Precision unification and the scale of supersymmetry

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Based on work with James D. Wells, `arXiv:hep-ph/2309.12954`

Supersymmetry: $Q\,|\text{Fermion}\rangle = |\text{Boson}\rangle$, $Q\,|\text{Boson}\rangle = |\text{Fermion}\rangle$

Standard Model

Spin 0	Spin 1/2	$SU(3)_c \times SU(2)_L \times U(1)_Y$
$(H^+ \;\; H^0)$		$(\,\mathbf{1}\,,\,\mathbf{2}\,,\,\frac{1}{2}\,)$
	$(u_L \;\; d_L)_i$	$(\,\mathbf{3}\,,\,\mathbf{2}\,,\,\frac{1}{6}\,)$
	$u^\dagger_{Ri}$	$(\,\overline{\mathbf{3}}\,,\,\mathbf{1}\,,\,-\frac{2}{3}\,)$
	$d^\dagger_{Ri}$	$(\,\overline{\mathbf{3}}\,,\,\mathbf{1}\,,\,\frac{1}{3}\,)$
	$(\nu \;\; e_L)_i$	$(\,\mathbf{1}\,,\,\mathbf{2}\,,\,-\frac{1}{2}\,)$
	$e^\dagger_{Ri}$	$(\,\mathbf{1}\,,\,\mathbf{1}\,,\,1\,)$

Spin 1/2	Spin 1	$SU(3)_c \times SU(2)_L \times U(1)_Y$
	g	$(\,\mathbf{8}\,,\,\mathbf{1}\,,\,0\,)$
	$W^\pm, W^0$	$(\,\mathbf{1}\,,\,\mathbf{3}\,,\,0\,)$
	B^0	$(\,\mathbf{1}\,,\,\mathbf{1}\,,\,0\,)$

For a detailed review: see, e.g. S. P. Martin, hep-ph/9709356 (SUSY primer); H. Dreiner, H. Haber, S. P. Martin, From Spinors to Supersymmetry (book)

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Minimal Supersymmetric Standard Model

Spin 0	Spin 1/2	$SU(3)_c \times SU(2)_L \times U(1)_Y$
$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\,\mathbf{1}\,,\,\mathbf{2}\,,\,\frac{1}{2}\,)$
$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\,\mathbf{1}\,,\,\mathbf{2}\,,\,-\frac{1}{2}\,)$
$(\widetilde{u}_L \;\; \widetilde{d}_L)_i$	$(u_L \;\; d_L)_i$	$(\,\mathbf{3}\,,\,\mathbf{2}\,,\,\frac{1}{6}\,)$
$\widetilde{u}^*_{Ri}$	$u^\dagger_{Ri}$	$(\,\overline{\mathbf{3}}\,,\,\mathbf{1}\,,\,-\frac{2}{3}\,)$
$\widetilde{d}^*_{Ri}$	$d^\dagger_{Ri}$	$(\,\overline{\mathbf{3}}\,,\,\mathbf{1}\,,\,\frac{1}{3}\,)$
$(\widetilde{\nu} \;\; \widetilde{e}_L)_i$	$(\nu \;\; e_L)_i$	$(\,\mathbf{1}\,,\,\mathbf{2}\,,\,-\frac{1}{2}\,)$
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$\widetilde{B}^0$	B^0	$(\,\mathbf{1}\,,\,\mathbf{1}\,,\,0\,)$

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- Origin of the weak scale
- A light Higgs $M_h = 125$ GeV
- Gauge coupling unification
- Viable dark matter candidate
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Theory: Superpartners can get their masses entirely from $\mathcal{L}_{\text{soft}}$, and therefore can be much heavier than weak scale

Precision unification conjecture:

Supersymmetry is a correct principle of nature, and the gauge couplings unify at a high scale with high-scale threshold corrections much smaller in magnitude than naive expectations from GUTs

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- MSSM with a common mass threshold $\tilde{m}$
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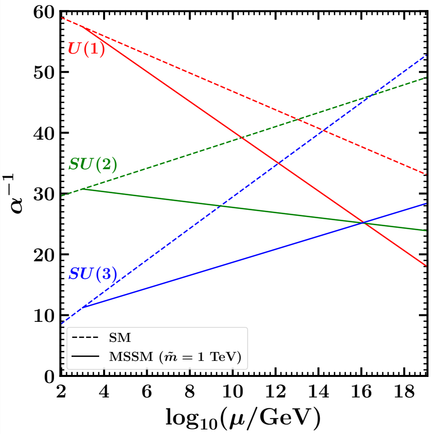
Used SPheno for generating MSSM spectra in high-scale scenarios

MSSM with a common threshold:

As a measure of unification of the gauge couplings, define

$$\frac{\rho_\lambda}{48\pi^2} \equiv \sqrt{\sum_{i\neq j}\left(\frac{1}{g_i^2}-\frac{1}{g_j^2}\right)^2}$$

with $\rho_\lambda^{\min} \equiv \rho_\lambda(\mu_\star)$.



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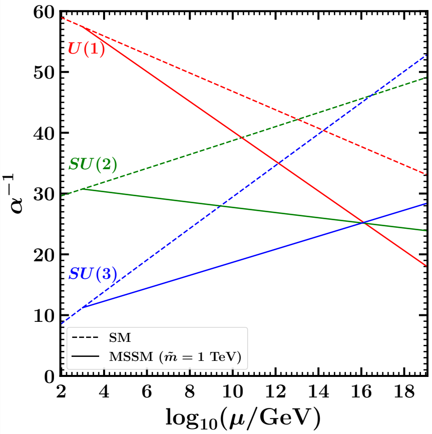
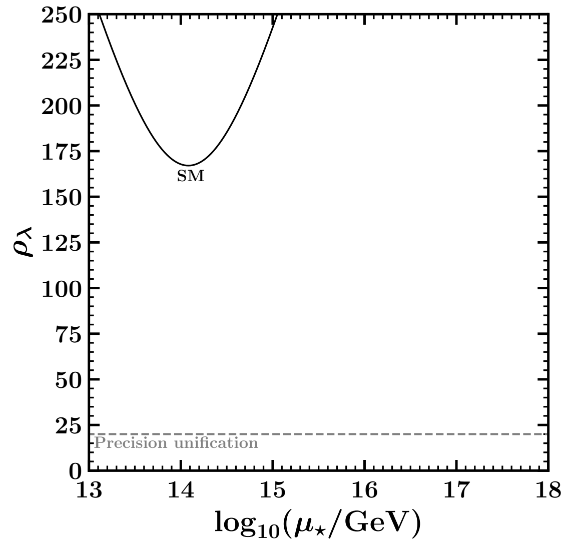
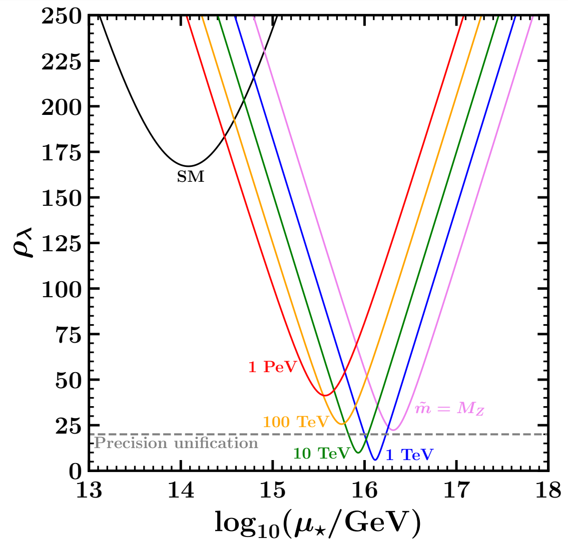


Standard GUTs: $\rho_\lambda^{\min} \sim \mathcal{O}(100)$ [S. Raby, SUSY GUTs, Vol. 939 (Springer, 2017)]

Precision unification: we require $\rho_\lambda^{\min} < 20$ $\left(\sim 3 \times \frac{\mu_\star}{M_P}\right)$


250
225
200
175
150
125
100
75
50
25
0
SM
Precision unification
ρ_λ
13
14
15
16
17
18
$\log_{10}(\mu_\star/\mathrm{GeV})$



Precision unification achieved if $\tilde{m} \sim 1 - 10$ TeV range!

High-scale scenarios:

Minimal supergravity:

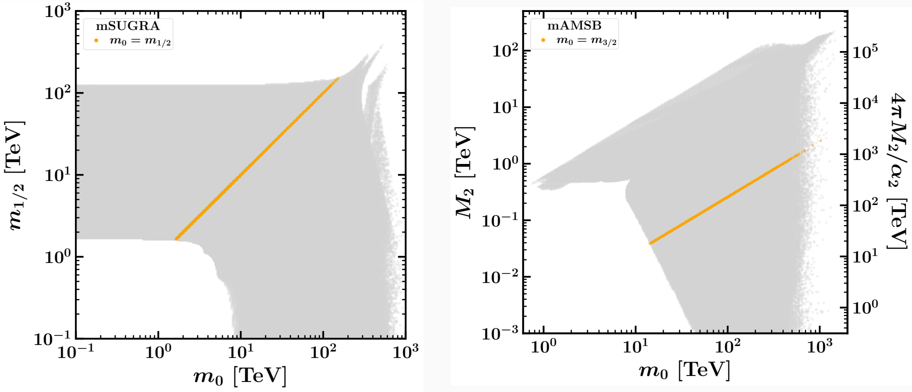
- Supersymmetry-breaking is gravity-mediated
- Inputs at GUT scale: $m_0, m_{1/2}, \tan\beta, \mathrm{sign}(\mu), A_0$ (= 0 in our analysis)
- $M_a = g_a^2/g_\star^2\, m_{1/2}$
- $M_1 : M_2 : M_3 \approx 1 : 2 : 6$ ($\widetilde{B}$ is the lightest gaugino)
- Lightest $\widetilde{N}$ can be bino/Higgsino-like

Minimal anomaly mediation:

- Supersymmetry-breaking via a superconformal Weyl anomaly
- Inputs at GUT scale: $m_0, m_{3/2}, \tan\beta, \mathrm{sign}(\mu)$
- $M_a = \beta_a/g_a\, m_{3/2}$
- $M_1 : M_2 : M_3 \approx 3.3 : 1 : 10$ ($\widetilde{W}$ is the lightest gaugino)
- Lightest $\widetilde{N}$ can be wino/Higgsino-like

High-scale scenarios

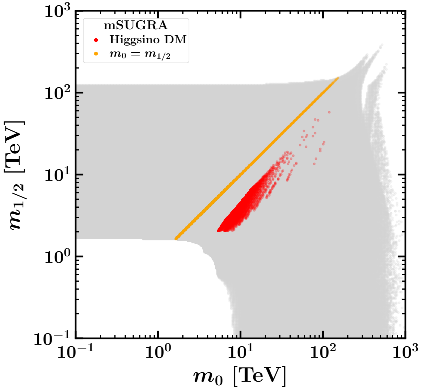
Minimal supergravity | Minimal anomaly mediation



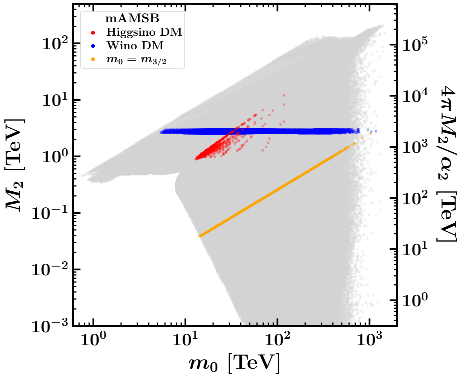
- Gray: precision unification and $M_h \sim 125$ GeV

High-scale scenarios

Minimal supergravity

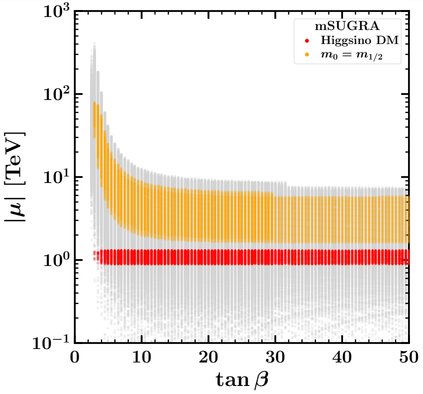


Minimal anomaly mediation

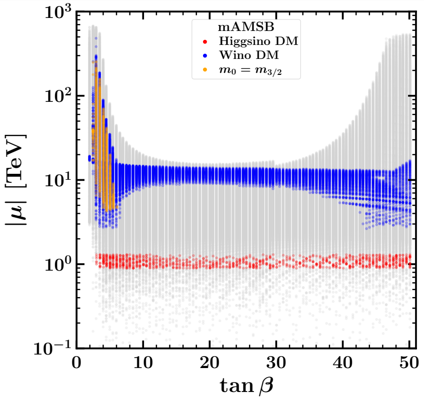


- Gray: precision unification and $M_h \sim 125$ GeV
- Red: candidate Higgsino DM assuming R-parity ($\mu \sim 1.1$ TeV)
- Blue: candidate wino DM assuming R-parity ($M_2 \sim 2.8$ TeV)

Minimal supergravity



Minimal anomaly mediation



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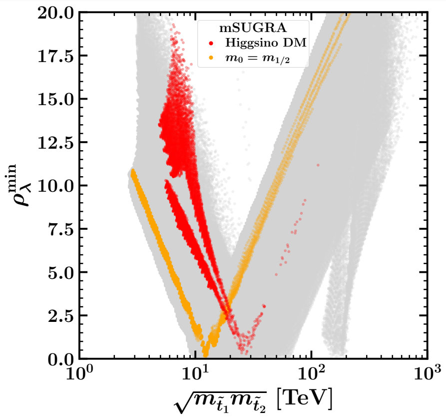

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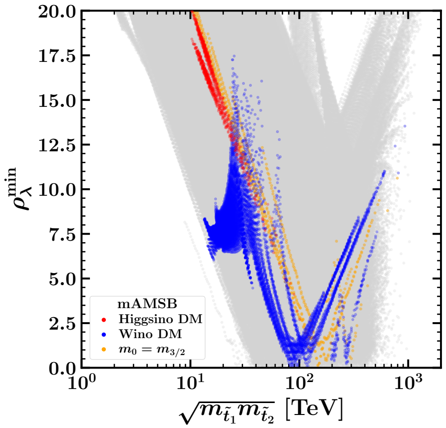
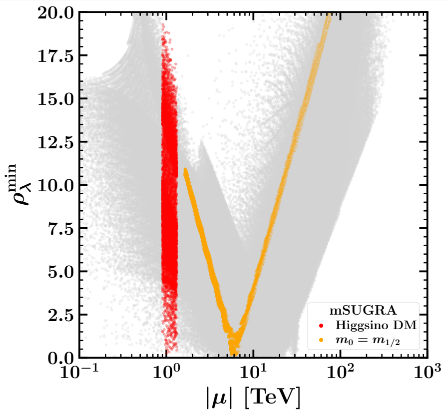
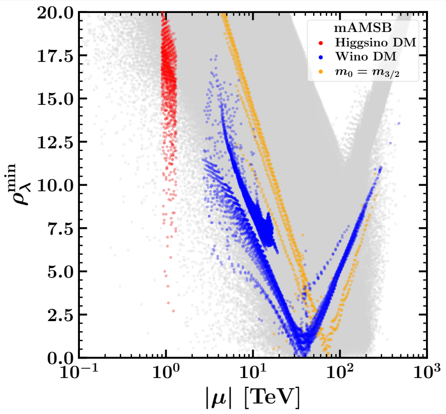


- Precision unification requires $M_{\text{SUSY}} \sim$ few TeV to PeV range!

Minimal supergravity



Minimal anomaly mediation



- Largely unexplored by LHC or lies well beyond its reach!
- Direct detection: $\widetilde{N}_1$ LSP extremely pure Higgsino for Higgsino DM
- Indirect detection: wino DM experimentally less viable

Conclusions

- Precise gauge coupling unification favors superpartner masses that are in the range of several TeV and well beyond!
- We demonstrated this in
  - MSSM with a common threshold
  - Minimal supergravity
  - Minimal anomaly mediation
- We further identified models with a Higgsino or wino DM candidate
- LHC results have had essentially no impact on the viability of supersymmetric unified theories - SUSY is alive and well!