Crosschecks for Unification at the LHC

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- Do present observations give us hints for a grand unification of gauge interactions?
- Can LHC confirm this picture and, if yes, how?

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Outline:

- GUTs: the good things and the problems
- Simple schemes for SUSY breakdown
- Gaugino masses
- Disentangling the schemes (with a bit of luck)

The Standard Model

What do we have?

- gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
- scalar Higgs doublet

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But there might be more:

- supersymmetry (SM extended to MSSM)
- neutrino masses and mixings

as a hint for a large mass scale around 10^{16} GeV

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Experimental findings suggest the existence of two new scales of physics beyond the standard model

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- Neutrino-oscillations and "See-Saw Mechanism"

  $m_\nu \sim M_W^2/M_{\mathrm{GUT}}$

  $m_\nu \sim 10^{-3}\mathrm{eV}$ for $M_W \sim 100\mathrm{GeV}$,

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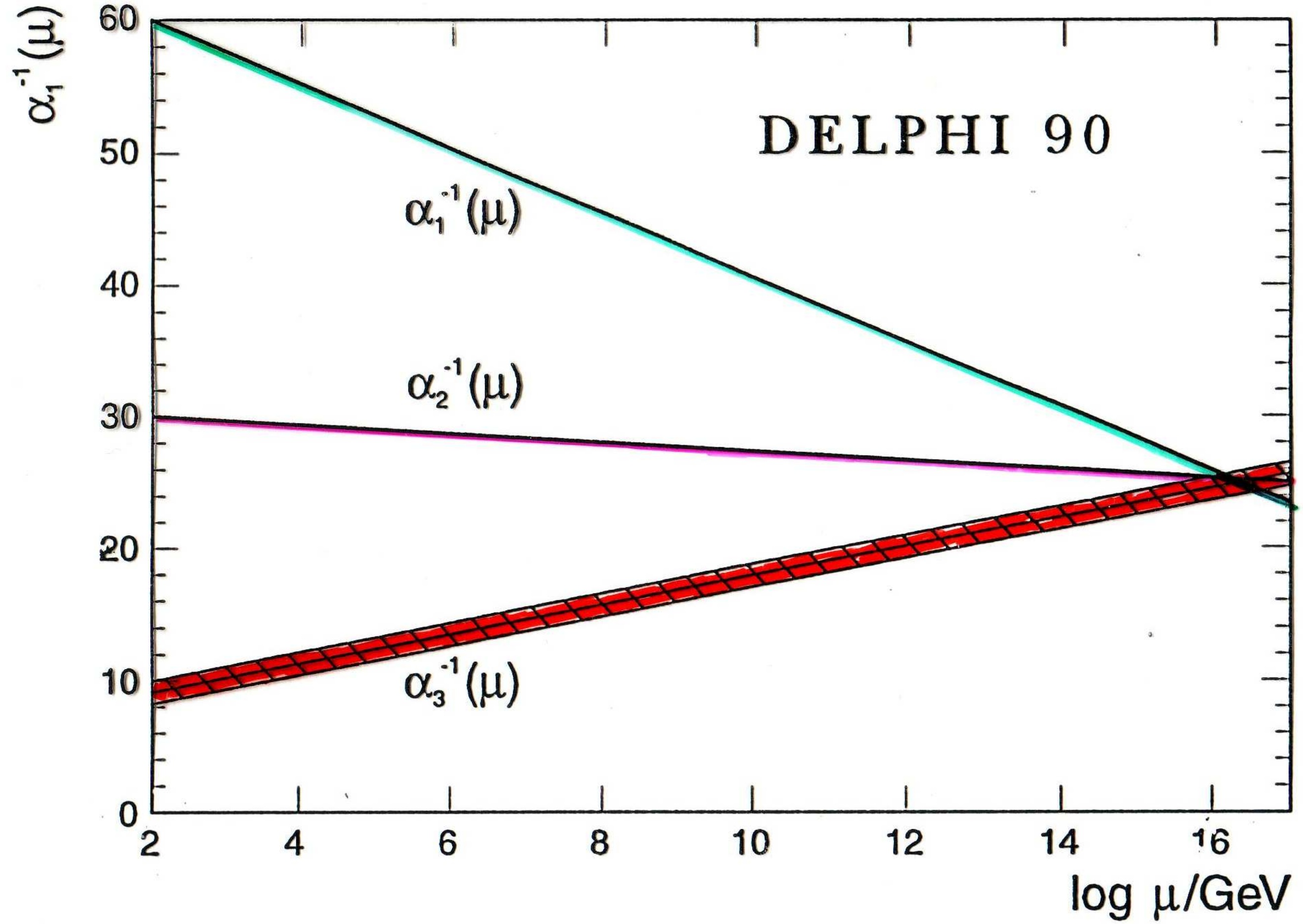
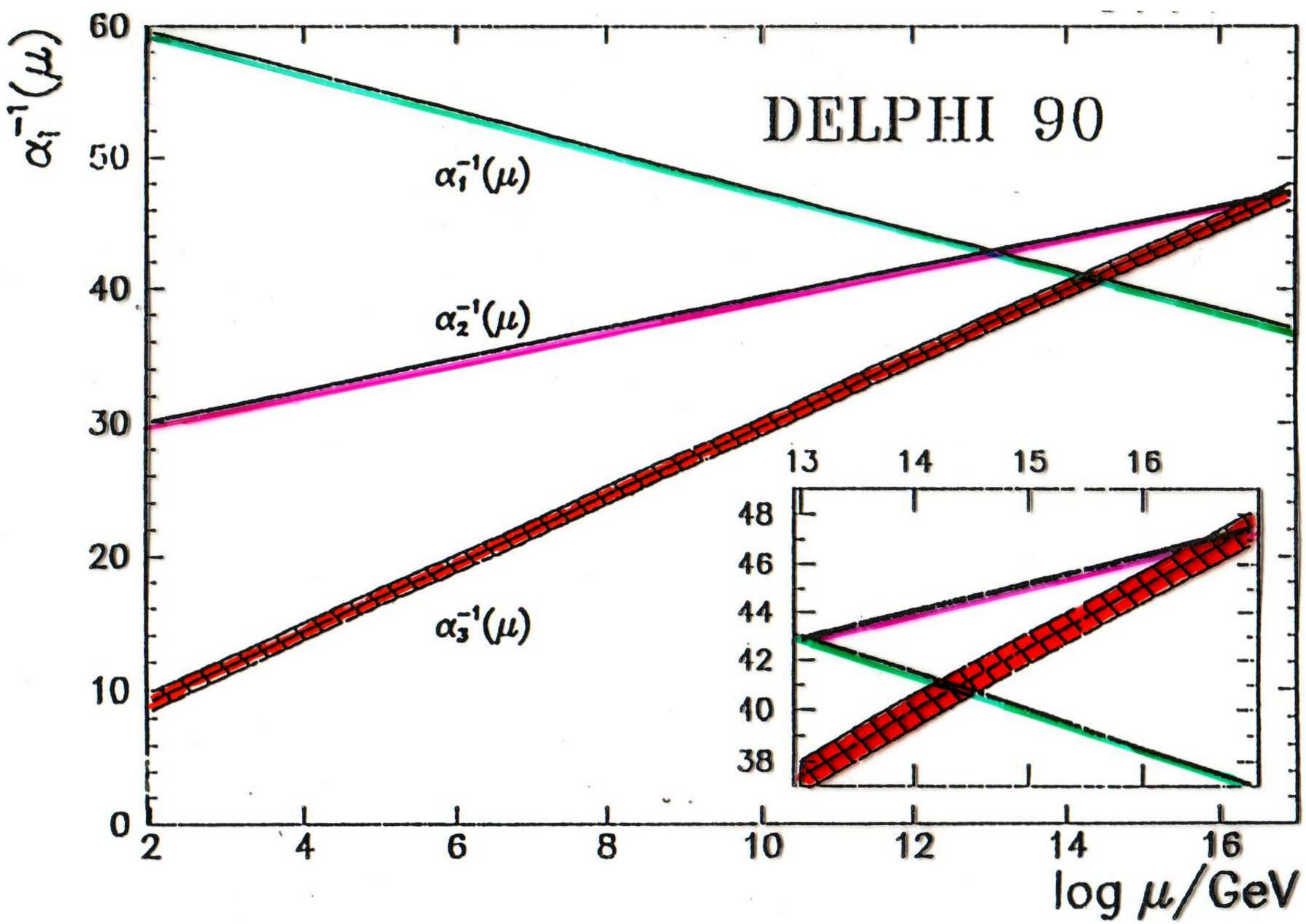
  $m_\nu \sim 10^{-3}\mathrm{eV}$ for $M_W \sim 100\mathrm{GeV}$,

- Evolution of couplings constants of the standard model towards higher energies.

MSSM (supersymmetric)



Standard Model



Grand Unification

This leads to SUSY-GUTs with nice things like

- unified multiplets (e.g. spinors of SO(10))
- gauge coupling unification
- Yukawa unification
- neutrino see-saw mechanism

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Working hypotheses:

- GUTs seem to require SUSY (MSSM)
- there is a desert between the weak scale and the GUT scale

SUSY breakdown

Much discussed mediation schemes:

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

SUSY breakdown

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

Grand unification would require absence of intermediate scales

- gauge mediation problematic for GUT schemes
- simplicity favours gravity and/or anomaly pattern
- controllable schemes (from low energy parameters)

Gravity Mediation

Simplest scheme is gravity mediation

- MSSM as observable sector,
- hidden sector breaks SUSY spontaneously
- gravitational interactions as messenger. (HPN, 1982)

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Soft breaking terms can be computed explicitely

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

(Arnowitt, Chamseddine, Nath, 1982; Barbieri, Ferrara, Savoy, 1982; HPN, Srednicki, Wyler, 1982; Hall, Lykken, Weinberg, 1982)

Controllable 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)

  (Randall, Sundrum, 1999)

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

(Kachru, Kallosh, Linde, Trevidi, 2003; Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)

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

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

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 Mediation

Mirage Mediation provides a

- characteristic pattern of soft breaking terms.

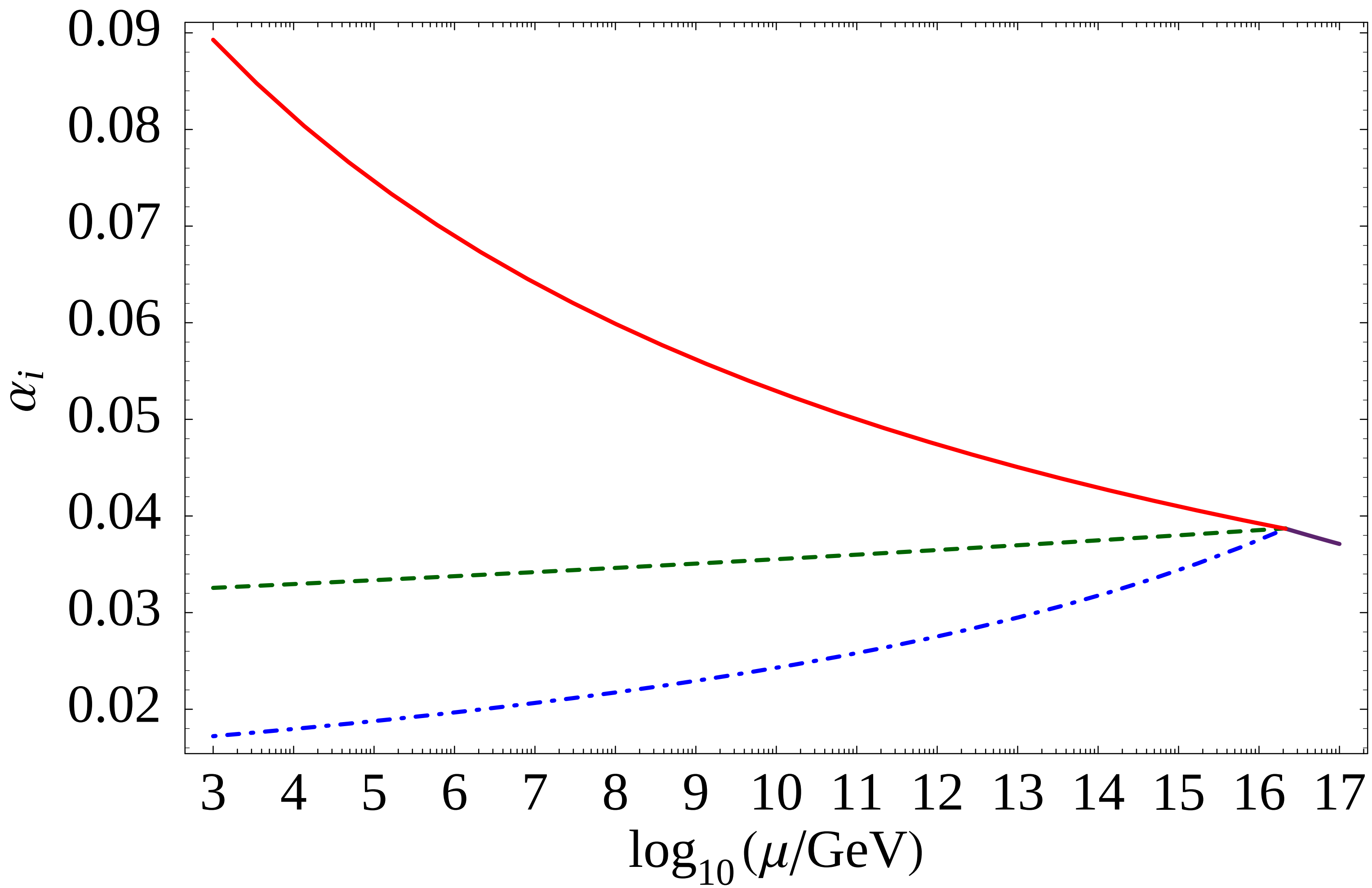
To see this, let us consider the gaugino masses

$$M_{1/2} = M_{\mathrm{modulus}} + M_{\mathrm{anomaly}} = \frac{m_m + \alpha m_a}{\sqrt{(1+\alpha^2)}}$$

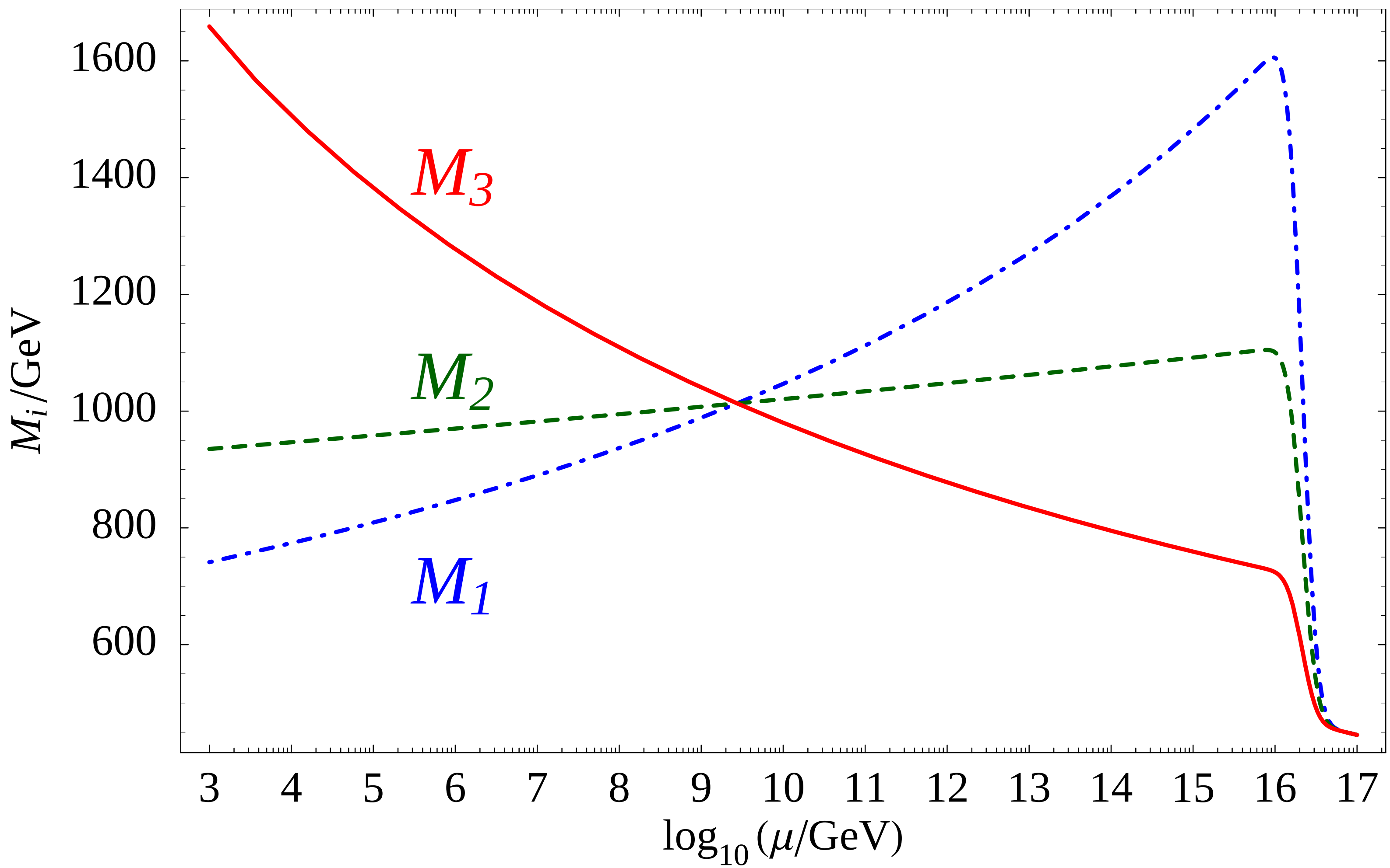
as a sum of two contributions of comparable size.

- 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 “MSSM hierarchy problem”

The scheme predicts a rather high mass scale

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One might worry about a fine-tuning to obtain

- the mass of the weak scale around 100 GeV from

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

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

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

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Mirage mediation improves the situation

- especially for large α
- 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

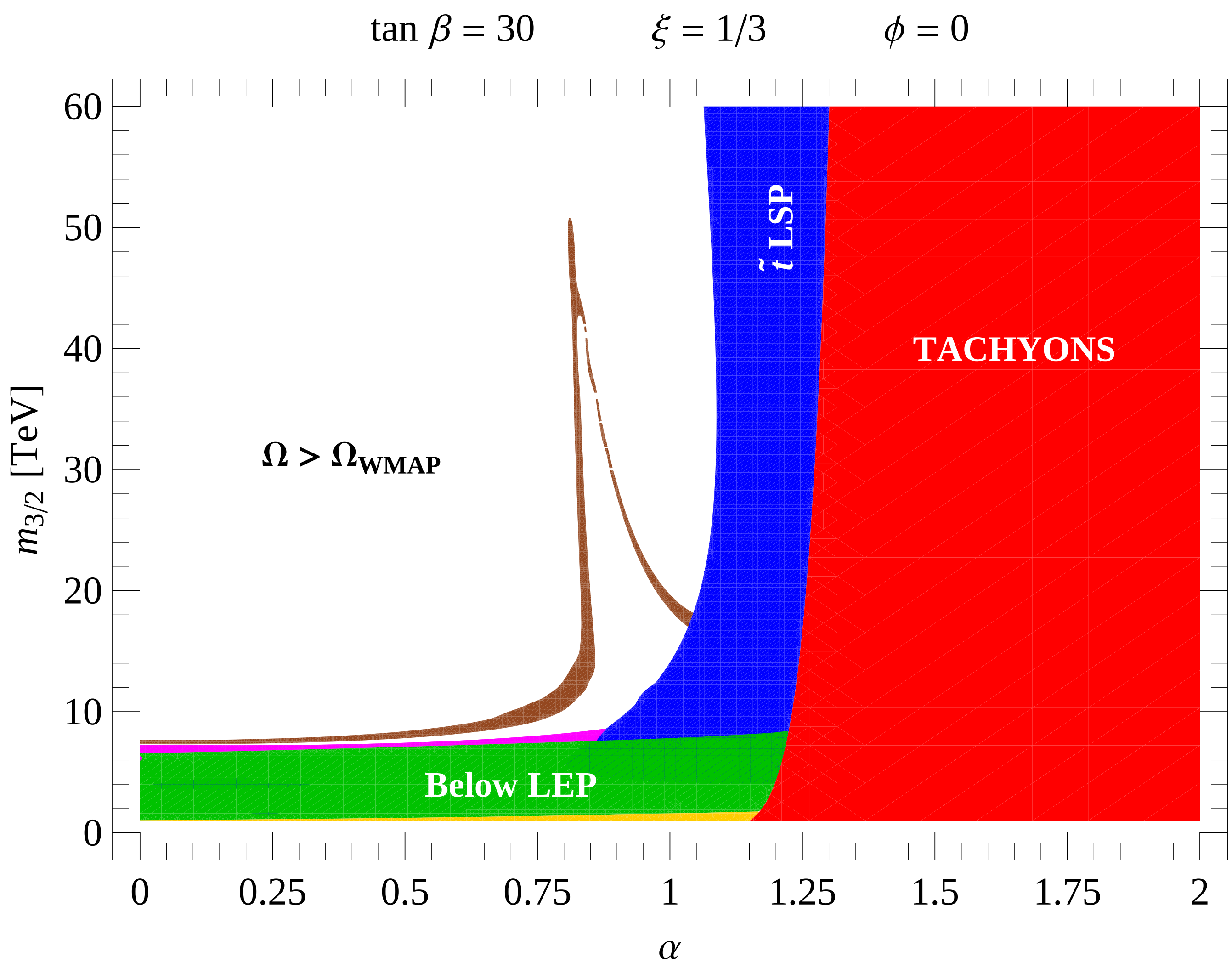
The different schemes depend on the mechanism of uplifting:

- uplifting with anti D3 branes

  (Kachru, Kallosh, Linde, Trivedi, 2003)

  - $\alpha = 1$ 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 α



Explicit schemes II

- uplifting via matter superpotentials

  (Lebedev, HPN, Ratz, 2006)

  - allows a continuous variation of α
  - leads to potentially new contributions to sfermion masses

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- uplifting via matter superpotentials

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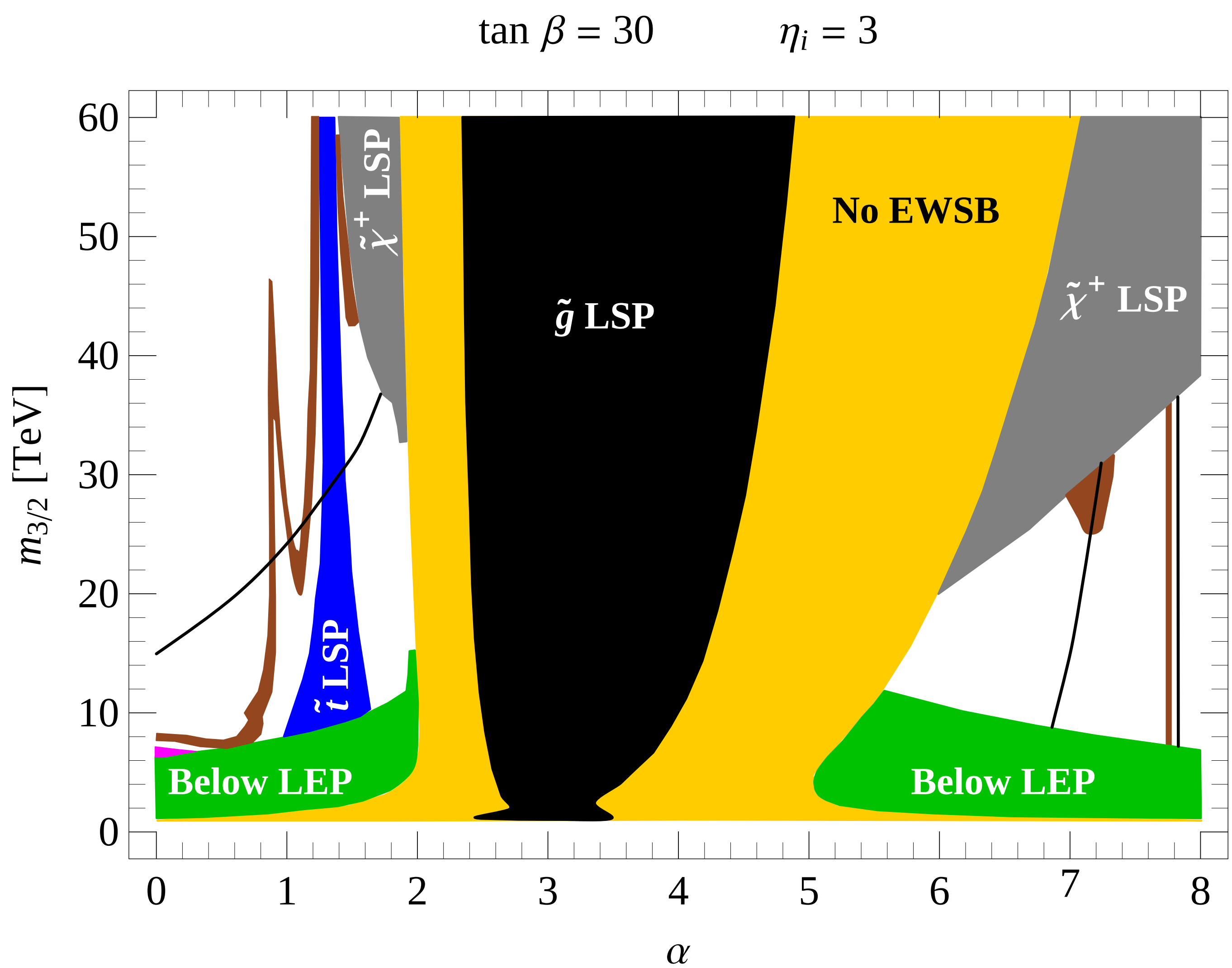
  - allows a continuous variation of α
  - leads to potentially new contributions to sfermion masses

- gaugino masses still meet at a mirage scale

- soft scalar masses might be dominated by modulus mediation

- similar constraints on the mixing parameter

Constraints on α (modified mirage)



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)
- although “pure” mirage mediation is possible as well

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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

LHC-Tests of Unification

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

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

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

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

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

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

FEW CHARACTERISTIC MASS PATTERNS

(Choi, HPN, 2007)

Controllable schemes

Assumptions to be made

- particle content of MSSM up to the GUT scale
- no intermediate thresholds
- controllable boundary conditions at the GUT scale

This implies that soft terms are determined by the parameters of the low energy effective theories such as

- particle content
- β-functions

In this case we can hope to obtain meaningful crosschecks for unification.

(Löwen, HPN, 2009)

Gravity Mediation

Universal gaugino mass at the GUT scale

- mSUGRA 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 dilaton-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 Mediation

Gaugino masses below the GUT scale are 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
- $G = M_{\mathrm{gluino}}/m_{\chi_1^0} \simeq 9$

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 α: the ratio of modulus to anomaly mediation.

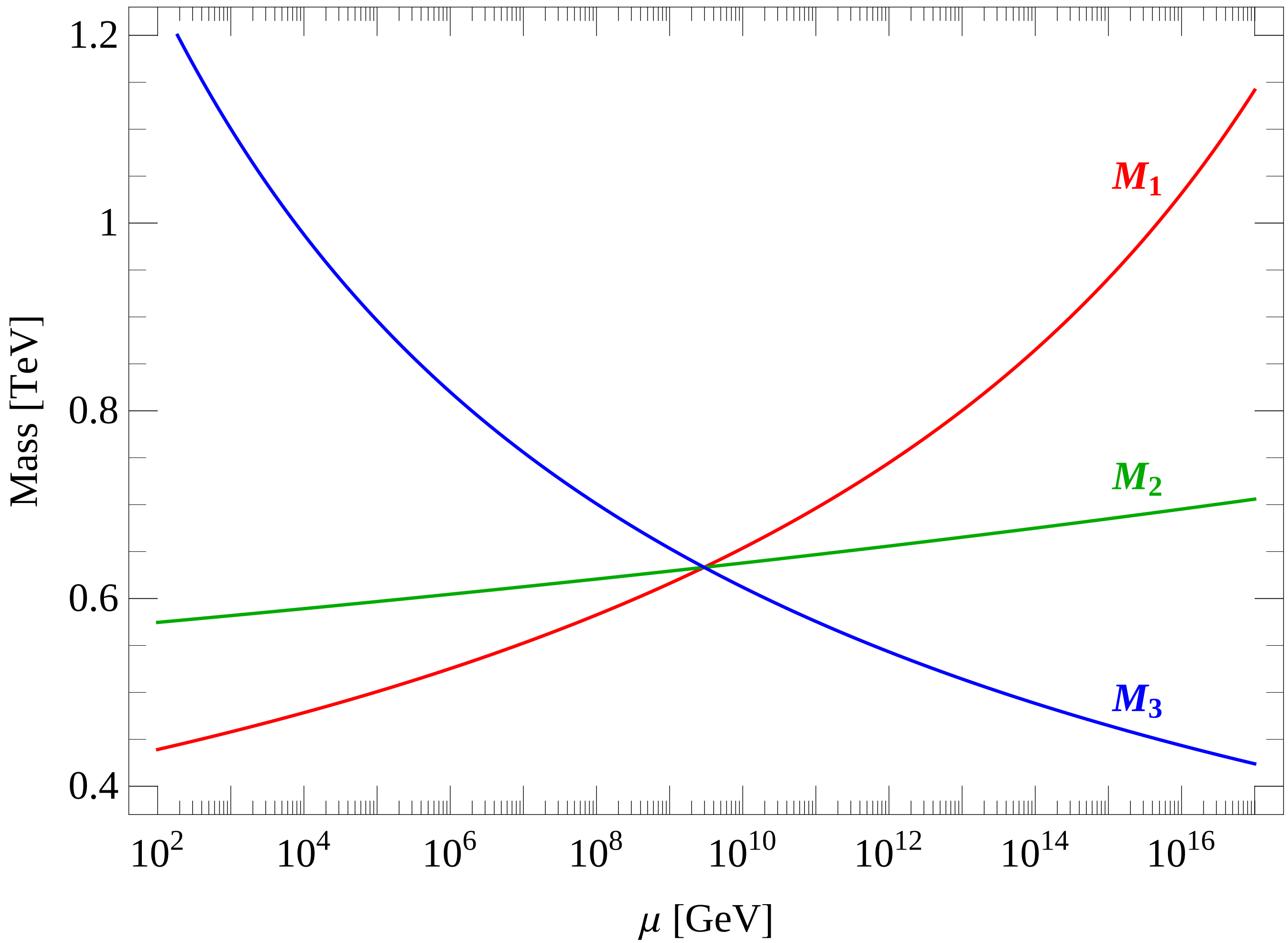
- $M_1 : M_2 : M_3 \simeq \ 1 : 1.3 : 2.5$ for $\alpha \simeq 1$
- $M_1 : M_2 : M_3 \simeq \ 1 : 1 : 1$ for $\alpha \simeq 2$

The mirage scheme leads to

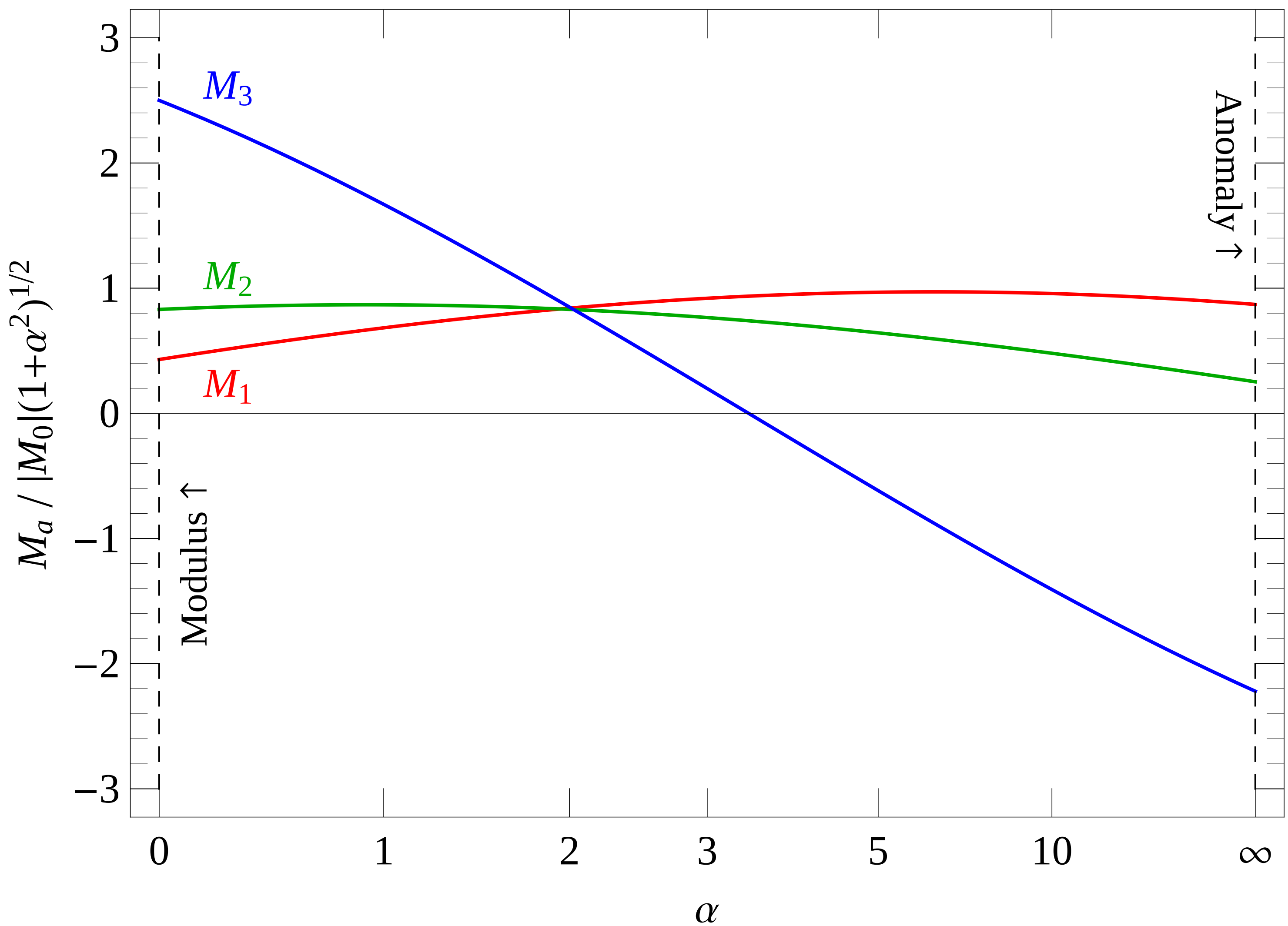
- LSP χ_1^0 predominantly Bino
- $G = M_{\rm gluino}/m_{\chi_1^0} < 6$
- a “compact” gaugino mass pattern.

Mirage Scale

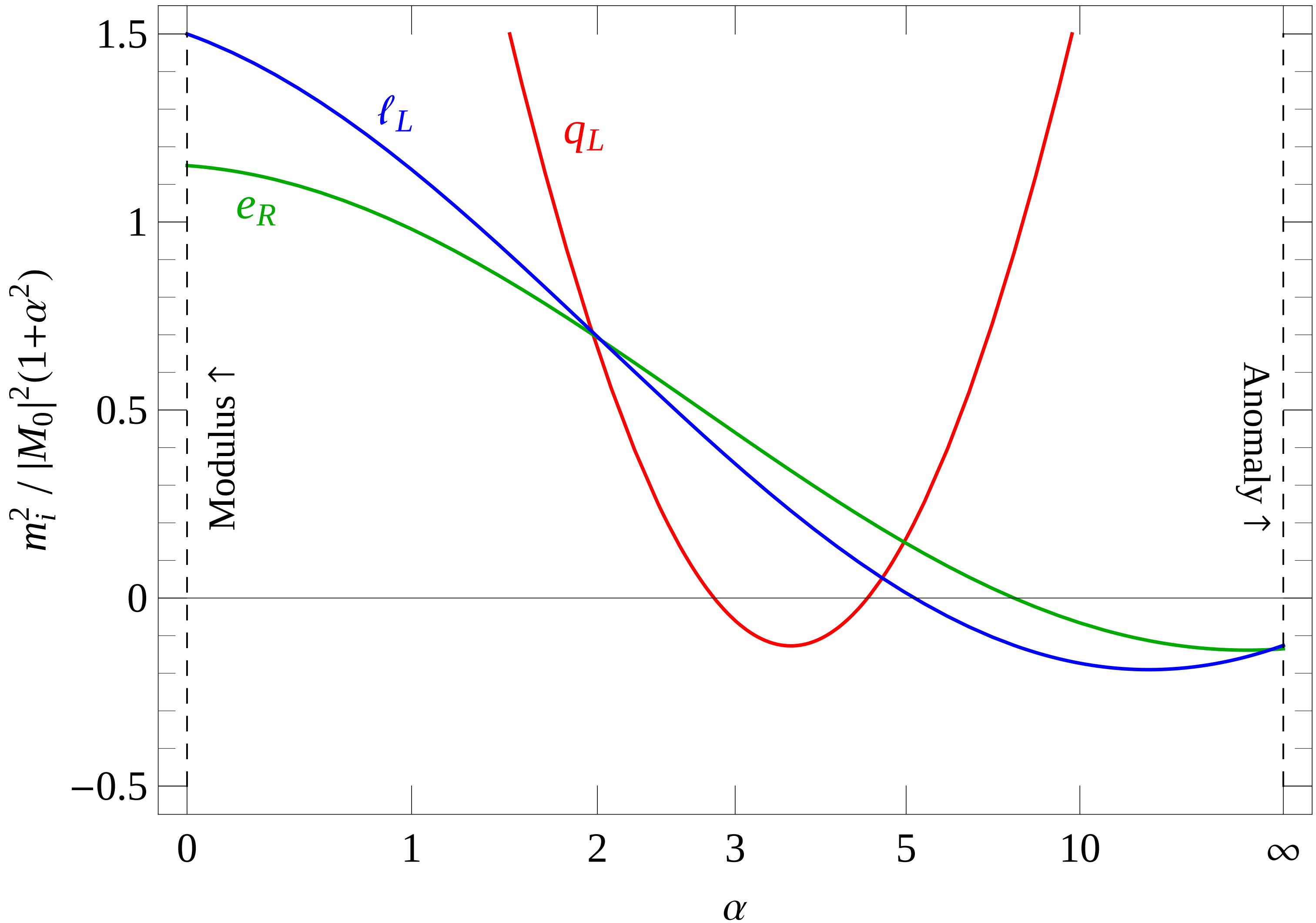
$\alpha = 1$ $m_{3/2} = 20$ TeV $\phi = 0$



Gaugino Masses



Scalar Masses



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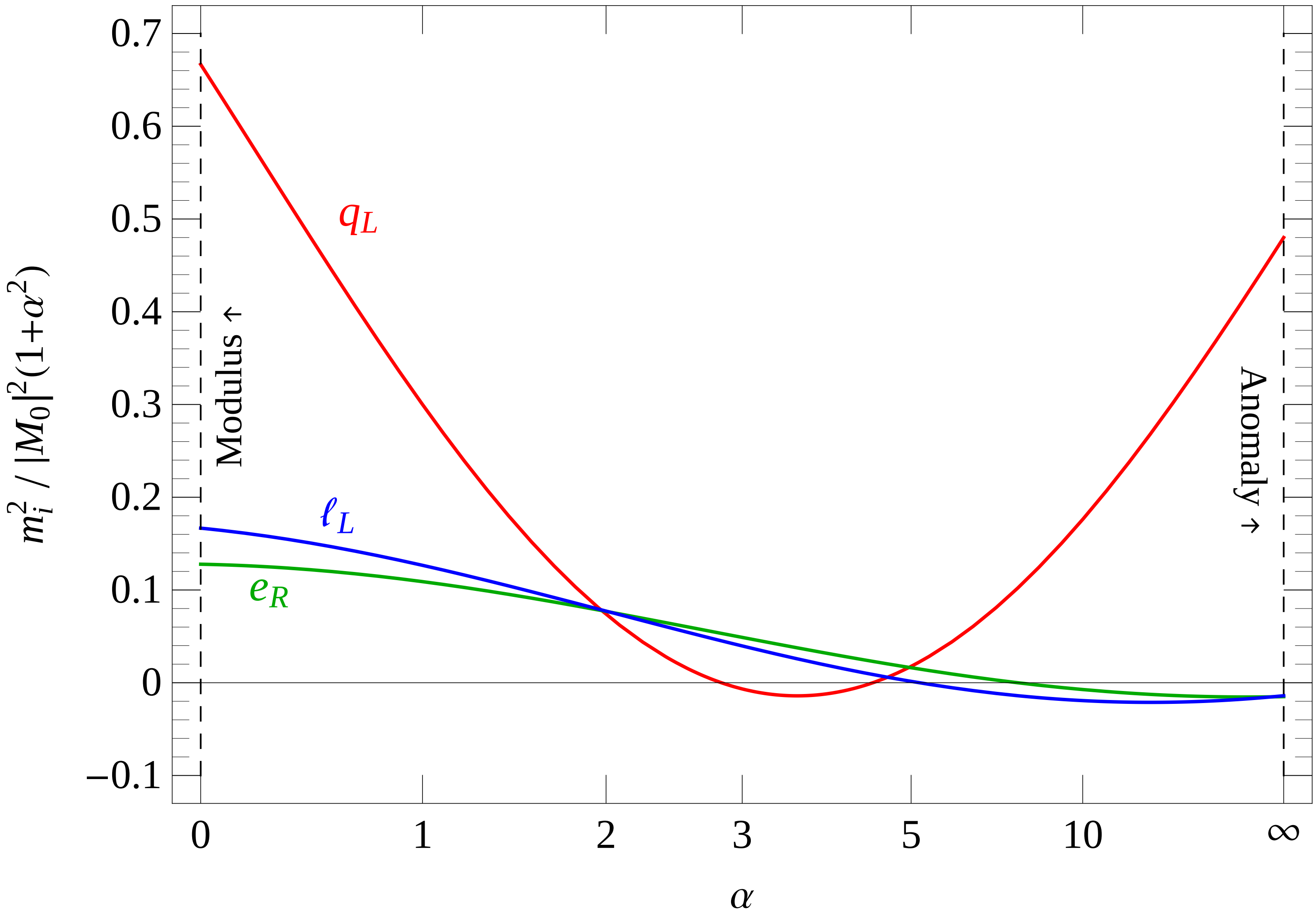
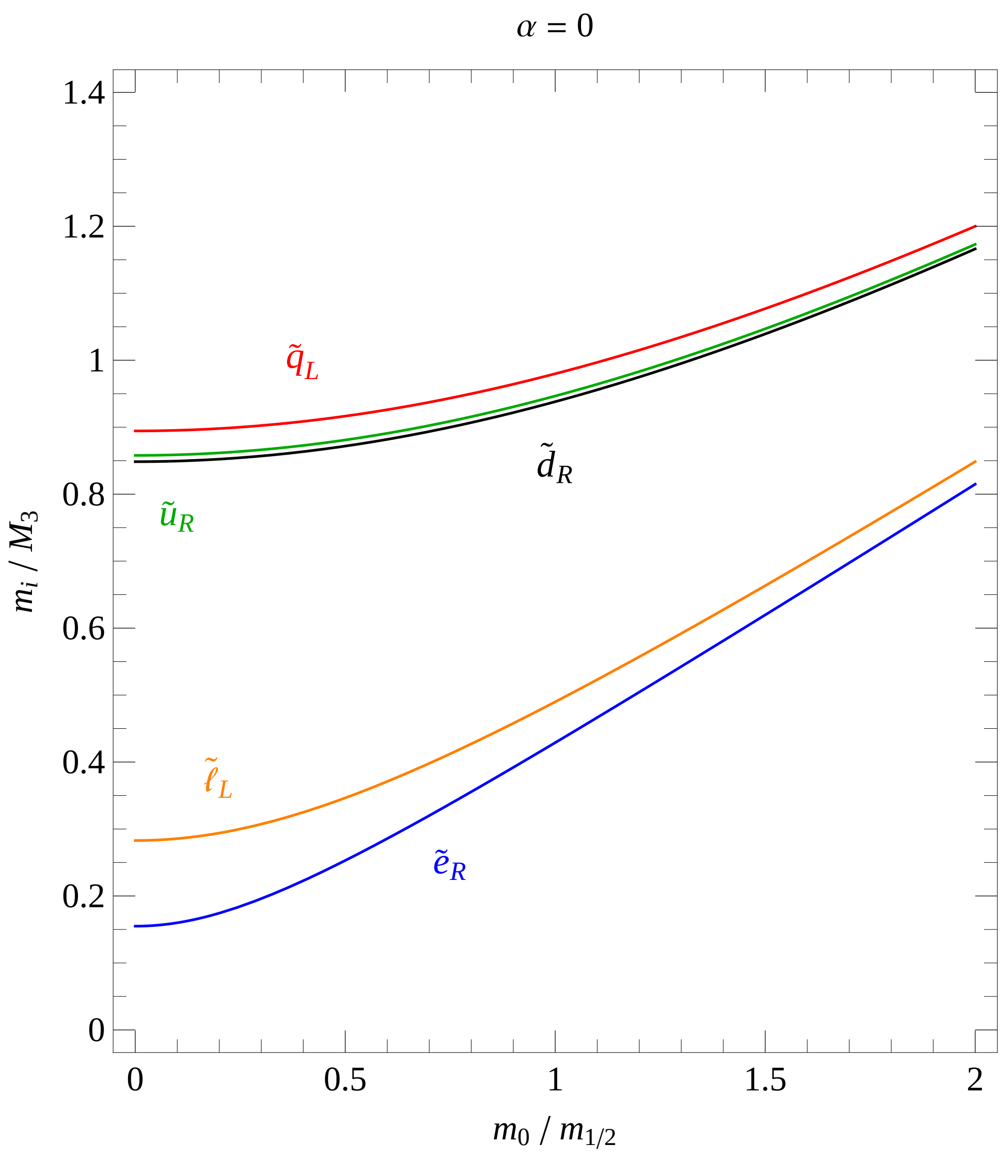
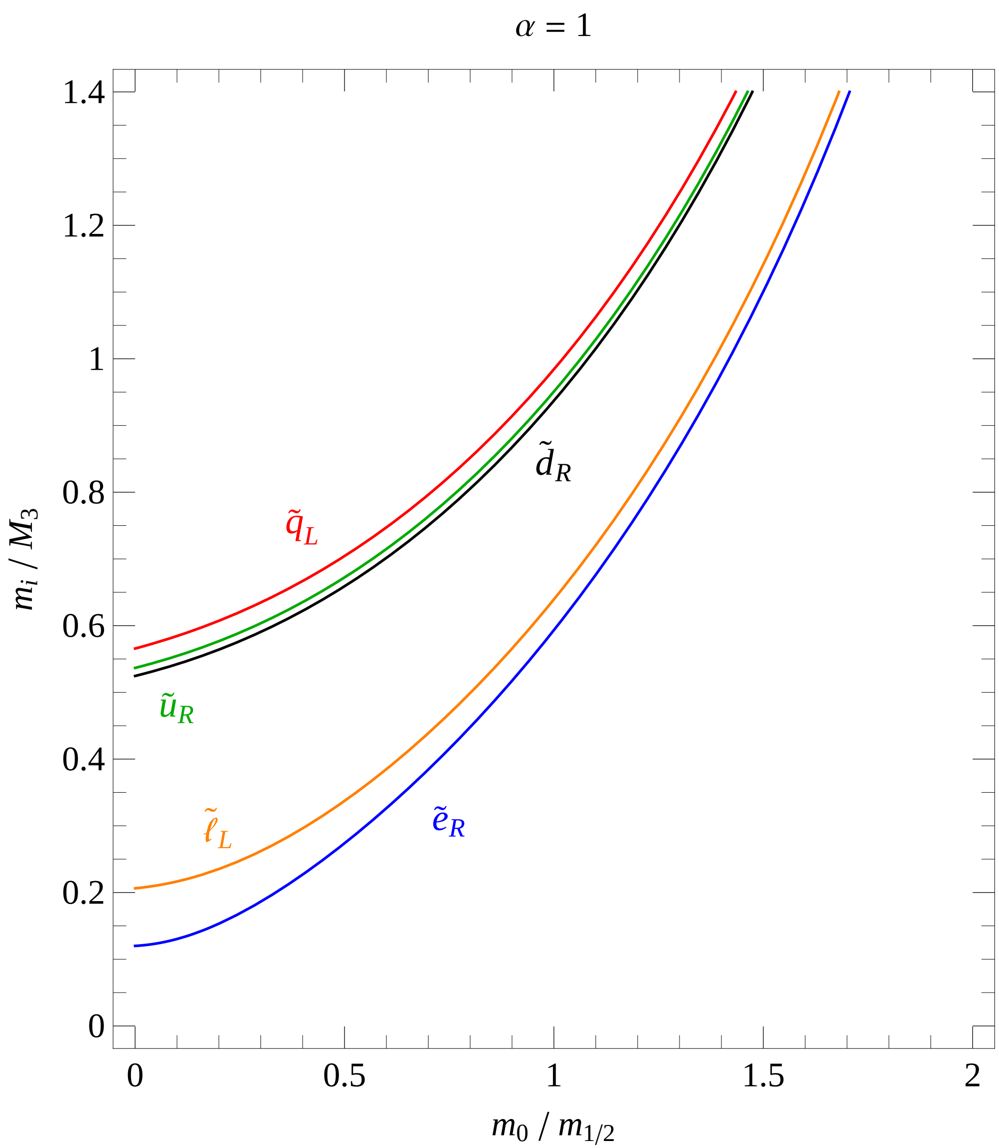


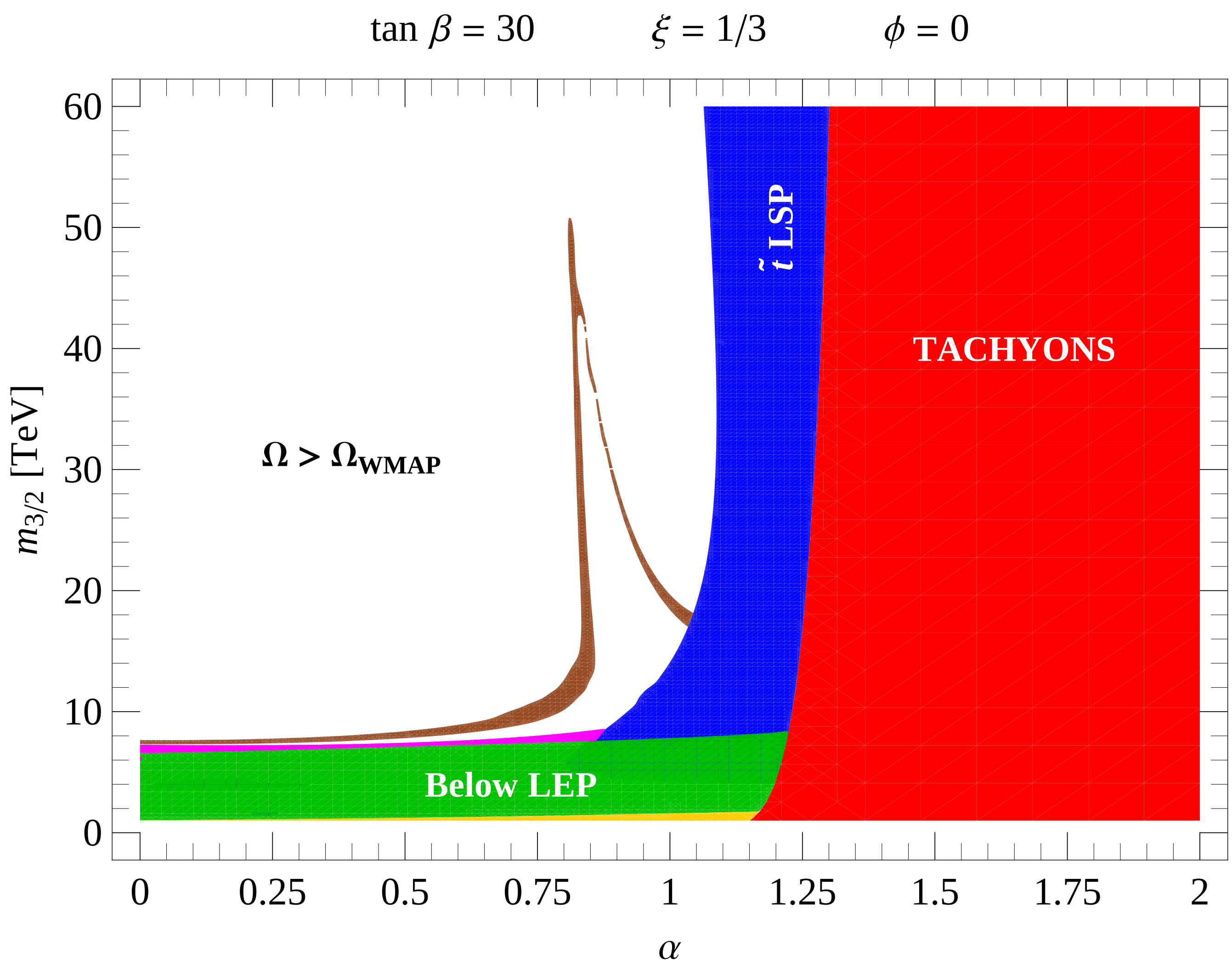
Gravity mediation



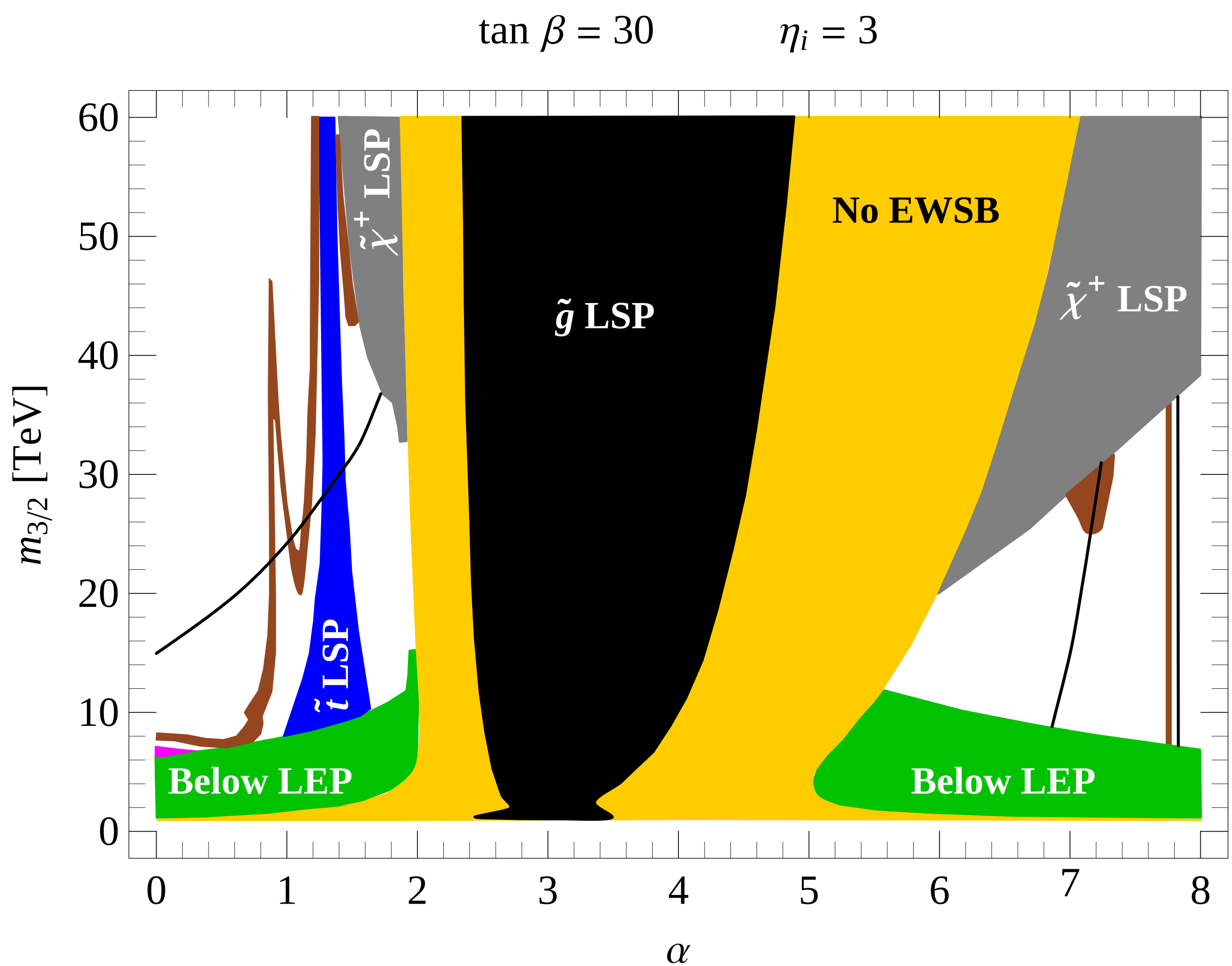
Mirage Mediation



Constraints on α



Constraints on α (modified mirage)



Uncertainties

Ultraviolet thresholds

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

Kähler corrections

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

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

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.

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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 prediction and simple patterns
- Mirage pattern rather generic

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

Identification of a grand unified scheme could be backed up with the determination of soft scalar mass terms and this might provide a crosscheck for unification.

(Löwen, HPN, 2009)