Compressed Supersymmetry from Gauge Coupling Unification

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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 provides strong motivation for Supersymmetry
  - Dimopoulos et al., Phys. Rev. D24 (1981)

- Running gauge couplings in the MSSM

![Graph showing running gauge couplings](image)

**BUT:**
Gauge coupling unification might not be exact in minimal models.
gauge coupling unification strong motivation for Supersymmetry
Dimopoulos et al., Phys. Rev. D24 (1981)

running gauge couplings in the MSSM

**BUT:** \( g_i \) miss by a few per cent in minimal models
\[
\frac{1}{g_i^2(M_{\text{GUT}})} = \frac{1}{g_i^2(M_Z)} - \frac{b_i}{8\pi^2} \ln \left( \frac{M_{\text{GUT}}}{M_Z} \right) + \frac{1}{g_i^2,\text{Thr}} + \ldots
\]

- gauge couplings at \( M_Z \)
- one-loop running
- \( b_i = \begin{cases} 
33/5 & 
1 
-3
\end{cases} \)
- thresholds
- higher orders

- thresholds:
  - heavy Standard Model fields (top, Higgs)
  - supersymmetric particles
  - GUT thresholds
in this talk: gauge coupling unification \textbf{without GUT thresholds}

- UV models with precision unification $\leftrightarrow$ talk by M. Ratz

- simple example: MSSM superpartners + heavy Higgs at $M_{\text{SUSY}}$

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

$\epsilon_3 = \left. \frac{g^2_3 - g^2_{1,2}}{g^2_{1,2}} \right|_{M_{\text{GUT}}}$
Precision unification in the MSSM

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

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

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

precision unification for \(M_{\text{SUSY}} \sim 2\text{ TeV}\)
Realistic models

- superpartners not mass-degenerate: define effective $M_{\text{SUSY}}$
  
  Carena et al., Nucl. Phys. B406 (1993)

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

\[
M_{\text{SUSY}} = \frac{m_{\tilde{W}}^{32/19} m_{\tilde{h}}^{12/19} m_{H}^{3/19}}{m_{\tilde{g}}^{28/19}} \prod_{i=1...3} \left( \frac{m_{\tilde{L}_i}^{3/19}}{m_{\tilde{D}_i}^{3/19}} \right) \left( \frac{m_{\tilde{Q}_{Li}}^{7/19}}{m_{\tilde{E}_i}^{2/19} m_{\tilde{U}_i}^{5/19}} \right) 
\]

- $X_{\text{sfermion}} = 1$ if sfermions mass-degenerate among SU(5) multiplets
  
  $\rightarrow$ 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 $m_{\tilde{W}}/m_{\tilde{g}}$
  $\rightarrow$ unfavorable for precision gauge unification
  Carena et al., Phys. Lett. B317 (1993), Roszkowski et al., Phys. Rev. D53 (1995)

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

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

- $M_{\text{SUSY}} \sim 2$ TeV requires super-heavy higgsinos $m_{\tilde{h}} \sim 10$ 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)
**Compressed gaugino masses**

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  Heterotic string string: Lowen et al., Phys. Rev. D77 (2005), Krippendorf et al., Phys. Lett. B712 (2012)
scalar masses model-dependent, but hardly affect gauge unification

- we set $m_{sfermion} = m_H = m_0$ which we fix such that $m_h = 126$ GeV
  $\Rightarrow m_0 = \mathcal{O}(10 \text{ TeV})$ (not unnatural due to focus point)

- precision unification can be achieved with small $\mu$
- compressed spectrum

\[ m_{\tilde{g}} < 2 m_{\tilde{\chi}_1} \]
Compressed spectrum at the LHC

- small mass splitting $\Delta m = m_{\tilde{g}} - m_{\tilde{\chi}_1}$
  $\rightarrow$ 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
  $pp \rightarrow \tilde{g}\tilde{g} \rightarrow 2 q\bar{q} + 2 \chi_1$ or
  $pp \rightarrow \tilde{g}\tilde{g} \rightarrow 2 b\bar{b} + 2 \chi_1$
  ATLAS-CONF-2012-109, CMS-PAS-SUS-13-007
- for gluino LSP: searches for stable R-hadrons
  ATLAS collaboration, Phys. Lett. B720 (2013)
many viable points with \( m_{\tilde{g}} < 1 \text{ TeV} \) we generated a large benchmark sample with random \( \varpi \approx 0.5 - 30 \), \( \varpi \mu \approx 0.1 - 2 \text{ TeV} \), \( \tan \beta \approx 10 - 50 \) required precision gauge coupling unification.
Precision unification at the LHC

- we generated a large benchmark sample with random

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

- required precision gauge coupling unification
we generated a large benchmark sample with random

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

required precision gauge coupling unification

many viable points with \( m_{\tilde{g}} < 1 \text{ TeV} \)
Gluino decays

\[ \Gamma \propto \text{higgsino fraction} \times \frac{\Delta m^3}{m_t^2} \]

\[ \Gamma \propto \text{gaugino fraction} \times \frac{\Delta m^5}{m_q^4} \]

- 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 $c/\Gamma_{\tilde{g}} = 10 \, \mu m - 10 \, mm$

- $\Gamma_{\tilde{g}}$ very sensitive to squark sector, could even be larger

- possibly detectable (e.g. transverse impact parameter)

- may affect $b$-tagging
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)
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

![Graph showing relic density with mirage boundaries](image)

- relic density with mirage boundaries
  - $\rightarrow$ without PGU (dashed)
  - $\rightarrow$ with PGU (solid)
Direct detection

- neutralino-nucleon interactions dominated by Higgs exchange

\[ \sigma_p \propto \text{higgsino-gaugino mixing} \]

- bino + wino coannihilation gives correct \( \Omega h^2 \) but tiny \( \sigma_p \)
  \( \rightarrow \) hides from direct detection

\[
\begin{align*}
\text{XENON 100}
\end{align*}
\]
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 $m_\tilde{g}/m_\tilde{W}$ improves gauge coupling unification

mirage mediation + precision unification predicts highly compressed gaugino spectrum, small $m_\tilde{g} - m_\tilde{\chi}_1$

LHC bounds relaxed, $m_\tilde{g} \sim 500$ GeV ok

neutralino LSP has “automatically” the correct relic density