Phenomenological Study of the Semi-constrained NMSSM

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arXiv:2002.05554 K. Wang and Jingya Zhu, JHEP 06, 078 (2020);
arXiv:2003.01662 K. Wang and Jingya Zhu, Phys. Rev. D 101, no.9, 095028 (2020);
arXiv:2011.12848 K. Wang and Jingya Zhu, Chin. Phys. C 45, no. 4, 041003 (2021);

wk2016@whu.edu.cn SUSY 2021 @ China 2021.08.23

Outline

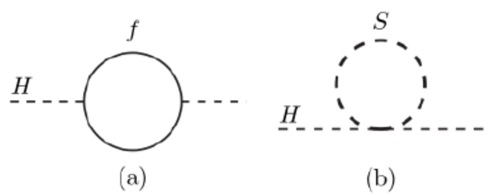
- **Introduction:** Why Supersymmetry (SUSY) ?
- **Model:** Semi-constrained NMSSM (scNMSSM)
- **Our work:** 1. Deep Learning in explore scNMSSM

  2. Light Dark Matter (LSP) in scNMSSM
- **Summary**

Introduction: Why SUSY ?

- **Problems in the SM:**

- Fine-turning



Martin, arXiv:9709356

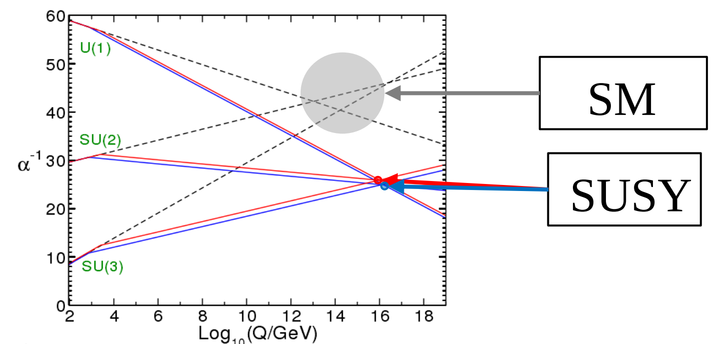
- Gauge couplings can't be unified at GUT scale

- Without dark matter candidate

- **How SUSY solve these:**

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

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



R parity:

The Lightest Supersymmetric Particle (LSP) is absolute stable, which can be dark matter candidate.

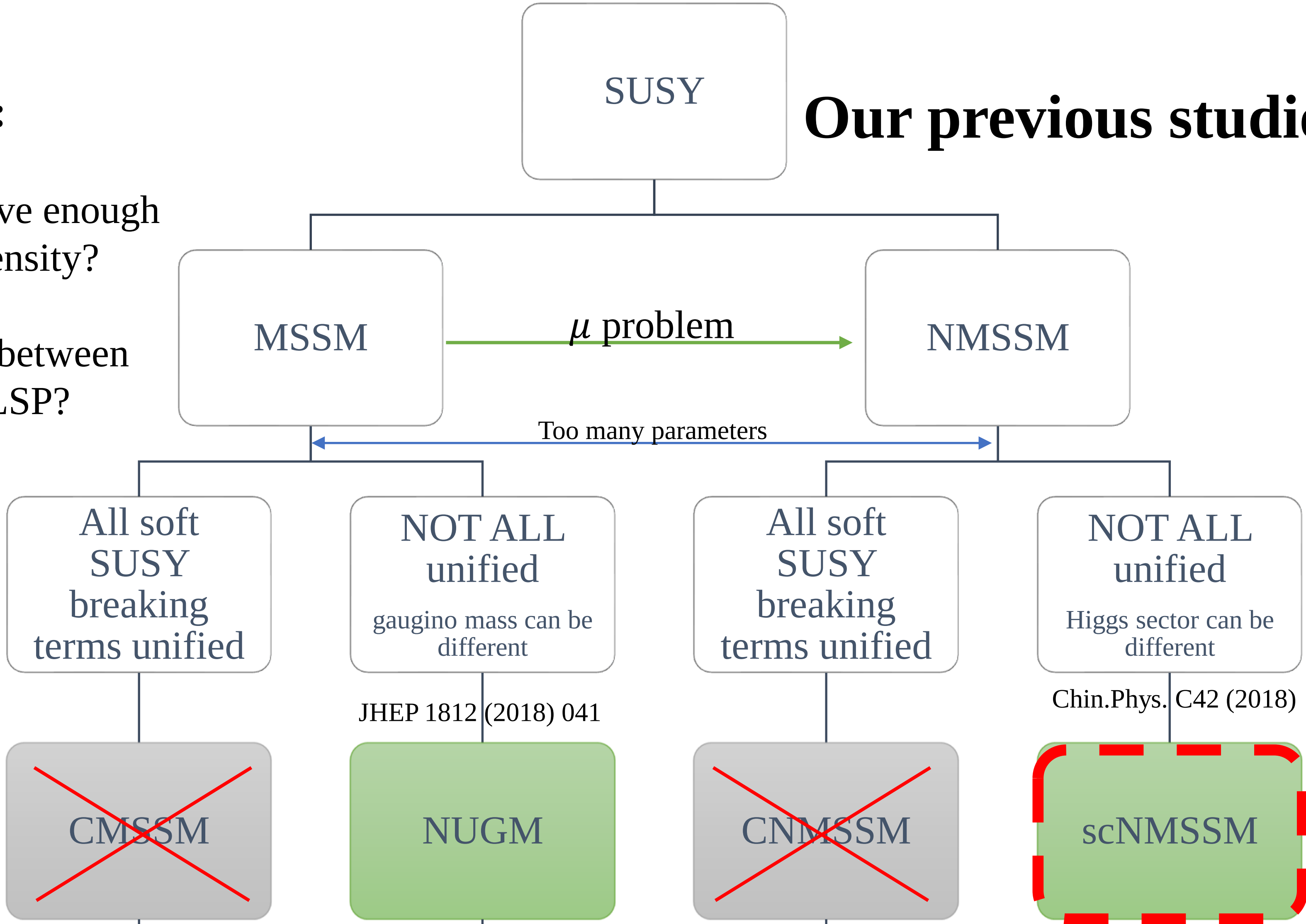
Introduction: Why scNMSSM ?

Question :

1. Can it have enough DM relic density?

2. Relation between Higgs and LSP?

Our previous studies:



Model: Semi-constrained NMSSM

- The superpotential of NMSSM:

$$W_{\rm NMSSM} = y_u \hat{Q} \cdot \hat{H}_u \hat{u}^c + y_d \hat{Q} \cdot \hat{H}_d \hat{d}^c + y_u \hat{L} \cdot \hat{H}_d \hat{e}^c + \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3$$

- The effective $\mu-$term:

$$\mu_{\rm eff} = \lambda v_s$$

- The soft breaking term:

$$-\mathcal{L}^{\rm soft}_{\rm NMSSM} = -\mathcal{L}^{\rm soft}_{\rm MSSM}|_{\mu=0} + m_S^2 |S|^2 + \lambda A_\lambda S H_u \cdot H_d + \frac{1}{3} \kappa A_\kappa S^3 + {\rm h.c.}$$

- **Semi-constrained:** The Higgs sector are considered non-universal, the Higgs soft mass and trilinear couplings are allowed to be different at GUT scale.

- In the scNMSSM, the complete parameter sector is:

$$\lambda,\ \kappa,\ \tan\beta = \frac{v_u}{v_d},\ \mu,\ A_\lambda,\ A_\kappa,\ A_0,\ M_{1/2},\ M_0$$

Model: electro-weak sector

- Higgs

CP-even Higgs

Light Higgs

SM-like

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = S_{ij} \begin{pmatrix} H_1 \\ H_2 \\ S^R \end{pmatrix}$$

CP-odd Higgs

Light Higgs

$$\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = P_{ij} \begin{pmatrix} A \\ S^I \end{pmatrix}$$

Charged Higgs

$$H^{\pm}$$

- Neutralino & Chargino

LSP

NLSP

Will decay to LSP

$$\begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \\ \tilde{\chi}_5^0 \end{pmatrix} = N_{ij} \begin{pmatrix} \tilde{B} \\ \tilde{W}^0 \\ \tilde{H}_d \\ \tilde{H}_u \\ \tilde{S} \end{pmatrix}$$

$$\begin{pmatrix} \tilde{\chi}_1^+ \\ \tilde{\chi}_2^+ \end{pmatrix} = V_{ij} \begin{pmatrix} \tilde{W}^+ \\ \tilde{H}_u^+ \end{pmatrix}$$

In scNMSSM, the Bino and Wino are very heavy, so they can be decoupled from the light sector.

Our work

Question :

1. Can it have enough DM relic density?

2. Relation between Higgs and LSP?

1. Deep Learning in explore scNMSSM

JHEP 06, 078 (2020)

We have developed a new search algorithm: the Heuristically Search (HS) and the Generative Adversarial Network (GAN). we successfully found a parameter space that satisfies all constraints.

2. Light Dark Matter in scNMSSM

Phys. Rev. D 101, no.9, 095028 (2020)
Chin. Phys. C 45, no. 4, 041003 (2021)

We found there are 4 funnel-annihilation mechanisms for the LSP in scNMSSM. We also verified that the spin-dependent DM-p/n cross section is proportional to the square of higgsino asymmetry. And it’s leading to the DM relic density is different in higgsino or singlino dominated LSP.

Explore parameter space

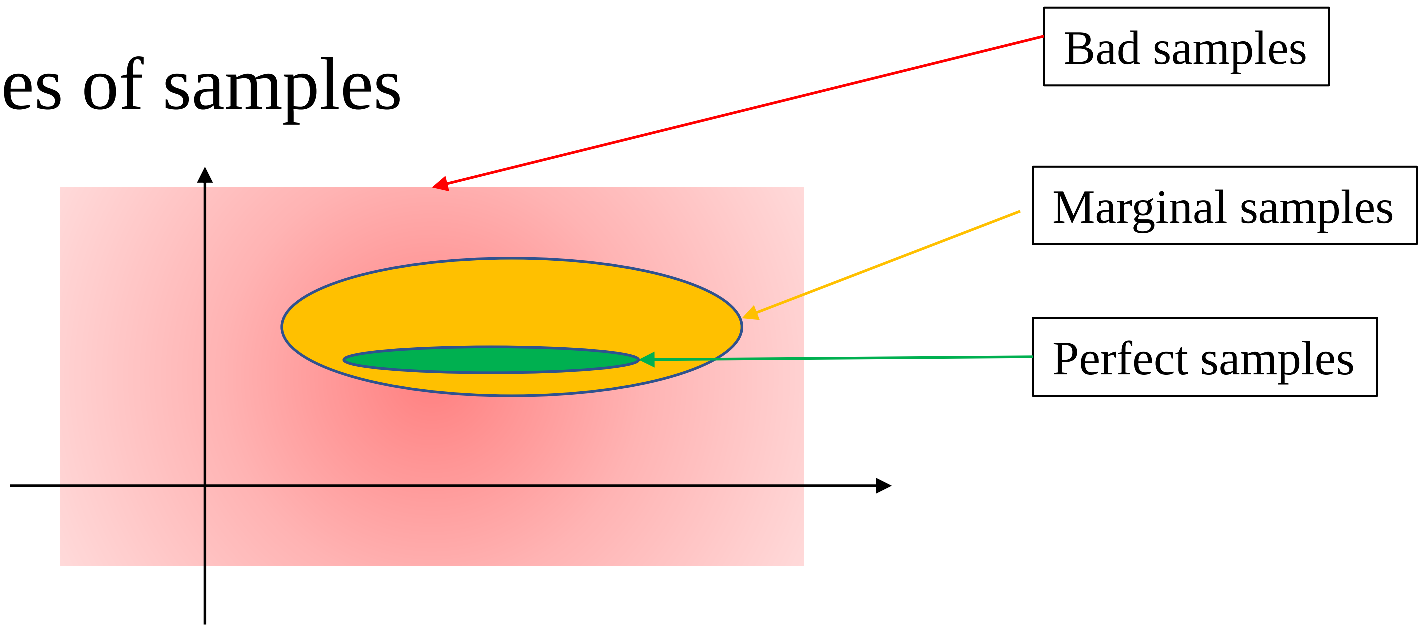
- Tranditional ways:
  - Random / Grid scan
  - MCMC / MultiNest scan

- New ways:
  - Machine learning (arXiv: 1708.06615, 1905.06047, 1906.03277)
    - Classification (discriminate physical or non-physical region)
    - Regression (predict physical observables)

  - The Heuristically Search and GAN (our new method, arXiv: 2002.05554)
    - HS: shift "not so good" samples to "good" samples
    - GAN: can generate samples with the similar distribution as the training samples

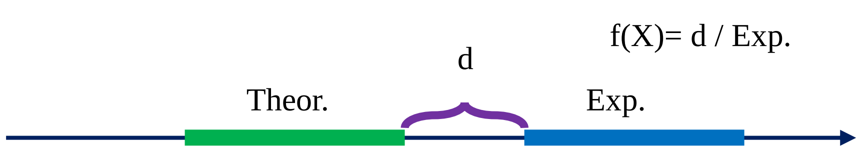
The Heuristically Search

- Three types of samples



- Score function: how much they violate the constraints

$$f(\mathbf{X}) = \sum_{i=1}^{N} \left\{ \max\left[1 - \frac{O^i_{\text{Theor.max}}}{O^i_{\text{Exp.min}}}, 0\right] + \max\left[\frac{O^i_{\text{Theor.min}}}{O^i_{\text{Exp.max}}} - 1, 0\right] \right\}$$



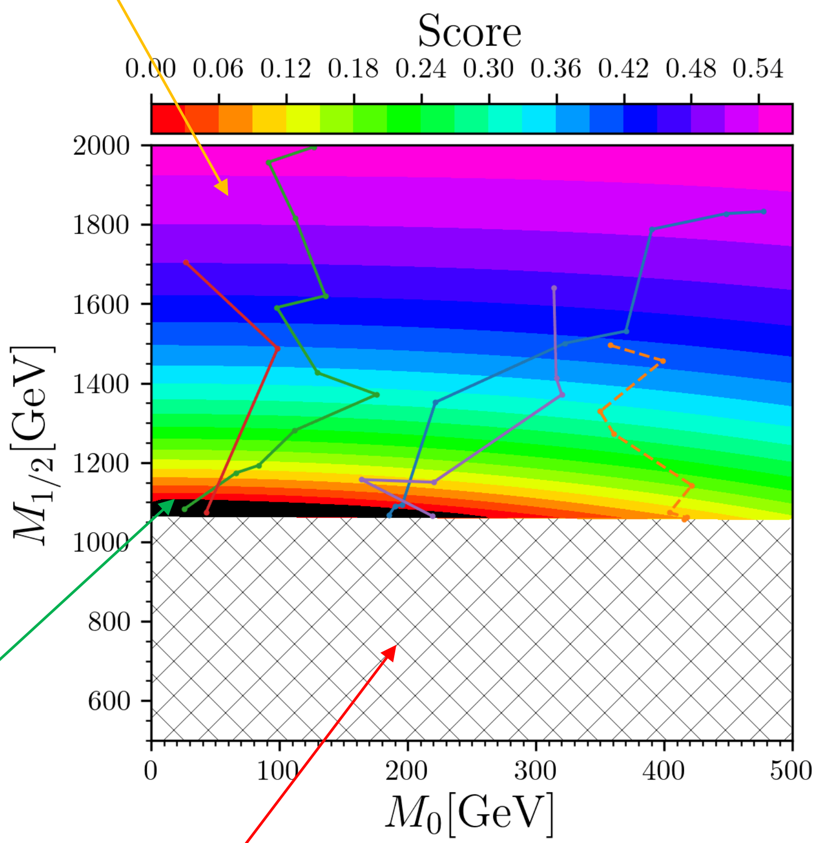
The Heuristically Search

- Steps：

- With a marginal sample, we search around it and try to find another marginal sample with a smaller score.

- we repeat this process, until we meet a perfect sample whose score is zero, or get failed

Marginal samples



Perfect samples

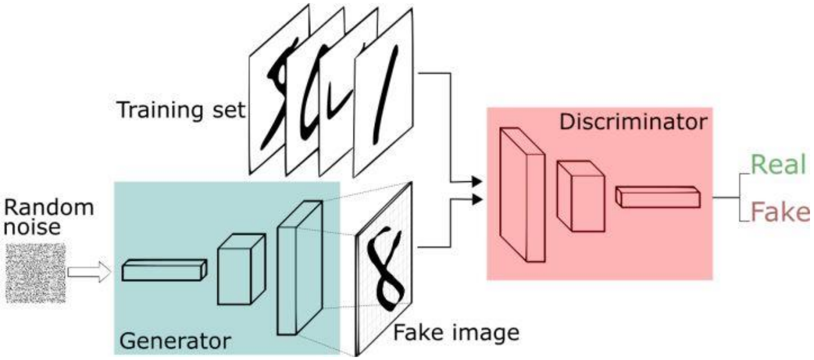
Bad samples

Soiled lines: success
Dashed lines: fail

GAN

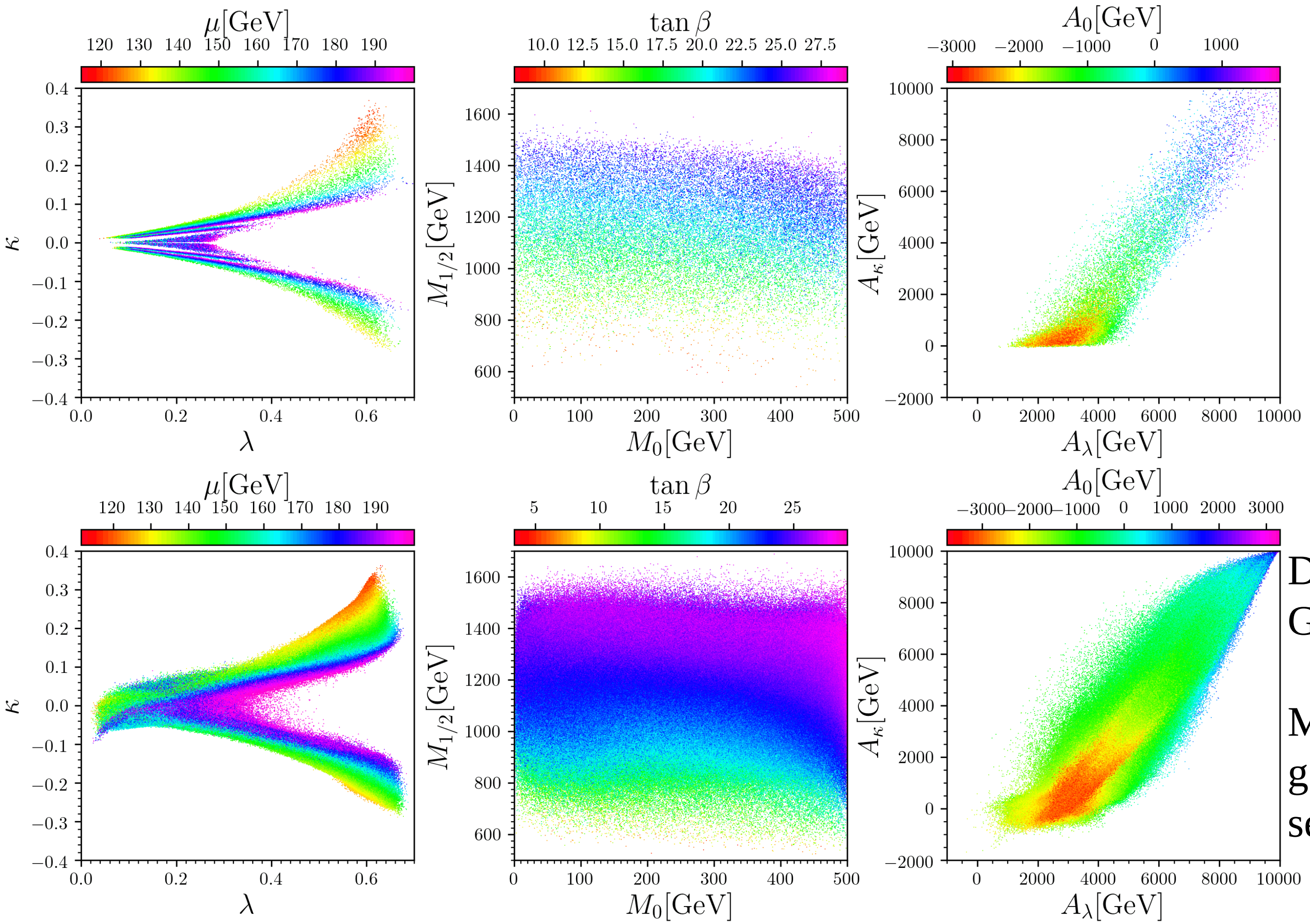
Proposed in 2014 by Ian Goodfellow
Goodfellow, et al. NIPS 2014
arXiv:1406.2661

- Generative Adversarial Network
- Two neural networks in GAN:
  - Generator: generate fake samples
  - Discriminator: classify samples into real and fake



- The basic ideas is:
  - G: try to generate almost 'real' samples, fool the D
  - D: try to find out fake samples which are generated by G

Samples recommend by GAN

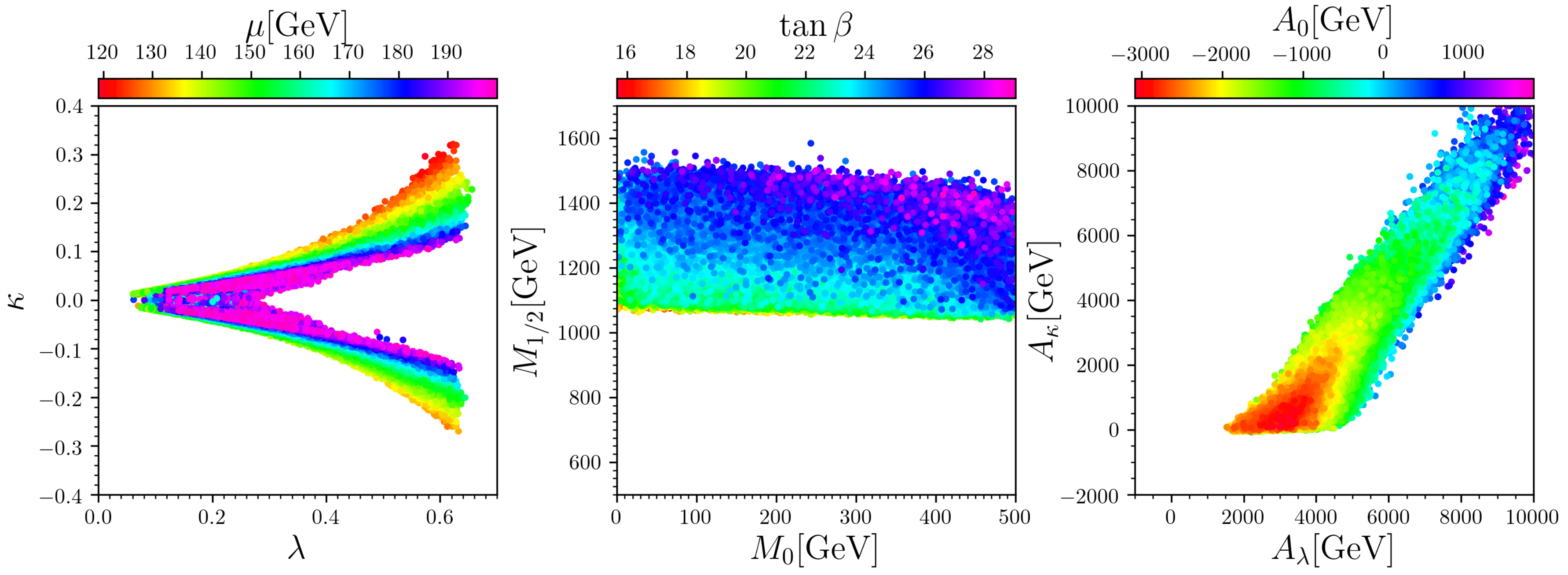


Training data

Data generated from GAN

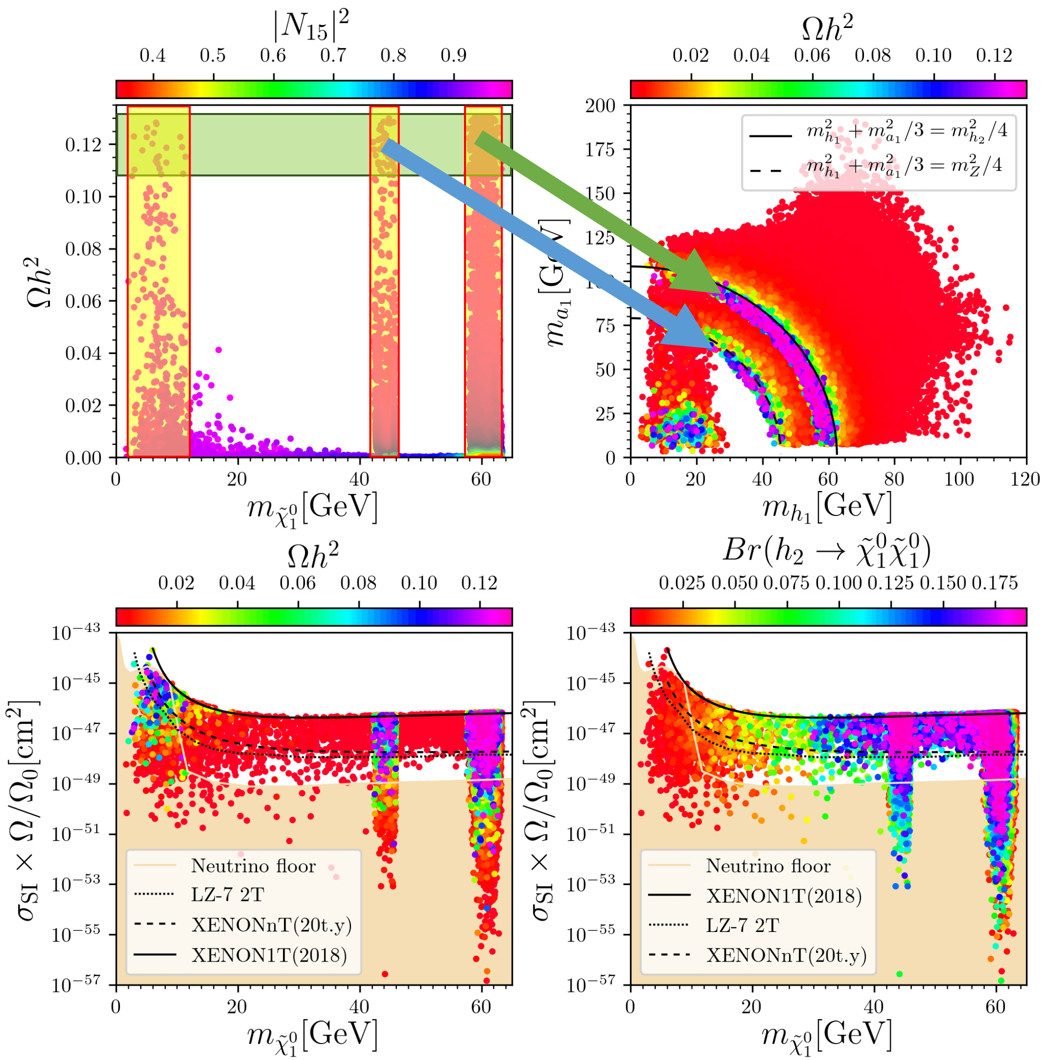
Millions samples generated in a few seconds

HS after the GAN recommend



- HS+GAN: 280k samples in 30 hours, much faster than previous
- Previous: 10k samples in 24 hours

Discussion

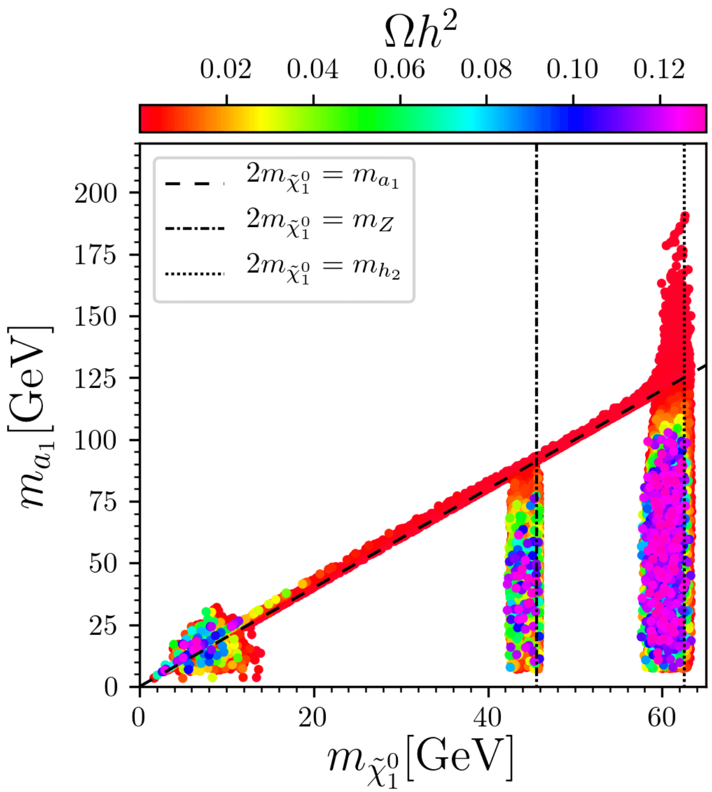


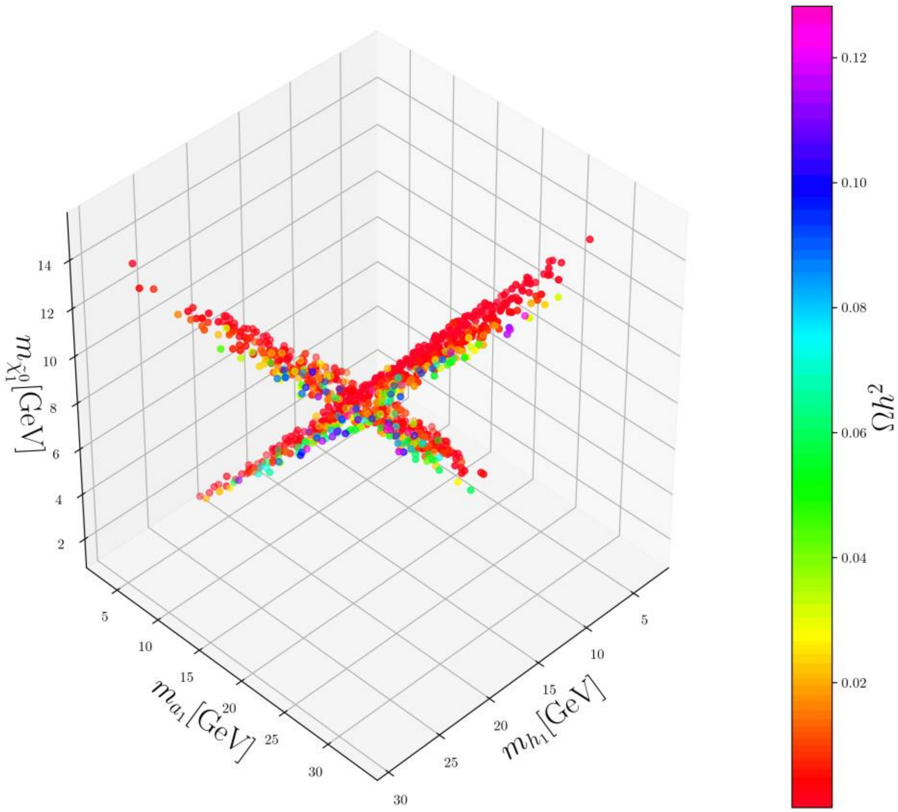
With small λ, κ, large $\tan\beta$:

$$m^2_{\tilde{\chi}_1^0} \approx m^2_{h_1} + \frac{1}{3} m^2_{a_1}$$

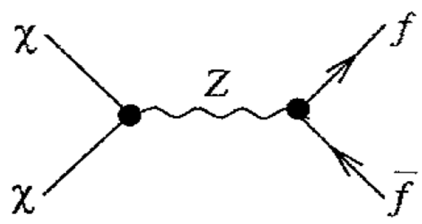
- Accoding to the mass of LSP, there are 3 case.
- The LSP with right DM relic density is highly singlino domainted.
- Lots of samples can be tested on the future DM experiments (LZ, XENONnT).
- When the mass of LSP is larger than 30GeV, Higgs invisible decay is large.

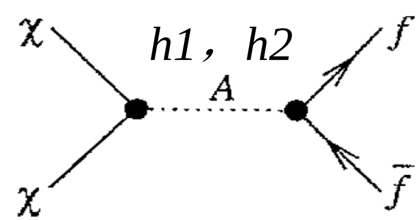
DM annihilation mechanisms



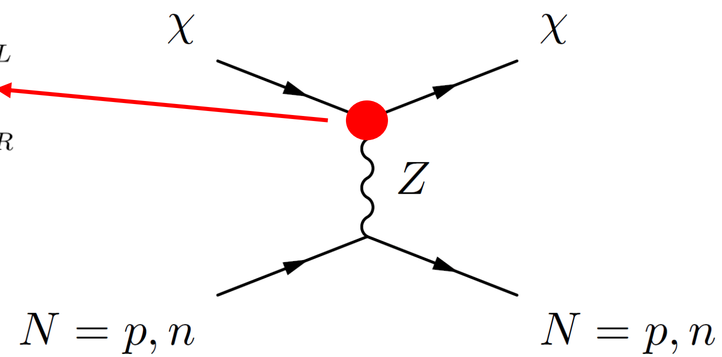


- 4 funnel-annihilation mechanisms

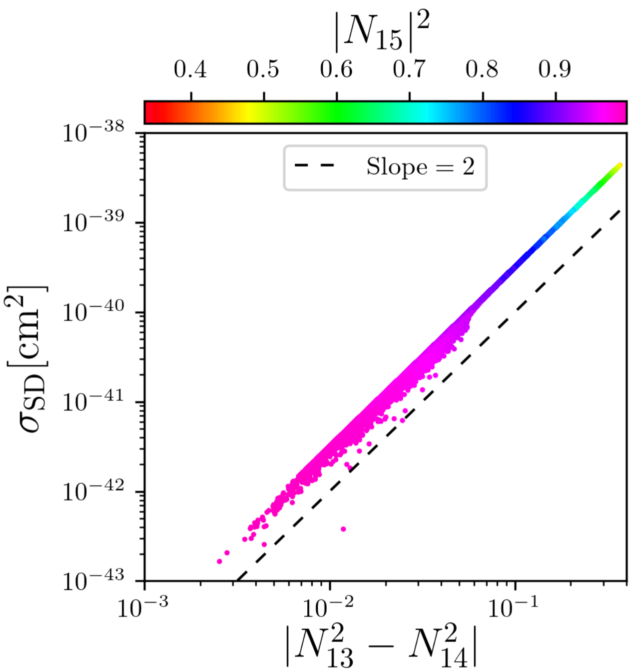




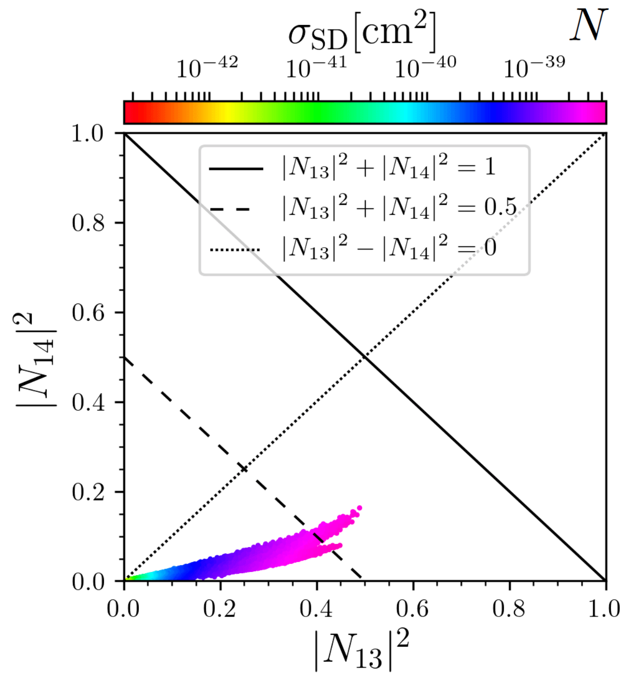
$$C_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} = -\frac{i}{2}(g_1 \sin\theta_W + g_2 \cos\theta_W)(N_{13}^2 - N_{14}^2)\gamma_\mu P_L + \frac{i}{2}(g_1 \sin\theta_W + g_2 \cos\theta_W)(N_{13}^2 - N_{14}^2)\gamma_\mu P_R$$



higgsino asymmetry



Higgsino asymmetry



- SD DM scattering cross section is proportional to the square of higgsino asymmetry.

$$\sigma_{\rm SD} \propto |N_{13}^2 - N_{14}^2|^2$$

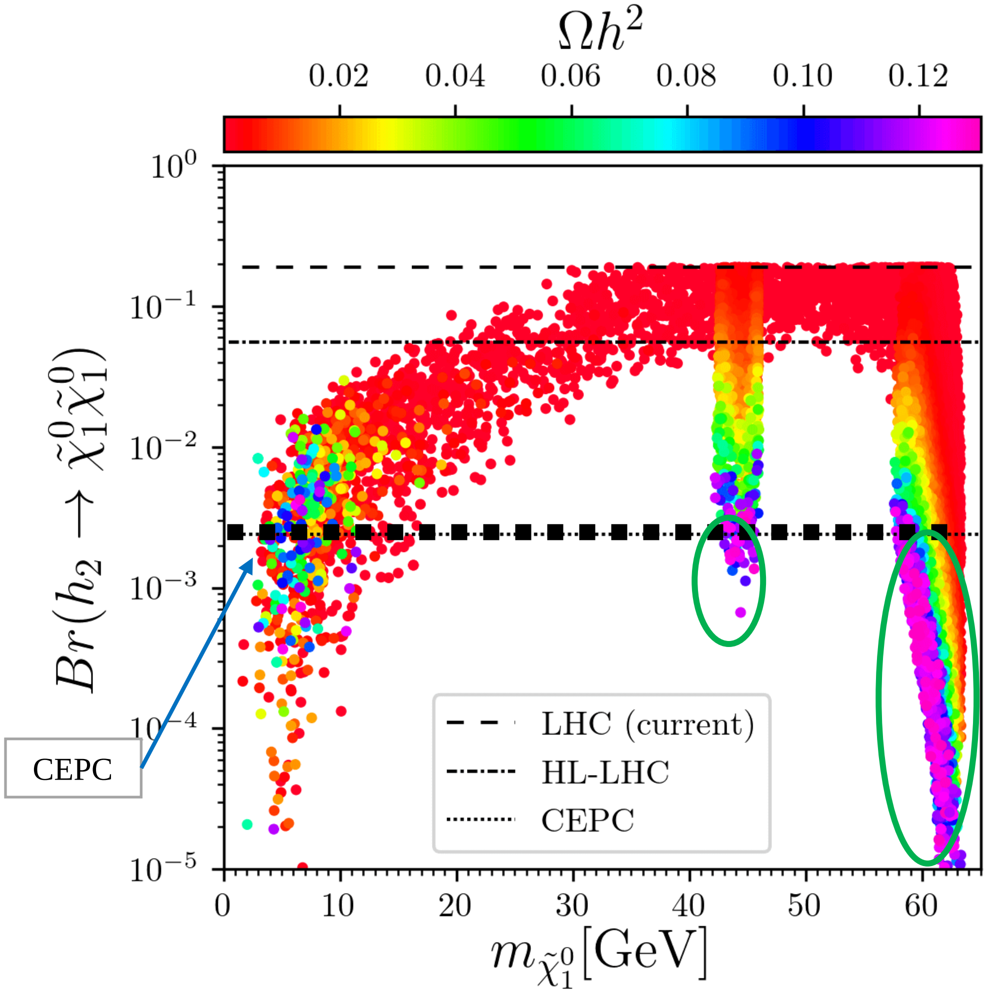
- In LSP, the higgsino asymmetry can't be small, unless the higgsino component is small.

Neglect the bino and wino component in LSP:

$$N_{13}^2 + N_{14}^2 + N_{15}^2 \approx 1$$

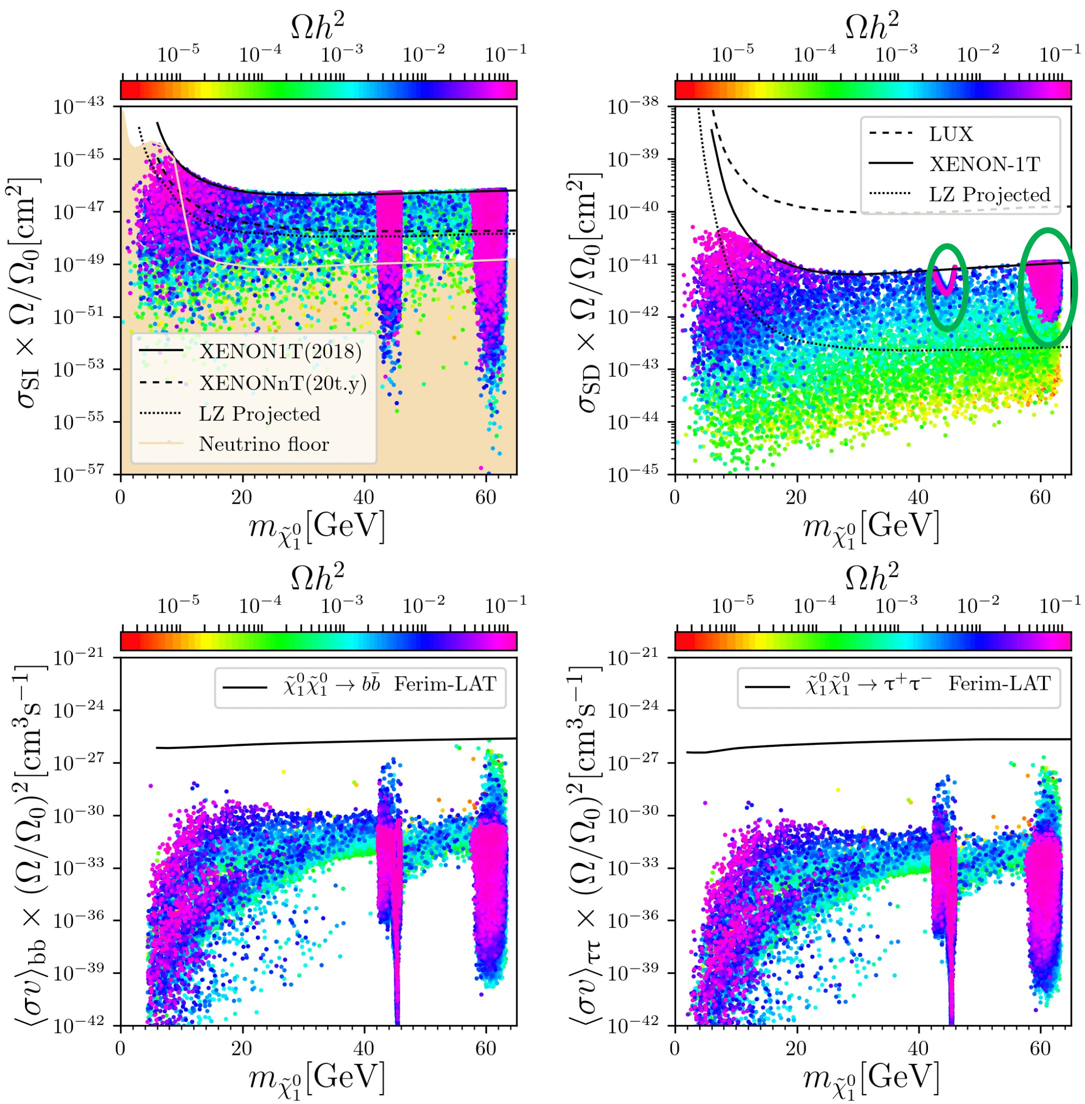
$$N_{13} : N_{14} : N_{15} = \frac{m_{\tilde{\chi}_1^0}}{\mu_{\rm eff}} : -1 : \frac{\mu_{\rm eff} - m_{\tilde{\chi}_1^0}}{\lambda v}$$

Higgs invisible decay



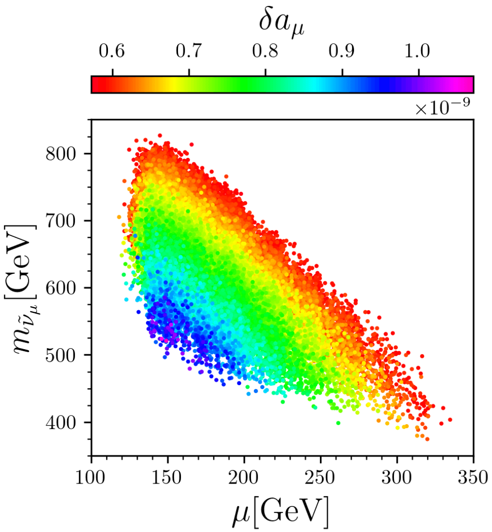
- With right DM relic density, Higgs invisible decay is small, that because λ is small.

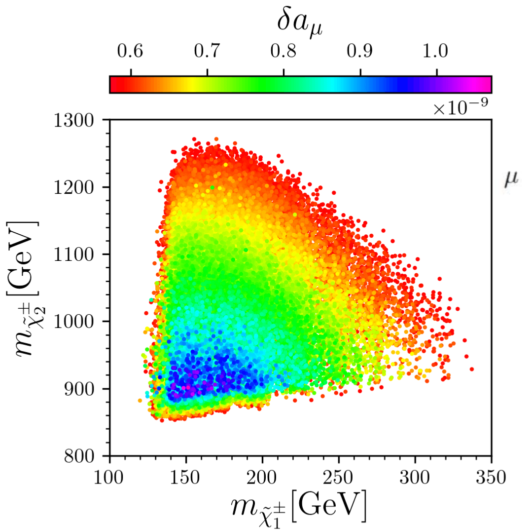
SI/SD scattering

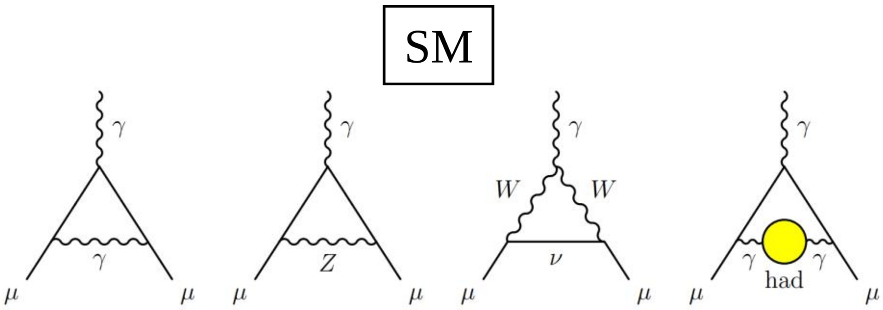


- For constraint, SI is more strong than SD， because SI is improved by the square of nucleons number.
- For samples, SD is larger than SI, because SD channel is Z, SI channel is Higgs.
- For higgsino LSP, SD is large, when it have right DM relic density, it will be excluded.
- For singlino LSP, SD is small, so it can have right DM relic density.

Muon g-2







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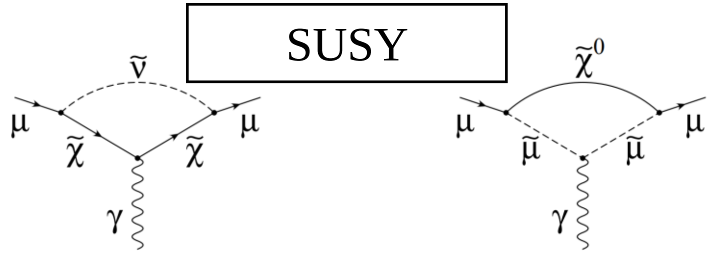

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- muon g-2 mainly contributes come from chargino - sneutrino loop.
- Light chargino is higgsino domaned， its mass is μ， heavy chargino is wino domaned, its mass is large.
- μ (mass of NLSP) maximum is 335 GeV , which is constrained by muon g-2 experiment.

Summary

- We have developed a new search algorithm
- There are 4 funnel-annihilation mechanisms
- SD DM scattering cross section is proportional to the square of higgsino asymmetry
- For higgsino LSP, SD is large, when it have right DM relic density, it will be excluded.
- For singlino LSP, SD is small, so it can have right DM relic density.
- μ (mass of NLSP) maximum is 335 GeV , which is constrained by muon g-2 experiment.

Thank you!

Backup

The Heuristically Search

- Three types of samples

	Type 1	Type 2	Type 3
The basic constraints	$\times$	$\checkmark$	$\checkmark$
The dark matter and muon g−2 constraints	—	$\times$	$\checkmark$
	bad samples	marginal sample	perfect samples
Score	None	> 0	$= 0$

Basic constraints:

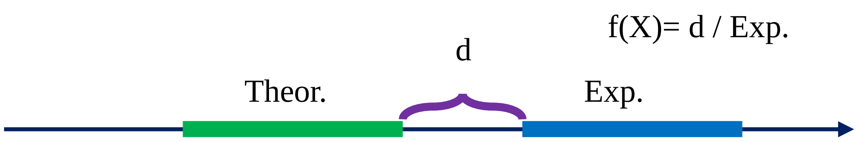
- Theoretical constraints
- Mass bounds from the LEP , LHC
- B physics
- SM-liked Higgs boson
- Higgs can have invisible decay

Dark matter and muon g-2 constraints:

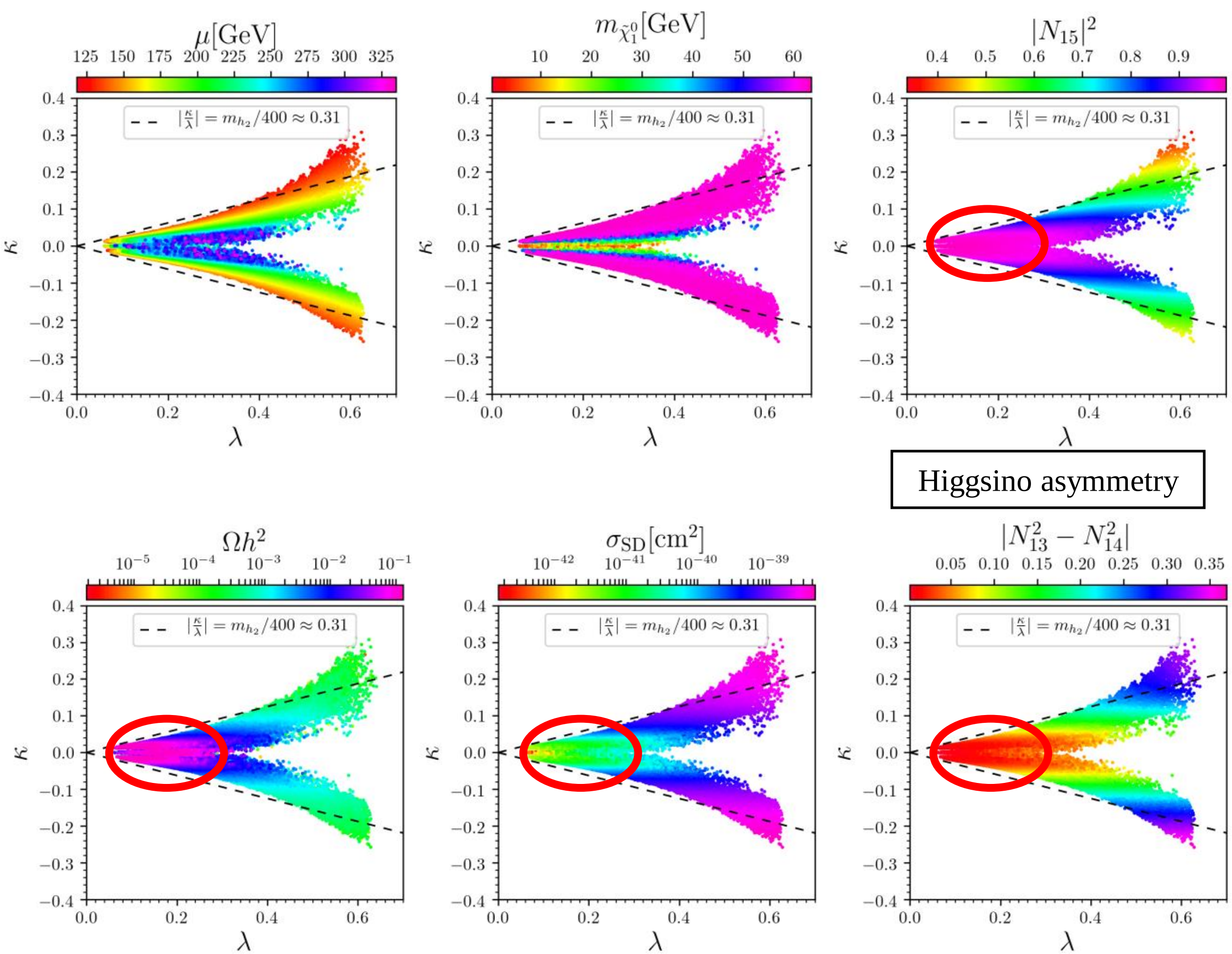
- Relic density
- Spin-independent cross section
- Spin-dependent cross section
- Muon g-2

- Score function: how much they violate the constraints

$$f(\mathbf{X}) = \sum_{i=1}^{N} \left\{ \max\left[1 - \frac{O^i_{\mathrm{Theor.max}}}{O^i_{\mathrm{Exp.min}}}, 0\right] + \max\left[\frac{O^i_{\mathrm{Theor.min}}}{O^i_{\mathrm{Exp.max}}} - 1, 0\right] \right\}$$



Discussion



- μ (mass of NLSP) maximum is 335 GeV
- With right DM relic density LSP is singlino domained.
- SD DM scattering have relation with higgsino asymmetry.
- Samples with right DM relic density LSP, SD and higgsino asymmetry are both small.