Beyond the Standard Model (after LHC 8TeV)

G. Ross, Corfu, September 2015

Beyond the Standard Model (after LHC 8TeV)

I. Introduction

II. Grand Unification

III. The Higgs era: re-evaluation of the hierarchy problem

IV. “Just” the Standard Model

V. SUSY

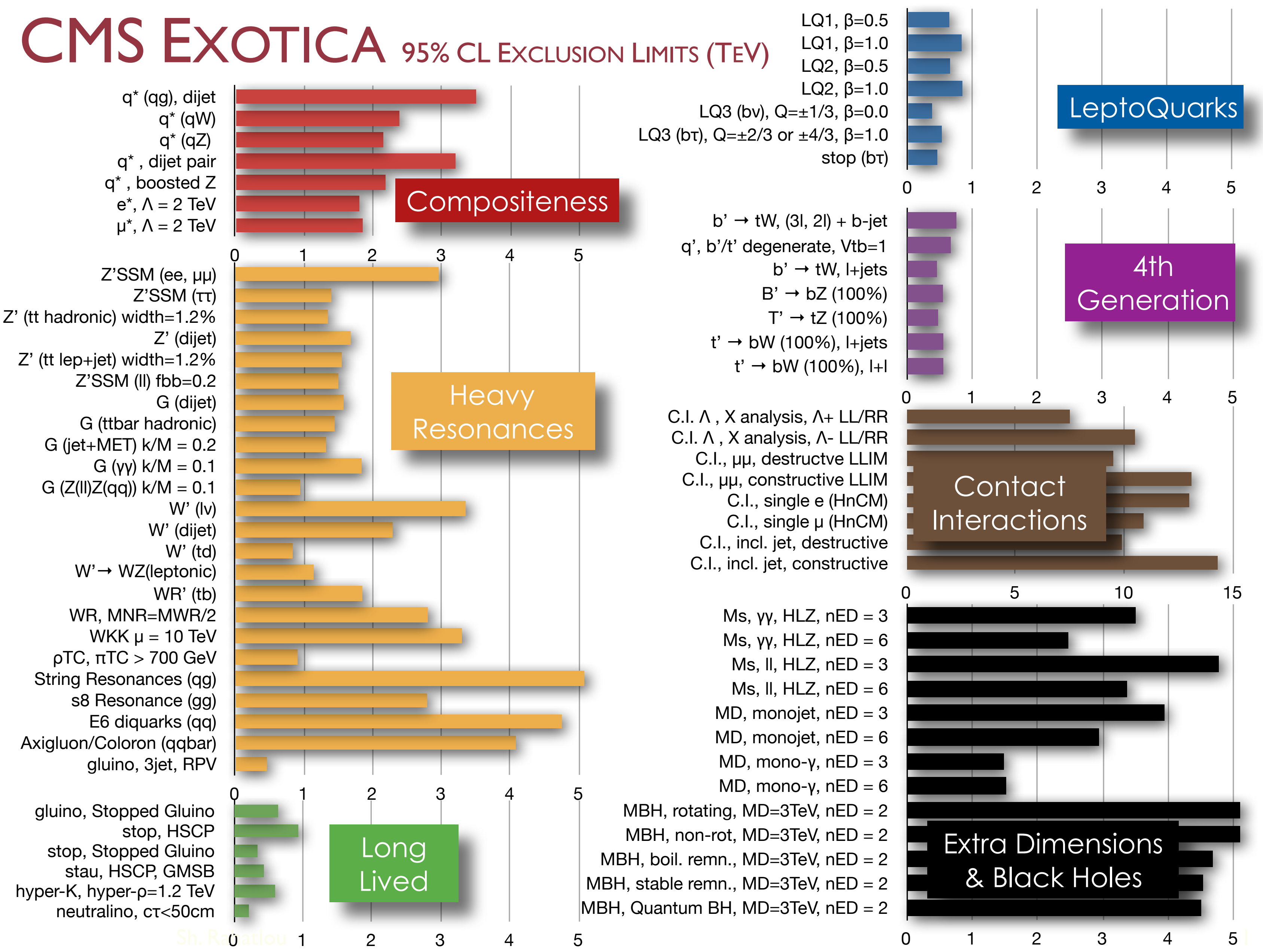
(VI. Composite Higgs)

(Lecture notes: http://goo.gl/eLpaCH)

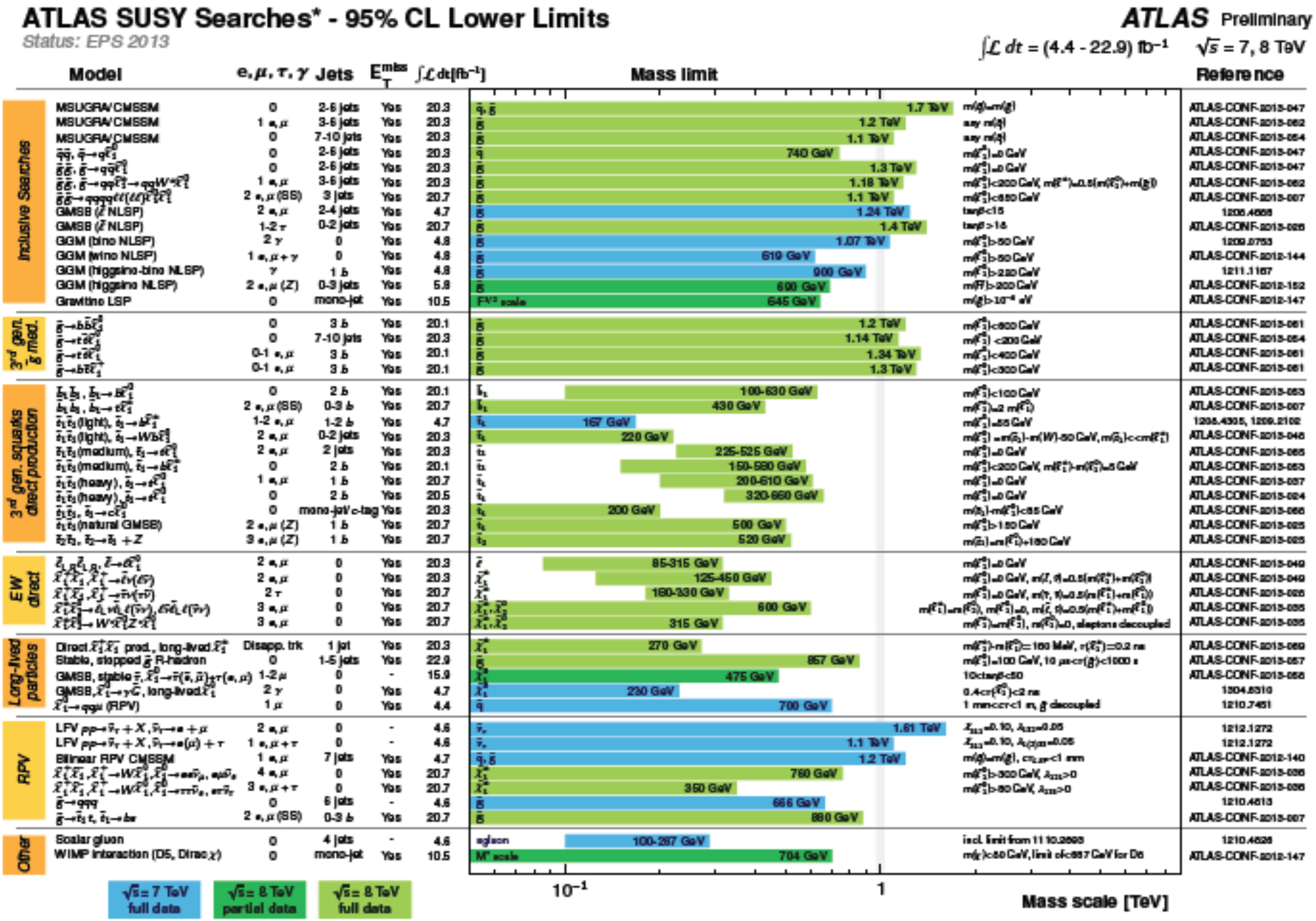
I. Introduction

I. Introduction

LHC 8: No evidence (yet) for BSM


CMS Exotica 95% CL Exclusion Limits (TeV)
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Heavy Resonances
Z'SSM (ee, μμ)
Z'SSM (ττ)
Z' (tt hadronic) width=1.2%
Z' (dijet)
Z' (tt lep+jet) width=1.2%
Z'SSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (γγ) k/M = 0.1
G (Z(ll)Z(qq)) k/M = 0.1
W' (lν)
W' (dijet)
W' (td)
W'→ WZ(leptonic)
WR' (tb)
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
neutralino, cτ<50cm
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bν), Q=±1/3, β=0.0
LQ3 (bτ), Q=±2/3 or ±4/3, β=1.0
stop (bτ)
4th Generation
b' → tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' → tW, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l
Contact Interactions
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., μμ, destructve LLIM
C.I., μμ, constructive LLIM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive
Extra Dimensions & Black Holes
Ms, γγ, HLZ, nED = 3
Ms, γγ, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-γ, nED = 3
MD, mono-γ, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
0 1 2 3 4 5
0 5 10 15

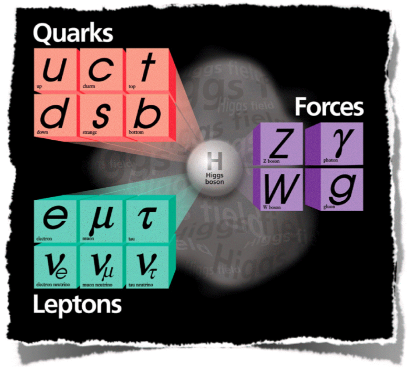
ATLAS Summary

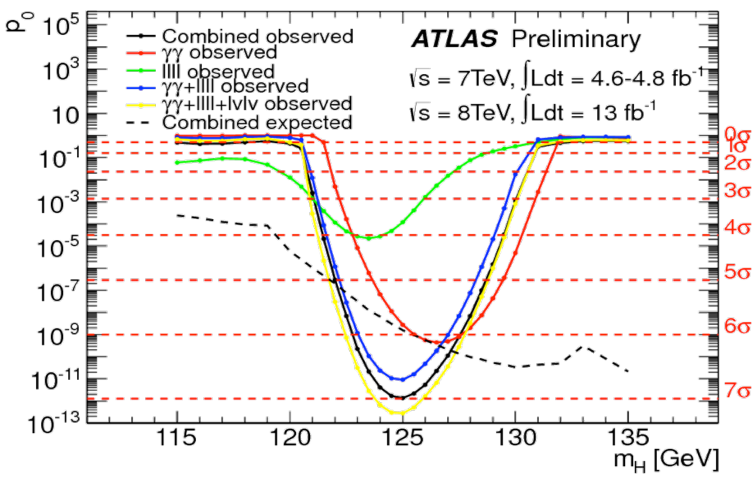


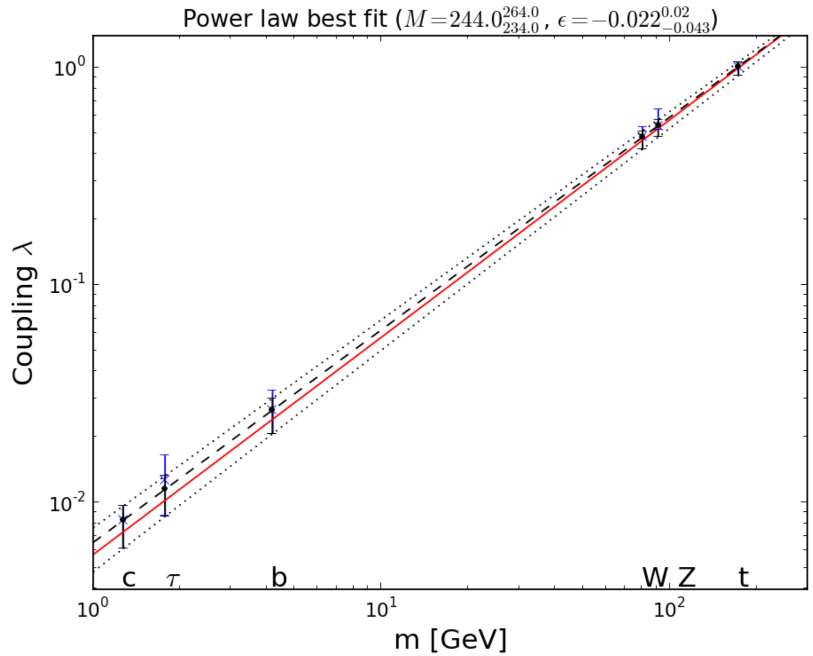
LHC 8

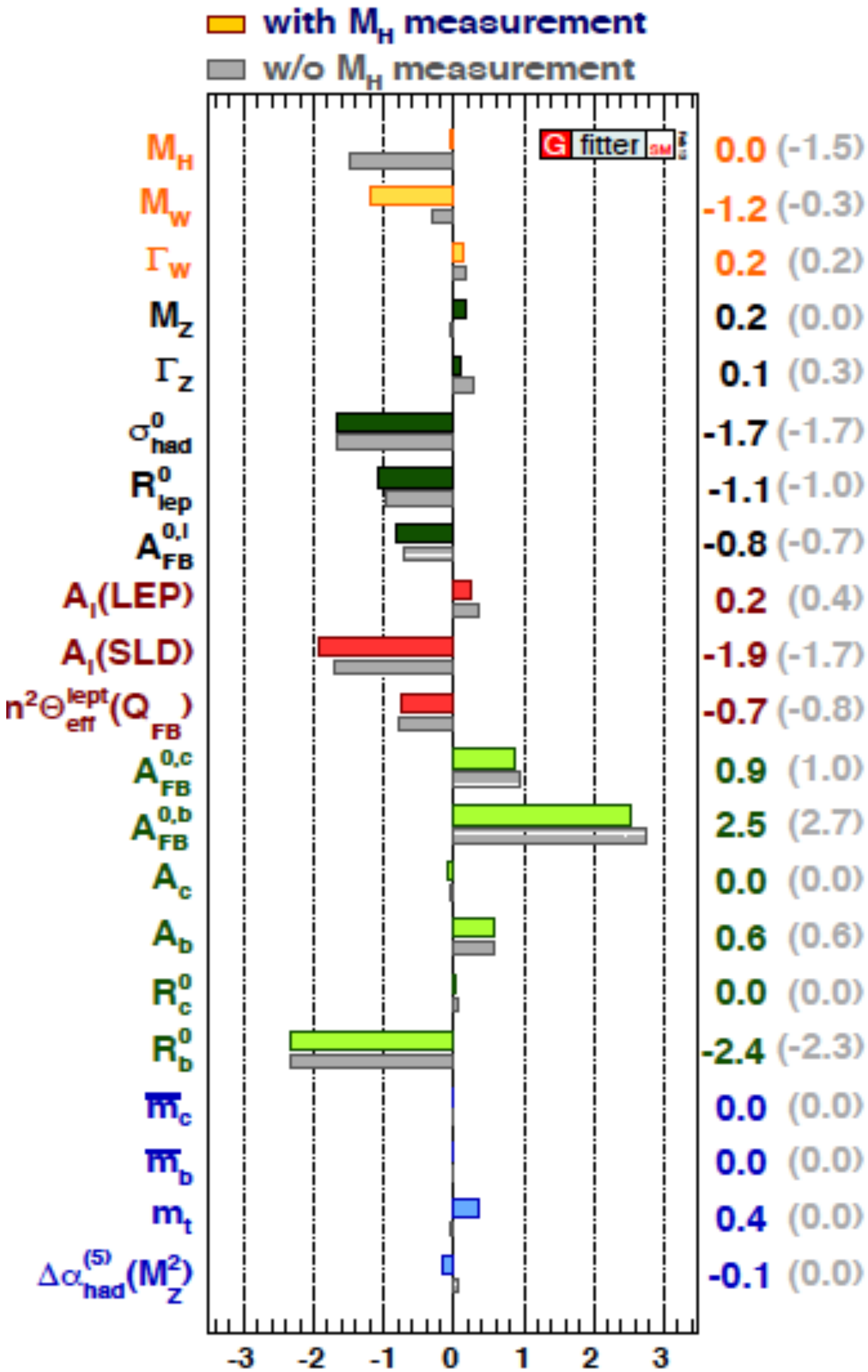
No evidence (yet) for BSM

Higgs discovery

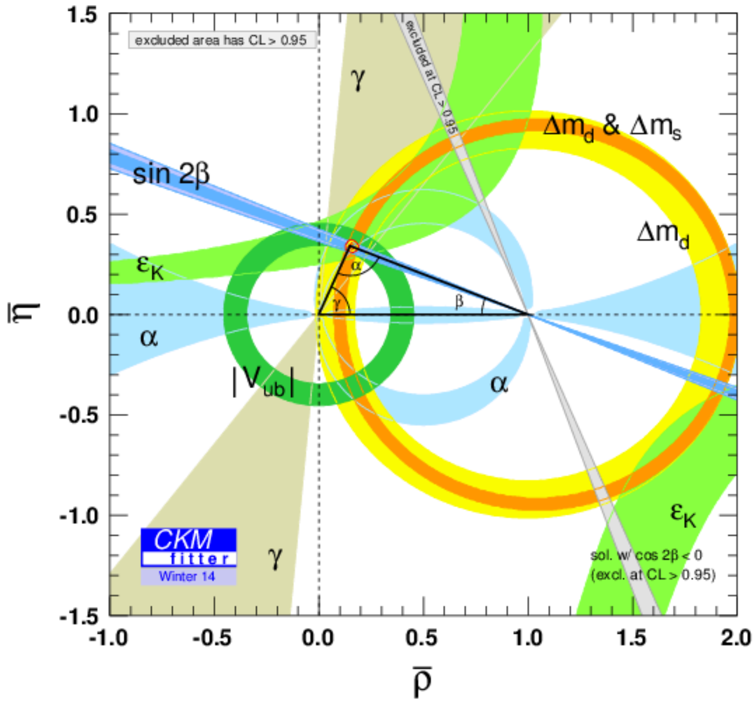




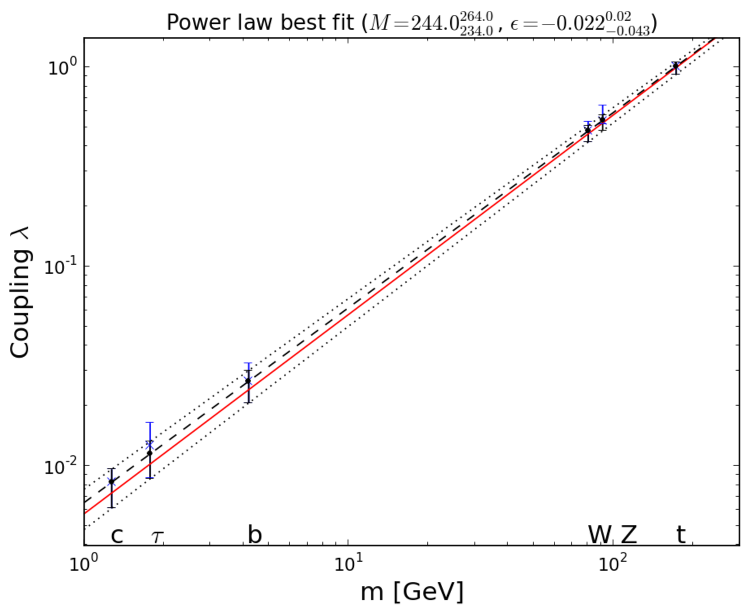




with M_H measurement
w/o M_H measurement
Gfitter SM
M_H 0.0 (-1.5)
M_W -1.2 (-0.3)
Γ_W 0.2 (0.2)
M_Z 0.2 (0.0)
Γ_Z 0.1 (0.3)
σ^0_{had} -1.7 (-1.7)
R^0_{lep} -1.1 (-1.0)
$A^{0,l}_{FB}$ -0.8 (-0.7)
A_l(LEP) 0.2 (0.4)
A_l(SLD) -1.9 (-1.7)
$\sin^2\Theta^{lept}_{eff}(Q_{FB})$ -0.7 (-0.8)
$A^{0,c}_{FB}$ 0.9 (1.0)
$A^{0,b}_{FB}$ 2.5 (2.7)
A_c 0.0 (0.0)
A_b 0.6 (0.6)
R^0_c 0.0 (0.0)
R^0_b -2.4 (-2.3)
$\overline{m}_c$ 0.0 (0.0)
$\overline{m}_b$ 0.0 (0.0)
m_t 0.4 (0.0)
$\Delta\alpha^{(5)}_{had}(M^2_Z)$ -0.1 (0.0)
-3 -2 -1 0 1 2 3



excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
$|V_{ub}|$
CKM fitter
Winter 14
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
$\bar{\eta}$
$\bar{\rho}$
1.5 1.0 0.5 0.0 -0.5 -1.0 -1.5
-1.0 -0.5 0.0 0.5 1.0 1.5 2.0



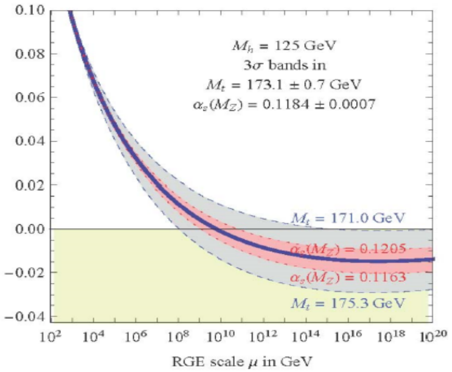
Power law best fit ($M = 244.0^{264.0}_{234.0}$, $\epsilon = -0.022^{0.02}_{-0.043}$)
Coupling λ
m [GeV]
10^0 10^{-1} 10^{-2}
10^0 10^1 10^2
c τ b W Z t

LHC 8

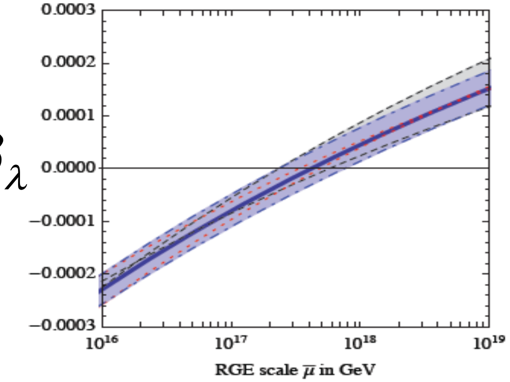
No evidence (yet) for BSM
Higgs discovery

} "Just" the SM (JSM)?

λ

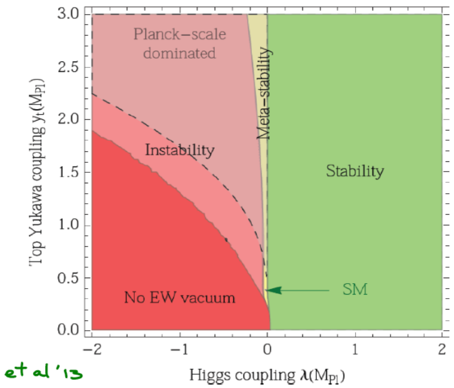


β_λ



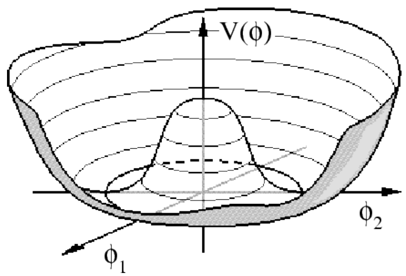
DeGrassi et al,...

Buttazzo et al '13



$$V(H) = -m^2 |\phi|^2 + \lambda |\phi|^4$$

$$m^2 \simeq \left(89 GeV^2\right), \lambda \simeq 0.13$$



Why go beyond the Standard Model?

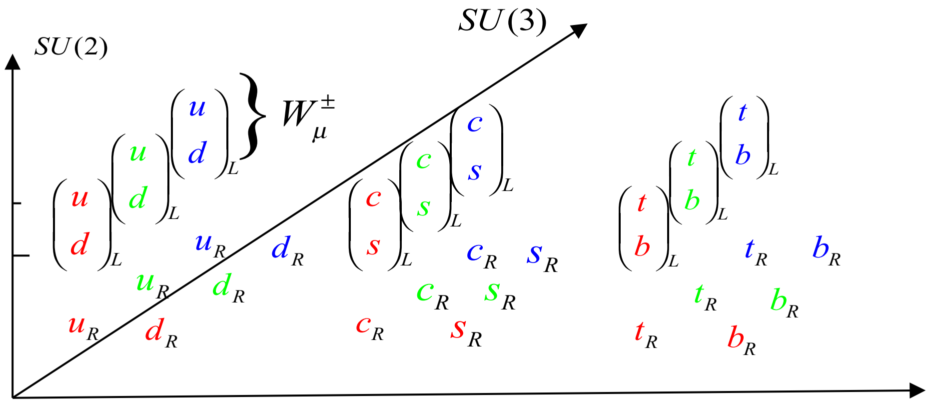
The Standard Model – unanswered questions

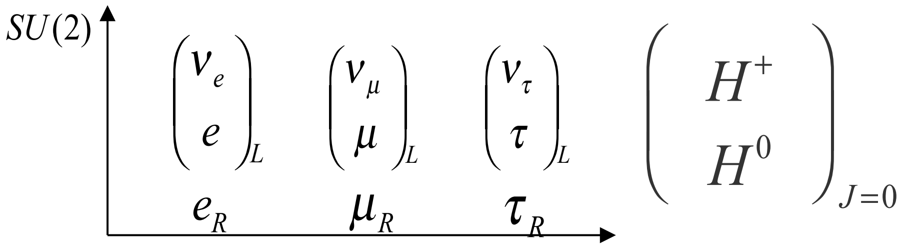
- Complicated choice of multiplets
- Fractional and integral charges?
- Neutrino masses?
- Many parameters 19 (28)
- Only partial unification $A_\mu^\gamma = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu$
- The hierarchy problem
- Strong CP problem
- Dark matter, baryogenesis, inflation.....

II. Grand Unification

- Unification incomplete:

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





19 (28) parameters: $g_i, m_i, \theta_i, \delta_i, M_{W,H}, \theta_{QCD}$

Gravity?

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

Georgi Glashow

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

Group of 5×5 complex unitary matrices with determinant 1

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

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

Covariant derivative: Gauge bosons V_μ^a

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

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

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

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

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

$$(\bar{3},1) + (1,2)$$

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

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

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

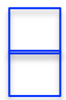
$$\boxed{Q_{d^c} = 1/3}$$

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

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

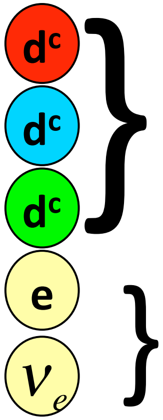
$$3Q_{d^c} + Q_{e^-} = 0$$

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

Remaining 10 states? $\quad T^{[\alpha,\beta]}$  $\quad \dfrac{n(n-1)}{1 \times 2} = 10$

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

$(\bar{5})_L$:

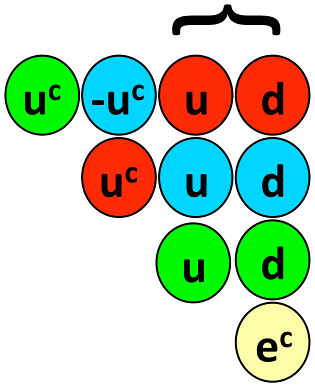


$SU(3)$

$SU(2)$

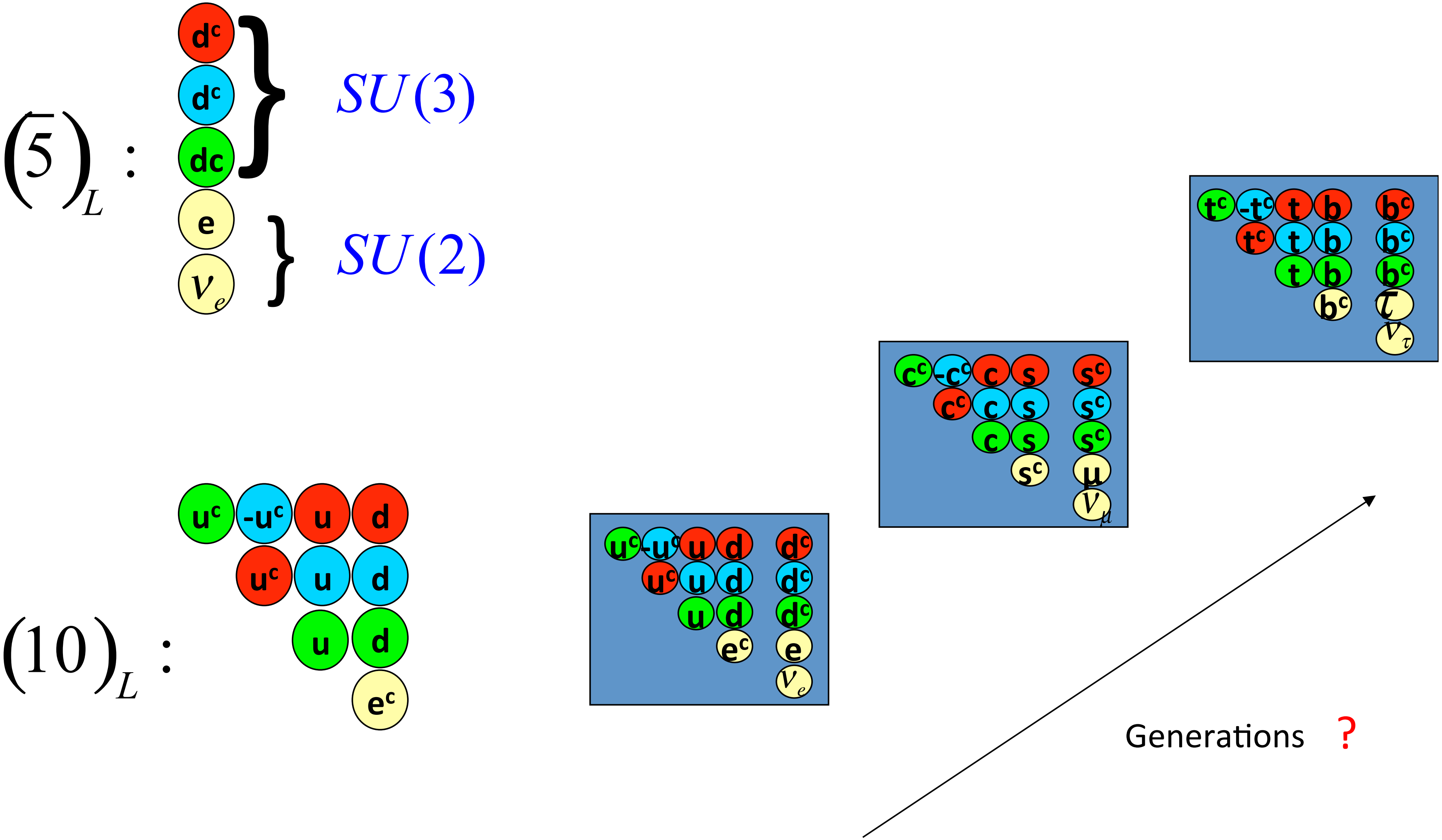
$(10)_L$

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



LH states SU(2) doublets

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



II. 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 $\quad O(n): \ n^2-(n^2+n)/2 = n(n-1)/2$

$SO(10)$ 45 gauge bosons

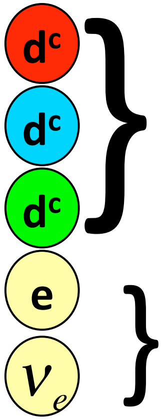
Spinorial (16 dim) representation:

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

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

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

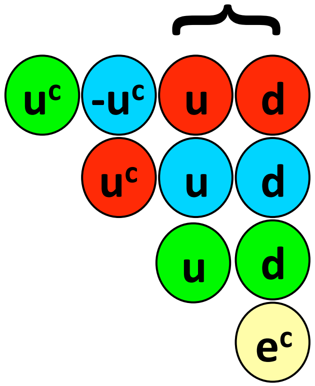
$(\bar{5})_L$:



$SU(3)$

$SU(2)$

$(10)_L$:



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

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

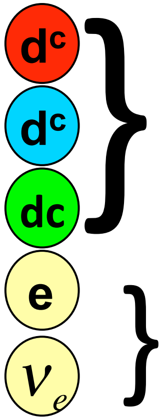
Gauge Couplings

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

$$M_X$$

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

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

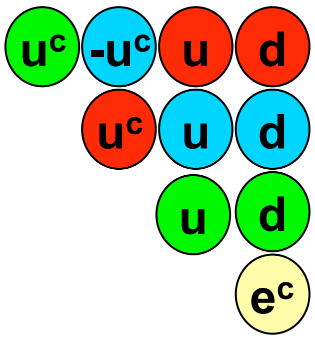


$SU(3)$

$SU(2)$

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

$(10)_L$:

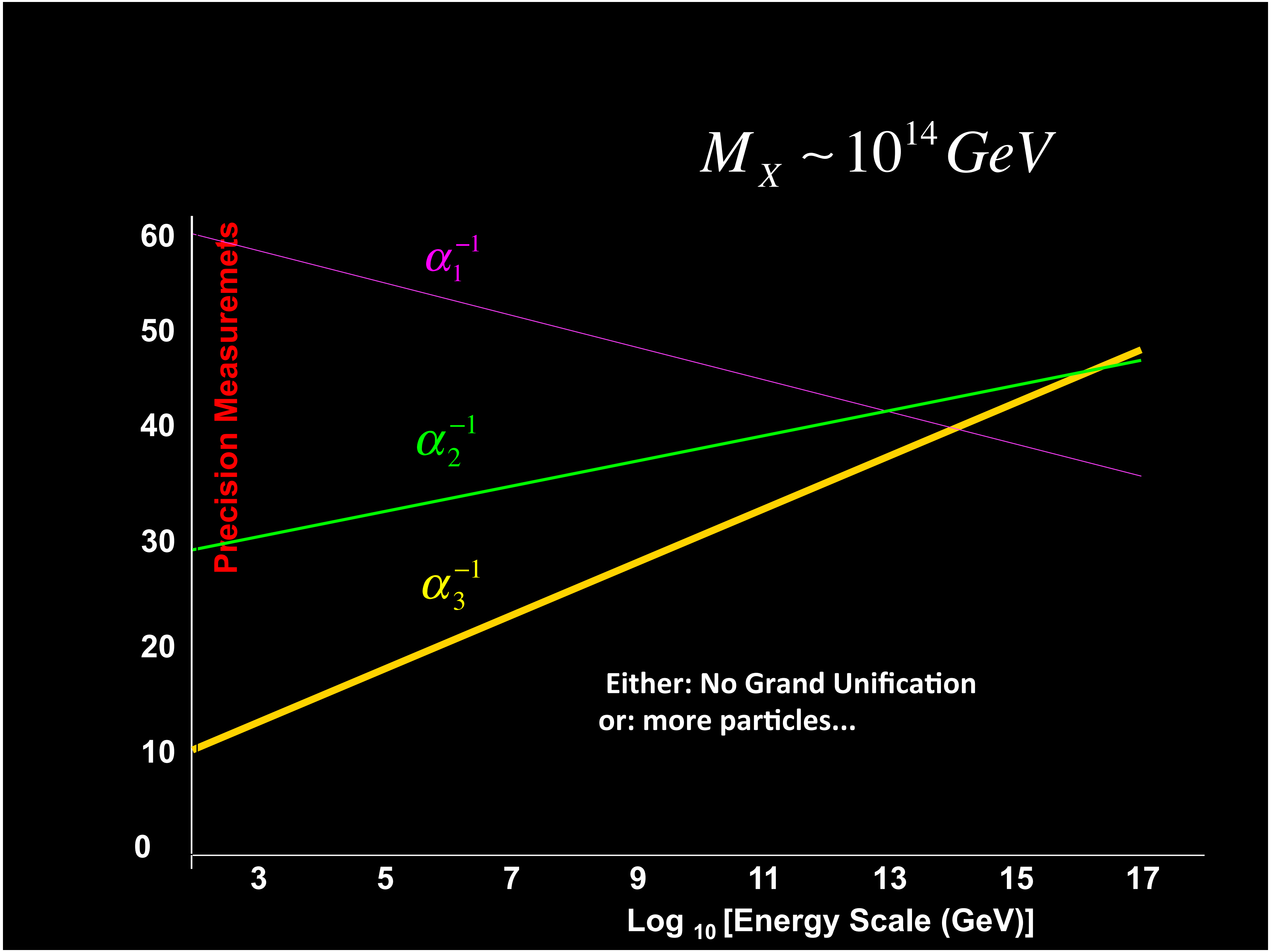


Gauge Couplings

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)]

Fermion masses

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

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

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

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

Fermion masses

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

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After diagonalising down quark mass matrix:

$$m_d = m_e \quad ✗$$

$$m_s = m_\mu \quad ✗$$

$$m_b = m_\tau \quad ✔?$$

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

Fermion masses

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

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

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

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

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

$$\varepsilon^{\mathrm{d}} = 0.15, \quad \mathrm{a}^s_{45} = 1$$

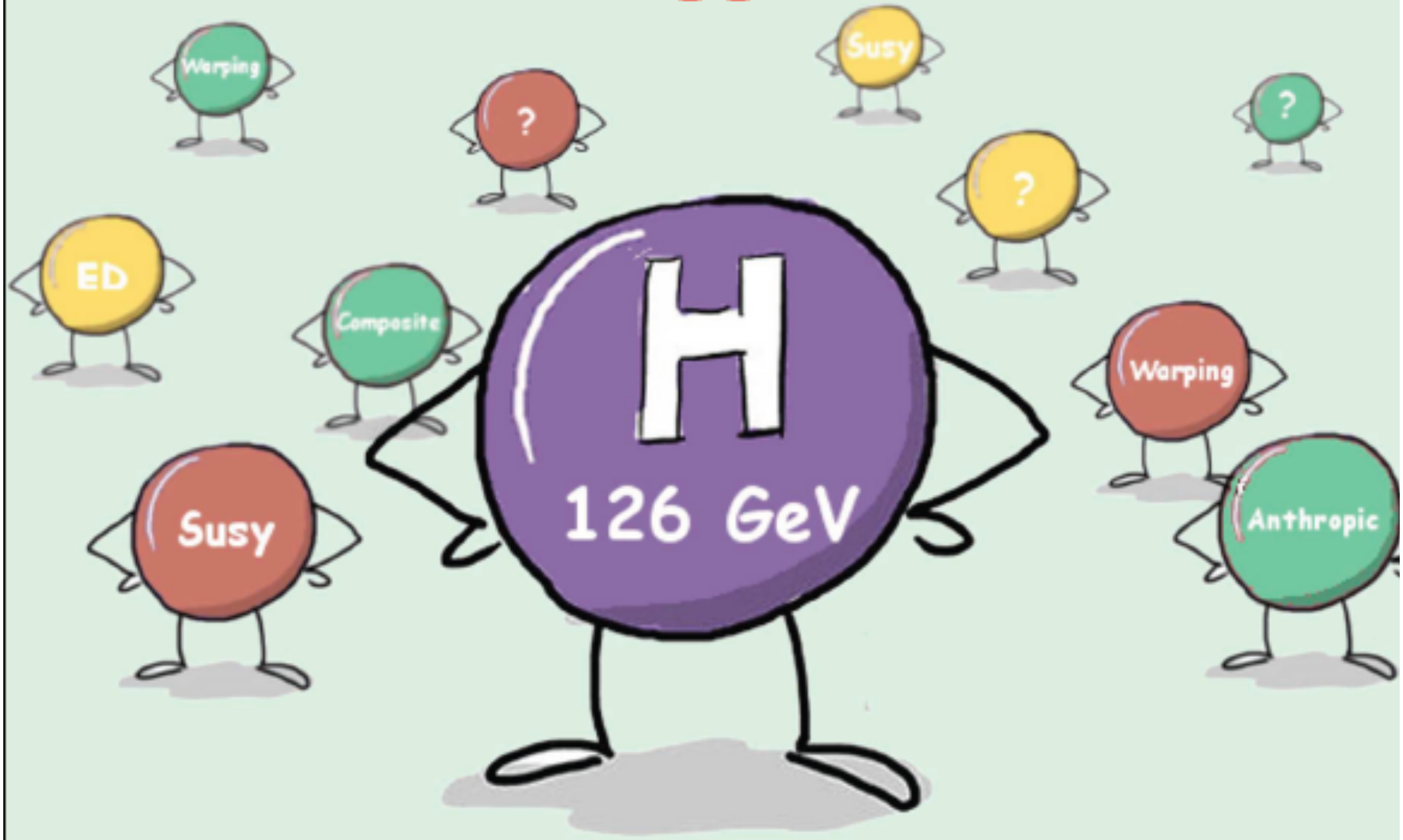
$$\varepsilon^{\mathrm{l}} = 0.15, \quad \mathrm{a}^\mu_{45} = -3$$

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

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

$$m_d = 3.3.m_e \checkmark$$

The Higgs Era



III. The Hierarchy Problem

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 $D \leq 4 + O(1/M)$ ✔
- $L_{effective}^{SM} \supset \cancel{M_A A_\mu A^\mu} + \cancel{m_f \bar{f}_L f_R}$ $\boxed{M_A, m_f \ll M_X, M_{Planck}}$

  Fermions chiral ✔

  Vector gauge bosons ✔

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

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 $D\leq 4+O(1/M)$ ✔

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

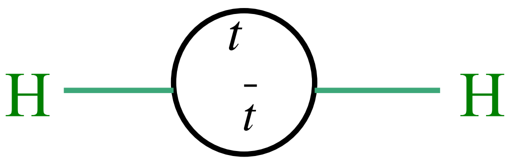
$$\boxed{M_A, m_f \ll M_X, M_{Planck}}$$

Fermions chiral ✔

Vector gauge bosons ✔

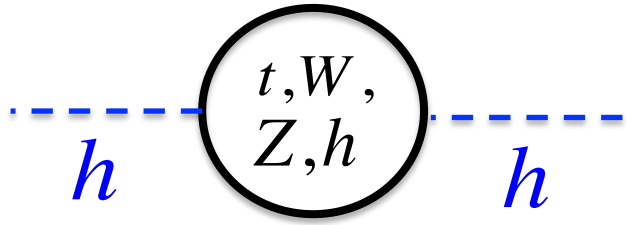
(Massless - vectorlike couplings; massive – chiral couplings)

- Light Higgs ✗ **The Hierarchy problem** $\Lambda\leq 1TeV$??



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

Hierarchy problem?



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

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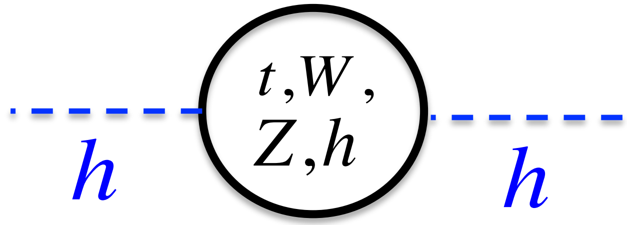

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Field theory: δm^2 not measureable

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

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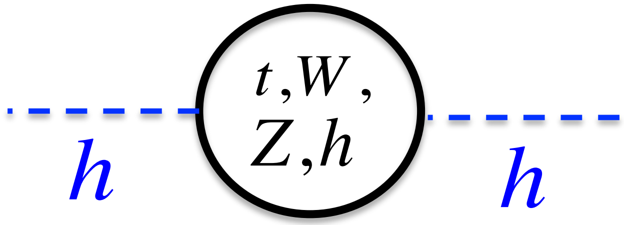

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$$\Rightarrow \quad \frac{d\,m_H^2}{d\,\ln\mu} = \frac{3m_H^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g_2^2}{4} - \frac{3g_1^2}{20}\right)$$

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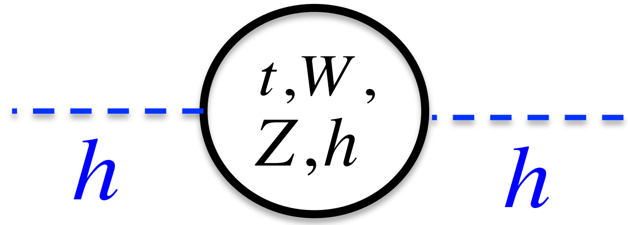

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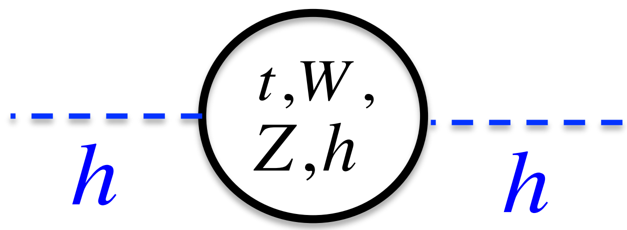
… but is the SM all there is?

Hierarchy problem?



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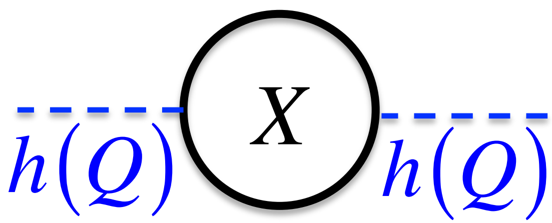
GUTS:

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



- "real hierarchy problem"

Solutions to the hierarchy problem

$\Lambda \leq 1 TeV$??

- Just the (scale invariant) Standard Model….no heavy states

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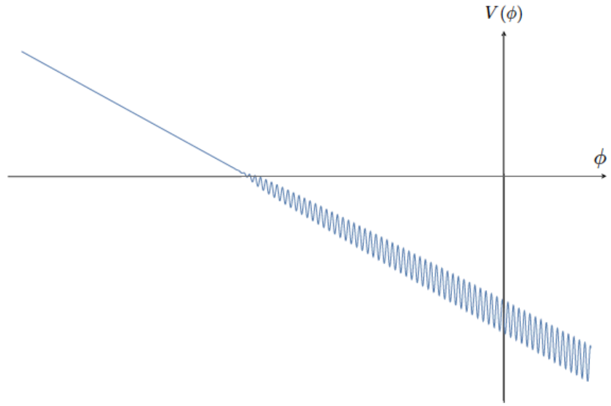

Slow roll - inflation

$$\left(-M^2+g\phi\right)|h|^2+(gM^2\phi+g^2\phi^2+\dots)+\Lambda^3 h\cos\left(\phi/f\right)$$

hierarchy problem term

QCD axion

$$\boxed{m_h^2 \sim g\, f}$$

g small controlled by shift symmetry: $\phi \rightarrow \phi + c$

Solutions to the hierarchy problem

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- Composite models: e.g. technicolour (no light Higgs)

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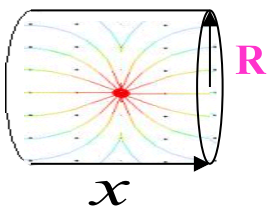
- $\Lambda_{fundamental} \sim 1TeV!$ Xtra dimensions



$$V(r) = \frac{1}{M_*^{2+d} R^d} \frac{m_1 m_2}{r}, \quad D = 4 + d, \quad r \ll R$$

$$\boxed{M^2_{Planck} = M_*^2 \left(M_* R\right)^d}$$

(or warped extra dimensions)

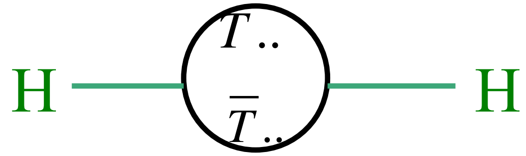
… covered in following lectures by Professor Antoniadis

Solutions to the hierarchy problem

$\Lambda \leq 1TeV$??

- Symmetry protection

Nambu - Goldstone



$e.g. \quad SU(3) \rightarrow SU(2)$

$8 \rightarrow 3$ 5 Goldstone bosons

$$\begin{pmatrix} . & . & H^{*+} \\ . & . & H^{*0} \\ H^- & H^0 & . \end{pmatrix}$$

Symmetry broken by gauge interactions – pseudo Goldstone bosons

…addresses little hierarchy problem only
….little Higgs

Solutions to the hierarchy problem

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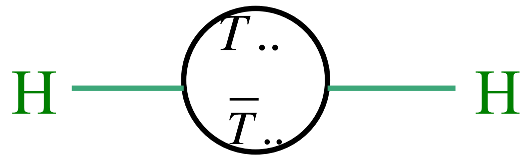

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(AdS/CFT: Composite $\Leftrightarrow$ χ dimensions)

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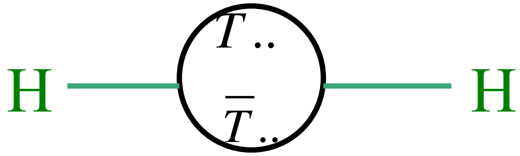

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- Symmetry protection - supersymmetry

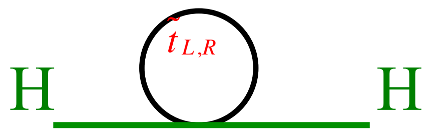
$$\psi_H = \begin{pmatrix} \widetilde{H} \\ H \end{pmatrix}$$

chiral symmetry

$$\cancel{\mu}\,\overline{\psi}_H \psi_H,$$

Radiative corrections

$m_{\tilde{t}} \leq 1TeV$



$$\delta^{\tilde{t}} M_H^2 \simeq \frac{\lambda_s}{8\pi^2}\left(\Lambda^2 - m_{\tilde{t}}^2 \ln\left(\frac{\Lambda^2}{m_{\tilde{t}}^2}\right)\right)$$

$$\boxed{\delta^{t+\tilde{t}} M_H^2 = \frac{h_t^2}{8\pi^2}\left(m_t^2 \ln\left(\frac{\Lambda^2}{m_t^2}\right) - m_{\tilde{t}}^2 \ln\left(\frac{\Lambda^2}{m_{\tilde{t}}^2}\right)\right)}$$

Solutions to the hierarchy problem

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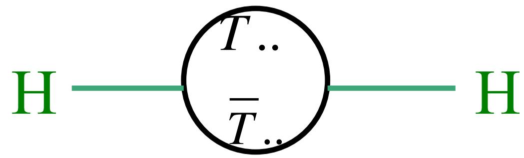

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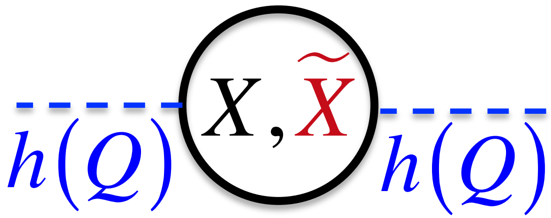
Radiative corrections

$$\boxed{GUTs \Rightarrow SUSY - GUTs}$$



Twin Higgs

- Tree-level Higgs scalar potential (fully SU(4)-symmetric):

8 real dof

$\Phi = \begin{pmatrix} H \\ H' \end{pmatrix}$ transforms as fundamental of global SU(4)

$$V_{tree}(\Phi) = -m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$
$$= -m^2(|H|^2 + |H'|^2) + \underbrace{\lambda(|H|^4 + |H'|^4 + 2|H|^2|H'|^2)}_{\text{SU(4)-invariant quartic}}$$

$$\Rightarrow \quad \langle|\Phi|^2\rangle = \langle|H|^2\rangle + \langle|H'|^2\rangle = \frac{m^2}{2\lambda} \equiv \left(\frac{f}{\sqrt{2}}\right)^2$$

SU(4) $\longrightarrow$ SU(3) $\rightarrow$ 7 Goldstone bosons!

(rather: O(8) $\longrightarrow$ O(7))

3 eaten by SU(2)

3 eaten by SU(2)'

1 left: the Higgs we've seen!

2 real scalars remain:

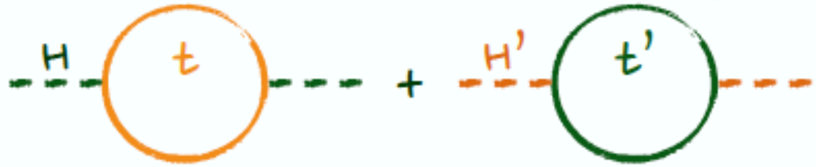
- Goldstone: $\hat{m}^2 = 0$
- 'Normal' Higgs: $\hat{M}^2 = 2\lambda f^2$

Slide courtesy of Isabel Garcia Garcia
c.f.talk by S. Pokorsky here

Twin Higgs

But, crucially:

uncoloured top partner

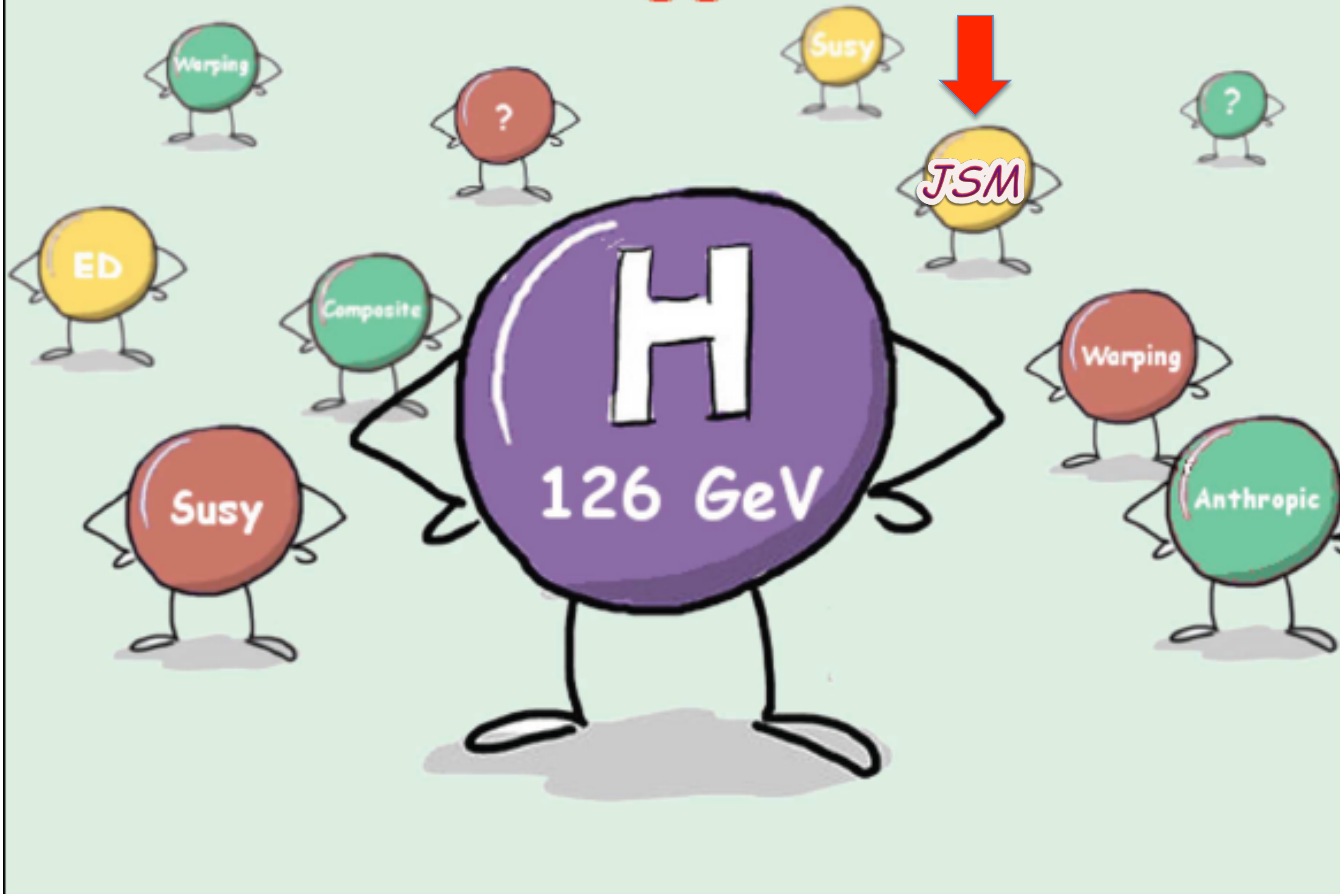


$$\Rightarrow \quad \delta V \sim -\frac{3y_t^2}{16\pi^2}\Lambda^2|H|^2 - \frac{3y_t'^2}{16\pi^2}\Lambda^2|H'|^2 = -\frac{3y_t^2}{16\pi^2}\Lambda^2(\underbrace{|H|^2 + |H'|^2}_{|\Phi|^2})$$

No correction to the (Pseudo-Goldstone) Higgs!

Slide courtesy of Isabel Garcia Garcia

The Higgs Era



IV. "Just" the Standard Model

Implications of a 125 GeV Higgs

RG equations:

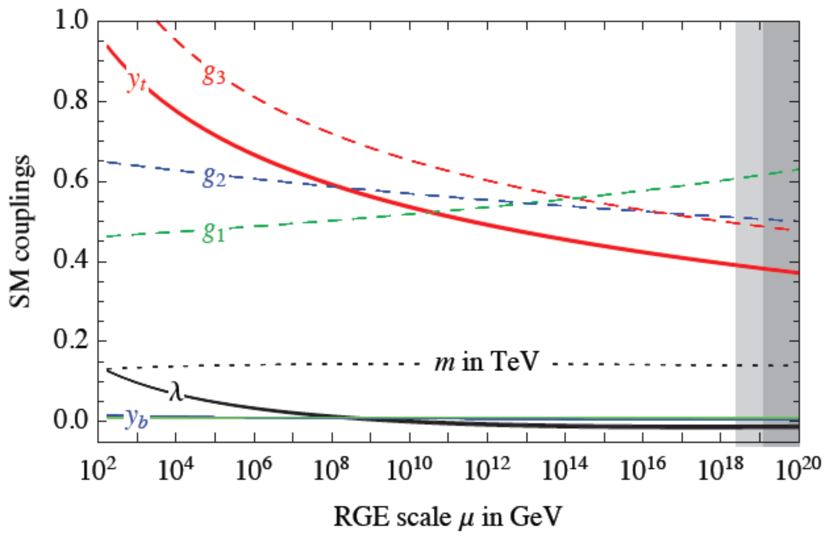
$$\beta_1^{\rm SM} = \frac{41}{96\pi^2} g_1^3\,, \quad \beta_2^{\rm SM} = -\frac{19}{96\pi^2} g_2^3\,, \quad \beta_3^{\rm SM} = -\frac{7}{16\pi^2} g_3^3$$

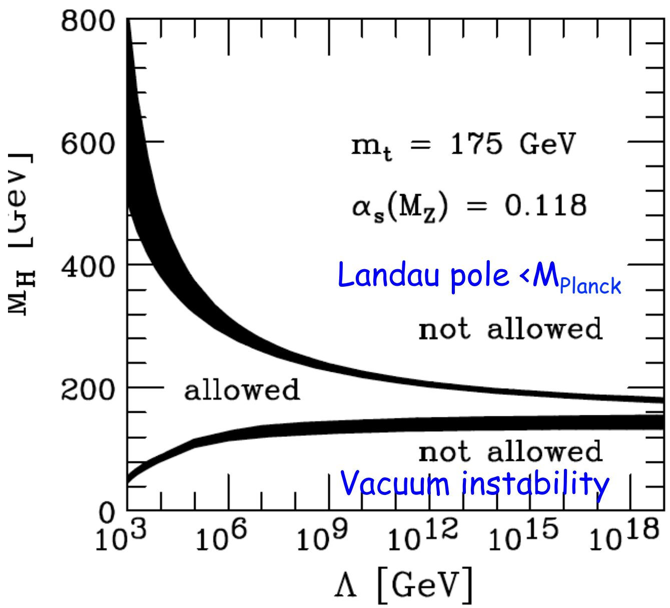
$$\beta_h^{\rm SM} = \frac{1}{16\pi^2}\left[\frac{9}{2}h^3 - 8g_3^2 h - \frac{9}{4}g_2^2 h - \frac{17}{12}g_1^2 h\right]$$

$$\beta_\lambda^{\rm SM} = \frac{1}{16\pi^2}\Big[24\lambda^2 + 12\lambda h^2 - 9\lambda\,(g_2^2 + \frac{1}{3}g_1^2)$$

$$-6h^4 + \frac{9}{8}g_2^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g_2^2 g_1^2\Big]\ .$$

Implications of a 125 GeV Higgs





RGE - just the Standard Model

Higgs coupling small

Hambye, Riesselmann

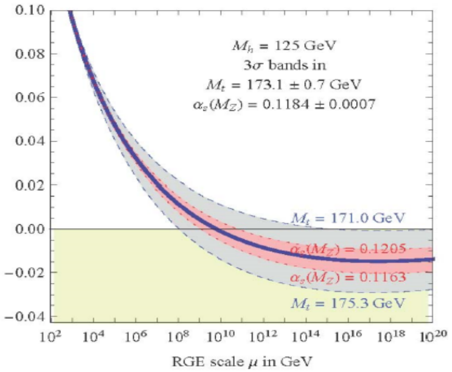
$$V_0 = -\frac{m_0^2}{2}|H_0|^2 + \lambda_0|H_0|^4$$

LHC 8

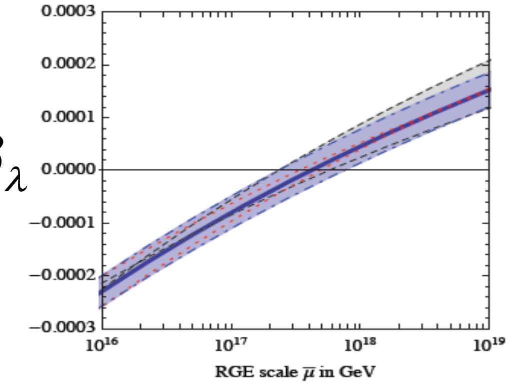
No evidence (yet) for BSM
Higgs discovery

} "Just" the SM (JSM)?

λ



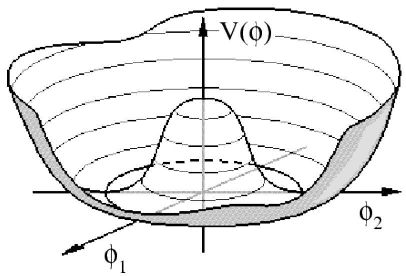
β_λ



DeGrassi et al,...

$$V(H) = -m^2 |\phi|^2 + \lambda |\phi|^4$$

$$m^2 \simeq \left(89GeV^2\right), \lambda \simeq 0.13$$



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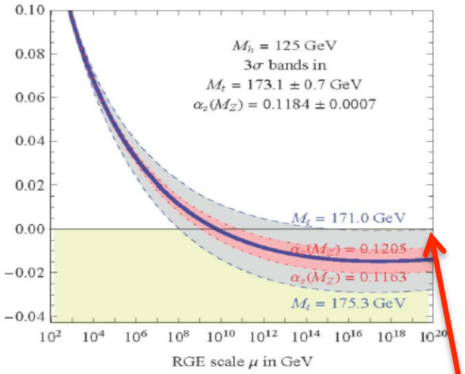
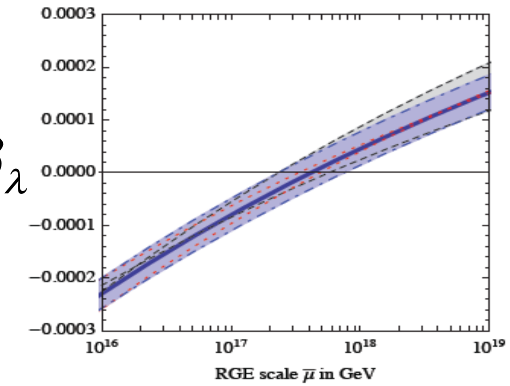


β_λ



DeGrassi et al,...

IR structure???

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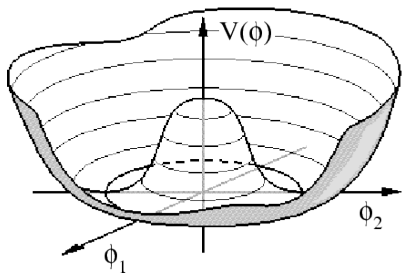

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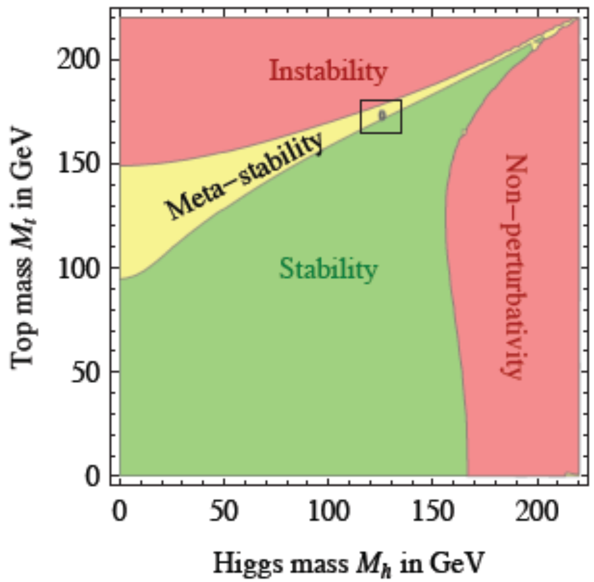

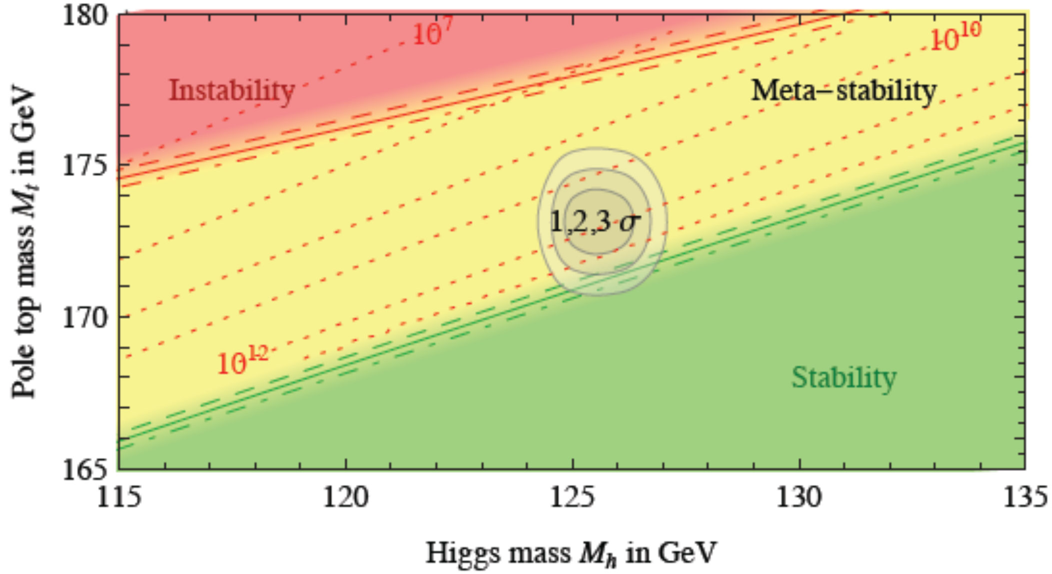

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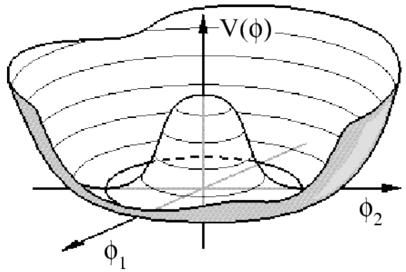

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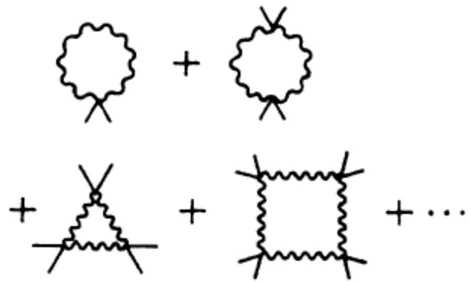
Coleman-Weinberg - dynamical symmetry breaking :

e.g. scalar electrodynamics

scale invariance broken by Trace anomaly

$$V = \left\{ \frac{\lambda}{4!}\phi^4 + \frac{3e^4}{64\pi^2}\phi^4 \ln\frac{\phi^2}{M^2} \right\}$$

$$= \frac{3e^4}{64\pi^2}\phi^4 \left(\ln\frac{\phi^2}{\langle\phi\rangle^2} - \frac{1}{2} \right)$$



$$m_\phi^2 = \frac{3e_\phi^2}{8\pi^2} m_X^2 \ll m_X^2$$

"real" hierarchy problem

..... many models with new Higgs interactions + no heavy states

No heavy states?

- Neutrino masses?
- Baryogenesis?
- Strong CP problem?
- Gravity?

No heavy thresholds?

- Neutrino masses?
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Neutrino masses:

Add singlet neutrinos ν_{Ra}

$$L_{mass} = h_a \bar{l}_a \nu_{Ra} H + \frac{M_{ab}}{2} \nu_{Ra}^T C \nu_{Rb}$$

$e.g. \quad h_a^2 = 5.10^{-14}, h_b^2 = 5.10^{-15}, M_a = 20 GeV$

$m_a \simeq 0.1 eV, \quad m_b \simeq 0.01 eV$

Ultra-weak:

Natural due to chiral symmetry

Baryogenesis

$$L_{mass} = h_a \bar{l}_a \nu_{Ra} H + \frac{M_{ab}}{2} \nu_{Ra}^T C \nu_{Rb}$$

- ν_{Ra} produced via Yukawa interactions $L_A = L_B = L_C = 0$

Baryogenesis

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- ν_{Ra} produced via Yukawa interactions $\quad L_A = L_B = L_C = 0$
- ν_{Ra} oscillate $\quad \cancel{CP}, \quad L_{A,B,C} \neq 0, \quad L_A + L_B + L_C = 0$

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Only

- ^ $\nu_{R\,a,b}$ in thermal equilibrium by t_{EW} when sphalerons inoperative

$$\Delta_{L\,AB} = L_A + L_B \xrightarrow[Sphalerons]{} \Delta B = \Delta_{L\,AB}/2 \quad ✔$$

Akhmedov, Rubakov, Smirnov

Strongly constrained if demand $\nu_{R\,c}$ is dark matter

Shaposhnikov et al

Strong CP problem:

$$\frac{\theta}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}, \quad \theta \leq 10^{-10}\ ??$$

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Make θ a dynamical variable the axion, a....θ=0 at minimum of its potential

Vafa, Witten

... complex scalar field, S

$$S = (|S| + f_a) e^{i\frac{a}{f_a}}, \qquad 10^{10}\, GeV \leq f_a \leq 10^{12}\, GeV$$

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DFSZ axion: 2 Higgs doublets $H_{1,2}$, complex singlet, S

$$\begin{aligned} V(H_1, H_2) &= \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 \\ &+ \lambda_4 |H_1^\dagger H_2|^2 + \zeta_1 |S|^2 |H_1|^2 + \zeta_2 |S|^2 |H_2|^2 \\ &+ \zeta_3 S^2 H_1 H_2 + h.c. + \zeta_4 |S|^4 \end{aligned}$$

PQ symmetry: $H_1 \to H_1 e^{i\alpha}, \quad H_2 \to H_2 e^{i\beta}, \quad S \to S e^{-i(\alpha+\beta)/2}$

Axion, a : Pseudo Goldstone boson of spontaneously broken PQ

Strong CP problem:

$$\frac{\theta}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}, \quad \theta \le 10^{-10} ??$$

$$S = (|S| + f_a) e^{i\frac{a}{f_a}}, \qquad 10^{10}\, GeV \le f_a \le 10^{12}\, GeV$$

DFSZ axion: 2 Higgs doublets $H_{1,2}$, complex singlet, S

$$\begin{aligned} V(H_1, H_2) &= \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 \\ &+ \lambda_4|H_1^\dagger H_2|^2 + \zeta_1|S|^2|H_1|^2 + \zeta_2|S|^2|H_2|^2 \\ &+ \zeta_3 S^2 H_1 H_2 + h.c. + \zeta_4\,|S|^4 \end{aligned}$$

PQ symmetry: $H_1 \to H_1 e^{i\alpha}, \quad H_2 \to H_2 e^{i\beta}, \quad S \to S e^{-i(\alpha+\beta)/2}$

Axion, a : Pseudo Goldstone boson of spontaneously broken PQ

Ultra weak sector: $$\zeta_{1,2,3} \le 10^{-20} \left(\frac{10^{12}\, GeV}{f_a} \right)^2$$

shift symmetry

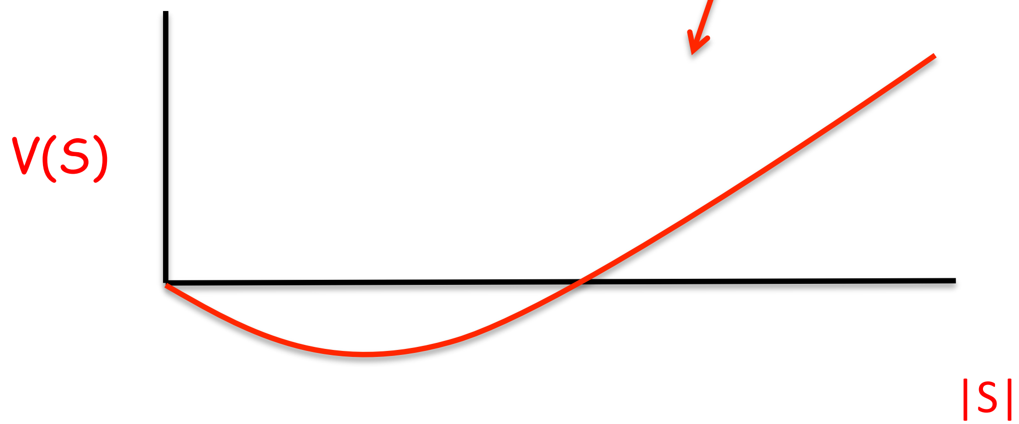
$S \to S + \delta$

Coleman Weinberg in DFSZ model

$\zeta_2 |S|^2 |H|^2$

$$V_{DFSZ}(H_1,H_2,S) \simeq \frac{\lambda_1}{2}\left(|H_1|^2 + \frac{\zeta_1}{\lambda_1}|S|^2\right)^2 + \frac{1}{64\pi^2}\left(\zeta_2 |S|^2\right)^2\left(-\frac{1}{2} + \ln\frac{|S|^2}{f_a^2}\right)$$

$$+\frac{\lambda_2}{2}|H_2|^4 + \zeta_3 S^2 H_1 H_2 + h.c.$$



$\langle H_1^2 \rangle = -\frac{\zeta_1}{\lambda_1}\langle S^2 \rangle$ triggers EW breaking

Coleman Weinberg in DFSZ model

$$V_{DFSZ}(H_1,H_2,S) \simeq \frac{\lambda_1}{2}\left(|H_1|^2 + \frac{\zeta_1}{\lambda_1}|S|^2\right)^2 + \frac{1}{64\pi^2}\left(\zeta_2|S|^2\right)^2\left(-\frac{1}{2}+\ln\frac{|S|^2}{f_a^2}\right)$$

$$+\frac{\lambda_2}{2}|H_2|^4 + \zeta_3 S^2 H_1 H_2 + h.c. \quad (\zeta_2 > \zeta_1 > \zeta_3 \text{ assumed})$$

$$\mathrm{v}_S = f_a, \quad \mathrm{v}_{H_1} = \frac{\zeta_1}{\lambda_1} f_a, \quad \mathrm{v}_{H_2} = \frac{\zeta_3}{2\zeta_2}\mathrm{v}_{H_1}$$

$$\boxed{m_{H_2^0}^2 = m_{H^\pm}^2 = m_X^2 = -\frac{\zeta_2}{2\zeta_1} m_h^2}$$

$$m_{|S|}^2 = -\left(\frac{\zeta_2^2}{32\pi^2\zeta_1}\right)^2 m_h^2 \simeq 13\left(\frac{10^{12}\,GeV}{\mathrm{v}_S}\right)^2\left(\frac{m_{H_2}}{m_h}\right)^4 eV^2$$

$|S|$ Pseudo-dilaton

K. Allison, C.Hill, GGR

Summary - IV

- "JSM" requires ultra-weak sectors – chiral and shift symmetries

- DFSZ axion + dimensional trasmutation $\Rightarrow f_a$

  …consistent with classical scale invariance (not KSVZ model)

- Requires two Higgs doublets (type II couplings), light pseudo-dilaton

  $$m^2_{H_2^0} = m^2_{H^\pm} = m^2_X = R^2 m^2_h$$

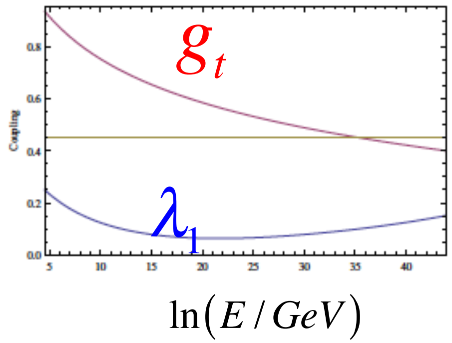
  h ≈ SM Higgs

  $$m_{|S|} \simeq 0.9 \left(\frac{10^{12}\, GeV}{f_a} \right) R^2 eV$$

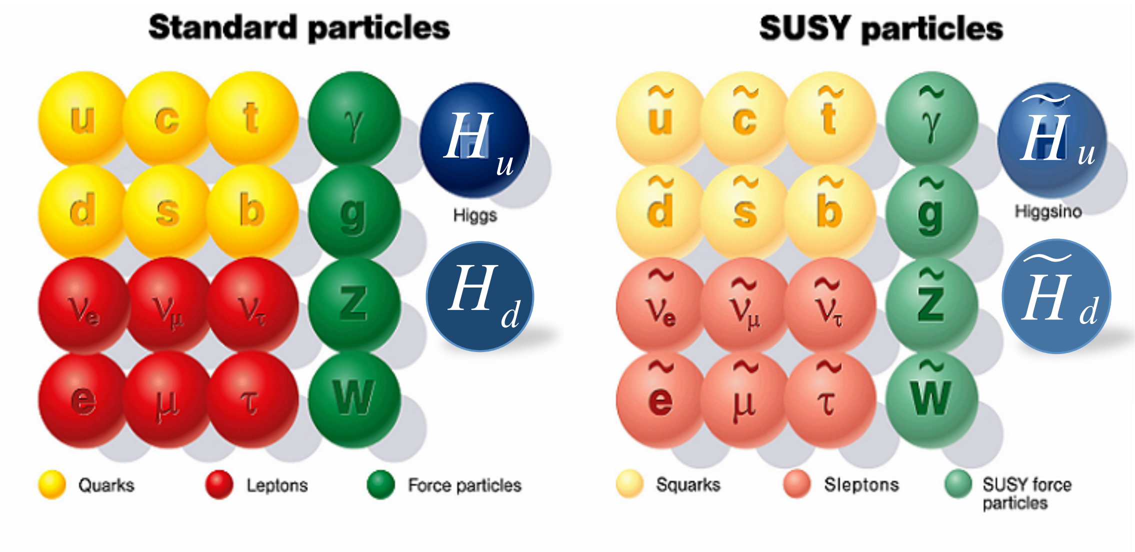
  Direct (axion-like) searches?

- Stable vacuum but loses simplicity of SM

  … and no unification

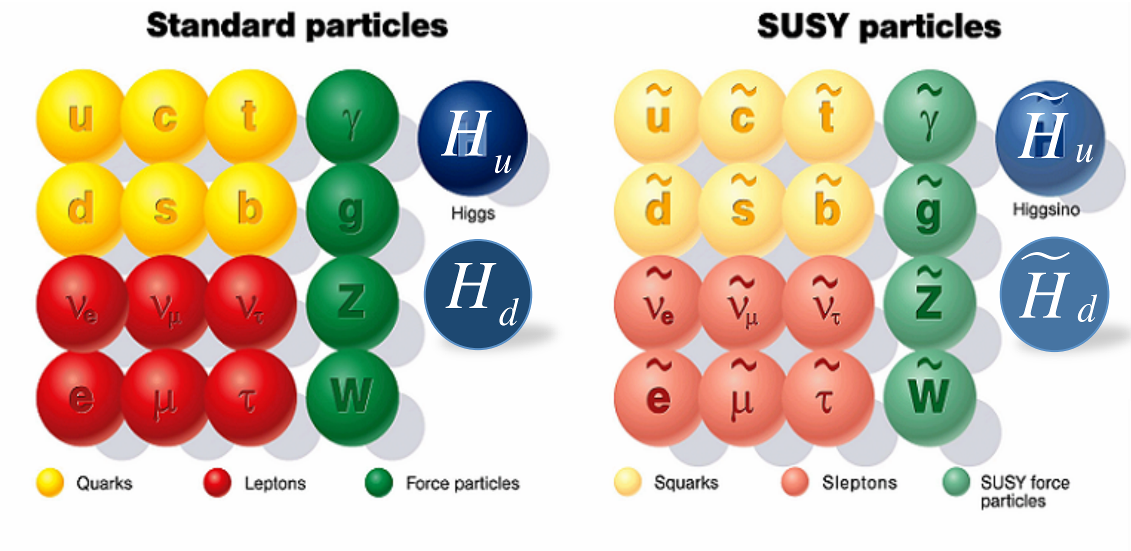


V. SUSY



Standard particles
u
c
t
γ
d
s
b
g
Z
W
e
μ
τ
Higgs
Quarks
Leptons
Force particles
SUSY particles
Higgsino
Squarks
Sleptons
SUSY force particles

V(i). SUSY GUTs



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

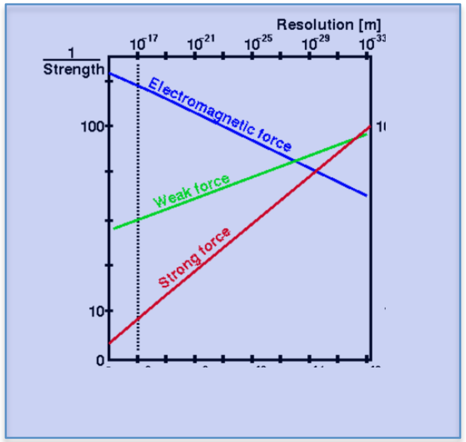
Supermultiplets

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

SUSY gauge coupling unification

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

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

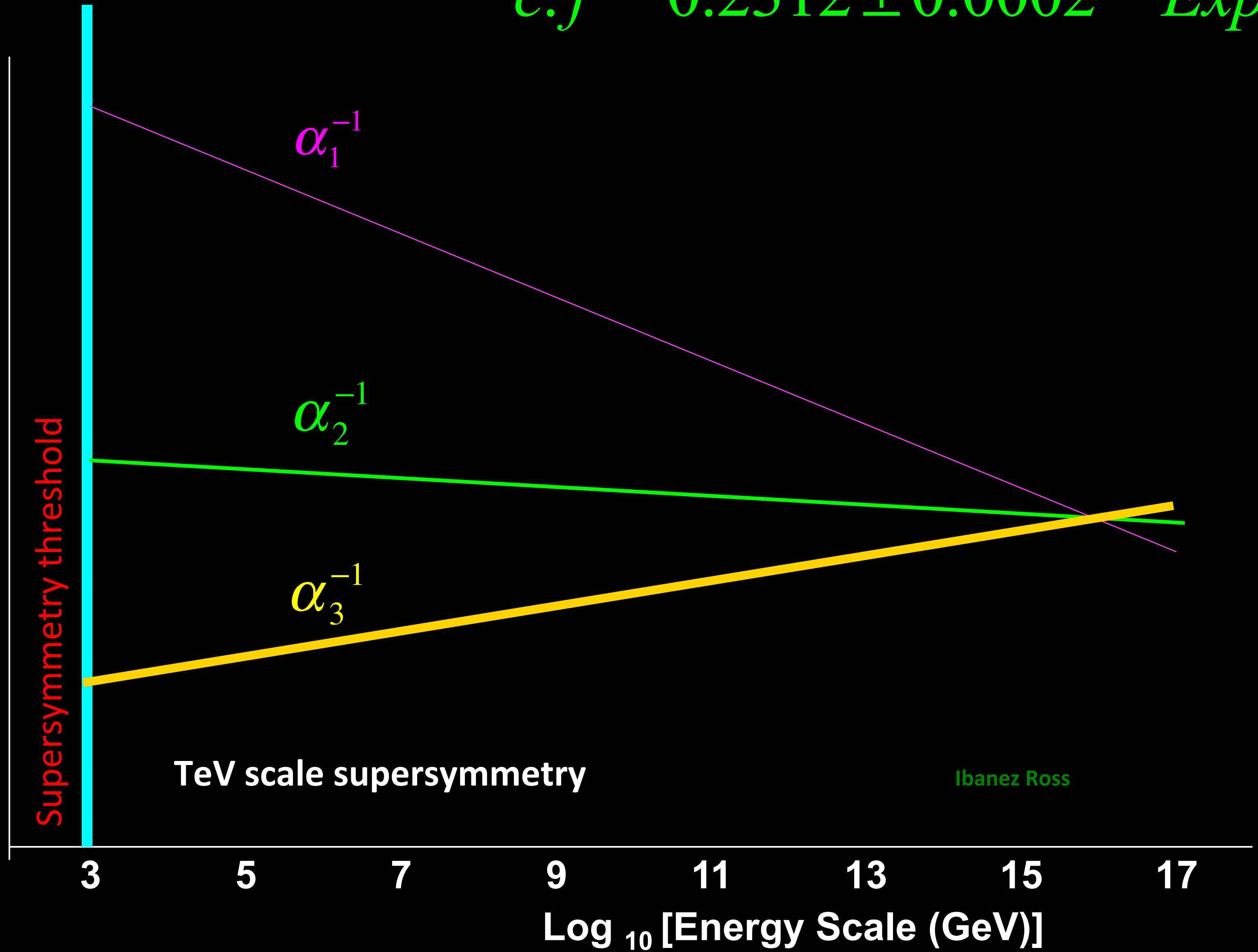


$$b_i^{MSSM} = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + H \begin{pmatrix} \frac{3}{10} \\ \frac{1}{2} \\ 0 \end{pmatrix}$$

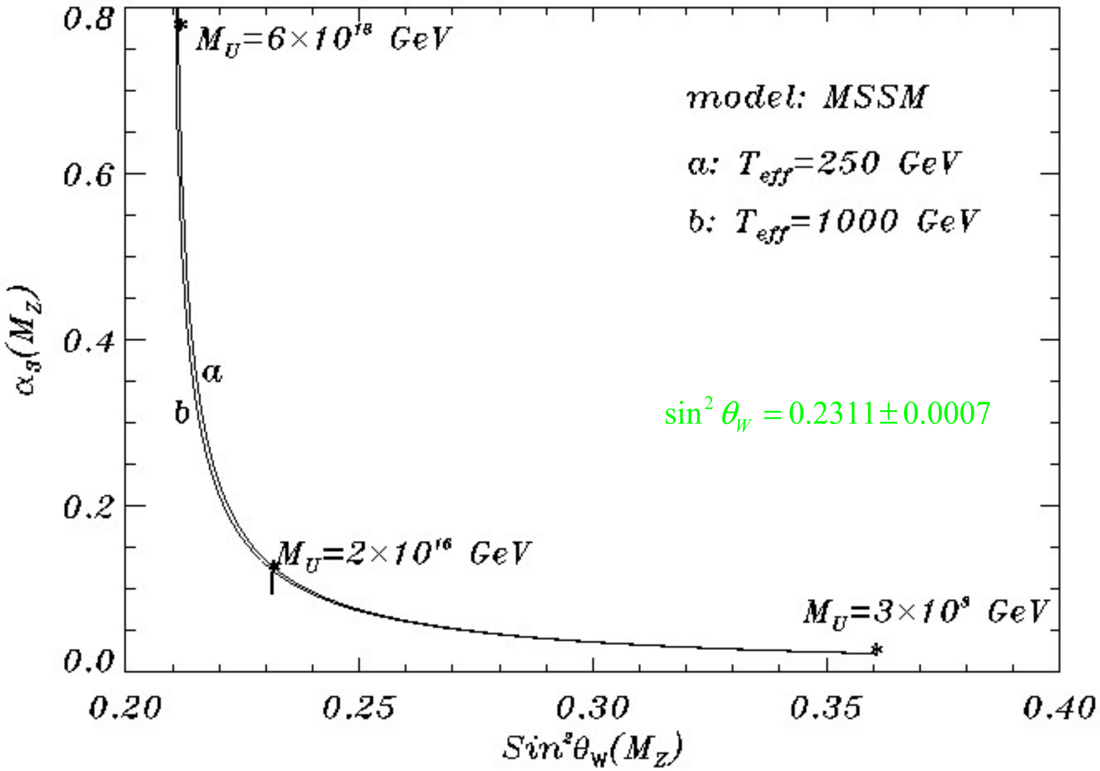
?

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

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



SUSY gauge coupling unification

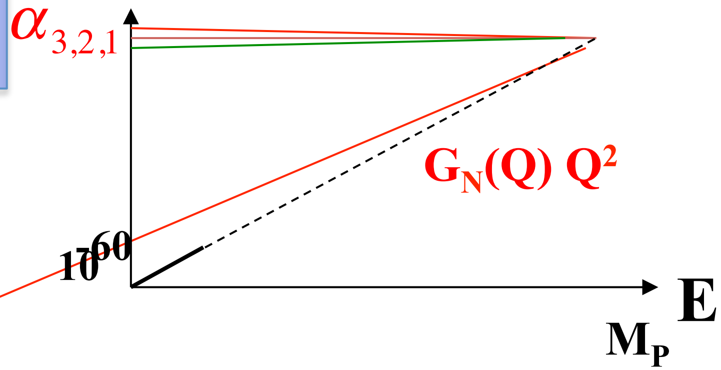


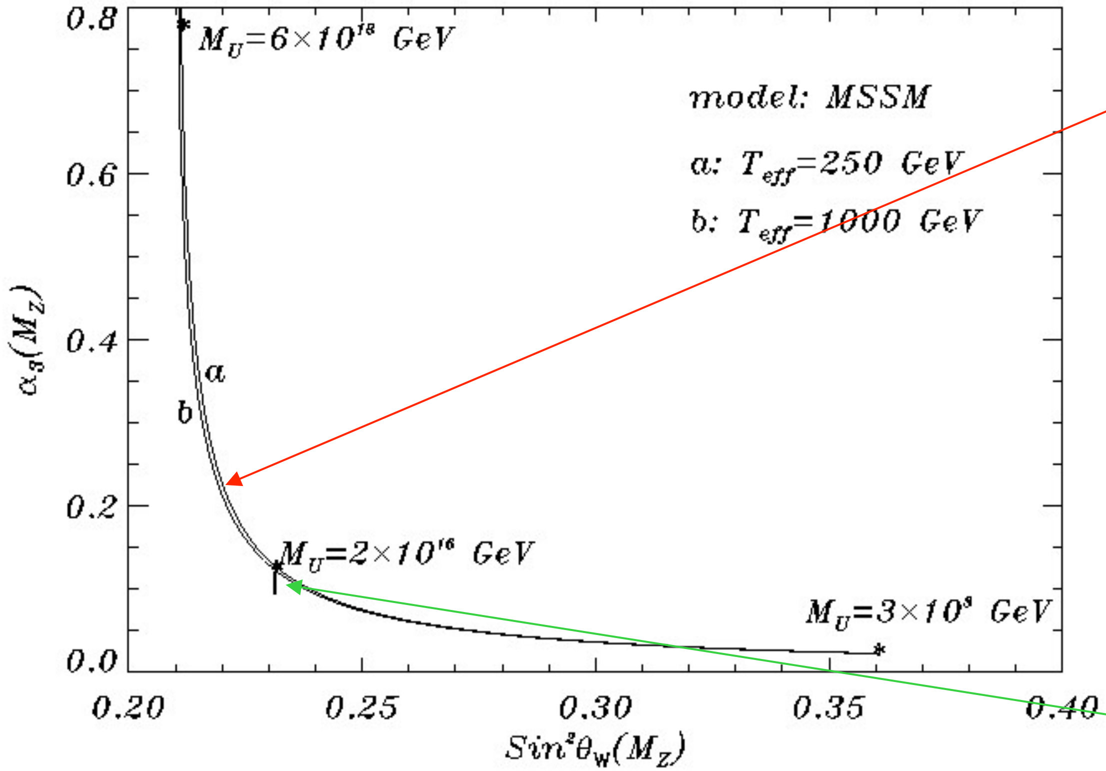
$$\sin^2\theta_W = 0.2334 \pm 0.0025 - 0.25(\alpha_s - 0.119) \quad = 0.2311 \pm 0.0007 \quad (Expt)$$

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

SUSY gauge coupling unification

Unification with gravity?





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

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

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

Gauge unification - Heterotic String

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

$k_i \rightarrow 1$

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

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

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

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

Spontaneous symmetry breaking

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

Spontaneous symmetry breaking

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

$$P=\frac{\beta_2}{2}M\,Tr\left(\Sigma^2\right)+\frac{\beta_3}{3}Tr\left(\Sigma^3\right)$$ superpotential

$$V(\Sigma)=\sum_a\left|\frac{\partial P}{\partial\Sigma^a}\right|^2=Tr\left|\beta_3\Sigma^2+\beta_2 M\Sigma-I\frac{\beta_3}{5}Tr\left(\Sigma^2\right)\right|^2$$

$$\left(\frac{\partial P}{\partial\Sigma^a}\rightarrow\frac{\partial P}{\partial\Sigma^i_j}-\frac{1}{N}\delta^i_j Tr\left(\frac{\partial P}{\partial\Sigma}\right),\quad i,j=1..5,\quad a=1..24\right)$$

$$\left.\begin{aligned}&\langle\Sigma\rangle=0\\&\langle\Sigma\rangle=\mathrm{v}_4\mathrm{Diagonal}(1,1,1,1,-4)\\&\langle\Sigma\rangle=\mathrm{v}_3\mathrm{Diagonal}(2,2,2,-3,-3)\end{aligned}\right\}$$ Degenerate

SUGRA

Radiative corrections

Spontaneous symmetry breaking

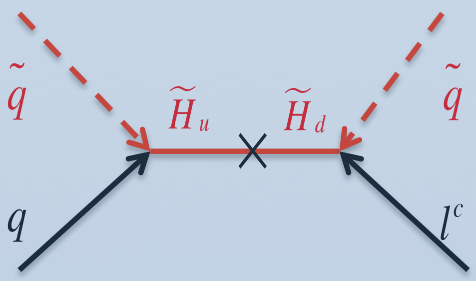
$$SU(5)\xrightarrow[\Sigma_{24}]{M_X}SU(3)\times SU(2)\times U(1)\xrightarrow[H_5]{M_W}SU(3)\times U(1)$$

$$P_{Higgs}=\mu H_u H_d+\lambda H_u \Sigma H_d$$

$$V=\left(\left|\mu H_u+\lambda H_u\Sigma\right|^2+\left|\mu H_d+\lambda \Sigma H_d\right|^2\right)+\left|H_u H_d-\frac{1}{5}(H_u H_d)\right|^2$$

Must forbid these terms by symmetry

+ doublet- triplet splitting



D=5 proton decay amplitude

$$A_{p\ decay}\propto\frac{1}{M_{\tilde{H}}}\ c.f.\frac{1}{M_{X,Y}^2}$$

Doublet -triplet splitting

Missing doublet mechanism

No (1,2) component

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

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

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

$$P_{MD}\supset bM\,\Theta_3H_{uT}+b'M\,\overline{\Theta}_3H_{dT}+\widetilde{M}\,\overline{\Theta}_3\Theta_3$$

Triplets get mass $\dfrac{M^2}{\widetilde{M}}$ (Still need to drive SSB)

Doublet -triplet splitting

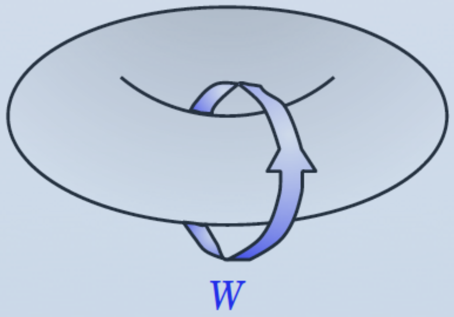
Higher dimensions (String unification)

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



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

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

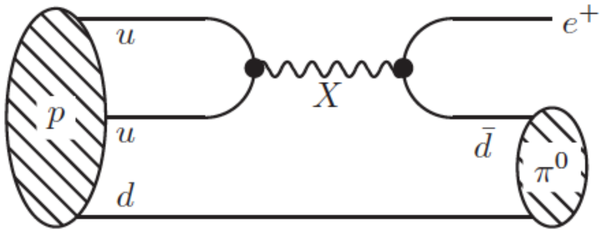
Breit, Ovrut, Segre

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

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

SUSY GUTS - Nucleon decay

SUSY GUTS - Nucleon decay

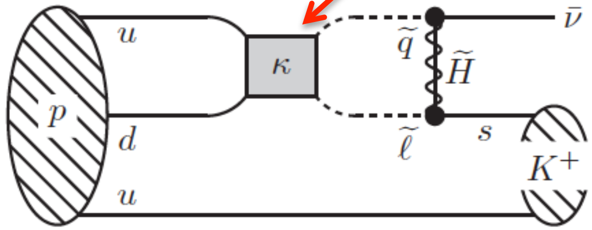


(a) Dimension 6.

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

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

$\frac{1}{\Lambda} QQQL|_F$

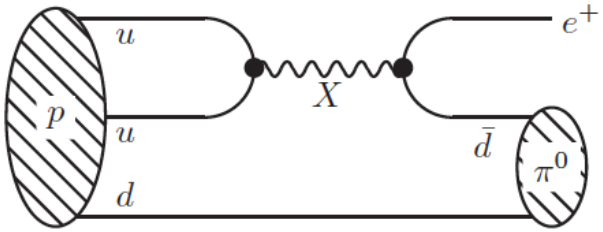


(b) Dimension 5.

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

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

SUSY GUTS - Nucleon decay



(a) Dimension 6.

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

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

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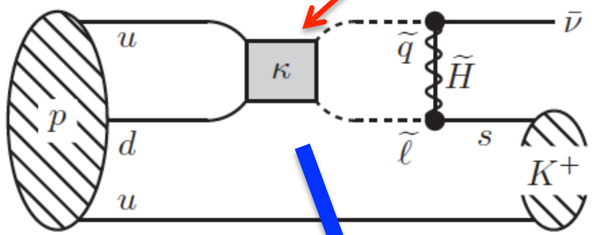


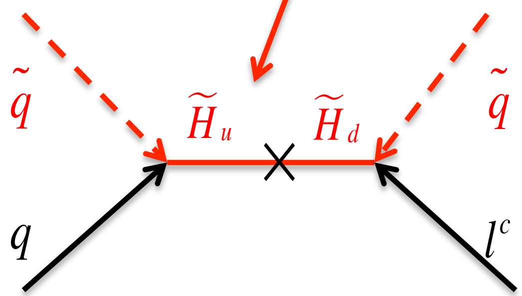
(b) Dimension 5.

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

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

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

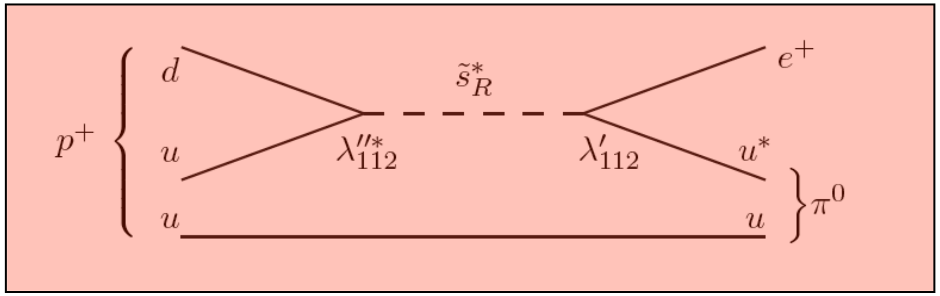
$$\frac{1}{M_{\widetilde{H}}} QQQL\big|_F$$



D=5 proton decay amplitude

SUSY extensions of the Standard Model

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



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

SUSY extensions of the Standard Model

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

$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + \ldots (\cancel{L}) \right)$$

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

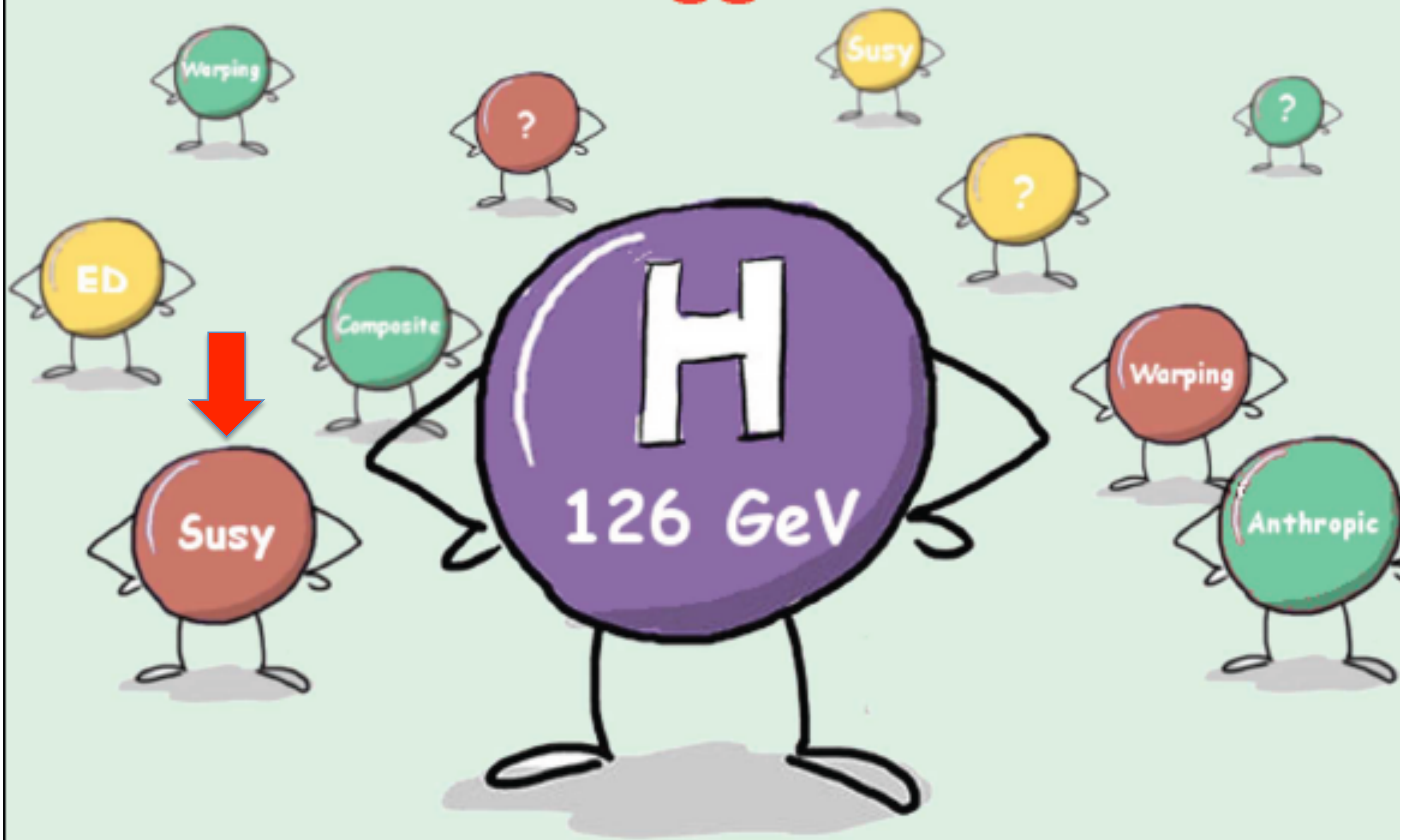
$$\tau^{SuperK}_{p\to e^+\pi^0} > 1\times 10^{34}\,\text{yrs}$$

Giudice, Romanino

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

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

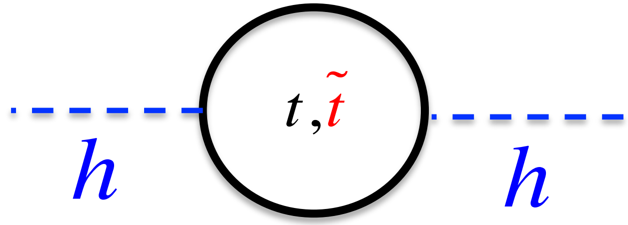
The Higgs Era

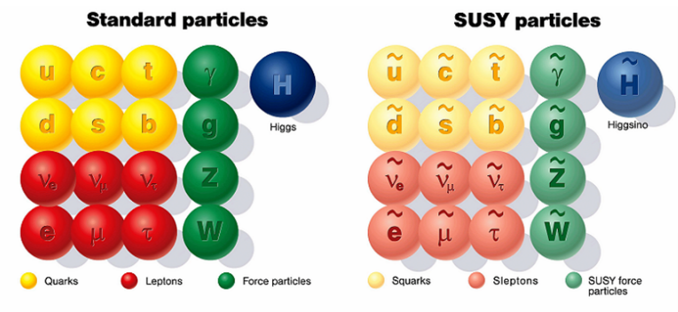


SUSY

V(ii):The Little hierarchy problem in SUSY

Low scale SUSY





$$m_h^2 = M_Z^2 + \frac{3 m_t^2 h_t^2}{4\pi^2}\left(\ln\left(m_{stop}^2 / m_t^2\right) + \delta_t\right) + \ldots \simeq 126\, GeV$$

Gauge coupling unification

$\Lambda \sim M_{GUT}$

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

$$\boxed{m_{\tilde{t},\tilde{g}} < 1 TeV\,??}$$

Little hierarchy problem

e.g. MSSM: 105 +(19) Parameters

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

$$m_{\tilde{q}} > 0.6 - 1 TeV \quad \Rightarrow \quad \Delta > a \frac{\widetilde{m}^2}{M_Z^2} \sim 100$$

(Unless light stop $m_{\tilde{t},LHC} > 250\ GeV$)

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

Little hierarchy problem

e.g. MSSM: 105 +(19) Parameters

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

Fine Tuning measure:

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

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

$\gamma_i = \widetilde{m}_i, \widetilde{M}_i, \ldots$

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Fine tuning from a likelihood fit:

"Nuisance" variable

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

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

Fine tuning not optional!

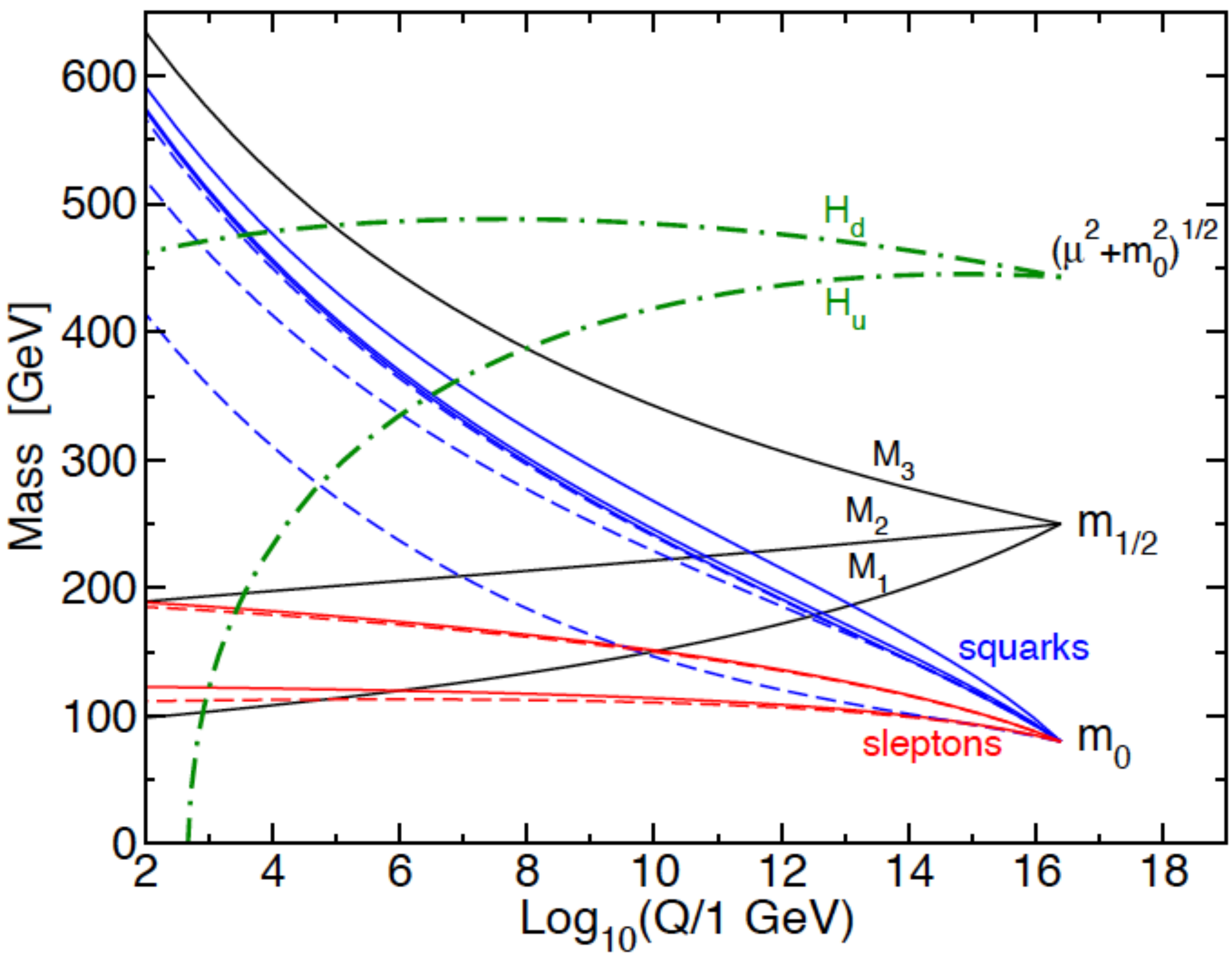
Ghilencea, GGR
Casas et al

Probabilistic interpretation:

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

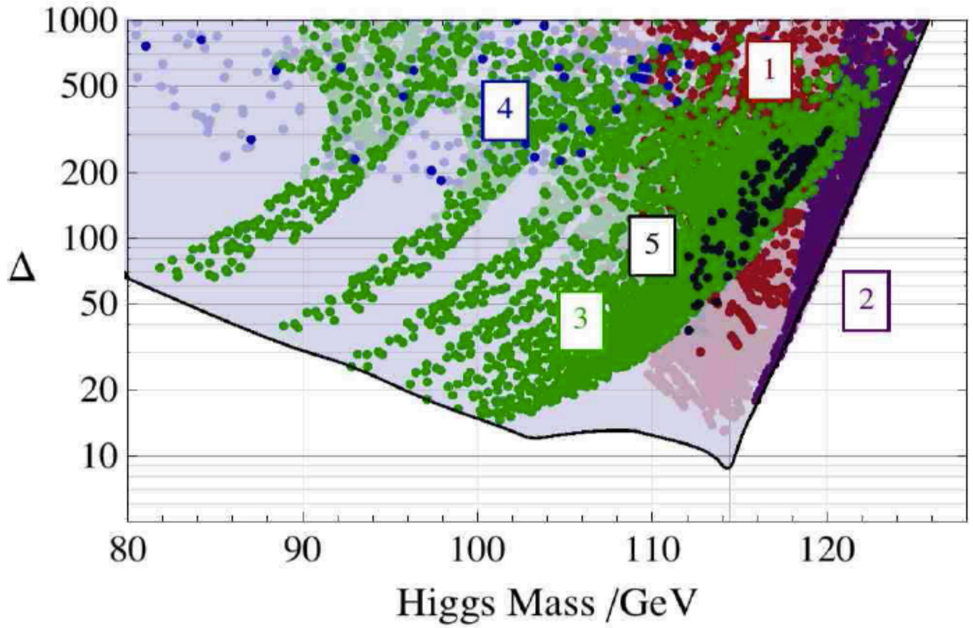
$$\Delta_q \ll 100$$

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



CMSSM: pre Higgs

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



Gauge unification required

Relic density restricted

1 h^0 resonant annihilation

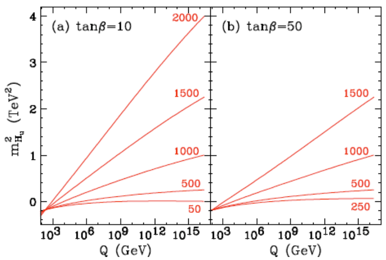
2 $\tilde{h}$ t-channel exchange

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

4 $\tilde{t}$ co-annihilation

• 5 A^0 / H^0 resonant annihilation

Focus point



$$m_0^2 \qquad \frac{3}{2}m_0^2$$

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

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

CMSSM: post Higgs

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

Gauge unification required

Relic density restricted

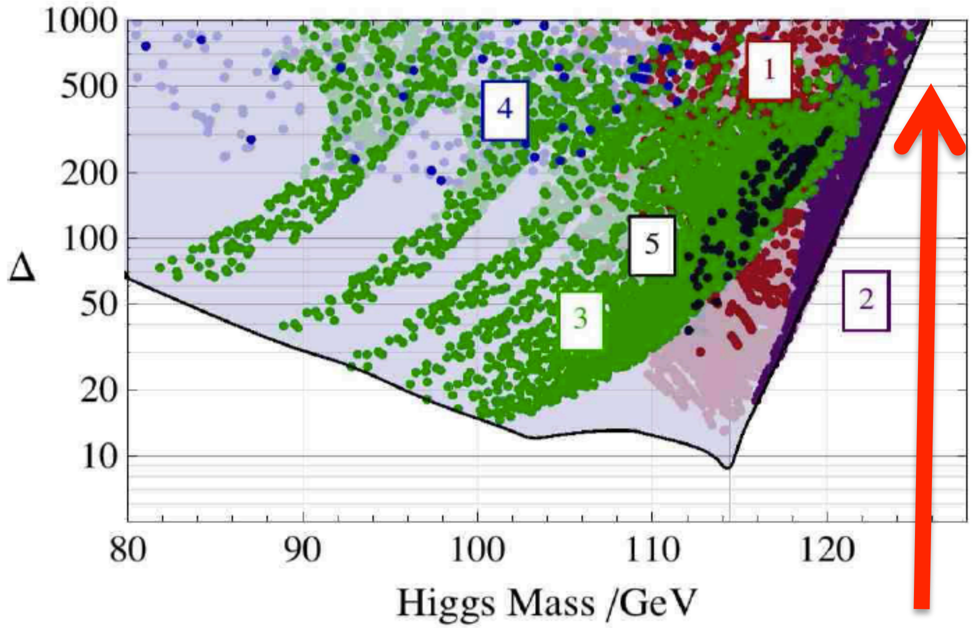
1 h^0 resonant annihilation

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

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

4 $\tilde{t}$ co-annihilation

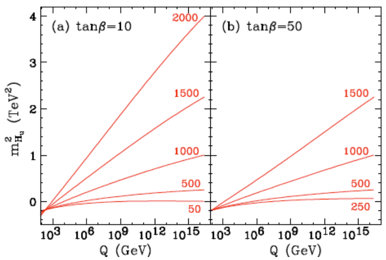
• 5 A^0 / H^0 resonant annihilation



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

Focus point

$$m_{H_u} = m_{\tilde{Q}_3} = m_{\tilde{u}_3}$$



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

Beyond the CMSSM

- New states and interactions

  (additional contributions to Higgs mass)

Further

- Correlations between SUSY breaking parameters

New (heavy) states- Singlet extensions

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

$$\delta V = \lambda^2 |H_u H_d|^2$$

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

$$\delta V = \frac{\mu}{\mu_S}\left(|H_u|^2 + |H_d|^2\right) H_u H_d$$

$\mu, \mu_s = O(m_{3/2}),\quad Z_{4,8R}$

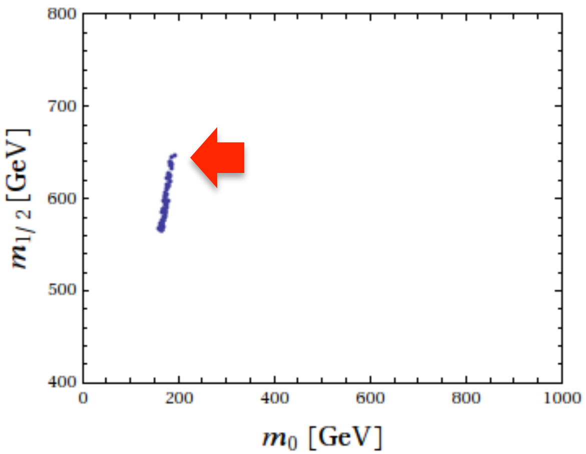
Fine tuning in the CGNMSSM $(\lambda \leq 0.7)$

$$\Delta_{Min} = 60\ (500), \quad m_h = 125.6 \pm 3GeV$$

LHC8 SUSY bounds ✗

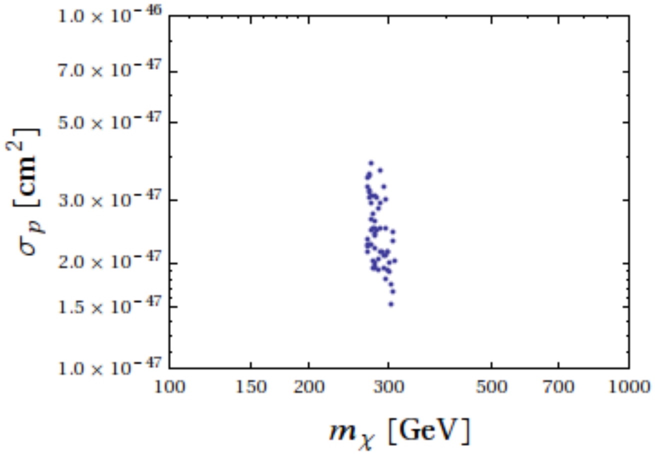
DM relic abundance ✔

DM searches ✔



LSP~Bino

Stau co-annihilation



DM searches insensitive

GGR, Schmidt-Hoberg , Staub

Correlation between SUSY breaking parameters

…non-universal gaugino masses

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

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

Horton, GGR

(Also improves precision of gauge coupling unification)

Shifman, Roszkowski
Krippendorf, Nilles, Ratz, Winkler

Natural ratios? e.g.:

GUT: $SU(5): \quad \Phi^N \subset (24 \times 24)_{symm} = 1 + 24 + 75 + 200; \quad SO(10): \quad (45 \times 45)_{symm} = 1 + 54 + 210 + 770$

$\eta_3 : 1 : \eta_1$ $\qquad$ $2.7\eta_3 : 1 : 0.5\eta_1$

Representation	$M_3 : M_2 : M_1$ at M_{GUT}	$M_3 : M_2 : M_1$ at M_{EWSB}
1	1:1:1	6:2:1
24	2:(-3):(-1)	12:(-6):(-1)
75	1:3:(-5)	6:6:(-5)
200	1:2:10	6:4:10

Fine tuning in the (C)MSSM

Non-universal gaugino masses ✔

$$\Delta_{Min} = 60\,(500)\,, \quad m_h = 125.6 \pm 3 GeV$$

LHC8 SUSY bounds ✔

DM relic abundance

DM searches ✔

Fine tuning in the (C)GNMSSM

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

LHC8 SUSY bounds ✔

DM relic abundance ✔

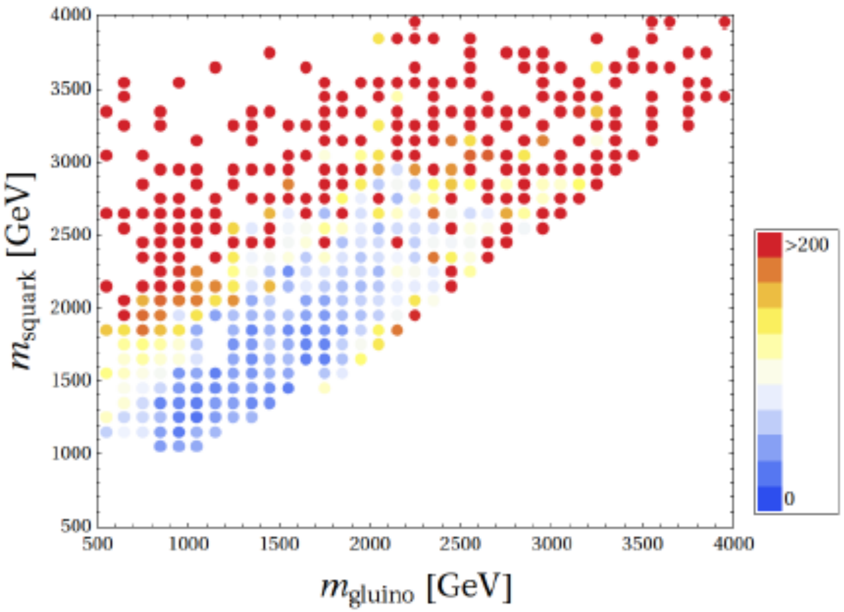
DM searches ✔

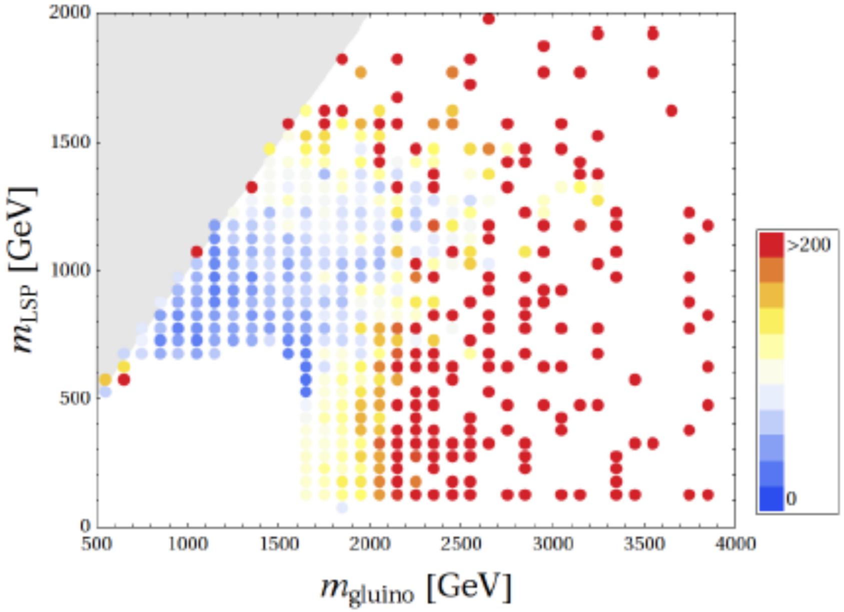
GGR, Kaminska, Schmidt-Hoberg

Masses v/s fine tuning

m_{squark}

m_{LSP}





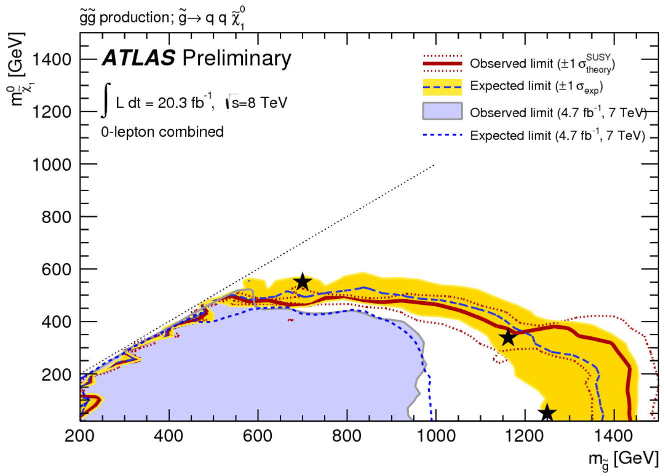
> 200

0

Δ

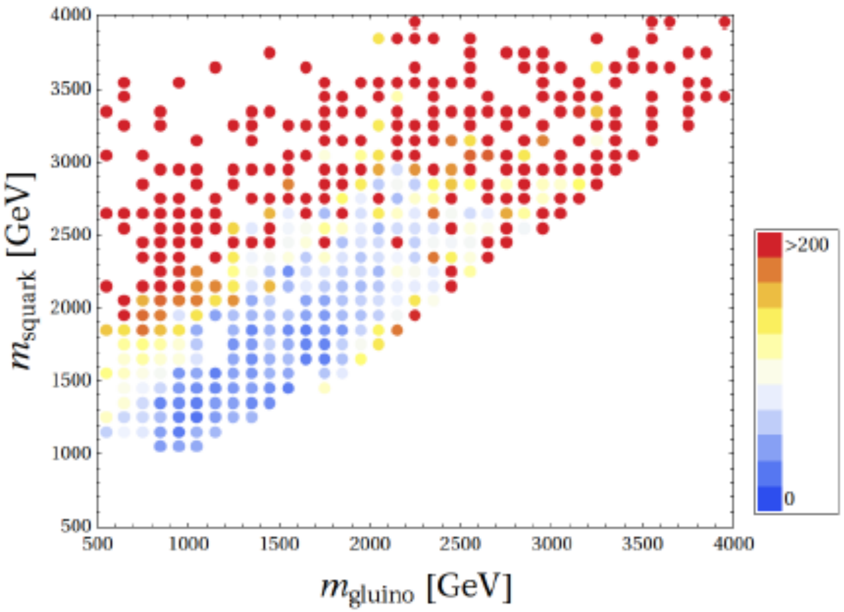
M_{gluino}

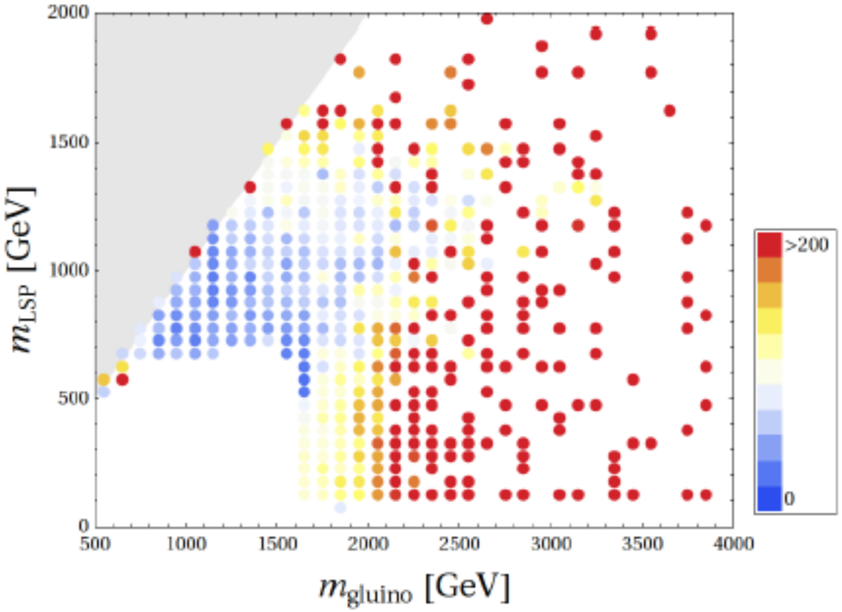
Masses v/s fine tuning



m_{squark}

m_{LSP}





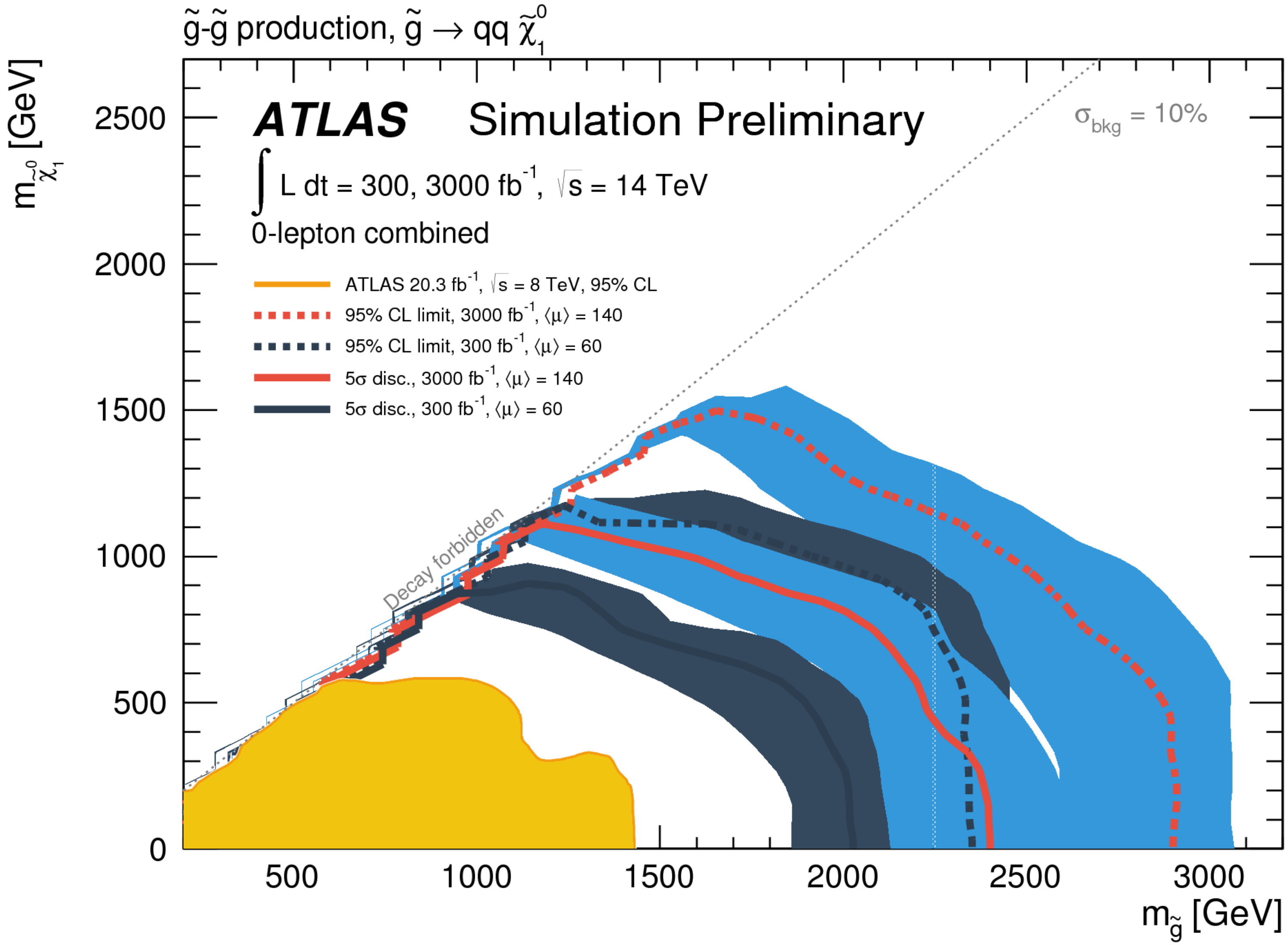
> 200

0

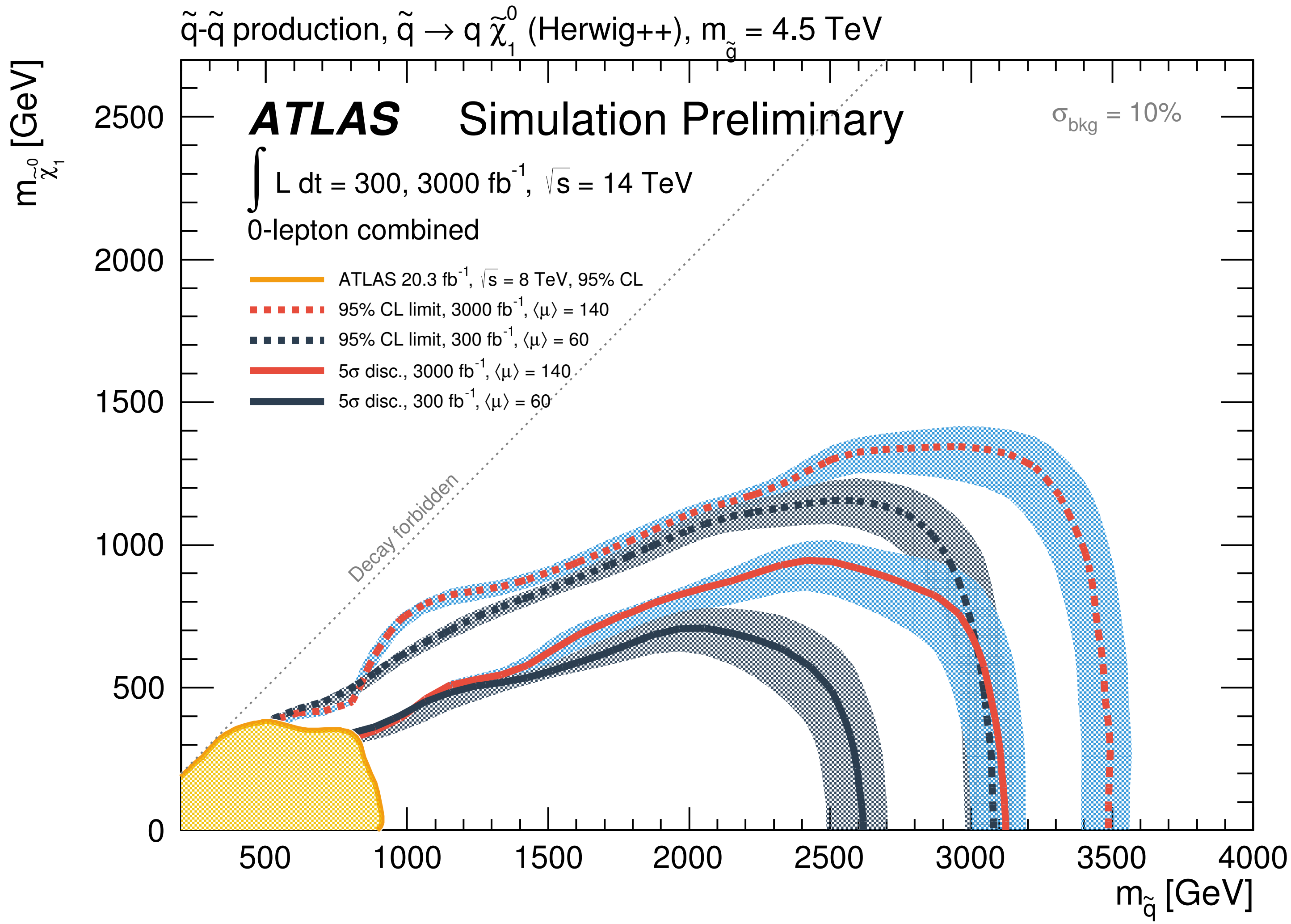
Δ

M_{gluino}

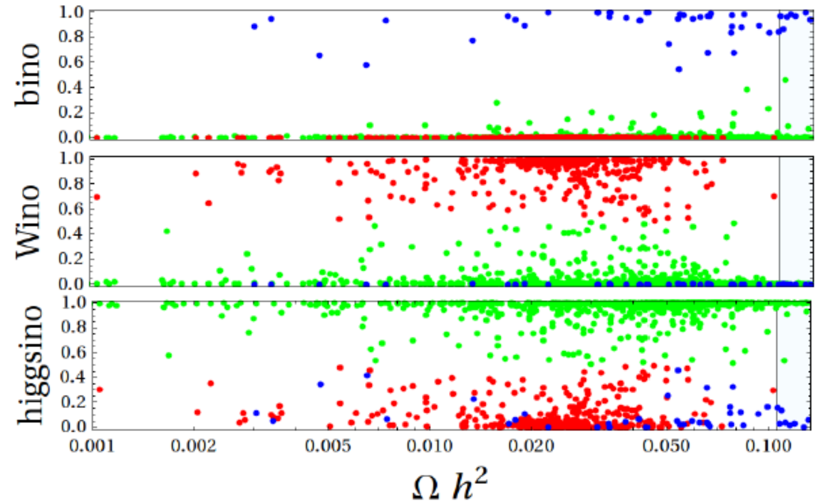
Heavy LSP reach



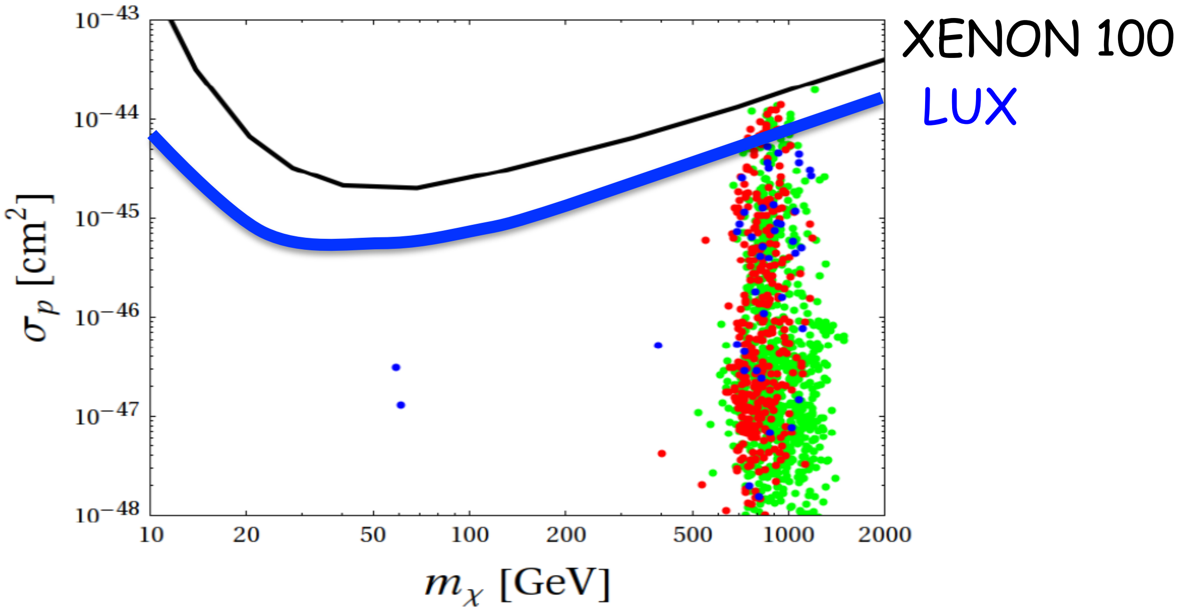
Heavy LSP reach



Dark matter



LSP composition



Direct DM searches

Summary - V

- GUTs $\Longrightarrow$ SUSY-GUTS (hierarchy problem)

  Gauge coupling unification ✔

- Fine tuning sensitive to SUSY spectrum

  ...scalar and gaugino focus points

  $\Delta^{CMSSM} > 350$ ✗ $\qquad \Delta^{(C)MSSM} > 60$ ✔

  $\Delta^{CGMSSM} > 60$ ✗ $\qquad \Delta^{(C)GNMMS} > 20$ ✔

  $c.f. \quad \Delta^{CMSSM}_{Low\ scale} = (10-30), \quad m_{\tilde{t}} = (1-5)TeV$

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  $c.f. \quad \Delta^{CMSSM}_{Low\ scale} = (10-30), \quad m_{\tilde{t}} = (1-5)TeV$

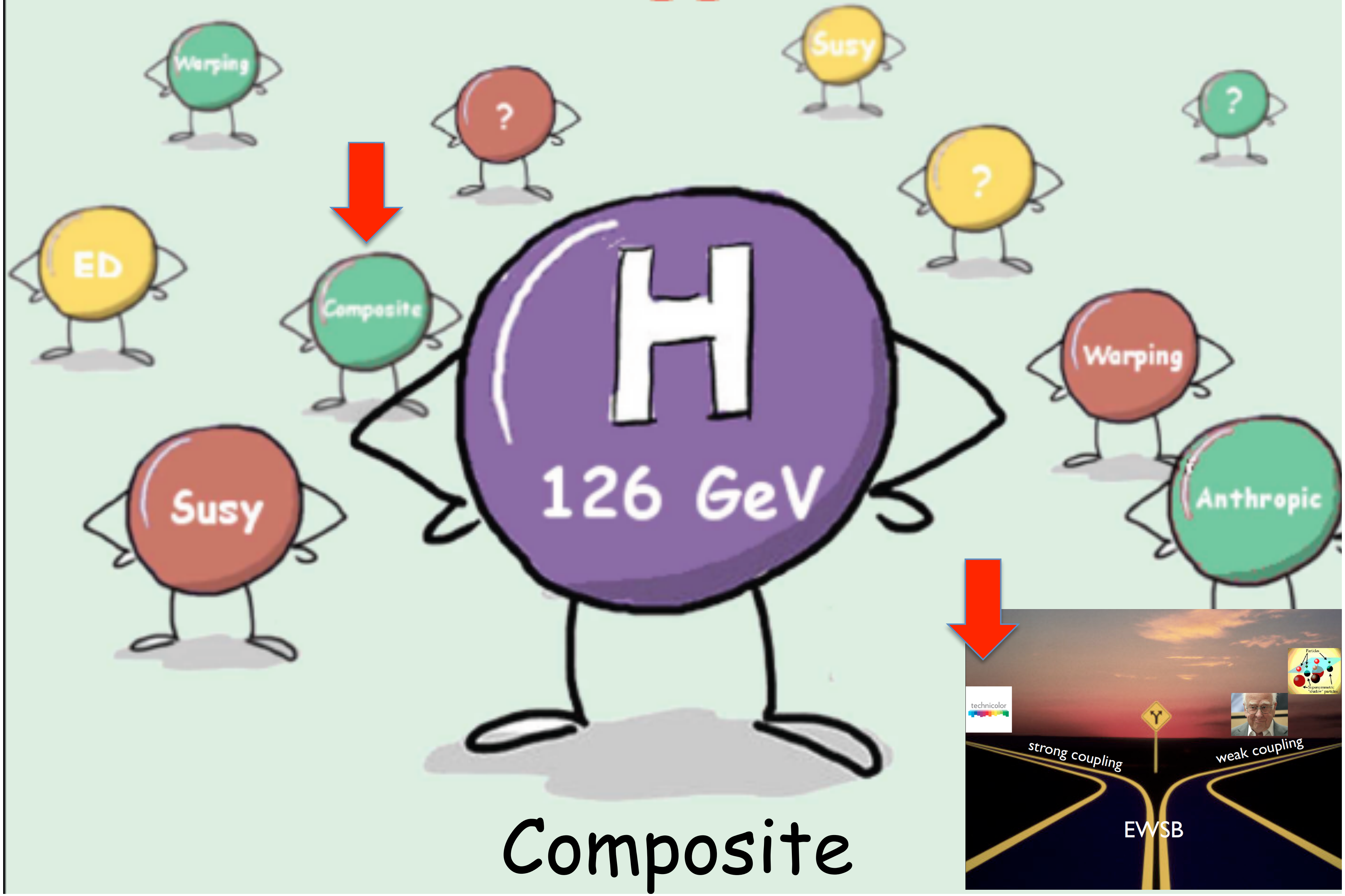
- Whither SUSY?

  ….well motivated SUSY models remain to be tested

  Compressed spectra, TeV squarks and gluinos LHC14?

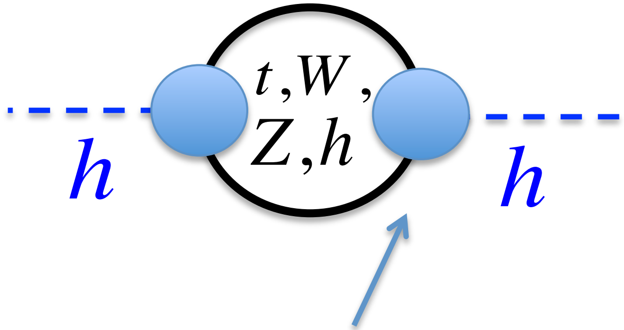
  Natural SUSY

The Higgs Era



Composite

VI. Composite models



Form factor $e^{-q^2/\Lambda^2_{composite}}$

Technicolour - modeled on QCD

$$QCD: \quad SU(2)_L \times SU(2)_R \times U(1)_B \xrightarrow[QCD]{\langle \bar{q}q \rangle} SU(2)_V \times U(1)_B$$

Goldstone modes, $\pi^{a=1,2,3}$ $\quad \Sigma(x) = \exp(i\sigma^a \pi^a(x)/f_\pi$ $\quad f_\pi = 92\ MeV$

QCD breaks the $SU(2) \times U(1)$ symmetry giving W, Z mass

with EM $(Q=T_{3L}+T_{3R}+B/2)$ unbroken

$$m_w = \frac{g f_\pi}{2} \simeq 29\ MeV$$

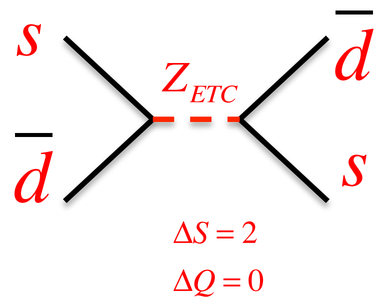
$SU(2)_V$ acts as custodial symmetry

NO LIGHT SCALAR RESONANCE (unitarity enforced by tower of heavier resonances, ρ…)

For a general review see: Contino 1005.4269

Technicolour models

- Avoids (large) hierarchy problem
- Light Higgs?
- Precision tests?
- Fermion masses?
  (FCNC ✗)



$\Longrightarrow$ Make Higgs a Pseudo Goldstone boson

Higgs (Standard) Model

$$H(x) = \frac{1}{\sqrt{2}}\, e^{i\sigma^a \chi^a(x)/v} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$\frac{1}{2}\left(D_\mu H\right)^\dagger \left(D^\mu H\right) = \frac{\mathrm{v}^2}{4}\left(D_\mu \Sigma\right)^\dagger \left(D^\mu \Sigma\right)\left(1+\frac{h}{\mathrm{v}}\right)^2 = \frac{\mathrm{v}^2}{4}\left(D_\mu \Sigma\right)^\dagger \left(D^\mu \Sigma\right)\left(1+2\frac{h}{\mathrm{v}}+\frac{h^2}{\mathrm{v}^2}\right)\ldots$$

Custodial symmetry

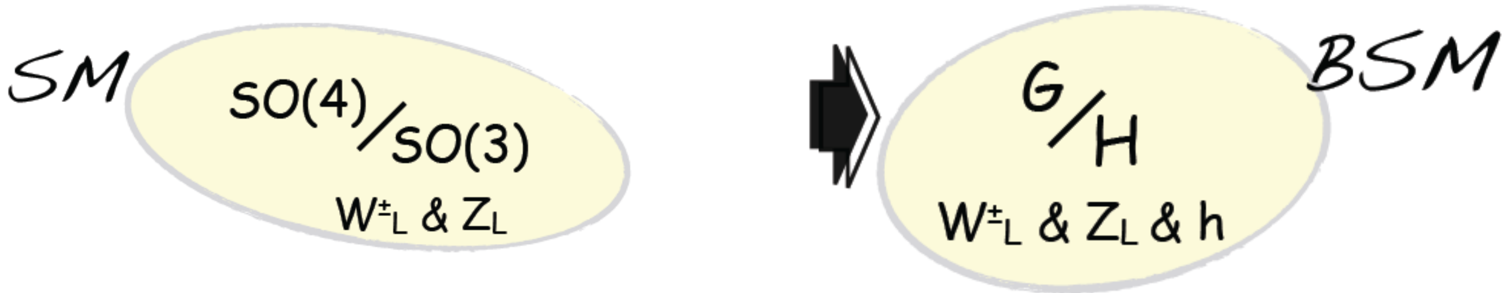
χ^a, h linear rep of $SU(2)_L \times SU(2)_R$

$H^\dagger H = \sum_1 h_i^2$ $\quad SO(4) \sim SU(2)_L \times SU(2)_R \xrightarrow[v]{} SO(3) \sim SU(2)_C$

Goldstone modes: SM $SO(4)/SO(3)$

$W^\pm_L$ & Z_L

The Higgs as a Pseudo Goldstone boson



e.g.

$$SO(5)/SO(3): W, Z, h$$

$$SO(6)/SO(3): W, Z, h, a$$

...

Fermion masses

- ETC ✗
- $$\mathcal{L}_{\rm mix} = f\, q_L^{\alpha} (\hat{\lambda}_L)^{\alpha}_{I} \mathcal{O}_L^{q\,I} + f\, t_R^{\alpha} (\hat{\lambda}_R)^{\alpha}_{I} \mathcal{O}_R^{t\,I} + \text{h.c.}$$

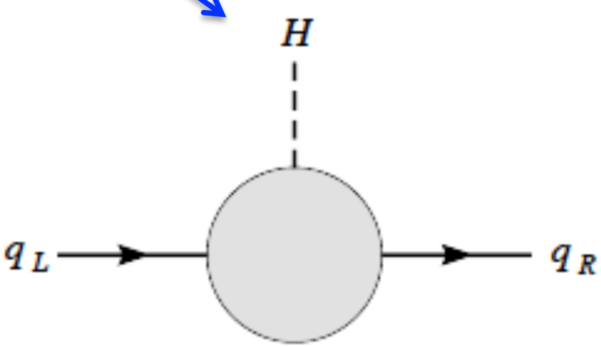
composite techni-fermion resonances, m_ψ

Partial compositeness:

$$t_{L,R}^{mass\ eigenstate} \approx t_{L,R} + \varepsilon_{L,R} O_{L,R}$$

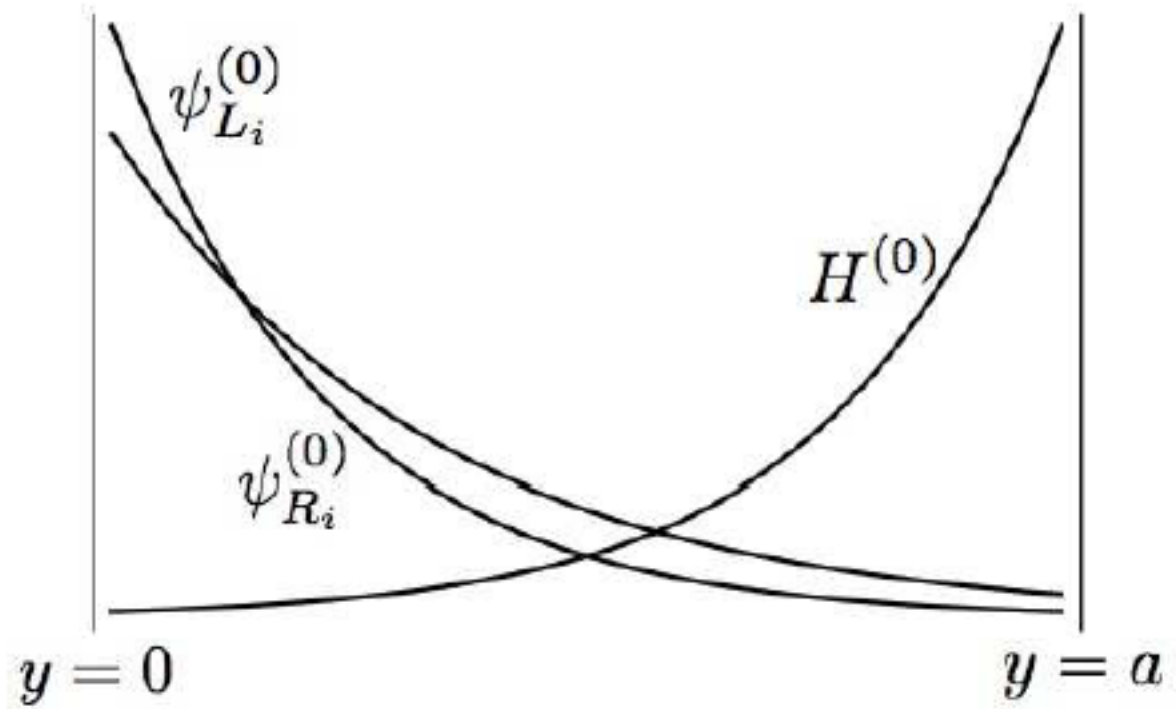
$$\varepsilon_{L,R} = \frac{\lambda_{L,R} f}{m_\psi} \equiv \frac{\lambda_{L,R}}{g_\psi}$$

$\sim O_L O_R$



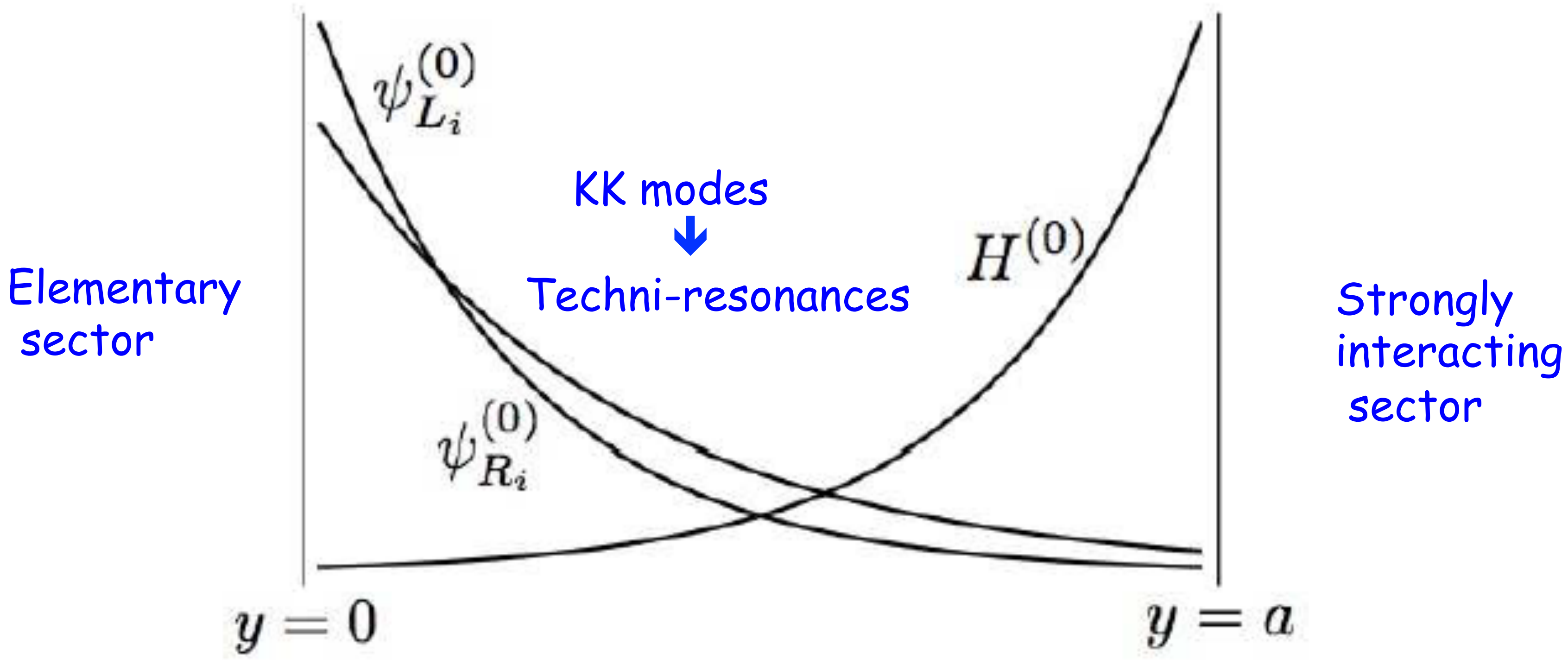
$$h_{q_i} \propto \varepsilon_L^{q_i} \varepsilon_R^{q_i}$$

5D Analogue of partial compositeness



$$(\Box_{5\mathrm{D}} + M^2)\phi^{(0)} e^{ip\cdot x} = e^{ip\cdot x}(-\partial_y^2 + M^2)\phi^{(0)} = 0$$

5D Analogue of partial compositeness



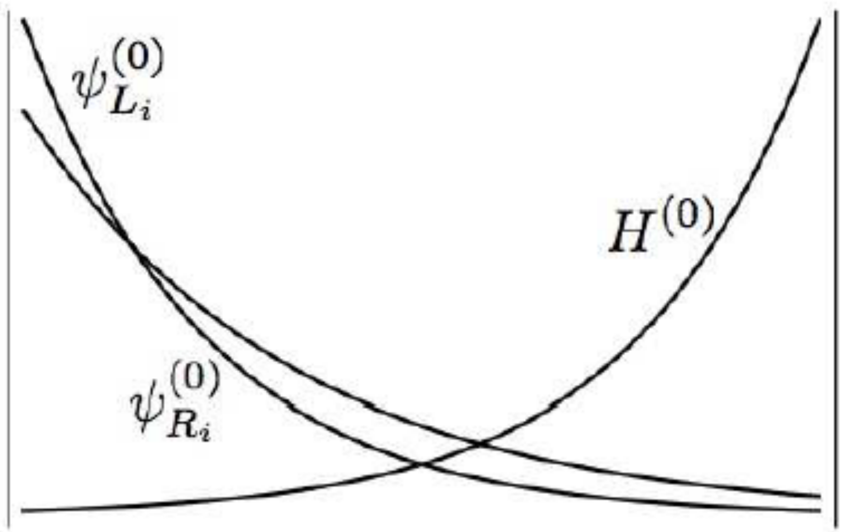
Heavier SM states – more composite

Light quarks and leptons almost elementary – evade composite tests

H, W_L, Z_L composite; W_T, Z_T partially composite

Exponential hierarchies of fermion masses

Elementary sector



Strongly interacting sector

$$Y_{4\mathrm{D},ij} \sim \int_0^a dy\, Y_{5\mathrm{D},ij}(y)\, e^{-(M_{L_i}+M_{R_j})y+M_H(y-a)}$$

$(M_{L_i}+M_{R_j}>M_H)$ $\quad$ $(M_{L_i}+M_{R_j}<M_H)$

$$\sim \widetilde{Y}_{0,ij}\, e^{-M_H a} \quad \ll \quad \sim \widetilde{Y}_{a,ij}\, e^{-(M_{L_i}+M_{R_j})a}$$

No flavour hierarchies in m, θ
- Dirac neutrinos?

Charged fermion hierarchies

The hierarchy problem and light top quark partners

New states needed< 1TeV

$$\delta m_h^2 = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \quad \Rightarrow \quad \Delta \geq \frac{\delta m_h^2}{m_h^2} = \left(\frac{\Lambda}{400\,\mathrm{GeV}}\right)^2 \left(\frac{125\,\mathrm{GeV}}{m_h}\right)^2$$

The hierarchy problem and light top quark partners

light vectorlike top quark < 1TeV

$$\delta m_h^2 = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \quad \Rightarrow \quad \Delta \geq \frac{\delta m_h^2}{m_h^2} = \left(\frac{\Lambda}{400\,\mathrm{GeV}}\right)^2 \left(\frac{125\,\mathrm{GeV}}{m_h}\right)^2$$

$but \quad m_\rho > 2.5 TeV$ (S-parameter)

Hence low cut-off for low Δ must be due to top-quark form factor

$\Rightarrow$ Technifermion top quark resonance < 1TeV

The hierarchy problem and light top quark partners

light vectorlike top quark < 1TeV

$$\delta m_h^2 = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \quad \Rightarrow \quad \Delta \geq \frac{\delta m_h^2}{m_h^2} = \left(\frac{\Lambda}{400\,\mathrm{GeV}}\right)^2 \left(\frac{125\,\mathrm{GeV}}{m_h}\right)^2$$

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Hence low cut-off for low Δ must be due to top-quark form factor

$\Rightarrow$ Technifermion top quark resonance < 1TeV

Fine tuning   Sensitive to top resonance representations…minimum

$\Delta \sim \xi^{-1} \geq 10$ for $SO(4)$ 9-plet top quark $\left(\xi = \frac{v^2}{f^2}\right)$

Top techni-resonance phenomenology

$QCD\ pair\ production: \quad \sigma_{m_t=500GeV} = 570\,fb, \quad \sigma_{m_t=1TeV} = 1.3\,fb \quad (8TeV\ CM)$

$$9 \sim 3_{5/3} \oplus 3_{2/3} \oplus 3_{-1/3} \quad (SU(2)_L \times U(1)_Y) \quad \supset 2 \times Q_{5/3} + Q_{8/3}$$

$$\searrow 3W^+ + b + \ldots$$

$$BR\left(Q_{5/3(8/3)} \to l^+ l^+ ..\right) = 5(6)\%, \quad BR\left(Q_{5/3(8/3)} \to lll..\right) = 3(6.5)\%$$

LHC$_{8:}$ $m_t > 770 GeV\ (95\%)$

Panico et al 1201.7114
Pappadopulo et al 1303.3062

Summary BSM after Higgs

- Need symmetry to keep Higgs light

  Scale, SUSY, Nambu-Goldstone

- Require new states

  More Higgs and/or Higgs interactions,
  SUSY partners,
  Top quark partners

- Fine tuning limits $\Longrightarrow$ LHC 13/14 discovery!

- Grand Unification still viable – but must find SUSY