Hidden SUSY from Gauge Coupling Unification

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

arXiv:1306.0574 (2013)

DESY Theory Seminar, Hamburg

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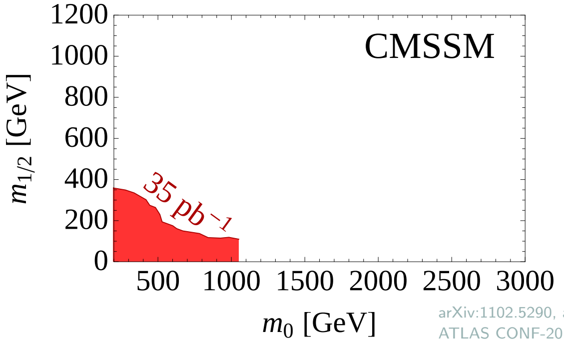

arXiv:1102.5290, arXiV:1109.6572
ATLAS CONF-2013-047

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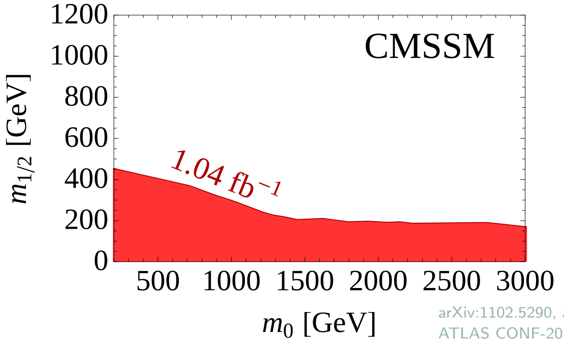

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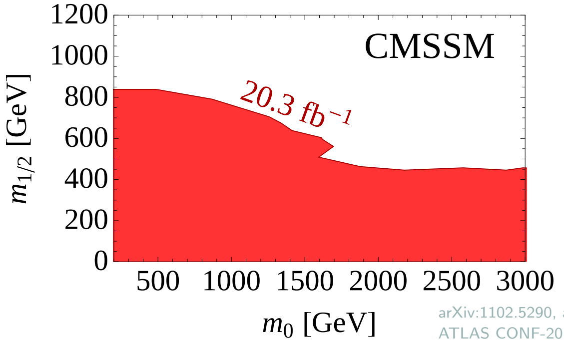

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Dark Matter

- Conserved R-parity $\hookrightarrow$ dark matter candidate
- thermal production

$$\Omega h^2 \simeq 0.1 \, \frac{\mathrm{pb}}{\langle \sigma v \rangle}$$

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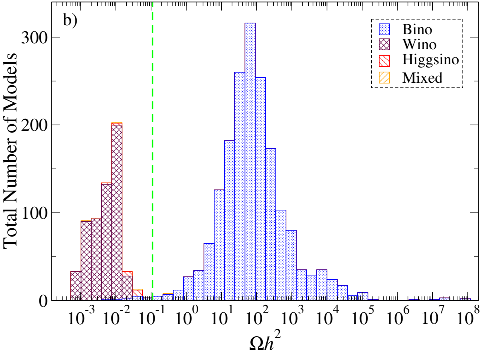
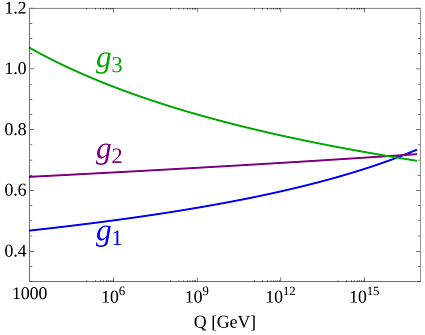


Baer et al., JHEP **1010** (2010)

Gauge coupling unification

- gauge coupling unification strong motivation for Supersymmetry
- running gauge couplings in the MSSM



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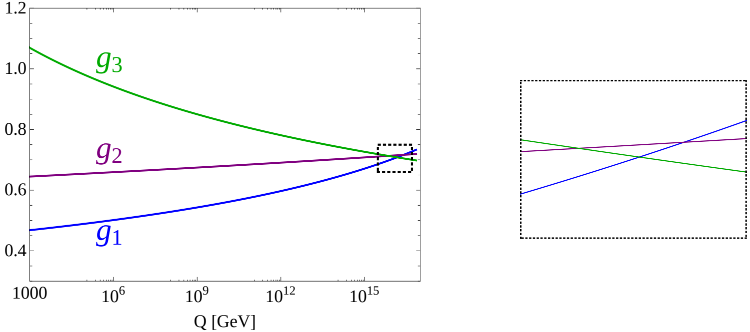


- BUT: g_i miss by a few per cent in minimal models

Outline

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

Gauge couplings at the high scale

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

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

Precision Unification in the MSSM

- In this talk: gauge coupling unification **without GUT thresholds**
  - Motivation:

    $\hookrightarrow$ candidates for UV models with PGU

    Hebecker, JHEP **0401** (2004), Hebecker et al., Nucl. Phys. **B713** (2005)
    Blaszczyk et al., Phys. Lett. **B683** (2010), Raby et al., Nucl. Phys. **B868** (2013)

    $\hookrightarrow$ proton decay

    $\hookrightarrow$ bottom up

- MSSM thresholds:

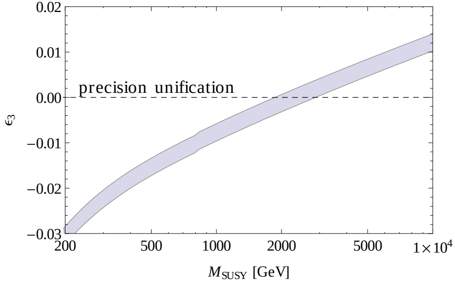
$$\frac{1}{g_{i,\mathrm{Thr}}^2} = \sum_\eta \frac{b_i^\eta}{8\pi^2} \ln\left(\frac{M_\eta}{M_Z}\right) ,$$

b_i^η: contribution of field η to beta function coefficient b_i

A simple example

- Simple example: MSSM superpartners + heavy Higgs at M_{SUSY}

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



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

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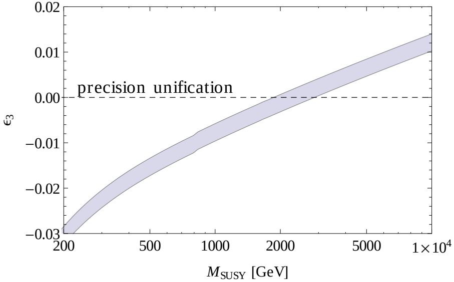

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precision unification for $M_{\mathrm{SUSY}} \sim 2$ TeV

Realistic Models

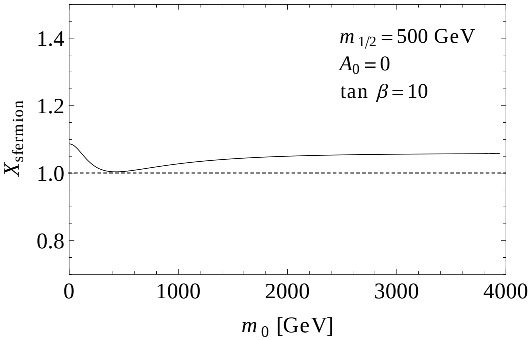
- superpartners not mass-degenerate: define effective M_{SUSY}
  Carena et al., Nucl. Phys. **B406** (1993)
- interpretation: same effect on gauge couplings as if all superpartners had a common mass M_{SUSY} (up to changes of g, M_{GUT})

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

- $X_{\text{sfermion}} = 1$ if sfermions mass-degenerate among SU(5) multiplets
  $\hookrightarrow$ Split SUSY does not destroy gauge unification
  Arkani-Hamed et al., JHEP **0506** (2005)

Sfermion Sctor

- 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
- 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

A string-inspired mediation scheme

- Heterotic MiniLandscape
  Lebedev et al., Phys. Lett. **B645** (2007), Phys. Lett. **B668** (2008), Phys. Rev. **D77** (2008)
- assume: U- and T-moduli fixed supersymmetrically
- dilaton stabilized by gaugino condensate + uplifting sector

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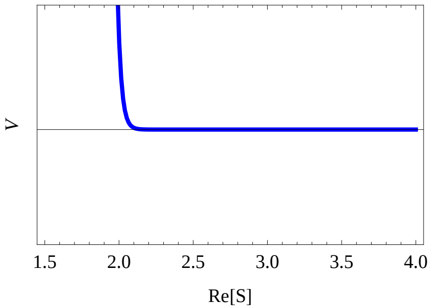

$$W = \underbrace{e^{-b\,s}}_{\text{gaugino condensate}}$$

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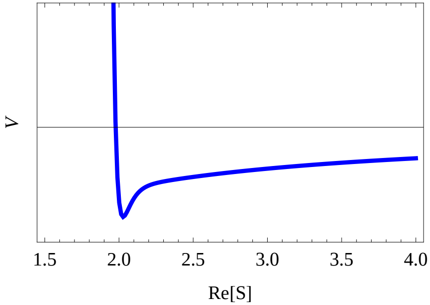

$$W = \underbrace{e^{-b\,s}}_{\text{gaugino condensate}} + \underbrace{const}_{\text{e.g. from approx R-symmetries}}$$

Brümmer et al., JHEP **1004** (2010)

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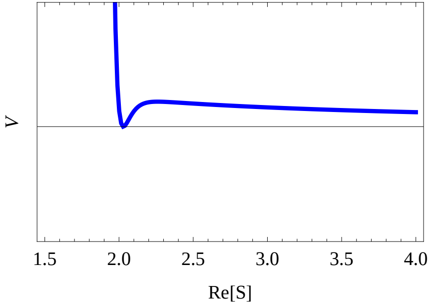

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Brümmer et al., JHEP **1004** (2010)

$$+ \underbrace{W_{\text{up}}}_{\text{uplifting by matter F-term } F_X}$$

Lebedev et al., Phys. Lett. **B636** (2006)

SUSY breaking

- SUSY breaking pattern fixed by modulus stabilization
- gravitino mass

$$m_{3/2} \sim e^{-b\,s}$$

- subdominant modulus contribution to SUSY breaking

$$F_S \simeq \frac{F_X}{b} \qquad \text{with} \qquad b \sim \log \frac{M_P}{m_{3/2}}$$

- in heterotic models gauge kinetic function $f_{ab} \sim s$
- gaugino masses suppressed compared to $m_{3/2}$

Compressed gaugino masses

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

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

- 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)
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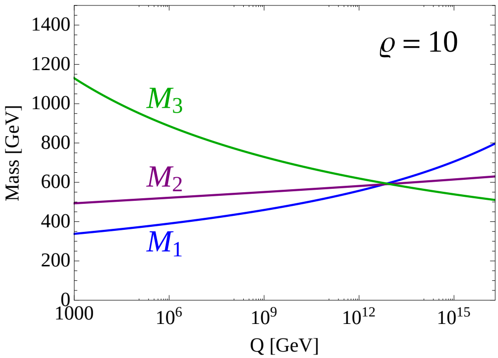

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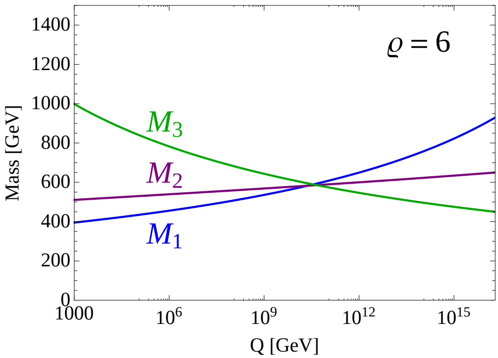

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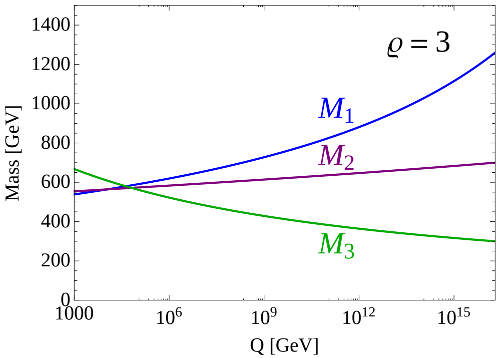
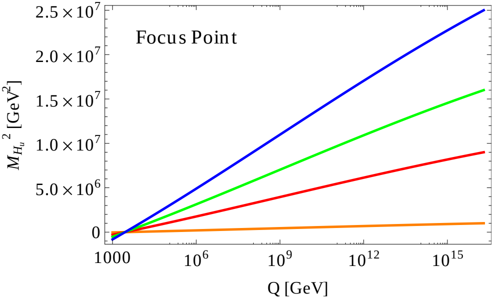


Scalar masses in mirage mediation

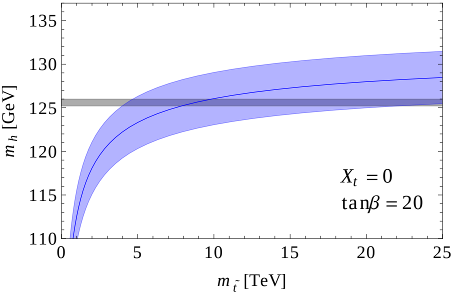
- scalar masses model dependent, but hardly affect gauge unification
- natural mass scale $m_{3/2}$, unless sequestering
  $\hookrightarrow$ hierarchy between gauginos and sfermions
- attractive possibility: universal scalar masses



- Multi-TeV scalars not unnatural due to focus point
  Feng et al., Phys. Rev. Lett. **84** (1999)

Fixing the scalar mass

- m_0 can be fixed by requiring $m_h = 126$ GeV



- large theoretical uncertainties in m_h

Feng et al., **arXiv:1306.2318** (2013)

$$m_0 = 3 \ldots 30 \text{ TeV}$$

A comment on electroweak symmetry breaking

- $m_0 \gg m_{1/2}$ potential problem with electroweak symmetry breaking
- heavy right-handed neutrinos give a small threshold Δm^2
  Asano et al., Phys. Lett. **B708** (2012), Moroi et al. **arXiv:1305.7357** (2013)

$$m_{H_u}^2 = m_0^2 - \Delta m^2 \qquad (\text{at } M_{\text{GUT}})$$

  allowing for successful EWSB with large universal m_0
- equivalent boundary conditions

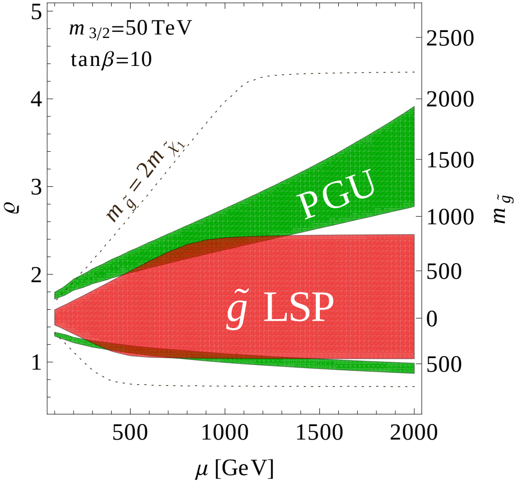
$$m_{\text{sfermion}} = m_H = m_0 \ , \qquad \mu \ll m_0$$

- after using the Higgs mass to fix m_0, the free parameters are

$$m_{3/2}, \quad \varrho, \quad \mu, \quad \tan\beta$$

Precision gauge unification in mirage mediation

- searching regions with precision unification



- precision unification with small μ
- **compressed spectrum**

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

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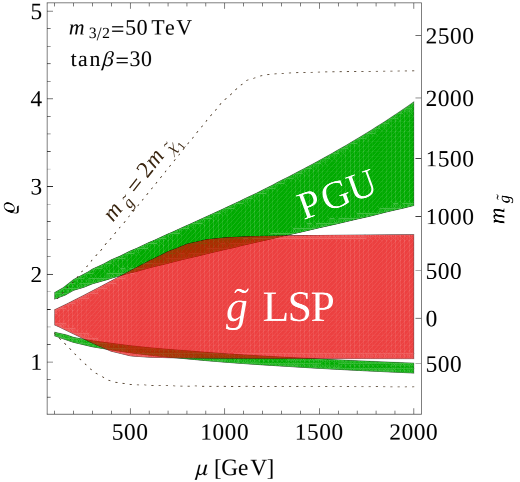

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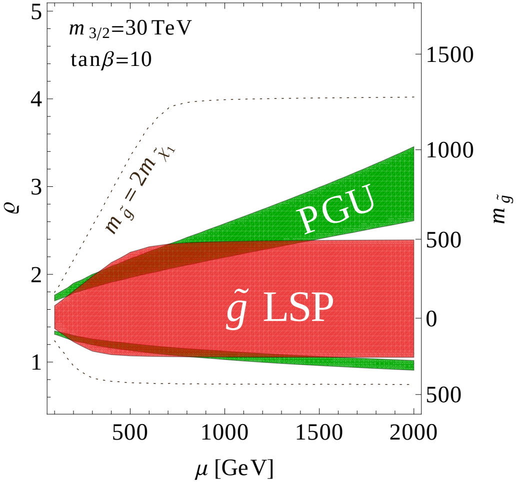


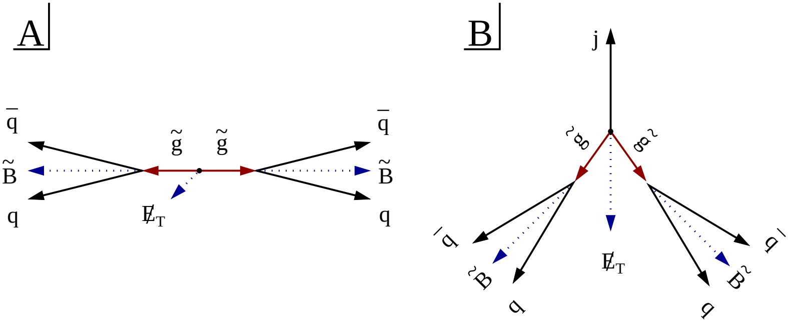
- precision unification with small μ
- **compressed spectrum**

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

Compressed spectrum at the LHC

- Small mass splitting $\Delta m = m_{\widetilde{g}} - m_{\widetilde{\chi}_1}$
- difficult to detect: soft jets, low $\not{E}_T$

LeCompte et al., Phys. Rev. **D84** (2011), Dreiner et al., Europhys. Lett. **99** (2012)



Alwall et al., Phys. Lett. **B666** (2008)

- initial state radiation required

LHC searches

- simplified models to estimate constraints
- ATLAS, CMS performed searches for

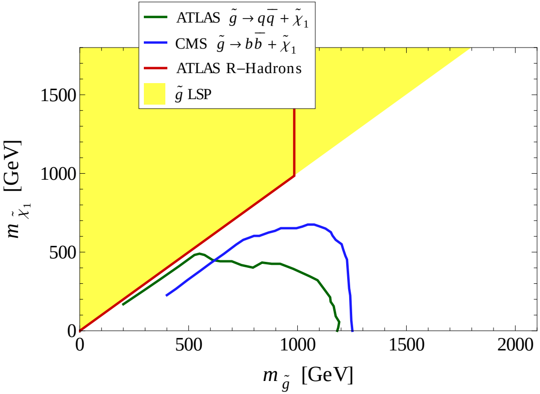
$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow 2\,q\bar{q} + 2\,\chi_1 \quad \text{or}$$
$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow 2\,b\bar{b} + 2\,\chi_1$$

ATLAS-CONF-2012-109, CMS-PAS-SUS-13-007

- for gluino LSP: searches for stable R-hadrons

ATLAS collaboration, Phys. Lett. **B720** (2013)

Precision Unification at the LHC



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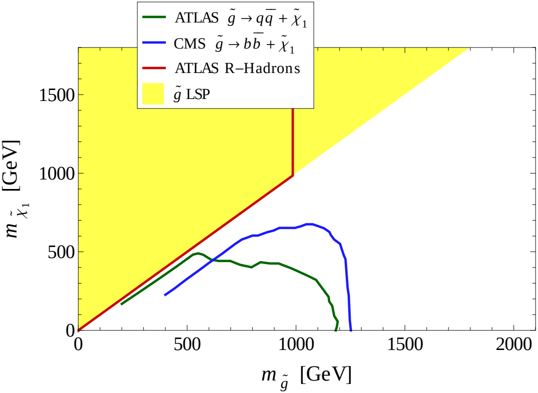
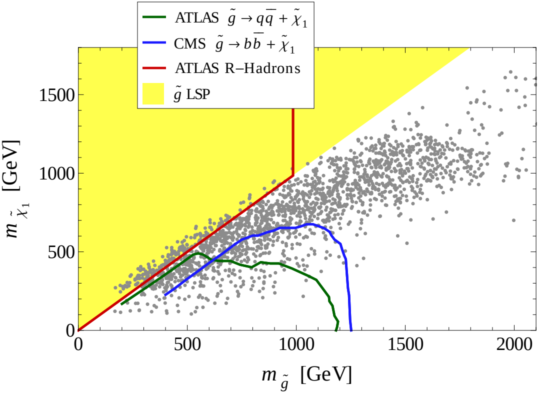


- we generated a large benchmark sample with random

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

- required precision gauge coupling unification

Precision Unification at the LHC



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

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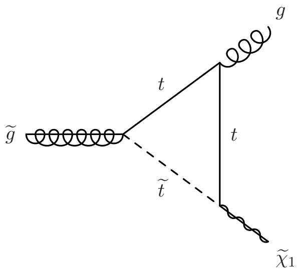
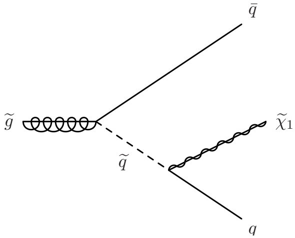
Gluino decays

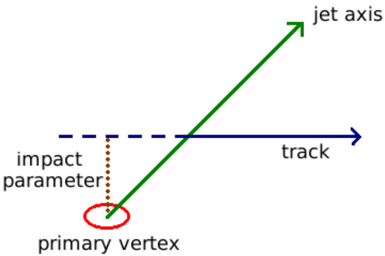


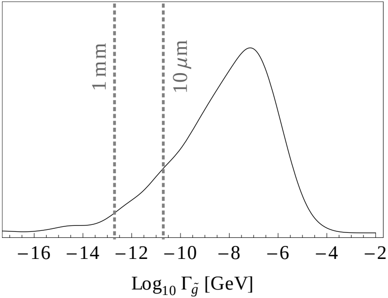


$$\Gamma \propto \text{higgsino fraction} \times \frac{\Delta m^3\, m_t^2}{m_{\widetilde{q}}^4} \qquad \Gamma \propto \text{gaugino fraction} \times \frac{\Delta m^5}{m_{\widetilde{q}}^4}$$

- gluino decay pattern encodes information about superpartner spectrum
- strong suppression of $\Gamma_{\widetilde{g}}$ especially for gaugino-like LSP
- displaced vertices?

Displaced vertices

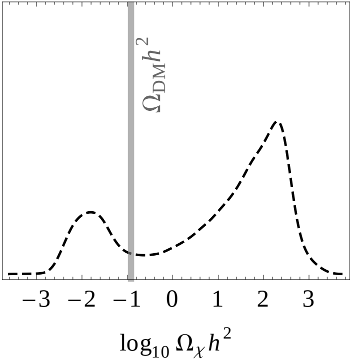




- distribution of $\Gamma_{\widetilde{g}}$ among benchmark sample
- $\sim$ 10% of benchmark points have $c/\Gamma_{\widetilde{g}} = 10\ \mu\mathrm{m} - 10\ \mathrm{mm}$
- $\Gamma_{\widetilde{g}}$ very sensitive to squark sector, could even be larger
- possibly detectable (e.g. transverse impact parameter)
- 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 affects relic density



- relic density with mirage boundaries
  $\hookrightarrow$ without PGU (dashed)

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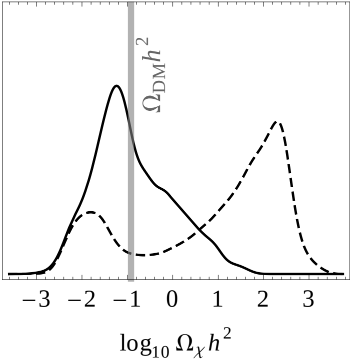


- relic density with mirage boundaries
  - ↪ without PGU (dashed)
  - ↪ with PGU (solid)

Coannihilations

- relic neutralino density

$$\Omega h^2 \simeq 0.1 \, \frac{\text{pb}}{\langle \sigma v \rangle}$$

- the problem:

$$\langle \sigma v \rangle_{\text{bino}} \sim 10^{-3\ldots4} \text{ pb} \qquad \langle \sigma v \rangle_{\text{wino}} \sim 10^{+2\ldots3} \text{ pb}$$

- coannihilations for $m_{\widetilde{W}} = m_{\widetilde{B}} + \Delta m$ with small Δm

$$\begin{aligned} \langle \sigma v \rangle_{\text{eff}} &\simeq B \, \langle \sigma v \rangle_{\text{wino}} \\ B &\simeq \exp\left(-2 \, \frac{\Delta m}{T_F} \right) \end{aligned}$$

- PGU typically yields $\Delta m \sim 0.1 m_{\widetilde{B}}$, which translates to $B \sim 10^{-2}$

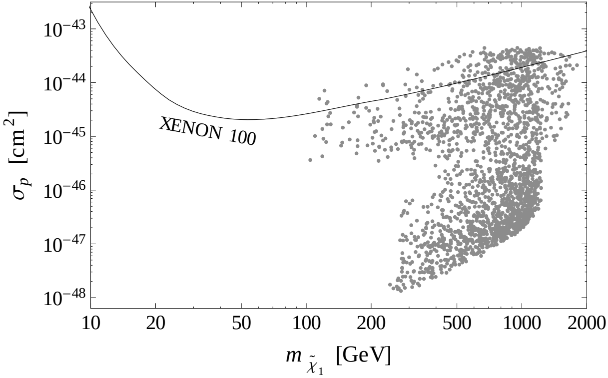
$$\langle \sigma v \rangle_{\text{eff}} \sim 1 \text{ pb}$$

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