SU(5) GUTs with or without SUSY?

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2026.04.11，Hangzhou

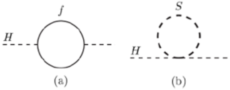
Based on: JHEP 03 (2025) 207, Y.Dong, K.Wang, H.Yuan, **JZ**, P.Zhu

Outline

1. Motivations
2. SUSY SU(5) GUT with non-universal gaugino masses (NUGM)
3. Results and discussions
4. Non-SUSY SU(5) GUT with adjoint fermions (24_F)
5. Summary and outlooks

1. Motivations: why GUT? why SUSY?

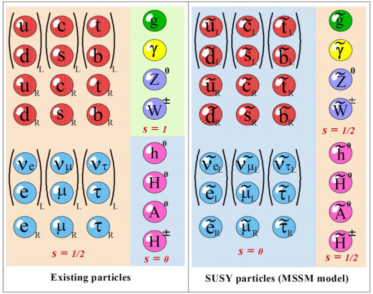
- **Standard Model (SM)** is very successful, but:
  - No explanation of the pattern of gauge couplings
  - No explanation for neutrino masses
  - No dark matter candidate
  - Tension in the muon anomalous magnetic moment $(g-2)_\mu$
- **Grand Unified Theories (GUTs), e.g. SU(5):**
  - Unify gauge interactions and matter multiplets
  - Give qualitative understanding of charge quantization
- **Supersymmetry (SUSY):**
  - Stabilizes the electroweak scale (solves hierarchy problem)
  - Predicts gauge coupling unification in the MSSM
  - Provides WIMP dark matter candidates
  - Can accommodate $\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM}$

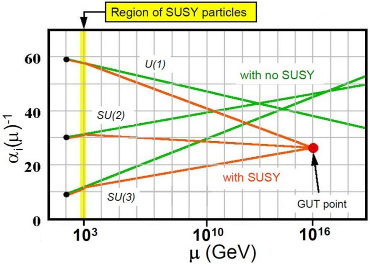


Martin, arXiv:9709356

$$\Delta m^2_{H(a)} = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2_{\rm UV} + \dots$$

$$\Delta m^2_{H(b)} = \frac{\lambda_S}{16\pi^2}\left[\Lambda^2_{\rm UV} - 2m_S^2\ln(\Lambda_{\rm UV}/m_S) + \dots\right]$$





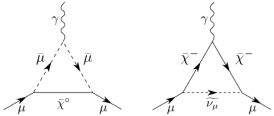
The minimal SU(5) GUT with SUSY: CMSSM/mSUGRA

Status of CMSSM under current constraints

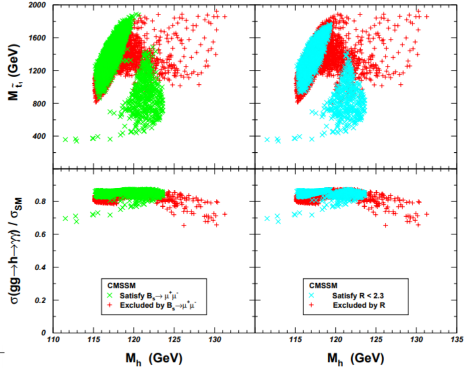
- 125 GeV SM-like Higgs mass
- High mass bound of the gluino

  $m_{\tilde{g}} \approx 2M_{1/2} \gtrsim 2$ TeV
- Dark matter relic density and direct detection

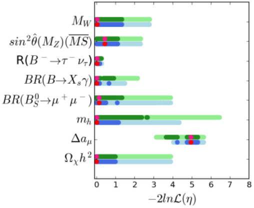
  $m_{\chi_1^0} \approx 0.4M_{1/2} \gtrsim 400$ GeV
- Muon g-2

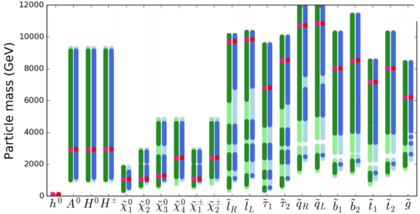


Cao, Heng, Li, Yang, arXiv:1112.4391



Han, Hikasa, Wu, Yang, Zhang, arXiv:1612.02296





$$R \equiv \frac{\eta}{\eta_{\rm SM}},$$

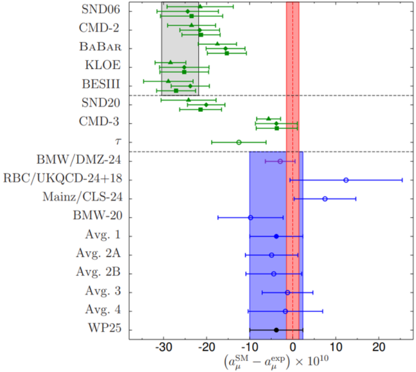
$$\eta \equiv \frac{\mathcal{B}r(B_s \to \mu^+\mu^-)/\mathcal{B}r(B_u \to \tau\nu_\tau)}{\mathcal{B}r(D_s \to \tau\nu_\tau)/\mathcal{B}r(D \to \mu\nu_\mu)}.$$

CMSSM tensions

- **CMSSM** (Constrained MSSM):
  - Universal scalar mass M_0, universal gaugino mass $M_{1/2}$, trilinear A_0, $\tan\beta$, sign(μ)
  - Very predictive in SU(5) unification
- Under current data:
  - LHC pushes gluino and squarks to multi-TeV
  - $m_h \simeq 125$ GeV requires heavy stops and/or large mixing

$$m_h^2 \approx m_Z^2 + \frac{1}{8\pi^2}\frac{m_t^4}{v^2}\left[24\ln\left(\frac{m_{\text{stop}}}{m_t}\right) + x_t^2\left(12 - x_t^2\right)\right]$$

  - Hard to simultaneously obtain:
    - Correct Higgs mass
    - Correct dark matter relic density
    - Large enough $(g-2)_\mu$
  - Recent Results (excluding $(g-2)_\mu$ anomaly)
    - PDG2025, the simplest AMSB/GMSB appear to be ruled out
    - arXiv:2507.09289 CMSSM heavy stops or large mixing
    - arXiv:2509.13437 SO(10) CMSSM with Yukawa unification
    - arXiv:2603.22418 CMSSM and NUHM2
- **Idea**: relax universal gaugino masses in an SU(5)-consistent way



2. The SUSY SU(5) GUT with NUGM

- CMSSM with non-universal gaugino masses: F. Wang, K. Wang, Yang, **JZ**, arXiv:1808.10851

In the most general case, gaugino masses can arise from non-renormalizable gauge kinetic terms

$$W \supseteq \frac{f_a}{4} \cdot \frac{1}{\Lambda}\left[W^a W^a + a_1 \frac{T}{\Lambda} W^a W^a + b_1 \frac{1}{\Lambda} W^a \Phi_{ab} W^b + c_1 \frac{T}{\Lambda^2} W^a \Phi_{ab} W^b\right],$$

with cutoff scale Λ upon the GUT scale and T a gauge singlet chiral superfield.

At the level of dimension-5 operators, this can be parametrized by the following non-universal gauge kinetic function:

$$\mathcal{L} = \int d^2\theta \left(\frac{f_a}{4} W^a W^b\right)\left[\delta_{ab} + \frac{1}{\Lambda}\left(c_0 T\,\delta_{ab} + c_1 (H_{24})_{ab} + c_2 (H_{75})_{ab} + c_3 (H_{200})_{ab}\right)\right] + \text{h.c.}$$

After the singlet T acquires an F-term VEV F_T and the chiral fields $H_{24,75,200}$ acquire only *scalar* VEVs to break the SU(5) gauge symmetry, soft SUSY breaking gaugino masses are generated by this non-universal gauge kinetic function.

In the SU(5) GUT, the adjoint index pair Φ_{ab} can lie in any irreducible representation appearing in the symmetric product of two adjoints:

$$(\mathbf{24} \otimes \mathbf{24})_{\text{symm}} = \mathbf{1} \oplus \mathbf{24} \oplus \mathbf{75} \oplus \mathbf{200}.$$

We consider the most general combination involving the **24**, **75** and **200** representations of SU(5) Higgs fields together with the gauge singlet T as shown in the gauge kinetic function above.

Only T acquires an F-term VEV, $\langle T \rangle = T_0 + \theta^2 F_T$, to break supersymmetry, while $H_{24,75,200}$ get only scalar VEVs to break the SU(5) symmetry. The VEVs of the Higgs field Φ_{24} can be expressed as a 5×5 matrix

$$\langle \Phi_{24} \rangle = v_U \sqrt{\frac{3}{5}} \,\mathrm{diag}\left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2}\right),$$

while the VEVs of the Higgs field Φ_{75} can be expressed as a 10×10 matrix

$$\langle \Phi_{75} \rangle = \frac{v_U}{2\sqrt{3}} \,\mathrm{diag}\left(\underbrace{1, \cdots, 1}_{3}, \underbrace{-1, \cdots, -1}_{6}, 3\right).$$

Similarly, the VEVs of the Higgs field Φ_{200} can be expressed as a 15×15 matrix

$$\langle \Phi_{200} \rangle = \frac{v_U}{2\sqrt{3}} \,\mathrm{diag}\left(\underbrace{1, \cdots, 1}_{6}, \underbrace{-2, \cdots, -2}_{6}, \underbrace{2, \cdots, 2}_{3}\right).$$

After substituting the lowest-component VEVs, the gauge kinetic term takes the form

$$W \supseteq \frac{f_a}{4} W^a W^b \left[\left(1 + a_1 \frac{T_0}{\Lambda}\right) \delta_{ab} + \sum_r c_i \frac{v_U}{\Lambda} \langle M^r_{ab} \rangle \right].$$

Naively, since $v_U \ll \Lambda$ and $T_0 \sim \Lambda$, the universal piece proportional to δ_{ab} would dominate. In our NUGM setup, however, we impose $1 + a_1 T_0/\Lambda \approx 0$. so that, after canonical normalization of the gauge fields, the non-universal SU(5)-breaking parts govern the gaugino mass ratios.

Gaugino mass ratios $M_1 : M_2 : M_3$ for different SU(5) representations:

Representation	GUT scale	EW scale
1	$1 : 1 : 1$	$1 : 2 : 6$
24	$1 : 1/3 : -1/2$	$3 : 2 : -9$
75	$-1/5 : 1/3 : 1$	$-3 : 10 : 90$
200	$1/10 : 1/2 : 1$	$1 : 10 : 60$

Arbitrary gaugino mass ratios at the GUT scale can be obtained with suitable linear combinations of the singlet, **24**, **75** and **200** contributions:

$$M_1 : M_2 : M_3 = \left[c_0 - \frac{c_1}{4\sqrt{15}} + \frac{5c_2}{4\sqrt{3}} + \frac{5c_3}{2\sqrt{3}}\right] : \left[c_0 - \frac{3c_1}{4\sqrt{15}} - \frac{3c_2}{4\sqrt{3}} + \frac{c_3}{2\sqrt{3}}\right] : \left[c_0 + \frac{c_1}{2\sqrt{15}} - \frac{c_2}{4\sqrt{3}} + \frac{c_3}{4\sqrt{3}}\right]$$

NUGM : $\boxed{\tan\beta,\ A_0,\ M_0,\ M_1,\ M_2,\ M_3}$

The $\tilde{g}$SUGRA scenario is characterized by

$$M_3 \gg M_1, M_2\,.$$

Correlations between parameters at SUSY- and GUT-scales according to RGE

For the GUT-scale input parameters

$$p_{j,k}^{\mathrm{GUT}} = A_0, M_0, M_1, M_2, M_3$$

For the linear-correlation parameters

$$p_i^{\mathrm{SUSY}} = A_t, A_\tau, A_\mu, M_1^{\mathrm{SUSY}}, M_2^{\mathrm{SUSY}}, M_3^{\mathrm{SUSY}}$$

we calculate the coefficients by

$$C_{ij} = \frac{\Delta p_i^{\mathrm{SUSY}}}{\Delta p_j^{\mathrm{GUT}}}$$

For the quadratic-correlation parameters

$$p_i^{\mathrm{SUSY}} = \mu^2, M_{H_u}^2, M_{H_d}^2, M_{Q_3}^2, M_{U_3}^2, M_{L_3}^2, M_{E_3}^2, M_{L_2}^2, M_{E_2}^2$$

we calculate the coefficients by

$$C_{ijk(k\geq j)} = \frac{n\Delta p_i^{\mathrm{SUSY}}}{\Delta p_j^{\mathrm{GUT}} \Delta p_k^{\mathrm{GUT}}} \quad (n = 2 \text{ for } k = j,\ n = 1 \text{ for } k > j)$$

3. Results and discussions: parameters and constraints

The NUGM scenario

6 free parameters

$M_1, M_2, M_3, M_0, A_0,$
$\tan\beta$, sign(μ)

Predict heavy gluino and squark to escape constraints

Give light wino bino to satisfy other observed results

$M_3 \gg M_1, M_2$

$\tilde{g}$SUGRA

$$\text{sign}(\mu) = +1$$
$$|A_0|, |M_3| < 10\ \text{TeV}$$
$$1 < \tan\beta < 50$$
$$0 < M_0 < 1\ \text{TeV}$$
$$|M_1|, |M_2| < 1\ \text{TeV}$$

Parameter select

JHEP 2025, Dong, Wang, Yuan, **JZ**, Zhu

Constraints

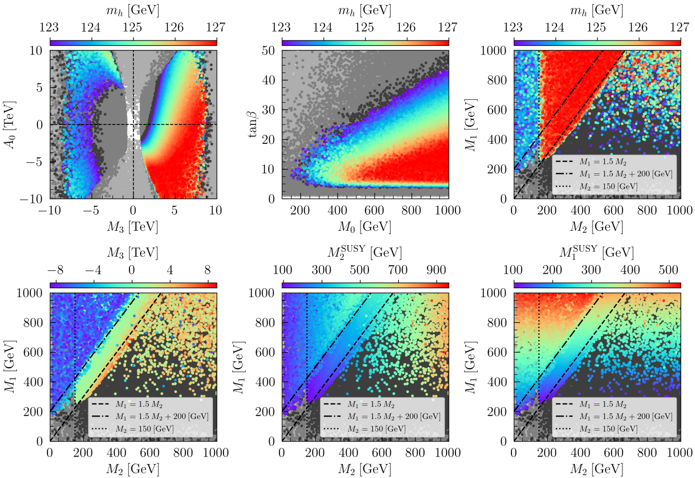
- The constraints of SM-like Higgs mass: $m_H = 125 \pm 2$ GeV
- The constraints on the squark, gluino, slepton, and chargino masses:

$$m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 2\ \text{TeV}, \quad m_{\tilde{t}} > 0.7\ \text{TeV},$$
$$m_{\tilde{\tau}} > 93.2\ \text{GeV}, \qquad m_{\tilde{\chi}^{\pm}} > 103.5\ \text{GeV}.$$

- The constraints from direct searches for Higgs and signal compatibility of SM-like Higgs.
- The constraints from dark matter relic density and direct search results for dark matter: $0 < \Omega h^2 < 0.12$.
- The constraints from B physics:

$$Br(B \to s\gamma) = (3.49 \pm 0.38) \times 10^{-4},$$
$$\text{Br}(B^+ \to \tau^+ \nu) = (1.09 \pm 0.48) \times 10^{-4},$$
$$\text{Br}(B_s \to \mu^+\mu^-) = (3.01 \pm 0.87) \times 10^{-9}.$$

Sample surviving conditions



Surviving samples in the A_0 versus M_3 plane (upper left), the $\tan\beta$ versus M_0 plane (upper middle), and the M_1 versus M_2 plane (upper right and lower three).

● Exclued by Higgs mass data

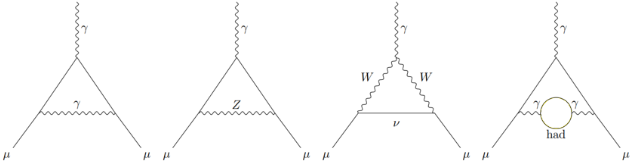
● Exclued by direct search Higgs data

● Exclued by dark matter relic density

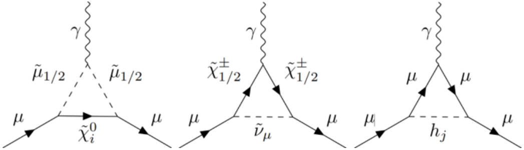
- Negative M_3 tends to yield a lighter Higgs, while positive M_3 tends to yield a heavier one
- Higgs data require $\tan\beta \geq 5$ and $M_0 \gtrsim 20\tan\beta$ GeV
- Dark matter relic density strongly constrains samples with $M_1 \lesssim 1.5 M_2$
- Negative M_3 can only survive when $M_1 \gtrsim 1.5 M_2 + 200$ GeV
- Negative M_3 can provide additional contributions to M_1 or M_2 at the SUSY scale

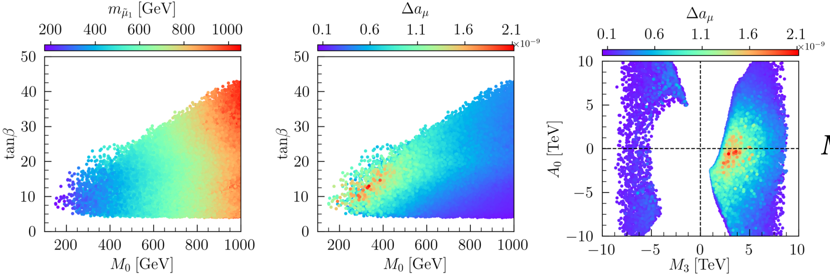
Discussions on muon anomalous magnetic moment

Feynman diagrams of SM contribution to a_μ,



SUSY contribution to a_μ





$M_0 \sim 250$ GeV,

$|A_0| \sim 1$ TeV,

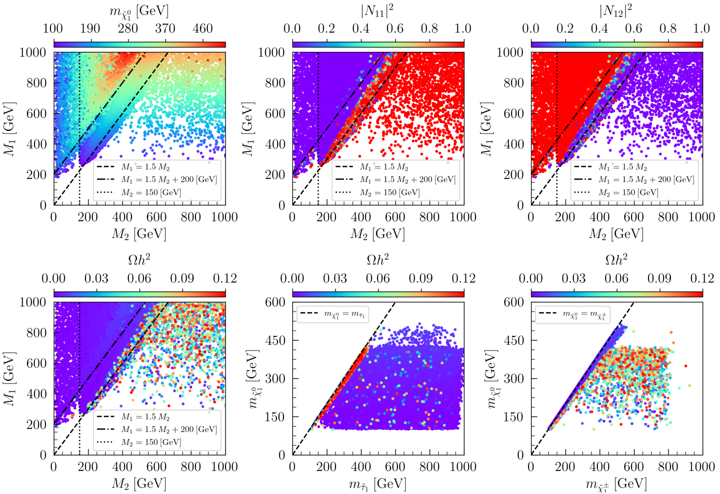
$M_3 \sim 4$ TeV

$$a_\mu^{\tilde{\mu}} = a_0 \frac{1+\delta^{2\mathrm{loop}}}{1+\Delta_\mu} \left(\frac{\tan\beta \cdot (100\ \mathrm{GeV})^2}{m^2_{\tilde{\mu}_L} m^2_{\tilde{\mu}_R}/(M_1 \mu)} \right) \frac{f_N}{1/6}$$

The contribution of smuon to a_μ

$\Delta a_\mu \sim 2.1 \times 10^{-9}$

Discussions on dark matter



Surviving samples in the M_1 versus M_2 planes (upper and lower left), the $m_{\tilde\chi_1^0}$ versus $m_{\tilde\tau_1}$ plane (lower middle), and the $m_{\tilde\chi_1^0}$ versus $m_{\tilde\chi_1^\pm}$ plane (lower right).

Samples can be divided into

- **Class A**: $M_3 > 0,\ M_1 \gtrsim 1.5 M_2$
- **Class B**: $M_3 > 0,\ M_1 \lesssim 1.5 M_2$
- **Class C**: $M_3 < 0,\ M_1 \gtrsim 1.5 M_2 + 200$ GeV

- Samples are **wion-like** in Class A and Class C, **bion-like** in Class B, and **wino-bino mixing** when $M_1/M_2 \approx 1.5$.
- Only **bion-like** and **bino-wino mixing** samples can give sizeable dark matter relic density.
- The mass of $\tilde\chi_1^0$ and $\tilde\tau_1$ are degenerate for the samples in Class B.

Discussions on dark matter

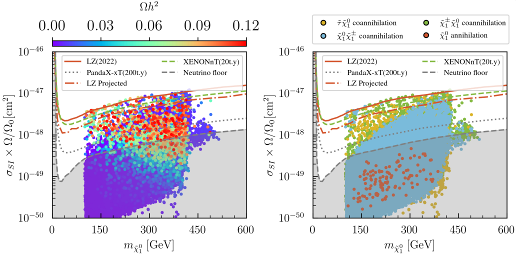
Main annihilation mechanism

$\tilde{\chi}_1^0\tilde{\chi}_1^0$ coann.: $\dfrac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_1^0}} \leq 1.1$

$\tilde{\chi}_1^0\tilde{\chi}_1^\pm$ coann.: $\dfrac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_1^\pm}} \leq 1.1,\ 1.05 \leq \dfrac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} \leq 1.05$

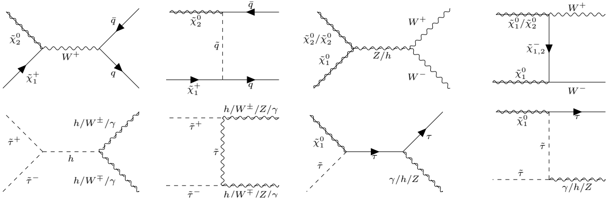
$\tilde{\chi}_1^0\tilde{\chi}_2^0$ coann.: $\dfrac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_2^0}} \leq 1.1,\ 1.05 \leq \dfrac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} \leq 1.1$

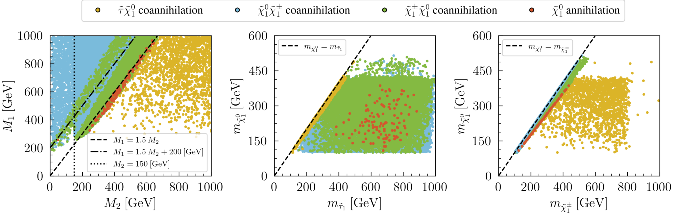
$\tilde{\chi}_1^0$ ann.: $\dfrac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} \geq 1.1,\ \dfrac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_1^0}} \geq 1.1$



The Ω/Ω_0-rescaled σ_{SI} vs $m_{\tilde{\chi}_1^0}$ planes

$\tilde{\chi}_1^0$ coann. (upper) and $\tilde{\tau}$ hybrid ann. (lower).

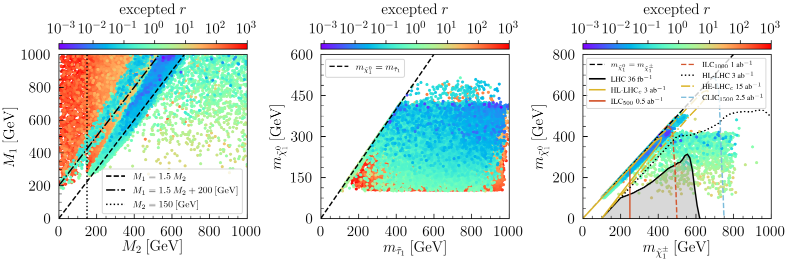




The M_1 vs M_2 planes (left), the $m_{\tilde{\chi}_1^0}$ versus $m_{\tilde{\tau}_1}$ plane (middle), and the $m_{\tilde{\chi}_1^0}$ versus $m_{\tilde{\chi}_1^\pm}$ plane (right).

Discussions on collider physics

Current constraints from direct SUSY searches, and the sensitivity of future colliders, such as HL-LHC, HE-LHC, ILC, and CLIC.



Surviving samples in the M_1 versus M_2 planes (left), the $m_{\tilde{\chi}_1^0}$ versus $m_{\tilde{\tau}_1}$ plane (middle), and the $m_{\tilde{\chi}_1^0}$ versus $m_{\tilde{\chi}_1^\pm}$ plane (right).

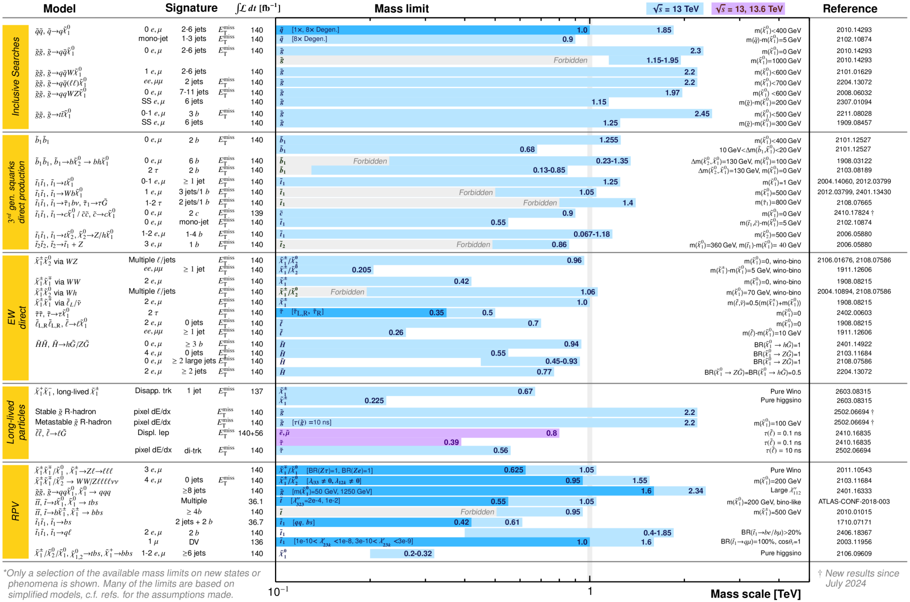
$$r = \frac{\sum_{\text{elements}}(\sigma \times Br \times \varepsilon)}{\text{upper limit}}$$

$r > 1(1.2)$ is considered excluded by experimental results without (with) 20% calculation error.

- Direct search SUSY particles experimental results have strong constraint on the samples with $M_1 \gtrsim 1.5 M_2$, expect $M_1 \approx 1.5 M_2$ or $M_1 \gtrsim 1.5 M_2 + 200$ GeV.
- Direct search SUSY particles experimental results have strong constraint on lighter $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}_1}$.
- When the integral luminosity of the HL-LHC reaches 3ab^{-1} and CLIC$_{1500}$ achieves 2.5ab^{-1}, all samples can be fully covered by collider experiments.

ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Preliminary $\sqrt{s}$ = 13, 13.6 TeV, 36-196 fb^{-1} March 2026



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]		Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{q}$	[1×, 8× Degen.] 1.0 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	E_T^{miss}	140	$\tilde{q}$	[8× Degen.] 0.9	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	140	$\tilde{g}$	2.3	m($\tilde{\chi}_1^0$)=0 GeV	2010.14293
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		140	$\tilde{g}$	2.2	m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	140	$\tilde{g}$	2.2	m($\tilde{\chi}_1^0$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	140	$\tilde{g}$	1.97	m($\tilde{\chi}_1^0$) <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	140	$\tilde{g}$	2.45	m($\tilde{\chi}_1^0$)<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	E_T^{miss}	140	$\tilde{b}_1$	1.255	m($\tilde{\chi}_1^0$)<400 GeV	2101.12527
						$\tilde{b}_1$	0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}_1^0$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	140	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	140	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	≥ 1 jet	E_T^{miss}	140	$\tilde{t}_1$	1.25	m($\tilde{\chi}_1^0$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden 1.05	m($\tilde{\chi}_1^0$)=500 GeV	2012.03799, 2401.13430
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	E_T^{miss}	140	$\tilde{t}_1$	Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	139	$\tilde{c}$	0.9	m($\tilde{\chi}_1^0$)=0 GeV	2410.17824 †
		0 e,μ	mono-jet	E_T^{miss}	140	$\tilde{t}_1$	0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	140	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	E_T^{miss}	140	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.96	m($\tilde{\chi}_1^0$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	≥ 1 jet	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	0.205	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via WW	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$	0.42	m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	Forbidden 1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	140	$\tilde{\tau}$	[$\tilde{\tau}_{L,R}$, $\tilde{\tau}_R$] 0.35 0.5	m($\tilde{\chi}_1^0$)=0	2402.00603
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	140	$\tilde{\ell}$	0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	≥ 1 jet	E_T^{miss}	140	$\tilde{\ell}$	0.26	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	E_T^{miss}	140	$\tilde{H}$	0.94	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	2401.14922
		4 e,μ	0 jets	E_T^{miss}	140	$\tilde{H}$	0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	≥ 2 large jets	E_T^{miss}	140	$\tilde{H}$	0.45-0.93	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	≥ 2 jets	E_T^{miss}	140	$\tilde{H}$	0.77	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=BR($\tilde{\chi}_1^0\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	$\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$, long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	E_T^{miss}	137	$\tilde{\chi}_1^{\pm}$	0.67	Pure Wino	2603.08315
						$\tilde{\chi}_1^{\pm}$	0.225	Pure higgsino	2603.08315
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$	2.2		2502.06694 †
	Metastable $\tilde{g}$ R-hadron	pixel dE/dx		E_T^{miss}	140	$\tilde{g}$	[$\tau(\tilde{g})$ =10 ns] 2.2	m($\tilde{\chi}_1^0$)=100 GeV	2502.06694 †
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		E_T^{miss}	140+56	$\tilde{e},\tilde{\mu}$	0.8	$\tau(\tilde{\ell})$ = 0.1 ns	2410.16835
						$\tilde{\tau}$	0.39	$\tau(\tilde{\ell})$ = 0.1 ns	2410.16835
		pixel dE/dx	di-trk	E_T^{miss}	140	$\tilde{\tau}$	0.56	$\tau(\tilde{\ell})$ = 10 ns	2502.06694
RPV	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$, $\tilde{\chi}_1^{\pm}\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$	[BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$	[$\lambda_{i33}\neq 0$, $\lambda_{12k}\neq 0$] 0.95 1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		≥8 jets		140	$\tilde{g}$	[m($\tilde{\chi}_1^0$)=50 GeV, 1250 GeV] 1.6 2.34	Large λ''_{112}	2401.16333
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$	[λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm}\to bbs$		≥ 4b		140	$\tilde{t}$	Forbidden 0.95	m($\tilde{\chi}_1^{\pm}$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$	[qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		140	$\tilde{t}_1$	0.4-1.85	BR($\tilde{t}_1\to be/b\mu$)>20%	2406.18367
		1 μ	DV		136	$\tilde{t}_1$	[1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0\to tbs$, $\tilde{\chi}_1^{+}\to bbs$	1-2 e,μ	≥6 jets		140	$\tilde{\chi}_1^0$	0.2-0.32	Pure higgsino	2106.09609

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

† New results since July 2024

4. Non-SUSY SU(5) GUTs: the minimal version

Gauge group and gauge bosons

$$SU(5) \supset SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

The 24 gauge bosons form an adjoint matrix

$$V_\mu = \left(\begin{array}{c|c} G_\mu - \frac{1}{\sqrt{30}} B_\mu \mathbf{1}_3 & X_\mu \\ \hline X_\mu^\dagger & W_\mu + \frac{3}{\sqrt{30}} B_\mu \mathbf{1}_2 \end{array}\right),$$

$$G_\mu = G_\mu^a \frac{\lambda^a}{2} \text{ (8 gluons)}, \quad W_\mu = W_\mu^i \frac{\sigma^i}{2} \text{ (3 weak bosons)}, \quad B_\mu \text{ (1 hypercharge)},$$

and X_μ is a 3×2 matrix containing the 12 heavy leptoquark gauge bosons X_μ, Y_μ. In SM notation

$$\mathbf{24_V} \to (8,1)_0 \oplus (1,3)_0 \oplus (1,1)_0 \oplus (3,2)_{-5/6} \oplus (\bar{3},2)_{5/6}.$$

Higgs sector

- Fundamental Higgs $\mathbf{5_H}$ contains the SM Higgs doublet:

$$H_5 = \begin{pmatrix} H_{C,r} \\ H_{C,g} \\ H_{C,b} \\ H^+ \\ H^0 \end{pmatrix} \to (3,1)_{-1/3} \oplus (1,2)_{1/2},$$

The minimal non-SUSY SU(5) GUT

- Adjoint Higgs $\mathbf{24_H}$ breaks $SU(5) \to SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$:

$$\mathbf{24_H} \to (8,1)_0 \oplus (1,3)_0 \oplus (1,1)_0 \oplus (3,2)_{-5/6} \oplus (\bar{3},2)_{5/6}.$$

Matter fermions (per generation)

The SM fermions of one generation sit in $\mathbf{\bar{5}_F} \oplus \mathbf{10_F}$:

$$\psi_{\bar{5}} = \begin{pmatrix} d_r^c \\ d_g^c \\ d_b^c \\ e^- \\ -\nu_e \end{pmatrix} \sim \mathbf{\bar{5}_F} \to (\bar{3},1)_{1/3} \oplus (1,2)_{-1/2},$$

$$\psi_{10} = \begin{pmatrix} 0 & u_b^c & -u_g^c & u_r & d_r \\ -u_b^c & 0 & u_r^c & u_g & d_g \\ u_g^c & -u_r^c & 0 & u_b & d_b \\ -u_r & -u_g & -u_b & 0 & e^c \\ -d_r & -d_g & -d_b & -e^c & 0 \end{pmatrix} \sim \mathbf{10_F} \to (3,2)_{1/6} \oplus (\bar{3},1)_{-2/3} \oplus (1,1)_1.$$

(Three copies: $(\mathbf{\bar{5}_F} \oplus \mathbf{10_F})_i$, $i = 1,2,3$.)

Non-SUSY GUTs: the SU(5)+24_F model, setup and motivations

- **non-SUSY** SU(5) GUT extended by a **fermionic adjoint** representation
  - B. Bajc, G. Senjanović, arXiv:hep-ph/0612029
  - B. Bajc, M. Nemevšek, G. Senjanović, arXiv:hep-ph/0703080
- Under the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, one has

$$\mathbf{24_F} \;\to\; (1,1)_0 \oplus (1,3)_0 \oplus (8,1)_0 \oplus (3,2)_{-5/6} \oplus (\bar{3},2)_{5/6}.$$

  - $(1,1)_0$: SM singlet fermion
  - $(1,3)_0$: weak triplet fermions
  - $(8,1)_0$: color octet fermions
  - $(3,2)_{-5/6} \oplus (\bar{3},2)_{5/6}$: vector-like leptoquark–like fermions
- **Motivation:**
  - New directions for collider physics
    - our past works on collider physics: arXiv 2402.11232, 2410.13636, 2506.21454, 2510.24662, ...
  - Neutrino masses via a combination of **Type-I or Type-III seesaw**:
    - Type-I with singlet fermion $(1,1)_0$, Type-III with triplet fermion $(1,3)_0$
  - Improve **gauge coupling unification** without SUSY: suitable mass splittings among the components of $\mathbf{24_F}$ can lead to successful unification
  - Keep the model **minimal and predictive**: only one extra GUT multiplet, no new gauge group

Phenomenology of the SU(5)+$\mathbf{24}_\mathrm{F}$ Model

- **Mass spectrum** of the adjoint fermion is typically split:
  - SU(2)$_L$ triplet $(1,3)_0$: can lie near the $\mathcal{O}(\mathrm{TeV})$ scale
  - Color octet $(8,1)_0$: intermediate scale (e.g. $10^7 - 10^9$ GeV) to aid unification
  - Vector-like $(3,2)_{-5/6} \oplus (\bar{3},2)_{5/6}$: typically heavy, close to M_GUT, to suppress proton decay
- **Gauge coupling unification and proton decay**:
  - Thresholds from the split $\mathbf{24}_\mathrm{F}$ modify the RGE running of $g_{1,2,3}$, allowing unification at M_GUT
  - The allowed spectrum must be consistent with current proton decay bounds, e.g. $p \to e^+\pi^0$, which typically requires heavy leptoquark–like components and appropriate scalar masses
- **Neutrino masses**:
  - Yukawa couplings $Y_{24}\, \bar{\mathbf{5}}_\mathrm{F}\, \mathbf{24}_\mathrm{F}\, \mathbf{5}_\mathrm{H}$ generate Majorana masses after SU(5) breaking
  - One can obtain light neutrino masses via mixed Type-I+III seesaw with only a few new parameters, leading to testable flavour structures
- **Baryon asymmetry via leptogenesis**
  - The heavy singlet N and triplet Σ components of $\mathbf{24}_\mathrm{F}$ decay out of equilibrium:
    $$N, \Sigma \;\to\; L\,H, \quad \bar{L}\,\bar{H},$$
    with CP violation asymmetries controlled by the same Yukawa matrices that generate neutrino masses
  - These decays produce a net lepton number, which is partially converted into a baryon asymmetry by electroweak sphaleron processes, in direct analogy with standard Type-I/III thermal leptogenesis
  - The SU(5)+$\mathbf{24}_\mathrm{F}$ setup is predictive: neutrino masses and mixings, leptogenesis, and (in extended versions) dark matter properties are linked by the same GUT-scale parameters

Dark matter in $SU(5) + \mathbf{24}_F$

- Decomposition under $SU(3)_C \times SU(2)_L \times U(1)_Y$:

$$\mathbf{24}_\mathrm{F} \;\to\; (8,1)_0 \oplus (1,3)_0 \oplus (1,1)_0 \oplus (3,2)_{-5/6} \oplus (\bar{3},2)_{5/6}.$$

  Only $(1,3)_0$ and $(1,1)_0$ are electrically neutral.

- Minimal Yukawa interaction:

$$\mathcal{L} \supset (Y_{24})_i\, (\bar{5}_F)_i\, \Psi\, 5_H + \text{h.c.}$$

  induces couplings $LH\Sigma$ and LHN, where $\Sigma^0 \sim (1,3)_0$ and $N \sim (1,1)_0$.

- For neutrino masses via type-I/III seesaw,

$$m_\nu \sim \frac{Y_{24}^2\, v^2}{M_{24}},$$

  the required Y_{24} implies a very short lifetime for N ($\tau \ll t_{\text{Universe}}$) $\Rightarrow$ the singlet is not a viable DM candidate in the minimal model.

- Stable DM from $\mathbf{24}_\mathrm{F}$ requires extra symmetry, e.g. a Z_2 parity with $\mathbf{24}'_\mathrm{F}$ odd and SM+$\mathbf{24}_\mathrm{F}$ even:
  - forbids $(\bar{5}_F)\Psi 5_H$ Yukawa term,
  - the lightest component of $\mathbf{24}'_\mathrm{F}$ (often the singlet N) can be stable and act as DM,
  - neutrino masses then originate from another $\mathbf{24}_\mathrm{F}$.

Collider signatures of the SU(5)+$\mathbf{24}_F$ triplet leptons

- **Triplet leptons in the SU(5)+$\mathbf{24}_F$**
  - The adjoint $\mathbf{24}_F$ contains an electroweak triplet $\Sigma \sim (1,3)_0$ with components $\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$.
  - Yukawa couplings $Y_\Sigma \, \overline{L} \, \Sigma \, \tilde{H}$ generate neutrino masses (Type-III seesaw) and govern the Σ decay
- **Production at hadron colliders**
  - Drell–Yan pair production $pp \to \Sigma^+\Sigma^-$, $pp \to \Sigma^\pm\Sigma^0$ via off-shell $\gamma/Z/W$
  - single production via Yukawa couplings is typically subleading.
- **Decay channels and multi-lepton signatures**
  - For $m_\Sigma \gg m_W$, the main decays are

    $$\Sigma^\pm \to W^\pm\nu,\ Z\ell^\pm,\ h\ell^\pm, \qquad \Sigma^0 \to W^\pm\ell^\mp,\ Z\nu,\ h\nu,$$

    with approximate branching ratios of order $\mathcal{O}(1/3)$
  - **Key LHC signatures**:
    - tri-lepton and four-lepton final states with jets and moderate missing energy;
    - lepton-number–violating same-sign di-leptons from Majorana Σ^0 decays as a “smoking gun” for Type-III seesaw.
- **Current limits and prospects**
  - Multilepton searches at the LHC exclude triplet masses up to $\sim 800-900$ GeV, depending on flavour structure and branching ratios
  - In the SU(5)+$\mathbf{24}_F$ framework, a TeV-scale triplet is motivated by gauge coupling unification and neutrino data, making future HL-LHC and 100 TeV colliders particularly sensitive to this scenario

5. Summary and outlooks

- **SU(5) GUT with SUSY**: CMSSM, CMSSM-NUGM
- **SU(5) GUT without SUSY**: minimal SU(5), SU(5)+$\mathbf{24}_\mathbf{F}$

	CMSSM	CMSSM-NUGM	minimal $SU(5)$	SU(5)+$\mathbf{24}_\mathbf{F}$
Gauge coupling unification	Y	Y	N	Y
Proton decay	N (Shihwen's talk)	?	N	Y
Neutrino masses (in minimal setup)	N	N	N	Y
Baryon asymmetry	N	N	N	Y
Dark matter candidates	Y	Y	N	Y
Hierarchy problem	Y	Y	N	N
muon $g-2$ anomaly?/light EWino	N	Y	N	Y
new particles at colliders	Y	Y	N	Y

Models	Typical collider signatures
CMSSM-NUGM	**EWino/stau/stop/gluino** production with cascade decays to a LSP: **(*b*-)jets +leptons +large** $\not{E}_\mathrm{T}$; **compressed states** and possibly **long-lived charginos/disappearing tracks**.
SU(5)+$\mathbf{24}_\mathbf{F}$	**Weak triplet leptons** (Type-III seesaw) leading to **multilepton** and **same-sign dilepton** events; potentially **long-lived charged tracks** if the triplet is quasi-degenerate; ......

Thank you!

Exploration

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*Exploration*由河南大学、中国生物物理学会纳米生物学分会和Wiley出版集团共同创办（2021年1月），入选中国科协高起点新刊，聚焦于学科交叉融合探索，跨界创新成果传播，旨在向公众传播生命科学、医学、材料、化学、能源、可持续、计算、植物科学及其交叉学科领域的研究成果。物质科学领域、智能科学与智造领域、生命科学与健康领域、宇宙与空间科学领域、大科学工程与技术应用领域

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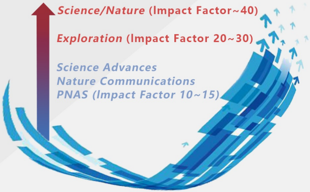

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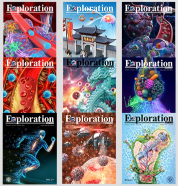
首个IF为22.5，跻身综合性期刊世界前4%行列，排名第5位；即时影响因子30.3；篇均被引46.1（Web of Science）；单篇最高被引300余次；百引耗时平均为5.9天；i10指数>200；CiteScore 2024为27.8，在Multidisciplinary中排名第4，跻身综合期刊世界前2%，CiteScore Track 2025为33.3（Scopus）；2026年将获得第二个影响因子预计28-30。



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Publisher: WILEY , 111 RIVER ST, HOBOKEN, USA, NJ, 07030-5774
ISSN / eISSN: 2766-8509 / 2766-2098
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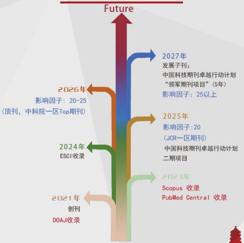

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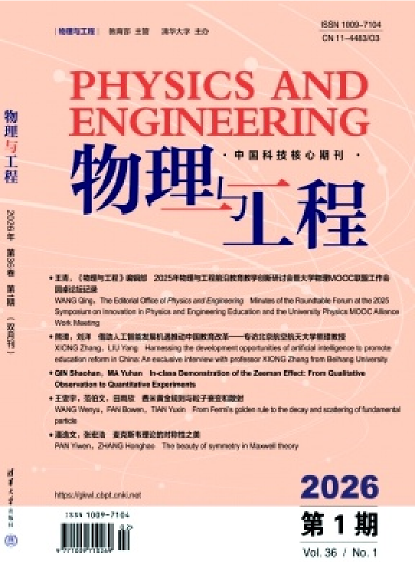
《物理与工程》 教育部 主管 清华大学 主办
ISSN 1009-7104
CN 11-4483/O3

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2026
第 1 期
Vol. 36 / No. 1
ISSN 1009-7104

- 《Exploration》是河南大学等主办、Wiley 出版的综合期刊，2021 年创刊，2024 年被 ESCI 等收录，2025 年 6 月获得首个 IF 22.5，排名多学科类全球第 5、前 4%，2025 年 12 月入选中国科技期刊卓越计划高起点新刊，2026 年 3 月入选新锐分区综合 1 区 top，即时 IF 30.3
- 《物理与工程》期刊由教育部主管、清华大学主办，是教育部高等学校大学物理课程教学指导委员会会刊，中国科技核心期刊
    - 科研论文到科普视频的转化——以 “光子-类轴子传播模式” 为例
    - 以跨学科项目实践培养师范生的科学教育能力——以《“暗物质与恐龙” 动画设计与制作》本科毕业设计为例
    - 一个绳杆复合摆问题的简单研究（大中衔接——中学物理奥赛题目剖析）
- Maybe 未来（若干年后）合作创办物理二学科主导的物理综合期刊《Exploration Physics and Engineering》，对标 Nature Physics、PRL、PRX，欢迎大家共同参与

Backup slides

The full renormalizable SU(5)+24_F Lagrangian before SU(5) symmetry breaking is

$$\boxed{\begin{aligned}\mathcal{L} = & -\frac{1}{4}F^A_{\mu\nu}F^{A\,\mu\nu} + i\,(\psi_{\bar 5})_i^{\dagger\,a}\,\bar\sigma^\mu(D_\mu\psi_{\bar 5})_{ia} + i\,(\psi_{10})^\dagger_{i\,ab}\,\bar\sigma^\mu(D_\mu\psi_{10})_i^{ab} + i\,\mathrm{Tr}\big[\Psi^\dagger\,\bar\sigma^\mu D_\mu\Psi\big] \\ & + (D_\mu H)^\dagger(D^\mu H) + \mathrm{Tr}\big(D_\mu\Phi\,D^\mu\Phi\big) \\ & - \frac{1}{2}M_F\,\mathrm{Tr}(\Psi\Psi) - \frac{1}{2}\lambda_F\,\mathrm{Tr}(\Psi\,\Phi\,\Psi) + \text{h.c.} \\ & + \frac{1}{4}(Y_{10})_{ij}\,\epsilon_{abcde}\,(\psi_{10})_i^{ab}\,(\psi_{10})_j^{cd}\,H^e + \sqrt{2}\,(Y_{\bar 5})_{ij}\,(\psi_{10})_i^{ab}\,(\psi_{\bar 5})_{ja}\,(H^*)_b + \text{h.c.} \\ & + (Y_{24})_i\,(\psi_{\bar 5})_{ia}\,\Psi^a{}_b\,H^b + \text{h.c.} \\ & - V(H,\Phi)\,.\end{aligned}}$$