Compressed Supersymmetry from Gauge Coupling Unification

Martin W. Winkler

in collaboration with S. Krippendorf, H.P. Nilles, M. Ratz

Planck 2013, Bonn

May 21 2013

Outline

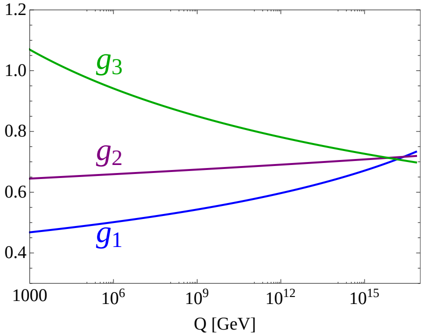
1. Analytic discussion of gauge coupling unification
2. Precision gauge unification in realistic models
3. Phenomenology: Implications for LHC, dark matter

Gauge coupling unification

- gauge coupling unification strong motivation for Supersymmetry

  Dimopoulos et al., Phys. Rev. **D24** (1981)

- running gauge couplings in the MSSM



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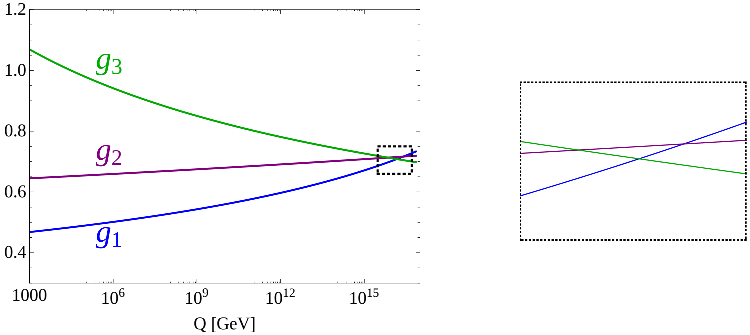


- **BUT:** g_i miss by a few per cent in minimal models

Gauge couplings at the high scale

$$\frac{1}{g_i^2(M_{\text{GUT}})} = \frac{1}{g_i^2(M_Z)} - \frac{b_i}{8\pi^2}\ln\left(\frac{M_{\text{GUT}}}{M_Z}\right) + \frac{1}{g_{i,\text{Thr}}^2} + \cdots$$

- $\frac{1}{g_i^2(M_Z)}$: gauge couplings at M_Z
- $\frac{b_i}{8\pi^2}\ln\left(\frac{M_{\text{GUT}}}{M_Z}\right)$: one-loop running

$$b_i = \begin{cases} 33/5 \\ 1 \\ -3 \end{cases}$$

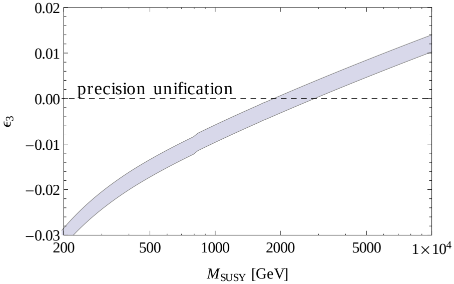
- $\frac{1}{g_{i,\text{Thr}}^2}$: thresholds
- $\cdots$: higher orders

- thresholds:
  - heavy Standard Model fields (top, Higgs)
  - supersymmetric particles
  - GUT thresholds

Precision unification in the MSSM

- in this talk: gauge coupling unification **without GUT thresholds**
  - UV models with precision unification $\hookrightarrow$ *talk by M. Ratz*
- simple example: MSSM superpartners + heavy Higgs at M_{SUSY}

$$\frac{1}{g_{i,\text{Thr}}^2} = \frac{b_i - b_i^{\text{SM}}}{8\pi^2} \ln\left(\frac{M_{\text{SUSY}}}{M_Z}\right)$$



$$\epsilon_3 = \left.\frac{g_3^2 - g_{1,2}^2}{g_{1,2}^2}\right|_{M_{\text{GUT}}}$$

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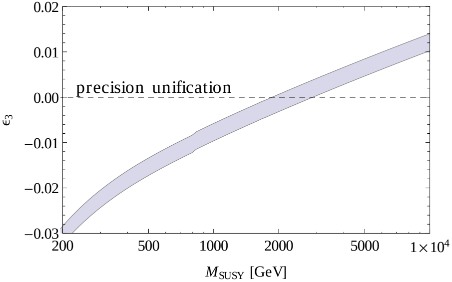

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precision unification for $M_{\text{SUSY}} \sim 2$ TeV

Realistic models

- superpartners not mass-degenerate: define effective M_{SUSY}

  Carena et al., Nucl. Phys. **B406** (1993)

- interpretation: same effect on gauge couplings as if all superpartners had a common mass M_{SUSY} (up to changes of g, M_{GUT})

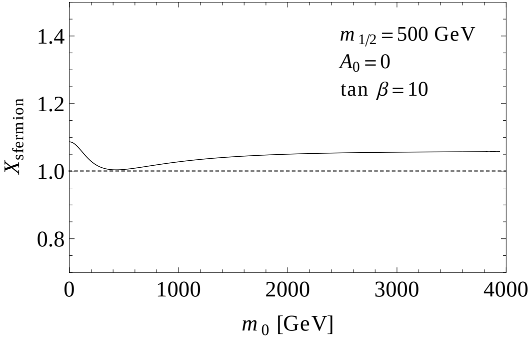
$$M_{\text{SUSY}} = \frac{m_{\widetilde{W}}^{32/19}\ m_{\tilde{h}}^{12/19}\ m_{H}^{3/19}}{m_{\tilde{g}}^{28/19}} \underbrace{\prod_{i=1\ldots3} \left(\frac{m_{\widetilde{L}_i}^{3/19}}{m_{\widetilde{D}_i}^{3/19}} \right) \left(\frac{m_{\widetilde{Q}_{L\,i}}^{7/19}}{m_{\widetilde{E}_i}^{2/19}\ m_{\widetilde{U}_i}^{5/19}} \right)}_{X_{\text{sfermion}}}$$

- $X_{\text{sfermion}} = 1$ if sfermions mass-degenerate among SU(5) multiplets
  $\hookrightarrow$ Split SUSY does not destroy gauge unification

  Arkani-Hamed et al., JHEP **0506** (2005)

Sfermion sector

- RGE running splits SU(5) multiplets
- but: effects on gauge coupling unification very small



- precision unification must be achieved in the gaugino / higgsino sector

Universal gaugino masses

- RGE running decreases $m_{\widetilde{W}}/m_{\widetilde{g}}$

  $\hookrightarrow$ unfavorable for precision gauge unification

  Carena et al., Phys. Lett. **B317** (1993), Roszkowski et al., Phys. Rev. **D53** (1995)

- for models with universal $m_{1/2}$

$$M_{\text{SUSY}} \simeq 0.3\, m_{\widetilde{h}} \left(\frac{m_{1/2}^4 \;\; m_H^3}{m_{\widetilde{h}}^7} \right)^{1/19}$$

- $M_{\text{SUSY}} \sim 2$ TeV requires super-heavy higgsinos $m_{\widetilde{h}} \sim 10$ TeV
- precision unification very unnatural in models with universal gaugino mass

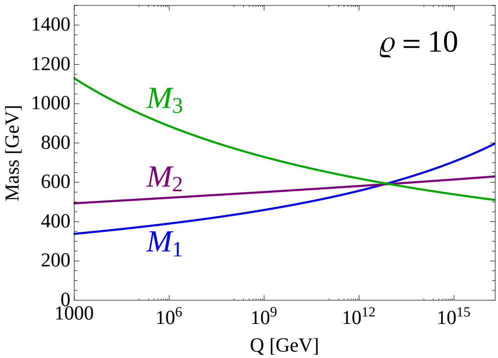
Compressed gaugino masses

- **mirage mediation**: mixed gravity / anomaly mediation

$$M_i = \frac{m_{3/2}}{16\,\pi^2}\,(\varrho + b_i\,g^2)$$

- naturally occurs in various string constructions

KKLT: Choi et al., Nucl. Phys. **B718** (2005), Choi et al. JHEP **0509** (2005), Falkowski et al. JHEP **0511** (2005)
Heterotic string string: Lowen et al., Phys. Rev. **D77** (2005), Krippendorf et al., Phys. Lett. **B712** (2012)



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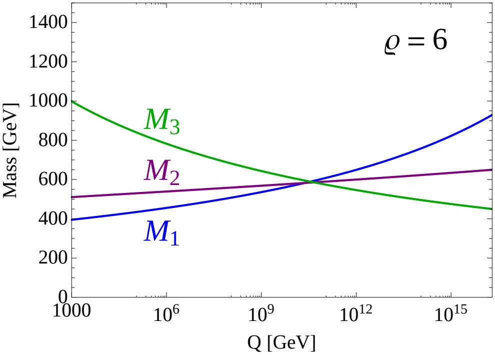

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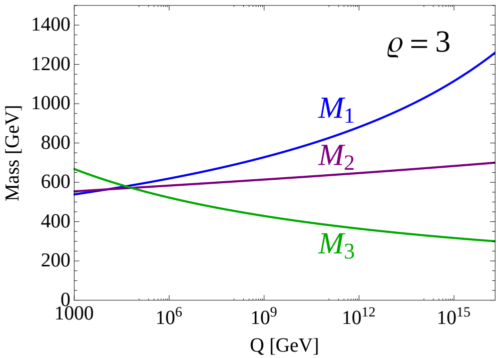
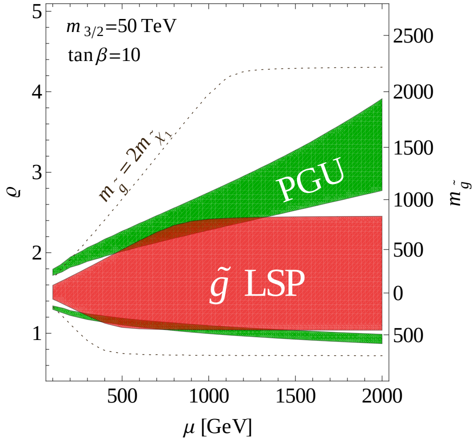


Precision gauge unification in mirage mediation

- scalar masses model-dependent, but hardly affect gauge unification
- we set $m_{\text{sfermion}} = m_H = m_0$ which we fix such that $m_h = 126$ GeV
  $\hookrightarrow m_0 = \mathcal{O}(10 \text{ TeV})$ (not unnatural due to focus point)



- precision unification can be achieved with small μ
- **compressed spectrum**

$$m_{\tilde{g}} < 2\, m_{\tilde{\chi}_1}$$

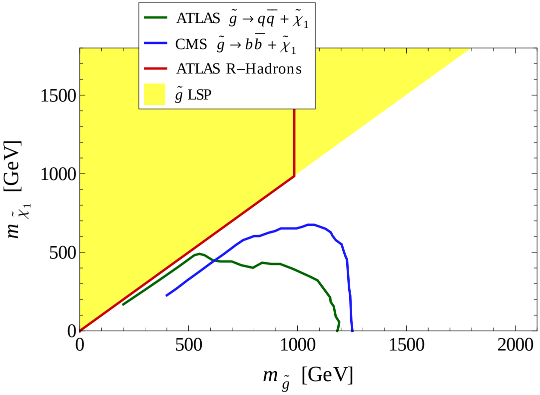
Compressed spectrum at the LHC

- small mass splitting $\Delta m = m_{\widetilde{g}} - m_{\widetilde{\chi}_1}$
  $\hookrightarrow$ gluino decay yields soft jets
- difficult to detect, initial state radiation required
  LeCompte et al., Phys. Rev. **D84** (2011), Dreiner et al., Europhys. Lett. **99** (2012)
- ATLAS, CMS performed searches in simplified models assuming

$$pp \rightarrow \widetilde{g}\widetilde{g} \rightarrow 2\,q\bar{q} + 2\,\chi_1 \quad \text{or}$$
$$pp \rightarrow \widetilde{g}\widetilde{g} \rightarrow 2\,b\bar{b} + 2\,\chi_1$$

  ATLAS-CONF-2012-109, CMS-PAS-SUS-13-007
- for gluino LSP: searches for stable R-hadrons
  ATLAS collaboration, Phys. Lett. **B720** (2013)

Precision unification at the LHC



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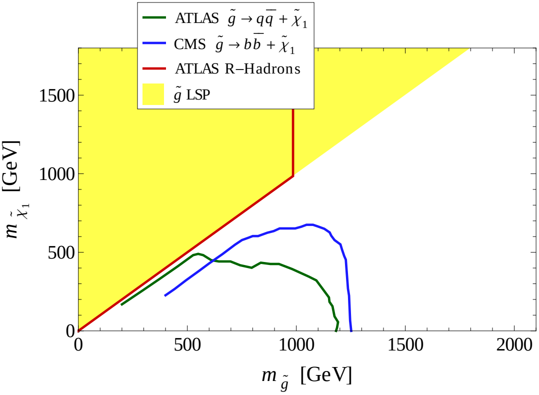
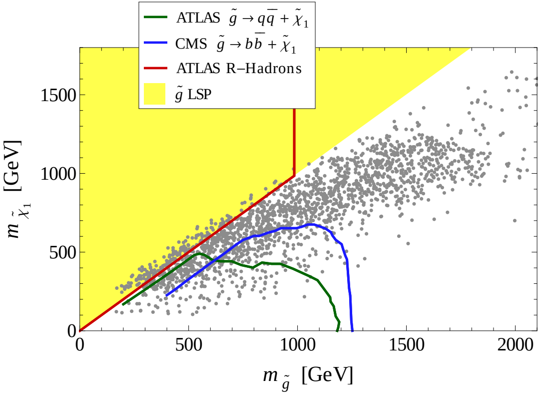


- we generated a large benchmark sample with random

$$\varrho = 0.5\text{–}30 \quad m_{3/2} = \frac{40 - 200\ \text{TeV}}{\varrho} \quad \mu = 0.1\text{–}2\text{TeV} \quad \tan\beta = 10\text{–}50$$

- required precision gauge coupling unification

Precision unification at the LHC



many viable points with $m_{\tilde{g}} < 1$ TeV

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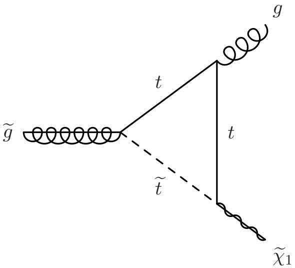
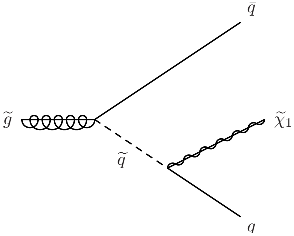
Gluino decays



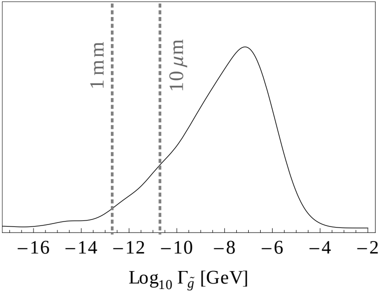


$$\Gamma \propto \text{higgsino fraction} \times \frac{\Delta m^3\, m_t^2}{m_{\tilde{q}}^4} \qquad \Gamma \propto \text{gaugino fraction} \times \frac{\Delta m^5}{m_{\tilde{q}}^4}$$

- gluino decay pattern encodes information about SUSY spectrum
  Haber et al., Nucl. Phys. **B232** (1984), Sato et al., JHEP **1211** (2012)
- strong suppression of $\Gamma_{\tilde{g}}$ especially for gaugino-like LSP
- displaced vertices?

Displaced vertices

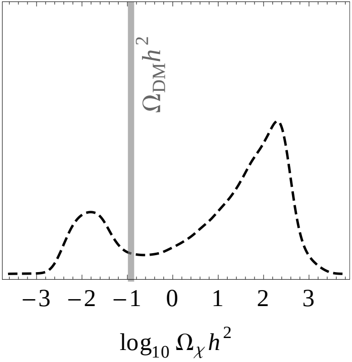
- distribution of $\Gamma_{\tilde{g}}$ among benchmark points with precision unification



- $\sim 10\%$ of benchmark points have $c/\Gamma_{\tilde{g}} = 10\,\mu\text{m} - 10\,\text{mm}$
- $\Gamma_{\tilde{g}}$ very sensitive to squark sector, could even be larger
- possibly detectable (e.g. transverse impact parameter)
- may affect *b*-tagging

Dark matter

- lightest neutralino very good dark matter candidate
- **BUT:** relic density typically too large (bino) or too small (higgsino)
  Baer et al., JHEP **1010** (2010)
- compressed spectrum preferred by precision gauge unification yields **neutralino mixing**, **wino coannihilations**



- relic density with mirage boundaries
  ↪ without PGU (dashed)

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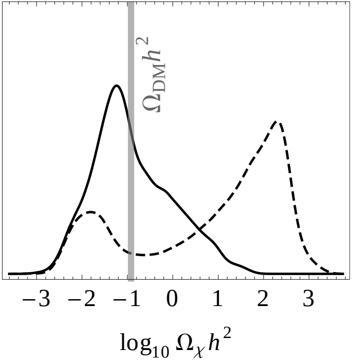


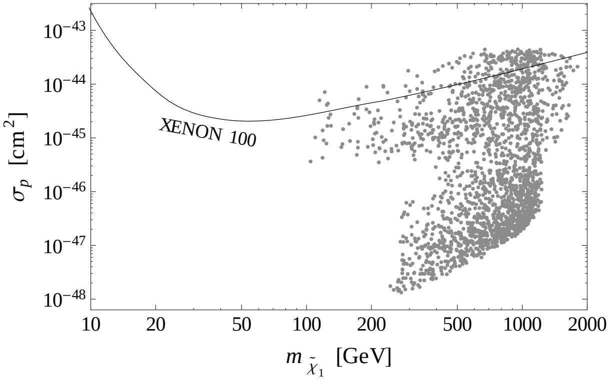
- relic density with mirage boundaries
  ↪ without PGU (dashed)
  ↪ with PGU (solid)

Direct detection

- neutralino-nucleon interactions dominated by Higgs exchange

$$\sigma_p \propto \text{higgsino-gaugino mixing}$$

- bino + wino coannihilation gives correct Ωh^2 but **tiny $\boldsymbol{\sigma_p}$**
  $\hookrightarrow$ hides from direct detection



Conclusion

- main motivations for Supersymmetry are the hierarchy problem, gauge coupling unification and dark matter
- **BUT:** non-observation of superpartners at the LHC
  gauge couplings typically miss by a few per cent
  neutralino relic density too small or too large
- in mirage mediation, the reduced ratio $m_{\widetilde{g}}/m_{\widetilde{W}}$ improves gauge coupling unification
- mirage mediation + precision unification predicts highly compressed gaugino spectrum, small $m_{\widetilde{g}} - m_{\widetilde{\chi}_1}$
- LHC bounds relaxed, $m_{\widetilde{g}} \sim 500$ GeV ok
- neutralino LSP has "automatically" the correct relic density