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Current Status of Supersymmetric Theories

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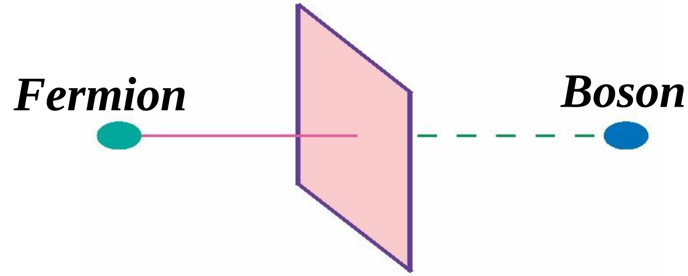
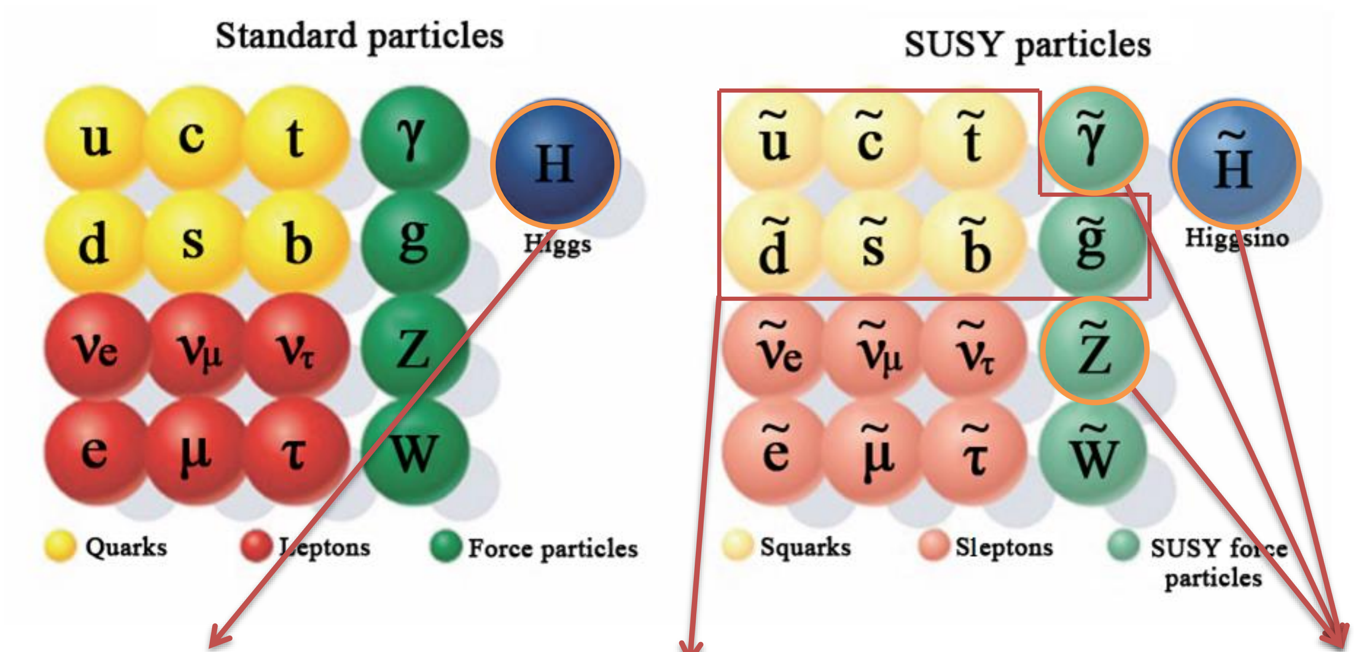
Supersymmetric Theory

What is Supersymmetry?





Responsible for EWSB and mass generation; discovered at LHC.

Produced by strong interaction; important goal of LHC search.

Mix to form neutralinos with the lightest one as DM candidate.

Supersymmetric Theory

➢ Originated in 1970s :

- 1967, Coleman-Madula Theorem (no-go theorem);
- 1971, Golfand and Likhtman extended Poincare algebra by spinor generators;
- 1974, Wess and Zumino introduced four-dimensional supersymmetric field theory;
- 1975, Haag-Lopuszanski-Sohnius Theorem (Supersymmetry Lie Algebra).

➢ Flourishing since 1980s :

- 1981, S. Dimopoulos and H. Georgi constructed supersymmetric SU(5) theory;
- 1982, SUSY was discussed to unify electroweak and strong forces;
- 1983, SUSY was applied to DM physics;
- 1984, Review articles on applications of SUSY in particle physics appeared.

Supersymmetric Theory

- **Least theoretical hypotheses:**

  Supersymmetry and R parity needed to protect proton stability.

- **Most promising benefits:**

  A bridge connecting low scale phenomenology with high scale physics.

  - Solving the gauge hierarchy problem;
  - Unifying different forces;
  - Radiative electroweak symmetry breaking;
  - Natural DM candidates;
  - Electroweak baryogenesis;
  - Possibly incorporating gravity;
  - … … … … … … … … … … …

Outline

1. Experimental constraints on SUSY
2. Have natural SUSY been ruled out?
3. Are there any hints of SUSY at LHC?
4. Summary

1.Experimental constraints on SUSY

Experimental Constraints

- 125GeV Higgs boson
- SUSY particle search
- Dark matter search
- Electroweak precision data
- B physics measurements

1.Experimental constraints on SUSY —— Higgs discovery

- **Higgs mass: m_h = 125.18±0.16 GeV.**
  - MSSM needs an unnaturally large radiative correction [1] !⟶ Non-minimal SUSY [2].
  - SUSY breaking mechanism is tightly limited:

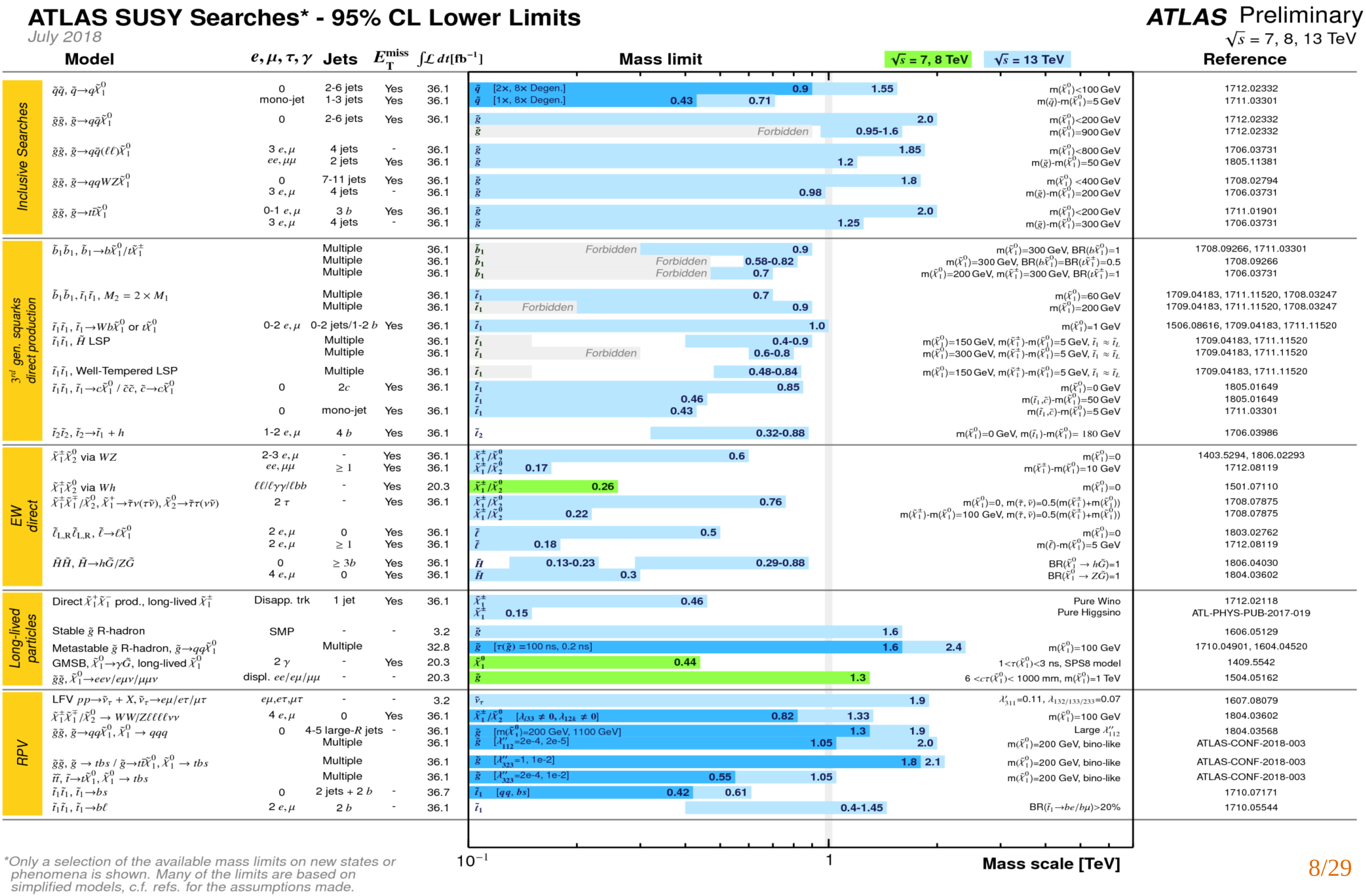
✓Both mGMSB and mAMSB are disfavored[1];
✓All minimal constrained SUSY, such as mSUGRA, fail to explain a_μ and m_h simultaneously [3].

⟶

Non-universal SUSY soft terms, Hybrid mediation, in more complex theoretical framework[4].

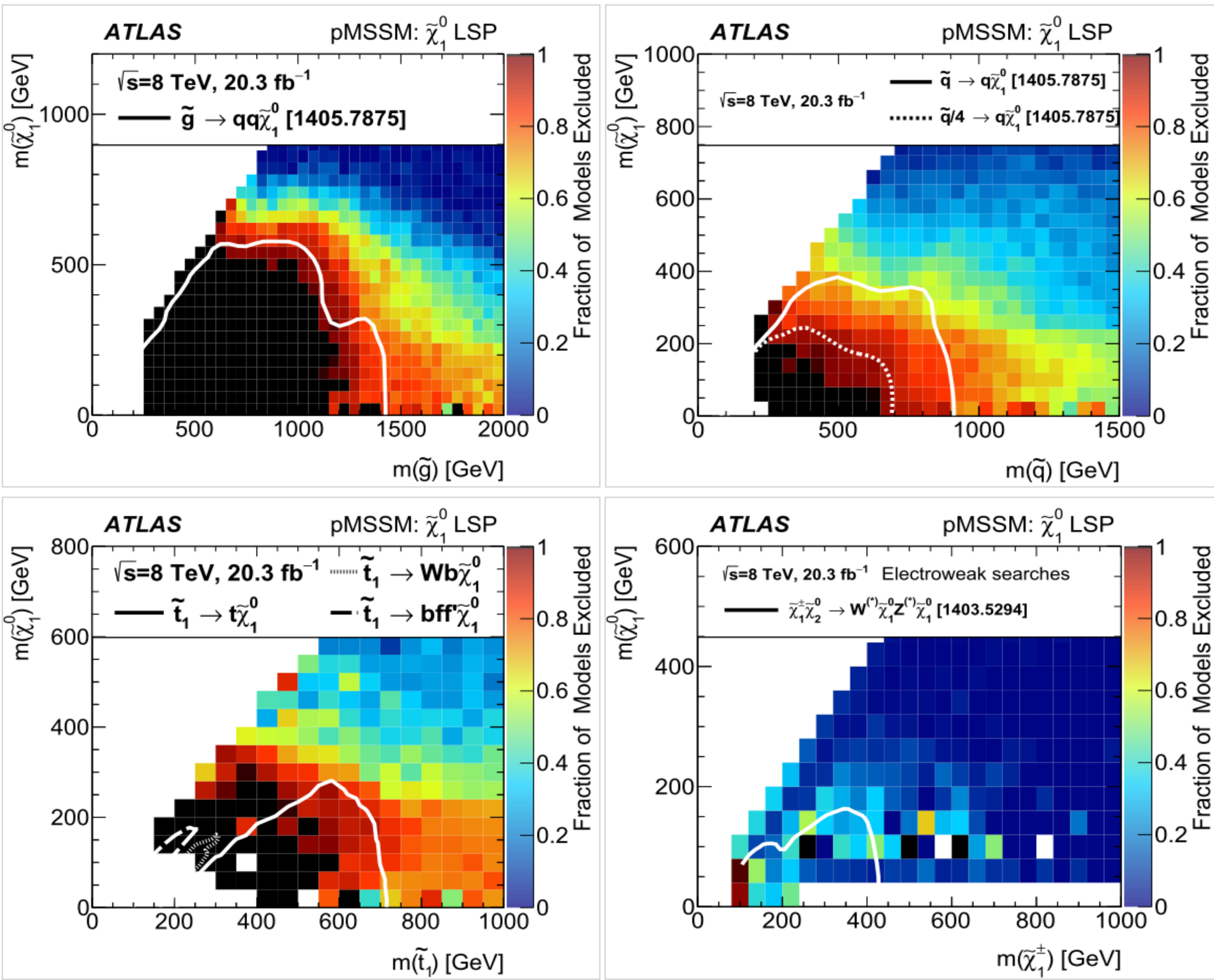
- **Higgs Data Fit: starting from Feb. and July in 2012 in EFT[5] and SUSY [6] respect.**
  - Sizable Non-SM Higgs component allowed, $V_{hX} \lesssim 30\%$ at 95% C. L.;
  - Sizable exotic decay modes allowed, $Br_{exo} \lesssim 24\%$ at 95% C.L.;
  - $m_H \gtrsim 400$ GeV favored, complementary to Heavy Higgs direct search at LHC [7];
  - Some less known SUSY models excluded, e.g. nMSSM[6].

[1] A. Arbey, et. al., 1112.3028. [2] L. J. Hall, et. al., 1112.2703; J. Cao, et. al., 1202.5821. [3] J. Cao, et. al., 1112.4391.
[4] Dr. T.J. Li and F. Wang have done lots of work in this field. [5] D. Carmi, et. al., 1202.3154;
[6] A. Arbey, et. al., 1207.1348; J. Cao, et. al., 1207.3698; [7] A. Arbey, et. al., 1811.12765.



ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV
Model | e, μ, τ, γ | Jets | E_T^{miss} | $\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$ | Mass limit | Reference
$\sqrt{s}$ = 7, 8 TeV
$\sqrt{s}$ = 13 TeV
Inclusive Searches
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{q}$ [2x, 8x Degen.] 0.9 1.55 | $m(\tilde{\chi}_1^0)$<100 GeV | 1712.02332
mono-jet | 1-3 jets | Yes | 36.1 | $\tilde{q}$ [1x, 8x Degen.] 0.43 0.71 | $m(\tilde{q})-m(\tilde{\chi}_1^0)$=5 GeV | 1711.03301
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{g}$ 2.0 | $m(\tilde{\chi}_1^0)$<200 GeV | 1712.02332
$\tilde{g}$ Forbidden 0.95-1.6 | $m(\tilde{\chi}_1^0)$=900 GeV | 1712.02332
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$ | 3 e,μ | 4 jets | - | 36.1 | $\tilde{g}$ 1.85 | $m(\tilde{\chi}_1^0)$<800 GeV | 1706.03731
$ee,\mu\mu$ | 2 jets | Yes | 36.1 | $\tilde{g}$ 1.2 | $m(\tilde{g})-m(\tilde{\chi}_1^0)$=50 GeV | 1805.11381
$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$ | 0 | 7-11 jets | Yes | 36.1 | $\tilde{g}$ 1.8 | $m(\tilde{\chi}_1^0)$ <400 GeV | 1708.02794
3 e,μ | 4 jets | - | 36.1 | $\tilde{g}$ 0.98 | $m(\tilde{g})-m(\tilde{\chi}_1^0)$=200 GeV | 1706.03731
$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 e,μ | 3 b | Yes | 36.1 | $\tilde{g}$ 2.0 | $m(\tilde{\chi}_1^0)$<200 GeV | 1711.01901
3 e,μ | 4 jets | - | 36.1 | $\tilde{g}$ 1.25 | $m(\tilde{g})-m(\tilde{\chi}_1^0)$=300 GeV | 1706.03731
3rd gen. squarks direct production
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$ | Multiple | 36.1 | $\tilde{b}_1$ Forbidden 0.9 | $m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=1 | 1708.09266, 1711.03301
Multiple | 36.1 | $\tilde{b}_1$ Forbidden 0.58-0.82 | $m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5 | 1708.09266
Multiple | 36.1 | $\tilde{b}_1$ Forbidden 0.7 | $m(\tilde{\chi}_1^0)$=200 GeV, $m(\tilde{\chi}_1^\pm)$=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1 | 1706.03731
$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2\times M_1$ | Multiple | 36.1 | $\tilde{t}_1$ 0.7 | $m(\tilde{\chi}_1^0)$=60 GeV | 1709.04183, 1711.11520, 1708.03247
Multiple | 36.1 | $\tilde{t}_1$ Forbidden 0.9 | $m(\tilde{\chi}_1^0)$=200 GeV | 1709.04183, 1711.11520, 1708.03247
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 0-2 e,μ | 0-2 jets/1-2 b | Yes | 36.1 | $\tilde{t}_1$ 1.0 | $m(\tilde{\chi}_1^0)$=1 GeV | 1506.08616, 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1, \tilde{H}$ LSP | Multiple | 36.1 | $\tilde{t}_1$ 0.4-0.9 | $m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$ | 1709.04183, 1711.11520
Multiple | 36.1 | $\tilde{t}_1$ Forbidden 0.6-0.8 | $m(\tilde{\chi}_1^0)$=300 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$ | 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP | Multiple | 36.1 | $\tilde{t}_1$ 0.48-0.84 | $m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$ | 1709.04183, 1711.11520
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$ | 0 | 2c | Yes | 36.1 | $\tilde{c}$ 0.85 | $m(\tilde{\chi}_1^0)$=0 GeV | 1805.01649
$\tilde{t}_1$ 0.46 | $m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)$=50 GeV | 1805.01649
0 | mono-jet | Yes | 36.1 | $\tilde{t}_1$ 0.43 | $m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)$=5 GeV | 1711.03301
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$ | 1-2 e,μ | 4 b | Yes | 36.1 | $\tilde{t}_2$ 0.32-0.88 | $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$= 180 GeV | 1706.03986
EW direct
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ | 2-3 e,μ | - | Yes | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6 | $m(\tilde{\chi}_1^0)$=0 | 1403.5294, 1806.02293
$ee,\mu\mu$ | ≥ 1 | Yes | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17 | $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=10 GeV | 1712.08119
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh | $\ell\ell/\ell\gamma\gamma/\ell bb$ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26 | $m(\tilde{\chi}_1^0)$=0 | 1501.07110
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$ | 2 τ | - | Yes | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76 | $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$) | 1708.07875
$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22 | $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=100 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$) | 1708.07875
$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 e,μ | 0 | Yes | 36.1 | $\tilde{\ell}$ 0.5 | $m(\tilde{\chi}_1^0)$=0 | 1803.02762
2 e,μ | ≥ 1 | Yes | 36.1 | $\tilde{\ell}$ 0.18 | $m(\tilde{\ell})-m(\tilde{\chi}_1^0)$=5 GeV | 1712.08119
$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$ | 0 | $\geq 3b$ | Yes | 36.1 | $\tilde{H}$ 0.13-0.23 0.29-0.88 | BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1 | 1806.04030
4 e,μ | 0 | Yes | 36.1 | $\tilde{H}$ 0.3 | BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1 | 1804.03602
Long-lived particles
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 36.1 | $\tilde{\chi}_1^\pm$ 0.46 | Pure Wino | 1712.02118
$\tilde{\chi}_1^\pm$ 0.15 | Pure Higgsino | ATL-PHYS-PUB-2017-019
Stable $\tilde{g}$ R-hadron | SMP | - | - | 3.2 | $\tilde{g}$ 1.6 | 1606.05129
Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$ | Multiple | 32.8 | $\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4 | $m(\tilde{\chi}_1^0)$=100 GeV | 1710.04901, 1604.04520
GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 γ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 0.44 | 1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model | 1409.5542
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to eev/e\mu v/\mu\mu v$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | $\tilde{g}$ 1.3 | 6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, $m(\tilde{\chi}_1^0)$=1 TeV | 1504.05162
RPV
LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ | - | - | 3.2 | $\tilde{\nu}_\tau$ 1.9 | λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079
$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$ | 4 e,μ | 0 | Yes | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.82 1.33 | $m(\tilde{\chi}_1^0)$=100 GeV | 1804.03602
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$ | 0 | 4-5 large-R jets | - | 36.1 | $\tilde{g}$ [$m(\tilde{\chi}_1^0)$=200 GeV, 1100 GeV] 1.3 1.9 | Large λ''_{112} | 1804.03568
Multiple | 36.1 | $\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0 | $m(\tilde{\chi}_1^0)$=200 GeV, bino-like | ATLAS-CONF-2018-003
$\tilde{g}\tilde{g}, \tilde{g}\to tbs / \tilde{g}\to t\tilde{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$ | Multiple | 36.1 | $\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1 | $m(\tilde{\chi}_1^0)$=200 GeV, bino-like | ATLAS-CONF-2018-003
$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0\to tbs$ | Multiple | 36.1 | $\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05 | $m(\tilde{\chi}_1^0)$=200 GeV, bino-like | ATLAS-CONF-2018-003
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$ | 0 | 2 jets + 2 b | - | 36.7 | $\tilde{t}_1$ [qq, bs] 0.42 0.61 | 1710.07171
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$ | 2 e,μ | 2 b | - | 36.1 | $\tilde{t}_1$ 0.4-1.45 | BR($\tilde{t}_1\to be/b\mu$)>20% | 1710.05544
10^{-1}
1
Mass scale [TeV]
*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.

➢ Distinction between MSSM and Simplified Model:



Difference in

production rate and branching ratio

Signal strengths and sometimes most sensitive SR[8].

[8] ATLAS Collaboration, 1508.06608.

➢ **Application: Fine-tuning argument[9,10].**

$$m_Z^2 = \frac{2\left(m_{H_d}^2 + \Sigma_d\right) - 2\left(m_{H_u}^2 + \Sigma_u\right)\tan^2\beta}{\tan^2\beta - 1} - 2\mu^2$$

where for $\tan\beta = 10$,

$$\Sigma_u = \sum_{i=1}^{2} \frac{3Y_t^2}{16\pi^2} \times m_{\tilde{t}_i}^2 \times \left(\log\frac{m_{\tilde{t}_i}^2}{Q^2} - 1\right) + \cdots,$$

$$\Sigma_d = \sum_{i=1}^{2} \frac{3g_Z^2}{16\pi^2} \times m_{\tilde{t}_i}^2 \times \left(\log\frac{m_{\tilde{t}_i}^2}{Q^2} - 1\right) + \cdots,$$

$$\mu(m_{SUSY}) = 1.09\mu(\Lambda_{GUT}), \qquad m_{\tilde{g}} = 2.91M_3(\Lambda_{GUT}),$$

$$-2m_{H_u}^2(m_{SUSY}) = 5.45M_3^2 - 1.31m_{H_u}^2 + 0.77A_tM_3 + 0.69m_{Q_3}^2 + 0.69m_{U_3}^2 + \cdots,$$

$$m_{Q_3}^2(m_{SUSY}) = 5.76M_3^2 - 0.12m_{H_u}^2 - 0.13A_tM_3 + 0.89m_{Q_3}^2 - 0.12m_{U_3}^2 + \cdots,$$

$$m_{U_3}^2(m_{SUSY}) = 4.85M_3^2 - 0.23m_{H_u}^2 - 0.26A_tM_3 - 0.23m_{Q_3}^2 + 0.77m_{U_3}^2 + \cdots,$$

$$A_t(m_{SUSY}) = 2.16M_3 + 0.27M_2 + 0.03M_1 + 0.31A_t + \cdots,$$

[9] H. Baer, et. al., 1212.2655; 1309.2984. [10] H. Abe, et. al., hep-ph/0703044.

1.Experimental constraints on SUSY

$$m_Z^2(m_{SUSY}) = 5.45M_3^2 - 1.31m_{H_u}^2 + 0.77A_tM_3 + 0.69m_{Q_3}^2 + 0.69m_{U_3}^2 - 2.4\mu^2 + \cdots,$$

$$\frac{\partial \ln m_Z^2}{\partial \ln M_3} = 10.9 \times \frac{M_3^2}{m_Z^2} + 0.77 \times \frac{A_tM_3}{m_Z^2} + \cdots \backsimeq 1.29 \times \frac{m_{\tilde{g}}^2}{m_Z^2} + \cdots$$

$$\frac{\partial \ln m_Z^2}{\partial \ln \mu} = -4.8 \times \frac{\mu^2}{m_Z^2} \backsimeq -4 \times \frac{m_{\tilde{\chi}_1^\pm}^2}{m_Z^2}$$

- **Fine-tuning Measure:**

$\Delta_{Z,BG} = \max_i \left|\frac{\partial log m_Z^2}{\partial log p_i}\right|$, with p_i denoting the input parameter at GUT scale [11].

If $m_{\tilde{g}} = 1\,TeV$, $\Delta_{Z,BG} \gtrsim 160$.

- **Solutions:**

1 Modify SUSY breaking (boundary condition and/or RGE running)

- Non-Universal Soft Terms [12];
- Maximally Natural Supersymmetry [13];
- Super-Natural Supersymmetry [14].

[11] R. Barbieri, et. al., NPB 306(1988) 63.
[12] S. Dimopoulos, et. al., hep-ph/9507282, S. Antusch, et. al., 1207.7236.
[13] S. Dimopoulos, et. al., 1504.7554.
[14] T. Li, et. al., 1508.4459, 1502.06893,1510.06851.

1.Experimental constraints on SUSY —— Sparticle search

2 Modify the topology of SUSY signals.

- Compressed Supersymmetry [15];
- Stealth Supersymmetry [16];
- Supersoft Supersymmetry [17];
- Displaced Supersymmetry [18];
- Double Invisible Supersymmetry [19];
- Folded Supersymmetry [20];
- Sneutrino DM Supersymmetry [21];
- R-parity Violating Supersymmetry [22];
- ……………………

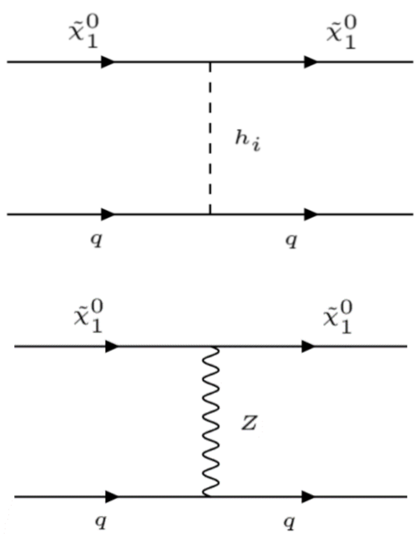
3 Modify the definition: there is no fine-tuning for low energy theory!

$\Delta_{Z,EW} = \max_i \left| \frac{\partial log m_Z^2}{\partial log p_i} \right|$, with p_i being the input parameter at EW scale[23].

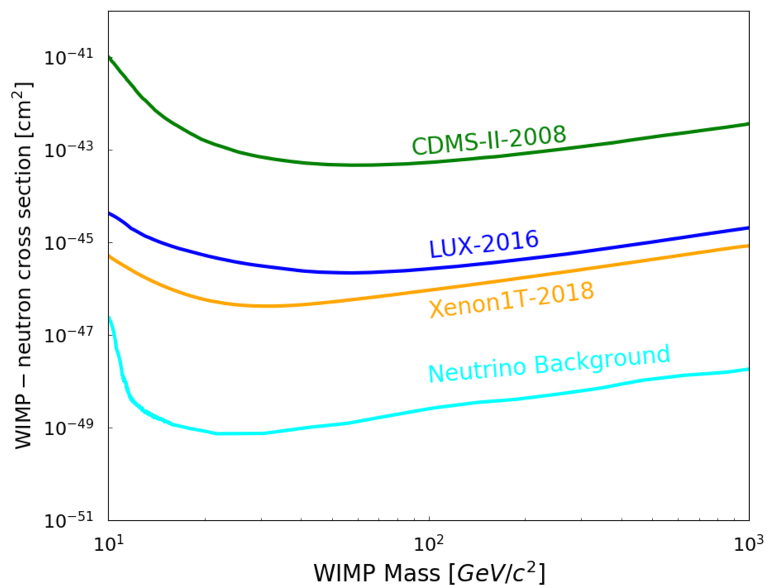
$\Delta_{Z,EW} \lesssim 30$ requires $\mu \lesssim 250\ GeV$, $m_{\tilde{t}} \lesssim 3\ TeV$ in the MSSM.

Historically, natural SUSY scenario is defined by $\Delta_{Z,EW} \lesssim 30$ [23].

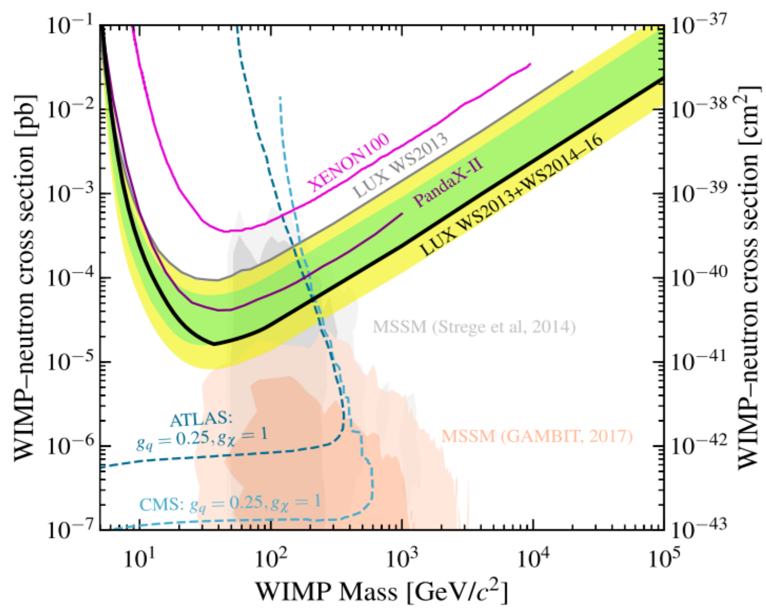
[15] T. J. LeCompte, et. al., 1105.4304. [16] J. Fan, et. al., 1201.4875. [17] G. D. Kribs, et. al., 1203.4821.
[18] P. W. Graham, et. al., 1204.6038. [19] J. Guo, et. al., 1312.2821, D. S. M. Alves, et. al., 1312.4965.
[20] N. Criag, et. al., 1510.6802. [21] J. Cao, et. al., 1807.03762. [22] R. Barbier, et. al., hep-ph/0406039.
[23] H. Baer, et. al., 1203.5539.



(a) SI cross section



(b) SD cross section



- **For Bino dominated DM in MSSM:**

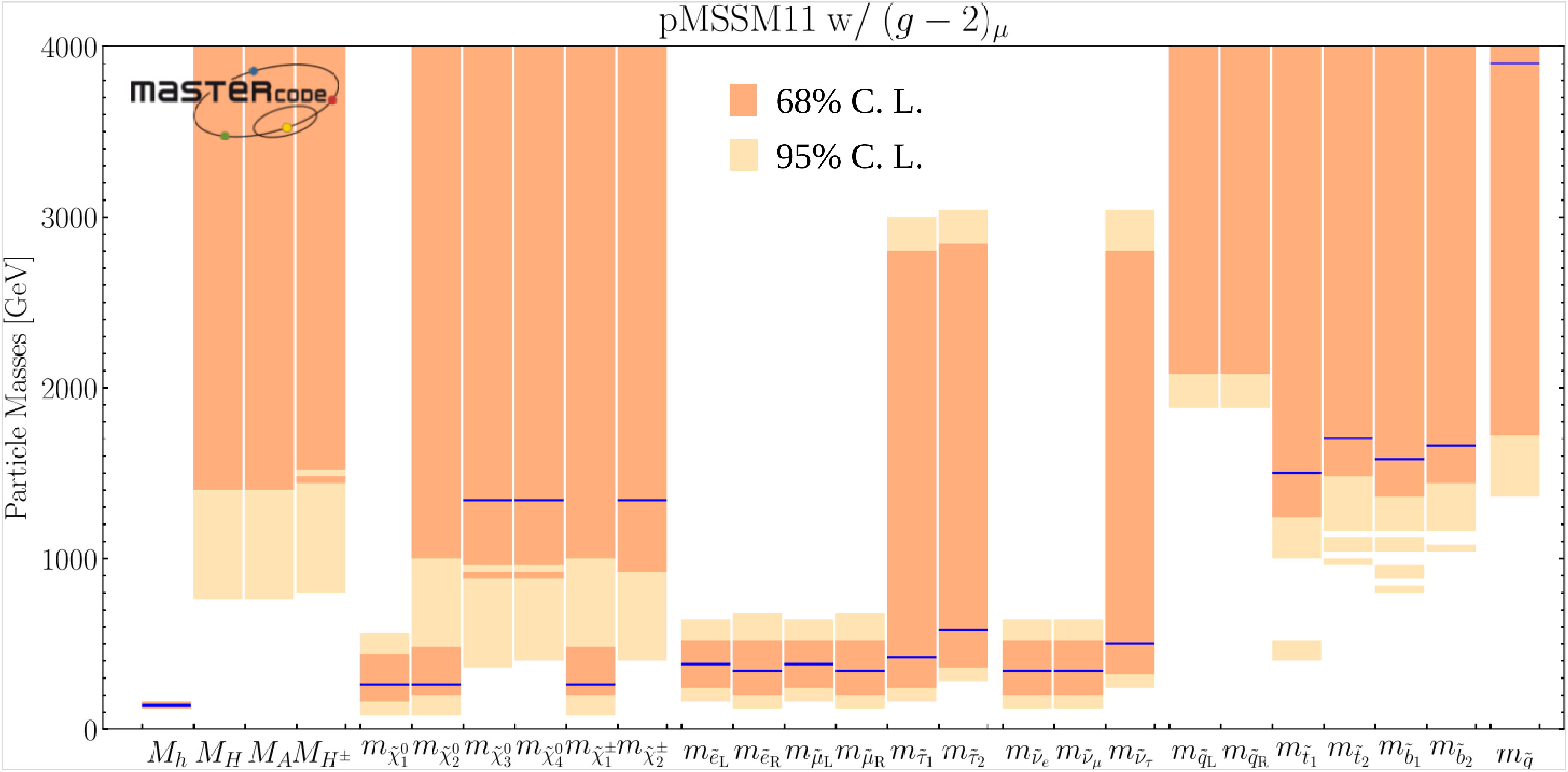
$$\sigma^{SI}_{\tilde{\chi}-p} \propto \frac{m_Z^2 \sin^2\theta_W \tan^2\theta_W}{\left(m_{\tilde{\chi}}^2 - \mu^2\right)^2} \left\{ \sum_q \left(\frac{Y_{hqq}}{m_q} \frac{(m_{\tilde{\chi}} + \mu \sin 2\beta)}{m_h^2} - \frac{Y_{Hqq}}{m_q} \frac{\mu \cos 2\beta}{m_H^2} \right) f_q^N \right\}^2$$

In general, $\sigma^{SI}_{\tilde{\chi}-p} \gtrsim 10^{-45}\ cm^2\ \ for\ \ \mu \lesssim 300\ GeV$.

Blind spot: $\sigma^{SI}_{\tilde{\chi}-p} \approx 0$ if μ takes a certain negative value.

1.Experimental constraints on SUSY

- **Global fit of MSSM: MSSM is unnatural[24] !** [24] MasterCode collaboration, 1710.11091.



- $\Delta_{Z,EW} \gtrsim 60$ for all parameter points; $\Delta_{Z,EW} \gtrsim 420$ for best point.
- Key reason: Both sparticle search and DM search favor heavy Higgsino case.

Outline

1. Experimental constraints on SUSY
2. Have natural SUSY been ruled out ?
3. Are there any hints of SUSY at LHC?
4. Summary

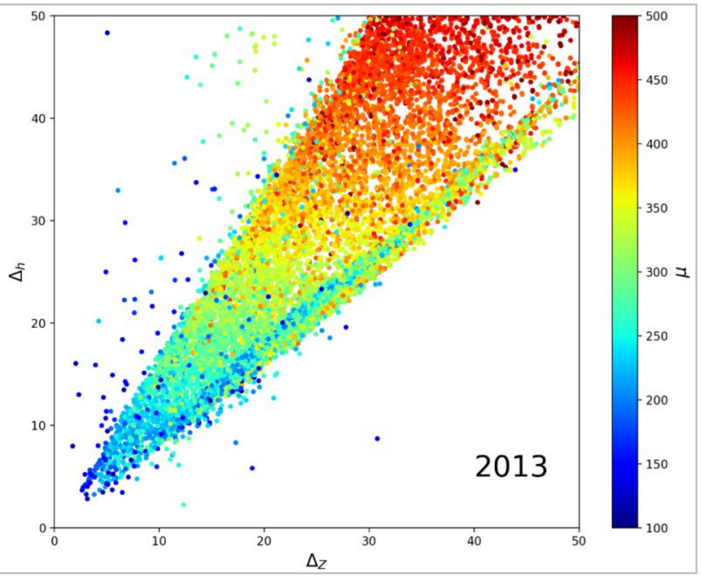
2.Have natural SUSY been ruled out?

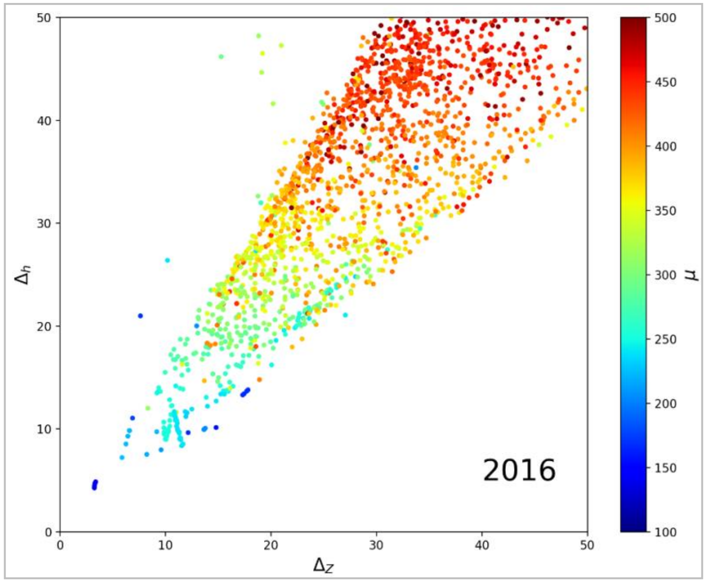
➢ NMSSM: Bino-dominated DM Scenario[25].

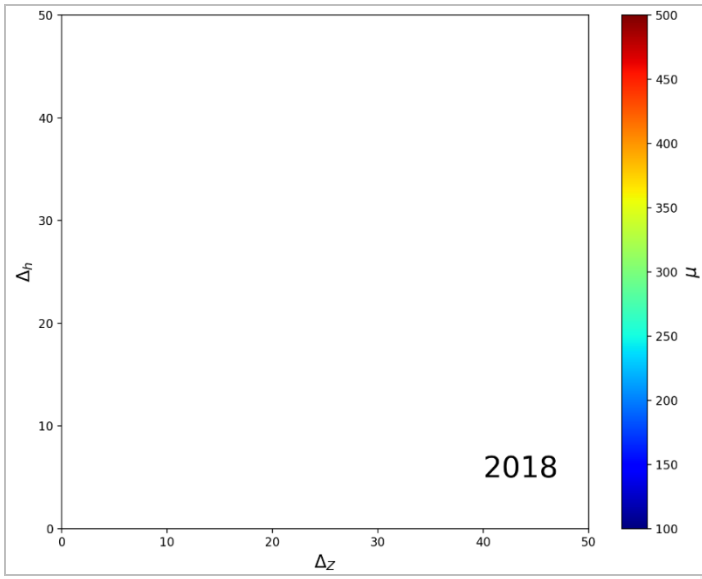
Constraints from:
- EWPD;
- B-Physics;
- Higgs Data Fit;
- DM constraints;

- LHC Run-I：
  ✓Stop search；
  ✓Electroweakino search；
  ✓Slepton search;
- LUX-2016 (SI + SD) ;

- LHC Run-II：
  ✓Electorweakino Search；
  ✓Slepton Search；
- XENON-2018 (SI);
- LUX-2017 (SD);







[25] J. Cao, et. al., 1606.04416, 1609.00204,1810.09153.

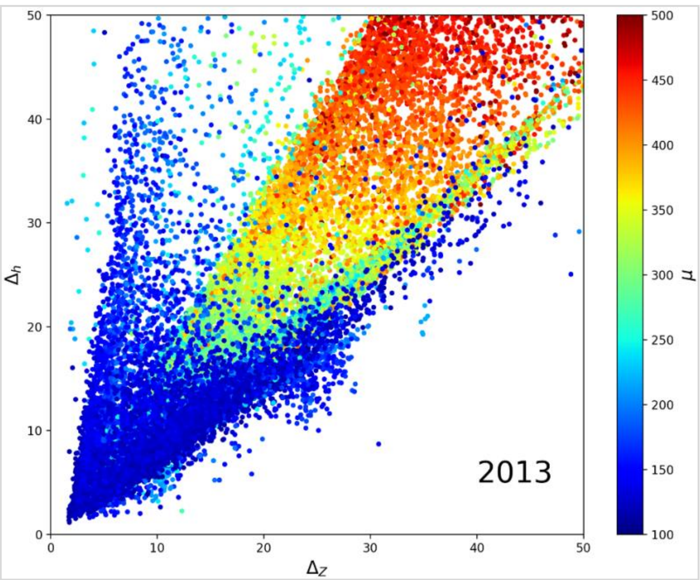
2.Have natural SUSY been ruled out?

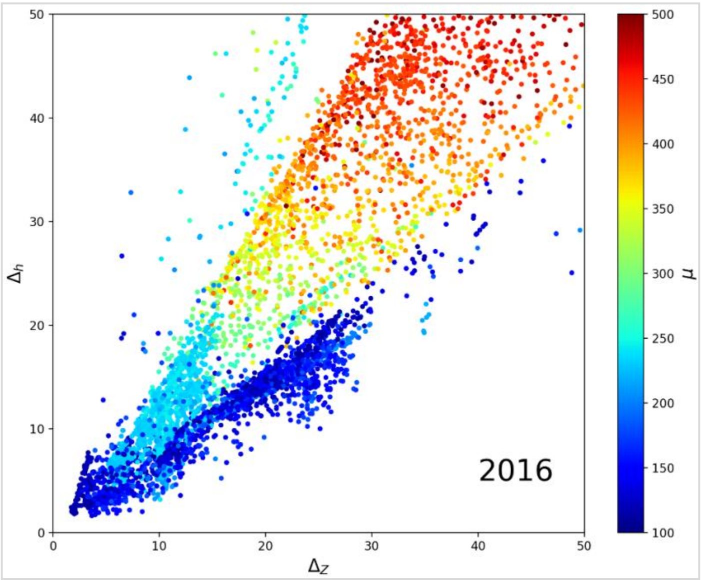
- $\Omega\, h^2 = 0.119 \pm 0.020$, **but no constraints on DM component**[25]**:**

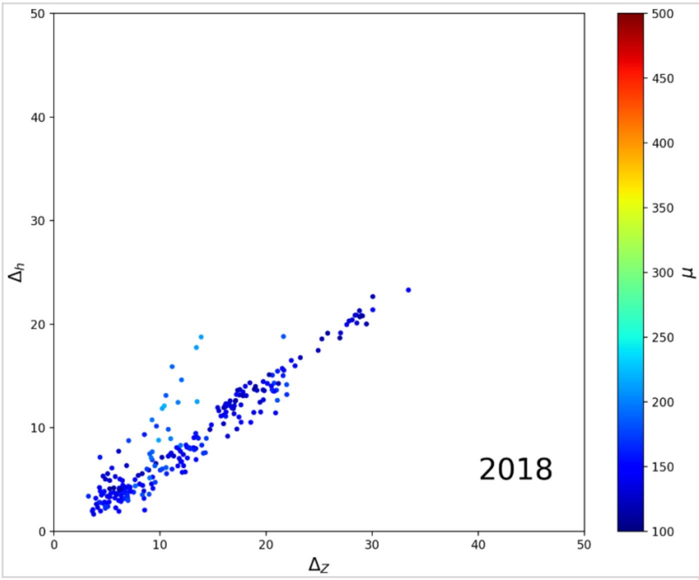
Constraints from:
- EWPD;
- B-Physics;
- Higgs Data Fit;
- DM constraints;

- LHC Run-I：
  ✓Stop search；
  ✓Electroweakino search；
  ✓Slepton search;
- LUX-2016 (SI + SD) ;

- LHC Run-II：
  ✓Electorweakino Search；
  ✓Slepton Search；
- XENON-2018 (SI);
- LUX-2017 (SD);







[25] J. Cao, et. al., 1606.04416, 1609.00204,1810.09153.

2.Have natural SUSY been ruled out?

- **Features of surviving samples: singlino-like DM, surviving rate at about $\frac{1}{300}$.**
  - $\sigma^{SI}_{\chi-N}$: Strong cancelations among different contributions, 1% fine-tuning introduced;
  - $\sigma^{SD}_{\chi-N}$: $|N_{13}|^2$ - $|N_{15}|^2 \lesssim 0.03$, usually requiring a sufficient large μ;
  - Compressed SUSY particle spectrum: $m_{\tilde{H}}$ - $m_{\tilde{\chi}_1^0} \lesssim 20$ GeV.

- **Intrinsic Reason: Naturalness⟶Light higgsino ⟶ Hard to evade constraints!**

NMSSM realizes natural SUSY in an unnatural way!

- **An aesthetic SUSY model should predict naturally:**
  - Z boson mass and Higgs boson mass simultaneously;
  - Low SI rate for DM-nucleon scattering ;
  - Low SD rate for DM-nucleon scattering;
  - Nearly degenerate sparticle spectrum.

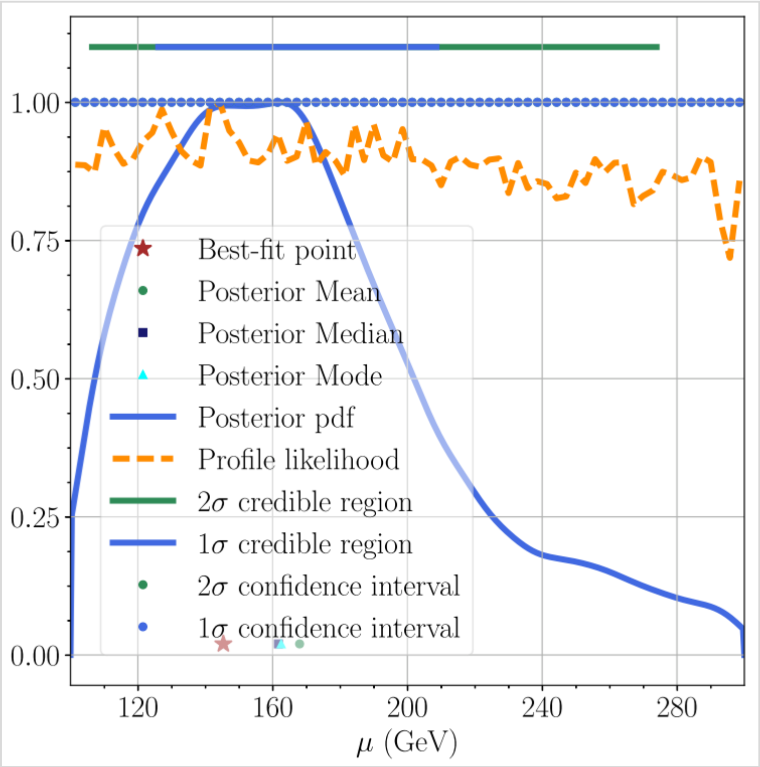
2.Have natural SUSY been ruled out?

[26] J. Cao, et. al., 1807.03762.

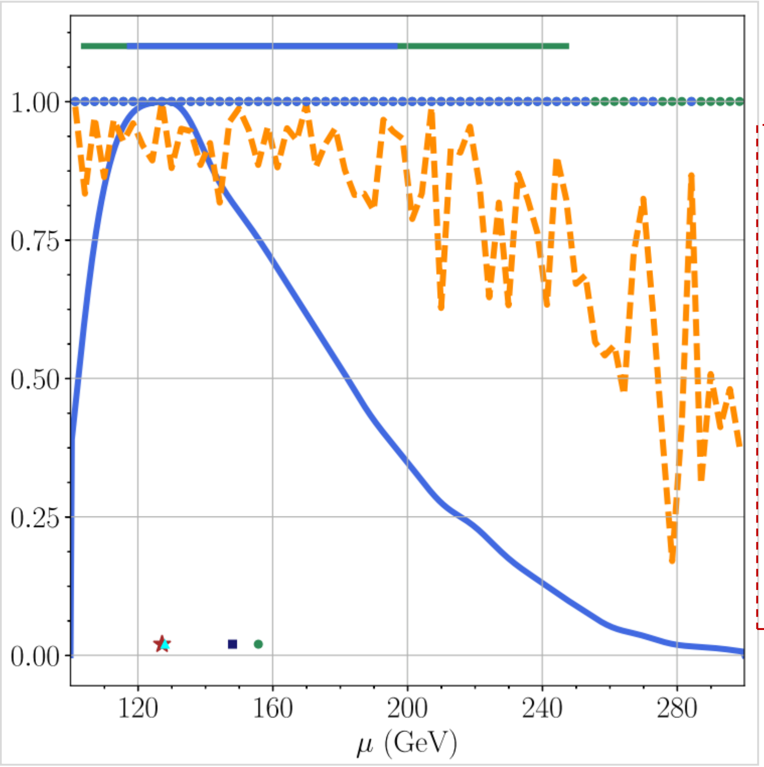
[27] J. Cao, et. al., 1707.09626.

➢ What is the improved theory?

- **Most economical solution:** Type-I Seesaw + NMSSM, 3 additional parameters[26].
- **Next economical solution:** Inverse Seesaw + NMSSM; 6 additional parameters[27].
- **Other advantages:** non-zero neutrino mass, unconventional SUSY signals.



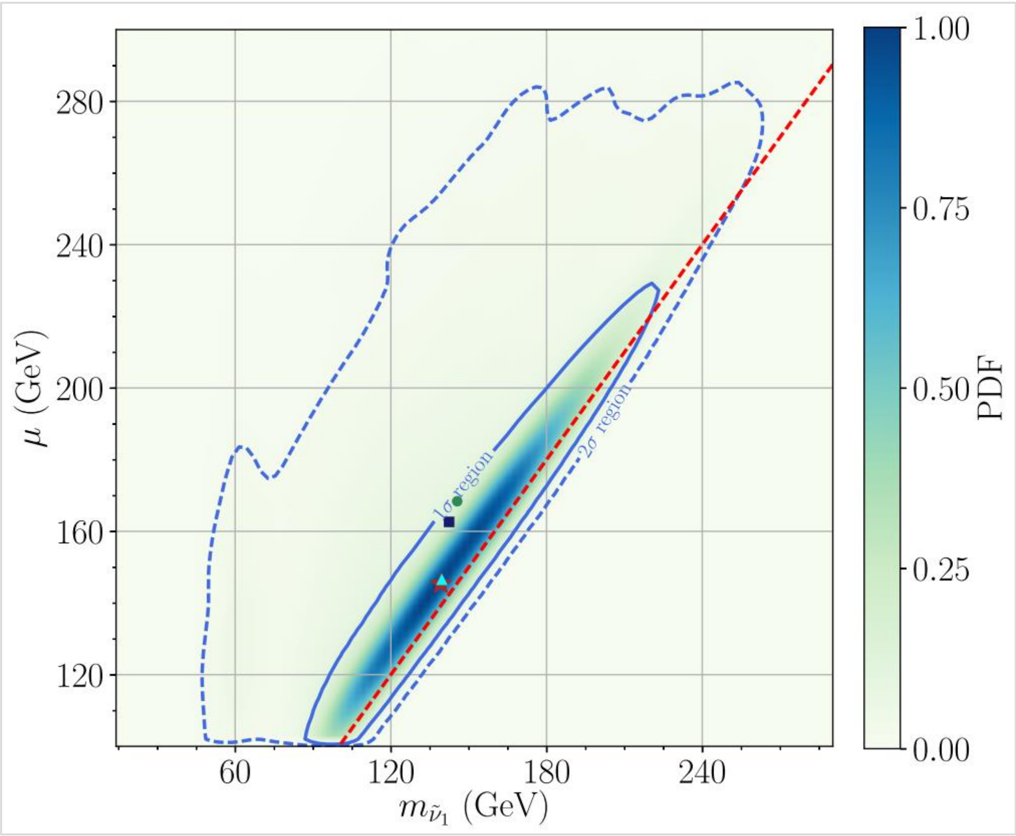
(a) Type-I Seesaw



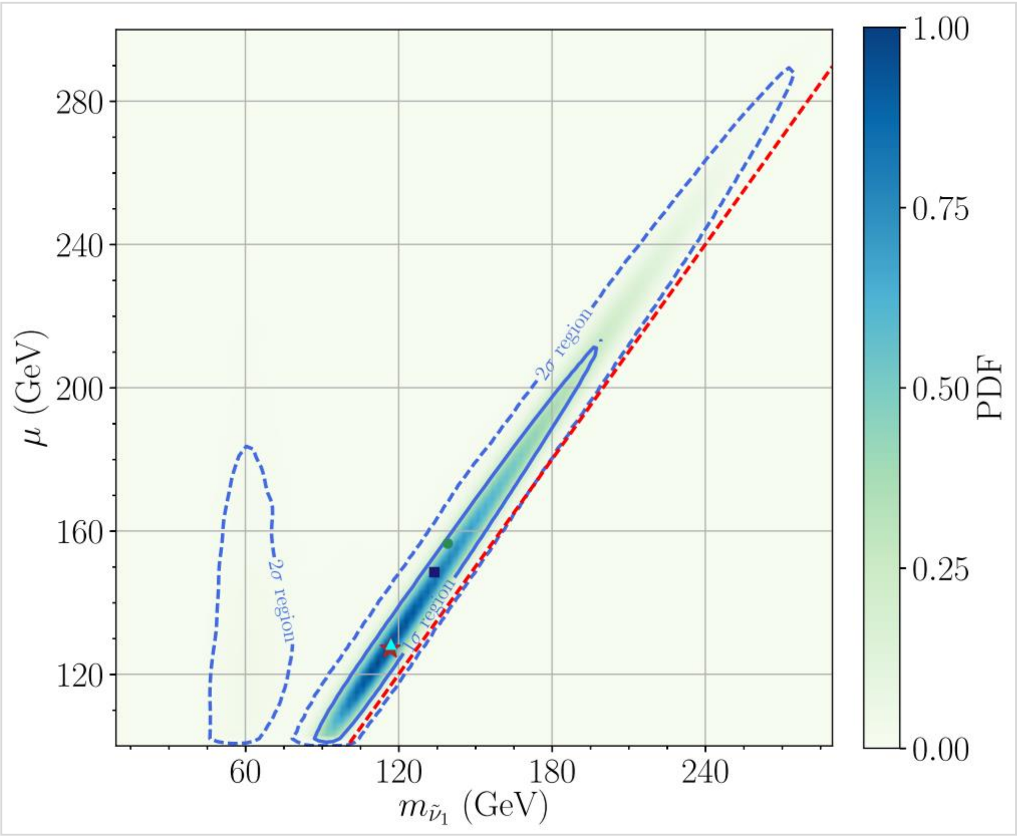
(b) Inverse Seesaw
(to appear soon)

Underlying reason: Sneutrino acts as DM candidate, and singlet Higgs field plays a major role in DM physics.

2.Have natural SUSY been ruled out?



(a) Type-I Seesaw

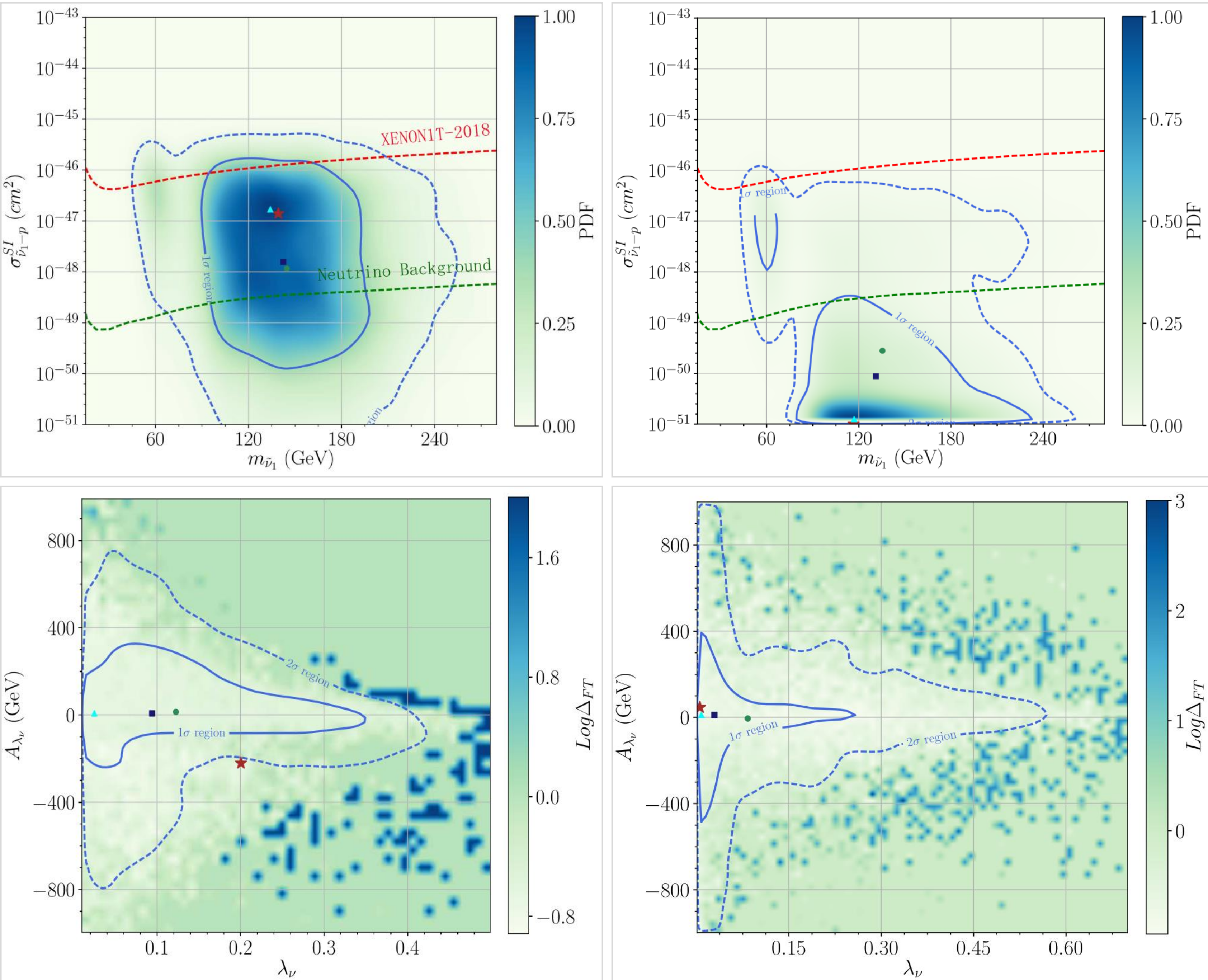


(b) Inverse Seesaw

- **Reason:** $\tilde{\nu}_1\ \tilde{\nu}_1 \leftrightharpoons h_s \leftrightharpoons \widetilde{H}\ \widetilde{H}$, DM and Higgsino were in thermal equilibrium in early universe; enhanced DM annihilation rate if they were nearly degenerate in mass.
- **Implication:** Higgsino decays invisibly to escape detection at LHC easily.

2.Have natural SUSY been ruled out?

Type-I Seesaw

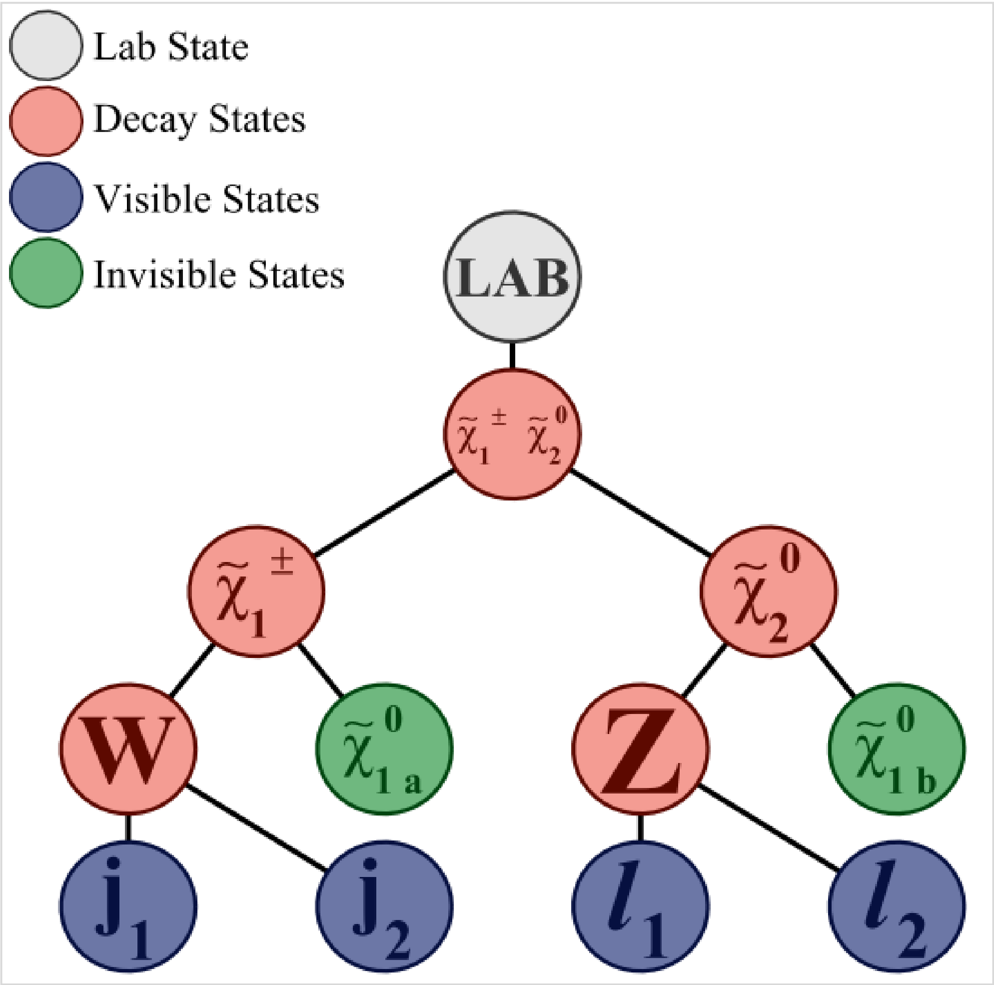


Inverse Seesaw

Outline

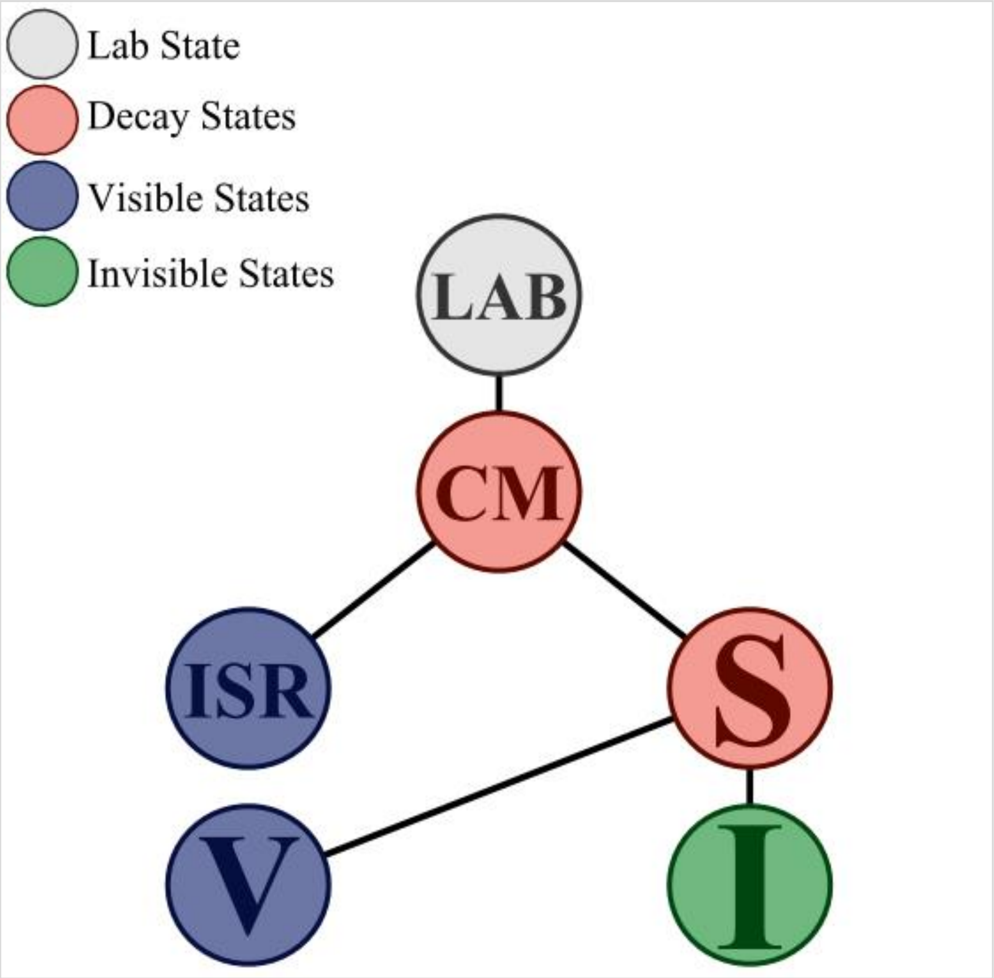
1. Experimental constraints on SUSY
2. Have natural SUSY been ruled out ?
3. Are there any hints of SUSY at LHC?
4. Summary

3.Are there any hints of SUSY at LHC?



Kinematic ambiguity elimination: Reasonably guess the momentum of neutralinos in the decay tree by Jigasw Rules.

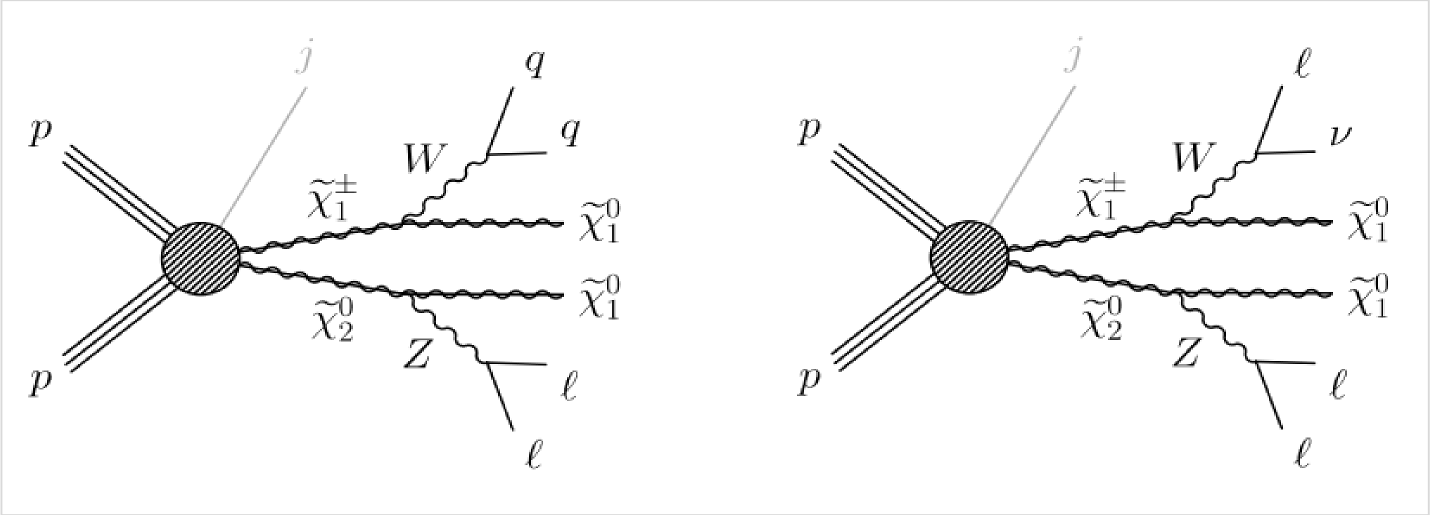
Combinatorial ambiguity elimination: Reasonably guess ISR jets or signal jets by Jigsaw Rules, especially useful in generic compressed scenario.



3.Are there any hints of SUSY at LHC?

➢ **ATLAS reported significant excess in $3l + E^T_{miss}$ signal by Jigsaw technique [28] .**

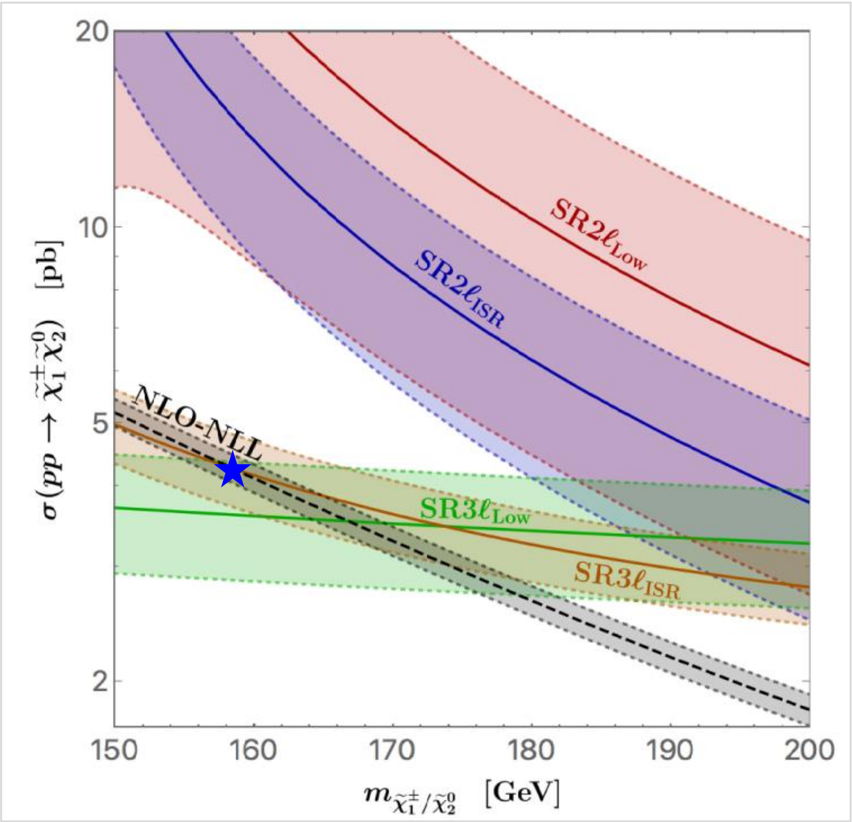
- The excess was highlighted by GAMBIT collaboration after global fit [29];
- Implication of the excess was discussed by M. Carena et. al. [30].

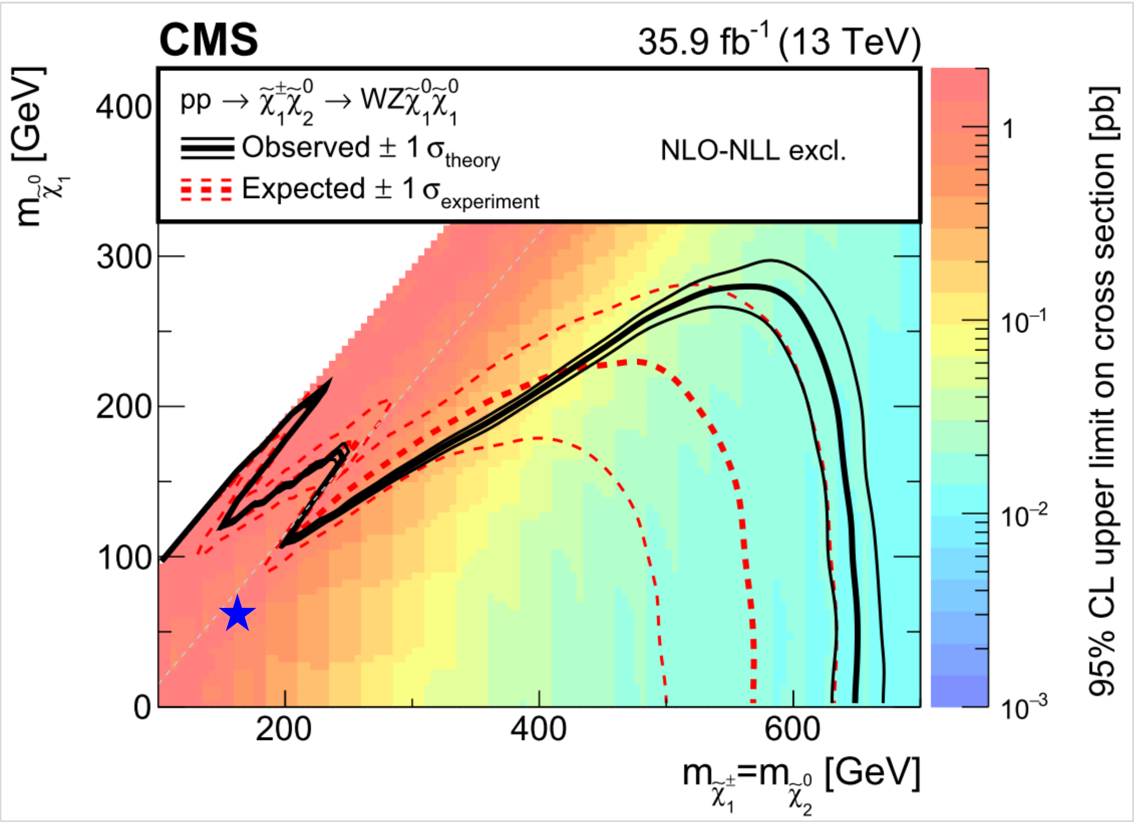


Signal Region	Observed Events	BG Events	Events above BG	Significance (Z)
SR2ℓ_{Low}	19	8.4 ± 5.8	10.6 ± 5.8	1.39
SR2ℓ_{ISR}	11	$2.7^{+2.8}_{-2.7}$	$8.3^{+2.8}_{-2.7}$	1.99
SR3ℓ_{Low}	20	10 ± 2	10 ± 2	2.13
SR3ℓ_{ISR}	12	3.9 ± 1.0	8.1 ± 1.0	3.02

[28] ATLAS Collaboration, 1806.02293. [29] GAMBIT Collaboration, 1809.02097.
[30] Marcela Carena, et. al., 1809.11082.

3.Are there any hints of SUSY at LHC?





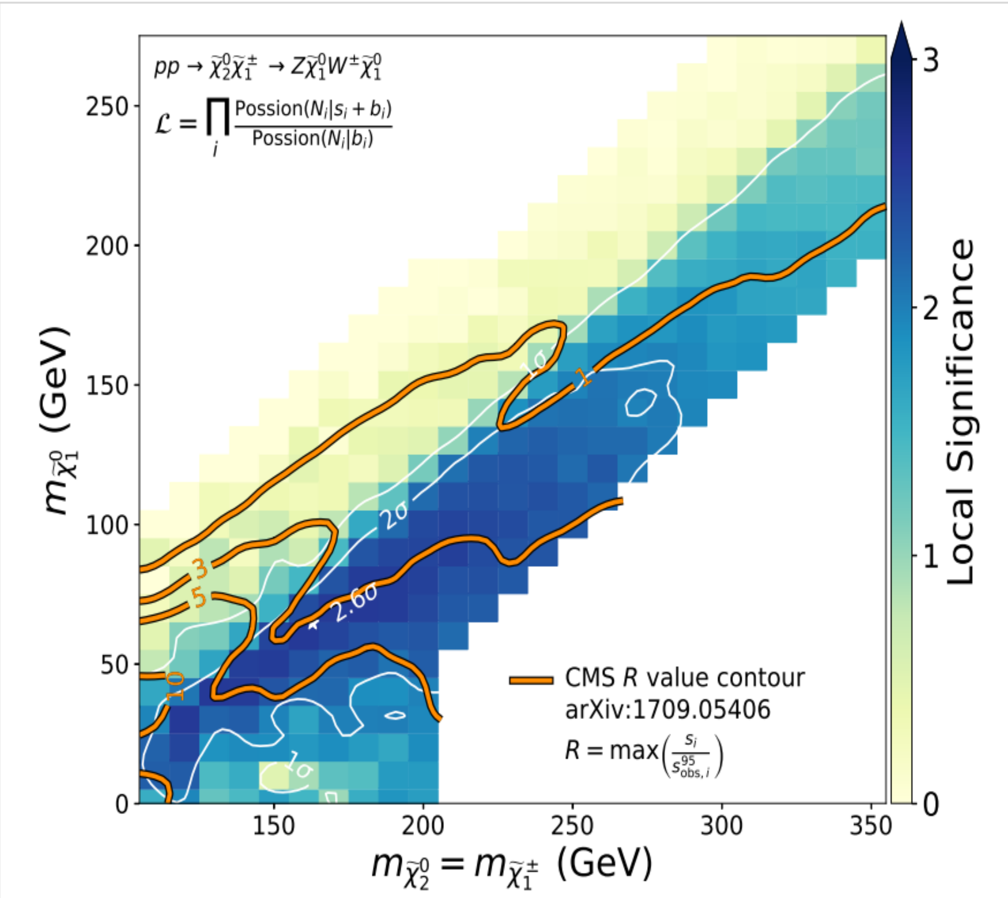
- The tri-lepton excess may be explained by $\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^0$ associated production [29, 30].
- However, we note the explanation is very tightly limited by relevant CMS analysis [31, 32]:

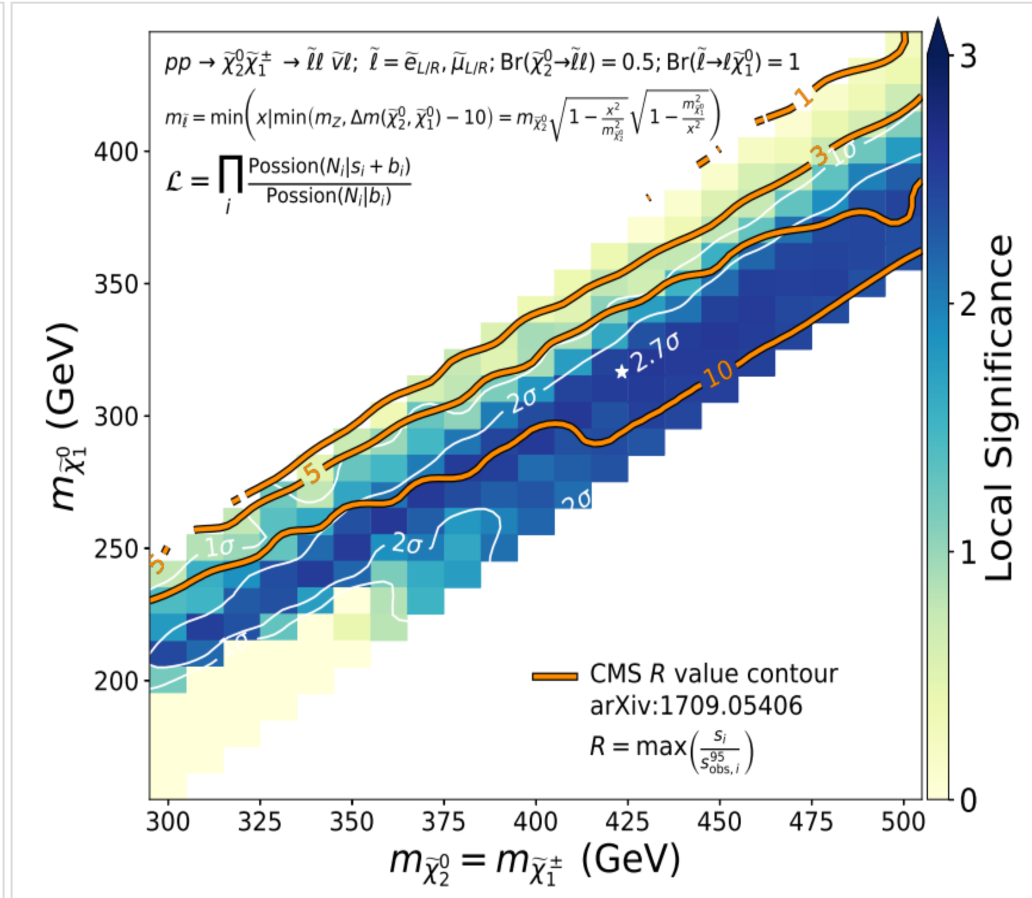
$$R = \frac{S}{S_{obs}^{95\%}} \approx 3.0 \qquad \text{for most sensitive SR.}$$

[31]CMS Collaboration, 1709.05406. [32] CMS Collaboration, 1801.03957.

3.Are there any hints of SUSY at LHC?

- **Explanation of the excess in simplified model VS Strong constraints from CMS analysis[33].**



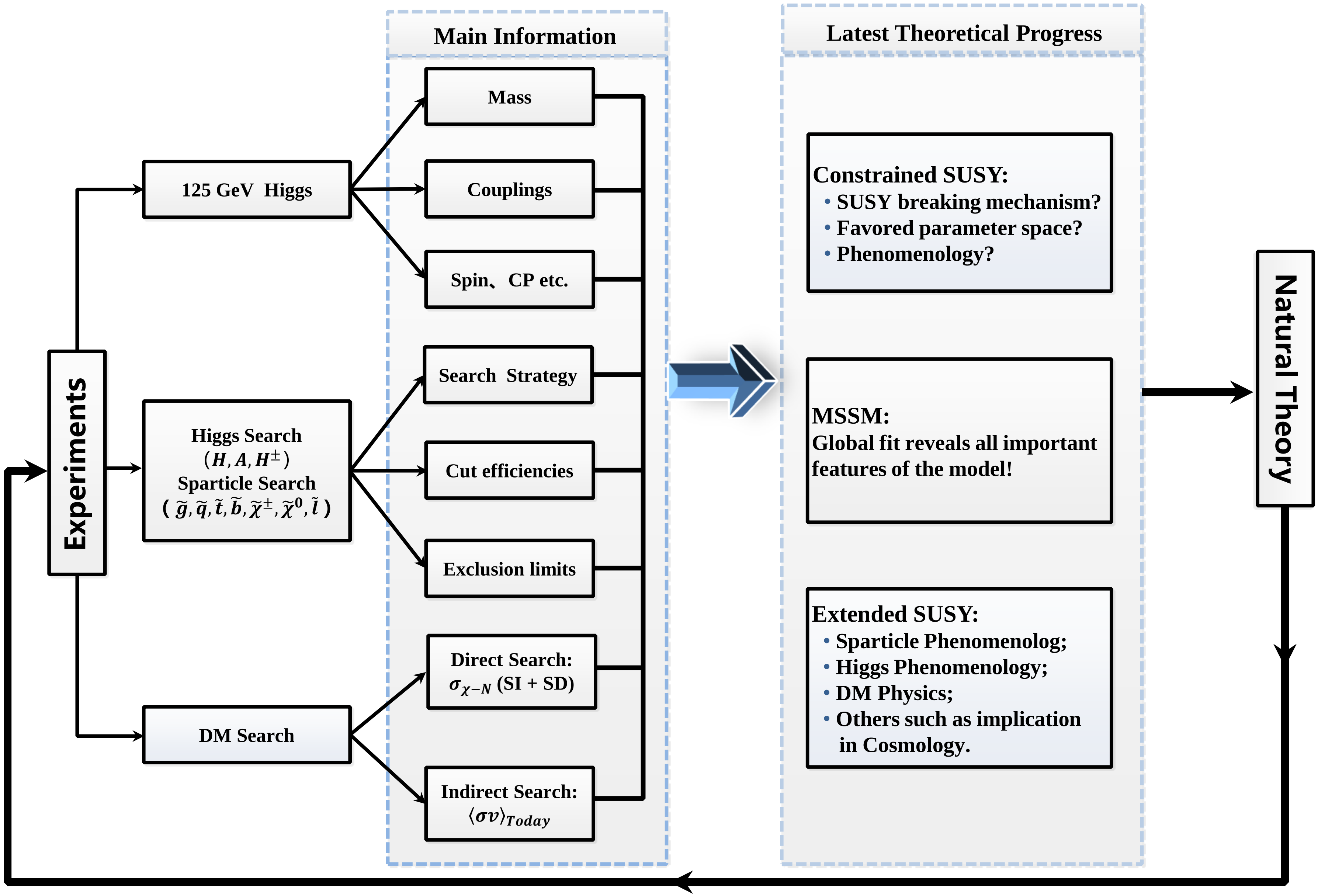


[33] Plotted by J. Cao, P. Zhu et. al..

Outline

1. **Experimental constraints on SUSY**
2. **Have natural SUSY been ruled out ?**
3. **Are there any hints of SUSY at LHC?**
4. **Summary**

4.Summary



Experiments
125 GeV Higgs
Higgs Search
($H, A, H^{\pm}$)
Sparticle Search
($\tilde{g}, \tilde{q}, \tilde{t}, \tilde{b}, \tilde{\chi}^{\pm}, \tilde{\chi}^{0}, \tilde{l}$)
DM Search
Main Information
Mass
Couplings
Spin、CP etc.
Search Strategy
Cut efficiencies
Exclusion limits
Direct Search:
$\sigma_{\chi-N}$ (SI + SD)
Indirect Search:
$\langle\sigma v\rangle_{Today}$
Latest Theoretical Progress
Constrained SUSY:
• SUSY breaking mechanism?
• Favored parameter space?
• Phenomenology?
MSSM:
Global fit reveals all important features of the model!
Extended SUSY:
• Sparticle Phenomenolog;
• Higgs Phenomenology;
• DM Physics;
• Others such as implication in Cosmology.
Natural Theory

4.Summary

- **LHC and DM experiments are complementary in limiting SUSY;**
  - Since MSSM fails to predict m_Z and experimentally allowed $\sigma_{\chi-N}$ without fine tuning, new theories are needed to naturally coincide with experimental results and guide experiments (personal opinion).

- **New theories should also address the theoretical problems of MSSM itself, e.g. μ problem, neutrino mass problem and lack of strong phase transition.**
  - Seesaw extension of NMSSM is one of economical solutions. Its distinguished features include:
    - ✓Right-handed neutrino and Higgsino are lighter than about 200 GeV.
    - ✓ Higgsino is degenerate with DM in mass to have small missing E_T at collider.
    - ✓At least two τ leptons in sparticle signals.

e^+e^-collider with $\sqrt{s}$ = 1 TeV is well suited to test the theory.

We are on the way

New methodology, techniques, experiments and thoughts.

- Automatic calculation packages like SARAH: change the way theorists work.
- Simulation tools like MadGraph and CheckMATE: bridge between theory and experiment.
- SUSY global fit: from concern of a few observables to assessment of model quality.

河南师范大学
HENAN NORMAL UNIVERSITY

THANKS!

SARAH: Model building tools

Basics

- **Input:** key ingredients of the model, e.g. lagrangian, symmetry, field, potential, rotation matrix etc.
- **Output:** particle mass, interaction vertex, tadpole and RGE etc.

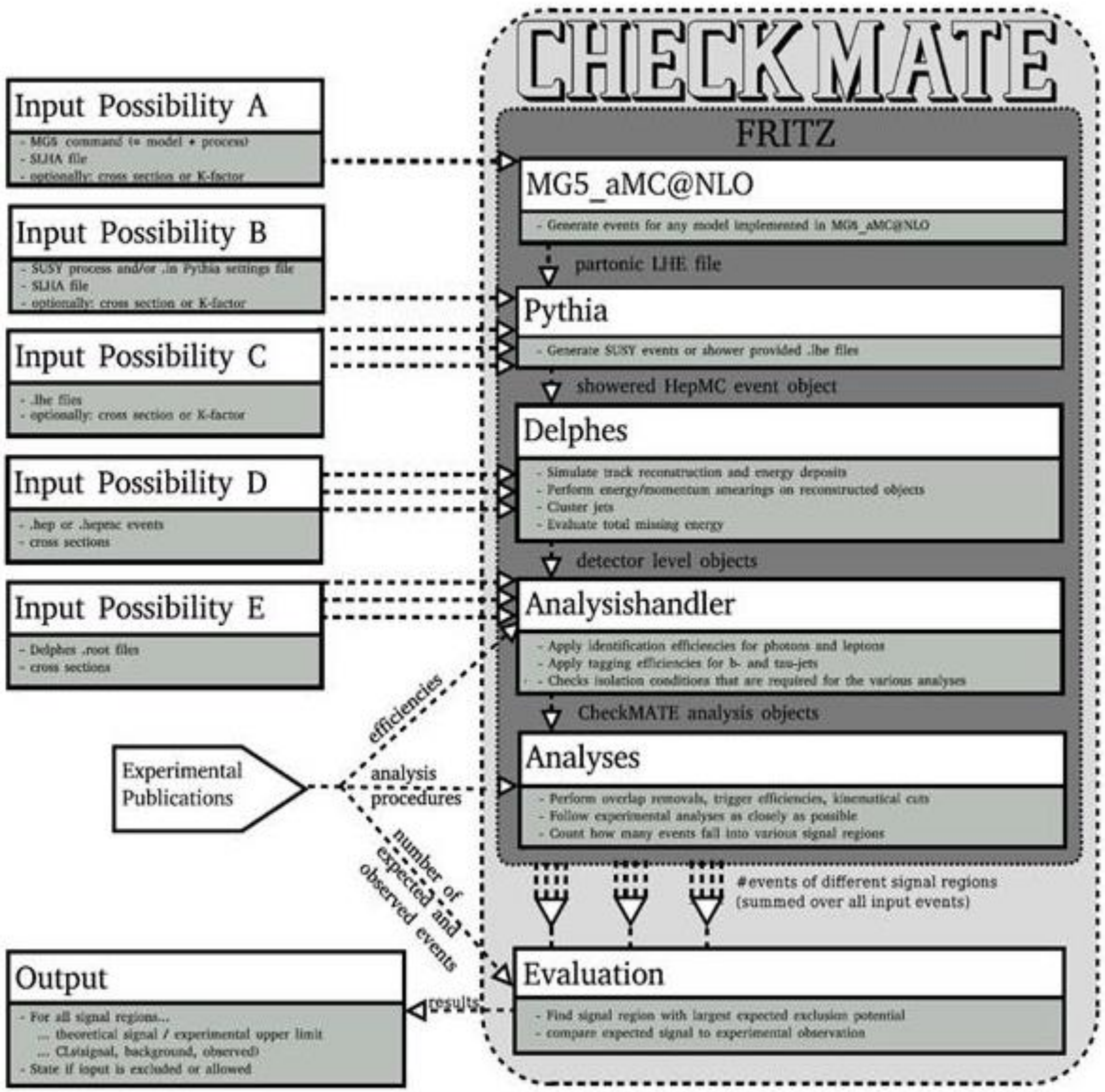
Applications

- Interface to SPheno: spectrum generator;
- Interface to micrOMEGAs: DM Physics research;
- Interface to MadGraph: Collider Simulation research;
- Interface to FlavorKit: flavor physics research;
- Interface to FeynArts + FormCalc: loop calculation;
- Interface to Vevacious: the stability of scalar potential.

CheckMATE

Input：
Event file can be fed into the chain at any level

Output：
judge whether the parameter point is excluded or not



Detector simulation by the cuts proposed by experimentalists.

Workflow：　MG5+Pythia+Delphes+Analyses

CheckMATE

	ATLAS				CMS			
	$\tilde{g},\tilde{q}$	$\tilde{t},\tilde{b}$	$\tilde{\chi}_i^{\pm},\tilde{\chi}_i^0$	$\tilde{l}$	$\tilde{g},\tilde{q}$	$\tilde{t},\tilde{b}$	$\tilde{\chi}_i^{\pm},\tilde{\chi}_i^0$	$\tilde{l}$
8TeV	15	10	4	2	4	4	1	0
13TeV	11	5	5	0	1	3	3	0
14TeV	3	2	2	0	0	0	0	0

Our TeV team contributed 15 analysis CARDS for CheckMATE2.

atlas_1308_1841 validation

Collaboration: ATLAS
Signal: >= 6 jets + Etmiss
Luminosity: 20.3 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Jin Min Yang and Yang Zhang
If you use this analysis in your study please cite: arXiv:1504.07869

atlas_1405_7875 validation

Collaboration: ATLAS
Signal: 2-6 jets + Etmiss
Luminosity: 20.3 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Jin Min Yang and Yang Zhang
If you use this analysis in your study please cite: arXiv:1504.07869

atlas_1501_07110 (only available in CM2) validation

Collaboration: ATLAS
Signal: 1 lepton + Higgs + MET
Luminosity: 20.3 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Peiwen Wu, Jin Min Yang, Yang Zhang

atlas_1503_03290 validation

Collaboration: ATLAS
Signal: 2 leptons + jets + Etmiss
Luminosity: 20.3 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Jin Min Yang and Yang Zhang
If you use this analysis in your study please cite: arXiv:1504.07869

atlas_1407_0350 validation

Collaboration: ATLAS
Signal: at least two taus and missing
Luminosity: 20.3 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Jin Min Yang, Yuanfang Yue and Yang Zhang

cms_1502_06031 validation

Collaboration: CMS
Signal: 2 leptons + jets + Etmiss
Luminosity: 19.5 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Jin Min Yang and Yang Zhang
If you use this analysis in your study please cite: arXiv:1504.07869

cms_1504_03198 validation

Collaboration: CMS
Signal: CMS, 1 lep, >=3 j, >=1 b-j, etmiss (DM +2top)
Luminosity: 19.7 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Peiwen Wu, Jin Min Yang, Yang Zhang
If you use this analysis in your study please cite: arXiv:1606.00072

cms_sus_16_025 validation

Collaboration: CMS
Signal: electroweakino and stop compressed spectra
Luminosity:12.9 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Yuanfang Yue and Yang Zhang

cms_sus_16_039 validation

Collaboration: CMS
Signal: electrowekinos in multilepton final state
Luminosity: 35.9 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Jinmin Yang, Yuanfang Yue, Yang Zhang, Pengxuan Zhu

cms_sus_16_048 validation

Collaboration: CMS
Signal: two soft opposite sign leptons
Luminosity: 35.9 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Jin Min Yang, Yuanfang Yue and Yang Zhang

atlas_conf_2016_050 validation MC cards

Collaboration: ATLAS
Signal: 1 lepton + (b) jets + Etmiss
Luminosity: 13.3 fb^(-1)
Authors: Junjie Cao, Liangliang Shang, Peiwen Wu, Jinmin Yang and Yang Zhang
Citations: Analysis uses the topness variable, please cite Phys.Rev.Lett. 111 (2013) no.12, 121802
Thanks to Michael Graesser and Jessie Shelton for the topness code.
Citations: Analysis uses the MT2bl variable, please cite JHEP 1207 (2012) 110
Notes: Dark matter signal regions, 'DM_low' and 'DM_high' are not yet included

atlas_conf_2016_076 validation

Collaboration: ATLAS
Signal: 2 lepton + jets + Etmiss
Luminosity: 13.3 fb^(-1)
Authors: Junjie Cao, Krzysztof Rolbiecki, Liangliang Shang, Jamie Tattersall, Peiwen Wu, JinMin Yang, Yuanfang Yue and Yang Zhang
Citations: Analysis uses the super razor variable, please cite Phys.Rev. D89 (2014) no.5, 055020
Thanks to Matthew Buckley, Alaettin Serhan Mete, Tommaso Lari, Federico Meloni, Iacopo Vivarelli and Daniel Antrim for the super razor code

atlas_conf_2016_054

Collaboration: ATLAS
Signal: 1 lepton + (b) jets + Etmiss
Luminosity: 13.3 fb^(-1)
Authors: Junjie Cao, Krzysztof Rolbiecki, Liangliang Shang, Jamie Tattersall, Peiwen Wu, JinMin Yang, Yuanfang Yue and Yang Zhang
Citations: Analysis uses the super razor variable, please cite Phys.Rev.Lett. 111 (2013) no.12, 121802
Thanks to Michael Graesser and Jessie Shelton for the topness code.

https://checkmate.hepforge.org/AnalysesList/