Status of low energy supersymmetry after the LHC-8TeV data

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arXiv: 1207.3698; 1203.0694; 1202.5821; 1112.4391; · · · · ·

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Outline

1 Introduction to low energy SUSY

2 LHC data and implications on SUSY

3 Conclusion and outlook

1 Introduction to low energy SUSY

--- Warm up SUSY

- **What is SUSY**
- **Models of SUSY**

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SUPERSYMMETRY -

EXTENSION OF SPECIAL RELATIVITY TO INCLUDE FERMIONIC SYMMETRIES

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

"supercharges"

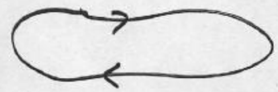
plus sign for fermionic symmetry!

DIRAC MATRIX

momentum

(26)

IN 1969-70 RAMOND (EXTENDED BY NEVEU & SCHWARZ) INTRODUCED A STRING THAT COULD BE A FERMION AS WELL AS A BOSON



GAMMA MATRICES TRAVELING UP AND DOWN THE STRING!

AND THIS LED TO THE CONCEPT OF SUPERSYMMETRY (WESS & ZUMINO 1974)

ALSO GOLFAND-LIKHTMAN 1971

(29)

SO SUPERSYMMETRY IS FASCINATING ... BUT IS IT RIGHT? DOES IT PLAY A ROLE IN NATURE? THERE ARE MANY HINTS IT DOES ... I'LL MENTION THREE

(1) COUPLING UNIFICATION

THE MEASURED VALUES OF THE STRONG, WEAK, AND ELECTROMAGNETIC COUPLINGS ARE IN EXCELLENT AGREEMENT

(34)

IF THESE CLUES HAVE BEEN CORRECTLY INTERPRETED, WHERE WILL SUPERSYMMETRY BE DISCOVERED?

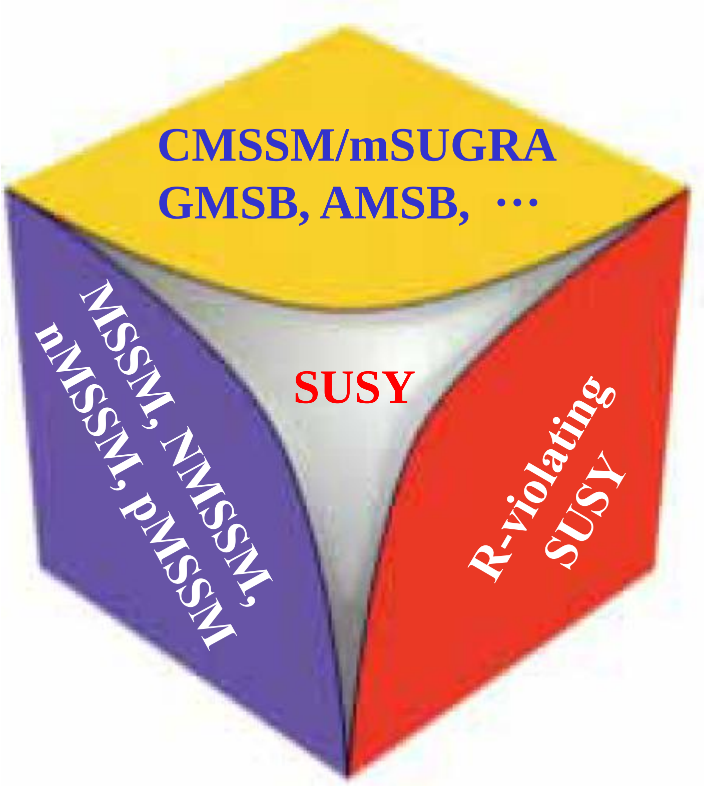
MAYBE AT RUN 2 AT FERMILAB

OTHERWISE AT THE LHC AT CERN, STARTING IN 2007

Witten: *超对称应该在Tevatron和LHC发现元芳，你怎么看？*

Yuanfang： *大人，这背后定有蹊跷 ....*

SUSY models on market:



NMSSM :

$$W = \lambda\varepsilon_{ij}\hat{H}_u^i\hat{H}_d^j\hat{S} + \frac{1}{3}\kappa\hat{S}^3 + \underline{Y_u\varepsilon_{ij}\hat{Q}^i\hat{U}\hat{H}_u^j - Y_d\varepsilon_{ij}\hat{Q}^i\hat{D}\hat{H}_d^j - Y_e\varepsilon_{ij}\hat{L}^i\hat{E}\hat{H}_d^j}$$

$U(1)_{B}$: Q(1/3), U(-1/3), D(-1/3), L(0), E(0), H_u(0), H_d(0), S(0)

$U(1)_{L}$: Q(0), U(0), D(0), L(1), E(-1), H_u(0), H_d(0), S(0)

$U(1)_{R}$: Q(1), U(1), D(1), L(1), E(1), H_u(1), H_d(1), S(1), W(3)

$\kappa \to 0$

$U(1)_{PQ}$: Q(-1), U(0), D(0), L(-1), E(0), H_u(1), H_d(1), S(-2)

Scalar Potential:

$$V_F = |\lambda H_u \cdot H_d + \kappa S^2|^2 + |\lambda S|^2\left(|H_d|^2 + |H_u|^2\right)$$

$$V_D = \frac{g_2^2}{2}\left(|H_d|^2|H_u|^2 - |H_u \cdot H_d|^2\right) + \frac{G^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2$$

$$V_{\rm soft} = m_d^2|H_d|^2 + m_u^2|H_u|^2 + m_s^2|S|^2 + \left(\underline{A_\lambda \lambda S H_u \cdot H_d + \frac{\kappa}{3}A_\kappa S^3} + h.c.\right)$$

$U(1)_R \to Z_3$ (non-R)

$U(1)_R$ ($A_\kappa \to 0$, $A_\lambda \to 0$): PGB

nMSSM:

$$W = \lambda\varepsilon_{ij}\hat{H}_u^i\hat{H}_d^j\hat{S} + \underline{Y_u\varepsilon_{ij}\hat{Q}^i\hat{U}\hat{H}_u^j - Y_d\varepsilon_{ij}\hat{Q}^i\hat{D}\hat{H}_d^j - Y_e\varepsilon_{ij}\hat{L}^i\hat{E}\hat{H}_d^j} + \xi_F M_n^2\hat{S}$$

$U(1)_{B:}$ Q(1/3), U(-1/3), D(-1/3), L(0), E(0), $H_u(0)$, $H_d(0)$, S(0)

$U(1)_{L:}$ Q(0), U(0), D(0), L(1), E(-1), $H_u(0)$, $H_d(0)$, S(0)

$U(1)_{R:}$ Q(1), U(1), D(1), L(1), E(1), $H_u(0)$, $H_d(0)$, S(2), W(2)

$\xi_F M_n^2\hat{S}$ **$\rightarrow$ 0**

$U(1)_{PQ}$: Q(-1), U(0), D(0), L(-1), E(0), $H_u(1)$, $H_d(1)$, S(-2)

$$V_{\text{soft}} = V_{MSSM} + \tilde{m}_d^2|H_d|^2 + \tilde{m}_u^2|H_u|^2 + \tilde{m}_S^2|S|^2$$
$$+(\underline{\lambda A_\lambda\varepsilon_{ij}H_u^iH_d^jS + \xi_S M_n^3 S + \text{h.c.})}$$

$U(1)_R \rightarrow Z_2$ matter parity

NMSSM motivated from top-down view

E6 models (superstring-inspired)

$\downarrow$ string scale

$SO(10) \times U(1) \times \cdots$

$\downarrow$

at low energy: S, H_u, H_d + heavy particles

U(1) global PQ

to explicitly break U(1) PQ: cubic term $\frac{\kappa}{3}\hat{S}^3$

2 LHC data and implication on SUSY

(7TeV, 5/fb; 8TeV, 5/fb)

new results (8 TeV 12-13/fb) will be released at

Hadron Collider Physics Symposium 2012 (HCP2012)
Nov 12 - 16, 2012
Kyoto, Japan

- **Sparticle search results and implications**
- **Higgs search results and implications**

2.1 Sparticle search results at LHC

------ null results

- **First two generations of squarks > 1 TeV**

- **If only 3rd generation sfermions are light, then**

  gluino > 600~800 GeV

  3rd generation squarks > 200~300 GeV

Any implication from sparticle search results ?

First two generations of squarks are heavy (> TeV)

The 3rd generation squarks may still be light

Low energy SUSY ($M_{SUSY} \lesssim$ TeV) seems not true

→ Effective SUSY

(Natural SUSY)

2.2 Higgs boson search results and implication

- LHC: 5-sigma at 125 GeV ($h \to \gamma\gamma$, ZZ^*, WW^*)

  (di-photon signal rate is above SM prediction)

- Tevatron: 2.5-sigma in 115-135 GeV ($h \to b\bar{b}$)

If a light fundamental Higgs boson exists,

then theoretically (naturalness, hierarchy problem):

- **SM is not a natural, comfortable place for Higgs**
- **SUSY is a paradise for Higgs**

  ---a peaceful, harmonious place for Higgs

SUSY:

M_h < 135 GeV in MSSM

M_h < 150 GeV in any low energy SUSY model

125 GeV Higgs: support SUSY !

However,

125 GeV Higgs is not so comfortable for minimal SUSY

It needs loop effects (mainly from stops)

→ heavy stops

little fine-tuning

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

$$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

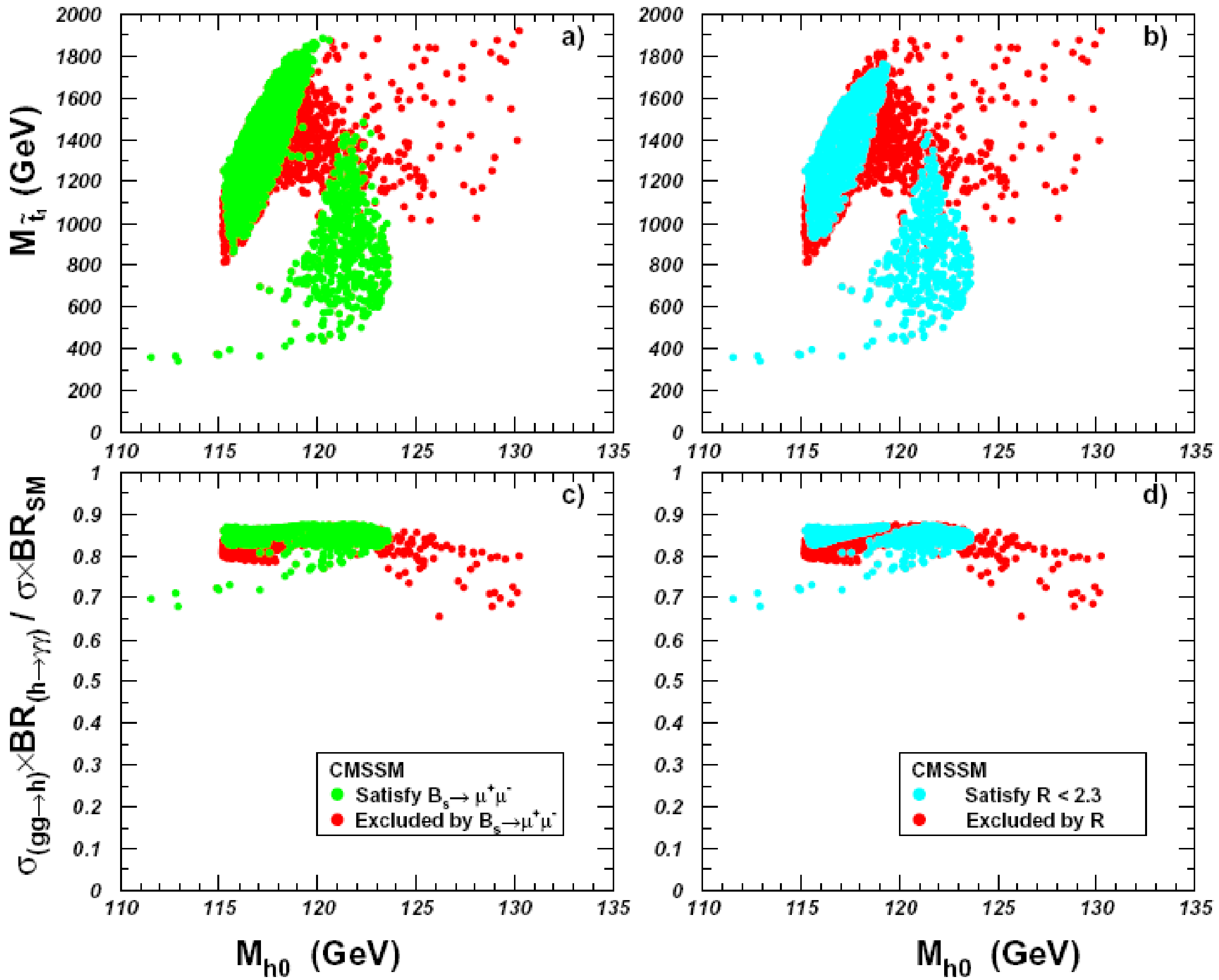
$$X_t \equiv A_t - \mu \cot\beta$$

Let's check Higgs mass and property in some SUSY Models:

- **CMSSM/mSUGRA, GMSB, AMSB,…**
- **MSSM, NMSSM, nMSSM, …**

First, look at the SM-like Higgs boson mass

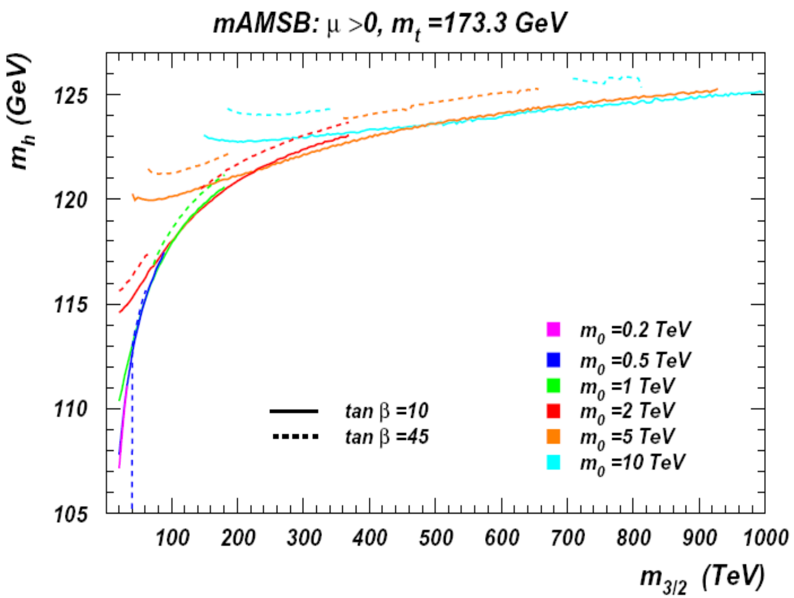
Higgs mass in CMSSM/mSUGRA (≤125 GeV)

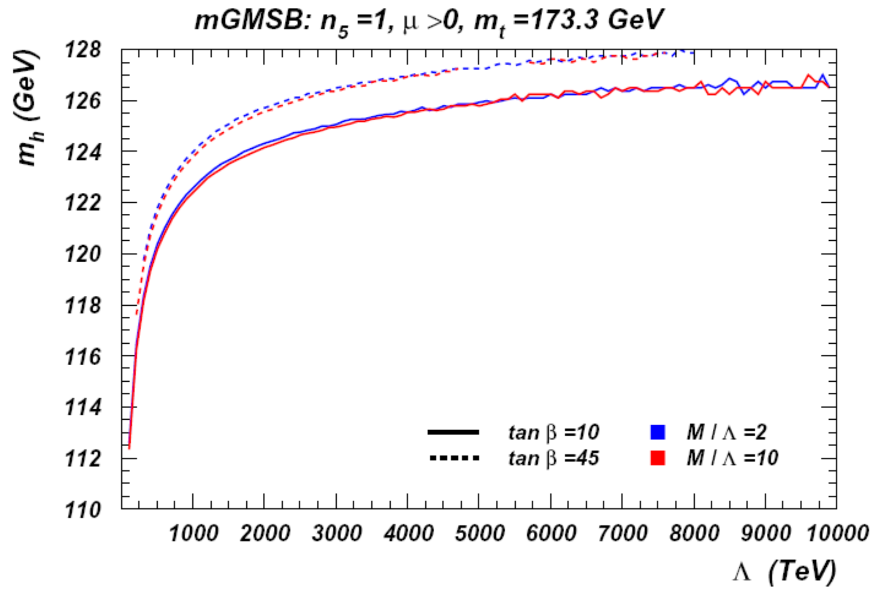


arXiv:1112.4391 (J.Cao, Z.Heng, D.Li, JMY)

(also see papers by J. Ellis et al)

Higgs mass in AMSB and GMSB (<125 GeV)





At $m_{3/2} = 600$ GeV and $\tan\beta = 45$

$$m_{\tilde{g}} \sim 10 \text{ TeV}, \quad m_{\tilde{t}_1} \sim 9 \text{ TeV}$$

At $\Lambda = 1500$ TeV, $\tan\beta = 45$

$$m_{\tilde{g}} \sim 10 \text{ TeV}, \quad m_{\tilde{t}_1} \sim 12 \text{ TeV}$$

Baer, Barger, Mustafayev, arXiv:1202.4038

How to repair GMSB to give a 125 GeV Higgs ?

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

$$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

$$X_t \equiv A_t - \mu \cot \beta$$

m_h reaches its maximum when $X_t / M_S = \sqrt{6}$

One way to repair GMSB:

arXiv:1203.2336

Z.Kang, T.Li, T.Liu, C.Tong, JMY

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

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

A large negative A_t is generated at the boundary

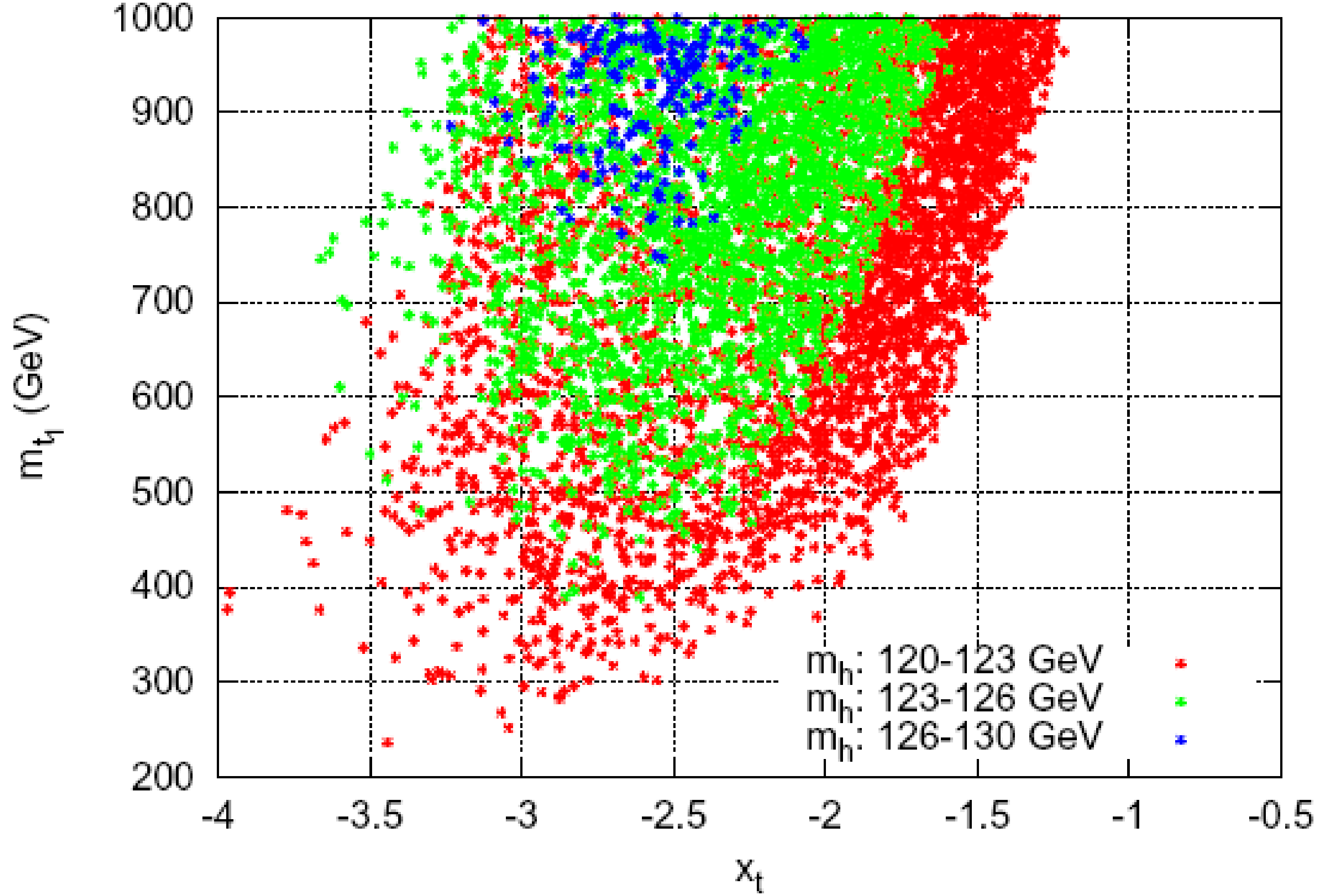
$$A_t = -\frac{\Lambda}{16\pi^2}\lambda_u^2,$$

And the stop soft mass squares get sizable corrections

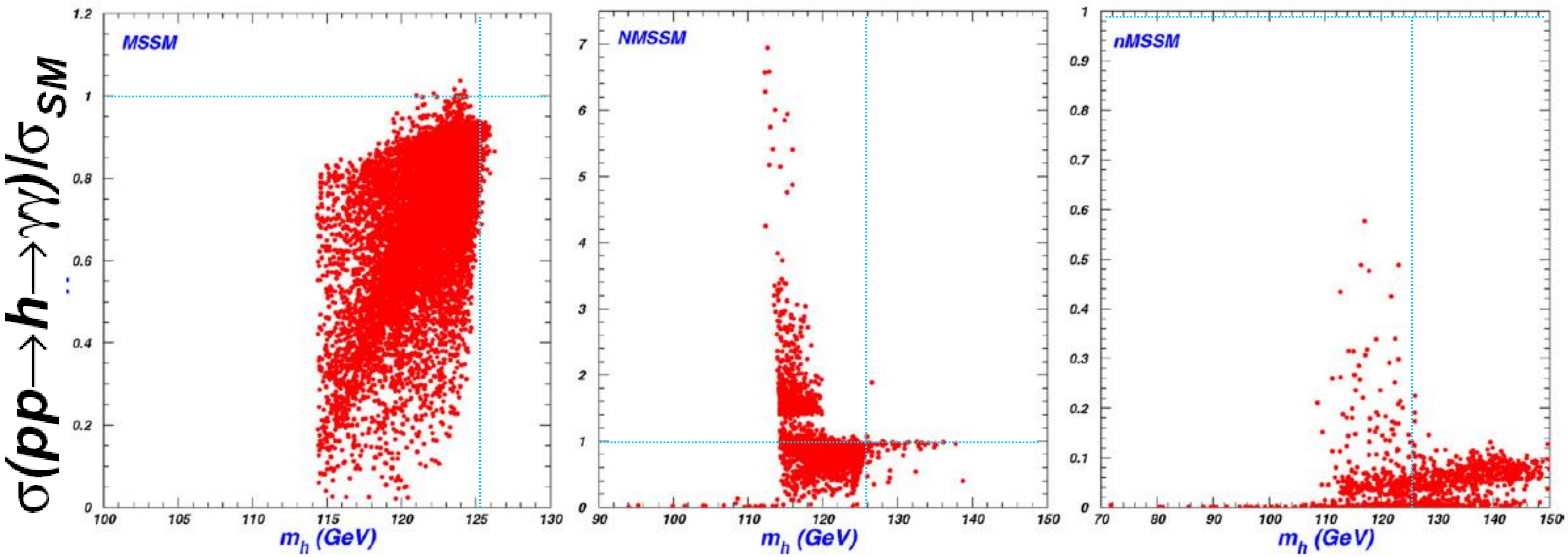
$$m_{\tilde{Q}}^2 = -\frac{\Lambda^2}{(16\pi^2)^2}\left(h_t^2\lambda_u^2 + h_b^2\lambda_d^2\right),$$

$$m_{\tilde{U}}^2 = -\frac{2\Lambda^2}{(16\pi^2)^2}h_t^2\lambda_u^2, \quad m_{\tilde{D}}^2 = -\frac{2\Lambda^2}{(16\pi^2)^2}h_b^2\lambda_d^2,$$

Yukawa-Deflected GMSB



Higgs mass in MSSM, NMSSM, nMSSM (125 GeV OK)



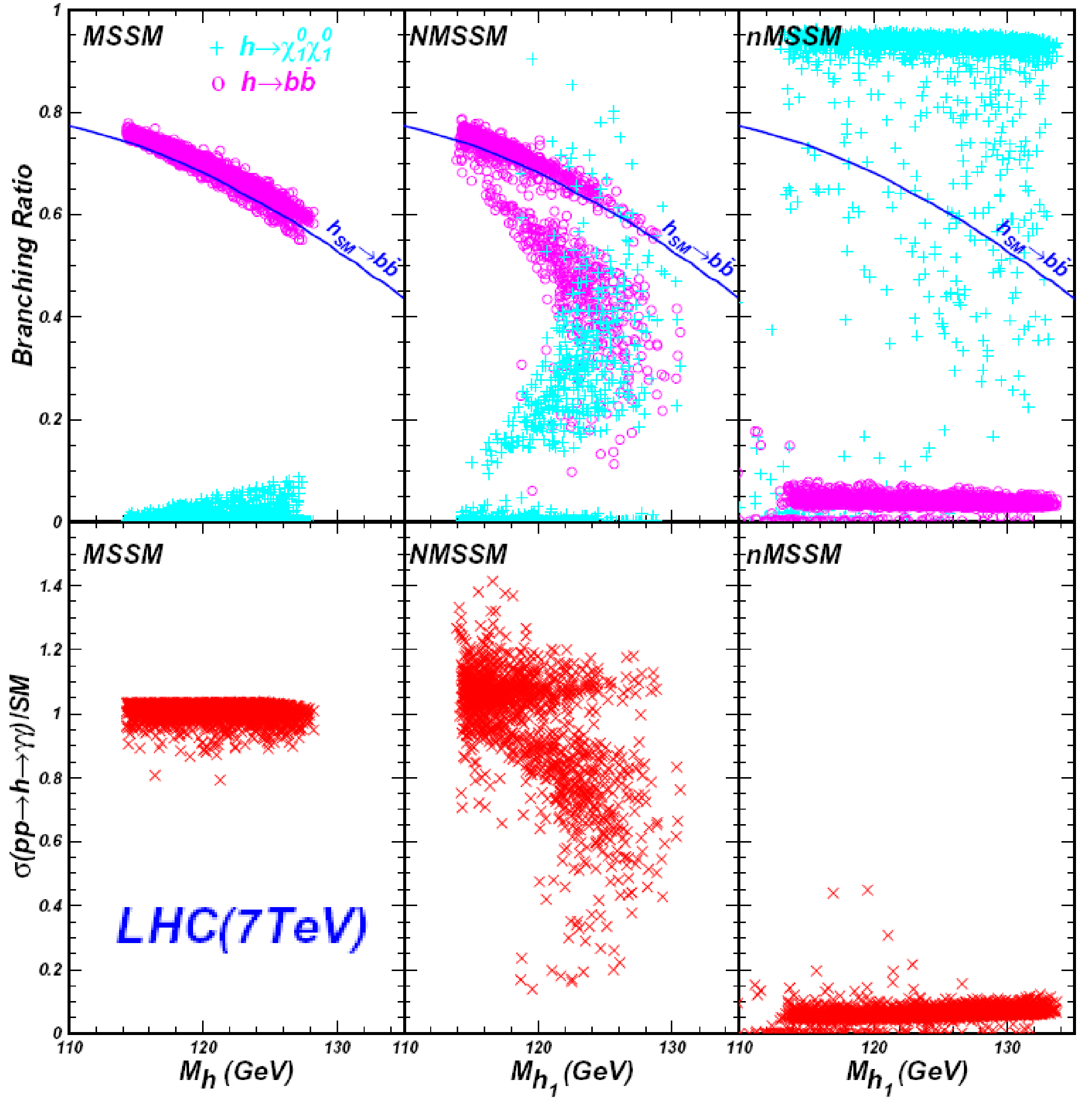
arXiv:1103.0631

J.Cao, Z.Heng, T.Liu, JMY

Then, look at the SM-like Higgs property

- invisible decay
- di-photon signal rate
- implication on stop
- ……

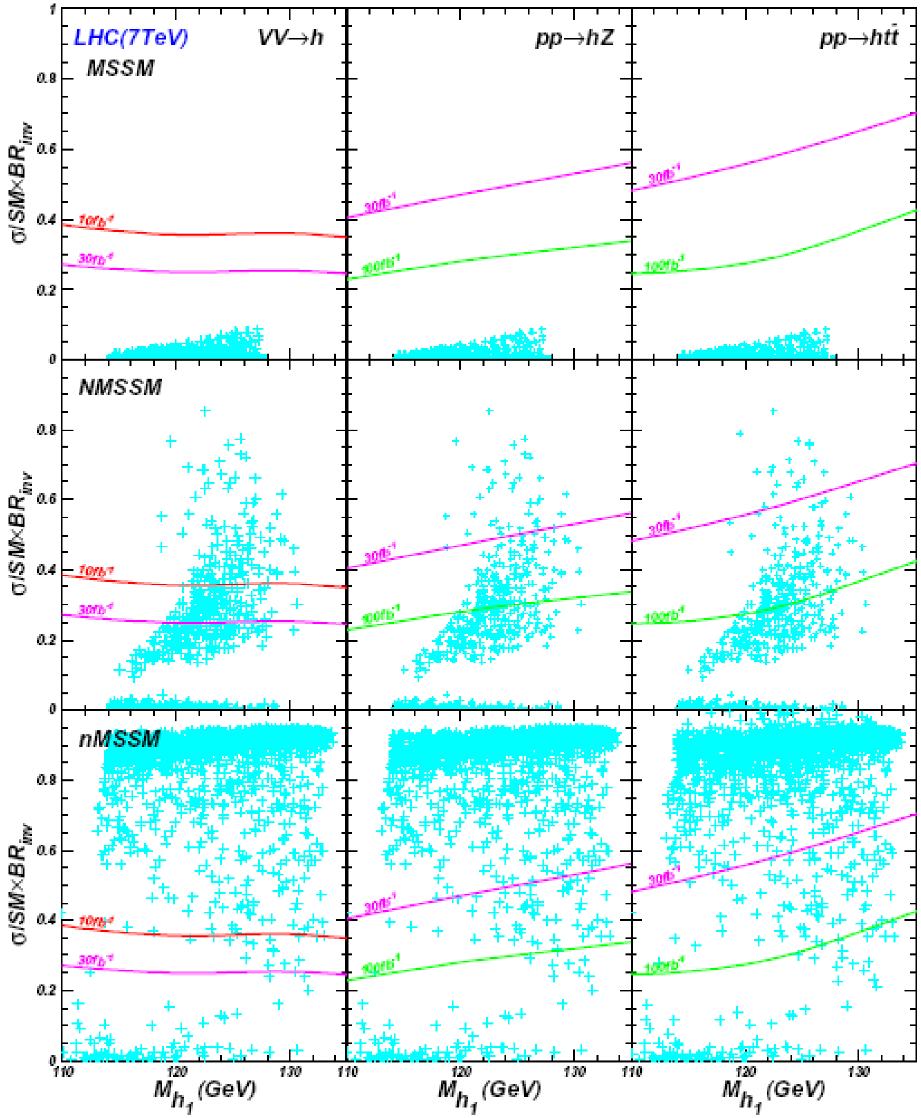
Higgs decay to dark matter in SUSY



arXiv:1203.0694

J.Cao, Z.Heng, JMY, J.Zhu

Higgs decay to dark matter in SUSY: detectable at LHC ?



arXiv:1203.0694

J.Cao, Z.Heng, JMY, J. Zhu

(curves from papers by T. Han et al)

Take a careful look at MSSM and NMSSM:

arXiv:1202.5821
J.Cao, Z.Heng, JMY, J.ZHu

$$123\text{GeV} \leq m_h \leq 127\text{GeV}$$

(for 125 GeV Higgs in MSSM,
there are many papers, say by
T. Han et al)

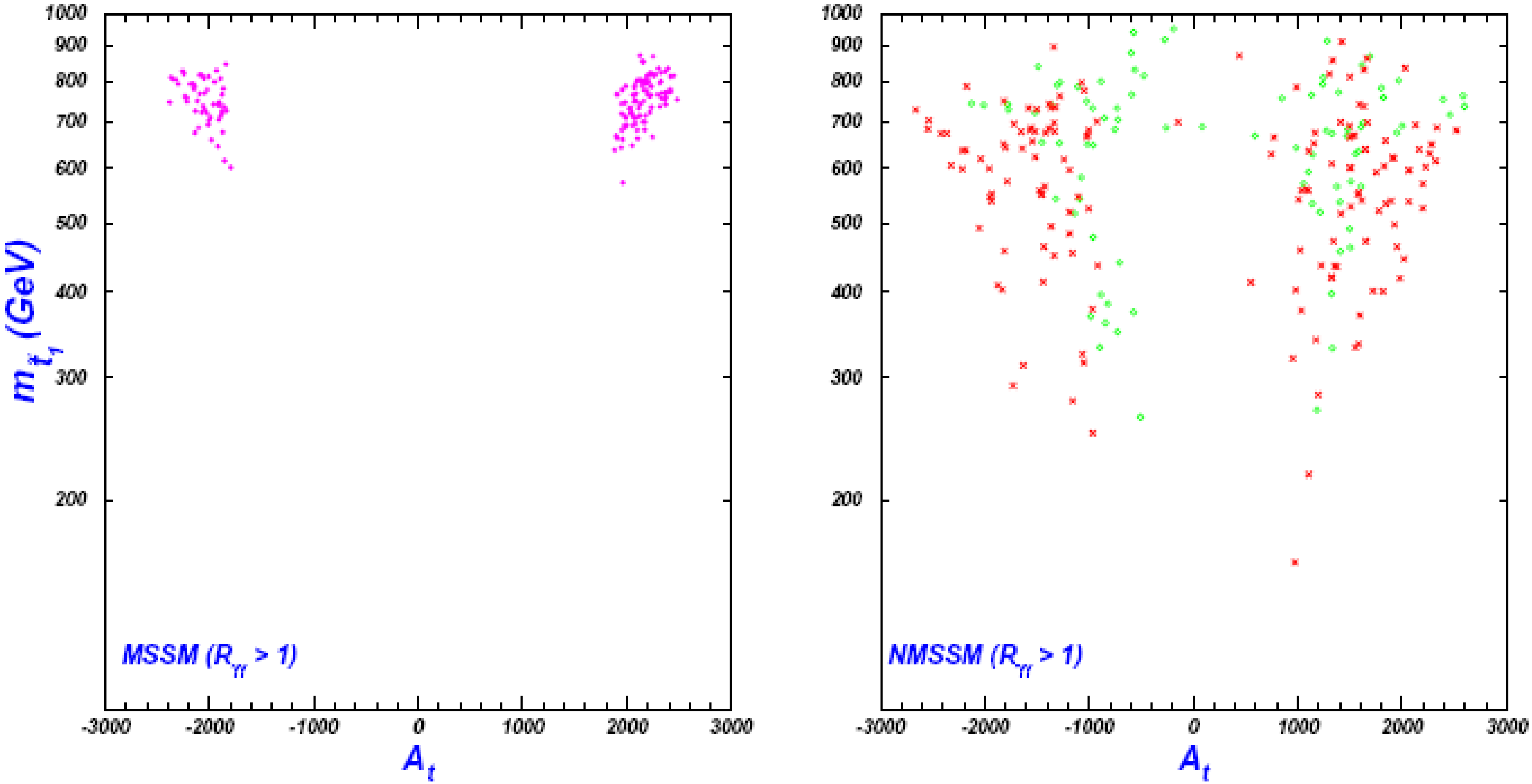
MSSM:

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

$$X_t \equiv A_t - \mu \cot \beta$$

NMSSM:

$$m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$



$$R_{\gamma\gamma} \equiv \sigma_{SUSY}(pp \to h \to \gamma\gamma)/\sigma_{SM}(pp \to h \to \gamma\gamma)$$

How to enhance the di-photon rate at the LHC ?

$$gg \to h \to \gamma\gamma$$

hgg coupling not enhanced

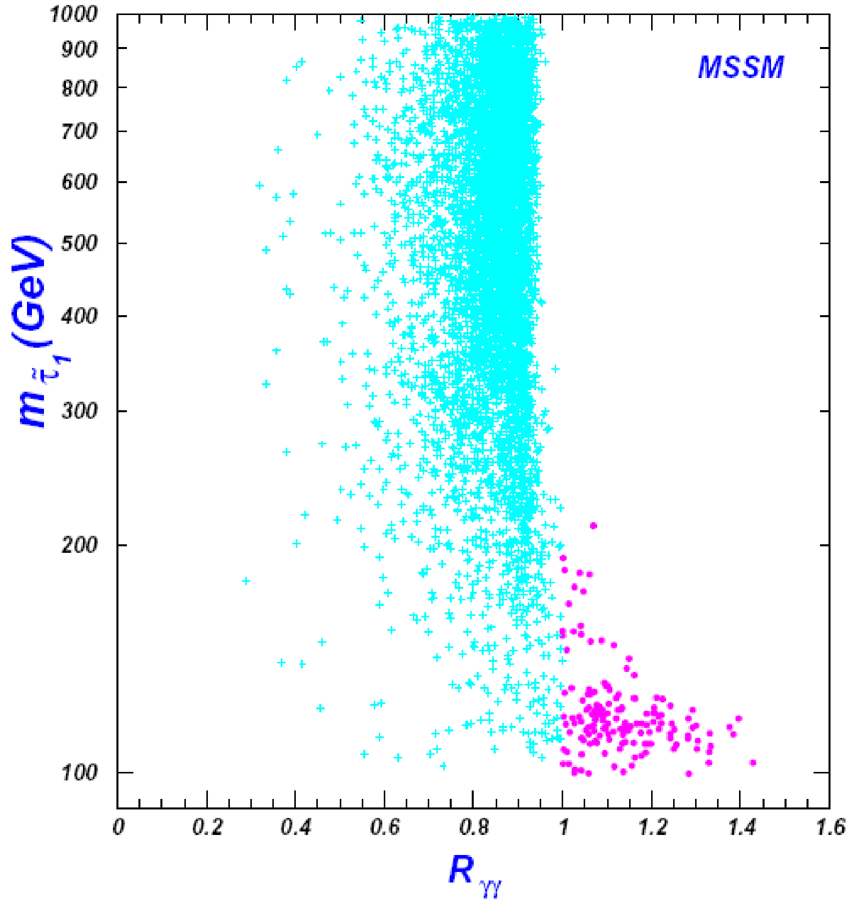
to enhance $B(h \to \gamma\gamma)$

NMSSM: it is easy

- h-b-b coupling can be suppressed
  so $B(h \to \gamma\gamma)$ can be enhanced

MSSM: it is hard

- h-b-b coupling cannot be suppressed
- need a light stau to enhance $h\gamma\gamma$ coupling



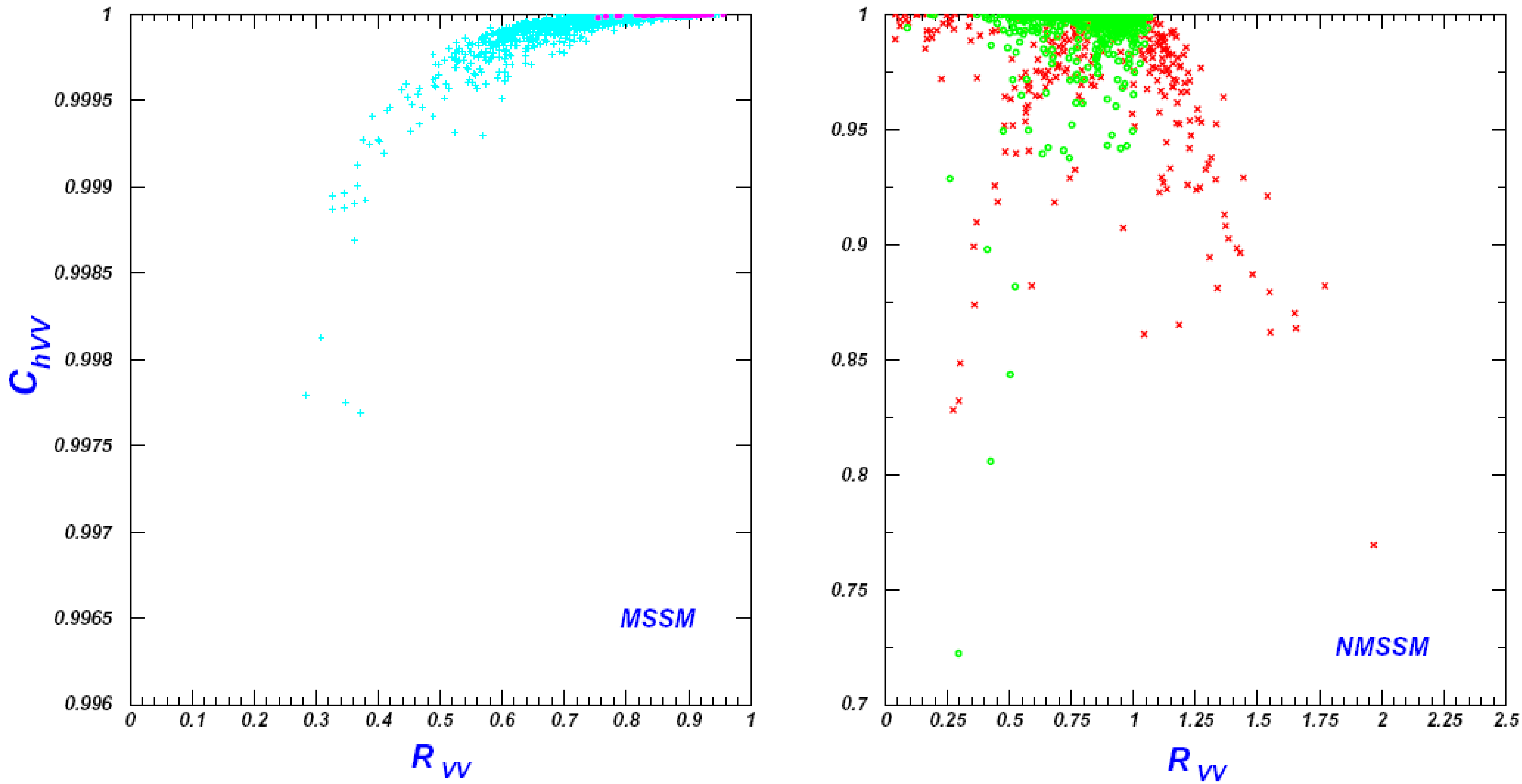
arXiv:1202.5821
J.Cao, Z.Heng, JMY, J.ZHu

(see also papers by M. Carena et al)

$$R_{\gamma\gamma} \equiv \sigma_{SUSY}(pp \to h \to \gamma\gamma)/\sigma_{SM}(pp \to h \to \gamma\gamma)$$

How about pp→h→ZZ* (WW*) at the LHC ?

arXiv:1202.5821



$$R_{VV} \equiv \sigma_{SUSY}(pp \to h \to VV^*)/\sigma_{SM}(pp \to h \to VV^*)$$

$$C_{hVV} \equiv C_{hVV}^{\rm SUSY}/C_{hVV}^{\rm SM}$$

$$V = W, Z$$

Finally, low energy SUSY models confronted with 7TeV+8TeV Data

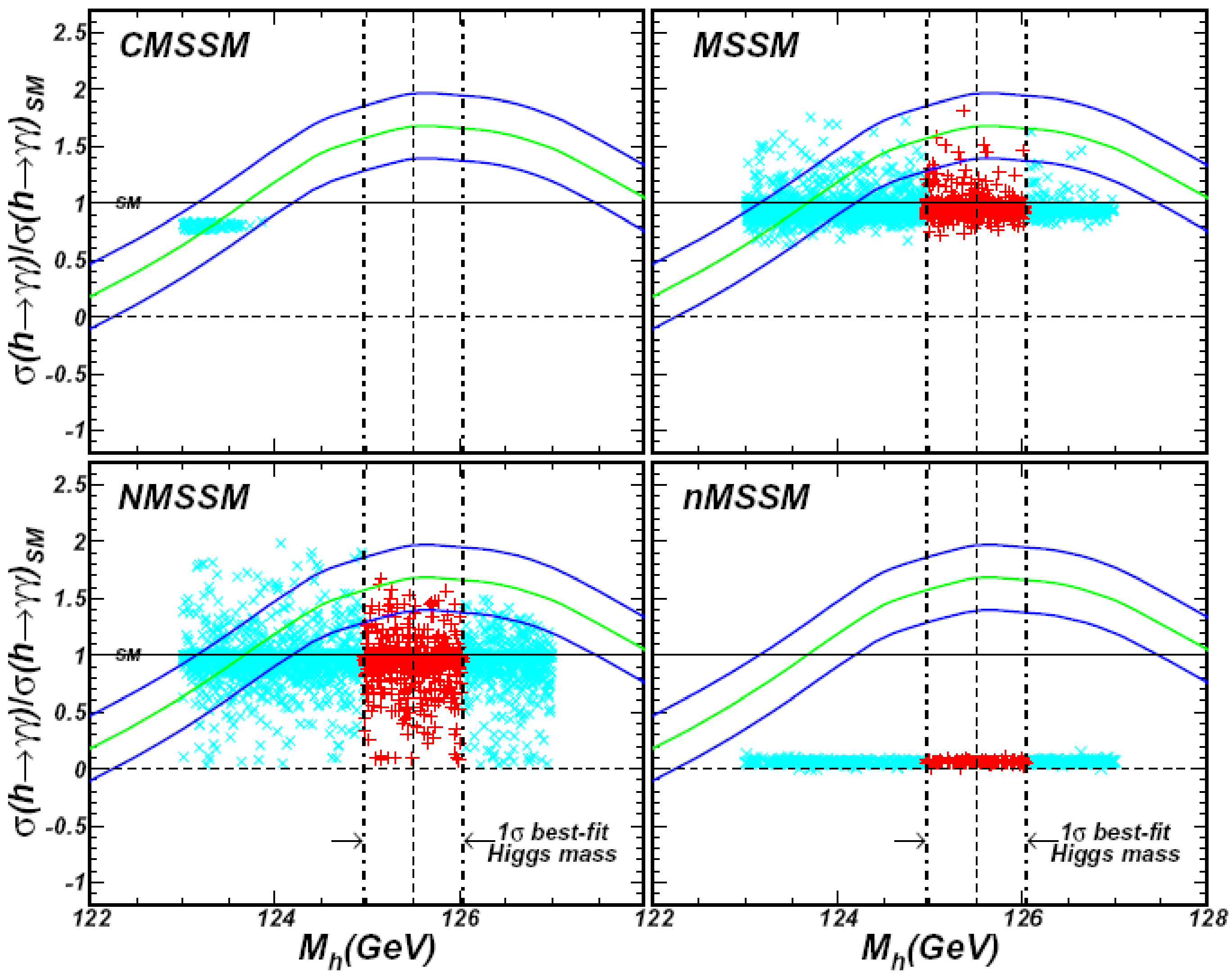
arXiv:1207.3698

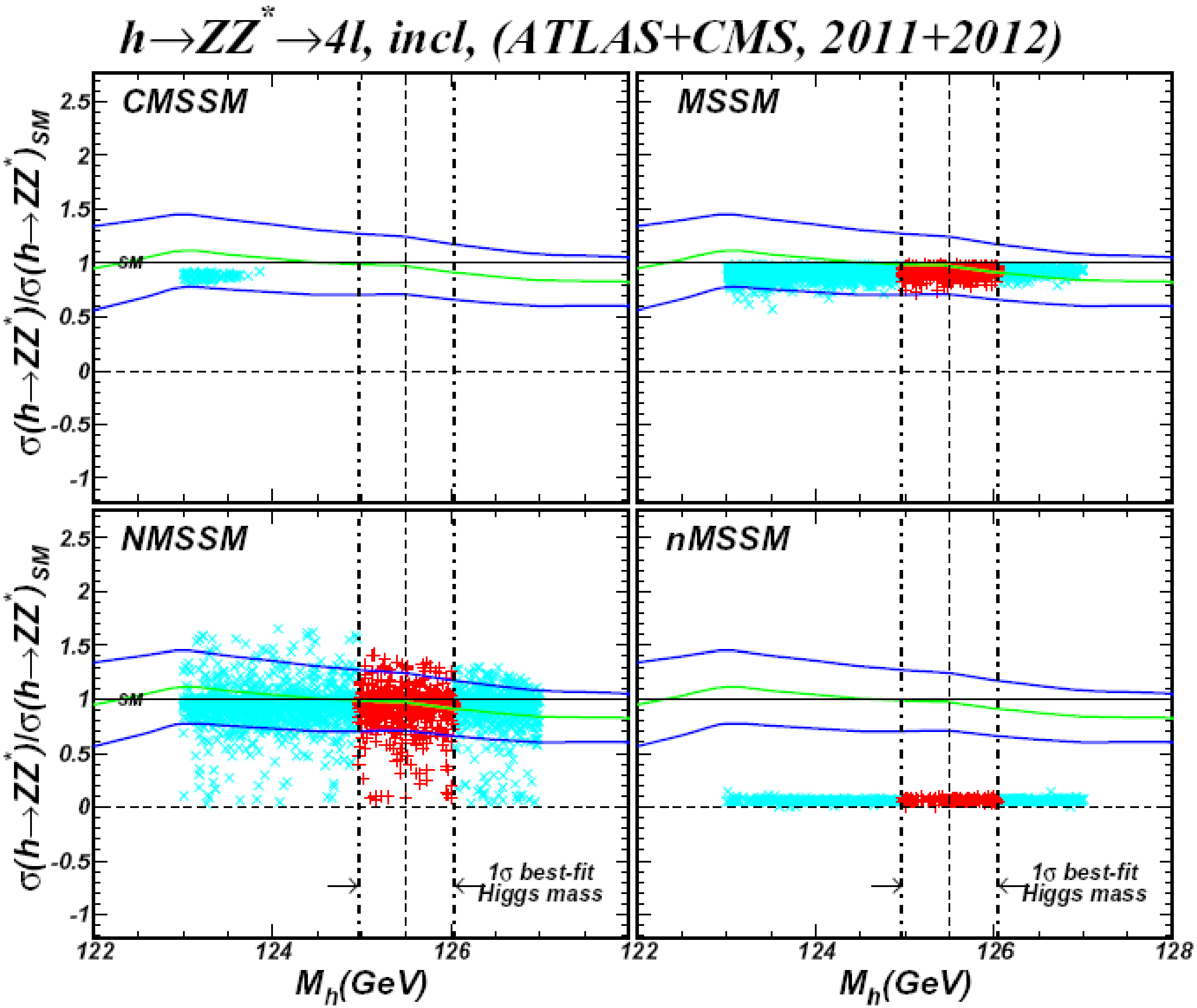
J.Cao, Z.Heng, JMY, J.Zhu

Use one word to describe the status of SUSY: *打不死的吴清华我还活在人间！*

---京剧“红色娘子军”

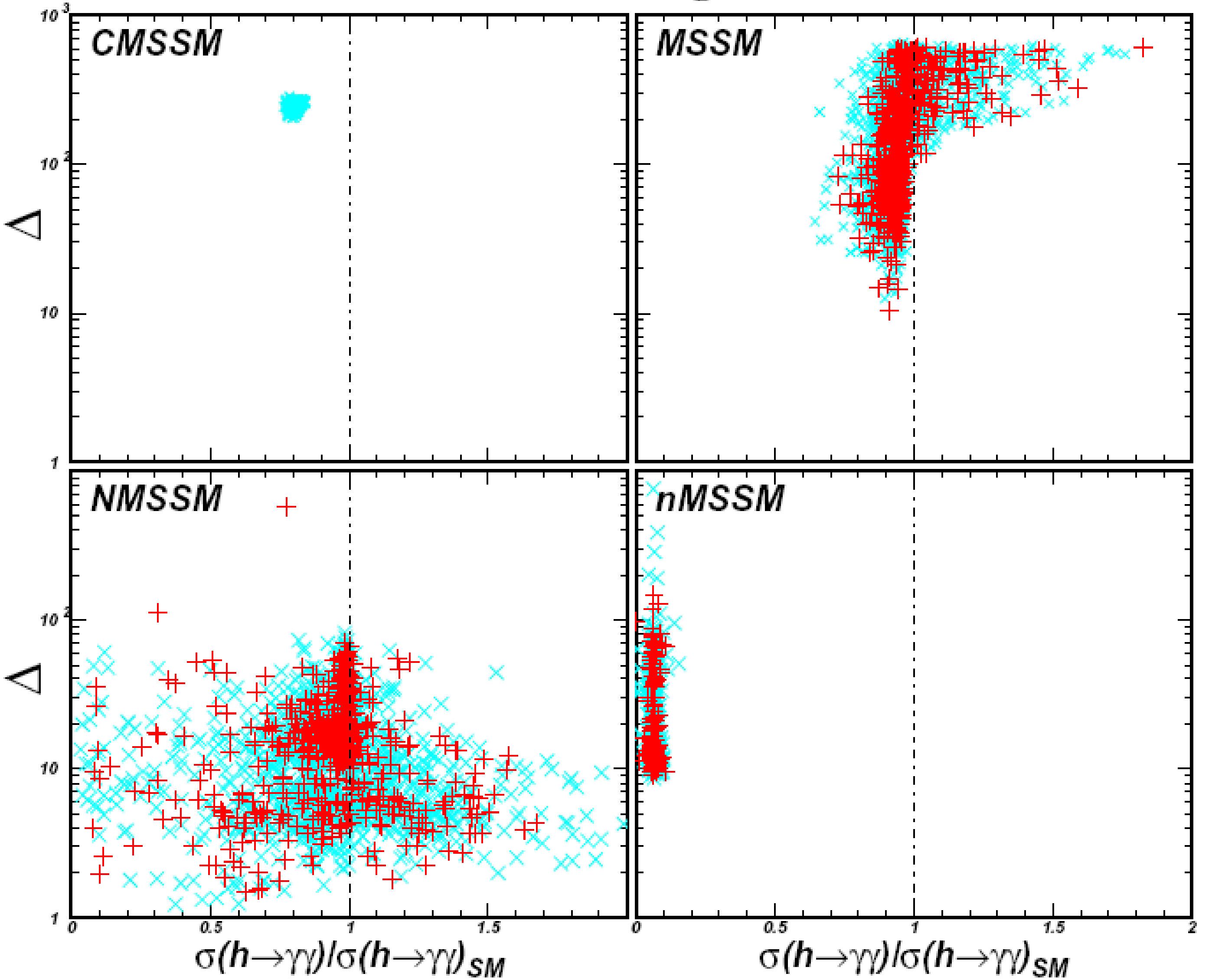
$h \to \gamma\gamma$, incl, (ATLAS+CMS, 2011+2012)

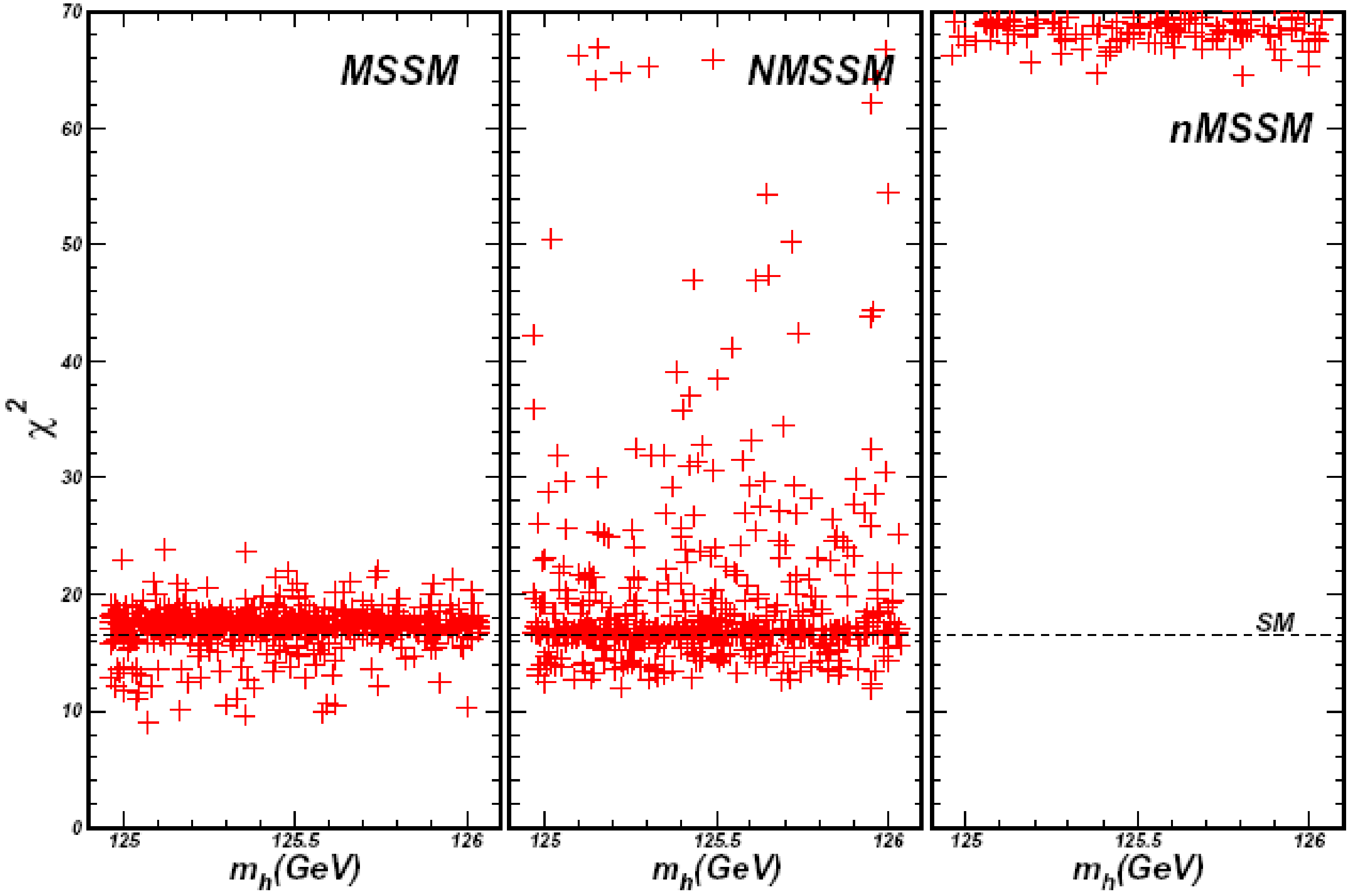




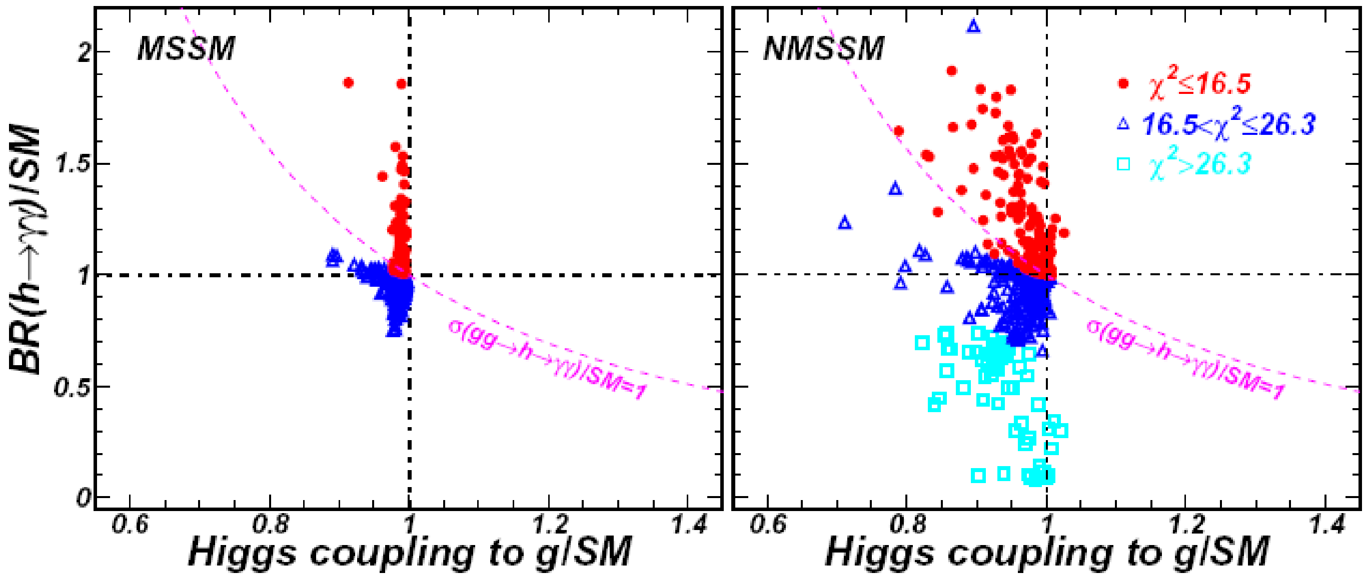
$h \to ZZ^* \to 4l$, incl, (ATLAS+CMS, 2011+2012)
CMSSM
MSSM
NMSSM
nMSSM
SM
$\sigma(h \to ZZ^*)/\sigma(h \to ZZ^*)_{SM}$
2.5
2
1.5
1
0.5
0
-0.5
-1
1σ best-fit
Higgs mass
122
124
126
128
M_h(GeV)

Fine-tuning

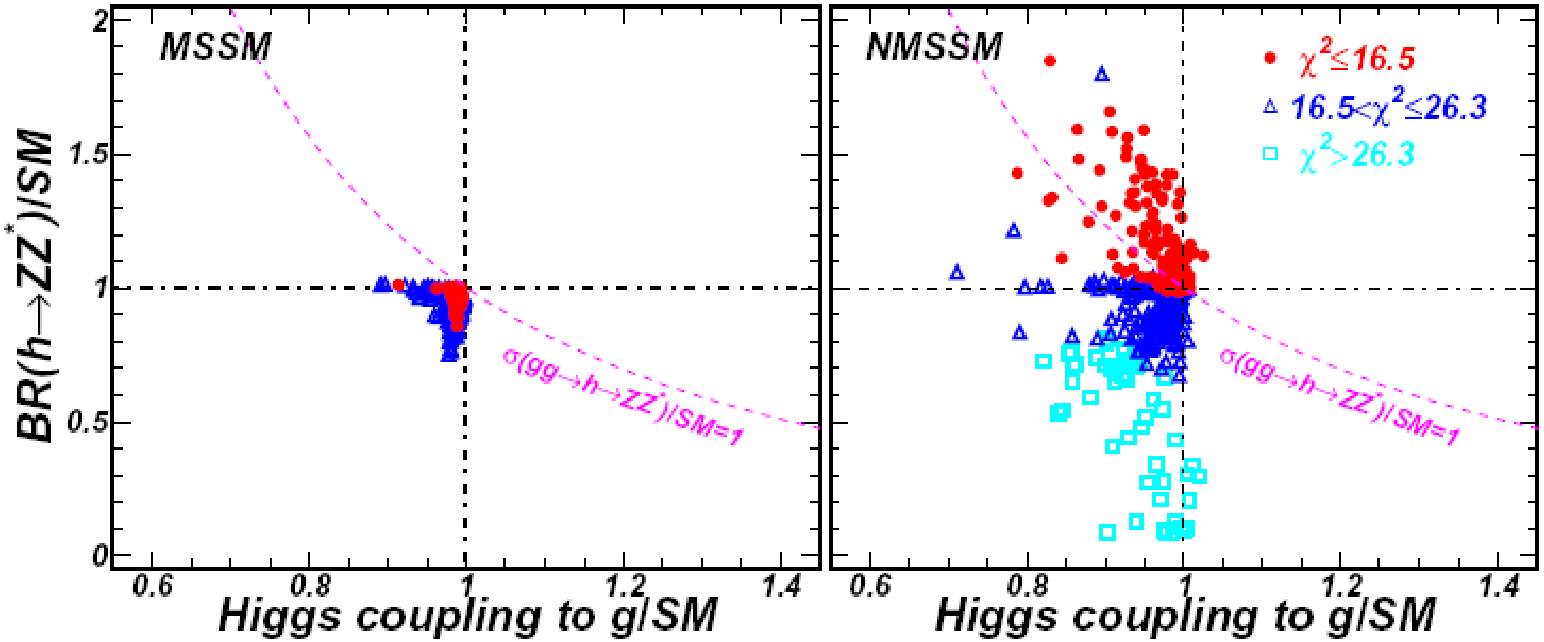

CMSSM
MSSM
NMSSM
nMSSM
Δ
Δ
10^3
10^2
10
1
10^2
10
1
0
0.5
1
1.5
0
0.5
1
1.5
2
σ(h→γγ)/σ(h→γγ)SM
σ(h→γγ)/σ(h→γγ)SM



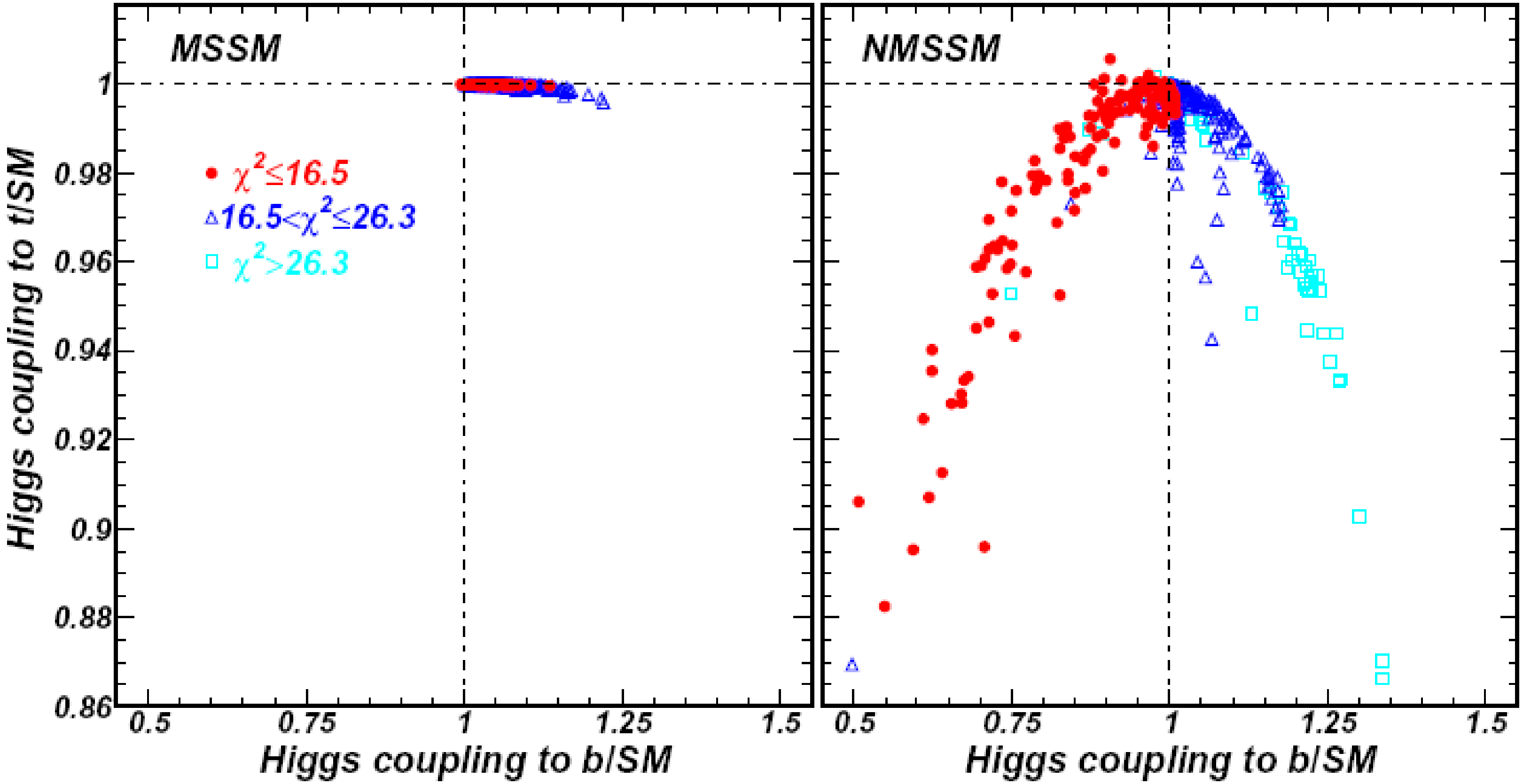
$$m_h = 125.5 \pm 0.54 \text{ GeV}$$



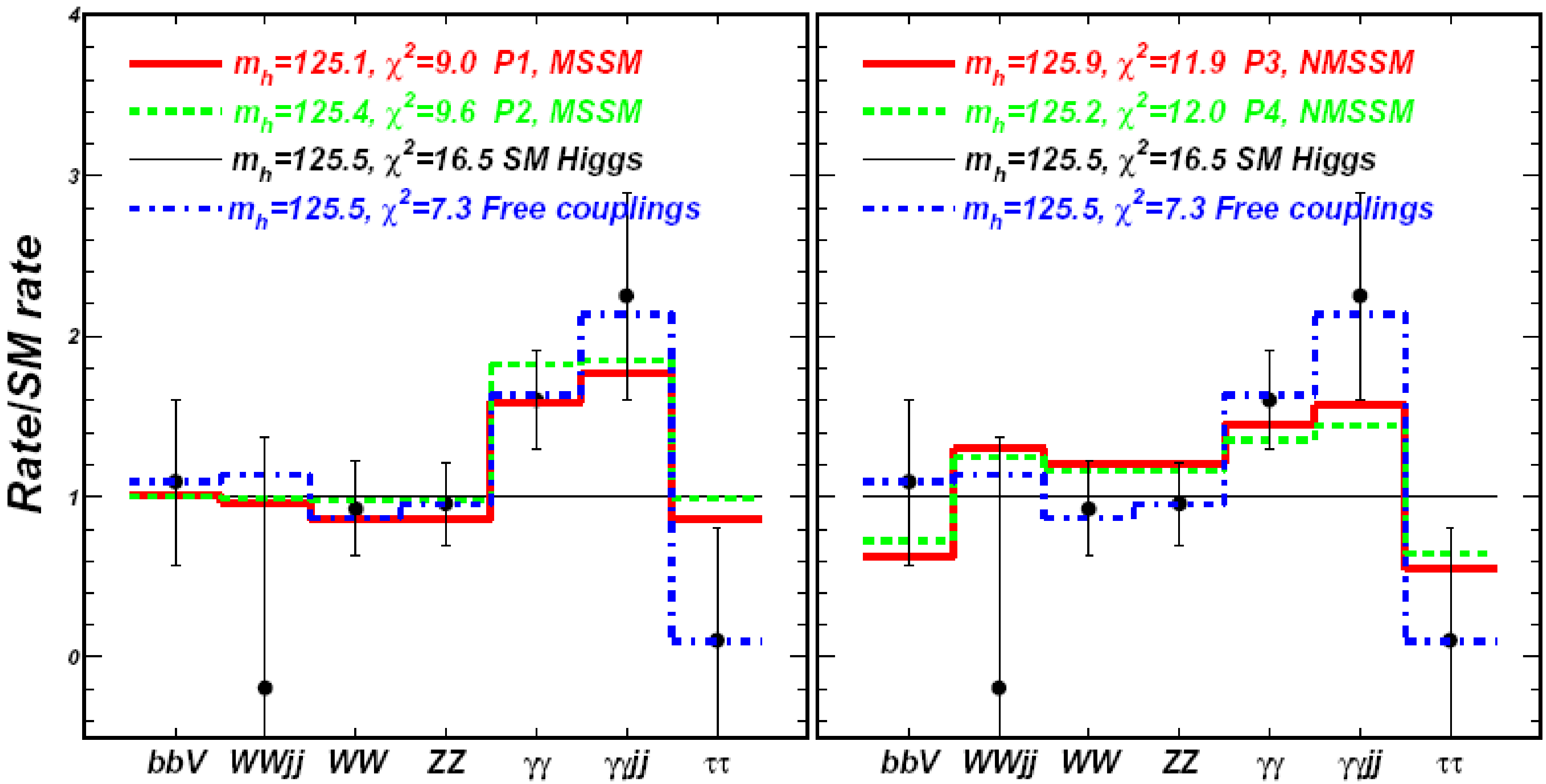
diphoton branching ratio versus hgg coupling



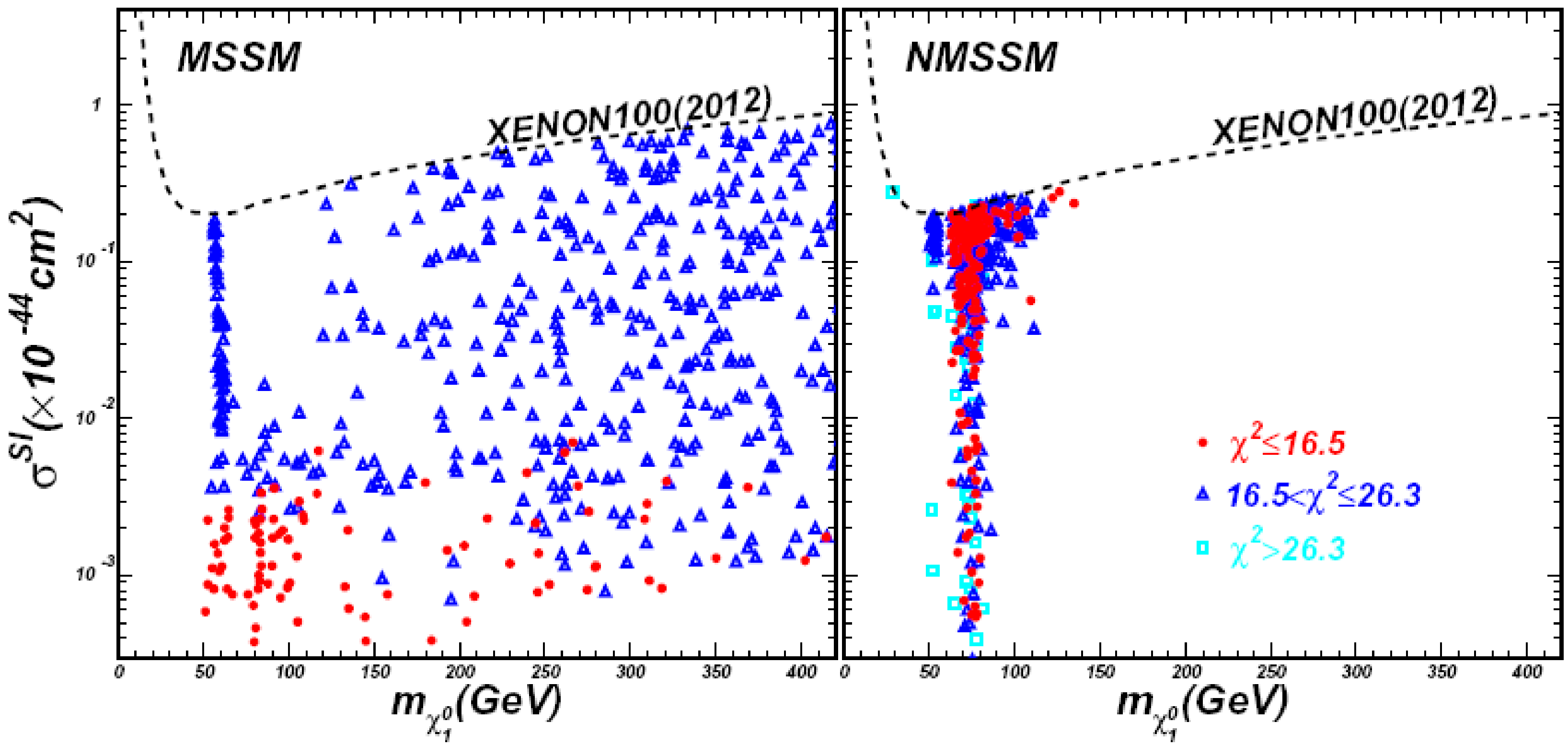
ZZ^* branching ratio versus hgg coupling



Higgs Yukawa couplings to top and bottom



Rate/SM rate
m_h=125.1, χ^2=9.0 P1, MSSM
m_h=125.4, χ^2=9.6 P2, MSSM
m_h=125.5, χ^2=16.5 SM Higgs
m_h=125.5, χ^2=7.3 Free couplings
m_h=125.9, χ^2=11.9 P3, NMSSM
m_h=125.2, χ^2=12.0 P4, NMSSM
m_h=125.5, χ^2=16.5 SM Higgs
m_h=125.5, χ^2=7.3 Free couplings
0
1
2
3
4
bbV
WWjj
WW
ZZ
$\gamma\gamma$
$\gamma\gamma jj$
$\tau\tau$



MSSM
NMSSM
XENON100(2012)
XENON100(2012)
$\sigma^{SI}(\times 10^{-44}cm^2)$
$m_{\chi_1^0}(GeV)$
$m_{\chi_1^0}(GeV)$
$\chi^2 \leq 16.5$
$16.5 < \chi^2 \leq 26.3$
$\chi^2 > 26.3$

3 Conclusion

From Higgs search (125 GeV Higgs):

GMSB/AMSB: give 125 GeV Higgs with very heavy stop, need to repair

CMSSM/mSUGRA: can marginally give 125 GeV Higgs; still survived

MSSM: can fit the data well but suffer from some extent of fine-tuning

nMSSM: nearly excluded (suppress diphoton rate)

NMSSM: most favored (can fit the data well without fine-tuning)

From sparticle search:

First two generations of squarks are heavy (> TeV)

The 3rd generation squarks may still be light

→ Natural SUSY

Higgs search:

Sparticle search:

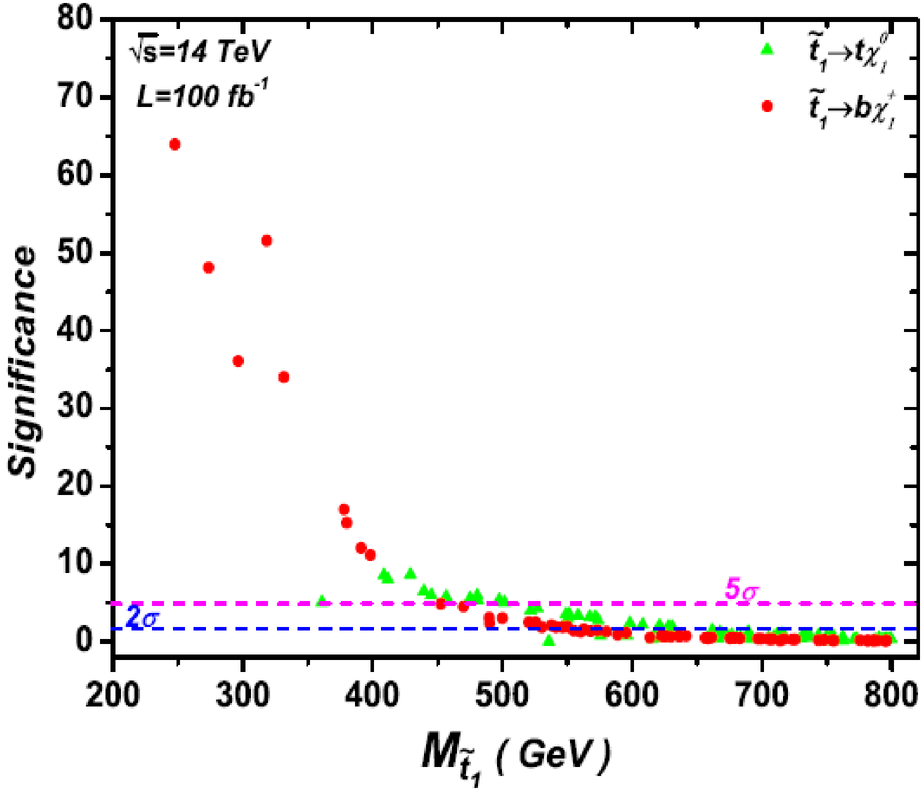
→ Natural NMSSM

3 possibilities:

(1) Natural SUSY

May discover stop, sbottom and gluino

(but no other squarks)



arXiv:1206.3865

J.Cao, C.Han, L.Wu, JMY, Y.Zhang

(2) Split-SUSY

May discover gluino and/or chargino

(but no any sfermions)

(3) High-scale SUSY

Discover nothing

(no sparticles)

If high-scale SUSY, is it still useful ?
(see talk by Chun Liu)

Thanks !