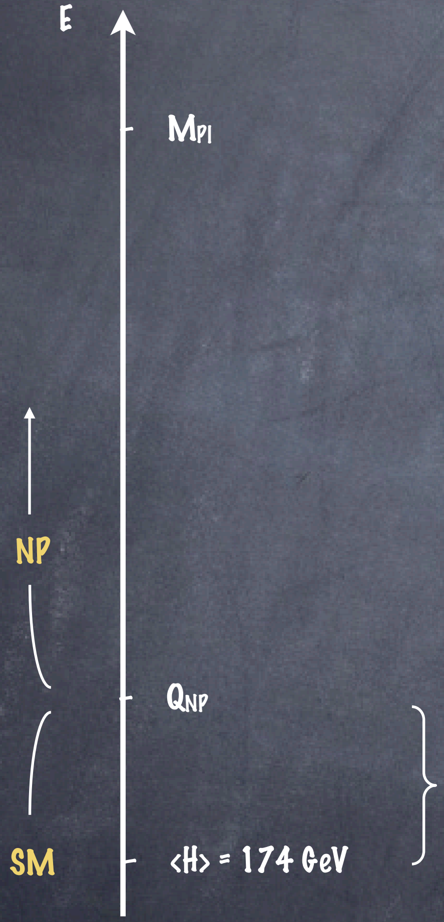
- Experimental “problems” of the SM
  - Gravity
  - Dark matter
  - Baryon asymmetry
- Experimental “hints” of physics beyond the SM
  - Neutrino masses
  - Quantum number unification
- Theoretical puzzles of the SM
  - $\langle H \rangle \ll M_{Pl}$
  - Family replication
  - Small Yukawa couplings,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

The naturalness argument

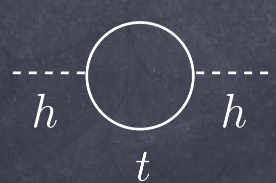
Known fields: g_A^μ W_a^μ B^μ Q_i u_i^c d_i^c L_i e_i^c G_a h

- A scalar field!
  - $m^2_h \approx (m^2_h)_0 + (125\text{GeV})^2\,(Q_{NP}/0.5\text{TeV})^2$
- $Q_{NP} \gg$ TeV needs delicate cancellations, therefore either
  - NP @ TeV cuts-off δm^2_h or
  - the electroweak scale is accidentally smaller than expected

Naturalness

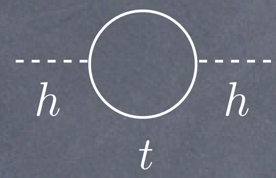


$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2$$



Analogously: contributions from gauge and Higgs self-interaction

More on renormalizability and naturalness

- $\delta m_h^2 \sim \delta m_h^2(\text{top}) \approx$ 

$= 12\,\lambda_t^2 \int \frac{k^3 dk}{8\pi^2}\frac{1}{k^2} + \ldots \xrightarrow{\text{cut-off}} \frac{3G_{\mathrm{F}}}{\sqrt{2}\pi^2} m_t^2 Q^2$

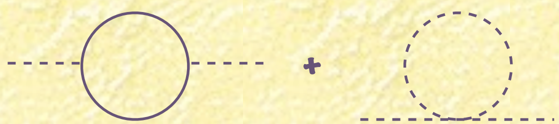
- Renormalization: $(m_h^2)_{\text{phys}} \approx (m_h^2)_{\text{tree}} + \frac{3G_{\mathrm{F}}}{\sqrt{2}\pi^2} m_t^2 Q^2, \quad Q \to \infty$

- The naturalness problem arises if Q corresponds to a physical threshold

Another caveat: the cosmological constant problem

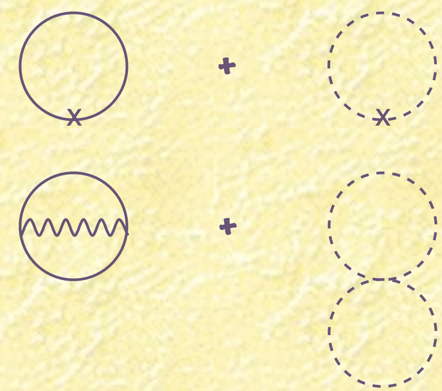
$\delta m_H^2 \propto Q_{\rm NP}^2 \rightarrow Q_{\rm NP} \sim m_H$

SUSY: $\delta m_H^2 \propto \tilde{m}^2 \log \frac{Q_{\rm SUSY}}{\tilde{m}}$



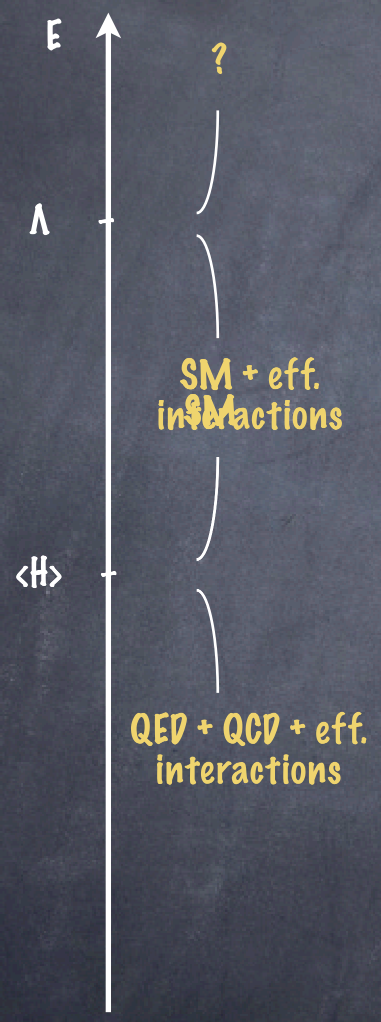
$\delta\Lambda \propto Q_x^4 \rightarrow Q_x \sim 10^{-3}\,{\rm eV???}$

SUSY: $\delta\Lambda \propto \tilde{m}^2 Q_{\rm SUSY}^2$



The SM
as an effective theory

The SM as an effective theory



Analogously..

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

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

The SM as an 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 renormalization at each order in (E/Λ)
- Low E effects suppressed by $(E/\Lambda)^n$
  (ren.bility not fundamental in 4D QFT?)
- Allows a general parameterization of any new physics at $\Lambda \gg E$ in terms of light fields only ("indirect effects")
- Identification of $O^{(n)}$ allows to understand the underlying physics (example: from Fermi theory to SM)
- No clear hint of $O^{(n)}$ from the TeV scale (only hint: neutrino masses)

- Best chance for indirect NP effects to emerge is if they violate symmetries $\mathcal{L}_{\mathrm{SM}}^{\mathrm{ren}}$, also called "accidental symmetries": L_i, B

- NP effects can also emerge if are suppressed in the presence of $\mathcal{L}_{\mathrm{SM}}^{\mathrm{ren}}$ only, e.g. if they contribute to

  - Flavour Changing Neutral Current (FCNC) processes

  - CP-violating (CPV) processes

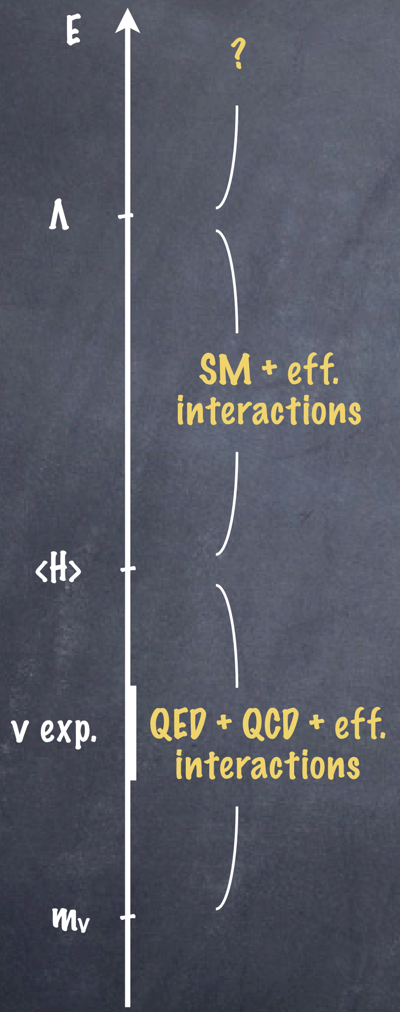
  - Electroweak precision tests (EWPT)

Lepton number violating operators

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

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

Neutrino masses



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

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

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

Summing up:

- Assume:
  - The origin of neutrino masses is at $\Lambda \gg M_Z$
- Then:
  - Whatever is the origin, neutrino masses are described in a model-independent way by the (LH)(LH) term in the SM effective lagrangian (caveat: higher-dim operators)
  - In particular, there are only three light neutrinos with Majorana masses
- But:
  - Could not ν have a light ν^c partner as all other SM fermions?

Right-handed neutrinos

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{matrix} u^c \\ d^c \end{matrix} \quad \begin{pmatrix} \nu \\ e \end{pmatrix} \quad \begin{matrix} \nu^c \\ e^c \end{matrix}$$

$SU(3)_C \times SU(2)_W \times U(1)_Y$

$$\lambda_\nu \nu_c L H \to m_\nu = \lambda_\nu v$$

(like the other fermions)

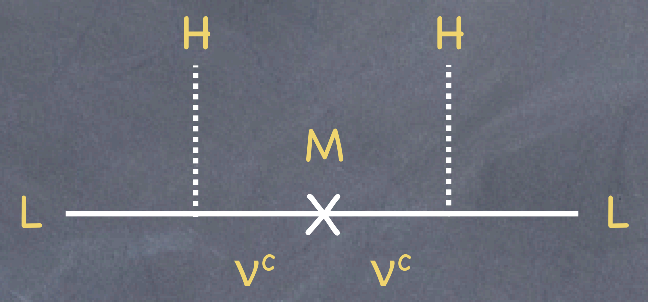
ν_c is a SM singlet and can therefore be heavy

$$\mathcal{L}_{\rm HE} \supset -\frac{M}{2}\nu^c\nu^c$$

(unlike the other fermions)

See-saw

Integrate out ν^c:



$$\frac{h}{\Lambda}(HL)(HL)$$

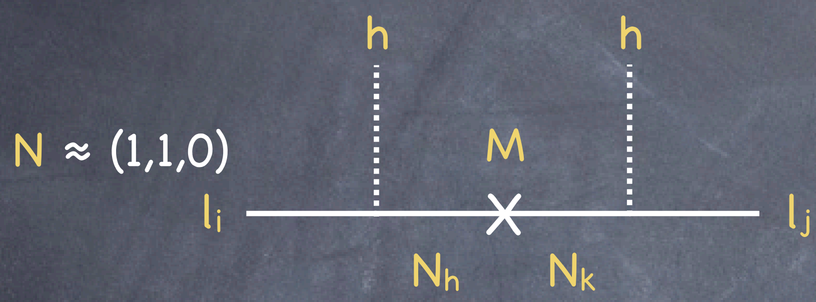
$$\frac{h}{\Lambda} \to -\lambda^T \frac{1}{M} \lambda$$

$$m_\nu = -m_{\rm D}^T \frac{1}{M} m_{\rm D}$$

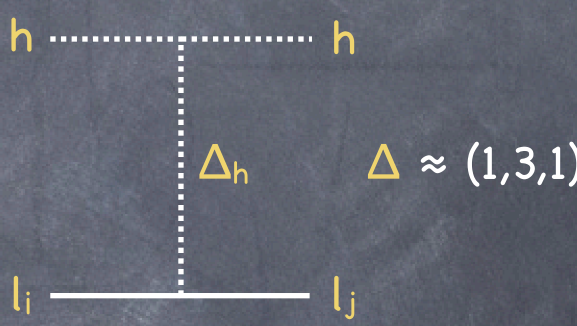
Majorana

Renormalizable origin of neutrino masses

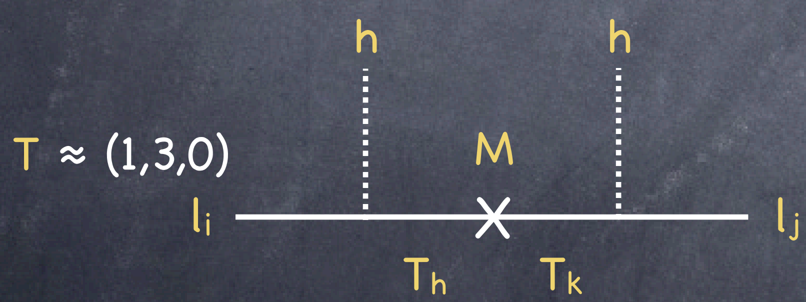
$$\mathcal{L}^{\rm eff}_{E\ll\Lambda} = \mathcal{L}^{\rm ren}_{\rm SM} + \frac{c_{ij}}{2\Lambda}(h\,l_i)(h\,l_j) + \dots$$



See-saw type I



See-saw type II



See-saw type III

(Any number of N_h, T_h, Δ_h)

$(SU(3)_c, SU(2)_L, Y)$

Baryon number violating operators

Bounds on NR terms

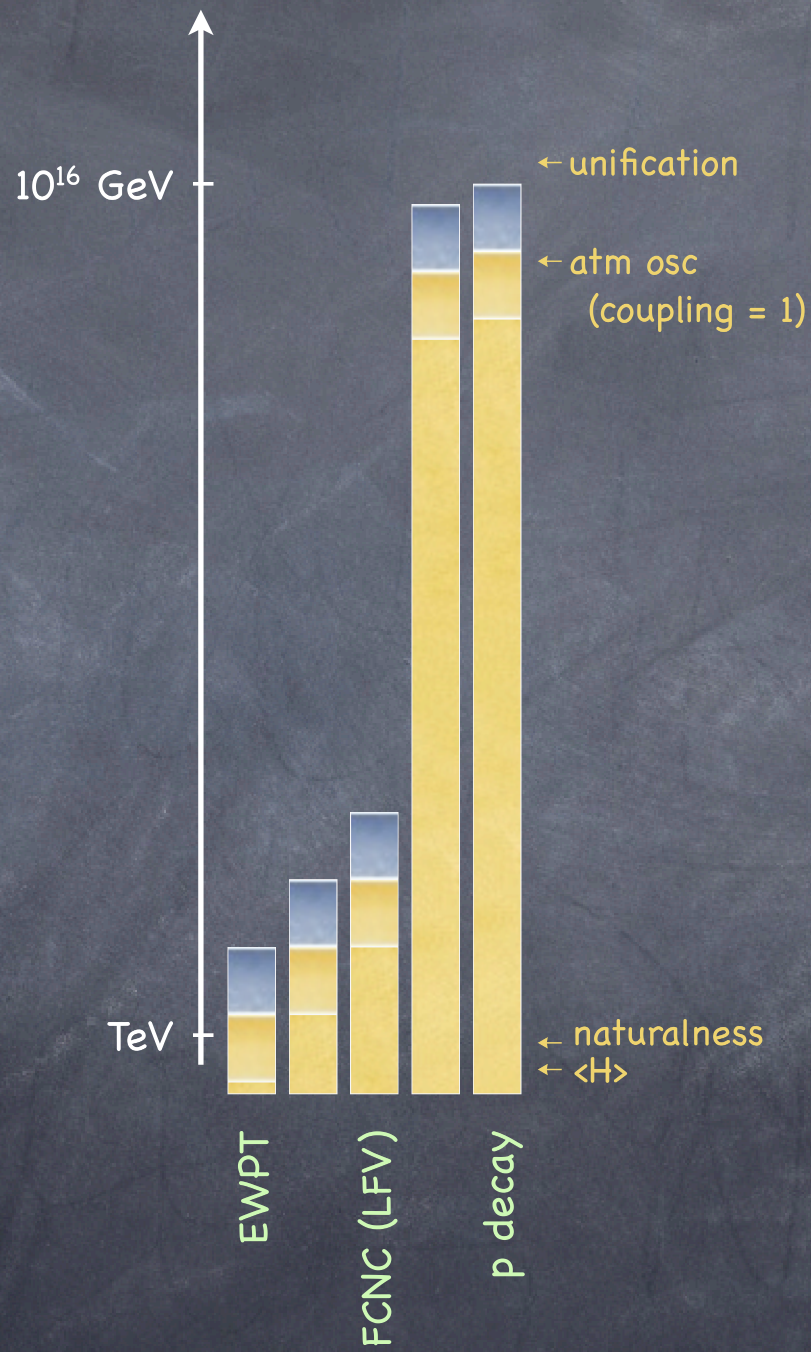
- B number e.g. $\frac{c}{\Lambda^2} qqql$ (proton decay) $\Lambda > c^{1/2}\ 10^{15}$ GeV
- L number e.g. $\frac{c}{\Lambda} llhh$ (neutrino masses) $\Lambda \approx c\ 0.5\ 10^{15}$ GeV
- L_i numbers e.g. $\frac{c}{\Lambda^2} \mu^c \sigma^{\mu\nu} l_e F_{\mu\nu} h$ ($\mu \to e\gamma$) $\Lambda > c^{1/2}\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

SM accidental symmetries

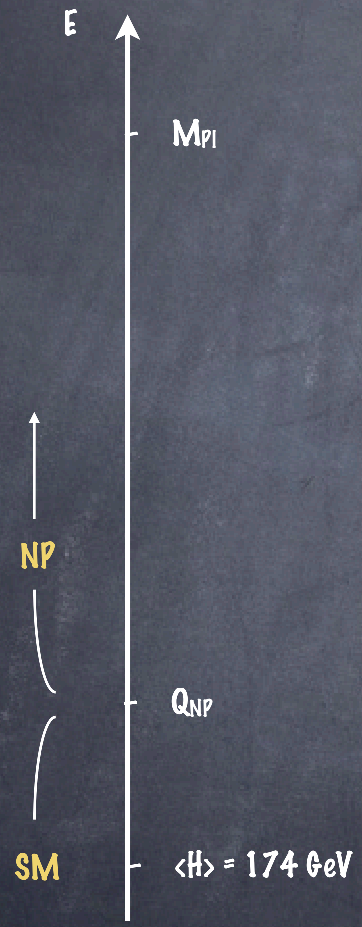
- Quark FCNC, CP e.g. $\frac{c}{\Lambda^2} \bar{s}\sigma^\mu d\, \bar{s}\sigma_\mu d$ (ε_K, Δm_K) $\Lambda > c^{1/2}$ 500 TeV

$c_{SM} \approx 10^{-8}$ (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
FCNC (LFV)
p decay

The little residual hierarchy



B, L-violating NP: $Q_{NP} > c^{1/2}\, 10^{12}$ TeV

ν's, p-decay, GUTs (4D, 5D)

B_i, L_i, CP-violating NP: $Q_{NP} > c^{1/2}\, 10^{3}$ TeV

why is TeV flavour violation "small"?

B, L, Fl, CP conserving: $Q_{NP} > c^{1/2}$ 5 TeV

EWPTs, conservative

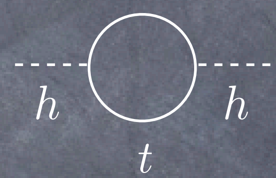
$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 = (115\,{\rm GeV})^2 \left(\frac{Q_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

$$Q_{\rm NP} \gtrsim \sqrt{c_i}\cdot 5\,{\rm TeV} \approx \begin{cases} 50\,{\rm TeV} & \text{composite } e \\ 5\,{\rm TeV} & \text{composite } G_a,\, h \\ 0.5\,{\rm TeV} & \text{1-loop perturbative} \end{cases}$$

MSSM

$$Q_{\rm NP} \gtrsim \sqrt{c_i} \cdot 5\,{\rm TeV} \approx 0.5\,{\rm TeV}$$

$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 \log \frac{M_{\rm Pl}^2}{Q_{\rm NP}^2}$$



$$\delta m_h^2 \sim \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{\rm NP}^2 = (115\,{\rm GeV})^2 \left(\frac{Q_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

Hints of NR terms?

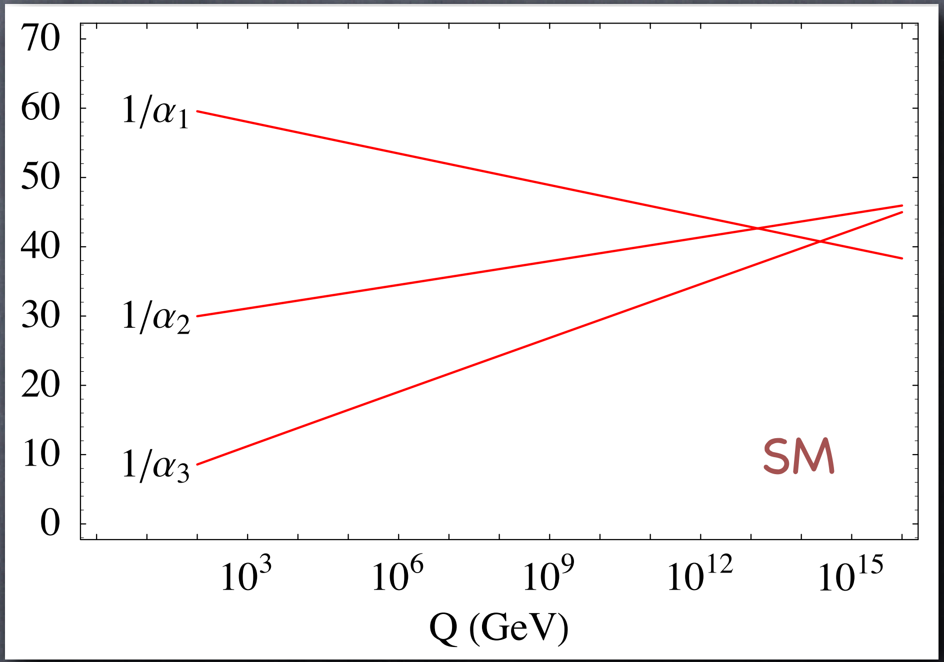
- Surprisingly, the most solid hints on new physics beyond the EW scale are associated to scales $\Lambda \gg$ TeV:
  - Neutrino masses
  - Unification

Grand Unified Theories (GUTs)

Unification

	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

SO(10)
16



+ M_{GUT} prediction: $\Lambda_B < M_{GUT} < M_{Pl}$