SUPERSYMMETRY AND THE REAL WORLD

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(I) The supersymmetric SM (structure & EW breaking)

Gravity as mediator of susy breaking (flavour problem)

(II) Gauge mediation, anomaly mediation, gaugino mediation

(III) Dark matter, unification, alternative approaches

At which energy do we expect new physics effects?

Any FT can be viewed as an effective theory below a UV cutoff

$$L_{eff} = L^{d=4}(g,\lambda) + \frac{1}{\Lambda} L^{d=5} + \frac{1}{\Lambda^2} L^{d=6} + \ldots$$

g gauge

λ Yukawa

Λ has physical meaning: maximum energy at which the theory is valid. Beyond Λ, new degrees of freedom

B number $\Rightarrow \frac{1}{\Lambda^2} qqql$ p - decay $\Rightarrow \Lambda \geq 10^{15}$ GeV

L number $\Rightarrow \frac{1}{\Lambda} llHH$ ν mass $\Rightarrow \Lambda \geq 10^{13}$ GeV

individual L $\Rightarrow \frac{1}{\Lambda^2} \bar{e} \sigma^{\mu\nu} \mu H F_{\mu\nu}$ $\mu \to e\gamma$ $\Rightarrow \Lambda \geq 10^{8}$ GeV

quark flavour $\Rightarrow \frac{1}{\Lambda^2} \bar{s}\gamma^{\mu} d\, \bar{s}\gamma_{\mu} d$ Δm_K $\Rightarrow \Lambda \geq 10^{6}$ GeV

LEP1,2 $\Rightarrow \left| H^{+} D_{\mu} H \right|^2,\ \bar{e}\gamma^{\mu} e\, \bar{l}\gamma_{\mu} l$ $\Rightarrow \Lambda \geq 10^{4}$ GeV

We are tempted to conclude that the scale of "compositeness" _ in the SM is extremely high

BUT Let us consider $V(H) = -\mu_H^2|H|^2 + \lambda|H|^4$

μ_H^2 very sensitive to high-energy corrections

$$\delta\mu_H^2 = \frac{3G_F}{8\sqrt{2}\pi^2}\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\Lambda^2 = -(0.2\,\Lambda)^2$$

$$\Lambda_{\max} = \mathrm{TeV}\left(\frac{m_H}{115\ \mathrm{GeV}}\right)\left(\frac{10\%}{\delta}\right)^{1/2}$$

No large tuning $\Rightarrow \Lambda <$ TeV

Can $m_H \sim$ 180–220 GeV reduce the tuning? NO!

Abuse of effective theories: finite (or log-div) corrections at Λ remain

Ex.: in SUSY quadratic divergences cancel, but $\delta\mu_H^2 \approx \tilde{m}^2$

HIERARCHY PROBLEM

2 possibilities:

1. $\Lambda >> v$
   - B,L, flavour conservation follows naturally
   - Mysterious separation of mass scales

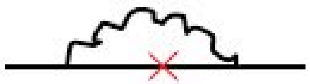
2. $\Lambda \approx v$ New theory
   - No Λ^2 corrections to μ_H^2
   - Must preserve accidental symmetries

- Considered a central problem
- Attempts to go beyond SM concentrate on its solution
- Linked to an energy scale that will be probed experimentally
- Difficulty to keep fundamental scalar particle much lighter than the scale of validity of the theory

FERMION

QED $$L = \overline{\psi}\left[\left(i\partial^{\mu} - eA^{\mu}\right)\gamma_{\mu} - m\right]\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

Mass renormalization



$$\delta m \approx \frac{\alpha}{4\pi} m \log\frac{\Lambda^2}{m^2}$$

- δm proportional to m
- only *log* divergent

It can be "naturally" small (*i.e.* $m \ll \Lambda$) [Setting it to zero enhances the symmetry of the theory. *'t Hooft*]

m is protected by a symmetry

Chiral symmetry $\psi_L \to e^{i\alpha}\,\psi_L, \psi_R \to e^{i\beta}\,\psi_R, \alpha \neq \beta \Rightarrow m$ not invariant

$\delta m \propto$ "symmetry breaking" $\approx m$

GAUGE BOSON

Gauge symmetry $A_\mu \rightarrow A_\mu + \partial_\mu \Lambda$

forbids $m^2 A_\mu A^\mu$

GOLDSTONE BOSON

$L = \partial_\mu \Phi^+ \partial^\mu \Phi - V\left(\Phi^+ \Phi\right)$ invariant under $\Phi \rightarrow e^{i\alpha}\Phi$

If $\langle \Phi \rangle = v \Rightarrow \Phi = \rho e^{i\varphi / v} \Rightarrow L = \partial_\mu \rho \partial^\mu \rho + \frac{\rho^2}{v^2} \partial_\mu \varphi \partial^\mu \varphi + V(\rho)$

$\Rightarrow \varphi$ massless

U(1) transf. $\Phi \rightarrow e^{i\alpha}\Phi \Rightarrow \rho \rightarrow \rho, \varphi \rightarrow \varphi + \alpha v$

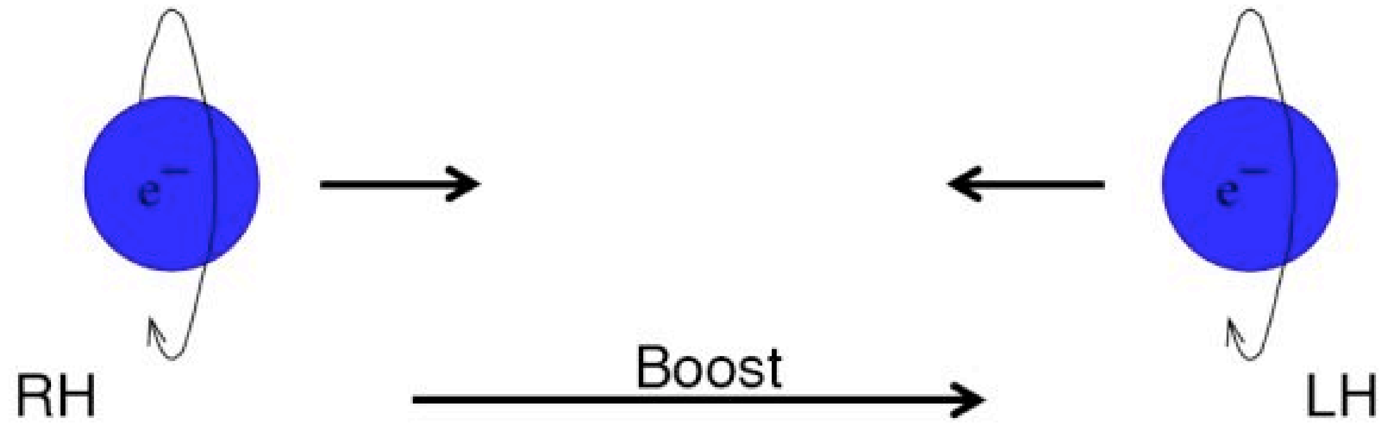
$\varphi \rightarrow \varphi + \alpha v$ forbids $m^2 \varphi^2$

What protects μ_H^2? $V(H) = -\mu_H^2 |H|^2 + \lambda |H|^4$

Setting $\mu_H^2 = 0$ does not increase the symmetry

Physical interpretation: For spin-1/2 and spin-1, mass is related to existence of new helicity states

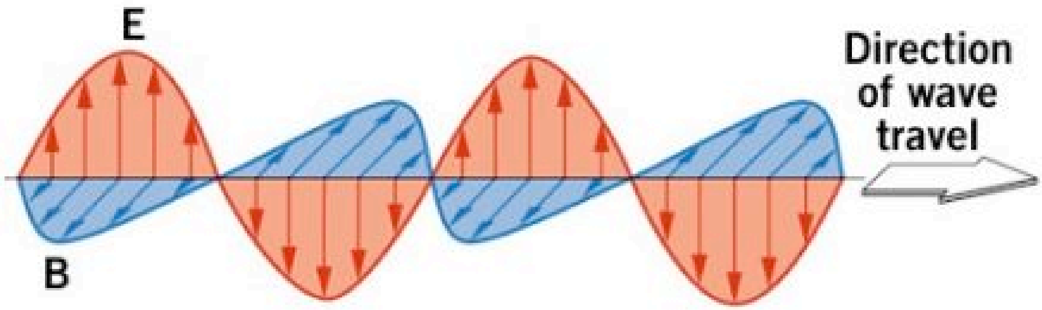
A massless spin-1/2 fermion has one helicity state



If e^- is massive, a new helicity state exists

Quantum corrections to mass are multiplicative

A massless photon has two helicity states



For a particle at rest, we cannot distinguish between transverse and longitudinal polarizations

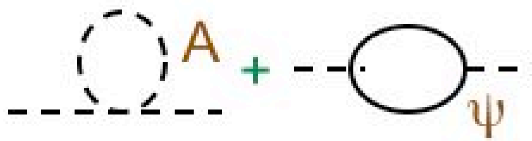
A massive photon has three helicities

SYMMETRY: relate scalars to fermions & use chiral symmetry

E.g.: complex scalar A, Weyl fermion ψ, no mass term

$$L = \partial_\mu A^+ \partial^\mu A + i\partial_\mu \overline{\psi}\,\overline{\sigma}^\mu \psi - \kappa\left(A^+A\right)^2 - \left(hA\psi\psi + \text{h.c.}\right)$$

- ψ massless because of chiral symmetry $\psi \to e^{i\alpha}\psi,\ A \to e^{-2i\alpha}A$
- scalar A mass =



$$= \frac{\kappa}{16\pi^2}\Lambda^2 - \frac{h^2}{16\pi^2}\Lambda^2$$

$m_A^2 = 0$ if $\kappa = h^2$

- Symmetry is needed to insure $m_A^2 = 0$ to all orders
- Symmetry has to relate bosons to fermions

SUPERSYMMETRY

(A solution in search of a problem)

Supersymmetry: invariance under exchange of particles with different spin $\Rightarrow$ involves space-time

Symmetry generators anticommute (transform bosons into fermions) and have non-trivial relations with Poincaré

$$\left\{Q_\alpha, \overline{Q}_{\dot{\alpha}}\right\} = 2\sigma^\mu_{\alpha\dot{\alpha}} P_\mu \qquad \left\{Q_\alpha, Q_\beta\right\} = \left\{\overline{Q}_{\dot{\alpha}}, \overline{Q}_{\dot{\beta}}\right\} = 0$$

$$\left[P_\mu, Q_\alpha\right] = \left[P_\mu, \overline{Q}_{\dot{\alpha}}\right] = 0 \qquad \left[P_\mu, P_\nu\right] = 0$$

Susy ~ $\sqrt{\text{translation}}$ Another *impossible* square root? $i = \sqrt{-1}$

To find representations of the algebra:

Superspace $x^\mu \rightarrow \left(x^\mu, \theta_\alpha, \overline{\theta}_{\dot{\alpha}}\right)$ $\theta, \overline{\theta}$ anticommuting variables

Susy algebra becomes a Lie algebra with anticommuting variables

SUPERSYMMETRIC ACTION

Chiral superfield $\bar{D}_{\alpha}\Phi = 0$

Vector superfield $V = V^{+}$ $W_{\alpha} = -\frac{1}{4}\bar{D}\bar{D}D_{\alpha}V$

$\int d^4x\, d^4\theta\, \Phi^{+}e^{V}\Phi$ → Kinetic term for chiral superfield

$\int d^4x\, d^2\theta\, W_{\alpha}W^{\alpha}$ → Kinetic term for vector superfield

$\int d^4x\, d^2\theta\, f(\Phi)$ → Superpotential: holomorphic function that defines interactions

E.g.:

$\kappa=h^2$ required for cancellation of Λ^2

$$W = \lambda\,\Phi^3 \quad \Rightarrow \quad L = -\lambda(\psi\psi A + \text{h.c.}) - \lambda^2\left(A^{+}A\right)^2$$

In general: no quadratic divergences in susy theory

MINIMAL SUPERSYMMETRIC SM

Choose:

gauge group SU(3)×SU(2)×U(1)

matter representation 3 gen. of quarks and leptons

2 Higgs doublets

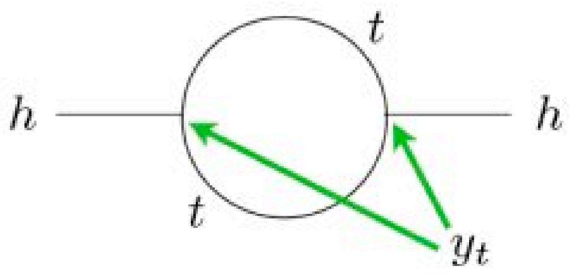
superpotential

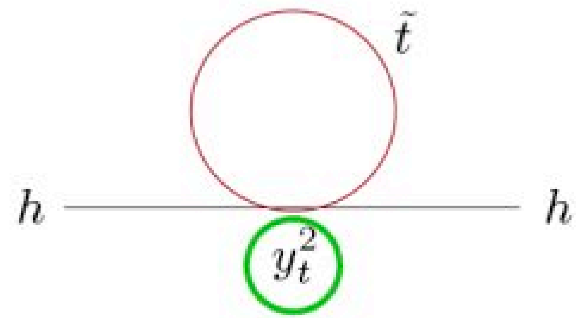
$$f = Y_u Q U^c H_2 + Y_d Q D^c H_1 + Y_e L E^c H_1 + \mu H_1 H_2$$

SUPERSYMMETRY BREAKING

See K. Intriligator's lectures

Break susy, but keep UV behavior ⇒ soft breaking





$$m_{\tilde{t}}^2 \neq m_t^2 \quad \longrightarrow \quad \delta m_h^2 \propto (m_{\tilde{t}}^2 - m_t^2) \ln \Lambda \qquad \text{Soft breaking}$$

$$y_{\tilde{t}}^2 \neq y_t^2 \quad \longrightarrow \quad \delta m_h^2 \propto (y_{\tilde{t}}^2 - y_t^2) \Lambda^2 \qquad \text{Hard breaking}$$

EFFECTIVE-THEORY APPROACH

Couple susy theory to (spurion) background ~~susy~~ chiral superfield $X = m_S\, \theta^2$

Rules:

- Write renormalizable couplings to X
- X has zero canonical dimension
- $X^n = 0$, for $n > 1$
- X^+ cannot appear in $\int d^2\theta$

$X = m_S\, \theta^2$

$$\int d^2\theta\; X W_\alpha W^\alpha \quad \to \quad m_S \lambda\lambda \qquad \text{gaugino mass}$$

$$\int d^4\theta\; X^+ X\, \Phi^+ e^V \Phi \quad \to \quad m_S^2\, \varphi^+ \varphi \qquad \text{scalar mass}$$

$$\int d^4\theta\; X^+ \Phi^+ e^V \Phi \quad \to \quad m_S\, \varphi\, F_\varphi^* = -m_S\, \varphi \frac{\partial f}{\partial \varphi} \qquad A\text{ - term}$$

$$\int d^2\theta\; X\, f(\Phi) \quad \to \quad m_S f(\varphi) \qquad A\text{ - term}$$

Recall:

$$W\left(x,\theta,\bar\theta\right) = -i\lambda(x) - \frac{i}{2}\sigma^\mu \bar\sigma^\nu \theta F_{\mu\nu} + \dots \qquad \Phi\left(x,\theta,\bar\theta\right) = \varphi(x) + \sqrt{2}\theta\psi(x) + \dots$$

- Soft susy breaking introduces a dimensionful parameter m_S
- Susy particles get masses of order m_S
- Susy mass terms are gauge invariant
- Treat soft terms as independent; later derive them from theory
- Different schemes make predictions for patterns of soft terms

μ TERM $f = \mu H_1 H_2$

- allowed by gauge and *R* symmetry
- necessary to break PQ and give mass to higgsinos

Naturalness problem: if $\mu = O(\Lambda)$, then Higgs mass $O(\Lambda)$

SM: hierarchy problem from one-loop effects

SUSY: " " tree level ⇒ μ problem

Assume $\mu = 0$ in susy theory (technically natural)

$$\int d^4\theta\, X^+ H_1 H_2 \quad \rightarrow \quad \mu \approx m_S$$

$$\int d^4\theta\, X X^+ H_1 H_2 \quad \rightarrow \quad B_\mu \approx m_S^2$$

To be tested in different schemes of susy breaking

R SYMMETRY

The symmetry generator $\left[R,Q\right]=iQ \quad \left[R,\overline{Q}\right]=-i\overline{Q}$

acts differently on different components of the supermultiplet

$$\Phi\left(x,\theta,\overline{\theta}\right)\mapsto e^{iR_\Phi\alpha}\Phi\left(x,e^{-i\alpha}\theta,e^{i\alpha}\overline{\theta}\right) \qquad V\left(x,\theta,\overline{\theta}\right)\mapsto V\left(x,e^{-i\alpha}\theta,e^{i\alpha}\overline{\theta}\right)$$

$$\varphi(x)\mapsto e^{iR_\Phi\alpha}\varphi(x) \qquad \lambda(x)\mapsto e^{i\alpha}\lambda(x)$$

$$\psi(x)\mapsto e^{i(R_\Phi-1)\alpha}\psi(x) \qquad V_\mu(x)\mapsto V_\mu(x)$$

$$F(x)\mapsto e^{i(R_\Phi-2)\alpha}F(x) \qquad D(x)\mapsto D(x)$$

Kinetic terms are *R*-invariant; superpotential if *R* [*f*] = 2

Susy SM is *R*-invariant with *R* [H_1,H_2] = 1, *R* [*Q*,*L*] = 1/2

Soft terms break *R*: $R\left[A,B \text{ terms}\right]=R\left[f\big|_{\theta=0}\right]=2$

$$R\left[\text{gaugino mass}\right]=R\left[WW\big|_{\theta=0}\right]=2$$

Connection between *R*-symmetry and susy breaking

(see K. Intriligator's lectures)

R-symmetry is a necessary condition for susy breaking
(for generic superpotentials)

Spontaneously-broken *R*-symmetry is a sufficient condition for susy breaking (if there are no non-compact flat directions in the classical potential)

Exact *R*-symmetry ⇒ no gaugino mass

Spont. broken *R*-symmetry ⇒ *R*-axion

In supergravity, cancellation of CC breaks *R*-symmetry

$$V \propto |F|^2 - \frac{3|f|^2}{M_P^2} \quad \Rightarrow \quad |f| \neq 0$$

Discrete subgroup (*R*-parity) survives after susy & EW breaking

$$\Phi\left(x,\theta,\bar\theta\right) \mapsto Z_\Phi \Phi\left(x,-\theta,-\bar\theta\right) \qquad V\left(x,\theta,\bar\theta\right) \mapsto V\left(x,-\theta,-\bar\theta\right)$$

$$\varphi(x) \mapsto Z_\Phi \varphi(x) \qquad \lambda(x) \mapsto -\lambda(x)$$

$$\psi(x) \mapsto -Z_\Phi \psi(x) \qquad V_\mu(x) \mapsto V_\mu(x)$$

$$F(x) \mapsto Z_\Phi F(x) \qquad D(x) \mapsto D(x)$$

with $Z_\Phi = -$ for Q, U^c, D^c, L, E^c and $Z_\Phi = +$ for H_1, H_2

R-parity = + for SM particles, *R*-parity = – for susy particles

Important for phenomenology:

- no tree-level virtual effects from susy
- susy particles only pair produced
- LSP stable (missing energy + dark matter)

R-parity does not follow from gauge & susy invariance

$$f = U^c D^c D^c + Q D^c L + L L E^c + H_2 L$$

Violate B or L $\qquad \tau_p = \frac{1}{\lambda^4}\left(\frac{m_S}{\text{TeV}}\right)^4 10^{-10}\ \text{sec}$

- Susy tree-level contributions: constraints from B, L, flavour, high-energy
- Special combinations are less constrained
- Small couplings can make LSP decay in cosmological times without collider effects
- *R*-parity could follow from gauge symmetry of underlying theory

ELECTROWEAK SYMMETRY BREAKING

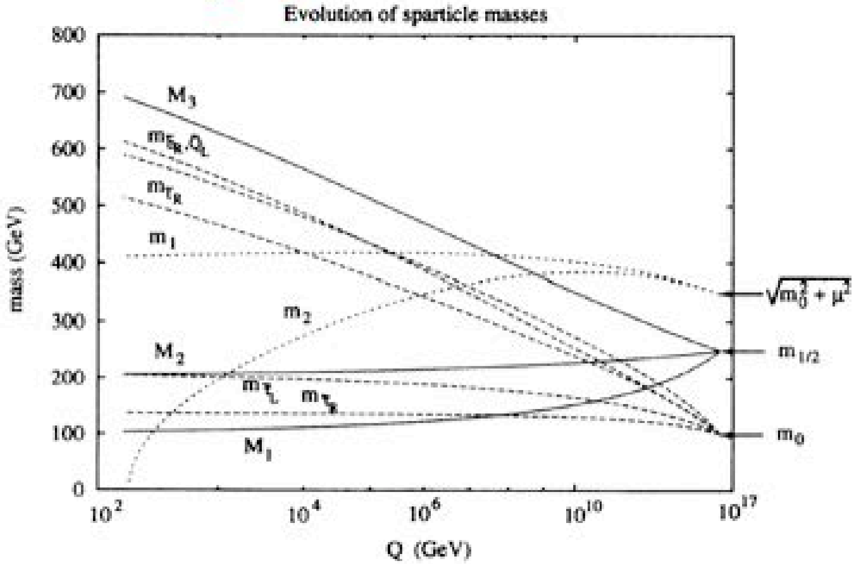
Higgs potential

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

- $m_{1,2,3}^2 \sim m_S^2$ determined by soft terms
- quartic fixed by supersymmetry

- Stability along $H_1 = H_2 \Rightarrow m_1^2 + m_2^2 > 2\,|m_3^2|$
- EW breaking, origin unstable $\Rightarrow m_1^2\, m_2^2 < m_3^4$

EW breaking induced by quantum corrections



RG running:

gauge effects

Yukawa effects

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

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

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

- If λ_t large enough $\Rightarrow$ *SU(2)×U(1)* spontaneously broken
- If α_s large enough $\Rightarrow$ *SU(3)* unbroken
- Mass spectrum separation m_2^2 < weak susy < strong susy

HIGGS SECTOR

8 degrees of freedom – 3 Goldstones = 5 degrees of freedom

2 scalars (h^0,H^0), 1 pseudoscalar (A^0), 1 charged ($H^{\pm}$)

3 parameters ($m_{1.2.3}{}^2$) – M_Z = 2 free parameters

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}} R_{\beta_0} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

$$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = R_{\beta_\pm} \begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

$$R_\alpha = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix},$$

$$R_{\beta_0} = \begin{pmatrix} \sin\beta_0 & \cos\beta_0 \\ -\cos\beta_0 & \sin\beta_0 \end{pmatrix}, \qquad R_{\beta_\pm} = \begin{pmatrix} \sin\beta_\pm & \cos\beta_\pm \\ -\cos\beta_\pm & \sin\beta_\pm \end{pmatrix}$$

At tree level $\beta_0 = \beta_\pm = \beta$ $$\frac{\tan 2\alpha}{\tan 2\beta} = \left(\frac{m_{A^0}^2 + m_Z^2}{m_{A^0}^2 - m_Z^2}\right)$$

In the decoupling limit $m_A >> m_Z$, h^0 is the SM Higgs

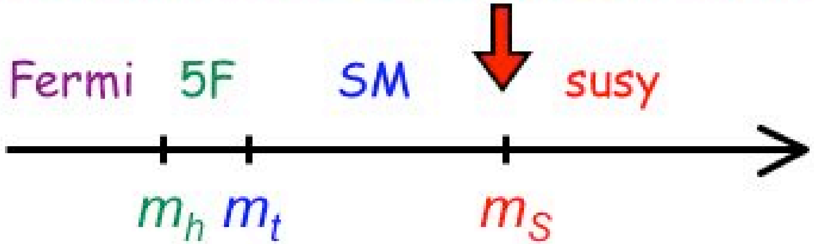
Several interesting tree-level mass relations

$$m_h \le m_Z |\cos 2\beta|, \quad m_h < m_A < m_H, \quad m_{H^\pm}^2 = m_A^2 + m_W^2$$

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

IMPORTANT RADIATIVE CORRECTIONS

Effective theory



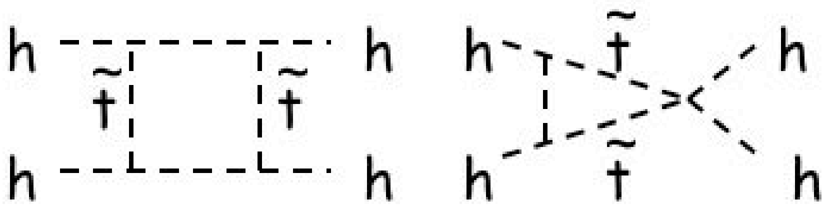
Matching at m_S:

$$h \equiv \cos\beta\, H_1 + \sin\beta\, H_2 \qquad V = \frac{\lambda}{4} h^4 + \frac{m^2}{2} h^2$$

$$\lambda(m_S) = \frac{g^2 + g'^2}{8} \cos^2 2\beta \qquad m^2 = -\cos 2\beta \cos^2\beta \left(m_2^2 \tan^2\beta - m_1^2 \right)$$

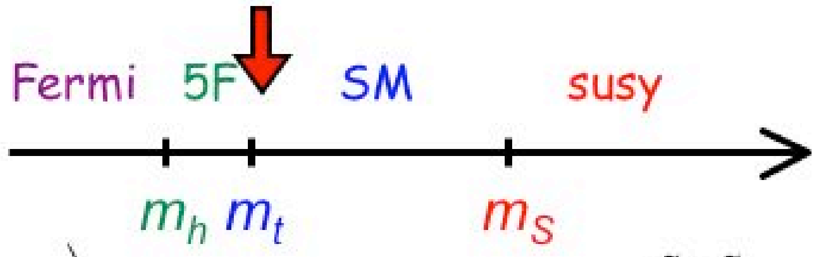
$$\langle h \rangle \equiv v = \sqrt{\frac{-m^2}{\lambda}} \qquad m_h^2 = \lambda v^2 \quad \Rightarrow \quad m_h = |\cos 2\beta|\, m_Z$$

A_t contribution



$$\delta\lambda = \frac{3\lambda_t^4}{4\pi^2} X_t \qquad X_t = \frac{2(A_t - \mu\cot\beta)^2}{\tilde{m}_{t_1}\tilde{m}_{t_2}} \left[1 - \frac{(A_t - \mu\cot\beta)^2}{12\tilde{m}_{t_1}\tilde{m}_{t_2}} \right]$$

Running the SM RG equation for λ



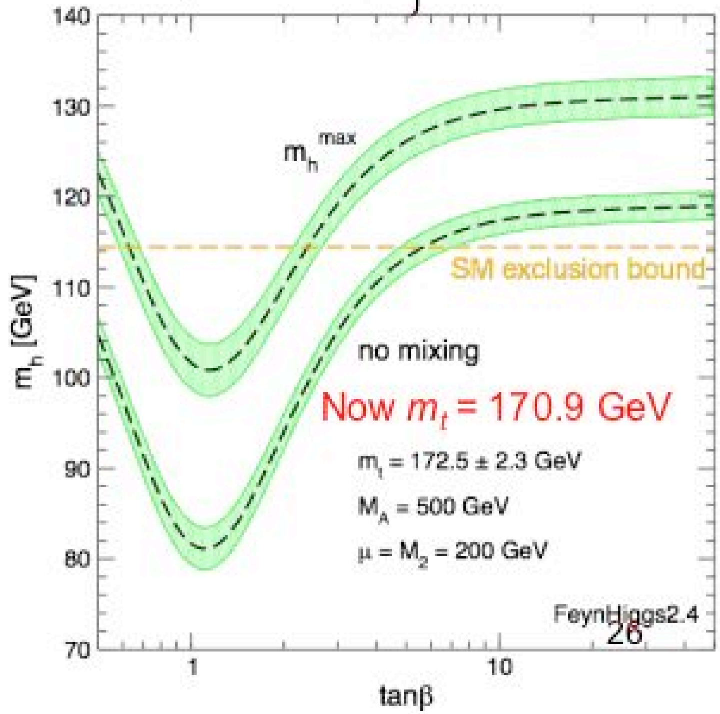
$$m_h^2 = m_Z^2 \cos^2 2\beta \left(1 - \frac{3\sqrt{2}}{4\pi^2} G_F m_t^2 t_S\right) + \frac{3\sqrt{2}}{2\pi^2} G_F m_t^4 \left\{ \frac{X_t}{2} + t_S + \frac{1}{16\pi^2}\left[3\sqrt{2} G_F m_t^2 - 32\pi\alpha_S\right](X_t + t_S) t_S \right\}$$

$$t_S \equiv \ln \frac{\tilde{m}_{t_1} \tilde{m}_{t_2}}{m_t^2}$$

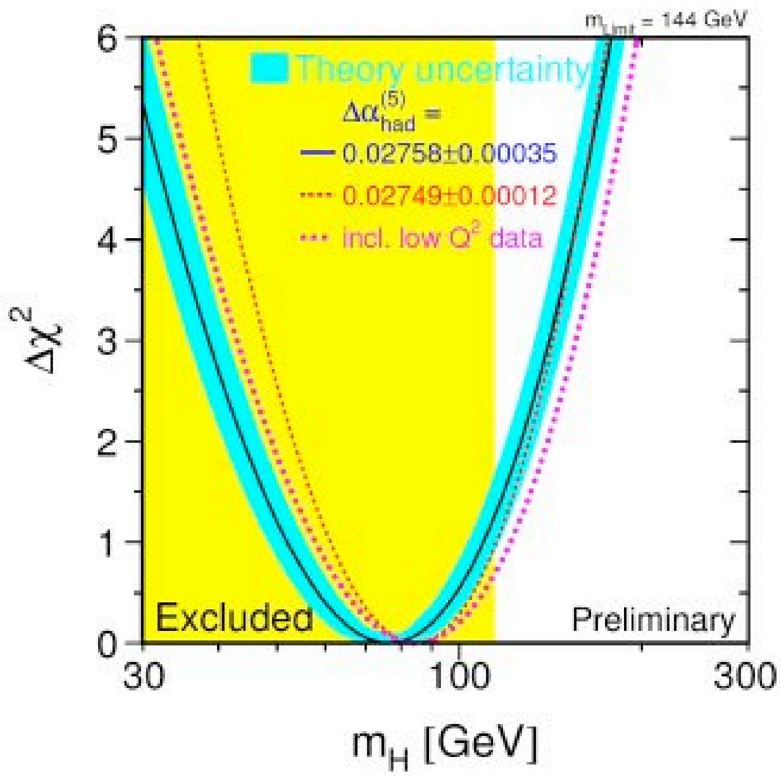
Important effect because:

1) small tree-level m_h,
2) large λ_t,
3) heavy susy particles
4) large loop factor

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3}{2\pi^2} \lambda_t^4 v^2 \ln \frac{\tilde{m}_t}{m_t}$$



LEP gives indications for a light Higgs

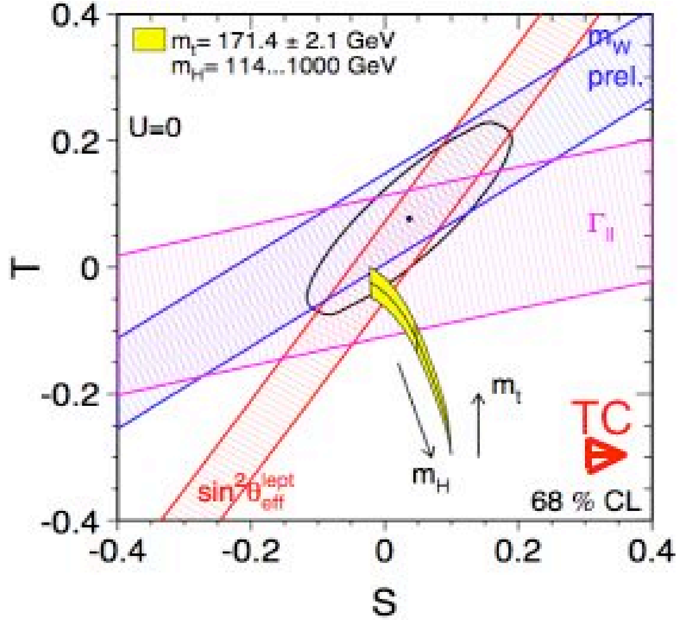


Preferred value $m_H = 76^{+33}_{-24}\,\mathrm{GeV}$ (68% CL)

Upper limit $m_H < 144\,\mathrm{GeV}$ (95% CL)

including direct limit of $114\,\mathrm{GeV}$:

$$m_H < 182\,\mathrm{GeV} \text{ (95\% CL)}$$



The decrease in m_t has worsen the SM fit

$$\text{LEP/SLD}/m_W/\Gamma_W: \quad m_t = 178.9^{+11.7}_{-8.6}\,\text{GeV}$$

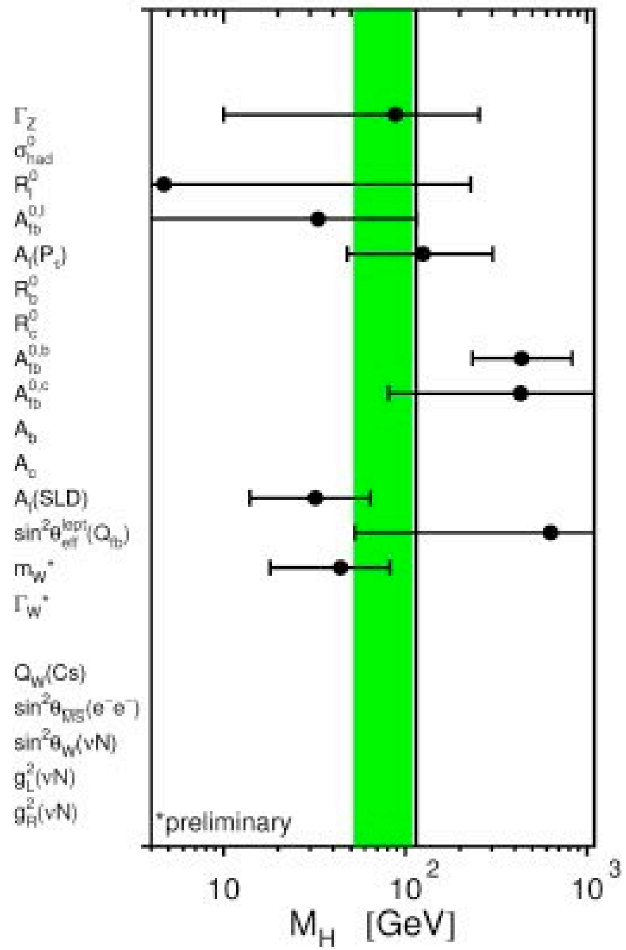
$$\text{CDF/D}\varnothing: \quad m_t = 170.9 \pm 1.8\,\text{GeV}$$

The two best measurements of $sin^2\theta_W$ do not agree

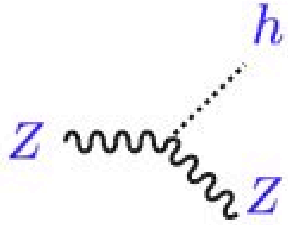
$$A_{fb}^{0,b} \quad \Rightarrow m_H = (230 - 800)\,\text{GeV}$$

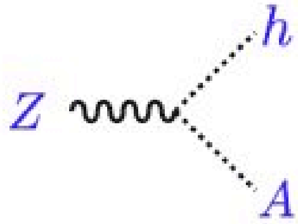
$$A_\ell(\text{SLD}) \Rightarrow m_H = (13 - 65)\,\text{GeV}$$

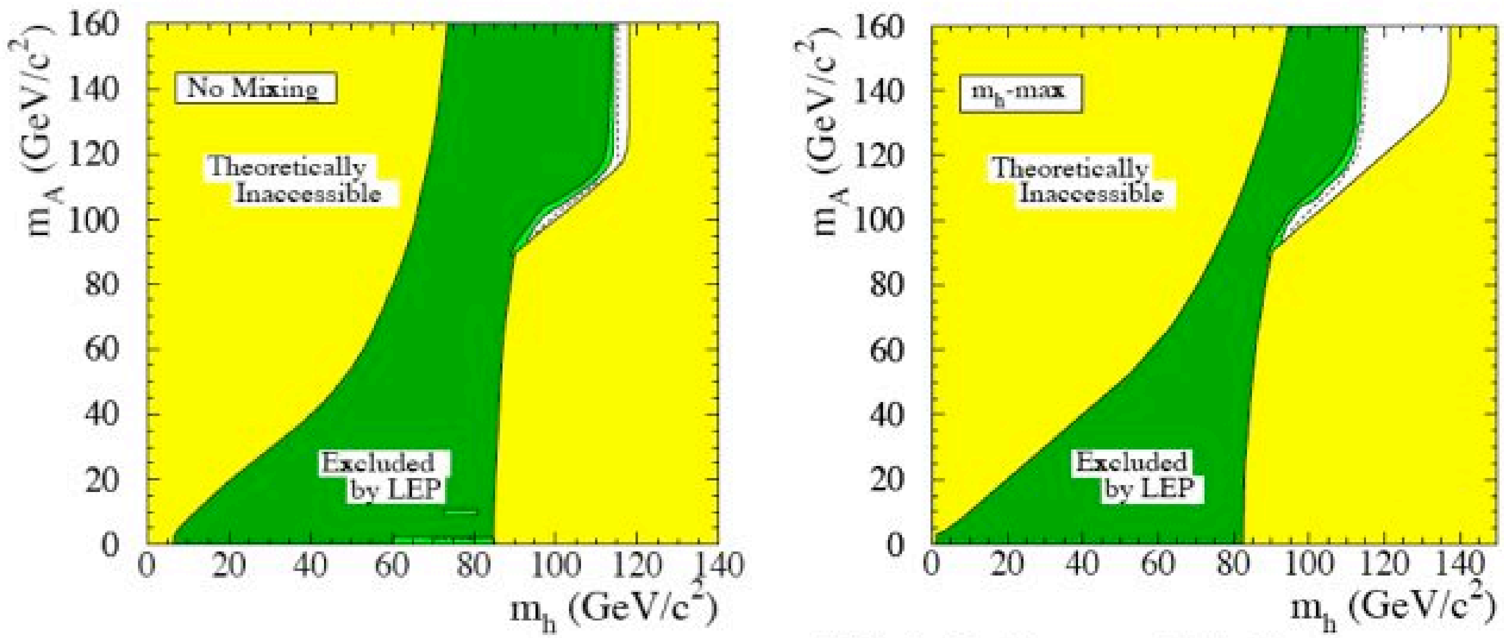
This makes the argument for a light Higgs less compelling



LEP LIMITS

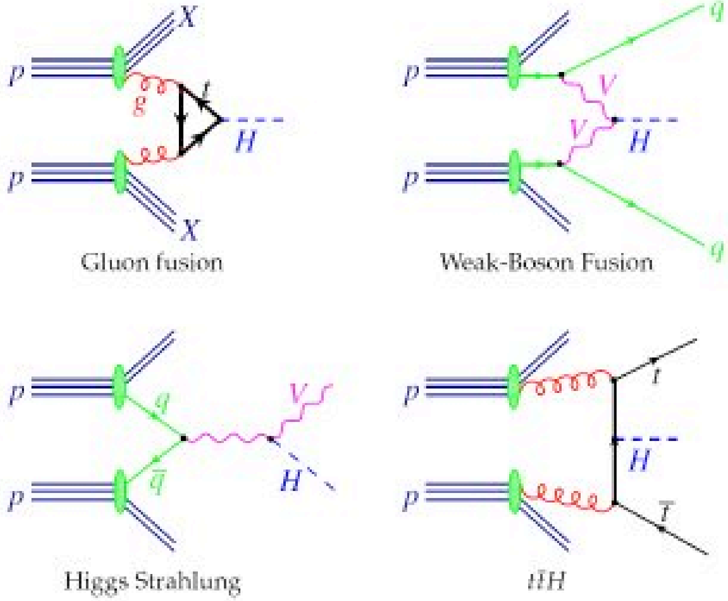
$\left|$  $\right|^2 \propto \sin^2(\beta-\alpha)$

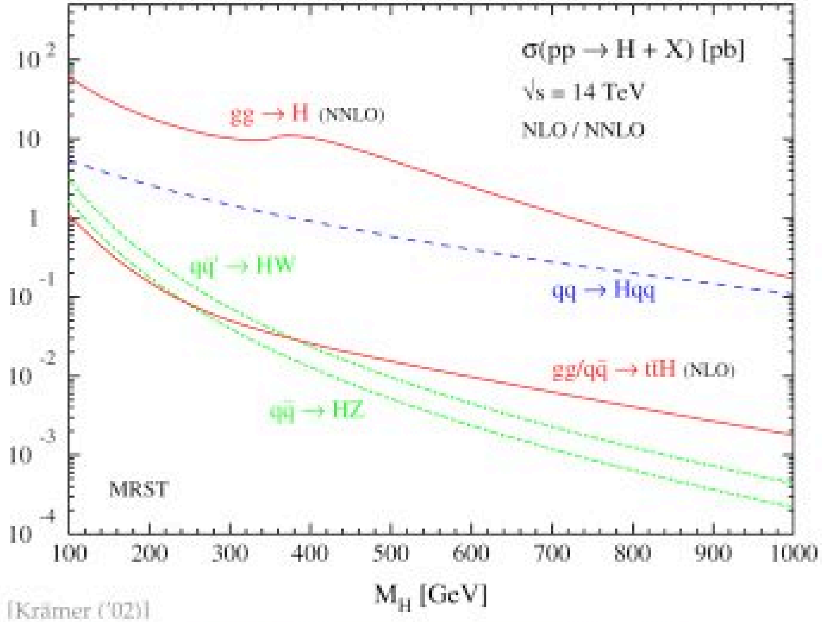
$\left|$  $\right|^2 \propto \cos^2(\beta-\alpha)$

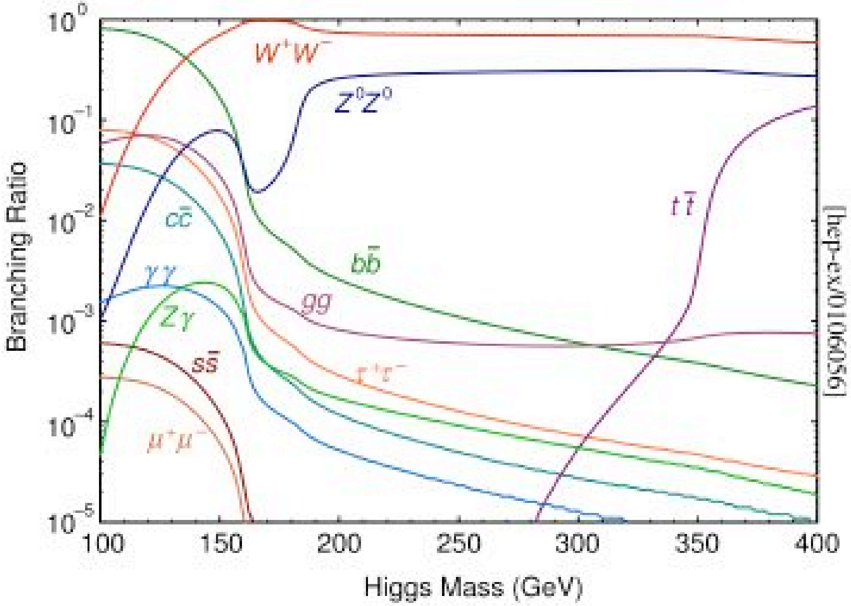


m_t=179.3 GeV m_S=1 TeV

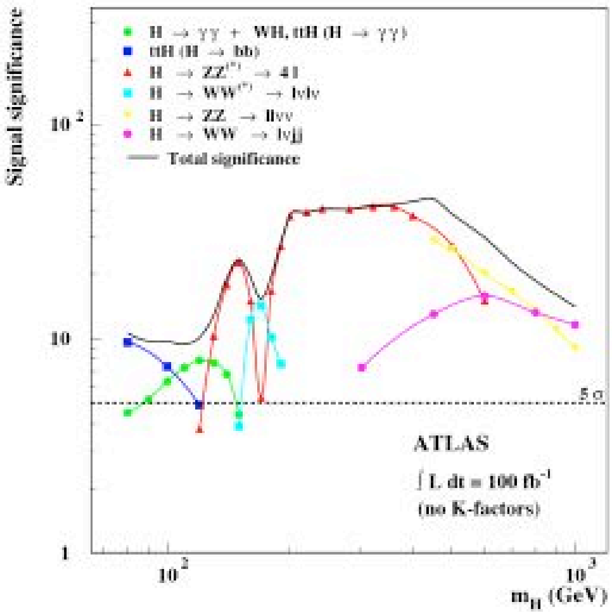
PRODUCTION AT THE LHC

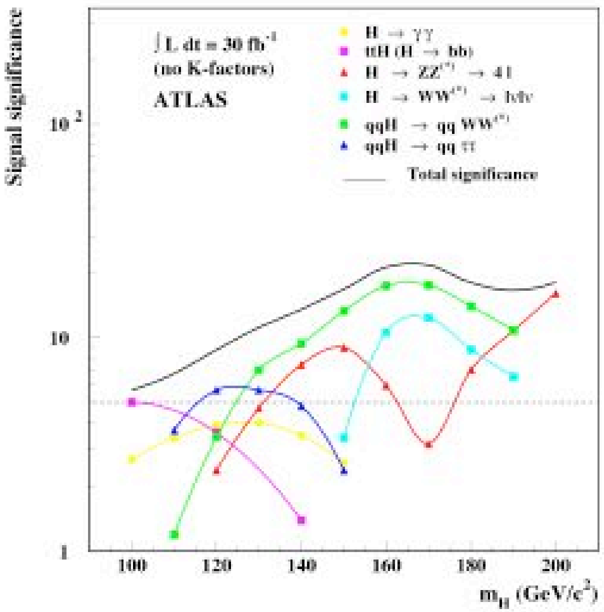






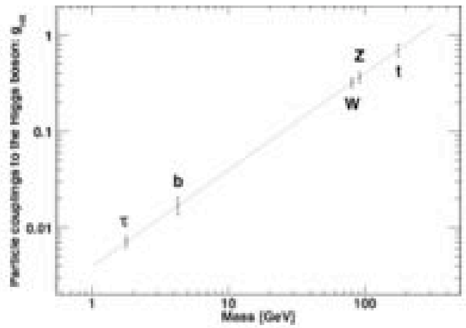
"The Higgs sector is a reincarnation of the Communist Party: it controls the masses"
Stalin





• Test different production and decay channels to verify that Higgs couplings are proportional to mass (5-15% errors can be reached)

• Test variations of Higgs mechanism with several fields



m_H = 120 GeV
L = 300 fb^{-1}

m_S IS THE SEED OF EW BREAKING

EW breaking is related to susy breaking, $m_S \Rightarrow m_Z$

$$\delta m_2^2 = -\frac{3\lambda_t^2}{8\pi^2}\int^{\Lambda^2}\frac{k^2dk^2}{k^2+m_t^2} + \frac{3\lambda_t^2}{8\pi^2}\int^{\Lambda^2}\frac{k^2dk^2}{k^2+m_t^2+m_S^2} = -\frac{3\lambda_t^2}{4\pi^2}m_S^2\ln\frac{\Lambda}{m_S}$$

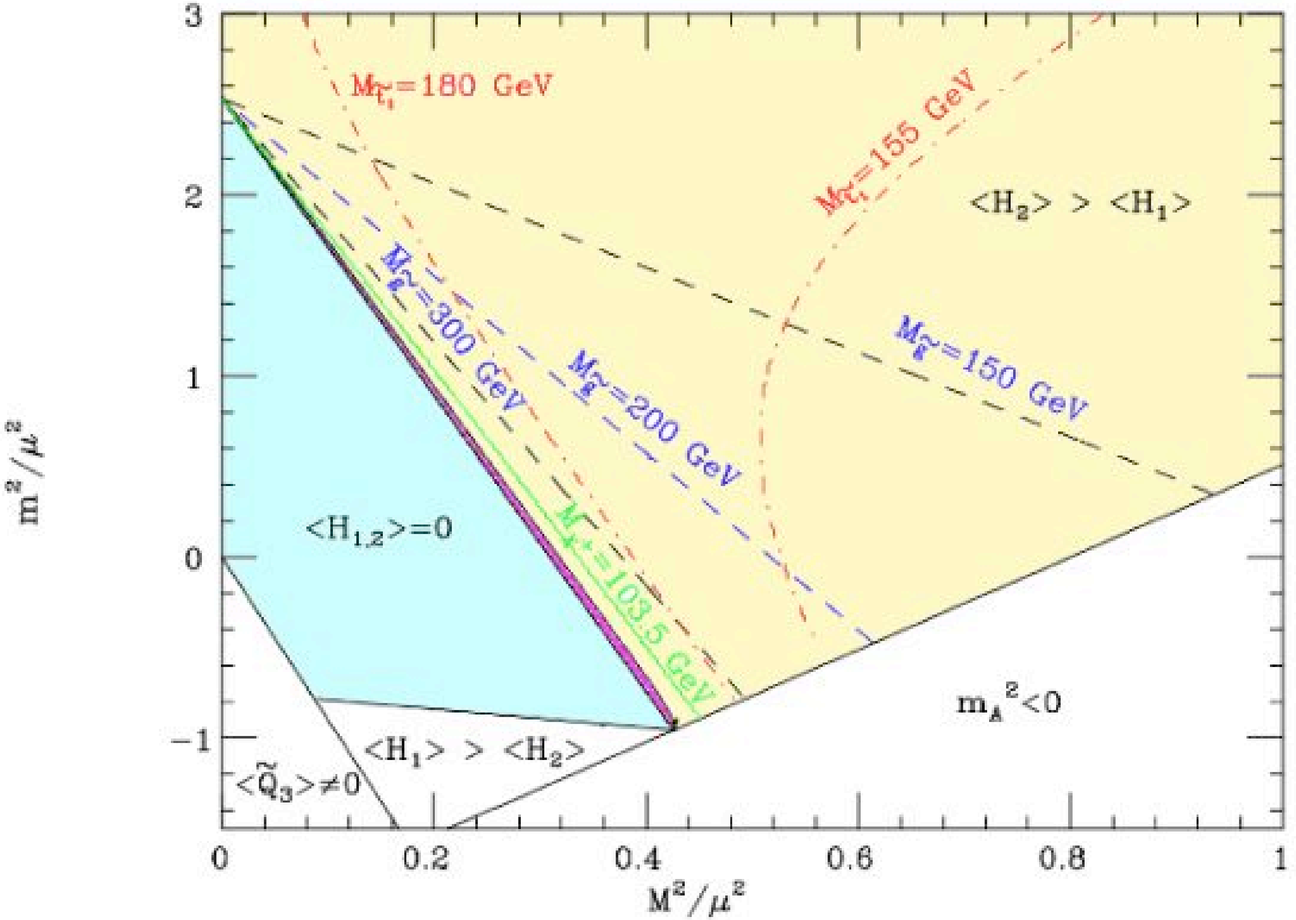
- m_S plays the role of Λ^2 cutoff
- The quantum correction is negative and drives EW breaking

Minimum of the potential $$m_Z^2 = \frac{2\left(m_1^2 - m_2^2\tan^2\beta\right)}{\tan^2\beta - 1} \approx -2m_2^2$$

$$\left|2\delta m_2^2\right| < \frac{m_Z^2}{\Delta} \quad \Rightarrow \quad \tilde{m}_t < 300 \text{ GeV} \left(\frac{10\%}{\Delta}\right)^{1/2}$$

$$m_h^2 \approx m_Z^2 + \frac{3}{2\pi^2}\lambda_t^4 v^2 \ln\frac{\tilde{m}_t}{m_t} > 114 \text{ GeV} \quad \Rightarrow \quad \tilde{m}_t > 1 \text{ TeV}$$

} Tension with data



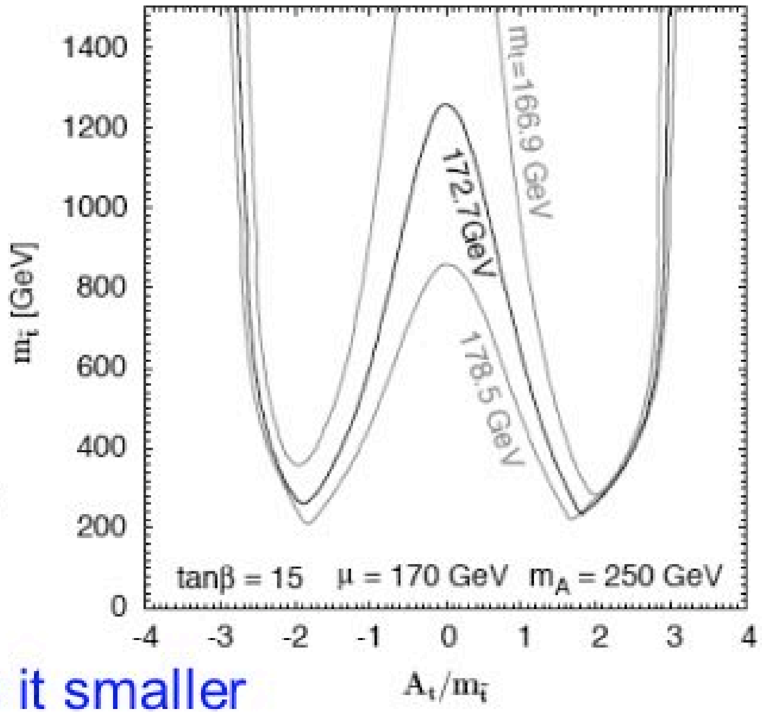
"Natural" supersymmetry has already been ruled out

To know what is "natural" we need to know the underlying probability of parameter distribution

Some schemes could improve the situation
(mirage mediation?)

- large A terms
- small Λ
- small μ

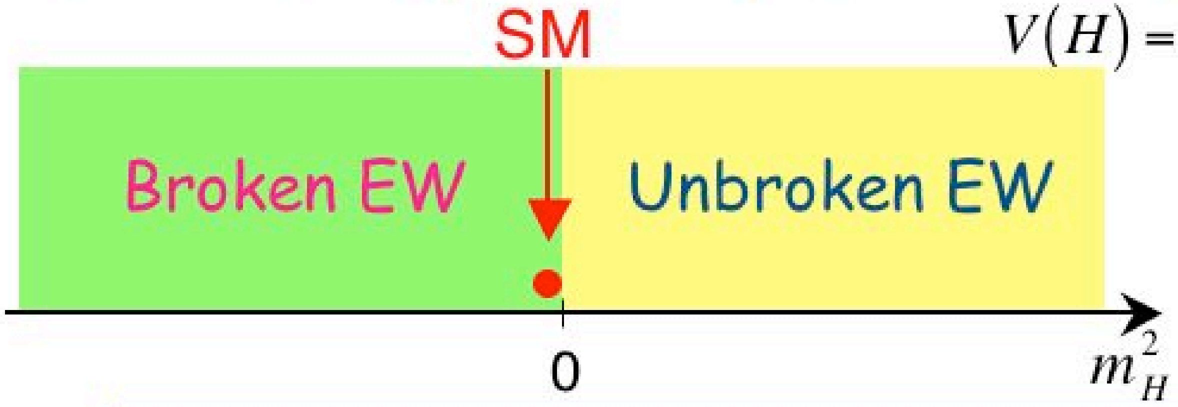
$$\frac{A_t}{\tilde{m}_t} \approx 1$$ when gaugino mass dominates



- scalar contribution makes it smaller
- large A_t / $\tilde{m}_t$ requires special choice of A_t (M_{GUT})

Characterizing the tuning as a "criticality" condition

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



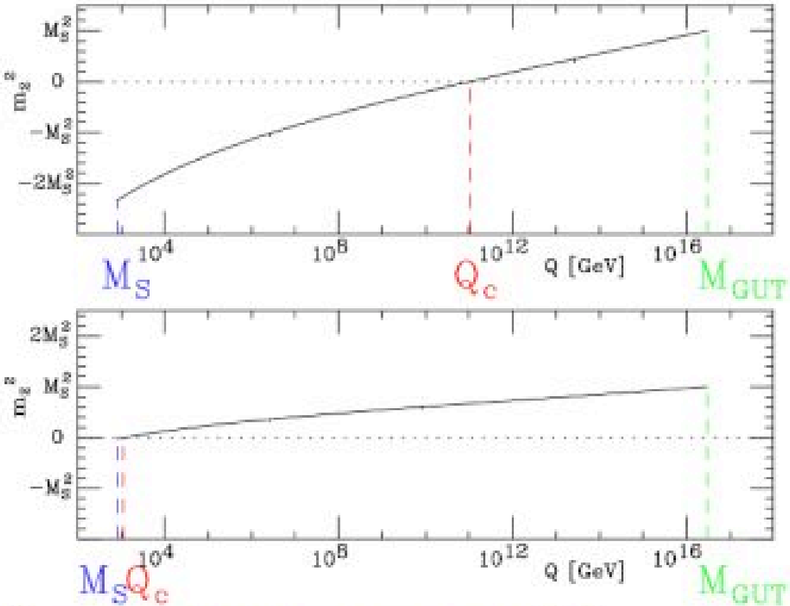
Why is nature so close to the critical line?

- Exact susy (and μ=0) $\Rightarrow$ critical line
- Dynamical susy breaking $M_S \sim M_P\, e^{-1/\alpha}$ $\Rightarrow$
  - small departure from critical line
  - stabilization of flat direction $|H_1|=|H_2|$

$\Rightarrow$ "natural" supersymmetry with $M_S \sim M_Z$

“natural” supersymmetry: $M_S \ll Q_C \ll M_P$

$Q_C \sim e^{-1/\alpha} M_P$
- unrelated to M_S (depends on ratios of soft terms and α_a)
- much smaller than UV scale



M_S and Q_C equal to few %

“tuned” supersymmetry: $M_S \sim Q_C \ll M_P$

$M_S < Q_C$ broken EW; $M_S > Q_C$ unbroken EW

Why supersymmetry should prefer to be near critical?

Connection susy breaking ⇔ EW breaking at the basis of low-energy supersymmetry

- Susy particle content dynamically determines EW breaking pattern
- Higgs interpreted as fundamental state, like Q and L
- Higgs mass determined by susy properties and spectrum

After LEP, “natural” susy is ruled out

- Source of “mild” tuning (is it observable at LHC?)
- Missing principle?

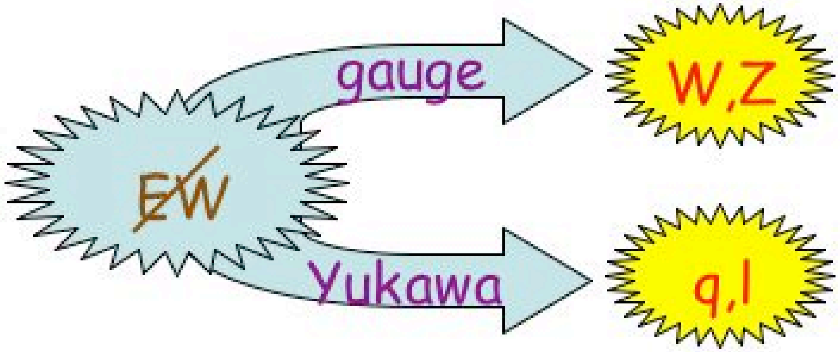
THEORY OF SOFT TERMS

- Explain origin of supersymmetry breaking
- Compute soft terms

Similar to EW breaking problem

- Origin of EW breaking ⇒ $V(H) = -m_H^2 |H|^2 + \lambda |H|^4$
- Compute EW breaking effects ⇒ $L = D_\mu H^+ D^\mu H - \lambda H \overline{\psi} \psi$

Gauge boson mass — Fermion mass



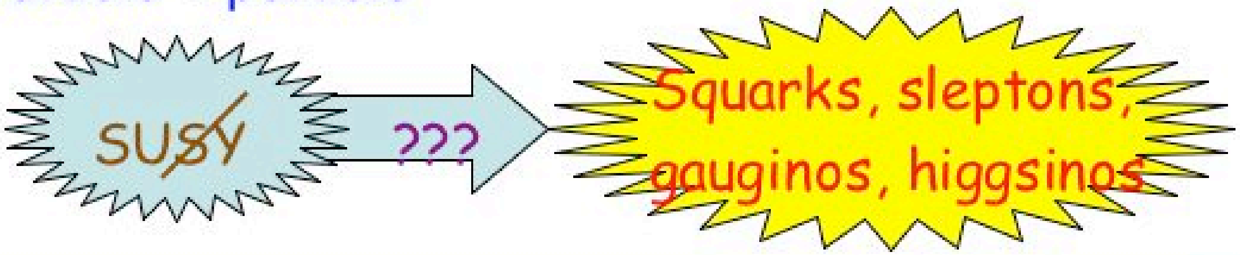
Invent a new sector which breaks supersymmetry
(ask K. Intriligator)

- Small mass (weak scale) stable against quantum corrections
- Even better: if susy unbroken at tree-level, it remains unbroken to all orders in perturbation theory
- Non-perturbative effects can break susy with $m_S \sim e^{-1/\alpha} M_P$

Couple the breaking sector to the SM superfields

But $\mathrm{STr}\, M^2 = \sum_J (-1)^{2J} (2J+1) M_J^2 = 0$ at tree level, with canonical kinetic terms

sparticle < particle



What force mediates susy-breaking effects?

GRAVITY AS MEDIATOR

Gravity couples to all forms of energy

Assume no force stronger than gravity couples the two sectors

Susy breaking in hidden sector parametrized by X with $<F_X>\neq 0$

$$\frac{1}{M_P}\int d^2\theta\, X W_\alpha W^\alpha \quad \to \quad m_S \lambda\lambda \quad \text{gaugino mass}$$

$$\frac{1}{M_P^2}\int d^4\theta\, X^+ X\, \Phi^+ e^V \Phi \quad \to \quad m_S^2 \varphi^+\varphi \quad \text{scalar mass}$$

$$\frac{1}{M_P}\int d^4\theta\, X^+ \Phi^+ e^V \Phi \quad \to \quad m_S\, \varphi\, F_\varphi^* = -m_S\, \varphi \frac{\partial f}{\partial \varphi} \quad A\text{ - term}$$

$$\frac{1}{M_P}\int d^2\theta\, X\, f(\Phi) \quad \to \quad m_S f(\varphi) \quad A\text{ - term}$$

$$\frac{1}{M_P}\int d^4\theta\, X^+ H_1 H_2 \quad \to \quad m_S \int d^2\theta\, H_1 H_2 \quad \mu\text{ term}$$

$$\frac{1}{M_P^2}\int d^4\theta\, X X^+ H_1 H_2 \quad \to \quad m_S^2 H_1 H_2 \quad B_\mu\text{ - term}$$

$m_S = F_X / M_P$

m_S = TeV $\Rightarrow$
$F_X^{1/2} = 10^{11}$ GeV

ATTRACTIVE SCENARIO

- Gravity a feature of local supersymmetry
- Gravity plays a role in EW physics
- No need to introduce *ad hoc* interactions
- Justification for $\mu \approx m_S$

BUT

- Lack of predictivity (10^2 parameters)
- Flavour problem

FLAVOUR PROBLEM

SM, Yukawa =0 $\Rightarrow$ $$L = \overline{\psi} i \gamma^{\mu} D_{\mu} \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

invariant under global $SU(3)^5$ — 3 generations; 5 species (q_L, u_R, d_R, l_L, e_R)

broken by λ_a ($a=e,u,d$) 3×3 matrices which generate

$$\overline{q}_L \lambda_u u_R H^* + \overline{q}_L \lambda_d d_R H + \overline{l}_L \lambda_e e_R H$$

The violation is special

- no FCNC at tree level $\overline{\psi} \gamma^{\mu} \psi A_{\mu} \rightarrow \overline{\psi} U^+ \gamma^{\mu} U \psi A_{\mu}$
- suppressed by GIM: FCNC = loop × CKM × Δm_q^2

Ex.:

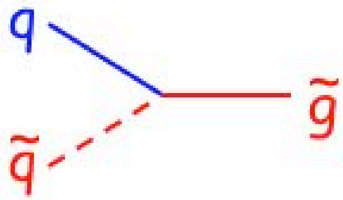
$$\frac{\Delta m_K}{m_K} \approx \frac{g^2}{16\pi^2} G_F f_K^2 \sin^2\theta_c \frac{m_c^2}{m_W^2} \approx 7 \times 10^{-15}$$

- individual L conserved (or m_{ν} suppressed)

These features are generally not preserved in BSM, as soon as new sources of *SU(3)*[5] breaking are present

$$\tilde{m}_i^2 \quad 1+8 \text{ of } SU(3)_i$$

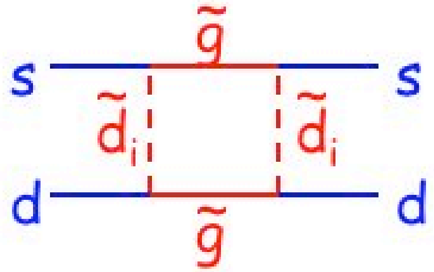
$$A_a \quad \left(3,\bar{3}\right) \text{ of } SU(3)_L \times SU(3)_R$$



$$\bar{q}\tilde{q}\tilde{g} \to \bar{q}U^{+}\tilde{U}\tilde{q}\tilde{g}$$

$$U^{+}\tilde{U} \neq 1$$

Ex.:



$$\frac{\Delta m_K}{m_K} \approx \frac{g_S^2}{16\pi^2}\frac{f_K^2}{\tilde{m}^2}\left(\frac{\tilde{m}_{ds}^2}{\tilde{m}^2}\right)^2$$

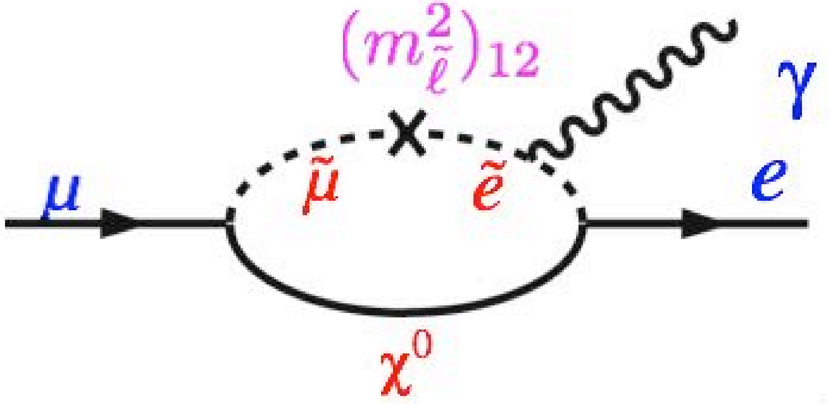
strong loop

no small CKM or Δm_q

$$\frac{\Delta m_K}{m_K} \Rightarrow \frac{\tilde{m}_{ds}^2}{\tilde{m}_q^2}\frac{500 \text{ GeV}}{\tilde{m}_q} < \begin{cases} 4\times10^{-2} & \text{LL} \\ 4\times10^{-3} & \text{LR} \end{cases}$$

100 times stronger limits on the imaginary part

INDIVIDUAL LEPTON NUMBER



BR($\mu \to e\gamma$)<1.2×10^{-11}

$$\mu \to e\gamma \Rightarrow \frac{\tilde{m}^2_{e\mu}}{\tilde{m}^2_l}\frac{100\text{ GeV}}{\tilde{m}_l} < \begin{cases} 8\times10^{-3} & \text{LL} \\ 2\times10^{-6} & \text{LR} \end{cases}$$

MEG at PSI will reach 10^{-13} with 2 years of 10^7/sec muon beam and eventually 10^{-14} with 10^8/sec

CP PROBLEM

- The flavour structure of soft terms include many new phases
- From ε_K most stringent limits on flavour structure
- CP violation present even in the absence of a flavour structure

Consider N_g = 1 (or universality)

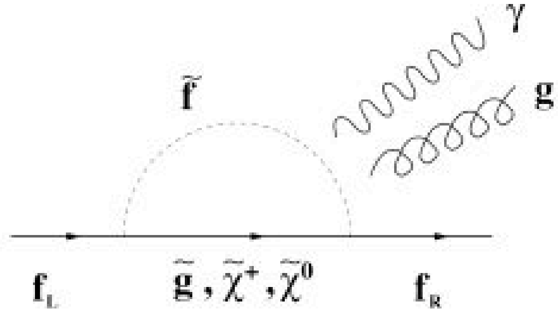
$$L = \left(\lambda_e H_d LE + \mu H_u H_d\right)_F + g\lambda f \tilde{f}^* +$$

$$M\lambda\lambda + \tilde{m}^2\left|\tilde{f}\right|^2 + \left(A\lambda_e H_d LE + B\mu H_u H_d\right)_S$$

- Superfield rotation to make superpotential parameters real (*g* in gaugino interactions remains real)
- R rotation to make *M* real $\Rightarrow$ phases in *A* and *B* cannot be removed

Two CP-violating invariants *arg* (MA^*) *arg* (MB^*)

Contribution to CP-violating observables



$$L = \theta \frac{\alpha_s}{8\pi} G\tilde{G} + \frac{c_g}{3} f^{abc} G^a \tilde{G}^b G^c$$

$$-\frac{i}{2} d_f \bar{f} F^{\mu\nu} \sigma_{\mu\nu} \gamma_5 f - \frac{i}{2} \tilde{d}_q \bar{q} G^{\mu\nu} \sigma_{\mu\nu} \gamma_5 q$$

In basis $\theta = 0$ electron EDM d_e

neutron EDM $d_n \approx 2d_d - 0.5 d_u + e\left(0.4\tilde{d}_d - 0.1\tilde{d}_u + 0.3\,\mathrm{GeV}\, c_g\right)$

$|d_e| < 2 \times 10^{-27}\,\mathrm{ecm}$ $\quad d_e \approx \left(\frac{300\,\mathrm{GeV}}{m_S}\right)^2 \sin\phi \times 10^{-25}\,\mathrm{ecm}$

$\Rightarrow \sin\phi < 10^{-2}$

$|d_n| < 3 \times 10^{-26}\,\mathrm{ecm}$ $\quad d_n \approx \left(\frac{300\,\mathrm{GeV}}{m_S}\right)^2 \sin\phi \times 10^{-24}\,\mathrm{ecm}$

Future: DeMille et al. (Yale) 10^{-29} *e*cm in 3 years and 10^{-31} *e*cm in 5 years.

Lamoreaux et al. (Los Alamos): 10^{-31} *e*cm and eventually 10^{-35} *e*cm.

Results from Hinds et al. (Sussex) and Semertzidis et al. (Brookhaven) plans to improve by 10^5 sensitivity on μ EDM

Special flavour structures of soft terms are needed

UNIVERSALITY: $\tilde{m}_i^2 \propto 1 \qquad A_a \propto \lambda_a$

Particular case of MFV: Yukawa only spurion breaking *SU(3)*^{5}

ALIGNMENT: small mixing angles in squark/slepton sector, although no small mass splitting

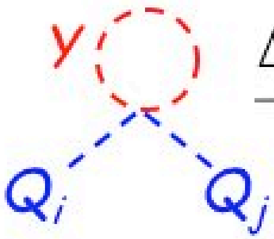
These structures are not stable under radiative corrections

Ex.:

$$f = h_{ij} Q_i Q_j Y$$

heavy field with mass Λ_F

light fields



$$\frac{\Delta \tilde{m}^2_{Q_i Q_j}}{\tilde{m}^2} \propto \frac{h_{ik} h^*_{jk}}{16\pi^2} \ln \frac{M_P}{\Lambda_F}$$

- effect does not decouple
- sensitive to high-energy physics

In gravity mediation, flavour symmetries are necessary:

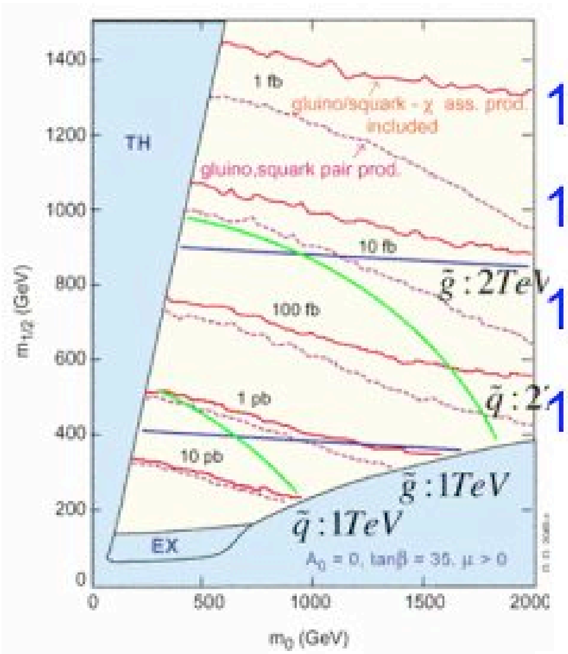
Why violations are present in Yukawa and not in soft terms?

Soft terms: 15 masses, 42 mixing angles, 40 phases

Most “sugra” or “CMSSM” analyses use: m_0, M, μ, A_0: why?

Is there a dynamical explanation for MFV?

Coloured particles have large cross sections at the LHC



1 month (low lum): 1 fb^{-1}; M_g ~ 1-1.5 TeV

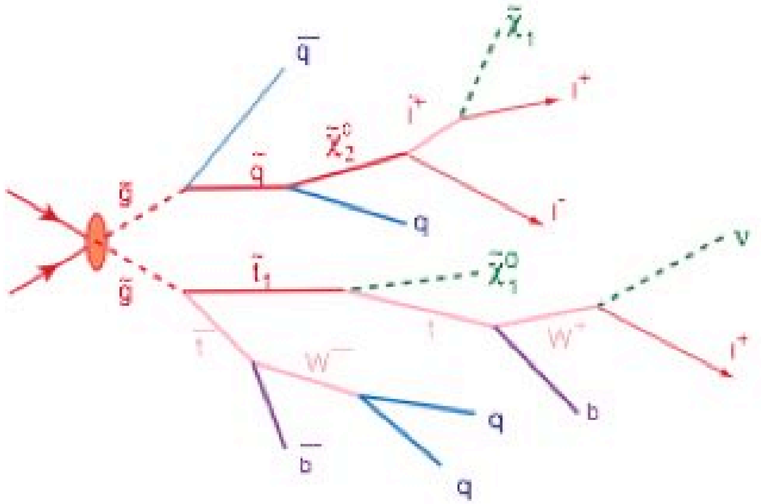
1 year (low lum): 10 fb^{-1} ; M_g ~ 1.5-2 TeV

1 year (high lum): 100 fb^{-1} ; M_g ~ 2-2.5 TeV

1 year (high lum): 300 fb^{-1} ; M_g ~ 2.5-3 TeV

Clear signal: $\sigma(\mathrm{TeV}\ \tilde{\mathrm{g}}) \approx \mathrm{pb}$

LHC with 100 fb^{-1} $\Rightarrow$ 10^4 € / gluino



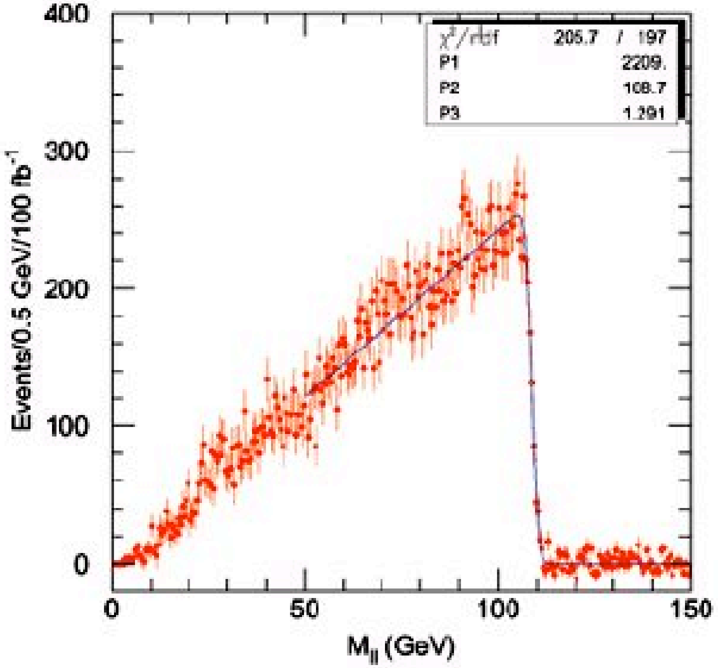


Figure 9. Dilepton kinematic edge in $\tilde{\chi}_2^0$ decay (Atlas TDR).

EXAMPLE:

$\tilde{\mu} \to \chi^0 \mu$ at linear collider

Max and Min of E_μ for forward and backward emission

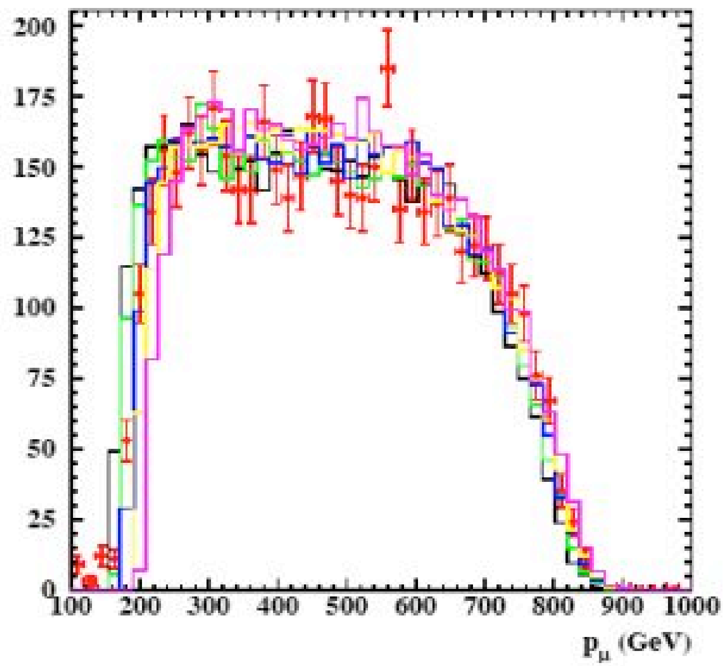
$$\tilde{\mu} = \left(E_{beam}, \sqrt{E_{beam}^2 - \tilde{m}_\mu^2} \right)$$

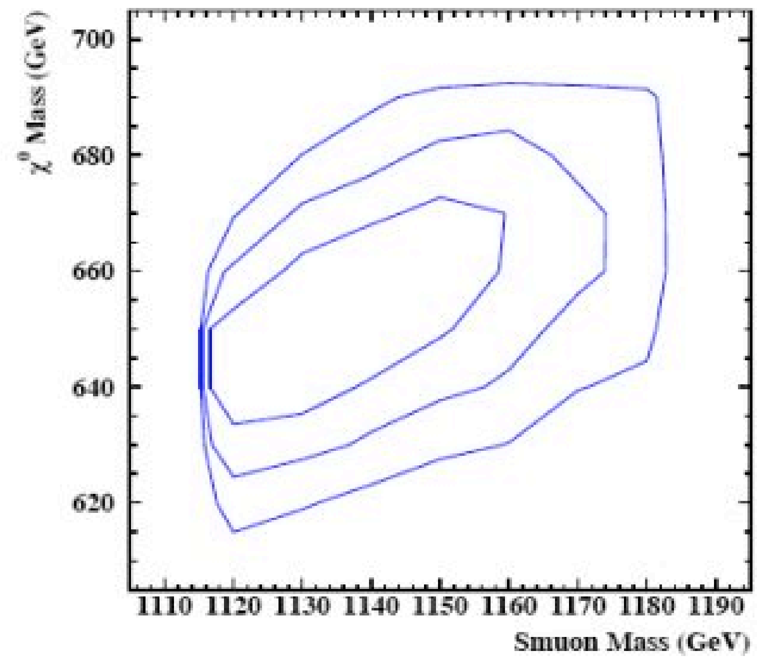
$$\chi^0 = \left(E_{beam} - E_\mu, \mp \sqrt{\left(E_{beam} - E_\mu\right)^2 - \tilde{m}_\chi^2} \right)$$

$$\mu = \left(E_\mu, \sqrt{E_{beam}^2 - \tilde{m}_\mu^2} \pm \sqrt{\left(E_{beam} - E_\mu\right)^2 - \tilde{m}_\chi^2} \right)$$

μ on mass shell

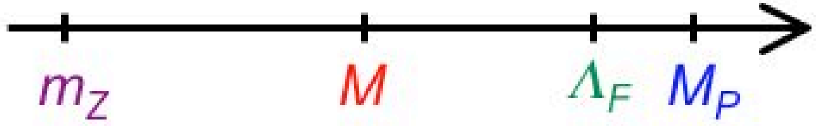
$$E_\mu^{\max/\min} = \frac{E_{beam}}{2}\left(1 - \frac{\tilde{m}_\chi^2}{\tilde{m}_\mu^2}\right)\left(1 \pm \sqrt{1 - \frac{\tilde{m}_\mu^2}{E_{beam}^2}}\right)$$


200
175
150
125
100
75
50
25
0
100 200 300 400 500 600 700 800 900 1000
p_μ (GeV)


χ^0 Mass (GeV)
700
680
660
640
620
1110 1120 1130 1140 1150 1160 1170 1180 1190
Smuon Mass (GeV)

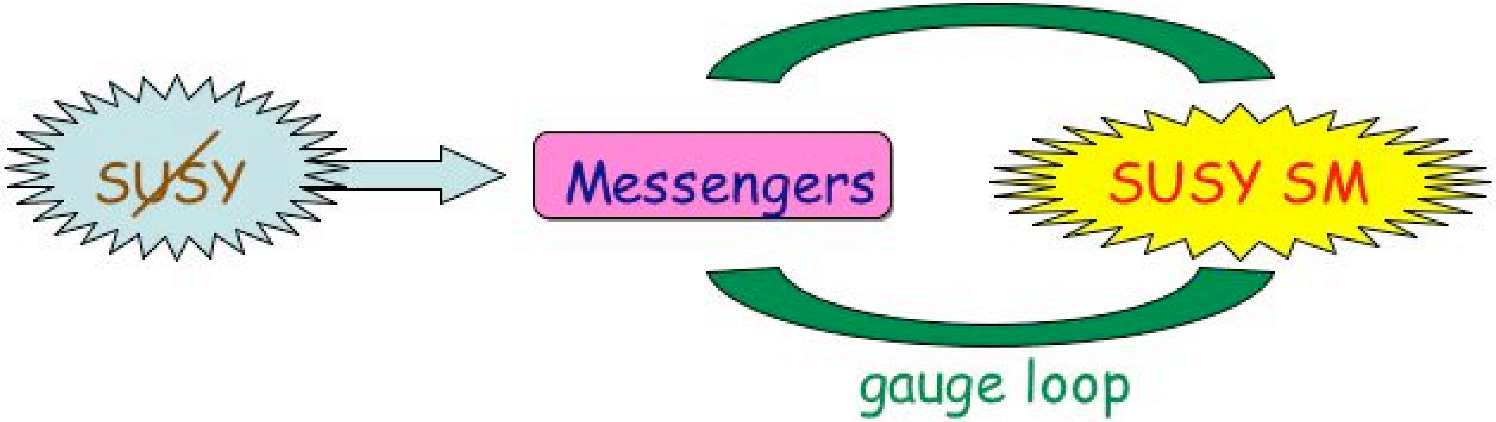
GAUGE MEDIATION

Soft terms are generated by quantum effects at a scale $M \ll M_P$



- If $M \ll \Lambda_F$, Yukawa is the only effective source of flavour breaking (MFV); flavour physics is decoupled (unlike sugra or technicolour)
- Soft terms are computable and theory is highly predictive
- Free from unknowns related to quantum gravity

BUILDING BLOCKS OF GAUGE MEDIATION



SUSY SM: observable sector with SM supermultiplets

SUSY: “hidden” sector with $\langle X \rangle = M + \theta^2 F$

Messengers: gauge charged, heavy (real rep), preserve gauge unification (complete GUT multiplet)

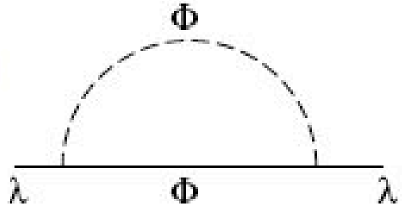
Ex.:

$\Phi + \overline{\Phi} = 5 + \overline{5}$ of $SU(5)$ with $f = X\Phi\overline{\Phi}$, $\quad V = M^2\left(|\varphi|^2 + |\overline{\varphi}|^2\right) + F\left(\varphi\overline{\varphi} + \text{h.c.}\right)$

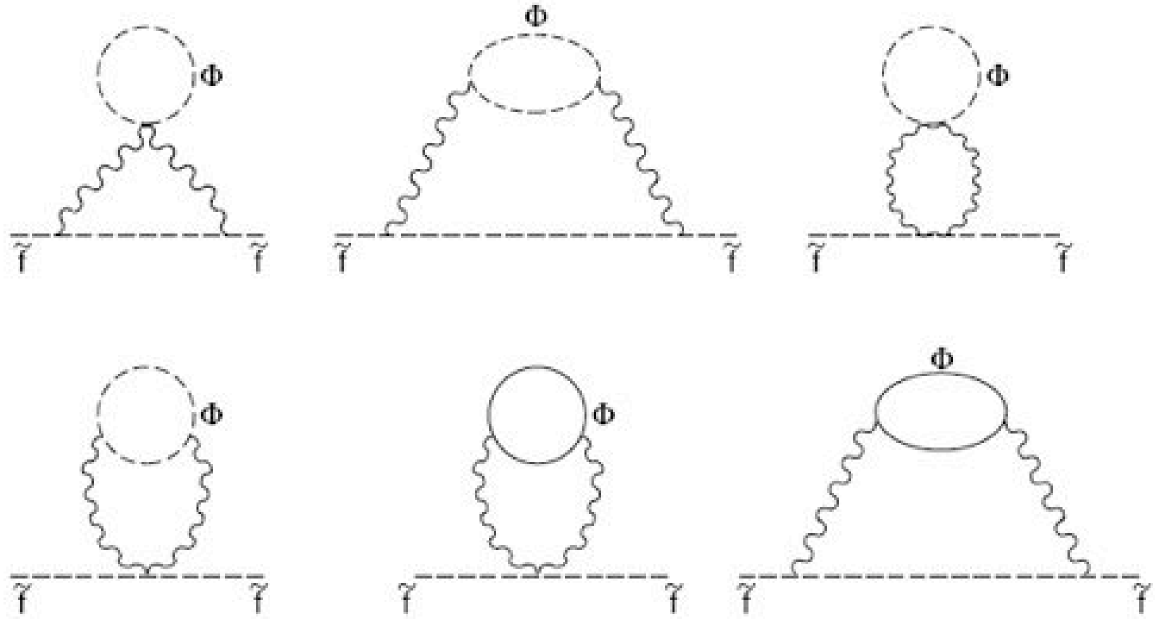
Parameters: *M, F, N* (twice Dynkin index; N=1 for $5+\overline{5}$)

COMPUTING THE SOFT TERMS

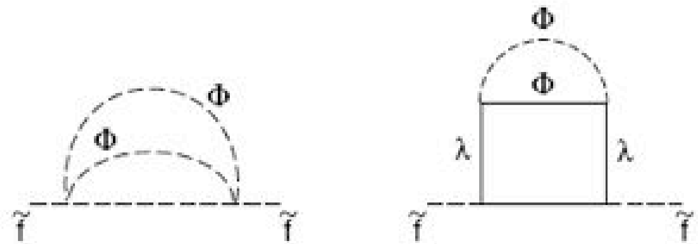
Gaugino mass: one loop



Scalar masses: two loops



Exploit properties of supersymmetry



Calculate in exact susy and then $M \to X = M + \theta^2 F$ to extract susy breaking effects (promote couplings to superfields)

Gauge kinetic term $L = \int d^2\theta\, S W^\alpha W_\alpha + \text{h.c.}$

S holomorphic chiral superfield such as $\mathrm{Re}\, S\big|_{\theta=0} = \dfrac{1}{4g^2}$

Gaugino mass $M_{\tilde g}(Q) = -\dfrac{1}{2} \dfrac{\partial \ln S(X,Q)}{\partial \ln X}\bigg|_{X=M} \dfrac{F}{M}$

$$\frac{d}{d\ln Q}\frac{1}{g^2} = \frac{b}{8\pi^2}$$ with $b = 3N_C - N_f$ in $SU(N_C)$ with N_f flavours

Choose $\Lambda > M > Q$
$$\mathrm{Re}\, S(M,Q) = \frac{1}{4g^2(Q)} = \frac{1}{4g^2(\Lambda)} + \frac{b'}{32\pi^2}\ln\frac{|M|}{\Lambda} + \frac{b}{32\pi^2}\ln\frac{Q}{|M|}$$
$$\Rightarrow S(X,Q) = S(\Lambda) + \frac{b'}{32\pi^2}\ln\frac{X}{\Lambda} + \frac{b}{32\pi^2}\ln\frac{Q}{X}$$

Taking derivatives
$$M_{\tilde g}(Q) = \frac{g^2(Q)}{16\pi^2} N \frac{F}{M}$$

Gaugino mass given by the discontinuity of the β-function

Consider the matter Lagrangian

$$L = \int d^4\theta Z\left(X, X^+\right) Q^+ Q + \left[\int d^2\theta\, f(Q) + \text{h.c.}\right]$$ Expand in θ

$$L = \int d^4\theta \left(Z + \frac{\partial Z}{\partial X} F\theta^2 + \frac{\partial Z}{\partial X^+} F^+ \bar{\theta}^2 + \frac{\partial^2 Z}{\partial X \partial X^+} F F^+ \theta^2 \bar{\theta}^2 \right)\Bigg|_{X=M} Q^+ Q + \left[\int d^2\theta\, f(Q) + \text{h.c.}\right]$$

Redefine $Q' \equiv Z^{1/2}\left(1 + \frac{\partial \ln Z}{\partial X} F\theta^2\right)\Big|_{X=M} Q$

$$L = \int d^4\theta \left(1 + \frac{\partial^2 \ln Z}{\partial X \partial X^+} F F^+ \theta^2 \bar{\theta}^2\right)\Bigg|_{X=M} Q'^+ Q' + \left[\int d^2\theta \left(f(Q') - \frac{\partial f}{\partial Q'} \frac{\partial \ln Z}{\partial X}\Big|_{X=M} F\theta^2 \right) + \text{h.c.}\right]$$

$$\tilde{m}_Q^2(Q) = -\frac{\partial^2 \ln Z\left(X, X^+, Q\right)}{\partial \ln X \partial \ln X^+}\Bigg|_{X=M} \frac{FF^+}{MM^+}$$

$$A(Q) = \frac{\partial \ln Z\left(X, X^+, Q\right)}{\partial \ln X}\Bigg|_{X=M} \frac{F}{M}$$

The equation for the wave-function renormalization is

$$\frac{d}{d\ln Q}\ln Z = \frac{c g^2}{4\pi} \qquad c = \frac{n^2-1}{2n} \text{ for fundamental of } SU(n)$$

$$Z\left(X, X^+, Q\right) = Z(\Lambda)\left[\frac{g^2(\Lambda)}{g^2(X)}\right]^{2c/b'}\left[\frac{g^2(X)}{g^2(Q)}\right]^{2c/b}$$

$$\frac{1}{g^2(Q)} = \frac{1}{g^2(\Lambda)} + \frac{b'}{16\pi^2}\ln\frac{XX^+}{\Lambda^2} + \frac{b}{16\pi^2}\ln\frac{Q^2}{XX^+}$$

Taking derivatives at $Q = M$

$$\tilde{m}_Q^2(M) = 2c\frac{g^4}{\left(16\pi^2\right)^2}N\frac{F^2}{M^2} \qquad A(M) = 0$$

Soft terms are given by discontinuities of
β and γ functions at the messenger scale

In general

$$M_{\tilde{g}} = \frac{\Delta\beta_g}{2}\frac{F}{M} \qquad\qquad \beta_\lambda \equiv \frac{d\lambda^2}{d\ln Q}$$

$$A_\alpha = \frac{\Delta\gamma_\alpha}{2}\frac{F}{M} \qquad\qquad \gamma_\alpha \equiv \frac{d\ln Z}{d\ln Q}$$

$$\tilde{m}_\alpha^2 = \frac{1}{4}\sum_i \left[\Delta\beta_i \frac{\partial\gamma_\alpha^{(-)}}{\partial\lambda_i^2} - \beta_i^{(+)}\frac{\partial\Delta\gamma_\alpha}{\partial\lambda_i^2}\right]\frac{F^2}{M^2}$$

In our case: $\Delta\beta_g = \dfrac{Ng_i^4}{8\pi^2}, \quad \gamma_Q = \dfrac{c_i g_i^2}{4\pi^2}$

Gaugino mass at one loop, scalar masses at two loops:

$$m_S \approx \frac{g^2}{16\pi^2}\frac{F}{M}$$

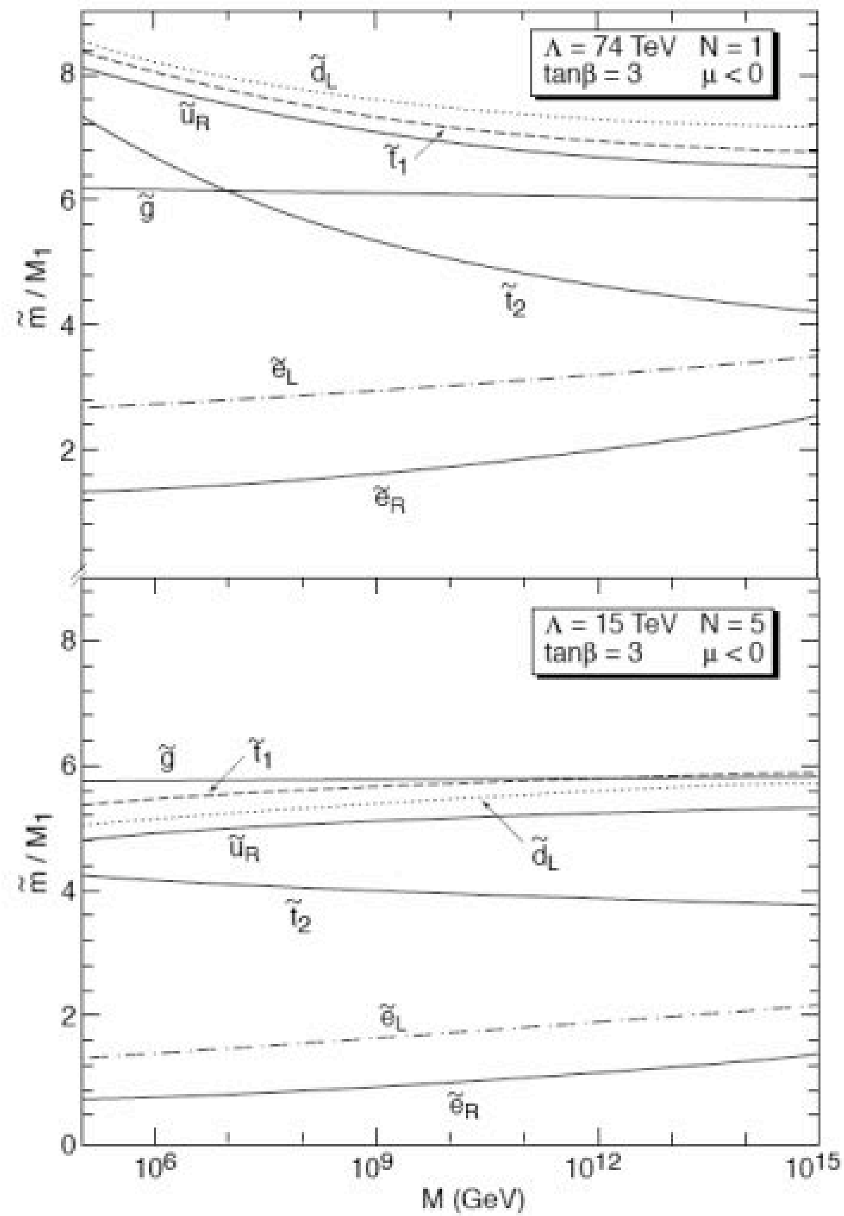
F/M ~ 10-100 TeV, but *M* arbitrary

To dominate gravity and have no flavour problem

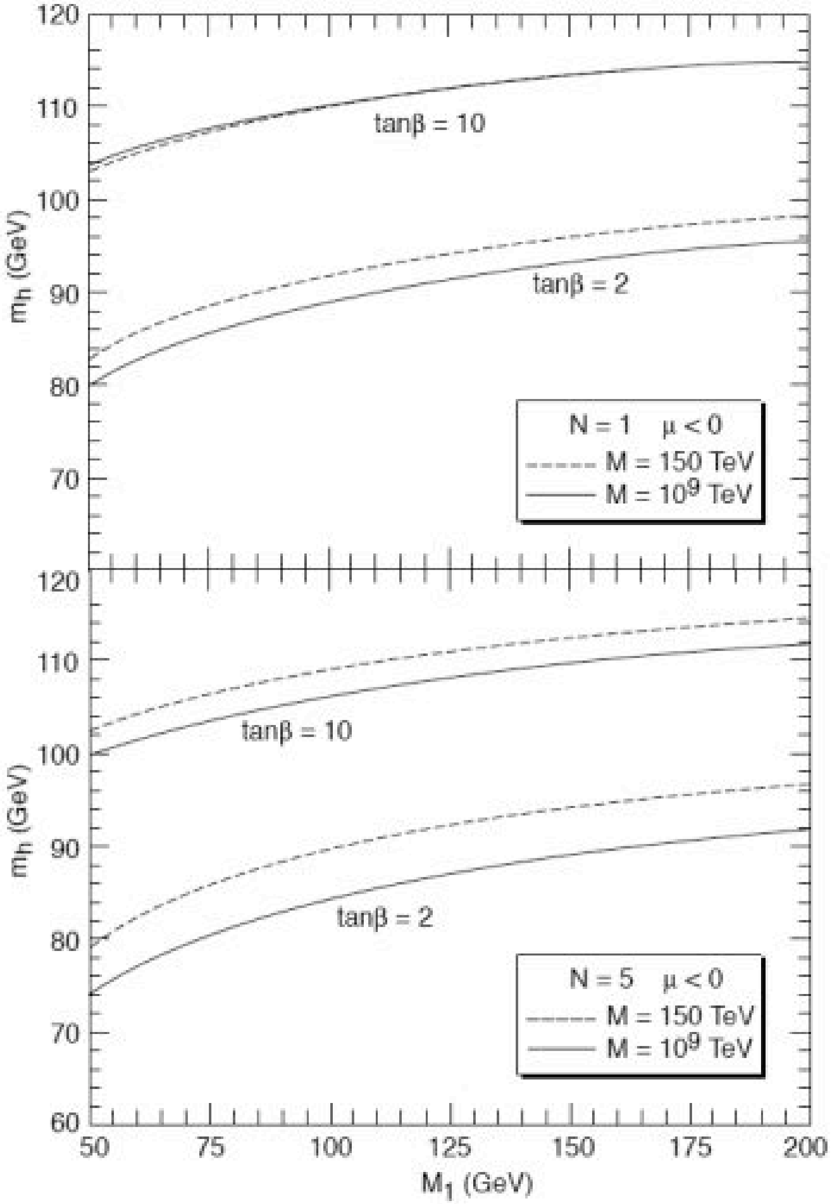
$$\frac{F}{M_P} < 10^{-2}\frac{g^2}{16\pi^2}\frac{F}{M} \quad \Rightarrow \quad M < 10^{15} \text{ GeV}$$

From stability: $F^{1/2} < M$

From perturbativity up to the GUT scale: $N < 150/\ln\frac{M_{GUT}}{M}$



- Theory is very predictive
- Gaugino masses are "GUT-related", although they are not extrapolated to M_{GUT}
- Gaugino/scalar mass scales like $N^{1/2}$
- Large squark/slepton mass ratio and small A do not help with tuning



Higgs mass is the strongest constraint: stop masses at several TeV

HOW IS μ GENERATED?

Messenger interactions do not violate PQ

We need new couplings

$$f = \lambda X H_1 H_2$$

Tuning λ to be one-loop is not sufficient

$$\mu = \lambda M, \qquad B_\mu = \lambda F \quad \Rightarrow \quad \frac{B_\mu}{\mu} = \frac{F}{M} \approx 10-100 \text{ TeV}$$

$$f = H_1 \Phi_1 \Phi_2 + H_2 \overline{\Phi}_1 \overline{\Phi}_2$$

at one loop $\frac{1}{16\pi^2} \int d^4\theta H_1 H_2 \frac{X^+}{X} + \text{h.c.} \quad \Rightarrow \quad \frac{B_\mu}{\mu} = \frac{F}{M}$

- In theories with a single scale, the relation $\frac{B_\mu}{\mu} = \frac{F}{M}$ is OK
- It is problematic, when soft terms are computed as loop factors times *F/M*

Alternative solutions

Generate μ from $\int d^4\theta H_u H_d \underbrace{D^2 f(X,X^+)}$

Antichiral: does not generate B_μ

New singlet superfield with $f = \lambda N H_u H_d - \frac{k}{3} N^3$

$<N> = \mu, \quad <F_N> = B_\mu$

Scalar potential for $v = 0$: $V = k^2 |N|^4 - \left(\frac{k}{3} A_k N^3 + \text{h.c.} \right) + \tilde{m}_N^2 |N|^2$

Non-trivial vacuum triggered by m_N^2 or A_k

In gauge mediation $m_N^2 = A_k = 0$ at messenger scale

Mass spectrum is unacceptable

Direct coupling of the singlet to the messenger sector

$$f = X\left(\overline{\Phi}_1\Phi_1 + \overline{\Phi}_2\Phi_2\right) + N\overline{\Phi}_1\Phi_2$$

Doubling of messengers necessary to avoid kinetic mixing NX^+

This can generate negative m_N^2 and large A_k

Singlet is sometimes introduced in gravity-mediation
(although there is no μ problem)

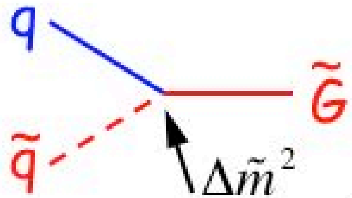
New Higgs quartic coupling $m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \ldots$

Perturbativity up to M_{GUT} requires $\lambda(m_S) < 0.5$; new contribution at small $\tan\beta$ smaller than old at large $\tan\beta$

Crucial difference between gauge and gravity mediation

$$m_{3/2} = \frac{F}{\sqrt{3}M_P} \Rightarrow \text{ in gravity } m_{3/2} \approx m_S, \text{ in gauge } m_{3/2} \approx \left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^2 2\text{ eV}$$

In gauge mediation, the gravitino is *always* the LSP



$$L = -\frac{1}{F} J_Q^{\mu} \partial_{\mu} \tilde{G} = -\frac{1}{F}\left(\tilde{m}_{\varphi}^2 \overline{\psi}_L \varphi + \frac{M_{\tilde{g}}}{4\sqrt{2}} \overline{\lambda}^a \sigma^{\mu\nu} F_{\mu\nu}^a\right) \tilde{G} + \text{h.c.}$$

$\frac{\Delta\tilde{m}^2}{F}$ on mass shell

Goldberger-Treiman*ino* relation

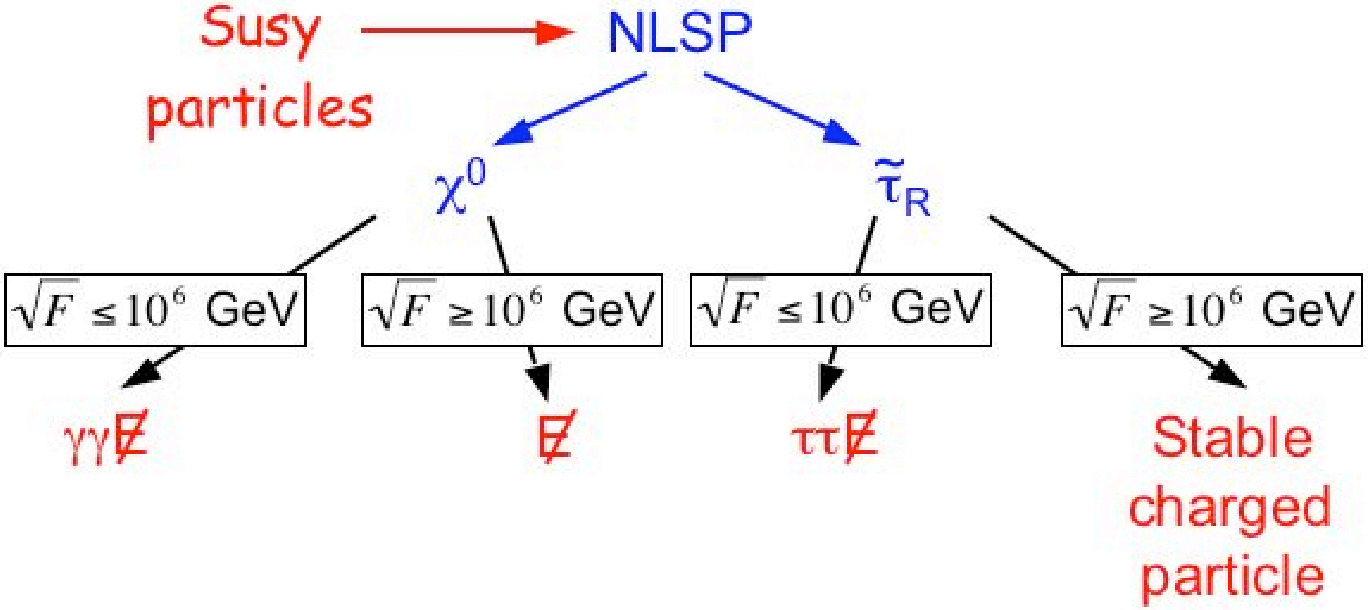
NLSP decays travelling an average distance

$$\ell \approx \left(\frac{100\text{ GeV}}{m_{NLSP}}\right)^5 \left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^4 \sqrt{\frac{E^2}{m_{NLSP}^2} - 1}\quad 0.1\text{ mm}$$

From microscopic to astronomical distances

χ^0 or $\tilde{\tau}_R$ are the NLSP (NLSP can be charged)

In gravity-mediation, "missing energy" is the signature



Intermediate region very interesting

(vertex displacement; direct measurement of *F*)

ANOMALY MEDIATION

• Supergravity mediation effects depend on higher-dimensional couplings of hidden-visible sector

• There is an "unavoidable" effect ⇒ anomaly mediation

• In many cases it is subleading. In some cases it can become the dominant effect

Consider coupling to gravity in superconformal formalism with the conformal compensator chiral superfield

$$\Phi = 1 - m_{3/2}\theta^2$$

Its couplings are dictated by conformal invariance

$$L = \int d^4\theta \Phi^+ \Phi Q^+ e^V Q + \int d^2\theta \left(\Phi^3 f(Q) + \frac{1}{g^2} W^\alpha W_\alpha + \text{h.c.} \right)$$

- One can construct allowed couplings by considering all visible fields with $d = R = 0$ and Φ with $d_\Phi = 1$, $R_\Phi = 2/3$
- By rescaling $Q \to Q/\Phi$, we can eliminate Φ, if $f(Q) \sim Q^3$ has no dimensionful couplings (it is the case of interest because μ has to come from susy breaking)
- Classically, but not quantum mechanically! (Scale anomaly)

$$L = \int d^4\theta Z\left(\frac{\mu}{|\Phi|}\right) Q^+ e^V Q + \int d^2\theta \left[f(Q) + S\left(\frac{\mu}{\Phi}\right) W^\alpha W_\alpha \right] + \text{h.c.}$$

Can depend on both Φ and Φ⁺, but R-symmetry implies dependence only on ΦΦ⁺

Holography implies dependence only on Φ

$$M_\lambda = -\frac{1}{2} \frac{\partial \ln S}{\partial \ln \Phi}\bigg|_0 F_\Phi$$

$$m_{\tilde{Q}}^2 = -\frac{\partial^2 \ln Z_Q}{\partial \ln \Phi \partial \ln \Phi^\dagger}\bigg|_0 F_\Phi^\dagger F_\Phi$$

$$A_{Q_i} = \frac{\partial \ln Z_{Q_i}}{\partial \ln \Phi}\bigg|_0 F_\Phi.$$

$$M_\lambda = -\frac{g^2}{2} \frac{dg^{-2}}{d \ln \mu} m_{3/2} = \frac{\beta_g}{g} m_{3/2}$$

$$m_{\tilde{Q}}^2 = -\frac{1}{4} \frac{d^2 \ln Z_Q}{d(\ln \mu)^2} m_{3/2}^2 = -\frac{1}{4} \left(\frac{\partial \gamma}{\partial g} \beta_g + \frac{\partial \gamma}{\partial y} \beta_y \right) m_{3/2}^2$$

$$A_y = \frac{1}{2} \sum_i \frac{d \ln Z_{Q_i}}{d \ln \mu} m_{3/2} = -\frac{\beta_y}{y} m_{3/2}.$$

- Form valid to all orders in perturbation theory
- Gaugino mass and trilinear at one loop, scalar mass square at two loops
- Gravitino is heavy, $m_{3/2}$ ~ 10-100 TeV
- Form of soft terms invariant under RG transformations
- β function and threshold effects of heavy states exactly compensate

Consider heavy fields in vector-like irrep of gauge group

$$L = \int d^2\theta M \Phi \bar{R} R + \text{h.c.}$$

Φ appears to compensate for conformal breaking of *M*

Because of gravity, *R* acts like a messenger with $F/M = -m_{3/2}$

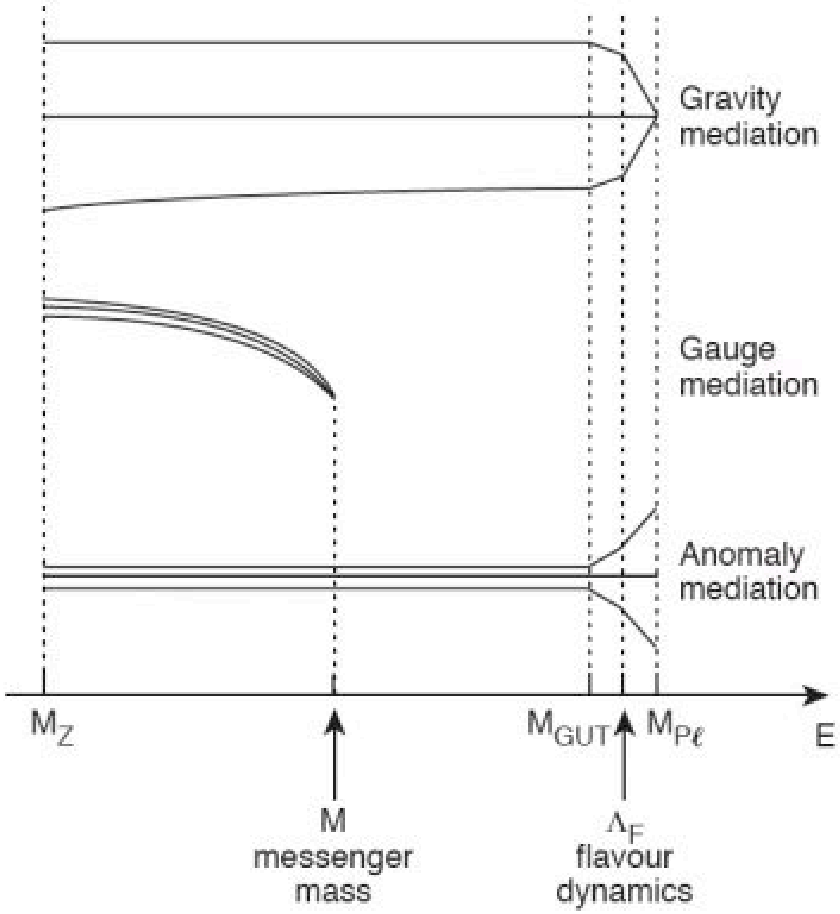
This gives gaugino mass contribution $\delta M_{\tilde{g}} = -\frac{\Delta\beta_g}{g} m_{3/2}$

Above $M \quad \Rightarrow \quad M_{\tilde{g}}^{(+)} = \frac{\beta_g^{(+)}}{g} m_{3/2}$

Below $M \quad \Rightarrow \quad M_{\tilde{g}}^{(-)} = M_{\tilde{g}}^{(+)} + \delta M_{\tilde{g}} = \frac{\beta_g^{(-)}}{g} m_{3/2}$

Gaugino mass remains on its anomaly-mediation RG trajectory

- Predictive power: all soft terms determined by low-energy parameters (up to overall scale $m_{3/2}$)
- UV insensitivity: solution to the flavour problem



Is anomaly-mediation a dominant source of susy breaking?

No gauge singlet in hidden sector: $\int d^2\theta \frac{X}{M_{Pl}} WW$ does not exist
gaugino mass only $M_S^3/M_P^2 \sim$ keV

Extra dimensional separation of hidden and visible sector

Conformal sequestering

$$L(M_P) = \frac{1}{M_P^{n-2}} Q^+ Q \, O_{hid}$$

$$L(\mu) = \left(\frac{\mu}{M_P}\right)^{\gamma} \frac{1}{M_P^{n-2}} Q^+ Q \, O_{hid}$$

n and γ canonical and anomalous dimensions of O_{hid}

Unfortunately sleptons have negative square masses

Neglecting Yukawas $\frac{\partial \gamma}{\partial g} > 0 \Rightarrow \tilde{m}_Q^2 \propto -\beta_g$

Both *SU(2)* and *U(1)* are not asymptotically free

Extra contributions?

Back to the flavour problem?

- universal scalar term m_0^2
- deflection from RG trajectory

Previous example suggests a solution

With a new gauge-mediation contribution $F/M \neq m_{3/2}$,
we deflect the anomaly-mediation RG trajectory

We want $F/M \sim m_{3/2}$, or else $\begin{cases} \text{irrelevant contribution} \\ \text{gauge mediation} \end{cases}$

Ex. $$\int d^2\theta \left[SR\overline{R} + \frac{S^n}{(M\Phi)^{n-3}} \right]$$

The potential is $V = M^4 \left\{ n^2 \left| \frac{S}{M} \right|^{2(n-1)} + \left[(n-3)\left(\frac{S}{M}\right)^n \frac{F_\Phi}{M} + \text{h.c.} \right] \right\}$

The minimum is $\left(\frac{\langle S \rangle}{M}\right)^{n-2} = \frac{n-3}{n(n-1)} \frac{\langle F_\Phi \rangle}{M}$. Therefore $\frac{\langle F_S \rangle}{\langle S \rangle} = nM\left(\frac{S}{M}\right)^n = \frac{n-3}{n-1}\langle F_\Phi \rangle$

For $n > 3$ and $M >> \langle F_\Phi \rangle$, we find $\langle F_\Phi \rangle << \langle S \rangle << M$ and $\langle F_S \rangle / \langle S \rangle \approx \langle F_\Phi \rangle = -m_{3/2}$

This gives the desired effect and the spectrum is modified

Characteristic features of anomaly mediation

With gaugino unification $\frac{M_2}{M_1} \approx 2 \quad \frac{M_3}{M_1} \approx 7$

In anomaly mediation $\frac{M_1}{M_2} \approx 3 \quad \frac{M_3}{M_2} \approx 7$

LSP nearly degenerate *W*-ino

$$m_{\chi^\pm} - m_{\chi^0} \approx \frac{\alpha M_W}{2(1+\cos\theta_W)} \approx 165 \text{ MeV (tree level is typically smaller)}$$

This allows the fast decay $\tilde{W}^\pm \to \pi^\pm \tilde{W}^0$

The pions are soft, making their detection difficult

Degeneracy of charged sleptons (if correction is universal)

$$\tilde{m}_{e_L}^2 - \tilde{m}_{e_R}^2 = \left(11\tan^4\theta_W - 1\right)\frac{3}{2}M_2^2 - \left(\frac{1}{2} - 2\sin^2\theta_W\right)M_Z^2\cos 2\beta + \text{loop}$$

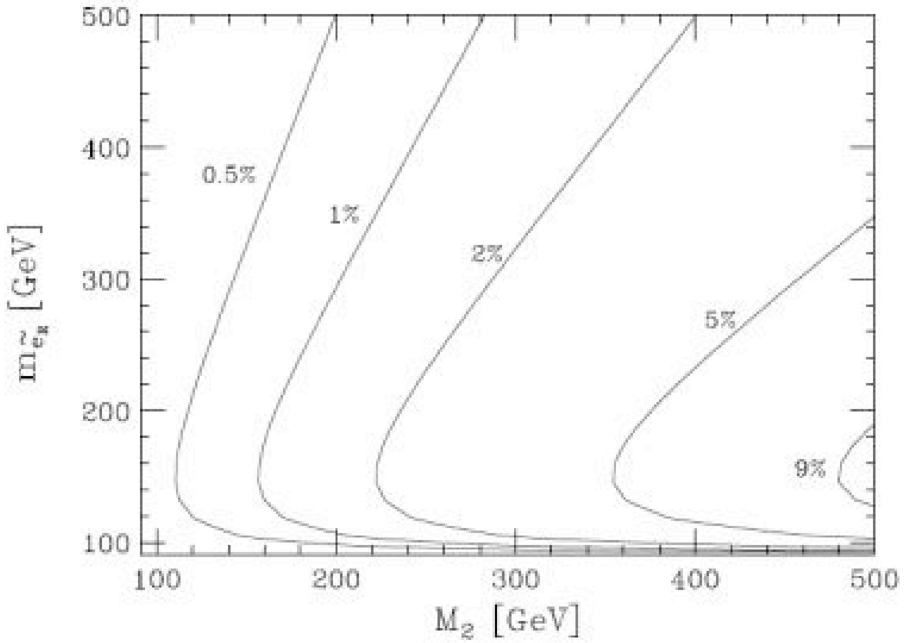
cancels for

$$\sin^2\theta_W = \frac{1}{1+\sqrt{11}} = 0.2317$$

$$\sin^2\theta_W(\text{exp}) = 0.2312$$

cancels for

$$\sin^2\theta_W = 1/4$$



MIRAGE UNIFICATION

It is possible to have a mixed modulus and anomaly mediation such that

$$\frac{F_T}{T} = M_0 \approx \frac{m_{3/2}}{\ln\left(M_P / m_{3/2}\right)}$$

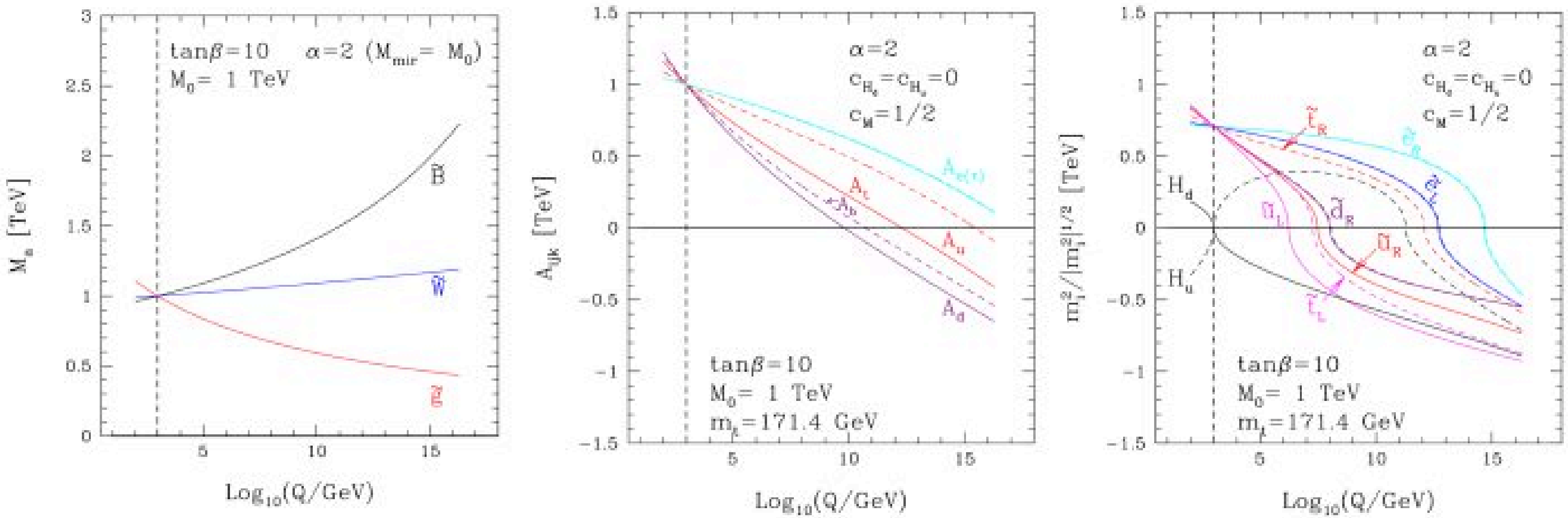
For $m_{3/2} \approx 10$ TeV, this is comparable to anomaly contribution

Although uplift potential not consistent with extra dim, one finds

$$M_{\tilde{g}} = A = \sqrt{2}\,\tilde{m} \quad \text{at} \quad M_{mir} = \frac{M_{GUT}}{\left(M_P / m_{3/2}\right)^{\alpha/2}}$$

α is the ratio of anomaly/modulus contributions

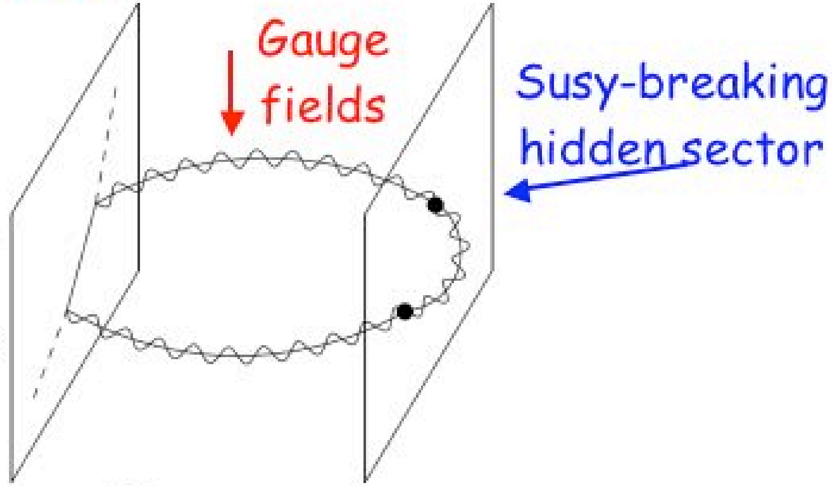
No physical threshold at M_{mir}



- small log
- large A
- compressed spectrum

is best to reduce tuning

GAUGINO MEDIATION



Motivated by extra dimensions

Gaugino masses at tree level $\int d^2\theta \frac{X}{M} W^{\alpha} W_{\alpha}$ with "GUT" relations

Scalar masses from RG evolution

$$\frac{d\tilde{m}^2}{d\ln Q} = \frac{c}{4\pi^2} g^2 M^2$$

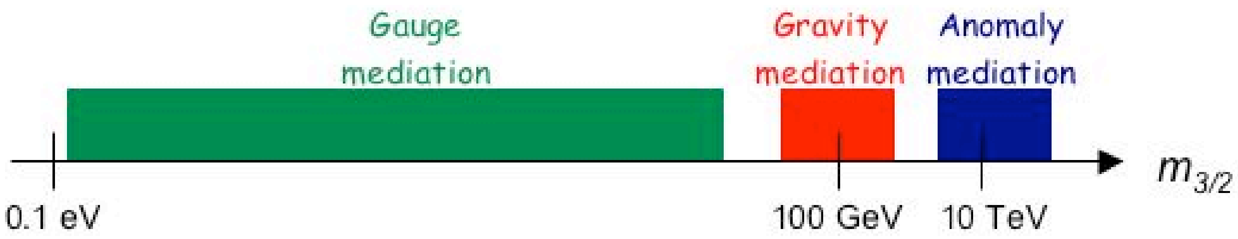
Gauge invariant

$$\tilde{m}^2(Q) = \frac{2c}{b}\left[g^4_{GUT} - g^4(Q)\right]\left(\frac{M_{\tilde{g}}}{g^2}\right)^2$$

$$\frac{b}{16\pi^2}\ln\frac{M_{GUT}}{Q}$$

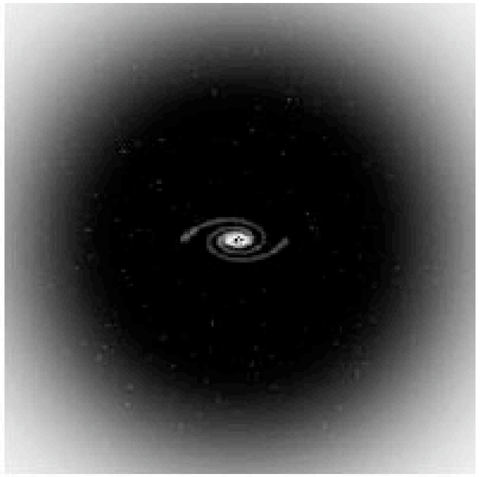
- All mass squared positive
- Scalar masses comparable to gaugino masses for large log

Many emerging possibilities for soft term structure



- Single scale (incalculable soft terms, flavour problem, μ OK)
- Multi scales (predictive, flavour OK, μ problem)
- Experimental signature quite distinct

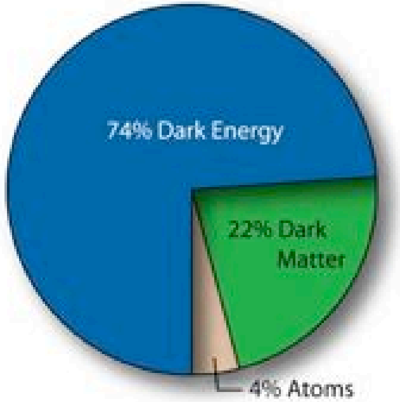
DARK MATTER



Indirect evidence for DM is solid

Cosmology lectures

- rotational curves of galaxies
- weak gravitational lensing of distant galaxies
- velocity dispersion of galaxy satellites
- structure formation in N-body simulations



- Opportunity for particle physics
- Intriguing connection weak-scale physics $\Leftrightarrow$ dark matter

Assume stable massive particle in thermal equilibrium at early times

$$\frac{dn}{dt} + 3Hn = -\sigma\left(n^2 - n_{eq}^2\right)$$

$$\sigma \equiv \langle \sigma_{ann} v \rangle_T \qquad n_{eq} \approx \begin{cases} T^3 & T >> m \\ (mT)^{3/2} e^{-m/T} & m >> T \end{cases}$$

During radiation dominance, $H = \dfrac{1}{2t} \quad t \propto T^{-2}$

Change variables $x \equiv \dfrac{m}{T}, \quad Y \equiv \dfrac{n}{s} \quad s \propto T^3$

$$\frac{dY}{dx} = -\frac{\sigma s}{xH}\left(Y^2 - Y_{eq}^2\right) = -\frac{c}{x^2}\left(Y^2 - Y_{eq}^2\right) \qquad \left(\text{Use } H \propto T^2/M_P\right)$$

Take σ independent of T (not always the case)

$$c \propto \left.\frac{\sigma n}{H}\right|_{T=m} \propto M_P m \sigma \quad = \frac{\text{annihilation rate}}{\text{expansion rate}} \text{ when particle becomes non-rel.}$$

$$\frac{dY}{dx} = -\frac{c}{x^2}\left(Y^2 - Y_{eq}^2\right)$$

At large T (small x): $Y_{eq} \approx$ constant $\Rightarrow Y(x) = Y_{eq}$

At small T (large x): $Y_{eq} \approx x^{3/2} e^{-x} \quad \Rightarrow \frac{1}{Y(x)} = -\frac{c}{x} + \frac{1}{Y_\infty}$

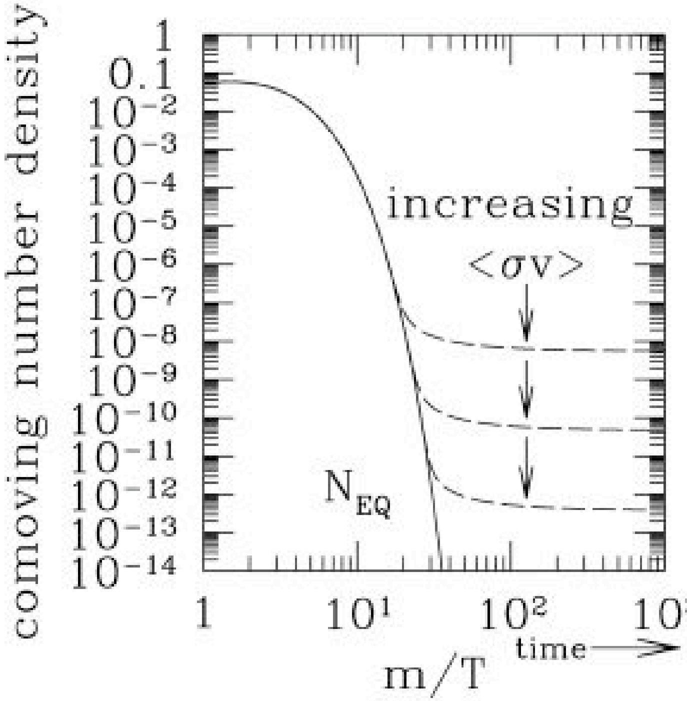
Call x_f the matching point (because of exponential the two regimes are quickly reached)

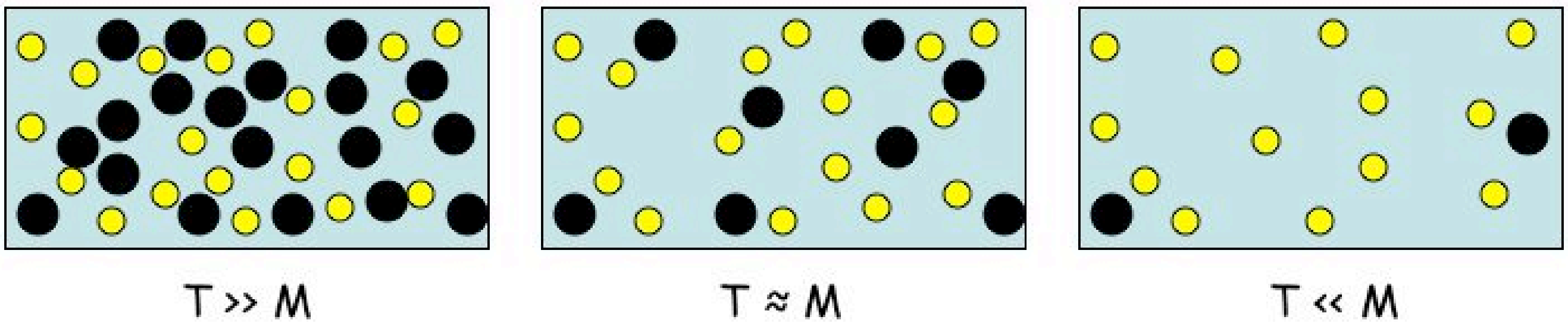
Since $Y_\infty << Y(x_f) \quad \Rightarrow \quad Y_\infty \approx \frac{x_f}{c}$

Matching the two branches at x_f :

$$Y_{eq}(x_f) \approx Y_\infty \quad \Rightarrow \quad x_f^{3/2} e^{-x_f} \approx \frac{x_f}{c} \quad \Rightarrow \quad x_f \approx \ln c$$

Relic density Y_∞ is roughly inversely proportional to annihilation / expansion rate at moment of non-rel. (up to log corrections)


comoving number density
1
0.1
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
increasing
<σv>
N_EQ
1
10¹
10²
10³
time
m/T


T >> M
T ≈ M
T << M

Putting constants back

$$\Omega_\chi = \frac{m n_\infty}{\rho_c} = \frac{(4\pi)^2}{3}\sqrt{\frac{\pi}{45}}\,\frac{x_f g_S(\gamma)}{g_*^{1/2}}\,\frac{T_\gamma^3}{H_0^2 M_P^3 \sigma}$$

$$\text{If } \sigma = \frac{k}{128\pi m^2} \quad \Rightarrow \quad \Omega_\chi = \frac{0.22}{k}\left(\frac{m}{\text{TeV}}\right)^2$$

Weak-scale particle candidate for DM

No parametric connection to the weak scale

Observation provides a link $M_{DM} \leftrightarrow \langle H \rangle$

Many BSM theories have a DM candidate

Susy has one of the most appealing

Supersymmetric Dark Matter

R-parity $\Rightarrow$ LSP stable

RG effects $\Rightarrow$ colour and electric neutral massive particle is LSP

Heavy isotopes exclude gluino, direct searches exclude sneutrino

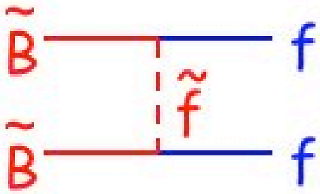
Neutralino or gravitino are the best candidates

NEUTRALINO

Because of strong exp limits on supersymmetry,
current eigenstates are nearly mass eigenstates:

Bino, Wino, Higgsino

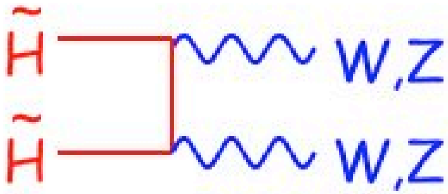
BINO



$$\langle \sigma_{\tilde{B}} v \rangle = \frac{3g^4 \tan^4\theta_W r(1+r^2)}{2\pi m_{\tilde{e}_R}^2 x(1+r)^4}, \quad x \equiv \frac{M_1}{T}, \quad r \equiv \frac{M_1^2}{m_{\tilde{e}_R}^2},$$

$$\Omega_{\tilde{B}} h^2 = 1.3 \times 10^{-2} \left(\frac{m_{\tilde{e}_R}}{100\,\mathrm{GeV}}\right)^2 \frac{(1+r)^4}{r(1+r^2)} \left(1 + 0.07 \log \frac{\sqrt{r}\,100\,\mathrm{GeV}}{m_{\tilde{e}_R}}\right)$$

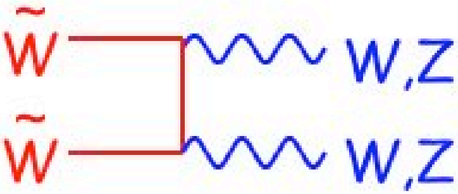
HIGGSINO



$$\langle \sigma_{eff} v \rangle = \frac{g^4}{512\pi\mu^2}\left(21 + 3\tan^2\theta_W + 11\tan^4\theta_W\right)$$

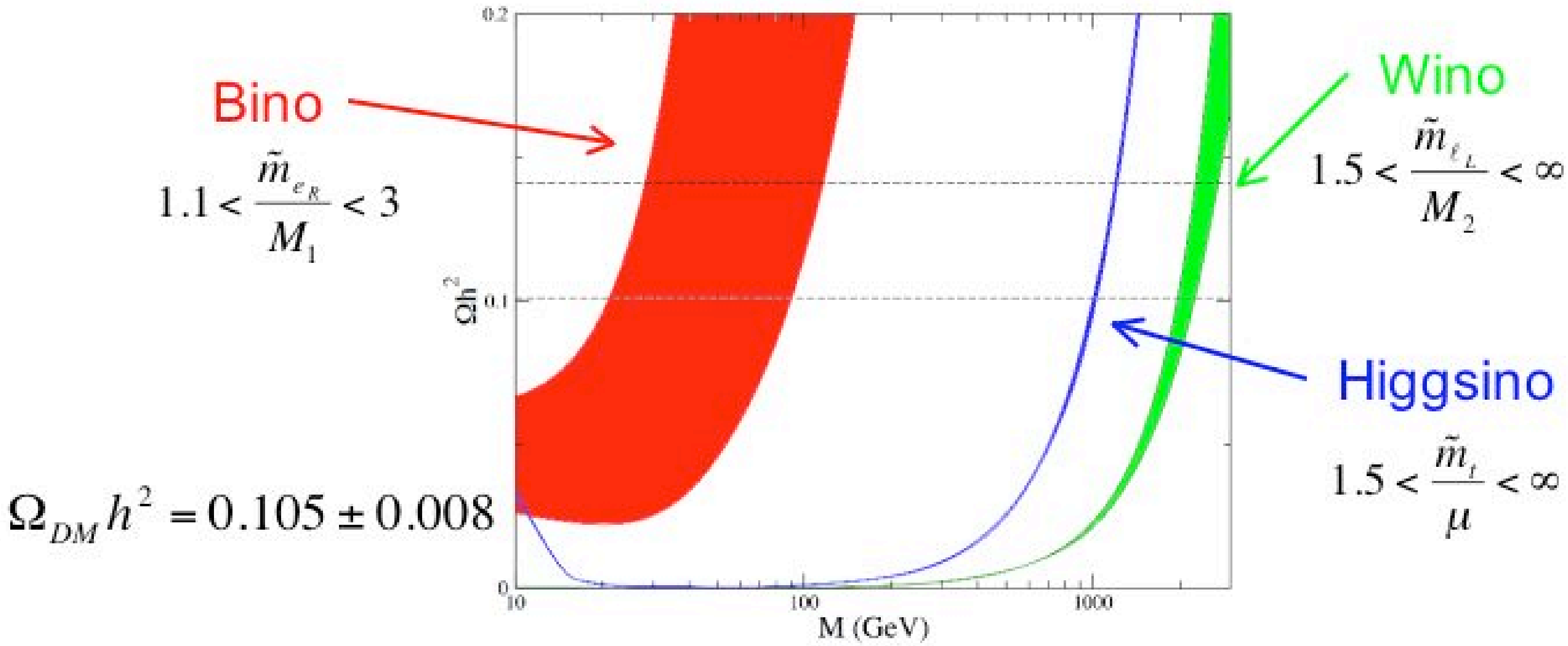
$$\Omega_{\tilde{H}} h^2 = 0.10 \left(\frac{\mu}{1\,\mathrm{TeV}}\right)^2,$$

WINO



$$\langle \sigma_{eff} v \rangle = \frac{3g^4}{16\pi M_2^2},$$

$$\Omega_{\tilde{W}} h^2 = 0.13 \left(\frac{M_2}{2.5\,\mathrm{TeV}}\right)^2.$$



Neutralino: natural DM candidate for light supersymmetry

Quantitative difference after LEP & WMAP

Both M_Z and Ω_{DM} can be reproduced by low-energy supersymmetry, but at the price of some tuning.

Unlucky circumstances or wrong track?

COANNIHILATION

Consider more particle species with $\delta m < T_f$

Since $x_f \approx 20-25 \quad \Rightarrow \quad \frac{\delta m}{m} \le 5\%$

Boltzmann equations for the different species

$$\sigma_{ij} = \sigma\left(\chi_i\chi_j \to XX'\right) \quad \sigma'_{ij} = \sigma\left(\chi_i X \to \chi_j X'\right) \quad \Gamma_{ij} = \Gamma\left(\chi_i \to \chi_j XX'\right)$$

$$\frac{dn_i}{dt} = -3Hn_i - \sum_{j,X}\left[\left\langle\sigma_{ij}v\right\rangle\left(n_i n_j - n_i^{eq} n_j^{eq}\right) - \left(\left\langle\sigma'_{ij}v\right\rangle n_i n_X - \left\langle\sigma'_{ji}v\right\rangle n_j n_{X'}\right) - \Gamma_{ij}\left(n_i - n_i^{eq}\right)\right]$$

Since all χ_i eventually decay into χ_1, we use $\quad n \equiv \sum_i n_i$

$$\frac{dn}{dt} = -3Hn - \left\langle\sigma_{eff}v\right\rangle\left(n^2 - n_{eq}^2\right)$$

$$\left\langle\sigma_{eff}v\right\rangle = \frac{\sum_{ij} w_i w_j \sigma_{ij}}{\left(\sum_i w_i\right)^2}, \quad w_i = \left(\frac{m_i}{m_1}\right)^{3/2} e^{-x\left(\frac{m_i}{m_1}-1\right)}$$

Annihilation rate of other species can be much larger than LSP

TO OBTAIN CORRECT χ RELIC ABUNDANCE

- Heavy susy spectrum: Higgsino (1 TeV) or Wino (2.5 TeV)
- Coannihilation Bino-stau (or light stop?)
- Nearly degenerate Bino-Higgsino or Bino-Wino
- S-channel resonance (heavy Higgs with mass $2m_\chi$)
- T_{RH} close to T_f

All these possibilities have a very critical behavior with underlying parameters

- Decay into a lighter particle (*e.g.* gravitino)

GRAVITINO

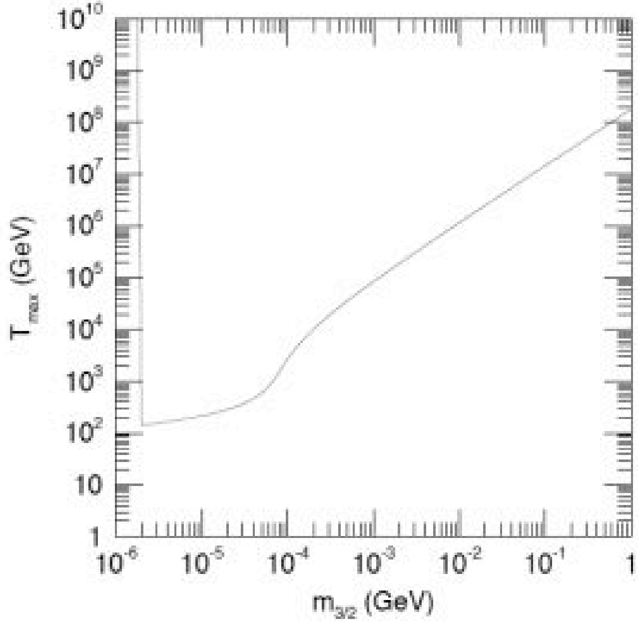
If gravitinos were in thermal equilibrium at early times

$$\Omega_{3/2}h^2 \approx 0.1\frac{m_{3/2}}{100\,\mathrm{eV}}$$

Possible in gauge mediation with $\sqrt{F} \approx 600\ \mathrm{TeV}$

Assume inflation and a maximum temperature T_{RH}

Light gravitinos are produced through their spin-1/2 component, with coupling constant $1/F \sim 1/(m_{3/2}M_P)$



Heavy gravitinos decay late

$$\tau(\tilde{G}) = \left(\frac{\mathrm{TeV}}{m_{3/2}}\right)^3 4\times 10^5\,\mathrm{sec}$$

From BBN, $T_{RH} < 10^6$ GeV for $m_{3/2}$ = TeV

Gravitinos can be produced by late NLSP decay

$$\Omega_{3/2} = \frac{m_{3/2}}{m_\chi} \Omega_\chi$$

This can dilute the excessive Bino relic abundance

However the case $\chi \rightarrow \tilde{G}\gamma$ is ruled out by BBN, and possibly a window remains for $\tilde{\tau} \rightarrow \tilde{G}\tau$

Gravitino DM requires a mixture of thermal and non-thermal components

The link DM $\leftrightarrow$ weak scale is lost

Slow NLSP decay detectable at the LHC?

How can we identify DM at the LHC?

Establishing the DM nature of new LHC discoveries will not be easy. We can rely on various hints

- If excess of missing energy is found, DM is the prime suspect
- Reconstructing the relic abundance (possible only for thermal relics and requires high precision; LHC + ILC?)
- Identify model-dependent features (heavy neutralinos, degenerate stau-neutralino, mixed states, $m_A = 2\ m_\chi$)
- Compare with underground DM searches

DIRECT DM DETECTION

MW has a halo filled with χ, and locally

ρ_{halo} = 0.3 GeV/cm^3, v = 300 km/sec

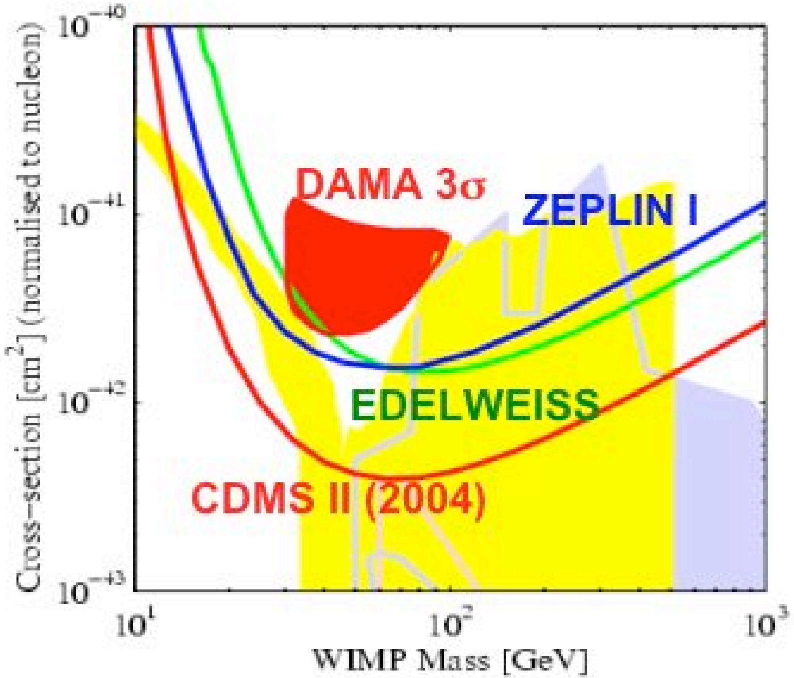
Scattering off nuclei leaves an energy deposition

$$E_{\max} \approx \frac{2m_N v^2}{\left(1+\frac{m_N}{M_\chi}\right)^2} = \left(1+\frac{76\mathrm{GeV}}{M_\chi}\right)^{-2} 150\mathrm{keV} \quad \text{on } Ge$$

visible in the form of scintillation light, ionization energy or thermal energy

Small rate: sheltering from cosmic rays

Annual modulation: Earth velocity around the Sun adds to the velocity of the solar system in the MW

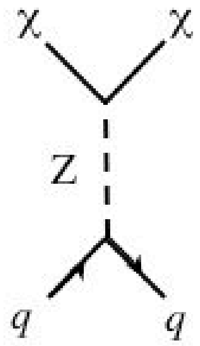


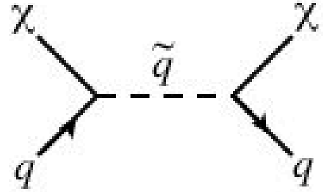
ν gives 3×10^{-38} cm^2

A weakly-interacting massive neutrino is ruled out

Why not the neutralino?

SCATTERING RATE

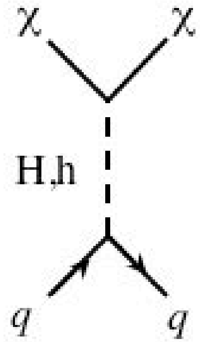


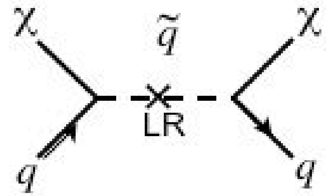


$\rightarrow \quad \bar{\chi}\gamma^{\mu}\gamma_5\chi\,\bar{q}\gamma_{\mu}\gamma_5 q$

Non-rel matrix element on the nucleon is proportional to nucleon spin

Scalar interaction only from



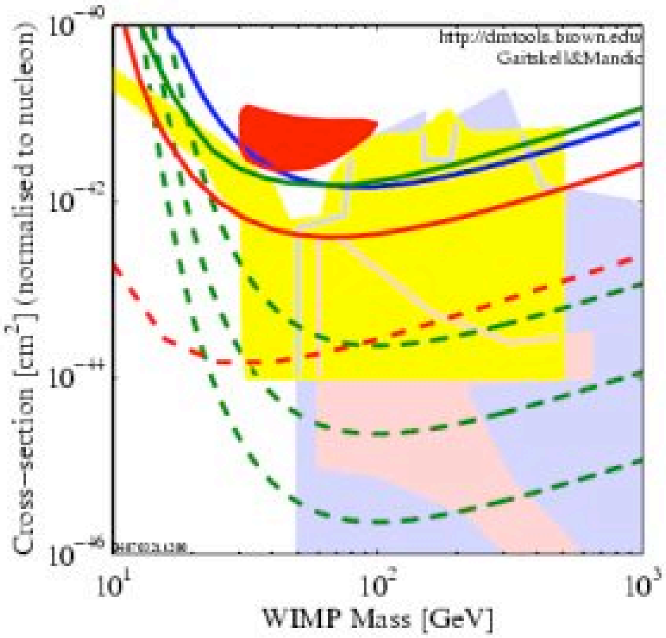


$\rightarrow \quad \bar{\chi}\chi\,\bar{q}q$

$$\frac{G_F M_W m_q}{m_h^2}\bar{\chi}\chi\bar{q}q$$

Only for mixed states

$$\langle N|m_q\bar{q}q|N\rangle = \frac{2m_N}{27}\bar{\psi}_N\psi_N$$



Improvements from CRESST, ZEPLIN, XENON will explore the most interesting region

Detection rate depends on local density

Use collider data to extract halo density

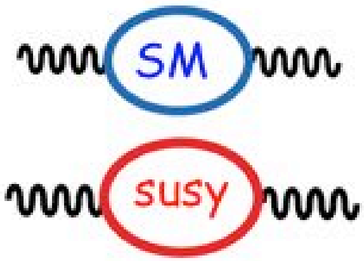
GRAND UNIFICATION

- Fundamental symmetry principle to embed all gauge forces in a simple group

- Partial unification of matter and understanding of hypercharge quantization and anomaly cancellation

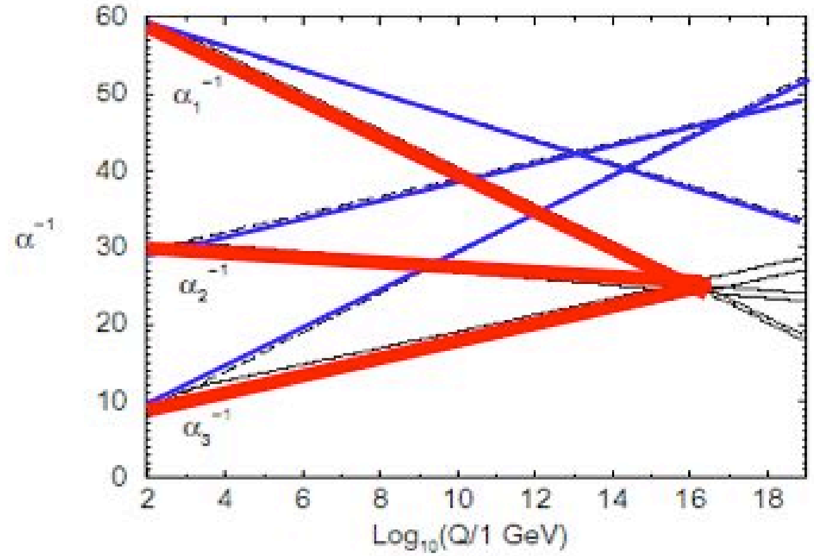
To allow for unification, we need to unify g, g', g_S from effects of low-energy degrees of freedom (depends on the GUT structure only through threshold corrections)

$$\frac{d g_i^{-2}}{d \ln Q} = \frac{b_i}{4\pi}$$



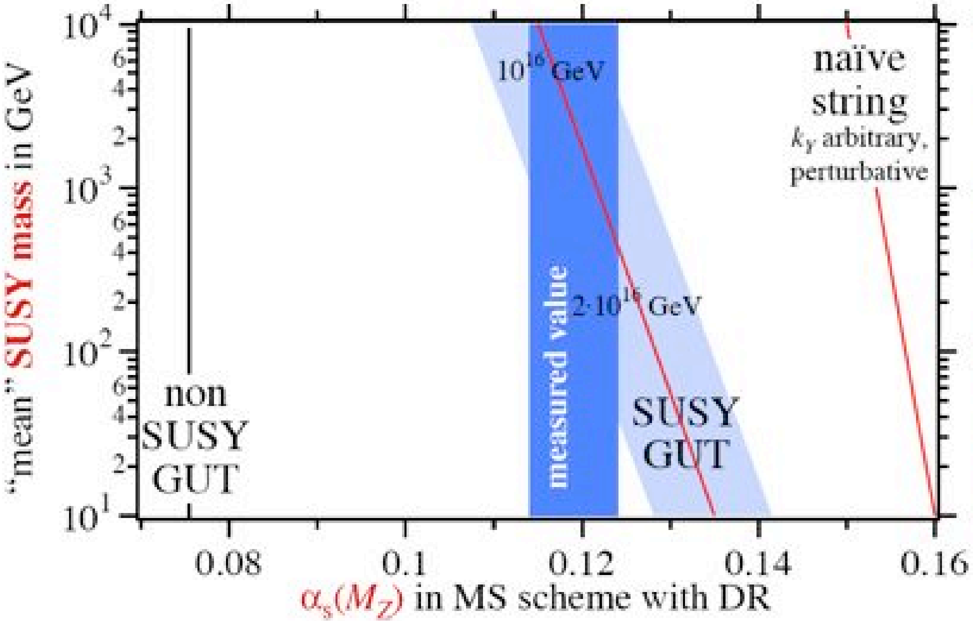
$b_3 = -7$, $b_2 = -19/6$, $b_1 = 41/6$

$b_3 = -3$, $b_2 = 1$, $b_1 = 11$



3 equations, 2 unknowns (α_{GUT}, M_{GUT}): predict α_S in terms of α and $sin^2\theta_W$

α_s^{exp} =0.1176±0.0020



- success of susy
- does not strongly depend on details of soft terms
- remarkable that M_{GUT} is predicted below M_P and above p-decay limit

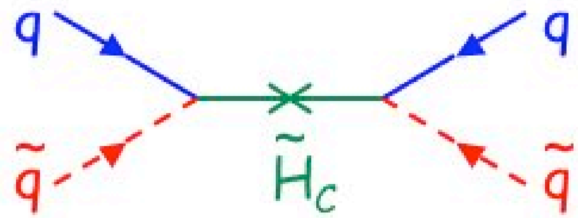
PROTON DECAY

New feature of supersymmetry: *p*-decay for $d = 5$

$$f = c_L O_L + c_R O_R \qquad O_L = Q_L^k Q_L^l Q_L^i L_L^j \quad O_R = \overline{U}_R^i \overline{D}_R^j \overline{U}_R^k \overline{E}_R^l$$

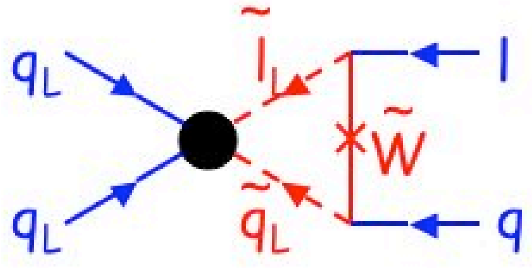
O_L vanishes if $k=l=i$ and O_R vanishes if $i=k$

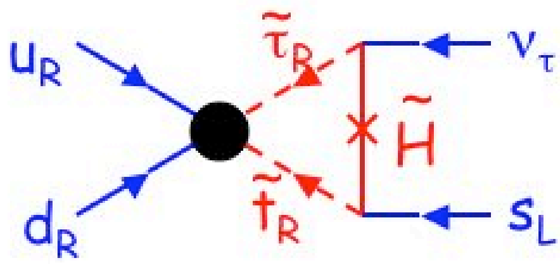
Generated by



Depends on Yukawa couplings (with naïve *SU(5)* relations), on M_H and on 2 new phases

DRESSING



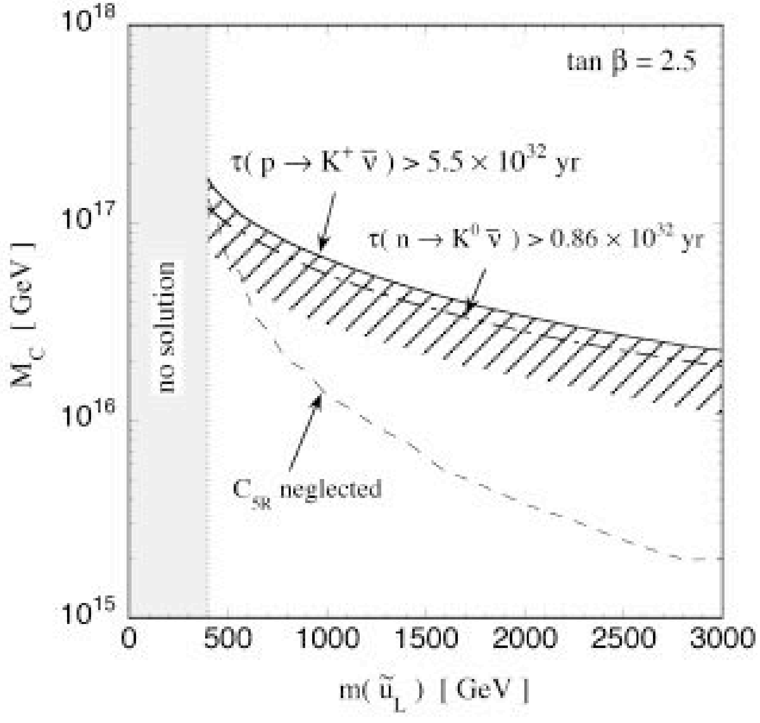


$p \to K^+ \bar{\nu}$ dominates over $p \to \pi^+ \bar{\nu}$ (Cabibbo suppressed)

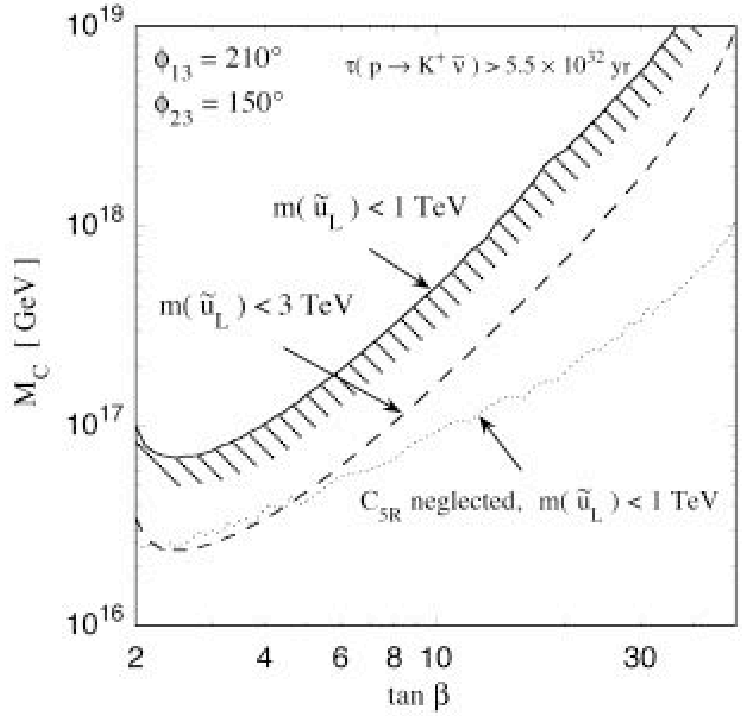
$p \to K^0 \mu^+$ (suppressed by m_u)

Rates depends upon

- susy mass spectrum
- flavour violations in susy-breaking sector
- couplings and mass of H_C
- new phases (possible cancellation in LLLL or RRRR, but not both)



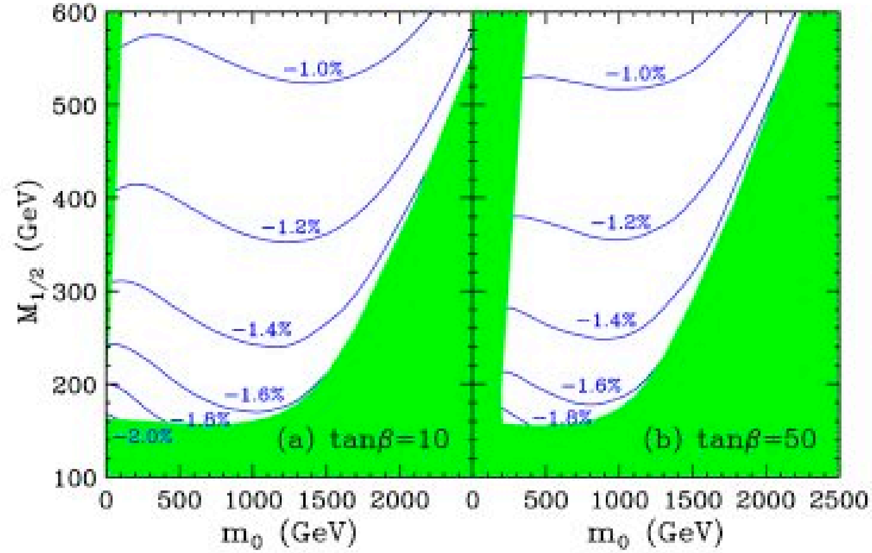
tan β = 2.5
τ(p → K⁺ ν̄) > 5.5 × 10^32 yr
τ(n → K⁰ ν̄) > 0.86 × 10^32 yr
no solution
C_5R neglected
M_C [GeV]
m(ũ_L) [GeV]



φ_13 = 210°
φ_23 = 150°
τ(p → K⁺ ν̄) > 5.5 × 10^32 yr
m(ũ_L) < 1 TeV
m(ũ_L) < 3 TeV
C_5R neglected, m(ũ_L) < 1 TeV
M_C [GeV]
tan β

Determining M_H from threshold corrections

Define $g_1(M_{GUT}) = g_1(M_{GUT})$ and $\varepsilon \equiv \frac{g_3(M_{GUT}) - g_1(M_{GUT})}{g_1(M_{GUT})}$



$$\delta\alpha_s \approx 0.7\varepsilon$$

$$\varepsilon_{H_C} = 0.3\frac{\alpha_{GUT}}{\pi}\ln\left(\frac{M_{H_C}}{M_{GUT}}\right) \Rightarrow 3.5\times10^{14} < \frac{M_{H_C}}{\mathrm{GeV}} < 3.6\times10^{15} \quad (90\%\ \mathrm{CL})$$

Thresholds from other GUT particles?

d = 5 PROTON DECAY

- depends on unknown aspects of susy GUT
  - doublet-triplet splitting
  - fermion mass relations
- most plausible estimate in conflict with observation
- need for mechanisms to suppress or eliminate d=5 operators
  - new symmetries
  - orbifold projections

d = 6 PROTON DECAY

Unavoidable contribution from X gauge boson exchange

$$\left(\overline{u}^c\right)_L \gamma_\mu q_L \left(\overline{e}^c\right)_L \gamma_\mu q_L \qquad \left(\overline{u}^c\right)_L \gamma_\mu q_L \left(\overline{d}^c\right)_L \gamma_\mu \ell_L$$

Neglecting GUT threshold effects

$$\tau_p\left(p \to e^+\pi^0\right) \approx 10^{36} - 10^{37}\ \mathrm{yrs}$$

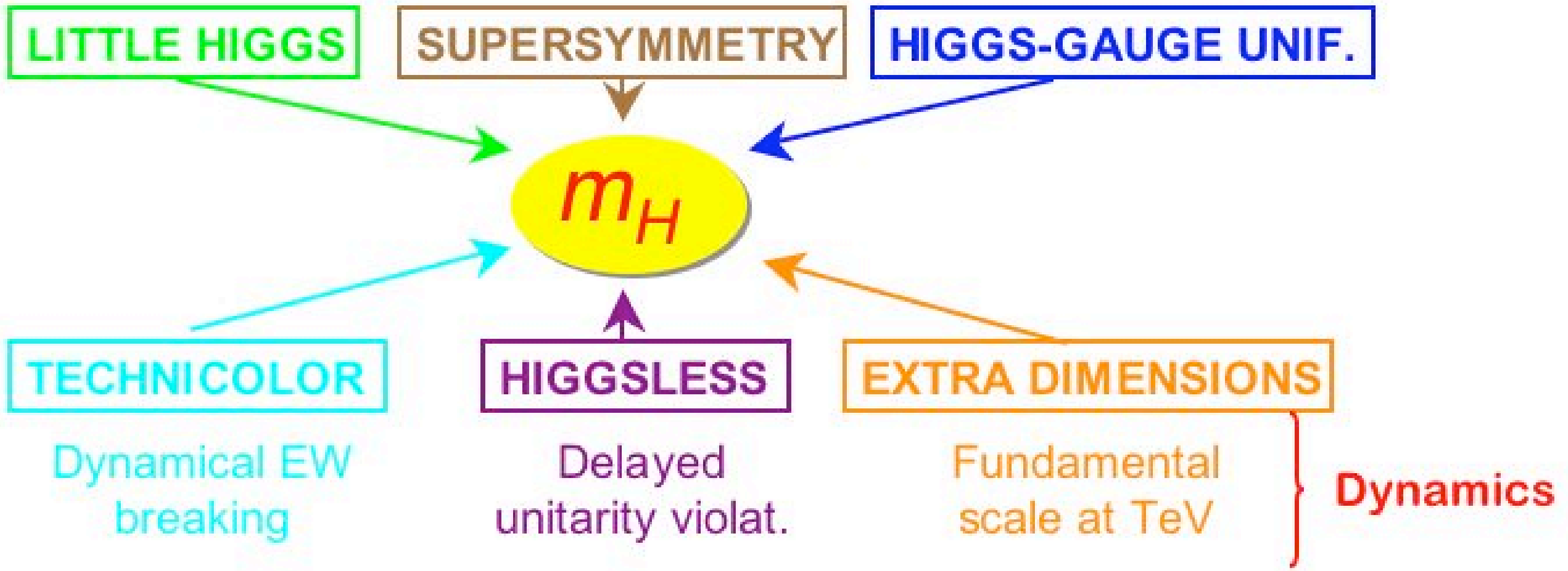
SuperKamikande $\tau_p\left(p \to e^+\pi^0\right) > 5 \times 10^{33}\ \mathrm{yrs}$

Future experiments can reach 10^{34} yrs or even 10^{35} yrs

What screens the Higgs mass?

boson	fermion	vector
$\phi \to \phi + a$	$\psi \to e^{i\alpha\gamma_5}\psi$	$A_\mu \to A_\mu + \partial_\mu a$
no $m^2\phi^2$	no $m\overline{\psi}\psi$	no $m^2 A_\mu A^\mu$
Spont. broken global symm.	Chiral symmetry	Gauge symmetry

} Symmetry



IS THERE A SYMMETRY OR DYNAMICAL PRINCIPLE BEHIND THE HIERARCHY?

Cancellation of	Existence of
electron self-energy	positron
π^+-π^0 mass difference	ρ
K_L-K_S mass difference	charm
gauge anomaly	top
cosmological constant	10^{-3} eV??

AN UNORTHODOX USE OF SUPERSYMMETRY

Abandon hierarchy problem (speculations on probability distributions of theories) and use only observational hints

Gauge-coupling unification: motivated by theory that addresses fundamental structure of SM and by measurements on α_i

Dark matter: connection between weak scale and new particle masses

$$\Omega_{\rm rel} h^2 \approx \frac{0.1\,\mathrm{pb}}{\langle \sigma\, v \rangle}$$

Proposal of SPLIT SUPERSYMMETRY: retain at the weak scale only gauginos, higgsinos and one Higgs boson (squarks, sleptons and extra Higgs at the scale $\widetilde{m}$)

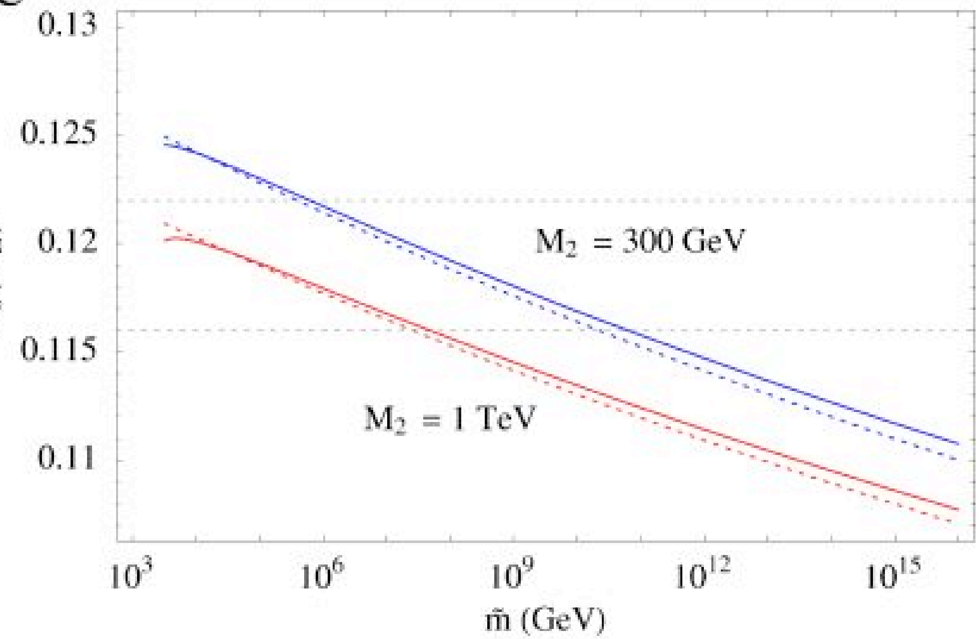
Eliminate :

- Excessive flavour and CP violation
- Fast dim-5 proton decay
- Tight constraints on the Higgs mass

Retain :

- DM & gauge-coupling unification

Gauge-coupling unification as successful (or better) than in ordinary SUSY



Why supersymmetry? (Bottom-up)

- Minimality: search for unification with single threshold, only fermions in real reps, and 10^{15} GeV < M_{GUT} < 10^{19} GeV ⇨ SpS has the minimal field content consistent with gauge-coupling unification and DM
- Splitting of GUT irreps: in SpS no need for new split reps either than SM gauge and Higgs
- Light particles: R-symmetry protects fermion masses
- Existence and stability of DM: R-parity makes χ stable
- Instability of coloured particles: coloured particles are necessary, but they decay either by mixing with quarks (FCNC!) or by interactions with scale < 10^{13} GeV

SpS not unique, but it has all the necessary features built in

Why supersymmetry? (Top-down)

$$X = 1 + \theta^2 \widetilde{m}$$

$$\int d^4\theta\, X^* X\, Q^* Q \to \widetilde{m}_Q^2 = \widetilde{m}^2 \qquad \int d^2\theta\, X W_\alpha W_\alpha \to M_{\widetilde{g}} = \widetilde{m}$$

$$\int d^4\theta\, X^* X\, H_1 H_2 \to B_\mu = \widetilde{m}^2 \qquad \int d^2\theta\, X Q^3 \to A = \widetilde{m}$$

$$\int d^4\theta\, X^*\, H_1 H_2 \to \mu = \widetilde{m}$$

R - invariant soft terms (choose $\mathrm{R}[H_1 H_2] = 0$ so that $\int d^2\theta\, H_1 H_2$ forbidden)

R - violating soft terms ($\mathrm{R}[X] = 0$, R - symmetry broken by F_X)

- R-symmetry "splits" the spectrum ($M_{\widetilde{g}}$ and μ mix through renorm.)
- R-invariant ⇨ dim = 2 R-violating ⇨ dim = 3

Split Supersymmetry determined by susy-breaking pattern

$$\text{D - breaking} \qquad Y = 1 + \theta^4 \widetilde{m}^2$$

$$\int d^4\theta \; YQ^* Q \to \widetilde{m}_Q^2 = \widetilde{m}^2 \qquad \int d^4\theta \; YH_1 H_2 \to B_\mu = \widetilde{m}^2$$

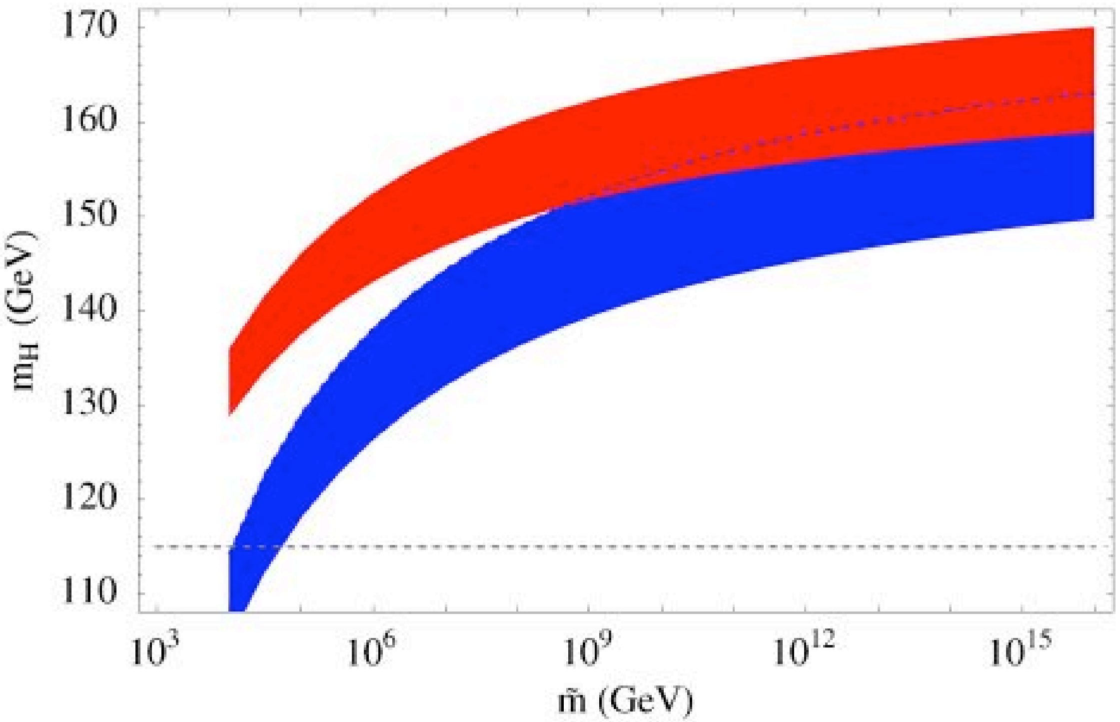
$$\text{Non renorm. operators} \qquad \frac{1}{M_*}\int d^4\theta \; YW_\alpha W_\alpha \to M_{\tilde{g}} = \frac{\widetilde{m}^2}{M_*}$$

$$\frac{1}{M_*}\int d^4\theta \; YQ^3 \to A = \frac{\widetilde{m}^2}{M_*} \qquad \frac{1}{M_*}\int d^4\theta \; YD^2 (H_1 H_2) \to \mu = \frac{\widetilde{m}^2}{M_*}$$

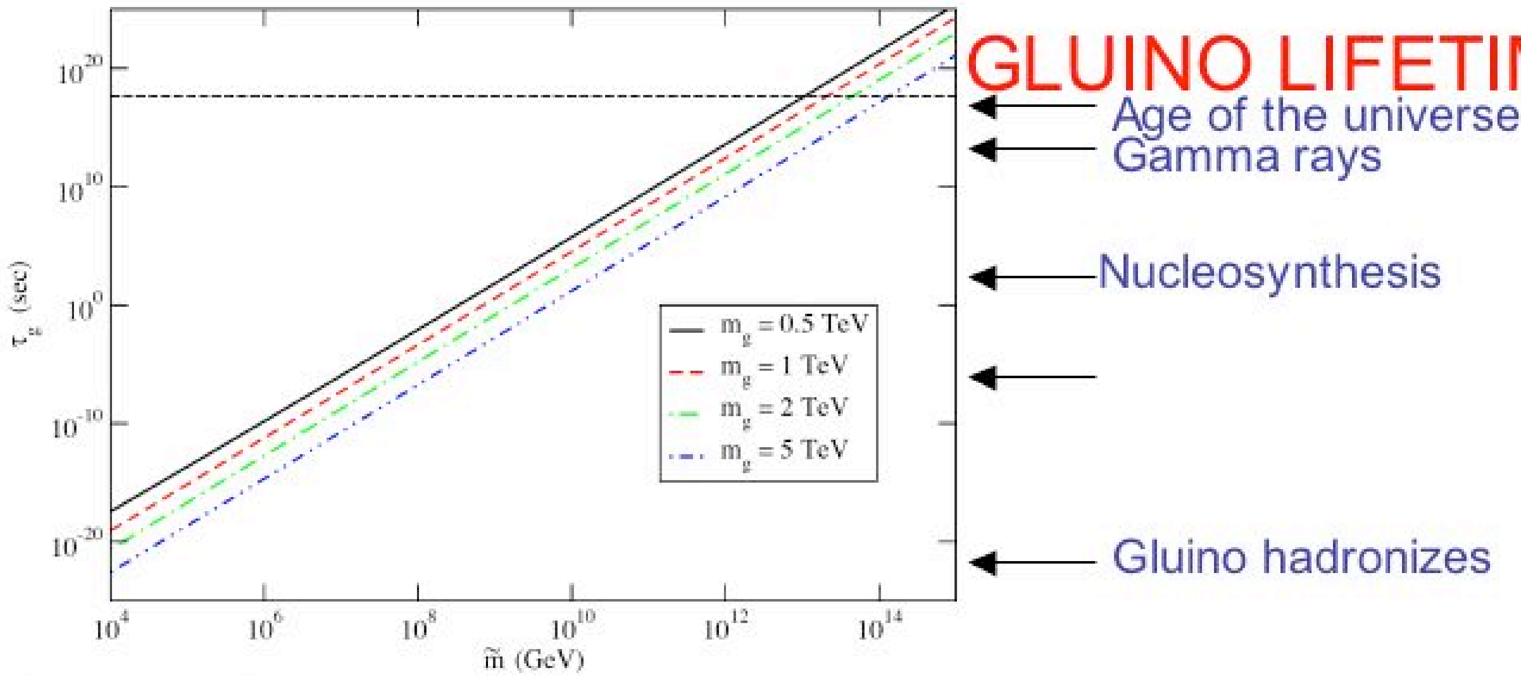
- Analogy: in SM, L not imposed but accidental. m_ν small, although L-breaking is O(1) in underlying theory
- In supergravity, μ not generated at $O(M_{Pl})$ but only $O(M_S^2/M_{Pl})$
- Here, $M_{\tilde{g}}$ and μ not generated at $O(\tilde{m})$ but only $O(\tilde{m}^2/M_*)$

OBSERVATIONAL CONSEQUENCES OF SPLIT SUPERSYMMETRY

- Only one Higgs boson with SM properties
- With respect to MSSM, larger log corrections to $\lambda = g^2$



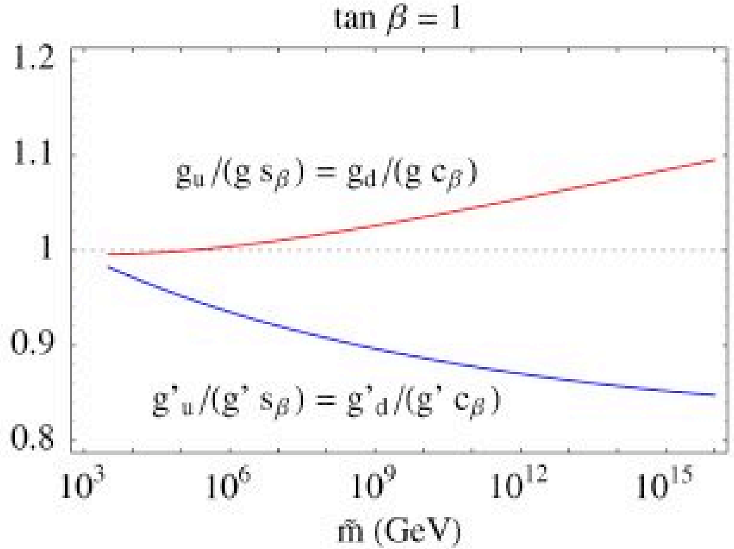
GLUINO LIFETIME

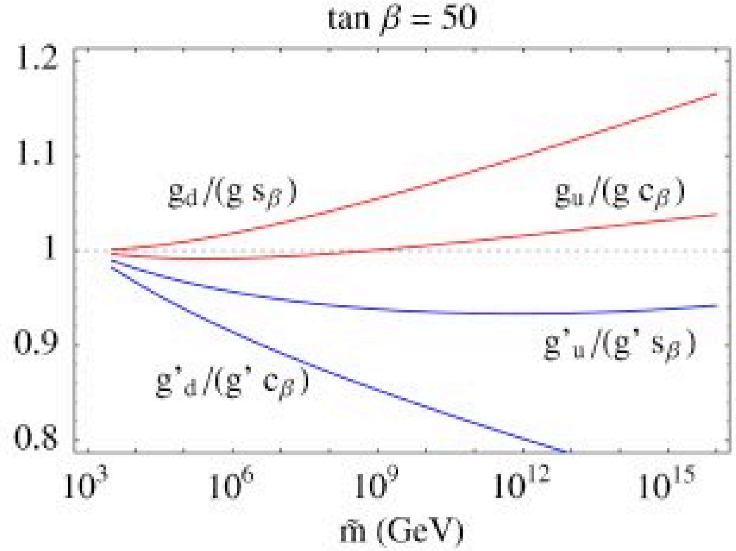


- Charged R-hadrons. Time delay & anomalous ionization energy loss. At LHC, M<2.5 TeV. Mass resolution better than 1%
- Neutral R-hadrons. Tagged jet M<1.1 TeV. Once tagged, identify gluino small energy deposition
- Flippers. Difficulty in tagging
- Gluinonium. M<1 TeV, direct mass reconstruction
- Stopped gluinos. Possibility of measuring long lifetimes

GAUGINO COUPLINGS

In SUSY, gauge (g) and gaugino ($\tilde{g}$) couplings are equal





- Fit of M, μ, $\tilde{g}_u$, $\tilde{g}_d$ from χ cross section and distributions
- H $\chi\,\chi$ final states
- BR(χ –> χ H)

At LHC $\Delta(\tilde{g}$ / g -1) = 0.2 - 0.5

At ILC $\Delta(\tilde{g}$ / g -1) = 0.01 - 0.05

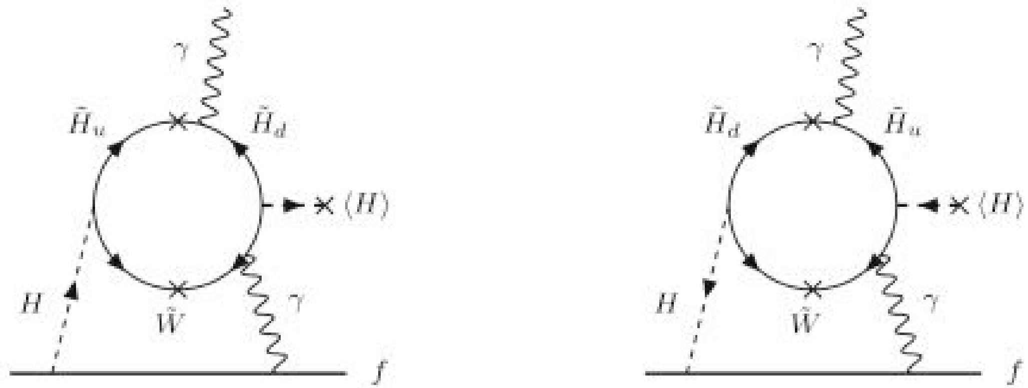
Heavy squarks and sleptons suppress flavour & CP violation, dim-5 proton decay

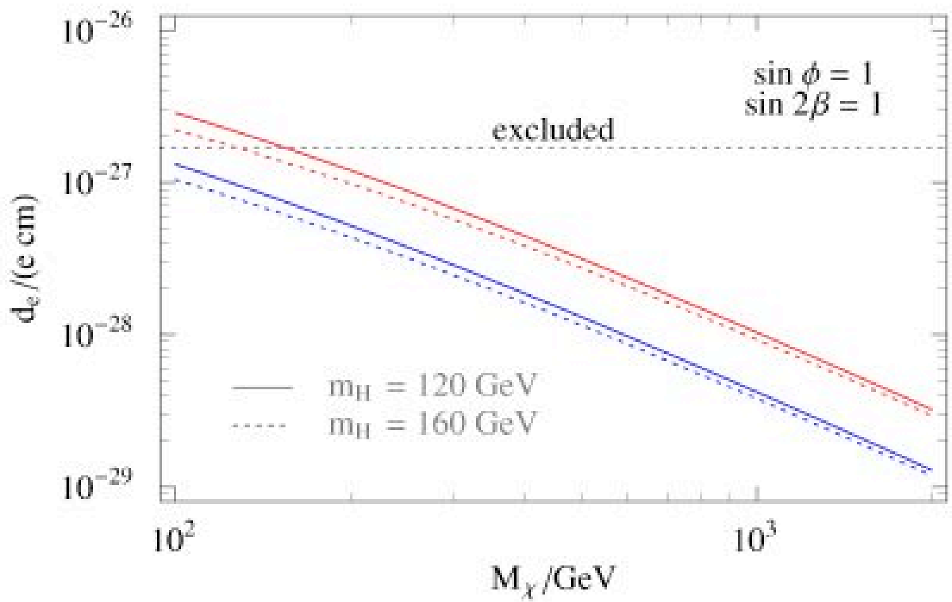
New source of flavour-diagonal CP violation remains

$$\mathcal{L} = \frac{M}{2}\widetilde{W}\widetilde{W} + \mu H_u H_d + \frac{\widetilde{g}_u}{\sqrt{2}} H^* \widetilde{W}\widetilde{H}_u + \frac{\widetilde{g}_d}{\sqrt{2}} H\widetilde{W}\widetilde{H}_d + \text{h.c.}$$

CP violation in $\mathrm{Im}\left(\widetilde{g}_u^* \widetilde{g}_d^* M\mu\right)$

Effects on SM matter at two loops: **EDM**





Present limit: $d_e < 1.7$ _ 10^{-27} $e$cm at 95% CL (DeMille et al.)

Future: DeMille et al. (Yale) 10^{-29} $e$cm in 3 years and 10^{-31} $e$cm in 5 years.

Lamoreaux et al. (Los Alamos): 10^{-31} $e$cm and eventually 10^{-35} $e$cm.

Results from Hinds et al. (Sussex) and Semertzidis et al. (Brookhaven) plans to improve by 10^5 sensitivity on μ EDM

STATISTICAL CRITICALITY

Assume soft terms are environmental parameters

Simplest case: $m_i = c_i\, M_S$ and M_S scans in multiverse

$Q_C = M_P \times F(c_i, \alpha_a, \lambda_t)$ is fixed

Two possibilities:

1) $M_S > Q_C$: unbroken EW

2) $M_S < Q_C$: broken EW

Impose prior that EW is broken

(analogy with Weinberg)

In "field-theoretical landscapes" we expect $N \propto M_S^n$

Probability distribution **dP** = $$\begin{cases} n\left(\frac{M_S}{Q_C}\right)^n \frac{dM_S}{M_S} & \text{for } M_S < Q_C \\ 0 & \text{for } M_S > Q_C \end{cases}$$

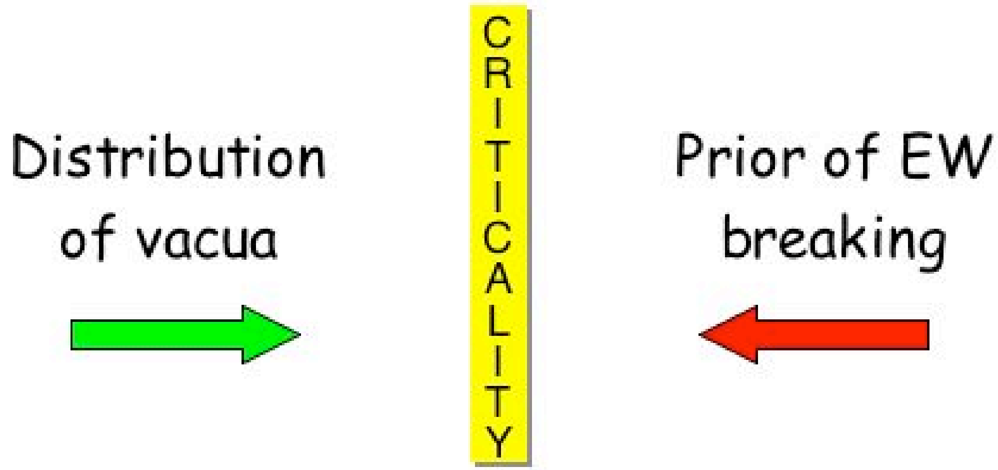
$$\left\langle \frac{M_Z^2}{M_S^2} \right\rangle = \frac{2\,dm_2^2}{M_S^2\, d\ln Q} \left\langle \ln \frac{Q_C}{M_S} \right\rangle$$

$$= \frac{9\lambda_t^2}{4\pi^2} \times \frac{1}{n} \approx \frac{0.15}{n}$$

- Susy prefers to be broken at high scale
- Prior sets an upper bound on M_S

} Susy near-critical

Little hierarchy: Supersymmetry visible at LHC, but not at LEP (*post*-diction)



Supersymmetry looks tuned because there many more vacua with $\langle H \rangle = 0$ than with $\langle H \rangle \neq 0$

The level of tuning is dictated by RG running, and it is of the order of a one-loop factor