With SUSY towards the LHC

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Outline

- Prehistory
- Hierarchy problem
- How to hide the hidden sector
- Gravity mediation
- Some support from string theory
- The quest for unification
- Where are we now?
- LHC as a gluino factory
- the gaugino code
- crosschecks for unification

Early history

Supersymmetry was discovered in the 1970's. The early work concentrated on field theory aspects of SUSY, including

- Wess-Zumino model and gauge theories,
- Superspace formalism,
- spontaneous F- and D-term Susy breakdown,
- local supersymmetry.

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Some attempts in particle physics model building were pioneered by Fayet in the framework of D-term susy breakdown. (Fayet, 1970's)

Hierarchy problem

Around the same time Grand Unified Theories (GUTs) came into the game and emphasized the so-called hierarchy problem with solutions like “Technicolour”.

(Weinberg, Susskind, 1970’s)

Susy entered the stage because of the

- nonrenormalization theorems
- possibility of dynamical susy breakdown

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Susy entered the stage because of the

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Early attempts in model building turned out to be difficult because of obstacles in spontaneous Susy breakdown

(Dimopoulos, Raby; Dine, Fischler, Srednicki, 1981)

MSSM

The minimal particle content of the susy extension of the standard model contains chiral superfields

- Q, U, D for quarks and partners
- L, E for leptons and partners
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with superpotential

$$W = QHD + Q\bar{H}U + LHE + \mu H\bar{H}.$$

Also allowed (but problematic) are

$$UDD + QLD + LLE.$$

Soft susy breakdown

We consider the MSSM with explicit soft susy breakdown terms as this is compatible with the supersymmetric solution to the hierarchy problem. (Girardello, Grisaru, 1981)

This scheme now is characterized by

- two problems and
- two predictions.

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- two predictions.

Still we would need to understand the origin of the soft susy breakdown terms, but there remain

- four obstacles to be removed.

Two predictions

The evolution of gauge coupling constants is modified

- $M_{\rm GUT}$ is raised by an order of magnitude (because of the presence of the gauginos),
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- M_{GUT} is raised by an order of magnitude (because of the presence of the gauginos),
- $\sin^2\theta_W \sim 0.23$.

There is an upper bound on the mass of the lightest Higgs boson (since the Higgs boson self-coupling is determined by the the gauge couplings)

- $m_h \leq M_Z$ at tree level
- $m_h \lesssim 130$ GeV for $m_{\mathrm{top}} \lesssim 175$ GeV

Two problems

The Higgs bilinear term $\mu H\bar{H}$ is allowed by susy:

- why is μ small compared to the GUT-scale?
- why is μ of order of the soft mass terms?

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We have to distinguish between L and H to avoid fast proton decay

- $UDD + QLD + LLE$ have to be forbidden
- need some discrete symmetry: R-parity

But there is a reward:
a stable particle (LSP) as dark matter candidate.

Four obstacles for model building

In spontaneous breakdown of susy we have

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We need a (weakly coupled) hidden sector and well as supergravity

Gravity Mediation

All of these problems can be solved by gravity mediation

- MSSM as observable sector,
- hidden sector breaks susy spontaneously
- gravitational interactions as messenger.

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Soft breaking terms can be computed explicitely

- $m_{3/2} \sim \Lambda^3/M_{\rm Planck}^2 \sim F/M_{\rm Planck}$,
- soft (mass) terms m_0, $m_{1/2}$, A and B.

(Arnowitt, Chamseddine, Nath, PRL 49, 1982; Barbieri, Ferrara, Savoy, PL 119B, 1982; HPN, Srednicki, Wyler, PR 120B, 1982; Hall, Lykken, Weinberg, PRD 27, 1982)

The golden era

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- successful model building was possible,
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One was tempted to say:

- Experiments within the next five to ten years will enable us to decide whether supersymmetry at the weak interaction scale is a myth or reality. (HPN, 1984)

This statement is still true today!

Early string theory

With the developments in string theory the optimism was still growing

- heterotic $E_8 \times E_8$,
- hidden and observable E_8 sector,
- gaugino condensation in the hidden sector.

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A new variant of gravity mediation emerged

- dilaton and/or
- modulus mediation.

LEP I

Results from LEP were eagerly awaited in 1989.
The first stage of LEP gave us:

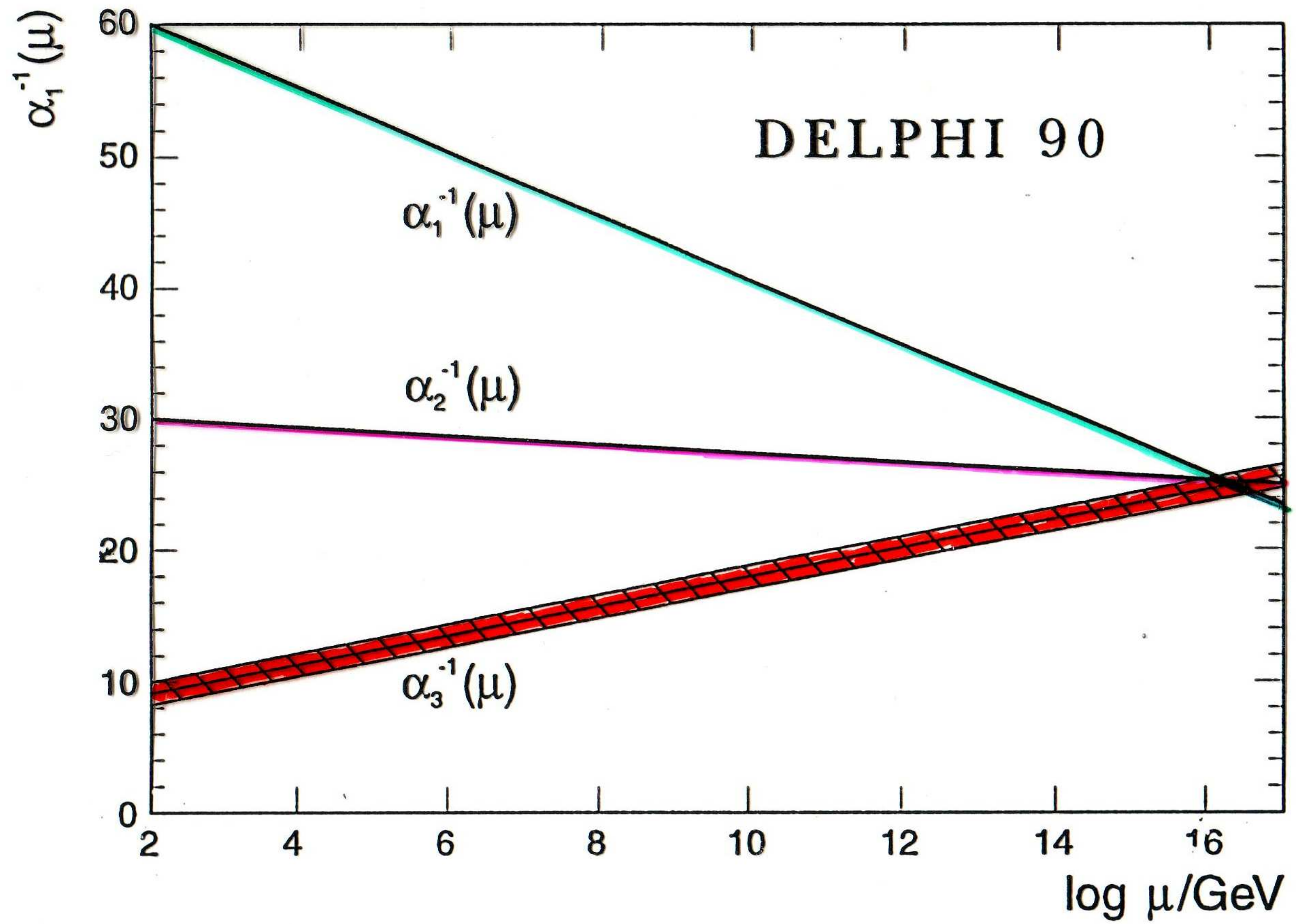
- no direct sign for SUSY, but
- indirect sign from evolution of gauge coupling constants
- the resurrection of (SUSY-) GUTs

A large fraction of the community got excited about susy:

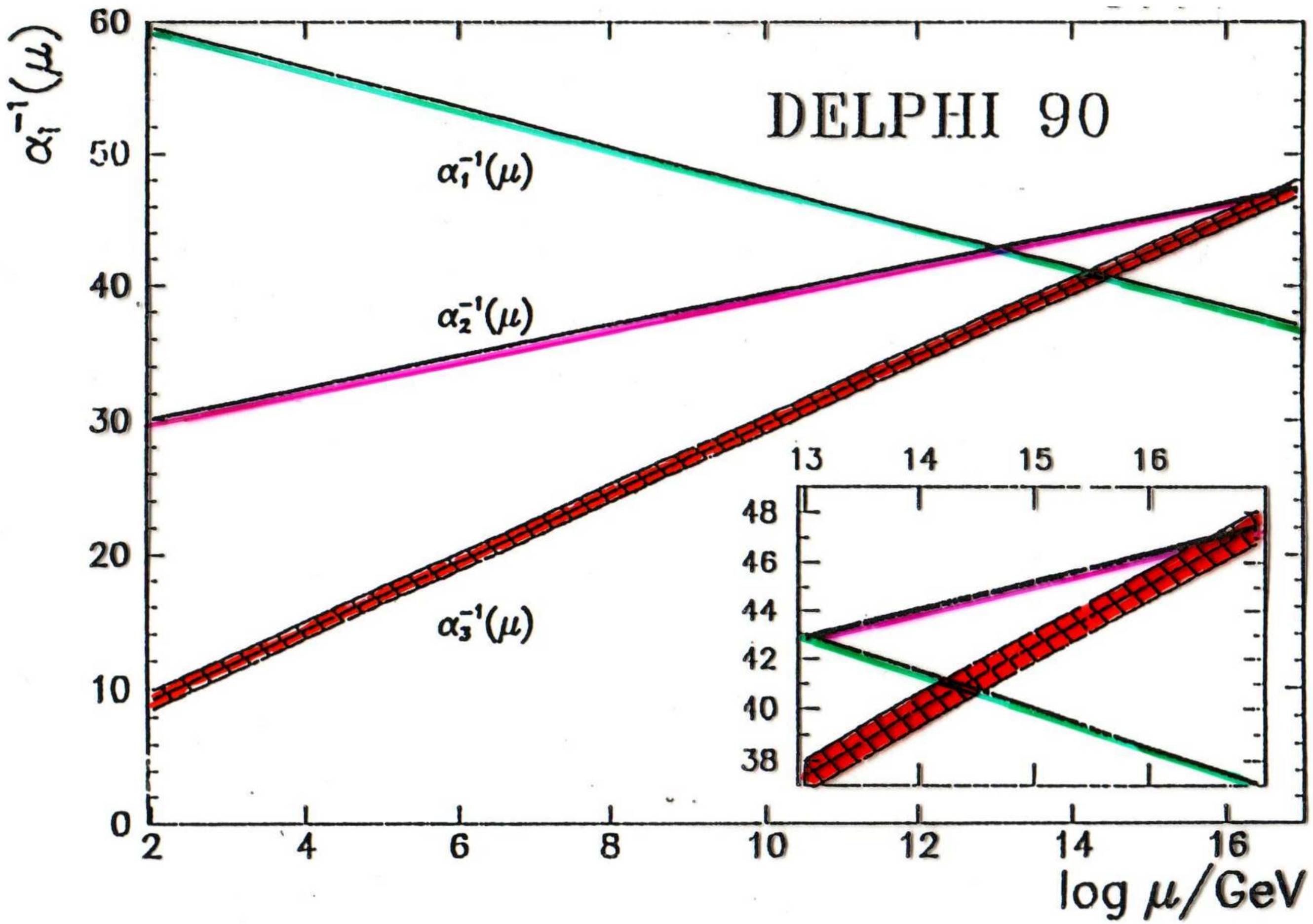
- all was set for the discovery at LEP II

But there was no clear answer.

MSSM (supersymmetric)



Standard Model



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The results of LEP II gave

- support for grand unification,
- Higgs mass $m_h > 114$ GeV,
- electroweak precision data
  - consistent with Standard Model,
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No direct sign for susy, but encouragement.....

- A large part of parameter space is gone.
- We are living in a corner of parameter space ("little hierarchy problem")

What keeps us going?

- unification of coupling constants
- dark matter candidate from R-parity
- electroweak precision data (S, T seem to fit)
- $(g-2)_\mu$ as a hint
- alternatives look much worse

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Where are we now?

- many different models
- many different mediation schemes

We need the LHC to judge.

The future is the LHC

Mediation schemes:

- gravity mediation $(m_{\rm soft} \sim m_{3/2})$
- anomaly mediation $(m_{\rm soft} \ll m_{3/2})$
- gauge mediation $(m_{\rm soft} \gg m_{3/2})$

The future is the LHC

Mediation schemes:

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Meanwhile we have to guess what might happen. This personal guideline is based on

- simplicity
- motivation from Grand Unification
- theoretical input (from string theory)

Questions

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Recent progress:

- explicit model building towards the MSSM
  - Heterotic brane world
  - local grand unification
- moduli stabilization and Susy breakdown
  - fluxes and gaugino condensation
  - mirage mediation

Mediation schemes

Supersymmetry is broken in a hidden sector and we have a variant of so-called gravity mediation

- tree level dilaton/modulus mediation

  (Derendinger, Ibanez, HPN, 1985; Dine, Rohm, Seiberg, Witten, 1985)

- radiative corrections in case of a sequestered hidden sector (e.g. anomaly mediation)

  (Ibanez, HPN, 1986; Randall, Sundrum, 1999)

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The importance of
the mechanism to adjust the cosmological constant
has only been appreciated recently

(Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)

Basic Questions

- origin of the small scale?
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Recent progress in

- moduli stabilization via fluxes in warped compactifications of Type IIB string theory

  (Dasgupta, Rajesh, Sethi, 1999; Giddings, Kachru, Polchinski, 2001)

- generalized flux compactifications of heterotic string theory

  (Becker, Becker, Dasgupta, Prokushkin, 2003; Gurrieri, Lukas, Micu, 2004)

- combined with gaugino condensates and “uplifting”

  (Kachru, Kallosh, Linde, Trivedi, 2003; Löwen, HPN, 2008)

Fluxes and gaugino condensation

Is there a general pattern of the soft mass terms?

We always have (from flux and gaugino condensate)

$$W = \text{something} - \exp(-X)$$

where "something" is small and X is moderately large.

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We always have (from flux and gaugino condensate)

$$W = \text{something} - \exp(-X)$$

where "something" is small and X is moderately large.

In fact in this simple scheme

$$X \sim \log(M_{\text{Planck}}/m_{3/2})$$

providing a "little" hierarchy.

(Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)

Mixed Mediation Schemes

The contribution from "Modulus Mediation" is therefore suppressed by the factor

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Thus the contribution due to radiative corrections becomes competitive, leading to mixed mediation schemes.

The simplest case for radiative corrections leads to anomaly mediation competing now with the suppressed contribution of modulus mediation.

For reasons that will be explained later we call this scheme

MIRAGE MEDIATION

(Loaiza, Martin, HPN, Ratz, 2005)

The little hierarchy

$$m_X \sim \langle X \rangle m_{3/2} \sim \langle X \rangle^2 m_{\text{soft}}$$

is a generic signal of such a scheme

- moduli and gravitino are heavy
- gaugino mass spectrum is compressed

(Choi, Falkowski, HPN, Olechowski, 2005; Endo, Yamaguchi, Yoshioka, 2005; Choi, Jeong, Okumura, 2005)

- such a situation occurs if SUSY breaking is e.g. “sequestered” on a warped throat

(Kachru, McAllister, Sundrum, 2007)

Mirage Unification

Mirage Mediation provides a

- characteristic pattern of soft breaking terms.

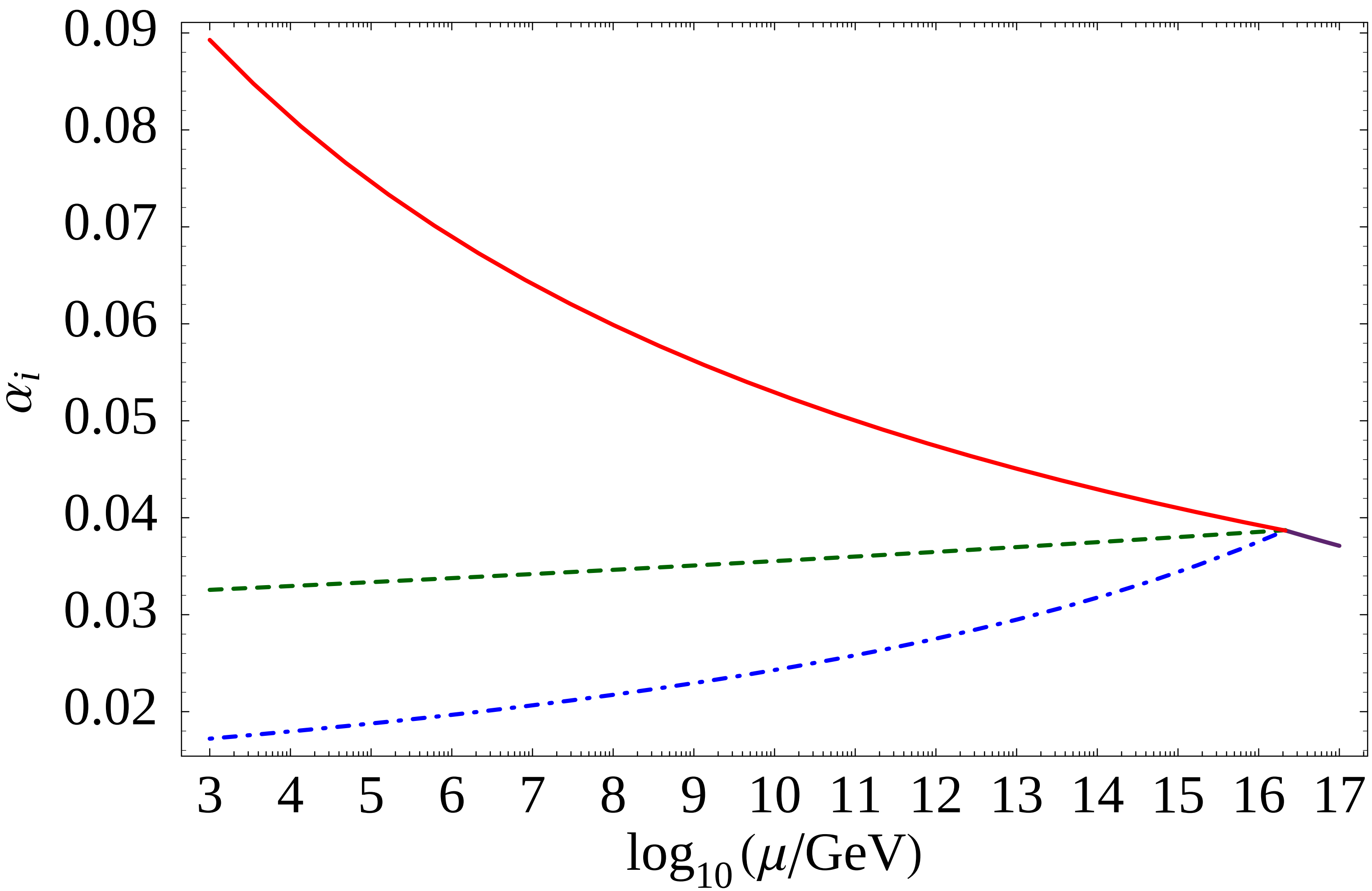
To see this, let us consider the gaugino masses

$$M_{1/2} = M_{\text{modulus}} + M_{\text{anomaly}}$$

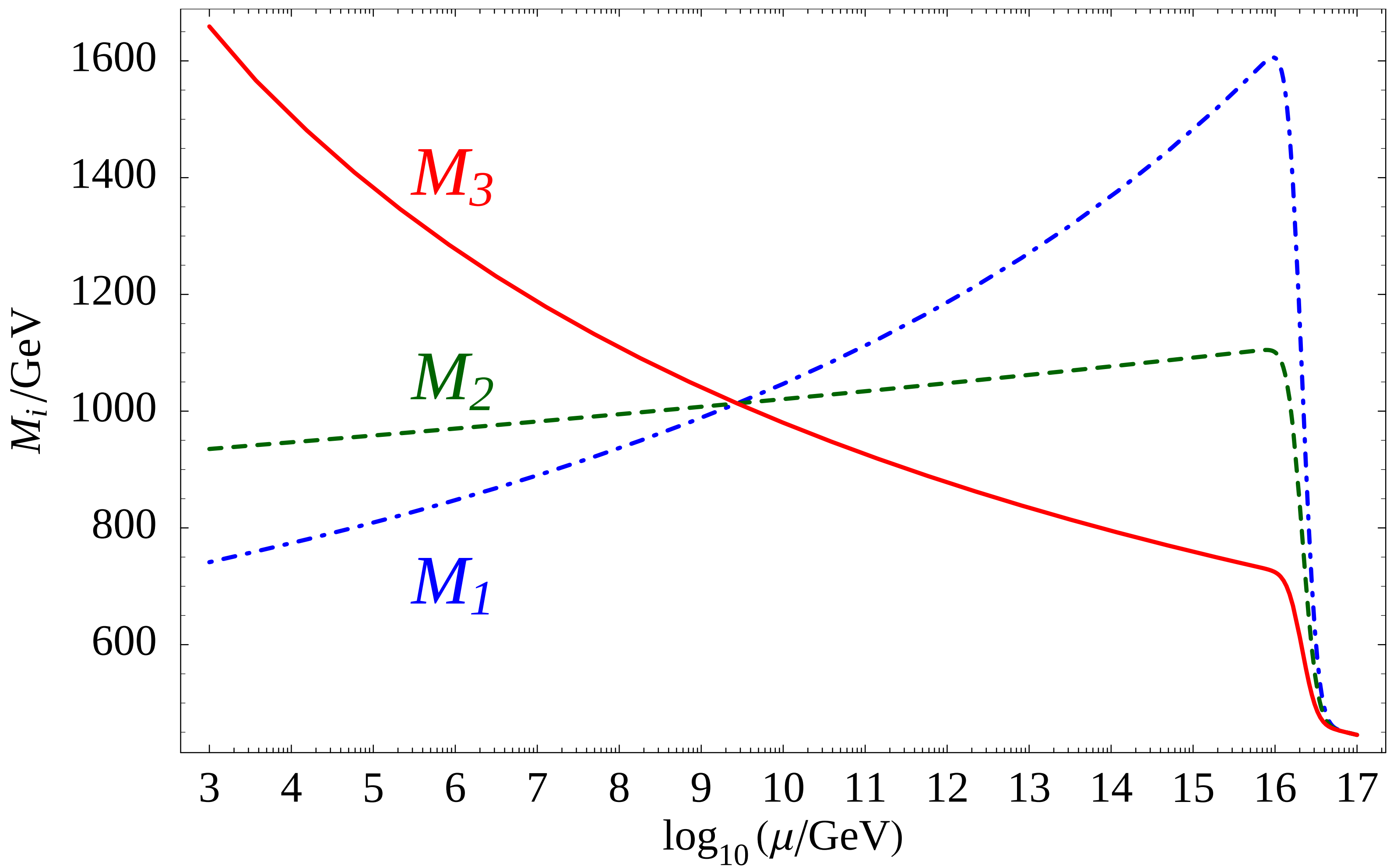
as a sum of two contributions of comparable size.

- M_{anomaly} is proportional to the β function, i.e. negative for the gluino, positive for the bino
- thus M_{anomaly} is non-universal below the GUT scale

Evolution of couplings



The Mirage Scale



(Lebedev, HPN, Ratz, 2005)

The Mirage Scale (II)

The gaugino masses coincide

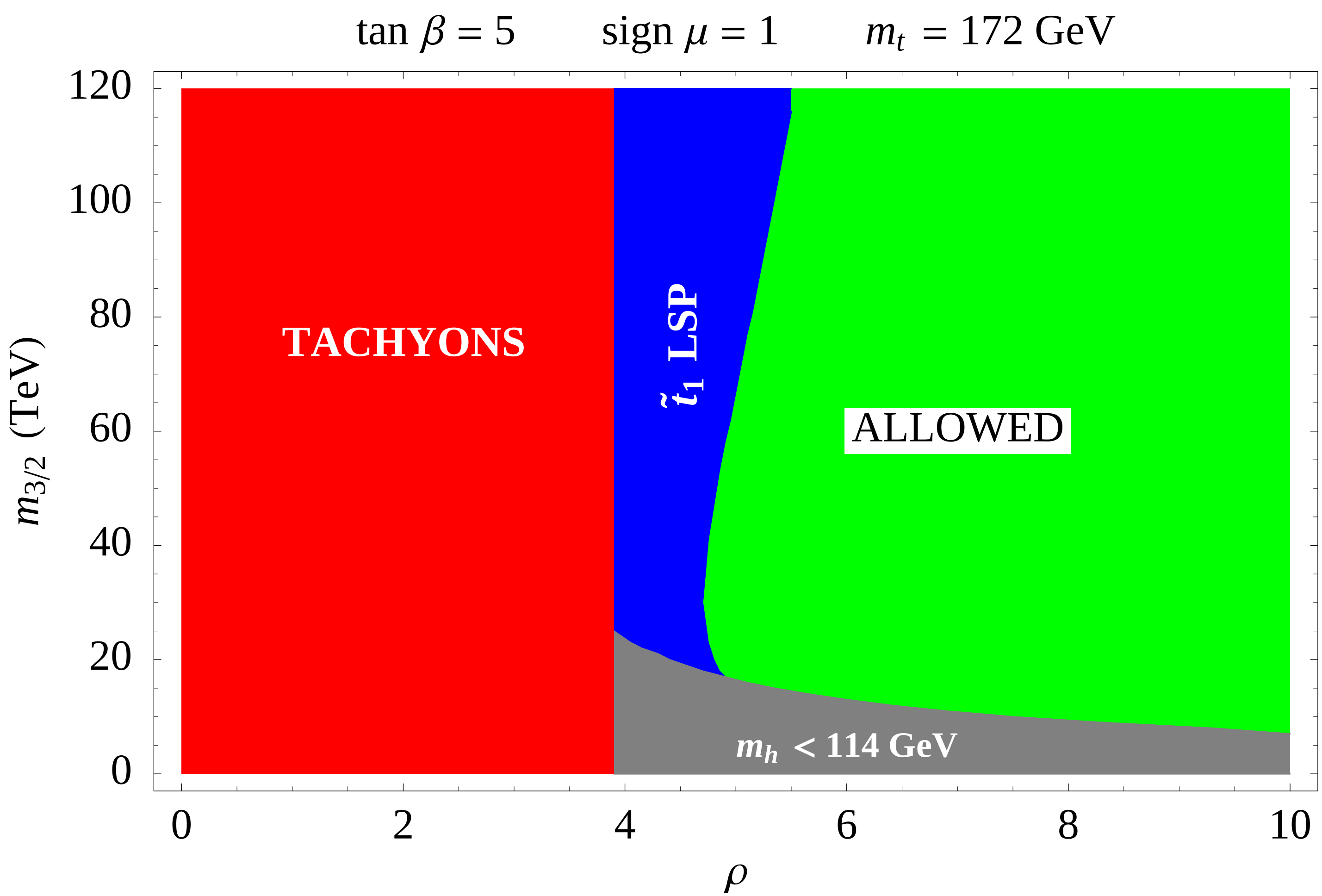
- above the GUT scale
- at the mirage scale $\mu_{\mathrm{mirage}} = M_{\mathrm{GUT}} \exp(-8\pi^2/\rho)$

where ρ denotes the “ratio” of the contribution of modulus vs. anomaly mediation. We write the gaugino masses as

$$M_a = M_s(\rho + b_a g_a^2) = \frac{m_{3/2}}{16\pi^2}(\rho + b_a g_a^2)$$

and $\rho \to 0$ corresponds to pure anomaly mediation.

Constraints on the mixing parameter



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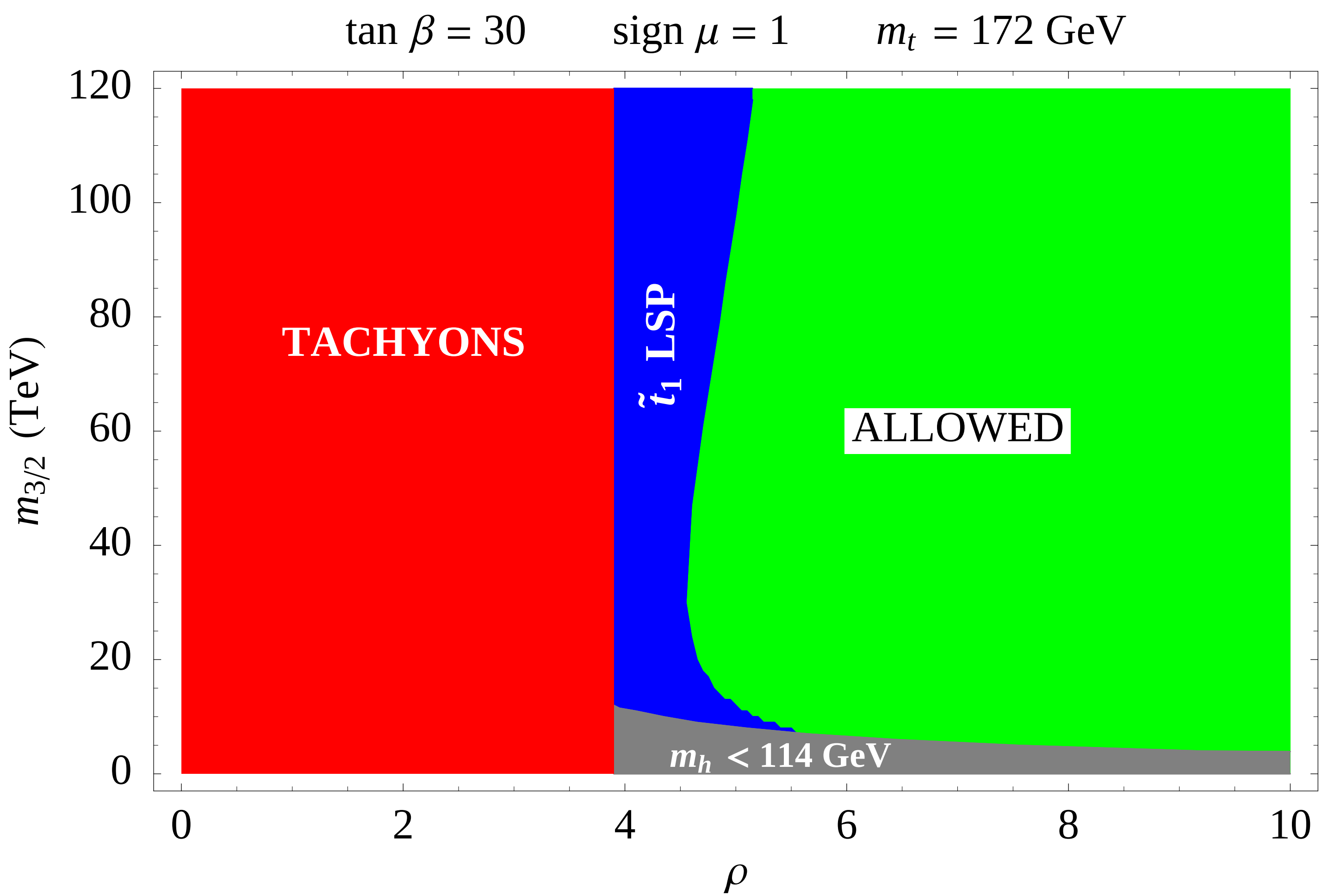
Constraints on ρ



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The “MSSM hierarchy problem”

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One might worry about a fine-tuning to obtain

- the mass of the weak scale around 100 GeV from

$$\frac{m_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1},$$

and there are large corrections to $m_{H_u}^2$......

(Choi, Jeong, Kobayashi, Okumura, 2005)

The “MSSM hierarchy problem”?

The influence of the various soft terms is given by

$$m_Z^2 \simeq -1.8\,\mu^2 + 5.9\,M_3^2 - 0.4\,M_2^2 - 1.2\,m_{H_u}^2 + 0.9\,m_{q_{\rm L}^{(3)}}^2 + \\ + 0.7\,m_{u_{\rm R}^{(3)}}^2 - 0.6\,A_t\,M_3 + 0.4\,M_2\,M_3 + \ldots$$

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Mirage mediation improves the situation

- especially for small ρ
- because of a reduced gluino mass and a “compressed” spectrum of supersymmetric partners

  (Choi, Jeong, Kobayashi, Okumura, 2005)
- explicit model building required

  (Kitano, Nomura, 2005; Lebedev, HPN, Ratz, 2005; Pierce, Thaler, 2006; Dermisek, Kim, 2006; Ellis, Olive, Sandick, 2006; Martin, 2007)

Explicit schemes I

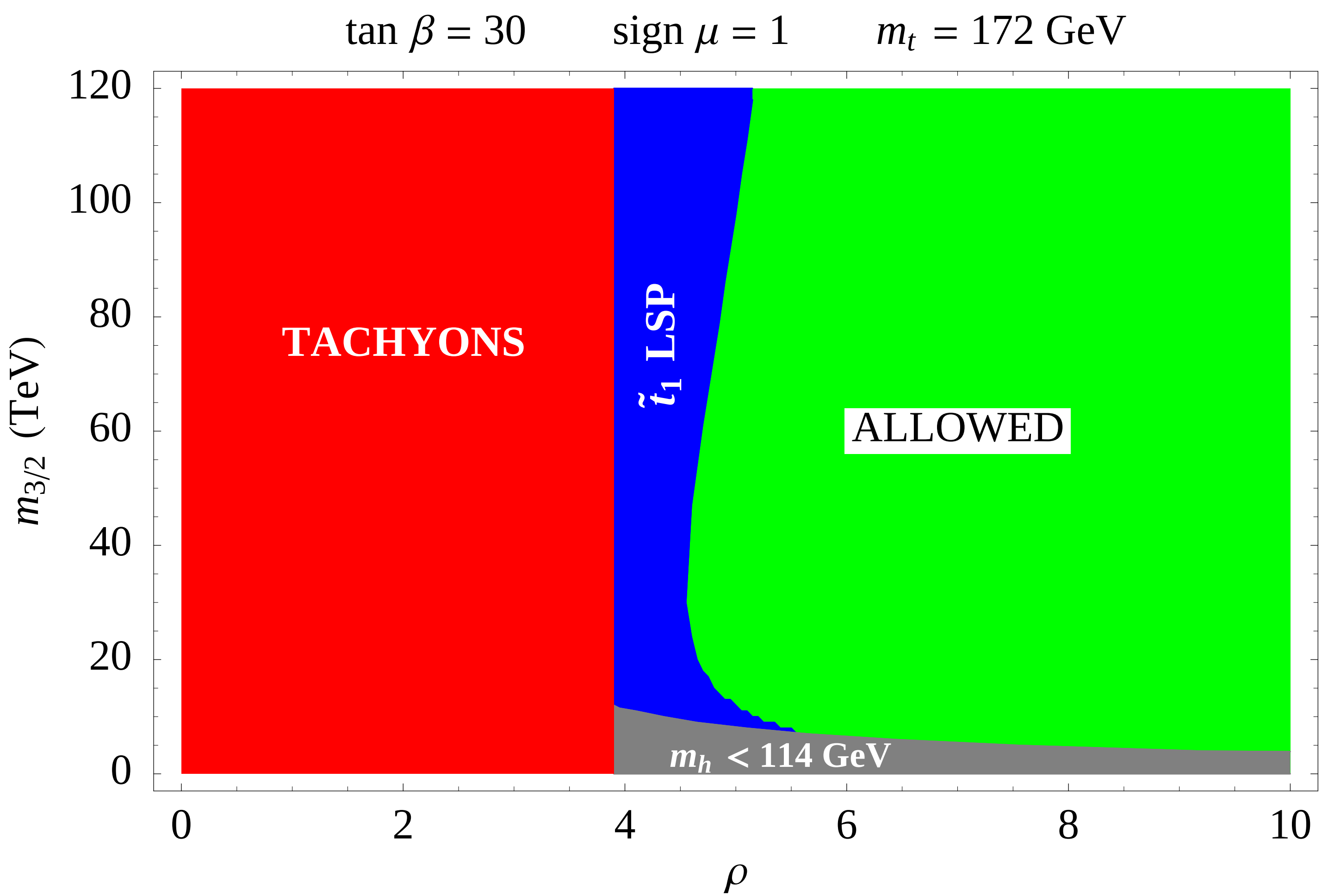
The different schemes depend on the mechanism of uplifting:

- uplifting with anti D3 branes

  (Kachru, Kallosh, Linde, Trivedi, 2003)

  - $\rho \sim 5$ in the original KKLT scenario leading to
  - a mirage scale of approximately 10^{11} GeV
- This scheme leads to pure mirage mediation:
  - gaugino masses and
  - scalar masses
- both meet at a common mirage scale

Constraints on ρ



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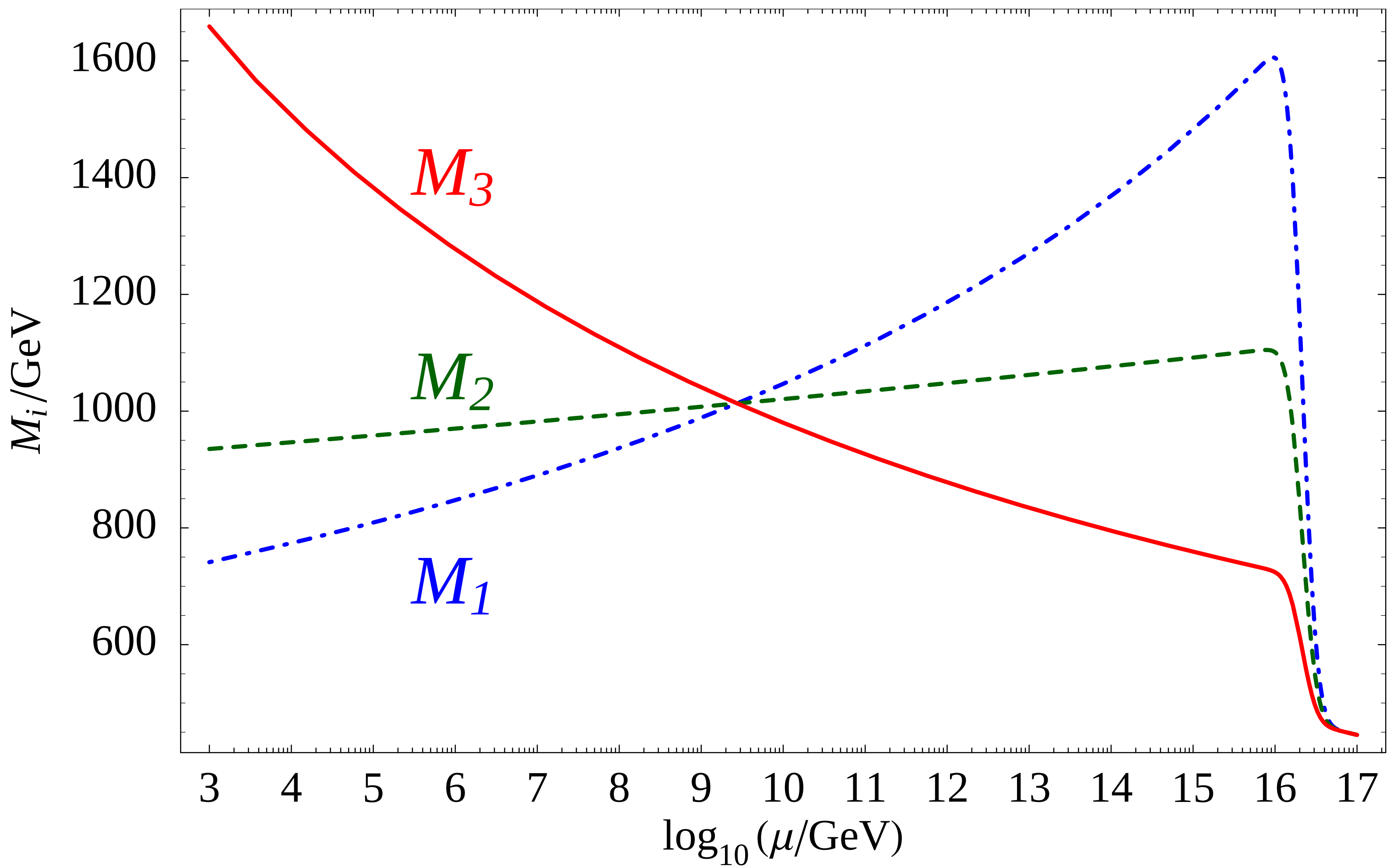

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Explicit schemes II

- uplifting via matter superpotentials

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- gaugino masses still meet at a mirage scale

- soft scalar masses might be dominated by modulus mediation

- similar constraints on the mixing parameter

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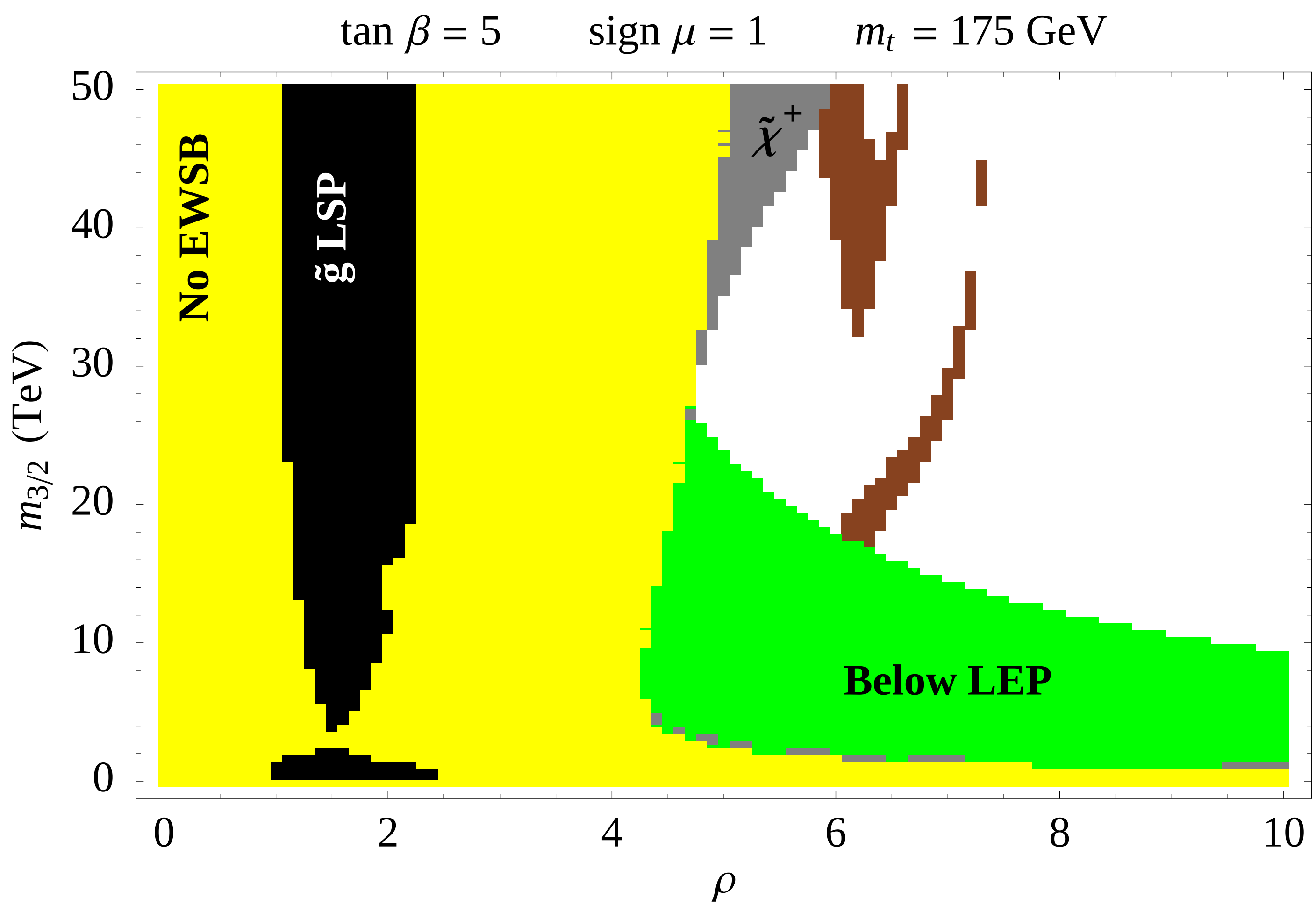

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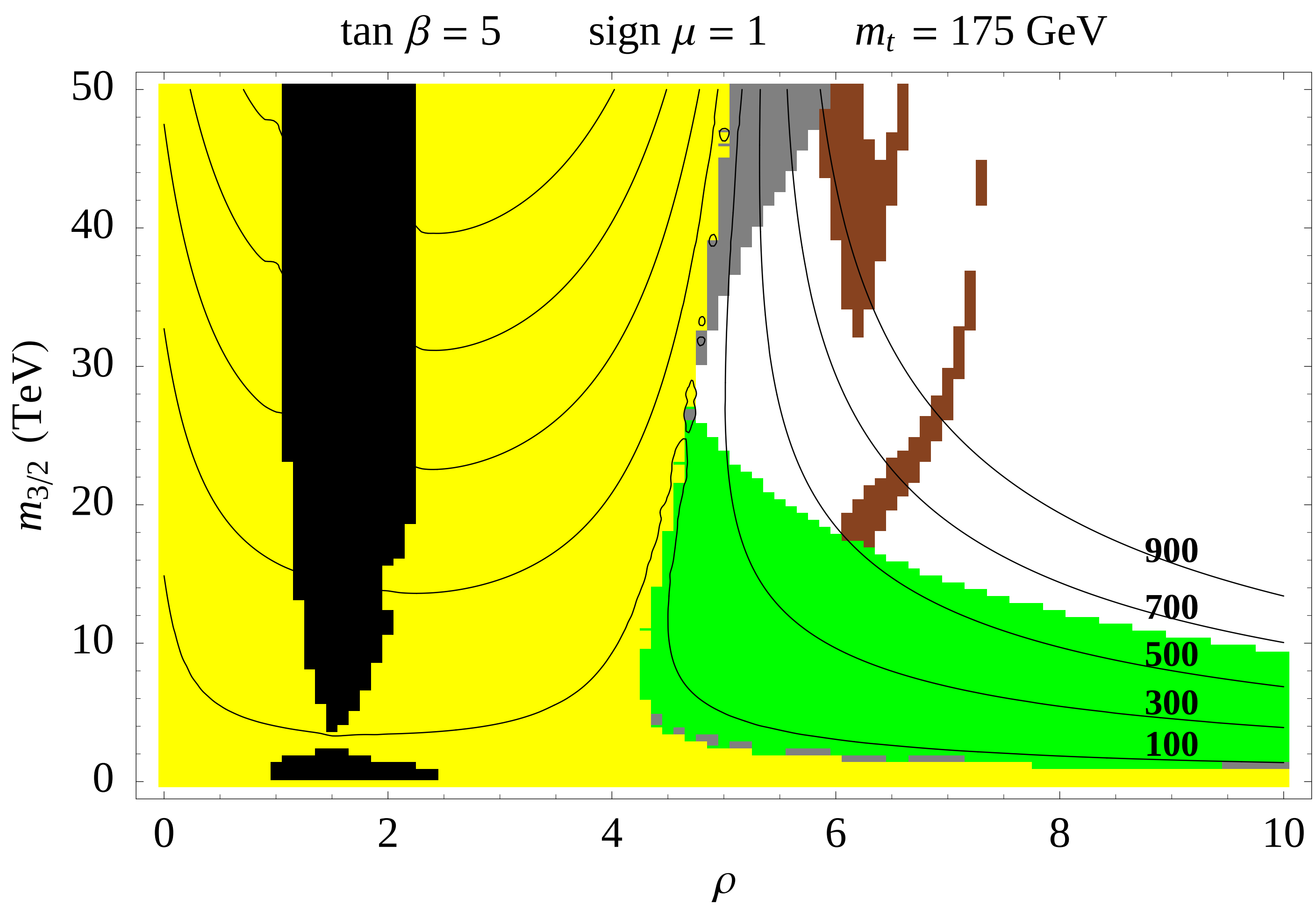

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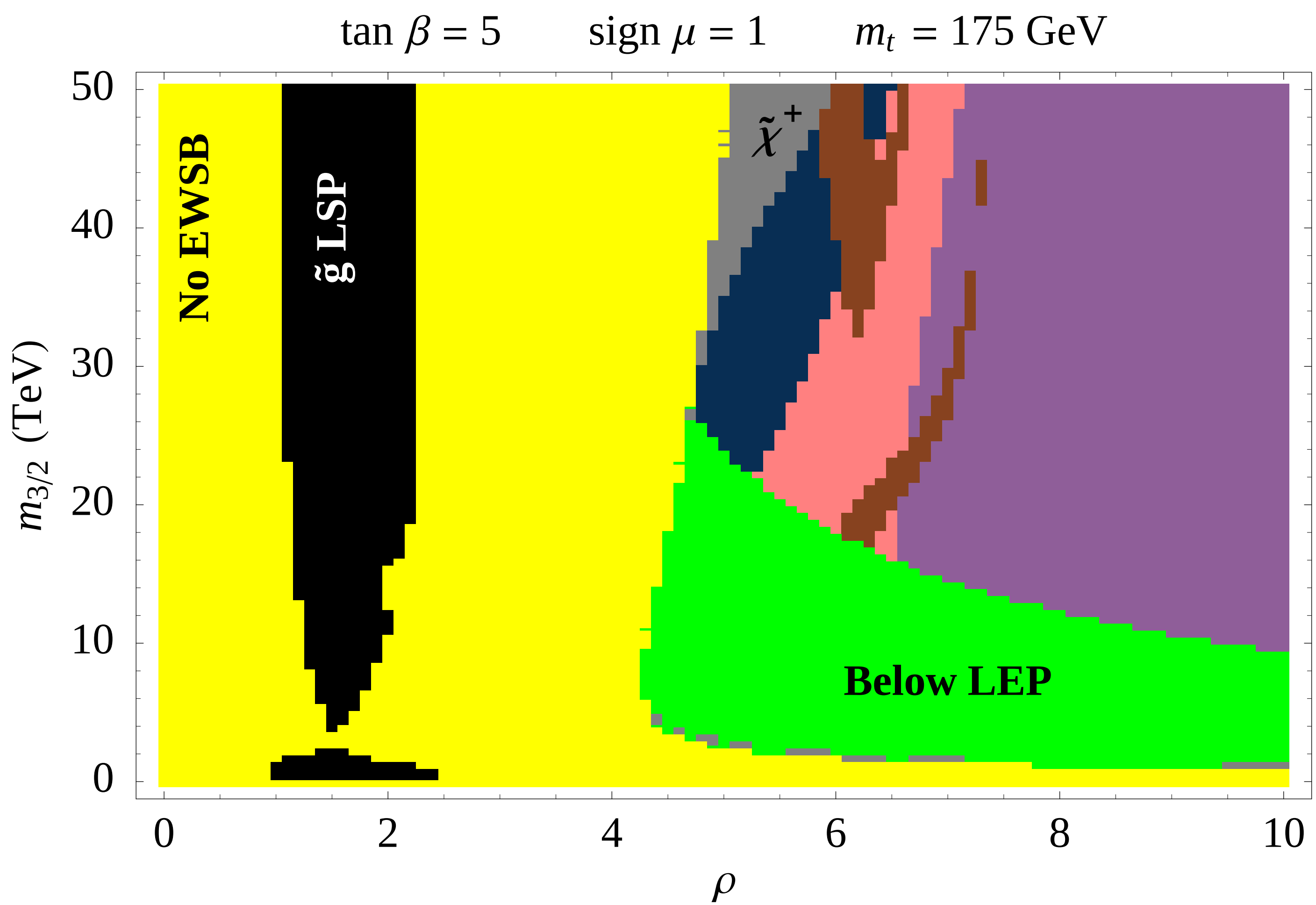

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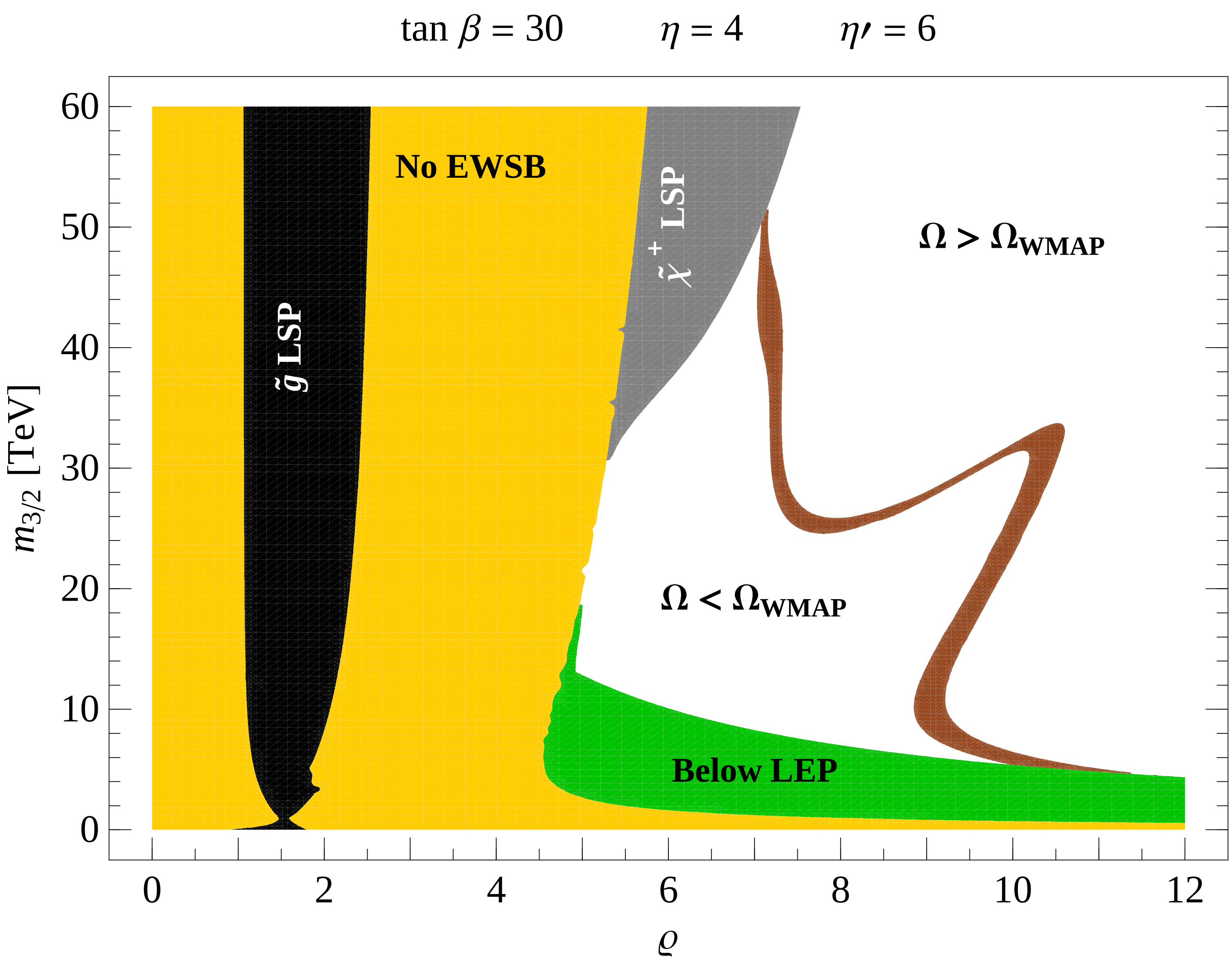

Explicit schemes III

- This “relaxed” mirage mediation is rather common for schemes with F-term uplifting
(Intriligator, Shih, Seiberg; Gomez-Reino, Scrucca; Dudas, Papineau, Pokorski; Abe, Higaki, Kobayashi, Omura; Lebedev, Löwen, Mambrini, HPN, Ratz ,2006)
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Main message

- predictions for gaugino masses are more robust than those for sfermion masses
- mirage (compressed) pattern for gaugino masses rather generic

Obstacles to D-term uplifting

In supergravity we have the relation

$$D \sim \frac{F}{W}$$

which implies that KKLT AdS minimum cannot be uplifted via D-terms.

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Moreover in these schemes we have

$$F \sim m_{3/2} M_{\text{Planck}} \quad \text{and} \quad D \sim m_{3/2}^2 .$$

So if $m_{3/2} \ll M_{\text{Planck}}$ the D-terms are irrelevant.

(Choi, Jeong, 2006)

What to expect from the LHC

At the LHC we scatter

- protons on protons, i.e.
- quarks on quarks and/or
- gluons on gluons

Thus LHC will be a machine to produce strongly interacting particles. If TeV-scale susy is the physics beyond the standard model we might expect LHC to become a

GLUINO FACTORY

with cascade decays down to the LSP neutralino.

The Gaugino Code

First step to test these ideas at the LHC:

look for pattern of gaugino masses

Let us assume the

- low energy particle content of the MSSM
- measured values of gauge coupling constants

$$g_1^2 : g_2^2 : g_3^2 \simeq \; 1 : 2 : 6$$

The evolution of gauge couplings would then lead to unification at a GUT-scale around 10^{16} GeV

Formulae for gaugino masses

$$\left(\frac{M_a}{g_a^2}\right)_{\mathrm{TeV}} = \tilde{M}_a^{(0)} + \tilde{M}_a^{(1)}|_{\mathrm{anomaly}} + \tilde{M}_a^{(1)}|_{\mathrm{gauge}} + \tilde{M}_a^{(1)}|_{\mathrm{string}}$$

$$\tilde{M}_a^{(0)} = \frac{1}{2} F^I \partial_I f_a^{(0)}$$

$$\tilde{M}_a^{(1)}|_{\mathrm{anomaly}} = \frac{1}{16\pi^2} b_a \frac{F^C}{C} - \frac{1}{8\pi^2} \sum_m C_a^m F^I \partial_I \ln(e^{-K_0/3} Z_m)$$

$$\tilde{M}_a^{(1)}|_{\mathrm{string}} = \frac{1}{8\pi^2} F^I \partial_I \Omega_a$$

The Gaugino Code

Observe that

- evolution of gaugino masses is tied to evolution of gauge couplings
- for MSSM M_a/g_a^2 does not run (at one loop)

This implies

- robust prediction for gaugino masses
- gaugino mass relations are the key to reveal the underlying scheme

3 CHARACTERISTIC MASS PATTERNS

(Choi, HPN, 2007)

SUGRA Pattern

Universal gaugino mass at the GUT scale

- SUGRA pattern:

$$M_1 : M_2 : M_3 \simeq \ 1 : 2 : 6 \simeq \ g_1^2 : g_2^2 : g_3^2$$

as realized in popular schemes such as gravity-, modulus- and gaugino-mediation

This leads to

- LSP χ_1^0 predominantly Bino
- $G = M_{\rm gluino}/m_{\chi_1^0} \simeq 6$

as a characteristic signature of these schemes.

Anomaly Pattern

Gaugino masses below the GUT scale determined by the β functions

- anomaly pattern:

$$M_1 : M_2 : M_3 \simeq\ 3.3 : 1 : 9$$

at the TeV scale as the signal of anomaly mediation.

For the gauginos, this implies

- LSP χ_1^0 predominantly Wino
- $G = M_{\rm gluino}/m_{\chi_1^0} \simeq 9$

Pure anomaly mediation inconsistent, as sfermion masses are problematic in this scheme (tachyonic sleptons).

Mirage Pattern

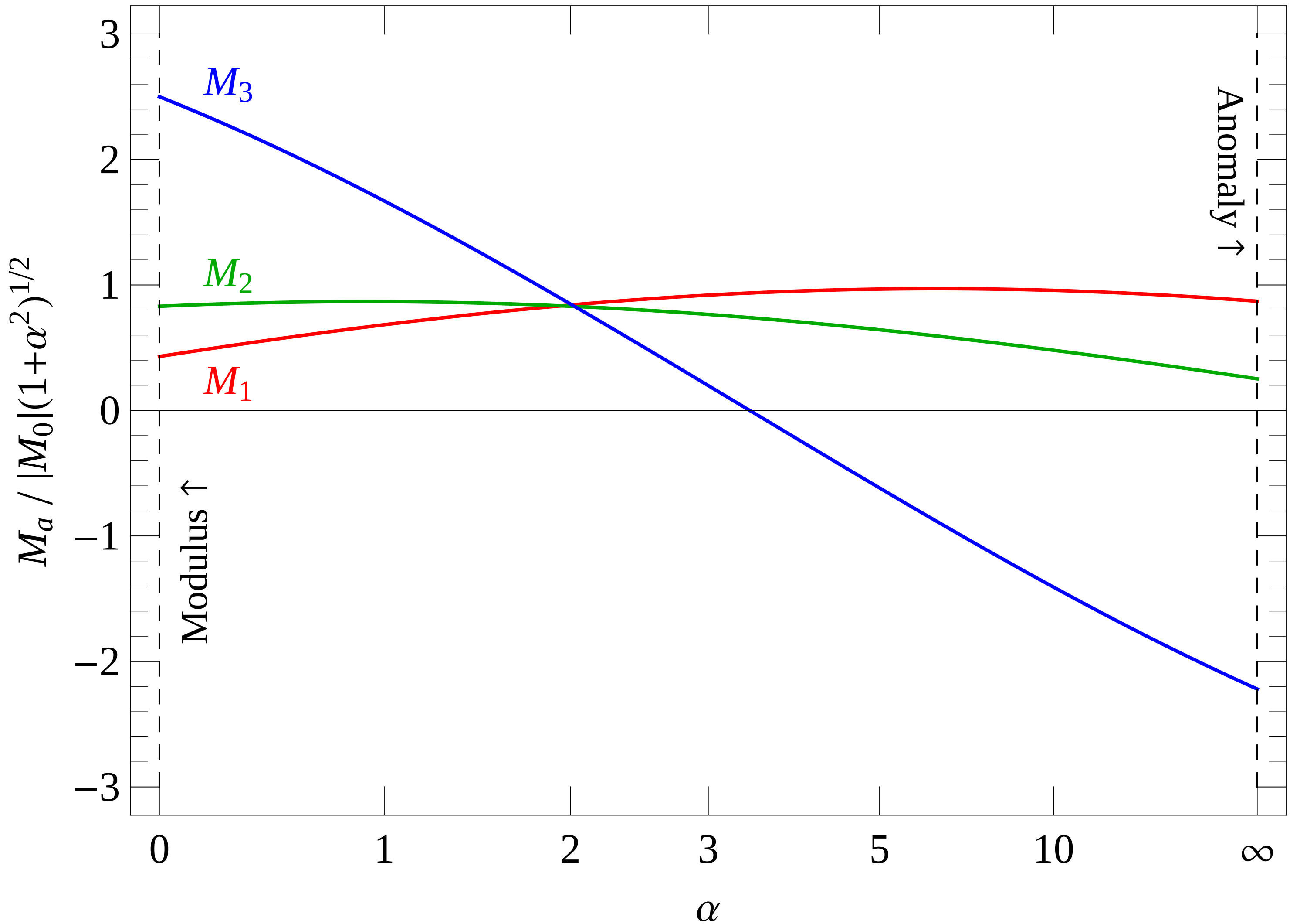
Mixed boundary conditions at the GUT scale characterized by the parameter ρ (the ratio of anomaly to modulus mediation).

- $M_1 : M_2 : M_3 \simeq\ 1 : 1.3 : 2.5$ for $\rho \simeq 5$
- $M_1 : M_2 : M_3 \simeq\ 1 : 1 : 1$ for $\rho \simeq 2$

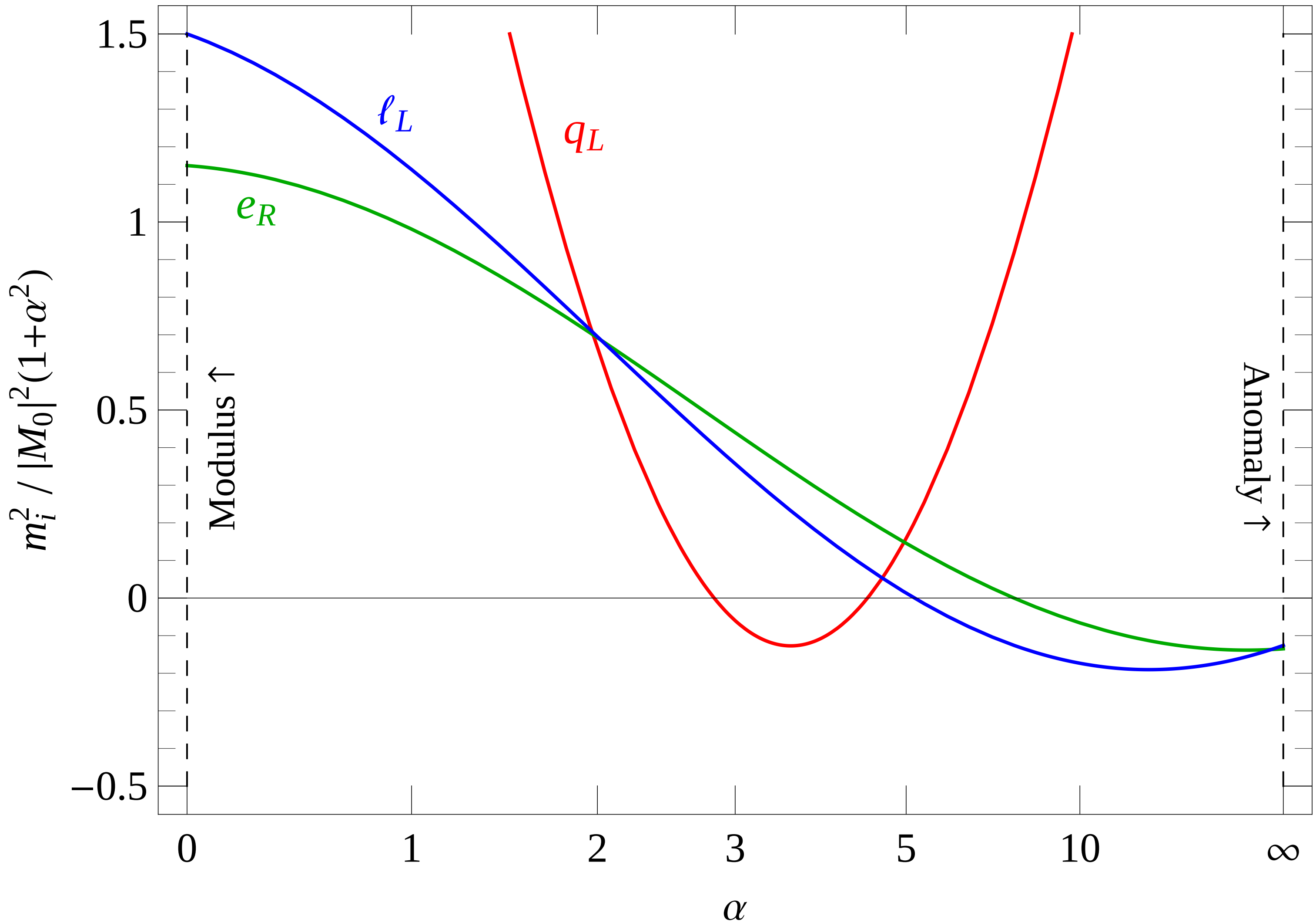
The mirage scheme leads to

- LSP χ_1^0 predominantly Bino
- $G = M_{\mathrm{gluino}}/m_{\chi_1^0} < 6$
- a “compact” gaugino mass pattern.

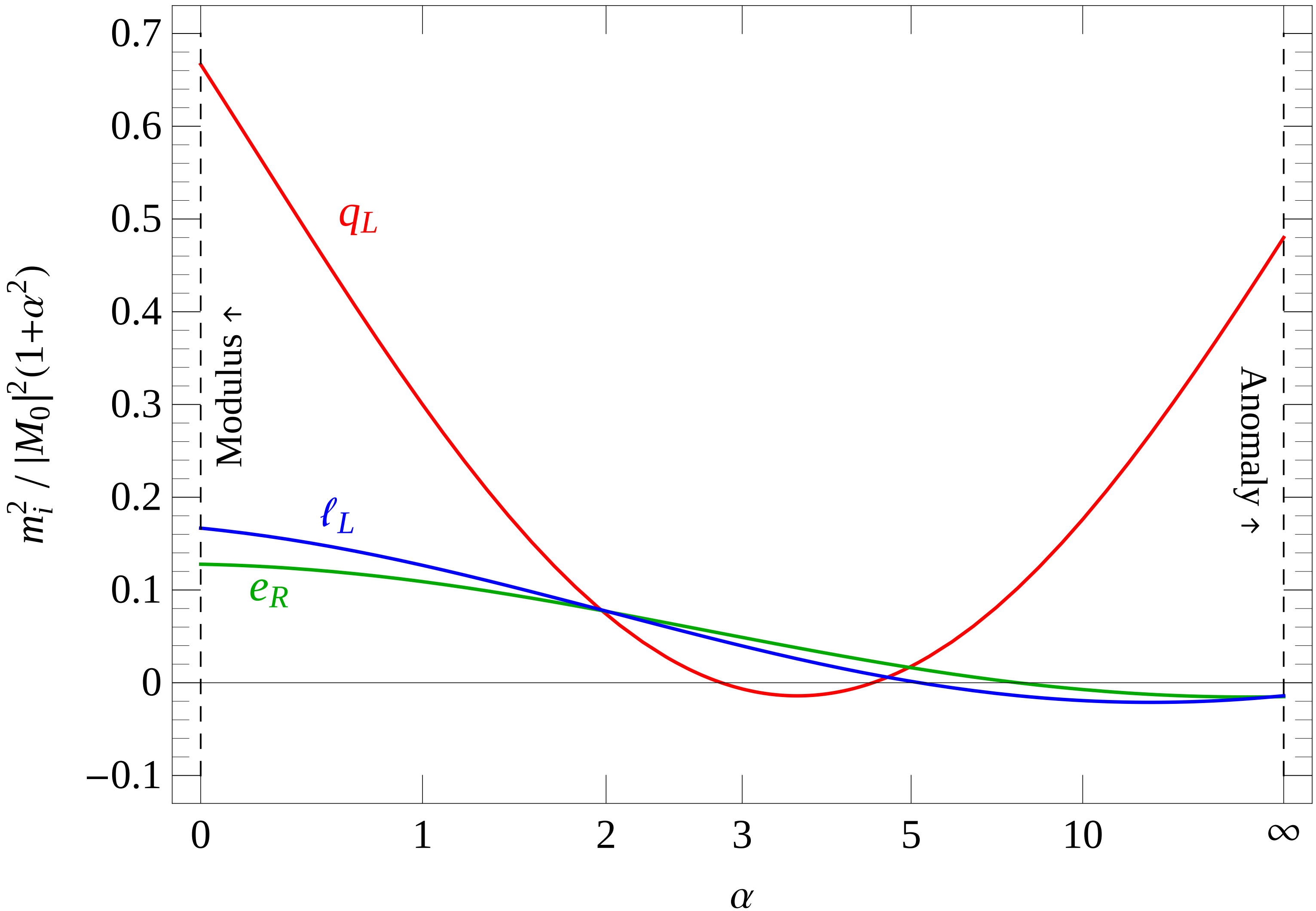
Gaugino Masses



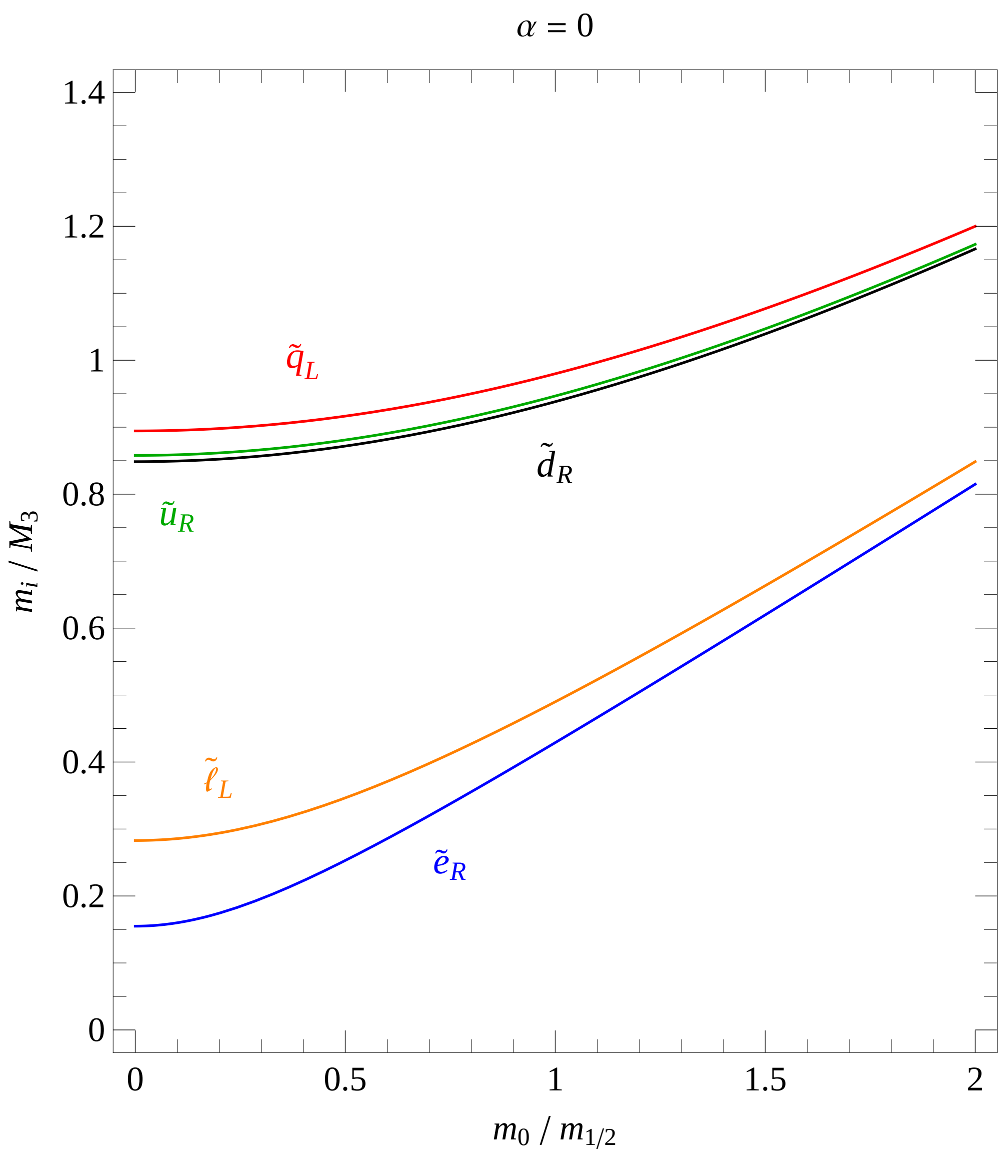
Scalar Masses



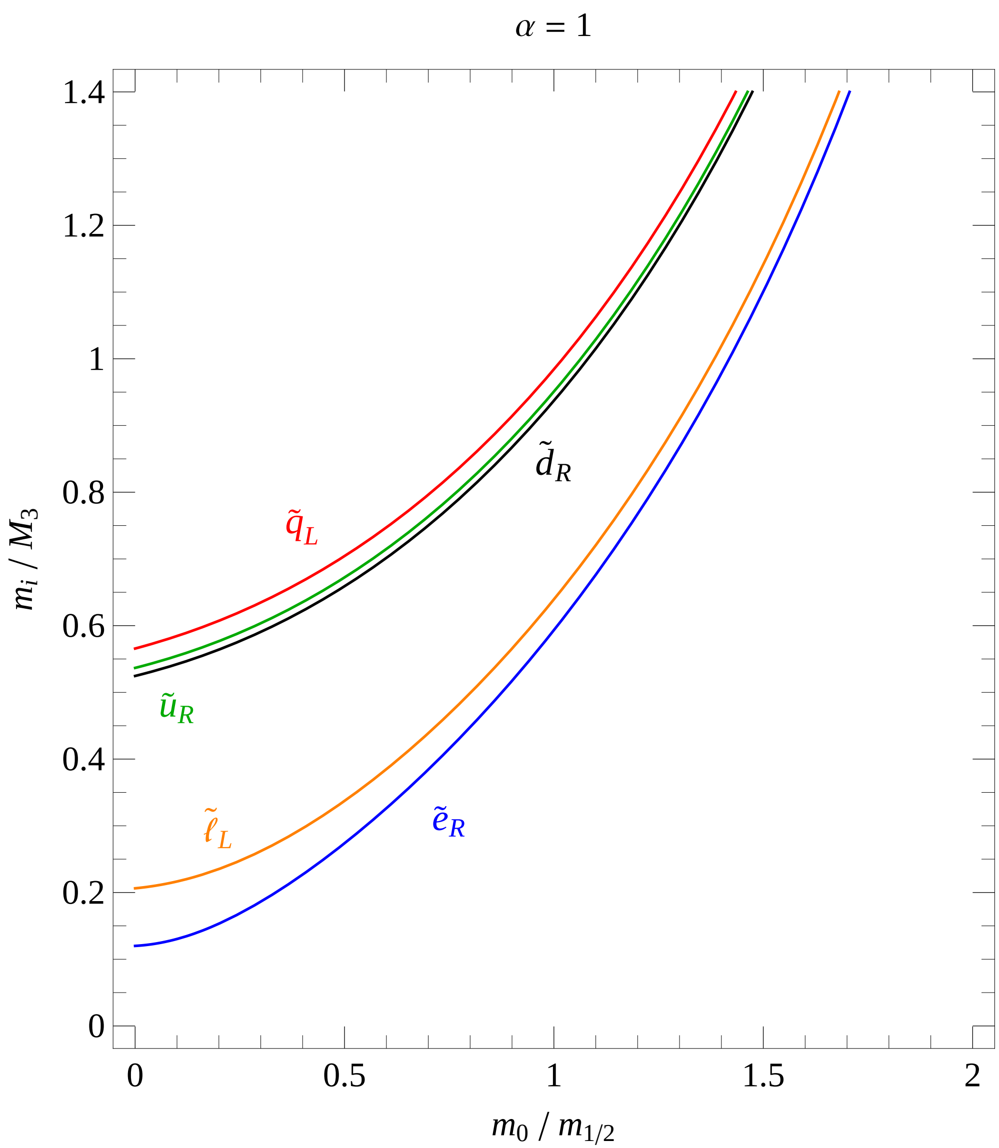
Scalar Masses



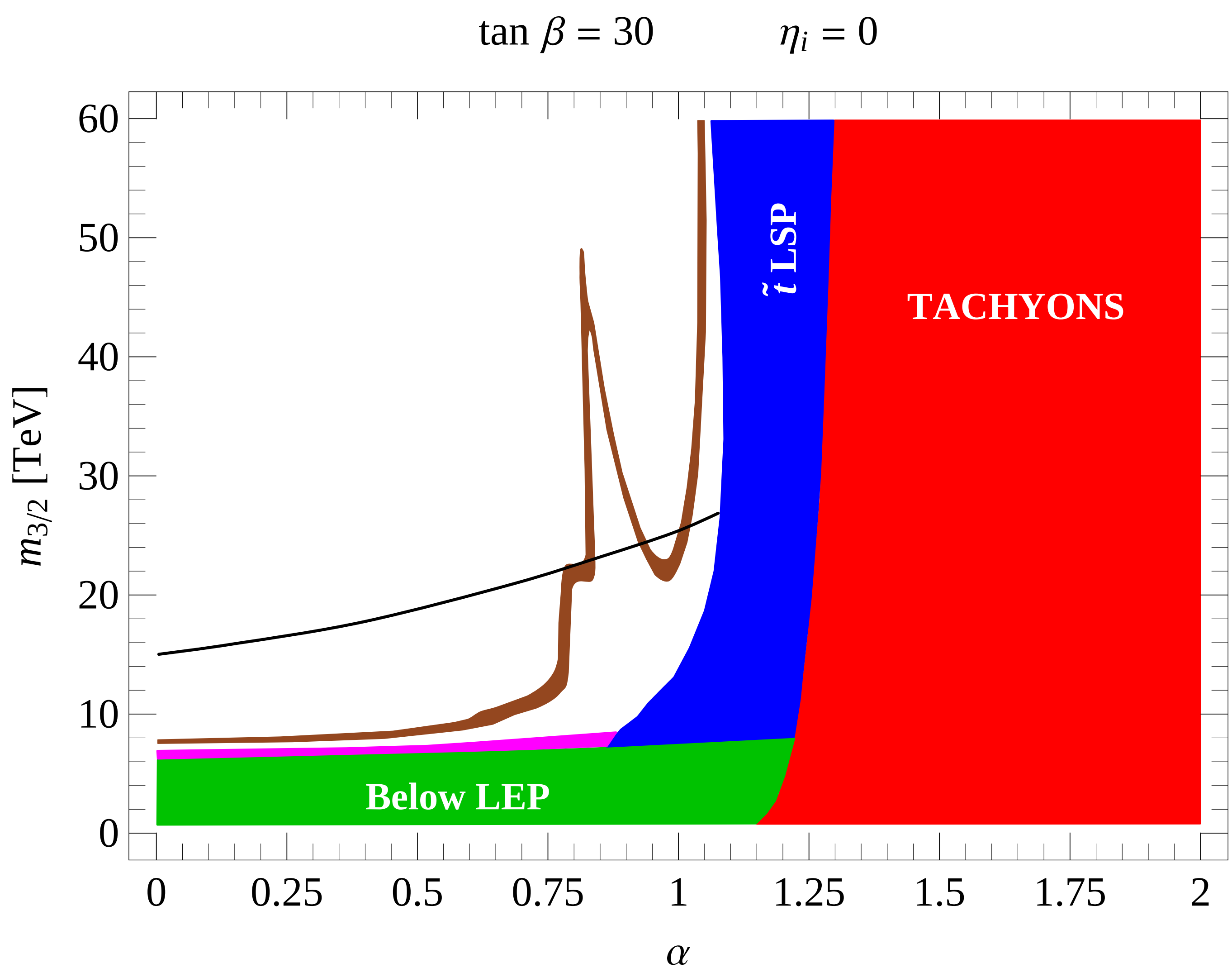
Gravity mediation



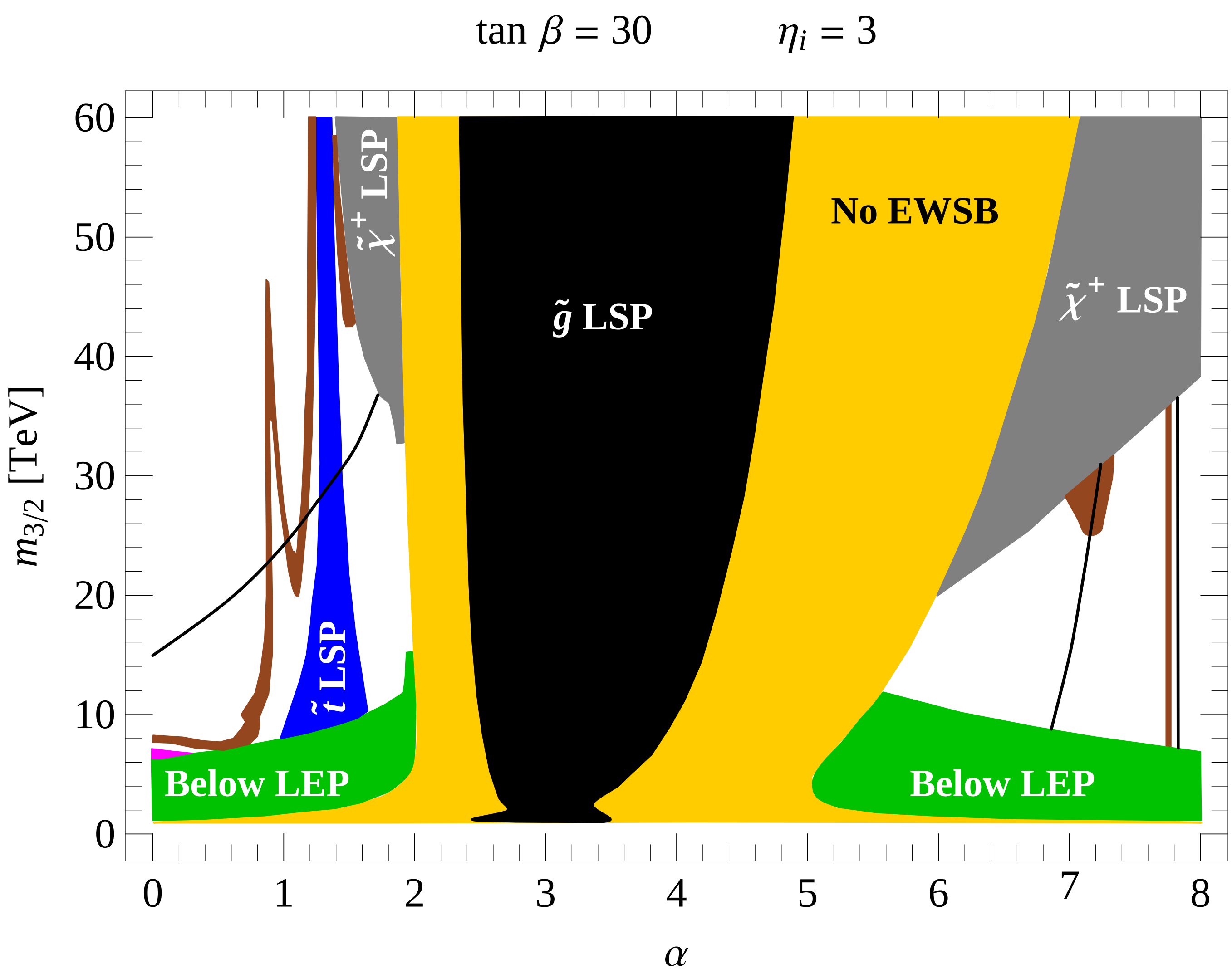
Mirage Mediation



Constraints on α (pure mirage)



Constraints on α (modified mirage)



Uncertainties

String thresholds

$$\tilde{M}_a^{(1)}|_{\text{string}} = \frac{1}{8\pi^2} F^I \partial_I \Omega_a$$

Kähler corrections

$$\tilde{M}_a^{(1)}|_{\text{anomaly}} = \frac{1}{16\pi^2} b_a \frac{F^C}{C} - \frac{1}{8\pi^2} \sum_m C_a^m F^I \partial_I \ln(e^{-K_0/3} Z_m)$$

Intermediate thresholds

$$\tilde{M}_a^{(1)}|_{\text{gauge}} = \frac{1}{8\pi^2} \sum_\Phi C_a^\Phi \frac{F^{X_\Phi}}{M_\Phi}$$

Keep in mind

In the calculation of the soft masses we get the most robust predictions for gaugino masses

- Modulus Mediation: (fWW with $f = f(\mathrm{Moduli})$)

If this is supressed we might have loop contributions, e.g.

- Anomaly Mediation as simplest example

Keep in mind

In the calculation of the soft masses we get the most robust predictions for gaugino masses

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- Anomaly Mediation as simplest example

How much can it be suppressed?

$$\log(m_{3/2}/M_{\mathrm{Planck}})$$

So we might expect

a mixture of tree level and loop contributions.

Conclusion

Gaugino masses can serve as a promising tool for an early test for supersymmetry at the LHC

- Rather robust predictions
- 3 basic and simple patterns (Sugra, anomaly, mirage)
- Mirage pattern rather generic

With some luck we might find such a simple scheme at the LHC and measure the ratio $G = M_{\text{gluino}}/m_{\chi_1^0}$!

Let us hope for a bright future of SUSY at the LHC.