Multi-Step Grand Unification — From Model Building to Pheno

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The Standard Model (SM) – Theorist's View

Renormalizable Quantum Field Theory (only with Higgs!) based on $SU(3)_c \times SU(2)_w \times U(1)_Y$ *non-simple* gauge group

$$L_L = \begin{pmatrix} \nu \\ \ell \end{pmatrix}_L \quad Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R^c \quad d_R^c \quad \ell_R^c \quad [\nu_R^c] \quad \left[\begin{pmatrix} h^+ \\ h^0 \end{pmatrix} \right]$$

Interactions:

- Gauge IA (covariant derivatives in kinetic terms):

$$\partial_\mu \longrightarrow D_\mu = \partial_\mu + i \sum_k g_k V_\mu^a T^a$$

- Yukawa IA:

$$Y^u \overline{Q}_L H_u u_R + Y^d \overline{Q}_L H_d d_R + Y^e \overline{L}_L H_d e_R \quad [+Y^n \overline{L}_L H_u \nu_R]$$

- Scalar self-IA:

$$(H^\dagger H) \qquad (H^\dagger H)^2$$

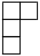
The group-theoretical bottom line

Things to remember:

Representations of $SU(N)$

- fundamental reps. $\phi_i \sim N$, $\psi^i \sim \overline{N}$, adjoint reps. $A_i^j \sim N^2 - 1$
- $SU(N)$ invariants: contract all indices

$\phi_i \psi^i \qquad \phi_i A_i^j \psi^j \qquad \epsilon_{ij} \phi_i \xi_j \qquad \epsilon_{ijk} \phi_i \xi_j \eta_k$

- [Symmetry properties: Young tableaux ]

The (group-theoretical) essence of the SM:

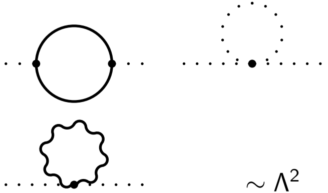
remember: $Q_{\text{el.}} = T_3 + \frac{Y}{2}$

Q_L	u_R^c	d_R^c	L_L	e_R^c	H_d	H_d	ν_R^c
$(\mathbf{2},\mathbf{3})_{\frac{1}{3}}$	$(\mathbf{1},\overline{\mathbf{3}})_{\frac{4}{3}}$	$(\mathbf{1},\overline{\mathbf{3}})_{-\frac{2}{3}}$	$(\mathbf{2},\mathbf{1})_{-1}$	$(\mathbf{1},\mathbf{1})_{2}$	$(\mathbf{2},\mathbf{1})_{1}$	$(\mathbf{2},\mathbf{1})_{-1}$	$(\mathbf{1},\mathbf{1})_{0}$

Loose Ends/Deficiencies of the Standard Model

Incompleteness

- Electroweak Symmetry Breaking
- Higgs boson
- Origin of neutrino masses
- Dark Matter: $m_{DM} \sim 100\,\text{GeV}$

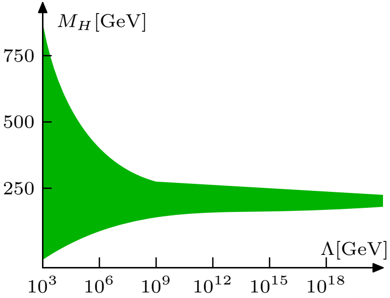


$\sim \Lambda^2$

$$m_h^2 = m_0^2 + \Lambda^2 \times \text{(loop factors)}$$

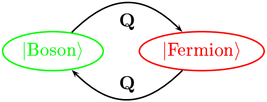
Theoretical Dissatisfaction

- 28 free parameters
- “strange” fractional $U(1)$ quantum numbers
- Hierarchy problem



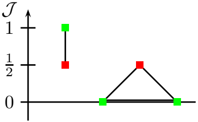
Supersymmetry

connects gauge and space-time symmetries

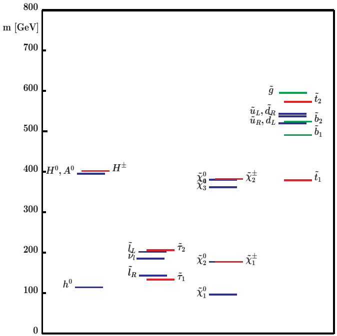


multiplets with equal-mass fermions and bosons

$\Rightarrow$ SUSY is broken in Nature



stabilizes the hierarchy



- Minimal Supersymmetric Standard Model (MSSM)
- Charginos, Neutralinos, Gluino Sleptons, Squarks, Sneutrinos
- R parity: discrete symmetry
- LSP: Dark matter
- Superpartners have *identical* gauge quantum numbers

Anatomy of MSSM

- Yukawa couplings $\Rightarrow$ Superpotential:

$$\mathcal{W} = \hat{\Phi}_1 \hat{\Phi}_2 \hat{\Phi}_3 \equiv \Phi_1 \Phi_2 \Phi_3 \quad \Longrightarrow \quad (\phi_1 \phi_2)^2, \ldots, \left(\overline{\psi}_1 \psi_2\right) \phi_3$$

- NB: part of scalar potential from gauge kinetic terms (light Higgs)
- MSSM superpotential

$$\mathcal{W}_{\text{MSSM}} = Y^u u^c Q H_u + Y^d d^c Q H_d + Y^e e^c L H_d + \mu H_u H_d$$

- Ignorance about SUSY breaking shows up as “soft-breaking terms”: Gaugino and sparticle masses, trilinear scalar potential terms
- μ problem: EWSB demands $\mu \sim \mathcal{O}(100\,\text{GeV} - 1\,\text{TeV})$
- Additional SUSY degrees of freedom modify vacuum polarization
  $\Rightarrow$ Unification of gauge couplings possible

(Gauge) Unification and the running of couplings

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure constant. Our hypotheses may be wrong and our speculations idle, but the uniqueness and simplicity of our scheme are reasons enough that it be taken seriously.

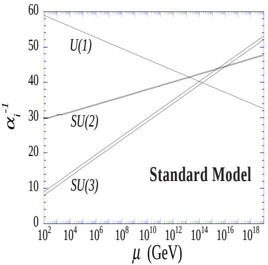
of the GIM mechanism with the notion of colored quarks[4] keeps the successes of the quark model and gives an important bonus: Lepton and hadron anomalies cancel so that the theory of weak and electromagnetic interactions is renormalizable.[5]

The next step is to include strong interactions. We assume that *strong interactions are mediated by an octet of neutral vector gauge gluons* associated with local color SU(3) symmetry, and that there are no fundamental strongly interacting scalar-meson fields.[6] This insures that

(Gauge) Unification and the running of couplings

Renormalization group (RG) running of gauge couplings:

$$\frac{dg_a}{d\log\mu} = \frac{g_a^3}{16\pi^2} B_a \qquad \begin{array}{rl} \text{SM} & B_a = \left(\frac{41}{10}, -\frac{19}{6}, -7\right) \\ \text{MSSM} & B_a = \left(\frac{33}{5}, 1, -3\right) \end{array}$$



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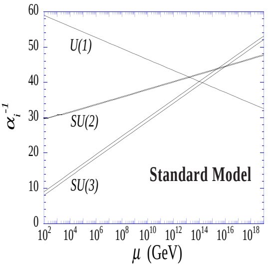

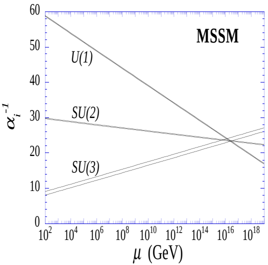

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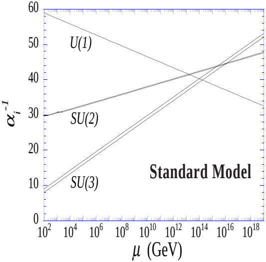

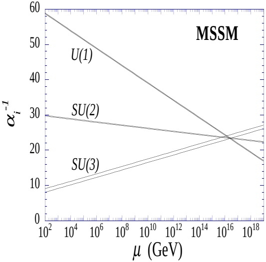

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

H. Georgi and H. D. Politzer, Phys. Rev. D (to be published); D. J. Gross and F. Wilczek, Phys. Rev. D 8, 3633 (1973), and Phys. Rev. D (to be published).

[16]A naive calculation indicates that the vector boson mass must be greater than 10^{15} GeV $\approx 10^{-9}$ g! Let the reader who finds this hard to swallow double the num-

The prime example: (SUSY) $SU(5)$

$$SU(5) \underset{M_X}{\longrightarrow} SU(3)_c \times SU(2)_w \times U(1)_Y \underset{M_Z}{\longrightarrow} SU(3)_c \times U(1)_{em}$$

$SU(5)$ has $5^2 - 1 = 24$ generators:

$$\mathbf{24} \to \underbrace{(\mathbf{8},\mathbf{1})_0}_{G_\alpha^\beta} \oplus \underbrace{(\mathbf{1},\mathbf{3})_0}_{W} \oplus \underbrace{(\mathbf{1},\mathbf{1})_0}_{B} \oplus \underbrace{(\mathbf{3},\mathbf{2})_{\frac{5}{6}}}_{X,Y} \oplus \underbrace{(\overline{\mathbf{3}},\mathbf{2})_{-\frac{5}{6}}}_{\bar{X},\bar{Y}}$$

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$$A = g \sum_{a=1}^{24} A^a \frac{\lambda^a}{2} = \frac{g}{\sqrt{2}} \left(\begin{array}{ccc|cc} & \sqrt{2} G^a \frac{\lambda^a_{\text{GM}}}{2} & & \bar{X} & \bar{Y} \\ & & & \bar{X} & \bar{Y} \\ & & & \bar{X} & \bar{Y} \\ \hline X & X & X & \multicolumn{2}{c}{\sqrt{2} W^a \frac{\sigma}{2}} \\ Y & Y & Y & & \end{array} \right)$$

$$- \frac{g}{2\sqrt{15}} B \left(\begin{array}{ccc|cc} -2 & & & & \\ & -2 & & & 0 \\ & & -2 & & \\ \hline & 0 & & +3 & \\ & & & & +3 \end{array} \right)$$

Quantum numbers

- Hypercharge: $\frac{\lambda_{12}}{2} = \sqrt{\frac{3}{5}} \frac{Y}{2}$ $\qquad Y = \frac{1}{3}\,\mathrm{diag}(-2, -2, 3, 3, 3)$

  Quantized hypercharges are fixed by non-Abelian generator
- Weak Isospin: $T_{1,2,3} = \lambda_{9,10,11}/2$
- Electric Charge: $Q = T^3 + Y/2 = \mathrm{diag}(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, 1, 0)$
- Prediction for the weak mixing angle (with RGE running):

  $\alpha^{-1}(M_Z) = 128.91(2), \alpha_s(M_Z) = 0.1176(20), s_w^2(M_Z) = 0.2312(3)$

$$\text{non-SUSY:}\quad s_w^2(M_Z) \;=\; \frac{23}{134} + \frac{\alpha(M_Z)}{\alpha_s(M_Z)}\frac{109}{201} \;\approx 0.207$$

☹

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$$\text{SUSY:}\quad s_w^2(M_Z) = \frac{1}{5} + \frac{\alpha(M_Z)}{\alpha_s(M_Z)}\frac{7}{15} \approx 0.231$$

New Gauge Bosons Two colored EW doublets:
(X,Y), $(\bar{X},\bar{Y})$ with charges $\pm\frac{4}{3}, \pm\frac{1}{3}$

Fermions (Matter Superfields)

The only possible way to group together the matter:

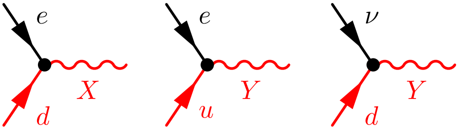
$$\overline{\mathbf{5}} = \begin{array}{|c|}\hline \\ \hline \\ \hline \\ \hline \\ \hline \end{array} : \quad \begin{pmatrix} d^c \\ d^c \\ d^c \\ \ell \\ -\nu_\ell \end{pmatrix} \qquad \mathbf{10} = \begin{array}{|c|}\hline \\ \hline \\ \hline \end{array} : \quad \frac{1}{\sqrt{2}} \left(\begin{array}{ccc|cc} 0 & u^c & -u^c & -u & -d \\ -u^c & 0 & u^c & -u & -d \\ u^c & -u^c & 0 & -u & -d \\ \hline u & u & u & 0 & -e^c \\ d & d & d & e^c & 0 \end{array} \right)$$

$$\overline{\mathbf{5}} = (\overline{\mathbf{3}}, \mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1}, \mathbf{2})_{-1} \qquad \mathbf{10} = (\mathbf{3}, \mathbf{2})_{\frac{1}{3}} \oplus (\overline{\mathbf{3}}, \mathbf{1})_{-\frac{4}{3}} \oplus (\mathbf{1}, \mathbf{1})_{2}$$

Remarks

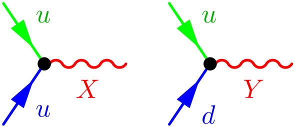
- $\mathbf{2} = \square = \overline{\mathbf{2}}, \qquad (\mathbf{5} \otimes \mathbf{5})_a = \mathbf{10}, \quad (\mathbf{3} \otimes \mathbf{3})_a = \overline{\mathbf{3}}, \quad (\square \otimes \square)_a = \begin{array}{|c|}\hline \\ \hline \\ \hline \end{array}$
- Quarks and leptons in the same multiplet
- Fractional charges from tracelessness condition (color!)
- $\overline{\mathbf{5}}$ and $\mathbf{10}$ have equal and opposite anomalies
- ν^c must be $SU(5)$ singlet

Interactions



Leptoquark couplings

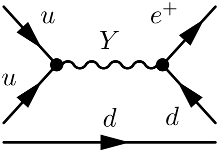
(and SUSY vertices)



Diquark couplings

(and SUSY vertices)

Vector bosons induce e.g. decay $p \to e^+\pi^0$



The doublet-triplet splitting problem

$SU(5)$ breaking: Higgs $\mathbf{\Sigma}$ in adjoint $\mathbf{24}$ rep.

$$\langle 0|\mathbf{\Sigma}|0\rangle = w \times \mathrm{diag}(1,1,1,-\tfrac{3}{2},-\tfrac{3}{2}) \qquad M_X = M_Y = \frac{5}{2\sqrt{2}}\, g\, w$$

other breaking mechanisms possible (e.g. orbifold)

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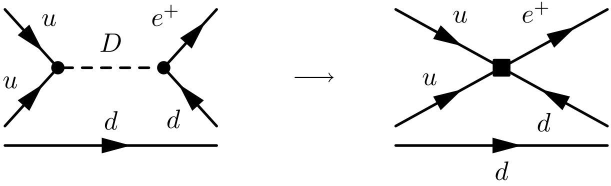
(MS)SM Higgs(es) included in $\mathbf{5} \otimes \overline{\mathbf{5}}$

$$\mathbf{5} = \square : \begin{pmatrix} D \\ D \\ D \\ h^+ \\ h^0 \end{pmatrix} \qquad \overline{\mathbf{5}} = \begin{smallmatrix}\square\\\square\\\square\\\square\end{smallmatrix} : \begin{pmatrix} D^c \\ D^c \\ D^c \\ h^- \\ -h^0 \end{pmatrix}$$

$$\mathbf{5} = (\mathbf{3},\mathbf{1})_{-\frac{2}{3}} \oplus (\mathbf{1},\mathbf{2})_1 \qquad \overline{\mathbf{5}} = (\overline{\mathbf{3}},\mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1},\mathbf{2})_{-1}$$

- D, D^c coloured triplet Higgses with charges $\pm\frac{1}{3}$
- also induces proton decay $\quad m_H \sim 100\,\text{GeV},\ m_D \sim 10^{16}\,\text{GeV}$
- **Doublet-triplet splitting problem**

Naive estimate of proton lifetime



Effective 4-fermion operator (analogy to muon decay)

$$\mathcal{L}_F = \frac{4G_F}{\sqrt{2}}(\overline{\mu}\gamma_\kappa\nu_\mu)(\overline{\nu}_e\gamma^\kappa e) \qquad \mathcal{L}_{GUT} = \frac{4G_{GUT}}{\sqrt{2}}(\overline{u}\Gamma u)(\overline{e}\Gamma d)$$

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8M_W^2} \qquad \frac{G_{GUT}}{\sqrt{2}} = \frac{g^2}{8M_{GUT}^2}$$

$$\tau(\mu \to e\nu_\mu\bar{\nu}_\mu) \sim \frac{192\pi^3}{G_F^2 m_\mu^5} \qquad \tau(p \to e^+\pi^0) \sim \frac{192\pi^3}{G_{GUT}^2 m_p^5}$$

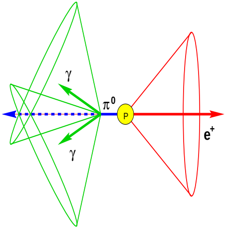
Proton lifetime for $\alpha(M_{GUT}) \sim 1/24$ and $M_{GUT} \sim 2 \times 10^{16}$ GeV:

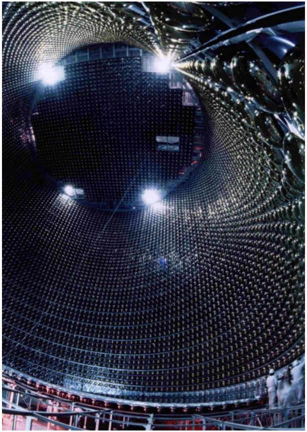
$\tau(p \to e^+\pi^0) \sim \frac{M_{GUT}^4}{[\alpha(M_{GUT})]^2 m_p^5} \to 10^{31\pm1}$ years

Compare: $\tau_p^{SM} \gtrsim 10^{150}$ years (gravity-induced)

Proton decay crucial for "GUT search"

- Tracking calorimeter (SOUDAN) or RICH Cherenkovs
- Super-Kamiokande: 50 kt water RICH
- measure change and time for reconstruction





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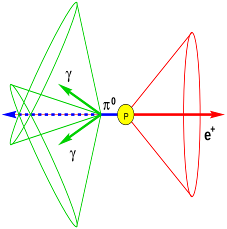


Channel	$\tau_p (10^{30}$ years)
$p \to$ invisible	0.21
$p \to e^+\pi^0$	1600
$p \to \mu^+\pi^0$	473
$p \to \nu\pi^+$	25
$p \to \nu K^+$	670
$p \to e^+\eta^0$	312
$p \to \mu^+\eta^0$	126
$p \to e^+\rho^0$	75
$p \to \mu^+\rho^0$	110
$p \to \nu\rho^+$	162
$p \to e^+\omega^0$	1000
$p \to \mu^+\omega^0$	117
$p \to e^+K^0$	150
$p \to \mu^+K^0$	1300
$p \to \nu K^+$	2300
$p \to e^+\gamma$	670
$p \to \mu^+\gamma$	478

New experiments:
HyperK (1 Mt), UNO (650 kt), European project Fréjus (1 Mt)

Precision: 10 years running $\Longrightarrow 10^{34} - 10^{35}$ years

Why chiral exotics?

Unification verification only with megatons? What about colliders?

- SPA: super precision accurately
- Look for chiral exotics
- Physics beyond MSSM provides handle to GUT scale

μ problem

- NMSSM trick
- Singlet superfield with TeV-scale VEV

Doublet-triplet splitting problem, Longevity of the proton

- Try to keep D, D^c superfields at TeV scale
- Need mechanism to prevent rapid proton decay
- Need to rearrange running for unification

Flavour problem

- Flavour might help protecting the proton

Sketch of a model

Superpotential: $\mathcal{W} = \mathcal{W}_{\text{MSSM}} + \mathcal{W}_D + \mathcal{W}_N$

$$\begin{aligned} \mathcal{W}_{\text{MSSM}} &= Y^u u^c Q H_u + Y^d d^c Q H_d + Y^e e^c L H_d \\ \mathcal{W}_D &= Y^D D u^c e^c + Y^{D^c} D^c Q L \\ \mathcal{W}_S &= Y^{S_H} S H_u H_d + Y^{S_D} S D D^c \end{aligned}$$

$U(1)_S$ symmetry

- gauged at high energies, radiative breaking of global left-over $U(1)$
- $\langle 0|S|0\rangle$ generates μ_H and μ_D

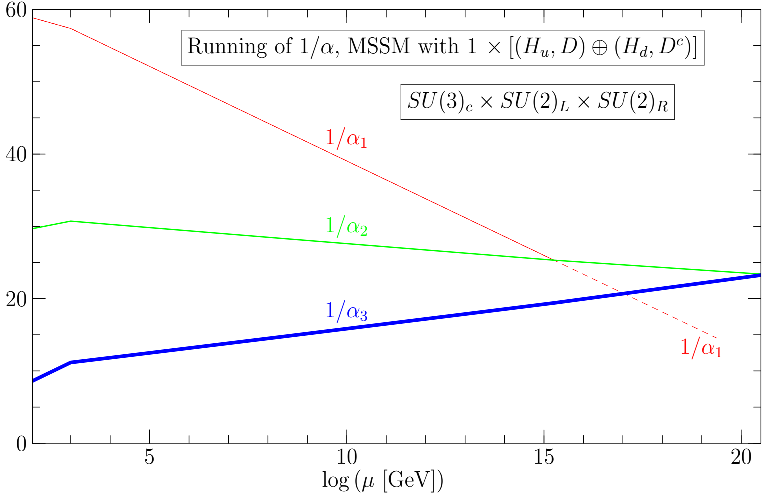
See-saw mechanism ν^c at $\sim M_\nu \sim 10^{14} - 10^{15}$ GeV

$$m_\nu \sim \frac{v^2}{M_\nu} \sim 10^{-1} - 10^{-2}\text{eV}$$

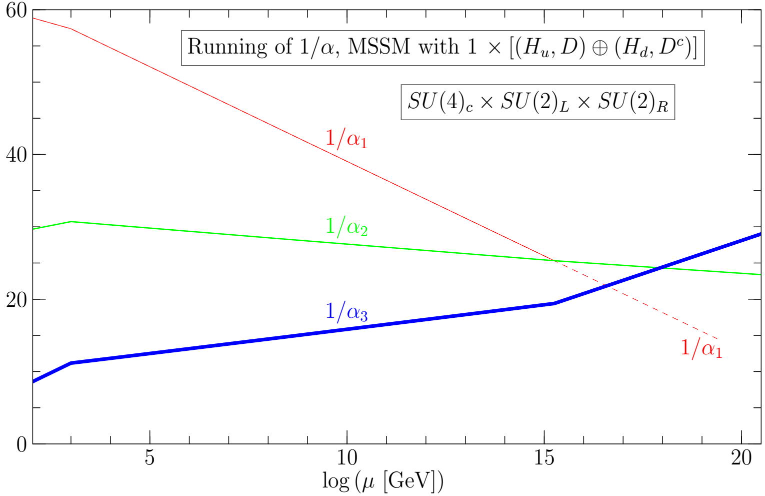
At M_ν left-right symmetric model: $SU(2)_L \times SU(2)$

$$Q_R = \begin{pmatrix} u^c \\ d^c \end{pmatrix}, \qquad L_R = \begin{pmatrix} \nu^c \\ \ell^c \end{pmatrix} \qquad H = \begin{pmatrix} H_u \\ H_d \end{pmatrix} \qquad D \qquad D^c$$

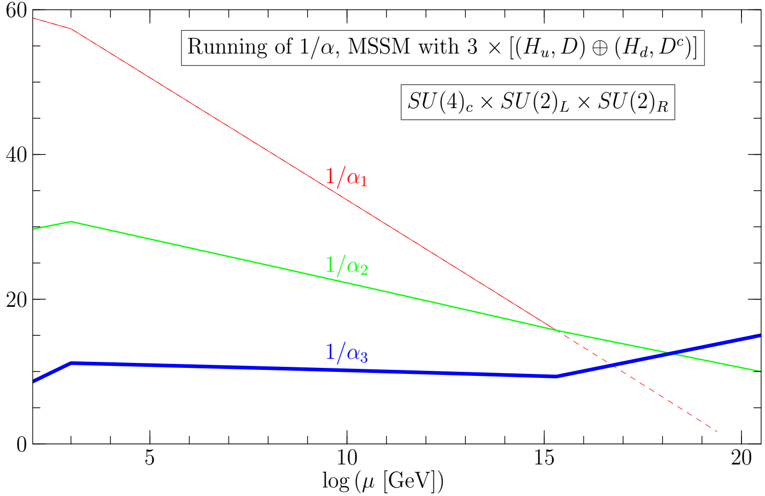
RGE running


Running of $1/\alpha$, MSSM with $1 \times [(H_u, D) \oplus (H_d, D^c)]$
$SU(3)_c \times SU(2)_L \times SU(2)_R$
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
$1/\alpha_1$
60
40
20
0
5
10
15
20
$\log(\mu \text{ [GeV]})$

RGE running


60
40
20
0
5
10
15
20
log (μ [GeV])
Running of 1/α, MSSM with 1 × [(H_u, D) ⊕ (H_d, D^c)]
SU(4)_c × SU(2)_L × SU(2)_R
1/α_1
1/α_2
1/α_3
1/α_1

RGE running


Running of $1/\alpha$, MSSM with $3 \times [(H_u, D) \oplus (H_d, D^c)]$
$SU(4)_c \times SU(2)_L \times SU(2)_R$
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
0
20
40
60
5
10
15
20
$\log(\mu$ [GeV]$)$

Matter-Higgs unification: E_6

- **Pati-Salam group** $SU(4)_c \times SU(2)_L \times SU(2)_R$

$$
\begin{aligned}
\mathbf{Q}_L = (Q, L) &= \; (\mathbf{4}, \mathbf{2}, \mathbf{1}) \\
\mathbf{Q}_R = ((u^c, d^c), (\nu^c, \ell^c)) &= \; (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{2}) \\
\mathbf{H} = (H_u, H_d) &= \; (\mathbf{1}, \mathbf{2}, \mathbf{2}) \\
\mathbf{D} = (D, D^c) &= \; (\mathbf{6}, \mathbf{1}, \mathbf{1}) \\
\mathbf{S} &= \; (\mathbf{1}, \mathbf{1}, \mathbf{1})
\end{aligned}
$$

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- Be radical: Embed everything in **fundamental rep. of** E_6
  - fundamental $\mathbf{27}$ contains exactly the stuff above
  - adjoint: $\mathbf{78}$
  - Matter and Higgs fields in one big multiplet
  - $\Rightarrow$ 3 generations of S and D
  - $\Rightarrow$ 3 generations of Higgs fields: Higgs (VEV) vs. “unhiggs” (no VEV)
  - Problem of FCNCs: Introduce Z_2 symmetry (H parity)

Flavour Symmetry and proton decay

Assume $SU(3)_F$ **or** $SO(3)_F$ **flavour symmetry**

- Left-right symmetry: $SU(2)_L \times SU(2)_R$, $SU(3)_c$, $SU(3)_F$
- Diquark couplings vanish identically:

$$DQ_L Q_L = \epsilon^{abc} \epsilon_{\alpha\beta\gamma} \epsilon_{jk} D^a_\alpha \left(Q_L\right)^b_{\beta j} \left(Q_L\right)^c_{\gamma k}$$

- Baryon number is symmetry of the superpotential
- $SU(2)_R$ and $SU(3)_F$ breaking spurions?
  symmetry breaking by condensates linear/bilinear in fundamental reps.:
  D, D^c *couple to other quarks only as singlets*
- Integrating out heavy fields: baryon number emerges as low-energy symmetry, flavour symmetry not
- Leptoquark couplings possible

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- Toy model: $E_8 \to E_6 \times SU(3)_F$
  - $\mathbf{248} = \mathbf{27_3} \oplus \mathbf{\overline{27}_{\overline{3}}} \oplus \mathbf{78_1} \oplus \mathbf{1_8}$
  - flavour-symmetric Kaluza-Klein tower of mirror mmatter $\mathbf{\overline{27}_{\overline{3}}}$ breaks E_8
  - mirror-Higgs superfields μ term breaks E_6 to PS, breaks flavour

A little bit of Pheno

Next step: Provide a viable low-energy spectrum

Extended MSSM Higgs sector

- relaxed Higgs bounds (light pseudoscalars)
- possibly large invisible decay ratio
- lightest unhiggs: H parity protected dark matter
- dark matter mix: interesting relic abundance
  (relaxes all neutralino bounds!)
- Pair production of unhiggses/unhiggsinos, cascade decays

(Down-type) **Leptoquarks, Leptoquarkinos**

- 3 generations at TeV scale
- produced in gluon fusion, single production
- final states: $t\tau, b\nu_\tau, \tilde{t}\tau, \ldots$
- if flavor symmetry leaves traces: $gq \to D\ell$ enhanced, decays $t\mu, te$

Extended neutralino sector like in NMSSM

no Z'

Some Unification needs time