# SUSY After LHC Higgs Discovery

Jin Min Yang （杨金民）

ITP, Beijing

Weihai（2016.08.15)

# Outline

1 Introduction to SUSY

2 Status of SUSY in light of LHC data

3 Future probes of SUSY

4 Conclusion

# 1 Introduction to SUSY

**Although there is no evidence, SUSY is still the most appealing candidate for new physics**

E. Witten

SUPERSYMMETRY –

EXTENSION OF SPECIAL RELATIVITY TO INCLUDE FERMIONIC SYMMETRIES

$$Q_\alpha Q_\beta + Q_\beta Q_\alpha = \Gamma^\mu_{\alpha\beta} \, P_\mu$$

"supercharges"

plus sign for fermionic symmetry!

DIRAC MATRIX

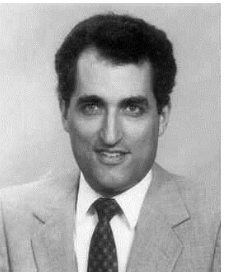
momentum

# Virtues of SUSY

* SUSY can make a “small” Higgs mass natural
* SUSY is part of a larger vision of physics, not just a technical solution
* measured value of $\sin^2\theta$ favors SUSY GUT
* survives electroweak tests
* heavy top mass, as needed

*E. Witten*

# Have not found any SUSY particles … …

E. Witten

It is disappointing that we have not found SUSY yet, but for the most part it is perhaps not too surprising….

If charged superpartners are just a little bit above $M_Z$, we would not have seen them yet.

Superpartners get masses from electroweak breaking *and* SUSY breaking so it is natural for them to be a bit above the Z, which gets mass only from electroweak breaking.

# SUSY Models

Although SUSY is simple and beautiful, its realizations in particle physics is various. We have **various SUSY models** in particle physics.

CMSSM
mSUGRA
GMSB
AMSB
… …

with boundary conditions

MSSM
NMSSM
nMSSM
… …

low energy effective

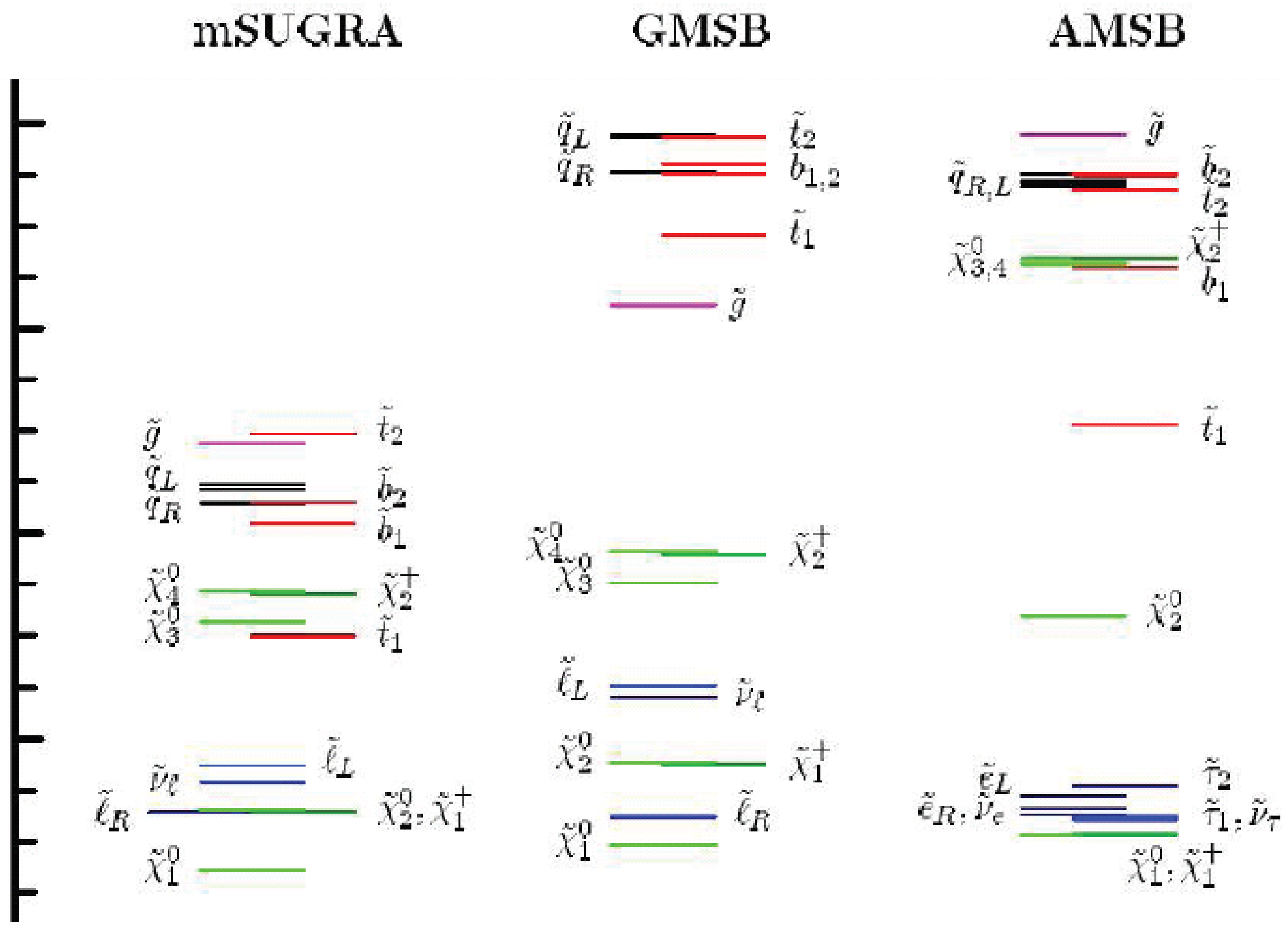
Split-SUSY

give up naturalness

… …

# Different numbers of free parameters

# Different patterns of spectrum




500 GeV

# Different particle contents

## NMSSM

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

$$W_{\mathrm{NMSSM}} = W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \frac{1}{3} \kappa \hat{S}^3,$$

$$W_{\mathrm{nMSSM}} = W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \xi_F M_n^2 \hat{S},$$

$$W_F = Y_u \hat{Q} \cdot \hat{H}_u \hat{U} - Y_d \hat{Q} \cdot \hat{H}_d \hat{D} - Y_e \hat{L} \cdot \hat{H}_d \hat{E}$$

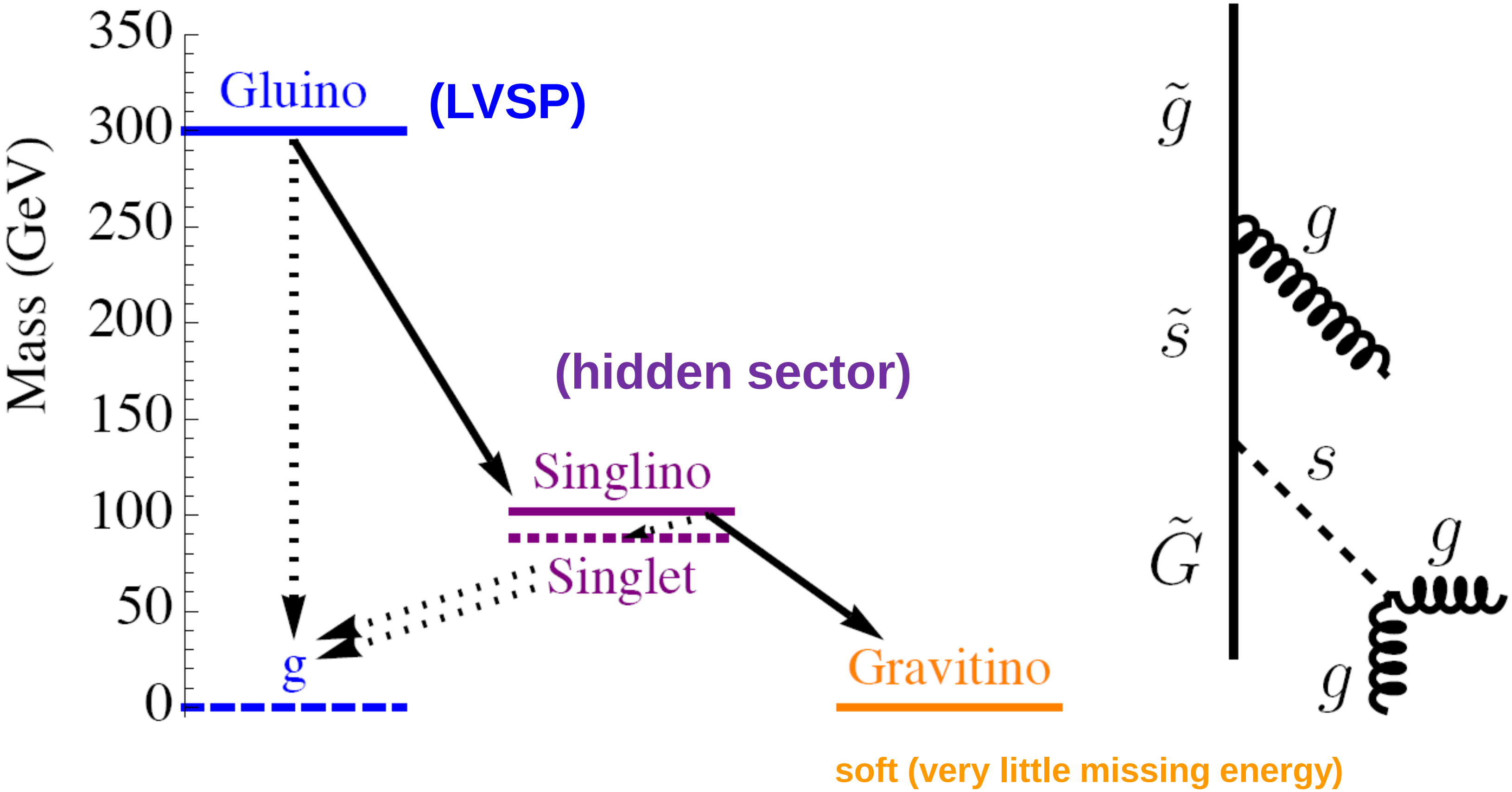
# Require naturalness

## Natural SUSY

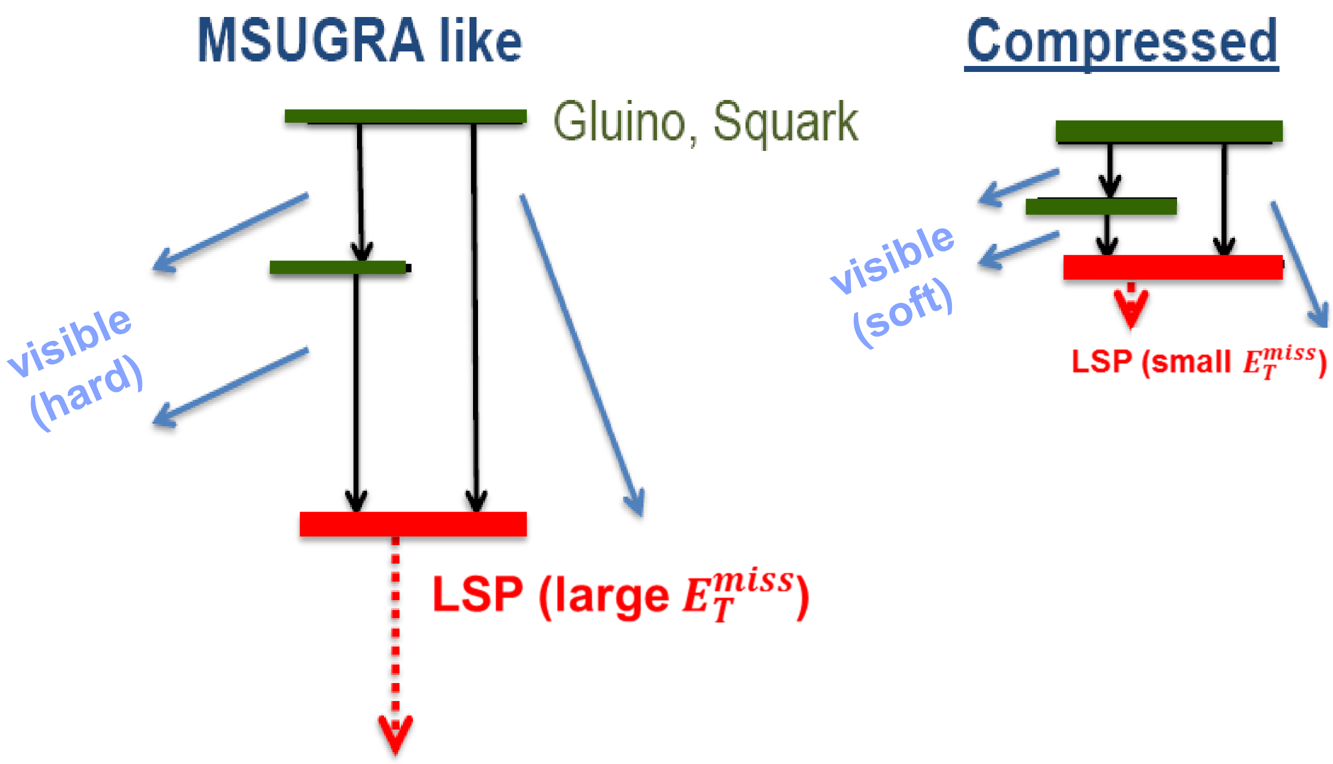
- Light Higgsinos  ~ 100-200 GeV
- Light 3rd generation squark (stop/sbottom)  < 1-2 TeV
- Gluino not very heavy  < 3 TeV
- Heavy 1$^{st}$ and 2$^{nd}$ generation squarks ~ 10-30 TeV

# Escape unobservation limits

## Stealth SUSY



# Compressed SUSY



# 2 Status of SUSY in light of LHC data

**Now, we have various expt data:**

- **Sparticle search results at LHC**
- **Higgs data at LHC**
- **Dark matter data (Planck, Xenon, LUX)**
- **Low energy collider data (EWPD, flavor physics, g-2, …)**

From flavor physics($B$-decays), no hints of SUSY

# BBC News

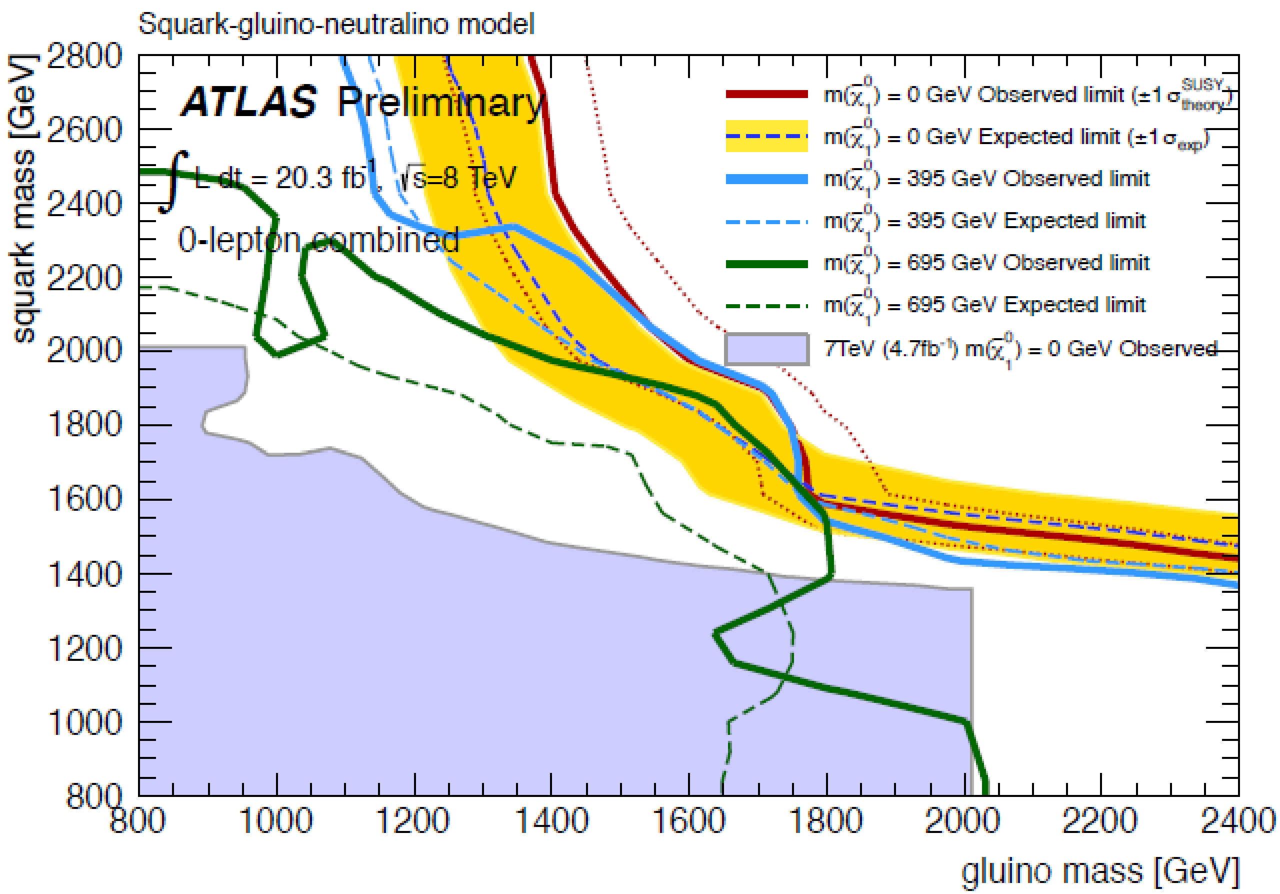
Nov 19, 2012

**SUSY may not be dead, but these latest results have certainly put it into hospital**

# LHC direct searches have not seen any sparticles

## Simple implication for SUSY:

## (push colored sparticles into TeV region)



## LHC discovery of a 125 GeV Higgs:

## has profound implication for SUSY !

- In general, it is a good news (or even an evidence) for SUSY

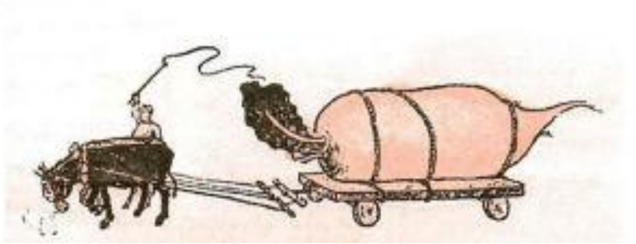
- Actually, it put high pressure on SUSY

# AMSB and GMSB:

Baer, Barger, Mustafayev, arXiv:1202.4038

**To give a 125 GeV Higgs,**

**SUSY particles are above 10 TeV**



- **not accessible at LHC**
- **fine-tuning**

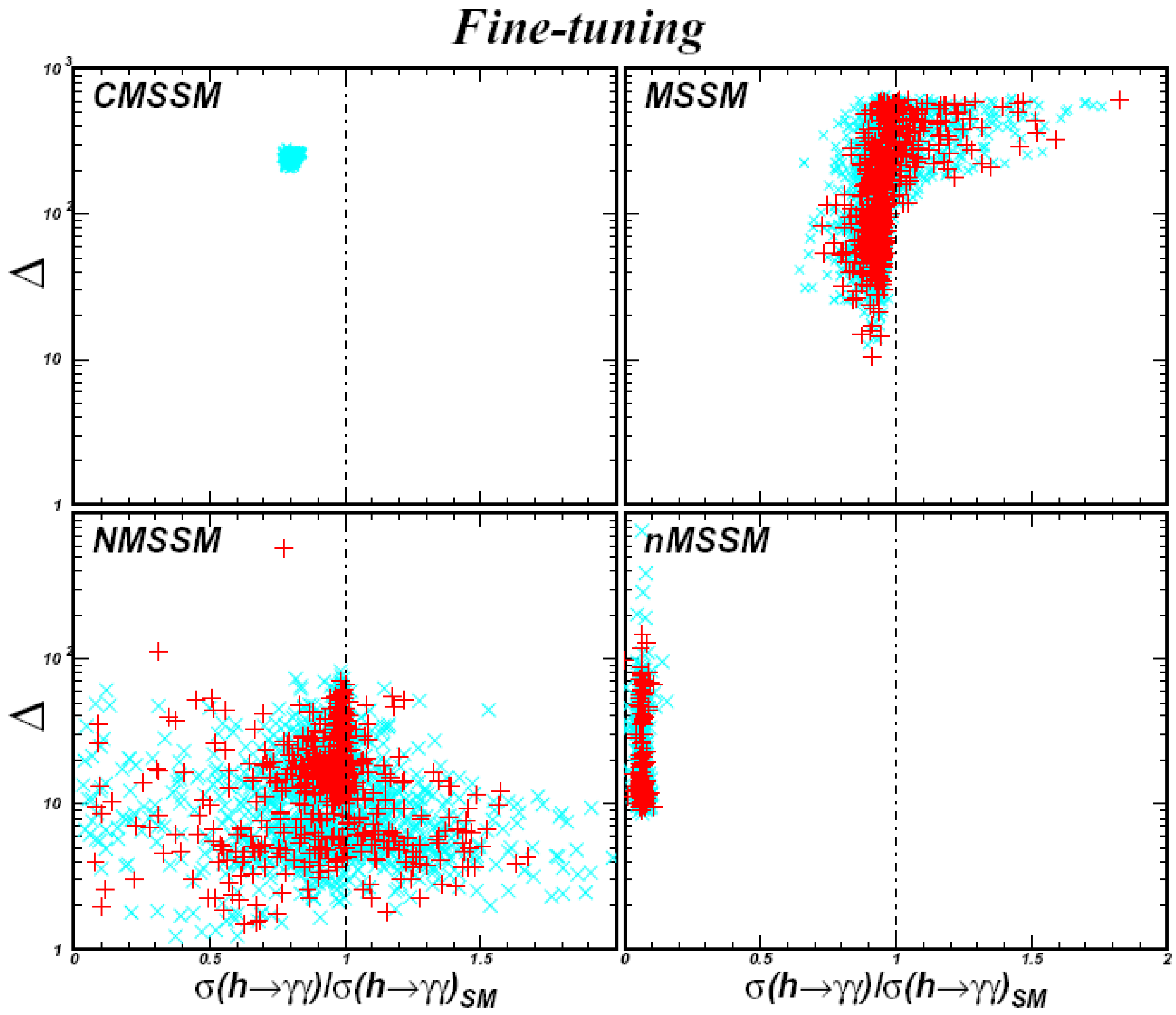
**In these models $A_t$ is generated at 2-loop, very small !**

**CMSSM/mSUGRA**

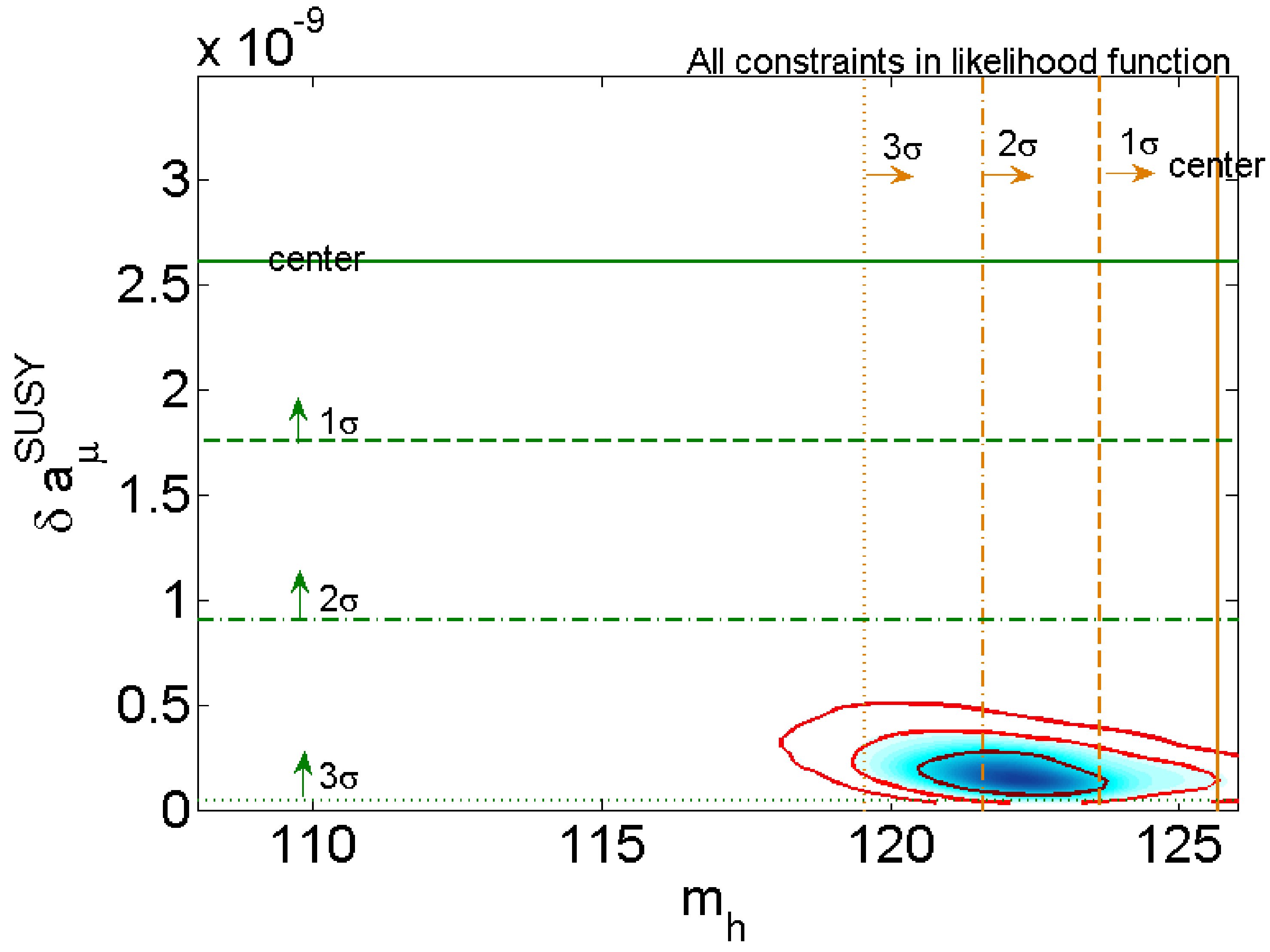
**MSSM, NMSSM, nMSSM:**

arXiv: 1207.3698; 1202.5821

Cao, Heng, Yang, Zhu

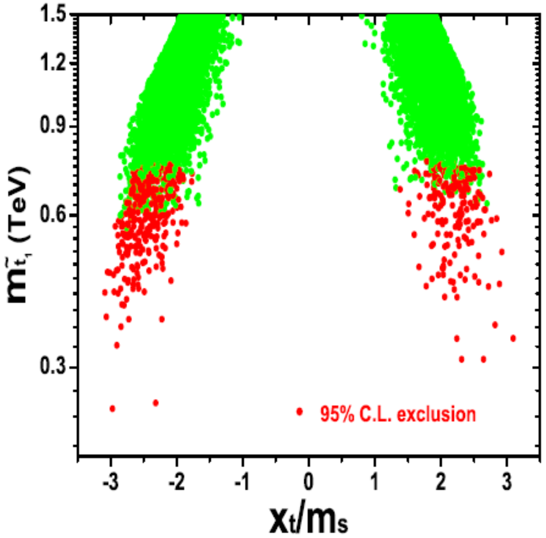


# CMSSM/mSUGRA



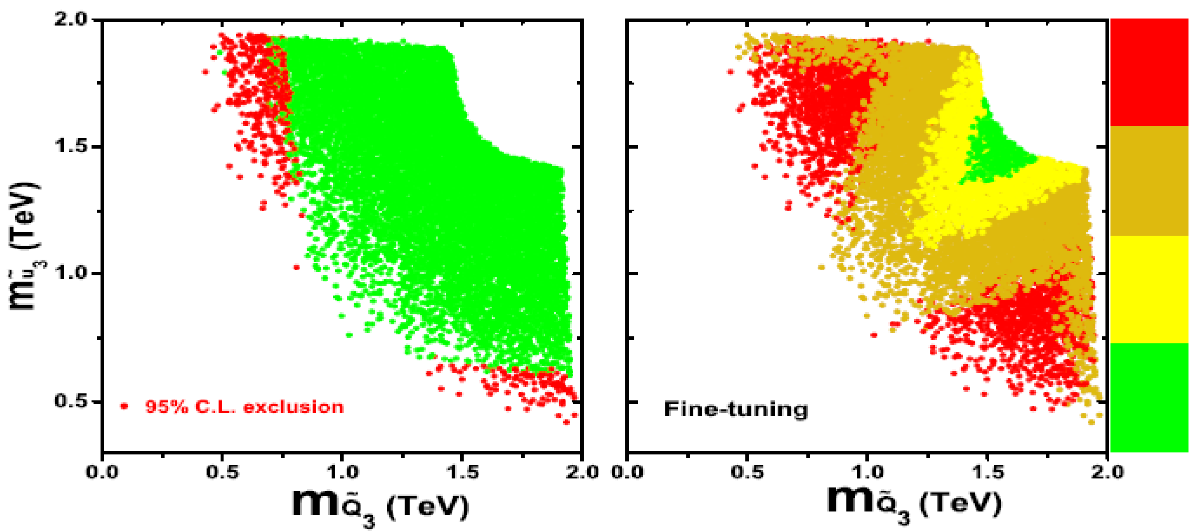
# Natural SUSY

arXiv:1308.5307
Han, Hikasa, Wu, Yang, Zhang



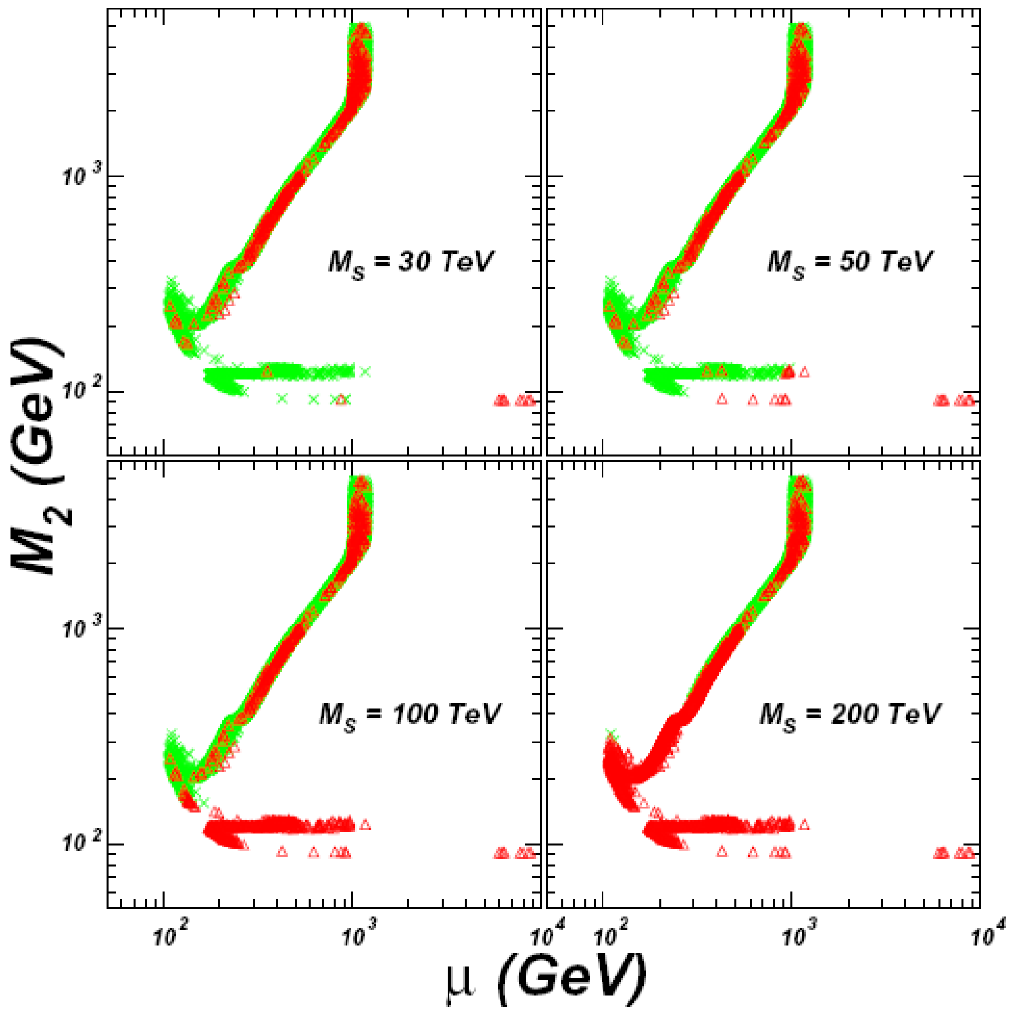

**Not so natural !**
**Natural space (light stop) has been excluded**

fine-tuning extent



# Split-SUSY

arXiv:1310.1750
Wang, Wang, Yang




$$\Omega_{DM} = 0.1199 \pm 0.0027$$

The triangles (red) cannot achieve gauge coupling unification

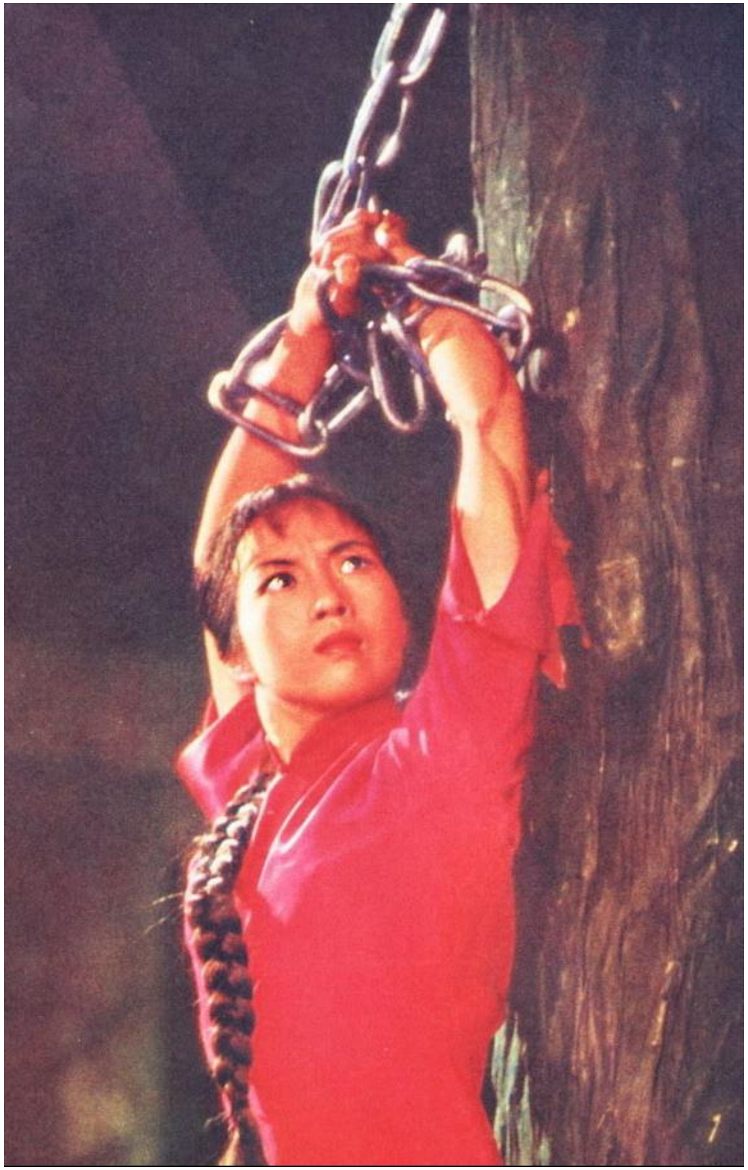
DM + GUT

# In summary, status of SUSY:

cannot explain muon g-2

| | |
|---|---|
| GMSB/AMSB: | can give 125 GeV Higgs, but with very heavy stop (fine-tuning) |
| CMSSM/mSUGRA: | can give 125 GeV Higgs; but cannot explain muon g-2 |
| MSSM: | can fit all data well, but suffer from little fine-tuning |
| nMSSM: | nearly excluded (suppress diphoton rate too much) |
| NMSSM: | most favored (can fit all data well without fine-tuning) |
| Split-SUSY: | no problem (give up naturalness) |
| Stealth SUSY: | no problem (can always escape detections) |
| Compressed SUSY: | no problem (can escape detection at LHC) |

# SUSY is alive and strong



打不死的吴清华
我还活在人间！

**These fancy models**

**(GMSB，CMSSM，mSUGRA, …)**

**are still our favorites**

**We can easily repair them**

# Repair GMSB:

Kang, Li, Liu, Tong, Yang, arXiv:1203.2336

A Heavy SM-like Higgs and a Light Stop from Yukawa-Deflected Gauge Mediation

$$W_1 = \lambda_u S \bar{\Phi}_L H_u + \lambda_d \bar{S} \Phi_L H_d,$$

**can have large $A_t$, giving 125 GeV Higgs without very heavy stops**

accessible at LHC

# Repair AMSB :

## Heavy colored SUSY partners from deflected AMSB

Wang, Wang, Yang, Zhang， arXiv:1505.02785

**We propose a deflected AMSB scenario from SUSY QCD.**

**Such a scenario can naturally give a SUSY spectrum in which all colored sparticles are heavy while sleptons are light.**

**As a result, the discrepancy between muon g-2 and LHC 125 GeV Higgs data can be reconciled in this scenario.**

# Repair AMSB :

## Natural-SUSY spectrum from deflected AMSB with messenger-matter interactions

**Wang, Yang, Zhang， arXiv:1602.01699**

A radiative natural-SUSY spectrum are proposed in deflected AMSB with general messenger-matter interactions. Due to the contributions from the new interactions, positive slepton masses as well as a large $|A_t|$ term can naturally be obtained.

In this scenario, in contrast to the ordinary (radiative) natural-SUSY scenario with under-abundance of dark matter (DM), the DM can be the mixed bino-higgsino and have the right relic density. The 125 GeV Higgs mass can also be easily obtained in our scenario.

# Repair CMSSM/SUGRA:

**Reconcile muon g-2 with 125 GeV Higgs mass in CMSSM/SUGRA with generalized gravity mediation**

**Wang, Wang, Yang, arXiv:1504.00505**

**From generalized gravity mediation we build a SUGRA scenario in which the gluino is much heavier than the electroweak gauginos at the GUT scale.**

**We find that such a non-universal gaugino scenario with very heavy gluino at the GUT scale can be naturally obtained with proper high dimensional operators in SU(5) GUT.**

**Due to the effects of heavy gluino, at the weak scale all colored sparticles are heavy while the uncolored sparticles are light, which can explain the Brookhaven muon $g$-$2$ measurement while satisfying the collider constraints (both the 125 GeV Higgs mass and the direct search limits of sparticles) and dark matter requirements.**

# Split-SUSY is ok, but how to build it ?

## A split SUSY model from SUSY GUT

Wang, Wang, Yang, arXiv:1501.02906

**We propose to split the sparticle spectrum from the hierarchy between the GUT scale and the Planck scale.**

**A split SUSY model, which gives non-universal gaugino masses, is built with proper high dimensional operators in the framework of SO(10) GUT.**

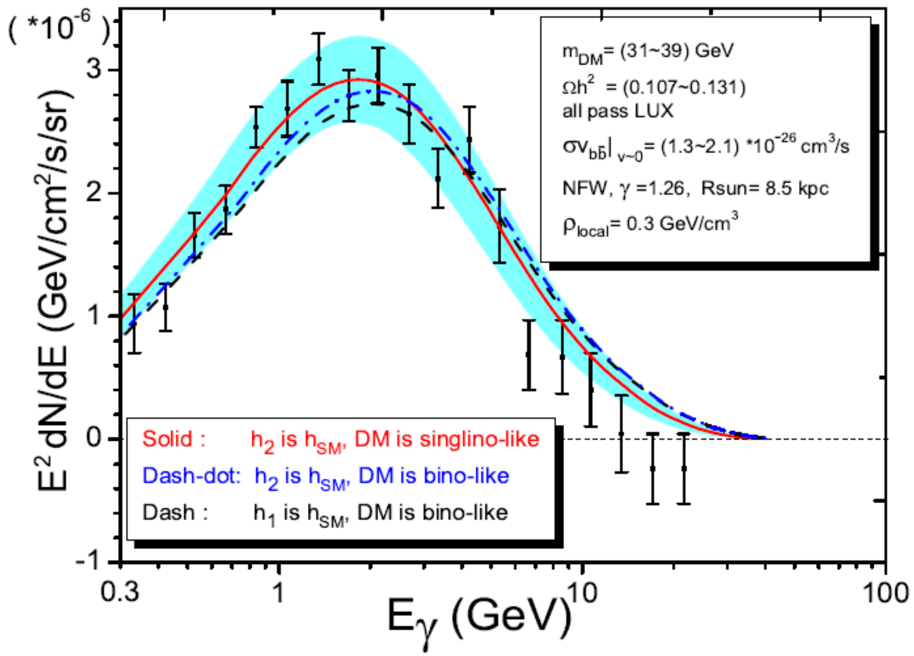
**Based on two-loop beta functions for gauge couplings, we find that our scenario can achieve the gauge coupling unification and satisfy the dark matter constraints (relic density and direct detections).**

# 3 Future Probes of SUSY

## 3.1 Possible hints from LHC Run 1 or Fermi-LAT ?

### (a) Fermi galactic center excess: SUSY explanation

arXiv:1409.8431; 1506.06471 (Cao, Shang, Wu, Yang, Zhang)

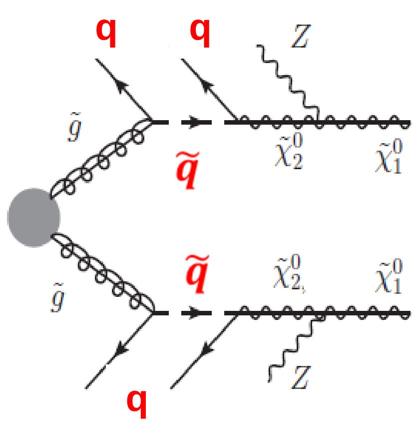


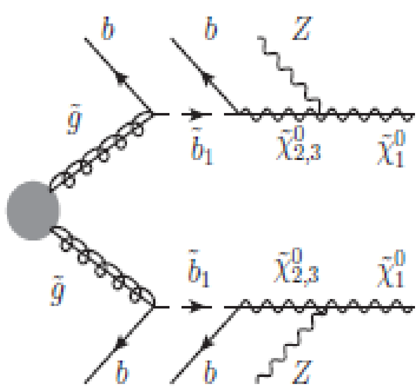
## (b) ATLAS 3$\sigma$ excess in Z+jets+mis-$E_T$: SUSY Explanation

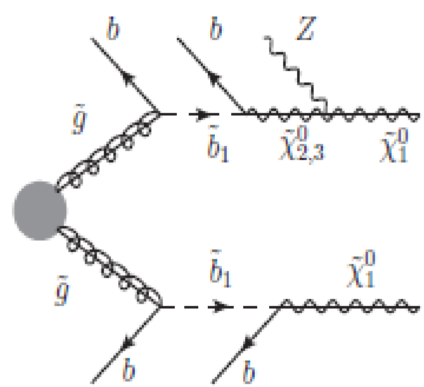
Gluino pair in NMSSM: 1504.07869 (Cao, Shang, Yang, Zhang)

Squark pair in NMSSM: 1507.08471 (Cao, Shang, Yang, Zhang)

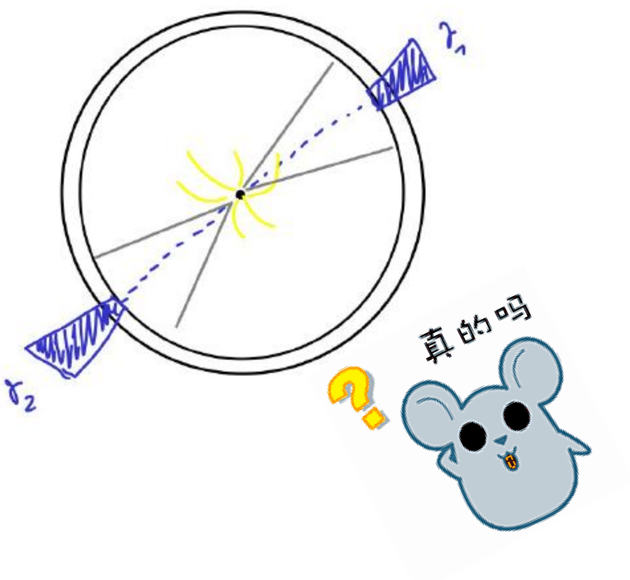
Gluino pair in MSSM: 1504.04390 (Koba, Saav, Wu, Yang)

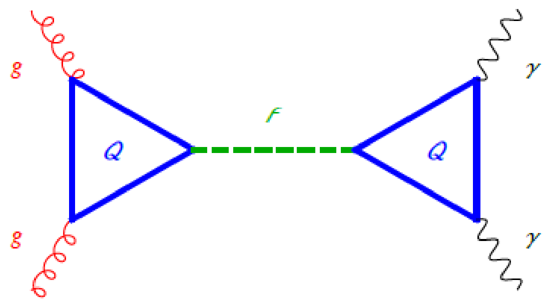


## (c) 750 GeV diphoton resonance: SUSY explanation




- **750 GeV diphoton resonance, 125 GeV Higgs and muon g-2 in deflected AMSB**
  Wang, Wu, Yang, Zhang, 1512.06715

- **Interpreting 750 GeV Diphoton Resonance in NMSSM with Vector-like Particles**
  Wang, Wang, Wu, Yang, Zhang, 1512.08434

**Let's forget these nightmares and look forward !**

**团结一致向前看！**

# 3.2 Probe SUSY at LHC Run-2

- **Through looking for sparticles (like stop, higgsinos)**

  Stop pair: arXiv:1206.3865 (Cao, Han, Wu, Yang, Zhang)

  Mono-stop: arXiv:1505.06006 (Hikasa, Li, Wu, Yang)

  Higgsino pair: arXiv:1206.3865 (Han, Koba, Liu, Saav, Wu, Yang)

  Electroweakino pair: arXiv:1411.6105 ( Liu, Wang, Yang) arXiv:1409.4533 ( Han, Wu, Yang, Zhang)

  Compressed bino/wino: arXiv:1409.4533 (Han, Wu, Yang, Zhang)

- **Through Higgs or rare processes**

  Higgs pair production arXiv:1301.6437 (Cao, Heng, Shang, Wan, Yang) arXiv:1307.3790 (Han, Ji, Wu, Wu, Yang)

  Higgs decay to Z-photon vs diphoton arXiv:1301.4641 (Cao, Wu, Wu, Yang)

  Higgs decay to dark matter arXiv:1311.0678 (Cao, Han, Wu, Yang)

  Higgs decay to pseudo-goldstino arXiv:1301.5479 (Liu, Wang, Yang)

  Top decay t->ch arXiv: 1404.1241 (Cao, Han, Wu, Yang, Zhang)

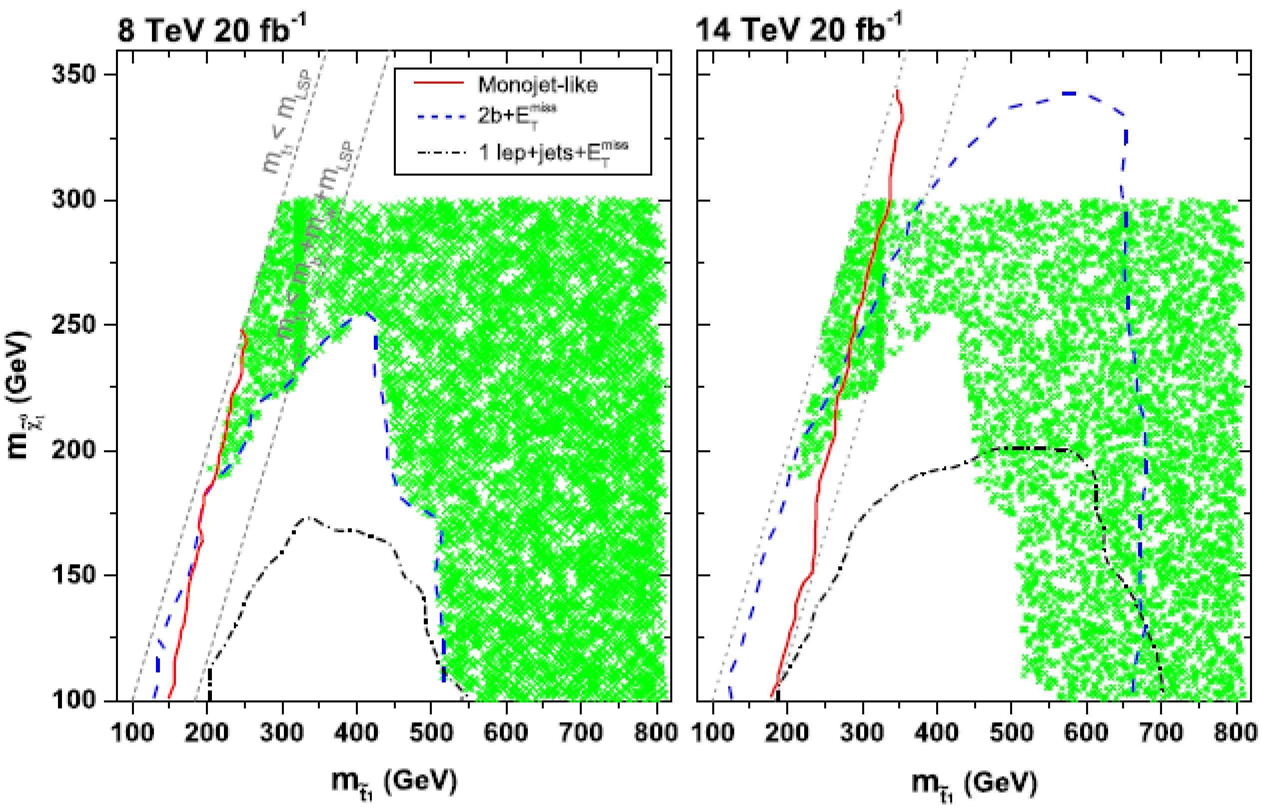
  Through hhh, htt, hVV coupling measurement Wu, Yang, Yuan, Zhang, arXiv:1504.06932

# • Search for stop pair in natural-SUSY

arXiv:1206.3865 (Cao, Han, Wu, Yang, Zhang)

arXiv:1511.02371 (Kobakhidze, Liu, Wu, Yang, Zhang)

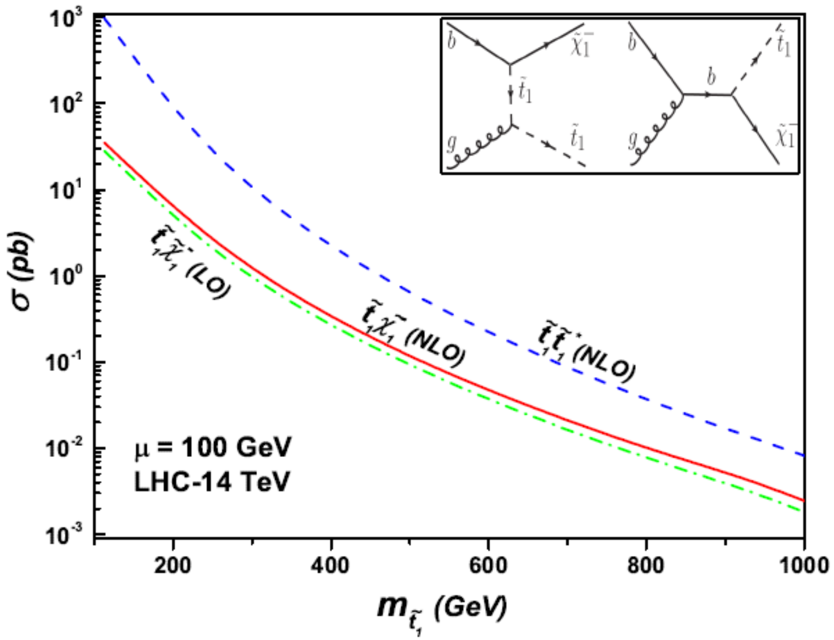
$$pp \to \tilde{t}_1 \tilde{t}_1 \;\; (\tilde{t}_1 \to t \tilde{\chi}^0_{1,2})$$
$$pp \to \tilde{t}_1 \tilde{t}_1 \;\; (\tilde{t}_1 \to b \tilde{\chi}^+_1)$$

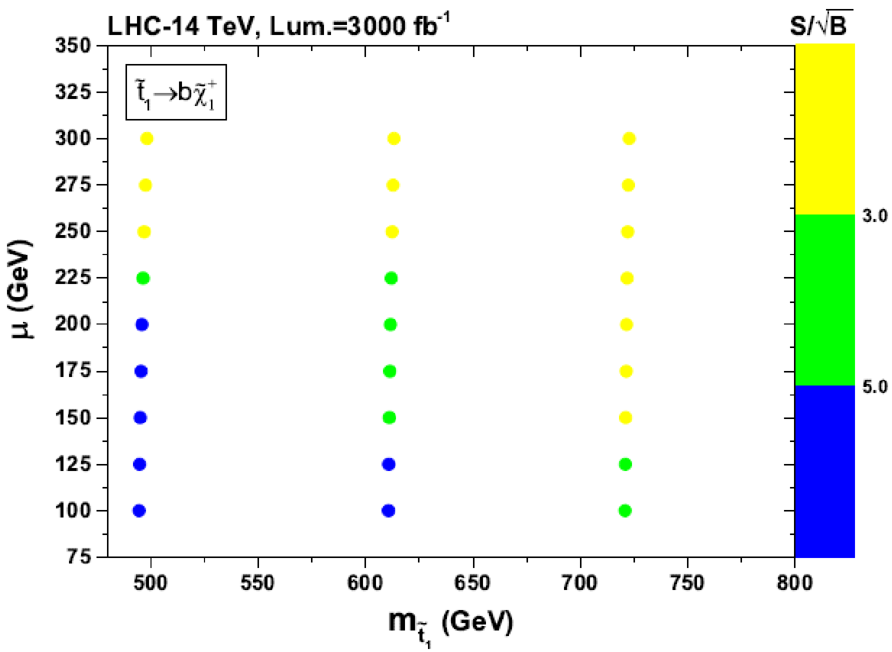



For the monojet search, the region to the left of the curve is its excluded region.

# • Search for single-stop in natural-SUSY

arXiv:1505.06006 (Hikasa, Li, Wu, Yang)



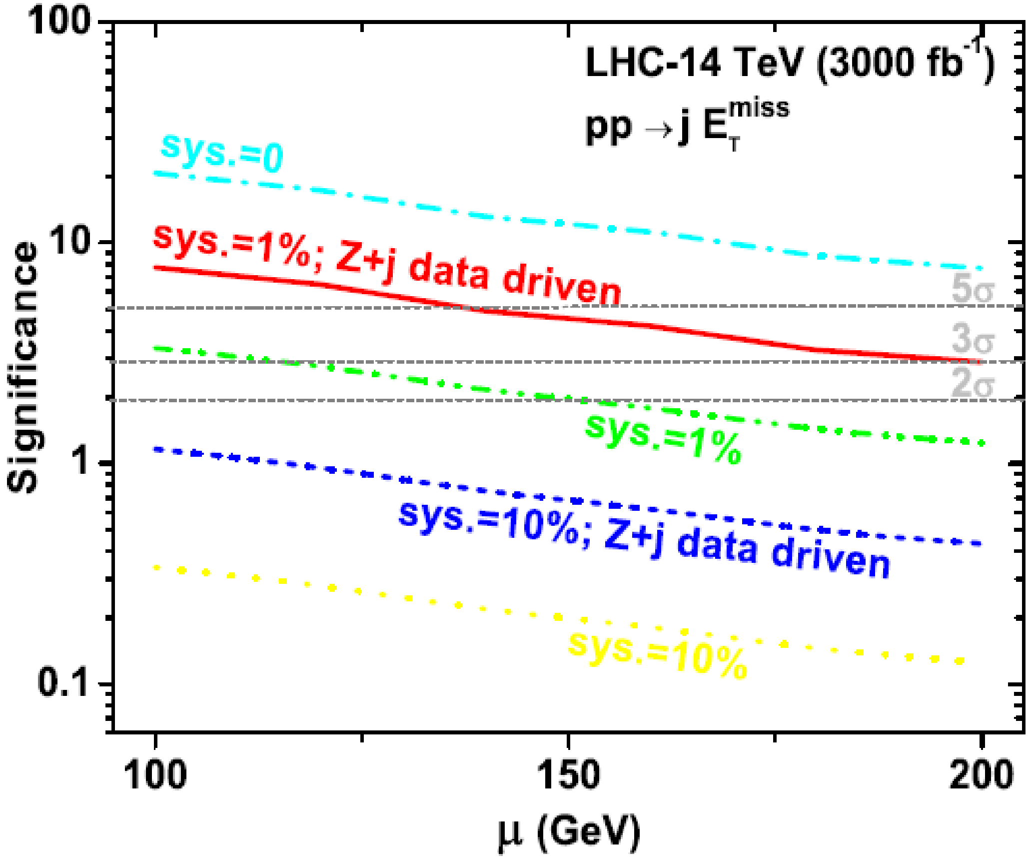




$$pp \to \tilde{t}_1\tilde{\chi}_1^- \to t\tilde{\chi}_{1,2}^0\tilde{\chi}_1^- \to bjj + \not{E}_T$$
$$pp \to \tilde{t}_1\tilde{\chi}_1^- \to b\tilde{\chi}_1^+\tilde{\chi}_1^- \to b + \not{E}_T.$$

- **Higgsino pair production in natural-SUSY**

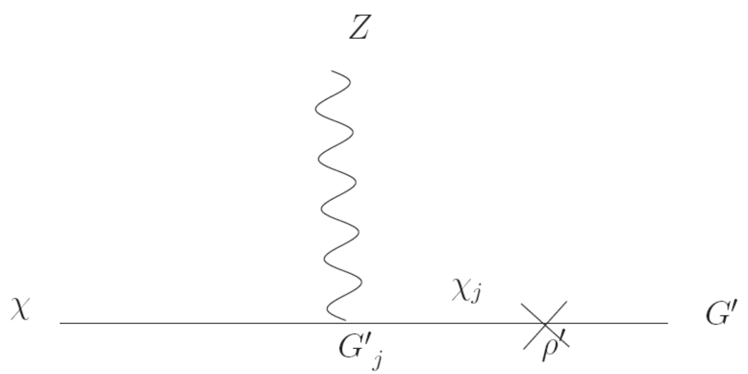
arXiv:1206.3865

Han, Koba, Liu, Saav, Wu, Yang



• **Higgsino pair production in multi-sector SUSY breaking**

arXiv:1403.5731
Hikasa, Liu, Wang, Yang




**pseudo-goldstino**

$$pp \to \chi^0_{1,2}\chi^\pm_1 \to ZG'W^\pm G' \to \ell^+\ell^-\ell^\pm \nu G'G' \to 3\ell + \not{E}_t, \quad (\ell = e, \mu, \tau)$$

| $\sqrt{S} = 14$ TeV | $100 fb^{-1}$ | $500 fb^{-1}$ | $1000\ fb^{-1}$ | $1500\ fb^{-1}$ | $2000\ fb^{-1}$ | $3000\ fb^{-1}$ |
|---|---|---|---|---|---|---|
| $S_{1[basic\ selection]}$ | 160 | 800 | 1600 | 2400 | 3200 | 4800 |
| $S_{2[passing\ all\ cut]}$ | 33 | 165 | 330 | 495 | 660 | 990 |
| $S_1/\sqrt{S_1+B_1}$ | 0.7 | 1.6 | 2.3 | 2.8 | 3.2 | 3.9 |
| $S_2/\sqrt{S_2+B_2}$ | 1.4 | 3.1 | 4.5 | 5.5 | 6.3 | 7.7 |

# • Compressed bino/wino

arXiv:1409.4533 (Han, Wu, Yang, Zhang)

bino (LSP $\tilde{\chi}_1^0$) and winos (NLSP $\tilde{\chi}_2^0$) may have rather small mass splitting in order to provide correct dark matter relic density through bino/wino co-annihilation.

$$pp \to j\tilde{\chi}_2^0\tilde{\chi}_1^\pm \qquad \begin{array}{l} \tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0 \\ \tilde{\chi}_1^\pm \to W^*\tilde{\chi}_1^0 \to \ell^\pm\nu\tilde{\chi}_1^0 \end{array}$$

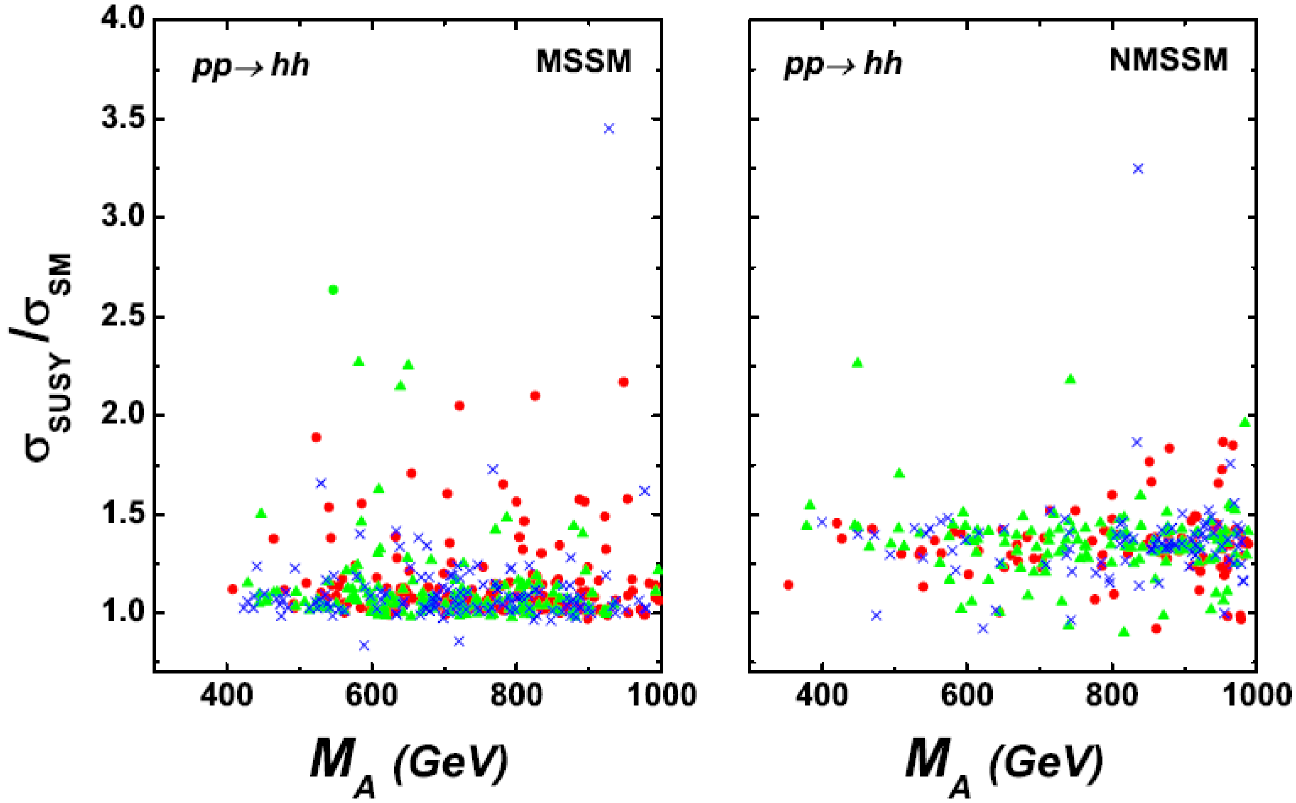
| $(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0})$ in GeV | (130,150) | (135,150) | (140,150) | (145,150) |
|---|---|---|---|---|
| $\mathrm{Br}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\gamma)$ | 0.101 | 0.2266 | 0.495 | 0.834 |

| | $W\gamma j$ (fb) | $Z(\tau\tau)+j$ (fb) | Signal (fb) | S/B | $S/\sqrt{B}$ $(300 fb^{-1})$ | $S/\sqrt{B}$ $(500 fb^{-1})$ |
|---|---|---|---|---|---|---|
| (130,150) | 1.14 | 0.03 | 0.04 | 0.03 | 0.58 | 0.75 |
| (135,150) | 1.14 | 0.03 | 0.10 | 0.09 | 1.66 | 2.15 |
| (140,150) | 1.14 | 0.03 | 0.22 | 0.19 | 3.54 | 4.57 |
| (145,150) | 1.14 | 0.03 | 0.26 | 0.22 | 4.16 | 5.38 |

- **Higgs pair production at LHC-14**

arXiv:1301.6437
Cao, Heng, Shang, Wan, Yang

arXiv:1307.3790
Han, Ji, Wu, Wu, Yang




**enhanced in SUSY but not much**

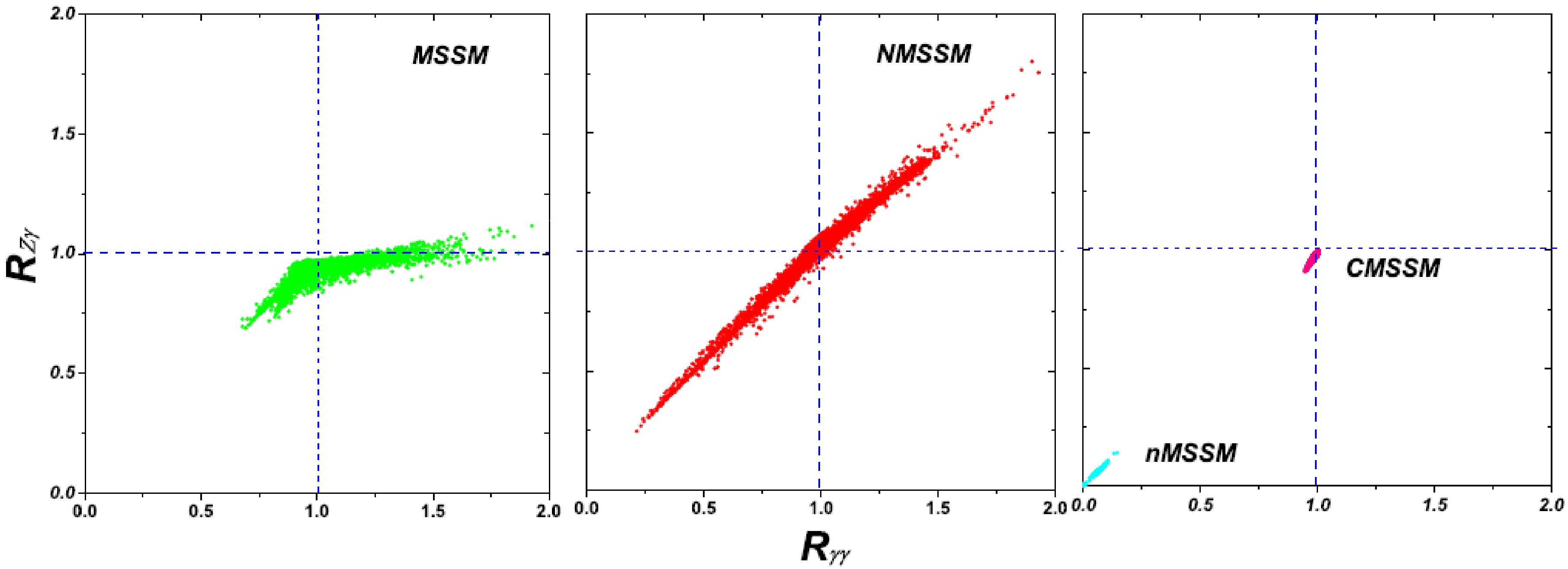
## • Zγ versus γγ at LHC-14

arXiv:1301.4641
Cao, Wu, Wu, Yang

$$R_{Z\gamma} \equiv \frac{\sigma(pp \to h \to Z\gamma)}{\sigma_{\rm SM}(pp \to h \to Z\gamma)}$$

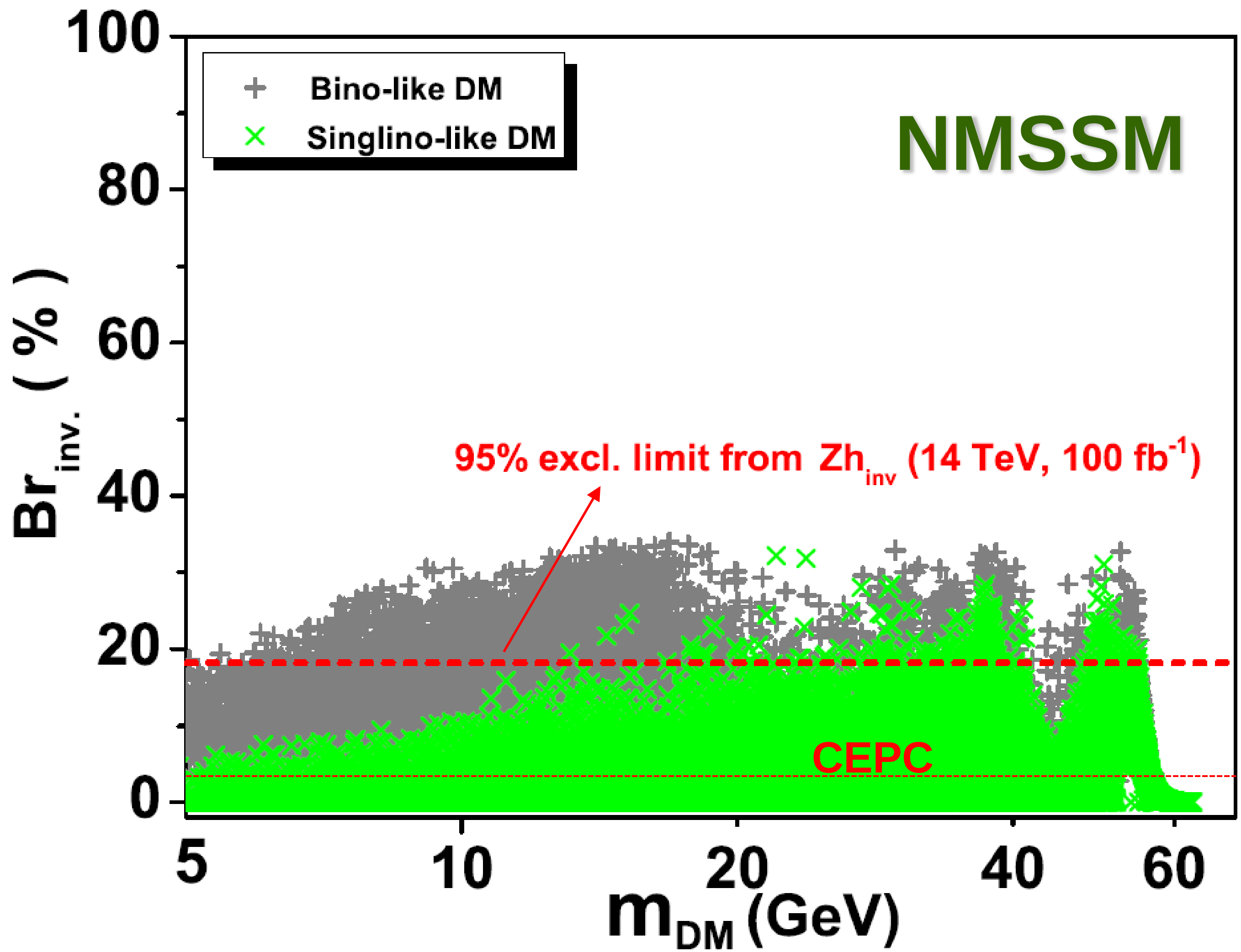
$$R_{\gamma\gamma} \equiv \frac{\sigma(pp \to h \to \gamma\gamma)}{\sigma_{\rm SM}(pp \to h \to \gamma\gamma)}$$

**Such correlation is useful for discriminating models**



• **Higgs decays to dark matter in NMSSM**

arXiv:1311.0678
Cao, Han, Wu, Yang

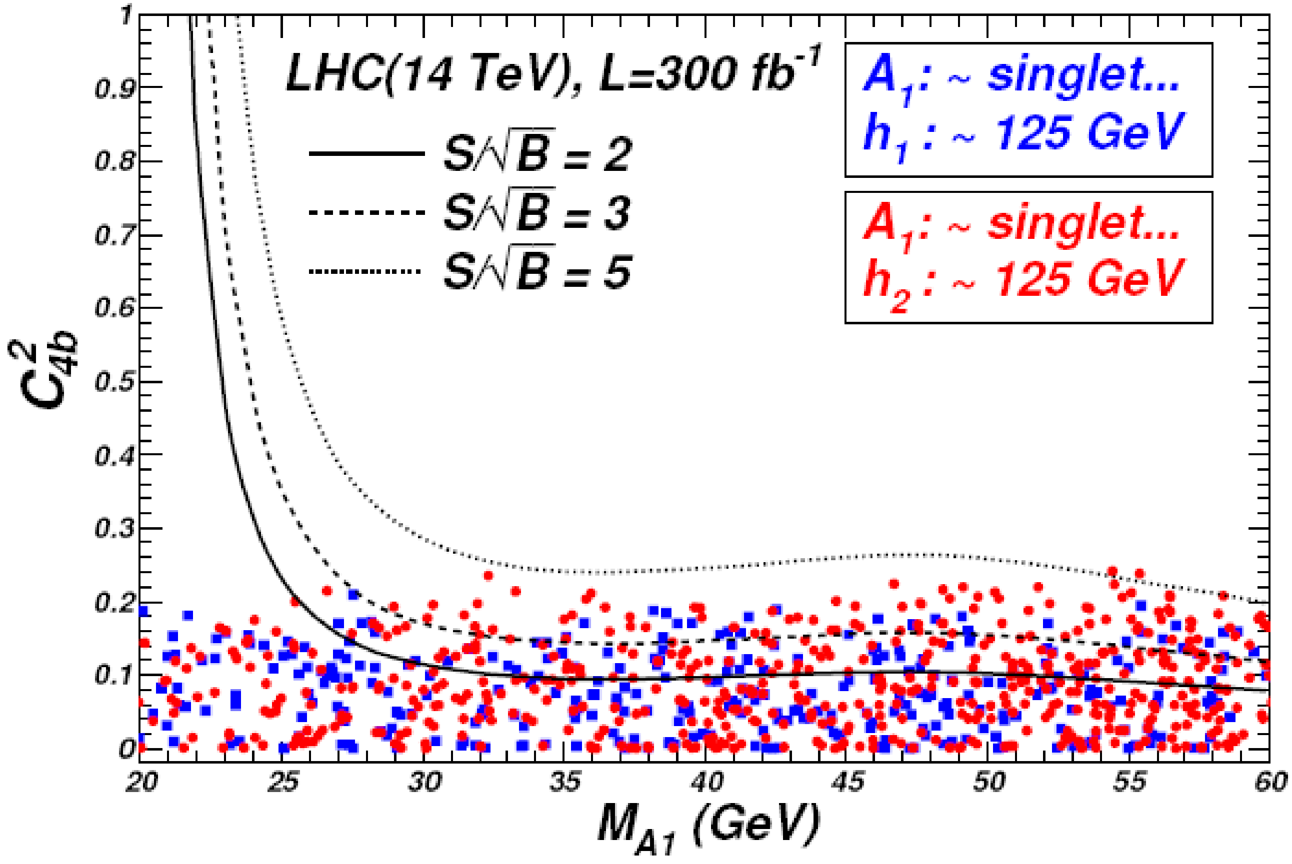



**can have a sizable rate**

- **Higgs decays to singlet-like scalar in NMSSM**

$$h \rightarrow A_1 A_1 \rightarrow 4b$$

arXiv:1309.4939
Cao, Ding,Han, Yang, Zhu




**Need high luminosity**

# • Higgs decays to pseudo-goldstino in multi-sector SUSY breaking

arXiv:1301.5479 (Liu, Wang, Yang)

$$G = \cos\theta\eta_1 + \sin\theta\eta_2, \quad G' = -\sin\theta\eta_1 + \cos\theta\eta_2,$$

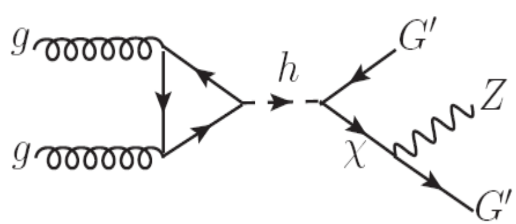
$$\tan\theta = F_2/F_1$$

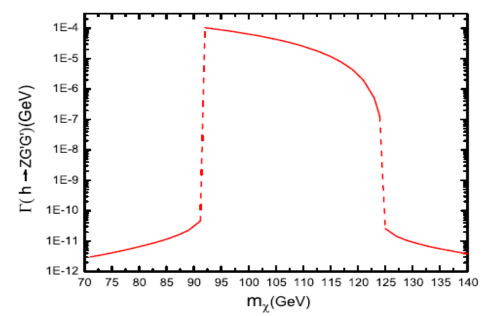
$$F = \sqrt{F_1^2 + F_2^2}$$

$$\mathcal{L}_G = \frac{m_\phi^2}{F} G\psi\phi^* - \frac{im_a}{\sqrt{2}F} G\sigma^{\mu\nu}\lambda^a F_{\mu\nu}^a + \frac{m_a}{F} G\lambda^a D^a,$$

$$\mathcal{L}_{G'} = \frac{\tilde{m}_\phi^2}{F} G'\psi\phi^* - \frac{i\tilde{m}_a}{\sqrt{2}F} G'\sigma^{\mu\nu}\lambda^a F_{\mu\nu}^a + \frac{\tilde{m}_a}{F} G'\lambda^a D^a,$$

$$m_{\phi/a} = m_{\phi/a,1} + m_{\phi/a,2}, \quad \tilde{m}_{\phi/a} = -m_{\phi/a,1}\tan\theta + m_{\phi/a,2}\cot\theta$$



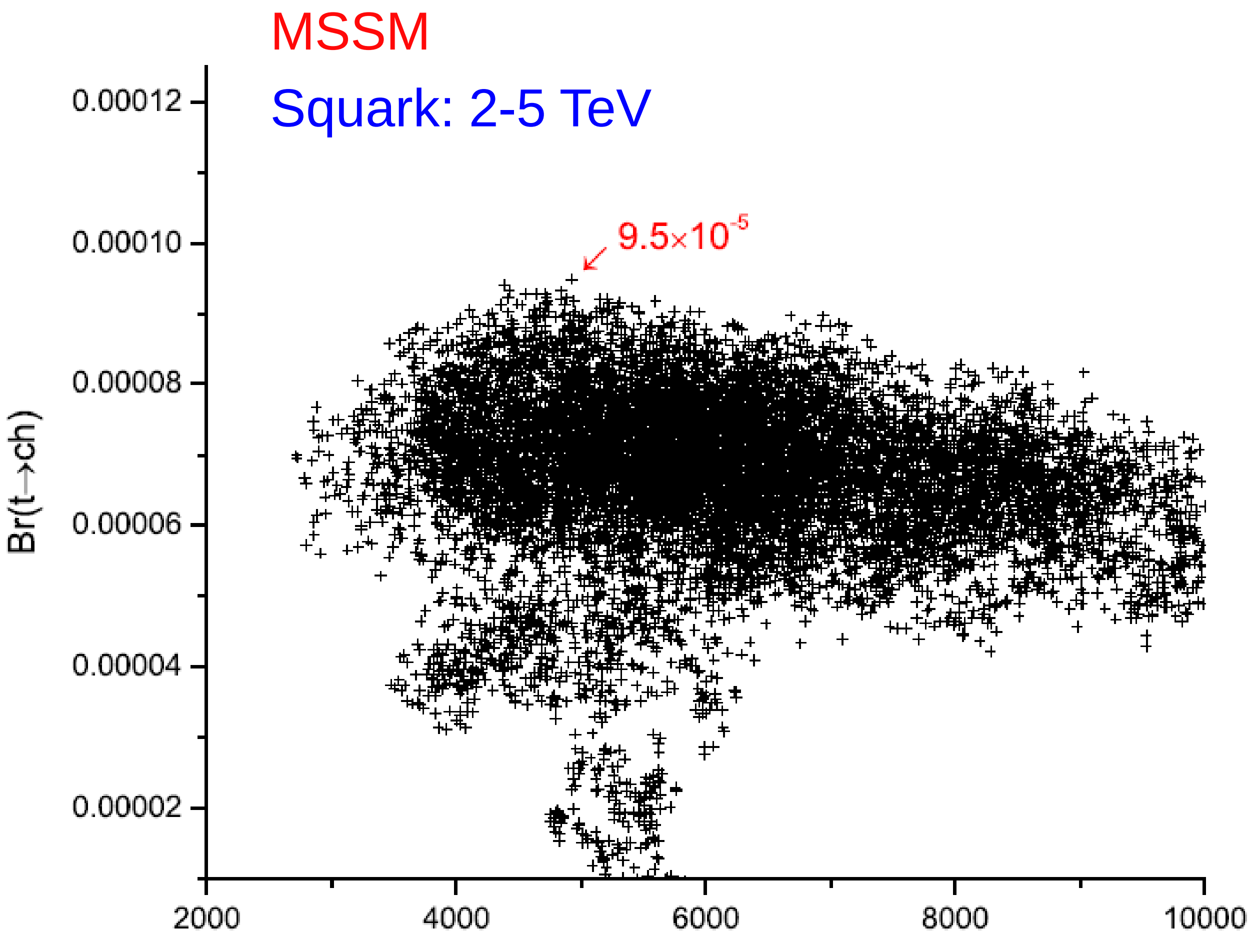




**Need high luminosity**

| $\sqrt{S} = 14$ TeV | $100 fb^{-1}$ | $500 fb^{-1}$ | $800\ fb^{-1}$ | $1000\ fb^{-1}$ | $2000\ fb^{-1}$ | $3000\ fb^{-1}$ |
|---|---|---|---|---|---|---|
| $S_{[selection\ criteria]}$ | 310 | 1550 | 2480 | 3100 | 6200 | 9300 |
| $S_{[passing\ all\ cut]}$ | 250 | 1250 | 2000 | 2500 | 5000 | 7500 |
| $S/\sqrt{S+B}$ | 1.3 | 2.8 | 3.5 | 4.0 | 5.6 | 6.8 |

• **SUSY effects in top decay**

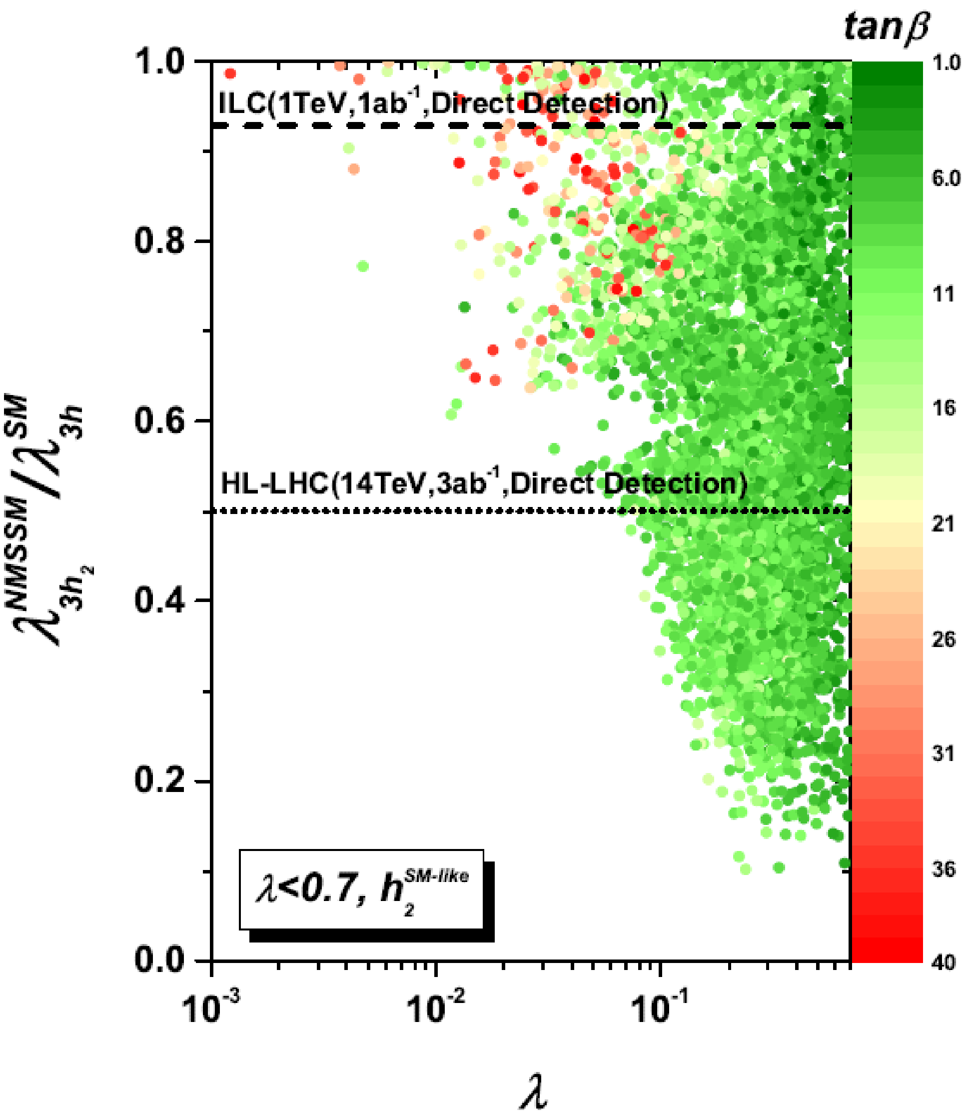
Cao, Han, Wu, Yang, Zhang
arXiv:1404.1241



- $hhh$ **coupling in NMSSM**

**(measure at HL-LHC)**

Wu, Yang, Yuan, Zhang, arXiv:1504.06932

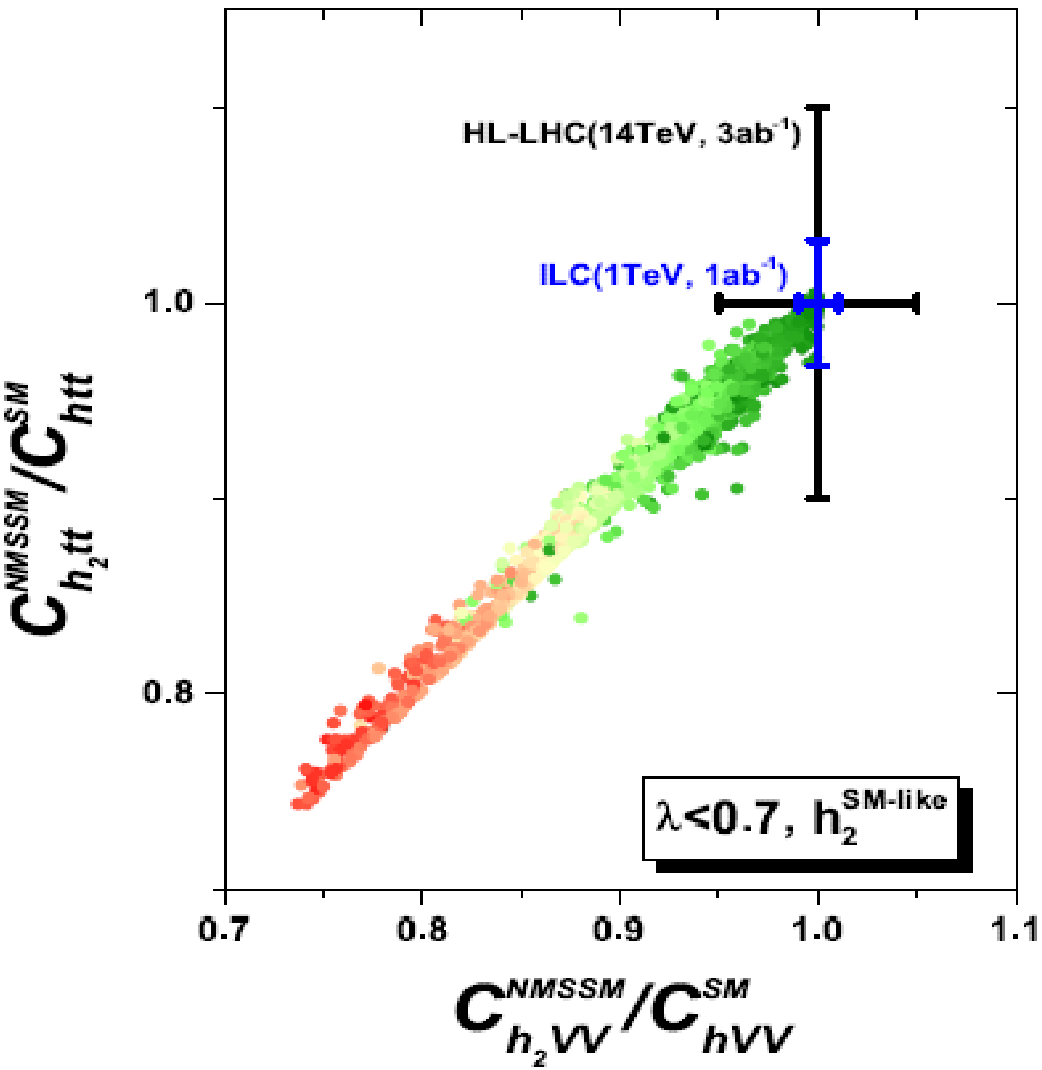



**Can be much suppressed !**

Wu, Yang, Yuan, Zhang, arXiv:1504.06932

- **$htt, hVV$ couplings in NMSSM**

**(measure at HL-LHC)**

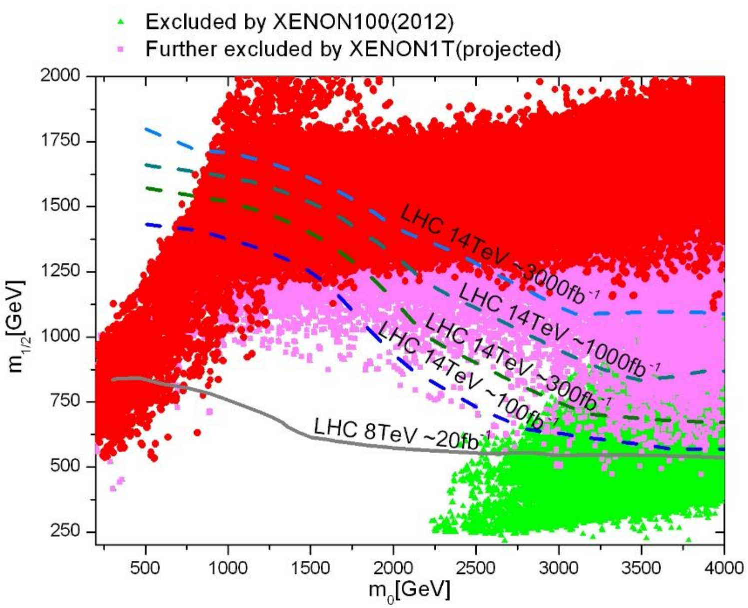


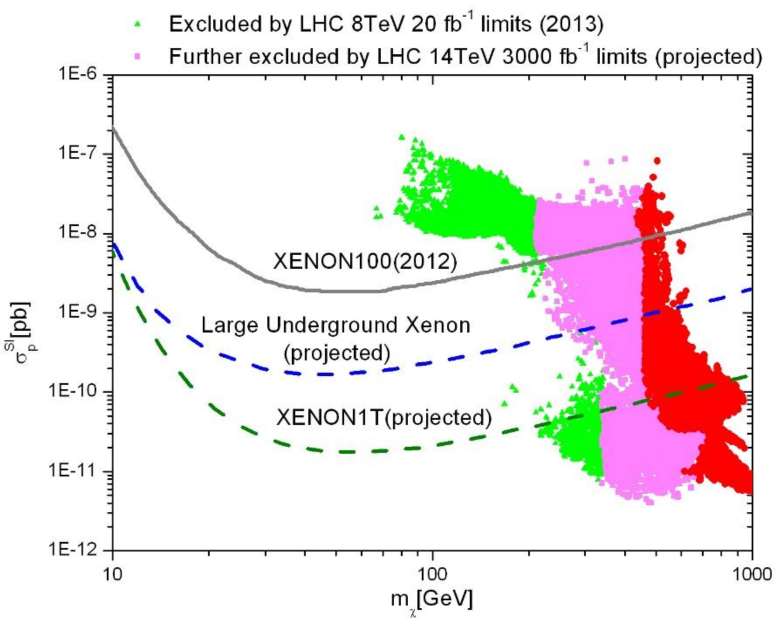

**Can be much suppressed !**

# 3.3 Probe SUSY via dark matter detection

## CMSSM/mSUGRA

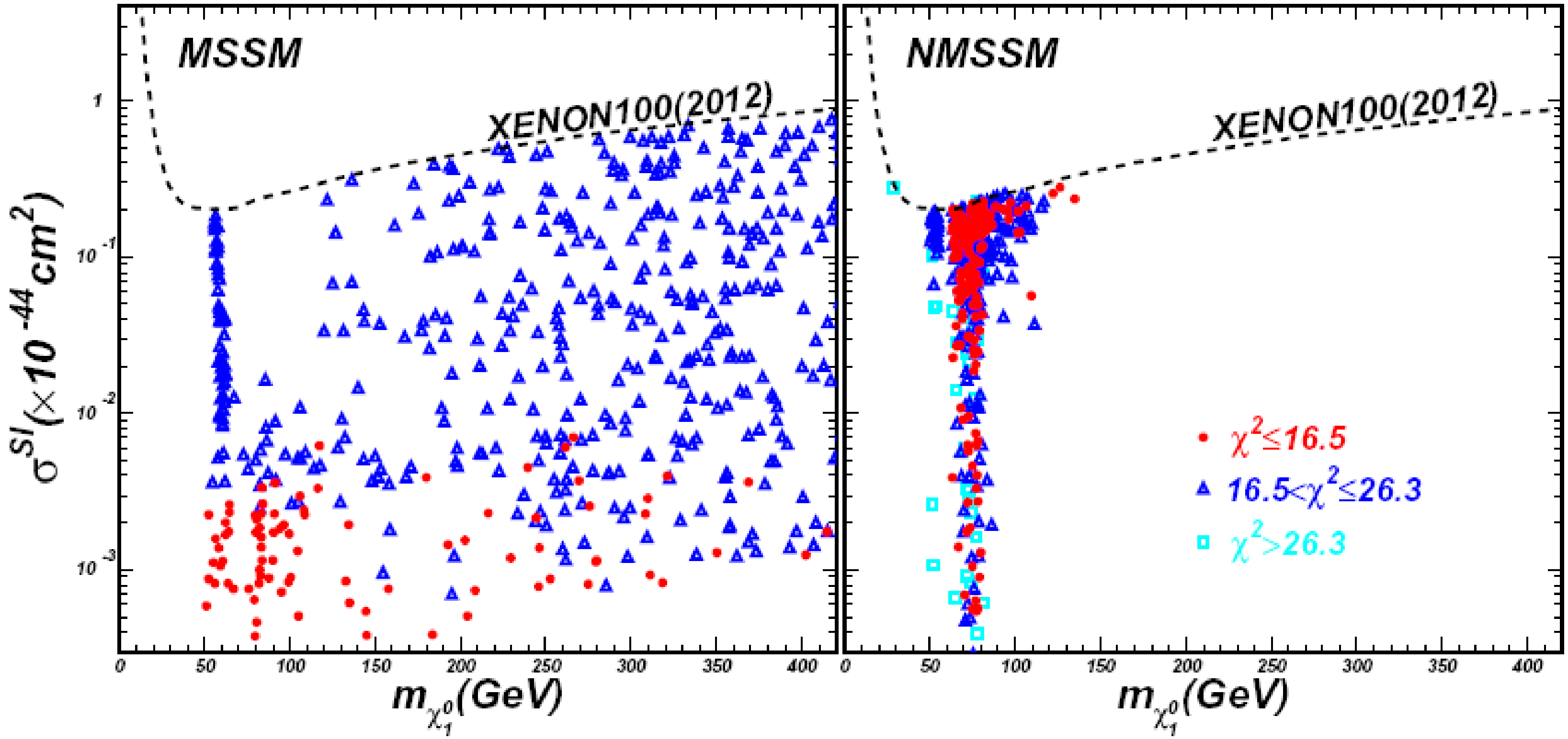
Han, Wu, Yang, Zhang, in progress



# MSSM, NMSSM

arXiv: 1207.3698
Cao, Heng, Yang, Zhu

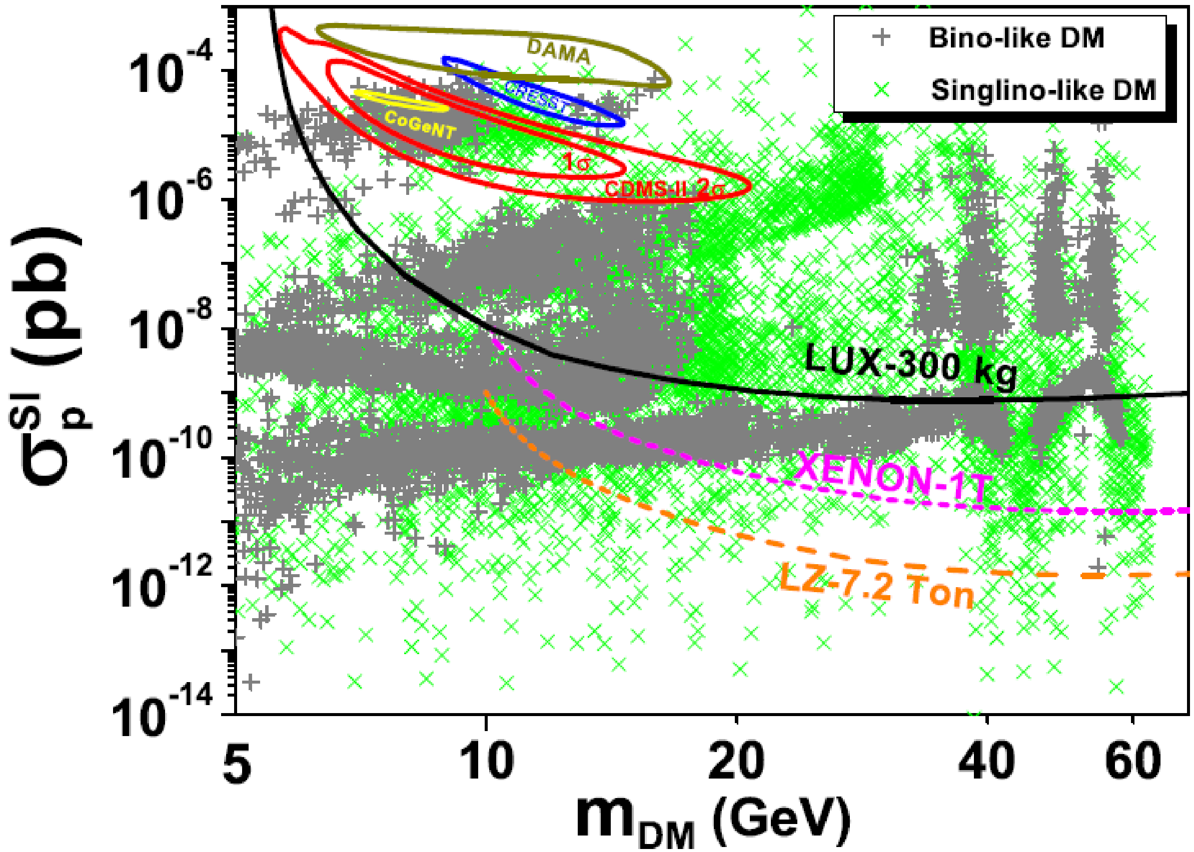



**A large part of parameter space has been excluded**

arXiv:1104.1754
Cao, Hikasa, Wang, Yang

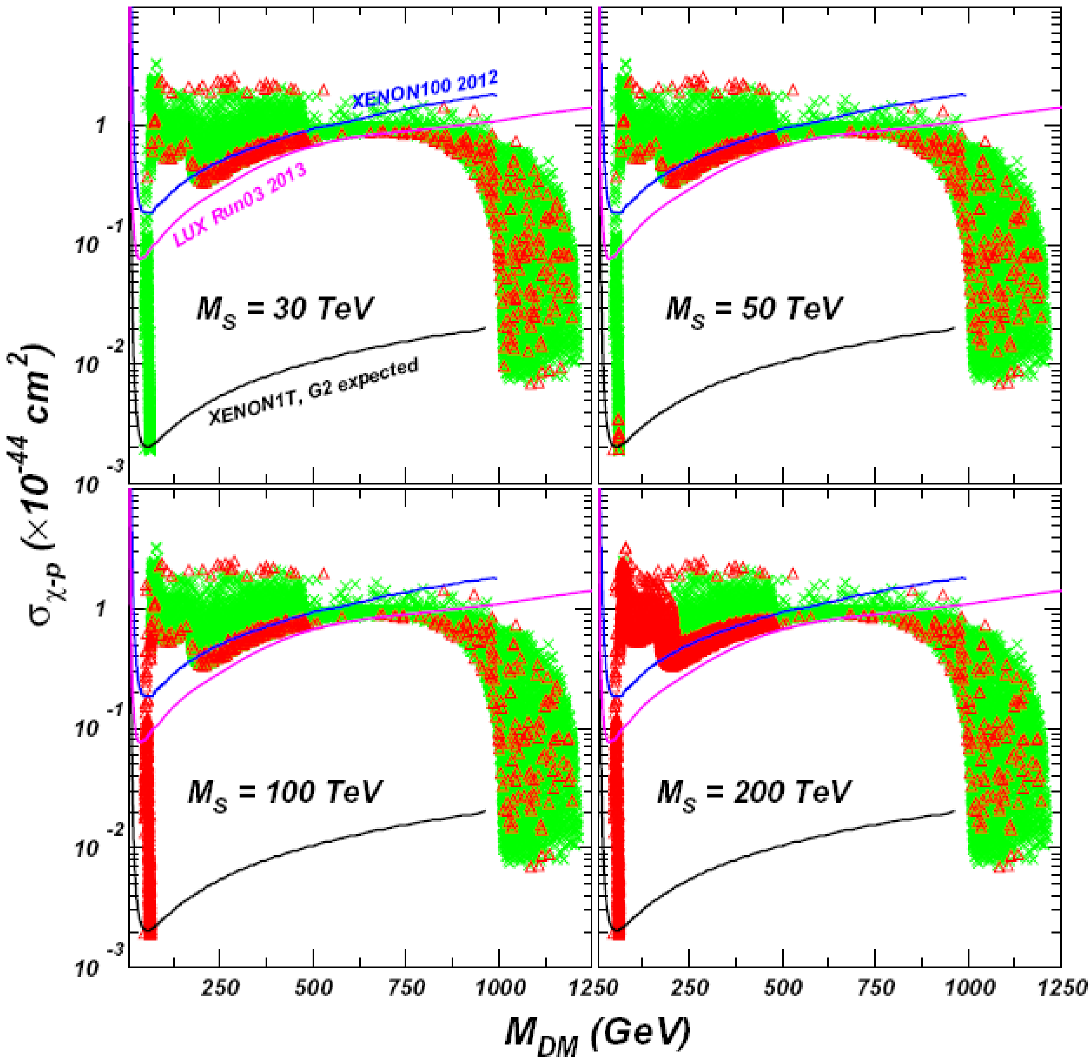
# NMSSM (light dark matter)

arXiv:1311.0678
Cao, Han, Wu, Yang



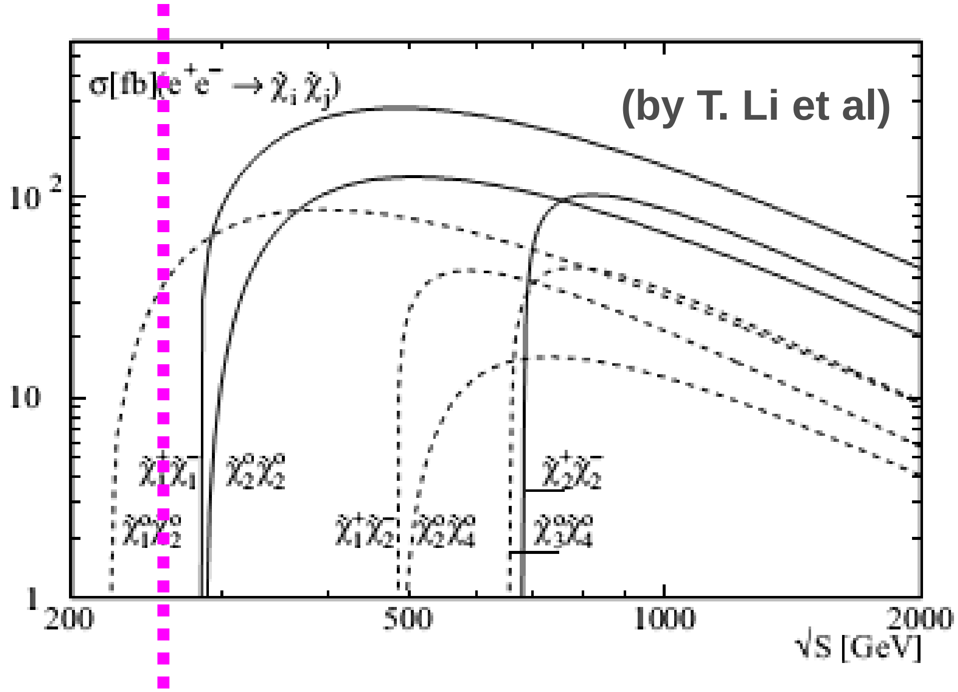
# Split-SUSY

arXiv:1310.1750
Wang, Wang, Yang



# 3.4 Probe SUSY at Higgs factory (CEPC)

**Direct production of sparticles: limited**



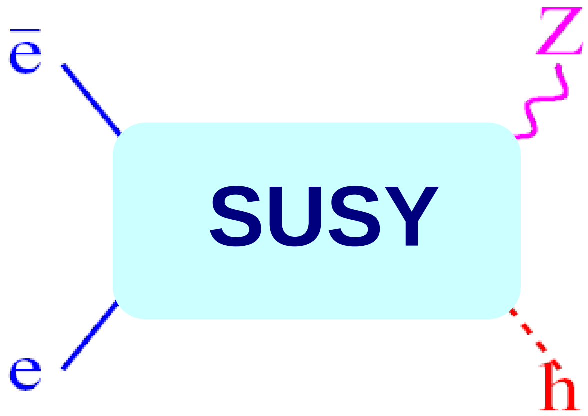

**For an e⁺e⁻ Higgs factory (250 GeV ) :**

**Direct search of SUSY is limited**

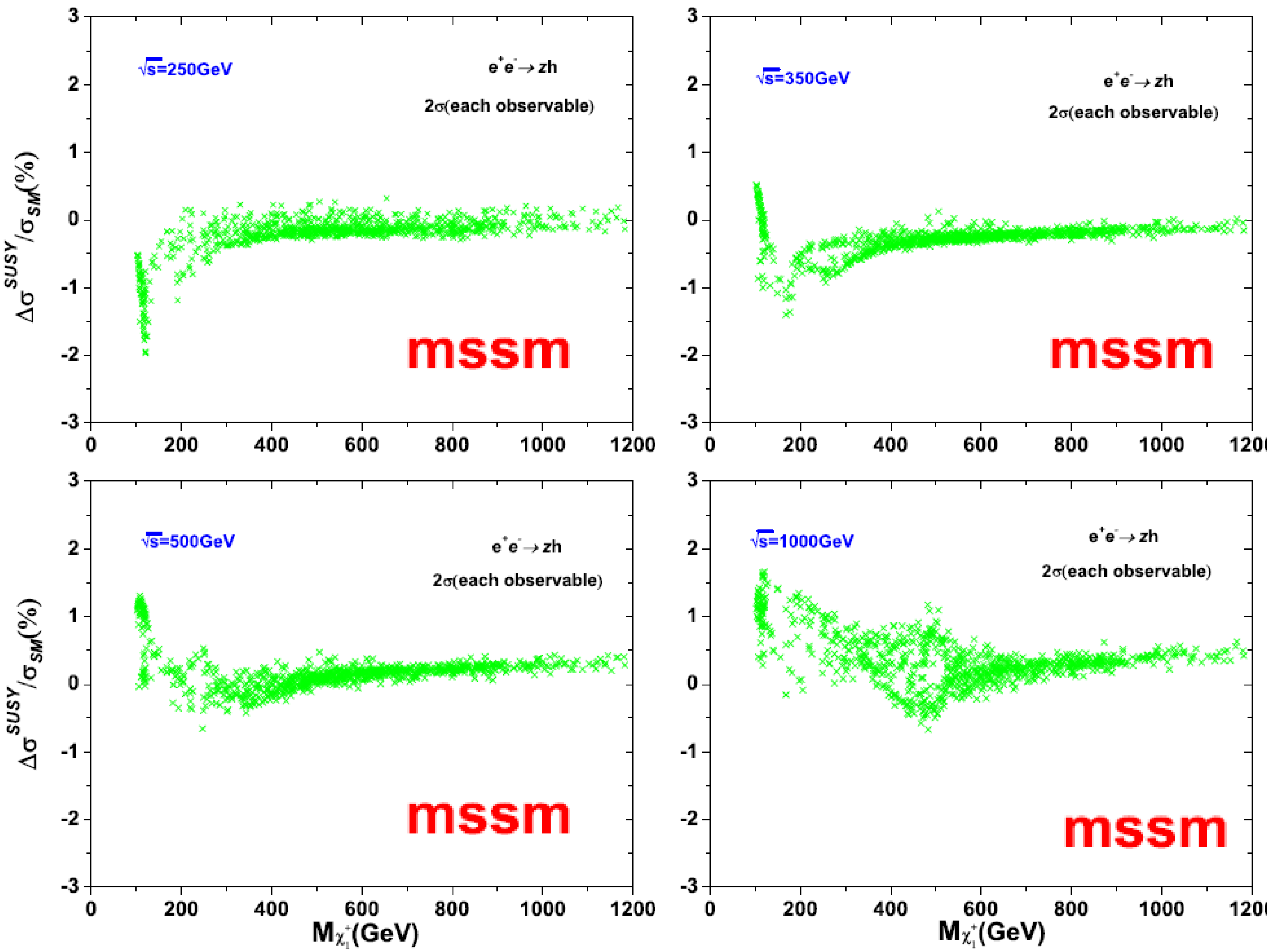
**We may look for quantum effects of SUSY**

## Higgs production at CEPC (250 GeV )

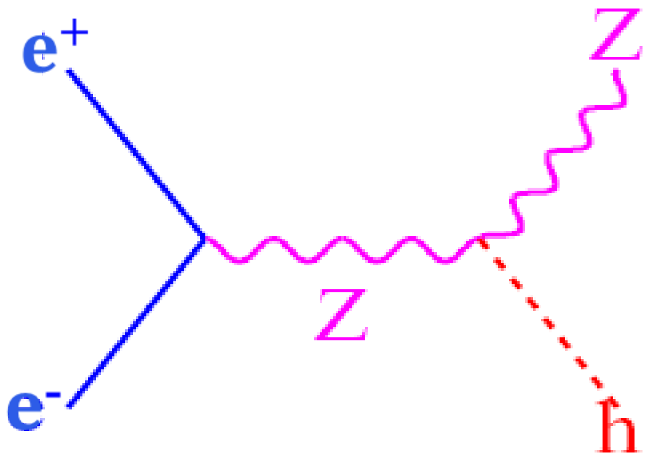
Cao, Han, Wu, Yang, Zhang,
arXiv: 1410.1018



## $\sigma(e^+e^- \to Zh)$ can differ from SM by 1-2%

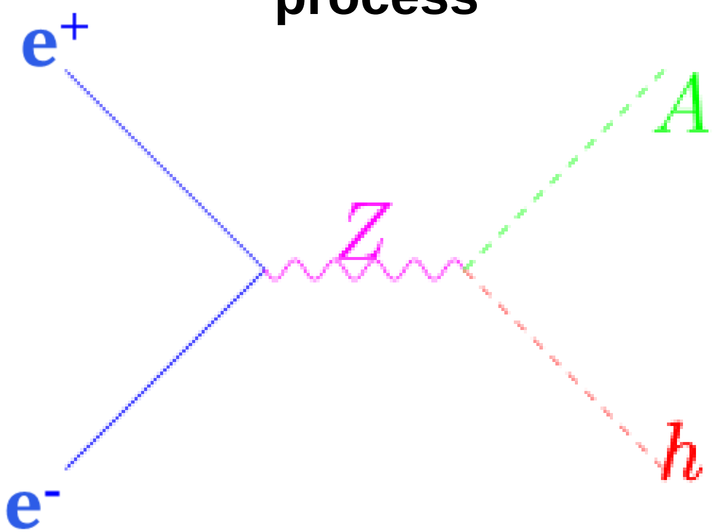


# In MSSM




$\sim \sin^2(\beta - \alpha)$

complementary process



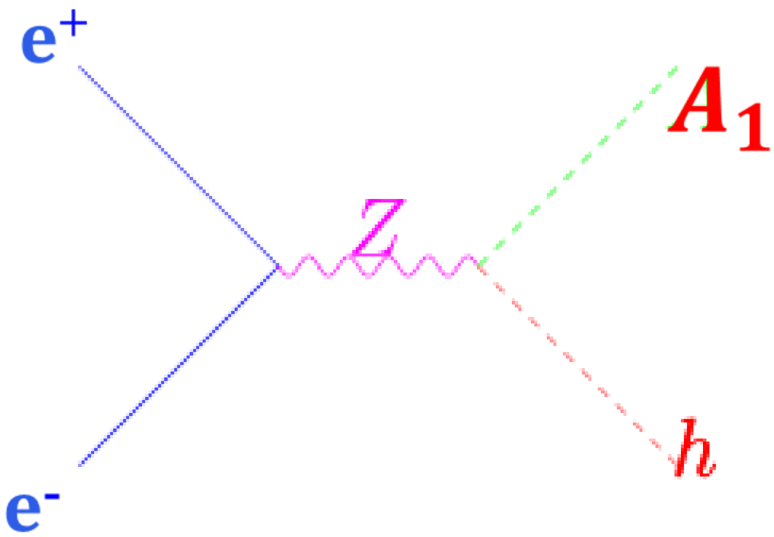

$\sim \cos^2(\beta - \alpha)$

However, $e^+e^- \to hA$ cannot occur at 250 GeV CEPC

**$A$ is too heavy**

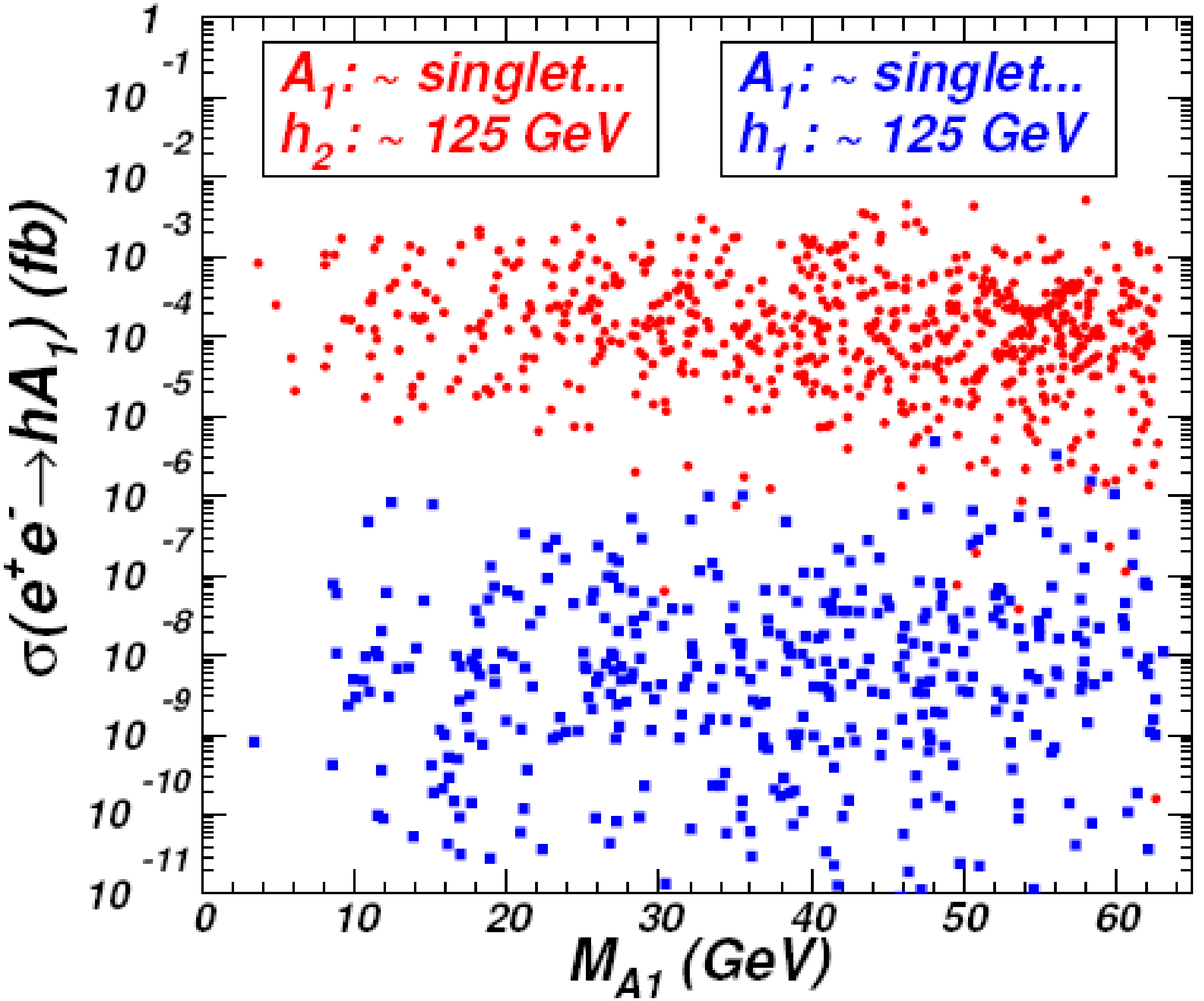
# In NMSSM

## $A_1$ can be much lighter than $h$



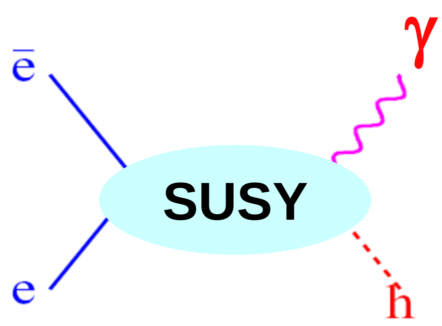

So, $e^+e^- \to hA_1$ can occur at 250 GeV CEPC

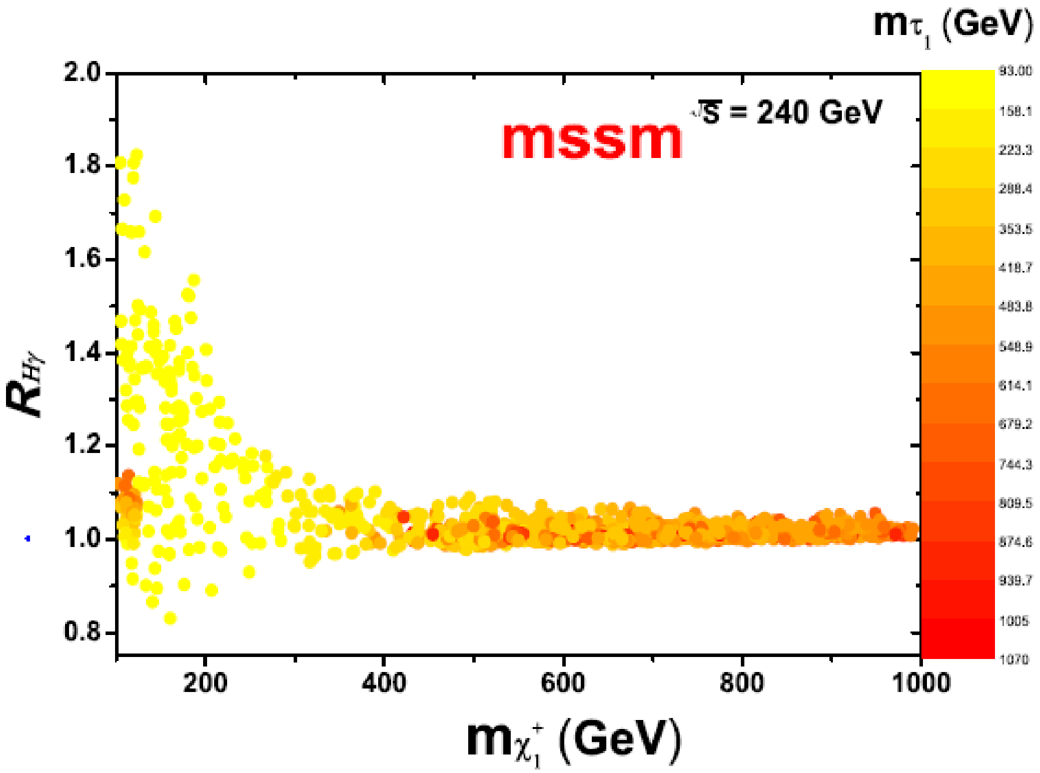
$e^+e^- \to hA_1$ at 250 GeV CEPC




**rate is small**

arXiv:1402.3050
Hu, Liu, Ren, Wu

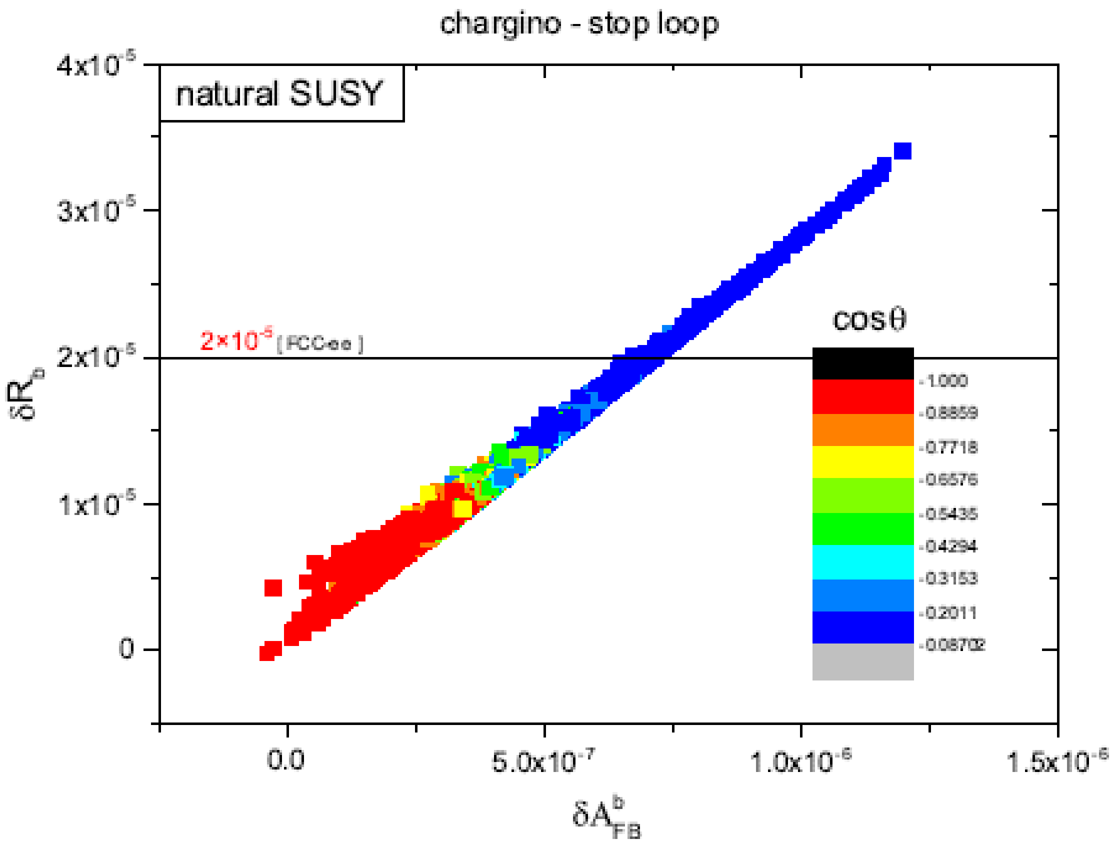



**rate is enhanced in SUSY**

- **SUSY effects in $R_b$**

Su, Yang
arXiv:1601.07758




**CEPC or FCC can be a super $Z$-factory**

# 3.5 Probe SUSY at SPPC (100 TeV)

夢想

**Roughly, can push gluino and squarks to 10 TeV**

T. Cohen et al, arXiv:1406.4512; 1310.0077; 1311.6480

M. Low, L.T. Wang, arXiv:1404.0682

N. Arkani-Hamed, T. Han, M. Mangano, L. T. Wang, arXiv:1511.06495

# 4 Conclusion

## Confronted with LHC data:

- Some SUSY models are healthy
- Some SUSY models need repairing

**Probe SUSY at LHC Run 2**

**Probe SUSY at Higgs factory**

**Probe SUSY at 100 TeV pp collider**


$\tilde{q}$
$\tilde{g}$
$\tilde{t}$
$\tilde{\chi}$
Fishing in SUSY sea

Thanks for your attention !