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Beyond the Standard Model - II

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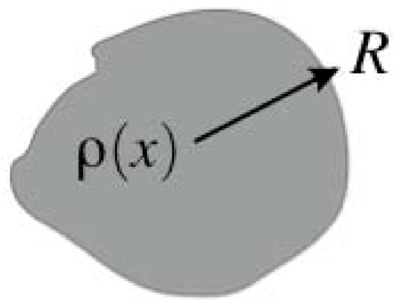
Natural and un-natural mass hierarchies

Particle mass versus size

- Classical computation



$$e \equiv \int \rho(x)\, d^3x$$

$$\Delta m \sim \frac{e^2}{4\pi}\frac{1}{R} \sim \frac{e^2}{4\pi}\Lambda$$

$$\Lambda \sim \frac{1}{R}$$

- Quantum result

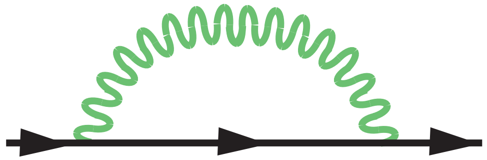
scalar $$m^2 = m_0^2 + \frac{3e^2}{16\pi^2}\Lambda^2 + O(e^4)$$

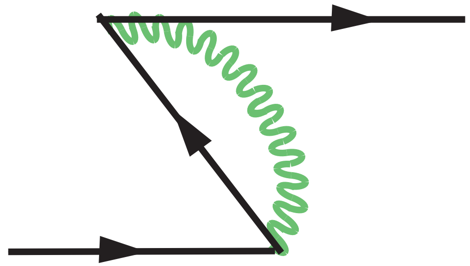
fermion $$m = m_0\left(1 + \frac{3e^2}{8\pi^2}\ln\frac{\Lambda}{m_0} + O(e^4)\right)$$

For a fermion only a mild logarithmic divergence remains !!

concrete example: $$\frac{e^2}{16\pi^2}\ln\frac{M_{\text{Planck}}}{m_{\text{electron}}} \sim 0.37 = O(1)$$

cancellation is due to virtual positron contribution to mass





$$\Delta m_e = +\frac{e^2}{4\pi}\Lambda \qquad -\frac{e^2}{4\pi}\Lambda \qquad = 0$$

This result is more directly understood in terms of symmetries

Naturally small masses ⟷ Symmetry

1) Fermion: $\mathcal{L}_{\text{electron}} = i\bar{\mathbf{e}}_{\mathbf{L}}\gamma^{\mu}D_{\mu}\mathbf{e}_{\mathbf{L}} + i\bar{\mathbf{e}}_{\mathbf{R}}\gamma^{\mu}D_{\mu}\mathbf{e}_{\mathbf{R}} + m_e\bar{\mathbf{e}}_{\mathbf{L}}\mathbf{e}_{\mathbf{R}} + m_e\bar{\mathbf{e}}_{\mathbf{R}}\mathbf{e}_{\mathbf{L}}$

electron + positron → limit $m_e = 0$ respects chiral symmetry

$\mathbf{e}_{\mathbf{L}} \rightarrow \mathbf{e}_{\mathbf{L}}$

$\mathbf{e}_{\mathbf{R}} \rightarrow e^{i\theta}\mathbf{e}_{\mathbf{R}}$

$$\delta m_e \propto \frac{\alpha}{4\pi} m_e$$

~~$\propto \frac{\alpha}{4\pi}\Lambda$~~

2) vector → gauge symmetry: $A_{\mu} \rightarrow A_{\mu} + \partial_{\mu} a$

mass term: $m_{\gamma}^2 A_{\mu}A^{\mu}$ not invariant

$$m_{\gamma} = 0$$

3) interacting massless scalar $\mathcal{L}_\varphi = \partial_\mu\varphi\partial^\mu\varphi + \lambda\varphi^4$

$\int d^4x\,\mathcal{L}_\varphi$ is classically invariant under dilatations $\varphi(x) \to k\varphi(kx)$

however the very existence of any UV scale explictly breaks dilatations

$$\delta m_\varphi^2 \sim \frac{\lambda}{16\pi^2}\Lambda^2$$

3a) Nambu-Goldstone boson $\varphi \to \varphi + c$

$$\mathcal{L} = \mathcal{L}(\partial\varphi) = (\partial_\mu \varphi)^2 + \frac{1}{\Lambda^4}(\partial_\mu \varphi)^2 (\partial_\nu \varphi)^2 + \dots$$

$E \ll \Lambda$ the scalar becomes a free particle

The Higgs looks only mildly like a NG boson!

$$\mathcal{L}_{top} = \lambda_t \bar{Q}_L H t_R + \text{h.c.}$$

$\downarrow$

$$\delta m_H^2 \sim \frac{3\lambda_t^2}{8\pi^2} \Lambda^2$$

OK as long as

$\Lambda \lesssim 1\,\text{TeV}$

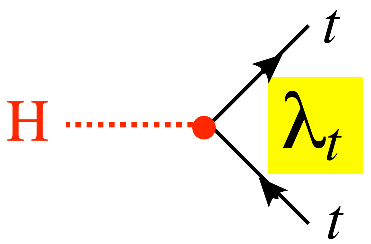
still interesting to build models at weak scale (see Pomarol)

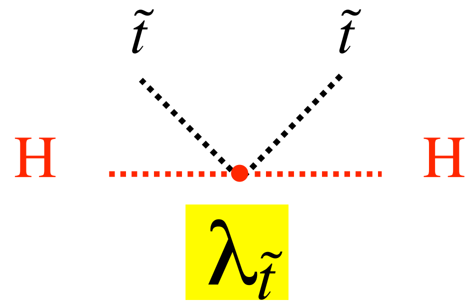
No *ordinary* symmetry can protect the mass of an interacting scalar particle

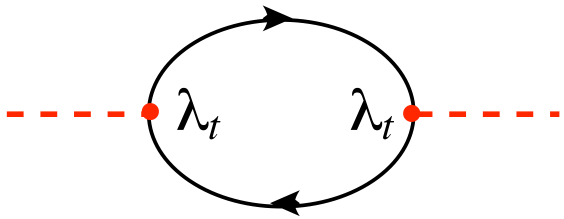
... we must speculate

▲ Try to make Higgs scalar naturally light by following positron example: add new particles

Ex: top quark contribution







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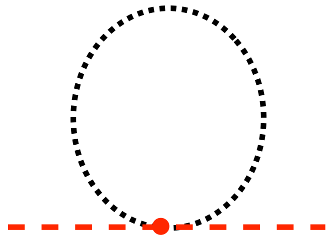


$$\delta\mu^2 = -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2 \qquad + \frac{3\lambda_{\tilde{t}}}{8\pi^2}\Lambda^2$$

fermion (−) boson (+)

- Fermion and boson loops cancel each other for $\lambda_t^2 = \lambda_{\tilde{t}}$

$\lambda_t^2 = \lambda_{\tilde{t}}$ needs a symmetry relating bosons to fermions

Does such a symmetry exist ?

YES !

SuperSymmetry

Volkov, Akulov 1973
Wess, Zumino 1974

Technical parenthesis: Weyl bi-spinor notation

irreducible fermionic reps of Lorentz group are chiral fermions

$$\Psi_L = \begin{pmatrix} \chi^\alpha \\ 0 \end{pmatrix} \qquad \Psi_R = \begin{pmatrix} 0 \\ \bar{\chi}^c_{\dot{\alpha}} \end{pmatrix}$$

$$\bar{\chi}^c = \varepsilon(\chi^c)^*$$

$$\varepsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Dirac fermion

$$\Psi = \begin{pmatrix} \chi^\alpha \\ \bar{\chi}^c_{\dot{\alpha}} \end{pmatrix} \qquad L_{mass} = m\bar{\Psi}\Psi = m\chi\varepsilon\chi^c + h.c.$$

$$\chi \overset{P}{\longleftrightarrow} \bar{\chi}^c$$

$$\chi \overset{C}{\longleftrightarrow} \chi^c$$

Majorana fermion

$$\Psi = \begin{pmatrix} \chi^\alpha \\ \bar{\chi}_{\dot{\alpha}} \end{pmatrix} \qquad L_{mass} = \frac{m}{2}\chi\varepsilon\chi + h.c.$$

Gamma matrices in Weyl basis (2x2 block notation)

$$\gamma_\mu = \begin{pmatrix} 0 & \sigma_\mu \\ \bar{\sigma}_\mu & 0 \end{pmatrix}$$

$$\sigma_\mu = (1, \sigma_i)$$

$$\bar{\sigma}_\mu = (1, -\sigma_i)$$

$$\gamma_5 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

Space-time symmetries

- translations

$x^\mu \longrightarrow x^\mu + a^\mu$

$$\delta\varphi(x) = \varphi(x+a) - \varphi(x) = a^\mu \partial_\mu \varphi(x) + \ldots$$

- Lorentz

$x^\mu \longrightarrow x^\mu + \omega^\mu_\nu x^\nu + \ldots$

$$\delta\varphi(x) = \omega^\mu_\nu x^\nu \partial_\mu \varphi(x) + \ldots$$

- Supersymmetry

$$\delta\varphi = \bar{\xi}^\alpha [(1-\gamma_5)\psi]_\alpha$$

$$\delta\psi = -i(1-\gamma_5)\gamma^\mu \xi \partial_\mu \varphi$$

- ξ^α = Majorana fermion parameter !
- ξ^α analogue of a^μ and ω^μ_ν

$$(\delta_1\delta_2 - \delta_2\delta_1)\,\varphi \quad = \quad \underbrace{2(\bar{\xi}_1\gamma_\mu\xi_2)}_{a^\mu}\,\partial_\mu\varphi$$

$$(\delta_{\text{SUSY}})^2 \quad \sim \quad \text{translation}$$

$$\delta_{\text{SUSY}} \quad \sim \quad \sqrt{\text{translation}}$$

- Similar to other *impossible* roots

$$\gamma^\mu\,\partial_\mu = \sqrt{\partial^\mu\partial_\mu}$$

$$i = \sqrt{-1}$$

Theorem (Coleman-Mandula, Haag-Lopusanski-Sohnius)

In local quantum field theory with well defined S-matrix

Supersymmetry Q is the unique non-trivial extension of the Poincarè group

⇕

$$[Q, M_{\mu\nu}] \neq 0$$

$$[\, Q_\alpha,\, P_\mu\,] = 0 \qquad\qquad [\, Q_\alpha,\, M_{\mu\nu}\,] = \frac{1}{2}\,(\sigma_{\mu\nu})_\alpha^{\ \beta}\, Q_\beta$$

$$\{\, Q_\alpha,\, Q_\beta\,\} = -2(\gamma^\mu C)_{\alpha\beta} P_\mu$$

Q_α has spin $\frac{1}{2}$

Q_α relates states whose spins differ by $\frac{1}{2}$

particle (spin = J) **SUSY** super-particle (spin = J ± $\frac{1}{2}$)

$$[\, Q_\alpha ,\, P_\mu \,] = 0 \longrightarrow M_J = M_{J \pm \frac{1}{2}}$$

Basic supermultiplets with mass = 0

vector supermultiplet

$$Q \circlearrowleft \begin{pmatrix} V_\mu \\ \lambda^\alpha \end{pmatrix}$$

real spin-1

majorana spin-$1/2$

chiral supermultiplet

$$\begin{pmatrix} \chi^\alpha \\ \varphi \end{pmatrix}$$

weyl spin-$1/2$

complex spin 0

by supersymmetry we can associate a \`chirality' to a complex scalar

$$\varphi \sim \text{left} \qquad \varphi^\dagger \sim \text{right}$$

gravity supermultiplet

$$\begin{pmatrix} g_{\mu\nu} \\ \psi_{\mu\alpha} \end{pmatrix}$$

real spin-2

majorana spin-$3/2$

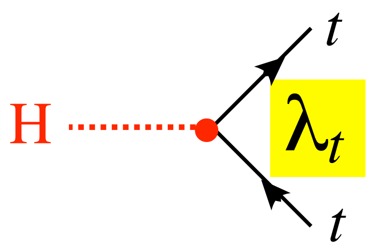
H = Higgs boson (J=0) **SUSY** $\tilde{H}$ = Higgs fermion ($J = \frac{1}{2}$)

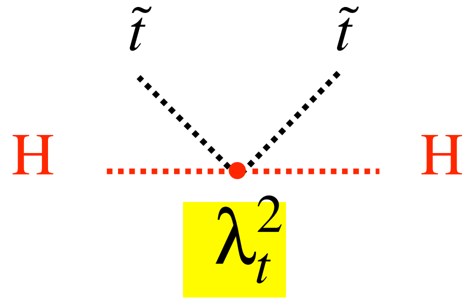
$$m_H = m_{\tilde{H}}$$

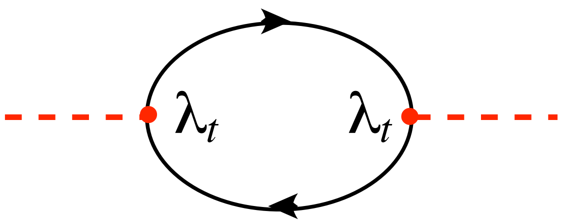
fermion mass
protected from UV effects
by chiral symmetry

- by supersymmetry also m_H is protected
- m_H only logarithmically divergent, like the electron mass
- Higgs scalar can be naturally light !!

Supersymmetry at work







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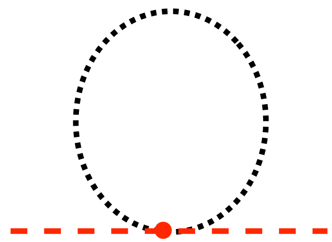


$$\delta\mu^2 = - \frac{3\lambda_t^2}{8\pi^2}\Lambda^2 + \frac{3\lambda_t^2}{8\pi^2}\Lambda^2 = 0$$

fermion　　　　boson

Supersymmetric Standard Model

	particles			Sparticles			
quarks	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R	d_R	*squarks*	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\tilde{u}_R$	$\tilde{d}_R$
leptons	$\begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$	e_R		*sleptons*	$\begin{pmatrix} \tilde{e}_L \\ \tilde{\nu}_L \end{pmatrix}$	$\tilde{e}_R$	
Higgs doublets	H_1 (hypercharge $= -1$) H_2 (hypercharge $= +1$)			*Higgsinos*	$\tilde{H}_1$ $\tilde{H}_2$		
	$W_\mu^\pm, W_\mu^3$			*winos*	$\tilde{\omega}^\pm, \tilde{\omega}^3$		
	B_μ			*bino*	$\tilde{b}$		
	G_μ^A	$A = 1, \ldots, 8$		*gluinos*	$\tilde{g}^A$		

Supersymmetric interactions

↓

(gauge) + (Superpotential)

↓

Yukawa interactions

&

scalar potential

Superpotential: formal tool to derive supersymmetric Yukawa and potential interactions

$$f[\varphi_i] = m_i^2 \varphi_i + \frac{1}{2} M_{ij} \varphi_i \varphi_j + \frac{1}{3} \lambda_{ijk} \varphi_i \varphi_j \varphi_k$$

- $f[\varphi_i]$ gauge invariant function of the chiral scalars; the anti-chiral fields $\varphi_i^\dagger$ do not appear

- renormalizability $\longleftrightarrow$ $f[\varphi_i]$ at most cubic

$$\mathcal{L}_{scalar} = -\sum_i \left| \frac{\partial f}{\partial \varphi_i} \right|^2$$

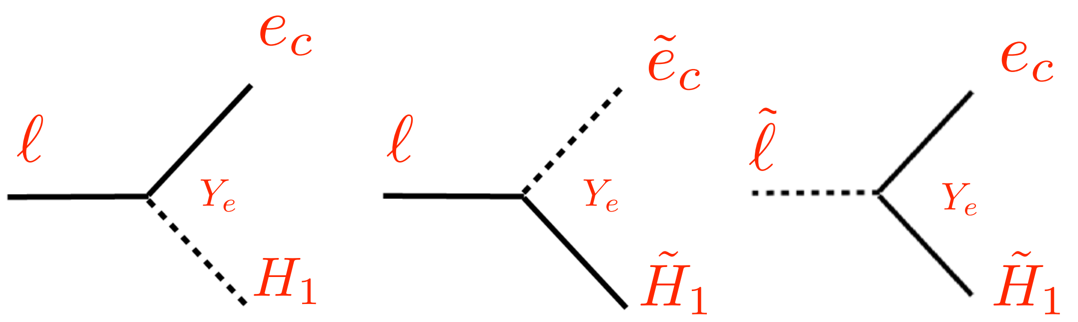
$$\mathcal{L}_{Yukawa} = -\frac{1}{2} \frac{\partial f}{\partial \varphi_i \partial \varphi_j} \chi_i \chi_j = -\frac{1}{2} M_{ij} \chi_i \chi_j - \lambda_{ijk} \varphi_i \chi_j \chi_k$$

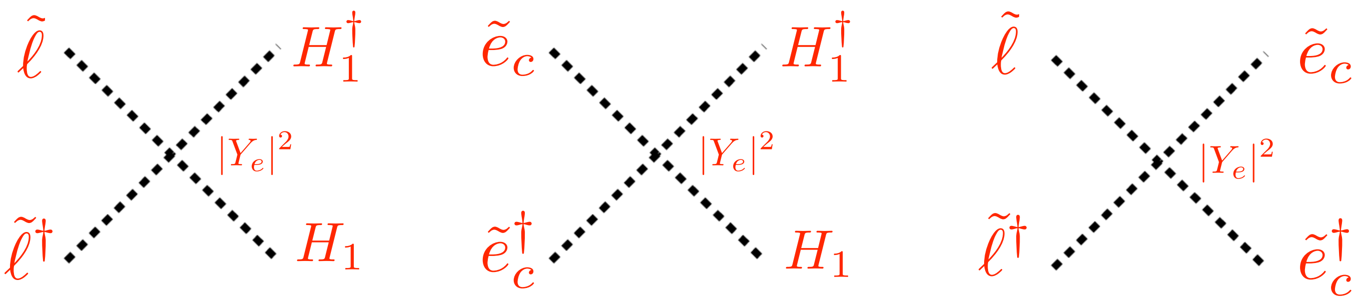
Superpotential in Supersymmetric Standard Model

$$f_{SM} = Y_u\, qH_2u_c + Y_d\, qH_1d_c + Y_e\, \ell H_1e_c + \mu H_1H_2$$

$\ell = \begin{pmatrix} e \\ \nu \end{pmatrix}$ $\qquad Y_e\langle H_1\rangle\, ee_c$

lepton mass

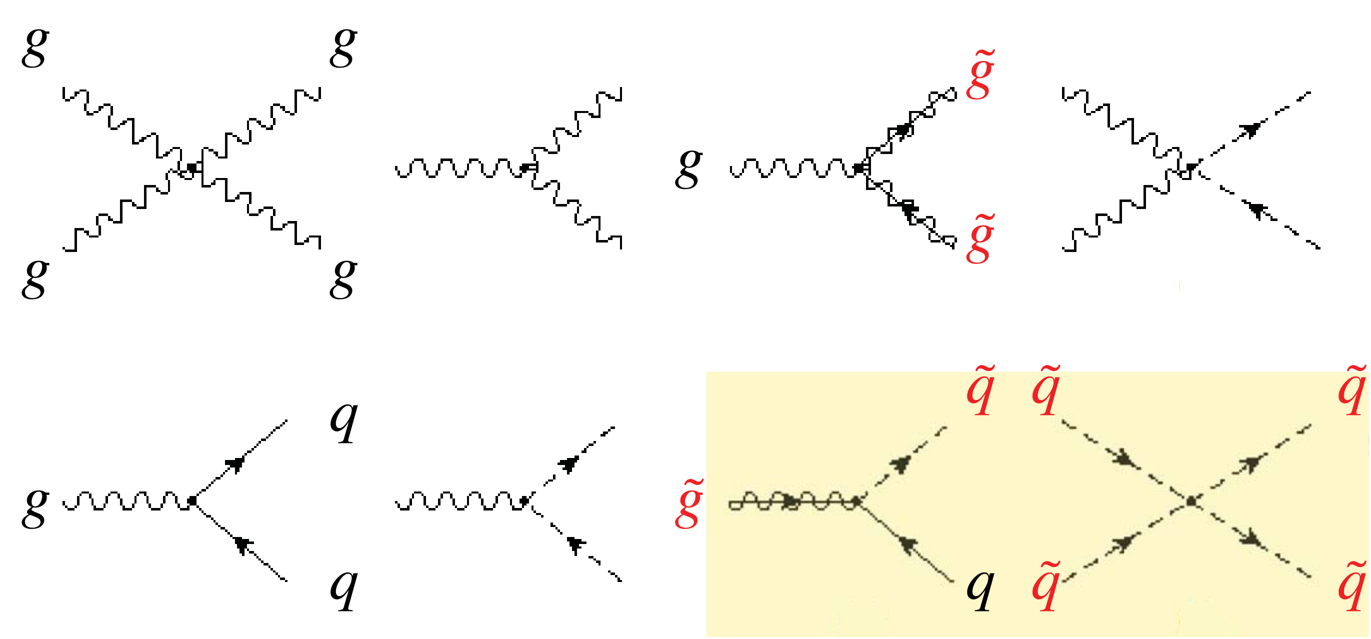


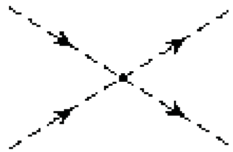


- sparticles enter interactions in pairs
- μ -term gives mass to Higgsinos
- no quartic interaction for Higgs scalar arises!!!

Supersymmetric gauge interactions

Ex: SU(3) color interactions



- all vertices controlled by the SU(3) coupling g_3
- there is a quartic scalar vertex  $\propto \; g_3^2$
- sparticles enter interactions in pairs:

sparticle parity = $(-1)^{\text{(number of sparticles)}}$ is conserved

$$V_{gauge} = \frac{g^2}{2} \sum_A (\varphi^\dagger T_A \varphi)^2$$

$T_A =$ gauge group generators

$$V_{weak} = \frac{g_W^2}{8} \left(H_1^\dagger \vec{\sigma} H_1 + H_2^\dagger \vec{\sigma} H_2 \right)^2 + \frac{g_Y^2}{8} \left(|H_1|^2 - |H_2|^2 \right)^2 + \ldots$$

$$V_{neutral} = \frac{g_W^2 + g_Y^2}{8} \left(|H_1^0|^2 - |H_2^0|^2 \right)^2$$

remember:
$m_h = \sqrt{2\lambda} v_F$

- while in SM $\lambda |H|^4$ is a free parameter

  in SUSY quartic is predicted! ....but there is > 1 Higgs boson

- mass of lightest Higgs bounded by Z-mass at tree level

  at quantum level $m_h \lesssim 130\,\mathrm{GeV}$

$$(-1)^{\text{(number of sparticles)}} \equiv \text{R-parity}$$

is a symmetry of the Supersymmetric SM

- sparticles produced and annihilated in pairs
- Lightest Supersymmetric Particle (LSP) is absolutely stable

■ typically LSP is a neutralino (mixture of bino, zino & neutral higgsino)

A) SUSY signal at collider: events with missing energy

B) LSP is an excellent dark matter candidate (weakly interacting massive particle)

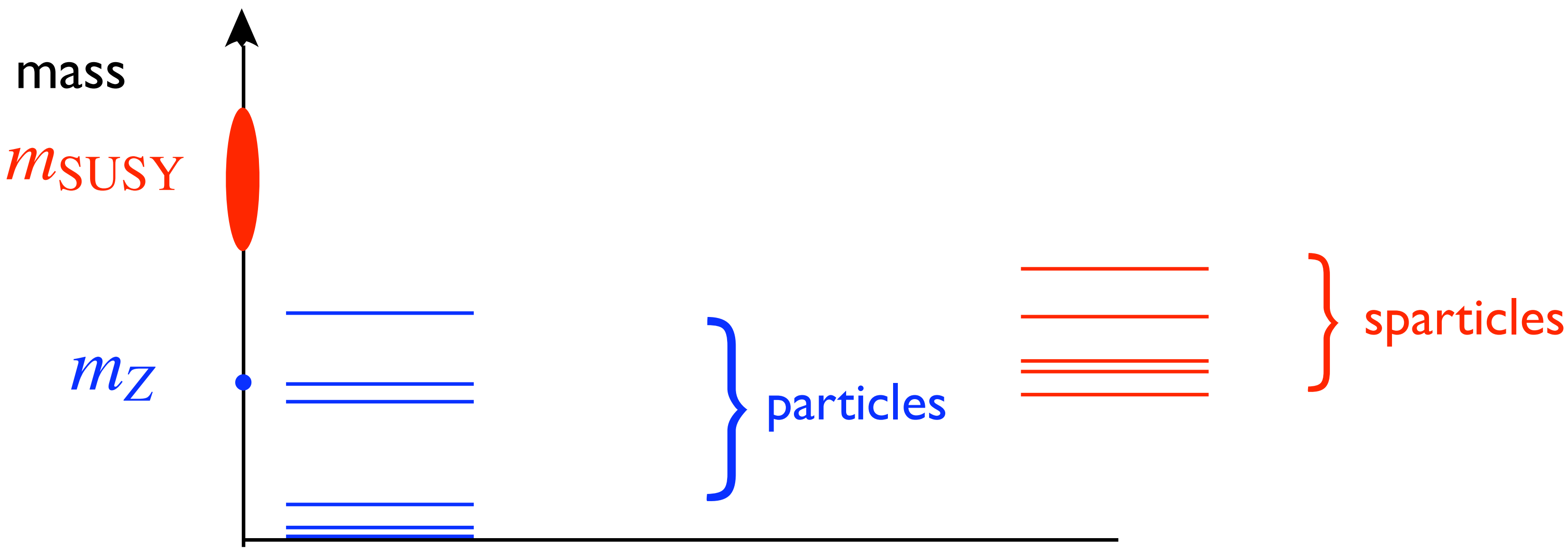
- exact supersymmetry $\Rightarrow$

$$m_e = m_{\tilde{e}}$$
$$m_\mu = m_{\tilde{\mu}}$$
$$\cdots$$

- but experimentally

$$m_e = 0.511 \text{ MeV} \qquad m_{\tilde{e}} \gtrsim 100 \text{ GeV}$$

- Supersymmetry must be slightly broken



- Spontaneous SUSY breaking within SM dynamics: difficult

Ex.: $m^2_{\tilde{e}_L} + m^2_{\tilde{e}_R} = 2m^2_e$ is a typical problem

- Phenomenological approach: SUSY broken by addition of *soft terms*

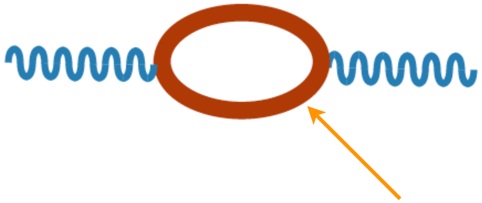
Dimopoulos-Georgi, Girardello-Grisaru '81

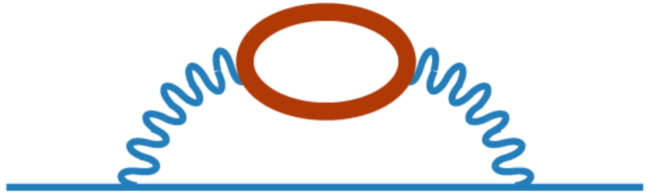
$$
\begin{aligned}
\mathcal{L}_{soft} \; = \; & M_3\,\tilde{g}\tilde{g} + M_2\,\tilde{\omega}\tilde{\omega} + M_1\,\tilde{b}\tilde{b} && \longleftarrow \text{gaugino masses} \\
+ \; & \sum_i m^2_{ij}\,\varphi_i\varphi^\dagger_j && \longleftarrow \text{sfermions and Higgs masses} \\
+ \; & A_u\,\tilde{q}H_2\tilde{u}_c + A_d\,\tilde{q}H_1\tilde{d}_c + A_e\,\tilde{\ell}H_1\tilde{e}_c && \longleftarrow \text{A-terms} \\
+ \; & B\mu\,H_1H_2 && \longleftarrow \text{B-term}
\end{aligned}
$$

All soft terms have positive mass dimension ➡ good UV behaviour is preserved

Soft terms are generated by a separated (hidden) sector which spontaneously breaks supersymmetry

- 'Low' scale mediation: gauge mediated models



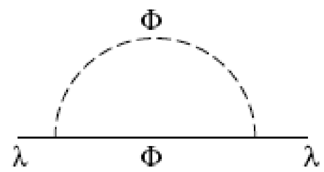


messenger super-multiplets are charged under SM gauge group

$$10^4\,\mathrm{GeV} \;<\; M_{mess} \;<\; 10^{16}\,\mathrm{GeV}$$

- 'High' scale mediation: gravity mediated models

hidden sector couples to SM via non-renormalizable interactions suppressed by powers of $\frac{1}{M_P^2} \sim G_N$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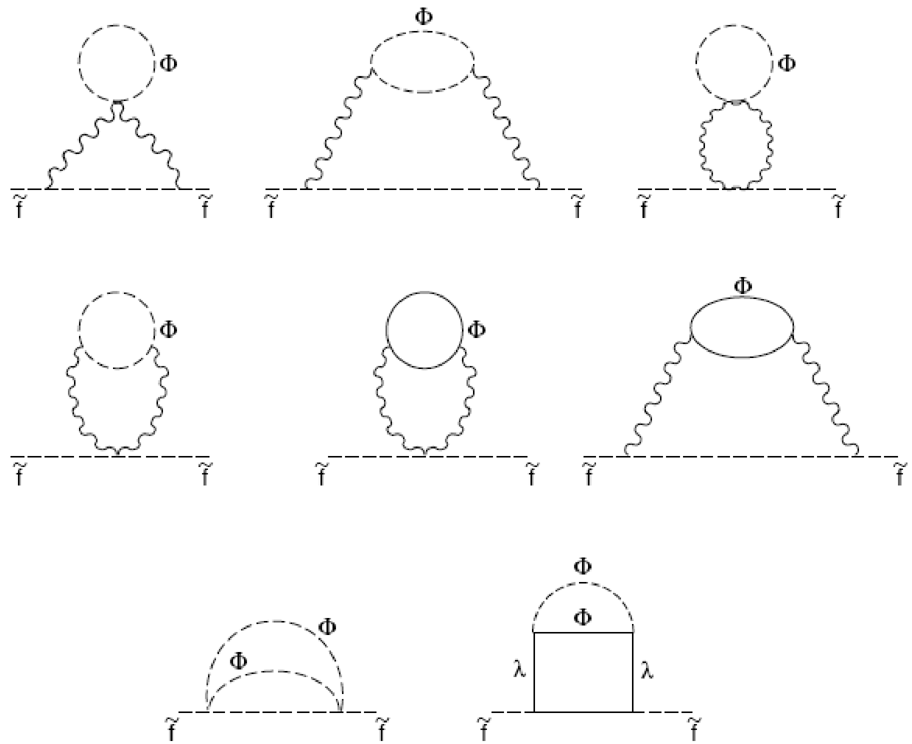
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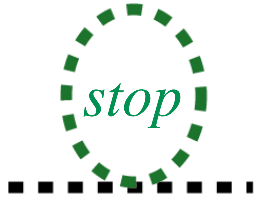


$$\delta m^2_{H_2} = -\frac{3\lambda_t^2}{8\pi^2}\int^{\Lambda^2}\frac{p^2 dp^2}{p^2+m_t^2} + \frac{3\lambda_t^2}{8\pi^2}\int^{\Lambda^2}\frac{p^2 dp^2}{p^2+m_t^2+m_{soft}^2} = -\frac{3\lambda_t^2}{4\pi^2}m^2_{soft}\ln\frac{\Lambda}{m_{soft}}$$

analogy with electron-positron: power-like divergence is changed to milder log

absence of fine tuning ⟺ m_{soft} ~ weak scale

$\delta m^2_{H_2} < 0$ for $m^2_{soft} > 0$: electroweak symmetry breaking can be triggered by quantum corrections

Electroweak symmetry breaking

$$V = m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 - m_3^2\left(H_1^0 H_2^0 + \text{h.c.}\right) + \frac{g_2^2 + g_Y^2}{8}\left(|H_1^0|^2 - |H_2^0|^2\right)^2$$

- stability along $H_1^0 = H_2^0$ ⟹ $m_1^2 + m_2^2 > 2|m_3^2|$
- EW breaking ⟹ $m_1^2 m_2^2 - (m_3^2)^2 < 0$

typically all scalar masses are positive at some high energy scale

Ex.: minimal supergravity at Planck scale

$$\begin{cases} m_{squark}^2 = m_{slepton}^2 \equiv m_0^2 > 0 \\ m_1^2 = m_2^2 \equiv \mu^2 + m_0^2 > 0 \\ m_1^2 m_2^2 - (m_3^2)^2 > 0 \end{cases}$$

m_2^2 is driven negative by the RG evolution from high to low scale

Radiative symmetry breaking

RG evolution from high to low energy

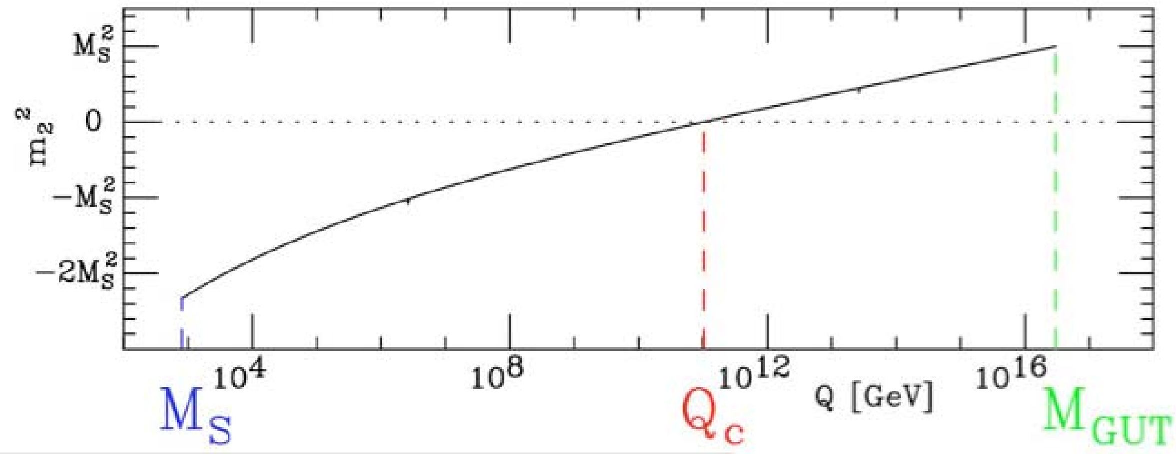
$$-8\pi^2 \frac{dM_3}{d\ln Q} = +3g_3^2 M_3$$

$$-8\pi^2 \frac{dm^2_{\tilde{t}_L}}{d\ln Q} = +\frac{16}{3} g_3^2 M_3^2 - \lambda_t^2 (m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} + |A_t|^2 + m_2^2 - \mu^2) + (\text{EW effects})$$

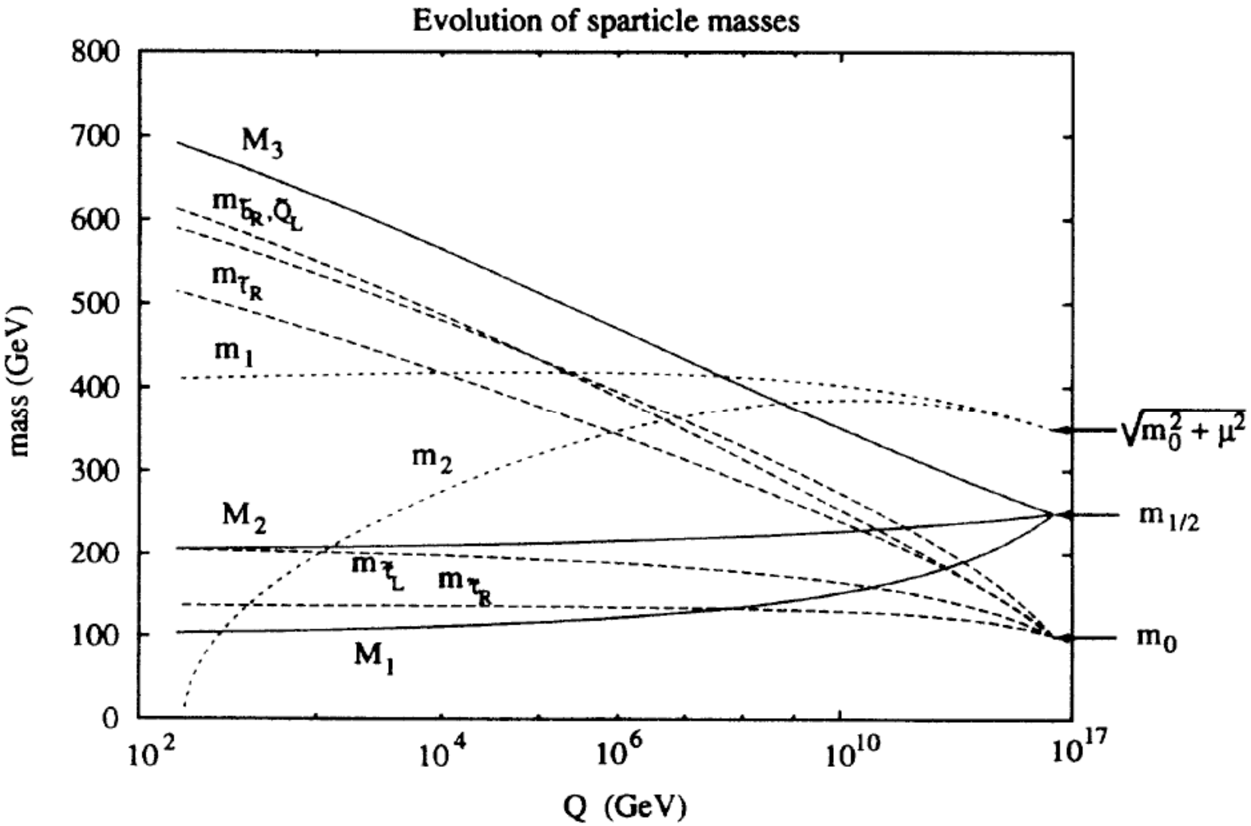
$$-8\pi^2 \frac{dm_2^2}{d\ln Q} = -3\lambda_t^2 (m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} + |A_t|^2 + m_2^2) + (\text{EW effects})$$

- QCD effects push the gluino and stops heavier: color is unbroken
- top Yukawa drives m_2^2 negative

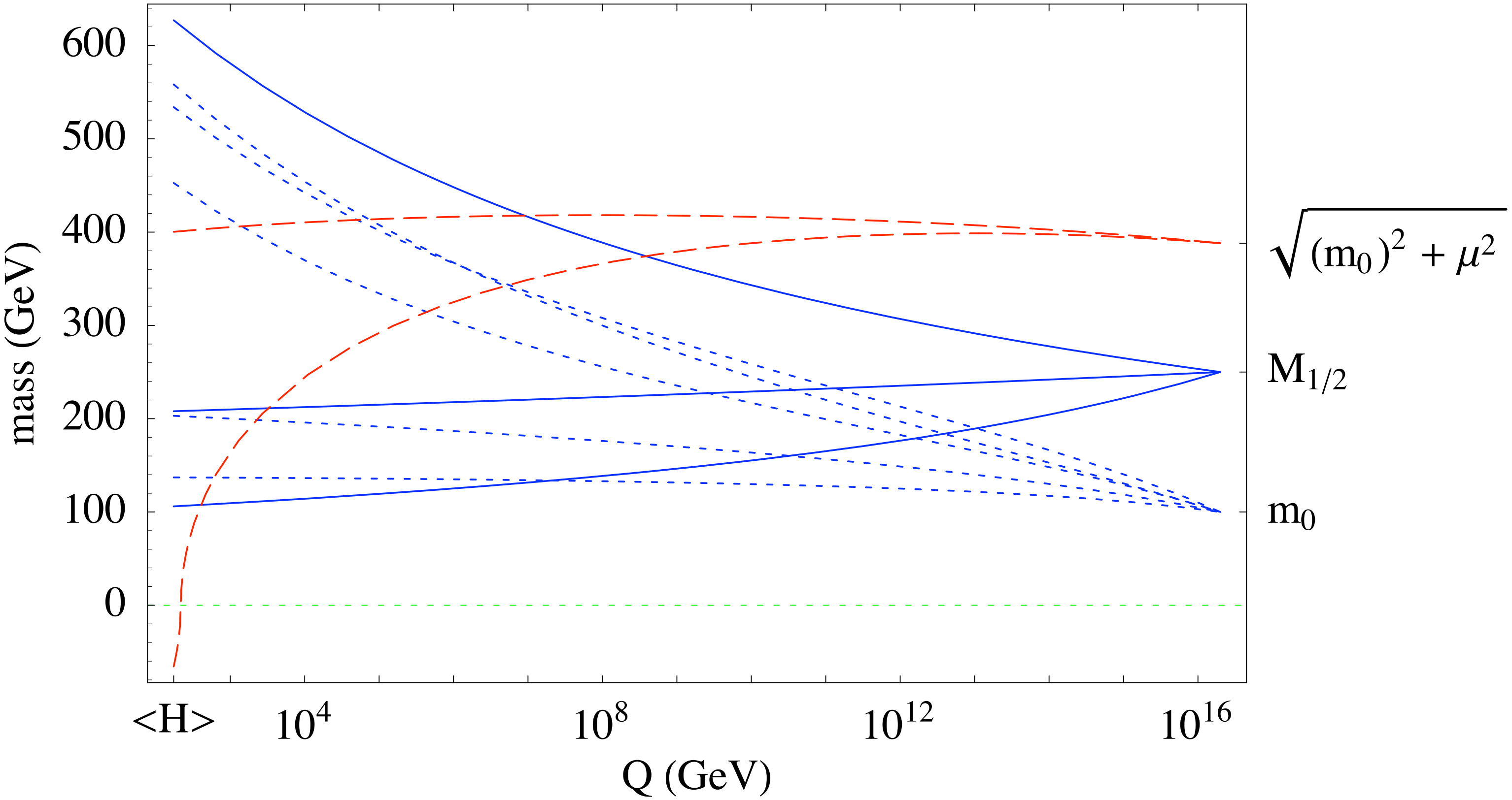
$\lambda_t \sim O(1)$ is crucial to beat EW effects that push m_2^2 up



M_S^2
0
$-M_S^2$
$-2M_S^2$
m_2^2
10^4
10^8
10^{12}
Q [GeV]
10^{16}
M_S
Q_c
M_{GUT}



Evolution of sparticle masses
mass (GeV)
Q (GeV)
M_3
$m_{\tilde{t}_R,\tilde{Q}_L}$
$m_{\tilde{\tau}_R}$
m_1
m_2
M_2
$m_{\tilde{\tau}_L}$
$m_{\tilde{\tau}_R}$
M_1
$\sqrt{m_0^2 + \mu^2}$
$m_{1/2}$
m_0



600
500
400
300
200
100
0
mass (GeV)
$\sqrt{(m_0)^2 + \mu^2}$
$M_{1/2}$
m_0
<H>
10^4
10^8
10^{12}
10^{16}
Q (GeV)

Higgs mass spectrum

(tree level first)

$$V = m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 - m_3^2\left(H_1^0 H_2^0 + \text{h.c.}\right) + \frac{g_2^2+g_Y^2}{8}\left(|H_1^0|^2 - |H_2^0|^2\right)^2$$

$$\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix} \qquad \sqrt{v_1^2+v_2^2} \equiv v_F = 174\,\text{GeV}$$

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

⮕ 8 real scalars - 3 'eaten' by $W^\pm, Z$
= 5 physical scalars

2 CP-even real neutral: $h,\ H$

1 CP-odd real neutral: A

1 complex charged: H^+

- parameters: $m_1^2,\ m_2^2,\ m_3^2 \longrightarrow v_F, \quad \tan\beta = \dfrac{v_1}{v_2}, \quad m_A$

$$m_Z^2 = \frac{2\left(m_1^2 - m_2^2 \tan^2\beta\right)}{\tan^2\beta - 1} \qquad \sin 2\beta = \frac{2m_3^2}{m_A^2}$$

$$m_A^2 = m_1^2 + m_2^2 \qquad m_{H^+} = m_A^2 + m_W^2$$

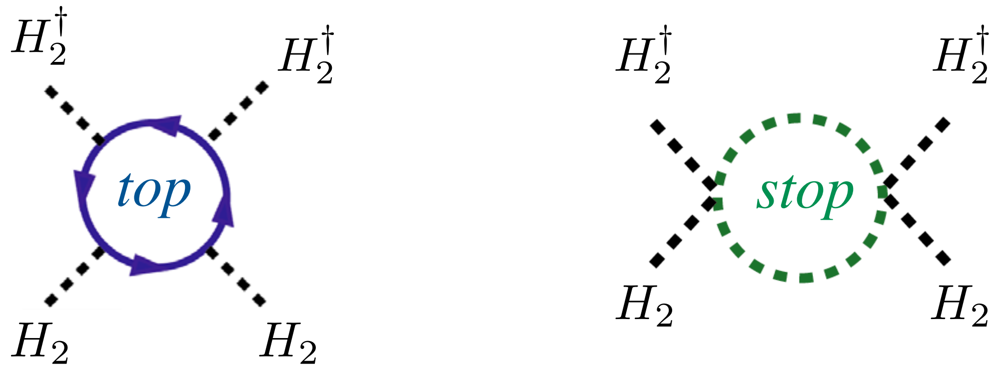
$$m_{h,H}^2 = \frac{1}{2}\left\{m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 - m_Z^2)^2 + 4\sin^2 2\beta\, m_A^2 m_Z^2}\right\}$$

$$m_h < m_A < m_H$$

$$m_h < m_Z$$

Important quantum corrections from top-stop

Haber, Hempfling '91
Okada, Yamaguchi, Yanagida '91
Ellis, Ridolfi, Zwirner '91



$$\Delta V_{loops} = \delta |H_2|^4$$

$$\delta = \frac{3\lambda_t^4}{16\pi^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + X_t + (2\text{–loops})\right]$$

$$X_t \equiv \frac{(A_t - \mu/\tan\beta)^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left[1 - \frac{(A_t - \mu/\tan\beta)^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right]$$

$$m_h^2 \le m_Z^2 \cos^2 2\beta + 4 v_F^2 \delta \sin^4 \beta$$

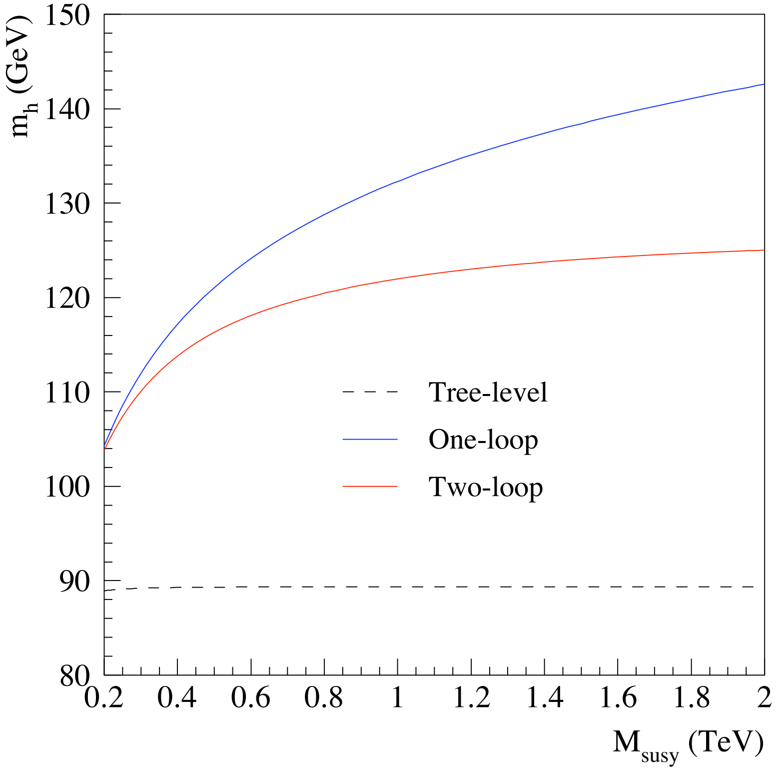
$$\sim \frac{3}{4\pi^2}\frac{m_t^4}{v_F^2}\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

$=$ for $m_A \gg m_Z$

stop mass matrix

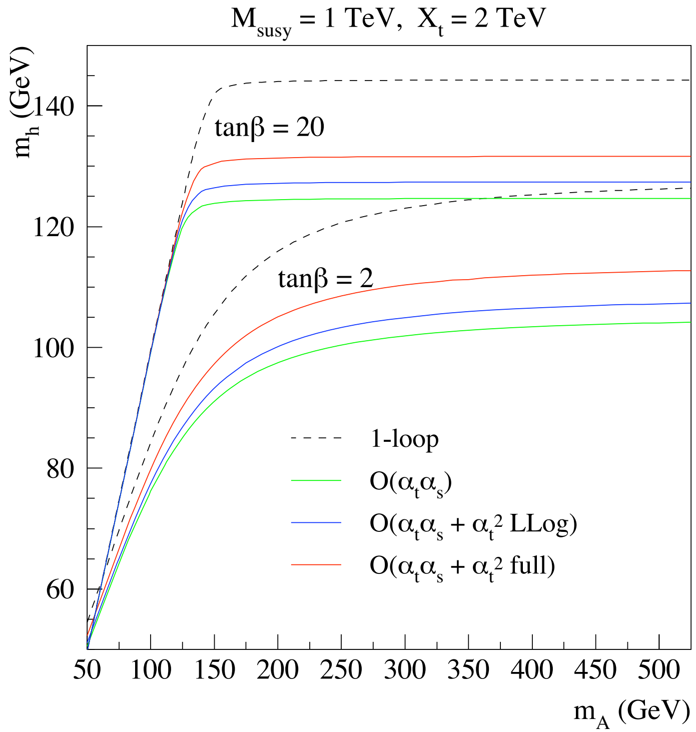
$$\begin{pmatrix} \tilde{t}_L^*, & \tilde{t}_R^* \end{pmatrix} \begin{pmatrix} m_{\tilde{t}_L}^2 & A m_t \\ A m_t & m_{\tilde{t}_R}^2 \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

eigenvalues: $m_{\tilde{t}_1}^2, \quad m_{\tilde{t}_2}^2$



Brignole,Degrassi,Slavich,Zwirner '02

Slavich '06

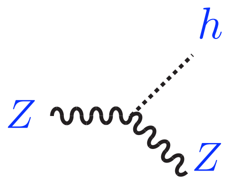


impact of loop effects is large because of

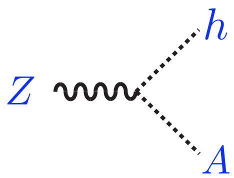
I) large top Yukawa

II) relatively small tree value forced on m_h by supersymmetry

SUSY Higgs phenomenology



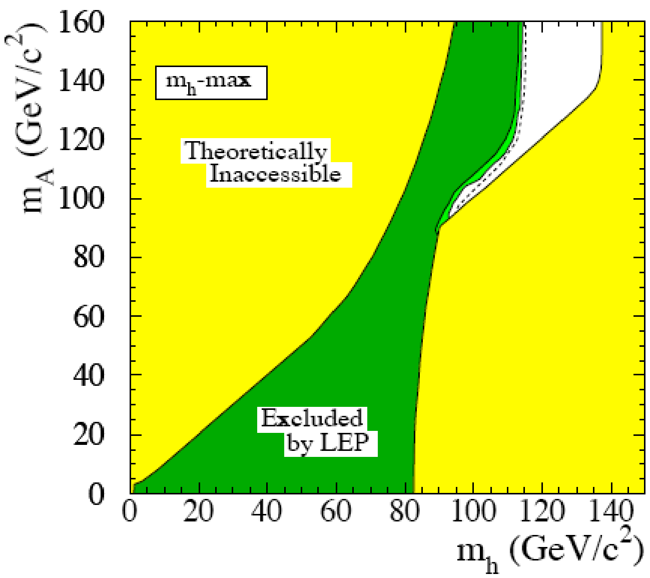
$$\left| \quad \right|^2 \propto \sin^2(\beta-\alpha) = \frac{1}{2}\left[1+\frac{m_A^2-(m_Z^2+\Delta)}{m_H^2-m_h^2}\right]$$

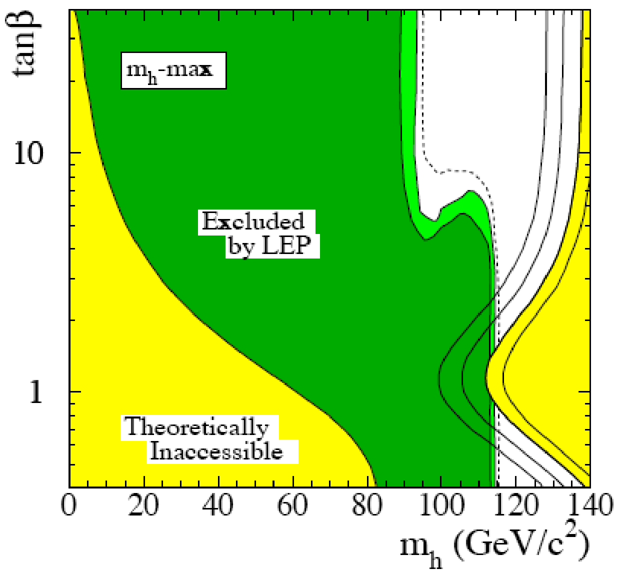


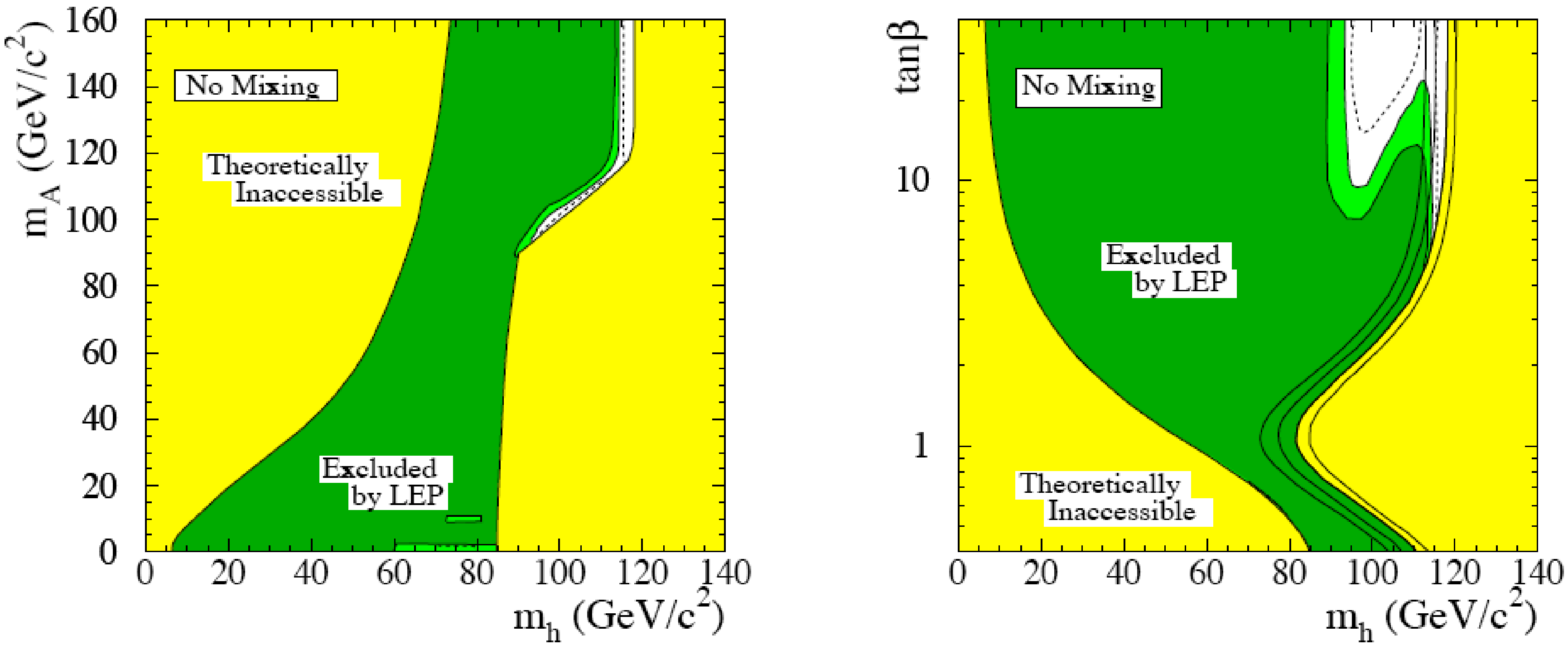
$$\left| \quad \right|^2 \propto \cos^2(\beta-\alpha)$$

hZ and hA are complementary channels at LEP

$$h \longrightarrow b\bar{b},\ \tau\bar{\tau}$$
$$A \longrightarrow b\bar{b},\ \tau\bar{\tau}$$







No Mixing
Theoretically Inaccessible
Excluded by LEP
m_A (GeV/c^2)
m_h (GeV/c^2)
No Mixing
Excluded by LEP
Theoretically Inaccessible
tanβ
m_h (GeV/c^2)

Electroweak-ino spectrum and masses

Chargino

$$\mathcal{L}^{CHA}_{mass} = -\frac{1}{2}\begin{pmatrix} \tilde{W}^+ & \tilde{H}_2^+ & \tilde{W}^- & \tilde{H}_1^- \end{pmatrix}\begin{pmatrix} 0 & \mathcal{M}_C^T \\ \mathcal{M}_C & 0 \end{pmatrix}\begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_2^+ \\ \tilde{W}^- \\ \tilde{H}_1^- \end{pmatrix} + \text{h.c.}$$

$$\mathcal{M}_C \qquad \begin{pmatrix} M_2 & \sqrt{2}m_W \sin\beta \\ \sqrt{2}m_W \cos\beta & \mu \end{pmatrix}$$

diagonalized by bi-unitary transformation

$$U^* \mathcal{M}_C V^\dagger = \begin{pmatrix} m_{\tilde{\chi}_1^\pm} & 0 \\ 0 & m_{\tilde{\chi}_2^\pm} \end{pmatrix}$$

= two charged Dirac fermions

Neutralino

$$\left(\tilde{\Psi}^0\right)^T \equiv \left(\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0\right)$$

$$\mathcal{L}_{mass}^{NEU} = -\frac{1}{2}\left(\tilde{\Psi}^0\right)^T \mathcal{M}_N \tilde{\Psi}^0 + \text{h.c.}$$

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

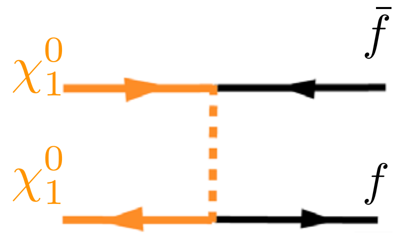
$$N^* \mathcal{M}_N N^\dagger = \text{diag}\left(m_{\tilde{\chi}_1^0}\ m_{\tilde{\chi}_2^0}\ m_{\tilde{\chi}_3^0}\ m_{\tilde{\chi}_4^0}\right)$$

Over a broad range of parameters the lightest neutralino is the LSP

thermal relic abundance
basically determined by
pair-annihilation cross section

$$\Omega_{LSP} \sim \frac{1}{\sigma}\frac{(T_\gamma^0)^3}{H_0^2 M_P^3} \sim \left(\frac{m_{LSP}}{100\,\text{GeV}}\right)^2$$

$$\sigma \sim \frac{4\pi\alpha^2}{m_{LSP}^2}$$



The two other naturalness problems of the SM

$$\mathcal{L}_{SM} = \mathcal{L}^{d=0} + \mathcal{L}^{d=2} + \mathcal{L}^{d=4} + \ldots$$

$$M^4$$

vacuum energy density
(cosmological constant)

$$\frac{\theta}{64\pi^2} G^A_{\mu\nu} G^A_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$$

CP violation in the
strong interactions

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

vacuum energy 'gravitates' $\mathcal{L}_{SM} \quad \rightarrow \quad \sqrt{\det g}\, \mathcal{L}_{SM} = \sqrt{\det g} \Big\{ M^4 - V(\langle H \rangle) + \ldots \Big\}$

Perlmutter el al., '98
Riess et al., '98

red-shift versus distance relation of type Ia supernovae ➡

$$\rho_{cosm} = -M^4 + V(\langle H \rangle) + \ldots \simeq 10^{-47} \mathrm{GeV}^4 \equiv (10^{-3} \mathrm{eV})^4$$

at quantum level $\delta M^4 = \sum_i \frac{(-1)^{F_i}}{2} \int \omega_i(k) \frac{d^3k}{(2\pi)^3} \quad \sim \quad \frac{1}{16\pi^2} \Lambda^4$

for $\Lambda \sim M_P$ a cancellation to one part in 10^{120} is needed!!!

Strong CP violation

Anomaly

$$\bar{q}\,\hat{M} e^{i\frac{\theta}{6}\gamma_5}\, q \quad \equiv \quad \bar{q}\,\hat{M}\,q + \frac{\theta}{64\pi^2} G^A_{\mu\nu} G^A_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$$

overall phase of the quark mass matrix is an observable in QCD

- neutron electric dipole moment $\quad \mathcal{H}_{int} = d_N\, \vec{\sigma}_N \cdot \vec{E}$

$$d_N \sim \theta \frac{e}{f_\pi m_n} \frac{m_u m_d}{m_d + m_u} \sim 5 \times 10^{-16} \times \theta\,\mathrm{cm}$$

$$\left|d_N\right|_{exper} < 6.3 \times 10^{-26}\, e\,\mathrm{cm} \quad \Rightarrow \quad |\theta| < 3 \times 10^{-10}$$

While the other phase $\quad \mathrm{Arg}(V_{ud} V^*_{ub} V_{tb} V^*_{td}) = O(1)$

Possible 'brilliant' solution: Peccei-Quinn axion mechanism

promote θ to a scalar field $a(x)$ $\mathcal{L}_{mass} = \bar{q}\,\hat{M} e^{i\frac{a(x)}{6}\gamma_5}\,q$

neglecting the anomaly, any constant shift $a(x) \to a(x) + c$

can be compensated by chiral rotation of quark fields $q \to e^{-i\frac{c}{6}\gamma_5} q$

$$\mathcal{L}(a) \equiv \mathcal{L}(\partial_\mu a) = \frac{f_a^2}{2}\partial_\mu a \partial^\mu a + \ldots$$

$\Lambda_{QCD} \neq 0$ ➡ a potential is generated: $V(a) = V(-a)$

$V(a) = \frac{1}{2} f_\pi^2 m_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}\left[a^2 + O(a^4)\right]$ ➡ $\theta \equiv \langle a \rangle = 0$

$$m_a = \frac{f_\pi m_\pi}{f_a}\frac{\sqrt{m_u m_d}}{(m_u + m_d)}$$

axion couples to matter with strength $\frac{1}{f_a}$

- at low f_a , axion emission cools stars too fast: $f_a > 10^9\ \mathrm{GeV}$

from observed neutrino flux in SN1987A

G. Raffelt

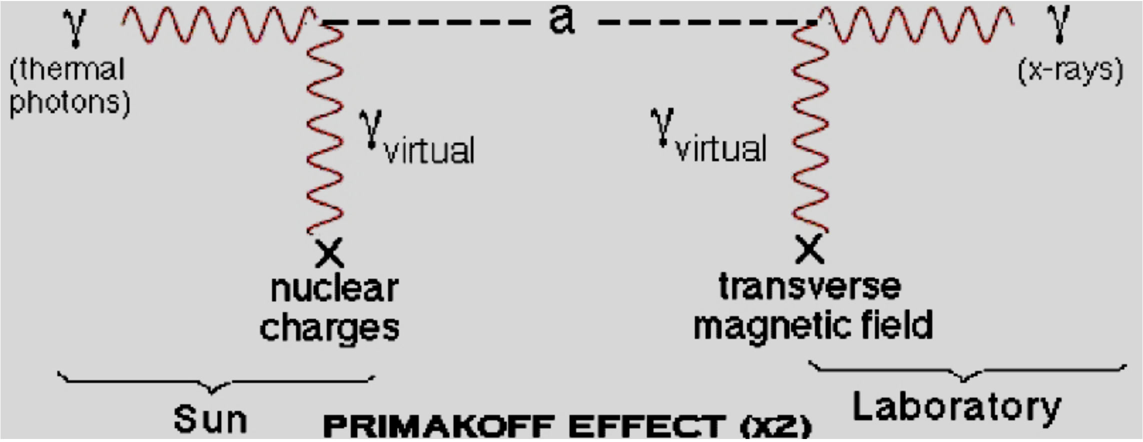
- cosmology: axion field oscillations around minimum of potential behave like non-relativistic dark matter

early $m_a < H$ oscillation is frozen

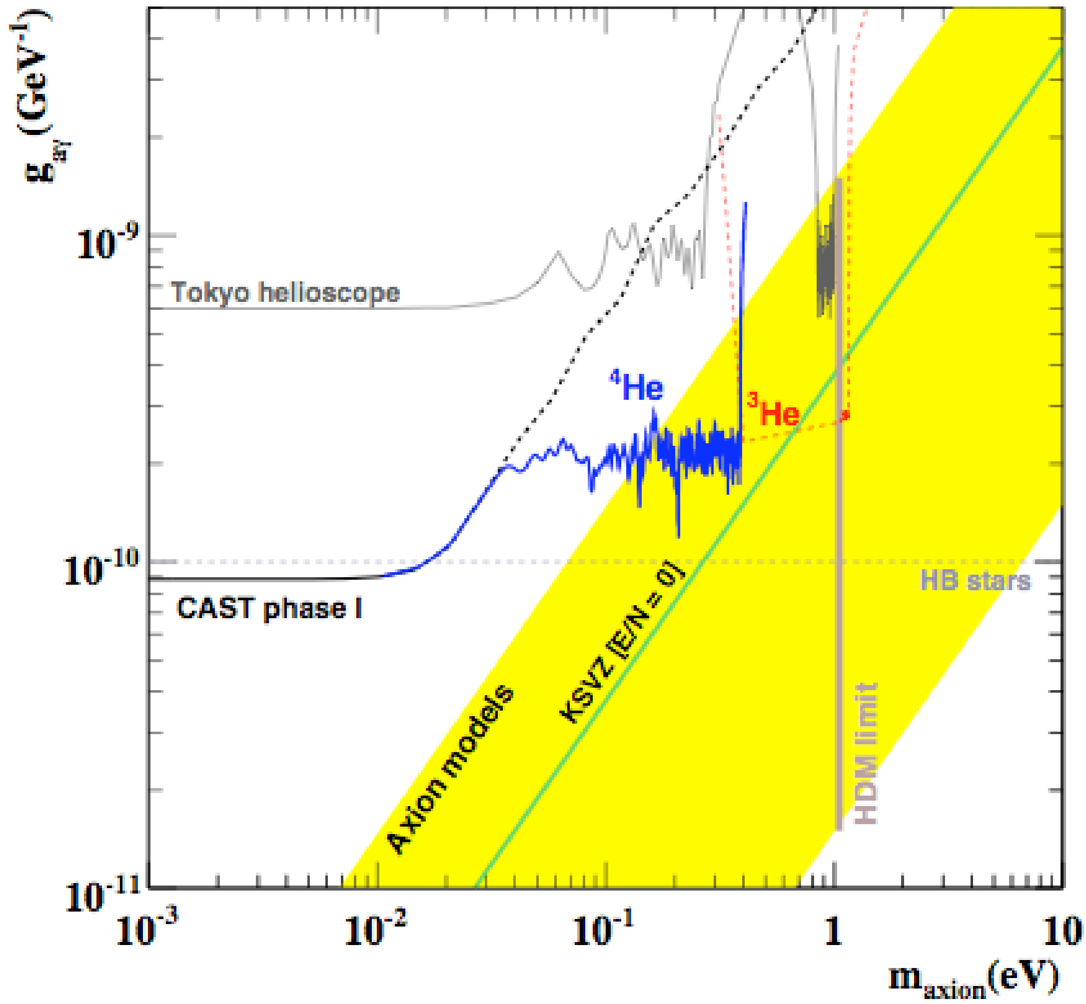
late $m_a > H$ axion energy density dilutes like non-rel dark matter $\sim R(t)^{-3}$

$$m_a \sim \frac{m_\pi f_\pi}{f_a}$$

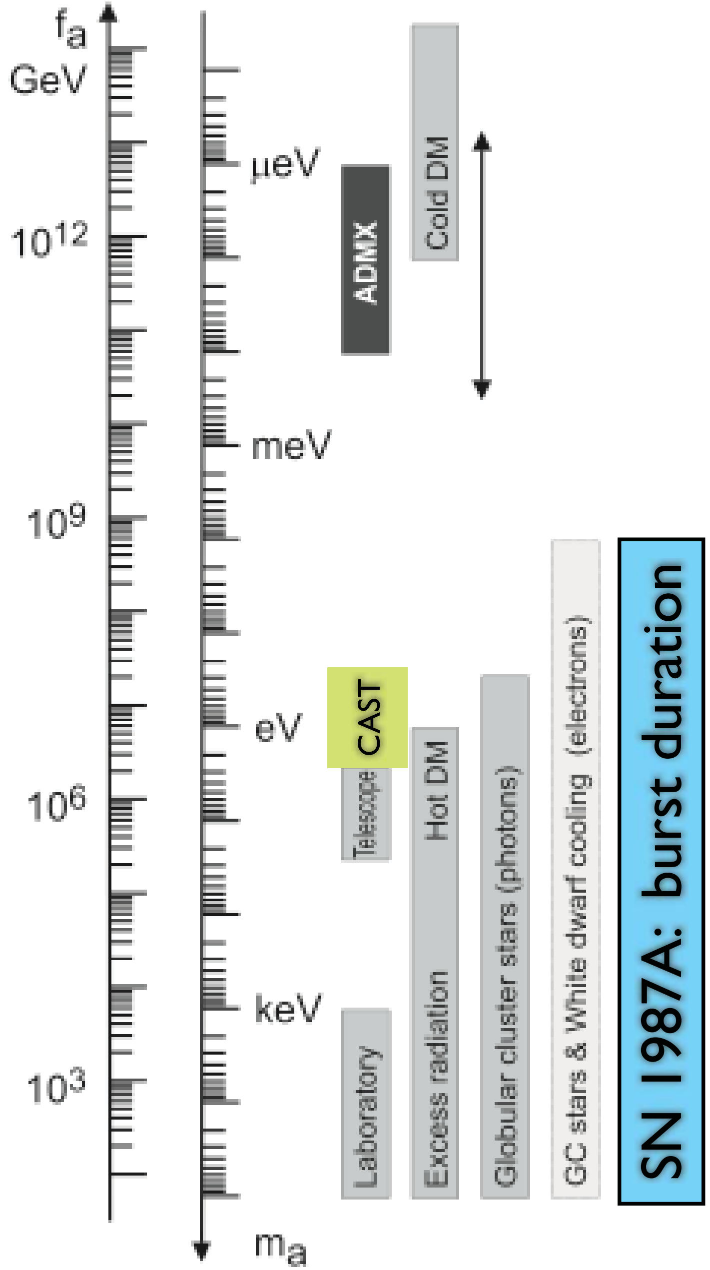
$f_a < 10^{12}\ \mathrm{GeV}$ to avoid overclosure


γ
(thermal
photons)
a
γ
(x-rays)
γvirtual
γvirtual
nuclear
charges
transverse
magnetic field
Sun
PRIMAKOFF EFFECT (x2)
Laboratory


CAST



$g_{a\gamma}$ (GeV^{-1})
10^{-9}
10^{-10}
10^{-11}
Tokyo helioscope
^{4}He
^{3}He
CAST phase I
HB stars
Axion models
KSVZ [E/N = 0]
HDM limit
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion}(eV)



f_a GeV
10^12
10^9
10^6
10^3
μeV
meV
eV
keV
m_a
ADMX
Cold DM
CAST
Telescope
Hot DM
Laboratory
Excess radiation
Globular cluster stars (photons)
GC stars & White dwarf cooling (electrons)
SN 1987A: burst duration

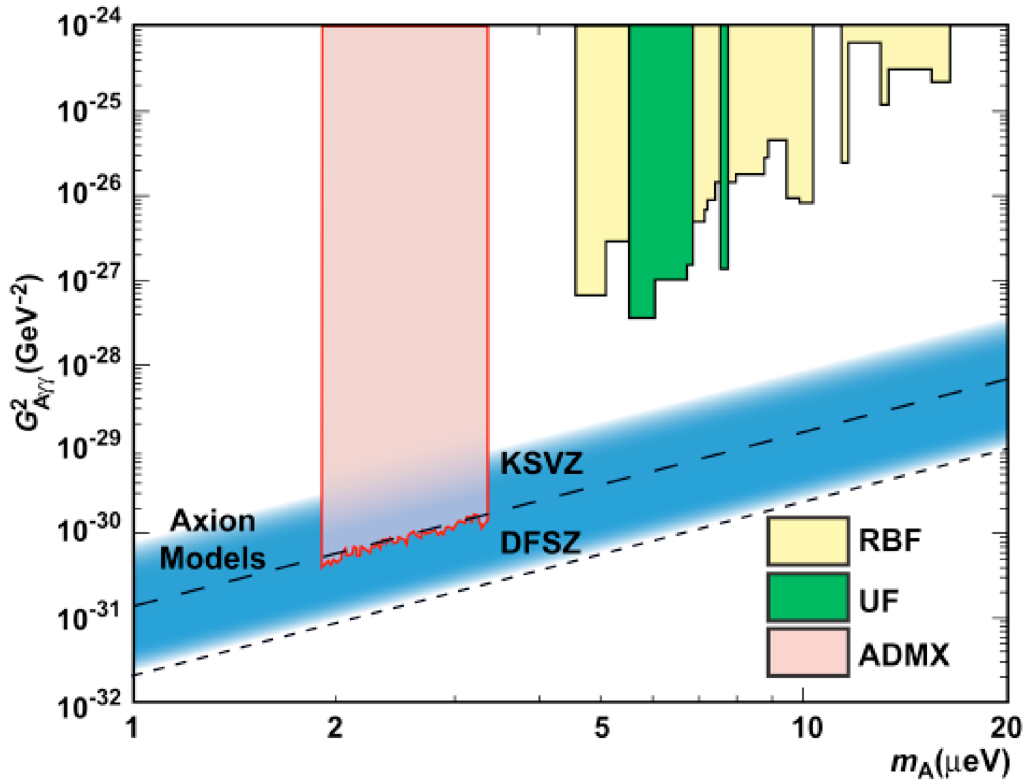


Figure 4: Exclusion region reported from the microwave cavity experiments RBF and UF [75] and ADMX [76]. A local dark-matter density of 450 MeV cm^{-3} is assumed.

Upgrade of ADMX should explore all the relevant mass range 1-100 μeV where axion is realistic dark matter candidate

Grand Unification

(GUT = Grand Unified Theory)

☆ **GUT hypothesis**: at a more fundamental level G_{SM} is embedded in a ***simple*** group G_U

Georgi 1974

$$G_U \supset SU(3) \times SU(2) \times U(1)_Y$$

- G_U interactions are described by just one coupling g_U

$$G_U \xrightarrow{M_U} SU(3) \times SU(2) \times U(1)_Y \xrightarrow{M_W} SU(3) \times U(1)_Q$$

g_U		g_3	g_2	g_1

$$G_{SM} = SU(3) \times SU(2) \times U(1)_Y$$

group of 3x3 matrices U_3 satisfying

$$U_3 U_3^\dagger = \mathbf{1}$$
$$\mathrm{Det}\, U_3 = 1$$

3 + 2 = 5 —minimal possibility→ $G_U = SU(5)$

group of 5 x 5 matrices satisfying

$$U_5 U_5^\dagger = \mathbf{1}$$
$$\mathrm{Det}\, U_5 = 1$$

Georgi 1974

subgroups of SU(5)

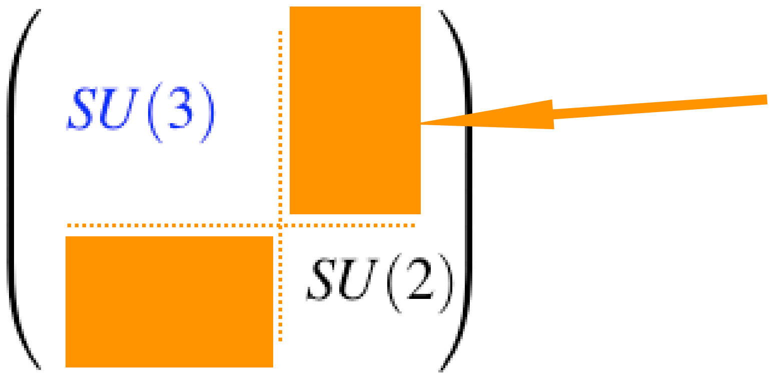
$SU(3)$ ➡ $$\left(\begin{array}{ccc|cc} & U_3 & & 0 & 0 \\ & & & 0 & 0 \\ & & & 0 & 0 \\ \hline 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{array}\right) = \left(\begin{array}{c|c} U_3 & 0 \\ \hline 0 & \mathbf{1}_{2\times 2} \end{array}\right)$$

$SU(2)$ ➡ $$\left(\begin{array}{ccc|cc} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \hline 0 & 0 & 0 & \multicolumn{2}{c}{\multirow{2}{*}{U_2}} \\ 0 & 0 & 0 & & \end{array}\right) = \left(\begin{array}{c|c} \mathbf{1}_{3\times 3} & 0 \\ \hline 0 & U_2 \end{array}\right)$$

$U(1)$ ➡ $$\begin{pmatrix} e^{i\frac{\theta}{3}} & & & & \\ & e^{i\frac{\theta}{3}} & & \mathbf{0} & \\ & & e^{i\frac{\theta}{3}} & & \\ & \mathbf{0} & & e^{-i\frac{\theta}{2}} & \\ & & & & e^{-i\frac{\theta}{2}} \end{pmatrix} = U(1)_Y$$

quantized hypercharge !

generators of SU(5)



12 new generators

$$T_{13} = \begin{pmatrix} & \mathbf{0} & & 1 & 0 \\ & & & 0 & 0 \\ & & & 0 & 0 \\ 1 & 0 & 0 & & \\ 0 & 0 & 0 & & \mathbf{0} \end{pmatrix} \qquad T_{14} = \begin{pmatrix} & \mathbf{0} & & i & 0 \\ & & & 0 & 0 \\ & & & 0 & 0 \\ -i & 0 & 0 & & \\ 0 & 0 & 0 & & \mathbf{0} \end{pmatrix} \qquad \ldots \qquad T_{24}$$

12 extra gauge bosons ~ 6 complex fields

$$SU(2) \updownarrow \begin{pmatrix} X_1 & X_2 & X_3 \\ Y_1 & Y_2 & Y_3 \end{pmatrix} = \left(\bar{3},\, 2,\, \frac{5}{3}\right)$$

$\longleftrightarrow$ $SU(3)$

Fermions

$$\mathbf{10} = \begin{pmatrix} 0 & \bar{u}_3 & -\bar{u}_2 & u_1 & d_1 \\ -\bar{u}_3 & 0 & \bar{u}_1 & u_2 & d_2 \\ \bar{u}_2 & -\bar{u}_1 & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & \bar{e} \\ -d_1 & -d_2 & -d_3 & -\bar{e} & 0 \end{pmatrix}$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$\bar{e}_R$$

$$\bar{\mathbf{5}} = \begin{pmatrix} \bar{d}_1 \\ \bar{d}_2 \\ \bar{d}_3 \\ e_L \\ \nu_L \end{pmatrix}$$

- quarks & leptons unified
- particles & anti-particles in the same multiplets

Baryon and lepton numbers are violated
by SU(5) gauge interactions

SU(5) Higgs mechanism

$$SU(5) \xrightarrow{\text{broken}} SU(3)\times SU(2)\times U(1)_Y$$

X_μ and Y_μ get a large mass

$$\mathcal{L}_{\text{mass}} = \frac{M_X^2}{2}\left(X_\mu^\dagger X^\mu + Y_\mu^\dagger Y^\mu\right)$$

in more detail: $\Sigma =$ scalar field in adjoint ($\mathbf{24}$) of $SU(5)$

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

at minimum of potential

$$\langle\Sigma\rangle = v\begin{pmatrix} 1 & & & & \\ & 1 & & \mathbf{0} & \\ & & 1 & & \\ & \mathbf{0} & & -\frac{3}{2} & \\ & & & & -\frac{3}{2} \end{pmatrix} \propto \mathbf{Y}$$

$$M_X^2 = \frac{25}{4}\, g_5^2\, v^2$$

decomposition of Σ under $SU(3) \times SU(2) \times U(1)_Y$

$\mathbf{24}$ ⇒

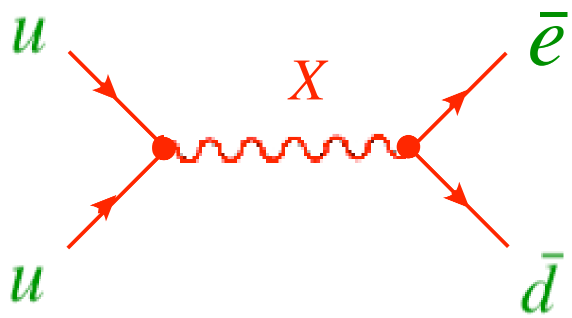
12 = Goldstone bosons eaten by X,Y

8 = massive color octect

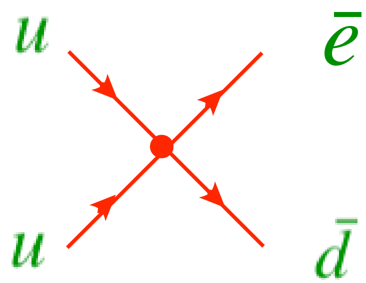
3 = massive weak triplet

1 = massive singlet

proton decay



$\sim$



$$\frac{1}{\Lambda_{\not{B}}^2} = \frac{g_5^2}{2M_X^2}$$

$$\tau(p \to e^+\pi^0) \; = \; 10^{35\pm1} \; \left(M_X/10^{16}\,\mathrm{GeV}\right)^4 \text{ years}$$

$$\tau(p \to e^+\pi^0) \; > \; 8.2 \times 10^{33}\,\text{years}$$

➡ $M_X \; > \; 3 \times 10^{15}\,\mathrm{GeV}$

Super-Kamiokande 2009

Gauge couplings

- unbroken SU(5)

$$g_3 = g_2 = \sqrt{\frac{5}{3}} g_Y = g_5$$

$$\sin^2\theta_W \equiv \frac{g_Y^2}{g_2 + g_Y^2} = \frac{3/5}{1+3/5} = \frac{3}{8} = 0.375$$

experimentally at E ~ 100 GeV

$$g_3^2 \simeq 1.5 \qquad g_2^2 \simeq 0.42$$

$$\sin^2\theta_W = 0.2315 \pm 0.0005$$

- but couplings depend on energy while SU(5) relations are valid at $E \gtrsim M_X \gg 100\,\mathrm{GeV}$

- must extrapolate SU(5) prediction down to $100\,\mathrm{GeV}$ and then compare with the data

NOTATION

customary when working with GUTs to define hypercharge coupling as

$$g_1^2 \equiv \frac{5}{3}\, g_Y^2$$

so that the SU(5) relation would simply read

$$g_3^2 = g_2^2 = g_1^2$$

Exact propagators of SM gauge group factors

$$\frac{g_i^2(p^2)}{p^2} = \frac{g_5^2}{p^2}\left\{ 1 + \frac{b_i\, g_5^2}{16\pi^2}\ln\left(\frac{p^2}{M_X^2}\right) + \dots \right.$$

only particles with mass $\ll M_X$ contribute a log enhanced loop

SM (or SSM) particles do not fill complete SU(5) multiplets $b_3 \neq b_2 \neq b_1$

$$g_3^2(m_Z^2) \neq g_2^2(m_Z^2) \neq g_1^2(m_Z^2)$$

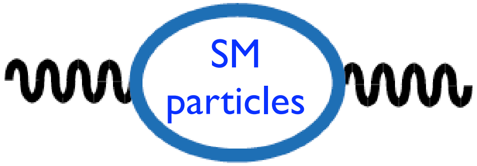
Conversely: 1) having measured the gauge couplings at the weak scale
2) assuming a particle spectrum above the weak scale

gauge coupling unification can be tested

2 inputs (g_5, M_X) → 3 outputs $g_3^2(m_Z^2),\quad g_2^2(m_Z^2),\quad g_1^2(m_Z^2)$

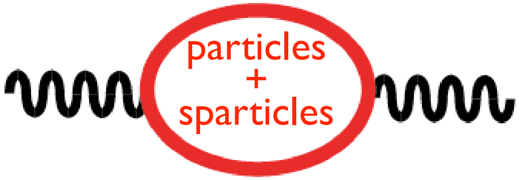
1 prediction !

Standard Model:

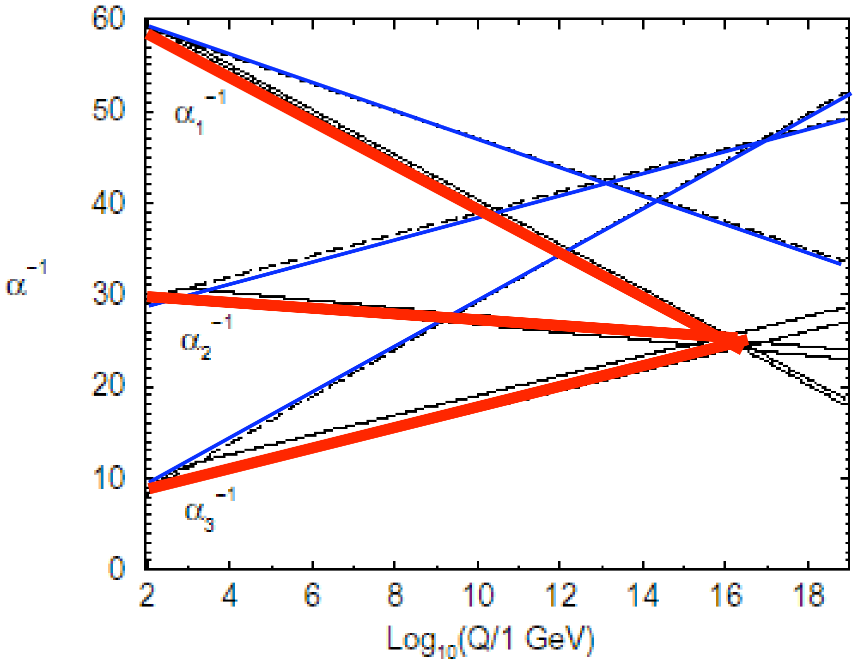


$g^2(E)$

Supersymmetric Standard Model:



$g^2(E)$



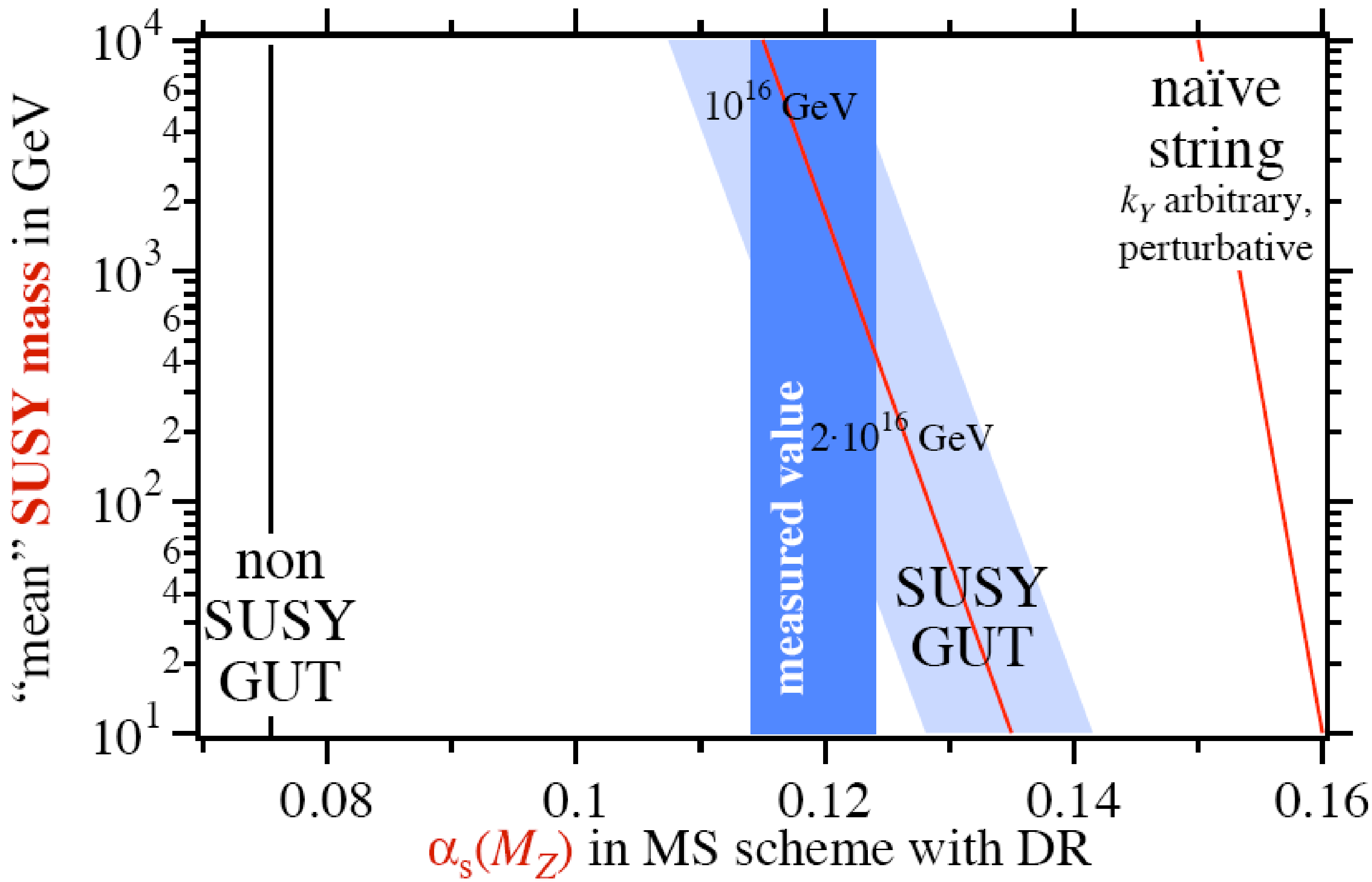
couplings beautifully unify in SUSY !

input $\alpha_{EM}(m_Z)$, $\sin^2\theta_W$

$g_2^2(m_Z^2)$, $g_1^2(m_Z^2)$

predict $\alpha_s(m_Z)$

Barbieri '97



the gauge couplings run only logarithmically

the scale where any two of them meet depends exponentially on their measured values at the weak scale

it is then quite remarkable that all three couplings meet at a scale $M_G \sim 10^{16}\,\mathrm{GeV}$ which is

- below, but close, to the Planck scale $M_P = 10^{19}\,\mathrm{GeV}$

  gravity and gauge interactions have comparable strength at $M_{str} \sim \sqrt{\alpha_5}\, M_P \sim 10^{18}\,\mathrm{GeV}$

- just above proton decay bound $M_G \equiv M_X > 3 \times 10^{15}\,\mathrm{GeV}$

we could have conceivably gotten crazy results like

$M_G \sim \times 10^{80}\,\mathrm{GeV}$ or $M_G \sim \times 10^{-20}\,\mathrm{GeV}$

Supersymmetry with Grand Unification seems a very convincing scenario beyond the Standard Model

....but there are a few dark corners in it

R-parity is not an accidental symmetry in the SSM

- One can write renormalizable R-violating terms in the superpotential

$$f_{\not R} = \lambda_{ijk}\, u_c^i d_c^j d_c^k + \lambda'_{ijk}\, q^i d_c^j \ell^k + \lambda''_{ijk}\, \ell^i \ell^j e_c^k + \mu_i\, H_2 \ell^i$$

$\Delta B = 1$ $\Delta L = 1$ $\Delta L = 1$ $\Delta L = 1$

- exact or approximate R-parity must be imposed in order to avoid unwanted fast proton decay or lepton number violation

Ex.: double nucleon decay $|\lambda_{usd}| < 10^{-15} \left(\frac{M_{susy}}{\Lambda_{QCD}}\right)^{5/2}$

Barbieri-Masiero '86
Allanach, Dedes, Dreiner '99

R could arise as accidental symmetry in SO(10) grand unification

Flavour is also not 'automatically' conserved in SSM

$$\mathcal{L}_{mass} = (m^2_{\tilde q})_{ij}\, \tilde q_i^\dagger \tilde q_j + (m^2_{\tilde u^c})_{ij}\, \tilde u_i^{c\dagger} \tilde u_j^c + (m^2_{\tilde d^c})_{ij}\, \tilde d_i^{c\dagger} \tilde d_j^c + (m^2_{\tilde \ell})_{ij}\, \tilde \ell_i^\dagger \tilde \ell_j + (m^2_{\tilde e^c})_{ij}\, \tilde e_i^{c\dagger} \tilde e_j^c$$

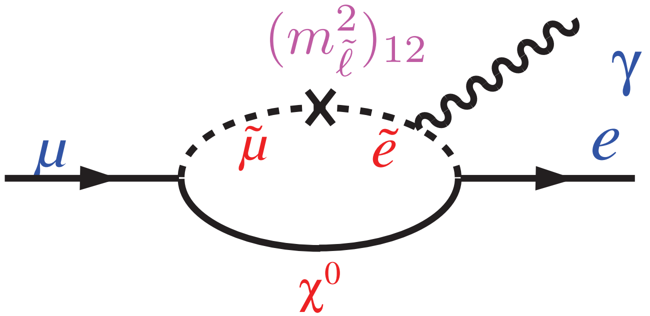
$$\mathcal{L}_A = (A_u)_{ij}\, \tilde q_i H_2 \tilde u_j^c + (A_d)_{ij}\, \tilde q_i H_1 \tilde d_j^c + (A_e)_{ij}\, \tilde \ell_i H_1 \tilde e_j^c$$

soft masses and A-terms are in general new sources of flavor violation

Ex. : lepton flavor violation

in general $(A_e)_{ij},\ (m^2_{\tilde\ell})_{ij},\ (m^2_{\tilde e^c})_{ij}$ not diagonal

in the basis where $(Y_e)_{ij} = \mathrm{diag}(\lambda_e,\ \lambda_\mu,\ \lambda_\tau)$



$= \quad \mu \to e\gamma$

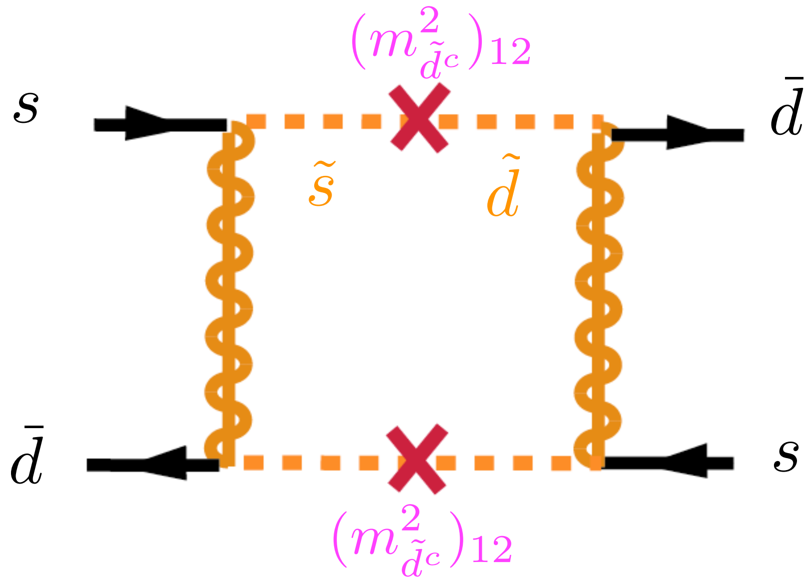
$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-11} \left(\frac{(m^2_{\tilde\ell})_{12}/m^2_{SUSY}}{0.001}\right)^2 \left(\frac{200\mathrm{GeV}}{m_{SUSY}}\right)^4$$

$\mathrm{Br}(\mu \to e\gamma) < 1.2 \times 10^{-11}$

MEGA 1999

$$\frac{(m^2_{\tilde\ell})_{12}}{m^2_{SUSY}} \lesssim 10^{-2} \div 10^{-3}$$

$\Delta m_K \quad \& \quad \epsilon_K$



$$\mathrm{Re}\left[\frac{(m^2_{\tilde{d}^c})_{12}}{m^2_{SUSY}}\right]^2 \lesssim 10^{-3}\left(\frac{m_{SUSY}}{500\,\mathrm{GeV}}\right)^2$$

$$\mathrm{Im}\left[\frac{(m^2_{\tilde{d}^c})_{12}}{m^2_{SUSY}}\right]^2 \lesssim 10^{-5}\left(\frac{m_{SUSY}}{500\,\mathrm{GeV}}\right)^2$$

Problem would not exist if (at some scale) the soft terms satisfied

I) $(m^2_{\tilde{d}^c})_{ij} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} m^2_D \equiv \mathbf{1}\, m^2_D$

$(m^2_{\tilde{q}})_{ij} = \mathbf{1}\, m^2_Q \qquad (m^2_{\tilde{u}^c})_{ij} = \mathbf{1}\, m^2_U \qquad (m^2_{\tilde{\ell}})_{ij} = \mathbf{1}\, m^2_L \qquad (m^2_{\tilde{e}^c})_{ij} = \mathbf{1}\, m^2_E$

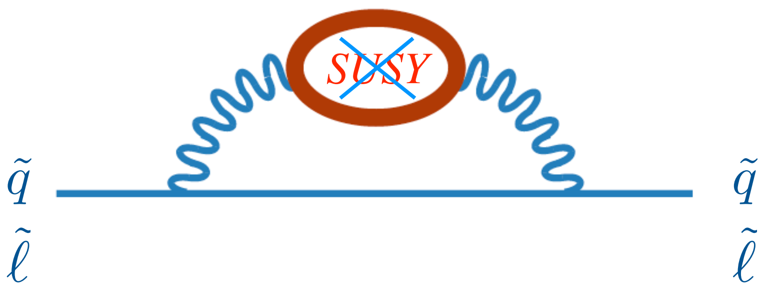
II) $(A_u)_{ij} \propto (Y_U)_{ij} \qquad (A_d)_{ij} \propto (Y_d)_{ij} \qquad (A_e)_{ij} \propto (Y_e)_{ij}$

This choice defines Natural Flavor Conservation (NFC):

all flavor mixing is due to Yukawa matrices

(now sometimes called ‘minimal flavor violation’)

- gauge mediated models: realize Natural Flavor Conservation



$(m^2_{\tilde{q}})_{ij} = \mathbf{1}\, m^2_Q$ $(m^2_{\tilde{d}^c})_{ij} = \mathbf{1}\, m^2_D$ $(m^2_{\tilde{u}^c})_{ij} = \mathbf{1}\, m^2_U$ $(m^2_{\tilde{\ell}})_{ij} = \mathbf{1}\, m^2_L$ $(m^2_{\tilde{e}^c})_{ij} = \mathbf{1}\, m^2_E$

only depend on
gauge quantum numbers

Yukawa couplings are generated at a scale $\Lambda_F \gg M_{messenger}$

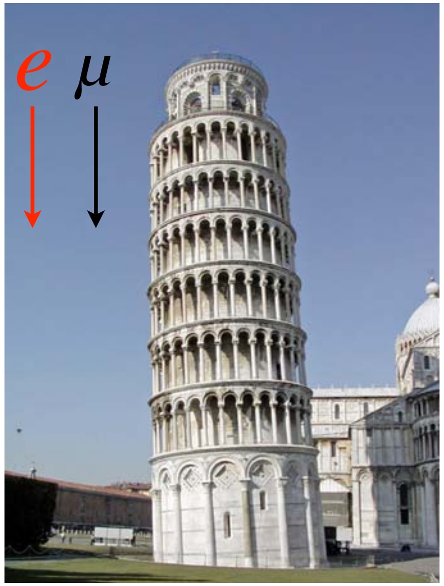
therefore, Yukawas are the only source of flavor mixing at the messenger scale

Higher loop corrections to soft masses do contain flavor mixing

but it is all coming from the Yukawa matrices ⟹ (NFC)

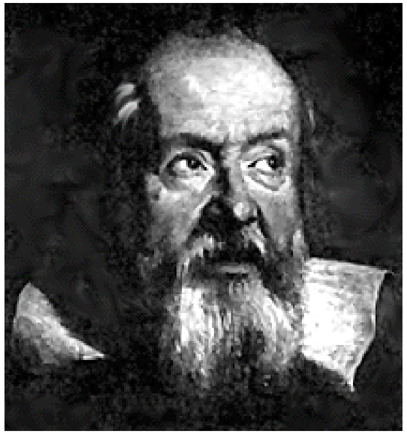
What about gravity mediated supersymmetry breaking ?

Gravity (as we know it) is flavor universal



Equivalence Principle:

all particles follow the same trajectories while falling in a gravitational field



The supersymmetric theory of gravity, Supergravity, provides a mechanism to give the superparticles a mass ☺

Arnowitt,Chamseddine,Nath '82
Barbieri, Ferrara, Savoy '82

However, we do not expect universality to hold in quantum gravity, at distances of the order of the Planck length $1/M_{\rm P} \sim 10^{-33}\,{\rm cm}$ ☹

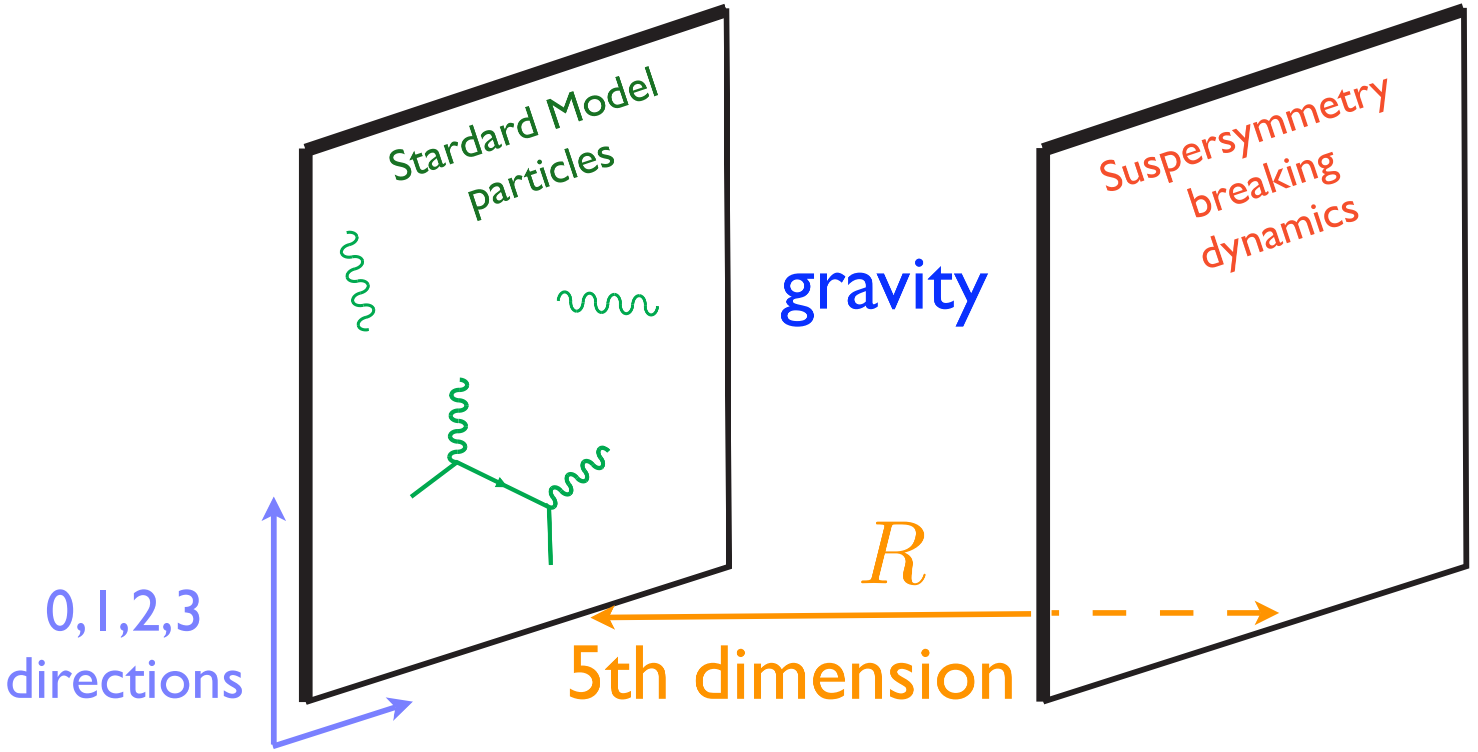
Quantum gravity (string theory) should provide the most fundamental description of all phenomena: in particular it should distinguish among the different flavors in order to account for their different masses

Gravity becomes universal only at distances $\gg 1/M_{\rm P}$
by the field theory analogue of multipole expansion

◆ How can one exploit the long distance (infrared) universality of gravity in order to give realistic mass to superparticles?

Extra space dimension(s)

Randall,Sundrum '98



$$R \gg \frac{1}{M_{\rm P}}$$

Superparticle masses are determined by two leading effects

- **Superconformal Anomaly contribution**

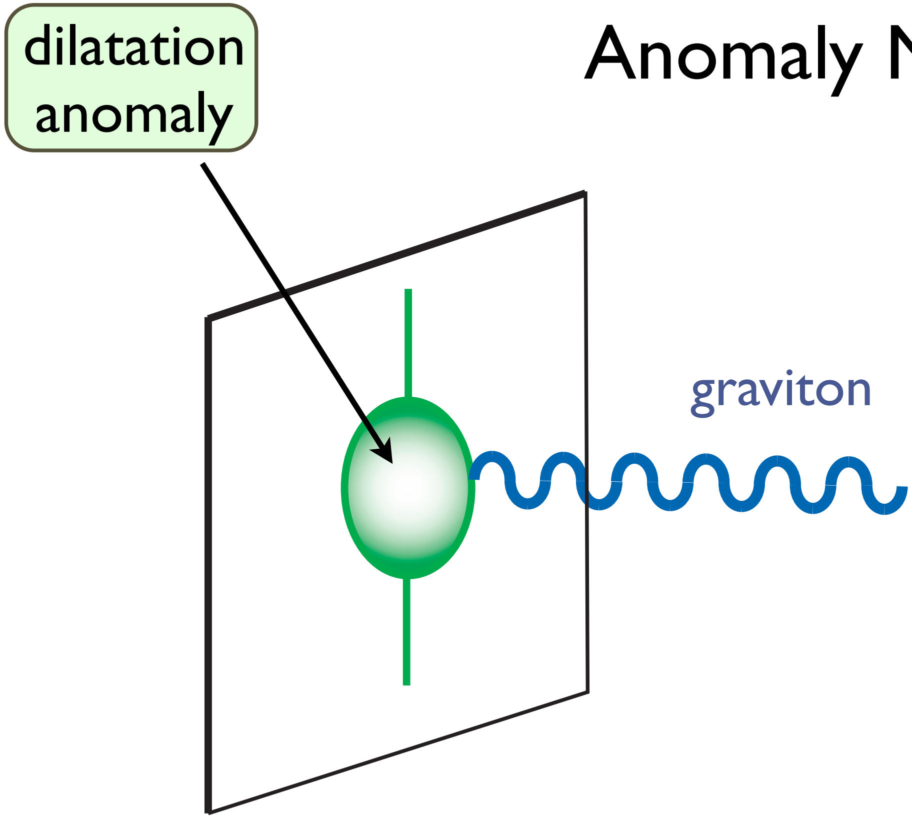
  (Anomaly Mediated Supersymmetry Breaking)

  Randall,Sundrum '98
  Giudice,Luty,
  Murayama,Rattazzi '98

- **Brane-to-Brane contribution**

  Chacko,Luty,Maksymik,Ponton '99
  Luty,Sundrum '99
  Rattazzi,Scrucca,Strumia '03
  Buchbinder,Gates,Goh,LinchIII,
  Luty,Ng,Phillips '03
  Gregoire,Rattazzi,Scrucca,Strumia,
  Trincherini '04

Anomaly Mediation



graviton supermultiplet $\supset$ dilatation supermultiplet

$$\phi = (h^\mu_\mu, \ldots, u)$$

$\Updownarrow$

ϕ couples to the anomaly supermultiplet $(T^\mu_\mu, \ldots, A)$

upon supersymmetry breaking $< u > = m_{3/2}$

⬇

superparticle masses $\propto$ beta functions & anomalous dimensions = Infrared Physics

Insensitive to Flavor violating UV physics !!

- Flavor mixing in soft terms $\propto$ CKM angles ☺

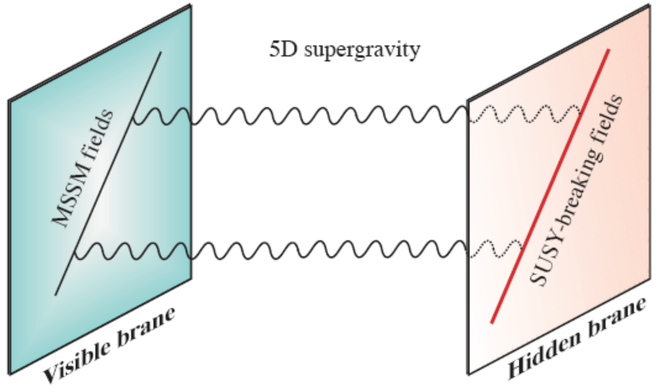
- Interesting prediction for gaugino masses $m_i = \frac{\beta_i(g_i^2)}{2g_i^2} m_{3/2}$

  ☺

- Sleptons are tachyons ☹

Brane-to-brane

2-graviton exchange contribution
to the Lagrangian



universal correction to the
masses of squarks & sleptons

$$\sim \frac{1}{6\pi^2}\frac{G_N}{R^2}\, m_{3/2}^2$$

all m^2 are positive and flavor preserving

Gregoire,Rattazzi,Scrucca '05

example of **calculable** leading effect in quantum gravity

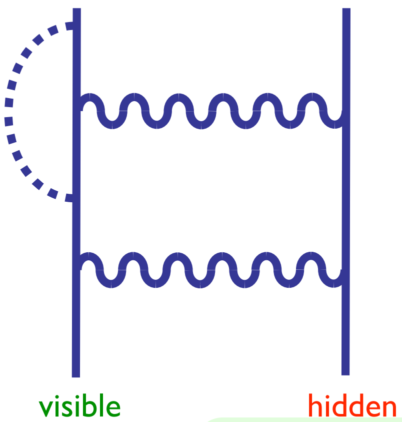
- Can give realistic mass spectrum at the weak scale in terms of 4 free parameters

- No Flavor violation other than CKM angles

Sure?

there is unavoidable, but small and `calculable', Flavor violation from Grand Unified Theory and from right-handed neutrini

Borzumati,Masiero '86
Hall,Kostelecky,Raby '86
Barbieri,Hall '94



UV finite diagram

$$Br(\mu \to e\gamma) \sim 5 \times 10^{-13} \left(\frac{\lambda_t}{0.8}\right)^4 \left(\frac{150GeV}{m_{\tilde{\ell}}}\right)^4$$

MEG experiment at PSI expects to reach sensitivity 10^{-13} by 2008 the worst drawback of Supersymmetry

is that we did not find it at LEP/SLC

minimum of potential

$$m_Z^2 = \frac{2\left(m_1^2 - m_2^2 \tan^2\beta\right)}{\tan^2\beta - 1} \sim -2m_2^2$$

RG evolution

$$m_2^2 = m_0^2 + \mu^2 - \frac{3}{4\pi^2}\lambda_t^2 m_{\tilde{t}}^2 \ln\frac{M_P}{m_{\tilde{t}}} + \ldots$$

$$\sim m_0^2 + \mu^2 - O(1)\, m_{\tilde{t}}^2 + \ldots$$

Natural expectation: $m_Z \sim m_{\tilde{t}} \sim \mu$

moreover weakly interacting gauginos and sleptons are lighter than colored stop

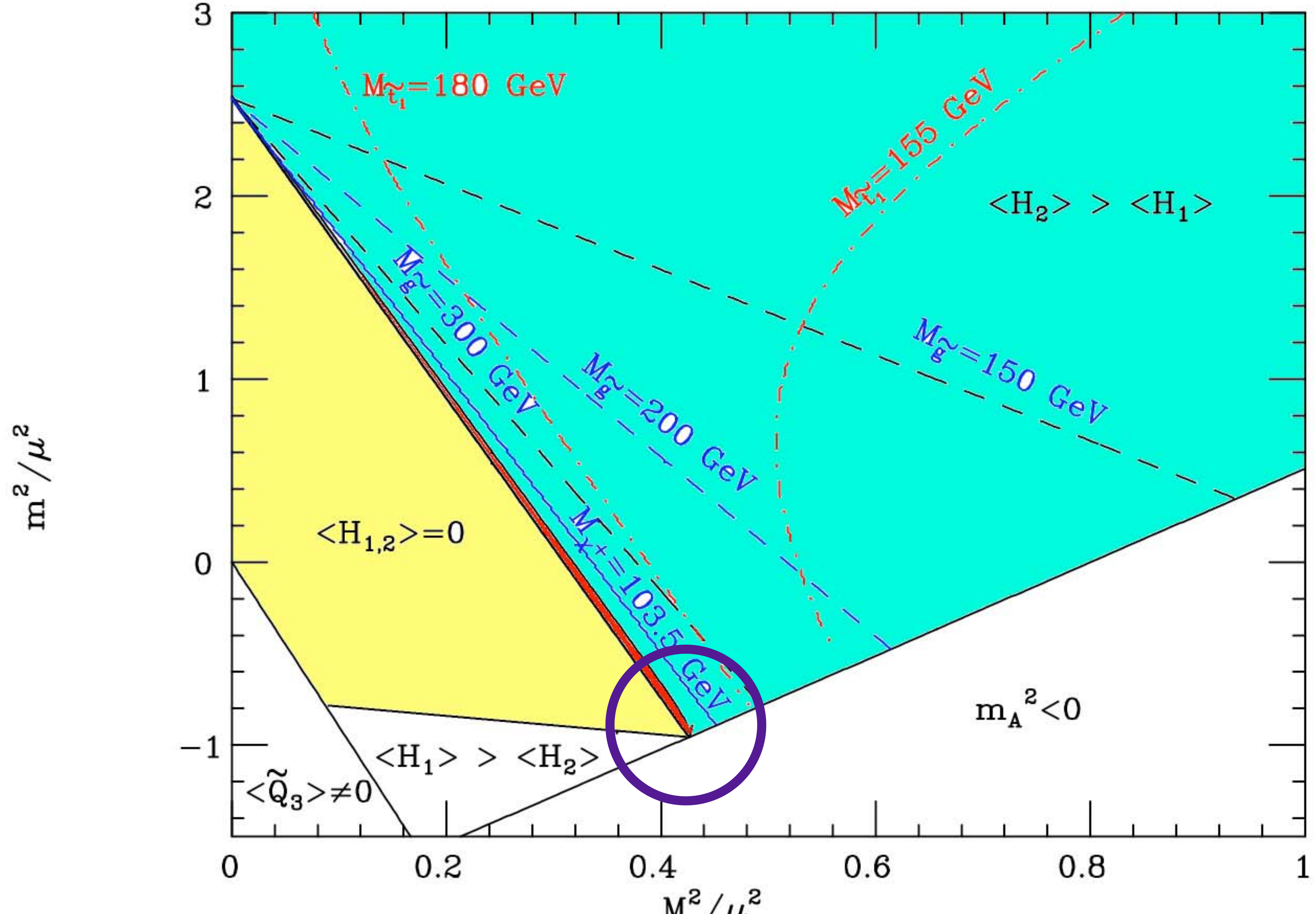
⇩

LEP scale SUSY !!

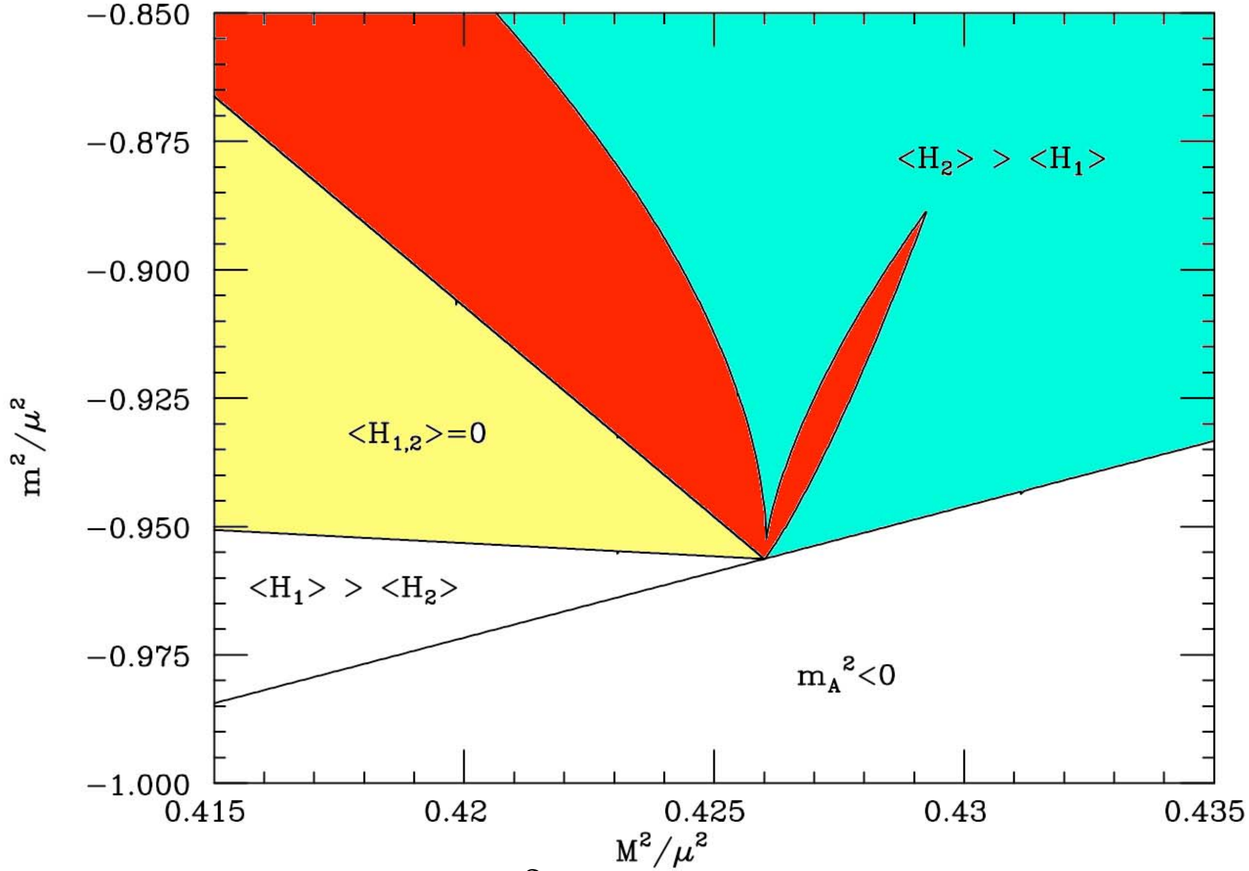
- upper bound on physical Higgs mass $m_h^2 \leq m_Z^2 + m_t^2 \frac{3\lambda_t^2}{2\pi^2} \ln m_{\tilde{t}}/m_t$

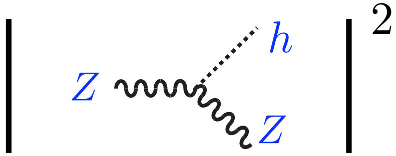
$m_h > 114.4\,\mathrm{G}eV$ ‘ ➡ ’ $m_{\tilde{t}} \gtrsim 500 \div 1000\,\mathrm{G}eV$

1 - 5 % cancellation in m_Z^2 is needed

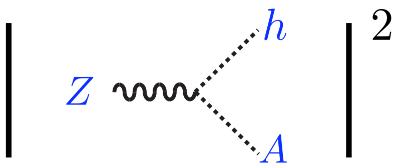


$M_{\tilde{t}_1}$=180 GeV
$M_{\tilde{t}_1}$=155 GeV
<H$_2$> > <H$_1$>
$M_{\tilde{g}}$=300 GeV
$M_{\tilde{g}}$=200 GeV
$M_{\tilde{g}}$=150 GeV
M_{χ^+}=103.5 GeV
<H$_{1,2}$>=0
<H$_1$> > <H$_2$>
<$\tilde{Q}_3$>≠0
$m_A{}^2$<0
m^2/μ^2
M^2/μ^2





$$\propto \quad \sin^2(\beta-\alpha) = \frac{1}{2}\left[1 + \frac{m_A^2 - (m_Z^2 + \Delta)}{m_H^2 - m_h^2}\right]$$



$$\propto \quad \cos^2(\beta-\alpha)$$

stop correction Δ to Higgs masses must be sizeable anyway