Ignoring the hiearchy problem

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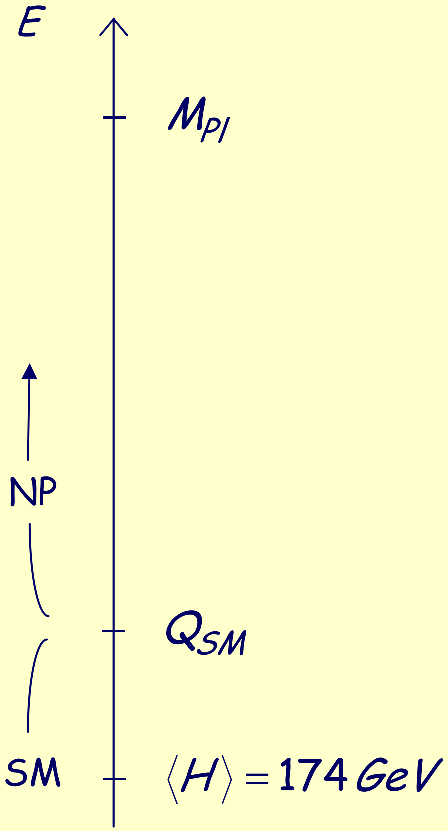
The hierarchy problem as a guideline for NP



The SM is an effective theory valid below Q_{SM}

- Where is Q_{SM} ?
- What type of physics above Q_{SM} ?

Where is Q_{SM} ?

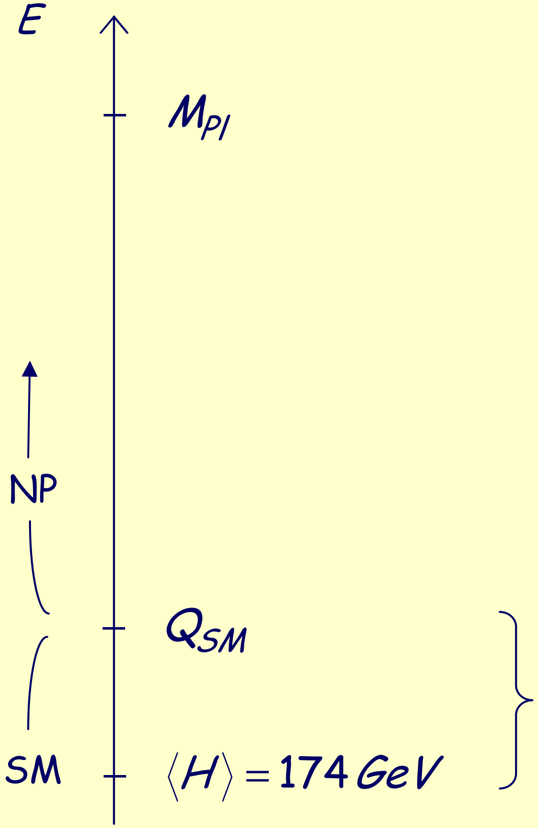
The main upper limit follows from solving the hierarchy problem

$$m_h^2 = m_h^2(Q_{SM}) + \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2 - 2M_W^2 - M_Z^2 - m_h^2)Q_{SM}^2$$

$$= \begin{cases} m_h^2(Q_{SM}) + m_h^2\left(\dfrac{Q_{SM}}{0.5\,\text{TeV}}\right)^2 & \text{if } m_h = 115\,\text{GeV} \\ m_h^2(Q_{SM}) + m_h^2\left(\dfrac{Q_{SM}}{2\,\text{TeV}}\right)^2 & \text{if } m_h = 250\,\text{GeV} \end{cases}$$

- Q_{SM} is the scale of the degrees of freedom cutting off the Higgs mass quadratic divergence
- $Q_{SM} \lesssim \text{TeV}$ barring accidental cancellations

Some solutions

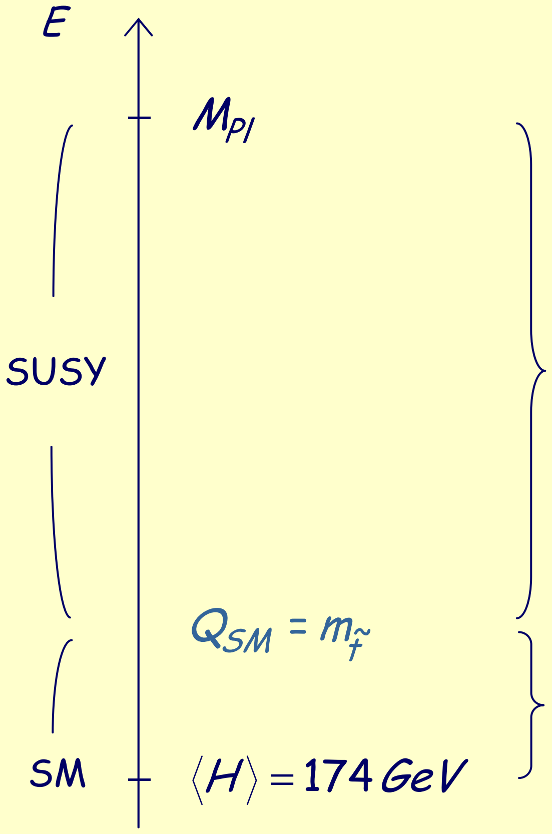


- Technicolor
- Little Higgs
- Extra-dimensions
- Warped compactification

EWPT: lower limit on Q_{SM}

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 Q_{SM}^2$$

MSSM



$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2\, Q_{SM}^2 \log \frac{M_{Pl}^2}{Q_{SM}^2}$$

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2\, Q_{SM}^2$$

UV fine tuning in the MSSM

$$M_Z^2 \sim (91\,\text{GeV})^2 \left[\left(\frac{\tilde{m}_Q}{70\,\text{GeV}} \right)^2 - \left(\frac{m_H}{80\,\text{GeV}} \right)^2 + \left(\frac{M_{1/2}}{40\,\text{GeV}} \right)^2 - \left(\frac{\mu}{70\,\text{GeV}} \right)^2 \right]$$

FT ~ maximum contribution in [...]

Benchmark points:

$$M_{1/2} = (250 - 1840)\,\text{GeV}: \quad \text{FT} \sim 40 - 2000$$

[Battaglia, De Roeck, Ellis, Gianotti, Olive, Pape]

$$\tilde{m}_Q = (1500 - 4300)\,\text{GeV}: \quad \text{FT} \sim 430 - 3700 \quad \text{or} \quad M_{1/2} = 500\,\text{GeV}: \quad \text{FT} \sim 150$$

[Lykken, Mrenna, Nelson, Wang, Wang]

Direct lower limits on squark and gluinos:

$$M_{\tilde{g}} \gtrsim \begin{cases} 195\,\text{GeV} \\ 260\,\text{GeV} \\ 500\,\text{GeV} \end{cases} \Rightarrow \text{FT} \gtrsim \begin{cases} 3 \\ 6 \\ 20 \end{cases} \qquad m_{\tilde{t}} \gtrsim \begin{cases} 300\,\text{GeV} \\ 260\,\text{GeV} \\ 100\,\text{GeV} \end{cases} \Rightarrow \text{FT} \gtrsim \begin{cases} 25 \\ 10 \\ 50 \end{cases}$$

Indirect lower limit on the stop masses

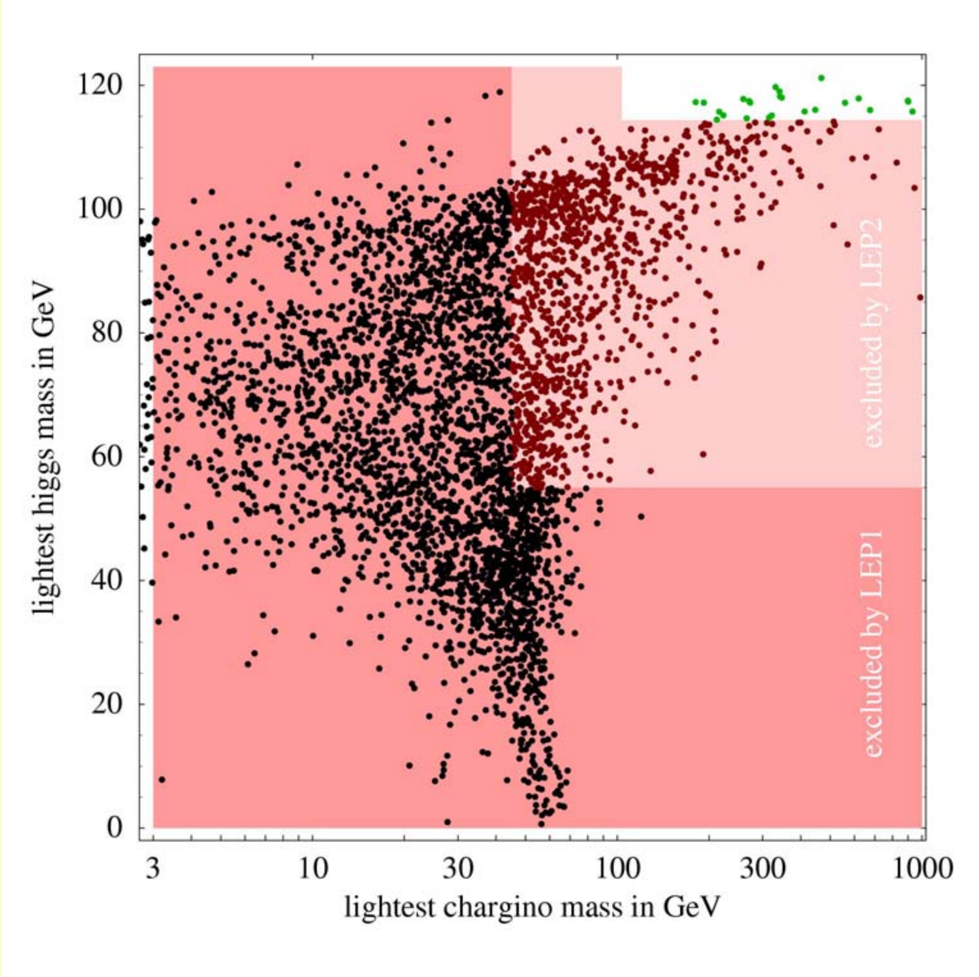
$$(114\,\text{GeV})^2 < m_h^2 < M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} h_t^2 m_t^2 \log \frac{m_{\tilde{t}}^2}{m_t^2} \Rightarrow \text{FT} \sim 50 - 100$$

What is left?

A quantitative measure of naturalness that nicely takes into account and combines all considerations above

- Scan the relative sizes of SUSY parameters and the SM parameters in their ranges
- Set overall scale of SUSY parameters from <H> = 174 GeV
- Calculate SUSY spectrum and compare with experiment

Few (~1) % of points satisfy all experimental constraints



[Giusti, AR, Strumia]

Ignoring the hierarchy problem

- Abandon the hierarchy problem as a guideline for NP
- Use gauge coupling unification and DM as guidelines instead. A more general version of the MSSM with light sfermions and $\langle H \rangle < \tilde{m} < M_{Pl}$ still emerges as the most simple and coherent possibility
  - $\tilde{m} \sim \langle H \rangle$: MSSM
  - $\tilde{m} \gg \langle H \rangle$: Split SUSY (SpS)
- SpS vs MSSM
  - – Exacerbates the FT problem
  - \+ Cleans up the MSSM while preserving the successes
  - \+ Well defined and predictive, with 4 (not 100's) additional parameters
  - \+ Different (new) phenomenology and experimental signatures
  - \+ New model building options, insights

The cosmological constant problem

$$\delta m_H^2 \propto Q_{SM}^2 \rightarrow Q_{SM} \sim m_H$$

$$\text{SUSY}: \quad \delta m_H^2 \propto \tilde{m}^2 \log \frac{Q_{SUSY}}{\tilde{m}}$$

$$\delta\Lambda \propto Q_x^4 \rightarrow Q_x \sim 10^{-3}\,\text{eV} ???$$

$$\text{SUSY}: \quad \delta\Lambda \propto \tilde{m}^2 Q_{SUSY}^2$$

The naturalness problem for the Higgs mass could follow the same fate as the cosmological constant problem (or not)

The anthropic principle

Assume that

- the fundamental theory has a huge number of vacua with different values of the CC [Bousso Polchinski]
- a sufficient number of them is populated [Linde]

Then the number of universes with CC ~ 0.001 eV is tiny, but those are the only (non-empty) universes in which we can live [Weinberg]

Analogously, the universes with <H> ~ 174 GeV are the only ones in which complex elements can form [Agrawal Barr Donoghue Seckel]

Note: the Yukawa couplings should not be scanned – same for the couplings generating primordial perturbations in Weinberg's argument [Arkani-Hamed Dimopoulos Kachru]

(assumptions, not a theorem, hard to prove, consequences)

Another example

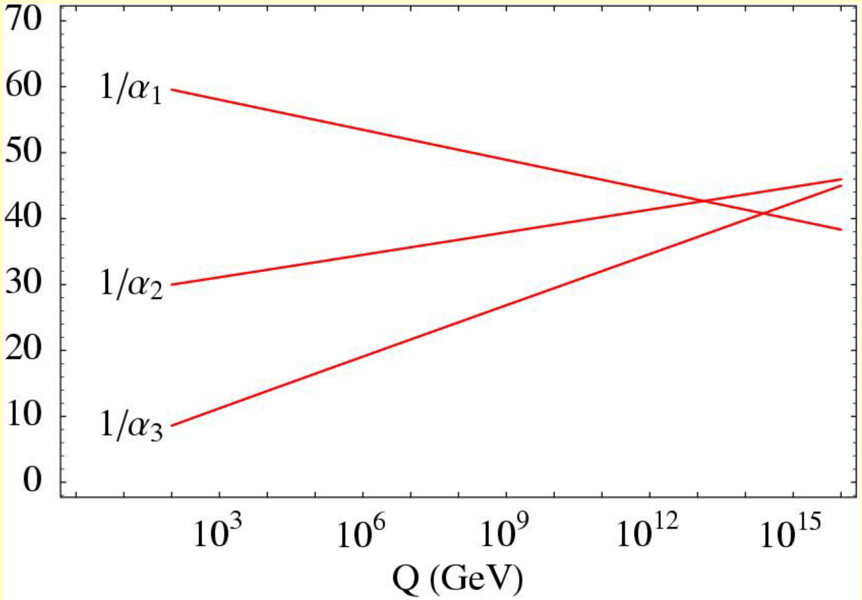
The Earth-Sun distance (it is the correct distance to allow for liquid water)

Suppose a dust cloud obscures the universe beyond the solar system.   Based on the low probability that the conditions for human life are fulfilled, we can infer the existence of a multitude of stars (and a lower limit on their number)

New guidelines on new physics

- The evidence for dark matter and the observation that a particle with weak cross-section and mass at the EW scale is a natural candidate for it (not the only possibility)

- Grand unification, as suggested by the SM quantum numbers and the SM running of gauge couplings



1-loop 1-step unification

$\alpha_s(M_Z), M_{GUT}, \alpha_{GUT} \leftrightarrow \alpha(M_Z), \sin^2\theta_W + N_1, N_2, N_3 \leftarrow$ Dynkin indexes of new matter (≥ 0)

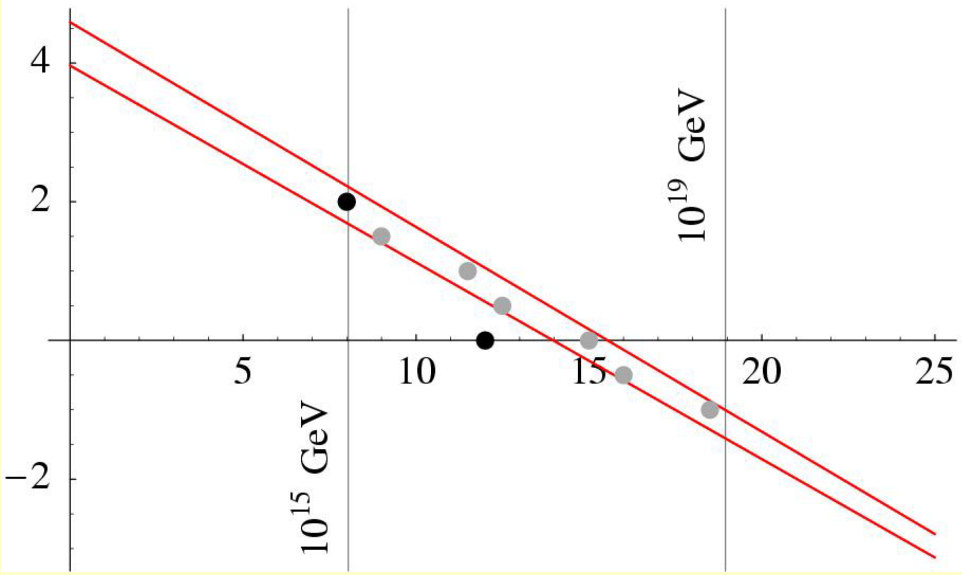
N2, N3: Vector fermions: +2
Chiral fermions: +1
Complex scalars: +1/2

$0 < \alpha_{GUT} < 1$

$10^{15}\mathrm{GeV} < M_{GUT} < 10^{19}\mathrm{GeV}$

$\alpha_s(M_Z) = 0.119 \pm 2 \cdot 0.003$

$N_2 - N_3 = 2A$, A integer



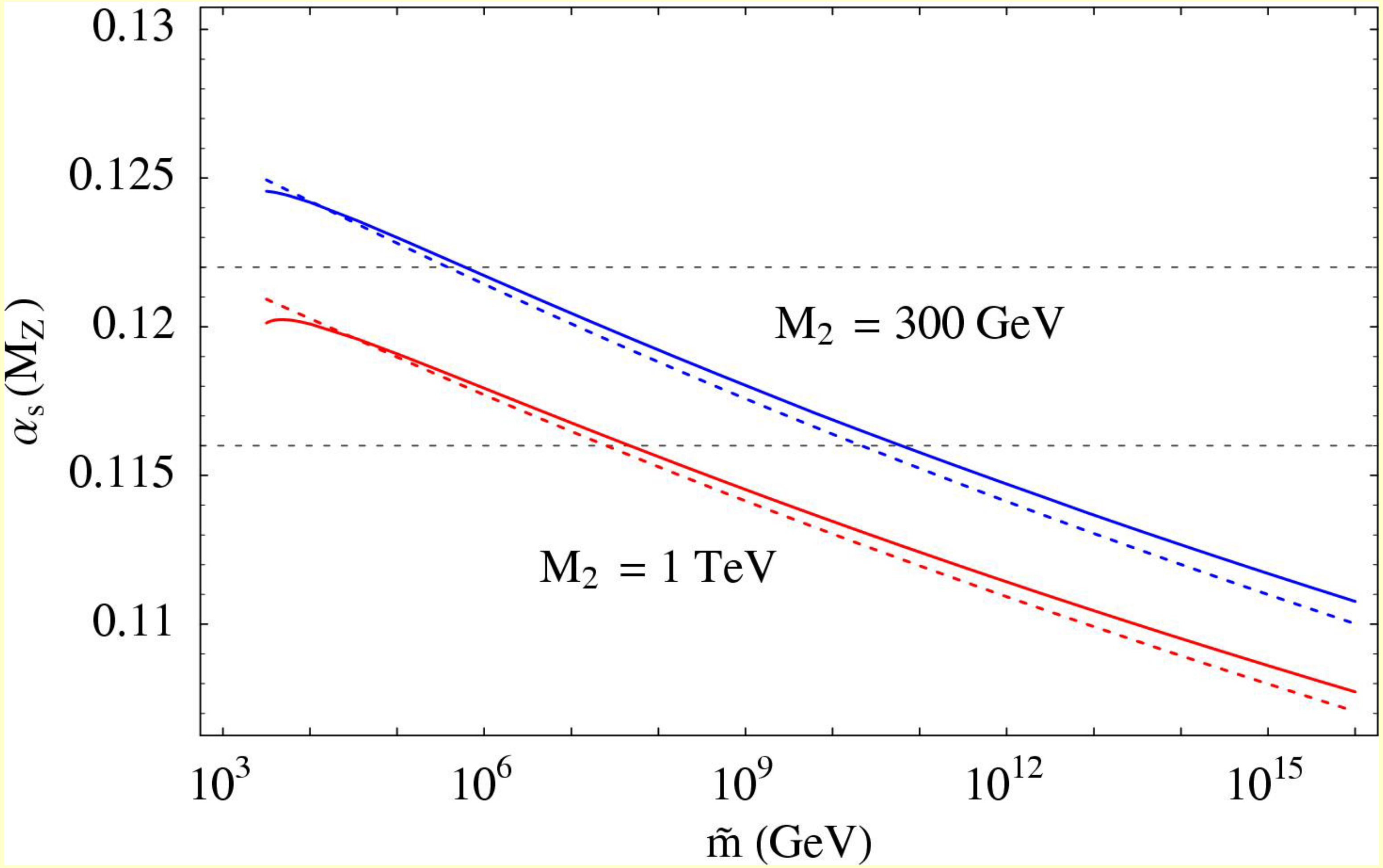
$\frac{5}{2}(N_2 - N_1) = 2A + 6B$, A, B integer

$A = 1: \quad d_c + \bar{d}_c + \tilde{W}$

$A = 0: \quad \tilde{H}_u + \tilde{H}_d + \tilde{W} + \tilde{G}$

Note: colored and weakly interacting particles are needed

2-loop unification in SpS



[Giudice AR]

Why supersymmetry?

- Explains the structure of the spectrum 'selected' by DM + unification
- SUSY helps splitting the low energy fermions from their SU(5) partners
- Symmetries accounting for
  - the lightness of the fermions
  - the stability of dark matter
  - lepton and baryon number conservation

  are built in (PQ, R-symmetry)
- The heavy scalars provide a (cosmologically relevant) decay channel for the gluino

Cleaning up the MSSM

- Successes of the MSSM
  - Gauge coupling unification
  - Natural dark matter candidate (with R-parity)

  } fermions

- Nuisances
  - Potentially > 100 parameters (CMSSM)
  - FCNCs and CP-violation in particular EDMs (SUSY breaking mechanism, symmetries)
  - Proton decay from dimension 5 operators (non minimal models)
  - Gravitino and moduli problem (low reheating T)
  - Fine-tuning (NMSSM)

  } scalars

- SpS: fermions ~ TeV, scalars (but 1 Higgs) » TeV
  (retains the successes, nuisances evaporate – except FT)

The structure of Split Supersymmetry

- Sfermion masses: $\langle H \rangle \ll \tilde{m} < 10^{13} GeV$

  $Q > \tilde{m}$: MSSM

  $Q < \tilde{m}$: $SM + \tilde{H}_u, \tilde{H}_d, \tilde{G}, \tilde{W}, \tilde{B}$

- Relevant new terms in the low energy theory (R-parity)

  $$\sqrt{2} H^{\dagger} (g_u \tilde{W} + g'_u \tilde{B}) \tilde{H}_u + \sqrt{2} H^T (g_d \tilde{W} + g'_d \tilde{B}) \tilde{H}_d$$

  $$\frac{M_3}{2} \tilde{G}\tilde{G} + \frac{M_2}{2} \tilde{W}\tilde{W} + \frac{M_1}{2} \tilde{B}\tilde{B} + \mu \tilde{H}_u \tilde{H}_d$$

- New parameters (using matching conditions, gaugino mass relation)

  $M_2, \mu, \tilde{m}, \tan\beta$

Phenomenology and signatures

- Unification
- Dark matter
- Higgs mass
- Quasi-stable gluino
- Sfermion spectrum
- SUSY couplings
- EDMs
- Proton decay
- R-parity

2-loop unification

Unification

Dark matter

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Proton decay

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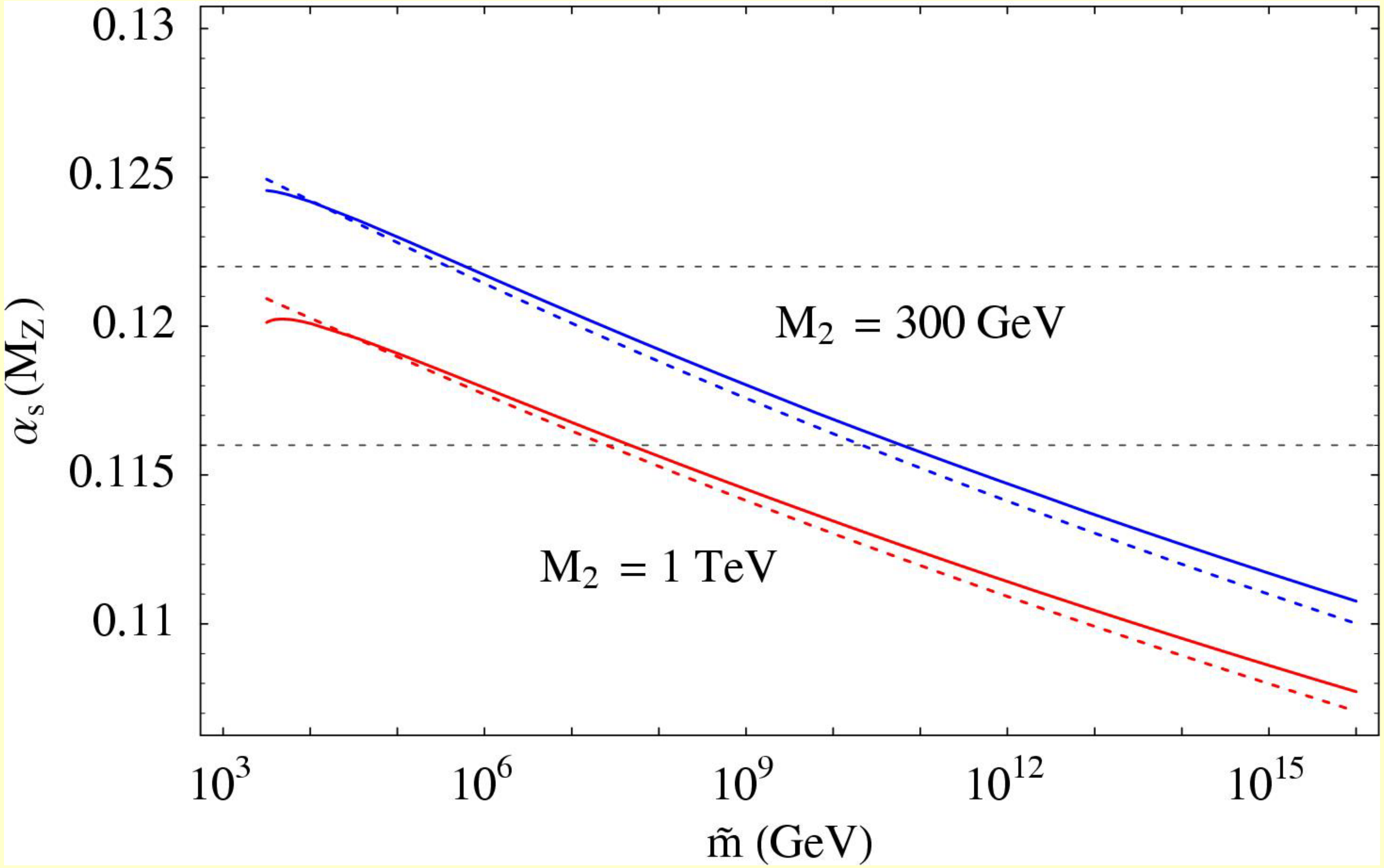
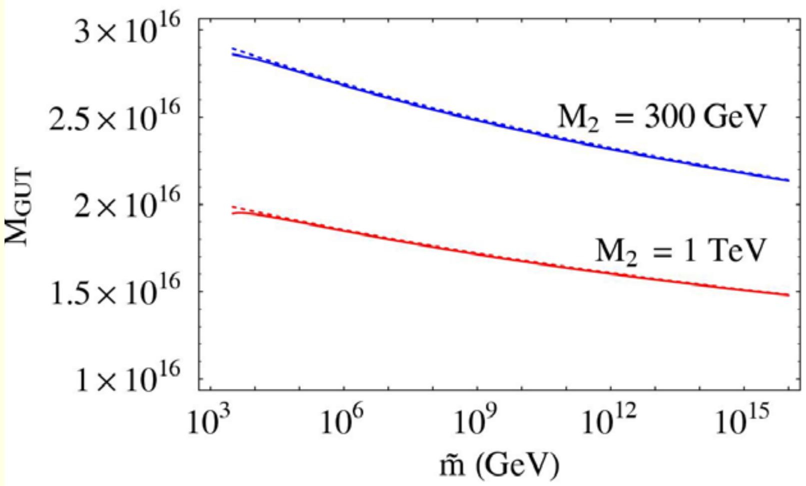
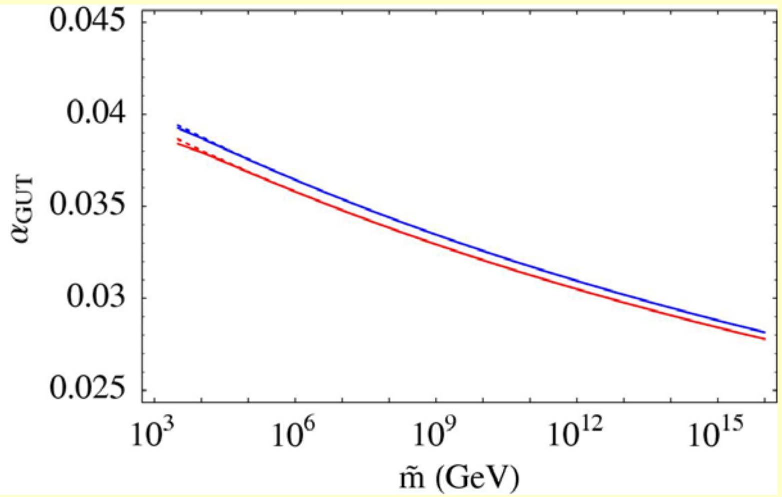


[Giudice AR]


3×10^{16}
2.5×10^{16}
2×10^{16}
1.5×10^{16}
1×10^{16}
M_{GUT}
$M_2 = 300$ GeV
$M_2 = 1$ TeV
10^3
10^6
10^9
10^{12}
10^{15}
$\tilde{m}$ (GeV)


0.045
0.04
0.035
0.03
0.025
α_{GUT}
10^3
10^6
10^9
10^{12}
10^{15}
$\tilde{m}$ (GeV)

Bottom-tau mass unification

Unification

Dark matter

Higgs mass

Quasi-stable gluino

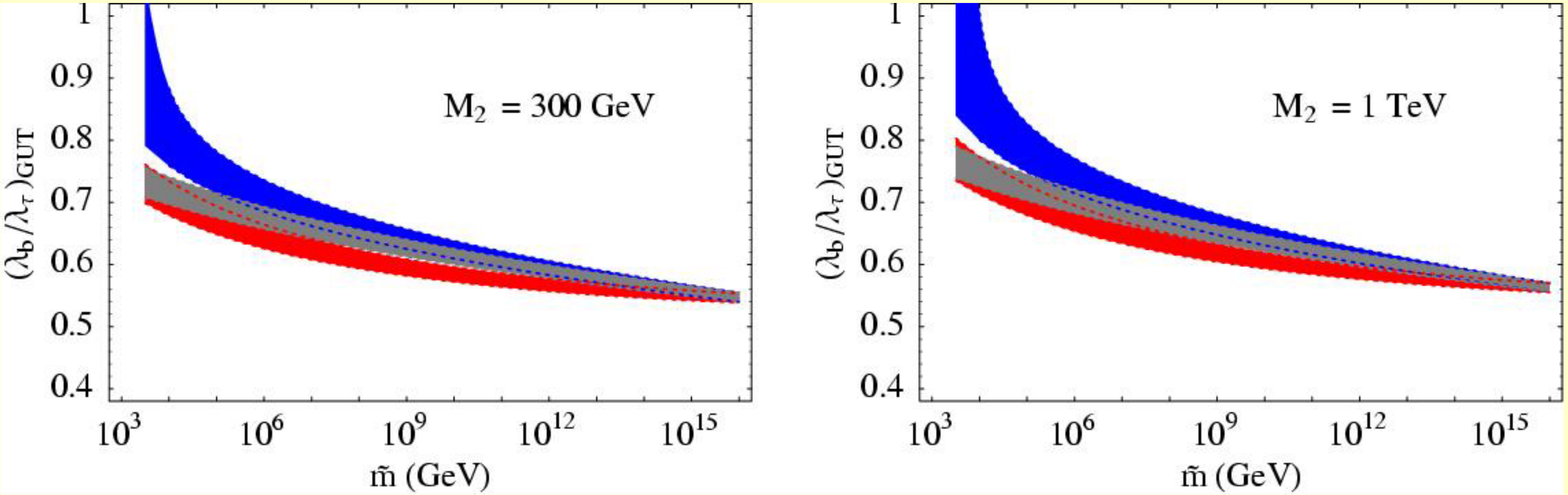
Sfermion spectrum

SUSY couplings

EDMs

Proton decay

R-parity

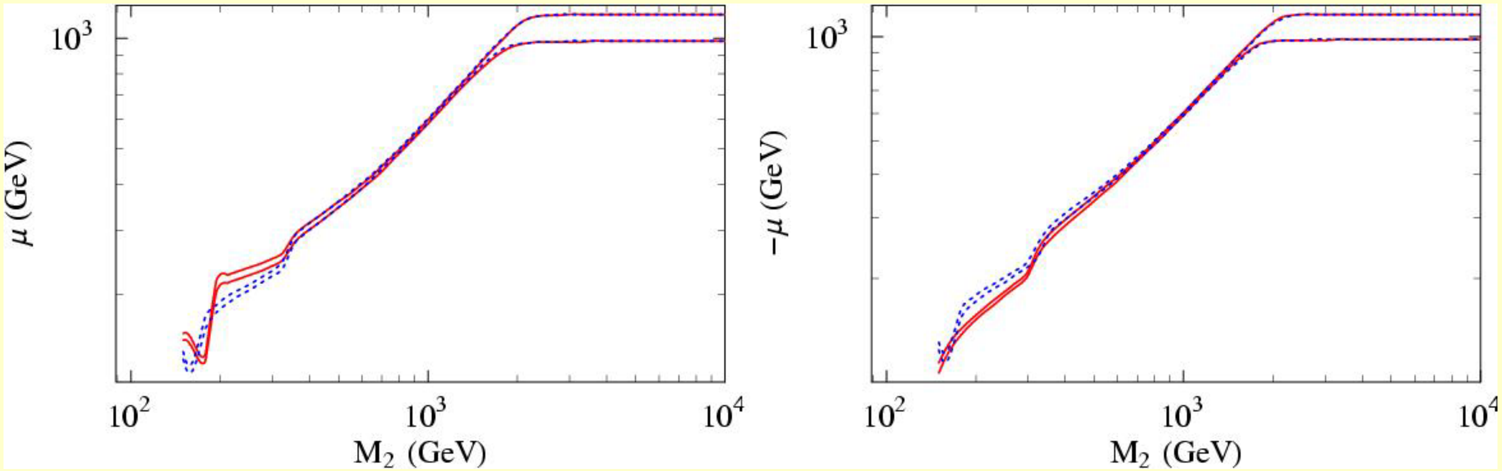


- The top Yukawa Landau pole is met later
- Smaller values of tanß are allowed
- The bottom mass can be enhanced by top radiative corrections when close to the Landau pole

Dark matter: relic abundance and detection rate

Unification
Dark matter
Higgs mass
Quasi-stable gluino
Sfermion spectrum
SUSY couplings
EDMs
Proton decay
R-parity

- Mostly Bino (mixed): $\Omega_\chi h^2 \approx 0.1\,\mu^2 \left(M_1^2 + \mu^2\right)^2 \big/ \left(m_\chi^4 \mathrm{TeV}^2\right)$
- Mostly Higgsino (pure): $\Omega_\chi h^2 \approx 0.09(\mu / \mathrm{TeV})^2, \quad \mu = 1.0 \quad 1.2\ \mathrm{TeV}$
- Mostly Wino (pure): $\Omega_\chi h^2 \approx 0.02(M_2 / \mathrm{TeV})^2, \quad M_2 = 2.0 \quad 2.5\ \mathrm{TeV}$



[Giudice AR, Pierce]

Unification

Dark matter

Higgs mass

Quasi-stable gluino

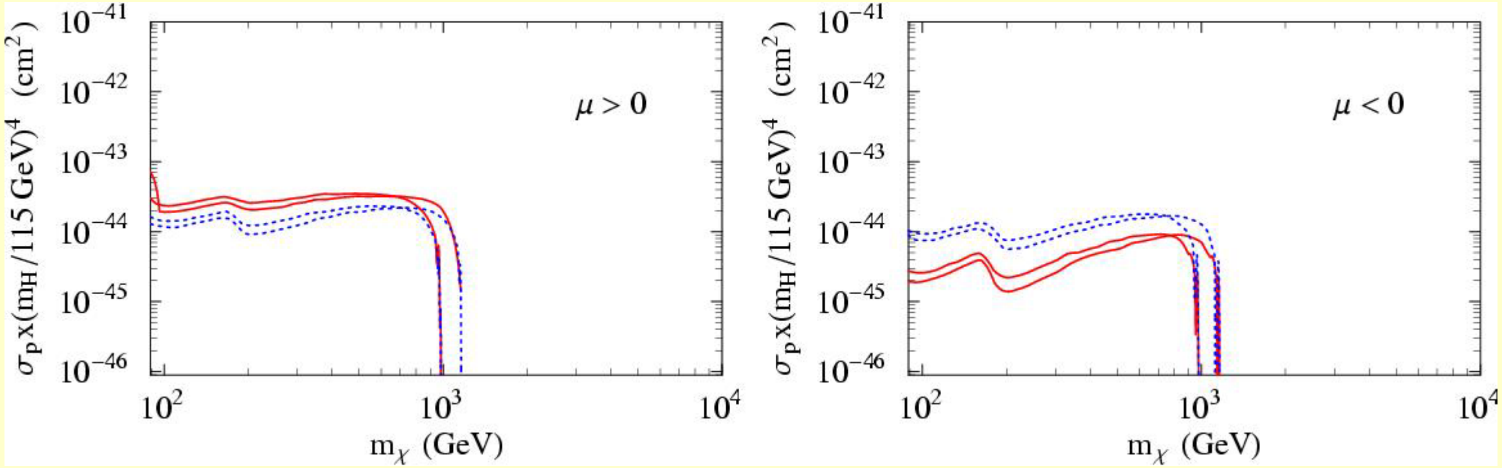
Sfermion spectrum

SUSY couplings

EDMs

Proton decay

R-parity



- Cross section = 0 if the LSP is pure gaugino or Higgsino
- The gravitino could decay giving a non-thermal population of DM neutralinos which adds to the freeze-out abundance
- Bound on masses reinforced, new particle more accessible at accelerators

Higgs mass

Unification

Dark matter

Higgs mass

Quasi-stable gluino

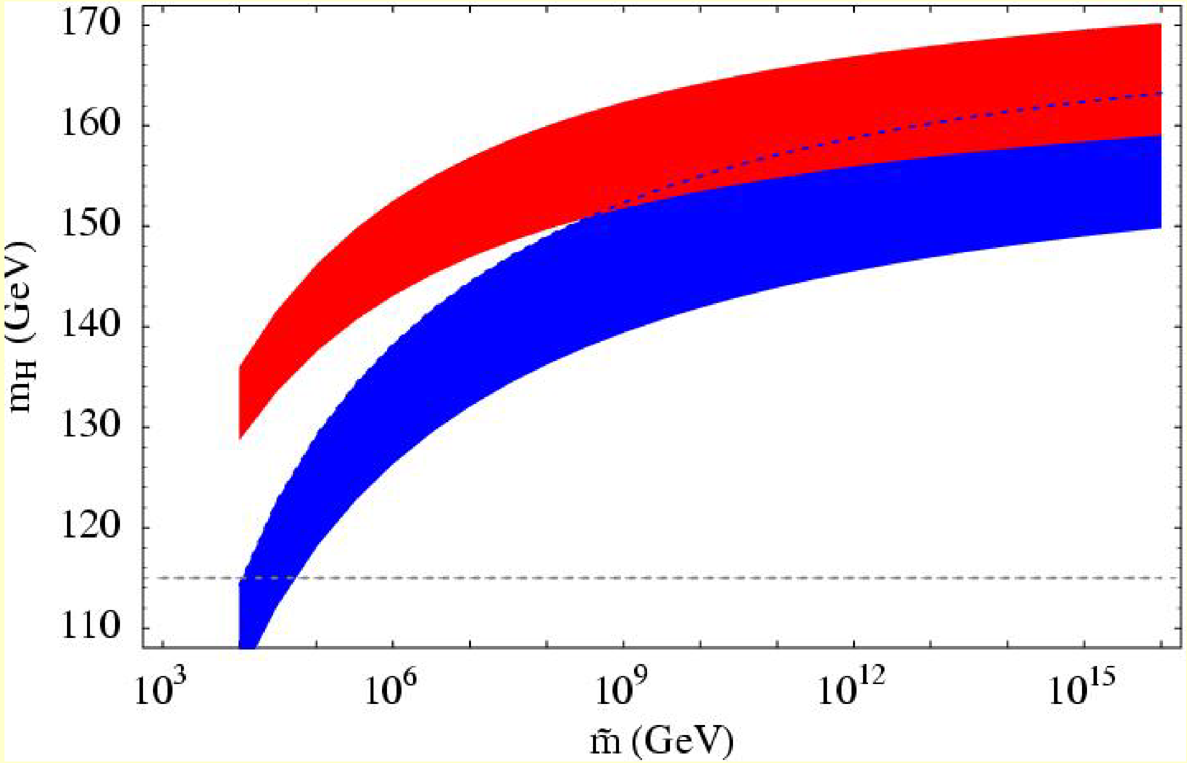
Sfermion spectrum

SUSY couplings

EDMs

Proton decay

R-parity



[Arvanitaki Davis Graham Wacker, Giudice AR]

The radiative corrections to the Higgs mass are enhanced by a large logarithm

(essentially no lower limit on tanß from Higgs searches)

Upper bound on the SUSY-breaking scale

Unification

Dark matter

Higgs mass

Quasi-stable gluino

Sfermion spectrum

SUSY couplings

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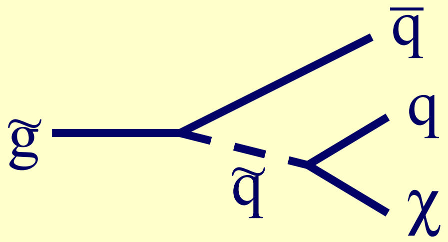
Proton decay

R-parity



$$\tau_{\tilde{g}} \approx \left(\frac{\text{TeV}}{M_{\tilde{g}}}\right)^5 \left(\frac{\tilde{m}}{10^{13}\,\text{GeV}}\right)^4 0.4\ \text{Gyr}$$

Searches for heavy isotopes : $\tau_{\tilde{g}} < 10^{16}$ sec $\Rightarrow \tilde{m} <$ few 10^{13} GeV

(if $M_{\tilde{g}} = 1$ TeV) [Smith et al, Smith, Hemmick et al, Starkman Gould Esmailzadeh Dimopoulos]

Caveats:

- Gluino mass heavier than 10 TeV
- Relic abundance not reflected in the local abundance of heavy isotopes
- Gluino not produced after reheating

Collider signatures

Unification

Dark matter

Higgs mass

Quasi-stable gluino

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R-parity

- The gluino is likely to be stable on detector time-scales
- It hadronizes in R-hadrons (-mesons, -baryons, -gluons)
- If charged: slow, highly ionizing track
- If neutral: missing energy, mild hadronic activity, triggered by single jet (gluon emission)
- Energy, charge, Baryon-number exchange
- Sensitivities:
  - Run II: ~200 GeV; LHC: 1 TeV (model independent)
  - Run II: ~400 GeV; LHC: 2.5 TeV (if charged)

  [Baer Cheung Gunion, Raby Tobe, Mafi Raby; recent studies: Kraan, Kilian Plehn Richardson Schmidt, Hewett Lillie Masip Rizzo]
- Also: gluinonium [Cheung, Keung]; gluinos from cosmic rays (if seen give a lower limit on the SUSY-breaking scale)

  [Albuquerque Farrar Kolb; recent studies: Anchordoqui Goldberg Nunez, Hewett Lillie Masip Rizzo]

Charginos and neutralinos

Unification

Dark matter

Higgs mass

Quasi-stable gluino

Sfermion spectrum

SUSY couplings

EDMs

Proton decay

R-parity

- Completing the measurement of the SUSY fermion spectrum

- Challenging at LHC; wrt the MSSM:
  - Production reduced (no gluino decay channels)
  - Trilepton channel suppressed

- A multi-TeV linear collider could cover the whole range of masses allowed by dark matter

Gaugino interactions

Unification
Dark matter
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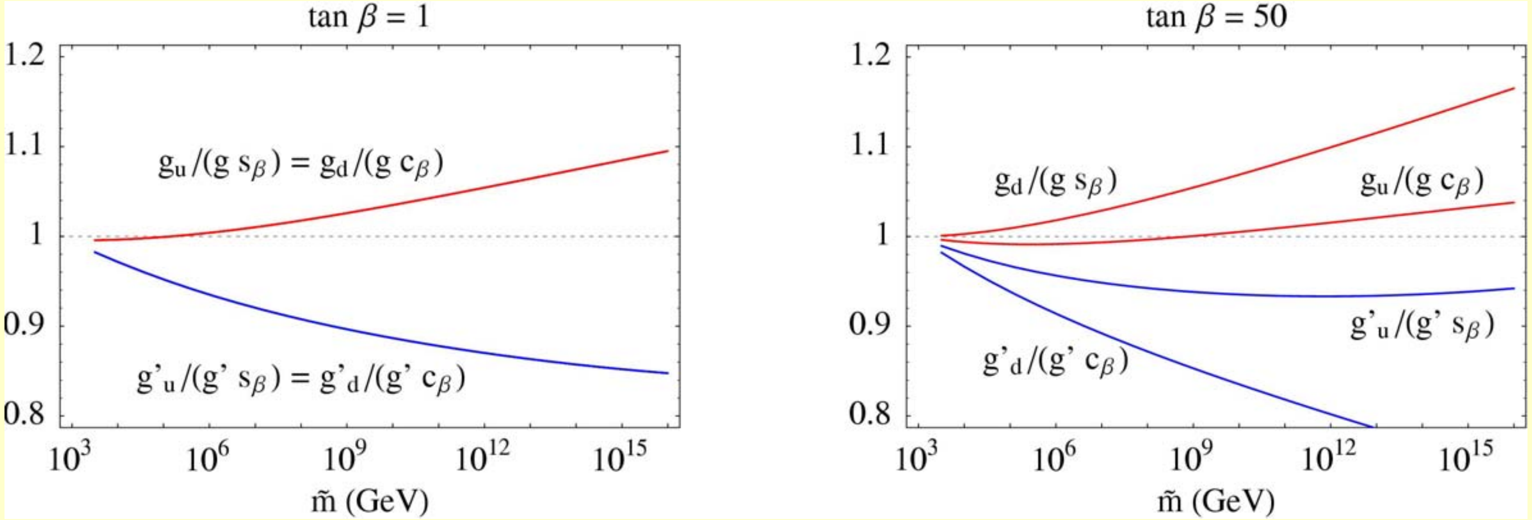
SUSY couplings
EDMs
Proton decay
R-parity



"Oblique corrections" to supersymmetric coupling enhanced by the long running

Can be measured at a linear collider at few % [Kilian Plehn Richardson Schmidt]

Provide evidence for SpS and constraint on the SUSY-breaking scale

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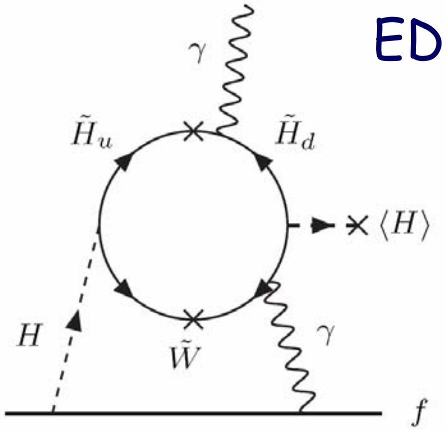
Heavy sfermions suppress flavour & CP violation

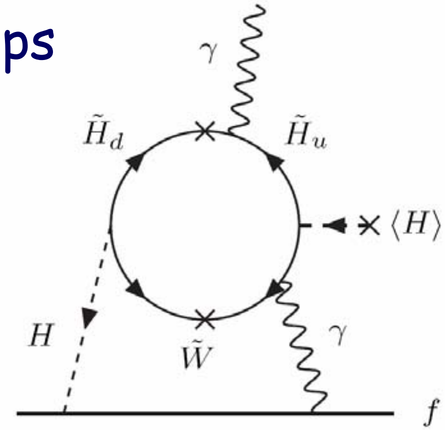
New source of flavour-diagonal CP violation remains:

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

CP violating invariant: $\text{Im}\left(g_u^* g_d^* M \mu\right)$

EDM at 2-loops





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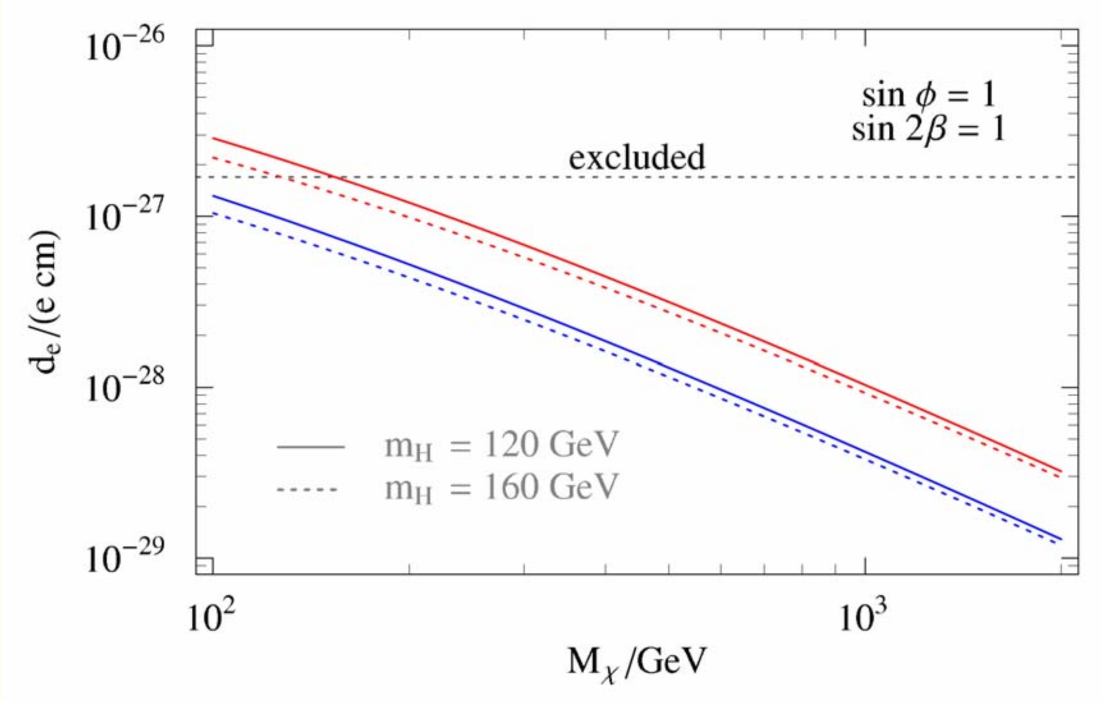


Present limit: $d_e < 1.7 \times 10^{-27}$ *ecm* at 95% CL (DeMille et al.)

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

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

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

Proton decay

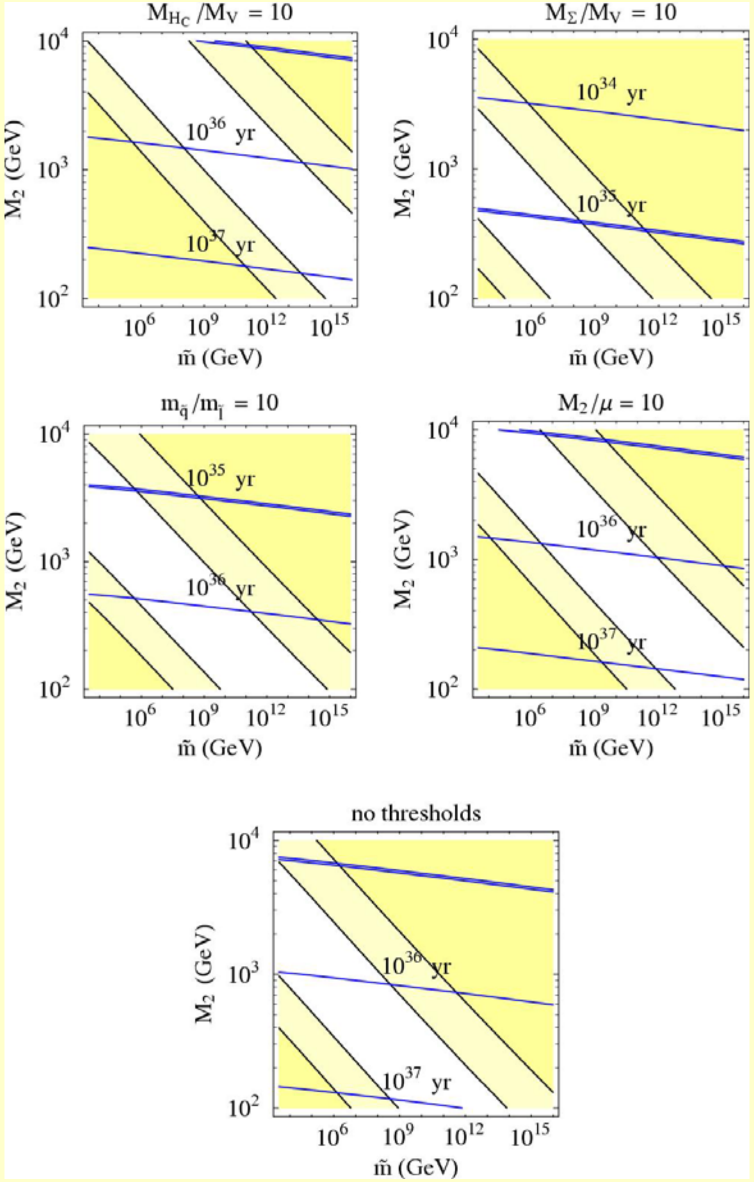
- From R-parity violating couplings λ (dimension 4):

$$\tau_P \sim 3\times10^{33}\,yr\left(\frac{\tilde{m}}{10^{13}\,GeV}\right)^4\left(\frac{10^{-3}}{\lambda}\right)^4$$

- From dimension 5 operators: negligible for

$$\tilde{m} > 100\,TeV$$

- From (relatively model-independent) dimension 6 operators: →



R-parity

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R-parity

- R-parity violation is in principle dangerous for proton decay, neutrino masses, dark matter
- The strongest constraint comes from the stability of DM: leptonic R-parity needs to be imposed (Dim-4 proton decay can be suppressed by heavy scalars + family structure)
- Baryogenesis, neutron-antineutron oscillations

  [Gupta Konar Mukhopadhyaya, Chun Park: effects of trilinears]

Model building

- How to make the scalars heavy while keeping the gauginos and the Higgsinos light?
  - Main tool: R-symmetry (PQ symmetry must be broken)
    Natural implementation: SUSY breaking without R-parity breaking ("D-term breaking") [Arkani-Hamed Dimopoulos Giudice AR]
  - Direct mediation [Arkani-Hamed Dimopoulos Giudice AR]
  - String Theory [Antoniadis Dimopoulos]

Origin of same-scale soft terms

$$\text{F-breaking}: \; X = \theta^2 \tilde{m}$$

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

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

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

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

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

- R-symmetry "splits" the spectrum (M_g and μ mix through renorm.)
- R-invariant ⇨ dim = 2 R-violating ⇨ dim = 3

Origin of split soft terms

$$\text{D-breaking}: \quad Y = X^* X = \theta^4 \tilde{m}^2$$

$$\int d^4\theta \, Y Q^* Q \to \tilde{m}_Q^2 = \tilde{m}^2 \qquad \frac{1}{M}\int d^4\theta \, Y W_\alpha W_\alpha \to M_{\tilde{g}} = \frac{\tilde{m}^2}{M}$$

$$\int d^4\theta \, Y H_1 H_2 \to B\mu = \tilde{m}^2 \qquad \frac{1}{M}\int d^4\theta \, Y Q^3 \to A = \frac{\tilde{m}^2}{M}$$

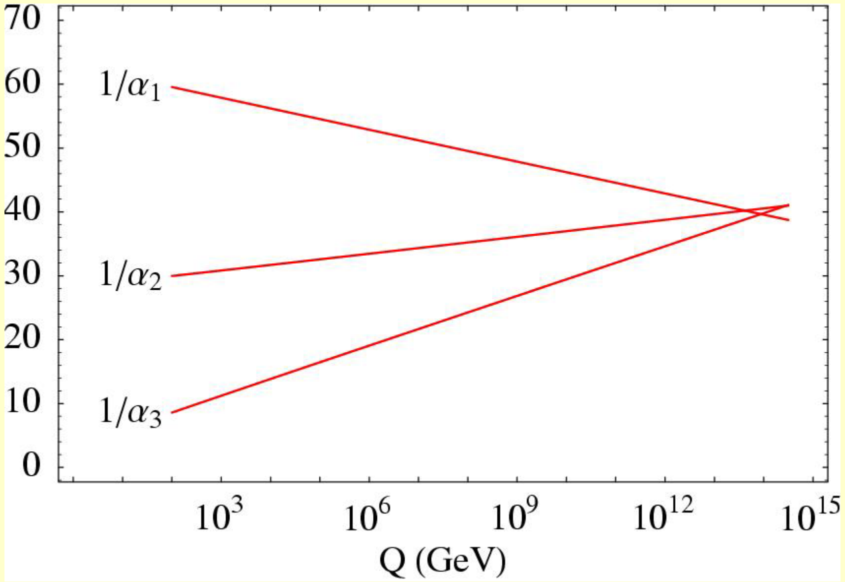
$$\frac{1}{M}\int d^4\theta \, Y D^2 (H_1 H_2) \to \mu = \frac{\tilde{m}^2}{M}$$

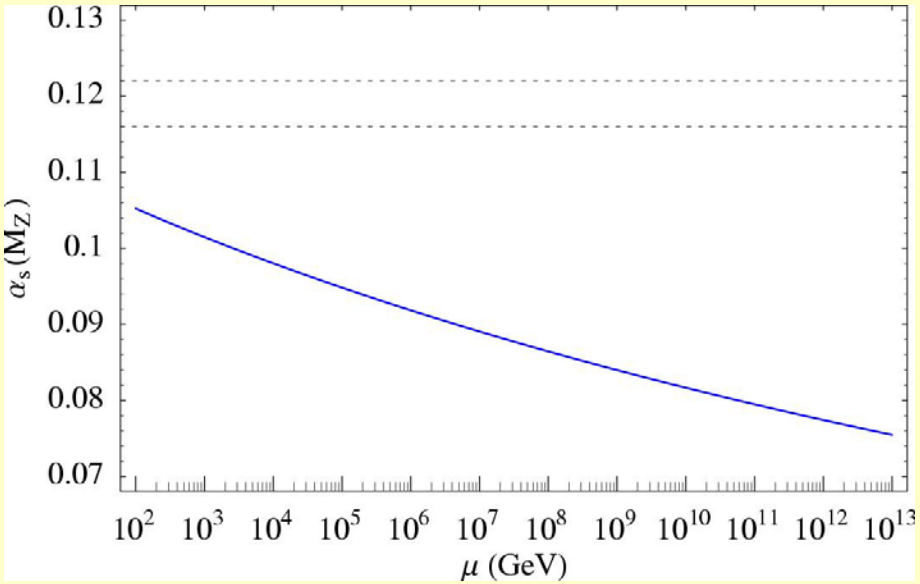
Analogy: in SM, L not imposed but accidental. m_ν small, although L-breaking is O(1) in underlying theory

Summary

- A theoretical argument, the naturalness criterium, has guided the theoretical investigation of new physics scenarios for decades, leading to several appealing options
- On the other hand, the possibility that naturalness is not relevant for physics at the TeV scale is worth not being neglected, also in the light of the failure of naturalness in the case of the CC
- The empirical evidences for dark matter and gauge coupling unification can then be fruitfully used as alternative guidelines
- Split Supersymmetry then emerges as a simple, compelling option
- Qualitatively new phenomena (e.g. gravitino physics) and model building insights (e.g. novel SUSY-breaking mechanisms) emerge
- Rich spectrum of phenomenological consequences and signatures: dark matter, Higgs mass, R-hadrons, colliders, oblique corrections to supersymmetric couplings , EDMs, proton decay, cosmic rays…
- In particular, the dark matter constraint shows that signals at LHC are likely but not guaranteed. A multi-TeV linear collider would on the contrary cover all the parameter space of the model.

Unification with Higgsinos only





$$M_{GUT} \sim 4 \times 10^{13}\,GeV$$

Unavoidable contributions from CC cancellation

$$V = e^{\frac{K}{M_{Pl}^2}}\left(|F|^2 - \frac{3|W|^2}{M_{Pl}^2}\right) \qquad |W| \neq 0 \text{ breaks R-symmetry} \Rightarrow m_{3/2} = e^{\frac{K}{2M_{Pl}^2}} \frac{|W|}{M_{Pl}^2}$$

$$\text{Loop effects} \Rightarrow M_{\tilde{g}} \approx \frac{m_{3/2}^3}{16\pi^2 M_{Pl}^2}$$

$$\text{Potentially larger effect from anomaly med.} \Rightarrow M_{\tilde{g}} = \frac{\beta(g)}{g} F_\varphi$$

$$\text{Eq. motion for conformal compensator} \qquad F_\varphi = m_{3/2} + \frac{K|_{\theta^2}}{3M_{Pl}^2}$$

In theories where susy breaking is tied to gravity and supersymmetry is restored in the flat limit, $F_\varphi \to 0$

$$\frac{m_{3/2}^3}{16\pi^2 M_{Pl}^2} \leq |M_{\tilde{g}}| \leq \frac{g^2}{16\pi^2} m_{3/2}$$

$m_{3/2}$ and $\tilde{m}$ are in general independent parameters of SpS