# Gauge Coupling Unification and Light Exotica

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*in collaboration with Stuart Raby*

arXiv:0705.0294 [hep-ph]

# Outline of my Talk

- Motivation
- Standard Model and Grand Unification: A Recap
- A Special Class of Light Exotic Particles
- In Theory: Beyond the Standard Model Constructions
- In Experiment: How can we observe them?
- Conclusions

# The Standard Model

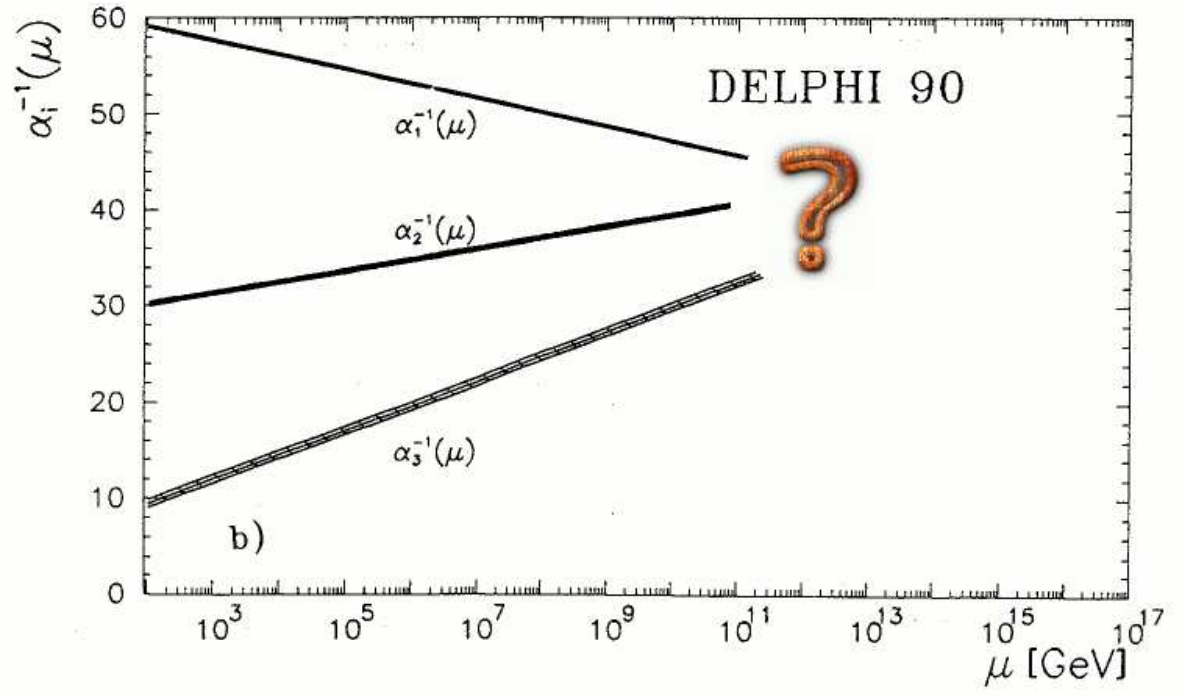
Gauge group:

$$\mathsf{SU}(\mathbf{3})_c \times \mathsf{SU}(\mathbf{2})_L \times \mathsf{U}(\mathbf{1})_Y$$

Particle content:

| | | | | | |
|---|---|---|---|---|---|
| $Q$ | $(\mathbf{3},\mathbf{2})_{1/3}$ | $L$ | $(\mathbf{1},\mathbf{2})_{-1}$ | $H$ | $(\mathbf{1},\mathbf{2})_{1}$ |
| $\bar{u}$ | $(\overline{\mathbf{3}},\mathbf{1})_{-4/3}$ | $\bar{e}$ | $(\mathbf{1},\mathbf{1})_{2}$ | $\bar{H}$ | $(\mathbf{1},\mathbf{2})_{-1}$ |
| $\bar{d}$ | $(\overline{\mathbf{3}},\mathbf{1})_{2/3}$ | $\bar{\nu}$ | $(\mathbf{1},\mathbf{1})_{0}$ | | |

# Hints at Physics Beyond the SM?




★ Running gauge couplings seem to meet at $10^{15}$ GeV ☺

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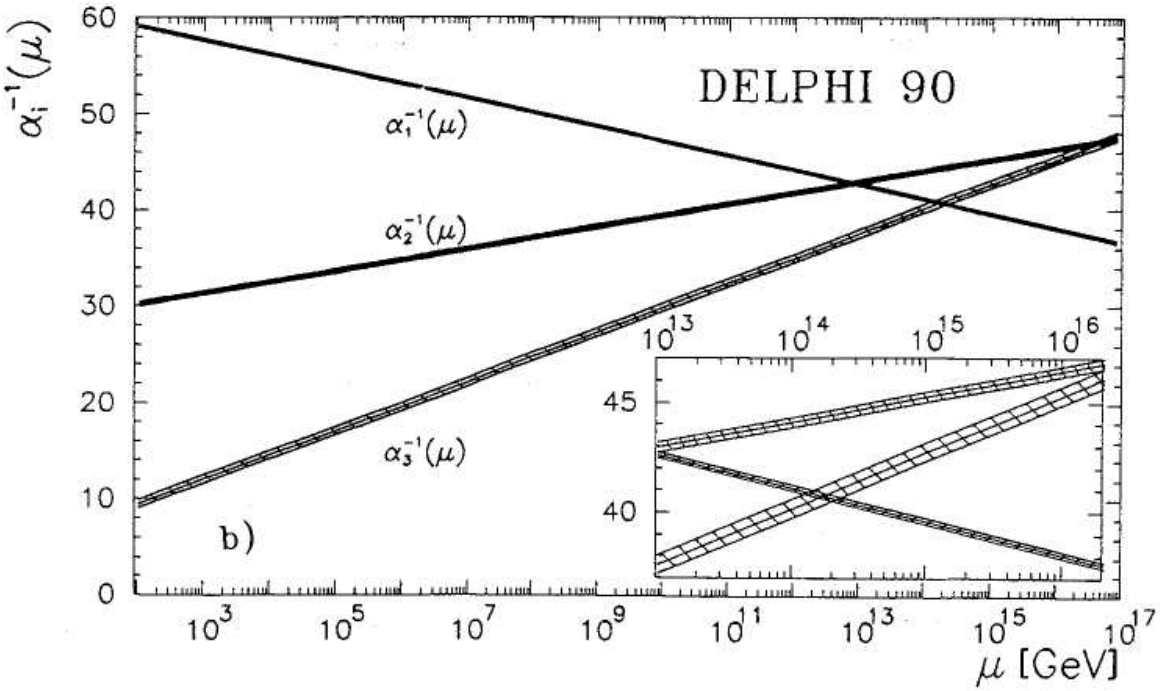


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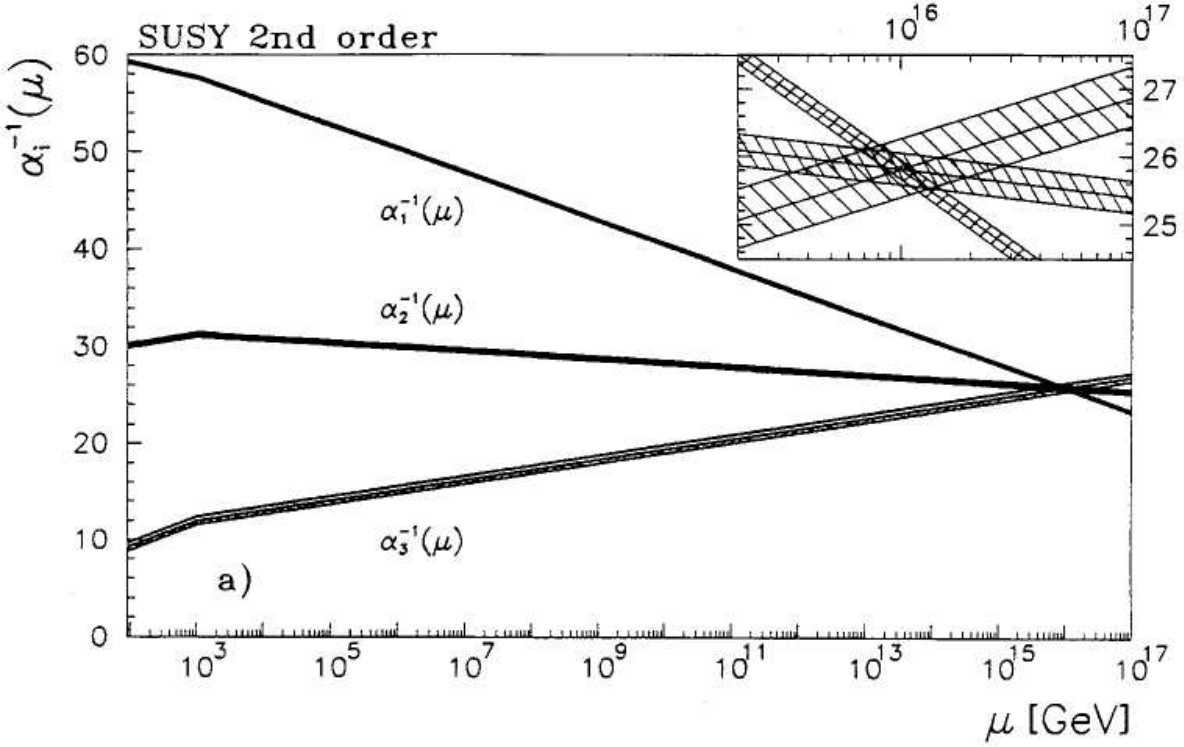


- ★ Running gauge couplings seem to meet at $10^{15}$ GeV ☺
- ★ Looking more closely, couplings do not unify ☹
- ★ Supersymmetry helps: Unification at $10^{16}$ GeV ☺

# Supersymmetric Grand Unification

Assume SU$(5)$ or SO$(10)$ at fundamental scale $\sim 10^{16}$ GeV

H. Georgi and S. L. Glashow, "Unity of all elementary particle forces," *Phys. Rev. Lett.* **32** (1974)

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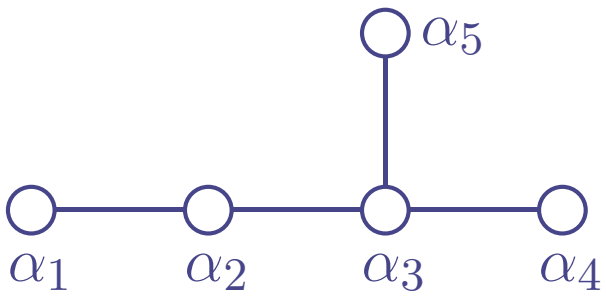


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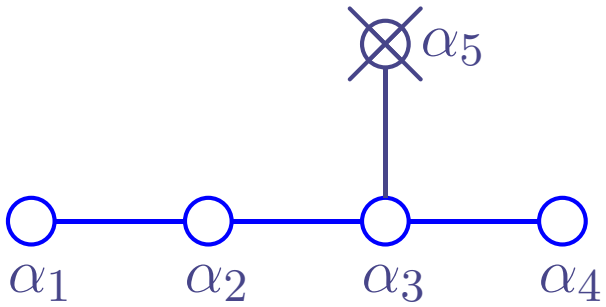


SO$(10)$ $\rightarrow$ SU$(5)\times$U$(1)_X$

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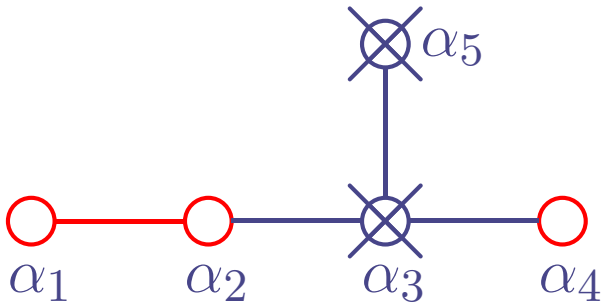


$$\mathrm{SO}(10) \quad \rightarrow \quad \mathrm{SU}(5)\times\mathrm{U}(1)_X \quad \rightarrow \quad \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_Y\times\mathrm{U}(1)_X$$

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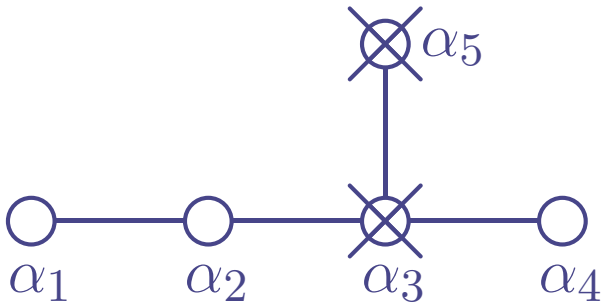


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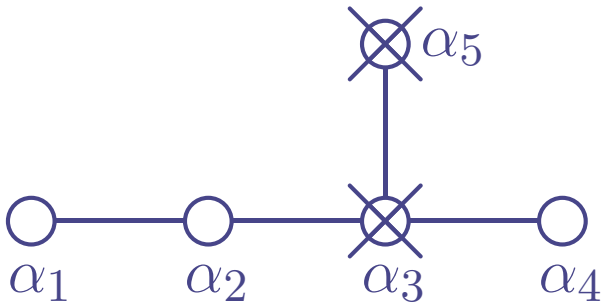


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$$\mathbf{16} \quad \rightarrow \quad \mathbf{10}+\overline{\mathbf{5}}+\mathbf{1}$$

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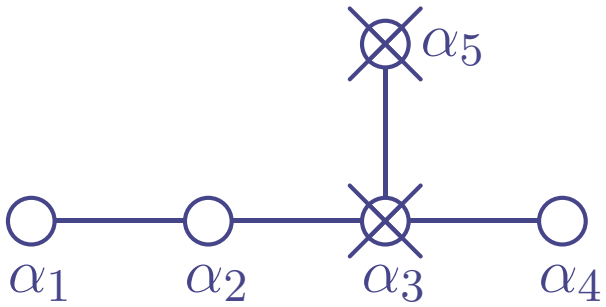


$$\mathrm{SO}(10) \rightarrow \mathrm{SU}(5)\times\mathrm{U}(1)_X \rightarrow \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_Y\times\mathrm{U}(1)_X$$

$$\mathbf{16} \rightarrow \mathbf{10}+\overline{\mathbf{5}}+\mathbf{1}$$

$$\rightarrow (\mathbf{3},\mathbf{2})_{1/3} + (\overline{\mathbf{3}},\mathbf{1})_{-4/3} + (\mathbf{1},\mathbf{1})_{-2} + (\overline{\mathbf{3}},\mathbf{1})_{2/3} + (\mathbf{1},\mathbf{2})_{-1} + (\mathbf{1},\mathbf{1})_{0}$$

$$Q \qquad \bar{u} \qquad \bar{e} \qquad \bar{d} \qquad L \qquad \bar{\nu}$$

# Predictions from Grand Unification

- Gauge coupling unification ★★★
- One family of quarks and leptons in one irrep ★★★
- Quantization of electric charge ★★★
- $\sin^2\theta_w$ in agreement w/experiment ★★
- $\frac{m_b}{m_\tau}$ ratio ★
- Right-handed neutrino ★
- Smallness of neutrino masses ★★

# Our Rationale ...

- We want to keep these nice predictions
- Matter comes in complete GUT multiplets

  In SU$(5)$ models:

  Quarks and leptons in $\mathbf{10} + \overline{\mathbf{5}} + \mathbf{1}$, Higgs in $\mathbf{5} + \overline{\mathbf{5}}$

  $\mathbf{24}$ to break SU$(5)$ to SM or $\mathbf{45}$ for realistic masses

  In SO$(10)$ models:

  Quarks and leptons in $\mathbf{16}$, Higgs in $\mathbf{10}$
- Incomplete multiplets spoil GUT relations ↯

# Heavy vs. Light Exotic Particles

- Standard ansatz:

  If exotics are present, make them heavy

  E.g. an exotic right-handed quark $\check{q} = (\mathbf{3}, \mathbf{1})_{1/3}$

  Electric charge $Q = T_3 + \frac{Y}{2} = 1/6$

  Bound state "exotic baryon" $[\check{q}uu]_{Q=3/2}$

  Presence of $\check{q}$ would spoil standard GUT relations

  Introduce mass term $M\check{q}\bar{\check{q}}$ and let $M \gg M_{\mathsf{GUT}}$

  $\check{q}$ does not contribute to renormalization group running

  $\rightsquigarrow$ everything is fine

# Heavy vs. Light Exotic Particles

- Non-standard ansatz:

  Can there light exotic particles, i.e. $M \ll M_{\mathsf{GUT}}$,
  such that all/most standard GUT predictions hold?

  S. Raby and A. Wingerter, " Gauge coupling unifi cation and light exotica in string theory", arXiv:0705.0294 [hep-ph]

  Consider following set of light exotics:

$$\begin{array}{ccccccc} (\mathbf{3},\mathbf{1})_{1/3} & + & (\mathbf{1},\mathbf{1})_{-1} & + & (\mathbf{1},\mathbf{2})_{0} & + & (\mathbf{1},\mathbf{1})_{\pm 1} \\ \check{q} & + & \check{e}_{-} & + & \check{L} & + & \check{e}_{\pm} \end{array}$$

  How do they affect the GUT predictions?

# Running Gauge Couplings

$\beta$-function

$$\beta(g) = -\frac{1}{16\pi^2}\left[\frac{11}{3}\ell(\text{vector}) - \frac{2}{3}\ell(\text{Weyl fermion}) - \frac{1}{6}\ell(\text{spinless})\right] g^3 + \ldots$$

or in supersymmetric form

$$\beta(g) = -\frac{1}{16\pi^2}\overbrace{\left[3\ell(\text{vector}) - \ell(\text{chiral})\right]}^{b_i} g^3 + \ldots$$

Here,

$$\ell(\Lambda) = \frac{1}{2}\frac{\dim(\Lambda)}{\dim(\mathfrak{g})}\langle\Lambda, \Lambda + 2\delta\rangle$$

is the index of the representation, $\mathfrak{g}$ the gauge group, $\Lambda$ the highest weight, $\delta = (1, \ldots, 1)$.

For the Standard Model particle content:

$$b_1 = -\frac{33}{5}, \qquad b_2 = -1, \qquad b_3 = 3$$

# How the Exotics Affect the Running

Consider now the contribution of

$$\begin{array}{ccccccc} (\mathbf{3},\mathbf{1})_{1/3} & + & (\mathbf{1},\mathbf{1})_{-1} & + & (\mathbf{1},\mathbf{2})_{0} & + & (\mathbf{1},\mathbf{1})_{\pm 1} \\ \check{q} & + & \check{e}_{-} & + & \check{L} & + & \check{e}_{\pm} \end{array}$$

to the renormalization group parameters:

$$\Delta b_3 = 3\ell(\text{vector}) - \ell(\text{chiral}) = 0 - 1/2 = -1/2$$

$$\Delta b_2 = 3\ell(\text{vector}) - \ell(\text{chiral}) = 0 - 1/2 = -1/2$$

$$\begin{aligned} \Delta b_1 &= 3\ell(\text{vector}) - \ell(\text{chiral}) \\ &= -\frac{3}{5}\cdot\frac{1}{4}\cdot\left[3\cdot\left(\tfrac{1}{3}\right)^2 + 1\cdot(-1)^2 + 2\cdot 0^2 + 1\cdot(+1)^2 + 1\cdot(-1)^2\right] \\ &= -1/2 \end{aligned}$$

($\times 2$ for vectorlike exotics)

# How the Predictions Change

Running gauge couplings . . .

$$\frac{1}{\alpha_i(\mu)} = \frac{1}{\alpha_{\mathsf{GUT}}} - \frac{1}{2\pi} b_i \log\left(\frac{M_{\mathsf{GUT}}}{\mu}\right), \quad i = 1, 2, 3, \quad \text{e.g.} \quad \mu = M_Z$$

3 equations, 1 unknown $M_{\mathsf{GUT}} \rightsquigarrow$ Calculate $M_{\mathsf{GUT}}$ and predict $\alpha_3$ or $\sin^2\theta$

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❶ GUT scale

$$M_{\mathsf{GUT}} = \mu \exp\left[\frac{2\pi}{b_2 - b_1}\left(\frac{3}{5\alpha_{\mathsf{em}}(\mu)} - \frac{8}{5\alpha_2(\mu)}\right)\right]$$

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## ❷ Strong coupling constant

$$\frac{8}{5\alpha_3(\mu)} = \frac{3}{5\alpha_{\mathsf{em}}(\mu)} - \frac{b_3 - b_1}{2\pi} \log\left(\frac{M_{\mathsf{GUT}}}{\mu}\right)$$

# How the Predictions Change

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3 equations, 1 unknown $M_{\mathsf{GUT}} \rightsquigarrow$ Calculate $M_{\mathsf{GUT}}$ and predict $\alpha_3$ or $\sin^2\theta$

## ❸ Weinberg angle

$$\sin^2\theta(\mu) = \frac{3}{8}\left[1 - \frac{1}{2\pi}(b_2 - b_1)\frac{5\alpha_{\mathsf{em}}}{3}\log\left(\frac{M_{\mathsf{GUT}}}{\mu}\right)\right]$$

# How the Predictions Change

Running gauge couplings . . .

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3 equations, 1 unknown $M_{\mathsf{GUT}} \rightsquigarrow$ Calculate $M_{\mathsf{GUT}}$ and predict $\alpha_3$ or $\sin^2\theta$

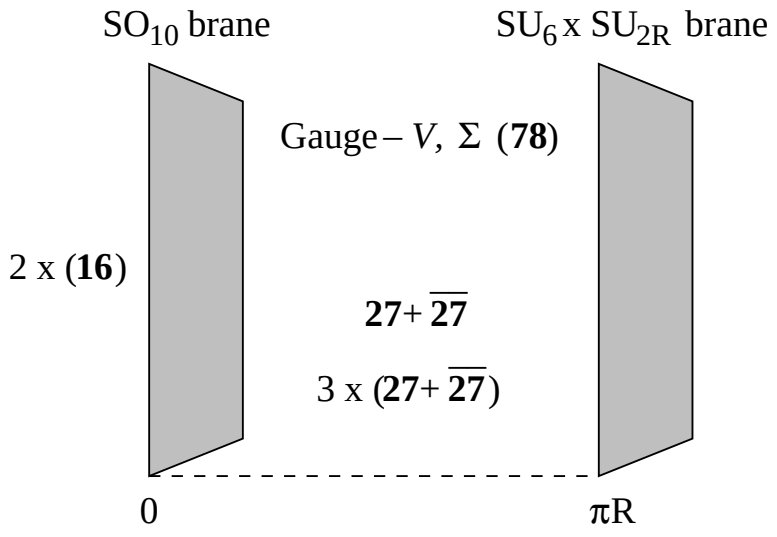
❹ GUT coupling constant

$$\frac{1}{\alpha_{\mathsf{GUT}}} = \frac{1}{\alpha_2(\mu)} + \frac{b_2}{b_2 - b_1}\left(\frac{3}{5\alpha_{\mathsf{em}}(\mu)} - \frac{8}{5\alpha_2(\mu)}\right)$$

# Models w/Light Exotics

## 5d orbifold GUT with 2 end-of-the-world-branes

T. Kobayashi, S. Raby, R. Zhang "Searching for realistic 4d string models. . . "
Nucl.Phys.B704:3-55,2005




$$\mathsf{SU}(6)\times\mathsf{SU}(2)_R \quad\rightarrow\quad \mathsf{SU}(4)\times\mathsf{SU}(2)_L\times\mathsf{SU}(2)_R \quad\rightarrow\quad \mathsf{SU}(\mathbf{3})_c\times\mathsf{SU}(\mathbf{2})_L\times\mathsf{U}(\mathbf{1})_Y$$

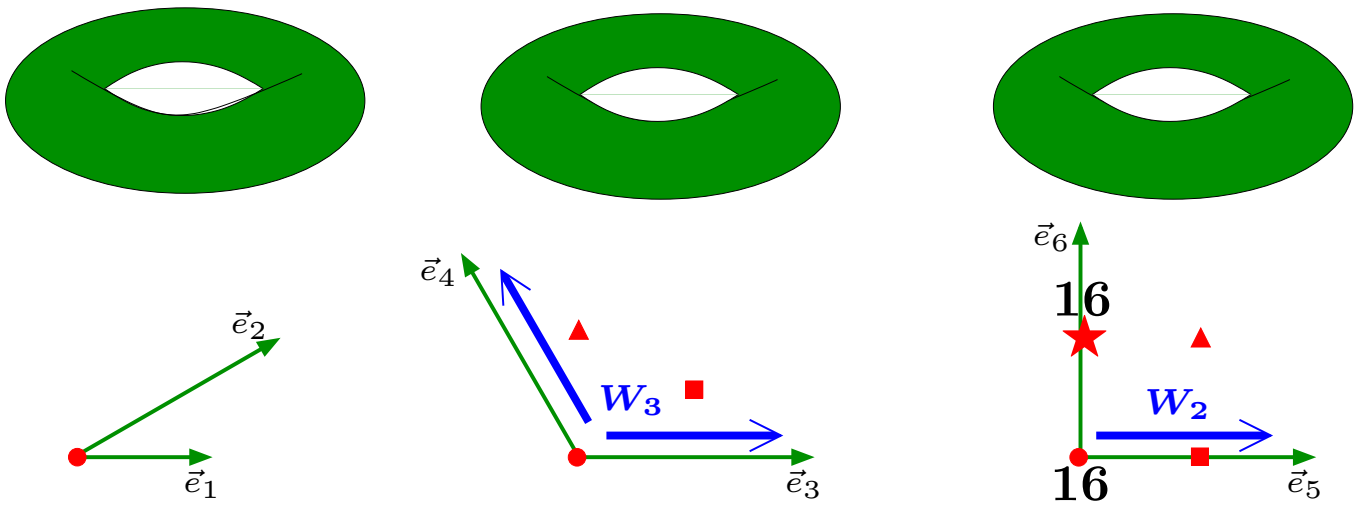
$$(\mathbf{6},\mathbf{1})+(\mathbf{1},\mathbf{2}) \quad\rightarrow\quad (\mathbf{4},\mathbf{1},\mathbf{1})+(\mathbf{1},\mathbf{2},\mathbf{1})+(\mathbf{1},\mathbf{1},\mathbf{2})$$

$$\rightarrow\quad (\mathbf{3},\mathbf{1})_{1/3} + (\mathbf{1},\mathbf{1})_{-1} + (\mathbf{1},\mathbf{2})_0 + (\mathbf{1},\mathbf{1})_{\pm 1}$$

$$\check{q} + \check{e}_- + \check{L} + \check{e}_\pm$$

# Models w/Light Exotics

Limit of 10d heterotic string orbifold




5th twisted sector of $\mathbb{Z}_6$-II orbifold

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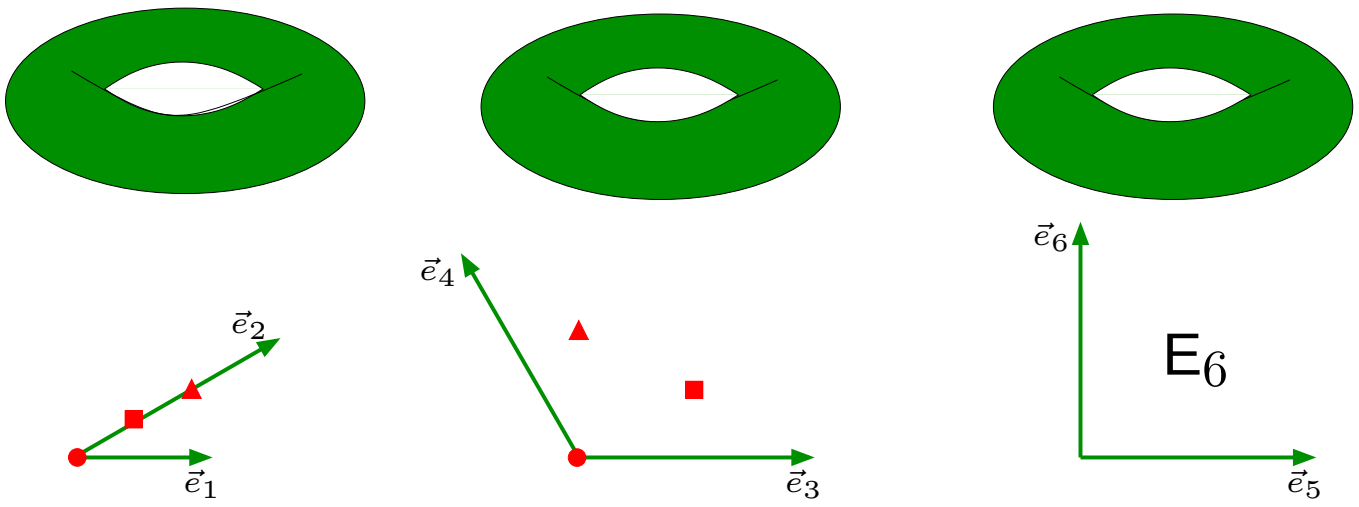


The $\mathbb{Z}_6$-II can be rewritten as a $\mathbb{Z}_2 \times \mathbb{Z}_3$ orbifold

$\rightsquigarrow$ First do the $\mathbb{Z}_3$ twist, then the $\mathbb{Z}_2$ twist

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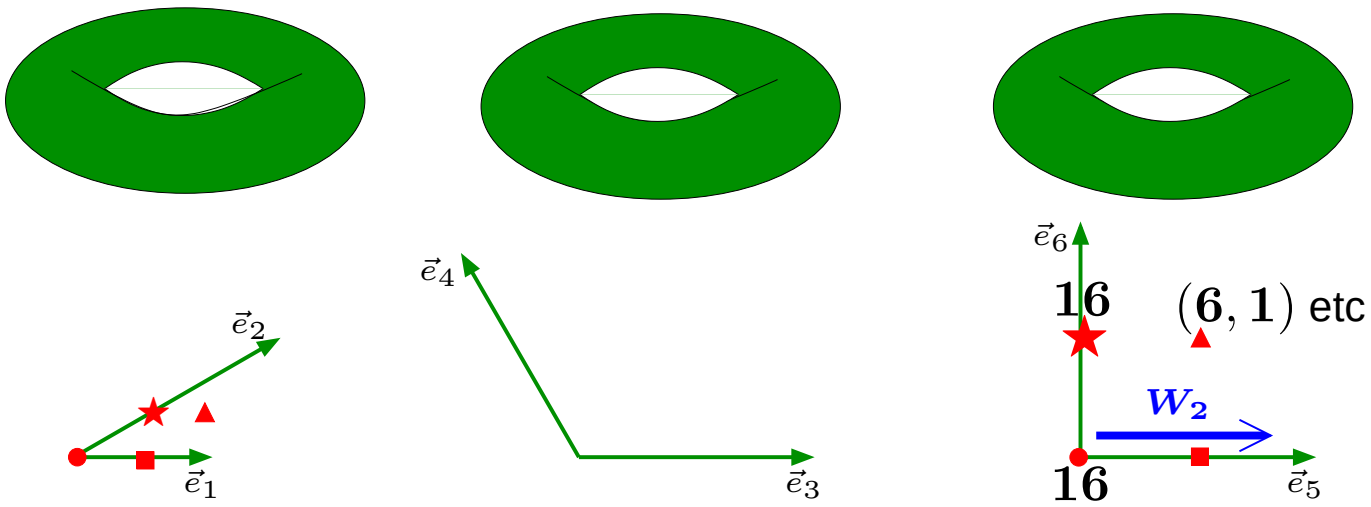


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# Experimental Consequences

Exotic particles (henceforth “exotica”)

$$\begin{array}{ccccccc} (\mathbf{3},\mathbf{1})_{1/3} & + & (\mathbf{1},\mathbf{1})_{-1} & + & (\mathbf{1},\mathbf{2})_{0} & + & (\mathbf{1},\mathbf{1})_{\pm 1} \\ \check{q} & + & \check{e}_{-} & + & \check{L} & + & \check{e}_{\pm} \end{array}$$

- Leptons

$$\check{e}_{-1/2}, \quad \check{L}_{\pm 1/2}, \quad \check{e}_{\pm 1/2}$$

- Baryons

$$[\check{\mathbf{q}}\mathbf{uu}]_{\mathbf{3/2}}, \quad [\check{\mathbf{q}}(\mathbf{ud})_{\mathbf{s}}]_{\mathbf{1/2}}, \quad [\check{\mathbf{q}}\mathbf{dd}]_{\mathbf{-1/2}}, \quad [\check{\mathbf{q}}(\mathbf{ud})_{\mathbf{a}}]_{\mathbf{1/2}}$$

- Mesons

$$[\bar{\check{\mathbf{q}}}\mathbf{u}]_{\mathbf{+1/2}}, \quad [\bar{\check{\mathbf{q}}}\mathbf{d}]_{\mathbf{-1/2}}$$

# Experimental Consequences

General, model independent features

- Fermionic exotica expected to be lighter than scalar partners (“s-exotica”)
- Scalar exotica decay to fermionic partners
- Fermionic partners will be stable, unless flavor symmetry is broken
- Fractionally charged particles cannot be screened by surrounding matter $\rightsquigarrow$ Clear signature
- Leptonic exotica will look like “heavy muons”

For more details on decay channels and generalization to models w/hidden sector see arXiv:0705.0294 [hep-ph]

# Conclusions

- Matter representations need not be in complete SU$(5)$ representations to preserve most successfull predictions of Grand Unification
- Only $\alpha_{\mathsf{GUT}}$ is affected
- As a consequence, exotic particles need not necessarily be of order GUT scale or higher
- New directions for string/GUT model building
- Novel signatures @ LHC and Tevatron
- "Generic" in string constructions ($\sim 5\%$), might thus be relevant for the real world