Crosschecks for Unification

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?

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Outline

- GUTs: the good things and the problems
- String theory and local grand unification
- Simple susy breakdown schemes
- Gaugino masses
- Disentangling the schemes (with a bit of luck)

The Standard Model

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

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

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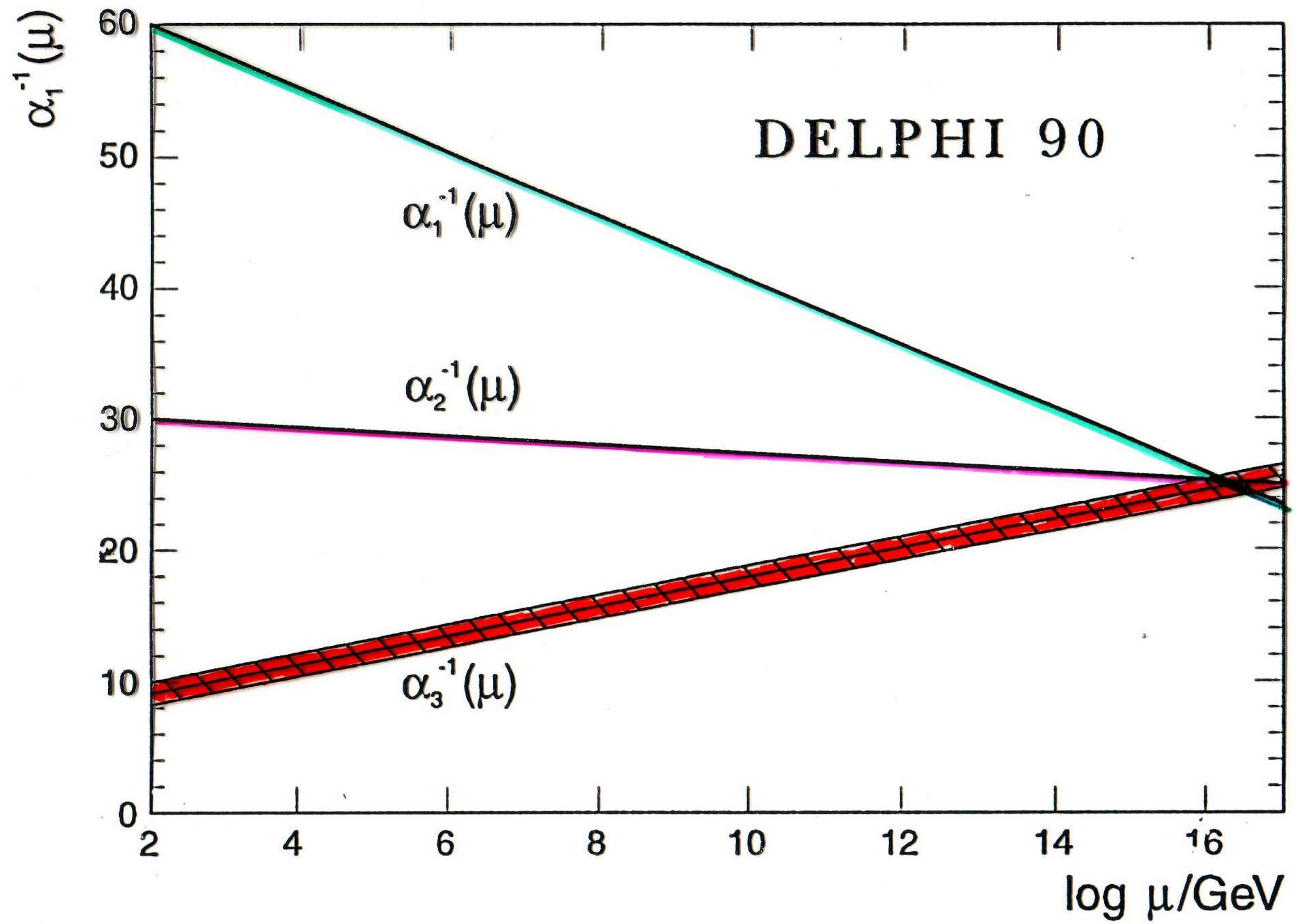
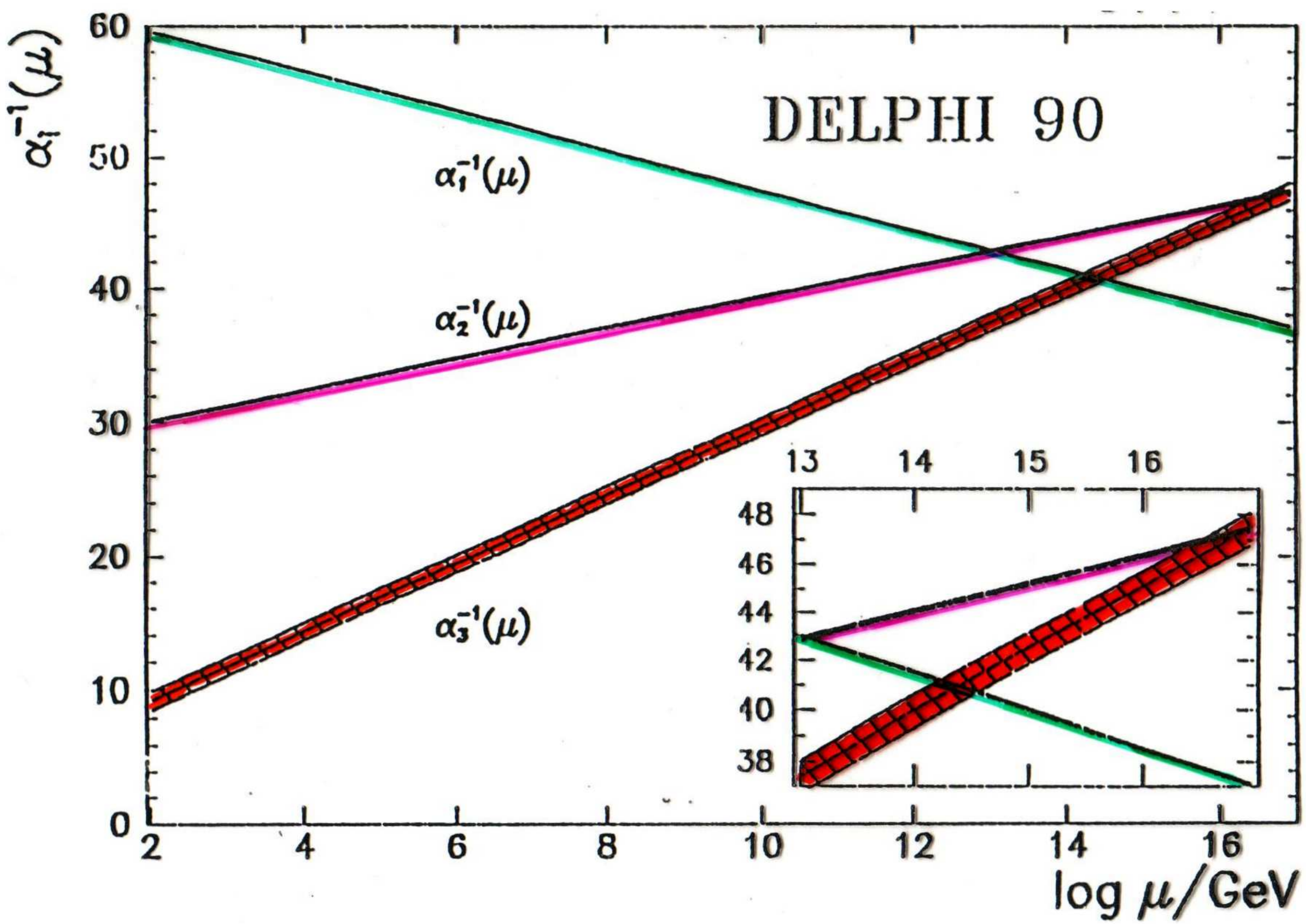
- Evolution of couplings constants of the standard model towards higher energies.

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
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But there remain a few difficulties:

- breakdown of GUT group (large representations)
- doublet-triplet splitting problem (incomplete multiplets)
- proton stability (need for R-parity)

String Theory

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- supersymmetry
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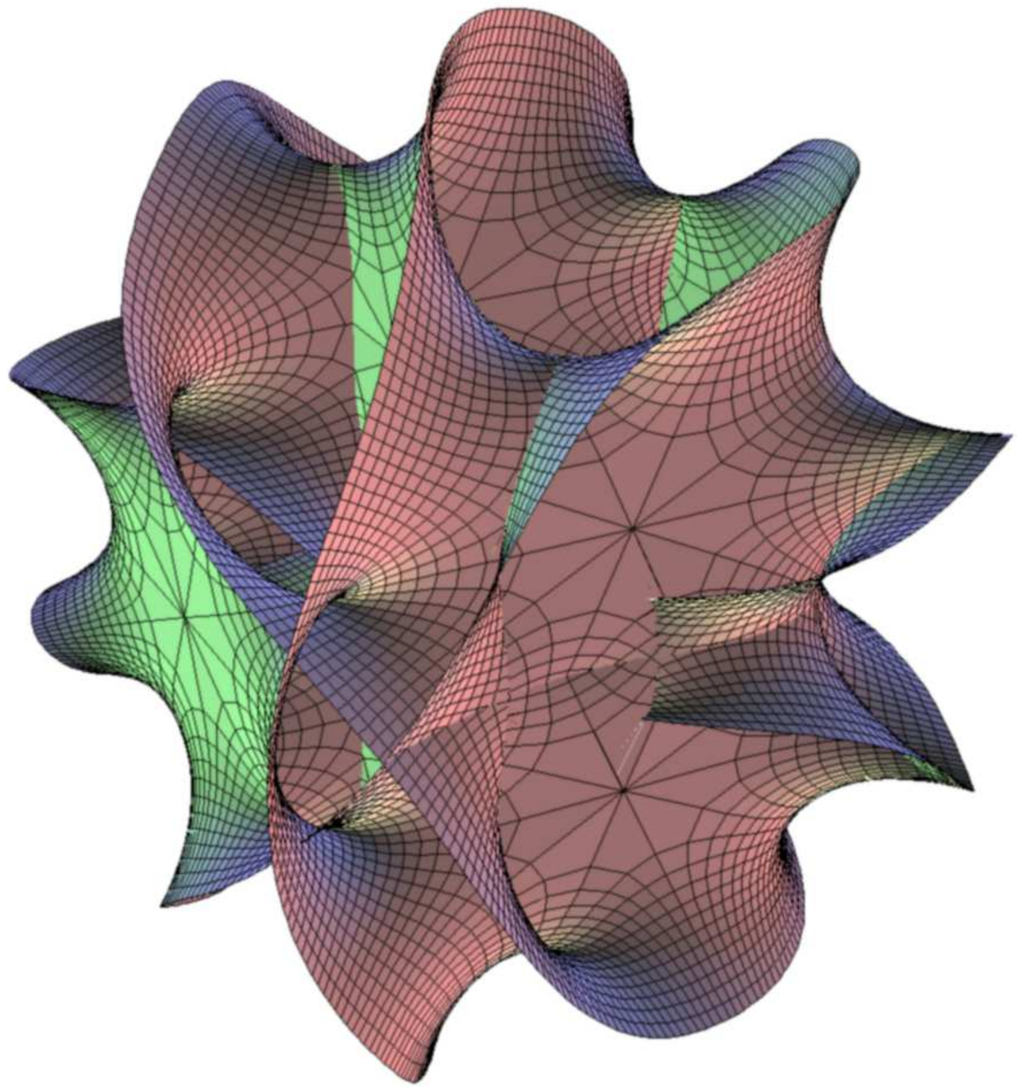
- extra spatial dimensions
- large unified gauge groups
- consistent theory of gravity

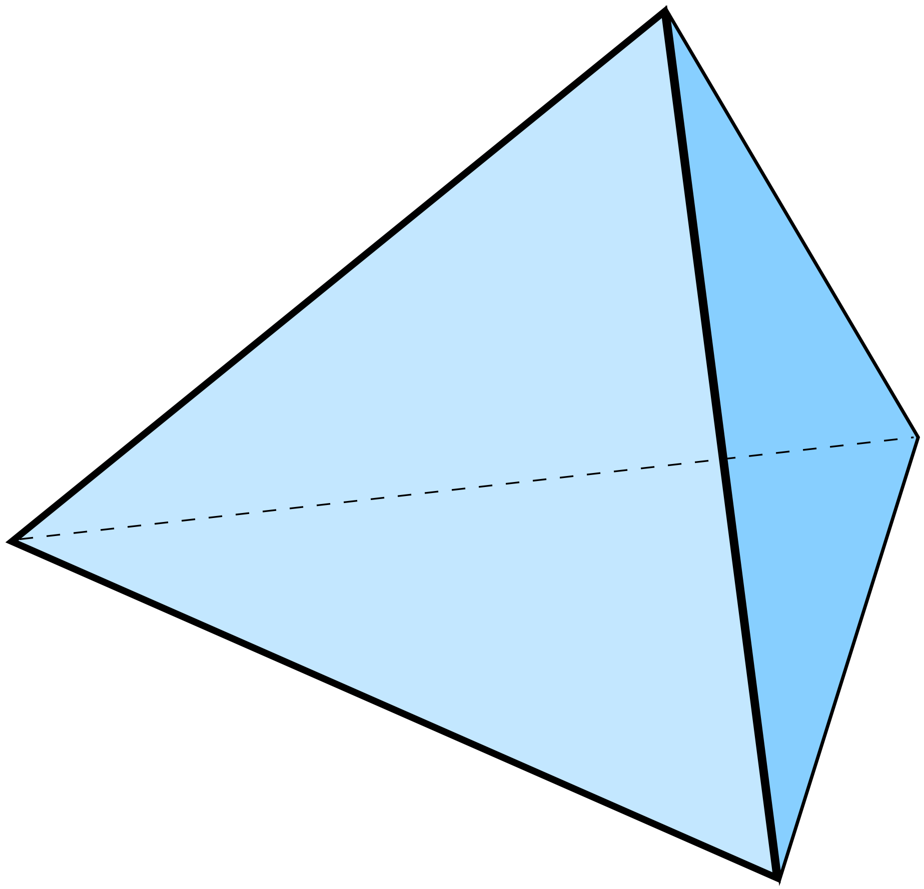
These are the building blocks for a unified theory of all the fundamental interactions.
But do they fit together, and if yes how?

We need to understand the mechanism of compactification of the extra spatial dimensions

Calabi Yau Manifold



Orbifold



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Localization

Quarks, Leptons and Higgs fields can be localized:

- in the Bulk ($d = 10$ untwisted sector)
- on 3-Branes ($d = 4$ twisted sector fixed points)
- on 5-Branes ($d = 6$ twisted sector fixed tori)

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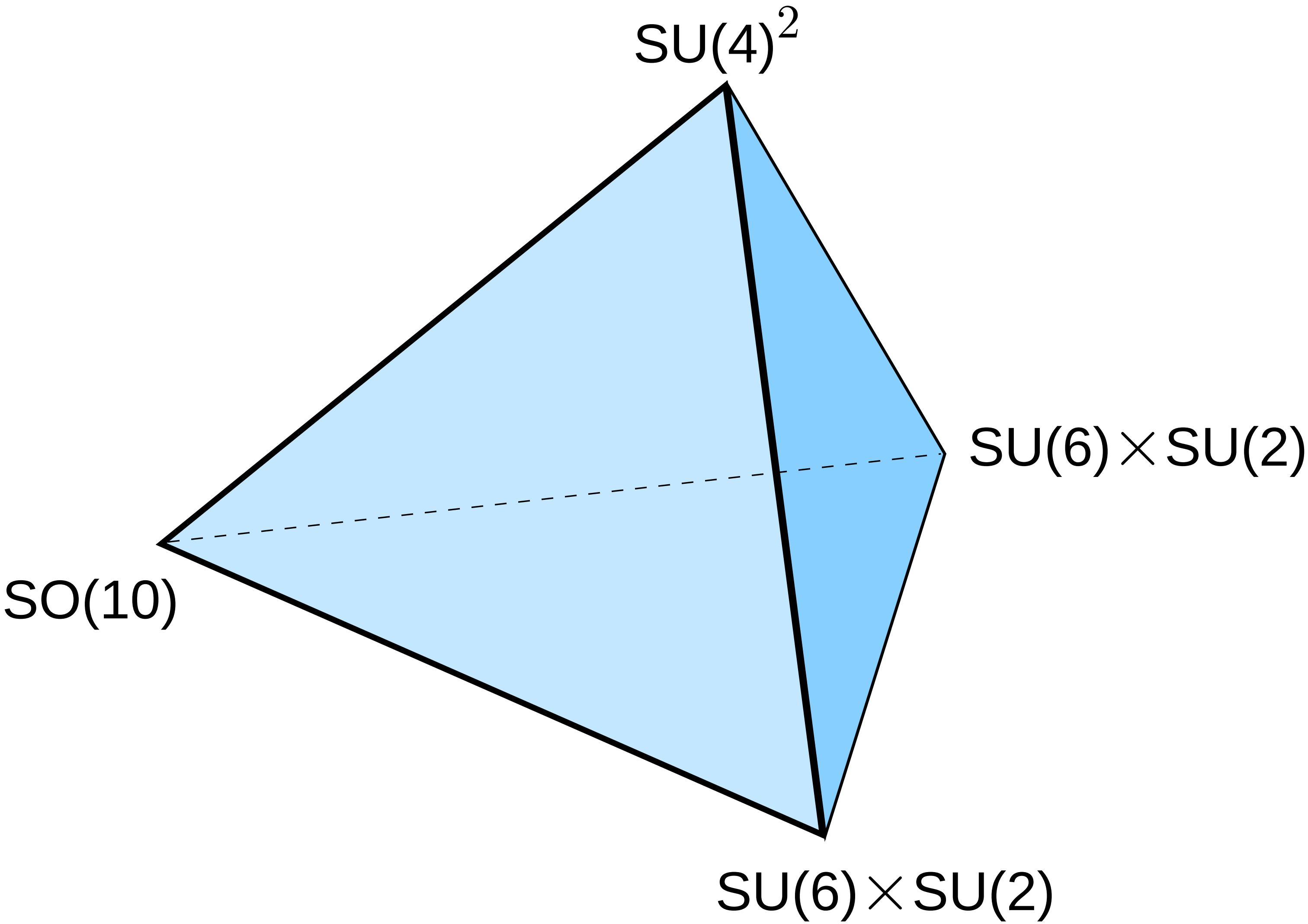
but there is also a “localization” of gauge fields

- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

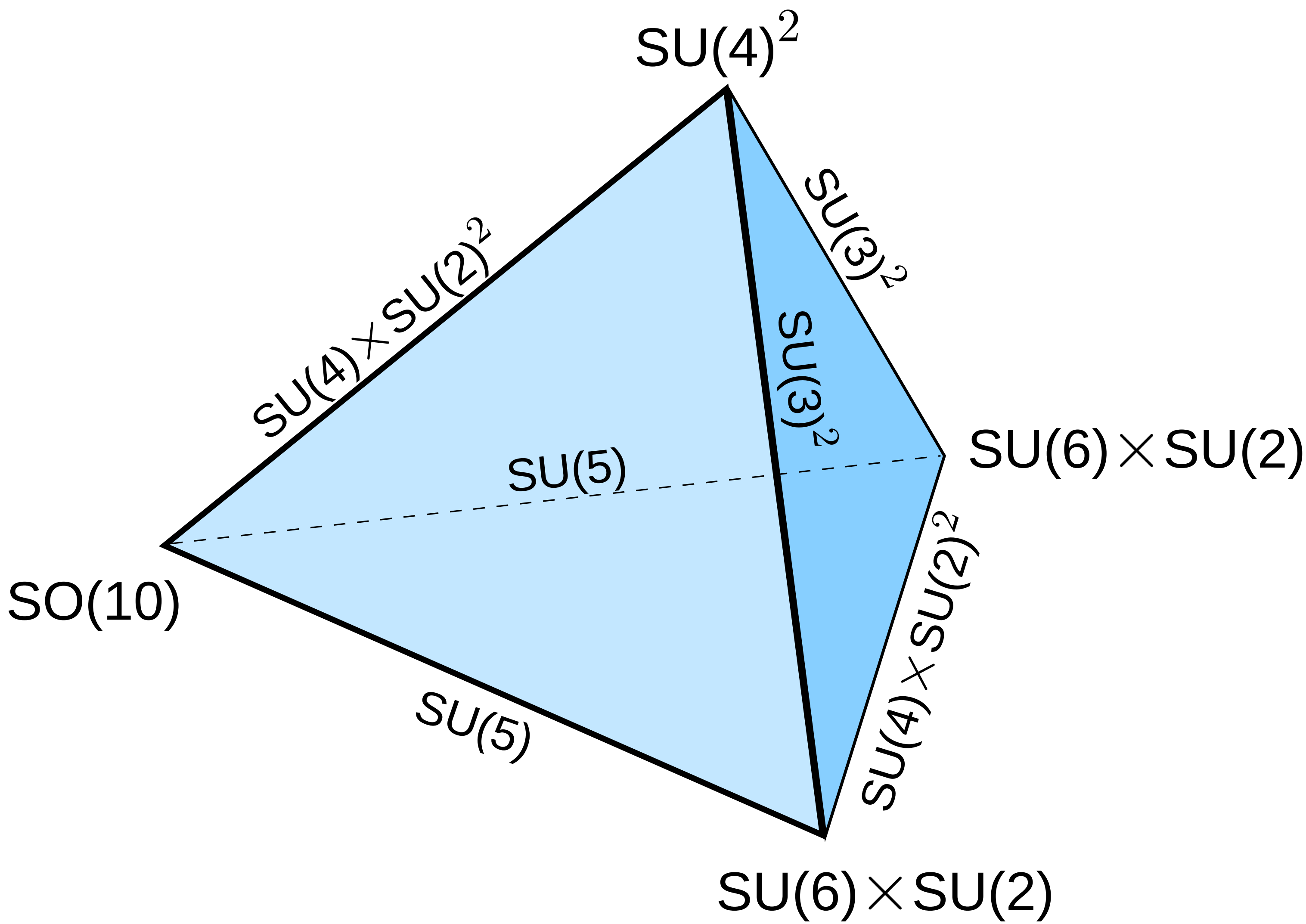
Observed 4-dimensional gauge group is common subroup of the various localized gauge groups!

Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Local Grand Unification

In fact string theory gives us a variant of GUTs

- complete multiplets for fermion families
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- partial Yukawa unification
- discrete (family) symmetries
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Key properties of the theory depend on the geography of the fields in extra dimensions.

This geometrical set-up is called local GUTs.

(Förste, HPN, Vaudrevange, Wingerter, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)

Local SO(10) GUTs

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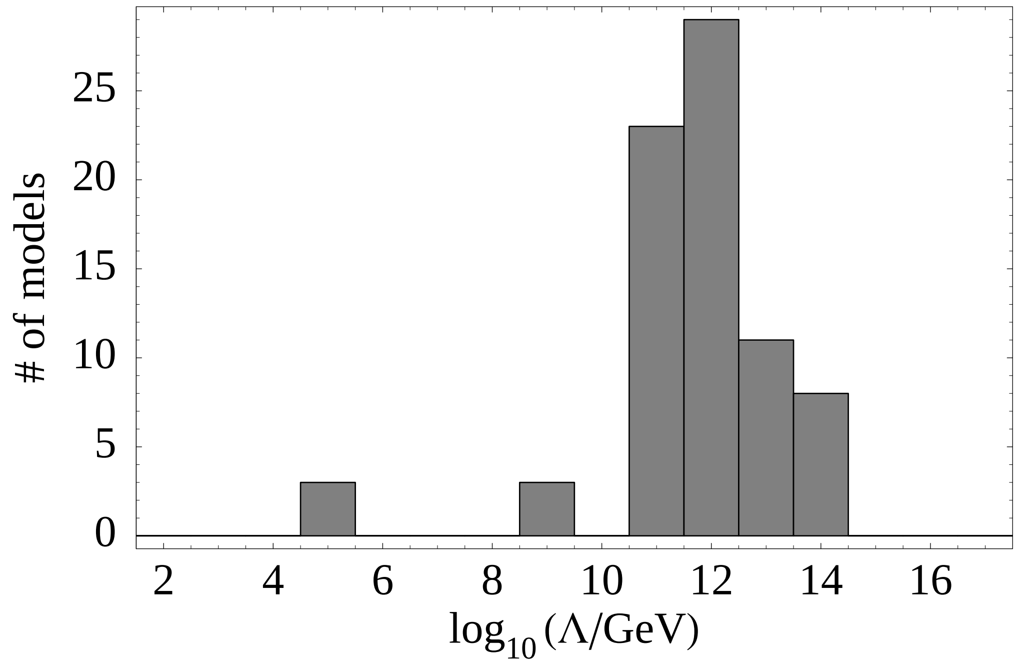
Still there could be remnants of $SO(10)$ symmetry

- 16 of SO(10) at some branes
- correct hypercharge normalization
- R-parity and discrete family symmetries
- simple susy breakdown and mediation schemes

that are very useful for realistic model building ...

Gaugino Condensation

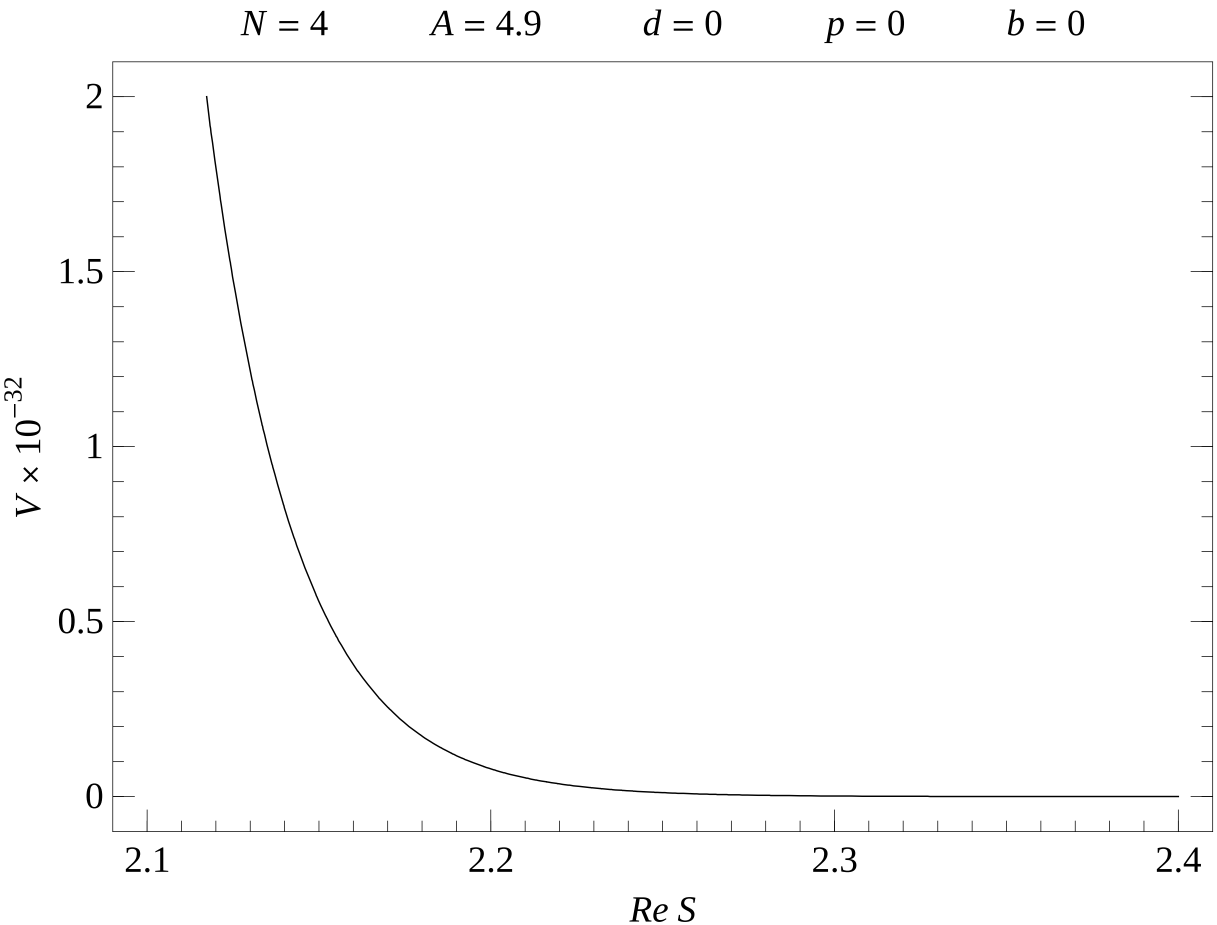


Gravitino mass $m_{3/2} = \Lambda^3/M_{\mathrm{Planck}}^2$ and $\Lambda \sim \exp(-S)$

We need to fix the dilaton!

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006)

Run-away potential

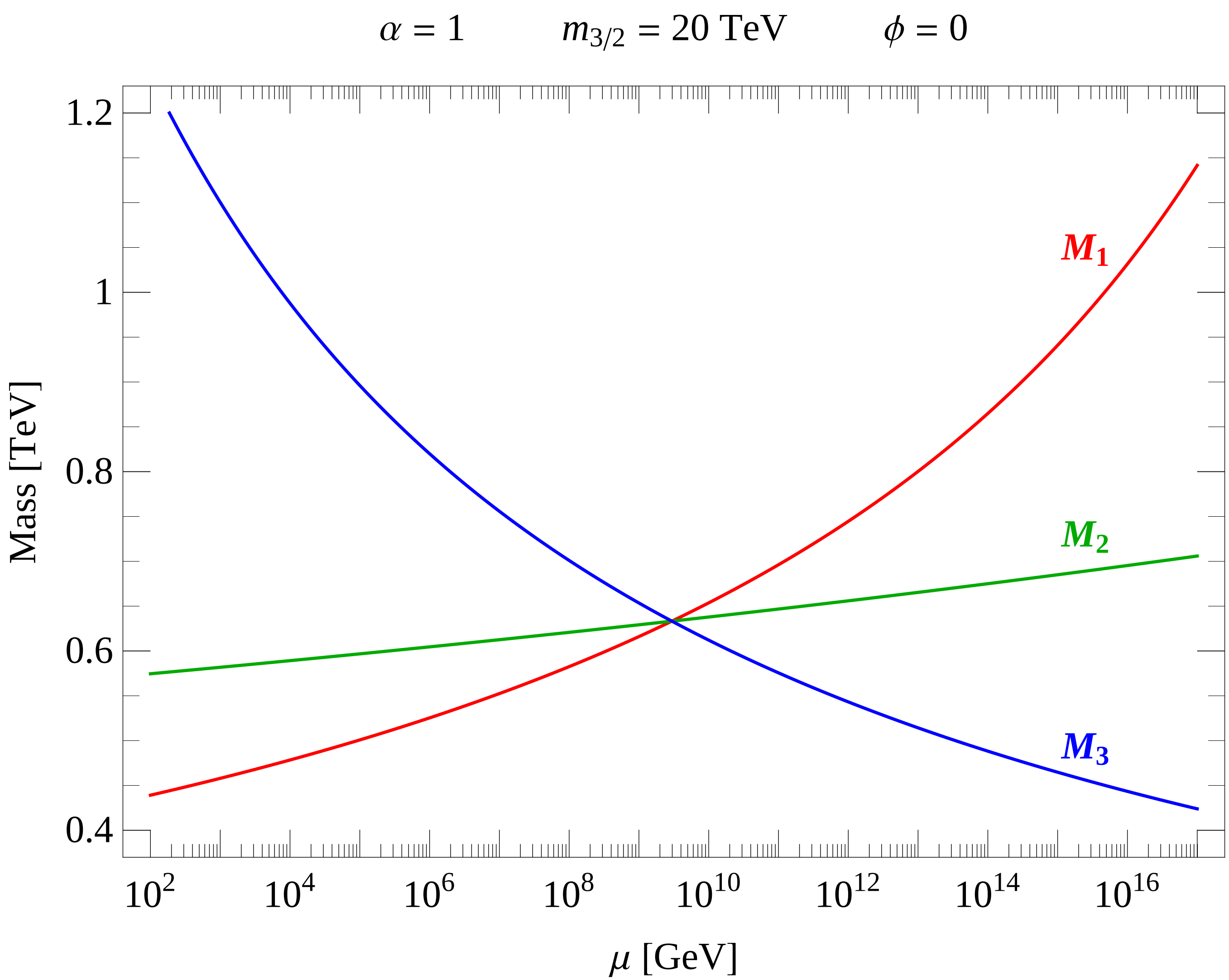


Dilaton Domination?

One needs a “downlifting” mechanism to adjust the vacuum energy:

- the analogue to the F-term “uplifting” in the type IIB case (Gomez-Reino, Scrucca, 2006; Lebedev, HPN, Ratz, 2006)
- “downlifting” mechanism fixes S as well (no need for nonperturbative corrections to the Kähler potential) (Löwen, HPN, 2008)
- this induces a suppression factor $\log(m_{3/2}/M_{\mathrm{Planck}})$
- mirage mediation for gaugino masses (Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)

Mirage Scale



Can we test this 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

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

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

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

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

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
- $G = M_{\mathrm{gluino}}/m_{\chi_1^0} < 3$

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

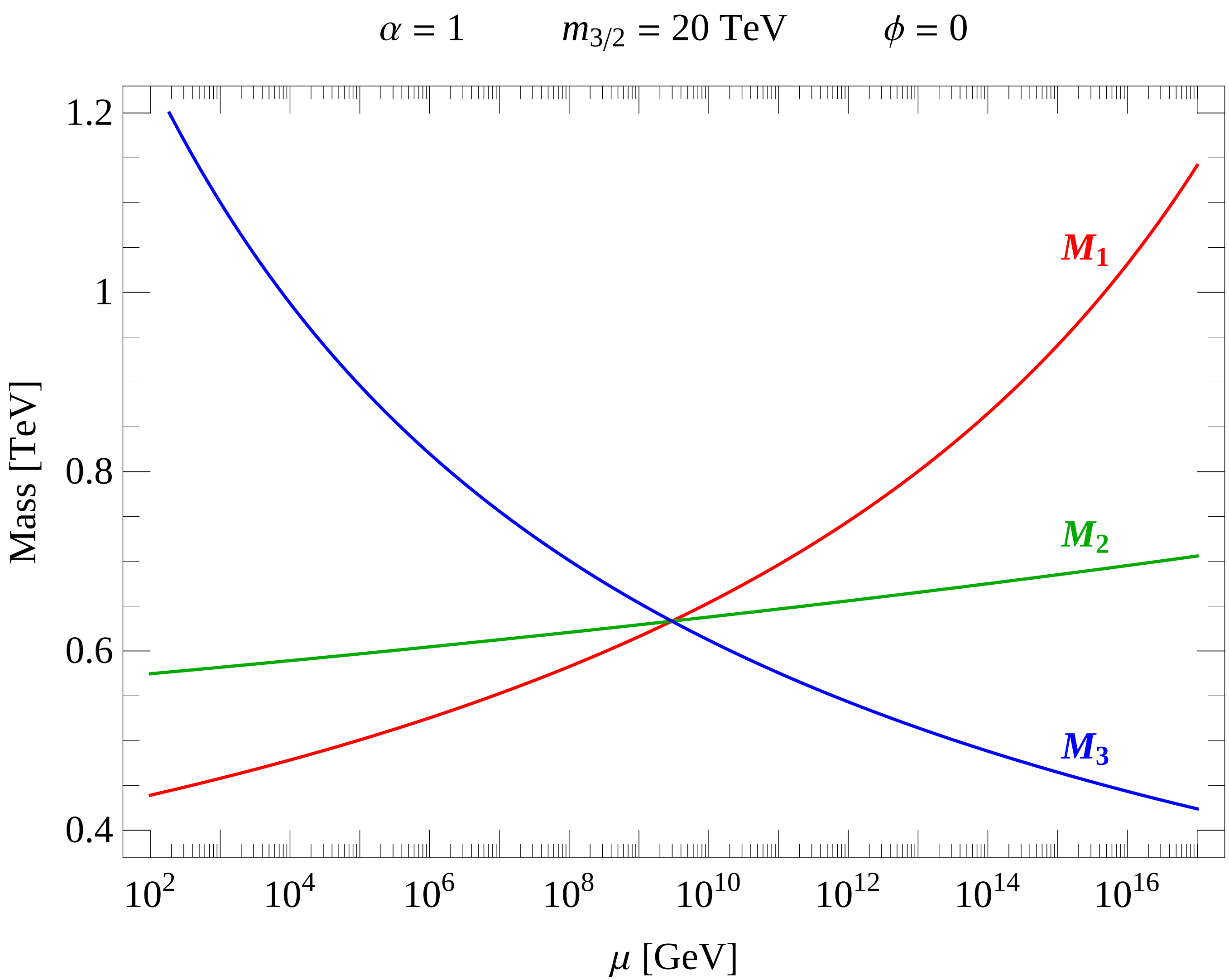
Mixed boundary conditions at the GUT scale
characterized by the parameter α:
the ratio of modulus to anomaly mediation.

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

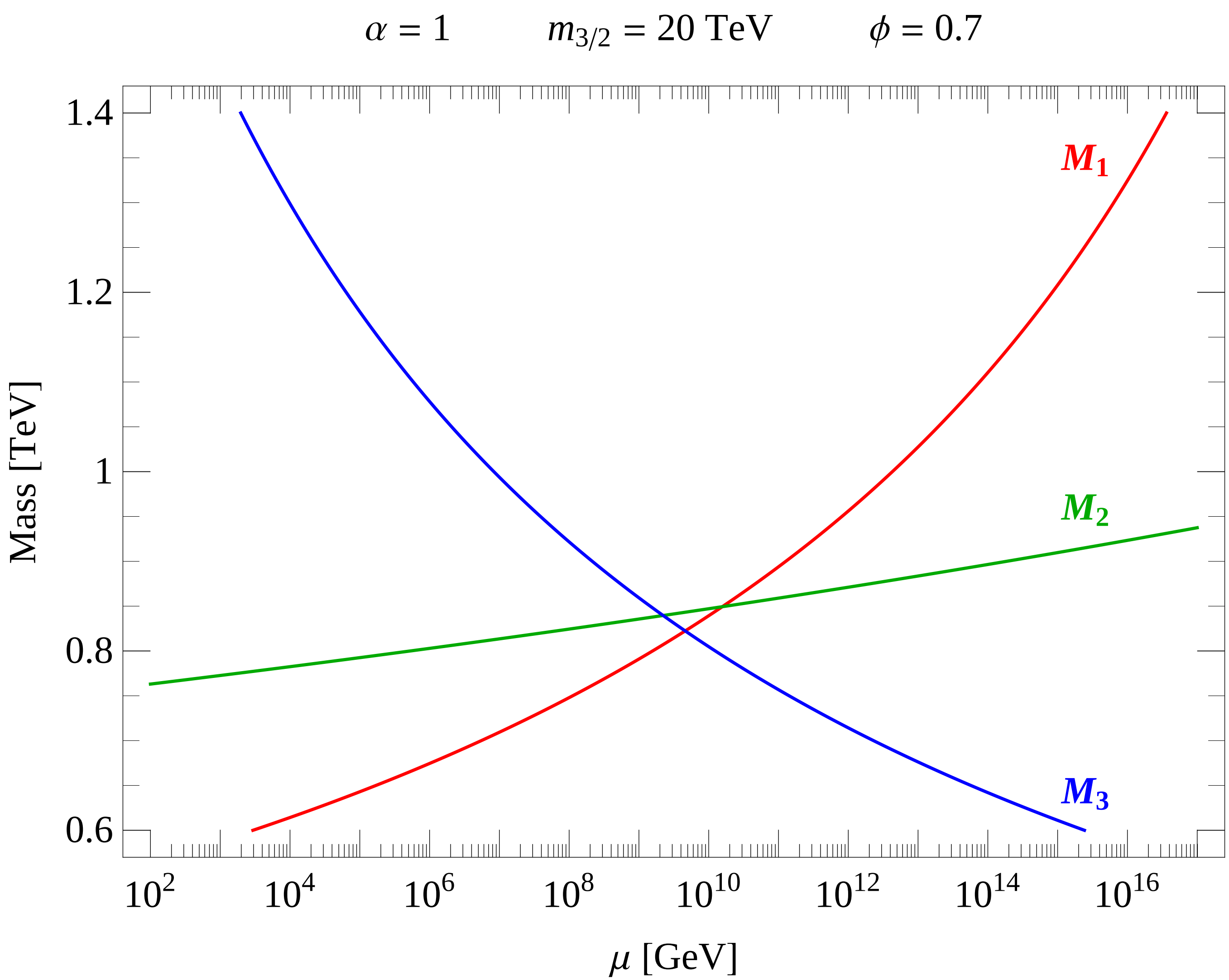
The mirage scheme leads to

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

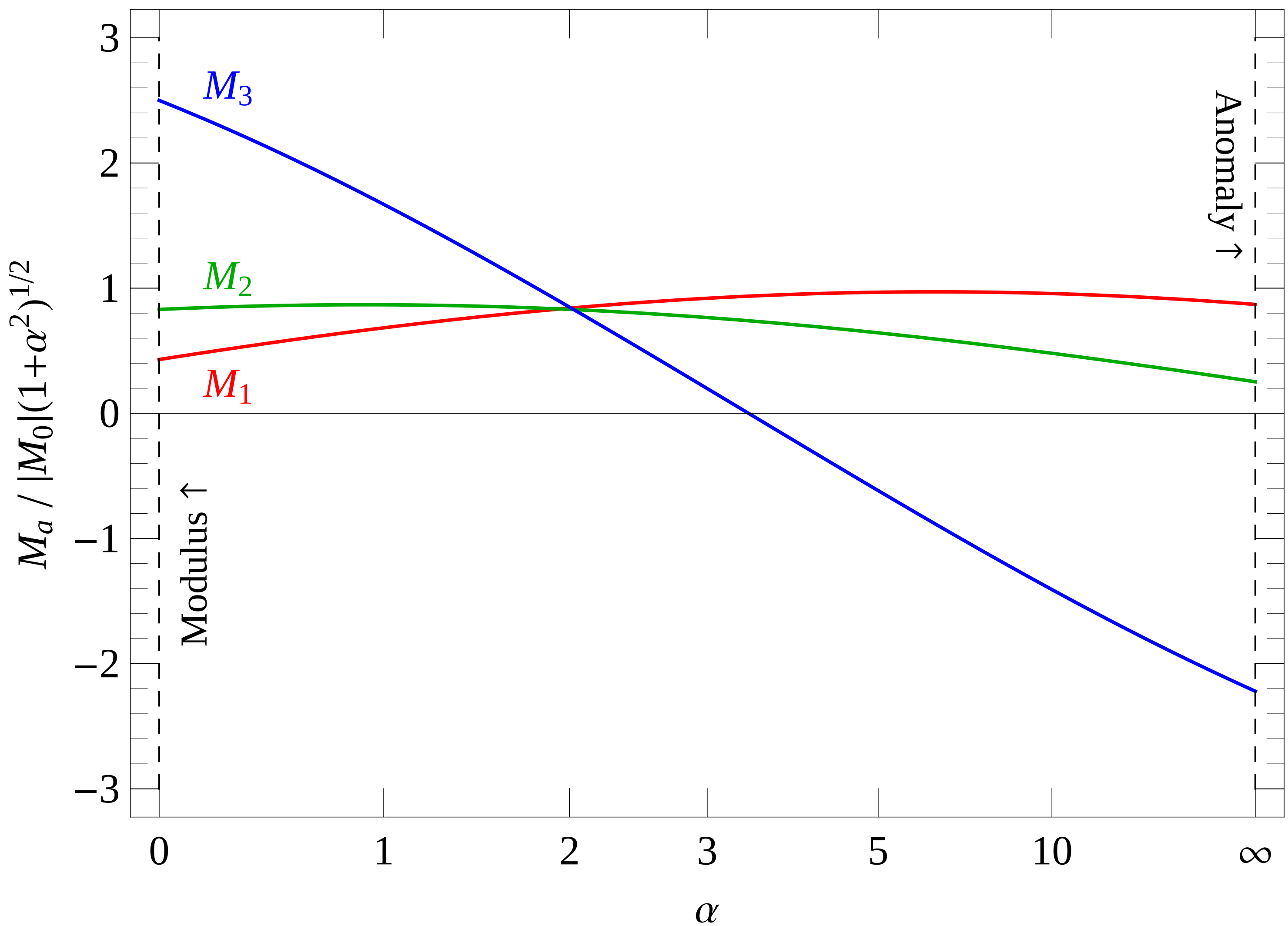
Mirage Scale



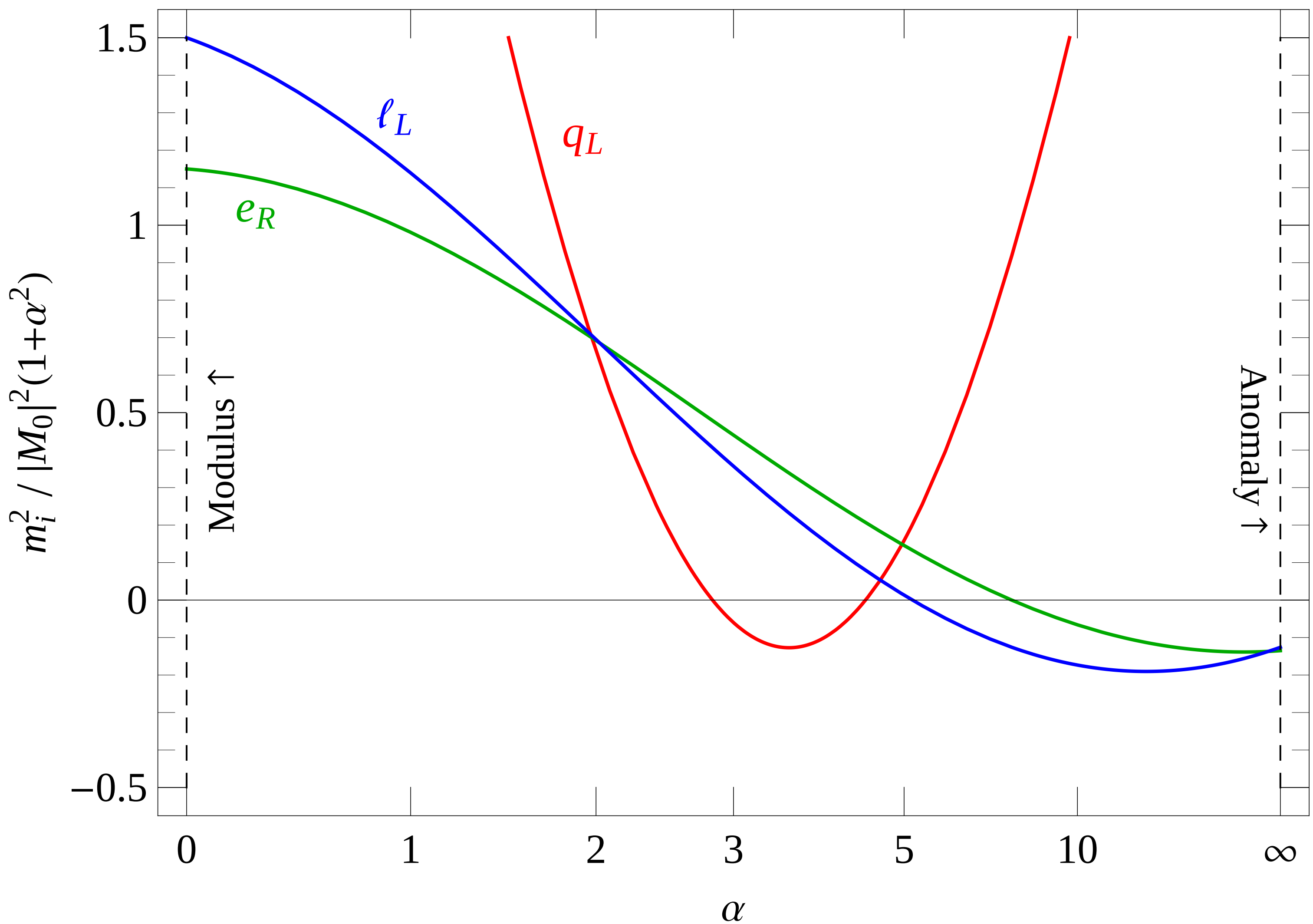
Loop Mirage Scale



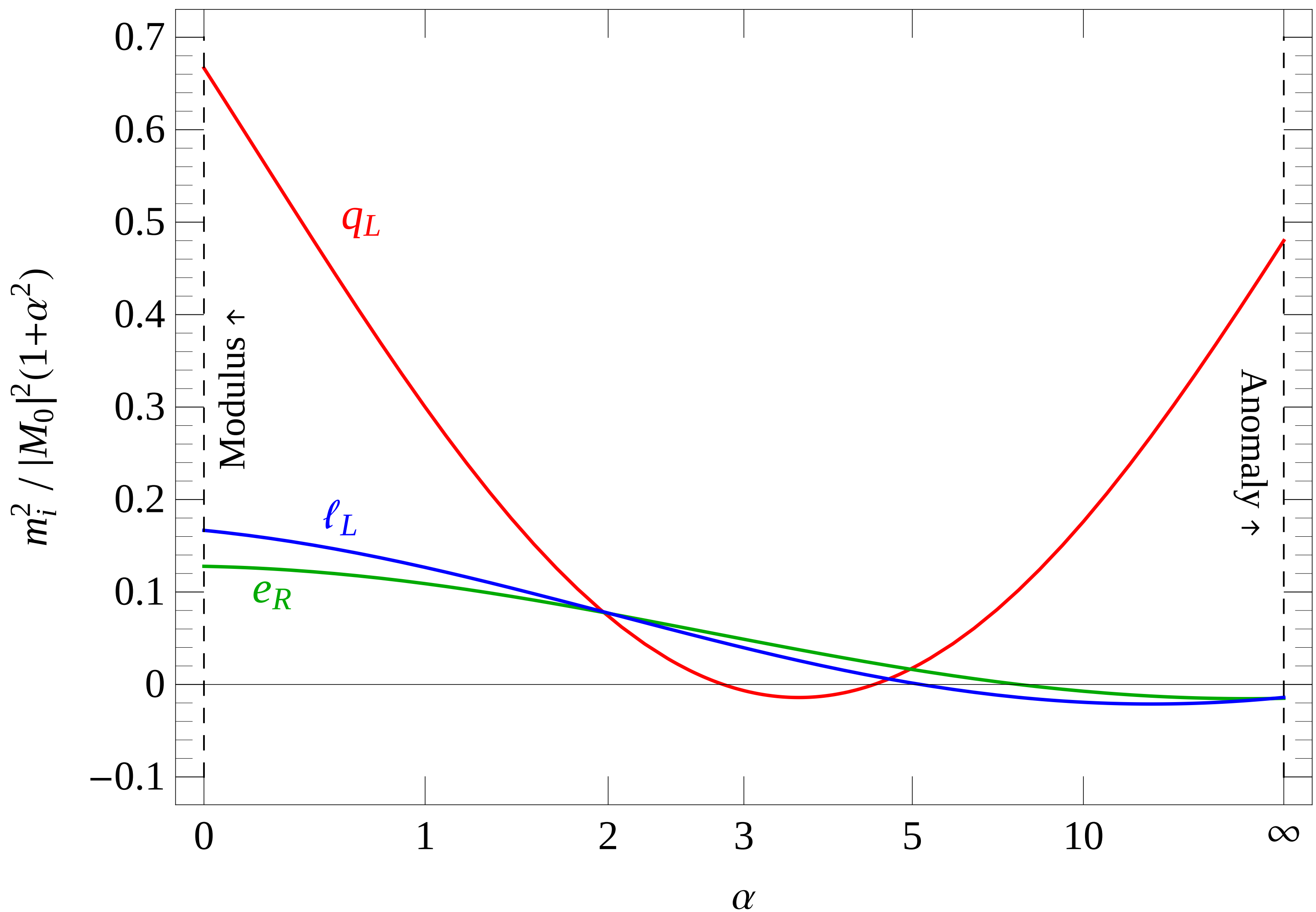
Gaugino Masses



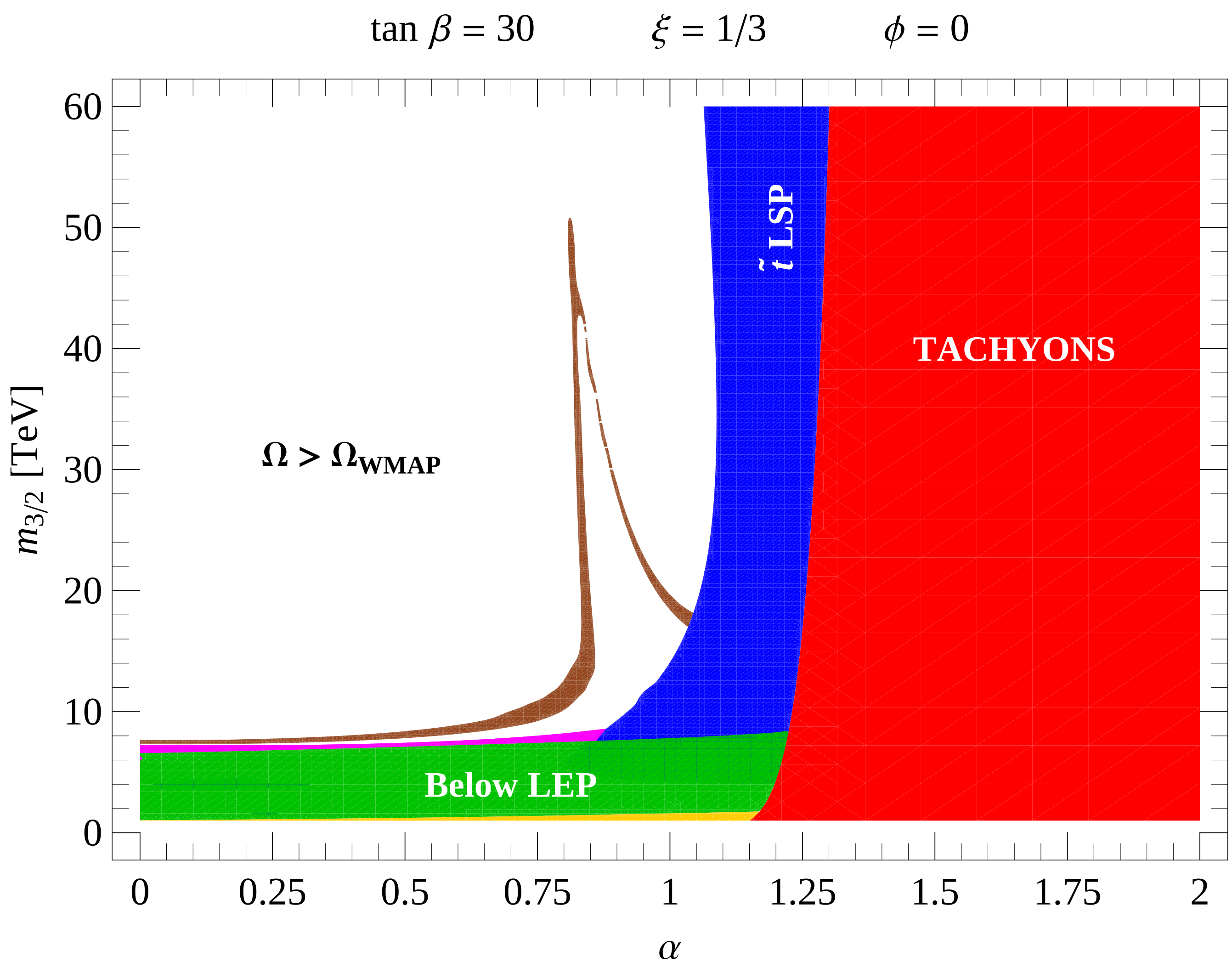
Scalar Masses



Scalar Masses



Constraints on α



Uncertainties

String thresholds

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

Kähler corrections

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Intermediate thresholds

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

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 and Kähler Mediation

Keep in mind

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

- Anomaly and Kähler Mediation

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 $G = M_{\mathrm{gluino}}/m_{\chi_1^0}$!

Identification of 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)