What do experimental data tell us?

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1. Criteria in Estimating the Goodness of a Theory
2. Example I: MSSM
3. Example II: Z_3-NMSSM
4. Example III: General NMSSM
5. Example IV: Type-I NMSSM
6. Example V: B-L NMSSM
7. Conclusion

CEGT: Available Experimental Data

Rich experimental data have been accumulated !

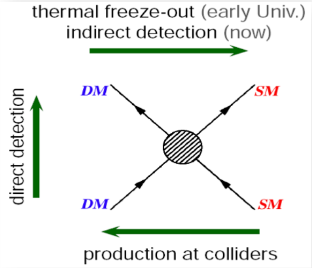
- Precision electroweak data;
- Heavy flavor data;
- Neutrino experiments;
- Higgs property measurement.
- Dark matter search experiments;
- LHC search for supersymmetry;
- Muon anomalous magnetic moment.

Global Fit: Combine all the data to analyze theories.

CEGT: WIMP DM direct search experiments

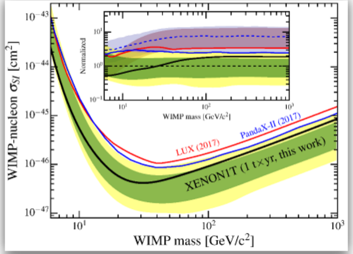
Fermi-LAT, AMS...

XENON
PandaX
LUX...

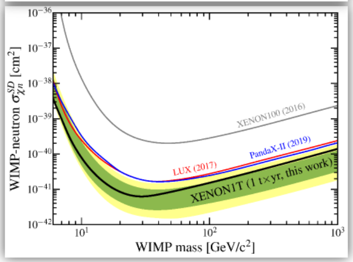


LEP, Tevatron, LHC...

No new physics signal !



arXiv:1805.12562



arXiv:1902.03234

Preliminary PandaX-4T results released!

CEGT: Implications of DM search experiments

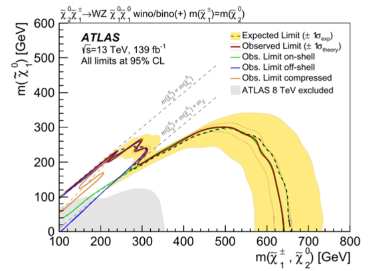
Popular WIMP DM candidate: Neutralino in SUSY

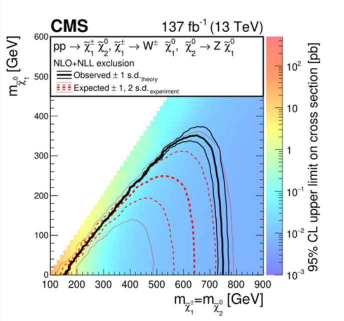
$$\sigma^{\rm SI}_{\tilde{\chi}^0_1-N} \simeq 5\times 10^{-45}\ {\rm cm}^2 \left(\frac{\rm C_{\tilde{\chi}^0_1\tilde{\chi}^0_1 h}}{0.1}\right)^2 \left(\frac{\rm m_h}{\rm 125GeV}\right)^2$$

$$\sigma^{\rm SD}_{\tilde{\chi}^0_1-N} \simeq 10^{-39}\ {\rm cm}^2 \left(\frac{\rm C_{\tilde{\chi}^0_1\tilde{\chi}^0_1 Z}}{0.1}\right)^2$$

1. Interactions of DM with SM particles are **feeble at most** when $m_{\tilde{\chi}^0_1} \sim 100$GeV.
2. Difficult to obtain the measured abundance if DM DM $\to$ SM SM. Exceptions: Co-annihilation, Resonance annihilation. **All corresponds to a small Bayesian evidence, fine-tunned!**
3. **Simple WIMP DM theories are becoming unnatural!**
4. Good theory: Naturally explaining experimental results. E.g., secluded DM theories in a more complex framework.

CEGT: LHC searches for SUSY





Latest LHC searches for tri- and bi-lepton signals.

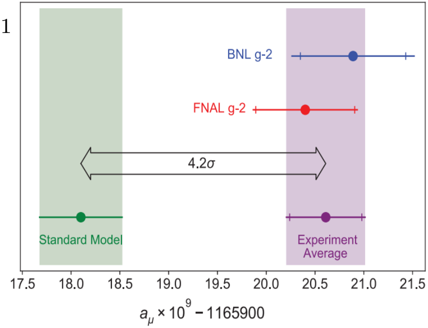
1. Simplified model for a specified process.
2. Invalid for a specific theory: complex decay chain, multiple production processes, and various signals to be analyzed.
3. Elaborated Monte Carlo simulations are necessary.

CEGT: Improved measurement of Muon g-2

$$\Delta a_\mu = a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}$$

Mass insertion method:
WHL, WHR, BHR, and BLR contributions.

$$a_\mu^{\text{SUSY}} \sim \frac{\alpha_i}{4\pi} \frac{m_\mu^2 \, \mu \tan\beta M_i}{M_{\text{SUSY}}^4}$$



1. Set an upper bound on LSP mass (about 600 GeV).
2. Set an upper bound on NLSP mass (about 700 GeV).
3. The other involved sparticles cannot be excessively heavy.
4. LHC search tightly limits SUSY explanantions: $1 + 1 \gg 2$.
5. Global fits with/without Muon g-2 differes significantly.

CEGT: Critical aspects of TeV-scale SUSY

Readily explain data, particularly those for correlated obs.!

1. **DM physics:** Ωh^2 versus $\sigma_{\tilde{\chi}_1^0 - p}$ / Bayesian Evidence.
   $\times/\checkmark$: explain the experimental results with/without tuning.
2. **LHC and Δa_μ:** SUSY searches versus sizable correction to a_μ.
   $\times/\checkmark$: tight/loose constraints on the explanation of Muon g-2.
3. **Natural EWSB:** $m_Z^2 = 2(m_{H_d}^2 - m_{H_u}^2 \tan^2\beta)/(\tan^2\beta - 1) - \mathbf{2\mu^2}$.
   $\times/\checkmark$: whether or not a moderately small μ is preferred.
4. **Neutrino physics:** neutrino masses and mixings.
   $\times/\checkmark$: whether or not providing reasonable mechanisms for ....
5. **Higgs physics:** unreasonably large mass, SM-like couplings
   $\times/\checkmark$: explain the mass with/without large radiative corrections.

Obtained by both analytic formulae and global fits, which are tough tasks.

Model	MSSM	Z_3-NMSSM		GNMSSM	Type-I NMSSM	B-L NMSSM
DM component	Bino	Bino	Singlino	Singlino	Sneutrino	Bino, Singlino, BLino, Bileptino, or sneutrino
DM physics	×	×	×	✓	✓✗	✓
LHC and Δa_μ	×	×	×	✓	✓	✓
EWSB	×	×	✓	✓	✓	✓
Neutrino	×	×	×	×	✓✗	✓
Higgs mass	×	×	×	×	✓✗	✓

GNMSSM: Motivation and superpotential

- Chiral Superfields

SF	Spin 0	Spin $\frac{1}{2}$	Generations	$(\mathrm{U}(1) \otimes \mathrm{SU}(2) \otimes \mathrm{SU}(3))$
$\hat{q}$	$\tilde{q}$	q	3	$(\frac{1}{6}, \mathbf{2}, \mathbf{3})$
$\hat{l}$	$\tilde{l}$	l	3	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_d$	H_d	$\tilde{H}_d$	1	$(-\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{H}_u$	H_u	$\tilde{H}_u$	1	$(\frac{1}{2}, \mathbf{2}, \mathbf{1})$
$\hat{d}$	$\tilde{d}_R^*$	d_R^*	3	$(\frac{1}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{u}$	$\tilde{u}_R^*$	u_R^*	3	$(-\frac{2}{3}, \mathbf{1}, \overline{\mathbf{3}})$
$\hat{e}$	$\tilde{e}_R^*$	e_R^*	3	$(1, \mathbf{1}, \mathbf{1})$
$\hat{s}$	S	$\tilde{S}$	1	$(0, \mathbf{1}, \mathbf{1})$

- Superpotential

$$W_{\mathrm{GNMSSM}} = W_{\mathrm{Yukawa}} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{1}{3}\kappa \hat{S}^3 + \mu \hat{H}_u \cdot \hat{H}_d + \frac{1}{2}\nu \hat{S}^2 + \xi \hat{S}$$

1. Solve domain wall and tadpole problems in Z_3-NMSSM.
2. Z_3-violating terms from an underlying theory with Z_4^n or Z_8^n symmetry.

GNMSSM: DM mass and couplings

- Neutralino mass matrix

$$m_{\tilde{\chi}_i^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & 0 \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu - \mu_{\rm eff} & -\frac{1}{\sqrt{2}}v_u\lambda \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu - \mu_{\rm eff} & 0 & -\frac{1}{\sqrt{2}}v_d\lambda \\ 0 & 0 & -\frac{1}{\sqrt{2}}v_u\lambda & -\frac{1}{\sqrt{2}}v_d\lambda & \frac{2\kappa}{\lambda}\mu_{\rm eff} \end{pmatrix}$$

Couplings of the singlino-dominated DM are given by:

$$C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 h_i} \simeq \frac{\mu+\mu_{\rm eff}}{v}\left(\frac{\lambda v}{\mu+\mu_{\rm eff}}\right)^2 \frac{Z_s V_{h_i}^{\rm SM}(m_{\tilde{\chi}_1^0}/(\mu+\mu_{\rm eff}) - \sin 2\beta)}{1-(m_{\tilde{\chi}_1^0}/(\mu+\mu_{\rm eff}))^2} + \ldots$$

$$C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 Z} \simeq \frac{m_Z}{2v}\left(\frac{\lambda v}{\mu+\mu_{\rm eff}}\right)^2 \frac{Z_s \cos 2\beta}{1-(m_{\tilde{\chi}_1^0}/(\mu+\mu_{\rm eff}))^2} ,$$

- **DM mass and κ are not correlated, λ and κ are not correlated!**
- DM properties are described by **five** independent parameters: $m_{\tilde{\chi}_1^0}$, λ, κ, $\tan\beta$, and $\mu_{\rm tot} \equiv \mu + \mu_{\rm eff}$.
- Small λ is preferred to suppress DM-nucleon scatterings.

GNMSSM: Dominant annihilation channels

Conditions to obtain the measured DM abundance:

1. $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to t\bar{t}$: s-channel exchange of Z and Higgs bosons.

$$|C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 G^0}| \simeq \frac{\lambda^2 v}{\mu_{\rm tot}} \frac{Z_s \left(m_{\tilde{\chi}_1^0}/\mu_{\rm tot}\right)\cos 2\beta}{1-\left(m_{\tilde{\chi}_1^0}/\mu_{\rm tot}\right)^2} \simeq 0.1.$$

2. $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_s A_s$: s-channel exchange of Higgs bosons, t-channel exchange of neutralinos.

$$|C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 h_s}| = |C_{\tilde{\chi}_1^0\tilde{\chi}_1^0 A_s}| = -\sqrt{2}\kappa \simeq 0.2 \times \left(\frac{m_{\tilde{\chi}_1^0}}{300~\rm GeV}\right)^{1/2}.$$

3. $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h A_s$: s-channel exchange of Higgs bosons, t-channel exchange of neutralinos.

$$\lambda^3 \sin 2\beta \simeq \left(\frac{\mu}{700~\rm GeV}\right)^2.$$

Singlet-dominated particles may form a secluded DM sector: measured abundance obtained by $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to h_s A_s$ (via adjusting κ); DM-nucleon scatterings suppressed by a small $\lambda v/\mu_{tot}$.

GNMSSM: Dominant annihilation channels

$h \equiv h_1$ scenario: lnZ = -65.79 $\pm$ 0.046			
$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \mathrm{h_s\ A_s}$	$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \mathrm{t\ \bar{t}}$	$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \mathrm{h_s\ h_s}$	Co-annihilation
88%	8%	3%	0.7%
$h \equiv h_2$ scenario: lnZ = -68.23 $\pm$ 0.051			
$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \mathrm{h_s\ A_s}$	$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \mathrm{t\ \bar{t}}$	Co-annihilation	h-funnel
76%	12%	11.6%	0.3%

Table 1: Dominant annihilation channels and their normalized posterior probabilities for $h \equiv h_1$ and $h \equiv h_2$ scenarios. In obtaining the values in this table, each sample's most critical channel for the abundance was identified and sequentially used to classify the samples. The posterior probability densities of the same type of samples were then summed.

$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to h_s A_s$ **always played a role in DM annihilation.**

GNMSSM: Explaining the Muon g-2 anomaly

Characteristics:

1. Roughly same loop contributions as the MSSM.
2. **DM physics is changed**.
3. **LHC constraints is alleviated significantly**.
4. **Vacuum becomes more stable**.

Mechanism to alleviate the LHC constraints:

1. DM must be heavy to achieve the measured relic density.
2. For singlino-dominated DM, heavy sparticles prefer to decay into NLSP or NNLSP first; their decay chains are lengthened.
3. Light singlet Higgs bosons may act as the sparticle decay products.

GNMSSM: Explaining the Muon g-2 anomaly

- The following processes are considered:

$$
\begin{aligned}
&pp \to \tilde{\chi}_i^0 \tilde{\chi}_j^\pm, && i = 2,3,4,5; \quad j = 1,2 \\
&pp \to \tilde{\chi}_i^\pm \tilde{\chi}_j^\mp, && i = 1,2; \quad j = 1,2 \\
&pp \to \tilde{\chi}_i^0 \tilde{\chi}_j^0, && i = 2,3,4,5; \quad j = 2,3,4,5 \\
&pp \to \tilde{\mu}_i \tilde{\mu}_j, && i = L,R; \quad j = L,R
\end{aligned}
$$

- All LHC searches for electroweakinos and sleptons are considered, a total of 14 analyses for Run-II data.
- Newly added analyses:
  1. ATLAS search for 3 lepton plus missing E_T signal, see CERN-EP-2021-059, or arXiv: 2106.01676.
  2. CMS search for 2 lepton plus missing E_T signal, arXiv: 2012.08600.

GNMSSM: Explaining the Muon g-2 anomaly

Analysis	Simplified Scenario	Signal of Final State	Luminosity
CMS-SUS-17-010 (arXiv:1807.07799)	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to W^\pm\tilde{\chi}_1^0 W^\mp\tilde{\chi}_1^0$ $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to \nu\tilde{\ell}/\ell\tilde{\nu} \to \ell\ell\nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$	$2\ell + E_{\rm T}^{\rm miss}$	35.9 $\rm fb^{-1}$
CMS-SUS-17-009 (arXiv:1806.05264)	$\tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$	$2\ell + E_{\rm T}^{\rm miss}$	35.9 $\rm fb^{-1}$
CMS-SUS-17-004 (arXiv:1801.03957)	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to Wh(Z)\tilde{\chi}_1^0\tilde{\chi}_1^0$	$\mathrm{n}\ell(\geq 0) + \mathrm{n}j(\geq 0) + E_{\rm T}^{\rm miss}$	35.9 $\rm fb^{-1}$
CMS-SUS-16-045 (arXiv:1709.00384)	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to W^\pm\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	$1\ell 2b + E_{\rm T}^{\rm miss}$	35.9 $\rm fb^{-1}$
CMS-SUS-16-039 (arxiv:1709.05406)	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to \ell\tilde{\nu}\ell\tilde{\ell}$ $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to \tilde{\tau}\nu\tilde{\ell}\ell$ $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to \tilde{\tau}\nu\tilde{\tau}\tau$ $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to WZ\tilde{\chi}_1^0\tilde{\chi}_1^0$ $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to WH\tilde{\chi}_1^0\tilde{\chi}_1^0$	$n\ell(\geq 0)(\tau) + E_{\rm T}^{\rm miss}$	35.9 $\rm fb^{-1}$
CMS-SUS-16-034 (arXiv:1709.08908)	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to W\tilde{\chi}_1^0 Z(h)\tilde{\chi}_1^0$	$\mathrm{n}\ell(\geq 2) + \mathrm{n}j(\geq 1) E_{\rm T}^{\rm miss}$	35.9 $\rm fb^{-1}$
CERN-EP-2017-303 (arXiv:1803.02762)	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to WZ\tilde{\chi}_1^0\tilde{\chi}_1^0$ $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to \nu\tilde{\ell}\ell\tilde{\ell}$ $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to \nu\tilde{\ell}/\ell\tilde{\nu} \to \ell\ell\nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$ $\tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$	$\mathrm{n}\ell(\geq 2) + E_{\rm T}^{\rm miss}$	35.9 $\rm fb^{-1}$
CERN-EP-2018-306 (arXiv:1812.09432)	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to Wh\tilde{\chi}_1^0\tilde{\chi}_1^0$	$\mathrm{n}\ell(\geq 0) + \mathrm{n}j(\geq 0) + \mathrm{n}b(\geq 0) + \mathrm{n}\gamma(\geq 0) + E_{\rm T}^{\rm miss}$	35.9 $\rm fb^{-1}$
CERN-EP-2018-113 (arXiv:1806.02293)	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to WZ\tilde{\chi}_1^0\tilde{\chi}_1^0$	$\mathrm{n}\ell(\geq 2) + \mathrm{n}j(\geq 0) + E_{\rm T}^{\rm miss}$	35.9 $\rm fb^{-1}$
CERN-EP-2019-263 (arXiv:1912.08479)	$\tilde{\chi}_2^0 v\tilde{\chi}_1^\pm \to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0 \to \ell\nu\ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$	$3\ell + E_{\rm T}^{\rm miss}$	139 $\rm fb^{-1}$
CERN-EP-2019-106 (arXiv:1908.08215)	$\tilde{\ell}\tilde{\ell} \to \ell\ell\tilde{\chi}_1^0\tilde{\chi}_1^0$ $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp \to \nu\tilde{\ell}/\ell\tilde{\nu} \to \ell\ell\nu\nu\tilde{\chi}_1^0\tilde{\chi}_1^0$	$2\ell + E_{\rm T}^{\rm miss}$	139 $\rm fb^{-1}$
CERN-EP-2019-188 (arXiv:1909.09226)	$\tilde{\chi}_2^0\tilde{\chi}_1^\pm \to Wh\tilde{\chi}_1^0\tilde{\chi}_1^0$	$1\ell + h(\to bb) + E_{\rm T}^{\rm miss}$	139 $\rm fb^{-1}$

Table 2: Signal of final state for electroweakino pair-production processes.

GNMSSM: Explaining the Muon g-2 anomaly

Consider h_1 as the SM-Like Higgs boson.

- Constraints on different NLSP.

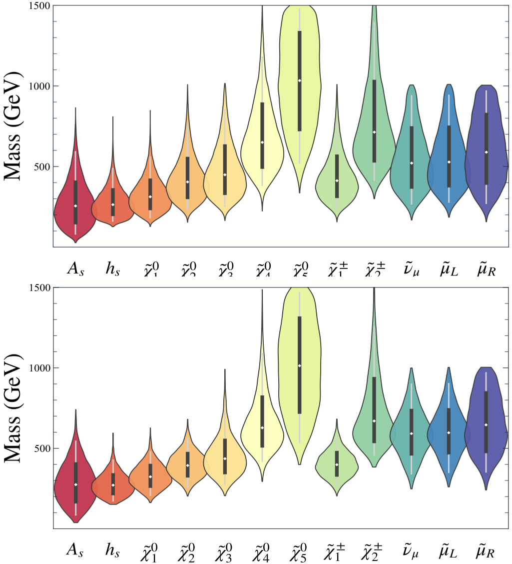
NLSP	$m_{\tilde{\chi}_1^0}$	$\mu + \mu_{\rm eff}$	M_2	$m_{\tilde{\mu}_L}$	$m_{\tilde{\mu}_R}$	$N_{\rm tot}$	$N_{\rm pass}^{\rm MC}$	$N_{\rm pass}^{\rm VS}$
$\tilde{\nu}_\mu$	200	250	370	250	300	1751	**127**	124
$\tilde{\mu}_R$	200	300	350	350	300	1071	**24**	24
$\tilde{B}$	200	300	300	350	350	310	**103**	103
$\tilde{W}$	200	300	250	350	350	1246	**792**	784
$\tilde{H}$	160	200	300	250	250	3162	**1606**	1606

Table 3: Summarization of the samples classified by their NLSP's dominant component. $N_{\rm tot}$ represents the total number of each type of samples surveyed by concrete Monte Carlo simulations. $N_{\rm pass}^{\rm MC}$ represents the corresponding number satisfing $R < 1$, and $N_{\rm pass}^{\rm VS}$ are that further stasfying vacuum stability constraint. The lower limits of parameters $(\mu + \mu_{\rm eff})$, M_2, $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\mu}_L}$ and $m_{\tilde{\mu}_R}$ for the samples surviving the constraints are given in units of GeV in each row.

About two thirds samples have been excluded!

GNMSSM: Explaining the Muon g-2 anomaly

- Mass spectra before and after considering the LHC constraints.



GNMSSM: Explaining the Muon g-2 anomaly

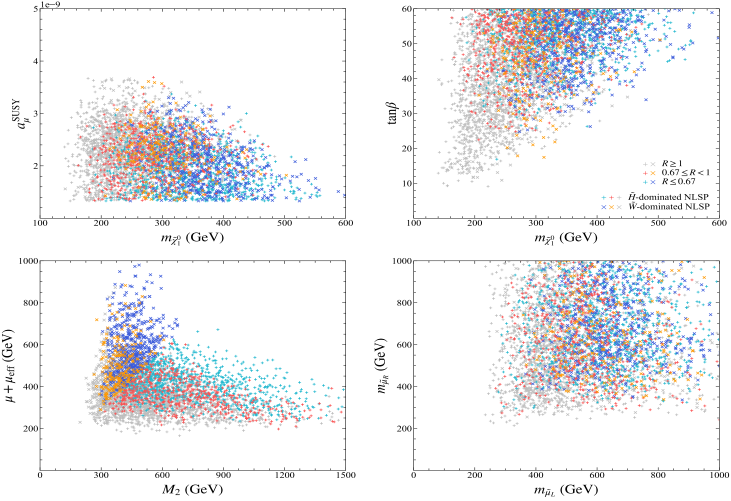
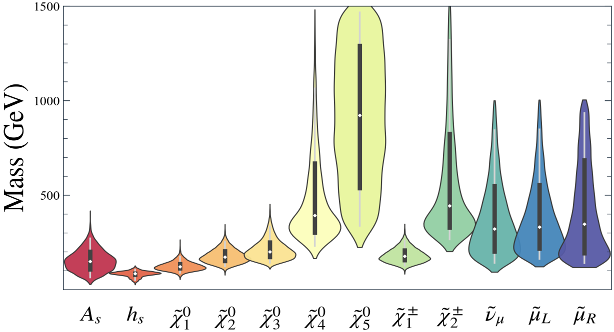


Figure 1: The samples with $\tilde{H}$- or $\tilde{W}$-dominated NLSP, which are denoted by $+$ and $\times$ symbols, respectively.

GNMSSM: Explaining the Muon g-2 anomaly

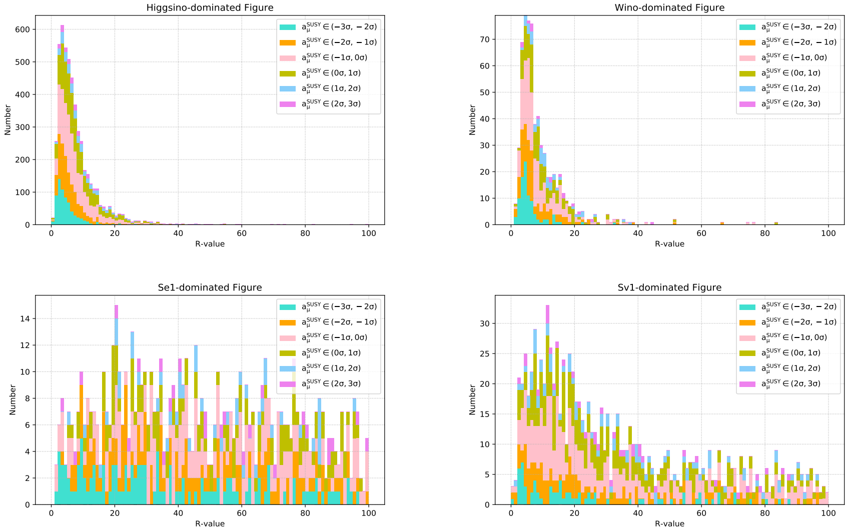
Results for h_2 as the SM-Like Higgs boson.

- Mass spectra for the samples of h_2 scenario before considering the LHC constraints.



GNMSSM: Explaining the Muon g-2 anomaly

- R-value for the samples in the h_2 scenario. **Strong tension**!



GNMSSM: Current Status

Model	MSSM	Z_3-NMSSM		GNMSSM	Type-I NMSSM	B-L NMSSM
DM candidate	Bino	Bino	Singlino	Singlino	Sneutrino	Bino, Singlino, BLino, Bileptino, and sneutrino
DM physics	×	×	×	✓	✓✗	✓
LHC and Δa_μ	×	×	×	✓	✓	✓
EWSB	×	×	✓	✓	✓	✓
Neutrino	×	×	×	×	✓✗	✓
Higgs mass	×	×	×	×	✓✗	✓

Conclusion

1. Experimental data provides many hints to fundamental physics.
2. Global fit deepens greatly our understanding of new physics.
3. Economic supersymmetric theories are facing increasingly strong experimental restrictions, and more complex theory becomes favored to alleviate the constraints.
4. Some seeming independent problems may have a common physical origin. Well motivated theories should be explored in a more sophisticated way.

thanks!