Status of natural NMSSM in light of LHC 13 TeV and XENON-1T Result

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Why supersymmetry (SUSY)

- Math

  A general mathematical symmetry.

  Supersymmetry is the only way to extend space-time symmetries!

  Coleman-Mandula "No-go theorem".

- Physics

  New principle: a symmetry between forces and matters.

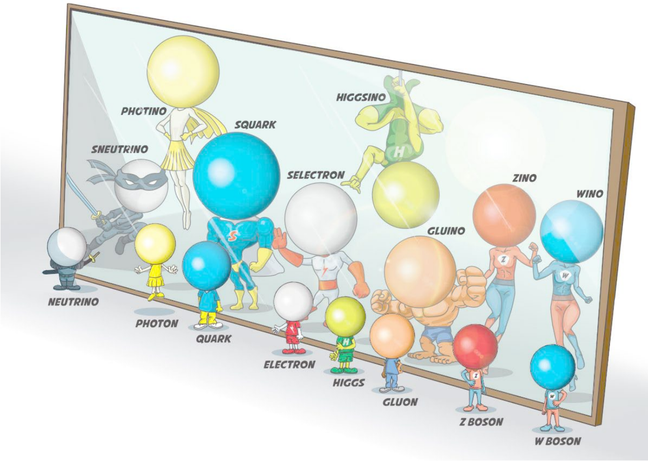
  Predictive: the 125 GeV Higgs lies in the '115-135' GeV window favored by SUSY.

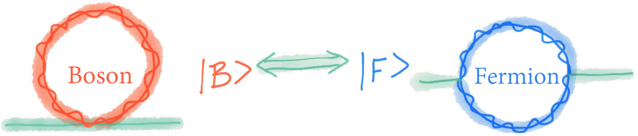
  Possible dark matter candidate. Natural dark matter candidates, many possible baryogenesis mechanism.

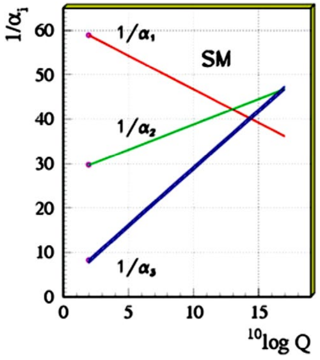
  Vacuum stability naturally in SUSY at tree-level.

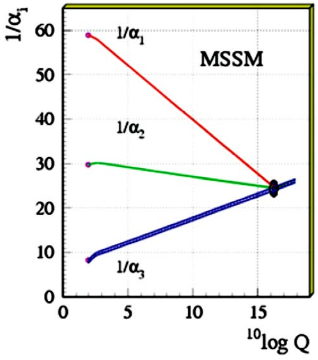
  Unification of forces.

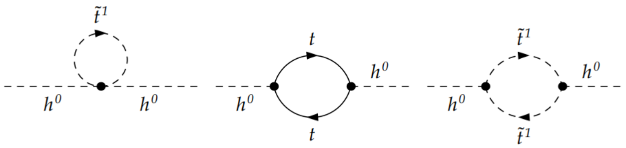
  Scale invariance: SUSY connect bosons and fermions, so quadratic divergence of boson mass is forbidden, just like fermion case.











Electroweak scale SUSY

In 2012, just after Higgs discovery

> "Supersymmetry may not be dead but these latest results have certainly put it into hospital."
>
> -Chris Parkes

- ➢ The SM-like Higgs boson mass

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

  - The tree level Higgs mass is smaller than Z boson mass.
  - Large top quarks/squarks loop corrections are needed.
  - Maximal stop mixing is needed to relax the fine-tuning, and the sum of the two stop mass squares $\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}$ is smaller than 1.2 TeV.
  - The gluino mass is needed lighter than 1.5 TeV.

Electroweak scale SUSY

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What is SUSY's disease?

- The SM-like Higgs boson mass

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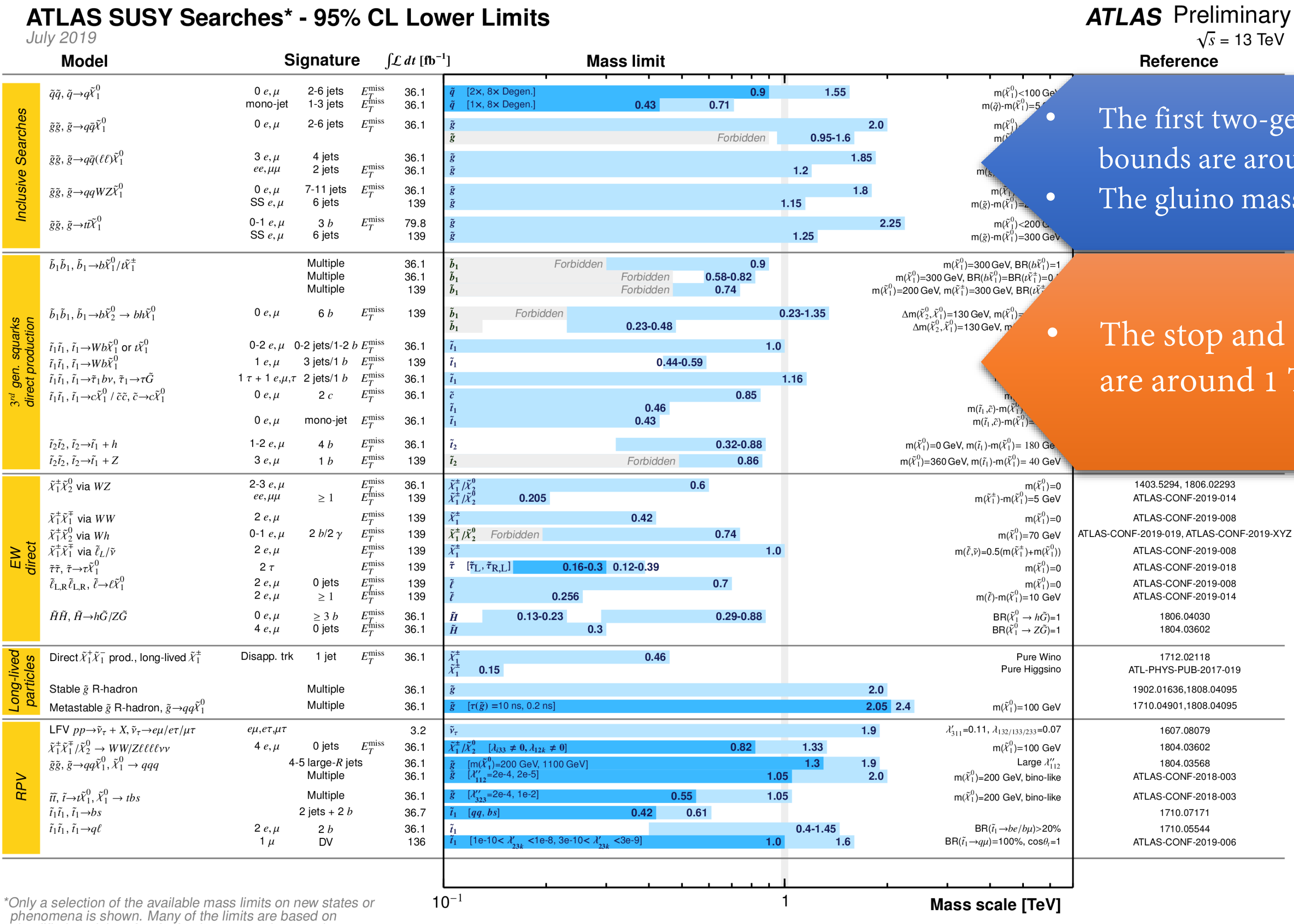
Patient Label
Name: SUSY

Symptom Checklist



*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.

- The first two-generation squark mass low bounds are around 1.6 TeV.
- The gluino mass low bound is around 2.0 TeV.

- The stop and sbottom mass low bounds are around 1 TeV, respectively.

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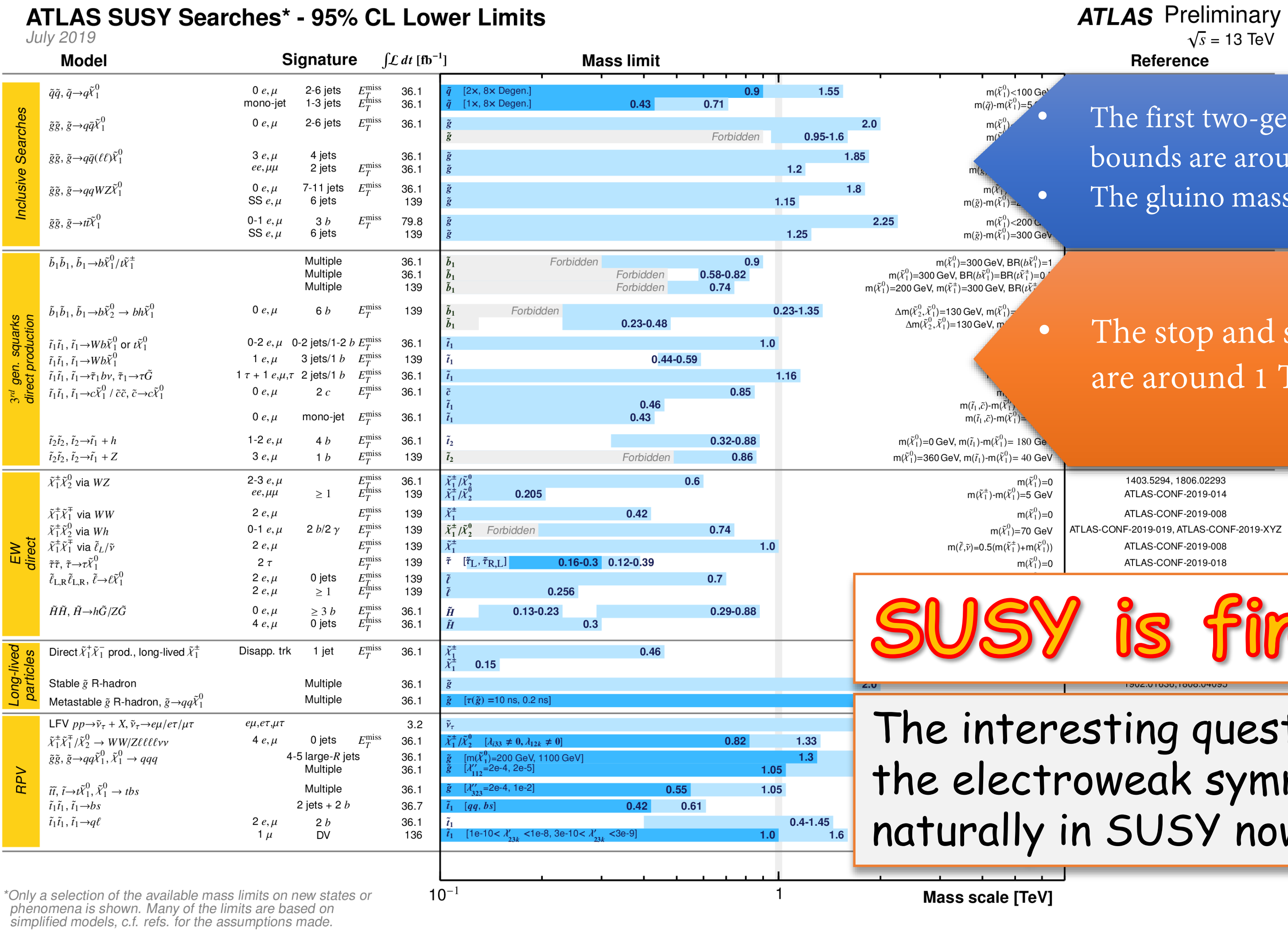

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SUSY is fine-tuned !!!

The interesting question: can we solve the electroweak symmetry breaking naturally in SUSY now?

Electroweak fine tuning & Naturalness

- Electroweak symmetry breaking condition

$$\frac{1}{2}m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1}$$

  - The potential of scalar Higgs doublets includes mass terms μ^2, and the potential must be unstable in order to trigger $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry breaking.
  - μ^2 must be cancelled by negative soft SUSY break terms
  - Requires fine tuning if $|\mu| \gg m_Z$

Fine tuning measure definition:

$$\Delta_{\mathcal{O}} = \max_i \left| \frac{\partial \ln \mathcal{O}}{\partial \ln p_i} \right| ,$$

$\mathcal{O}$ is a physical observable ;
p_i is the input parameter at EW scale.

Define: $\Delta_Z \equiv \max_i \left| \frac{\partial \ln m_Z^2}{\partial \ln p_i} \right|$ for tuning in EW symmetry breaking.

$\Delta_h \equiv \max_i \left| \frac{\partial \ln m_h^2}{\partial \ln p_i} \right|$ for the tuning of SM-like Higgs boson mass.

Both quantities Δ_Z and Δ_h should be small in a natural SUSY theory.

Points:
- Small μ
- Large enough tree level Higgs mass

Naturalness & Dark matter

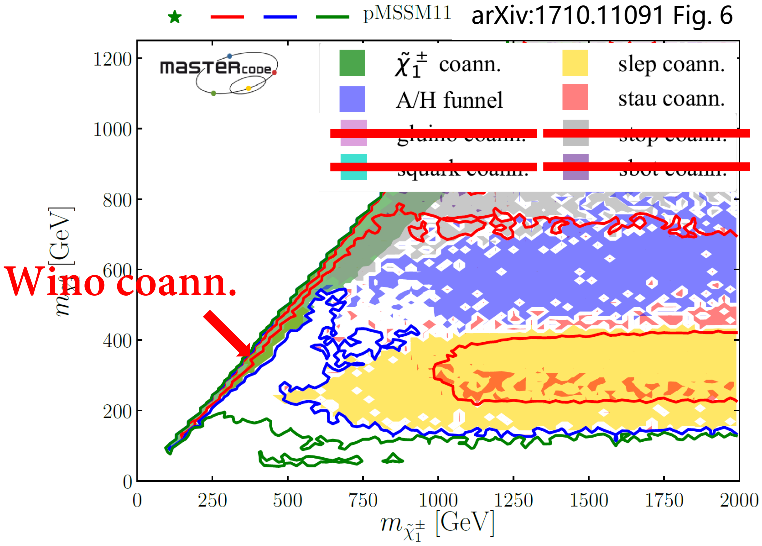
Light Higgsinos are natural, but are no good dark matter (DM) candidates.

- Relic density too small.
- Large direct detection rates (spin-dependent via Z-exchange).

MSSM

$$W_{\mathrm{MSSM}} = W_{\mathrm{Yukawa}} + \mu \hat{H}_u \cdot \hat{H}_d$$

• Bino LSP	Relic density too large
• Higgsino-Bino mixing	Too large direct detection rates unless $m_{\mathrm{LSP}} \geq 700$ GeV



arXiv:1710.11091 Fig. 6

NMSSM

$$W_{\mathrm{NMSSM}} = W_{\mathrm{Yukawa}} + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

- **μ is achieved by EW symmetry breaking**

  $\mu_{\mathrm{eff}} = \lambda \langle \hat{S} \rangle$ naturally at EW scale

- **The SM-like Higgs boson mass**

$$m_{h_{125}}^2 \approx m_Z^2 \cos^2 2\beta + \triangle_t + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2}{\kappa^2} v^2 (\lambda - \kappa \sin 2\beta)^2 .$$

Additional contribution compared with MSSM

- **The Singlino is a good DM candidate**

Observed relic density through annihilation via

- Singlet-like CP-odd Higgs A_1 funnel
- Z or CP-even Higgs funnel
- Coannihilation with Higgsino

DM in Natural NMSSM (nNMSSM)

In R parity conserved SUSY model, if Lightest SUSY Particle is $\widetilde{\chi}_1^0$, it can act as a DM candidate. It's property depends on the magnitude of its component N_{1i}.

$0.0959 < \Omega h^2 < 0.1439$

$\Delta_Z < 50$ & $\Delta_h < 50$

LHC Run I Data

DM direct detection Data (2016)

In the gauge-eigenstate basis:

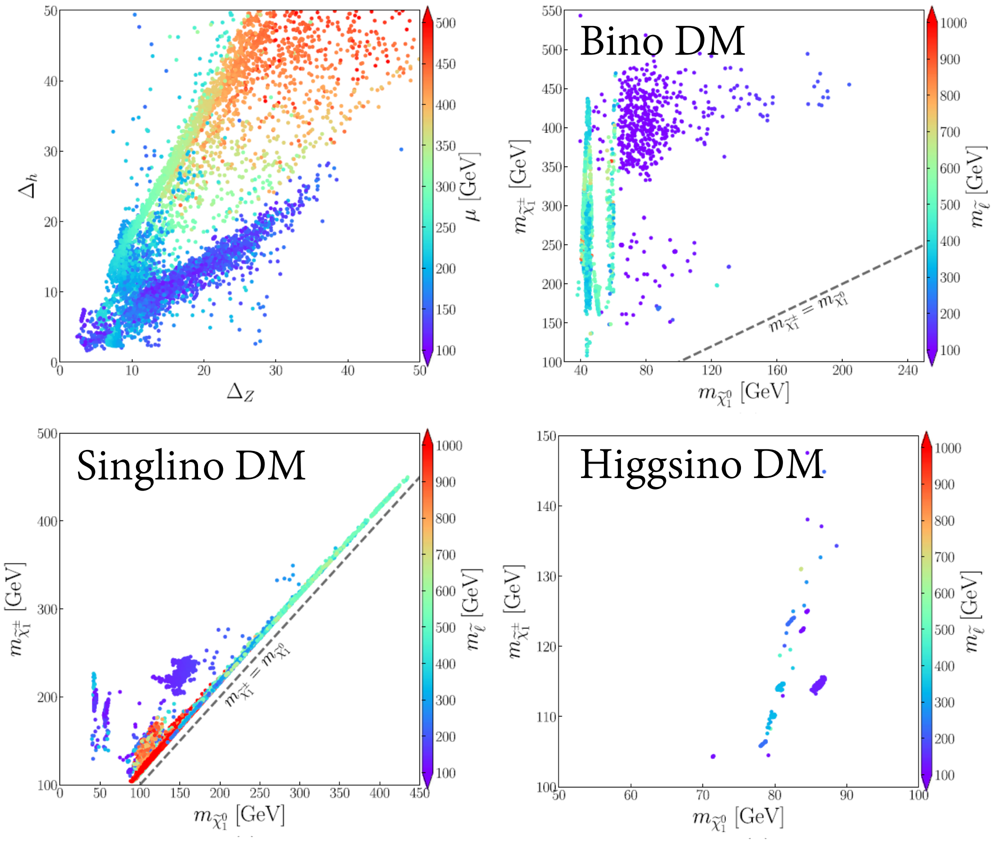
$$\psi^0 = (\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S})$$

$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi^0)^{\mathrm{T}} \mathcal{M}_0 \psi^0 + \text{c.c.}$$

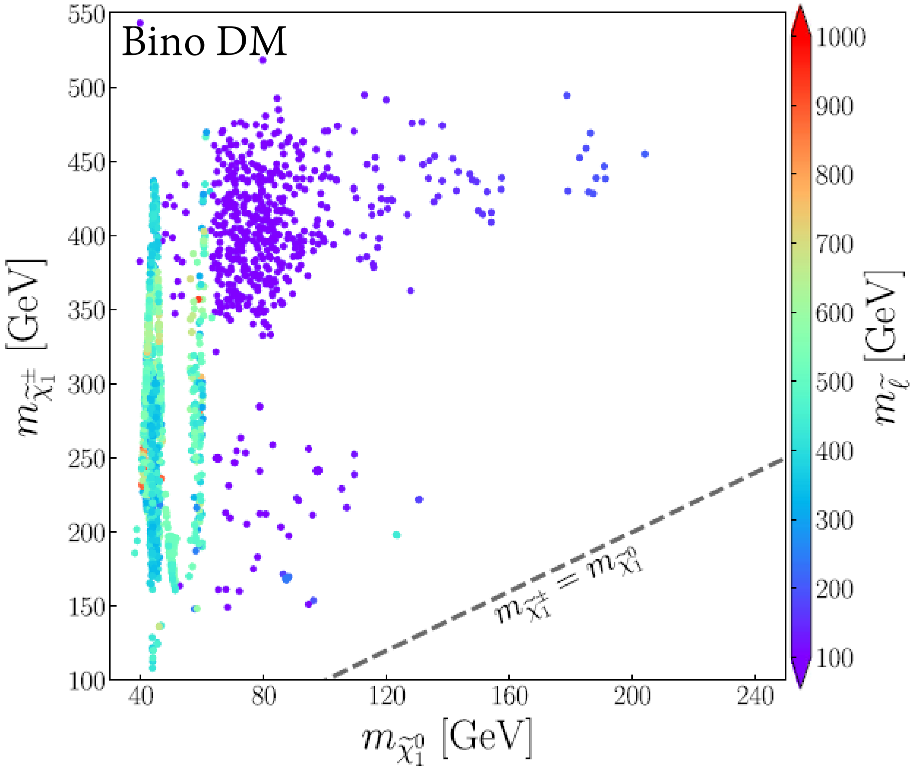
$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_1 v_u}{\sqrt{2}} & 0 \\ & M_2 & \frac{g_2 v_d}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 \\ & & 0 & -\mu & -\lambda v_u \\ & & & 0 & -\lambda v_d \\ & & & & 2\kappa v_s \end{pmatrix}$$

Mass eigenstate (Majorana Fermion):

$$\widetilde{\chi}_i^0 = \sum_{j=1}^{5} N_{ij} \psi_j$$



DM in Natural NMSSM (nNMSSM)



Bino DM in nNMSSM

- $m_{\tilde\chi} \leq 200$ GeV
- DM annihilation mechanisms :

1. Z/h_1 funnel;

$$\sigma(\tilde\chi_1^0\tilde\chi_1^0 \xrightarrow{Z/h_1} XX') \propto \left|\frac{C_{Z/h_1\tilde\chi_1^0\tilde\chi_1^0}C_{Z/h_1XX'}}{s-m_{h_1}^2+i\Gamma_{h_1}m_{h_1}}\right|^2$$

$$C_{h_1\tilde\chi_1^0\tilde\chi_1^0} \simeq \sqrt{2}\lambda N_{13}N_{15} - g_1N_{11}N_{14} + g_2N_{12}N_{14},$$

$$C_{Z\tilde\chi_1^0\tilde\chi_1^0} = \frac{g_2}{2\cos\theta_W}\left(-|N_{13}|^2+|N_{14}|^2\right)$$

in Wino and Singlino decouple limit,

$$N_{13} \propto \frac{v_u}{\mu} \quad N_{14} \propto (v_d\mu + v_u m_{\tilde\chi})/\mu^2$$

relic density provide an upper limit on μ

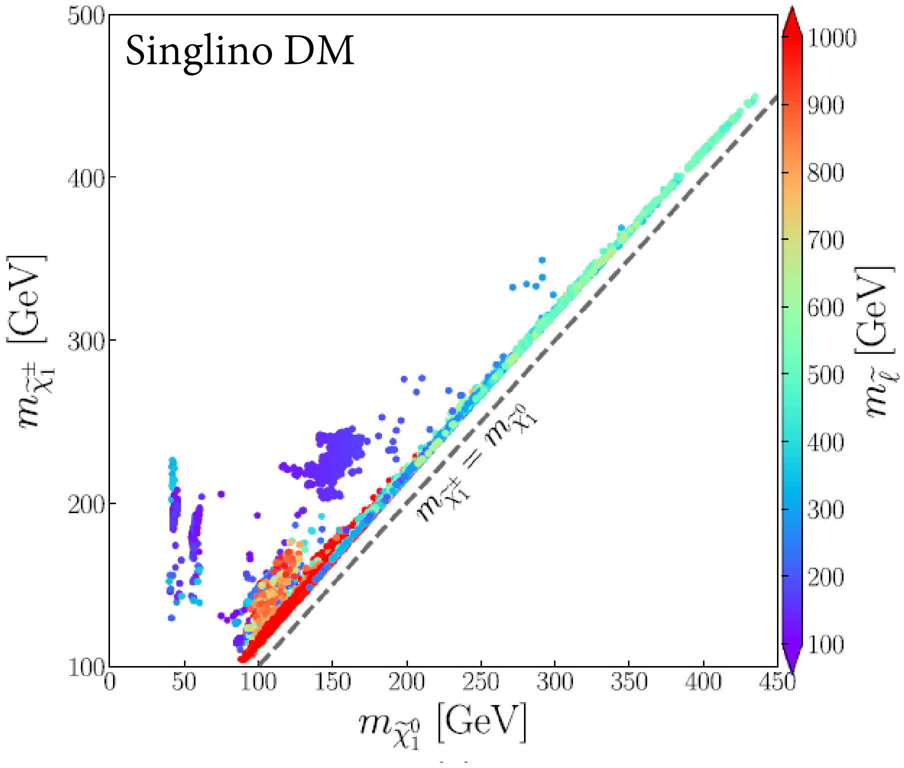
2. $\tilde\chi\tilde\chi \to h_1h_2$ via t-channel exchange of a neutralino.

$$m_{\tilde\chi} \simeq (m_{h_1}+m_{h_2})/2$$

$$\sigma(\tilde\chi_1^0\tilde\chi_1^0 \xrightarrow{\tilde\chi_i^0} XX') \propto C^2_{h_1\tilde\chi_i^0\tilde\chi_1^0}C^2_{h_2\tilde\chi_i^0\tilde\chi_1^0}$$

3. Coannihilation with slepton.

DM in Natural NMSSM (nNMSSM)



Singlino DM in nNMSSM

- $m_{\tilde{\chi}} < 450$ GeV
- DM annihilation mechanisms :

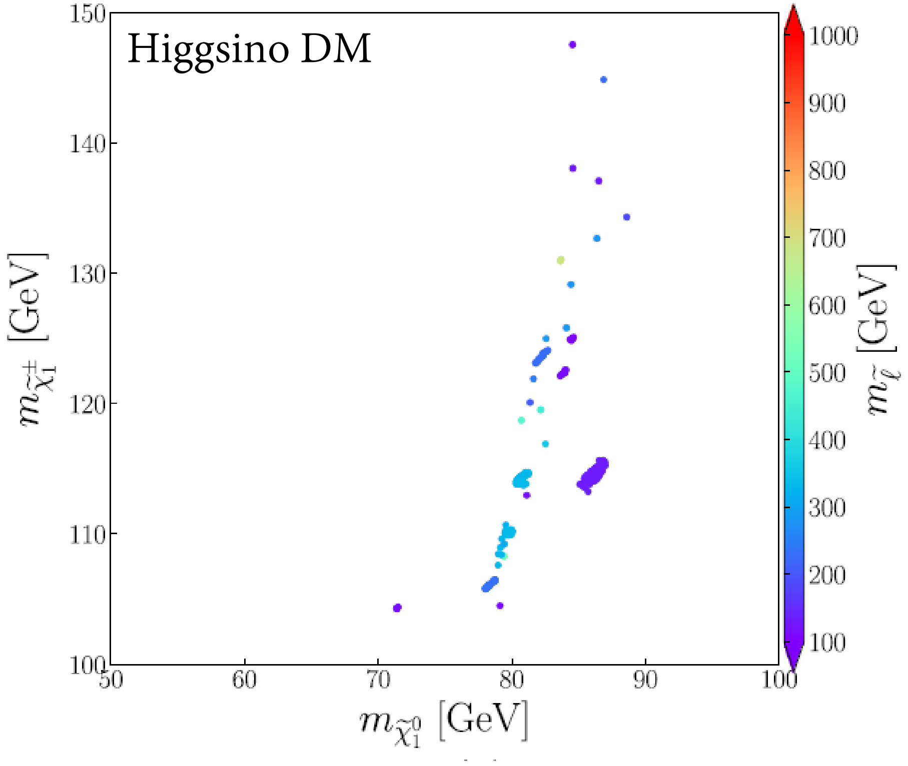
1. Z/h_1 funnel;
2. $\tilde{\chi}\tilde{\chi} \to h_1 h_2$ via t-channel exchange of a neutralino.
3. Coannihilation with slepton.
4. Coannihilation with Higgsino

   in the Bino and Wino decouple limit,
   $2|\kappa| \lesssim \lambda,\ m_{\tilde{\chi}} \lesssim \mu,\ m_{\tilde{\chi}} > 100$ GeV.

5. CP-odd Higgs $A_1^{(\star)}$ funnel.

   Singlet sum rule
   $$m_{\tilde{\chi}}^2 \simeq m_{h_s}^2 + \frac{1}{3} m_{A_1}^2$$
   - singlet Higgs boson mass prefers to smaller than 125 GeV.
   - m_{A_1} prefers to smaller than $\sqrt{3} m_{\tilde{\chi}}$
   - If m_{h_s} is small, $\tilde{\chi}\tilde{\chi} \to A_1^\star \to A_1 h_s$

DM in Natural NMSSM (nNMSSM)



Higgsino DM in nNMSSM

- $m_{\tilde{\chi}} \sim 85$ GeV
- Large λ induce sizable mixing between Higgsino and Singlino in the neutralino mass matrix. Singlino component is around 30%.
- This scenario is tightly restricted by DM direct detections

Spin-independent cross section

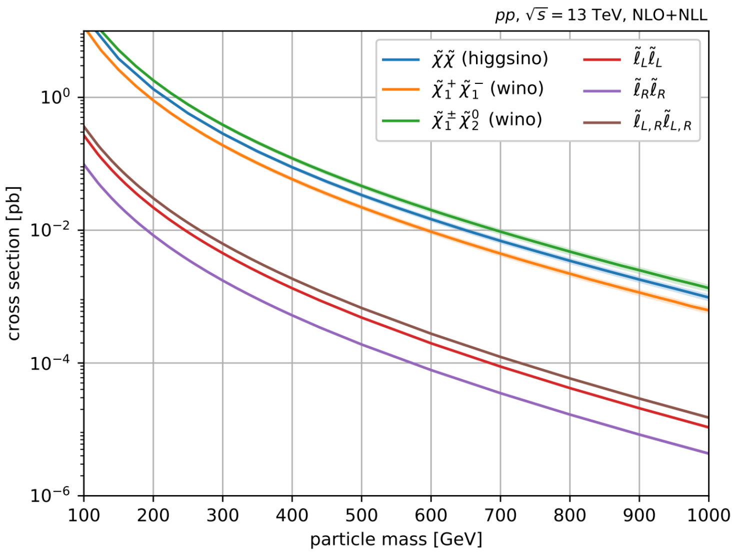
$$\sigma^{SI}_{\tilde{\chi}-(n)} = \frac{4\mu_r^2}{\pi} \left| f^{(n)} \right|^2$$

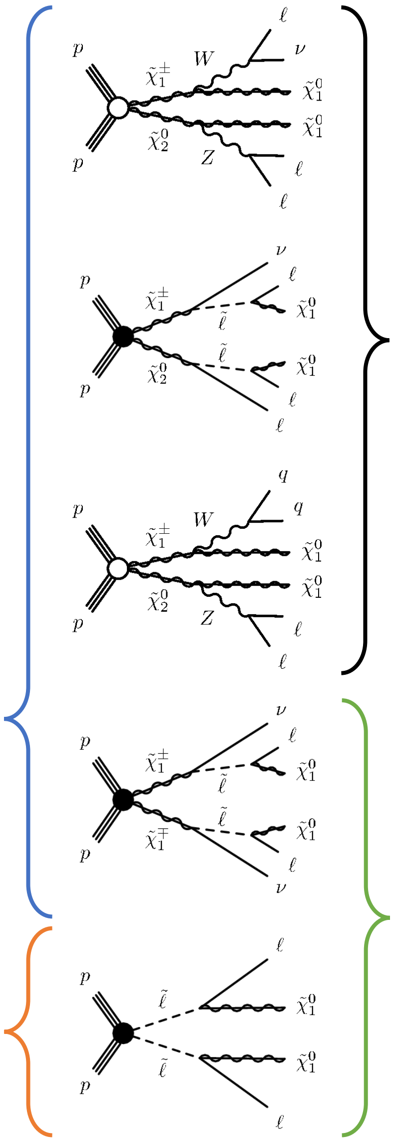
$$f^{(n)} \approx \sum_{i=1}^{3} f^{(n)}_{h_i} = \sum_{i=1}^{3} \frac{C_{h_i \tilde{\chi}_1^0 \tilde{\chi}_1^0} C_{h_i nn}}{2 m_{h_i}^2}$$

Spin-dependent cross section

$$\sigma^{SD}_{\tilde{\chi}-n/p}/\mathrm{pb} \simeq C^{n/p} \times 10^{-4} \times \left(\frac{|N_{13}|^2 - |N_{14}|^2}{0.1} \right)^2$$

Naturalness & LHC





Leptons + Etmiss Signal

$3\ell + E_{\mathrm{T}}^{\mathrm{miss}}$

$2\ell 2j + E_T^{\mathrm{miss}}$

$2\ell(\mathrm{SS}) + E_{\mathrm{T}}^{\mathrm{miss}}$

1709.05406
1801.03957
1801.01846
1803.02762
1806.02293
1709.08908

$2\ell(\mathrm{OS}) + E_{\mathrm{T}}^{\mathrm{miss}}$

1708.07875
1712.08119
1806.05264
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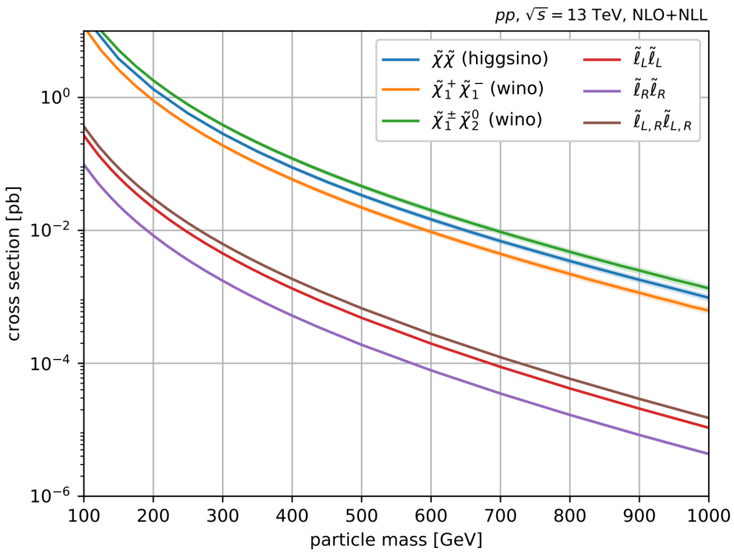
Light Higgsinos could be tested by Electroweakino pair production

Slepton Pair Production could test the samples with light slepton

Naturalness & LHC



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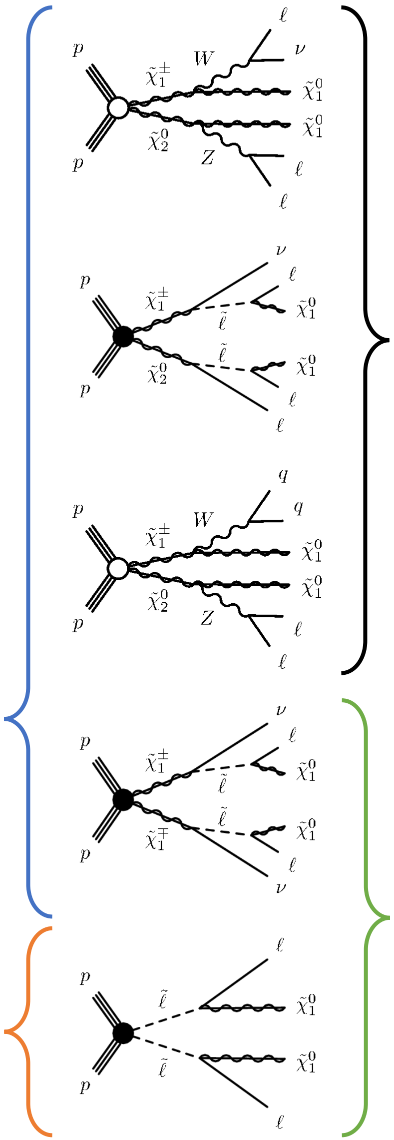

Leptons + Etmiss Signal

CMS 36 fb^{-1}

$3\ell + E_\text{T}^\text{miss}$

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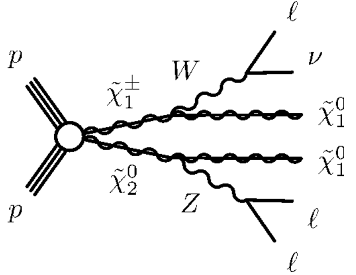
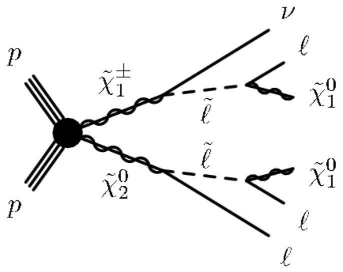
Naturalness & LHC

Heavy slepton case:



$$\mathrm{BR}(\tilde\chi_2^0 \to \tilde\chi_1^0 Z) \simeq 60\%$$
$$\mathrm{BR}(\tilde\chi_2^0 \to \tilde\chi_1^0 h) \simeq 40\%$$
$$\mathrm{BR}(\tilde\chi_1^\pm \to \tilde\chi_1^0 W^\pm) \simeq 100\%$$
$$\mathrm{BR}(WZ \to 3\ell\ \nu) \simeq 3\%$$

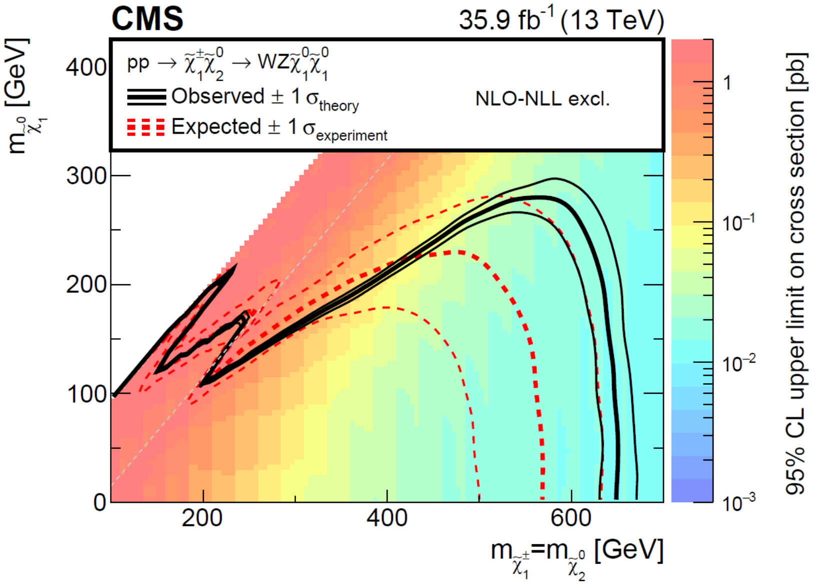
Light slepton case:



$$\mathrm{BR}(\tilde\ell \to \ell\tilde\chi_1^0) = 1$$

arXiv: 1801.03957

Search	Signal topology				
	WZ	WH	ZZ	ZH	HH
1ℓ 2b		✓			
4b					✓
2ℓ on-Z	✓		✓	✓	
2ℓ soft	✓				
$\geq 3\ell$	✓	✓	✓	✓	✓
H($\gamma\gamma$)		✓		✓	✓



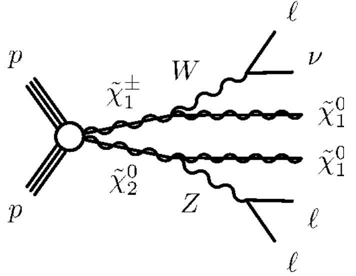
➡ The black curve assumes Wino-like $\tilde\chi_1^\pm$, $\tilde\chi_2^0$ production cross section, Not Higgsino-like

Wino-like cross section is about 3 to 4 times larger than Higgsino's

Higgsino-like $\tilde\chi_1^\pm$ with mass $\sim \mu$
Higgsino-like $\tilde\chi_{2,3}^0$ with masses $\sim \mu \pm \Delta_\pm$
($\Delta_\pm \sim 10$ GeV due to mixing)

Naturalness & LHC

Heavy slepton case:



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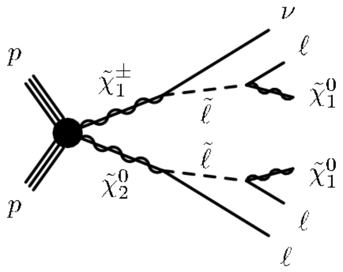

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4b					✓
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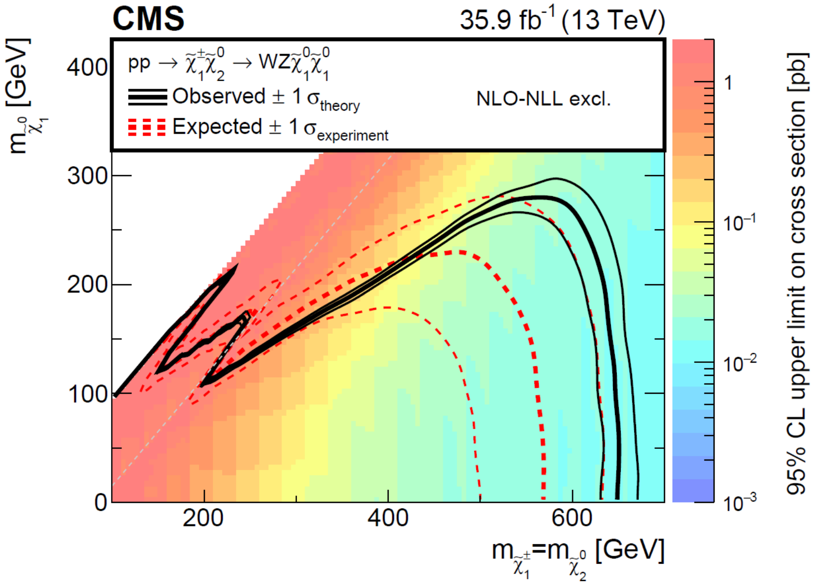
2ℓ soft	✓				
$\geq 3\ell$	✓	✓	✓	✓	✓
$\mathrm{H}(\gamma\gamma)$		✓		✓	✓

Combine them together though the **CLs** method



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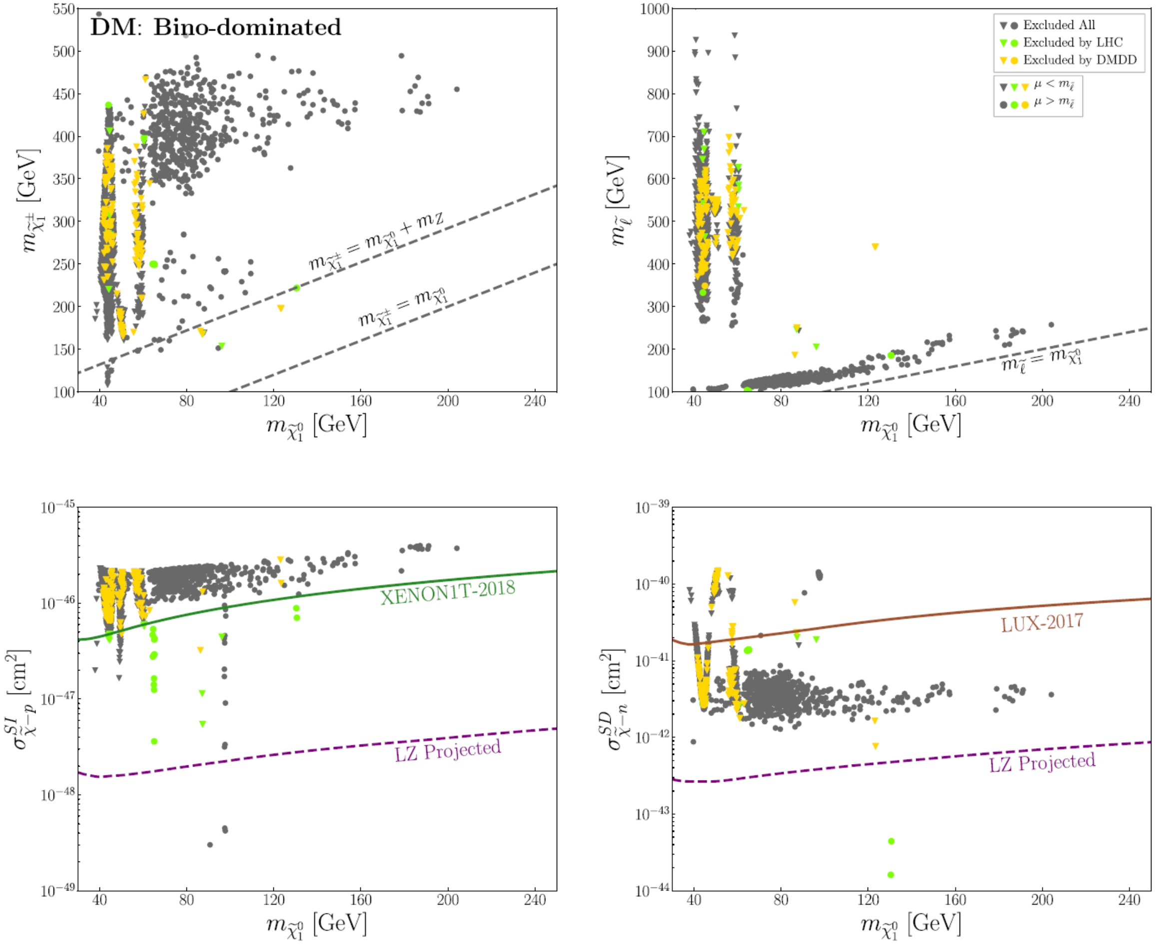
Impacts on nNMSSM



Bino DM in nNMSSM

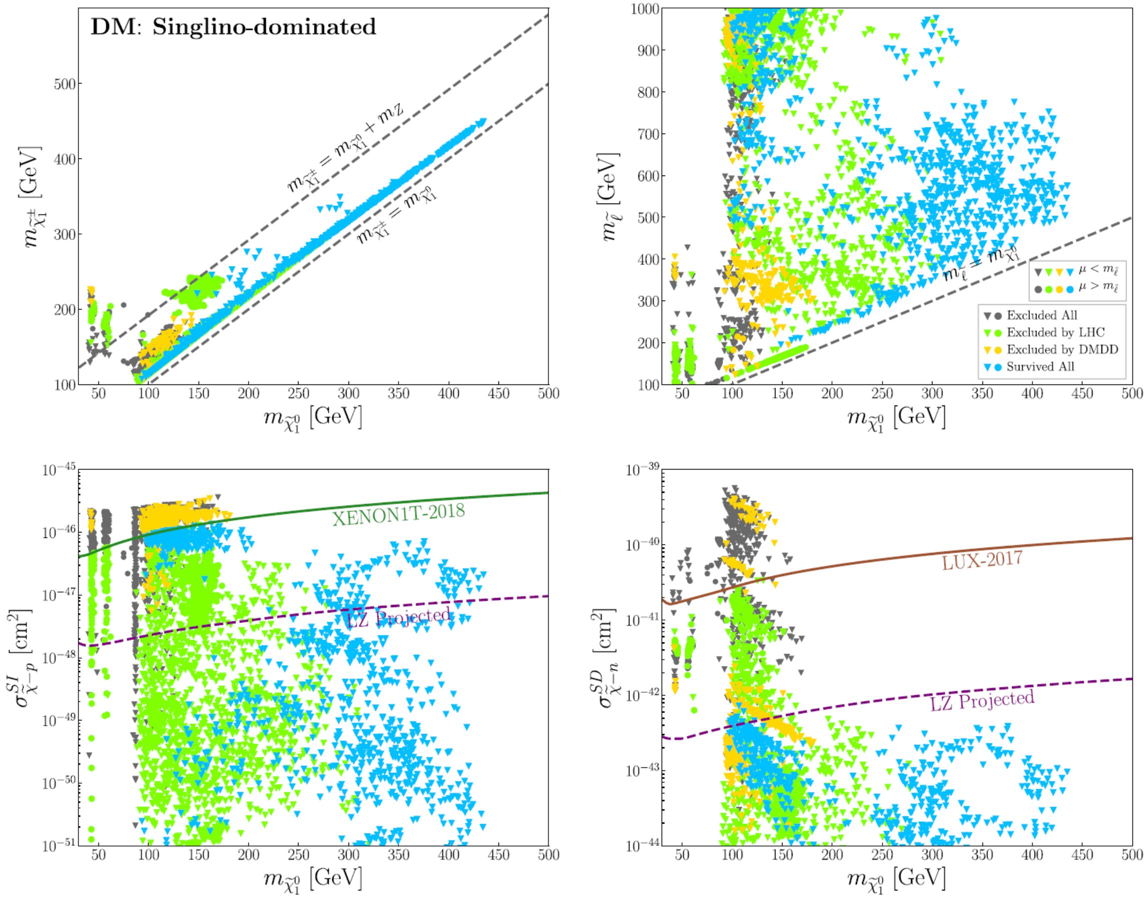
1. ~~Z/h_1 funnel;~~
2. ~~$\widetilde{\chi}\widetilde{\chi} \to h_1 h_2$ via t-channel exchange of a neutralino.~~
3. ~~Coannihilation with slepton.~~

$\sigma^{\rm SI}_{\widetilde{\chi}-{\rm n}}$ too large

$3\ell + E_{\rm T}^{\rm miss}$ too large

If relax the fine-tuning constraint, some parameter space region still can survive. Such parameter space will test by the upcoming DM direct detection, unless the blind-spot.

Impacts on nNMSSM



Singlino DM in nNMSSM

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3. Coannihilation with slepton.
4. Coannihilation with Higgsino
5. ~~CP-odd Higgs $A_1^\star$ funnel.~~

The surviving region:

- $m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm} \in (90, 440)$ GeV
- Singlino decouple case:

  $N_{15}^2 > 99\%$

  Can not be detectable

- Singlino-Higgsino mixing case:

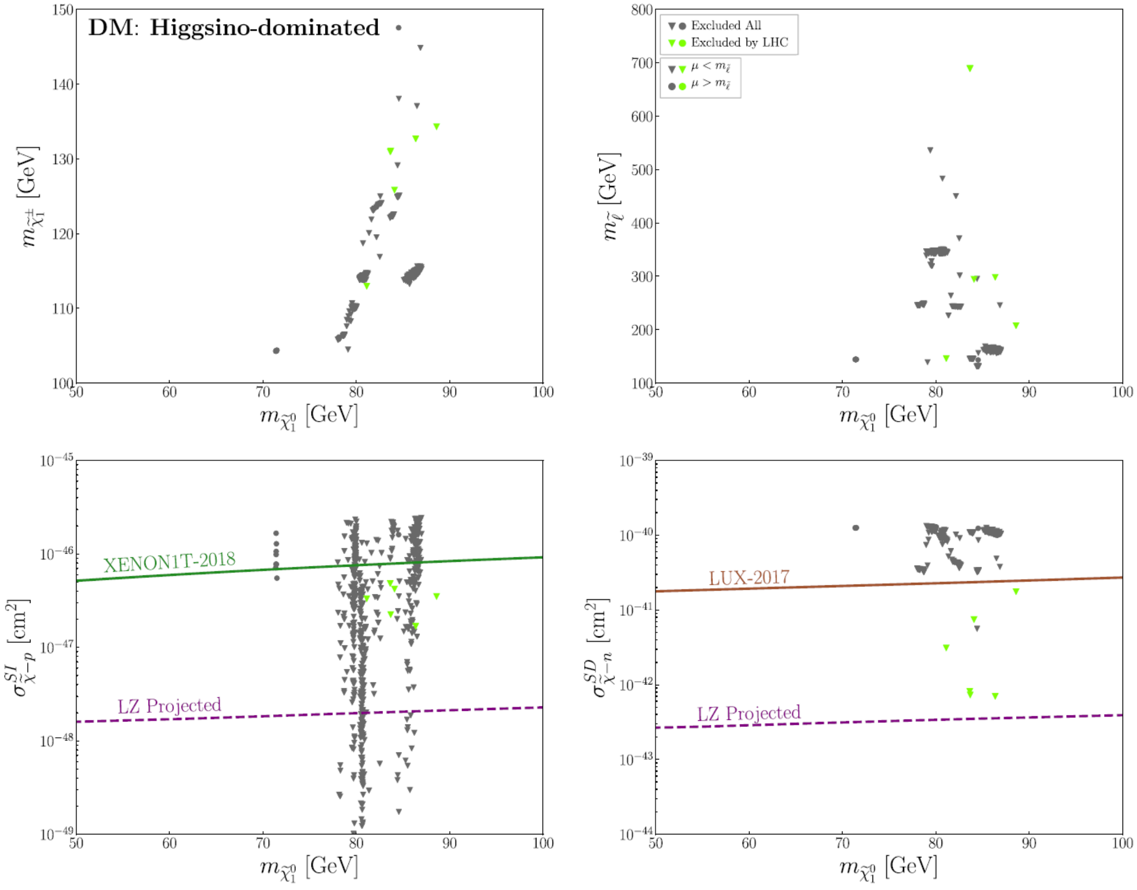
  90 GeV $< m_{\tilde{\chi}_1^0} <$ 220 GeV

  A singlet-like Higgs lighter than 125 GeV

  Detectable SI DM-nucleon Xsect

  $$\sigma^{\rm SI}_{\tilde{\chi}-{\rm n}} > 10^{-47}\ {\rm cm}^2$$

Impacts on nNMSSM



~~Higgsino DM in nNMSSM~~

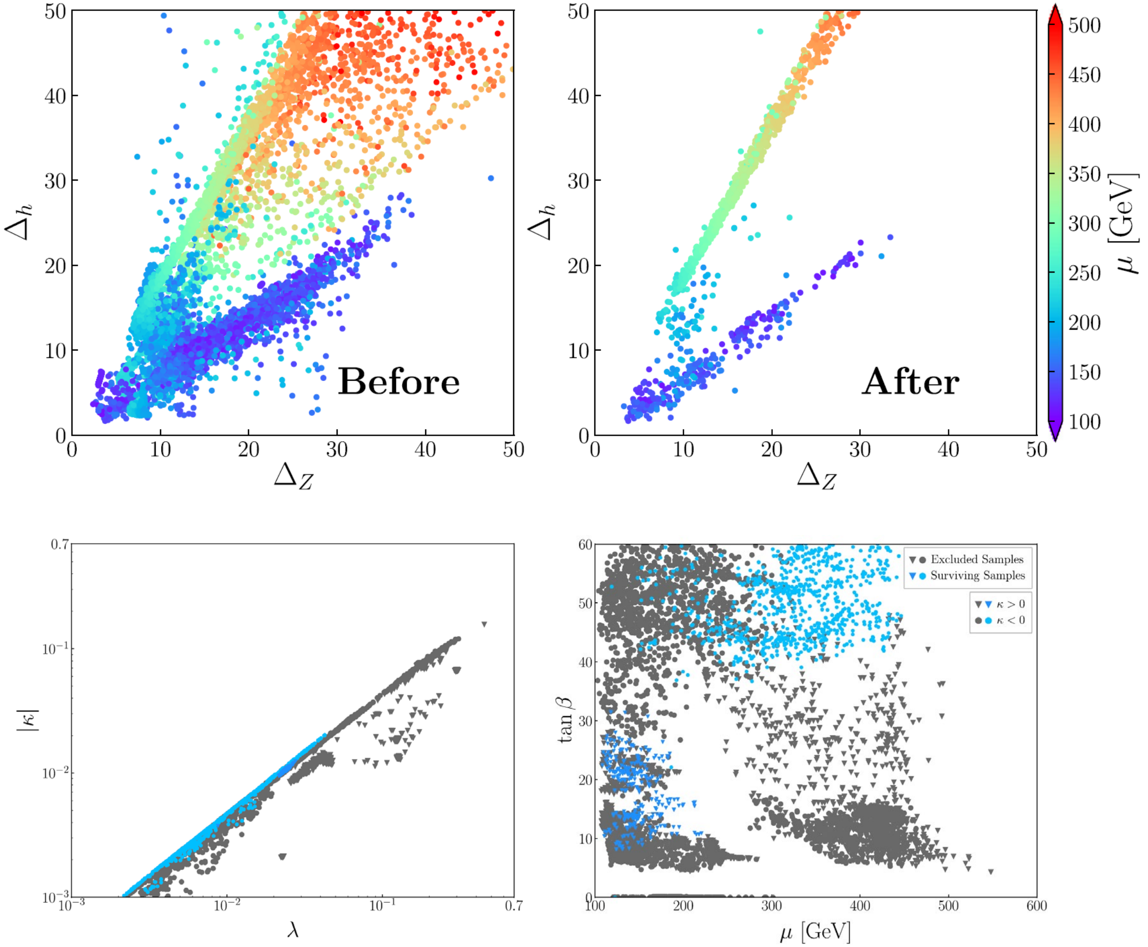
Higgsino can not be a DM candidate under the current experimental limits.

$\sigma^{\mathrm{SD}}_{\tilde{\chi}-\mathrm{n}}$ too large

LHC Data full cover the blindspot region

Status of the nNMSSM

Naturalness



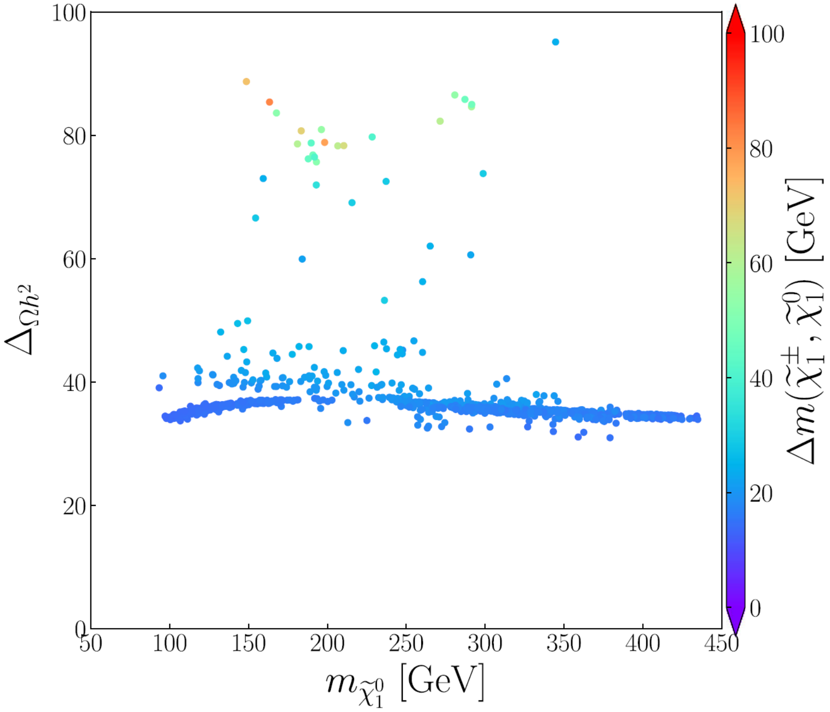
- In the NMSSM, a Singlino-like LSP can satisfy the constraints on DM.
- The surviving parameter space allows relative small μ, which naturally trigger the Electroweak symmetry breaking.
- Singlino decoupled case prefers large $\tan\beta$, while RGE not.

- In our work, the research of 3rd generation sparticles is not fine enough:
  1. The value of stau parameters are same to the first two generations'. While the constraint on stau pair production is much weaker than selectron's and smuon's.
  2. Stop and sbottom searches at LHC are not take into consideration.

Status of the nNMSSM

Naturalness in DM phenomenology

$$\Delta_{\Omega h^2} \equiv \max_i \left| \frac{\partial \log \Omega h^2}{\partial \log p_i} \right|$$



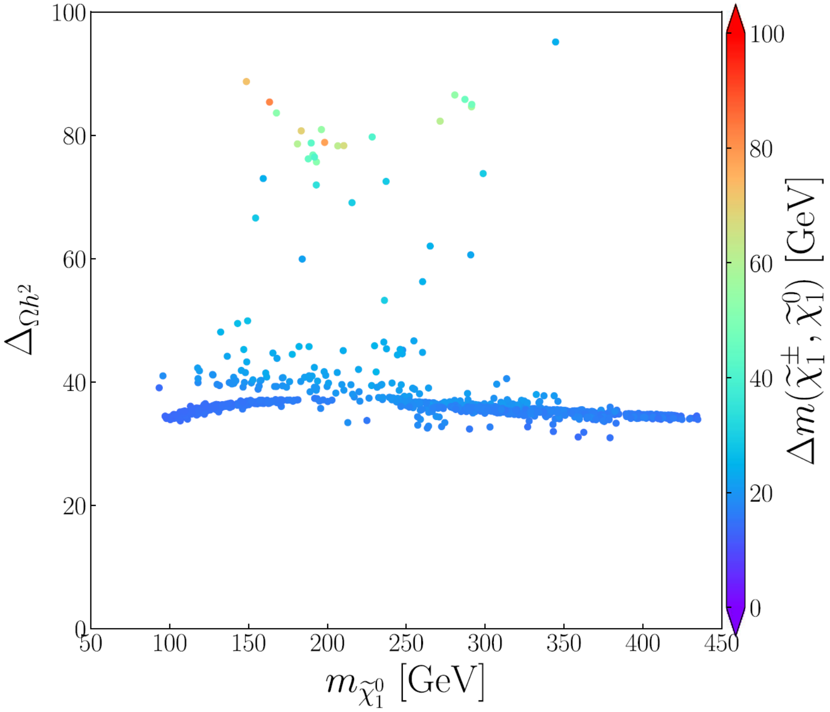
- Singlino-like DM is natural in getting relic density
- there is cancellation effect in DM-nucleon scatter rate for Singlino-Higgsino mixing case:
  1. Blind-spot needed in the σ^{SI};
  2. $|N_{13}|^2 \approx |N_{14}|^2$ needed in the σ^{SD}.

- Singlino-Higgsino sector forms a secluded DM scenario for Singlino decoupled case:
  1. Higgsino act as mediator between DM and SM particles to get correct relic density.
  2. Singlet nature of DM keeps small direct detection rates.
- Compressed mass spectrum: final state particles are too soft!!! Recursive Jigsaw Reconstruction (RJR) technique may help us testing this region.

Status of the nNMSSM

Naturalness in DM phenomenology

$$\Delta_{\Omega h^2} \equiv \max_i \left| \frac{\partial \log \Omega h^2}{\partial \log p_i} \right|$$



- Singlino-like DM is natural in getting relic density
- there is cancellation effect in DM-nucleon scatter rate for Singlino-Higgsino mixing case:

1. Blind-spot needed in the σ^{SI};
2. $|N_{13}|^2 \approx |N_{14}|^2$ needed in the σ^{SD}.

Fine-tuned structure in DM-nucleon scatter

- Singlino-Higgsino sector forms a secluded DM scenario for Singlino decoupled case:
  1. Higgsino act as mediator between DM and SM particles to get correct relic density.
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Hard & Long & Many DM searches find the expensive inequality:

$$\frac{\langle \sigma v \rangle}{\sigma^{\mathrm{SI}}} \geq 10^9$$

- Zhaofeng Kang(康昭峰), 9/6/2019, Chengdu

Summary

Light Higgsino in the NMSSM remains an natural scenario for a light supersymmetric “WIMP” consistent the dark matter relic density, constraints from direct detection and CMS Sparticle search.

A light μ in this framework is favored in predicting:

- Electroweak symmetry breaking
- SM-like Higgs boson mass
- DM relic density

While, low DM-nucleon scatter rate in a SUSY theory need some unknown mechanism to protect the naturalness of the theory.

Singlino DM candidate in natural NMSSM tell us there are two choices:

1. Blindspot: both SI and SD
2. Secluded DM scenario

Thank you！

Status of natural NMSSM in light of LHC 13 TeV and XENON-1T Result

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October 24, 2019 Dalian

In collaboration with Junjie Cao, Yangle He, Liang Shang and Yang Zhang

Based on PRD 99, 075020 (2019). arXiv:1810.09143

Backup

To examine the nNMSSM in a wider model scope and with more experimental constaint, we scan the following parameter space:

$$0 < \lambda < 0.75, \quad 0 < \kappa < 0.75, \quad 2 < \tan\beta < 60, \quad |A_\kappa| \le 2\ \text{TeV},$$
$$100\ \text{GeV} \le \mu \le 1\ \text{TeV}, \quad 50\ \text{GeV} \le M_A \le 2\ \text{TeV},$$

General Higgs parameters setting to get correct Higgs Physics

$$100\ \text{GeV} \le M_{Q_3}, M_{U_3} \le 2\ \text{TeV}, \quad |A_t| \le \min(3\sqrt{M_{Q_3}^2 + M_{U_3}^2}, 5\ \text{TeV}),$$

Stop mass and mixing for getting obvious loop correction for 125 GeV SM-like Higgs boson

$$100\ \text{GeV} \le M_{\tilde{\ell}} \le 1.2\ \text{TeV},$$

Common slepton soft breaking mass in slepton sector

$$20\ \text{GeV} \le M_1 \le 800\ \text{GeV}, \quad 100\ \text{GeV} \le M_2 \le 1.2\ \text{TeV},$$

Gaugino soft mass setting

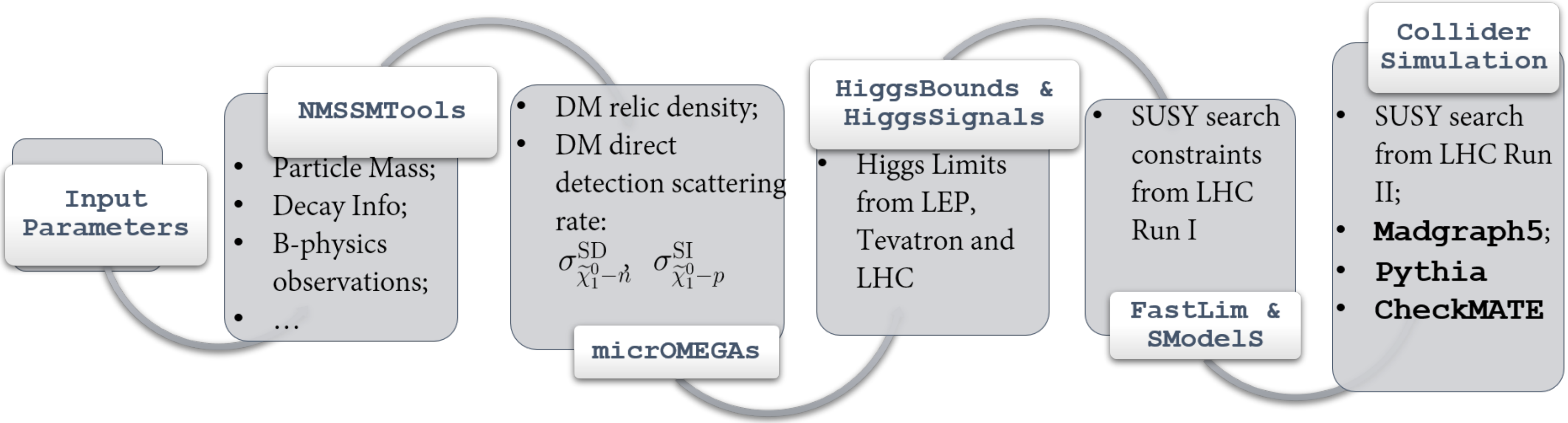
The mass of the gluino and the first two generation squarks are fixed to 2 TeV.

Constraints:

- B-physics constraints: such as the precise measurements of $B \to X_s\gamma$, $B_s \to \mu^+\mu_-$ $B_d \to X_s\mu^+\mu^-$, and mass difference ΔM_d, ΔM_s
- Constraints on the Higgs sector included in the packages HiggsBounds and HiggsSignal.
- Electroweak precision test
- DM relic density: PLANCK 2015
- DM direct detection:
  - **Xenon-1T 2018** data for Spin-independent Xsect;
  - **LUX 2017** data for Spin-dependent Xsect.
- $\Delta_Z < 50, \ \Delta_h < 50$
- LHC Run-II: CMS 36 fb^{-1} data

Backup

WorkFlow:



`Input Parameters`

`NMSSMTools`

- Particle Mass;
- Decay Info;
- B-physics observations;
- …

`micrOMEGAs`

- DM relic density;
- DM direct detection scattering rate: $\sigma^{\rm SD}_{\tilde{\chi}_1^0-n}$ $\sigma^{\rm SI}_{\tilde{\chi}_1^0-p}$

`HiggsBounds & HiggsSignals`

- Higgs Limits from LEP, Tevatron and LHC

`FastLim & SModelS`

- SUSY search constraints from LHC Run I

`Collider Simulation`

- SUSY search from LHC Run II;
- **`Madgraph5`**;
- **`Pythia`**
- **`CheckMATE`**

- Scan Algorithm: Monte-Carlo Markov Chain
- Likelihood: $L = L_\Omega \times L_{m_h}$

$$L_\Omega = \exp\left[-\frac{(\Omega_{\rm th}-\Omega_{\rm obs})^2}{2\,(\delta\Omega)^2}\right] \quad L_{m_h} = \exp\left[-\frac{(m_{th}-m_{obs})^2}{2(\delta m_h)^2}\right]$$