International Workshop On the CEPC

Implication of Future Higgs and Z precision on MSSM

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Based on work:
1601.07758 (with J. Yang)
1711.xxxxx (with H. Li, H. Song, S. Su, J. Yang)

Outline

- Precision from e^+e^- colliders
- Higgs precision on MSSM
  - MSSM and its Higgs sector
  - Current researches
  - Results from Higgs precision
- Z pole precision on MSSM
  - $\mathrm{R_b}$
  - Constraints on parameter space
- Conclusion

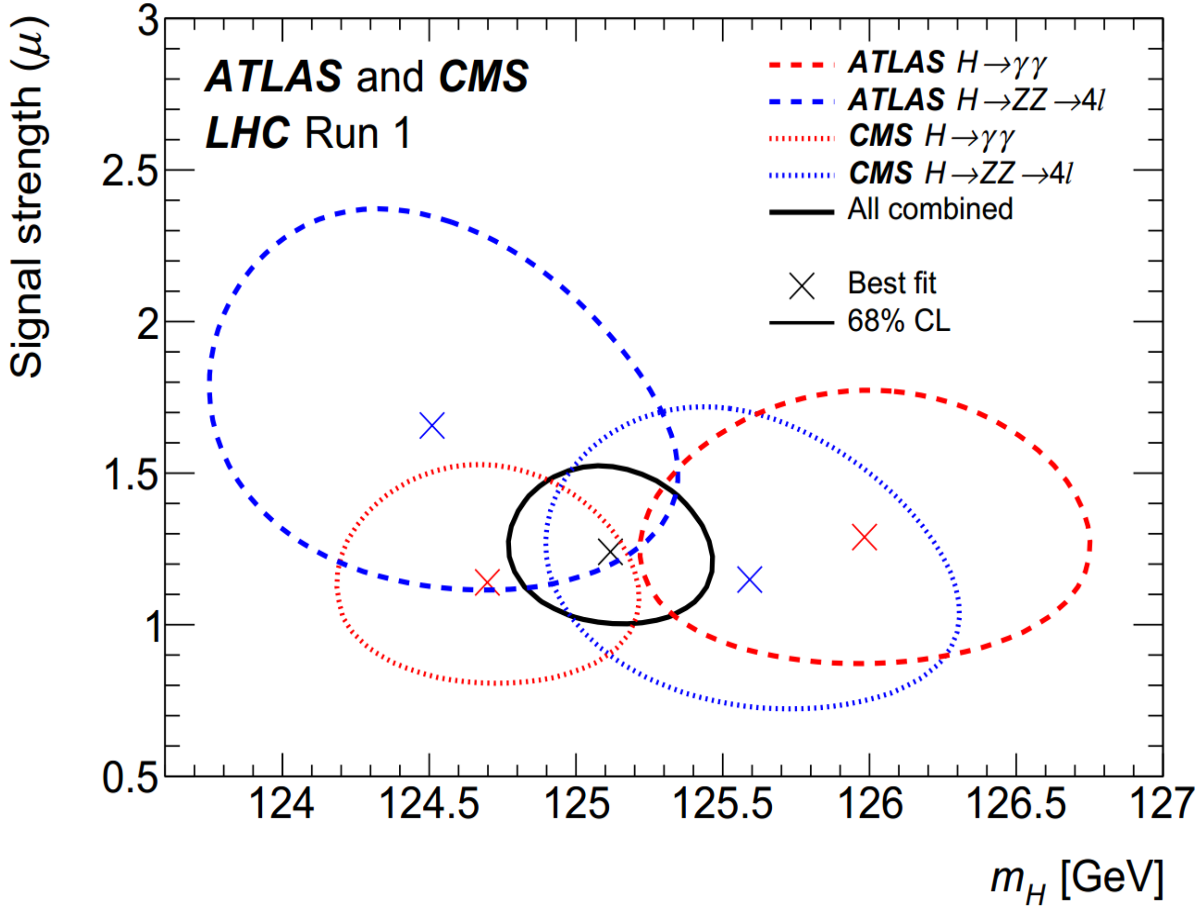
Precision: Higgs mass

CMS-HIG-14-042
ATLAS-HIGG-2014-14

LHC Run-I:
$m_h = 125.09 \pm 0.24$ GeV

CEPC: $\Delta \mathrm{m}_h = 5.9$ MeV

Theory: $\delta \mathrm{m}_h = 3$ GeV



Precision: Higgs couplings

- **Yukawa and gauge Higgs couplings**

collider	CEPC	FCC-ee	ILC					
$\sqrt{s}$ $\int \mathcal{L}dt$	240 GeV 5 ab^{-1}	240 GeV 10 ab^{-1}	250 GeV 2 ab^{-1}	350 GeV 200 fb^{-1}		500 GeV 4 ab^{-1}		
production	Zh	Zh	Zh	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$
$\Delta\sigma/\sigma$	0.51%	0.4%	0.71%	2.1%	-	1.06	-	-
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$							
$h \to b\bar{b}$	0.28%	0.2%	0.42%	1.67%	1.67%	0.64%	0.25%	9.9%
$h \to cc$	2.2%	1.2%	2.9%	12.7%	16.7%	4.5%	2.2%	-
$h \to gg$	1.6%	1.4%	2.5%	9.4%	11.0%	3.9%	1.5%	-
$h \to WW^*$	1.5%	0.9%	1.1%	8.7%	6.4%	3.3%	0.85%	-
$h \to \tau^+\tau^-$	1.2%	0.7%	2.3%	4.5%	24.4%	1.9%	3.2%	-
$h \to ZZ^*$	4.3%	3.1%	6.7%	28.3%	21.8%	8.8%	2.9%	-
$h \to \gamma\gamma$	9.0%	3.0%	12.0%	43.7%	50.1%	12.0%	6.7%	-
$h \to \mu^+\mu^-$	17%	13%	25.5%	97.6%	179.8%	31.1%	25.5%	-
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	2.2%	3.7%	-	-	-	-	-

Precision: Higgs couplings

- **Loop-induced Higgs couplings**

collider	CEPC	FCC-ee	ILC					
$\sqrt{s}$ $\int \mathcal{L}dt$	240 GeV 5 ab^{-1}	240 GeV 10 ab^{-1}	250 GeV 2 ab^{-1}	350 GeV 200 fb^{-1}		500 GeV 4 ab^{-1}		
production	Zh	Zh	Zh	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$
$\Delta\sigma/\sigma$	0.51%	0.4%	0.71%	2.1%	-	1.06	-	-
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$							
$h \to b\bar{b}$	0.28%	0.2%	0.42%	1.67%	1.67%	0.64%	0.25%	9.9%
$h \to c\bar{c}$	2.2%	1.2%	2.9%	12.7%	16.7%	4.5%	2.2%	-
$h \to gg$	1.6%	1.4%	2.5%	9.4%	11.0%	3.9%	1.5%	-
$h \to WW^*$	1.5%	0.9%	1.1%	8.7%	6.4%	3.3%	0.85%	-
$h \to \tau^+\tau^-$	1.2%	0.7%	2.3%	4.5%	24.4%	1.9%	3.2%	-
$h \to ZZ^*$	4.3%	3.1%	6.7%	28.3%	21.8%	8.8%	2.9%	-
$h \to \gamma\gamma$	9.0%	3.0%	12.0%	43.7%	50.1%	12.0%	6.7%	-
$h \to \mu^+\mu^-$	17%	13%	25.5%	97.6%	179.8%	31.1%	25.5%	-
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	2.2%	3.7%	-	-	-	-	-

MSSM

General SUSY : symmetry between the fermions and bosons:

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times 3$ families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+ \;\; H_u^0)$	$(\widetilde{H}_u^+ \;\; \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\ \mathbf{1}\,,\ 0)$
winos, W bosons	$\widetilde{W}^\pm \;\; \widetilde{W}^0$	$W^\pm \;\; W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

Physical particle: $h\,, H, A, H^{\pm}$

m_h=125 GeV

$m_A \approx m_H \approx m_{H^\pm}$

arxiv: hep-ph/9709365

MSSM Higgs sector

Mass

$$\mathcal{M}_{\mathrm{Higgs}} = \underbrace{\frac{\sin 2\beta}{2}\begin{pmatrix} \cot\beta\ M_Z^2 + \tan\beta\ M_A^2 & -M_Z^2 - M_A^2 \\ -M_Z^2 - M_A^2 & \tan\beta\ M_Z^2 + \cot\beta\ M_A^2 \end{pmatrix}}_{\text{Tree-level}} + \underbrace{\begin{pmatrix} \Delta_{11} & \Delta_{12} \\ \Delta_{12} & \Delta_{22} \end{pmatrix}}_{\text{Loop-level}}$$

$$M^2_{H,h,eff} = \frac{M_A^2 + M_Z^2}{2} \pm \left(\frac{(M_A^2 + M_Z^2)^2}{4} - M_A^2 M_Z^2 \cos^2 2\beta\right)^{1/2}$$

$$\mathrm{m}_{h,\mathrm{tree}} \leq \mathrm{m}_Z = 91.18\ \mathrm{GeV} < 125\ \mathrm{GeV}$$

LHC Run-I: $m_h = 125.09 \pm 0.24$ GeV

MSSM Higgs sector

Mass

Loop-level $M_h^2 = m_h^{2,\text{tree}} + \frac{3}{2}\frac{G_F\sqrt{2}}{\pi^2}\overline{m}_t^4\left\{-\ln\left(\frac{\overline{m}_t^2}{M_S^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{1}{12}\frac{X_t^2}{M_S^2}\right)\right\}$

$\boldsymbol{m_A}$, $\boldsymbol{m_{SUSY} = m_{\tilde{Q}} = m_{\tilde{u}}}$,

tan β $\boldsymbol{X_t = A_t - \mu \tan\beta}$

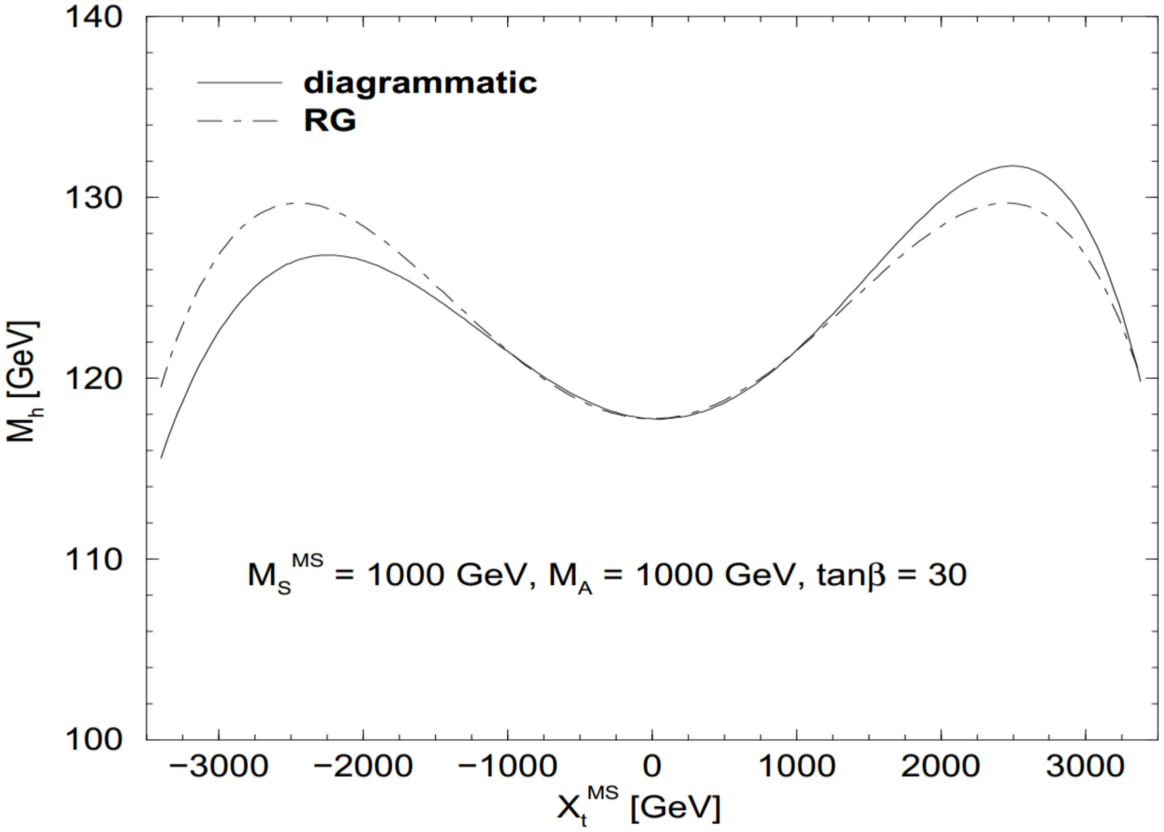
Package: FeynHiggs

$\delta m_h = 3$ GeV, MSSM uncertainty

> 0.24 GeV, LHC Run-I

>> 5.9 MeV, CEPC

0407244: S. Heinemeyer



MSSM Higgs couplings

Yukawa and gauge couplings

Tree-level: mixing angle α $\Rightarrow$ Loop-level: α_{eff}

$$\binom{H}{h} = \begin{pmatrix} \cos\alpha_{eff} & \sin\alpha_{eff} \\ -\sin\alpha_{eff} & \cos\alpha_{eff} \end{pmatrix} \binom{H^d}{H^u}$$

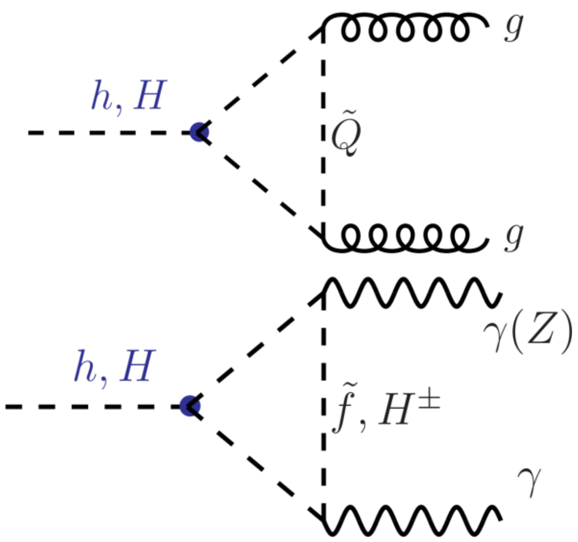
Loop modified effective Higgs couplings

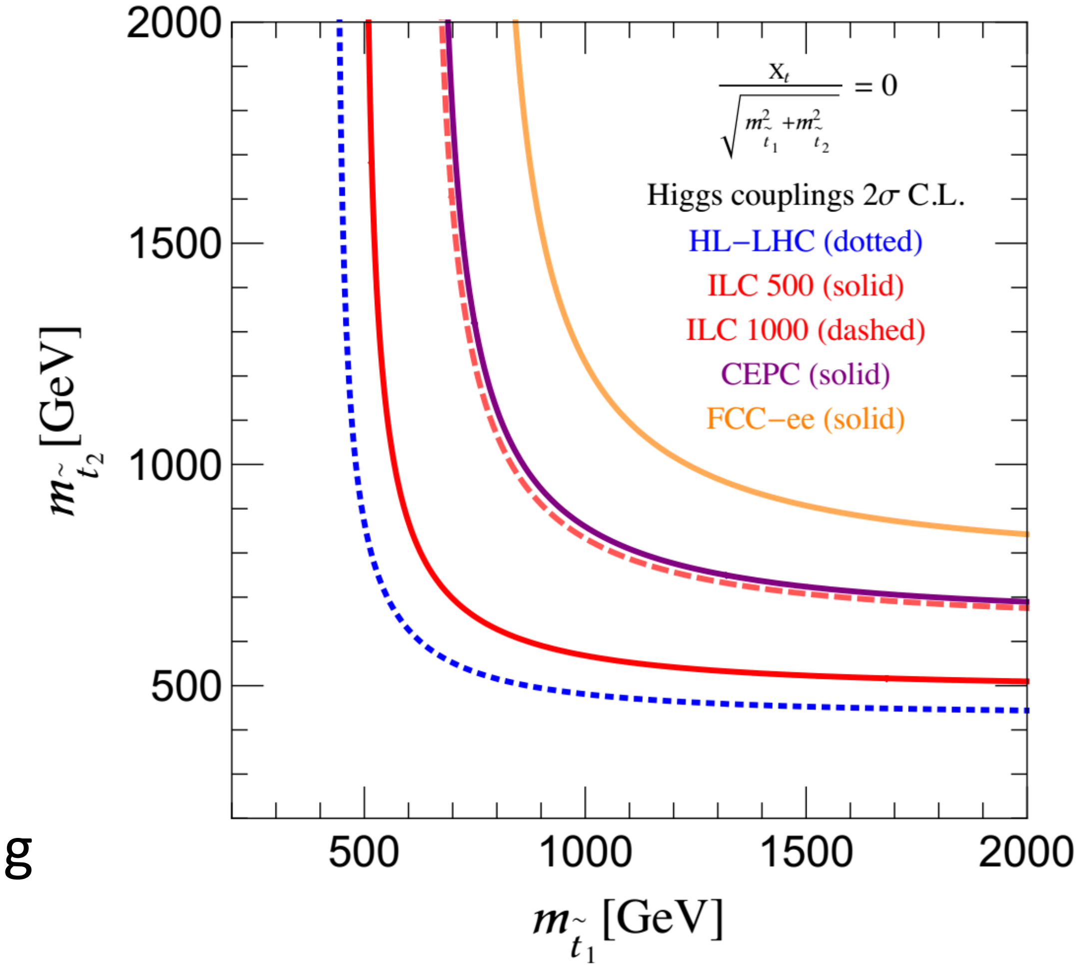
hZZ: $\sin(\beta - \alpha_{eff})$

hbb: $-\sin\alpha_{eff} \,/\cos\beta$ ...

MSSM Higgs couplings

$h\gamma\gamma$ and hgg couplings





1412.3107 J. Fan, M. Reece, L. Wang

Study strategy

Higgs mass + $h\gamma\gamma$ and hgg + Yukawa and gauge (FeynHiggs)

χ^2 → $$\chi^2_{Total} = \chi^2_{mass} + \chi^2_{\mu}$$

Higgs mass → $$\chi^2_{mass} = \frac{(m_h^{MSSM} - m_h^{obs})^2}{(\Delta m_h)^2}$$ Δm_h = 3 GeV

$h\gamma\gamma$ and hgg, Yukawa and gauge → $$\chi^2_{\mu} = \sum_{i=f,V..} \frac{(\mu_i^{MSSM} - \mu_i^{obs})^2}{(\Delta \mu_i)^2}$$

Study strategy

- Relevant parameters and some considerations

$$\mathrm{m_A}, \tan\beta,\ \mathrm{m_{SUSY}}, \mathrm{X_t}, \mu = 500\ \mathrm{GeV}$$

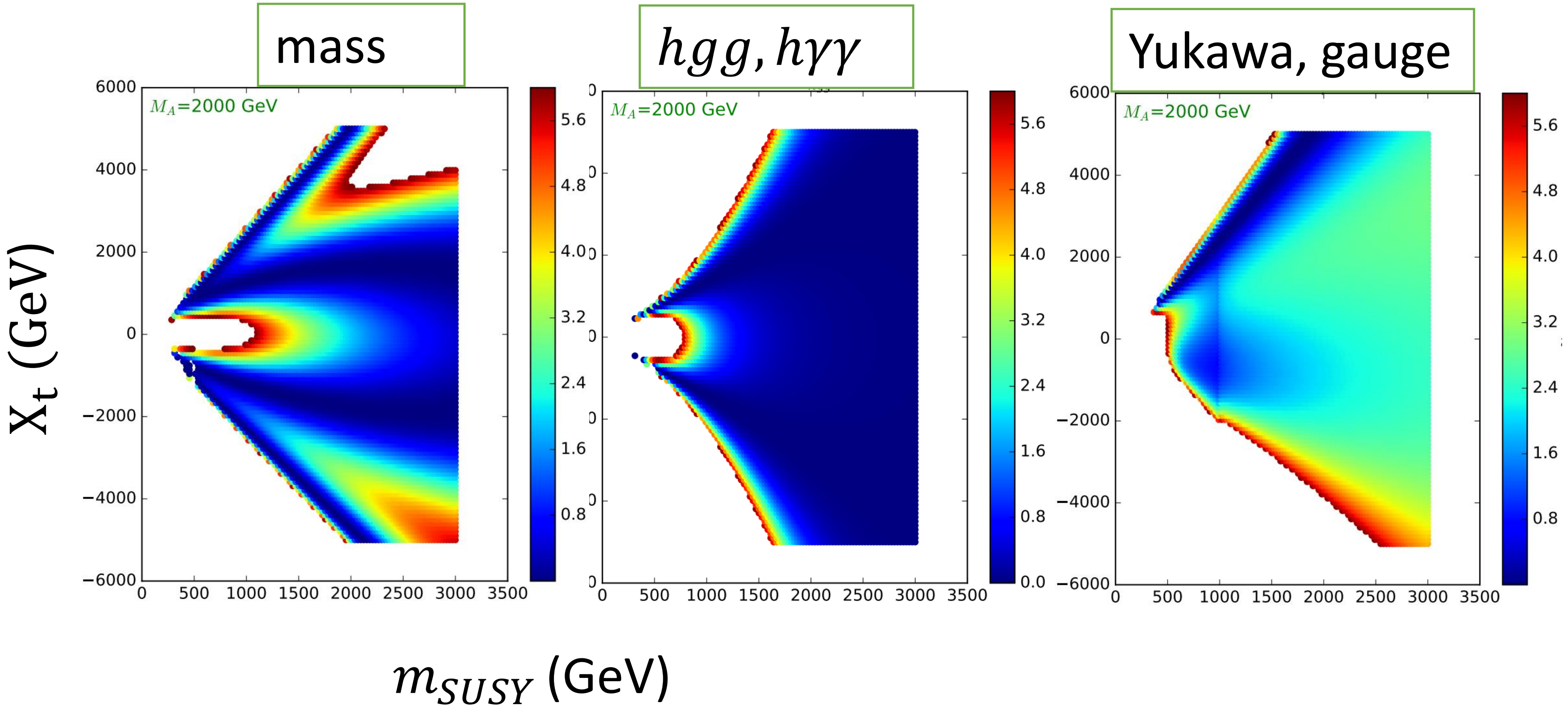
- Plane: $\mathrm{m_{SUSY}}$ vs $\mathrm{X_t}$
- Plane: $\mathrm{m_{SUSY}}$ vs $\mathrm{m_A}$
- Plane: $\mathrm{m_A}$ vs $\tan\beta$

Three-dimension fit, projected to two-dimension plane: $\Delta\chi^2 = 7.82$

Not discussed here: $\mathrm{m_{\tilde{b}}}, \mathrm{X_{\tilde{b}}}, \mathrm{m_{\tilde{g}}}, \mathrm{M_1}, \mathrm{M_2}$ ...

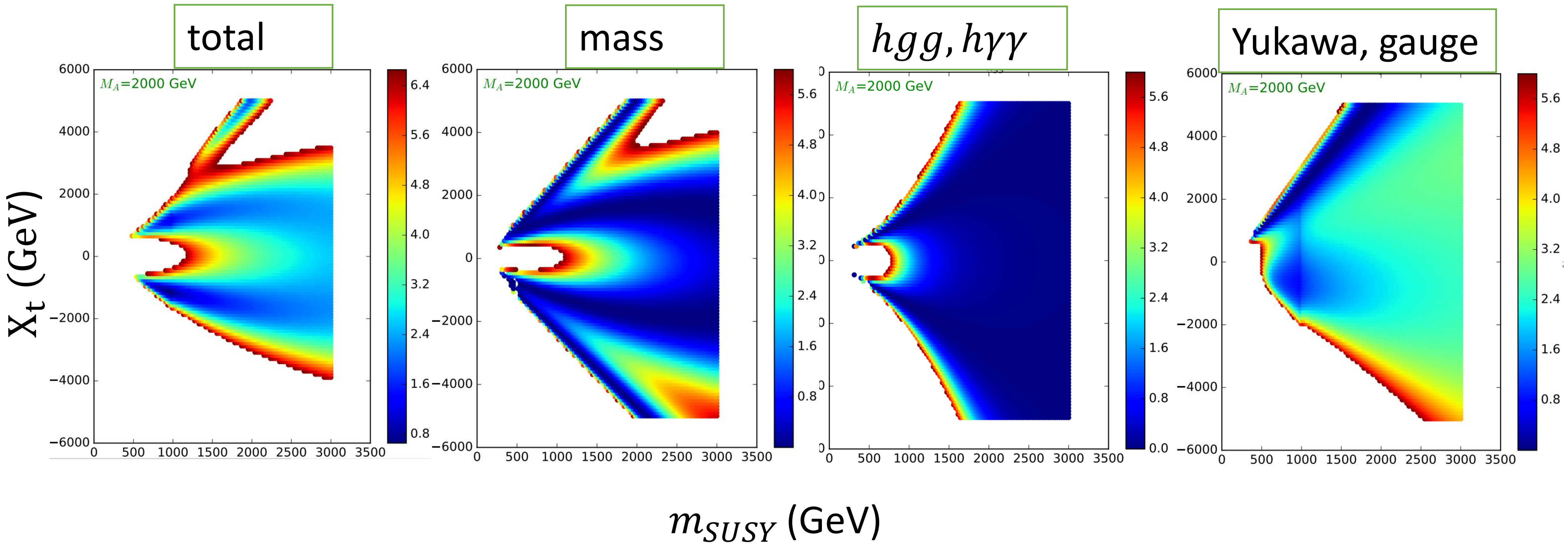
Results: $\mathrm{m_{SUSY}}$ vs $\mathrm{X_t}$

$$\tan\beta = 30, \mu = 500 \text{ GeV}, m_A = 2000 \text{ GeV}$$



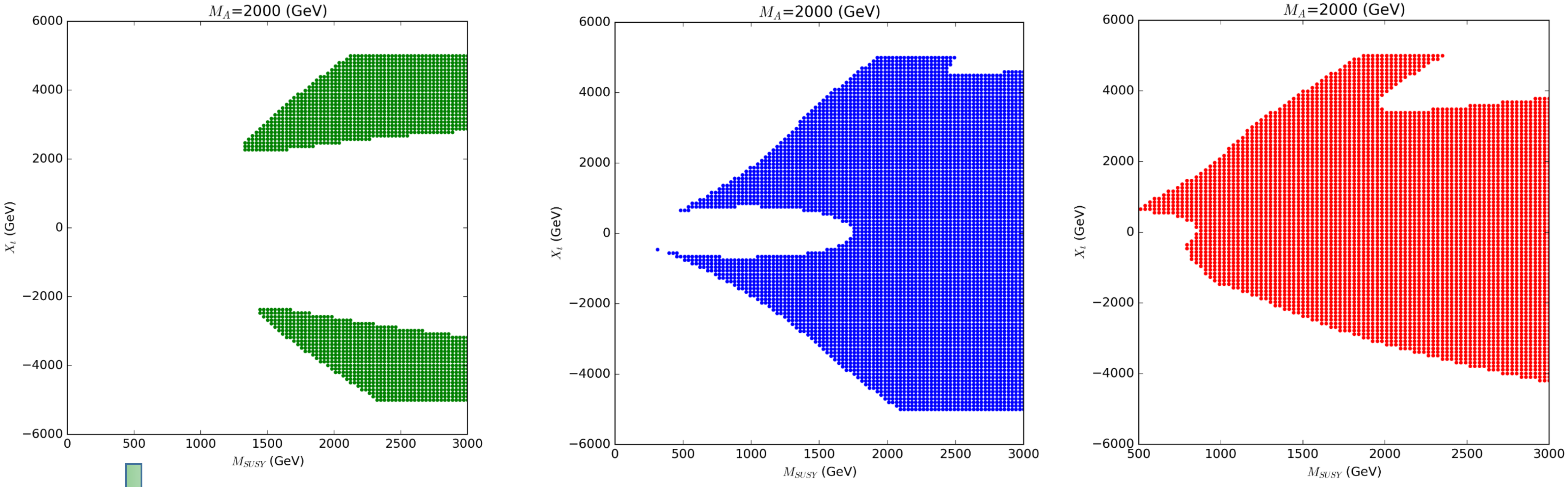
Results: $\mathrm{m_{SUSY}}$ vs $\mathrm{X_t}$

$$\tan\beta = 30, \mu = 500\ \mathrm{GeV}, m_A = 2000\ \mathrm{GeV}$$



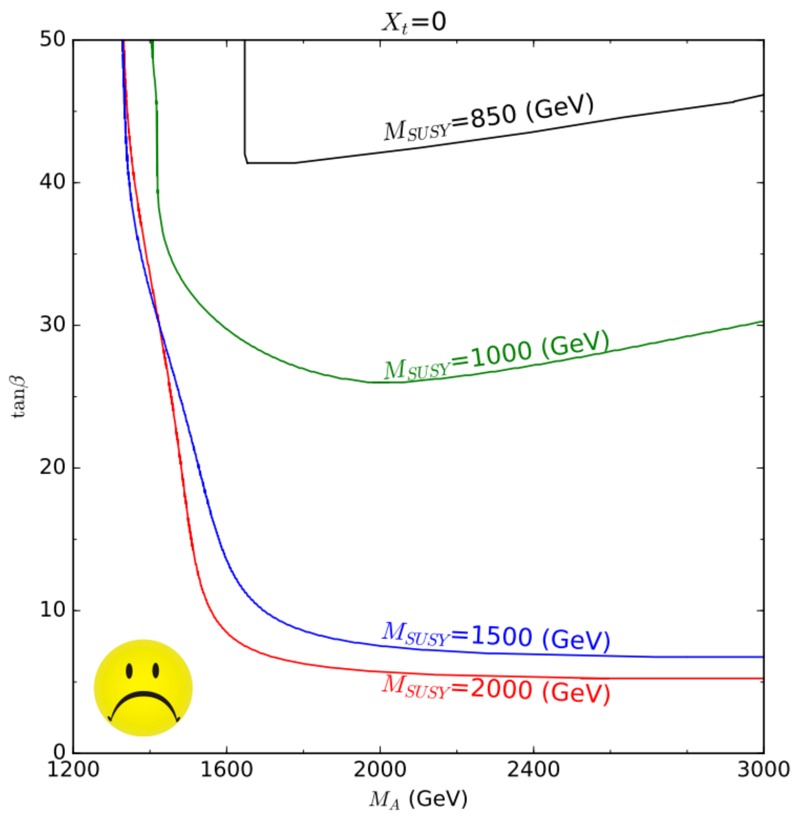
Results: m_{SUSY} vs X_t

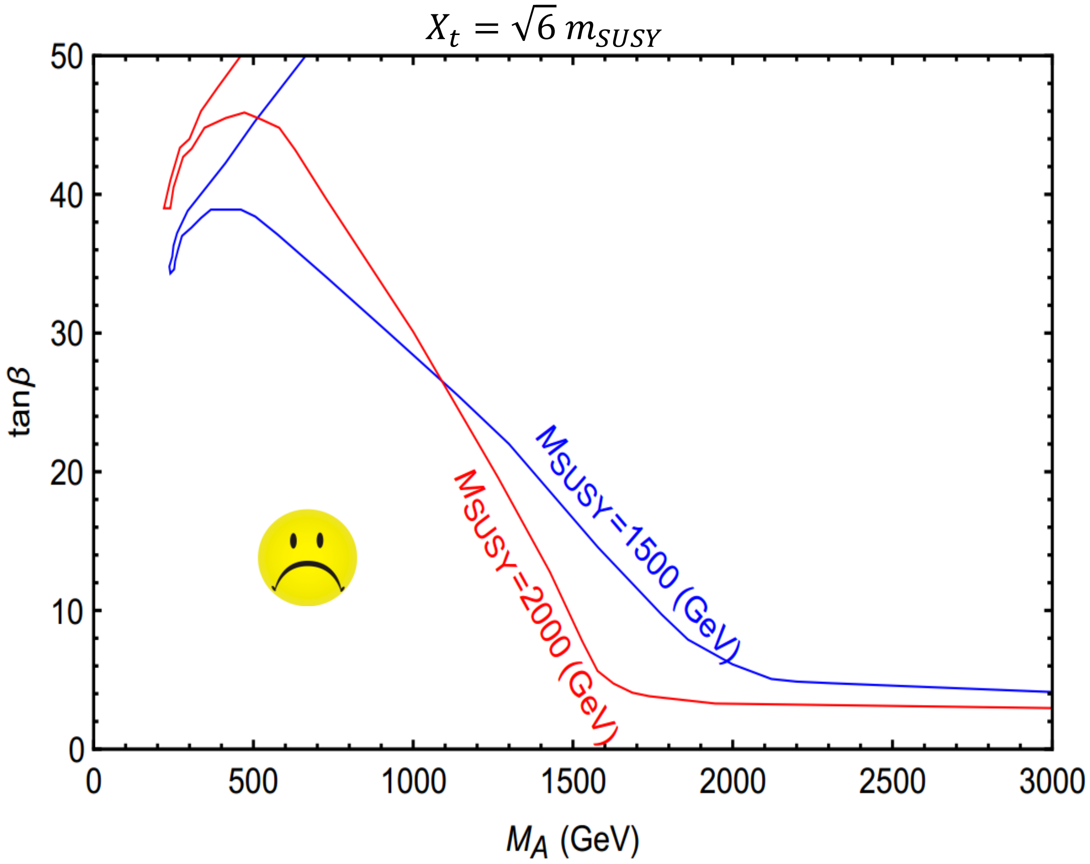
$\tan\beta = 3, \tan\beta = 7, \tan\beta = 50$



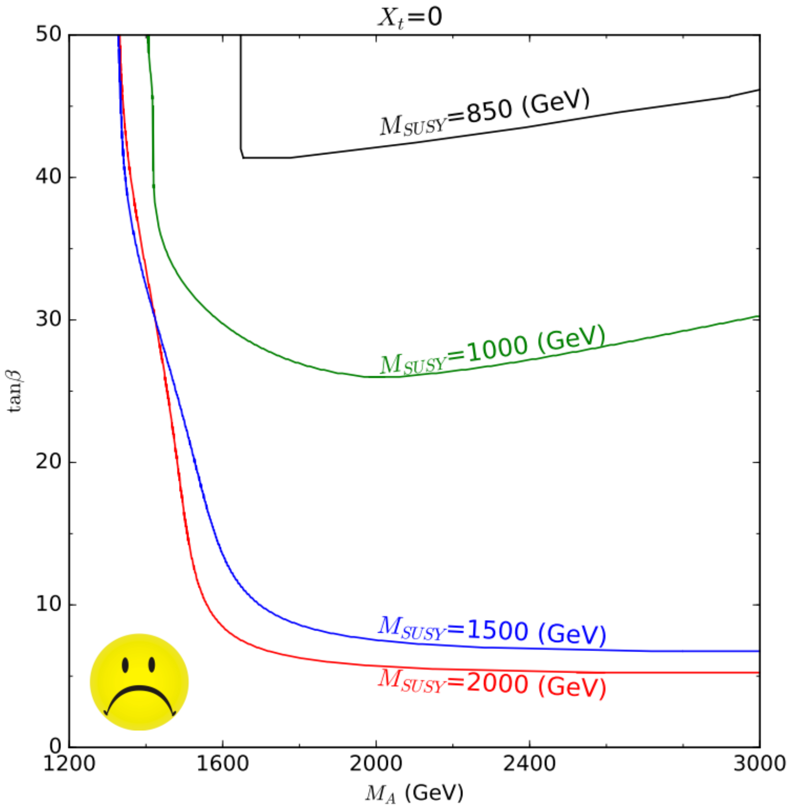
Strongly constrained by Higgs mass precision

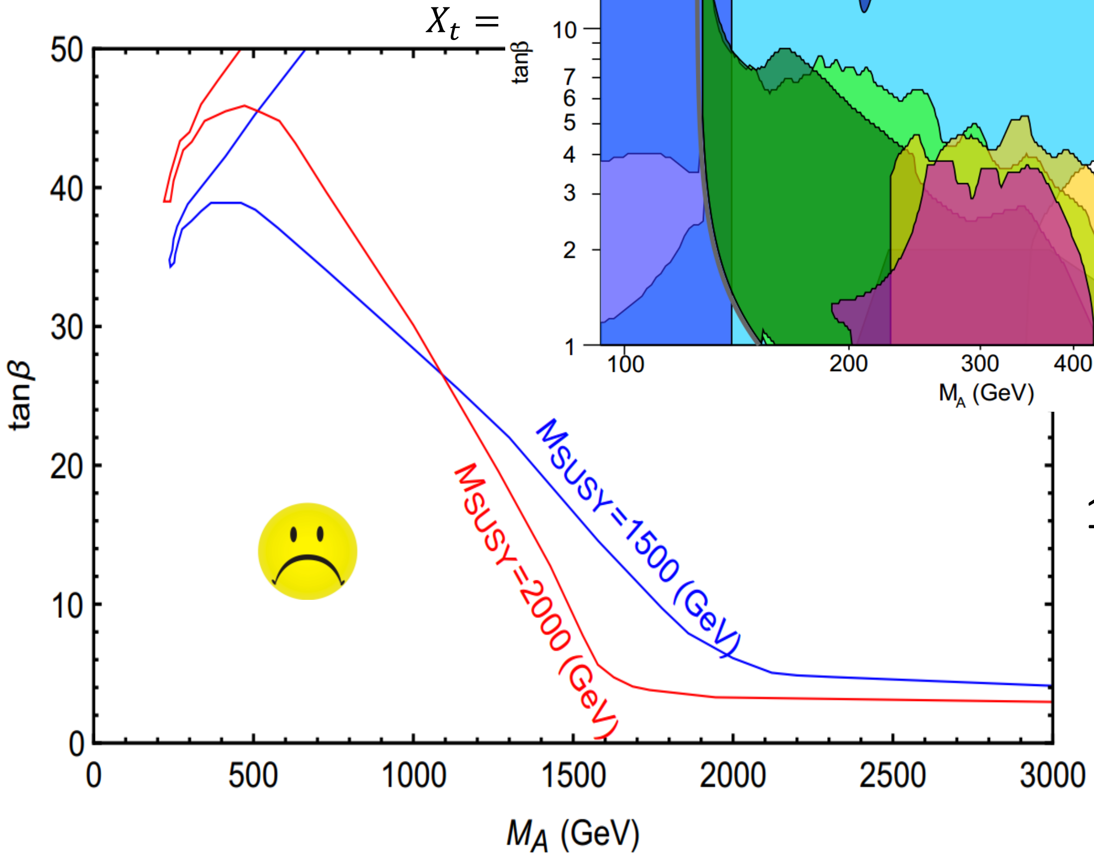
Results: m_A vs $\tan\beta$

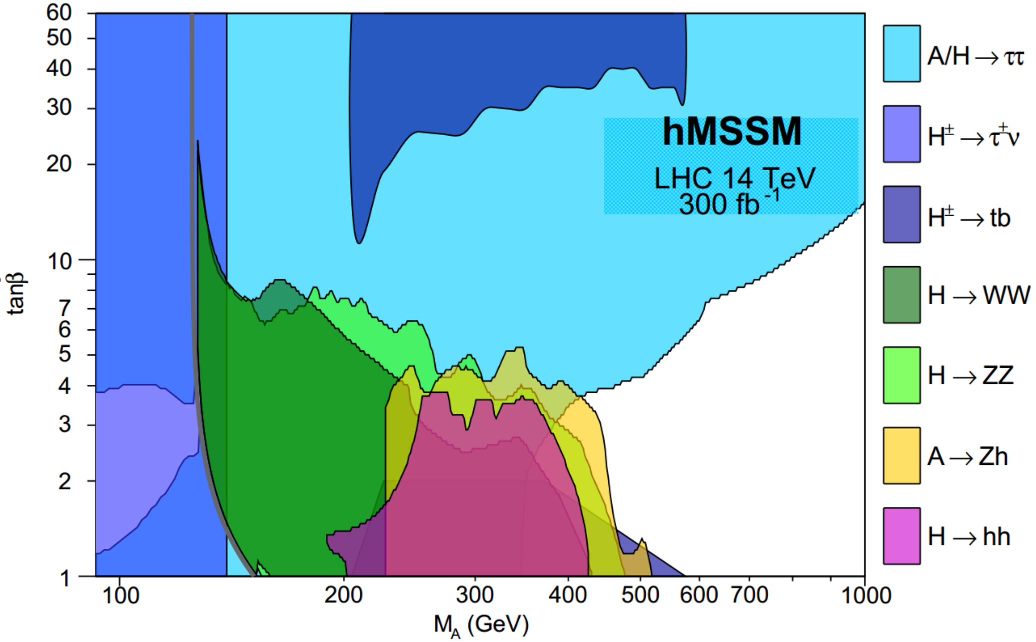




Results: m_A vs $\tan\beta$







1502.05653, A. Djouadi

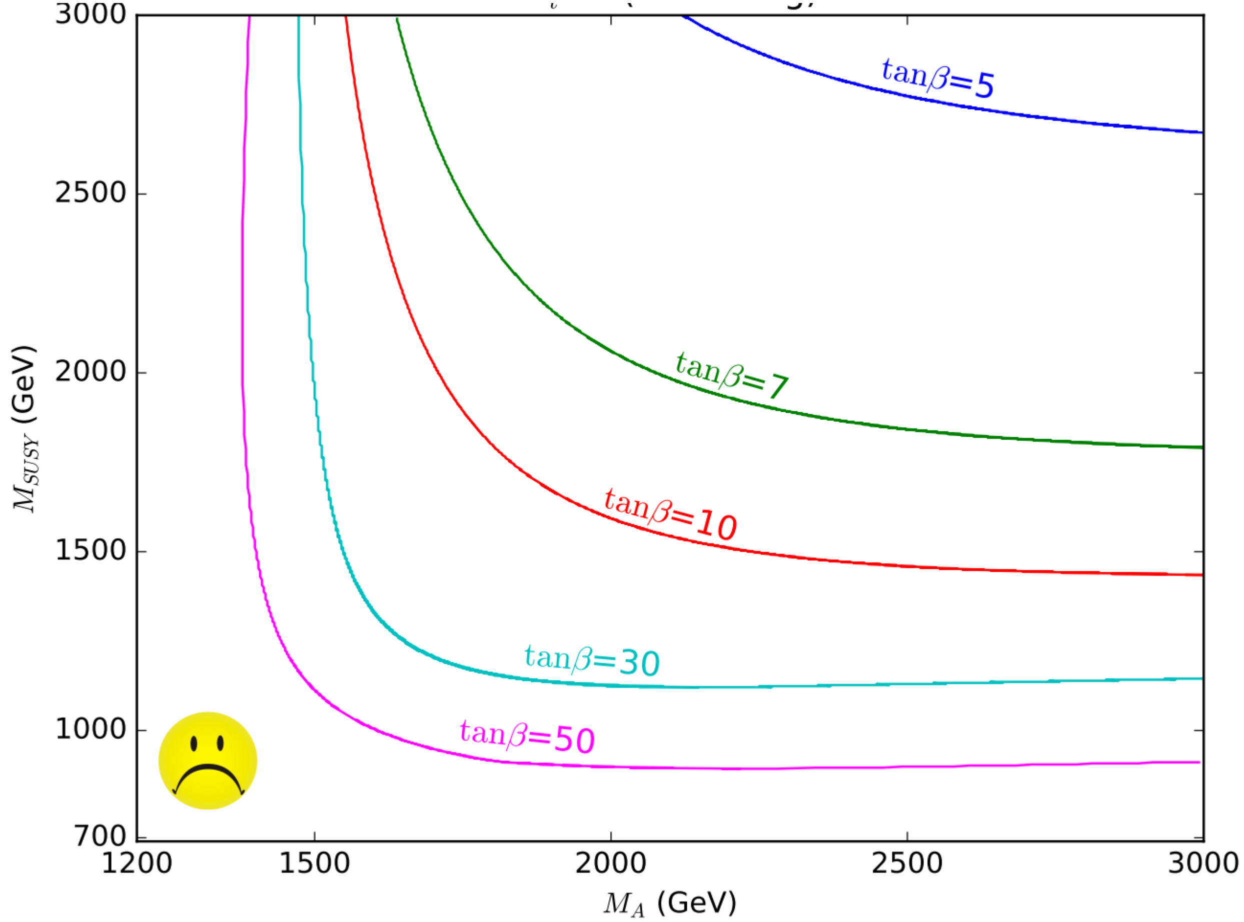
For $\tan\beta \leq 20$, $m_A \leq 1000$ GeV excluded, complementary with LHC Run-II

Results:m_{SUSY} vs m_A

m_A:
Yukawa,gauge

m_{SUSY}:
Small tan β , mass precision
Large tan β, mass + Yukawa,gauge

$X_t = 0$

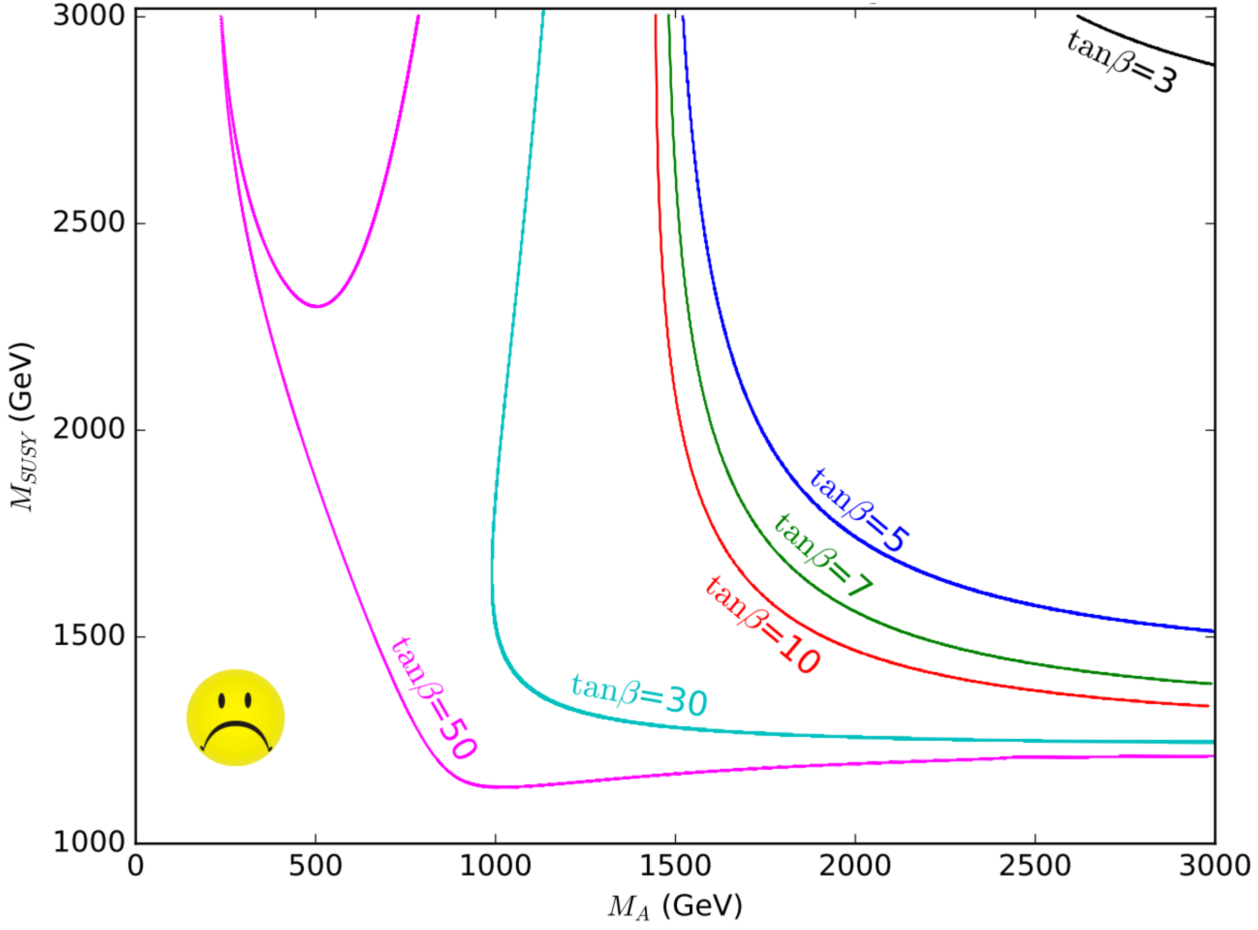


Results: m_{SUSY} vs m_A

m_A:
Yukawa,gauge

m_{SUSY}:
$\tan\beta \geq 7, hgg + h\gamma\gamma$

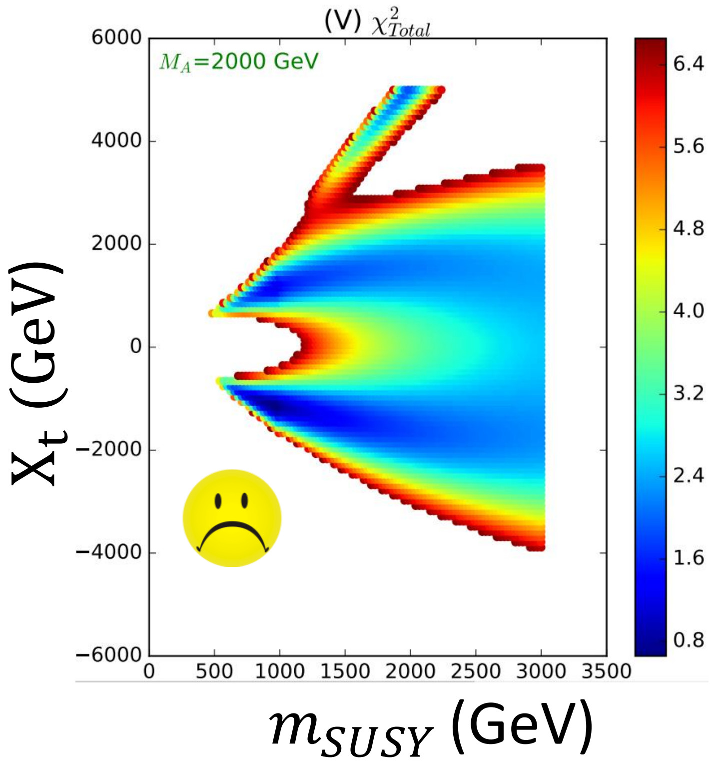
$$X_t = \sqrt{6}\, m_{SUSY}$$

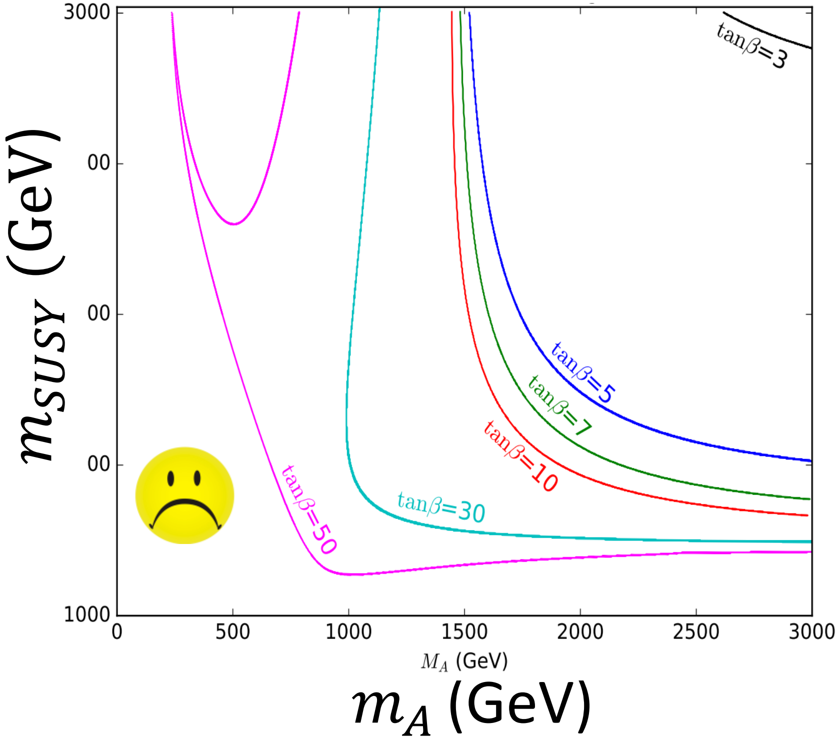


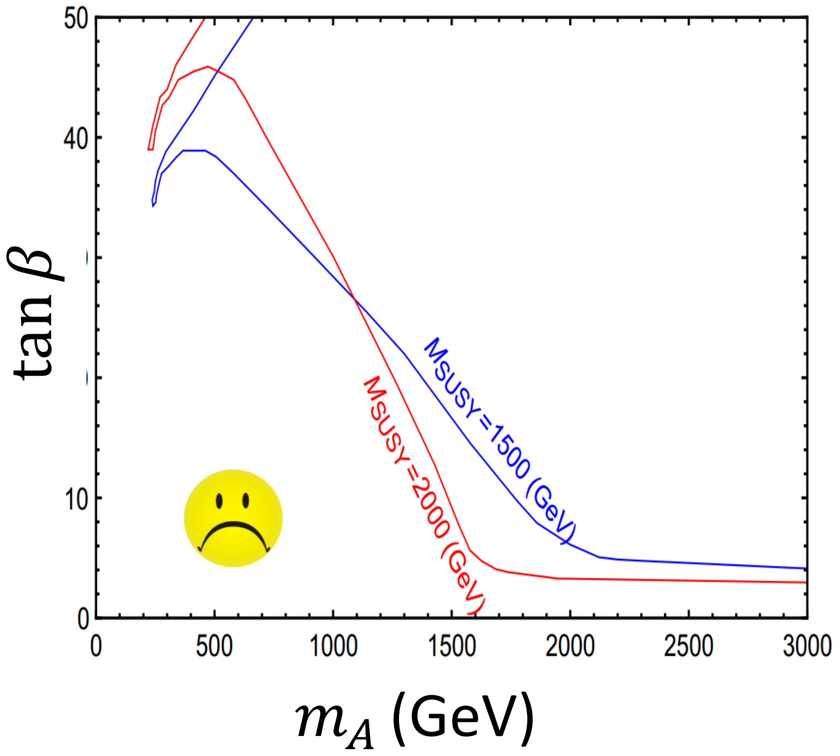
Summary of Higgs precision

$$\boxed{\chi^2_{Total} = \chi^2_{mass} + \chi^2_{\mu}}$$

$$X_t = \sqrt{6}\, m_{SUSY}$$







Z pole precision on MSSM

Z pole precision on MSSM

EWPT (Electroweak Precision Test)

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^{0} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480

FCC-ee, ILC, CEPC $10^{10}\sim10^{12}$,
precision of $\mathrm{R_b}$ $10^{-4}\sim10^{-5}$

$$\delta R_b = 2 \times 10^{-5}$$

Z pole precision on MSSM

R_b:

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}$$

$$\Delta^{\text{SUSY}}(R_b) = 0.2196\{0.78[\nabla_b^{\text{SUSY}}(m_t) - \nabla_b^{\text{SUSY}}(0)]$$

Advantages:

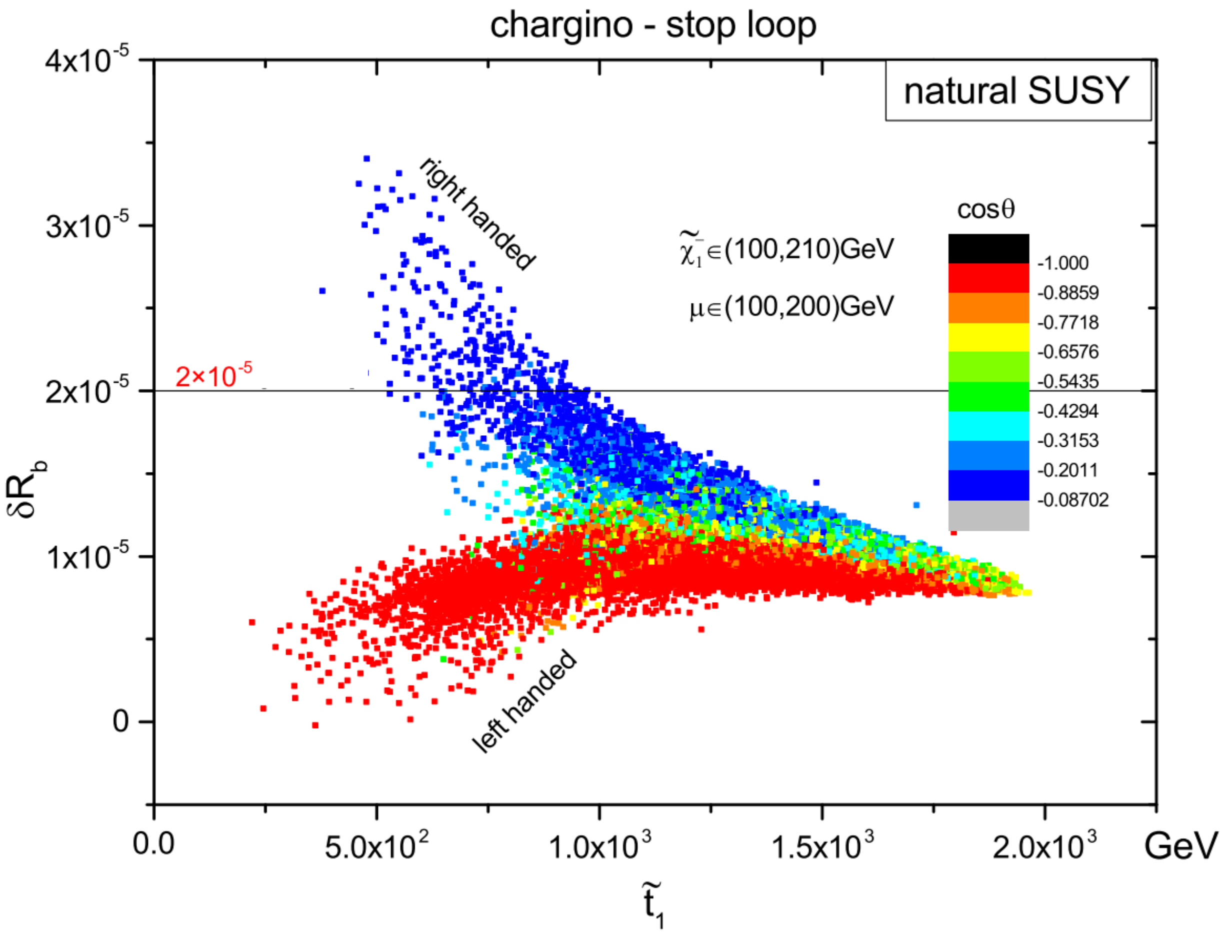
1、 Loop-level $Z \to b\bar{b}$ vertex effects are sizable

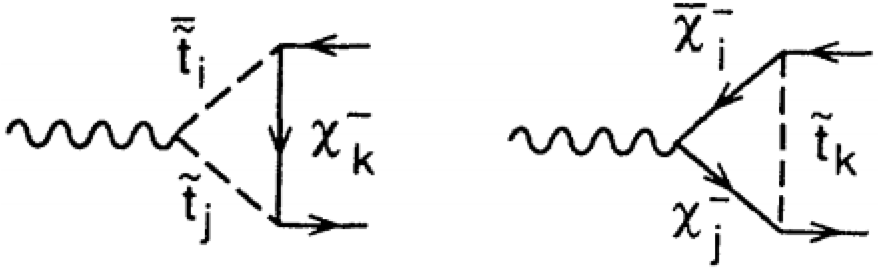
stop, sbottom, charged Higgs, neutral Higgs

2、 Weak dependence on oblique corrections

3、 Measurable

Results: stop correction





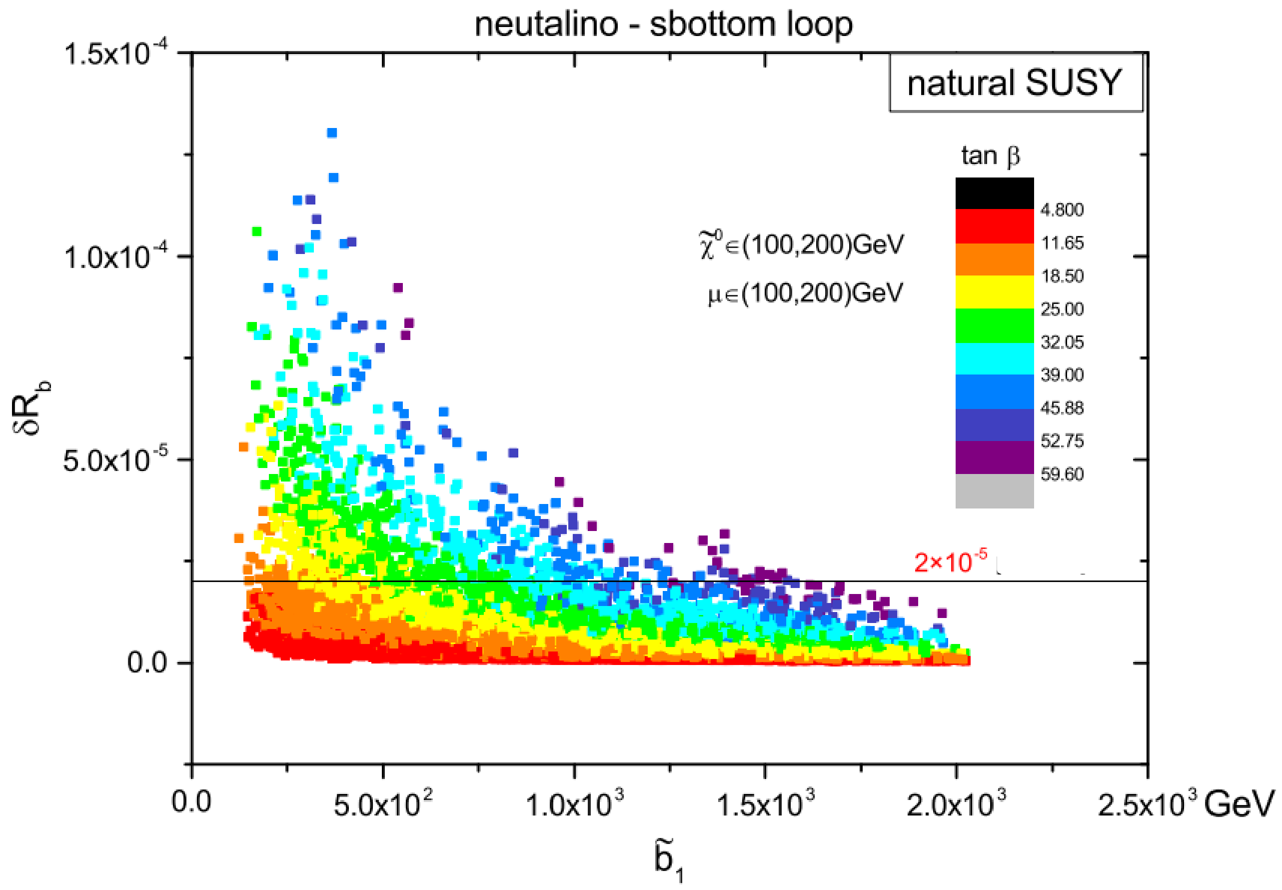
- Condition：

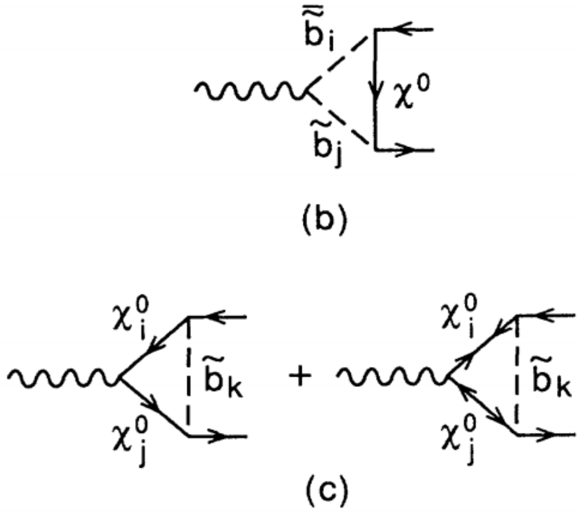
  $\tilde{\chi}_1{}^{\pm}$: 100 - 200GeV

- Result:

  $\tilde{t}_1^R$ > 530 GeV

Results: sbottom correction





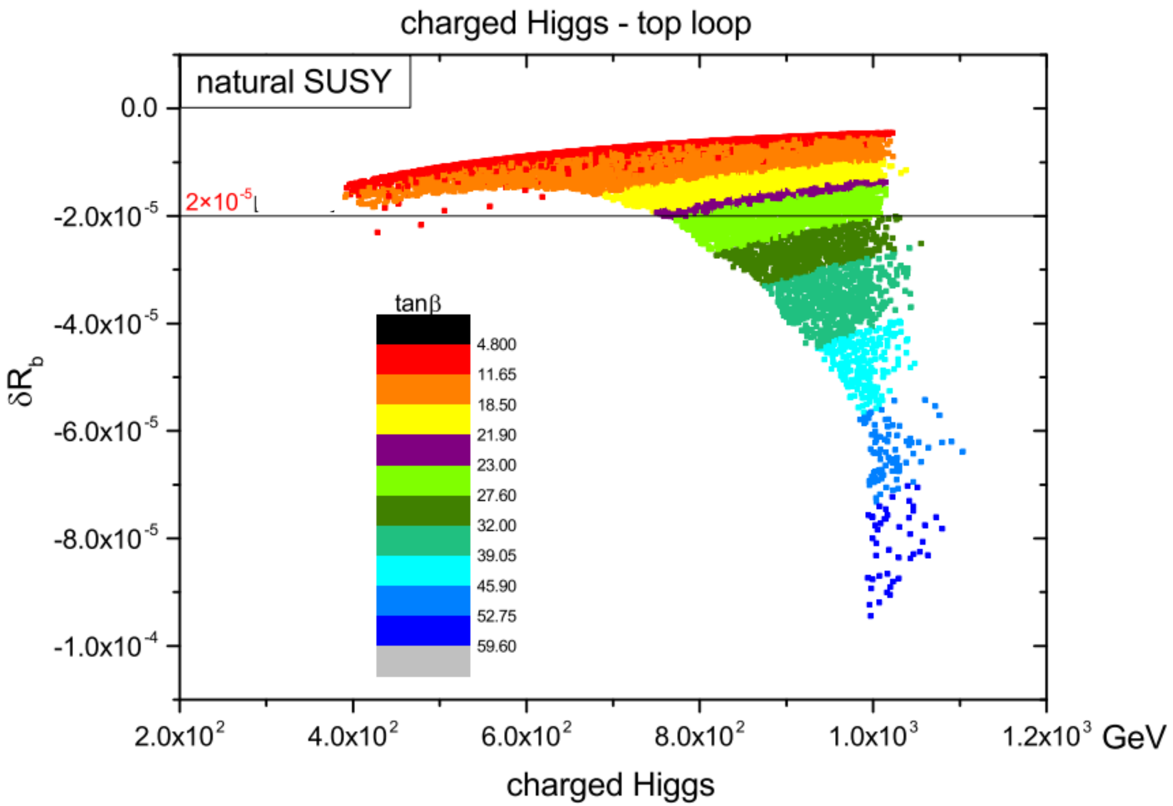
Condition：

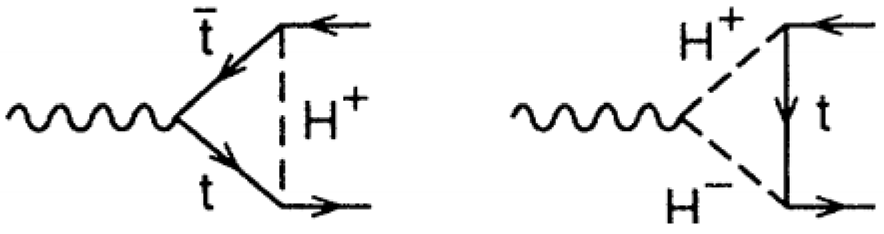
$\tilde{\chi}_1^0$: 100 - 200GeV

Conclusion:

$\tilde{b}_1$ > 850 GeV if $\tan\beta > 32$

Results: charged Higgs correction

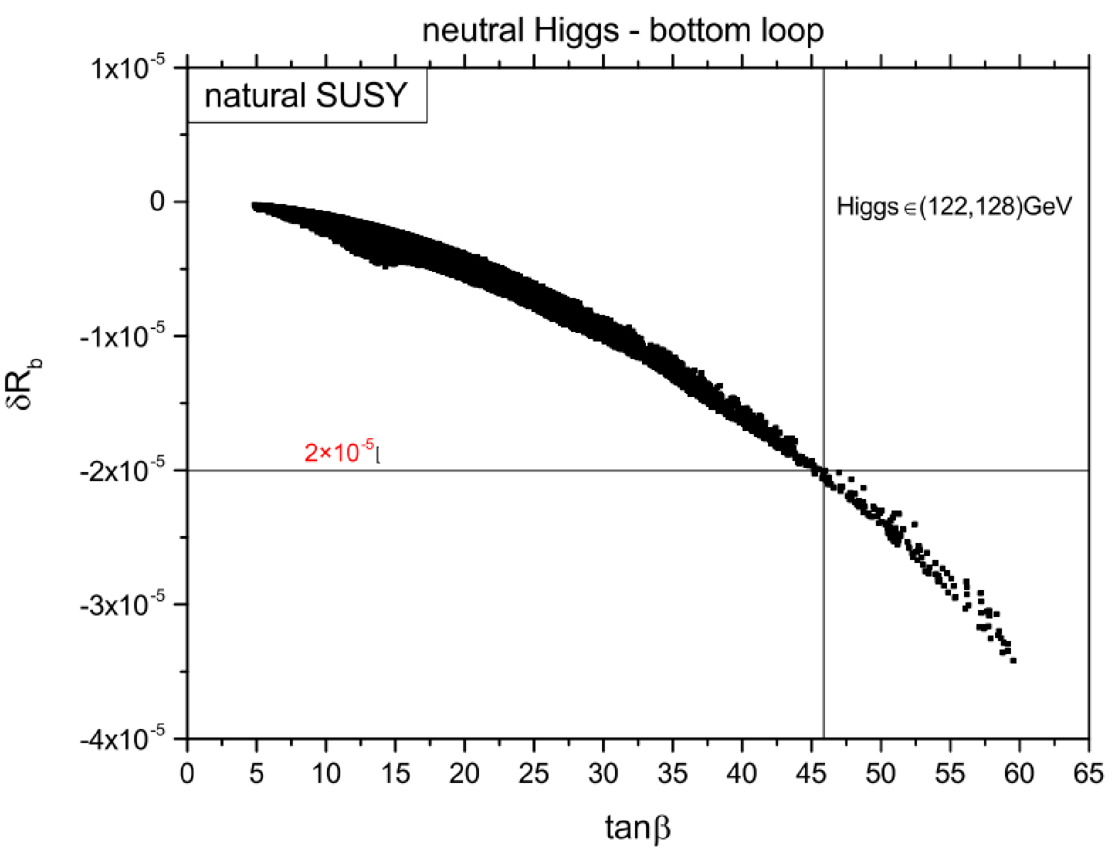


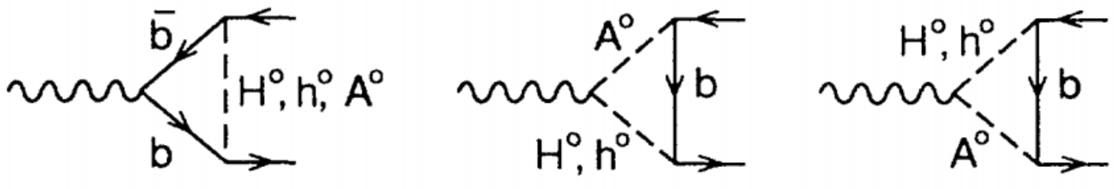


- Conclusion:

  $m_{H^\pm} > 1000$ GeV if $\tan\beta > 28$

Results: neutral Higgs correction





- Conclusion:

$\tan\beta < 46$ is allowable

conclusion

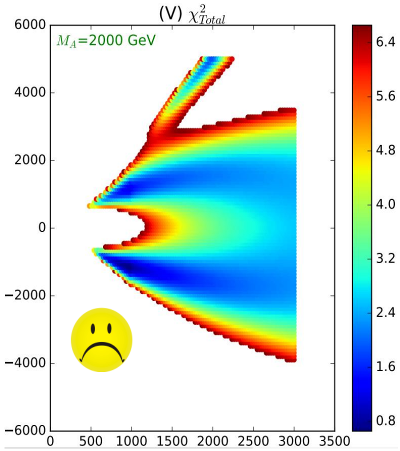
- Higgs Precision

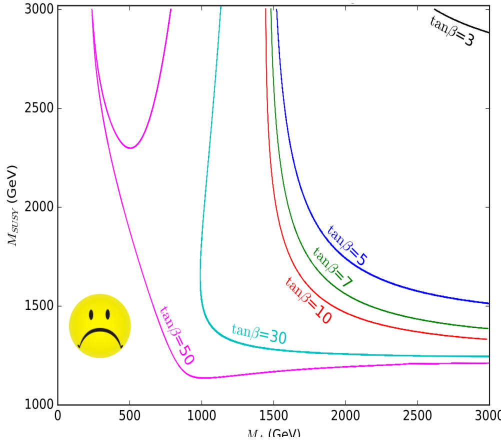
Higgs mass + $h\gamma\gamma$ and hgg + Yukawa and gauge

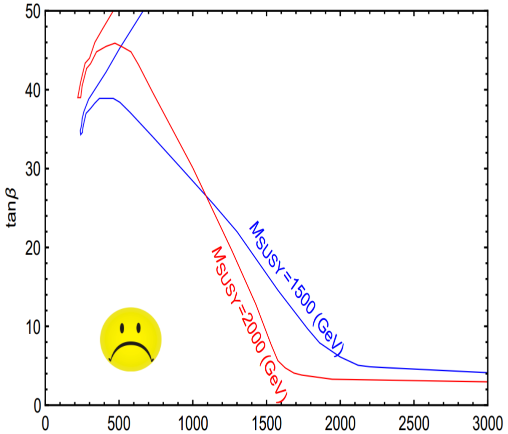
- $\mathrm{m_{SUSY}}$ vs $\mathrm{X_t}$: strong constraint on stop sector
- $\mathrm{m_A}$ vs $\mathrm{m_{SUSY}}$: precision to constraints
- m_A vs $tan\beta$: complementary with LHC Run-II

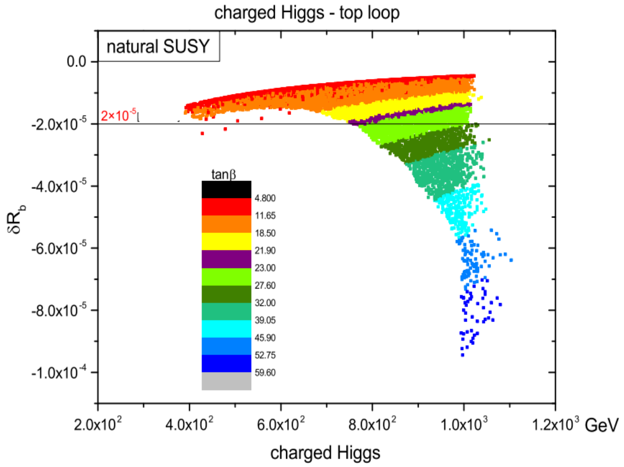
- Z Precision: R_b

  - stop, sbottom, charged Higgs, neutral Higgs







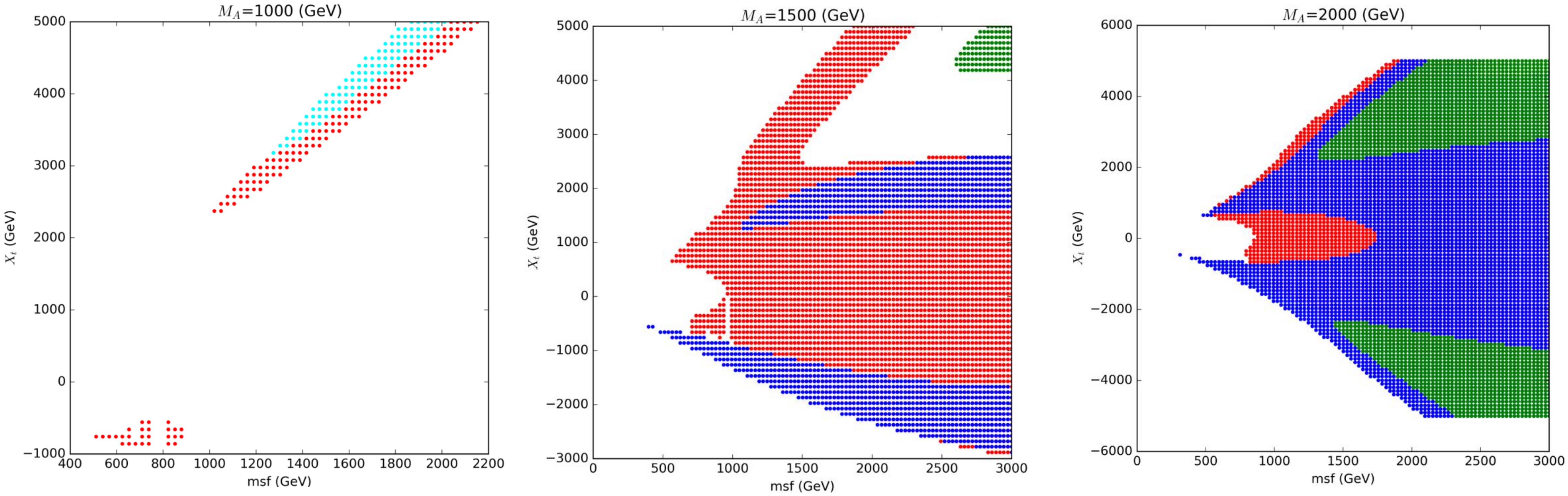


Thanks for your attention

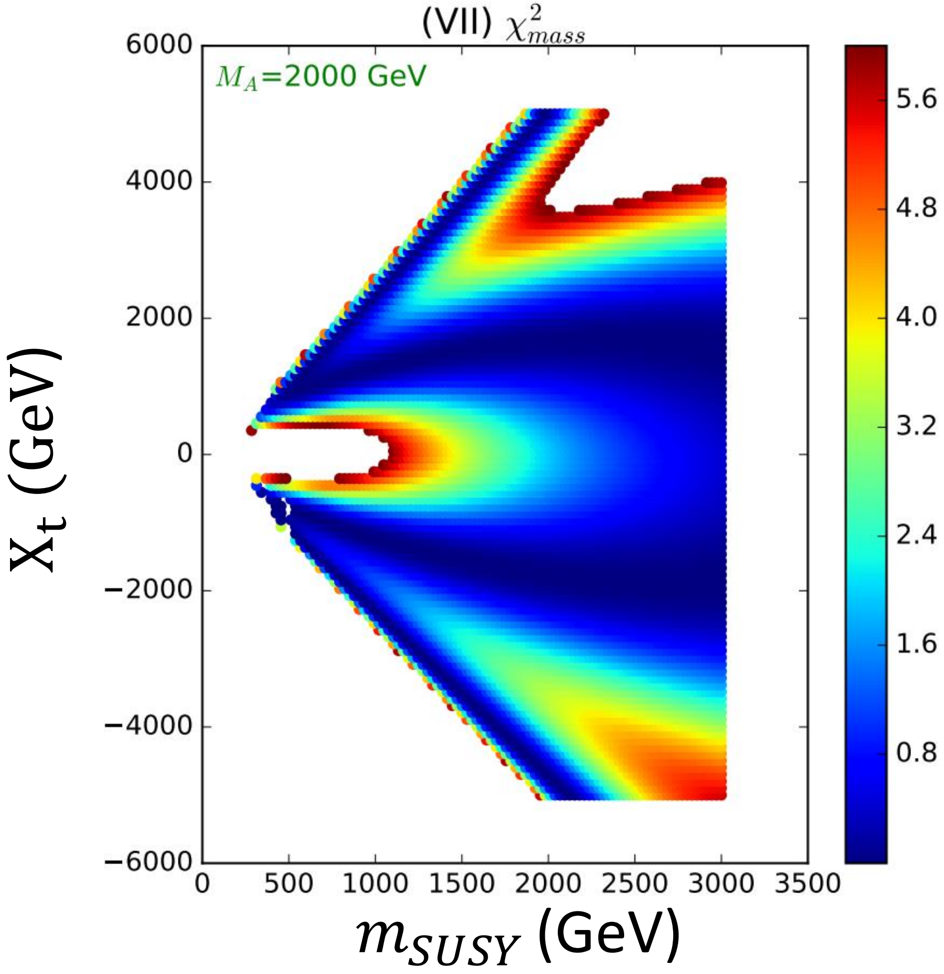
Results: $\mathrm{m_{SUSY}}$ vs $\mathrm{X_t}$

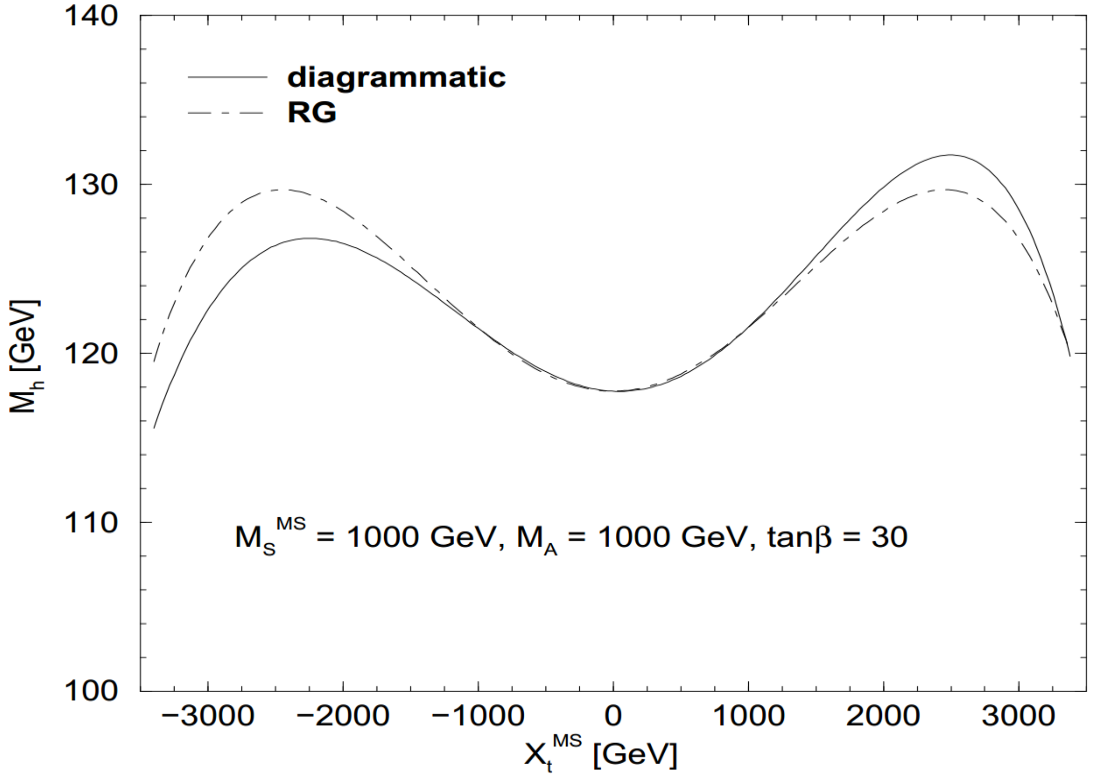
$\mathrm{m_{SUSY}}$ vs $\mathrm{X_{\tilde{t}}}$

$\tan\beta = 3, \tan\beta = 7, \tan\beta = 50$

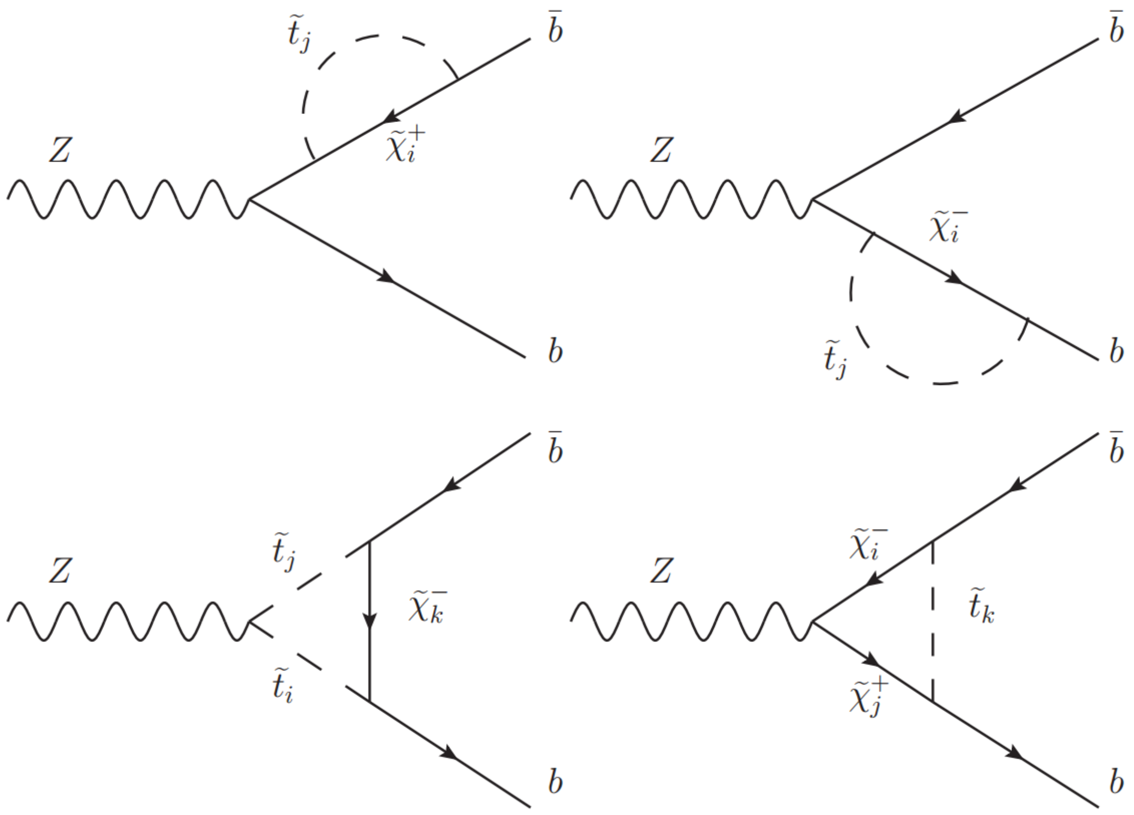


Yukawa and Gauge couplings


(VII) χ^2_{mass}
M_A=2000 GeV
6000
4000
2000
0
−2000
−4000
−6000
0 500 1000 1500 2000 2500 3000 3500
5.6
4.8
4.0
3.2
2.4
1.6
0.8
X_t (GeV)
m_{SUSY} (GeV)


diagrammatic
RG
140
130
120
110
100
M_h [GeV]
M_S^{MS} = 1000 GeV, M_A = 1000 GeV, tanβ = 30
−3000 −2000 −1000 0 1000 2000 3000
X_t^{MS} [GeV]

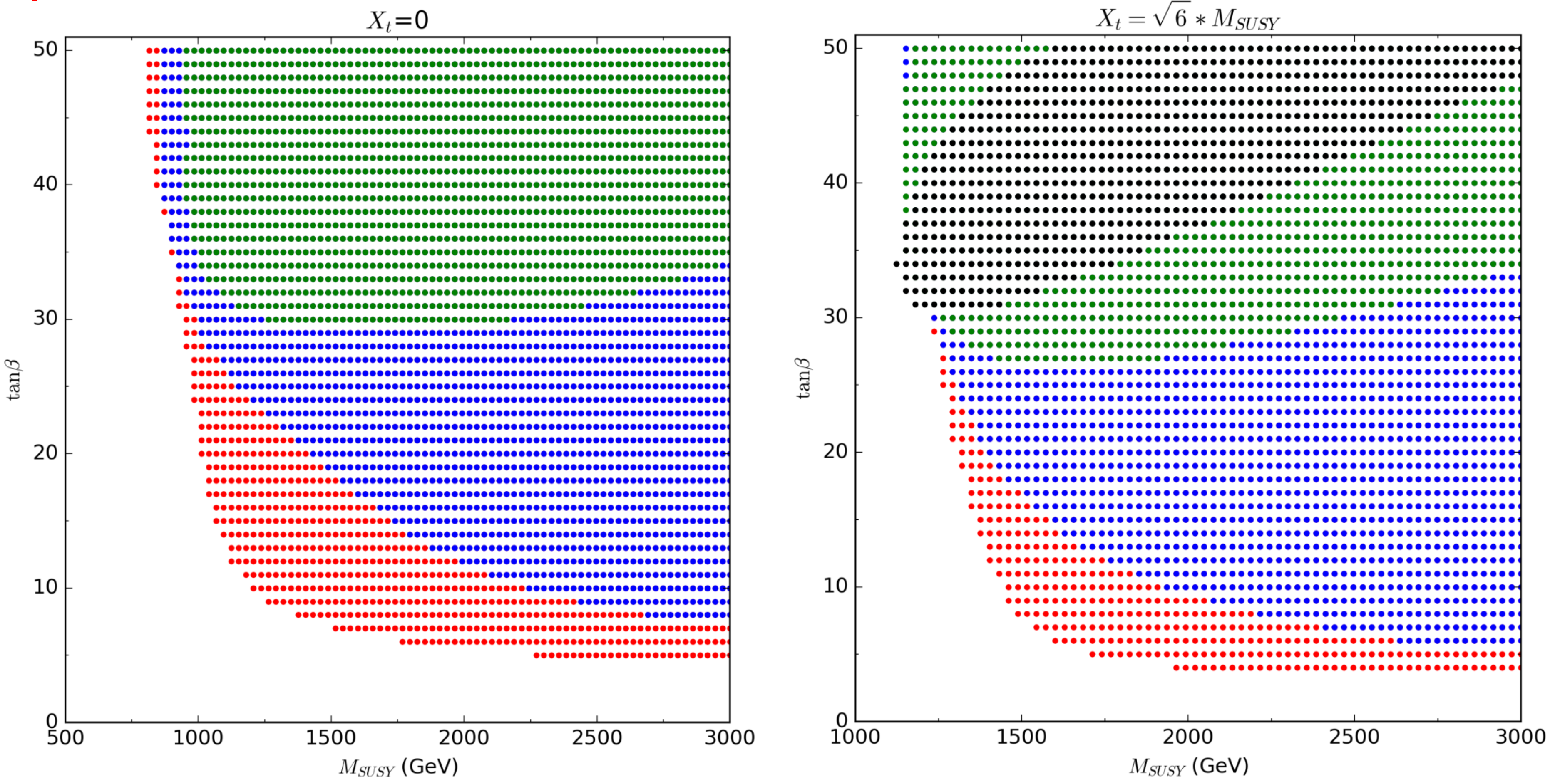
$$
\begin{aligned}
\Delta m_b^{SEW} &= \frac{h_t^2}{16\pi^2}\mu A_t \tan\beta I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) \\
&- \frac{g^2}{16\pi^2}\mu M_2 \tan\beta \Big[\cos^2\theta_{\tilde{t}} I(m_{\tilde{t}_1}, M_2, \mu) + \sin^2\theta_{\tilde{t}} I(m_{\tilde{t}_2}, M_2, \mu) \\
&+ \frac{1}{2}\cos^2\theta_{\tilde{b}} I(m_{\tilde{b}_1}, M_2, \mu) + \frac{1}{2}\sin^2\theta_{\tilde{b}} I(m_{\tilde{b}_2}, M_2, \mu)\Big]
\end{aligned}
$$


$\tilde{t}_j$
$\bar{b}$
Z
$\tilde{\chi}_i^+$
b
$\bar{b}$
Z
$\tilde{\chi}_i^-$
$\tilde{t}_j$
b
$\bar{b}$
Z
$\tilde{t}_j$
$\tilde{\chi}_k^-$
$\tilde{t}_i$
b
$\bar{b}$
$\tilde{\chi}_i^-$
Z
$\tilde{t}_k$
$\tilde{\chi}_j^+$
b

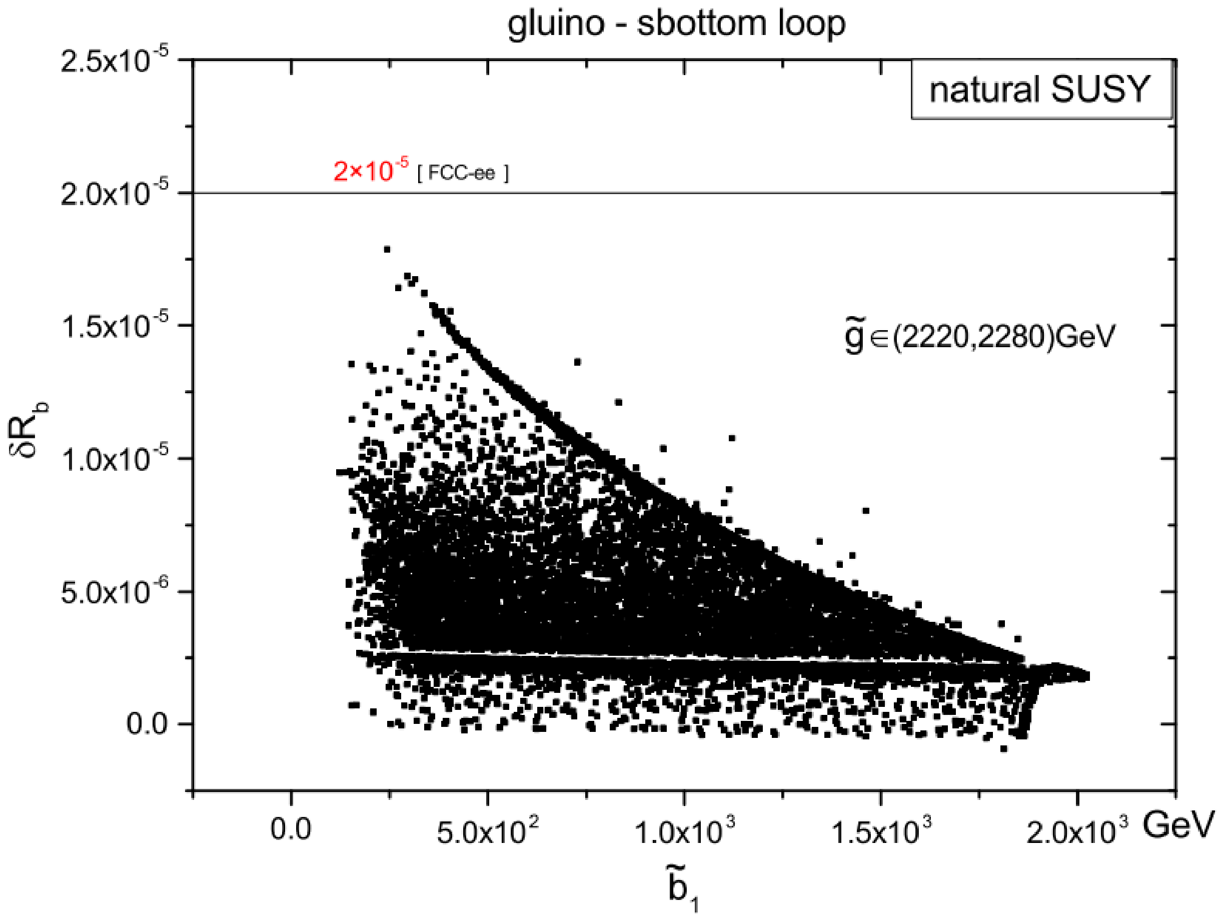
Higgs precision on MSSM

m_{SUSY} vs $\tan\beta$

$m_A = 700$
$m_A = 1000$
$m_A = 1500$
$m_A = 2000$



Results: gluino correction



Because gluino and neutralino are both electroneutral, they have same Feynman diagrams

- Conclusion:

Because gluino required by experiments is so heavy that its correction is negligible.

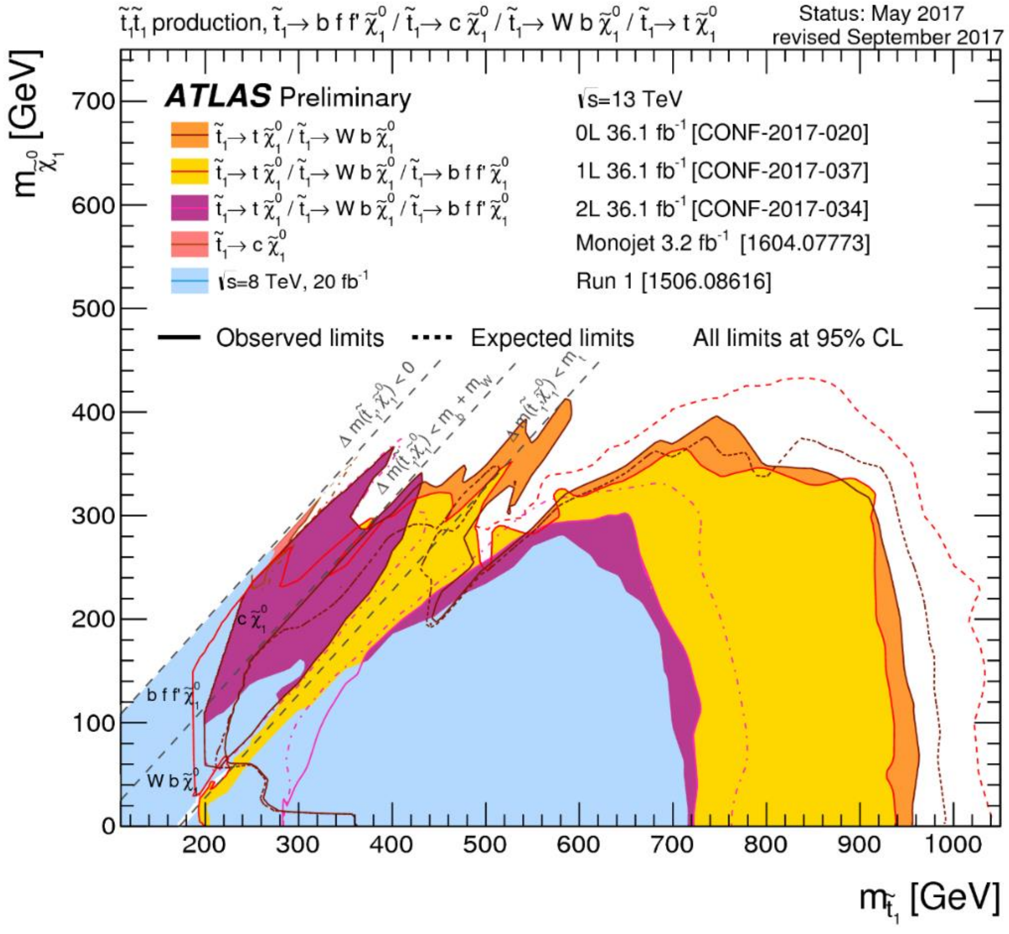
Higgs precision on MSSM

Current researches

- Higgs mass is well-measured (compared to theory estimation)
- $h\gamma\gamma$ and hgg channels are well studied

$$r_G^{\tilde{t}} \equiv \frac{c_{hgg}^{\tilde{t}}}{c_{hgg}^{\mathrm{SM}}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

$$r_\gamma^{\tilde{t}} \equiv \frac{c_{h\gamma\gamma}^{\tilde{t}}}{c_{h\gamma\gamma}^{\mathrm{SM}}} = \frac{\mathcal{A}_{\tilde{t}}^{\gamma}}{(\mathcal{A}_W^{\gamma} + \mathcal{A}_t^{\gamma})^{\mathrm{SM}}} \approx -0.28 r_G^{\tilde{t}}$$



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$
Status: May 2017
revised September 2017
ATLAS Preliminary
$\sqrt{s}$=13 TeV
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$
0L 36.1 fb^{-1} [CONF-2017-020]
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$
1L 36.1 fb^{-1} [CONF-2017-037]
$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}_1^0$
2L 36.1 fb^{-1} [CONF-2017-034]
$\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$
Monojet 3.2 fb^{-1} [1604.07773]
$\sqrt{s}$=8 TeV, 20 fb^{-1}
Run 1 [1506.08616]
Observed limits
Expected limits
All limits at 95% CL
$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0) < 0$
$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0) < m_b + m_W$
$\Delta m(\tilde{t}_1,\tilde{\chi}_1^0) < m_t$
$c \tilde{\chi}_1^0$
$b f f' \tilde{\chi}_1^0$
$W b \tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
100
200
300
400
500
600
700
200
300
400
500
600
700
800
900
1000

Higgs precision on MSSM

Current researches

fit with 13 TeV data

1710.11091

	Best fit
M_1	0.25 TeV
M_2	0.25 TeV
M_3	- 3.86 TeV
$m_{\tilde{q}}$	4.0 TeV
$m_{\tilde{q}_3}$	1.7 TeV
$m_{\tilde{\ell}}$	0.35 TeV
$m_{\tilde{\tau}}$	0.46 TeV
M_A	4.0 TeV
A	2.8 TeV
μ	1.33 TeV
$\tan\beta$	36

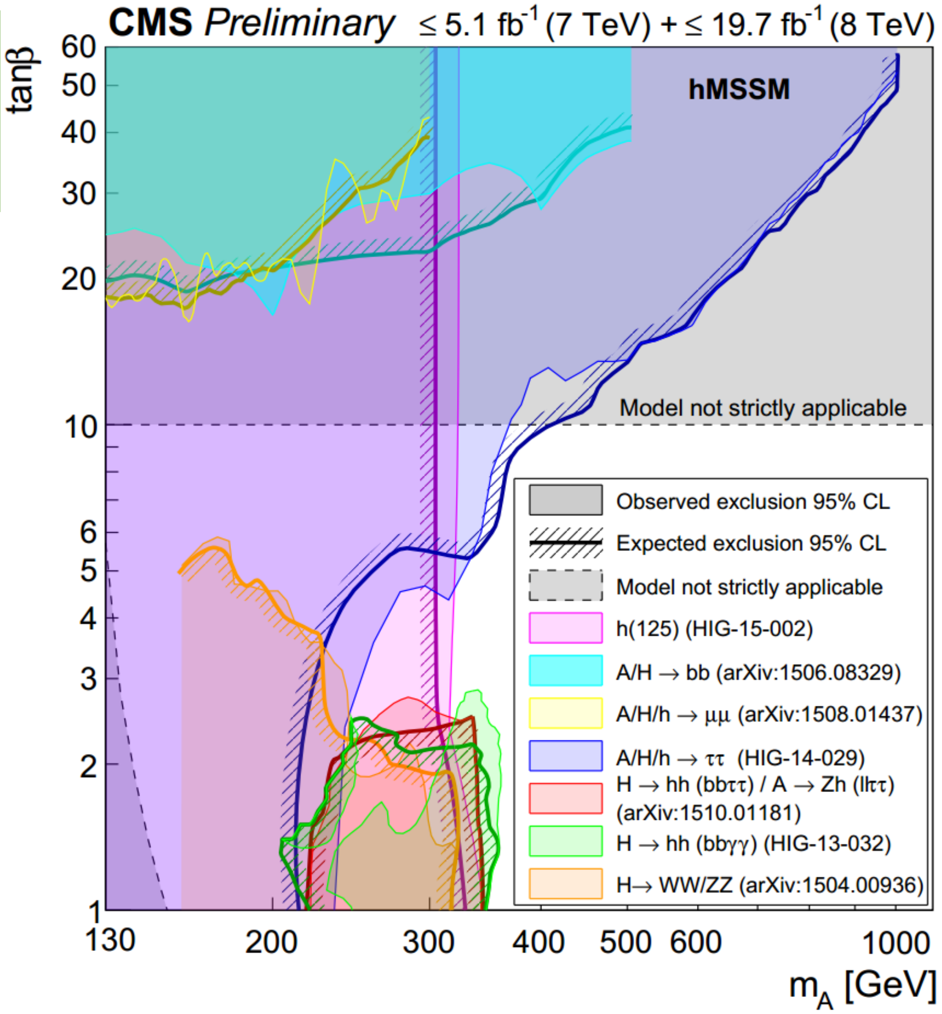
Further research

- Direct search
- Higgs precision
- Electroweak Precision
- Theoretical constraints(1310.4174)
- Dark Matter

Higgs precision on MSSM

Current researches

Direct search
7+8 TeV

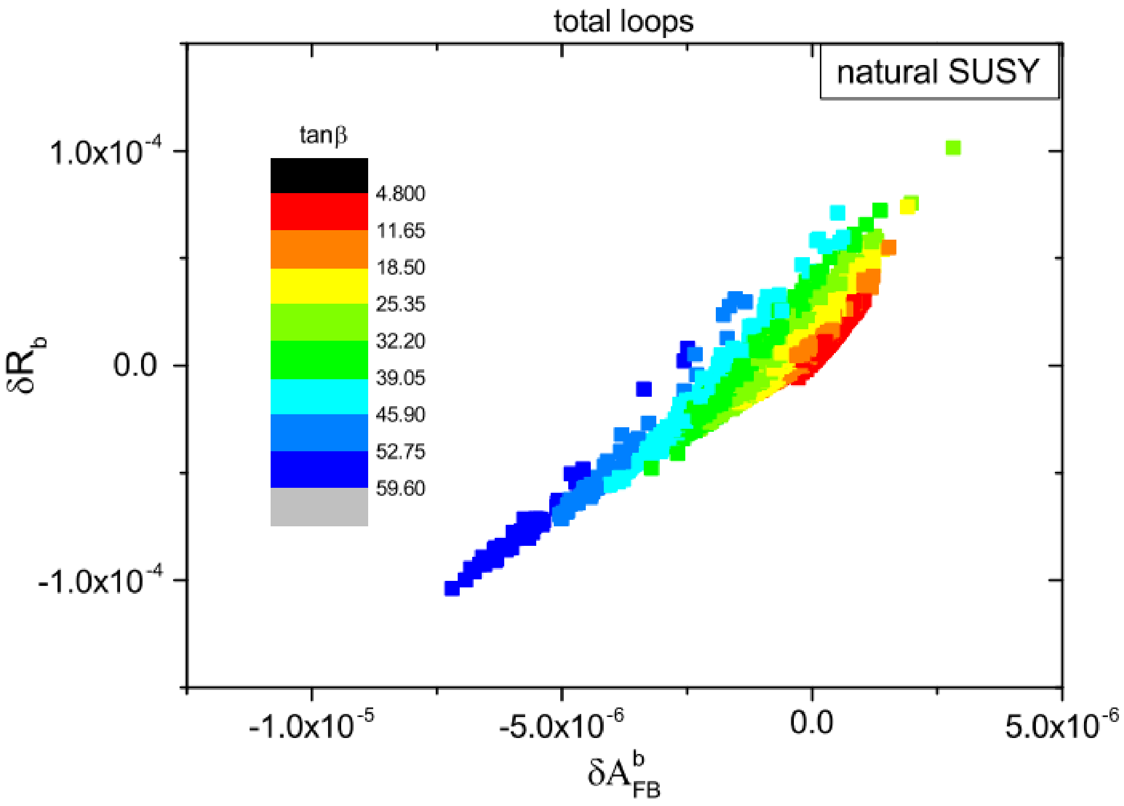


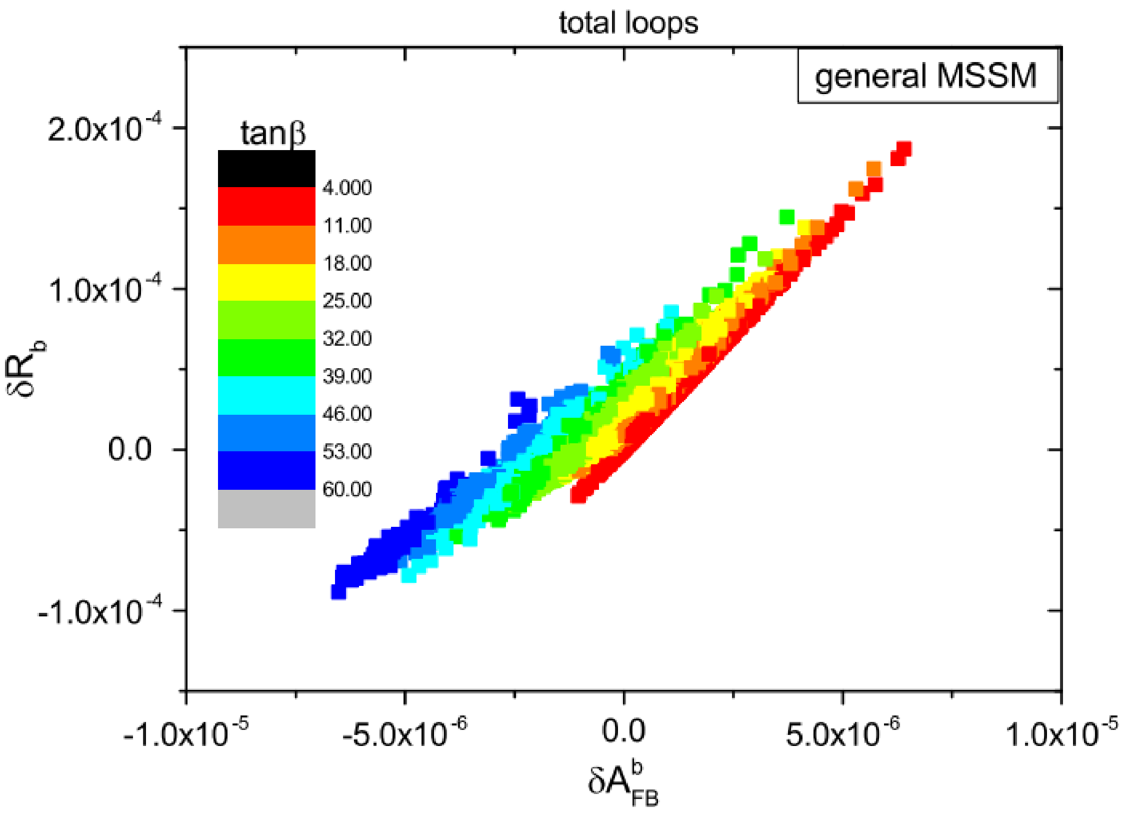
CMS-HIG-16-007-pas

Results: δA_{FB}^{b}

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta$$





Two order in need for δA_{FB}^{b}