Crosschecks for Grand Unification at the LHC

Hans Peter Nilles

Physikalisches Institut

Universität Bonn

Questions

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

Questions

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

Outline

- GUTs: the good things and the problems
- Simple SUSY breakdown schemes
- simple boundary conditions
- 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

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

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

Indirect evidence

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

$M_{\rm GUT} \sim 10^{16}{\rm GeV}$ and $M_{\rm SUSY} \sim 10^{3}{\rm GeV}$:

Indirect evidence

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

$M_{\rm GUT} \sim 10^{16}{\rm GeV}$ and $M_{\rm SUSY} \sim 10^{3}{\rm GeV}$:

- Neutrino-oscillations and "See-Saw Mechanism"

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

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

Indirect evidence

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

$M_{\mathrm{GUT}} \sim 10^{16}\mathrm{GeV}$ and $M_{\mathrm{SUSY}} \sim 10^{3}\mathrm{GeV}$:

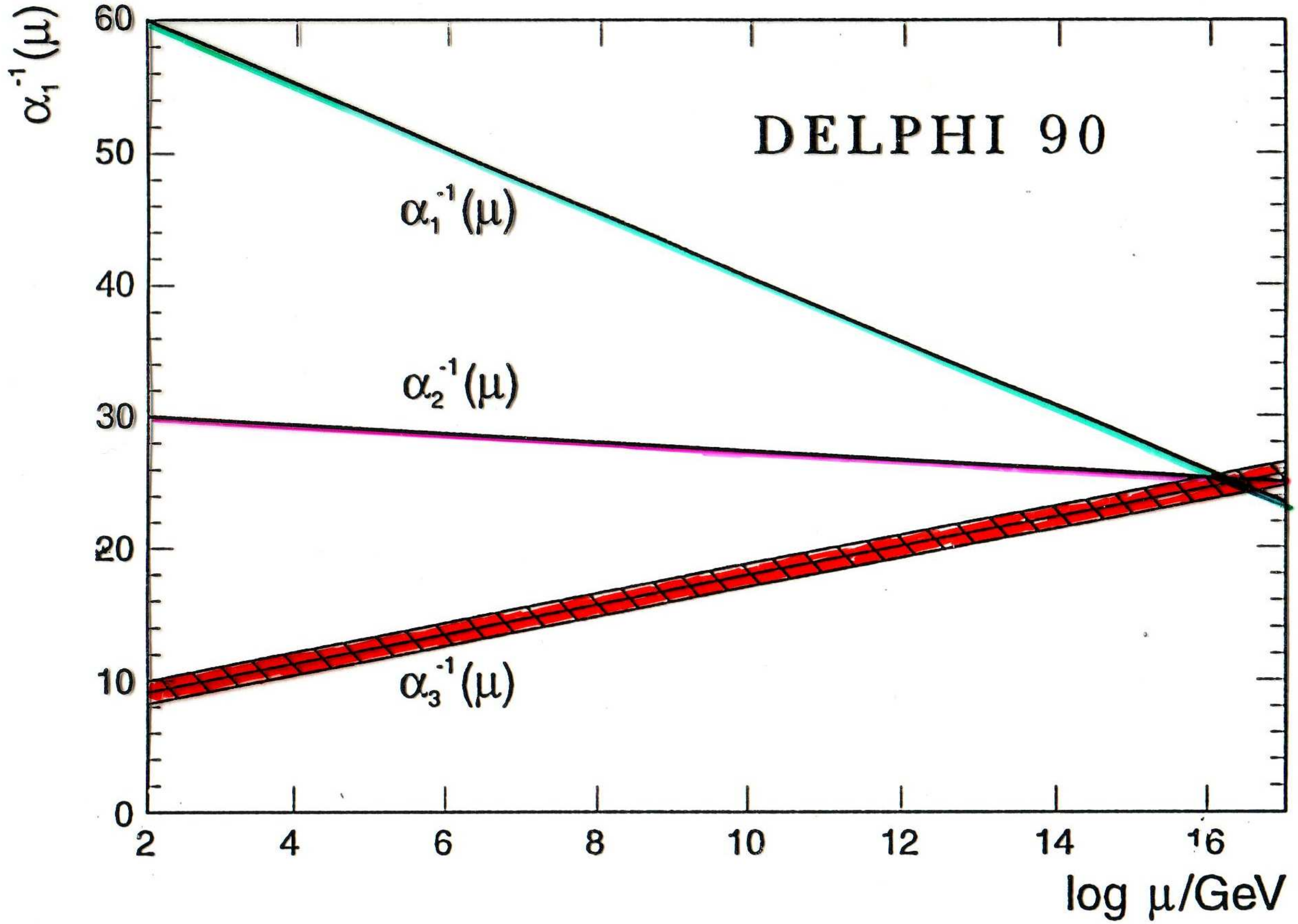
- Neutrino-oscillations and "See-Saw Mechanism"

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

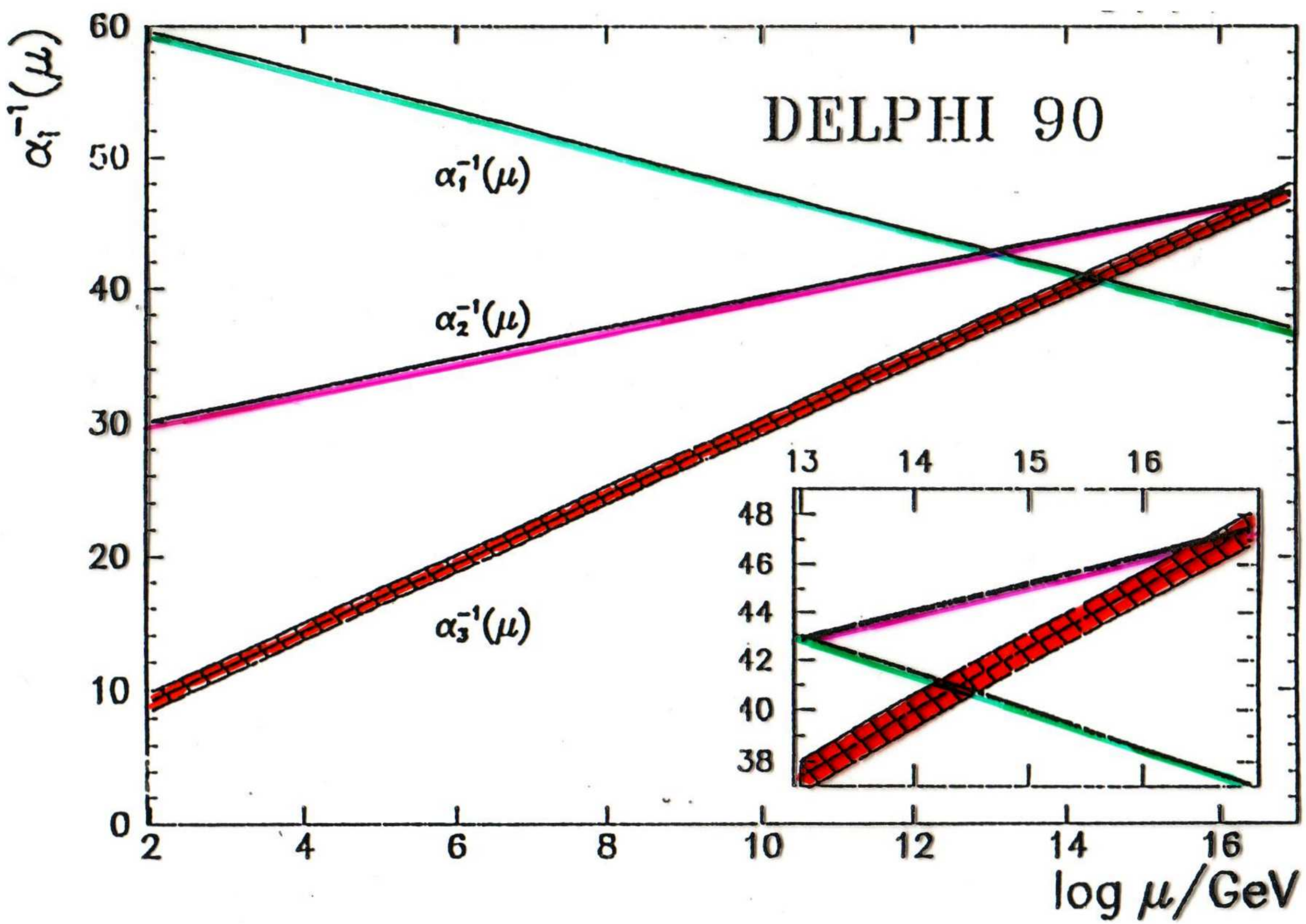
  $m_\nu \sim 10^{-3}\mathrm{eV}$ for $M_W \sim 100\mathrm{GeV}$,

- 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

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

Working hypotheses:

- GUTs seem to require SUSY (MSSM)
- the desert between the weak scale and the GUT scale is assumed to be empty or transparent

GUT is more than that

We have to worry about

- doublet-triplet splitting
- μ problem
- proton stability (discrete symmetries).

GUT is more than that

We have to worry about

- doublet-triplet splitting
- μ problem
- proton stability (discrete symmetries).

Supersymmetry breakdown and soft masses

- gaugino masses
- scalar masses, A- and B-terms
- gravitino mass and its relation to the μ-term

SUSY breakdown

Much discussed mediation schemes:

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

SUSY breakdown

Much discussed mediation schemes:

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

Tests for GUTs require

- simple schemes
- simple boundary conditions at GUT scale
- "transparency" of desert
- schemes controlled by low energy parameters

How to proceed

We need new physics from LHC

- establish SUSY
- assume simple boundary conditions at the GUT scale
- consider soft terms with robust prediction
- be lucky (the hope for a controllable scheme)

How to proceed

We need new physics from LHC

- establish SUSY
- assume simple boundary conditions at the GUT scale
- consider soft terms with robust prediction
- be lucky (the hope for a controllable scheme)

We need an *a priori* definition for a test of Grand Unification in a given scheme

- you have to place your bet now
- even simple schemes might not allow a test of grand unification

Gravity Mediation

A simple scheme is gravity mediation. We consider

- universal boundary conditions at GUT scale
- soft terms closely linked to the size of the gravitino mass
- robust prediction for gaugino masses

Gravity Mediation

A simple scheme is gravity mediation. We consider

- universal boundary conditions at GUT scale
- soft terms closely linked to the size of the gravitino mass
- robust prediction for gaugino masses

In some cases soft terms are universal but supressed (or even zero) at tree level

- radiative corrections become important
- soft terms small compared to gravitino mass
- is there an upper limit for the gravitino mass?

Controllable Schemes

Soft terms determined through known parameters of the low energy theory

- evolution of soft terms is determined by spectrum and β-function of low energy theory
- radiative corrections could be determined by low-energy parameters (e.g. anomaly mediation)

Controllable Schemes

Soft terms determined through known parameters of the low energy theory

- evolution of soft terms is determined by spectrum and β-function of low energy theory
- radiative corrections could be determined by low-energy parameters (e.g. anomaly mediation)

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)

Mixed Mediation Schemes

Readadjustment of the vacuum has influence on the soft terms, e.g. in flux compactification,

where we have (from flux and gaugino condensate)

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

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

Mixed Mediation Schemes

Readjustment of the vacuum has influence on the soft terms, e.g. in flux compactification,

where we have (from flux and gaugino condensate)

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

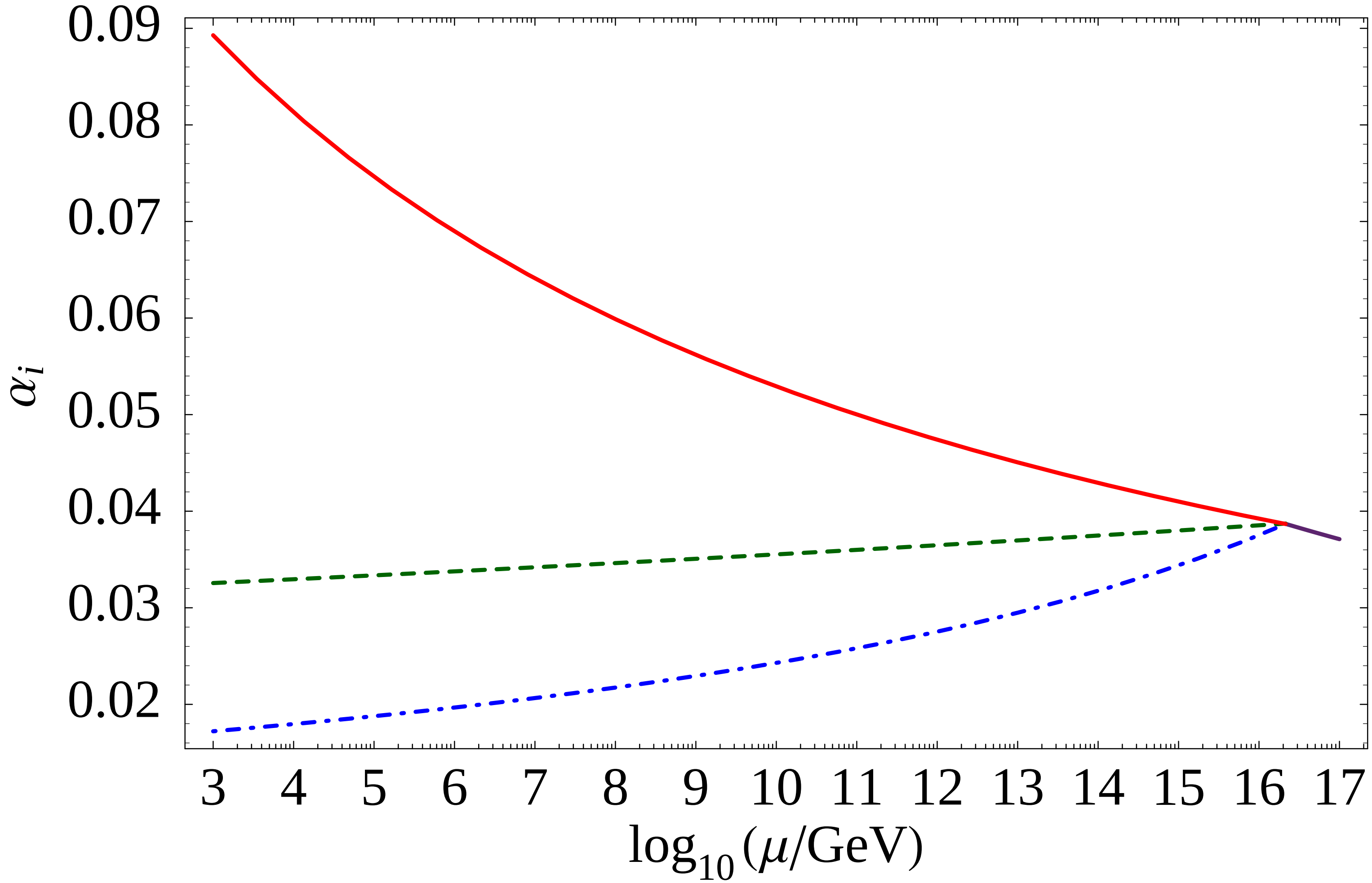
where "something" is small and X is moderately large.

In this scheme

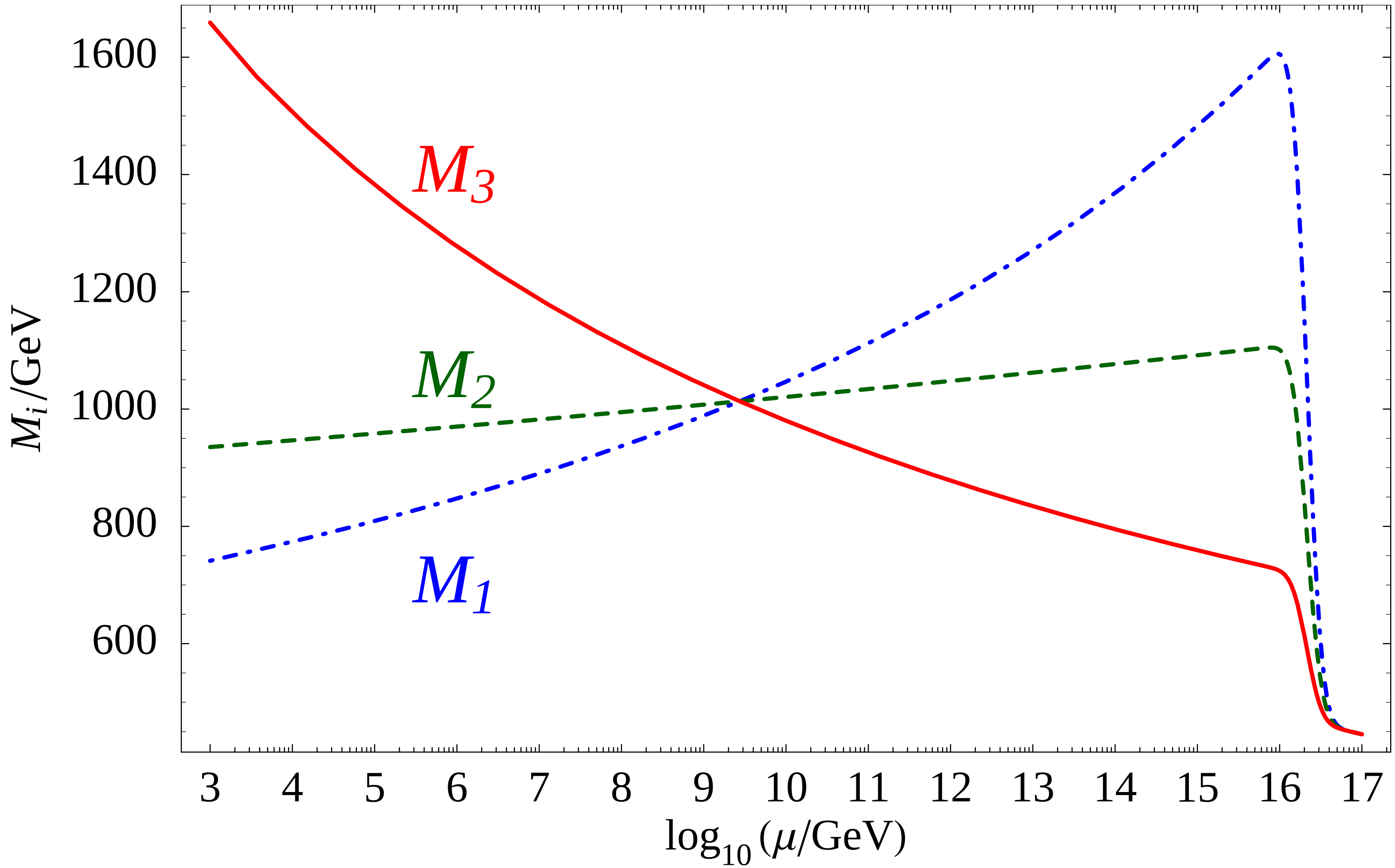
$$X \sim \log(M_{\text{Planck}}/m_{3/2}) \sim 4\pi^2$$

suppresses the contribution from gravity mediation and radiative corrections become competitive (with mirage mediation as the simplest scheme).

Evolution of couplings



The Mirage Scale



(Lebedev, HPN, Ratz, 2005)

Tests at 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

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

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

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

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

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)

SUGRA Pattern

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 gaugino-mediation

This leads to

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

as a characteristic signature of these schemes.

Loop Mediation

If the tree level masses vanish we have contributions from radiative corrections

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

Which can be written as a sum

$$\tilde{M}_a^{(1)}|_{\rm loop} = \tilde{M}_a^{(1)}|_{\rm anomaly} + \tilde{M}_a^{(1)}|_{\rm Kähler}$$

- where the first term is proportional to $b_a = (33/5, 1, -3)$
- and the second to $b'_a = (33/5, 5, 3)$.

Anomaly Pattern

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

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

Kähler Pattern

Gaugino masses below the GUT scale determined by the β' functions

- Kähler pattern:

$$M_1 : M_2 : M_3 \simeq \; 3.3 : 5 : 9$$

at the TeV scale as the signal of Kähler mediation.

For the gauginos, this implies

- LSP χ_1^0 predominantly Bino
- $G = M_{\rm gluino}/m_{\chi_1^0} < 3$

Kähler mediation depends on a parameter ϕ (the vev of a hidden sector field)

We again expect problems with tachyons.

Loop Pattern

is a combination of Anomaly and Kähler contribution

- Loop pattern:
  $$M_1 : M_2 : M_3 \simeq (3.3 + 3.3\phi) : (1 + 5\phi) : (-9 + 9\phi)$$

at the TeV scale as the signal loop mediation.

For the gauginos, this implies

- LSP χ_1^0 could be Bino or Wino
- gluino could be rather light as well

The loop scheme will have problems with tachyons and needs additional contributions to scalar masses.

In any case we seem to need tree level contributions to scalar (and gaugino) masses.

Mirage Pattern

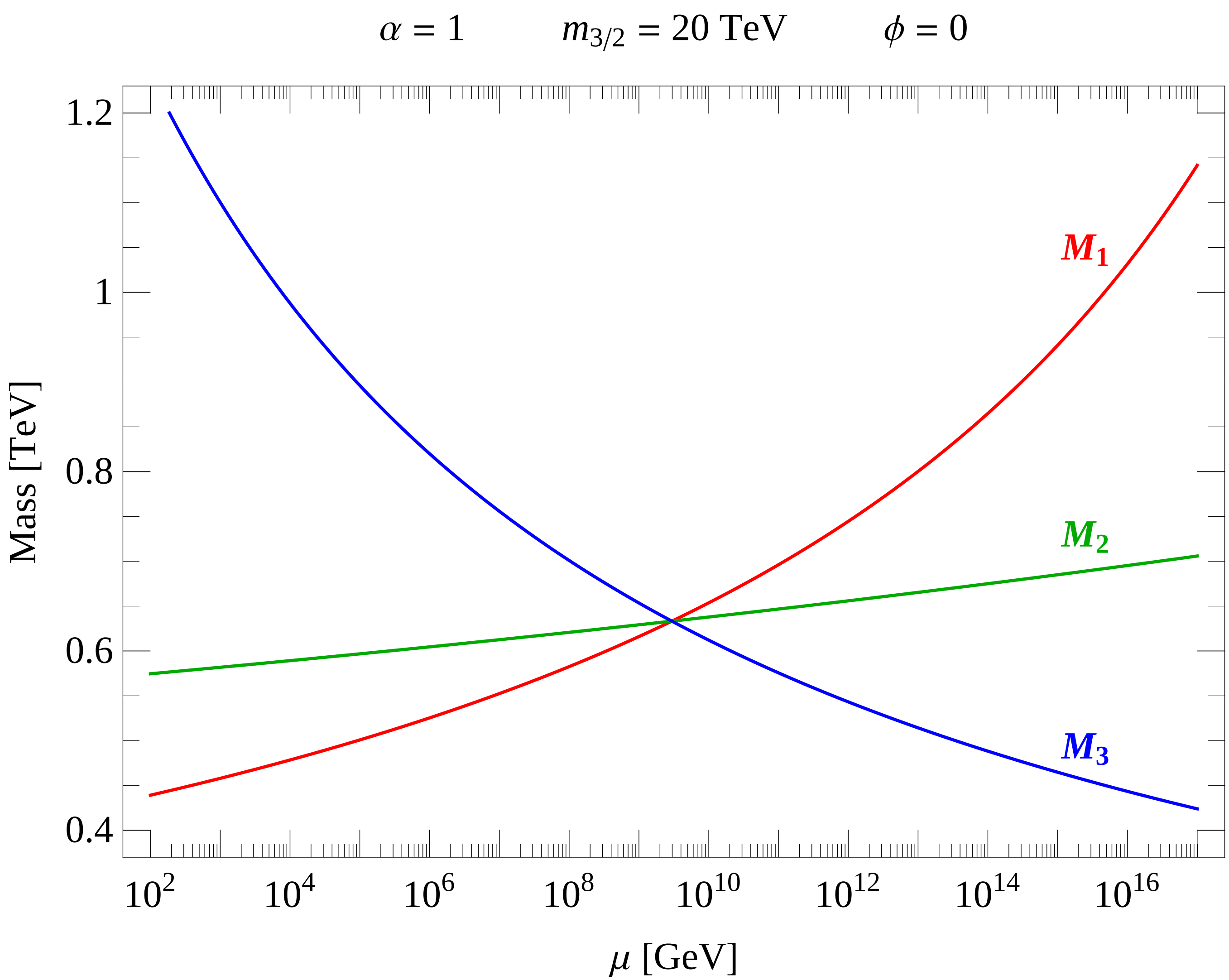
Mixed boundary conditions at the GUT scale
characterized by the parameter α:
the ratio of modulus to anomaly mediation.

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

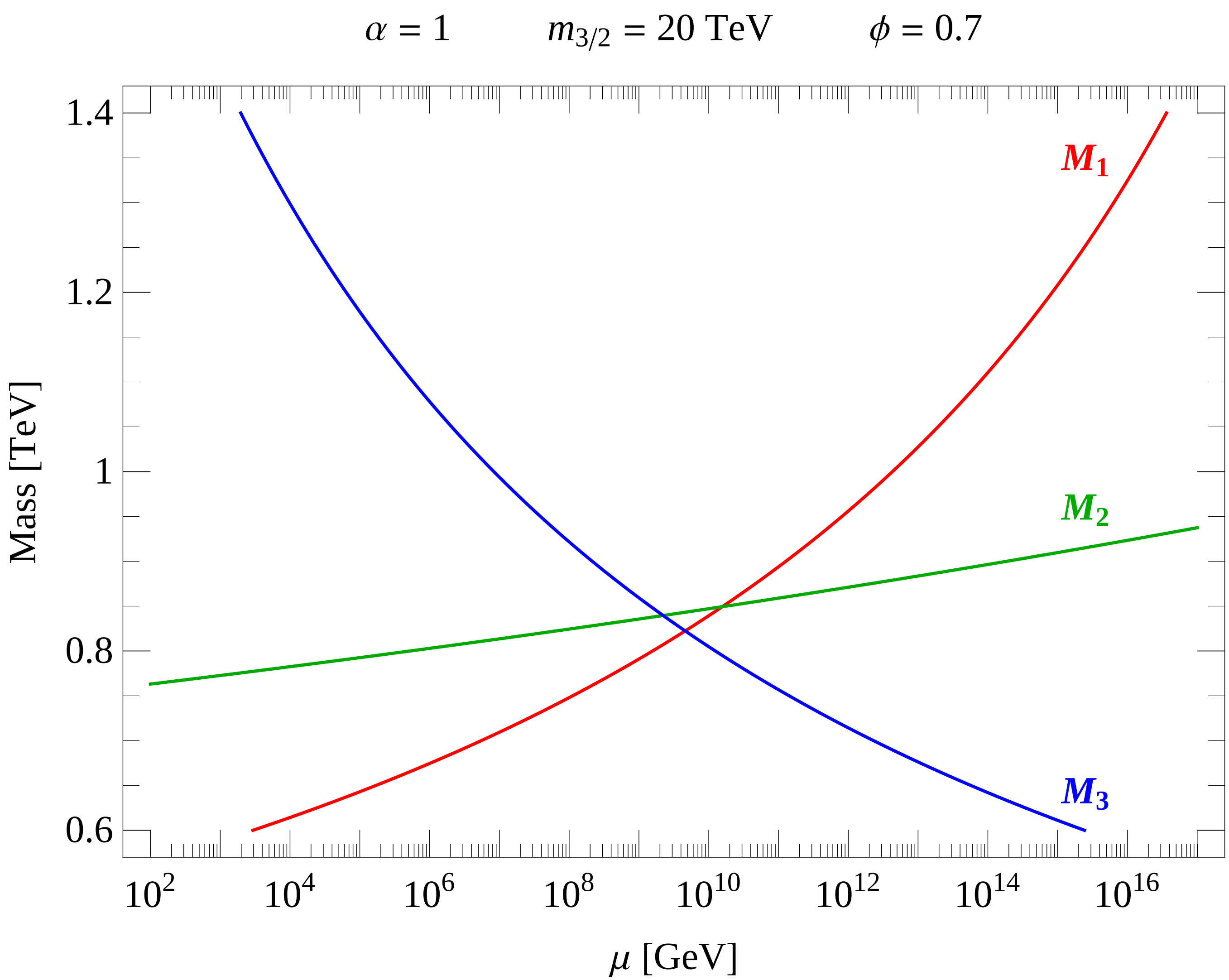
The mirage scheme leads to

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

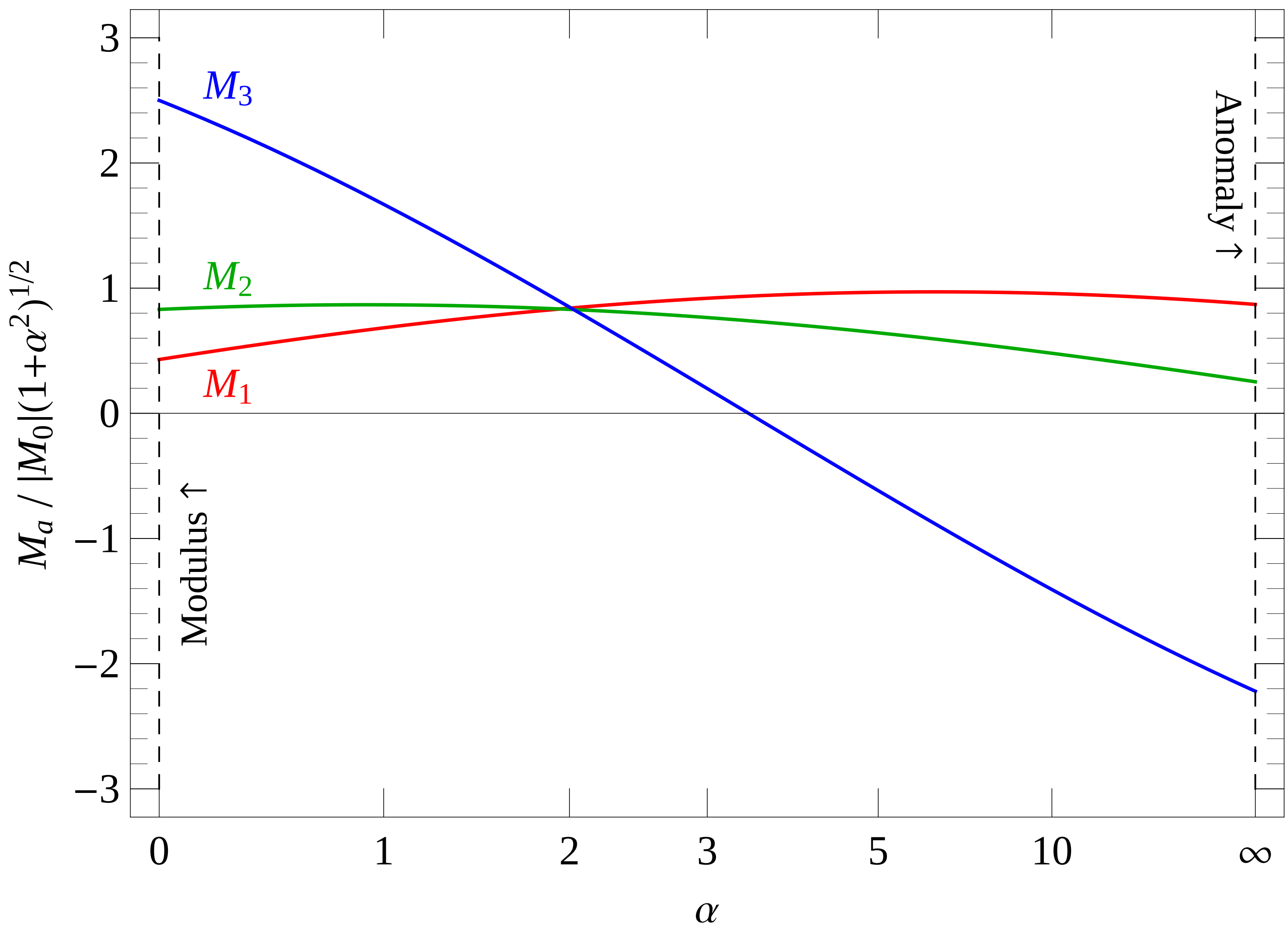
Mirage Scale



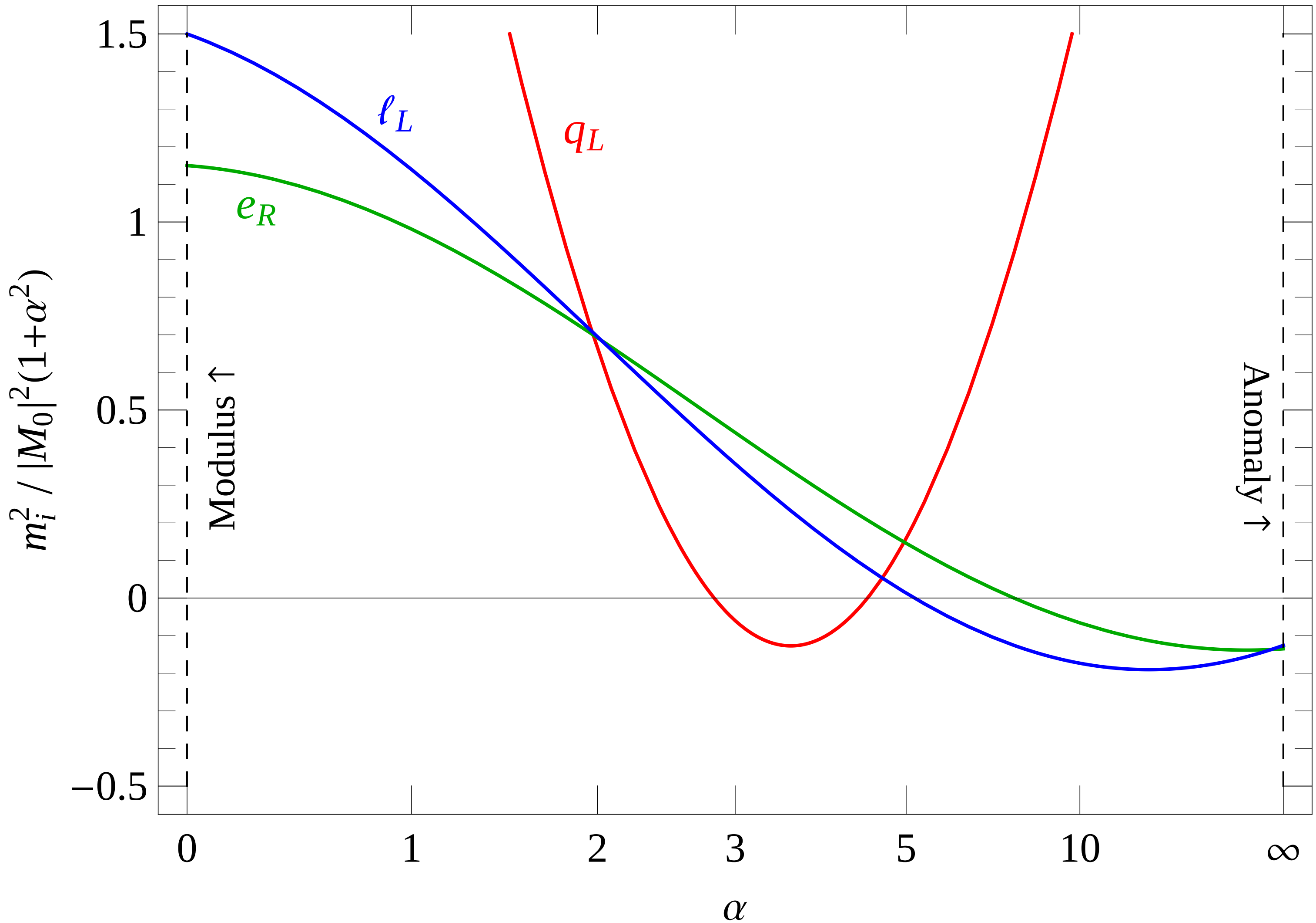
Loop Mirage Scale



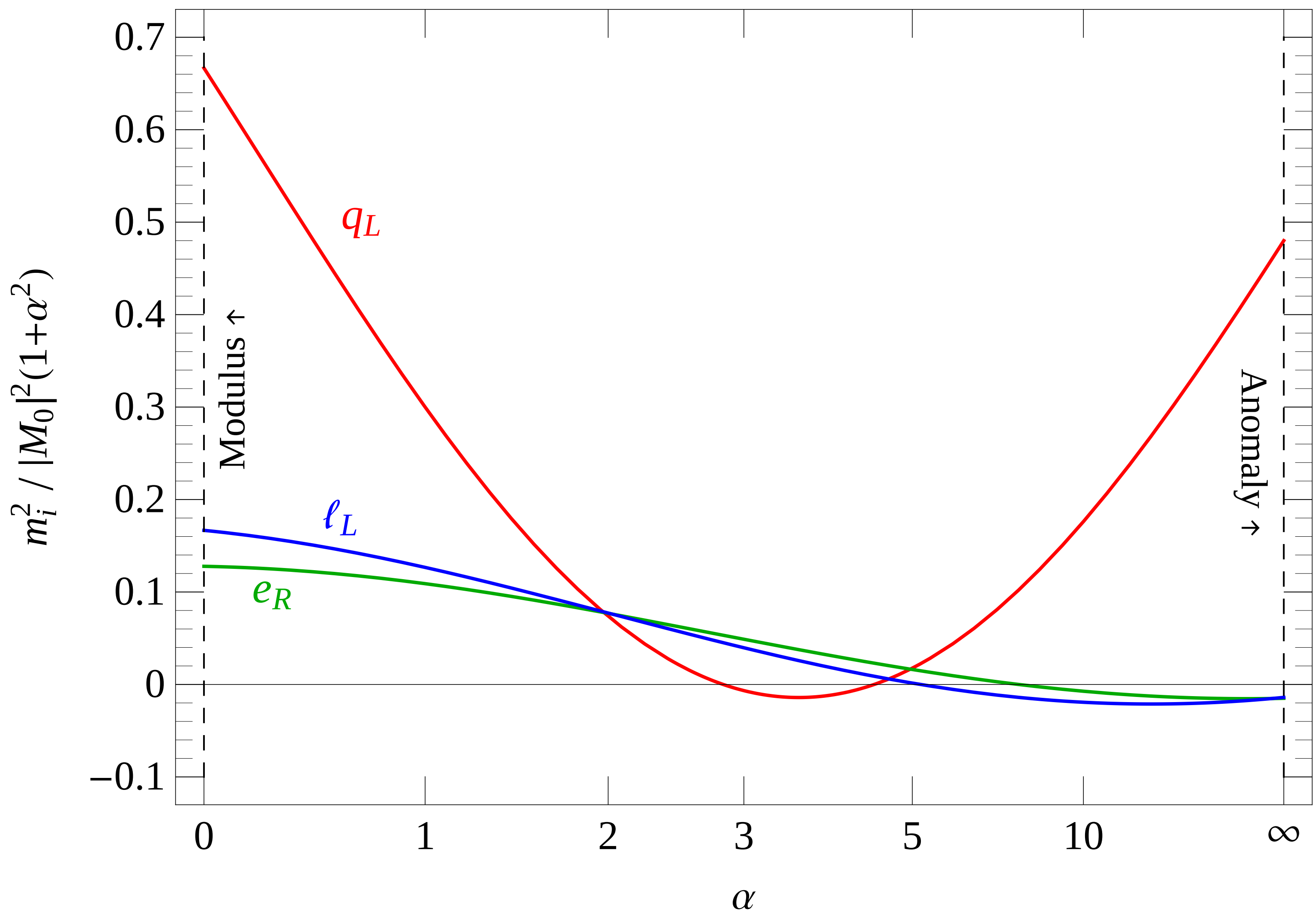
Gaugino Masses



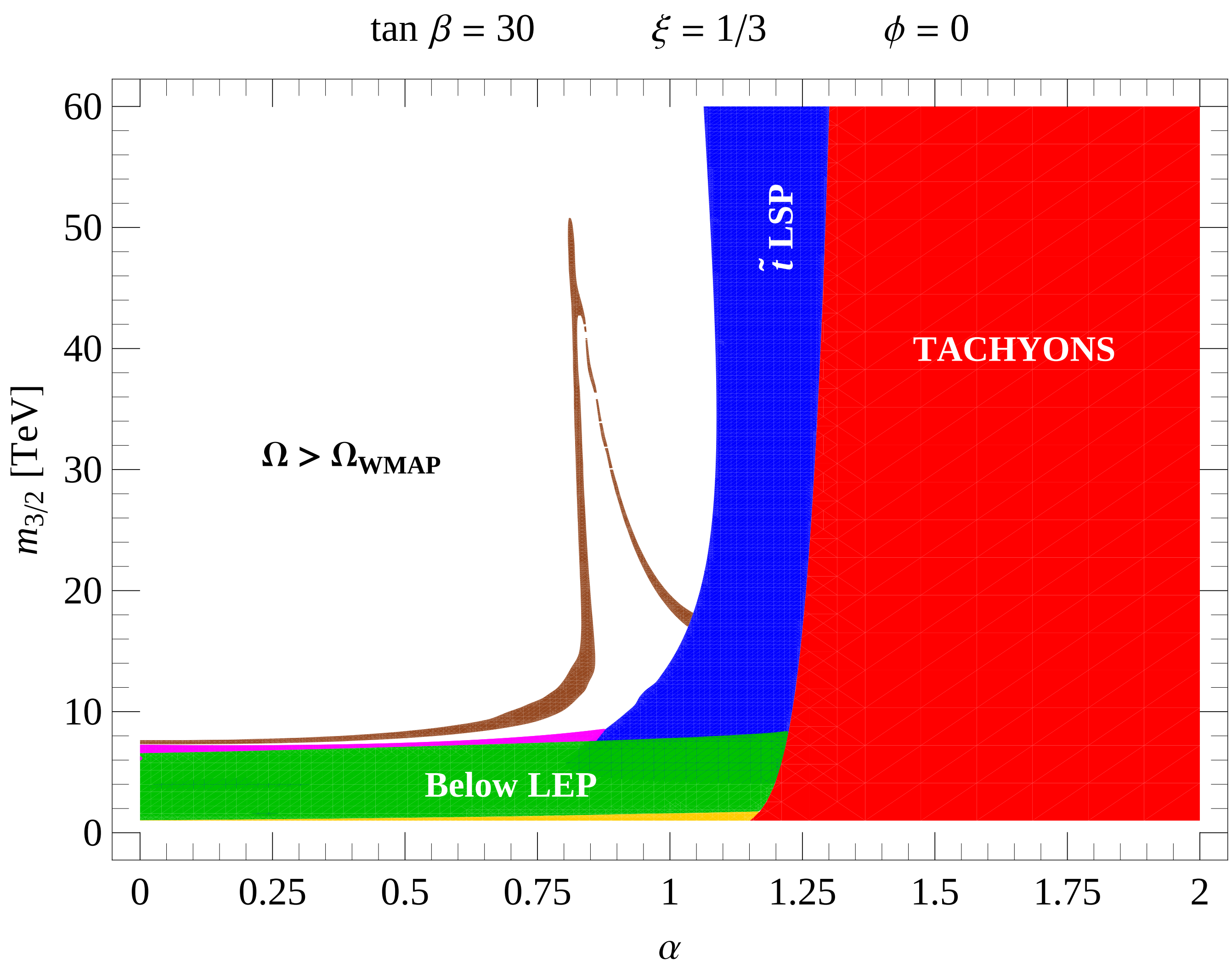
Scalar Masses



Scalar Masses



Constraints on α



Uncertainties

GUT thresholds

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

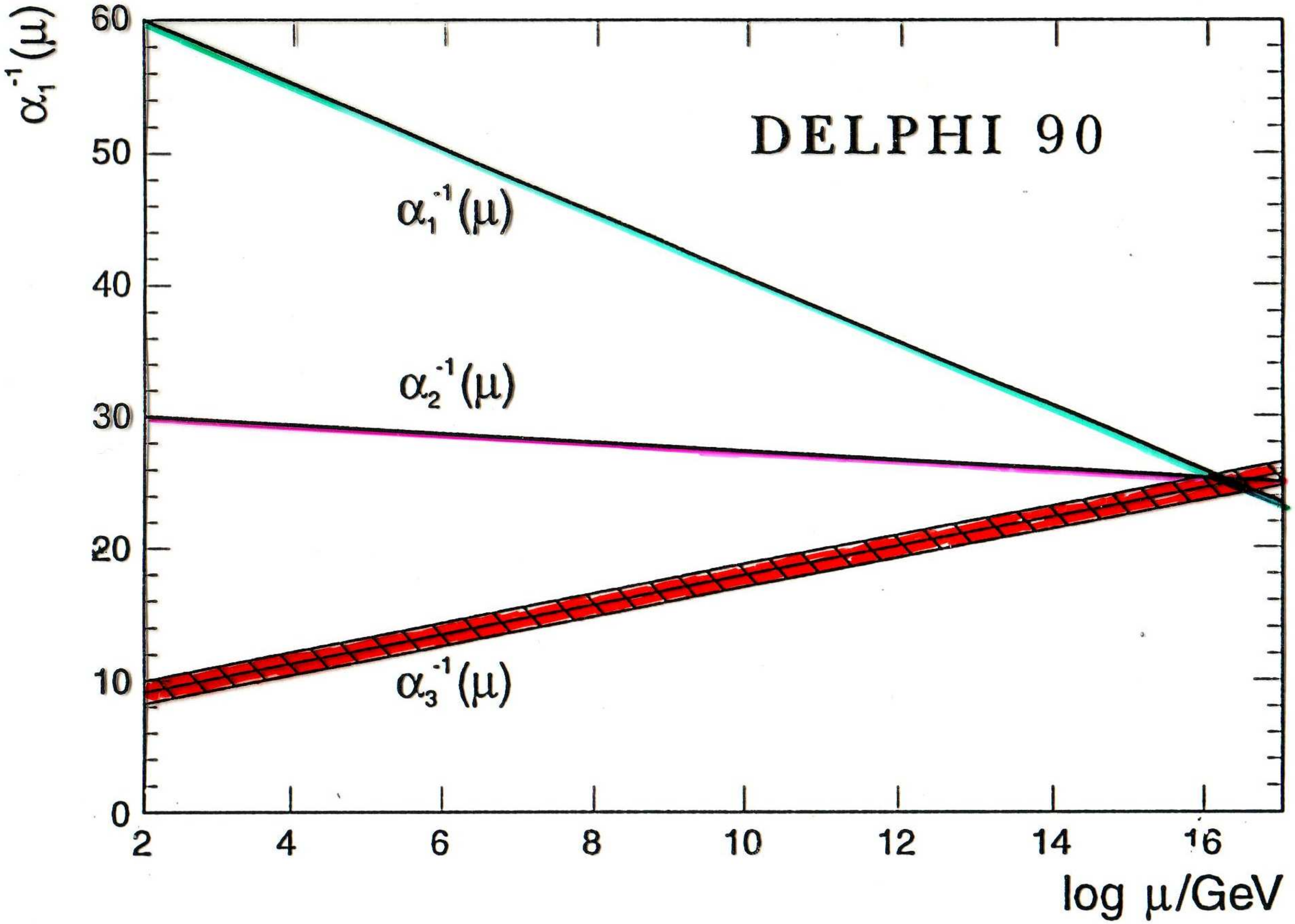
Kähler corrections

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

Intermediate thresholds

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

From LEP we have



What can we expect from LHC

We need

- simple schemes
- simple boundary conditions at the GUT scale
- robust predictions for soft terms
- luck

What can we expect from LHC

We need

- simple schemes
- simple boundary conditions at the GUT scale
- robust predictions for soft terms
- luck

In many schemes we might not be able to test the GUT idea

- check your scheme with respect to possible GUT predictions
- place your bet now