Split Supersymmetry

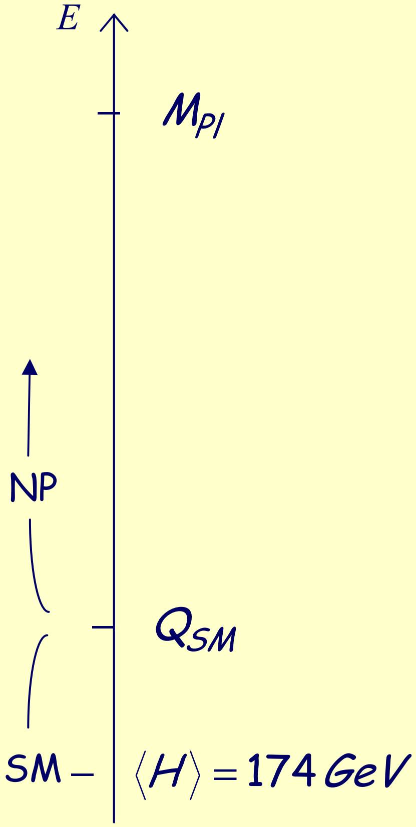
Andrea Romanino
CERN

Arkani-Hamed Dimopoulos hep-th/0405159
Giudice Romanino hep-ph/0406088
Arkani-Hamed Dimopoulos Giudice Romanino hep-ph/0409232

Outline

- The Higgs mass hierarchy problem: is it necessarily relevant to TeV physics?
- Split SUSY from data: dark matter and gauge coupling unification
- Split SUSY from SUSY breaking
- Phenomenology and signatures

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

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

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

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

Is the hierarchy problem relevant to TeV physics?

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

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

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

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

What if the naturalness problem for the Higgs mass follows the same fate as the cosmological constant problem?

The anthropic principle

Assume that

- the fundamental theory has a huge number of vacua with different values of the CC
- A sufficient number of them is populated

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]

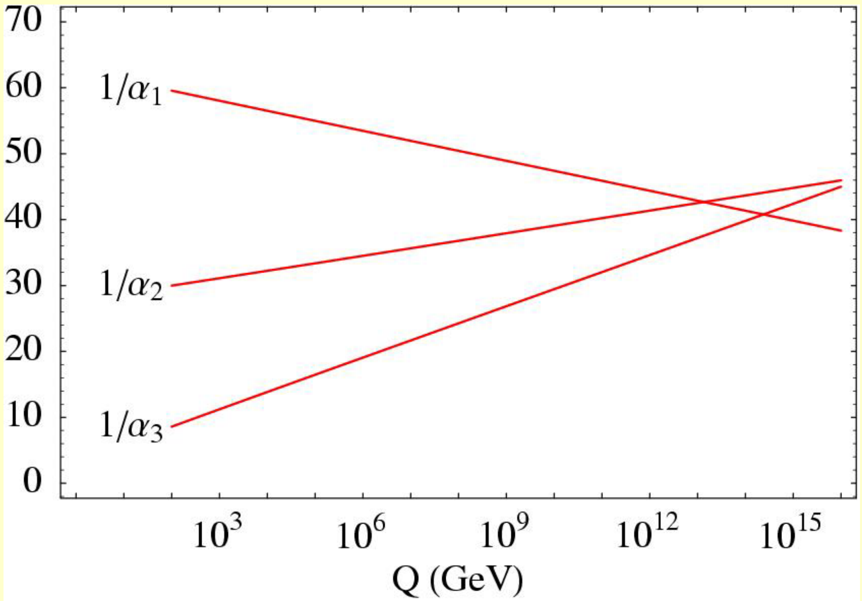
Analogously, the universes with <H> ~ 174 GeV are the only ones in which complex elements can form [Agrawal Barr Donoghue Seckel]

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

Which guideline 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



Split Supersymmetry (SpS)

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

- 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)

Split Supersymmetry (SpS)

- 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)

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)

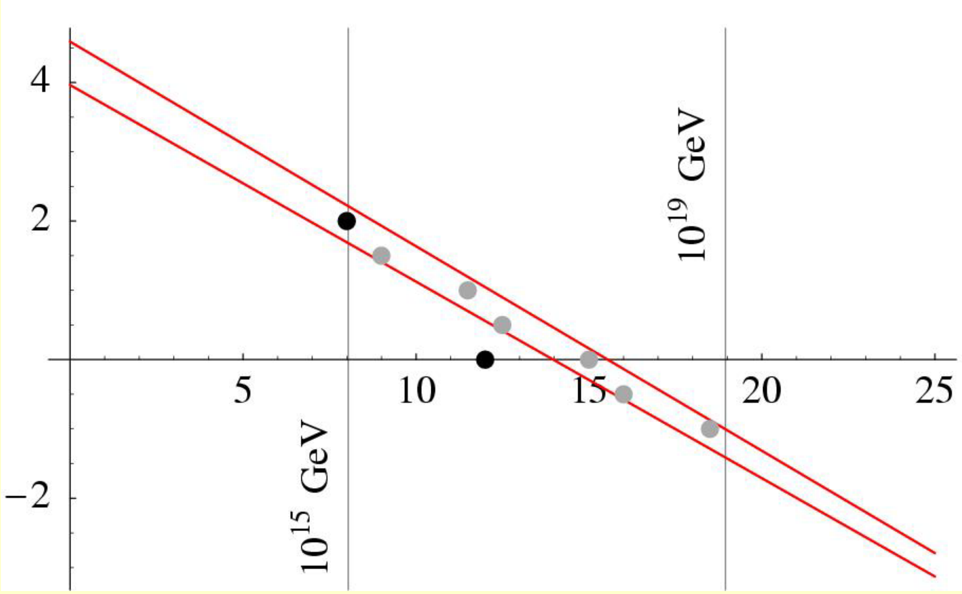
N2, N3: Vector fermions: +2
Chiral fermions: +1
Complex scalars: +1/2

$0 < \alpha_{GUT} < 1$

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

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

$N_2 - N_3$ = 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

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

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

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)

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

Model building

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

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

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

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

R-invariant soft terms (choose $\mathrm{R}[H_1 H_2] = 0$ 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_g and μ mix through renorm.)
- R-invariant ⇨ dim = 2 R-violating ⇨ dim = 3

SpS determined by susy-breaking pattern

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

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

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

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

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

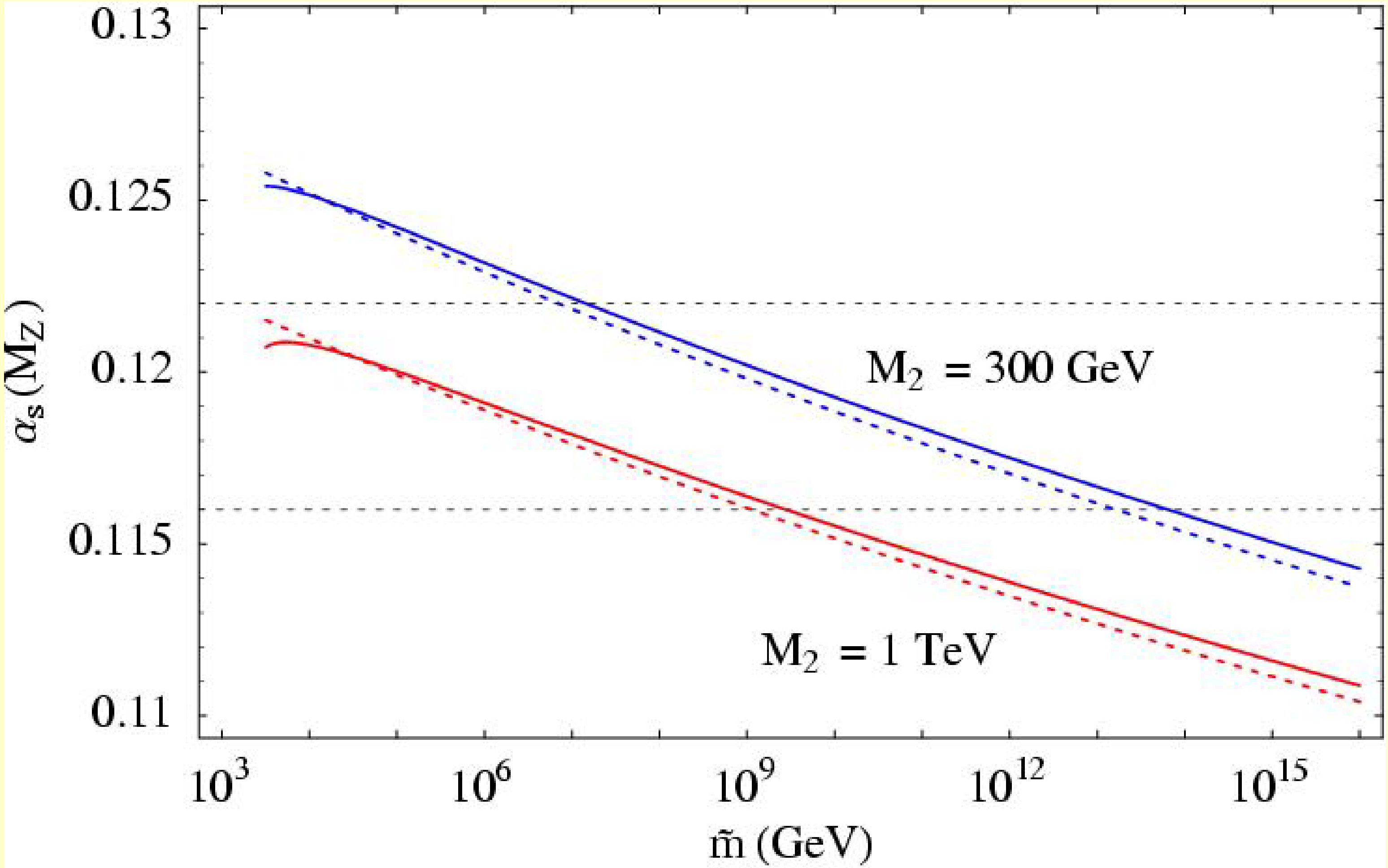
Phenomenology and signatures

- Unification revisited
- Dark matter revisited
- Higgs mass
- Quasi-stable gluino
- SUSY fermion spectrum
- SUSY couplings
- EDMs
- Proton decay

Phenomenology and signatures

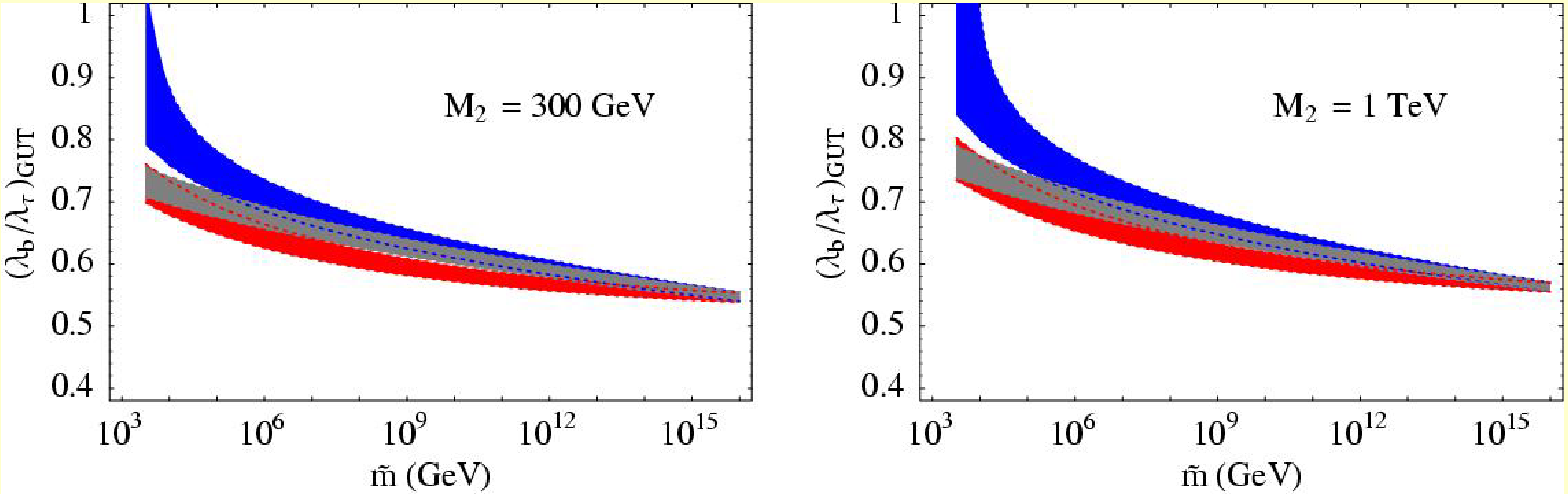
- Unification revisited
- Dark matter revisited
- Higgs mass
- Quasi-stable gluino
- SUSY fermion spectrum
- SUSY couplings
- EDMs
- Proton decay

2-loop unification



[Giudice AR]

Bottom-tau mass unification



The top Yukawa Landau pole is met later

Smaller values of tanß are allowed

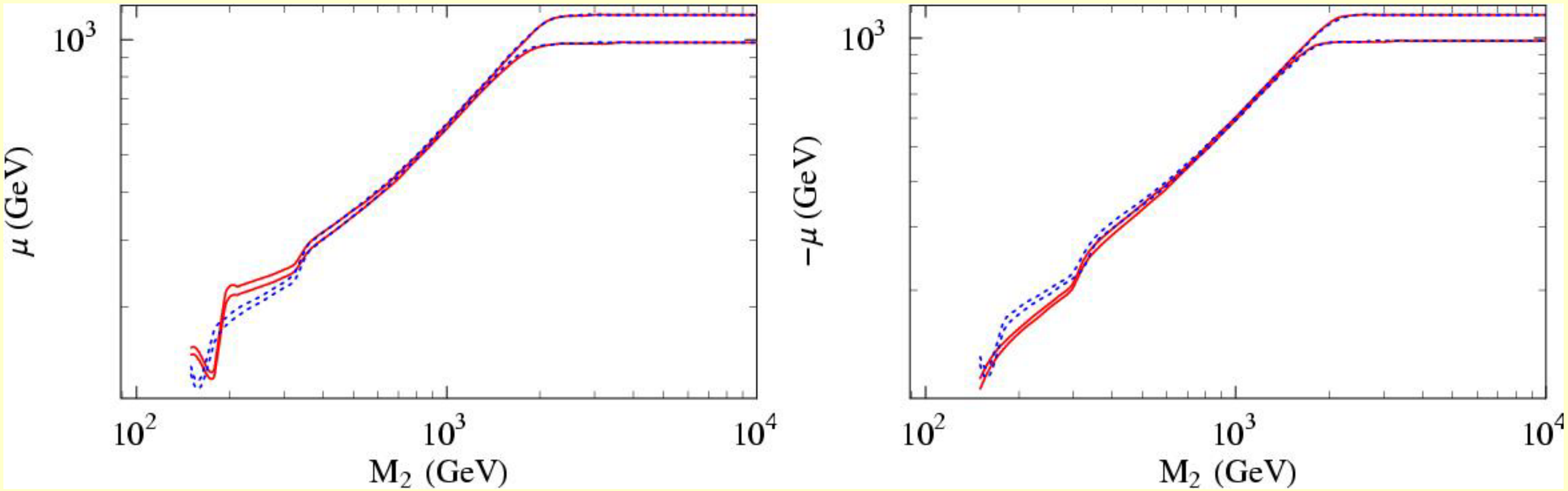
The bottom mass can be enhanced by top radiative corrections when close to the Landau pole

Phenomenology and signatures

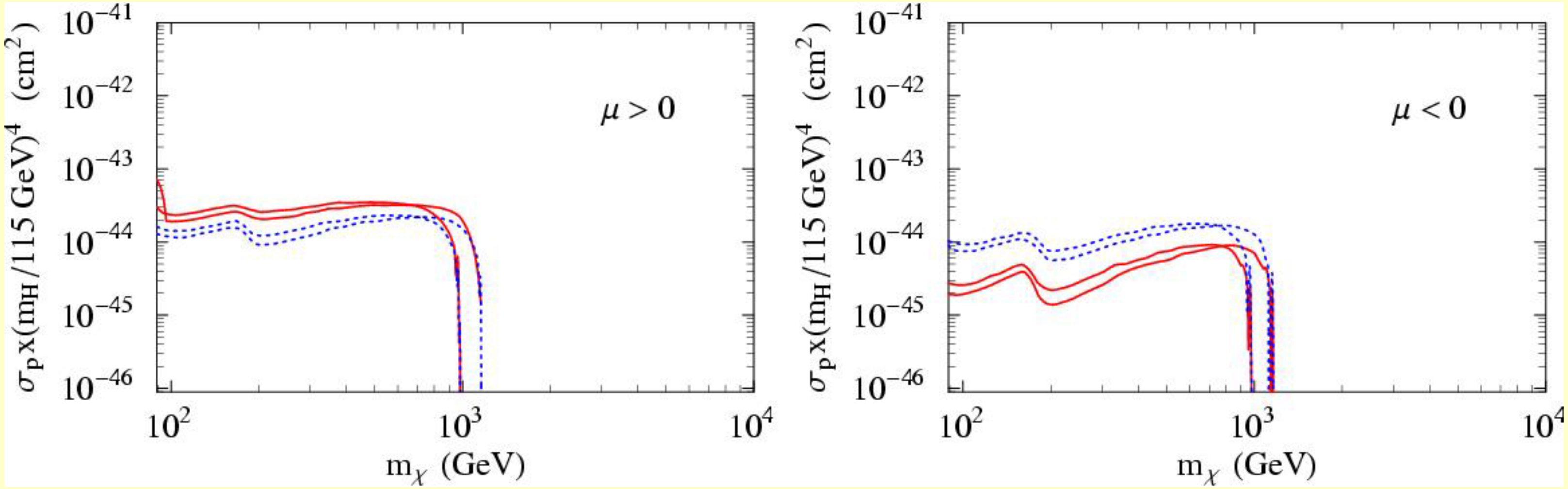
- Unification revisited
- Dark matter revisited
- Higgs mass
- Quasi-stable gluino
- SUSY fermion spectrum
- SUSY couplings
- EDMs
- Proton decay

Dark matter: relic abundance and detection rate

- 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): $\Omega_\chi h^2 \approx 0.09(\mu/\mathrm{TeV})^2, \quad \mu = 1.0 - 1.2\ \mathrm{TeV}$
- Mostly Wino (pure): $\Omega_\chi h^2 \approx 0.02(M_2/\mathrm{TeV})^2, \quad M_2 = 2.0 - 2.5\ \mathrm{TeV}$



[Giudice AR, Pierce]

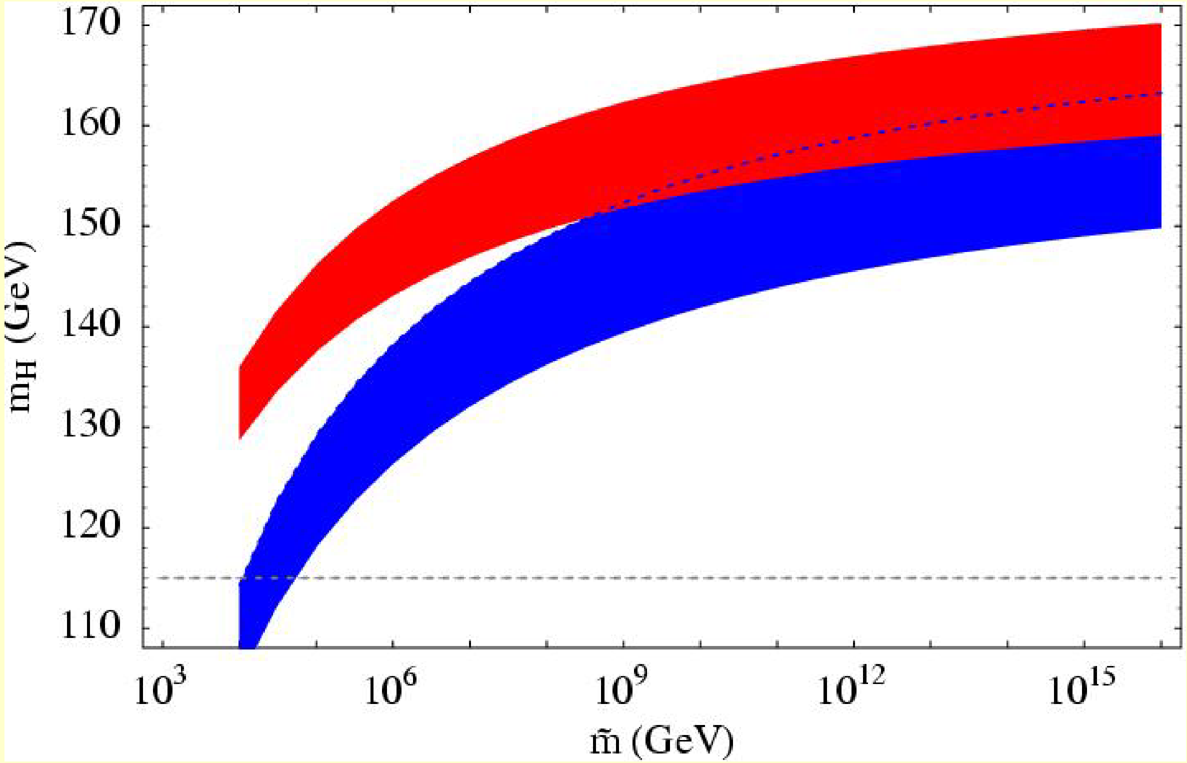


- Cross section = 0 if the LSP is pure gaugino or Higgsino
- The gravitino could decay giving a non-thermal population of DM neutralinos which adds to the freeze-out abundance
- Bound on masses reinforced, new particle more accessible at accelerators

Phenomenology and signatures

- Unification revisited
- Dark matter revisited
- Higgs mass
- Quasi-stable gluino
- SUSY fermion spectrum
- SUSY couplings
- EDMs
- Proton decay

Higgs mass



[Arvanitaki Davis Graham Wacker, Giudice AR]

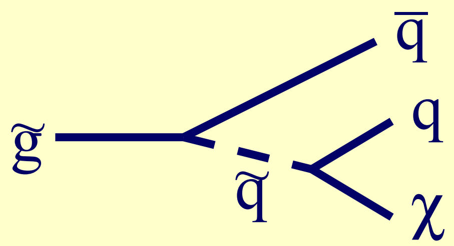
The radiative corrections to the Higgs mass are enhanced by a large logarithm

(essentially no lower limit on tanß)

Phenomenology and signatures

- Unification revisited
- Dark matter revisited
- Higgs mass
- Quasi-stable gluino
- SUSY fermion spectrum
- SUSY couplings
- EDMs
- Proton decay

Upper bound on the SUSY-breaking scale



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

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

(if $M_{\tilde{g}} = 1\,\text{TeV}$) [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

- The gluino is 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: gluinium [Cheung, Keung]; gluinos from cosmic rays (if seen give a lower limit on the SUSY-breaking scale)
  [Hewett Lillie Masip Rizzo, Anchordoqui Goldberg Nunez]

Phenomenology and signatures

- Unification revisited
- Dark matter revisited
- Higgs mass
- Quasi-stable gluino
- SUSY fermion spectrum
- SUSY couplings
- EDMs
- Proton decay

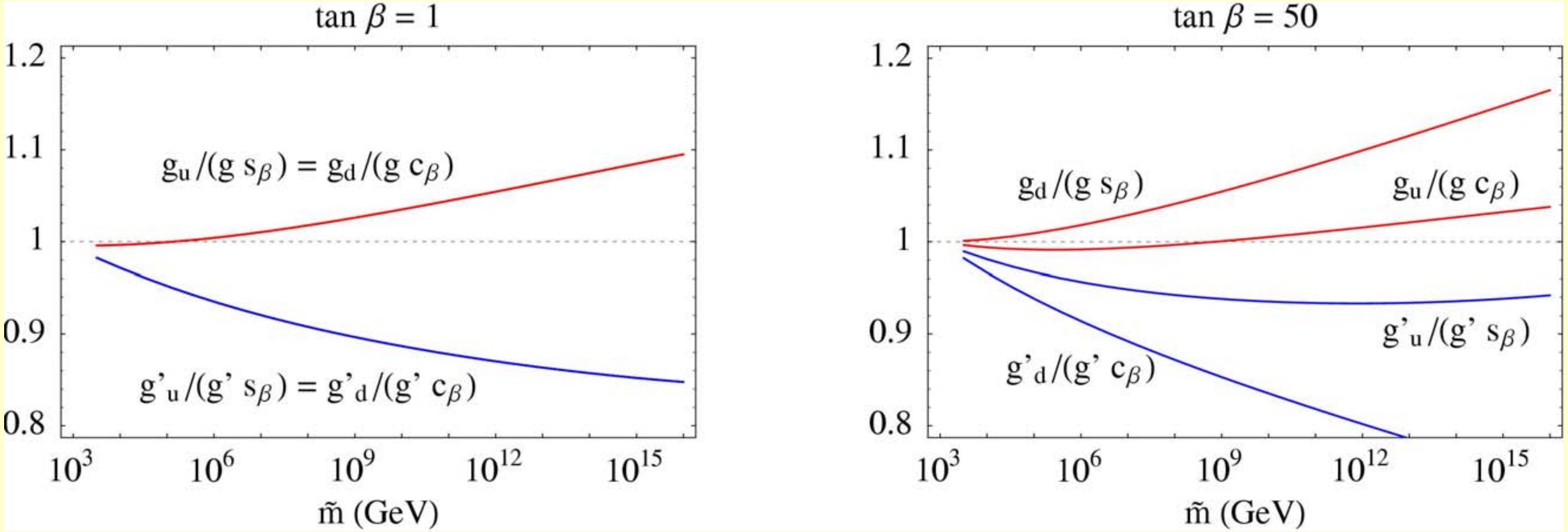
Charginos and neutralinos

- 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

Phenomenology and signatures

- Unification revisited
- Dark matter revisited
- Higgs mass
- Stable gluino
- SUSY fermion spectrum
- SUSY couplings
- EDMs
- Proton decay

Gaugino interactions



"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

Phenomenology and signatures

- Unification revisited
- Dark matter revisited
- Higgs mass
- Quasi-stable gluino
- SUSY fermion spectrum
- SUSY couplings
- EDMs
- Proton decay

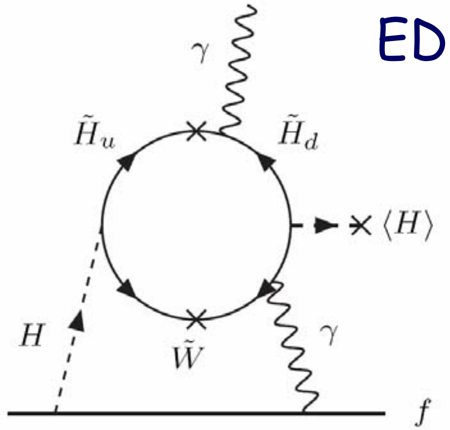
Heavy sfermions suppress flavour & CP violation

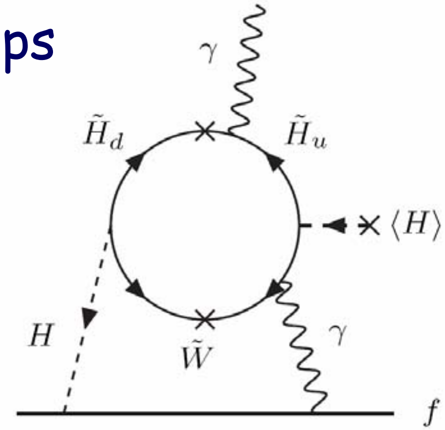
New source of flavour-diagonal CP violation remains:

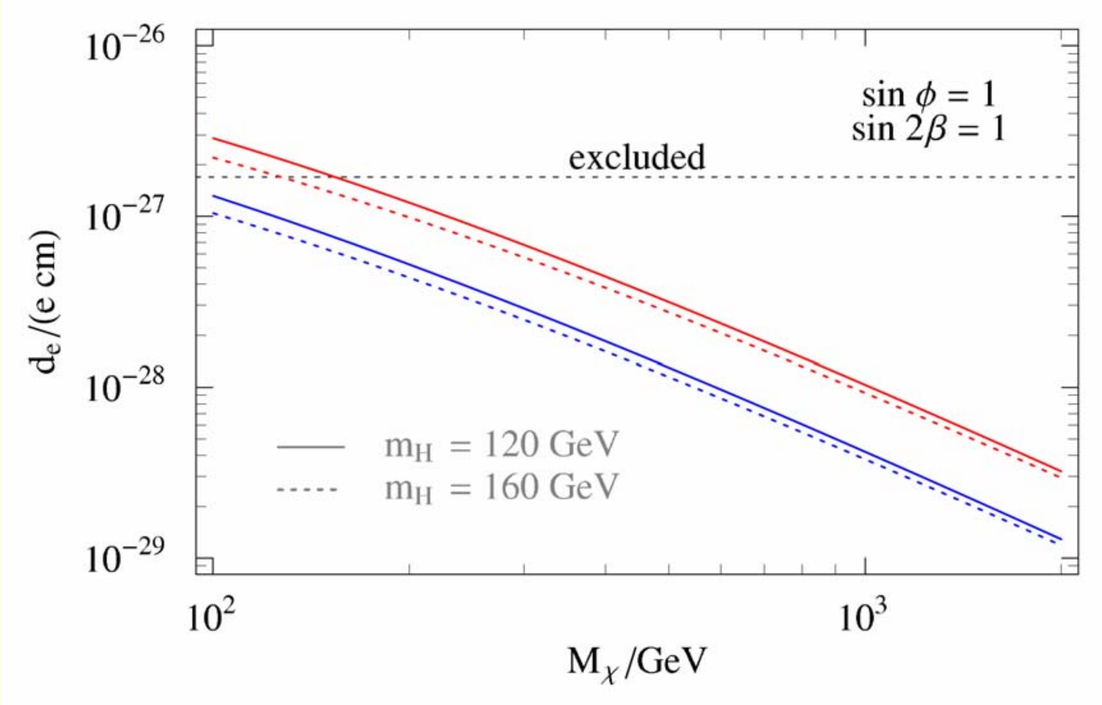
$$\mathcal{L} = \frac{M}{2}\tilde{W}\tilde{W} + \mu H_u H_d + \frac{g_u}{\sqrt{2}} H^* \tilde{W}\tilde{H}_u + \frac{g_d}{\sqrt{2}} H \tilde{W}\tilde{H}_d + \text{h.c.}$$

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

EDM at 2-loops







Present limit: $d_e < 1.7 \times 10^{-27}$ *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 m EDM

Phenomenology and signatures

- Unification revisited
- Dark matter revisited
- Higgs mass
- Quasi-stable gluino
- SUSY fermion spectrum
- SUSY couplings
- EDMs
- Proton decay

Proton decay

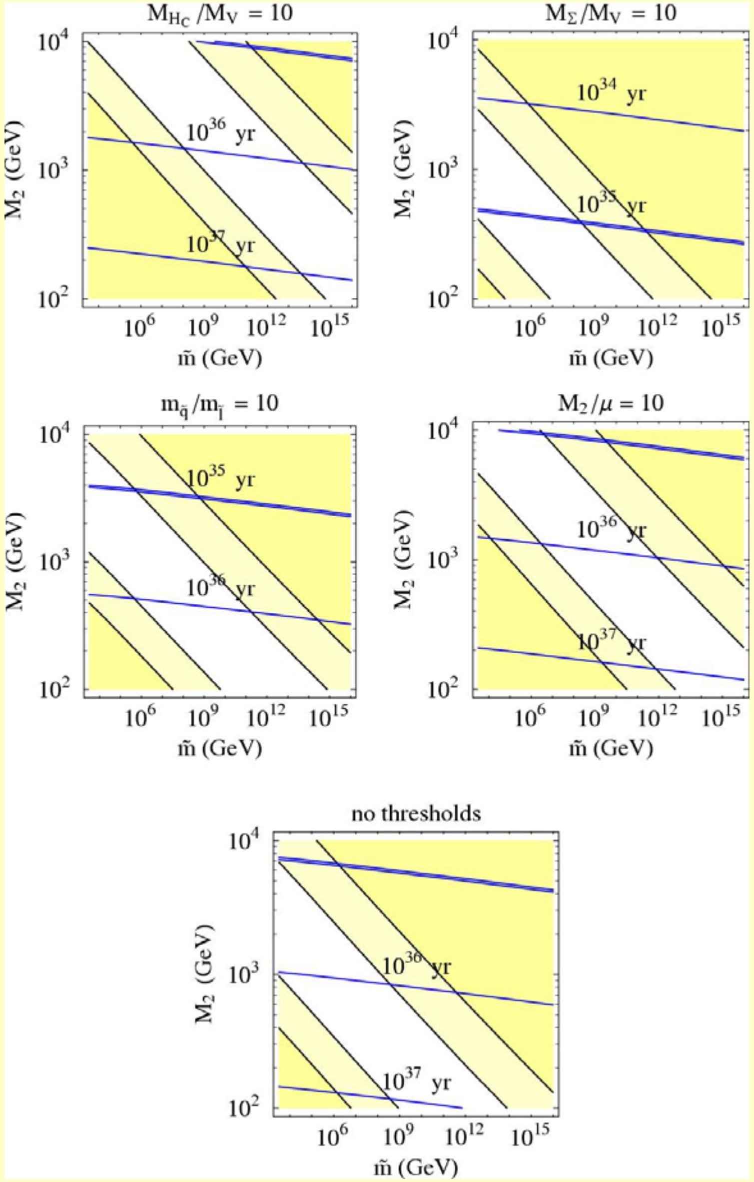
- From R-parity violating couplings λ (dimension 4):

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

- From dimension 5 operators: negligible for

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

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



R-parity

- R-parity violation is dangerous for proton decay, neutrino masses, dark matter
- Family hiearchical R-parity violating Yukawas are not necessarily dangerous if the scalars are very heavy (proton decay is suppressed and there is a window in which the neutralino is sufficiently stable and the gluino is sufficiently unstable)
- R-parity violating bilinears must be suppressed in order to avoid prompt neutralino decay and large neutrino masses

[see Gupta Konar Mukhopadhyaya, Chun Park for effects of trilinears]

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.