LIGHT GLUINOS?

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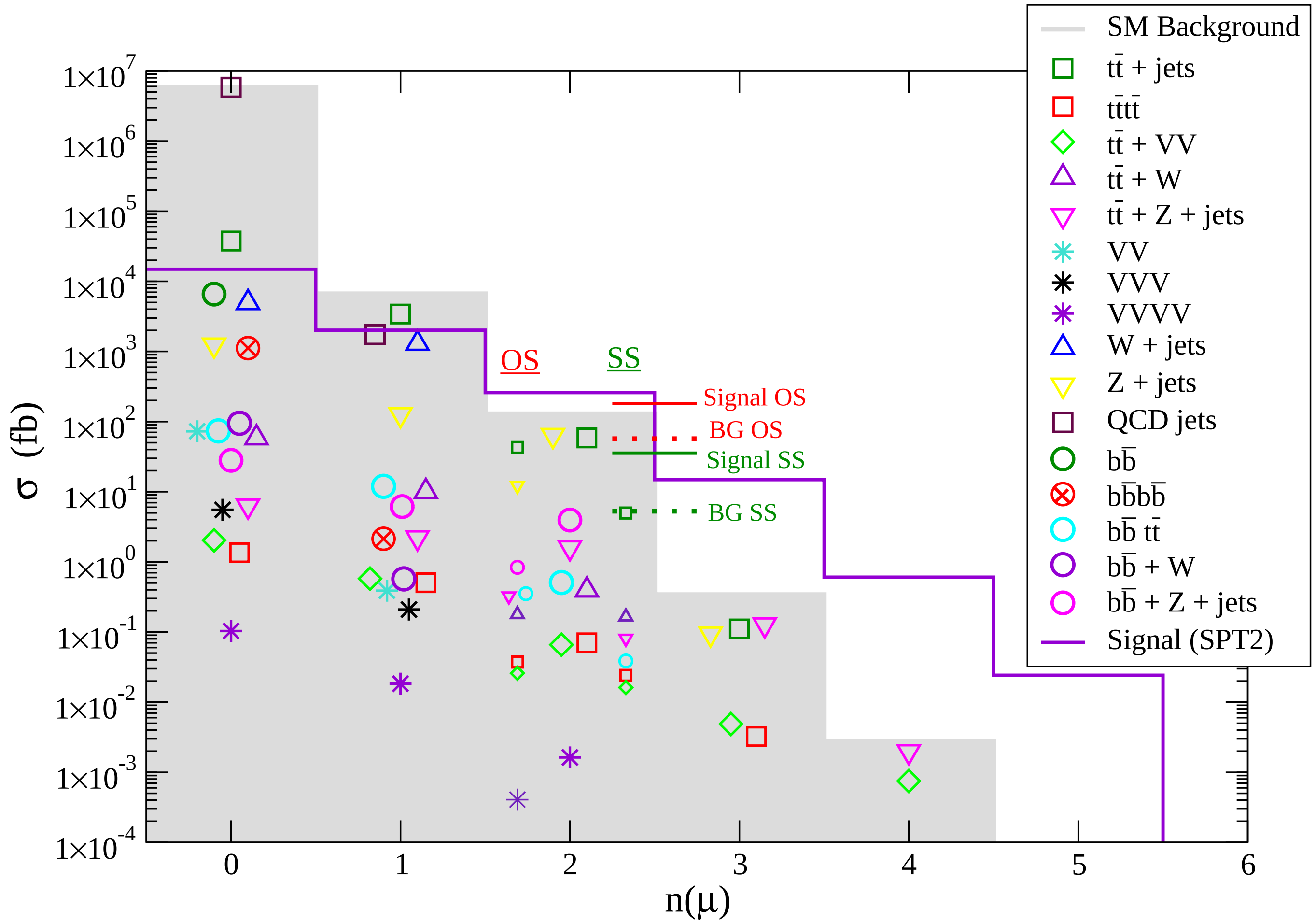
LIGHT GLUINOS?

- Early supersymmetry discovery potential of the LHC
- Phenomenology of models with light gluinos
  - radiative electroweak symmetry breaking
  - focus point
  - large $\tan\beta$
  - non-universal boundary values of soft terms
- Theoretical models of soft SUSY breaking terms
- Summary

Early supersymmetry discovery potential of the LHC

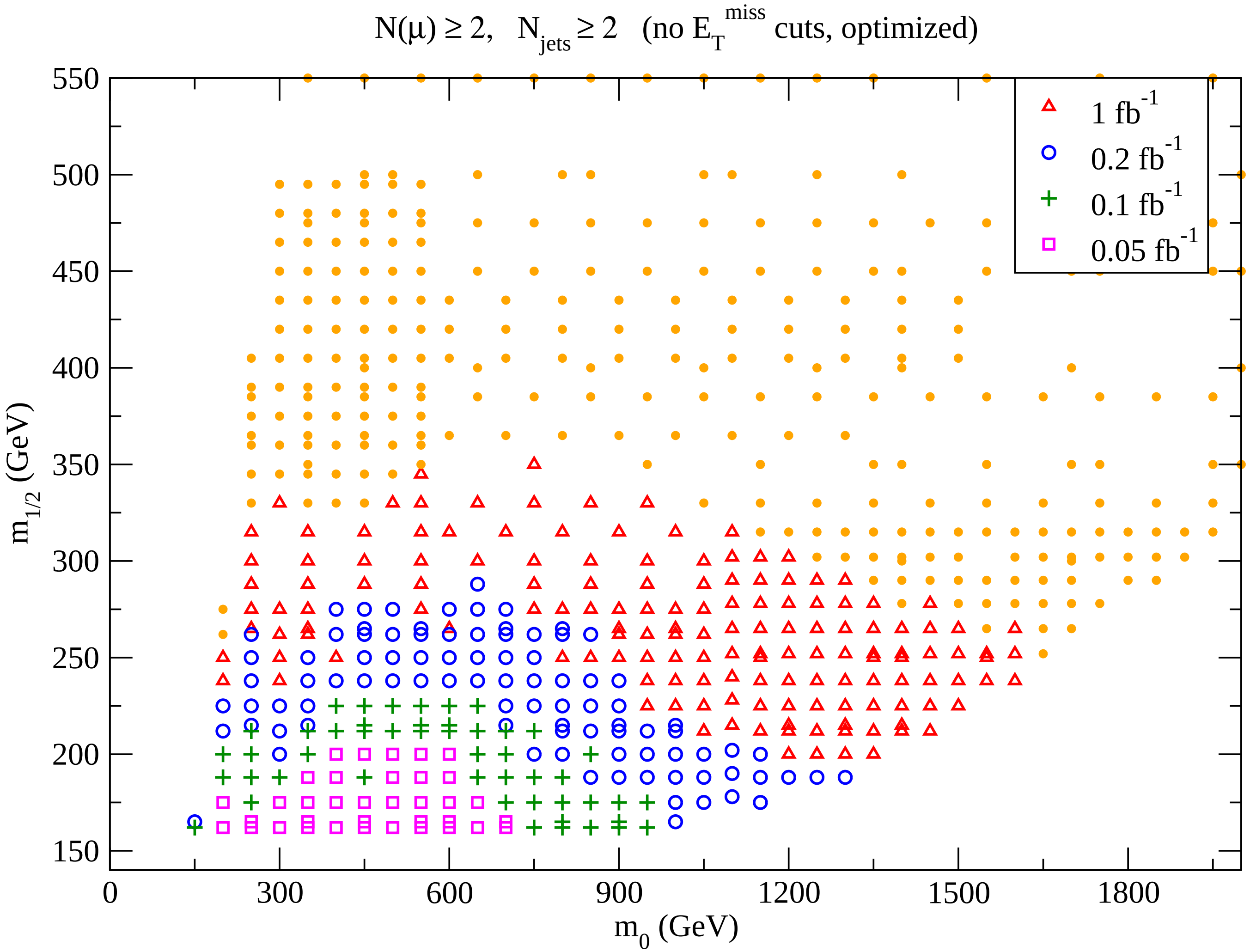
- Typical SUSY signals:
  - ⋆ high E_T jets
  - ⋆ high p_T isolated leptons
  - ⋆ hard isolated photons
  - ⋆ missing transverse energy E_T^{miss}
    - – most powerful
    - – most difficult
- At the early stage of the LHC, reliable data should be available on:
  - ⋆ high E_T jets
  - ⋆ high p_T isolated muons
- Is it possible to discover SUSY without information on E_T^{miss}?
- Yes, if SUSY scale is relatively low
- One has to concentrate on events with high jet/muon multiplicity

Cross sections for processes with at least 4 jets at $\sqrt{s}$=10 TeV
mSUGRA: $m_0 = 450$ GeV, $M_{1/2} = 170$ GeV, A_0=0, $\tan\beta = 45$, $\mu > 0$

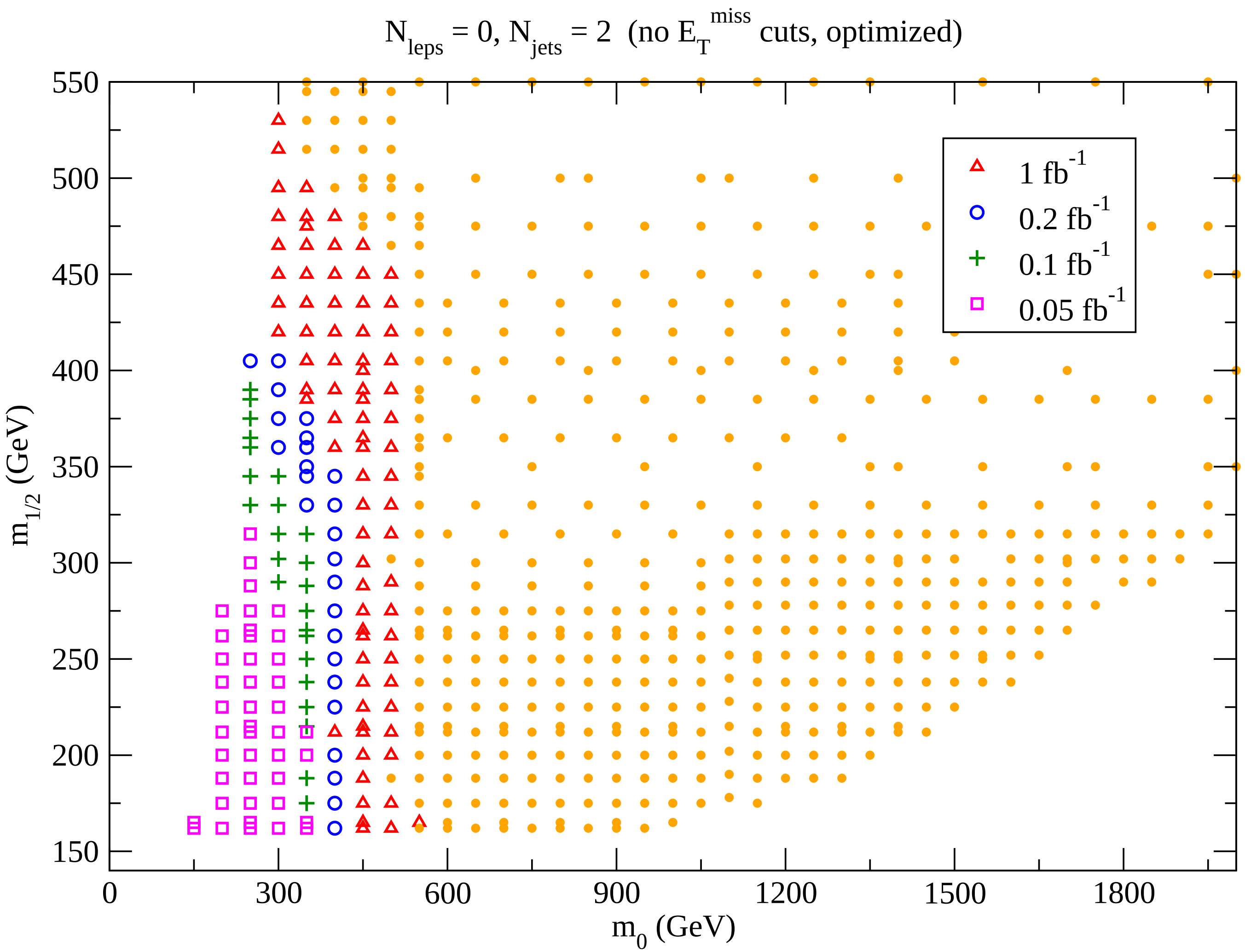


H. Baer, V. Berger, A. Lessa and X. Tata, JHEP 09 (2009) 063

Reach of LHC at $\sqrt{s}$=10 TeV (without any E_T^{miss} requirements) for mSUGRA with A_0=0, $\tan\beta = 45$, $\mu > 0$

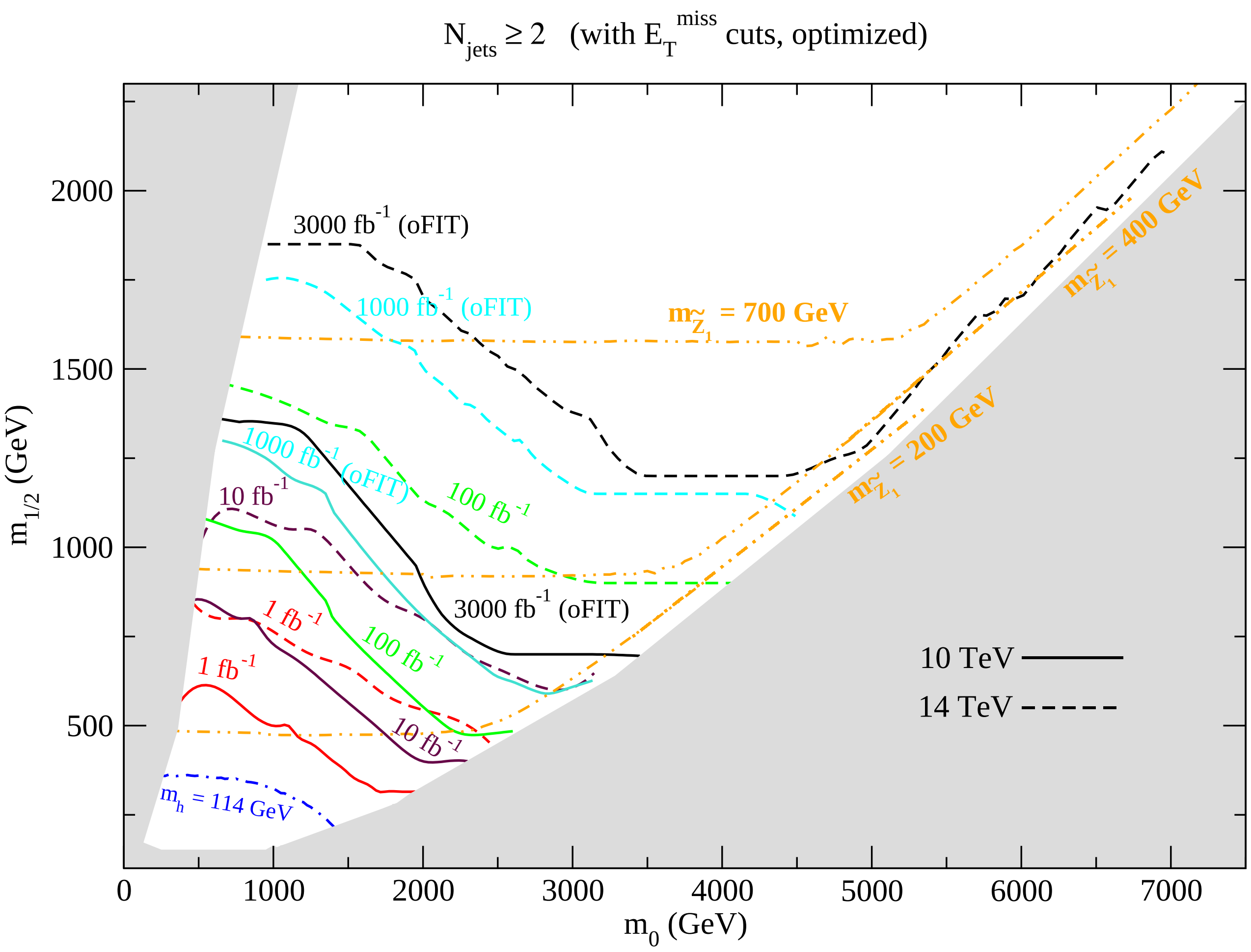


Gluino with mass up to ∼650 GeV for integrated luminosity 200 pb^{-1} (up to ∼500 GeV if $m_0 > 1$TeV)



With electron identification (but still without information on E_T^{miss}) one can test the gluino masses up to about 1 TeV with 200 pb^{-1} (for small boundary value of soft scalar mass)

Unfortunately, in mSUGRA there is a problem with the Higgs mass!



To have $m_h > 114$ GeV one needs $M_{\tilde{g}} > 900$ GeV or $m_0 > 1500$ GeV

RG running of soft parameters

Softy SUSY breaking masses at the electroweak scale, M_i and m_a^2, are determined by their initial high energy values, $\overline{M}_i$ and $\overline{m}_b^2$, and the RG running

$$M_i = \frac{\alpha_i}{\overline{\alpha}_i} \overline{M}_i$$

$$m_a^2 = \sum_b c_a^b \, \overline{m}_b^2 + \sum_{i,j} C_a^{ij} \, \overline{M}_i \overline{M}_j + \ldots$$

The coefficients c_a^b and C_a^{ij} depend on the energy scale as well as on the gauge and the Yukawa couplings (effectively also on $\tan\beta \equiv v_2/v_1$)

Radiative EW symmetry breaking

When the SU(2)×U(1) symmetry is broken, the Z boson becomes massive

$$\frac{1}{2}M_{\mathrm{Z}}^2 \approx \frac{m_{\mathrm{H}_1}^2 - m_{\mathrm{H}_2}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

For not too small $\tan\beta$, radiative EWSB is triggered by negative $m_{\mathrm{H}_2}^2$:

$$\frac{1}{2}M_{\mathrm{Z}}^2 \approx -m_{\mathrm{H}_2}^2 - \mu^2$$

The soft H_2 mass squared may turn negative at some energy scale because the top Yukawa coupling is large $\left[t = (4\pi)^{-2} \ln\left(M_{\mathrm{GUT}}^2/Q^2\right)\right]$

$$\frac{\mathrm{d}}{\mathrm{d}t} m_{\mathrm{H}_2}^2 = 3g_2^2 M_2^2 + g_1^2 M_1^2 - 3\sum_F \left(h_{\mathrm{U}}^F\right)^2 \left(m_{\mathrm{Q_F}}^2 + m_{\mathrm{U_F}}^2 + m_{\mathrm{H}_2}^2 + A_{\mathrm{U_F}}^2\right)$$

There is no explicite M_3-dependence but gluino mass is essential for the evolution of $m_{\mathrm{H}_2}^2$ via e.g.

$$\frac{\mathrm{d}}{\mathrm{d}t} m_{\mathrm{Q_F}}^2 = \frac{16}{3} g_3^2 M_3^2 + \ldots - \left(h_{\mathrm{U}}^F\right)^2 \left(m_{\mathrm{Q_F}}^2 + m_{\mathrm{U_F}}^2 + m_{\mathrm{H}_2}^2 + A_{\mathrm{U_F}}^2\right)$$

Fine tuning

For the universal boundary conditions: $\overline{m}_a^2 = m_0^2$, $\overline{M}_i = M_{1/2}$

$$\frac{1}{2}M_Z^2 \approx -m_{H_2}^2 - \mu^2 = -\Big(\mathcal{O}(-3)M_{1/2}^2 + c_{H_2}^0\, m_0^2 + \ldots\Big) - \mu^2$$

The electroweak scale ($\sim M_Z$) is fine tuned if the individual terms on the r.h.s. are much bigger than $\frac{1}{2}M_Z^2$

For positive $c_{H_2}^0$, the r.h.s. is dominated by the first term

Heavy Higgs (>114 GeV) requires heavy stops (at least 1-2 TeV)

$$m_Q^2 = \mathcal{O}(5)M_{1/2}^2 + \mathcal{O}(0.5)m_0^2 + \ldots$$

$\Rightarrow$ strong fine tuning if the gaugino contribution makes stops heavy

The fine tuning may be weaker if

- $M_{1/2}^2 \lesssim 0.1 m_0^2$
- $|c_{H_2}^0| \lesssim 0.3$

Focus point

$|c^0_{\mathrm{H}_2}|$ indeed is small for some values of m_t and $\tan\beta$

In some cases $c^0_{\mathrm{H}_2}$ is small and negative
so $m^2_{\mathrm{H}_2}$ may be negative even for very small $M_{1/2}$

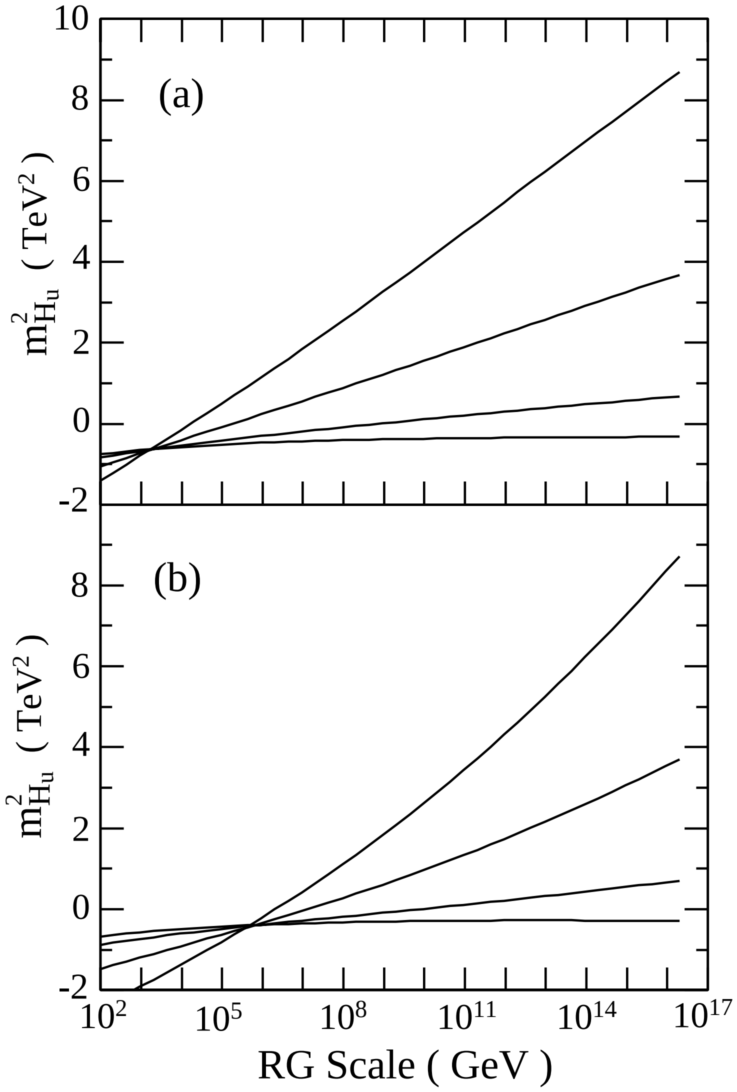
Soft scalar masses (instead of gaugino masses) may drive the radiative EWSB

M. O. and S. Pokorski, Nucl. Phys. B404 (1993) 590

M. O. and S. Pokorski, Phys. Lett. B344 (1995) 201

J.L. Feng and T. Moroi, Phys. Rev. D61 (2000) 095004

Focus point



focus point:
energy scale at which $c^0_{H_2} = 0$

smaller $|c^0_{H_2}| \Rightarrow$ weaker fine tuning
negative $c^0_{H_2} \Rightarrow$ gluino may be light

most desirable position of focus point:
just above the electroweak scale

the actual position depends on $\tan\beta$
(also on gauge couplings and top mass)

J.L. Feng and T. Moroi, Phys. Rev. D61 (2000) 095004

Focus point

Approximate RGE running of $m^2_{H_2}$ for large $\tan\beta$ $\qquad\qquad [Y = h^2/(16\pi^2)]$

$$m^2_{H_2}(t) \approx \left(1 - \frac{9}{7}\frac{Y_t(t)}{Y_{\rm fix}(t)}\right) m_0^2 + \ldots \approx \left(1 - \frac{9}{7 + \frac{4\pi}{\overline{Y}_t F(t)}}\right) m_0^2 + \ldots$$

$$F(t) = \int_0^t (1 + 4\pi\overline{\alpha}_3 b_3\, t')^{\frac{16}{3b_3}} (1 + 4\pi\overline{\alpha}_2 b_2\, t')^{\frac{3}{b_2}} (1 + 4\pi\overline{\alpha}_1 b_1\, t')^{\frac{13}{9b_1}}\, dt'$$

Approximate position of the focus point t: $F(t) = 4\pi / \left[(9 - 7)\overline{Y}_t\right]$

For small (close to 1) values of $\tan\beta$: 7 should be replaced with 6

$\Rightarrow F(t_{\rm f.p.})_{\rm large\,\tan\beta} > F(t_{\rm f.p.})_{\rm small\,\tan\beta}$

$\Rightarrow (Q_{\rm f.p.})_{\rm large\,\tan\beta} < (Q_{\rm f.p.})_{\rm small\,\tan\beta}$

Asymptotic (very large t) values of $c^0_{H_2}$:

$c^0_{H_2} \rightarrow -\frac{2}{7}$ for large $\tan\beta$

$c^0_{H_2} \rightarrow -\frac{2}{6}$ for small $\tan\beta$

Focus point and large $\tan\beta$

Models with large $\tan\beta$ are very interesting

M. O. and S. Pokorski, Phys. Lett. B214 (1988) 393

- Better working focus point
  - ⋆ less fine tuning for heavy stops
  - ⋆ lighter gluinos allowed
- Motivated by SO(10) GUTs
  - ⋆ $\left(\overline{Y}_t \approx \overline{Y}_b\right) \Rightarrow (\tan\beta \approx m_t/m_b)$

But:

- Radiative EWSB requires more care
  - ⋆ $m^2_{\mathrm{H}_1}$ may evolve faster and become smaller than $m^2_{\mathrm{H}_2}$
  - ⋆ solution: non-universal initial soft scalar masses

D. Matalliotakis and H.P. Nilles, Nucl. Phys. B435 (1995) 115

M. O. and S. Pokorski, Phys. Lett. B344 (1995) 201

Radiative EWSB for large $\tan\beta$ with non-universal soft masses

Approximate RGE solutions for $\overline{m}_a^2 = (1+\delta_a)\, m_0^2$:

$$m_{\mathrm{H}_2}^2 \approx \left\{ 1 - \frac{9Y_t}{7Y_{\mathrm{fix}}} + \delta_{H_2} - \frac{3Y_t}{14Y_{\mathrm{fix}}} \left(2\delta_Q + \delta_U + \delta_D + \delta_{H_1} + \delta_{H_2}\right) + \frac{3}{10}\left[1 - \left(1 - \frac{Y_t}{Y_{\mathrm{fix}}}\right)^{5/7}\right] \left(\delta_U - \delta_D + \delta_{H_2} - \delta_{H_1}\right) \right\} m_0^2 + \ldots$$

$$m_{\mathrm{H}_1}^2 - m_{\mathrm{H}_2}^2 \approx \left\{ \left[\frac{2}{5} + \frac{3}{5}\left(1 - \frac{Y_t}{Y_{\mathrm{fix}}}\right)^{\frac{5}{7}}\right] \left(\delta_{H_1} - \delta_{H_2}\right) + \frac{3}{5}\left[1 - \frac{3}{5}\left(1 - \frac{Y_t}{Y_{\mathrm{fix}}}\right)^{\frac{5}{7}}\right] \left(\delta_U - \delta_D\right) \right\} m_0^2 + \ldots$$

- $\{\ldots\}$ in $m_{\mathrm{H}_1}^2 - m_{\mathrm{H}_2}^2$ should be positive (correct EWSB)
  - ⋆ $\delta_{\mathrm{H}_1} > \delta_{\mathrm{H}_2}$ and/or $\delta_{\mathrm{U}} > \delta_{\mathrm{D}}$
- $\{\ldots\}$ in $m_{\mathrm{H}_2}^2$ should be small (focus point close to the weak scale)
  - ⋆ $\delta_{H_2} > \left(2\delta_Q + \delta_U + \delta_D + \delta_{H_1}\right)/5$ (but not too big)
  - ⋆ negative: very light gluino possible
  - ⋆ positive: moderately light gluino and higgsino LPS

M. O. and S. Pokorski, Phys. Lett. B344 (1995) 201

Soft scalar masses in SO(10) GUT

The soft scalar masses just below the SO(10) GUT scale are non-universal even if they are universal at the Planck scale. There are two reasons:

- In SO(10) GUT
  matter fields belong to 16-dim. representations
  Higgs fields belong to a 10-dim. representation
  Their soft masses evolve differently between the Planck scale and the GUT scale

- Non-vanishing charge-dependent D-terms are generated
  when the rank of the gauge symmetry group is reduced

$$\left\{ \begin{array}{c} \overline{m}^2_{\mathrm{H}_1} \\ \overline{m}^2_{\mathrm{H}_2} \end{array} \right\} = \overline{m}^2_{10} + \left\{ \begin{array}{r} 2 \\ -2 \end{array} \right\} M^2_D \qquad \left\{ \begin{array}{c} \overline{m}^2_{\mathrm{Q}} \\ \overline{m}^2_{\mathrm{U}} \\ \overline{m}^2_{\mathrm{D}} \end{array} \right\} = \overline{m}^2_{16} + \left\{ \begin{array}{r} 1 \\ 1 \\ -3 \end{array} \right\} M^2_D$$

Y. Kawamura, H. Murayama and M. Yamaguchi, Phys. Rev. D51 (1995) 1337

N. Polonsky and A. Pomarol, Phys. Rev. D51 (1995) 6532

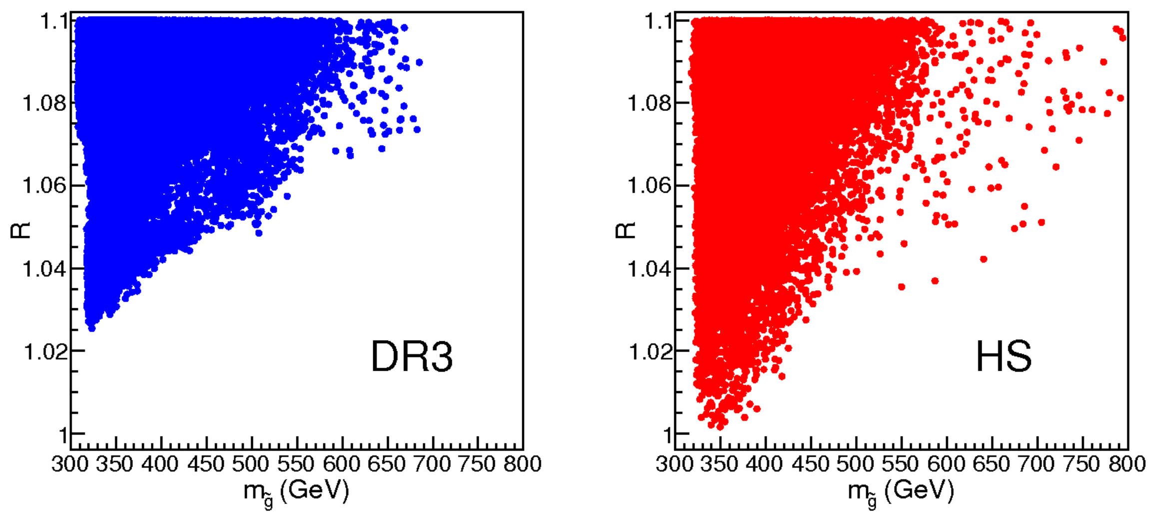
H. Murayama, M. O. and S. Pokorski, Phys. Lett. B371 (1996) 57

Early LHC discovery potential for SUSY SO(10) GUT

Parameters at the GUT scale: $M_{1/2}$, $\overline{m}^2_{16}$, $\overline{m}^2_{10}$, M^2_D, A_0, $\tan\beta$, $\mathrm{sgn}(\mu)$

Better unification of Yukawa couplings may be achieved for lighter gluino

Two types of interesting models:
DR3: D-term splitting + Y_{ν_R} effects + $\overline{m}^2_{16}(3) \neq \overline{m}^2_{16}(1,2)$
HS: "just-so" Higgs splitting model with D-term corrections only to Higgs soft masses



$$R \equiv \frac{\max(Y_t, Y_b, Y_\tau)}{\min(Y_t, Y_b, Y_\tau)}$$

$m_{\tilde{q},\tilde{l}}(1,2) \sim 10$ TeV

$m_{\tilde{q},\tilde{l}}(3), \mu \sim 1-3$ TeV

$m_{\tilde{g}} \sim 300-500$ GeV

$m_{\chi_1^+} \sim 100-180$ GeV

$m_{\chi_1^0} \sim 50-90$ GeV

Unification of the Yukawa couplings with a given precision
$\Rightarrow$ upper bound on the gluino mass

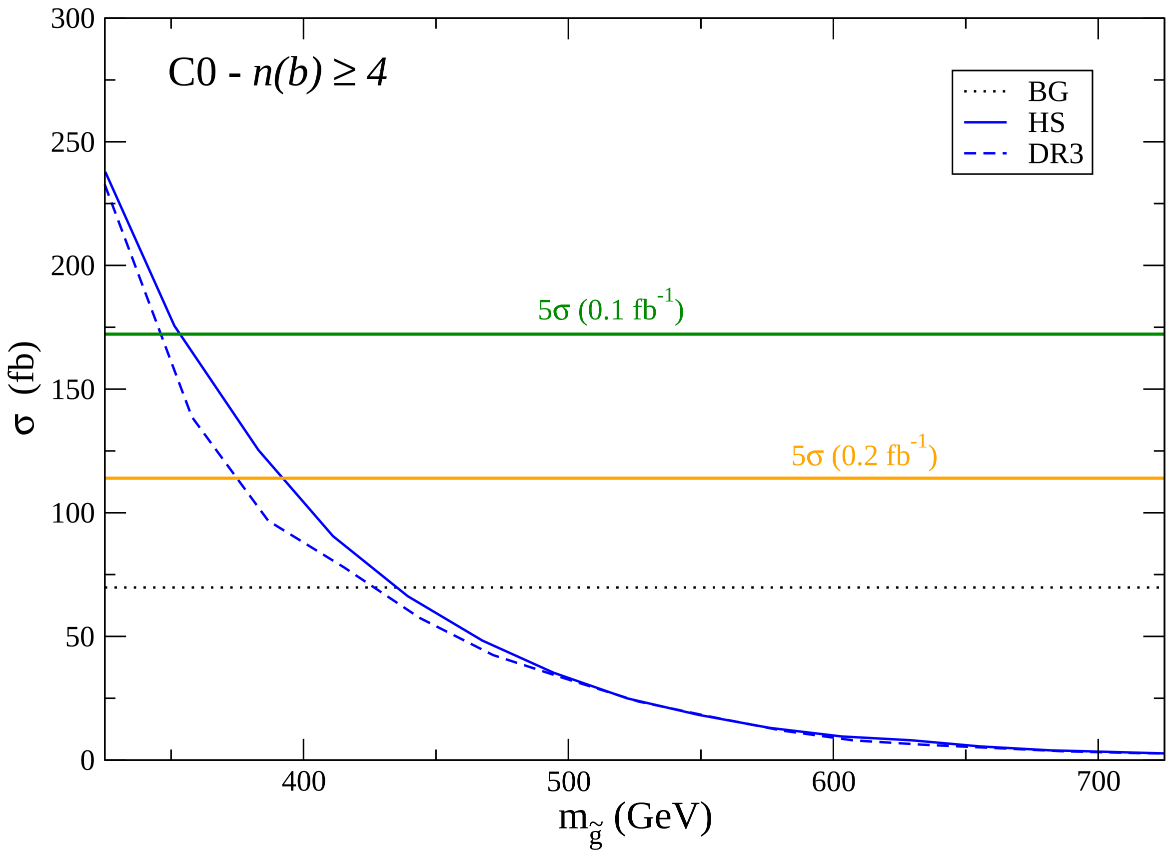
H. Bear, S. Kraml and S. Sekmen, JHEP 09 (2009) 005

CO-cuts:

$n(\text{jets}) \geq 4$, $E_T(j) \geq 50$ GeV, $\eta(j) \leq 3$, $E_T(j_1) \geq 100$ GeV

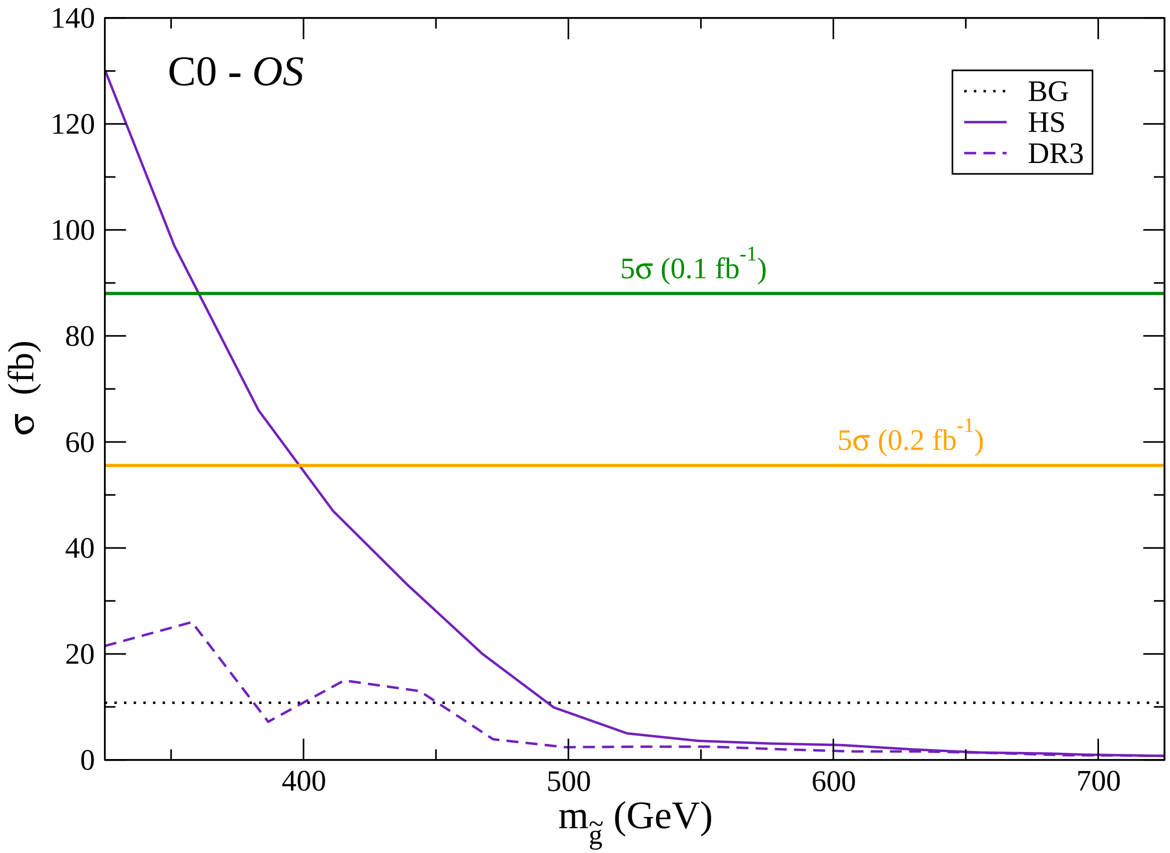
$E_T(\mu) \geq 10$ GeV, $\eta(\mu) \leq 2$

$S_T \geq 0.2$



$\sqrt{s} = 7$ TeV

	HS	DR3
$\overline{m}_{16}(1,2)$	10000.0	11805.6
$\overline{m}_{16}(3)$	10000.0	11840.1
$\overline{m}_{10}$	12053.5	13903.3
M_D	3287.1	1850.6
A_0	-19947.3	-22786.2
$\tan\beta$	50.398	50.002
$M_{1/2}$	30–180	
R	1.03–1.13	1.03–1.16



OS:
opposite sign muons

Muons come from:

$$\tilde{g} \longrightarrow \chi_2^0 + b\bar{b}$$
$$\hookrightarrow \chi_1^0 + \mu\bar{\mu}$$

DR3: $\tilde{b}_1 \sim \tilde{b}_R$
HS: $\tilde{b}_1 \sim \tilde{b}_L$
in both models $\chi_2^0 \sim \tilde{Z}$

BR($\tilde{g} \longrightarrow \chi_2^0 + b\bar{b}$):
HS $> 60\%$
DR3 $\approx 10\%$

Early LHC discovery potential for SO(10) GUT models

- $m_{\tilde{g}}$ up to $\sim$400 GeV for 200 pb^{-1} at $\sqrt{s} = 7$ TeV, without E_T^{miss} data
- $m_{\tilde{g}}$ up to $\sim$630 GeV for 1 fb^{-1} at $\sqrt{s} = 7$ TeV, with E_T^{miss} data

Boundary condition for gaugino masses

- For universal gaugino masses at the GUT scale we obtain $M_1 \approx \frac{1}{2}M_2 \approx \frac{1}{6}M_3$ at the electroweak scale
- For $M_3 \lesssim 500$ GeV: not much room for neutralino (chargino) masses between the present experimental lower limits and 1/6 (1/3) of a light gluino mass
- But:
  light gluinos do not necessarily require very light neutralinos and/or charginos because the gaugino masses may be non-universal at the GUT scale
- Gluinos lighter than $6M_1$ ($3M_2$) may help in solving the gravitino problem in supergravity models
- There are models giving non-universal boundary gaugino masses
  - ⋆ Compressed SUSY
  - ⋆ Mirage mediation of SUSY breaking
  - ⋆ General gauge mediation of SUSY breaking

Compressed SUSY, SU(5) example:

SUSY broken by F-term transforming as $(24 \times 24)_S = (1 + 24 + 75 + 200)$

$$\overline{M}_1 = M_{1/2}(1 + C_{24} + 5C_{75} + 10C_{200})$$
$$\overline{M}_2 = M_{1/2}(1 + 3C_{24} - 3C_{75} + 2C_{200})$$
$$\overline{M}_3 = M_{1/2}(1 - 2C_{24} - C_{75} + C_{200})$$

For $C_{24} = 0.2$, $C_{75} = C_{200} = 0$ we get: $\overline{M}_1 : \overline{M}_2 : \overline{M}_3 = 6 : 8 : 3$
After RGE running we get $M_3 \sim M_2$ at the electroweak scale

Proposed to solve simultaneously two problems:

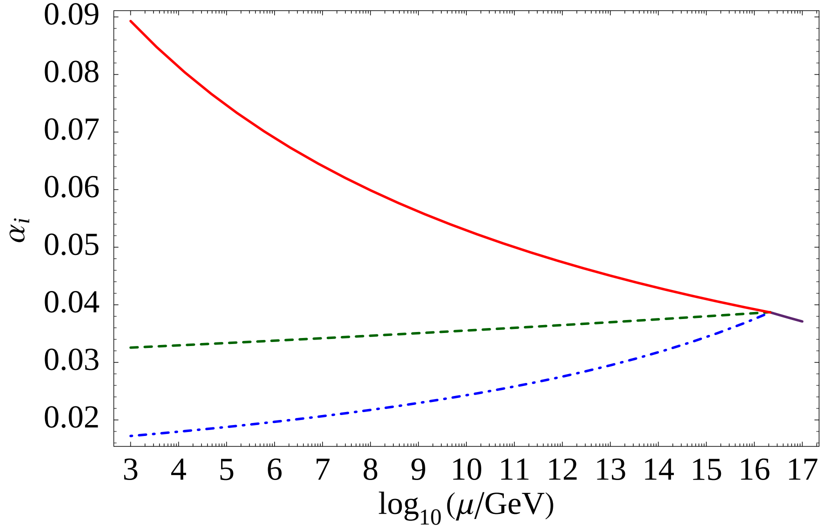
- supersymmetric little hierarchy problem
- problem of typically too high relic abundance of bino-like neutralino LSP

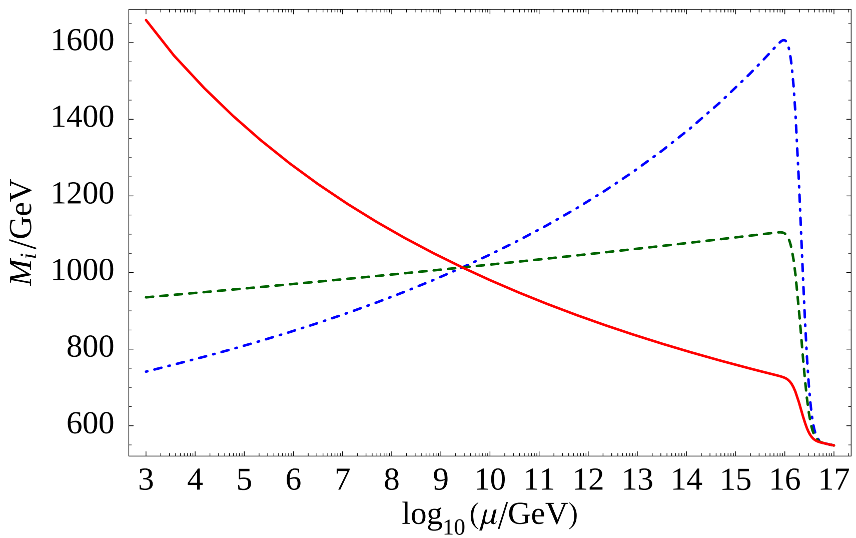
S.P. Martin, Phys. Rev. D75 (2007) 115005

Mirage mediation of SUSY breaking

Competition between gravity (modulus) and anomaly (loop) mediation of SUSY breaking

$$\overline{M}_i \approx \frac{m_{3/2}}{16\pi^2}\left(a + b_i g_i^2\right)$$





K. Choi, K.S. Jeong, T. Kobayashi and K. Okumura, Phys. Lett. B633 (2005) 355

O. Loaiza-Brito, J. Martin, H.P. Nilles and M. Ratz, Proceeding of PLANCK'05, hep-ph/0509158

General Gauge Mediation of SUSY breaking

SUSY breaking is communicated to the visible sector by N messenger pairs $R^{(r)} + \bar{R}^{(r)}$, $r = 1, \ldots, N$

$R^{(r)}$ - GUT representation decomposing into N_r representations $R_1^{(r)}, \ldots, R_{N_r}^{(r)}$ of the SM gauge group.

$$\overline{M}_i = \frac{g_i^2}{16\pi^2} \Lambda_i = \frac{g_i^2}{16\pi^2} \sum_{r=1}^{N} \sum_{s=1}^{N_r} d_{r,s} \xi_{r,s}$$

$$\overline{m}_a^2 = 2 \sum_{i=1}^{3} \left(\frac{g_i^2}{16\pi^2} \right)^2 C_r^{(a)} \widetilde{\Lambda}_i^2 = 2 \sum_{i=1}^{3} \left(\frac{g_i^2}{16\pi^2} \right)^2 C_r^{(a)} \sum_{r=1}^{N} \sum_{s=1}^{N_r} d_{r,s} \xi_{r,s}^2$$

$C_r^{(a)}$ - Casimir invariants; $d_{r,s}$ - Dynkin indices; $\xi_{r,s}$ - mass scales (F/X)

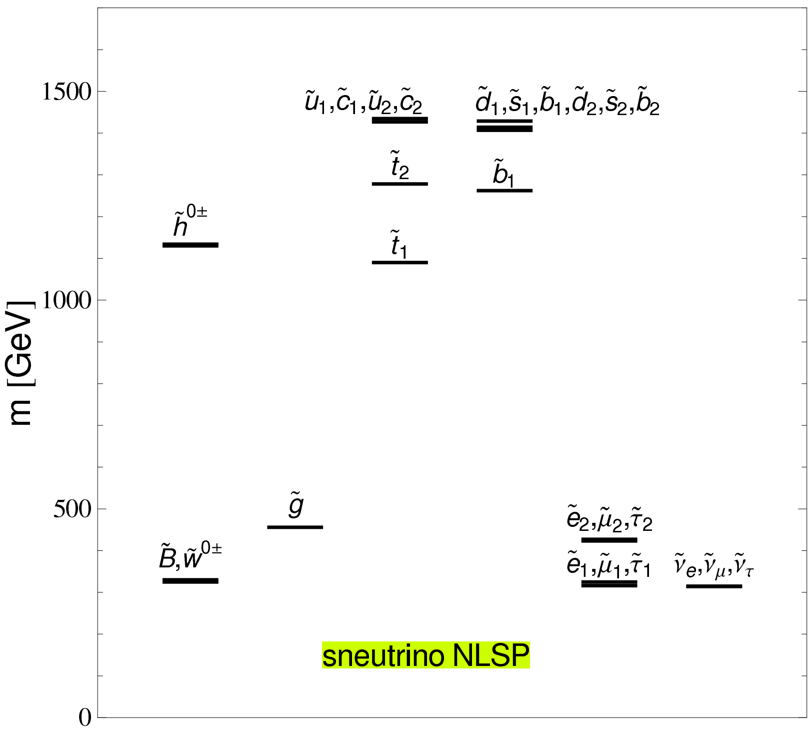
Much freedom but one should not spoil e.g. the perturbative unification of the SM gauge coupling constants

P. Maeda, N. Seiberg and D. Shih, Prog. Theor. Phys. Suppl. 177 (2009) 143

L.M. Carpenter, M. Dine, G. Festuccia and J.D. Mason, Phys. Rev. D79 (2009) 035002

Example:

Just one pair of messengers (e.g. $40 + \overline{40}$ or $45 + \overline{45}$ of SU(5)) may produce small boundary value of the gluino mass $\overline{M}_3$ as compared to other gaugino masses and to squark masses



Example of spectrum giving:

- heavy enough Higgs
- interesting relic abundance of the LSP (gravitino)
- small enough corrections to BBN
- maximal reheating temperature high enough for leptogenesis
- $M_{\tilde{g}} \sim 1.5 m_{NLSP}$

M. O., S. Pokorski, K. Turzyński and J.D. Wells, JHEP 0912 (2009) 026

SUMMARY

- Some supersymmetric models with light gluino can be tested during the first year of the LHC operation
- Examples of "light gluino" for integrated luminosity of 200 pb^{-1}
  - $M_{\tilde{g}}$ up to ∼600 (1000) GeV in mSUGRA ($\sqrt{s} = 10$ TeV) (m_h?)
  - $M_{\tilde{g}}$ up to ∼400 GeV in SO(10) GUT ($\sqrt{s} = 7$ TeV)
- Light gluino is attractive from a phenomenological point of view
  - radiative EWSB and fine tuning
  - focus point and large $\tan\beta$
  - reheating temperature and BBN constraints
- Non-universal boundary values of soft masses needed and interesting
- Gluino must be light and $\tan\beta$ is large in SUSY SO(10) models
- Interesting models in which gluino mass is smaller than in mSUGRA
  - more general soft SUSY breaking terms (e.g. compressed SUSY)
  - mirage mediation of SUSY breaking
  - general gauge mediation of SUSY breaking