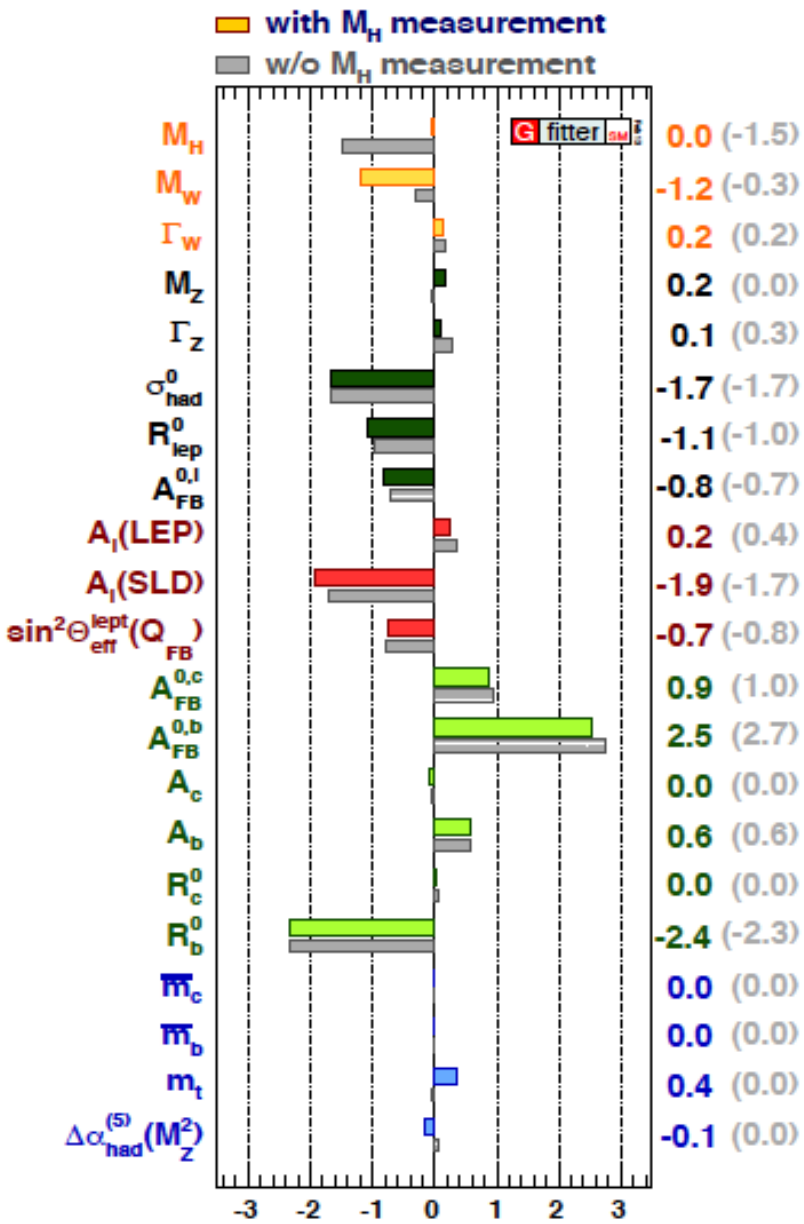
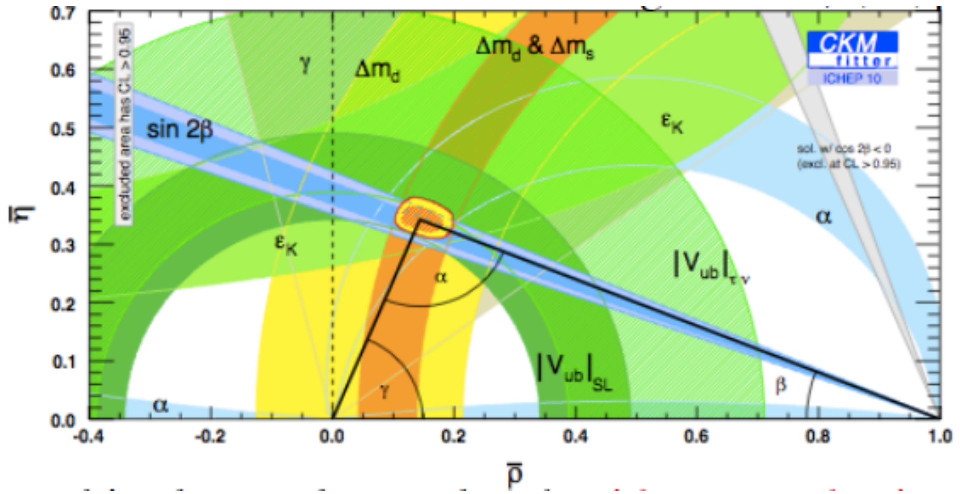
Grand Unification

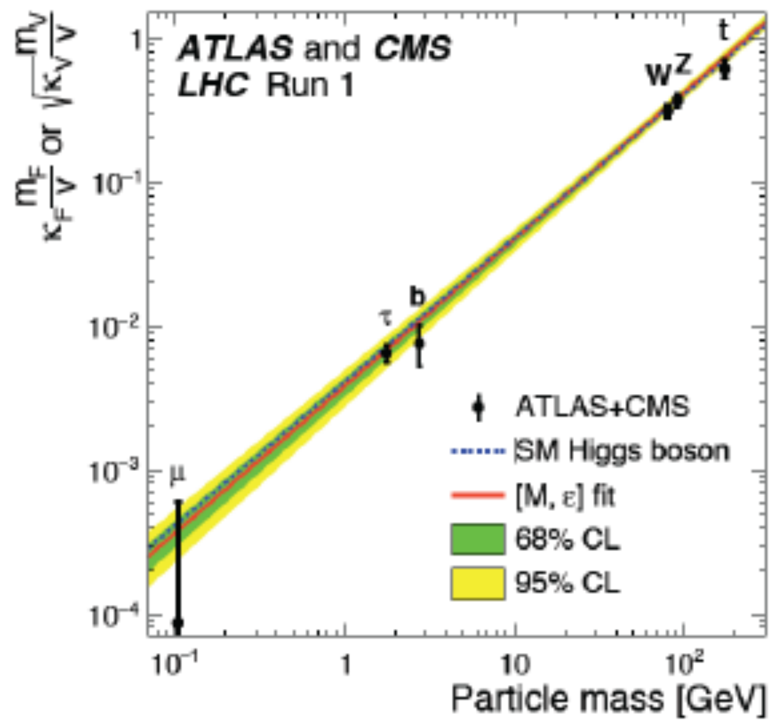
(Beyond the Standard Model after LHC 13TeV)

G. Ross, Corfu, September 2016

Experimentally the Standard Model reigns supreme :







But leaves many questions unanswered….

Outstanding Questions in Particle Physics *circa* 2016

… there has never been a better time to be a particle physicist!

Higgs boson and EWSB
- ❑ m_H natural or fine-tuned ?
- → if natural: what new physics/symmetry?
- ❑ does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate CP ?
- ❑ cosmological EW phase transition

Quarks and leptons:
- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:
- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:
- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:
- ❑ ν masses and and their origin
- ❑ what is the role of $H(125)$?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation
- ❑ additional species → sterile ν ?

The two epochs of Universe's accelerated expansion:
- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ❑ today: dark energy (why is Λ so small?) or gravity modification ?

ICHEP 2016 – I. Shipsey

I Shipsey, ICTP 2016

Most promising…new symmetries….

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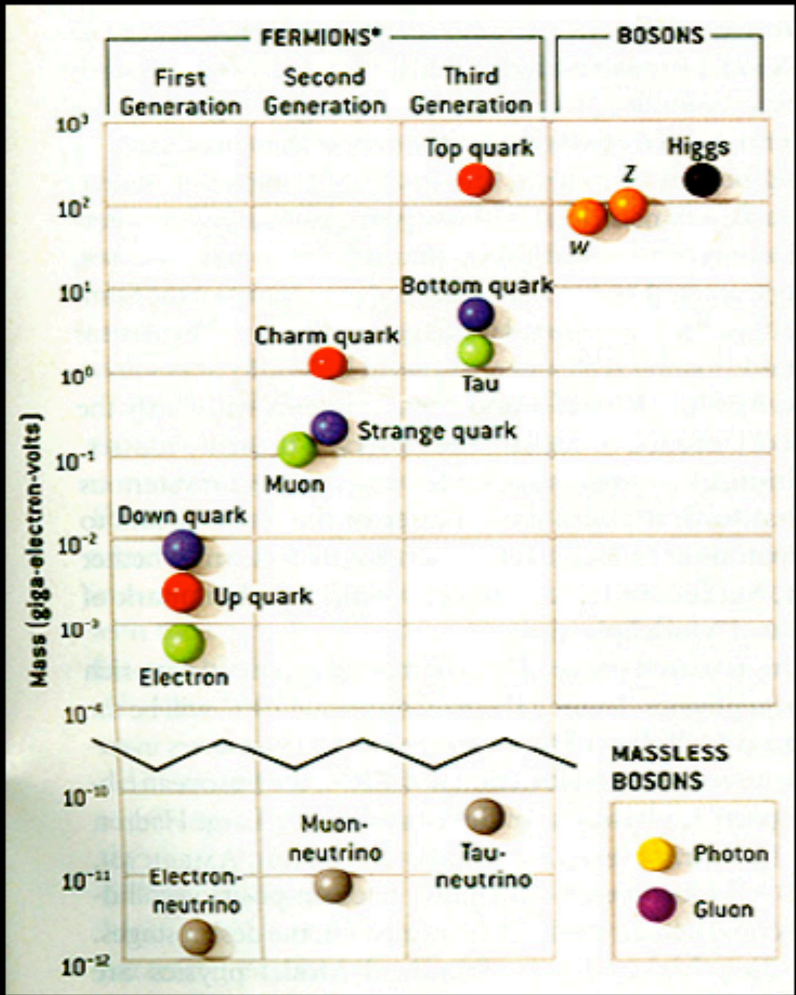
ICHEP 2016 – I. Shipsey

Mystery: Why are there so many types of particles?



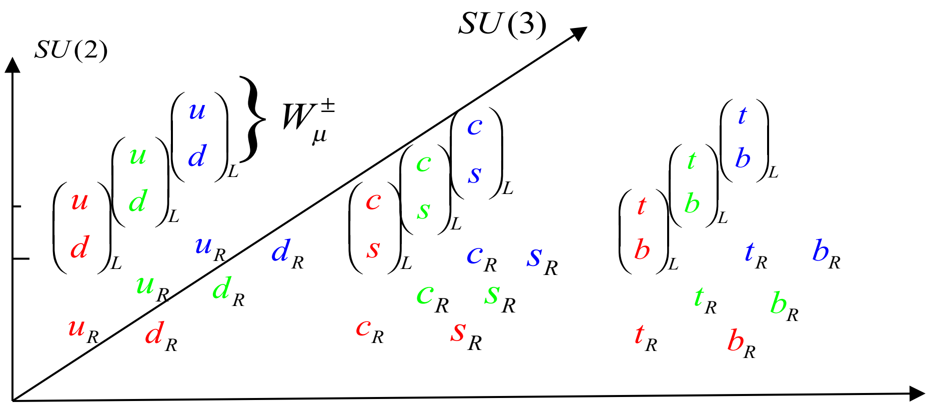
Why do the particles have such a large range of masses?

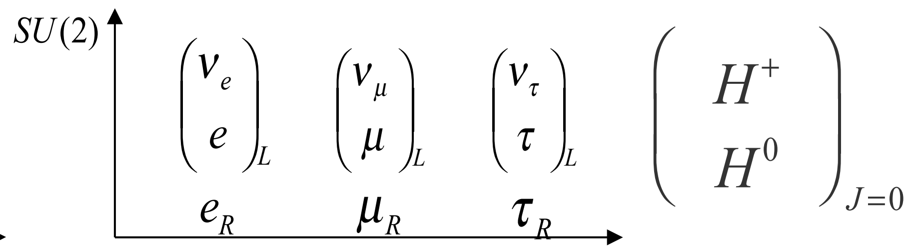
Why does the pattern of particles repeat three times?

Why do neutrinos have mass at all (in the Standard Model they are massless)?

Characteristic multiplet structure

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





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

Georgi Glashow

Group of 5×5 complex unitary matrices with determinant 1

Grand Unification

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

$$
\left(\bar{5}\right)_{La} : \begin{array}{l} \left.\begin{array}{c} d^c \\ d^c \\ d^c \end{array}\right\} SU(3) \\ \left.\begin{array}{c} e \\ \nu_e \end{array}\right\} SU(2) \end{array}
$$

$$
3Q_{d^c} + Q_{e^-} = 0
$$

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

Grand Unification

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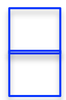
$$3Q_{d^c} + Q_{e^-} = 0$$

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

Remaining 10 states? $T^{[\alpha,\beta]}$

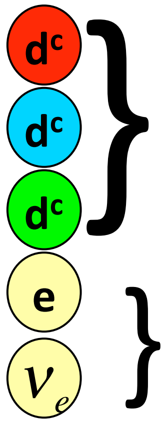


$$\frac{n(n-1)}{1 \times 2} = 10$$

Grand Unification

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

$(\bar{5})_L$:

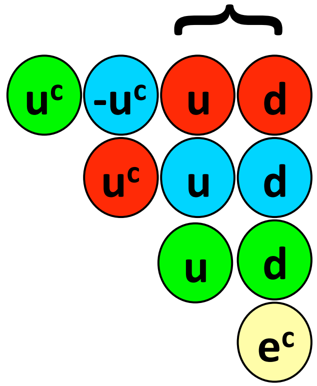


$SU(3)$

$SU(2)$

$(10)_L$

$T^{[\alpha,\beta]}$



LH states SU(2) doublets

Grand Unification

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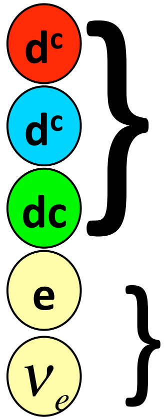
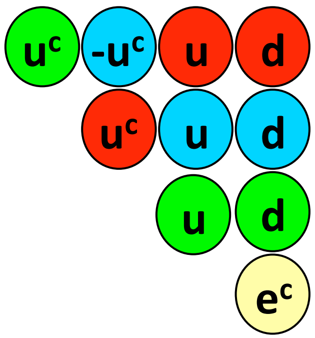
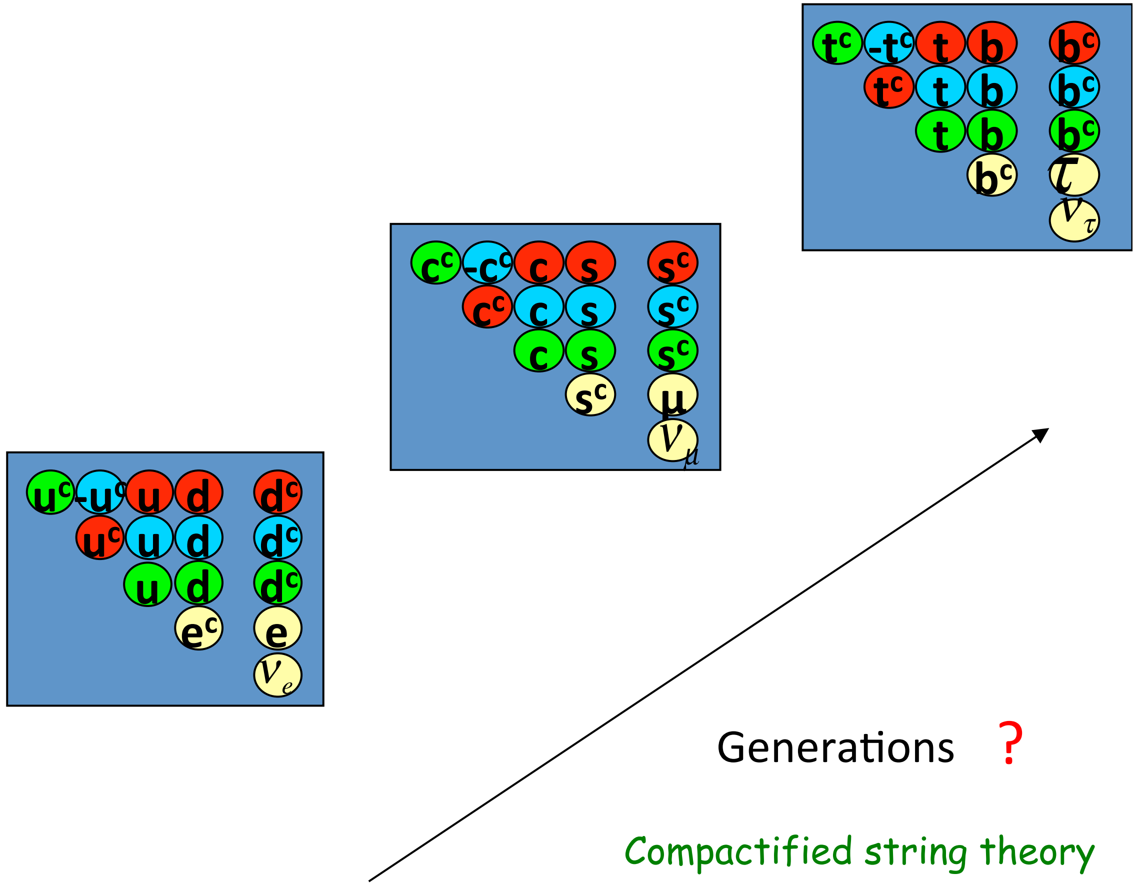


$SU(3)$

$SU(2)$

$(10)_L$:





Gauge boson structure $SU(5)$

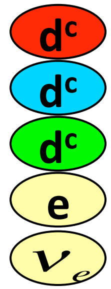
Group of 5×5 complex unitary matrices with determinant 1

$50-25-1=24$ independent matrices - adjoint representation

$$U=\exp\left(-i\sum_{i=1}^{24}\beta^i L^i\right),\qquad U^\dagger U=1\quad\Rightarrow\quad L^i \text{ Hermitian generators}$$

$(3,1)+(1,2)$

Covariant derivative: Gauge bosons V_μ^a



Define $\frac{1}{\sqrt{2}}V_\mu\equiv\frac{1}{2}\sum_{a=1}^{24}V_\mu^a L^a,\qquad \left(D_\mu\psi_5\right)^i=\left[\delta_j^i\partial_\mu-\frac{ig}{2}\sum_{a=1}^{24}V_\mu^a\left(L^a\right)_j^i\right]\psi_5^j$

$$V_\mu=\begin{bmatrix} G_1^1-\frac{2B}{\sqrt{30}} & G_2^1 & G_2^1 & \bar{X}_1 & \bar{Y}_1 \\ G_1^2 & G_2^2-\frac{2B}{\sqrt{30}} & G_3^2 & \bar{X}_2 & \bar{Y}_2 \\ G_1^3 & G_2^3 & G_3^3-\frac{2B}{\sqrt{30}} & \bar{X}_3 & \bar{Y}_3 \\ X_1 & X_2 & X_3 & \frac{W_\mu^3}{\sqrt{2}}+\frac{3B}{\sqrt{30}} & W^+ \\ Y_1 & Y_2 & Y_3 & W^- & -\frac{W_\mu^3}{\sqrt{2}}+\frac{3B}{\sqrt{30}} \end{bmatrix},$$

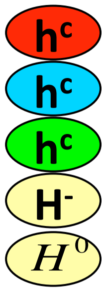
Lepto-quark interactions

Spontaneous symmetry breaking

$$SU(5) \xrightarrow[\Sigma_{24}]{M_X} SU(3)\times SU(2)\times U(1) \xrightarrow[H_{\bar{5}}]{M_W} SU(3)\times U(1)$$

$$\langle \Sigma \rangle = \mathrm{v}_3 \mathrm{Diagonal}(2,2,2,-3,-3)$$

$$\langle H_{\bar{5}} \rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \mathrm{v} \end{pmatrix}$$



$$\Big\} \; M_T \gtrsim 10^{12}\mathrm{GeV}$$

Grand Unification $SO(10) \supset SU(5) \supset SU(3) \otimes SU(2) \otimes U(1)$

Anomaly free

$SO(10)$: Group of matrices R that leave invariant length of 10-dim vector

$R^T R = RR^T = 1$

Adjoint representation $SO(n):\ n^2 - (n^2+n)/2 = n(n-1)/2$

$SO(10)$ 45 gauge bosons

Rank 5

$$SO(10) \nearrow SU(5) \times U(1) \qquad 45 = 24 + 1 + 10 + \overline{10}$$

$$SO(10) \searrow SU(4) \times SU(2)_L \times SU(2)_R$$

$SO(10)$ **:** Group of matrices R† that leave invariant length of 10-dim vector

$$R^T R = RR^T = 1$$

†Adjoint representation $O(n):\ n^2 - (n^2 + n)/2 = n(n-1)/2$

$SO(10)$ 45 gauge bosons

Spinorial (16 dim) representation:

$c.f.\ SO(3) \sim SU(2)$ $\psi_{\alpha=1,2}$, $R = e^{i\omega^{ab}\sigma_{ab}}$, $\sigma_{ab} = \frac{1}{2}\varepsilon_{abc}\sigma_c \equiv \frac{i}{2}[\sigma_a, \sigma_b]$

$$SO(10) \quad \underbrace{\chi_{16}^{\pm}}_{2^4} = \psi_1 \times \psi_2 \times \psi_3 \times \psi_4 \times \psi_5 \quad \text{with} \quad \sum_{i=1}^{5} \sigma_3^i = \pm 1$$

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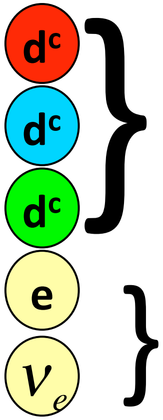

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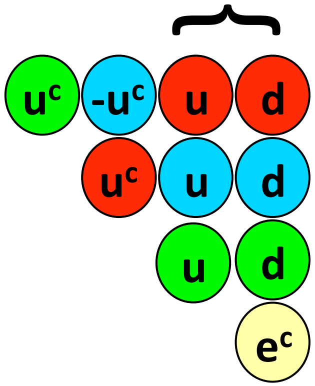

$$\nu_{e,L}{}^{c} \equiv \nu_{e,R}$$

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

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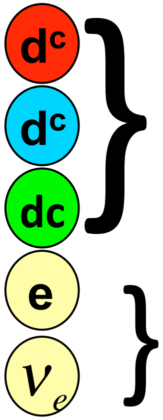
Gauge Couplings

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

$$M_X$$

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

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

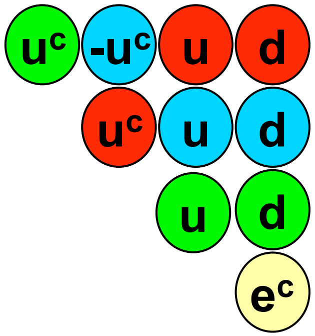


$SU(3)$

$SU(2)$

$$\boxed{g_1(M_X) = g_2(M_X) = g_3(M_X) = g_5}$$

$(10)_L$:

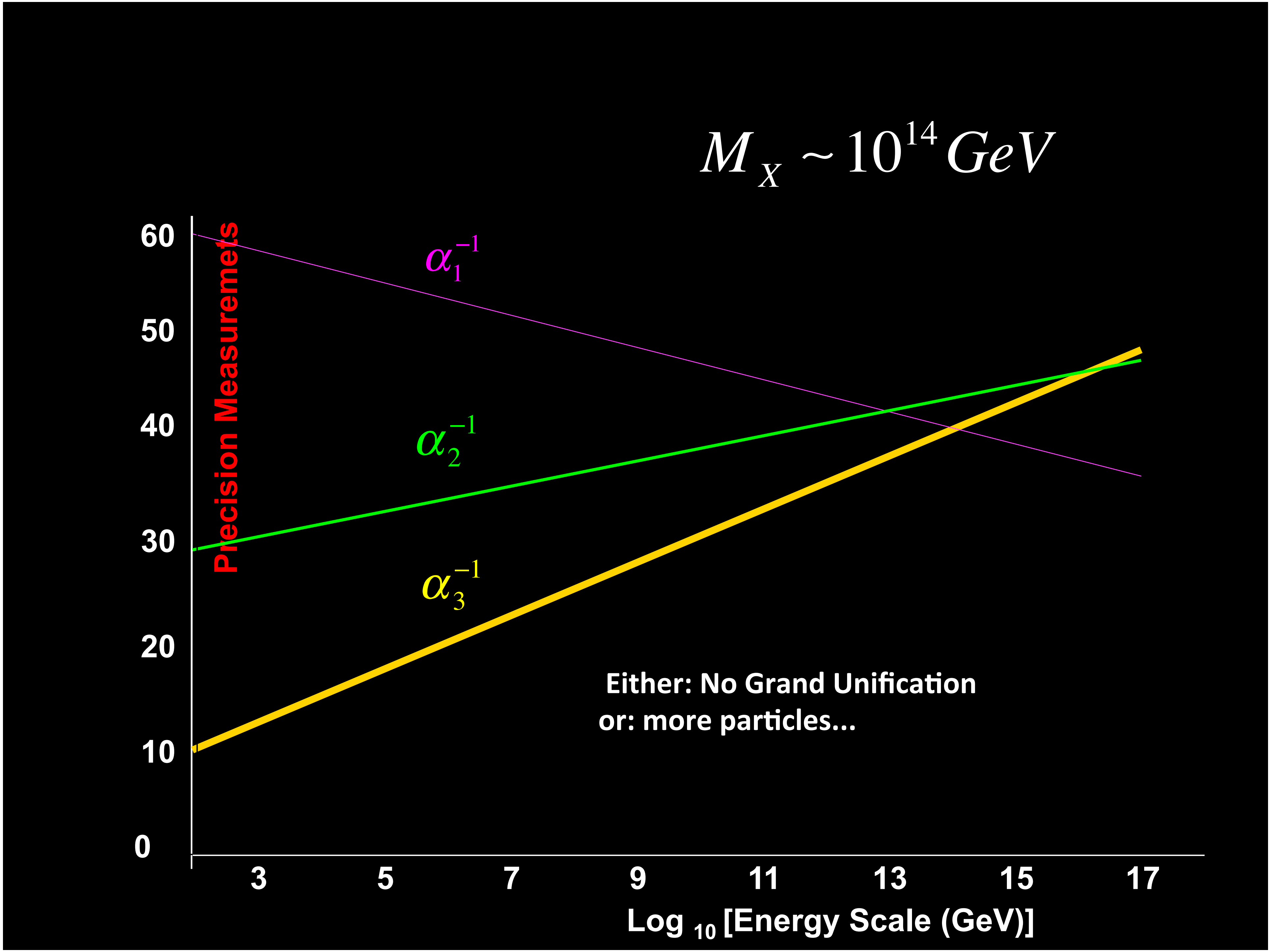


Gauge Couplings

SM evolution of gauge couplings

$$\alpha_i^{-1}(\mu) = \alpha^{-1}(M_X) + \frac{1}{2\pi} b_i \ln\left(\frac{M_X}{\mu}\right) + ..$$

$$b_i^{SM} = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + N_g \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + H \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}$$



$M_X \sim 10^{14} GeV$
60
50
40
30
20
10
0
Precision Measuremets
α_1^{-1}
α_2^{-1}
α_3^{-1}
Either: No Grand Unification
or: more particles...
3
5
7
9
11
13
15
17
Log 10 [Energy Scale (GeV)]

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The Standard model as an effective field theory…

A renormalisable, spontaneously broken, local gauge quantum field theory

$$\boxed{L_{eff}\left(\phi_{light},\psi_{heavy},M,E\right)\xrightarrow{E\ll M}L_{eff}\left(\phi_{light},E\right)+O\left(\frac{1}{M}\right)}$$

- Renormalisable $D\leq 4+O(1/M)$ ✔

- $L^{SM}_{effective}\supset M_A \cancel{A_\mu} A^\mu + m_f \cancel{\overline{f}_L} f_R$

$$\boxed{M_A, m_f \ll M_X, M_{Planck}}$$

Fermions chiral ✔

Vector gauge bosons ✔

(Massless - vectorlike couplings; massive – chiral couplings)

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  Vector gauge bosons ✔

  (Massless - vectorlike couplings; massive – chiral couplings)
- Light Higgs ? $\quad L^{SM}_{effective}\supset M_H^2\left|H\right|^2$

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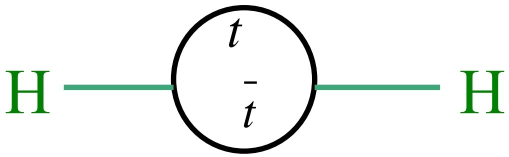
  Fermions chiral ✔

  Vector gauge bosons ✔

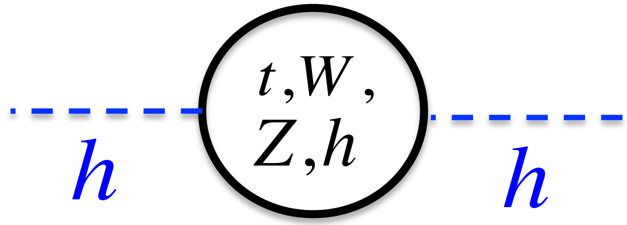
  (Massless - vectorlike couplings; massive – chiral couplings)

- Light Higgs ✗ **The Hierarchy problem**



$$\delta^t M_H^2 \simeq -\frac{h_t^2}{8\pi^2}\int_0^{\Lambda^2} dk^2 = \frac{h_t^2}{8\pi^2}\Lambda^2 + O(m_t^2 \ln(\frac{m_t}{\Lambda}))$$

Hierarchy problem?

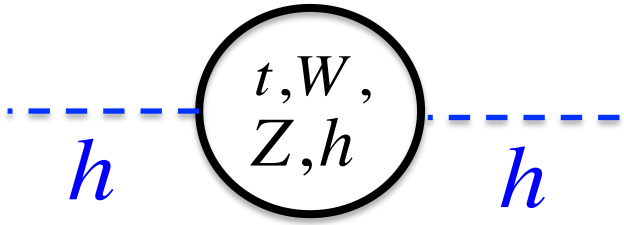


$$\delta m_h^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 = \left(\frac{\Lambda}{500GeV}\right)^2$$

Field theory: δm^2 not measureable

…only $m^2 = m_0^2 + \delta m^2$ "physical"

Hierarchy problem?



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Field theory: δm^2 not measureable

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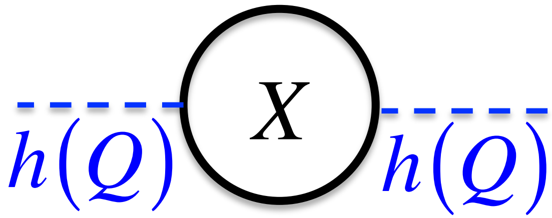
GUTS:

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

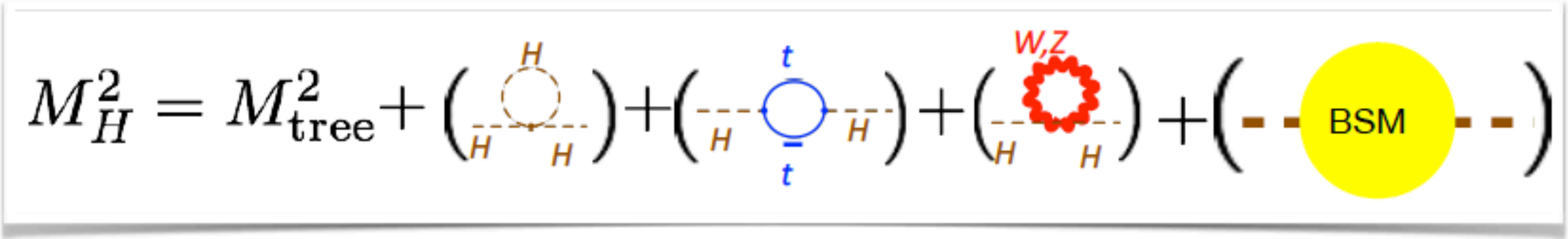


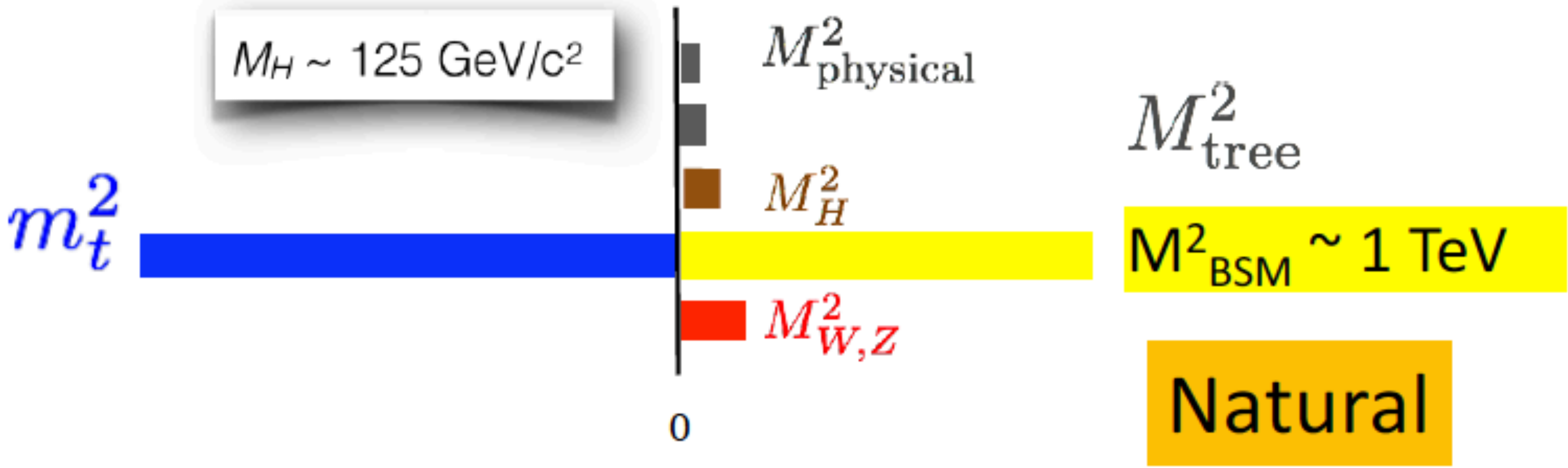
- "real hierarchy problem"

Perhaps a huge hint?

- of something “BSM”?

no shortage of ideas





Categories of BSM

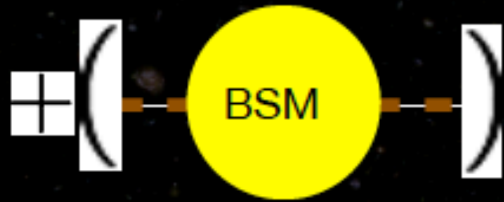
Supersymmetric theories – a Bose-like top

Little Higgs-like theories – a Vector-like top

Composite Higgs – a Cooper Pair-like H

Extra dimensions

Categories of BSM



Supersymmetric theories – a Bose-like top

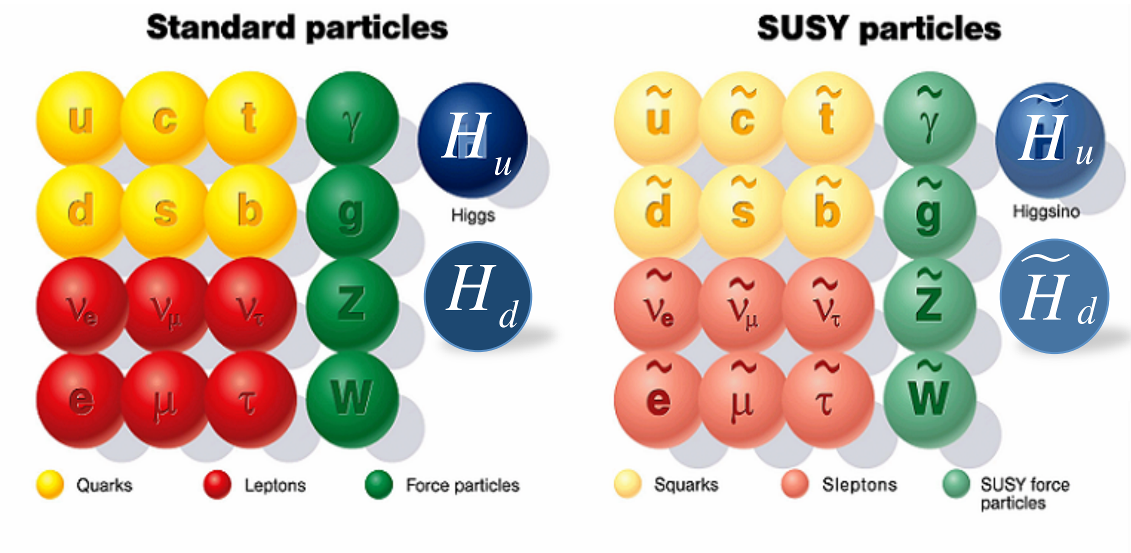
SUSY GUTS

Little Higgs-like theories – a Vector-like top

Composite Higgs – a Cooper Pair-like H

Extra dimensions

SUSY GUTs



$$\underbrace{}$$

$$G_{GUT} \times G_{Flavour} \times (N = 1\,\mathrm{SUSY})$$

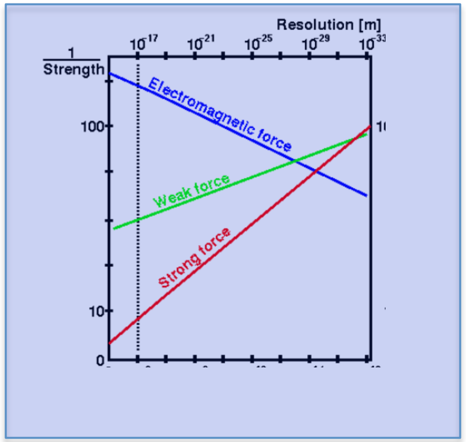
Supermultiplets

SO(10): V_{45} Vector +3 φ_{16} chiral + H_{10} chiral +...

SUSY gauge coupling unification

$$\alpha_i^{-1}(\mu) = \alpha^{-1}(M_X) + \frac{1}{2\pi} b_i \ln\left(\frac{M_X}{\mu}\right) + ..$$

$$b_i^{SM} = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + N_g \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + H \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}$$

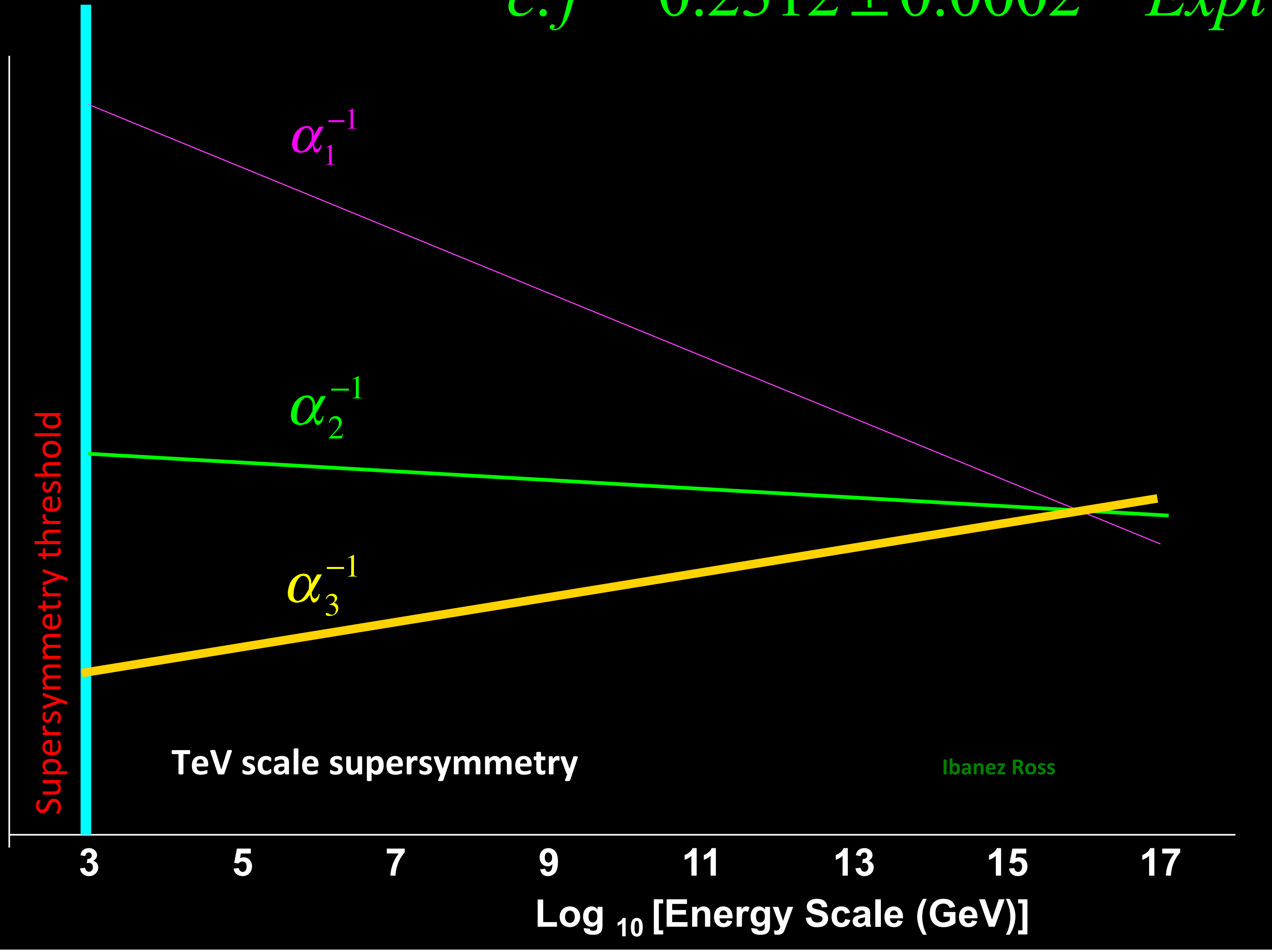


$$b_i^{MSSM} = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + H \begin{pmatrix} \frac{3}{10} \\ \frac{1}{2} \\ 0 \end{pmatrix}$$

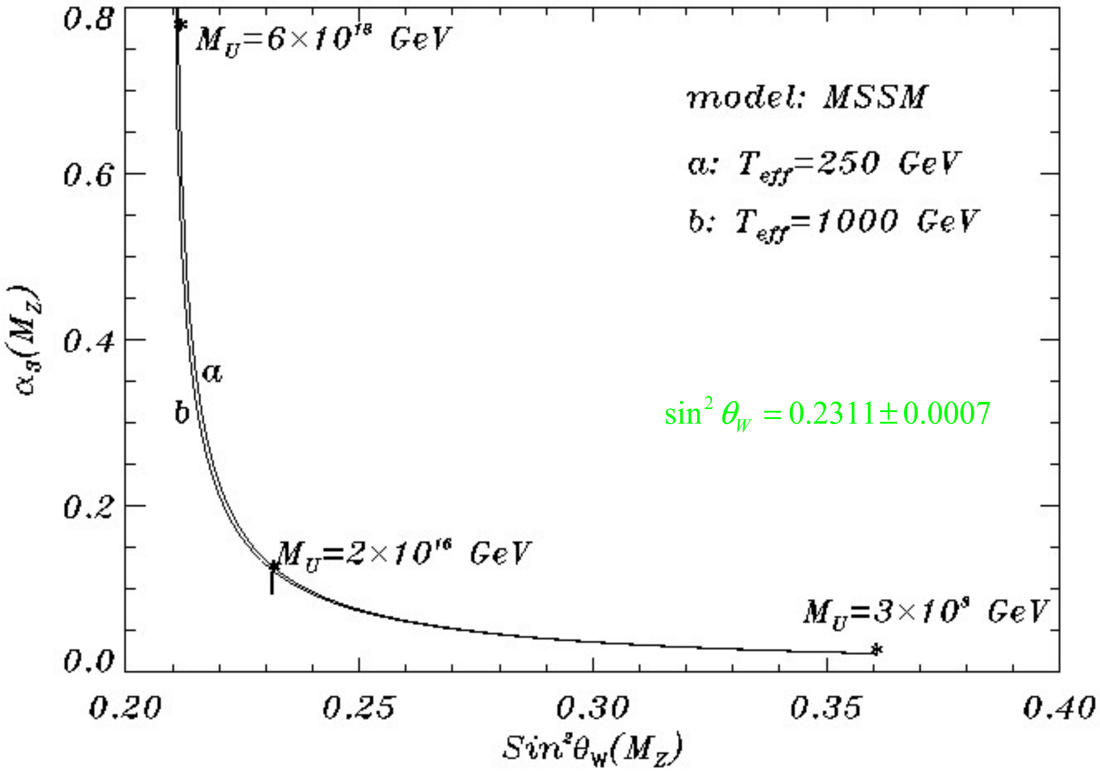
?

$$\sin^2\theta_W = 0.2337 \pm 0.0015$$

$$c.f \quad 0.2312 \pm 0.0002 \quad Expt$$



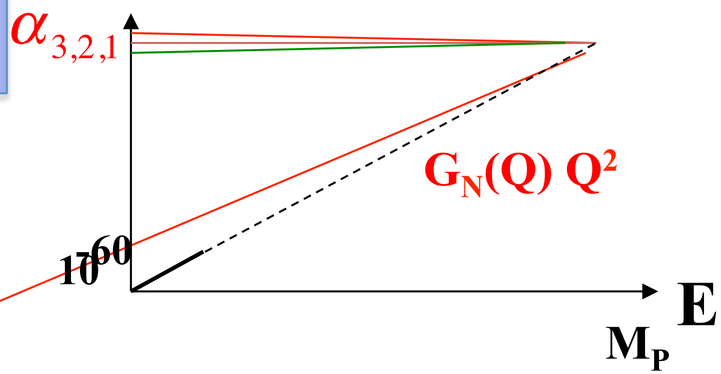
SUSY gauge coupling unification

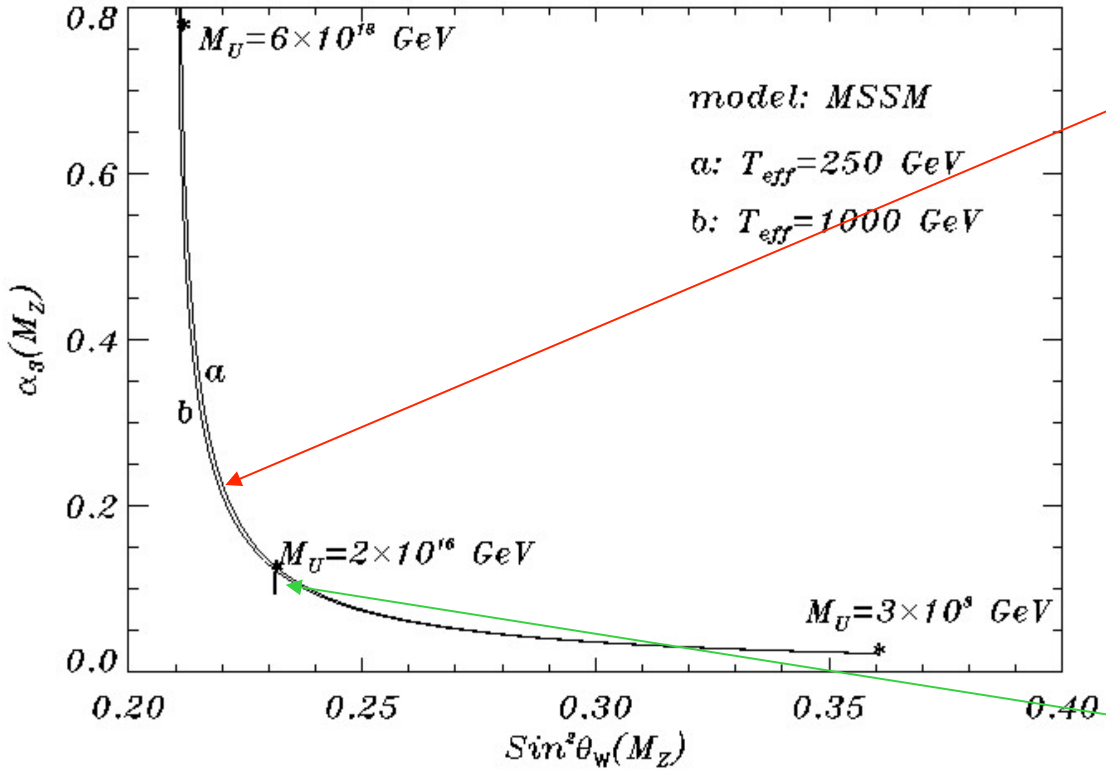


$$\sin^2\theta_W = 0.2334 \pm 0.0025 - 0.25(\alpha_s - 0.119) \quad = 0.2311 \pm 0.0007 \quad (Expt)$$

$$\alpha_s = 0.134 \pm 0.01 - 4(\sin^2\theta_W - 0.2334) \quad = 0.119 \pm 0.01 \quad (Expt)$$

SUSY gauge coupling unification





$$M_U = (2.6 \pm 2).10^{16}\,GeV$$

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

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

Gauge unification - Heterotic String

$$\boxed{L_{eff}^{HS} = \int \underbrace{d^{10}x}_{\int d^4x\, V} \sqrt{g}\, \overbrace{e^{-\phi}}^{\alpha_{10}^{-1}} \left(\frac{4}{\alpha'^4} R + \frac{\overset{\nearrow 1}{k_i}}{\alpha'^3} TrF_i^2 + \ldots \right)}$$

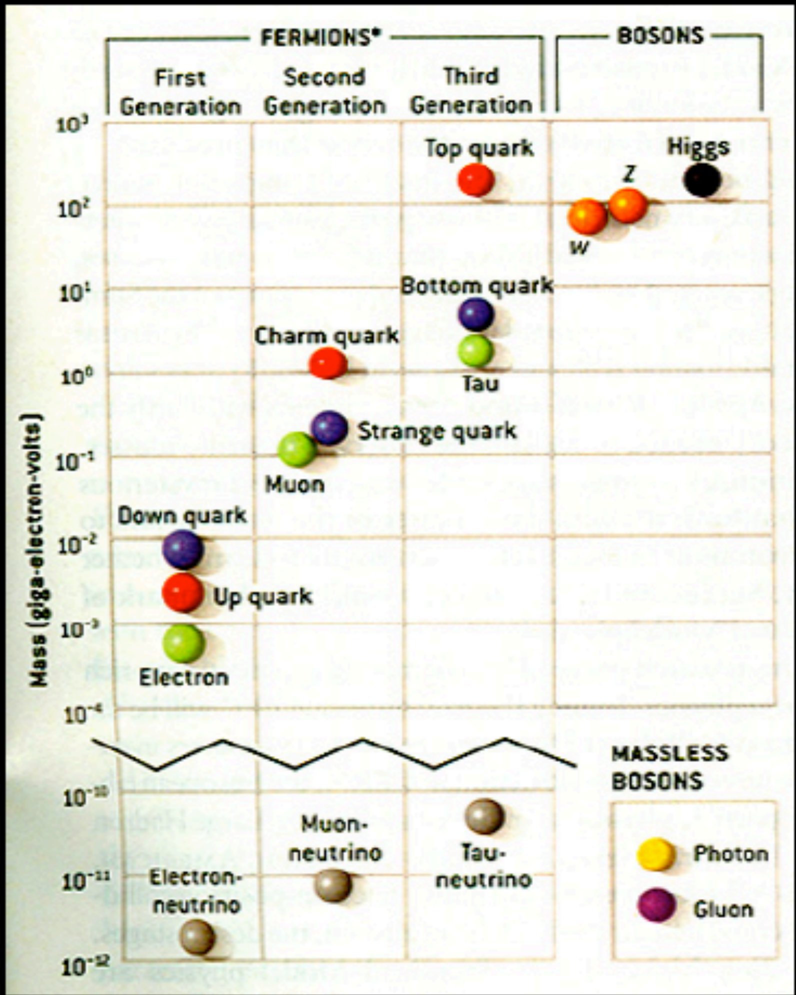
$\alpha' = 1/M_{string}^2$ only scale

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

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

$$\underline{M_{string} = g_{string}.M_{Planck} = 3.6\times 10^{17}\, GeV} \qquad c.f.\, M_U^{\text{"expt"}} = (2.6\pm 2).10^{16}\, GeV$$

Mystery: Why are there so many types of particles?



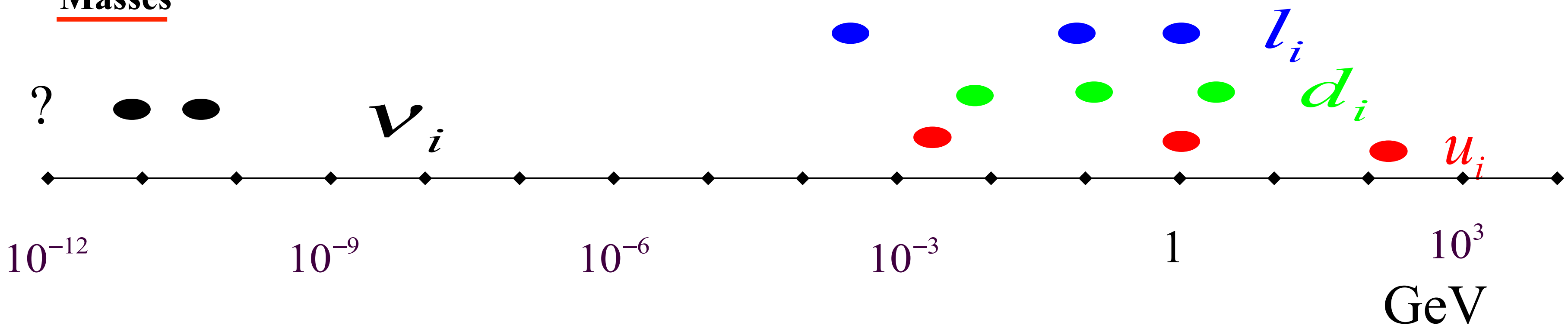
Why do the particles have such a large range of masses?

Why does the pattern of particles repeat three times?

Why do neutrinos have mass at all (in the Standard Model they are massless)?

DATA :

Masses



Mixing

Quarks

Leptons

$$V_{CKM} \approx \begin{pmatrix} 1 & 0.218-0.224 & 0.002-0.005 \\ 0.218-0.224 & 1 & 0.032-0.048 \\ 0.004-0.015 & 0.03-0.048 & 1 \end{pmatrix} \quad V_{MNS} = \begin{pmatrix} 0.79-0.88 & 0.48-0.61 & <0.2 \\ 0.27-0.49 & 0.45-0.71 & 0.52-0.82 \\ 0.28-0.5 & 0.51-0.65 & 0.57-0.81 \end{pmatrix}$$

Masses – IR fixed points in the SM

$$16\pi^2 \frac{dg_t}{dt} = g_t\left[\tfrac{9}{2} g_t^{\,2} - 8g_c^{\,2} - \kappa_t(t)\right], \qquad \kappa_t(t) = \tfrac{9}{4} g^2(t) + \tfrac{17}{12} g'^2(t)$$

$$16\pi^2 \frac{d}{dt}\left[\ln(g_t/g_c)\right] = \tfrac{9}{2} g_t^{\,2} - (8 - b_0) g_c^{\,2}, \qquad g_t^{\,2} = \tfrac{2}{9}(8 - b_0) g_c^{\,2}\Big|_{\mathrm{IRFP}}$$

$$\Rightarrow m_t = 110 GeV$$

Masses – IR fixed points in the SM

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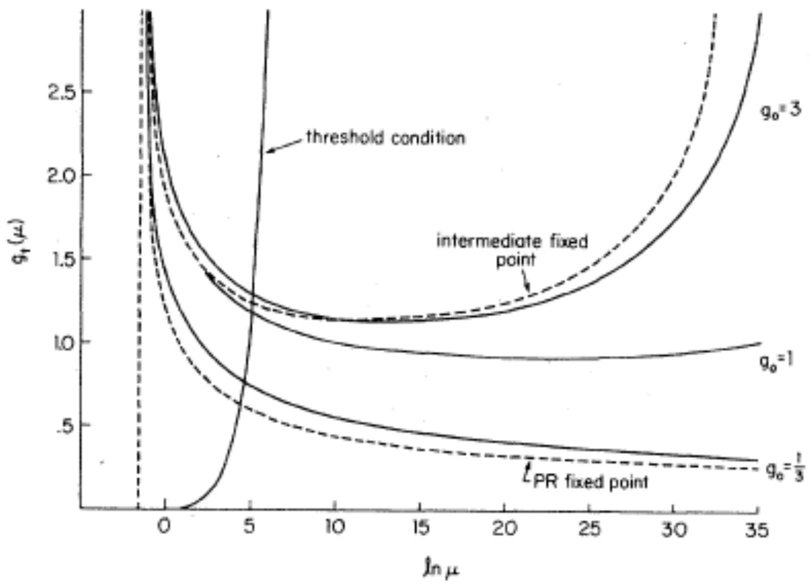
$$\Rightarrow m_t = 110 GeV$$ …but



Masses – IR fixed points in the SM

$$\mathcal{D}\lambda = 4\lambda^2 + 12\lambda g_t^2 - 36 g_t^4 - 3\lambda(3g^2 + g'^2)$$
$$+ \tfrac{9}{4} - [2g^4 + (g^2 + g'^2)^2] ,$$

$$m_H = (\tfrac{2}{3}\lambda^{\text{eff}} v^2)^{1/2} = 72 \text{ GeV}$$

Mass matrix structure:

$$L_{Yukawa} = Y_{ij}^{u}\; Q^{i} u^{c,j} H + Y_{ij}^{d}\; Q^{i} d^{c,j} \overline{H}$$

$$M_{ij}^{u} = Y_{ij}^{u} < H^{0} > \qquad M_{ij}^{d} = Y_{ij}^{d} < \overline{H}^{0} >$$

$$M^{u} = V_{L}^{\dagger} \underline{M_{Diag}^{u}} V_{R}$$

$$M^{d} = U_{L}^{\dagger} \underline{M_{Diag}^{d}} U_{R}$$

$$\underline{V_{CKM}} = V_{L}^{\dagger} U_{L}$$

The data for quarks is *consistent* with a very symmetric structure :

$$\frac{M^{d,u}}{m^{b,t}} \simeq \begin{pmatrix} <\varepsilon^{4} & \varepsilon^{3} & \varepsilon^{3} \\ \varepsilon^{3} & \varepsilon^{2} & \varepsilon^{2} \\ \varepsilon^{3} & \varepsilon^{2} & 1 \end{pmatrix} \qquad \begin{array}{l} \varepsilon^{d} = 0.15 \\ \\ \varepsilon^{u} = 0.05 \end{array}$$

O(1) coefficients suppressed

Texture zero

$\leq \varepsilon^5$

$$\frac{M^d}{m_b} = \begin{pmatrix} 0 & \varepsilon^3 & \leq \varepsilon^3 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^2 \\ ? & ? & 1 \end{pmatrix}$$

symmetric

GATTO, SARTORI, TONIN

$\not{CP}$ SM phase?

$$\boxed{|V_{us}| = \left| \sqrt{\frac{m_d}{m_s}} - e^{i\delta} \sqrt{\frac{m_u}{m_c}} \right|}$$

Fritzsch, Weinberg Roberts, Romanino, GGR,Velasco

$$0.217 - 0.222 \quad c.f. \ |(0.216 - 0.214) - (0.07 - 0.076)e^{i\delta}|$$

$$= 0.213 - 0.223, \ \delta = 90^0$$

$q \leftrightarrow l$ symmetry?

Charged leptons are consistent with a similar form

$$\frac{M^{d,l,u}}{m^{b,\tau,t}} \simeq \begin{pmatrix} <\varepsilon^4 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & a\varepsilon^2 & a\varepsilon^2 \\ \varepsilon^3 & a\varepsilon^2 & 1 \end{pmatrix}$$

$$\varepsilon^{\mathrm{d}} = 0.15, \quad \mathrm{a}^{\mathrm{d}} = 1$$

$$\varepsilon^{\mathrm{l}} = 0.15, \quad \mathrm{a}^{\mathrm{l}} = -3$$

$$\varepsilon^{\mathrm{u}} = 0.05, \quad \mathrm{a}^{\mathrm{u}} = 1$$

SU(5): Charged fermion masses

$$\overline{5} \times 10 = 5 + \overline{45}$$

$$10 \times 10 = \overline{5} + 45 + 50$$

$$\overline{5} \times \overline{5} = \overline{10} + \overline{15}$$

$$L^{5}_{Yukawa} = \left(\psi^{\dagger}_{Ri\alpha}\right) m^{D}_{ij} \chi^{\alpha\beta}_{Lj} H^{\dagger}_{\beta} - \tfrac{1}{4} \varepsilon_{\alpha\beta\gamma\delta\varepsilon} \left(\chi^{T}\right)^{\alpha\beta}_{Li} \sigma^{2} m^{U}_{ij} \chi^{\gamma\delta}_{Lj} H^{\varepsilon} + h.c.$$

Charged fermion masses

$$\bar{5} \times 10 = 5 + \overline{45}$$

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After diagonalising down quark mass matrix:

$$m_d = m_e \quad ✗$$

$$m_s = m_\mu \quad ✗$$

$$m_b = m_\tau \quad ✓?$$

Charged fermion masses

$$\bar{5}\times 10 = 5 + \overline{45}$$

$$10\times 10 = \bar{5} + 45 + 50$$

$$\bar{5}\times\bar{5} = \overline{10} + \overline{15}$$

$$L^{5}_{\ Yukawa} = \left(\psi^{\dagger}_{Ri\alpha}\right) m^{D}_{ij} \chi^{\alpha\beta}_{Lj} H^{\dagger}_{\beta} - \tfrac{1}{4}\varepsilon_{\alpha\beta\gamma\delta\varepsilon}\left(\chi^{T}\right)^{\alpha\beta}_{Li}\sigma^{2} m^{U}_{ij}\chi^{\gamma\delta}_{Lj} H^{\varepsilon} + h.c.$$

$$L^{45}_{Y} = \left(\psi^{\dagger}_{Ri\alpha}\right) m^{d}_{ij}\chi^{\beta\gamma}_{Lj} H^{\dagger\alpha}_{\beta\gamma} + \varepsilon_{\alpha\beta\gamma\rho\tau}\left(\chi^{T}\right)^{\alpha\beta}_{Li}\sigma^{2} m^{u}_{ij}\psi^{\gamma\delta}_{Lj} H^{\rho\tau}_{\delta} + h.c.$$

$$-3m_d = m_e \text{ ✗}$$

$$-3m_s = m_\mu \text{ ✓}$$

$$-3m_b = m_\tau \text{ ✗}$$

$$\left\langle H^{b5}_{a}\right\rangle = \mathrm{v}_{45}\left(\delta^{b}_{a} - 4\delta^{4}_{a}\delta^{b}_{4}\right), a,b = 1..4$$

SU(2)XU(1) invariant component

GUT relations

$$c.f. \quad SU(4) \subset SO(10)$$

$$\psi_\alpha = \begin{pmatrix} d \\ d \\ d \\ l \end{pmatrix}$$

$$\langle \Sigma_{45} \rangle \propto B - L$$

$$\parallel$$

$$\overline{\psi}^\alpha \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -3 \end{pmatrix} \psi_\alpha$$

$$\frac{m_s}{m_\mu}(M_X) = \frac{1}{3}$$

Georgi Jarlskog

$$\frac{M^{d,l}}{m_3} = \begin{pmatrix} < \varepsilon^4 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & a\varepsilon^2 & a\varepsilon^2 \\ \varepsilon^3 & a\varepsilon^2 & 1 \end{pmatrix}$$

$$\varepsilon^d = 0.15, \quad a^d = 1$$

$$\varepsilon^l = 0.15, \quad a^l = -3$$

GUT relations

Georgi-Jarlskog $\left(L^5\right)_{33+12+21} + \left(L^{45}\right)_{22}$

$$Det(M^l) = Det(M^d)|_{M_X}$$ (Texture zero)

$$\frac{m_b}{m_\tau}(M_X) = 1$$

$$\frac{m_b}{m_\tau}(M_X) = 1$$

$$\frac{M^{d,l}}{m_3} = \begin{pmatrix} \sim 0 & \varepsilon^3 & \varepsilon^3 \\ \varepsilon^3 & a\varepsilon^2 & a\varepsilon^2 \\ \varepsilon^3 & a\varepsilon^2 & 1 \end{pmatrix}$$

$$\varepsilon^{\mathrm{d}} = 0.15, \quad \mathrm{a}^{\mathrm{d}} = 1$$

$$\varepsilon^{\mathrm{l}} = 0.15, \quad \mathrm{a}^{\mathrm{l}} = -3$$

$$m_b = 3 m_\tau \checkmark$$

$$m_s = 3 . \frac{1}{3} . m_\mu \checkmark$$

$$m_d = 3 . 3 . m_e \checkmark$$

Parameters	Input SUSY Parameters					
$\tan\beta$	1.3	10	38	50	38	38
γ_b	0	0	0	0	-0.22	$+0.22$
γ_d	0	0	0	0	-0.21	$+0.21$
γ_t	0	0	0	0	0	-0.44
Parameters	**Corresponding GUT-Scale Parameters with Propagated Uncertainty**					
$y^t(M_X)$	6^{+1}_{-5}	0.48(2)	0.49(2)	0.51(3)	0.51(2)	0.51(2)
$y^b(M_X)$	$0.0113^{+0.0002}_{-0.01}$	0.051(2)	0.23(1)	0.37(2)	0.34(3)	0.34(3)
$y^\tau(M_X)$	0.0114(3)	0.070(3)	0.32(2)	0.51(4)	0.34(2)	0.34(2)
$(m_u/m_c)(M_X)$	0.0027(6)	0.0027(6)	0.0027(6)	0.0027(6)	0.0026(6)	0.0026(6)
$(m_d/m_s)(M_X)$	0.051(7)	0.051(7)	0.051(7)	0.051(7)	0.051(7)	0.051(7)
$(m_e/m_\mu)(M_X)$	0.0048(2)	0.0048(2)	0.0048(2)	0.0048(2)	0.0048(2)	0.0048(2)
$(m_c/m_t)(M_X)$	$0.0009^{+0.001}_{-0.00006}$	0.0025(2)	0.0024(2)	0.0023(2)	0.0023(2)	0.0023(2)
$(m_s/m_b)(M_X)$	0.014(4)	0.019(2)	0.017(2)	0.016(2)	0.018(2)	0.010(2)
$(m_\mu/m_\tau)(M_X)$	0.059(2)	0.059(2)	0.054(2)	0.050(2)	0.054(2)	0.054(2)
$A(M_X)$	$0.56^{+0.34}_{-0.01}$	0.77(2)	0.75(2)	0.72(2)	0.73(3)	0.46(3)
$\lambda(M_X)$	0.227(1)	0.227(1)	0.227(1)	0.227(1)	0.227(1)	0.227(1)
$\bar\rho(M_X)$	0.22(6)	0.22(6)	0.22(6)	0.22(6)	0.22(6)	0.22(6)
$\bar\eta(M_X)$	0.33(4)	0.33(4)	0.33(4)	0.33(4)	0.33(4)	0.33(4)
$J(M_X)\times 10^{-5}$	$1.4^{+2.2}_{-0.2}$	2.6(4)	2.5(4)	2.3(4)	2.3(4)	1.0(2)
Parameters	**Comparison with GUT Mass Ratios**					
$(m_b/m_\tau)(M_X)$	$1.00^{+0.04}_{-0.4}$	0.73(3)	0.73(3)	0.73(4)	1.00(4)	1.00(4)
$(3m_s/m_\mu)(M_X)$	$0.70^{+0.8}_{-0.05}$	0.69(8)	0.69(8)	0.69(8)	0.9(1)	0.6(1)
$(m_d/3\,m_e)(M_X)$	0.82(7)	0.83(7)	0.83(7)	0.83(7)	1.05(8)	0.68(6)
$(\frac{\det Y^d}{\det Y^e})(M_X)$	$0.57^{+0.08}_{-0.26}$	0.42(7)	0.42(7)	0.42(7)	0.92(14)	0.39(7)

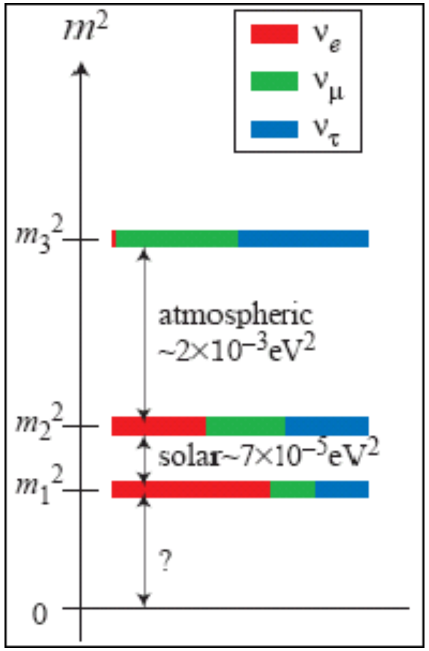
Table 2: The mass parameters continued to the GUT-scale M_X for various values of $\tan\beta$ and threshold corrections $\gamma_{t,b,d}$. These are calculated with the 2-loop gauge coupling and 2-loop Yukawa coupling RG equations assuming an effective SUSY scale $M_S = 500$ GeV.

GGR, M. Serna, 0704.1248

Neutrinos ???

$$L^{\nu}_{eff} = m_3\, \bar{\phi}^{\,i}_{23} \nu_i \bar{\phi}^{\,j}_{23} \nu_j + m_2\, \bar{\phi}^{\,i}_{123} \nu_i \bar{\phi}^{\,j}_{123} \nu_j$$

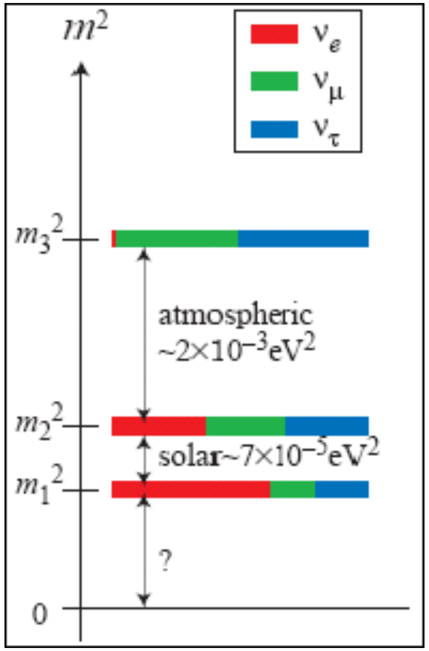
$$< \bar{\phi}_{23} >^i = (0,1,-1), \quad < \bar{\phi}_{123} >^i = (1,1,1)$$



Can one have a unified description of quark, charged lepton and neutrinos?

$$c.f.\ L^{q,l}_{Dirac} = m_{t,b,l}\, \bar{\phi}^{\,i}_3 \psi_i \bar{\phi}^{\,j}_3 \psi^c_j + \ldots \qquad < \bar{\phi}_3 >^i = (0,0,1) \quad ???$$

Neutrinos ???



$$L^{\nu}_{eff} = m_3\, \bar\phi^{i}_{23}\nu_i \bar\phi^{j}_{23}\nu_j + m_2\, \bar\phi^{i}_{123}\nu_i \bar\phi^{j}_{123}\nu_j$$

$$<\bar\phi_{23}>^i = (0,1,-1), \quad <\bar\phi_{123}>^i = (1,1,1)$$

See-Saw

Quarks, charged leptons, neutrinos can have similar Dirac mass :

$$L^{q,l,\nu}_{Dirac} = \alpha^{q,l,\nu}\, \psi_i \bar\phi^{i}_{3} \psi^c_j \bar\phi^{j}_{3} + \beta^{q,l,\nu}\left(\psi_i \bar\phi^{i}_{123} \psi^c_j \bar\phi^{j}_{23} + \psi_i \bar\phi^{i}_{23} \psi^c_j \bar\phi^{j}_{123}\right) + \gamma^{q,l}\, \psi_i \bar\phi^{i}_{23} \psi^c_j \bar\phi^{j}_{23}\Sigma \qquad \alpha > \beta$$

$$\frac{M^{Dirac}}{m_3} = \begin{pmatrix} 0 & \varepsilon^3 & -\varepsilon^3 \\ \varepsilon^3 & a\varepsilon^2+\varepsilon^3 & -a\varepsilon^2+\varepsilon^3 \\ -\varepsilon^3 & -a\varepsilon^2+\varepsilon^3 & 1 \end{pmatrix}$$

$\varepsilon^{d} = 0.15, \quad a^{d} = 1$

$\varepsilon^{l} = 0.15, \quad a^{e} = -3$

$\varepsilon^{u} = 0.05, \quad a^{u} = 1$

$\varepsilon^{\nu} = 0.05, \quad a^{\nu} = 0$

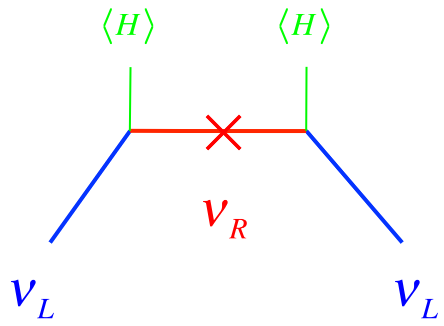
$\subset 120_{eff}\ SO(10)$

$\langle\Sigma\rangle \propto B-L+2T_3^R$

- "See-saw" with sequential domination $M_\nu = M_D^\nu \, M_M^{-1} \, M_D^{\nu T}$

Minkowski
Gell-Mann,
Ramond,
Slansky;
Yanagida,
King

$$M_M \approx \begin{pmatrix} M_1 & & \\ & M_2 & \\ & & M_3 \end{pmatrix} \qquad M_1 << M_2 << M_3$$



$$L^\nu_{Dirac} = \alpha\, \psi_i \bar{\phi}_3^i \psi_j^c \bar{\phi}_3^j + \beta \left(\psi_i \bar{\phi}_{123}^i \psi^c{}_j \bar{\phi}_{23}^j + \psi_i \bar{\phi}_{23}^i \psi^c{}_j \bar{\phi}_{123}^j \right) \qquad \alpha > \beta$$

$$L^\nu_{eff} = \frac{\beta^2}{M_1} \psi_i \phi^i_{123} \psi_j \phi^j_{123} + \frac{\beta^2}{M_2} \psi_i \phi^i_{23} \psi_j \phi^j_{23} + \frac{(\alpha+\beta)^2}{M_3} \psi_i \phi^i_3 \psi_j \phi^j_3$$

- "See-saw" with sequential domination $M_\nu = M_D^\nu M_M^{-1} M_D^{\nu T}$

Minkowski
Gell-Mann,
Ramond,
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King

$$M_M \approx \begin{pmatrix} M_1 & & \\ & M_2 & \\ & & M_3 \end{pmatrix} \qquad M_1 << M_2 << M_3$$

small

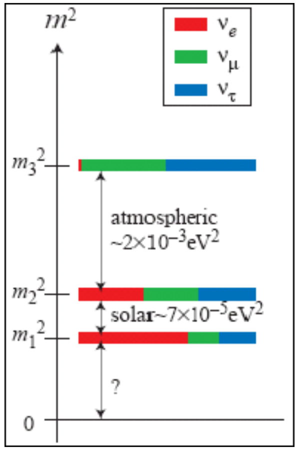
$$L^\nu_{Dirac} = \alpha\, \psi_i \bar{\phi}_3^i \psi_j^c \bar{\phi}_3^j + \beta\left(\psi_i \bar{\phi}_{123}^i \psi^c{}_j \bar{\phi}_{23}^j + \psi_i \bar{\phi}_{23}^i \psi^c{}_j \bar{\phi}_{123}^j\right) \quad \alpha > \beta$$

$$\sim \beta\begin{pmatrix} \psi_i\phi^i_{123} & \psi_i\phi^i_{23} \end{pmatrix}\begin{pmatrix} 0 & -1 \\ 1 & 1 \end{pmatrix}\begin{pmatrix} \psi_1^c \\ \psi_2^c \end{pmatrix}$$

$$\boxed{L^\nu_{eff} = \frac{\beta^2}{M_1}\psi_i\phi^i_{123}\psi_j\phi^j_{123} + \frac{\beta^2}{M_2}\psi_i\phi^i_{23}\psi_j\phi^j_{23} + \frac{(\alpha+\beta)^2}{M_3}\psi_i\phi^i_3\psi_j\phi^j_3}$$

Origin of fermion mass structure?

Family symmetry



Non-Abelian family symmetry

Promote ϕ_i to fields transforming under $SU(3)_{family}$

$$\frac{\phi_3}{M} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad \frac{\phi_{23}}{M} = \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \varepsilon \qquad \frac{\phi_{123}}{M} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \varepsilon^2$$

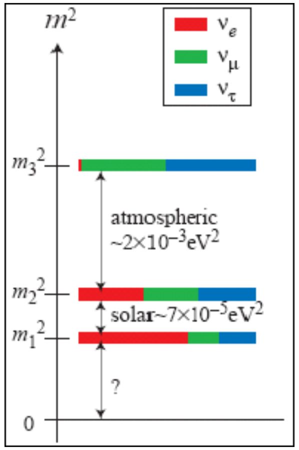
Messenger mass

...can differ for u,d,l,ν

Family symmetry

Non-Abelian family symmetry

Promote ϕ_i to fields transforming under $SU(3)_{family}$

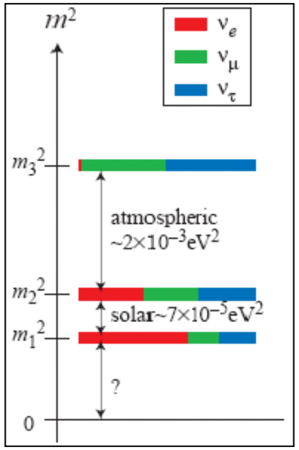


$$\frac{\phi_3}{M} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad \frac{\phi_{23}}{M} = \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix}\varepsilon \qquad \frac{\phi_{123}}{M} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}\varepsilon^2$$

Vacuum alignment ???

Family symmetry

Non-Abelian family symmetry



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Vacuum alignment ??? $\Rightarrow$ Discrete non Abelian symmetry

Non Abelian discrete symmetries

$e.g.$ $$Z_3 \ltimes Z_n$$

ϕ_i	$Z_3\phi_i$	$Z'_n\phi_i$
ϕ_1	$\to \phi_2$	$\to \alpha\, \phi_1$
ϕ_2	$\to \phi_3$	$\to \alpha^2 \phi_2$
ϕ_3	$\to \phi_1$	$\to \alpha^{-3} \phi_3$

$$\alpha^n = 1$$

$$\Delta\left(3n^2\right)$$

$$n = 2, \quad \Delta\left(12\right) \equiv A_4$$

$$n = 3, \quad \Delta\left(27\right)$$

Non Abelian discrete symmetries

$e.g.$ $\quad Z_3 \ltimes Z_n$

ϕ_i	$Z_3\phi_i$	$Z_n'\phi_i$
ϕ_1	$\rightarrow \phi_2$	$\rightarrow \alpha\,\phi_1$
ϕ_2	$\rightarrow \phi_3$	$\rightarrow \alpha^2\phi_2$
ϕ_3	$\rightarrow \phi_1$	$\rightarrow \alpha^{-3}\phi_3$

$$\alpha^n = 1$$

Choice of discrete symmetry

- Vacuum structure : $Z_3 \ltimes Z_n \rightarrow \begin{cases} Z_3, & \langle\phi\rangle = (1,1,1) \quad \lambda > 0 \\ Z_n, & \langle\phi\rangle = (0,0,1) \quad \lambda < 0 \end{cases}$

$$V(\phi) = -m^2\,\phi^{\dagger i}\phi_i + \ldots + \lambda\, m^2 \phi^{\dagger i}\phi_i \phi^{\dagger i}\phi_i$$

A simple example

$$\Delta(27)\times U(1)$$

	Q
S,θ_{23}	$+1$
Σ,θ_{123}	-2

$$L^{D,eff}_{a,mass}=\psi_i\left(\frac{1}{M^2_{3,a}}\theta^i_3\theta^j_3+\frac{1}{M^3_{23,a}}\theta^i_{23}\theta^j_{23}\Sigma+\frac{1}{M^3_{123,a}}(\theta^i_{123}\theta^j_{23}+\theta^i_{23}\theta^j_{123})S\right)\psi^c_j H_5,\ a=u,d,l,\nu$$

$$\langle\Sigma\rangle\propto B-L+2T^R_3$$

A simple example

$$\Delta(27)\times U(1)$$

	Q
S,θ_{23}	$+1$
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$$L^{D,eff}_{\nu\ mass}=\psi_i\left(\frac{1}{M^2_{3,a}}\theta^i_3\theta^j_3+\frac{1}{M^3_{123,a}}(\theta^i_{123}\theta^j_{23}+\theta^i_{23}\theta^j_{123})S\right)\psi^c_j H_5$$

$$L^{\nu}_{Majorana\ mass}=\psi^c_i\left(\frac{1}{M}\phi^i\phi^j+\frac{1}{M^4}[\alpha\theta^i_{23}\theta^j_{23}(\phi^a\phi^a\theta^a_{123})+\beta(\theta^i_{23}\theta^j_{123}+\theta^i_{123}\theta^j_{23})(\phi^a\phi^a\theta^a_{23})]\right)\psi^c_j$$

$$\langle\phi\rangle|_{\Delta L=1}=\begin{pmatrix}0\\0\\1\end{pmatrix}M$$

A simple example

$$\Delta(27)\times U(1)$$

	Q
S,θ_{23}	$+1$
Σ,θ_{123}	-2

$$L^{D,eff}_{a,mass}=\psi_i\left(\frac{1}{M^2_{3,a}}\theta^i_3\theta^j_3+\frac{1}{M^3_{23,a}}\theta^i_{23}\theta^j_{23}\Sigma+\frac{1}{M^3_{123,a}}(\theta^i_{123}\theta^j_{23}+\theta^i_{23}\theta^j_{123})S\right)\psi^c_j H_5,\ a=u,d,l,\nu$$

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$$M_\nu=M^\nu_D\,M^{-1}_M\,M^{\nu T}_D$$

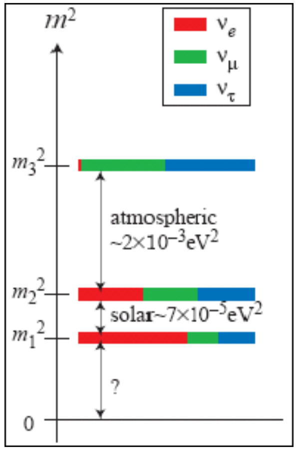
$$M_{Dirac}\propto\begin{pmatrix}0 & \sqrt{3/2}\\ 1 & 1\end{pmatrix},\quad M_{Majorana}\propto\begin{pmatrix}0 & \beta\\ \beta & \alpha+2\beta\end{pmatrix}$$

$$\propto\begin{pmatrix}0 & -\sqrt{3/2}\beta\\ -\sqrt{3/2}\beta & \alpha\end{pmatrix}$$

Texture zero

$$M_\nu \propto \begin{pmatrix} 0 & -\sqrt{3/2}\beta \\ -\sqrt{3/2}\beta & \alpha \end{pmatrix}$$

$$\frac{m_2}{m_1} \approx \frac{3\beta^2}{2\alpha^2}, \qquad \nu_1 \propto \nu_{23} - \sqrt{\frac{m_2}{m_1}}\nu_{123}$$



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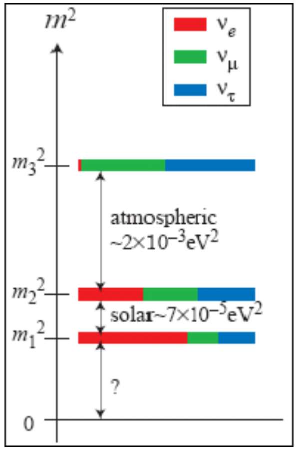

$$\frac{m_2}{m_1} \approx \frac{3\beta^2}{2\alpha^2}, \qquad \nu_1 \propto \nu_{23} - \sqrt{\frac{m_2}{m_1}}\nu_{123}$$

$$\sin\theta_{13}|_\nu = \sqrt{\frac{m_2}{3m_1}} = 0.24$$

$$\delta\sin\theta_{13}|_{lepton} = \frac{\sin\theta_c}{3} = 0.075$$

$c.f.\ 0.15|_{exp}$

Texture zero

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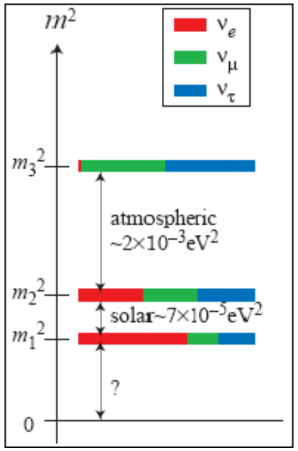

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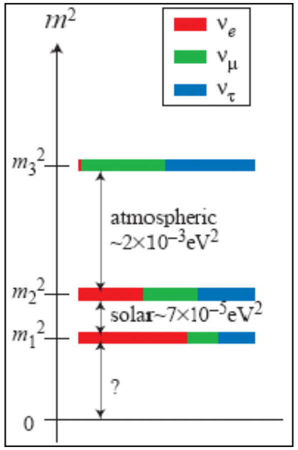
$$\Bigg\} \quad c.f.\ \left.0.15\right|_{exp}$$

$$\sin^2\theta_{12} = \tfrac{1}{3}, \quad c.f. \quad \left.\sin^2\theta_{12}\right|_{\exp} = 0.308^{+0.013}_{-0.012}$$

Texture zero

$$M_\nu \propto \begin{pmatrix} 0 & -\sqrt{3/2}\beta \\ -\sqrt{3/2}\beta & \alpha \end{pmatrix}$$



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$$\sin^2\theta_{12} = \tfrac{1}{3}, \quad c.f. \quad \sin^2\theta_{12}|_{\exp} = 0.308^{+0.013}_{-0.012}$$

$$\sin\theta_{23} = \frac{1}{\sqrt{2}} - e^{i\delta}\sin\theta_{13}|_\nu \qquad c.f. \quad \sin^2\theta_{23} = 0.574^{+0.026}_{-0.144}$$

$$75^0 < \delta < 138\ or\ 222^0 < \delta < 285^0.$$

Long Baseline Experiments

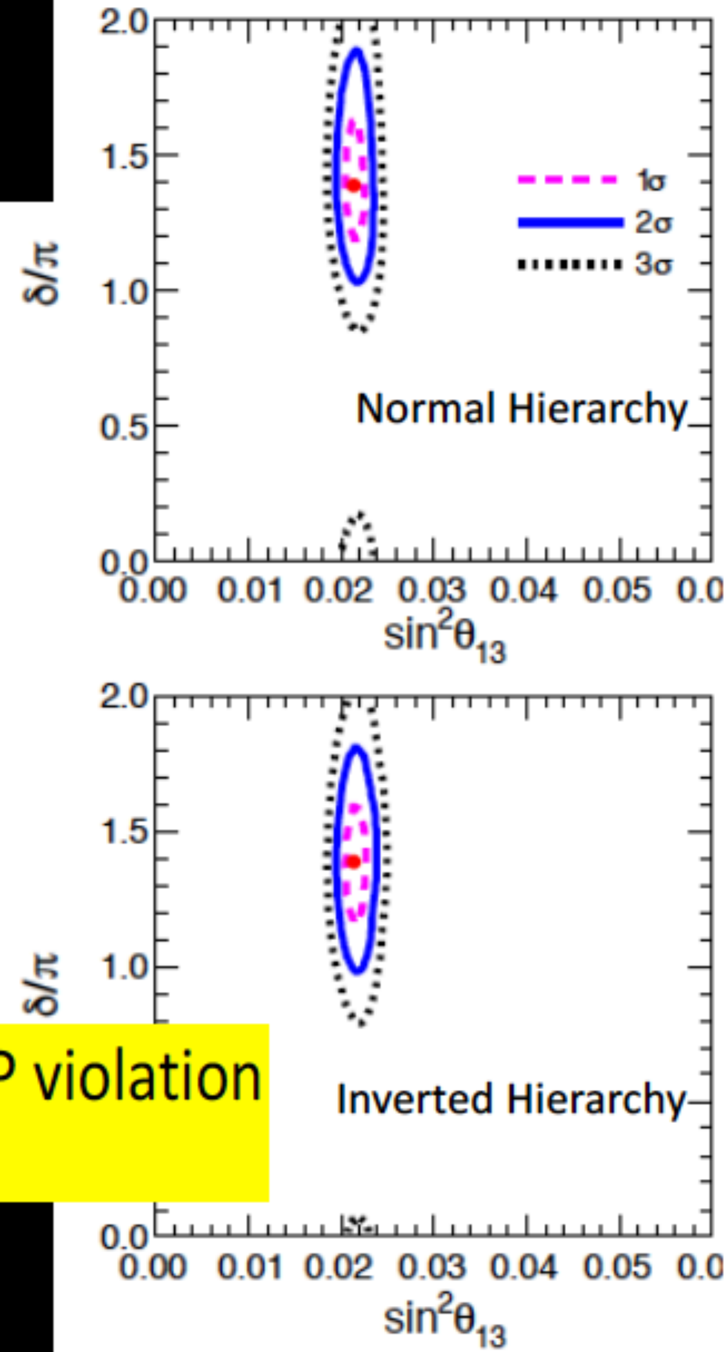
Long baseline oscillation experiments:
an international campaign to test the
3-flavor paradigm, measure CP violation and
go beyond.

Generation 2 expts

By combining with SK in a global fit
Marrone @ Neutrino 2016

CP conservation excluded at >2 σ

For the first time robust indication of CP violation in the leptonic sector



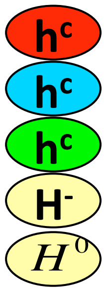
SUSY GUTS - Nucleon decay

Coloured Higgs mediation

$$SU(5)\xrightarrow[\Sigma_{24}]{M_X}SU(3)\times SU(2)\times U(1)\xrightarrow[H_{\bar{5}}]{M_W}SU(3)\times U(1)$$

$$\langle\Sigma\rangle = \mathrm{v}_3\mathrm{Diagonal}(2,2,2,-3,-3)$$

$$\langle H_{\bar{5}}\rangle = \begin{pmatrix} 0\\ 0\\ 0\\ 0\\ \mathrm{v}\end{pmatrix}$$



$M_T \gtrsim 10^{12}\mathrm{GeV}$

$$\mathcal{L}_Y(T) \;=\; T^*\left(LY_5Q - d^cY_5u^c\right) - \left(\frac{1}{2}QY_{10}Q + u^cY_{10}e^c\right)T$$

$$\mathcal{L}_{d=6} = \frac{1}{2M_T^2}\left(QY_{10}Q\right)\left(QY_5^TL\right) + \frac{1}{M_T^2}\left(d^cY_5u^c\right)\left(u^cY_{10}e^c\right)$$

Nucleon decay

Doublet -triplet splitting

Missing doublet mechanism

No (1,2) component

$$\Theta_{50} = (8,2) + (6,3) + (\bar{6},1) + (3,2) + (\bar{3},1) + (1,1)$$

Doublet -triplet splitting

Missing doublet mechanism

No (1,2) component

$$\Theta_{50} = (8,2) + (6,3) + (\bar{6},1) + (3,2) + (\bar{3},1) + (1,1)$$

$$P_{MD} = b\Theta\Sigma_{75}H_u + b'\overline{\Theta}\Sigma_{75}H_d + \widetilde{M}\overline{\Theta}\Theta$$

$\langle \Sigma_{75} \rangle \propto M$ breaks SU(5) to SM

$$P_{MD} \supset bM\Theta_3 H_{uT} + b'M\overline{\Theta}_3 H_{dT} + \widetilde{M}\overline{\Theta}_3\Theta_3$$

Only Higgs colour triplets get mass $m_T \propto \frac{M^2}{\widetilde{M}}$

Doublet -triplet splitting

Higher dimensions (String unification)

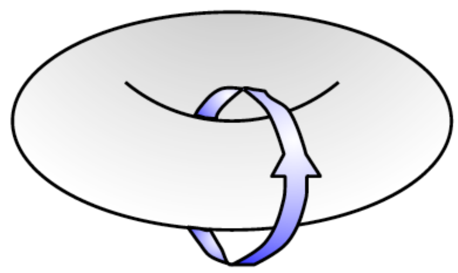
Compactification: $K = K_0 / H$

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



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

Breit, Ovrut, Segre

Doublet -triplet splitting

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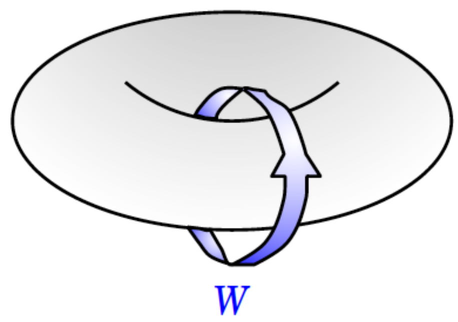

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Massless states: $H \otimes \overline{H}$ singlets

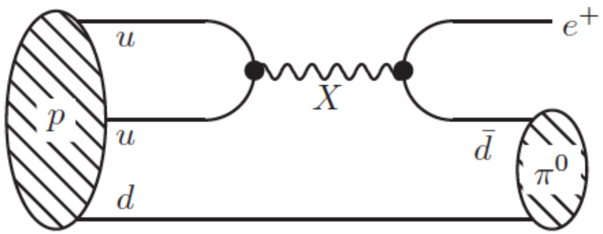
Breit, Ovrut, Segre

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

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

SUSY GUTS - Nucleon decay

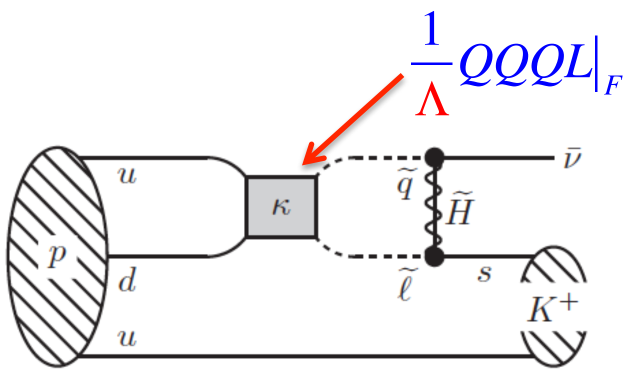
Gauge boson and Higgsino mediation



(a) Dimension 6.

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

$$\tau_{p\to e^+\pi^0} > 2\times10^{34}\,\text{yrs}, \; M_X > 10^{16}\,GeV$$



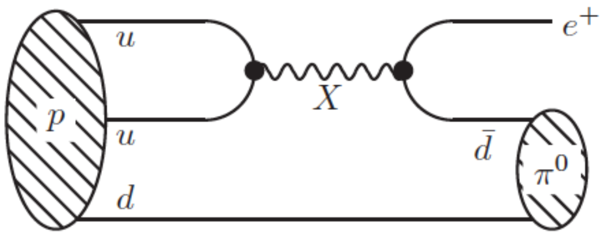
(b) Dimension 5.

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

$$\tau_{p\to K^+\bar{\nu}} > 7\times10^{33}\,yrs$$

Super-K

Gauge boson and Higgsino mediation



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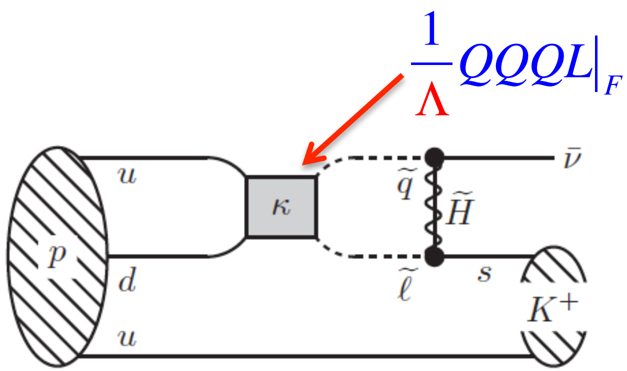


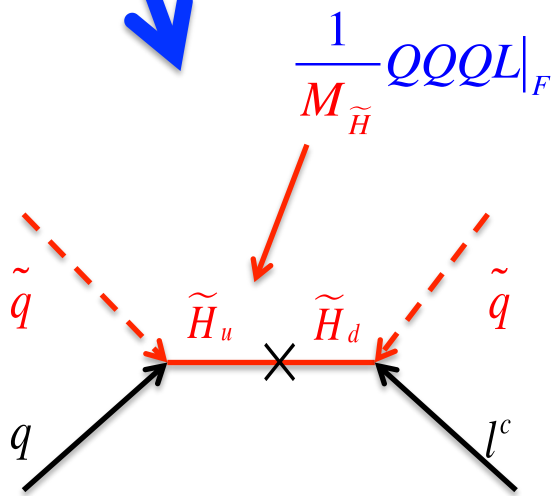
(b) Dimension 5.

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

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

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

$\tau_{p \rightarrow K^+ \bar{\nu}} > 3.3 \times 10^{33} yrs$



D=5 proton decay amplitude

$M_{\tilde{H}} > 10^{27} GeV, 10^9 M_{Planck}$???

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$

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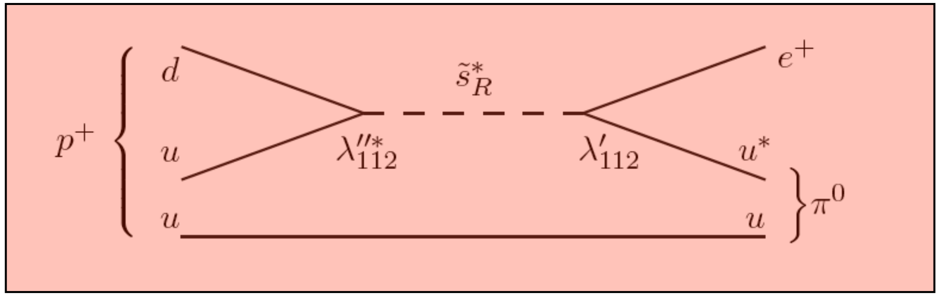
$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$
$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$



SUSY extensions of the Standard Model

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$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$
$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + \ldots (LLHH) \right)$$

$$M_{\widetilde{H}} > 10^{27}\, GeV,\ 10^{9}\, M_{Planck}\ ???$$

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$

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$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + \ldots (\not{L}) \right)$$

R-parity: Z_2

SUSY states odd

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$
$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$
$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + \ldots (\not{L}) \right)$$

R-parity: Z_2 — SUSY states odd

$Q_W^R = 2$

Z_N^R R-symmetry — N=4,6,8,12,24 — LSP stable

Z_4^R special:

MSSM spectrum
No perturbative μ term
Commutes with SO(10)
Anomaly cancellation

N	q_{10}	$q_{\bar{5}}$	q_{H_u}	q_{H_d}	q_N
4	1	1	0	0	2

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange
Babu, Gogoladze, Wang

Nucleon decay outlook

- 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

$$\tau^{SuperK}_{p \to e^+\pi^0} > 2 \times 10^{34}\,\rm yrs$$

Giudice, Romanino

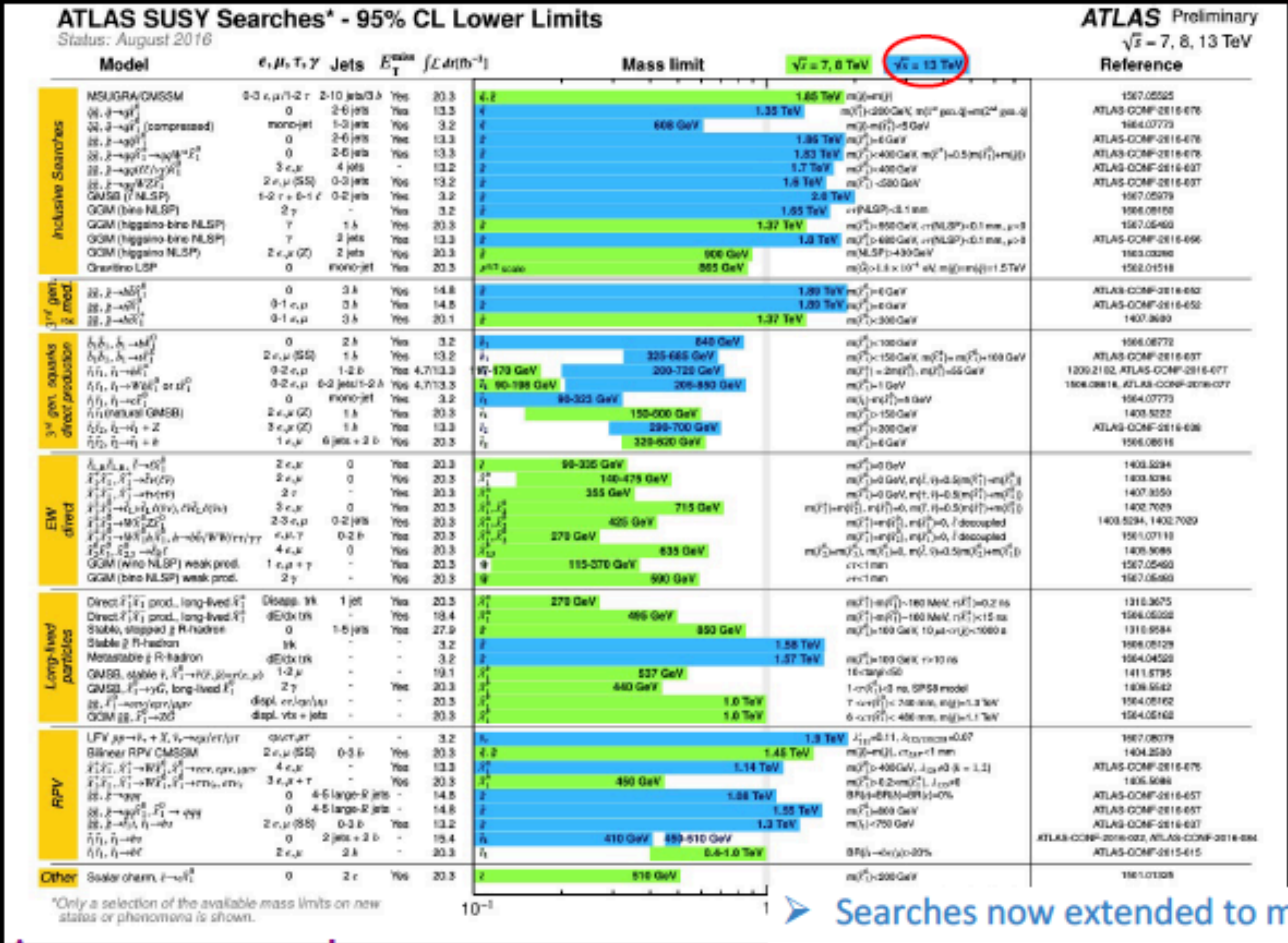
$$M_{\rm GUT} > \left(\frac{\alpha_{\rm GUT}}{1/35}\right)^{1/2} \left(\frac{\alpha_N}{0.015\ \rm GeV^3}\right)^{1/2} \left(\frac{A_L}{5}\right)^{1/2} 6 \times 10^{15}\ \rm GeV$$

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

GUTs need SUSY

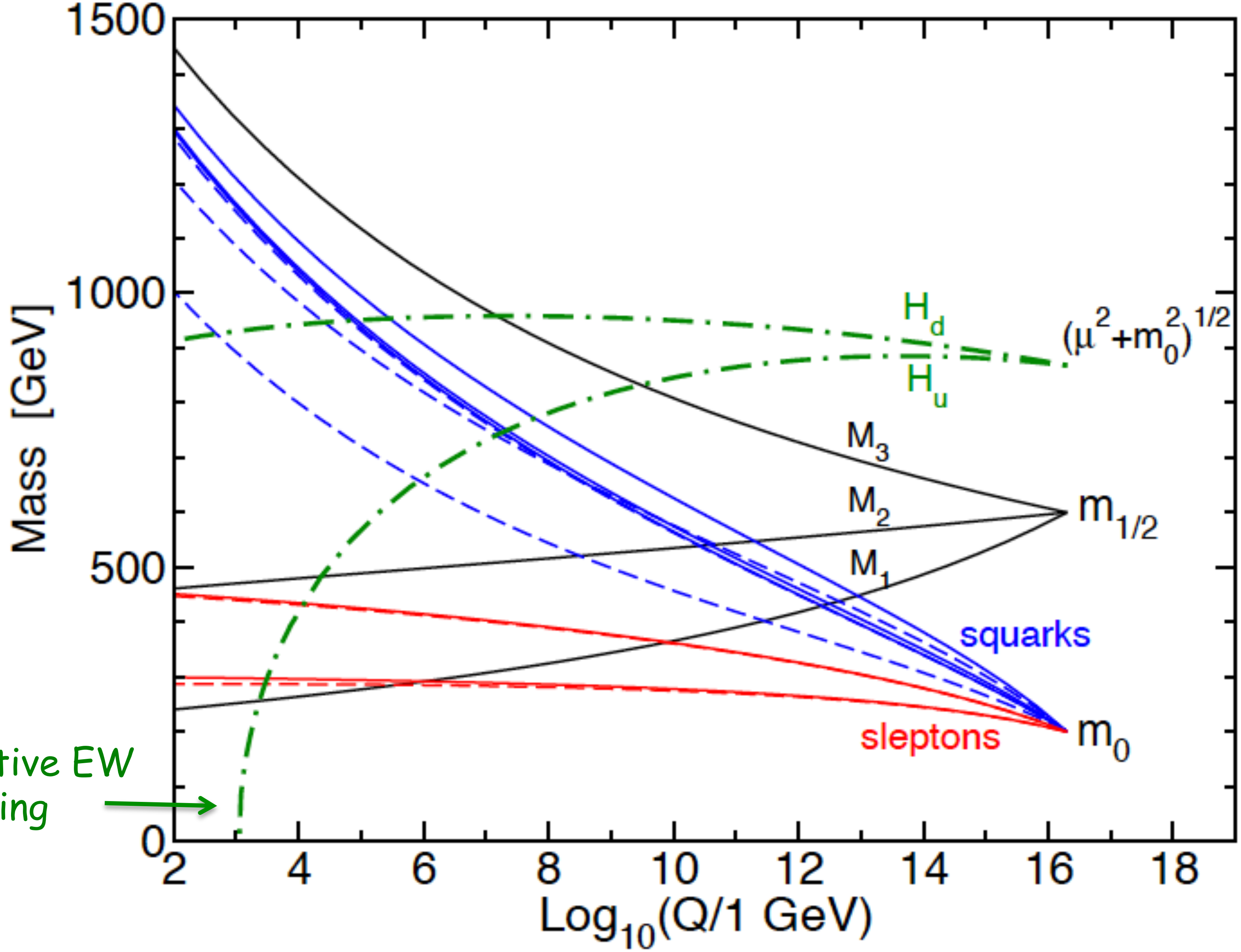
… but where is SUSY?

Run 2 SUSY Searches



- ➢ Searches now extended to more challenging scenarios
  - Electroweak production, compressed mass spectra, …
  - Can expect many more after end of 2016 data taking!
- ➢ Mass limits (in simplified model spectra!)
  - pushed to about 1.9 TeV (gluinos) and 900 GeV (top squarks); limits on EW production even for small mass differences

SUSY GUTs: low energy spectrum



Radiative EW breaking

Little hierarchy problem:

$\text{GUTs } \Lambda \sim M_{GUT}$

$$\mathrm{v}^2 \sim \delta m_{H_u}^2 \simeq -\frac{3y_t^2}{4\pi^2}\left(m_{stop}^2 + \frac{g_s^2}{3\pi^2} m_{gluino}^2 \log\left(\frac{\Lambda}{m_{gluino}}\right)\right)\log\left(\frac{\Lambda}{m_{stop}}\right) \quad ?$$

breaking

Little hierarchy problem $\Rightarrow$ definite SUSY ^ structure

MSSM:

105 +(19) Parameters

$$M_Z^2 = \sum_{\tilde{q},\tilde{l}} a_i \widetilde{m}_i^2 + \sum_{\tilde{g},\widetilde{W},\widetilde{B}} b_i \widetilde{M}_i^2 + \ldots$$

$$M_{\tilde{g}} > 1TeV \quad \Rightarrow \quad \Delta > b\frac{\widetilde{M}^2}{M_Z^2} \sim 100$$

$\Rightarrow$ Correlations between SUSY breaking parameters and/or additional low-scale states breaking

Little hierarchy problem $\Rightarrow$ definite SUSY ^ structure

MSSM:

105 +(19) Parameters

$$M_Z^2 = \sum_{\tilde{q},\tilde{l}} a_i \widetilde{m}_i^2 + \sum_{\tilde{g},\widetilde{W},\widetilde{B}} b_i \widetilde{M}_i^2 + \dots$$

$$M_{\tilde{g}} > 1TeV \quad \Rightarrow \quad \Delta > b\frac{\widetilde{M}^2}{M_Z^2} \sim 100$$

$\Rightarrow$ Correlations between SUSY breaking parameters and/or additional low-scale states

Fine Tuning measure:

$$\Delta(a_i) = \left| \frac{a_i}{M_Z} \frac{\partial M_Z}{\partial a_i} \right|,$$

$$\Delta_{\rm m} = Max_{a_i} \Delta(a_i), \quad \Delta_q = \left(\sum \Delta_{\gamma_i}^2\right)^{1/2}$$

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Fine tuning from a likelihood fit:

If v included as a “Nuisance” variable

$$L(\mathrm{data}\mid\gamma_i) \propto \int d\mathrm{v}\,\delta\left(m_Z - m_Z^0\right)\delta\left(\mathrm{v}\text{-}\left(-\frac{m^2}{\lambda}\right)^{1/2}\right)L\left(\mathrm{data}\mid\gamma_i;\mathrm{v}\right)$$

$$=\frac{1}{\Delta_q}\delta\left(n_q(\ln\gamma_i - \ln\gamma_i^S)\right)L\left(\mathrm{data}\mid\gamma_i;\mathrm{v}_0\right)$$

Fine tuning

Ghilencea, GGR
Cabrera, Casas, de Austri

Fine tuning from a likelihood fit:

If v included as a "Nuisance" variable

$$L(\text{data} \mid \gamma_i) \propto \int d\text{v}\,\delta\left(m_Z - m_Z^0\right)\delta\left(\text{v-}\left(-\frac{m^2}{\lambda}\right)^{1/2}\right)L(\text{data} \mid \gamma_i;\text{v})$$

$$= \frac{1}{\Delta_q}\delta\left(n_q(\ln\gamma_i - \ln\gamma_i^S)\right)L(\text{data} \mid \gamma_i;\text{v}_0)$$

Fine tuning

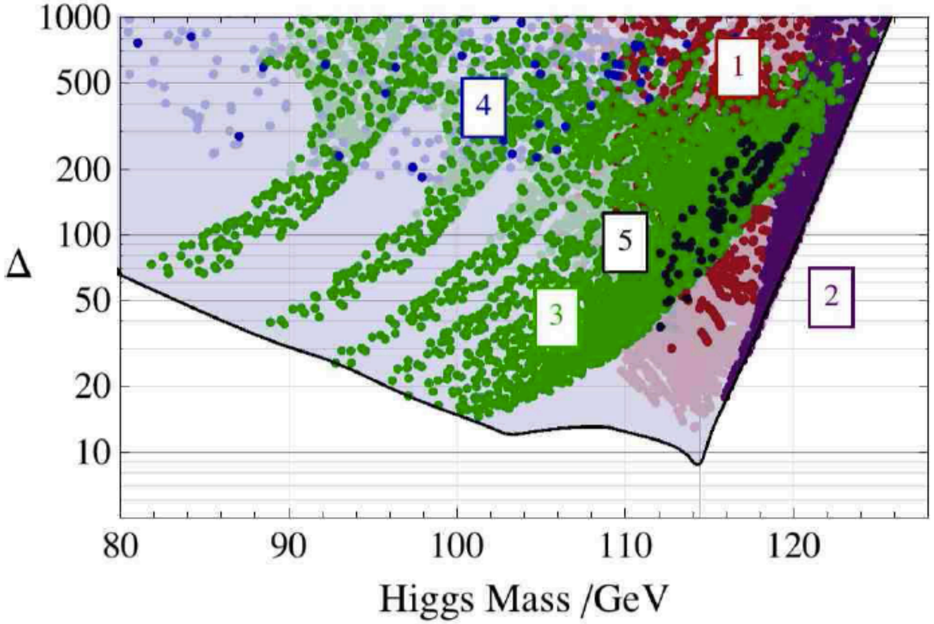
Probabilistic interpretation:

$$\chi^2_{new} = \chi^2_{old} + 2\ln\Delta_q \qquad \Delta_q \ll 100$$

The CMSSM - before LHC

$$\gamma_i = \mu_0, m_0, m_{1/2}, A_0, B_0$$

$$v^2 = -\frac{m_{eff}^{\ \ 2}}{\lambda_{eff}}$$



Relic density restricted

1 h^0 resonant annihilation

2 $\tilde{h}$ t-channel exchange

3 $\tilde{\tau}$ co-annihilation

4 $\tilde{t}$ co-annihilation

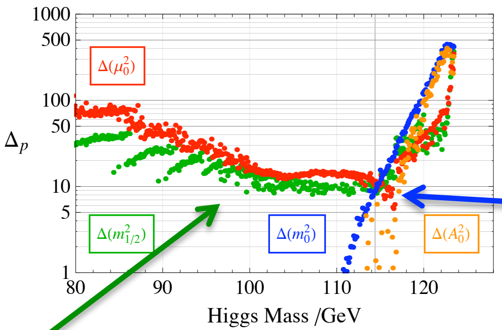
• 5 A^0 / H^0 resonant annihilation

Within 3σ WMAP:

$$\Delta^{EW}_{Min} = 15, \quad m_h = 114.7 \pm 2 GeV$$

< 3σ WMAP:

$$\Delta^{EW}_{Min} = 18, \quad m_h = 115.9 \pm 2 GeV$$



$\Delta(m_0^2)$

Limit of focus point

λ_{eff} increases with m_H

$$\Delta^{\Omega} = \max \left| \frac{\partial \ln \Omega h^2}{\partial \ln q} \right|_{q = m_0, m_{1/2}, A_0, B_0}$$

$$\Delta^{EW+\Omega}_{Min} = 29, \quad m_h = 117 \pm 2 GeV$$

Cassel, Ghilencea, GGR

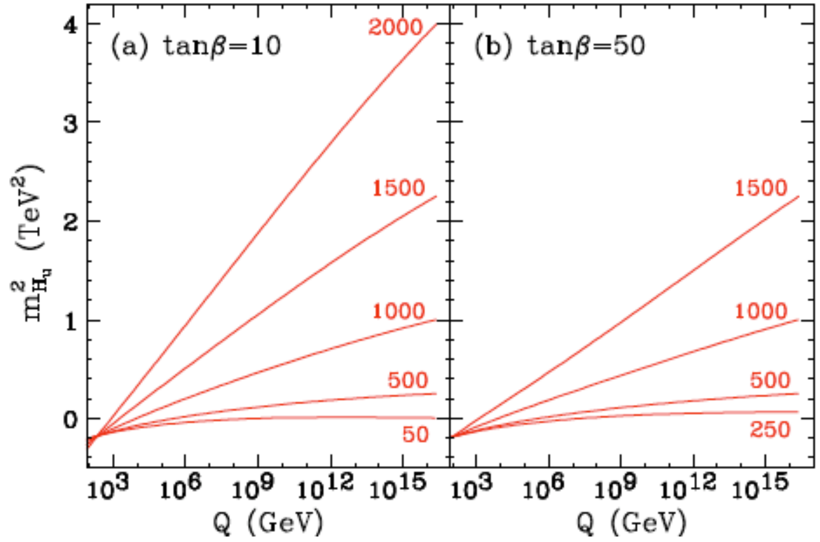
Focus Point

$$2|y_t|^2 (m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}3}^2) + 2|a_t|^2$$

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3X_t - 6g_2^2 |M_2|^2 - \frac{6}{5} g_1^2 |M_1|^2$$

$$16\pi^2 \frac{d}{dt} m_{Q_3}^2 = X_t + X_b - \frac{32}{3} g_3^2 |M_3|^2 - 6g_2^2 |M_2|^2 - \frac{2}{15} g_1^2 | M$$

$$16\pi^2 \frac{d}{dt} m_{\bar{u}3}^2 = 2X_t - \frac{32}{3} g_3^2 |M_3|^2 - \frac{32}{15} g_1^2 |M_1|^2$$



$$\boxed{m_{H_u}^2(Q^2) = m_{H_u}^2(M_P^2) + \frac{1}{2}\left(m_{H_u}^2(M_P^2) + m_{Q_3}^2(M_P^2) + m_{\bar{u}3}^2(M_P^2)\right)\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}} - 1\right]}$$

m_0^2 $\quad$ $3m_0^2$ $\quad$ $\simeq -\frac{2}{3},\ Q^2 \simeq M_Z^2$

"Focus point": $m_{H_u}^2(0) = m_{Q_3}^2(0) = m_{\bar{u}3}^2(0) \equiv m^2$

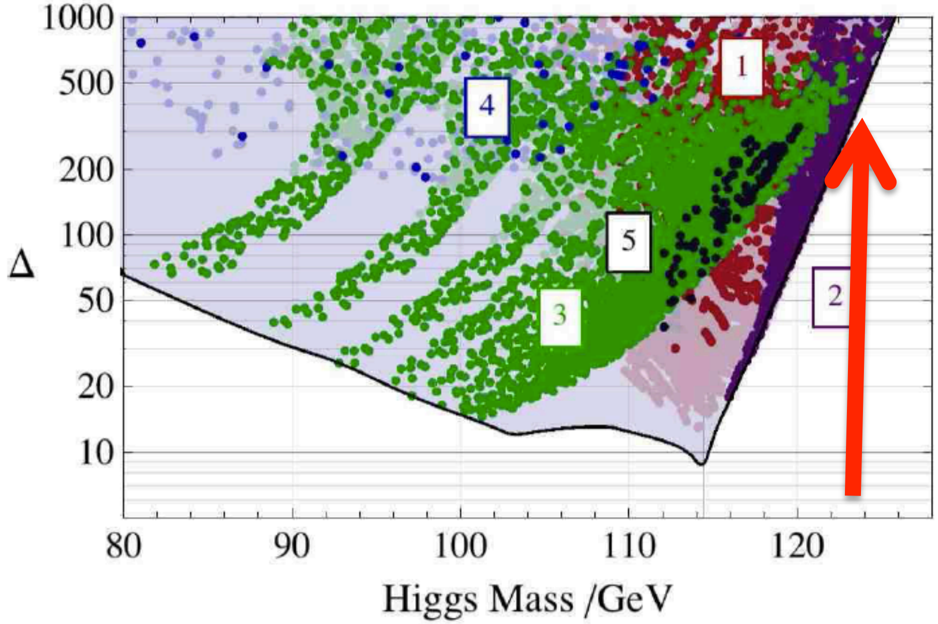
$$\boxed{m_{H_u}^2(t_0) = a_0\, m^2 + \ldots,\ a_0 \le 0.1}$$

Natural choice

Feng, Matchev, Moroi
Chan, Chattopadhay, Nath
Barbieri, Giudice
Feng, Sanford

$i.e.\ m_{Q_3}^3, m_{\bar{u}3}^2 \gg M_Z^2$ possible

- The CMSSM - after Higgs discovery



$M_S^2 = m_{q_3} m_{U_3}$

$$M_{h^0}^2 = M_Z^2 \cos^2 2\beta + \frac{3M_t^2 h_t^2}{4\pi^2}\left(\ln(\frac{M_S^2}{M_t^2}) + \delta_t\right) + \cdots$$

$$\boxed{\Delta_{Min} > 350\,, \quad m_h = 125.6 \pm 3GeV}$$

Reduced fine tuning (c.f. CMSSM)

- New focus points?

Gauginos: $M_{\tilde{g},\widetilde{W},\widetilde{B}}$ Non-universal gaugino correlations

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3\left(2\,|\,y_t\,|^2\,(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}3}^2) + 2\,|\,a_t\,|^2\right) - 6g_2^2\,|\,M_2\,|^2 - \frac{6}{5}g_1^2\,|\,M_1\,|^2$$

New focus point: cancellation between M_3 and M_2 contributions if $\left|M_2\right|^2 \simeq \left|M_3\right|^2$ at M_{SUSY}

Horton, GGR
Choi et al...

Reduced fine tuning (c.f. CMSSM)

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New focus point: cancellation between M_3 and M_2 contributions if $|M_2|^2 \simeq |M_3|^2$ at M_{SUSY}

- New degrees of freedom

Horton, GGR
Choi et al…

e.g. $W = W_{\text{Yukawa}} + (\mu + \lambda S) H_u H_d + \frac{\mu_S}{2} S^2 + \frac{\kappa}{3} S^3 + \xi S$

Reduced fine tuning : New heavy states - higher dimension operators

$$\delta L = \int d^2\theta \frac{1}{M_*}(\mu_0 + c_0 S)(H_u H_d)^2, \quad S = m_0\theta\theta$$ Dimension 5

$$\delta V = \varsigma_1\left(|h_u|^2 + |h_d|^2\right)h_u h_d + \varsigma_2 (h_u h_d)^2; \quad \varsigma_1 = \frac{\mu_0}{M_*}, \ \varsigma_2 = \frac{c_0 m_0}{M_*}$$

$$\varsigma_2 \propto \frac{m_0^2}{M_*^2}$$

but see Lu et al

Singlet extensions

$$W = W_{\text{Yukawa}} + \lambda S H_u H_d + \frac{\kappa}{3}S^3$$ NMSSM

$$W = W_{\text{Yukawa}} + (\mu + \lambda S)H_u H_d + \frac{\mu_S}{2}S^2 + \frac{\kappa}{3}S^3 + \xi S$$ GNMSSM

$$\mu_S >> m_{3/2}: \quad W_{eff}^{GNMSSM} = (H_u H_d)^2/\mu_s + \mu H_u H_d$$

$$\delta V = \frac{\mu}{\mu_S}\left(|H_u|^2 + |H_d|^2\right)H_u H_d$$ ✔ $(Z_4^R \Rightarrow \mu, \mu_s$ naturally small)

Fine tuning in the (C)GNMSSM $(\lambda \leq 0.7^{\dagger})$

Non-universal gaugino masses

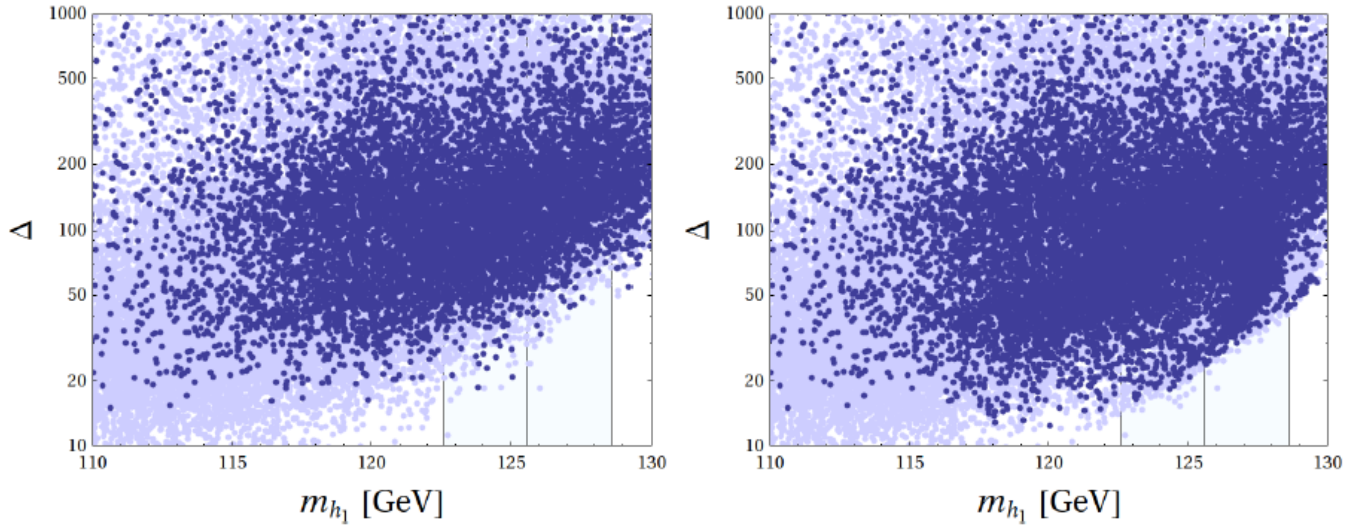
$$\boxed{\Delta_{Min} = 20\,, \quad m_h = 125.6 \pm 3GeV}$$

LHC8 SUSY bounds ✔

DM relic abundance ✔

DM searches ✔

Δ

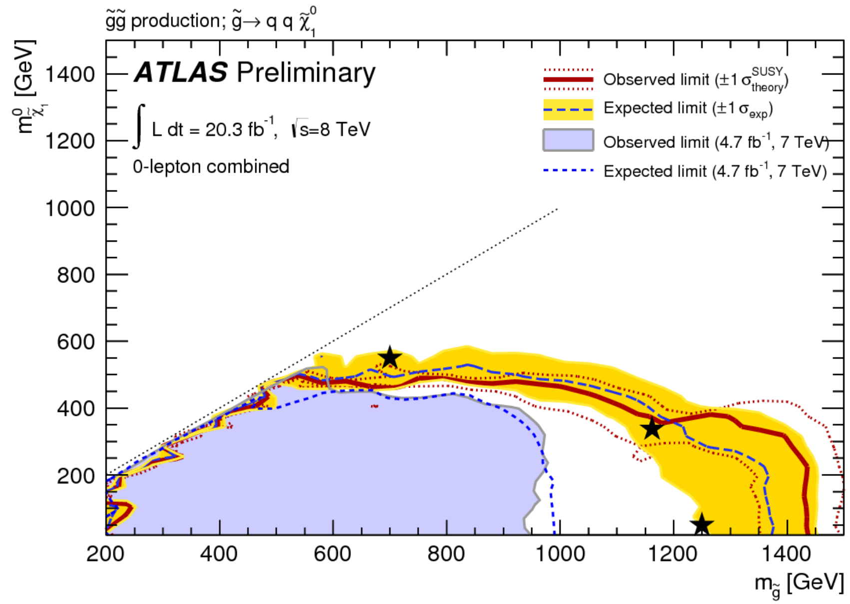


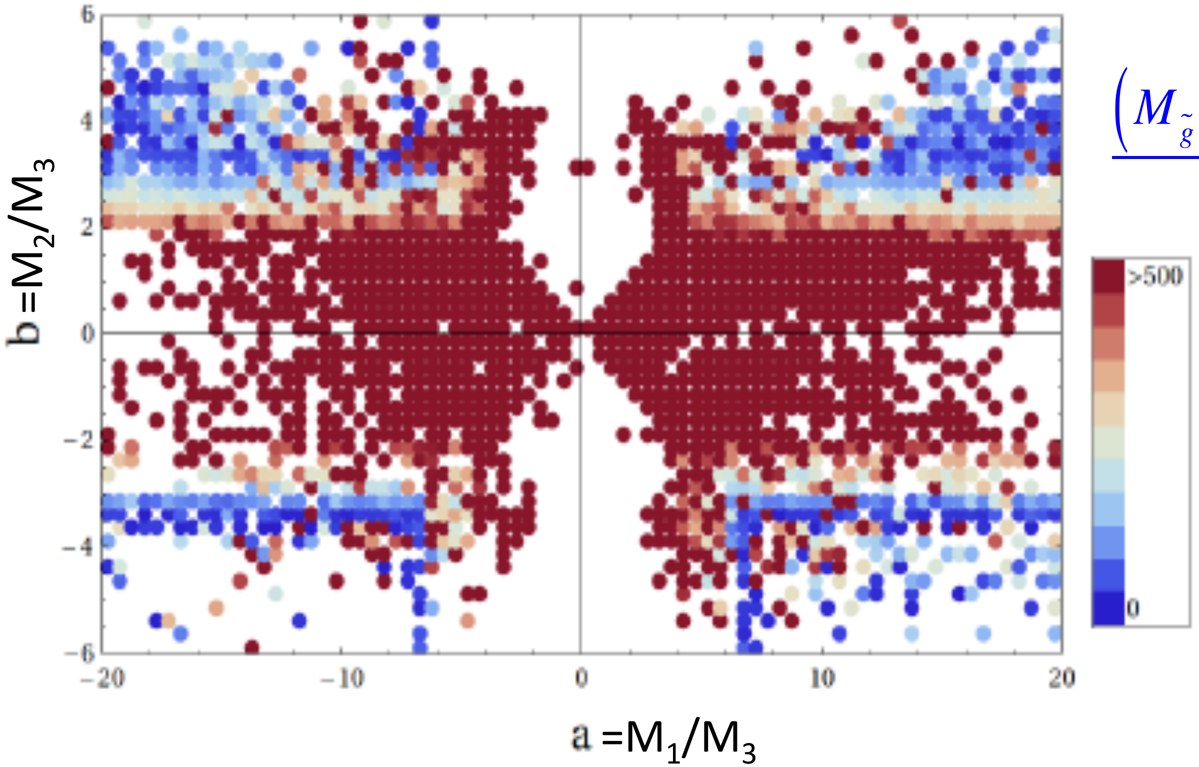
(uniform scan)

GGR, Kaminska, Schmidt-Hoberg

Compressed spectrum

LHC 8 TeV



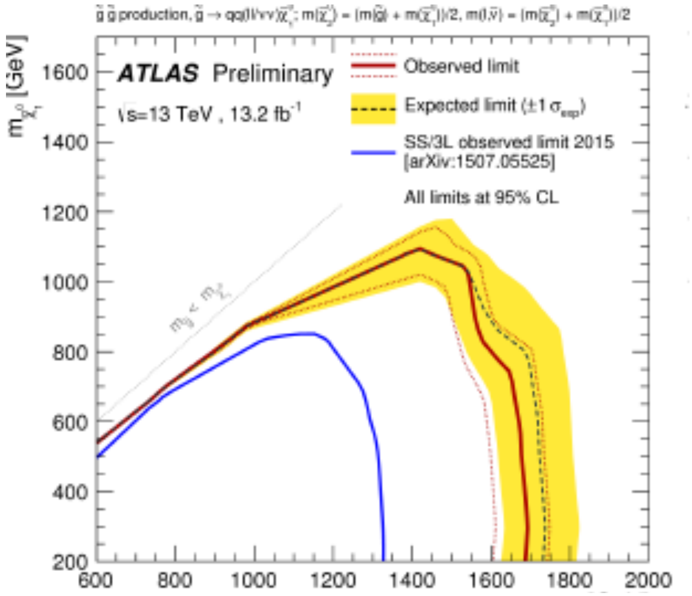


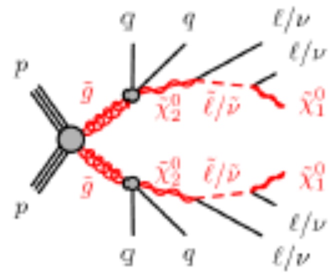
$$\frac{\left(M_{\tilde{g}} - M_{LSP}^{neutralino}\right)}{GeV}$$

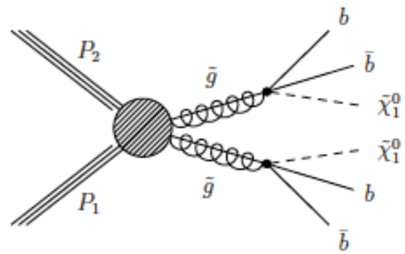
> 500

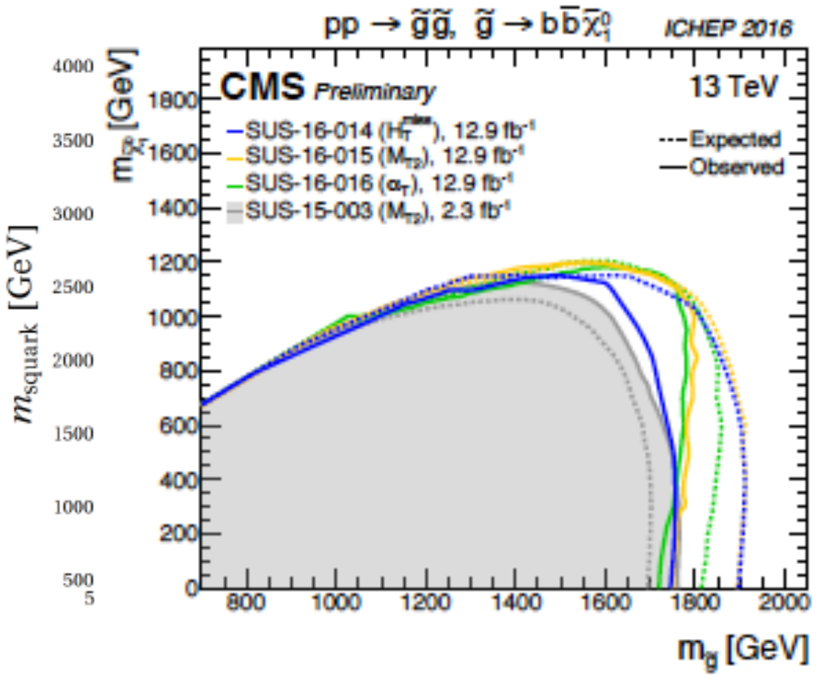
0

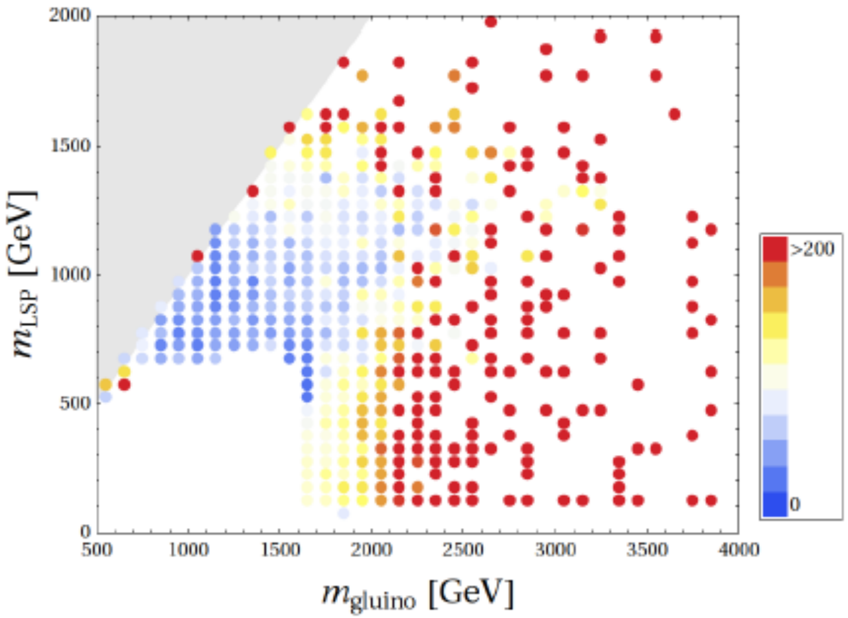
LHC 13 TeV


ATLAS Preliminary
√s=13 TeV , 13.2 fb⁻¹
Observed limit
Expected limit (±1 σ_exp)
SS/3L observed limit 2015
[arXiv:1507.05525]
All limits at 95% CL
m_g̃ < m_χ̃
m_χ̃₁⁰ [GeV]






pp → g̃g̃, g̃ → bb̄χ̃₁⁰
ICHEP 2016
CMS Preliminary
13 TeV
SUS-16-014 (H_T^miss), 12.9 fb⁻¹
SUS-16-015 (M_T2), 12.9 fb⁻¹
SUS-16-016 (α_T), 12.9 fb⁻¹
SUS-15-003 (M_T2), 2.3 fb⁻¹
Expected
Observed
m_g̃ [GeV]
m_χ̃₁⁰ [GeV]
m_squark [GeV]


m_LSP [GeV]
m_gluino [GeV]
>200
0

Reduced fine tuning (c.f. CMSSM)

- New focus points?

Gauginos: $M_{\tilde{g},\widetilde{W},\widetilde{B}}$ Non-universal gaugino correlations

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3\left(2|y_t|^2 (m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}3}^2) + 2|a_t|^2\right) - 6g_2^2 |M_2|^2 - \frac{6}{5} g_1^2 |M_1|^2$$

New focus point: cancellation between M_3 and M_2 contributions if $|M_2|^2 \simeq |M_3|^2$ at M_{SUSY}

- New degrees of freedom

Horton, GGR
Choi et al…

e.g. $W = W_{\rm Yukawa} + (\mu + \lambda S)H_u H_d + \frac{\mu_S}{2} S^2 + \frac{\kappa}{3} S^3 + \xi S$

- New SUSY breaking soft terms

$m_0, m_{1/2}, A_0, \tan\beta, \mu, B\mu, \mu'$

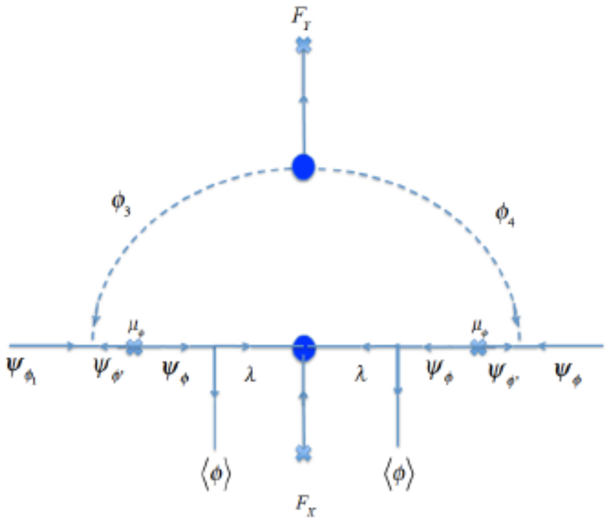
$$\begin{aligned}\mathcal{L}_{NH} = & T'_{u,ij} H_d^* \tilde{u}_{R,i}^* \tilde{q}_j + T'_{d,ij} H_u^* \tilde{d}_{R,i}^* \tilde{q}_j + \\ & T'_{e,ij} H_u^* \tilde{e}_{R,i}^* \tilde{l}_j + \underline{\mu' \tilde{H}_d \tilde{H}_u} + \text{h.c.}\end{aligned}$$

Higgsino mass origin

- Gaugino mediation

$$\int d^4\theta X X^\dagger \overline{D}_\alpha \left(\Phi_1^\dagger e^V\right) \overline{D}^\alpha e^{-V} \Phi_2^\dagger$$

$$m_{\psi_{\phi_1}\psi_{\phi_2}} \propto \frac{\mu_\phi^2 \langle\phi\rangle^2 F_Y F_X}{M^7}$$



ϕ link field coupled to hidden sector and visible sector via Higgs portal

- Sequestering

Hidden sector running drives Higgs mass to zero leaving Higgsino mass unchanged

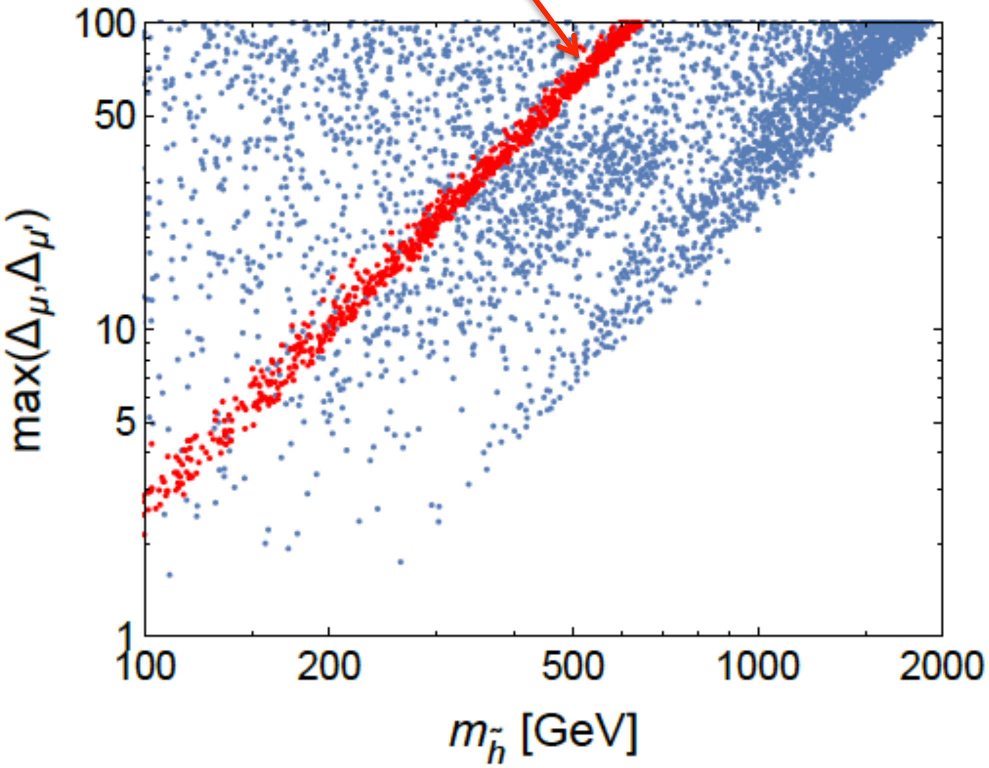
Perez, Roy, Schmaltz

- New SUSY breaking soft terms

$m_0, m_{1/2}, A_0, \tan\beta, \mu, B\mu, \mu'$

$$\mathcal{L}_{NH} = T'_{u,ij} H_d^* \tilde{u}_{R,i}^* \tilde{q}_j + T'_{d,ij} H_u^* \tilde{d}_{R,i}^* \tilde{q}_j + T'_{e,ij} H_u^* \tilde{e}_{R,i}^* \tilde{l}_j + \underline{\mu' \tilde{H}_d \tilde{H}_u} + \text{h.c.}$$

$\mu' = 0$



LHC 13 TeV

$\Delta_{CMSSM} \geq 350$

$\Delta_{CMSSM+\mu'} \geq 20$

Summary

- SM leaves many questions unanswered

- GUT answers:
  - -Multiplet structure
  - -Gauge couplings
  - -quark –lepton symmertry
  - -neutrino masses (see saw)

- Further symmetry:
  - -SUSY
  - -family symmetry (non-Abelian discrete)
  - - discrete R- symmetry

- Phenomena:
  - -SUSY (compressed spectra)
  - -nucleon decay
  - -squark and slepton masses