THE DREAM OF GRAND UNIFIED THEORIES AND THE LHC

Latsis symposium, Zurich, 2013

Graham Ross

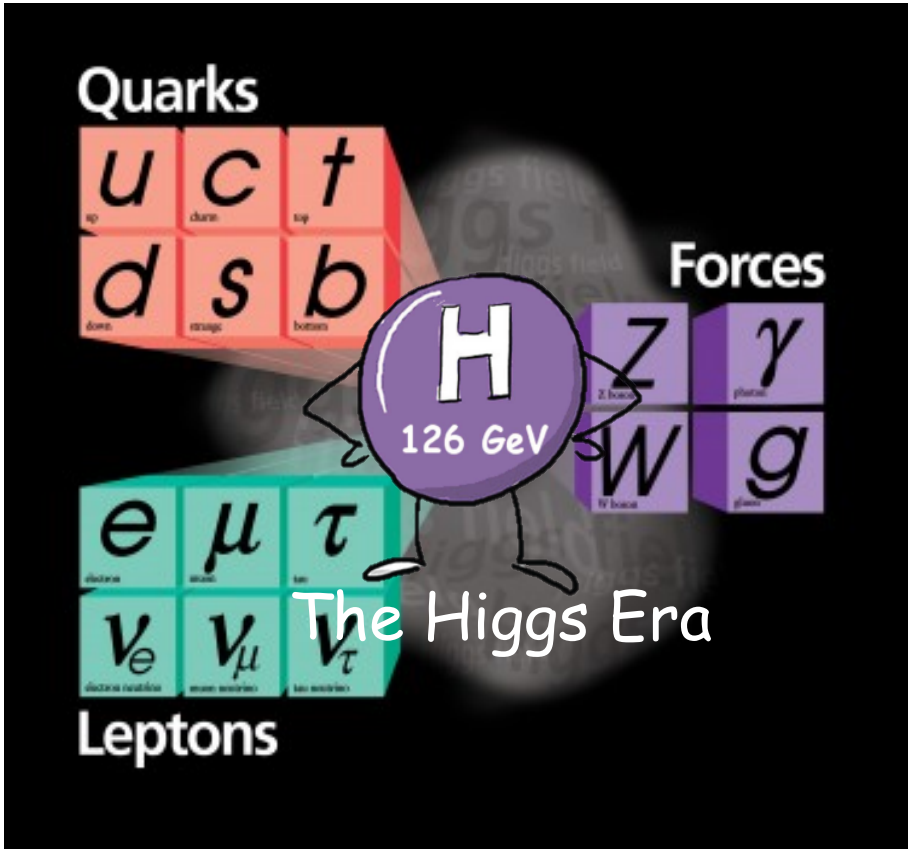
The Standard Model after LHC 8

- Symmetries ➔ Dynamics

Gauge bosons $SU(3)\times SU(2)\times U(1)$

Chiral Matter $\begin{pmatrix} u_i \\ d_i \end{pmatrix}_L, u_{iR}, d_{iR}, \begin{pmatrix} l_i \\ \nu_i \end{pmatrix}_L, l_{iR}, \nu_{iR}$

Higgs $\begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \rightarrow W_L^{\pm}, Z_L, h^0$



- Unanswered questions

- Gauge and multiplet structure?
- Charges?
- 18(27) parameters?
- Neutrino masses?
- Baryogenesis?
- Dark matter?
- Strong CP problem?

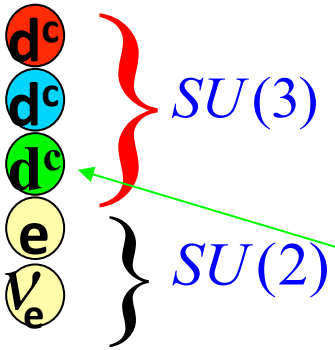
Grand Unification (String Unification)

- Unanswered questions
  - Gauge and multiplet structure(?)
  - Charges
    - 18 (27) parameters?
    - Neutrino masses?
    - Baryogenesis?
    - Dark matter?
    - Strong CP problem?

Georgi Glashow 1974

$$e.g.\quad SO(10) \supset SU(5) \supset SU(3) \otimes SU(2) \otimes U(1)$$

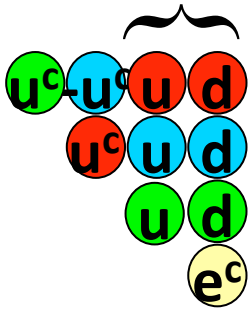
$$(\bar{5})_L :$$



$$3Q_? + Q_{e^-} = 0$$

$$Q_{d^c} = 1/3$$

$$(10)_L :$$



LH states SU(2) doublets

$$\nu_{e,L}{}^c \equiv \nu_{e,R}$$

$$(16)_L = (10)_L + (\bar{5})_L + (1)_L$$

Grand Unification (String Unification)

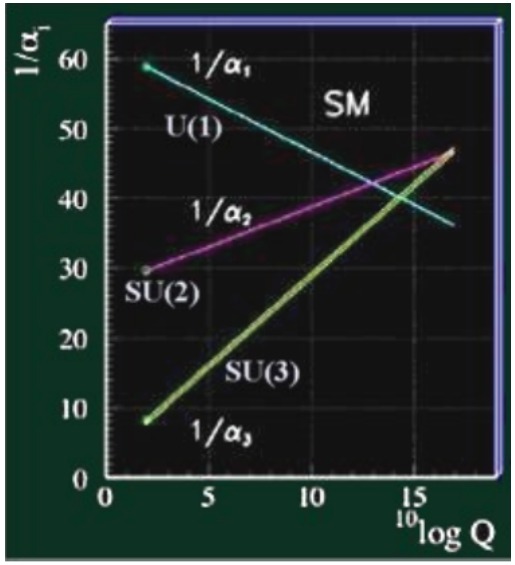
$$e.g.\quad \underset{45}{SO(10)} \supset \underset{24}{SU(5)} \supset \underset{12}{SU(3)\otimes SU(2)\otimes U(1)}$$

$$g_5 \qquad g_3 \qquad g_2 \qquad g_1$$

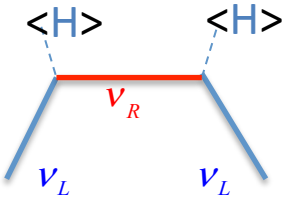
$(\bar{5})_L$: d^c d^c d^c e ν_e — $SU(3)$, $SU(2)$ $\Big\}(X,Y)_\mu,\ M_X \sim 10^{15-16}\,GeV$

$(10)_L$: u^c u^c u d / u^c u d / u d / e^c

$$(16)_L = (10)_L + (\bar{5})_L + (1)_L$$



- Unanswered questions
  - Gauge and multiplet structure(?)
  - Charges
    - 23 parameters?
    - Neutrino masses
    - Baryogenesis
    - Dark matter?
    - Strong CP problem



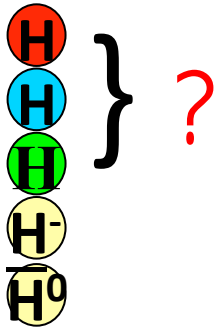
$$m_{\nu_L} \propto \frac{<H>^2}{m_{\nu_R}} \sim \frac{m_{l,q}^2}{m_{\nu_R}}$$

Smirnov

BUT…

Doublet-Triplet splitting problem:

Higgs doublet $\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ ✔ …but no SU(5) colour triplet partner



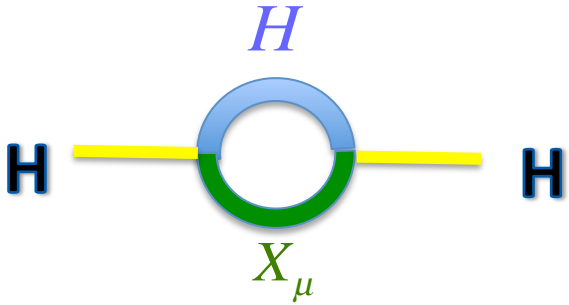
The Standard Model as an EFT:

A_μ ✔, Ψ ✔ H ✗

$$m_h^2(Q^2) = m_h^2 + \delta m_h^2(Q^2)$$

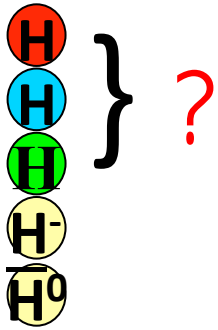
$$\delta m_h^2 \propto M_X^2 \ln\left(\frac{Q^2 + M_X^2}{\mu^2}\right) = O(10^{15}\,GeV)$$

The hierarchy problem !



Doublet-Triplet splitting problem:

Higgs doublet $\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$ ✔ …but no SU(5) colour triplet partner

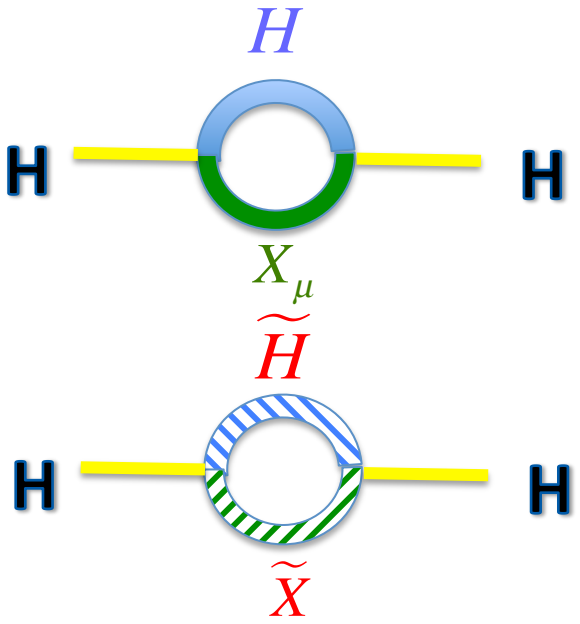


The Standard Model as an EFT:

A_μ ✔, Ψ ✔ H ✔

$$m_h^2(Q^2) = m_h^2 + \delta m_h^2(Q^2)$$

$$\delta m_h^2 \propto M_{SUSY}^2 \ln\left(\frac{Q^2 + M_X^2}{\mu^2}\right)$$



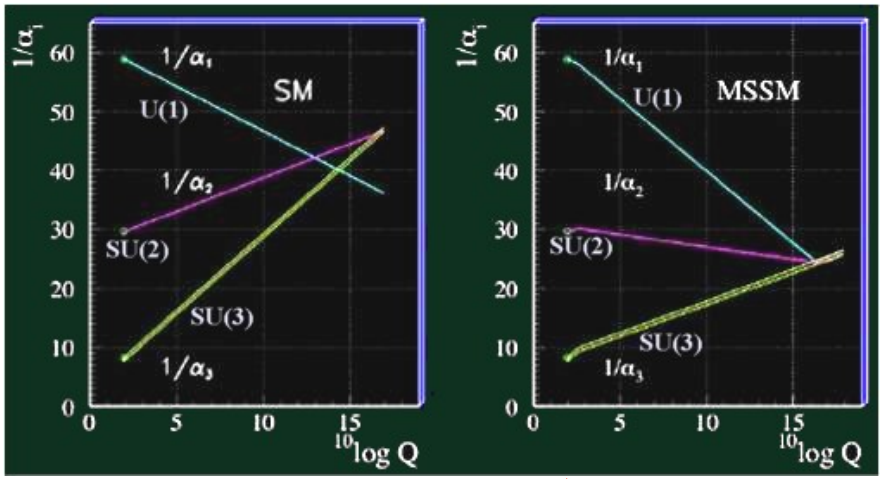
Solution – Supersymmetric GUTs - $M_{SUSY} \sim 1TeV$

- Grand Unification, String Unification

$e.g.\quad SO(10) \supset SU(5) \supset SU(3) \otimes SU(2) \otimes U(1)$

$g_5 \qquad g_3 \qquad g_2 \qquad g_1$ gauge coupling unification

$(\bar{5})_L$: d^c d^c d^c } $SU(3)$; e ν_e } $SU(2)$



$M_{SUSY} \sim TeV$

$(10)_L$: u^c u^c u d ; u^c u d ; u d ; e^c

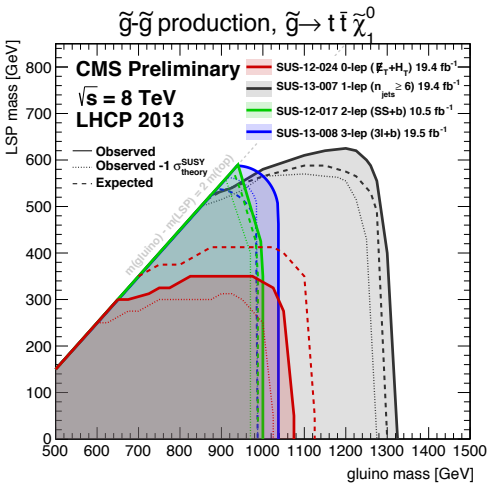
$(16)_L = (10)_L + (\bar{5})_L + (1)_L$

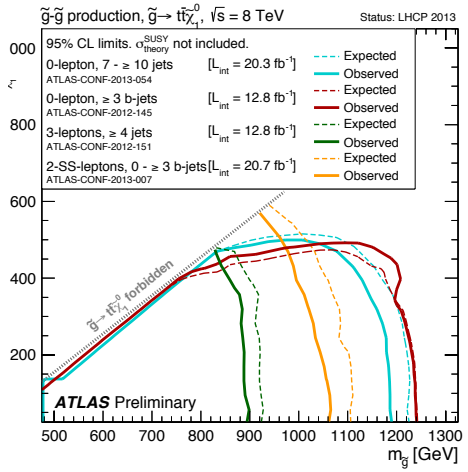
Dimopoulos. Georgi
Ibanez, GGR
Dimopoulos, Raby, Wilczek

SUSY@TeV ?

LHC SUSY searches so far negative

$$m_{\tilde{g},\tilde{q}} > 1 - 1.5\ GeV$$





Significance? -Fine tuning measure Δ (not optional in likelihood fit!)

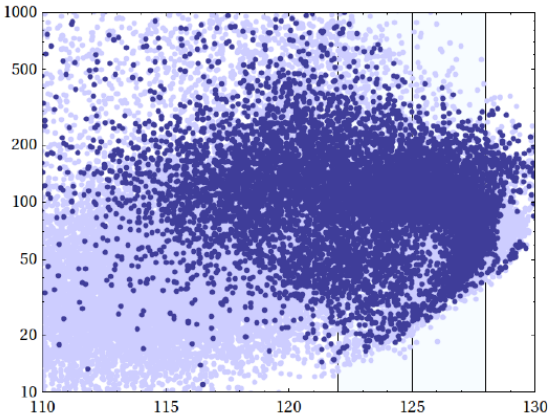
Ghilencea, GGR

Casas et al

$$\delta m_h^2 \sim \sum_{\tilde{q},\tilde{l}} a_i \widetilde{m}_i^2 + \sum_{\tilde{g},\widetilde{W},\widetilde{B}} b_i \widetilde{M}_i^2 + \ldots, \quad a_i, b_i \propto \log\left(\frac{M_X}{m_h}\right)$$

$$\frac{\left(\delta m_h^2\right)_i}{m_h^2} \geq 20$$ still room for SUSY!

$$\Delta \approx \frac{\delta m_{h,i}^2}{m_h^2}$$



(C)GNMSSM

Kaminska, GGR, Schmidt-Hoberg

GUTs - Nucleon decay

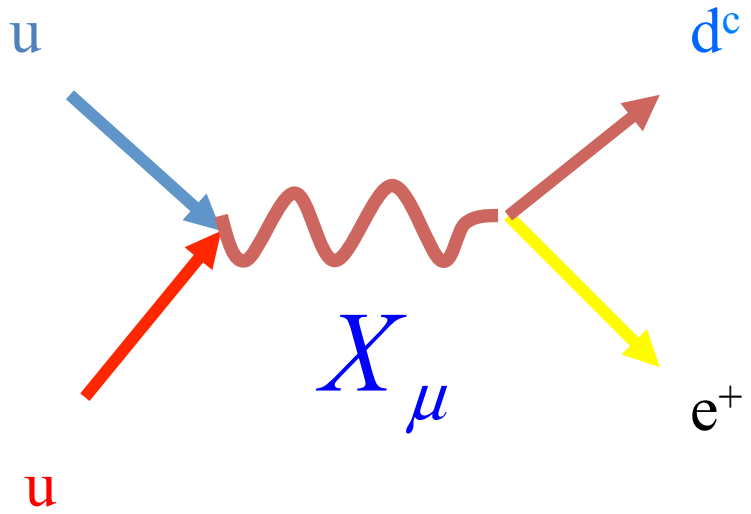
$$SU(5) \supset SU(3) \otimes SU(2) \otimes U(1)$$

M_X

$(\bar{5})_L$: d^c d^c d^c e ν_e } X_μ : New lepto-quark gauge interactions

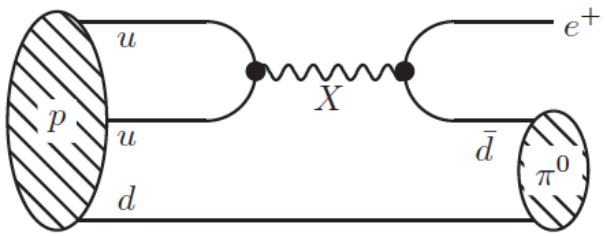
$$p \to \pi^0 e^+$$

$(10)_L$: u^c $-u^c$ u d / u^c u d / u d / e^c



$$\tau \propto M_X{}^4, \quad \tau_{p \to e^+ \pi^0} > 1 \times 10^{34} \text{ yrs}, \quad M_X > 10^{16} GeV$$

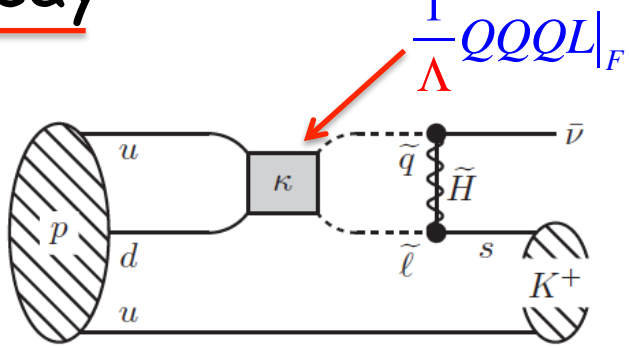
SUSY GUTS – Nucleon decay



(a) Dimension 6.

$$p \rightarrow \pi^0 + e^+$$

$$\tau_{p\rightarrow e^+\pi^0} > 1\times10^{34}\,\text{yrs},\ M_X > 10^{16}\,GeV$$



(b) Dimension 5.

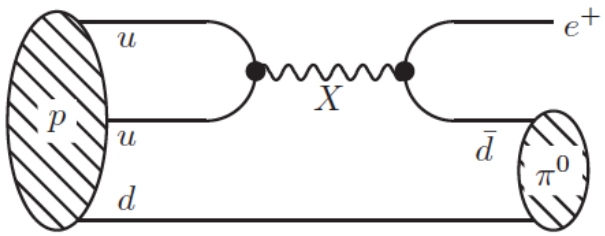
$$p \rightarrow K^+ + \bar{\nu}$$

$$\tau_{p\rightarrow K^+\bar{\nu}} > 3.3\times10^{33}\,yrs$$

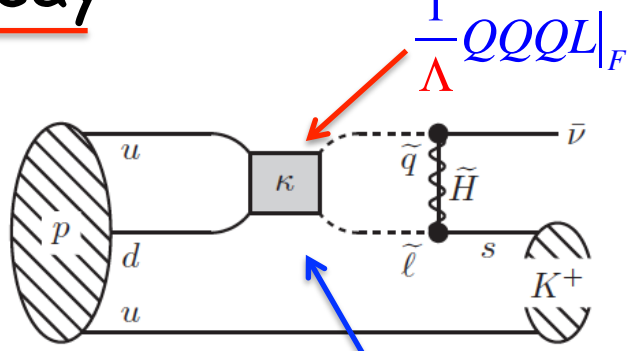
$$\Lambda > 10^{27}\,GeV,\ 10^9\,M_{Planck}$$

Raby
Murayama et al

SUSY GUTS – Nucleon decay



(a) Dimension 6.



(b) Dimension 5.

$$p \rightarrow \pi^0 + e^+$$

$$\tau_{p\rightarrow e^+\pi^0} > 1\times10^{34}\,\text{yrs},\ M_X > 10^{16}\,GeV$$

$$p \rightarrow K^+ + \bar{\nu}$$

$$\tau_{p\rightarrow K^+\bar{\nu}} > 3.3\times10^{33}\,yrs,\ \Lambda > 10^{27}\,GeV,\ 10^8\,M_{Planck}$$

No D=5 ✔

Lee et al

Recent developments:

GUT SU(5), SO(10)

μ-term small (Higgsino mass)

Anomaly free (discrete) symmetry

⇒

Discrete R-symmetry Z_4^R ...

Split multiplets (Higgs) †

Higher dimension †
e.g.string unification

Ratz et al

† Doublet – Triplet splitting

Doublet-Triplet splitting from higher dimensions

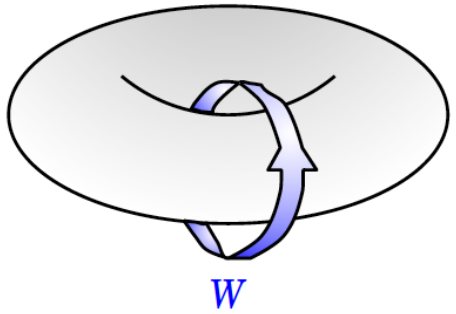
Compactification: $K = K_0 / H$

freely acting discrete group

Wilson line breaking: $W : \quad \overline{H} \subset G$

embedding of H into gauge group G

Massless states: $H \otimes \overline{H}$ singlets



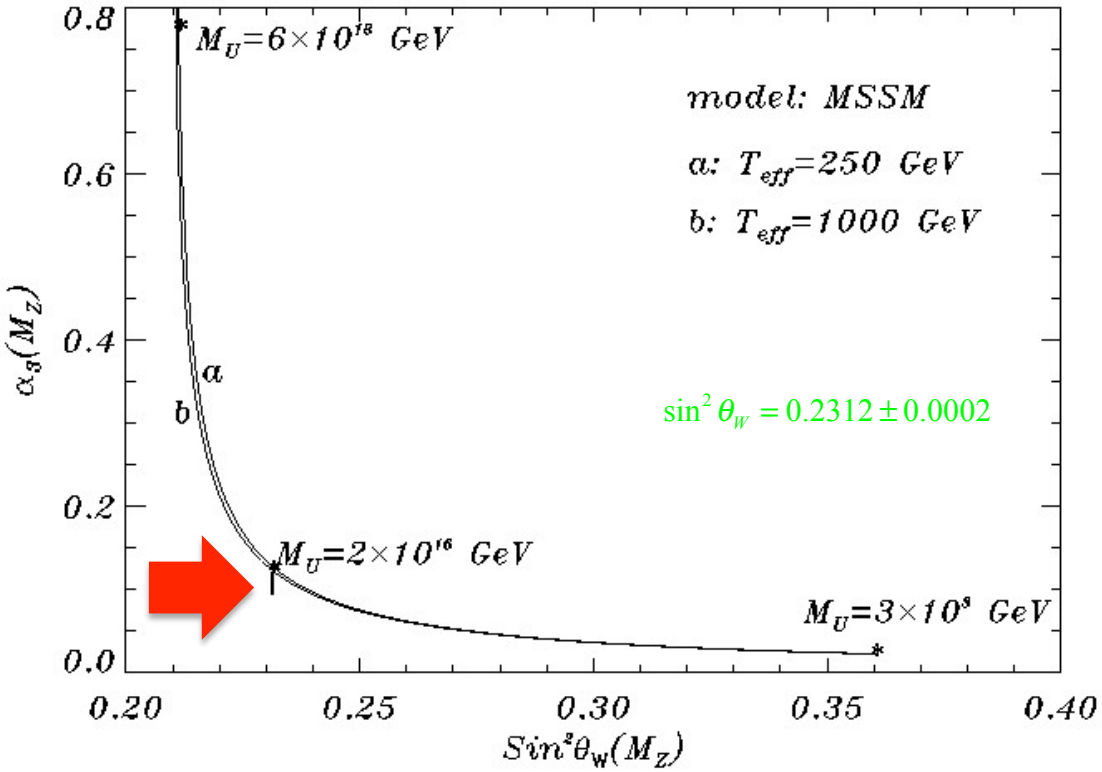
$$W = P \exp\left(-i \int_{\gamma} T^a A^a_m \, dx^m \right)$$

Breit, Ovrut, Segre

$$e.g. \quad SU(5): \quad H = Z_3, \quad \overline{H} = Diag(\alpha,\alpha,\alpha,1,1), \quad \alpha = e^{2i\pi/3}$$

$$\left(R \otimes \overline{R}\right): \quad (1 \otimes \overline{5}) \to \begin{pmatrix} H^- \\ \overline{H}^0 \end{pmatrix}_1, \quad \left(3,\overline{5}\right) \to \begin{pmatrix} e \\ \nu_e \end{pmatrix}_1 \oplus \begin{pmatrix} d^c \\ d^c \\ d^c \end{pmatrix}_{\alpha^2}, \quad \text{Matter} \quad \to \quad \left(3,\overline{5}+10\right)$$

SUSY-GUT gauge coupling unification



Ghilencea, GGR

$$\sin^2\theta_W = 0.23116(12) \quad (Expt)$$

$$\alpha_s = 0.134 \pm 0.01 - 4(\sin^2\theta_W - 0.23116) \qquad c.f. \quad 0.1184(7) \quad (Expt)?$$

c.f. String Unification - Weakly Coupled Heterotic String

Gross, Harvey,Martinec, Rohm

$$L_{eff}^{HS} = \int d^{10}x\sqrt{g}e^{-\phi}\left(\frac{4}{\alpha'^4}R + \frac{k_i}{\alpha'^3}TrF_i^2 + \ldots\right)$$

$\int d^4x\, V$ $\quad$ α_{10}^{-1} $\quad$ $\alpha' = 1/M_{string}^2$ only scale

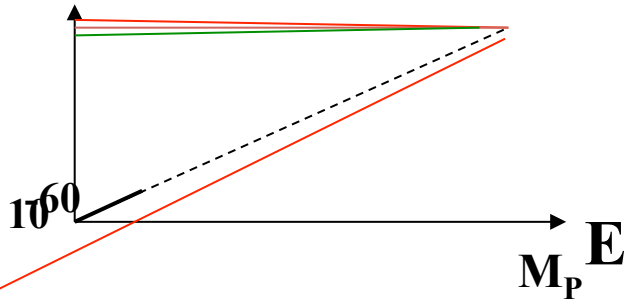
$$G_N = \frac{\alpha_{10}\alpha'^4}{64\pi V}, \quad \alpha_{String} = \frac{\alpha_{10}\alpha'^3}{16\pi V} \Rightarrow G_N = \frac{\alpha_{String}\alpha'}{4}$$

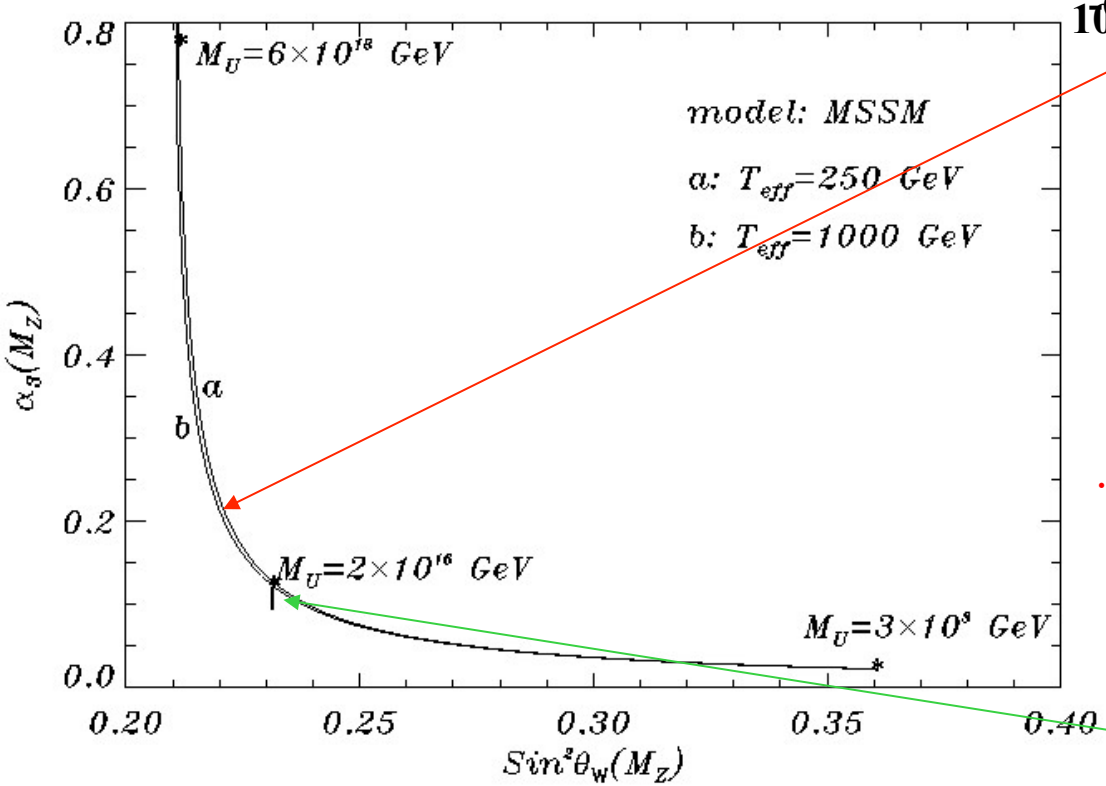
$$\frac{1}{g_i^2(M_Z)} = \frac{k_i}{g_{string}^2} + b_i \ln\left(\frac{M_{string}}{M_Z}\right) + \Delta_i$$

$$M_{string} = g_{string}.M_{Planck} = 3.6\times 10^{17}\, GeV$$

Kaplunovsky

String unification with gravity





$$M_U^{WCHS} = 3.6\times10^{17}\,GeV\,?$$

..close..but not close enough!

..string threshold corrections, Δ_i ?

$$M_U = (2.5\pm2).10^{16}\,GeV$$

GGR, D.Ghilencea

$$\sin^2\theta_W = 0.23116(12) \quad (Expt)$$

$$\alpha_s = 0.134\pm0.01-4(\sin^2\theta_W - 0.23116) \qquad c.f. \quad 0.1184(7) \quad (Expt)$$

String threshold effects, Δ_i : Wilson line breaking

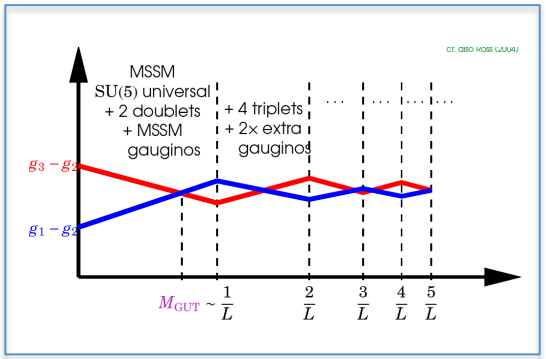
GGR
Raby
Ratz

$$SU(5) \to SU(3) \otimes SU(2) \otimes U(1)$$

X, Y

$n = \pm 1$ ——— ——— 3, 2, 1 } $M_n^2(\sigma) = \chi^2 + \frac{1}{R^2}(n + \rho_\sigma)^2$

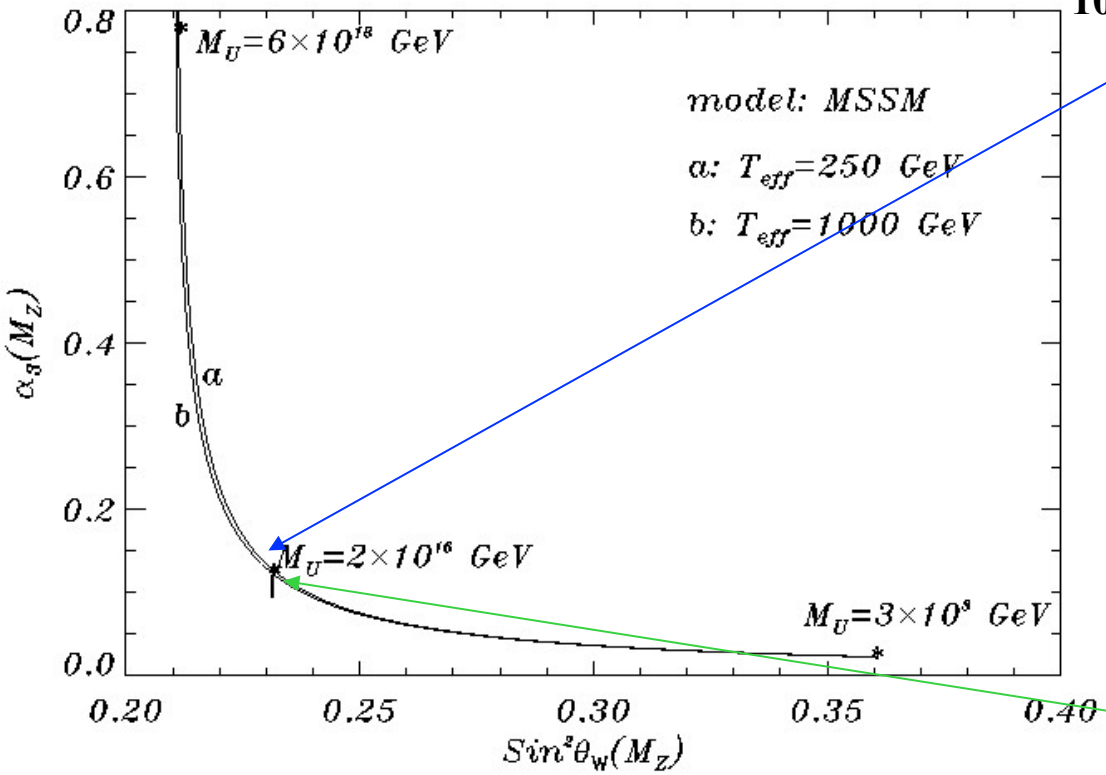
$n = 0$ ——— ——— 3, 2, 1



$$\frac{\beta_i^{X,Y}(\sigma)}{4\pi}\left(\log(m+\rho)+\log(m-\rho)\right) = \frac{\beta^{SU(5)} - \beta_i(\sigma)}{4\pi}\log(m^2-\rho^2).$$

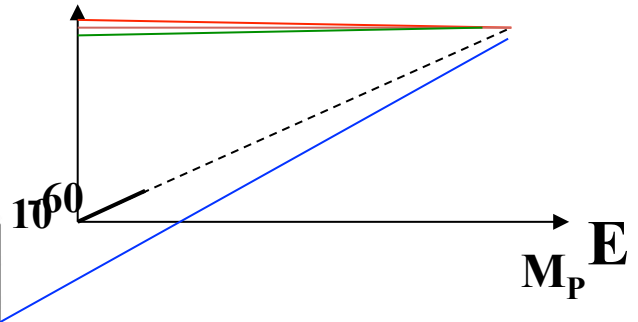
Reduction in X,Y boson contribution - equivalent to reduction in unification scale.

Precision Unification possible



GGR, D.Ghilencea

String unification with gravity



+ Wilson line breaking

$$e.g. \quad Z_3 : SU(5) \to SM$$
$$M_U^{WCHS} = 6.10^{16} GeV,$$
$$\delta(\alpha_s) = -0.008$$

GGR

$$M_U = (2.5 \pm 2).10^{16} GeV$$

$$\sin^2\theta_W = 0.23116(12) \quad (Expt)$$

$$\alpha_s = 0.126 \pm 0.01 - 4(\sin^2\theta_W - 0.23116) \qquad c.f. \quad 0.1184(7) \quad (Expt)?$$

Summary

- Gauge, matter multiplets $\Rightarrow$ $GUT \quad SU(5),\ SO(10),\ldots$

  Hierarchy problem $\Rightarrow$ $SUSY\ GUT$

  μ-term $\Rightarrow$ $Z_4^R \subset$ Lorentz symmetry D>4

  Doublet-triplet splitting $\Rightarrow$ Wilson line breaking

- Precision gauge and gravity coupling unification possible

$$\alpha_s = 0.126 \pm 0.01 - 4(\sin^2\theta_W - 0.23116) \qquad M_U = (2.5 \pm 2).10^{16} GeV$$

- Family replication and masses

  String compactification

  GUT relations $m_b = m_\tau, \quad Det[M_d] = Det[M_l]$

  Family symmetries. . . (?)

Summary

- Gauge, matter multiplets $\Rightarrow$ $GUT \quad SU(5),\ SO(10),\ldots$

  Hierarchy problem $\Rightarrow$ $SUSY\ GUT$

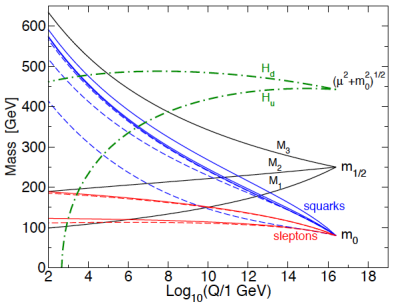
  μ-term $\Rightarrow$ $Z_4^R \subset$ Lorentz symmetry D>4

  Doublet-triplet splitting $\Rightarrow$ Wilson line breaking

- Precision gauge and gravity coupling unification possible

$$\alpha_s = 0.126 \pm 0.01 - 4(\sin^2\theta_W - 0.23116) \qquad M_U = (2.5 \pm 2).10^{16}\, GeV$$

- Family replication and masses



String compactification

GUT relations $m_b = m_\tau, \quad Det[M_d] = Det[M_l]$

Family symmetries. . . (?)

Soft masses – radiative breaking

Ibanez,GGR

Outlook – indirect signals

- Nucleon decay D=6 operators

Operator renormalisation

$$\tau(p \to \pi^0 e^+) = \left(\frac{M_{\rm GUT}}{10^{16}\ {\rm GeV}}\right)^4 \left(\frac{1/35}{\alpha_{\rm GUT}}\right)^2 \left(\frac{0.015\ {\rm GeV}^3}{\alpha_N}\right)^2 \left(\frac{5}{A_L}\right)^2 4.4 \times 10^{34}\ {\rm yr.}$$

Hadronic matrix element

$$\tau^{SuperK}_{p\to e^+\pi^0} > 1\times 10^{34}\,\text{yrs}$$

Giudice, Romanino

$$M_{\rm GUT} > \left(\frac{\alpha_{\rm GUT}}{1/35}\right)^{1/2} \left(\frac{\alpha_N}{0.015\ {\rm GeV}^3}\right)^{1/2} \left(\frac{A_L}{5}\right)^{1/2} 6 \times 10^{15}\ {\rm GeV}$$

$$c.f.\ M_U = (2.5 \pm 2).10^{16}\,GeV$$

Outlook – indirect signals

- Nucleon decay D=6 operators

- Neutrino masses – see-saw

$$m_{\nu_L} \propto \frac{< H >^2}{m_{\nu_R}} \sim \frac{m_{l,q}^2}{m_{\nu_R}}$$

Majorana mass – L violation:

Baryogenesis – via Leptogenesis – ν_R decay:

Thermal leptogenesis

$$\frac{\Gamma(N_1 \to l\phi) - \Gamma(N_1 \to \bar{l}\bar{\phi})}{\Gamma(N_1 \to l\phi) + \Gamma(N_1 \to \bar{l}\bar{\phi})} \simeq \frac{3}{16\pi} \frac{M_1}{(h_\nu^\dagger h_\nu)_{11} v^2} \mathrm{Im}\left(h_\nu^\dagger m_\nu h_\nu^*\right)_{11}$$

$$\Rightarrow m_\nu < 0.1 eV, \quad m_{\nu_{R1}} > 4 \times 10^8 GeV$$

Buchmuller review

Outlook – indirect signals

- Nucleon decay D=6 operators

- Neutrino masses – see-saw

- FCNC

  $\tilde{q}, \tilde{l}, \tilde{\nu}$ mixing

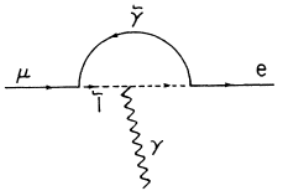
Egede
Beneke

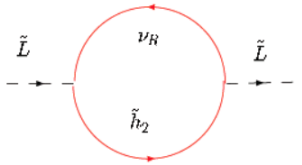
e.g. Lepton FCNC:

$$\Gamma(\mu \to e\gamma) \propto \left(m_{\tilde{L}}^{\ 2}\right)_{12}$$

$$L = f_l \bar{e}_R L h_1 + f_\nu \bar{\nu}_R L h_2 + m_{\nu_R} \nu_R \nu_R$$

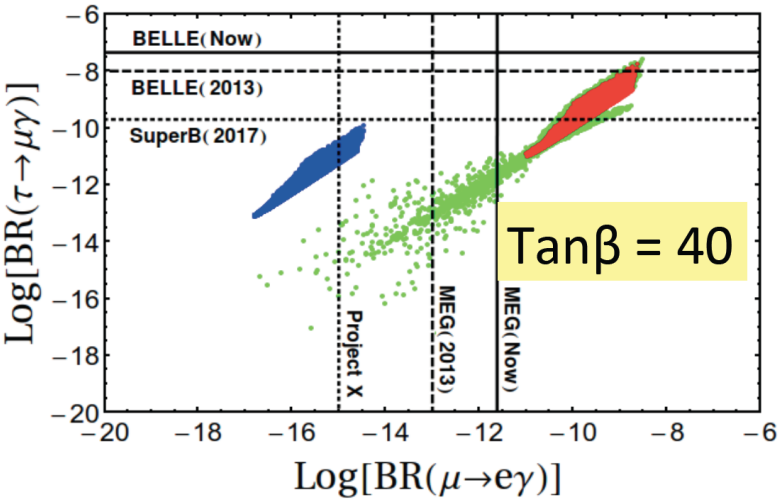
$$\left(m_{\tilde{L}}^{\ 2}\right)_{ij} \simeq \frac{1}{8\pi^2}\left(3m_0^2 + A_0^2\right)\left(f_\nu^{\ \dagger} f_\nu\right)_{ij} \log\frac{m_{\nu_R}}{M_U}$$



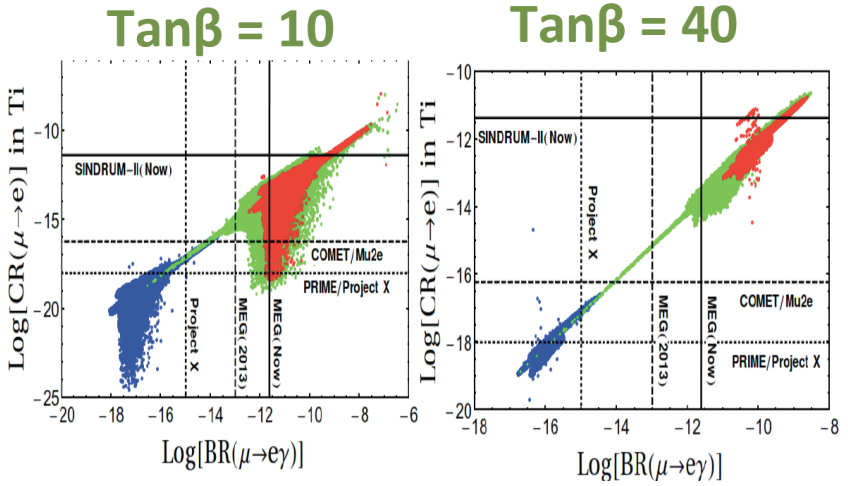


Borzumati, Masiero

τ → μγ vs. μ → eγ sensitivities



μ – e conversion vs μ → eγ



Outlook – indirect signals

- Nucleon decay D=6 operators

- Neutrino masses – see-saw

- FCNC

  $\tilde{q}, \tilde{l}, \tilde{\nu}$ mixing

- SUSY @ LHC, SUSY Higgs

Sphicas

- Dark Matter

SUSY WIMP, Axions $f_{axion} > 10^9 GeV$

Sarkar, Aprile

Outlook – indirect signals

- Nucleon decay D=6 operators
- Neutrino masses – see-saw
- FCNC

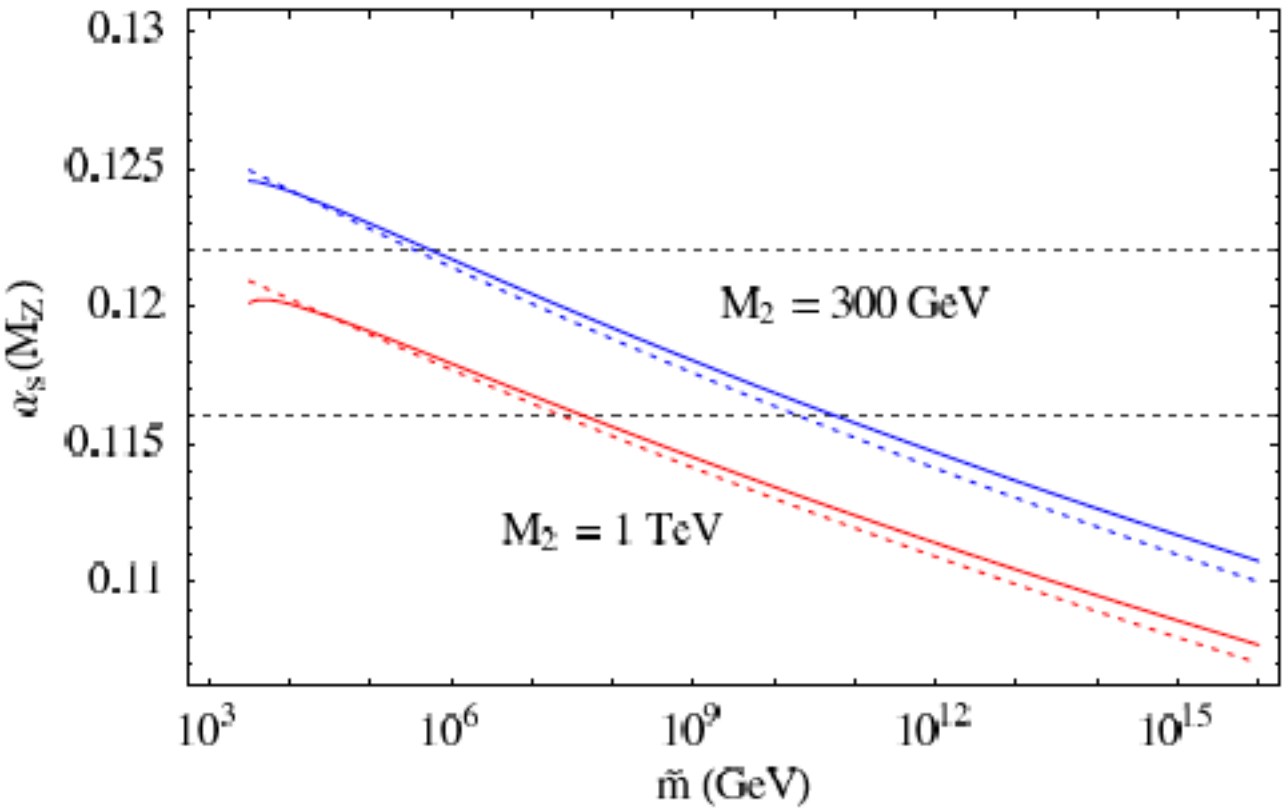
  $\tilde{q}, \tilde{l}, \tilde{\nu}$ mixing
- SUSY @ LHC, SUSY Higgs
- Dark Matter

LHC 14!

Sphicas

SUSY WIMP, Axions $f_{axion} > 10^9 GeV$

Sarkar, Aprile



Unification in split SUSY

Giudice, Romanino