MSSM
at Future Higgs Factories

Shufang Su • U. of Arizona

Lomonosov Conference
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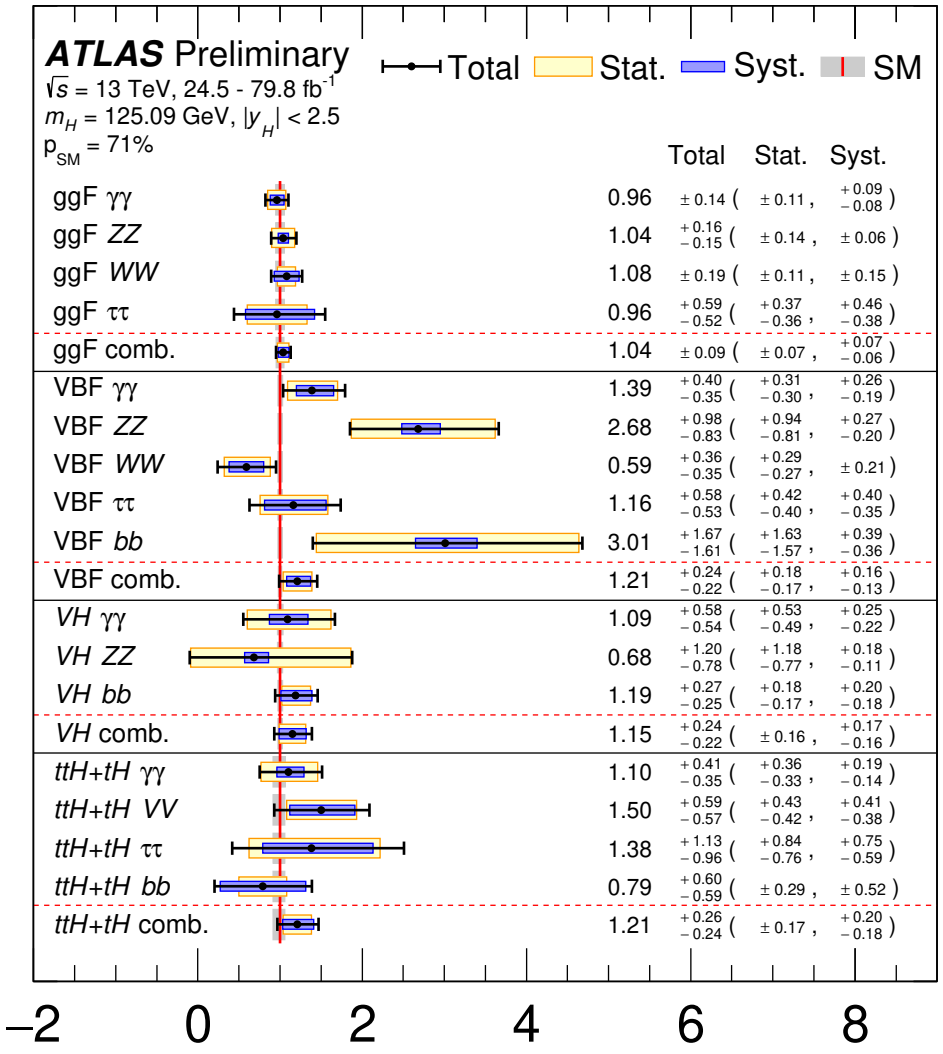
H. Li, SS, W. Su, J. Yang, 2010.09782

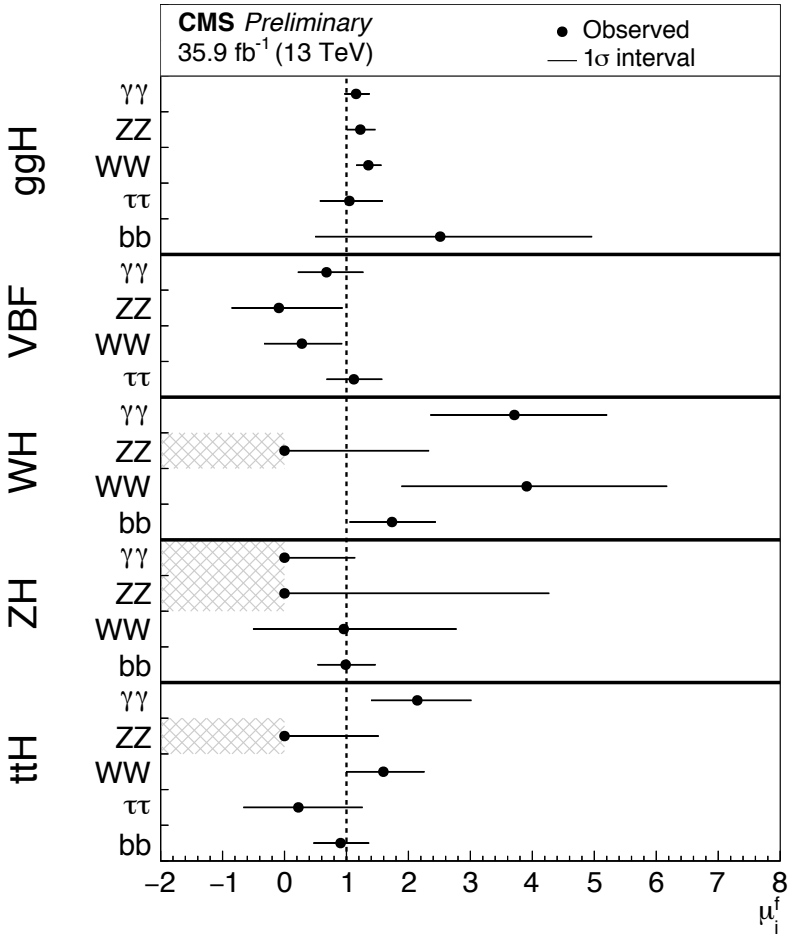
Outline

- Higgs precision measurements
- Global fit framework
- Explore MSSM parameter space
- Complementarity with direct search
- Conclusion

Higgs Precision Measurements

LHC: 13 TeV

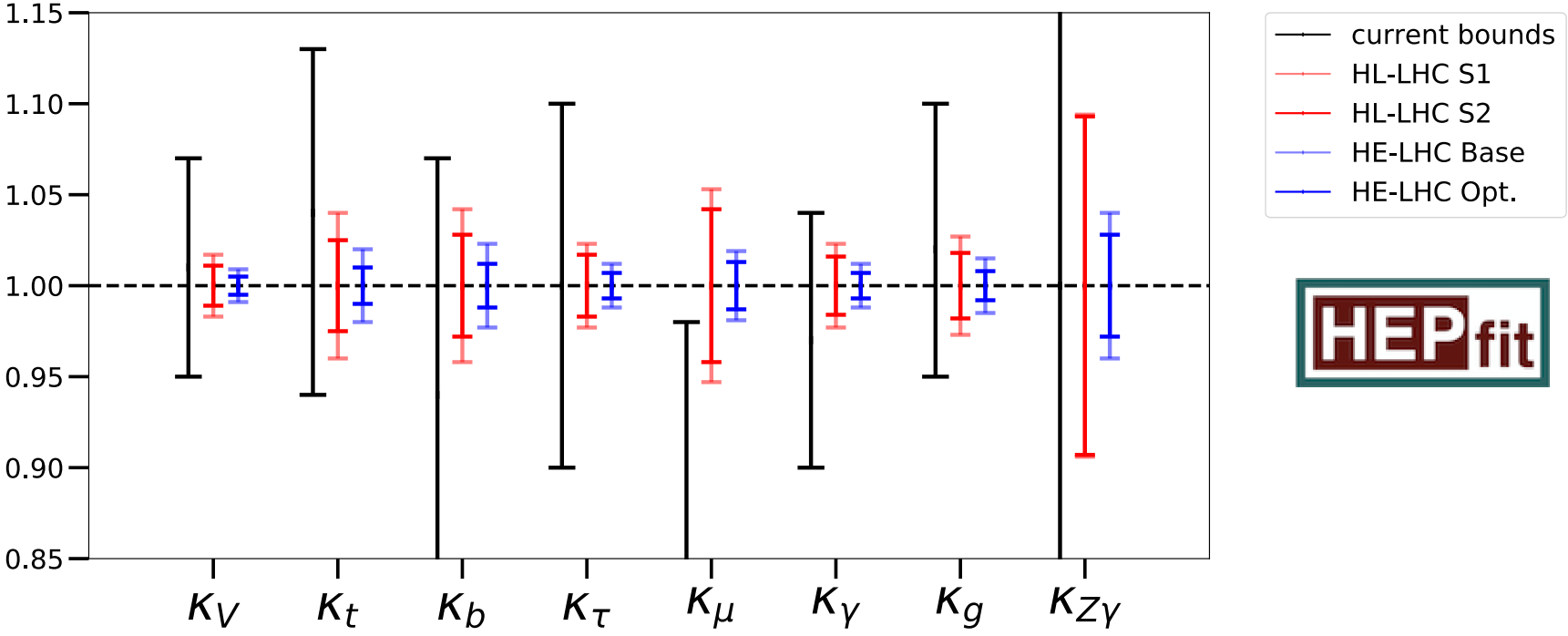




ATLAS-CONF-2019-005
CMS-PAS-HIG-17-031

Higgs Precision Measurements

LHC: 14 TeV, 300 fb^{-1}, 3000 fb^{-1}



1902.00134

Higgs Precision Measurements

CEPC / FCC / ILC

collider	CEPC	FCC-ee	ILC					
$\sqrt{s}$	240 GeV	240 GeV	250 GeV	350 GeV		500 GeV		
$\int \mathcal{L}dt$	5 ab^{-1}	5 ab^{-1}	2 ab^{-1}	200 fb^{-1}		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%	0.57%	0.71%	2.1%	-	1.06	-	-
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$							
$h \to b\bar{b}$	0.28%	0.28%	0.42%	1.67%	1.67%	0.64%	0.25%	9.9%
$h \to c\bar{c}$	2.2%	1.7%	2.9%	12.7%	16.7%	4.5%	2.2%	-
$h \to gg$	1.6%	1.98%	2.5%	9.4%	11.0%	3.9%	1.5%	-
$h \to WW^*$	1.5%	1.27%	1.1%	8.7%	6.4%	3.3%	0.85%	-
$h \to \tau^+\tau^-$	1.2%	0.99%	2.3%	4.5%	24.4%	1.9%	3.2%	-
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$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	3.1%	3.7%	-	-	-	-	-

S. Su CEPC-CDR, FCC Physics Opportunities, ILC 1903.01629.

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2HDM in one slide

- **Type-II Two Higgs Doublet Model**

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad \begin{aligned} A &= -G_1 \sin\beta + G_2 \cos\beta \\ H^\pm &= -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta \end{aligned}$$

after EWSB, 5 physical Higgses

CP-even Higgses: h^0, H^0 , CP-odd Higgs: A^0, Charged Higgses: $H^\pm$

- **h^0/H^0 VV coupling**

$$g_{H^0VV} = \frac{m_V^2}{v}\cos(\beta-\alpha), \quad g_{h^0VV} = \frac{m_V^2}{v}\sin(\beta-\alpha).$$

alignment limit: $\cos(\beta-\alpha)=0$, h^0 is the SM Higgs with SM couplings.

MSSM

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

MSSM parameters: m_A, tanβ, M_{SUSY}, X_t,
μ=500 GeV, others less important (large m_{sb}, m_{gluino},…)

- **Higgs mass (full 1-loop, leading 2-loop, some 3 & 4 loop)**

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

~ 3 GeV uncertainties (higher loops, m_t,…)

show effect of Δm_h: 3 GeV, 2 GeV, 1 GeV

MSSM

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show effect of Δm_h: 3 GeV, 2 GeV, 1 GeV

MSSM

- gauge and Yukawa couplings (α_{eff})

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha_{eff} & \sin\alpha_{eff} \\ -\sin\alpha_{eff} & \cos\alpha_{eff} \end{pmatrix} \begin{pmatrix} \mathrm{Re}H_u^0 - v_u \\ \mathrm{Re}H_d^0 - v_d \end{pmatrix}$$

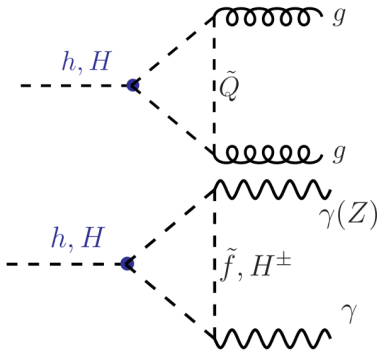
hZZ: sin(β-α_{eff}); huu: cos(α_{eff})/sin(β), hdd, hll: -sin(α_{eff})/cos(β);

hbb: + large vertex cor.

$$\kappa_b = -\frac{\sin\alpha_{eff}}{\cos\beta}\tilde{\kappa}_h^b, \quad \tilde{\kappa}_h^b = \frac{1}{1+\Delta m_b}\left(1 - \Delta m_b \frac{1}{\tan\alpha_{eff}\tan\beta}\right)$$

- hgg and hγγ

(same order as SM)



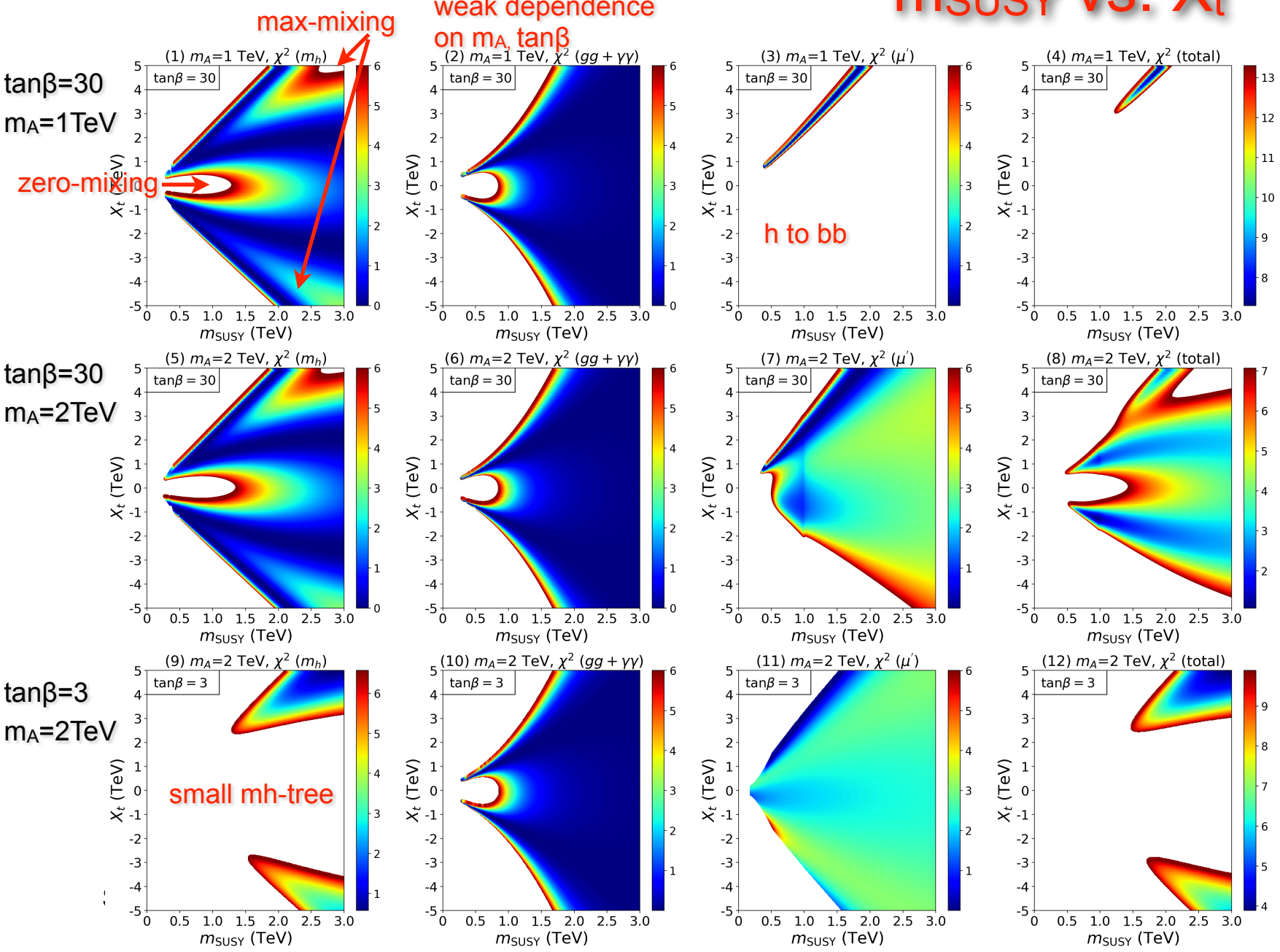
MSSM

$$\chi^2_{total} = \chi^2_{m_h} + \chi^2_{\mu} = \frac{(m_h^{\rm MSSM} - m_h^{\rm obs})^2}{(\Delta m_h)^2} + \sum_{i=f,V..} \frac{(\mu_i^{\rm MSSM} - \mu_i^{\rm obs})^2}{(\Delta \mu_i)^2}$$

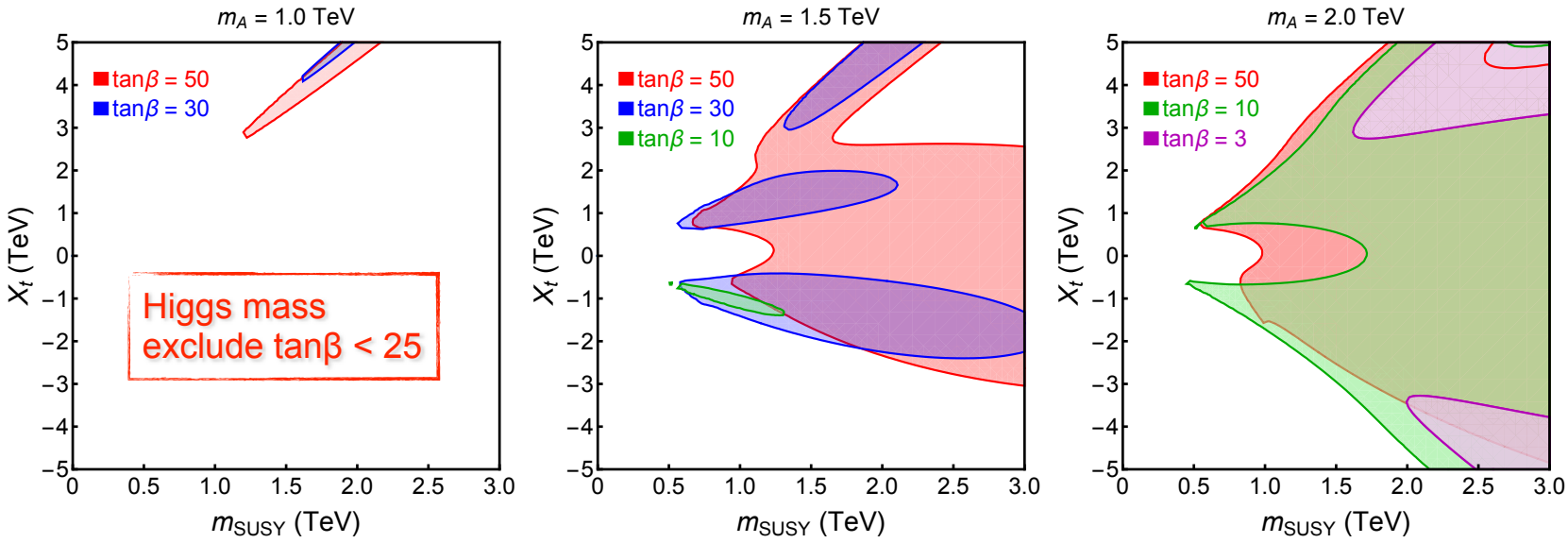
- **earlier work: h→gg, h→γγ** Fan, Reece, Wang, 1402.3107; Fan and Reece, 1401.7671, Drozd, Ellis, Quevillon and You, 1504.02409, 1512.03003
- **FeynHiggs: m_h, $\alpha_{\rm eff}$, Δm_b**
- **assume no deviation, 95% C.L. region**

$$m_A \in (200, 3000)\ {\rm GeV}, \tan\beta \in (1, 50),$$
$$X_t \in (-5000, 5000)\ {\rm GeV}, m_{\rm SUSY} \in (200, 3000)\ {\rm GeV},$$

m_{SUSY} vs. X_t

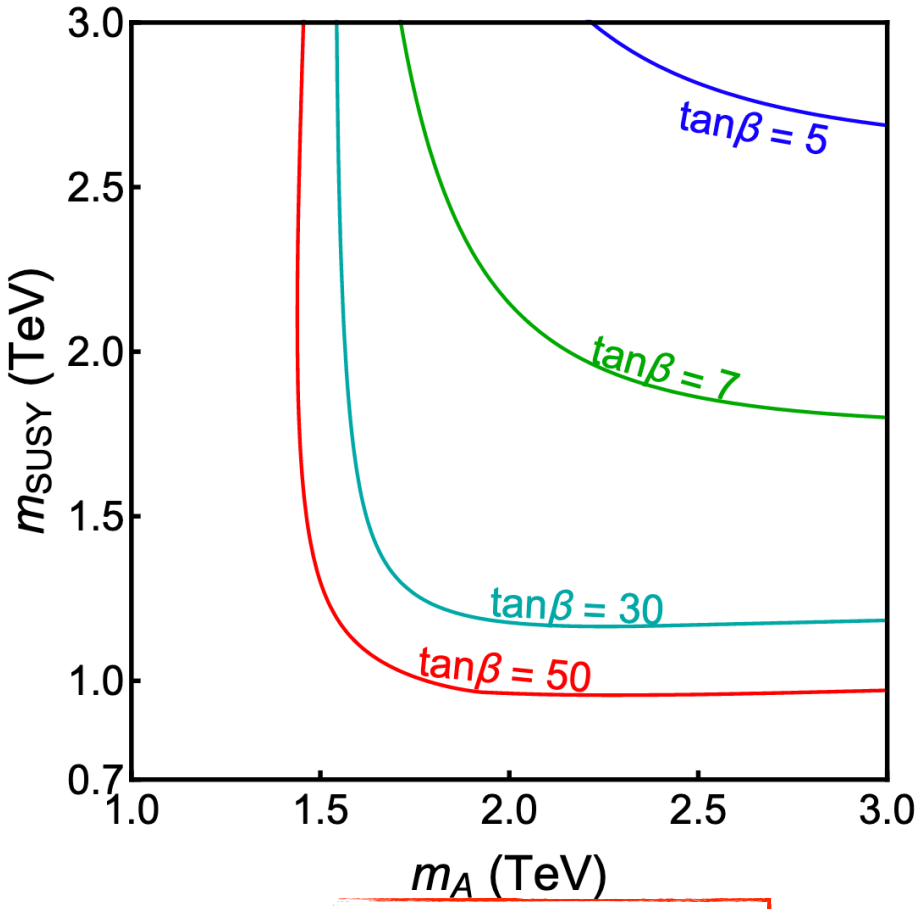

max-mixing
weak dependence on m_A, tanβ
tanβ=30
m_A=1TeV
zero-mixing
(1) m_A=1 TeV, χ^2 (m_h)
(2) m_A=1 TeV, χ^2 ($gg+\gamma\gamma$)
(3) m_A=1 TeV, χ^2 (μ')
(4) m_A=1 TeV, χ^2 (total)
h to bb
tanβ=30
m_A=2TeV
(5) m_A=2 TeV, χ^2 (m_h)
(6) m_A=2 TeV, χ^2 ($gg+\gamma\gamma$)
(7) m_A=2 TeV, χ^2 (μ')
(8) m_A=2 TeV, χ^2 (total)
tanβ=3
m_A=2TeV
(9) m_A=2 TeV, χ^2 (m_h)
(10) m_A=2 TeV, χ^2 ($gg+\gamma\gamma$)
(11) m_A=2 TeV, χ^2 (μ')
(12) m_A=2 TeV, χ^2 (total)
small mh-tree
X_t (TeV)
m_{SUSY} (TeV)

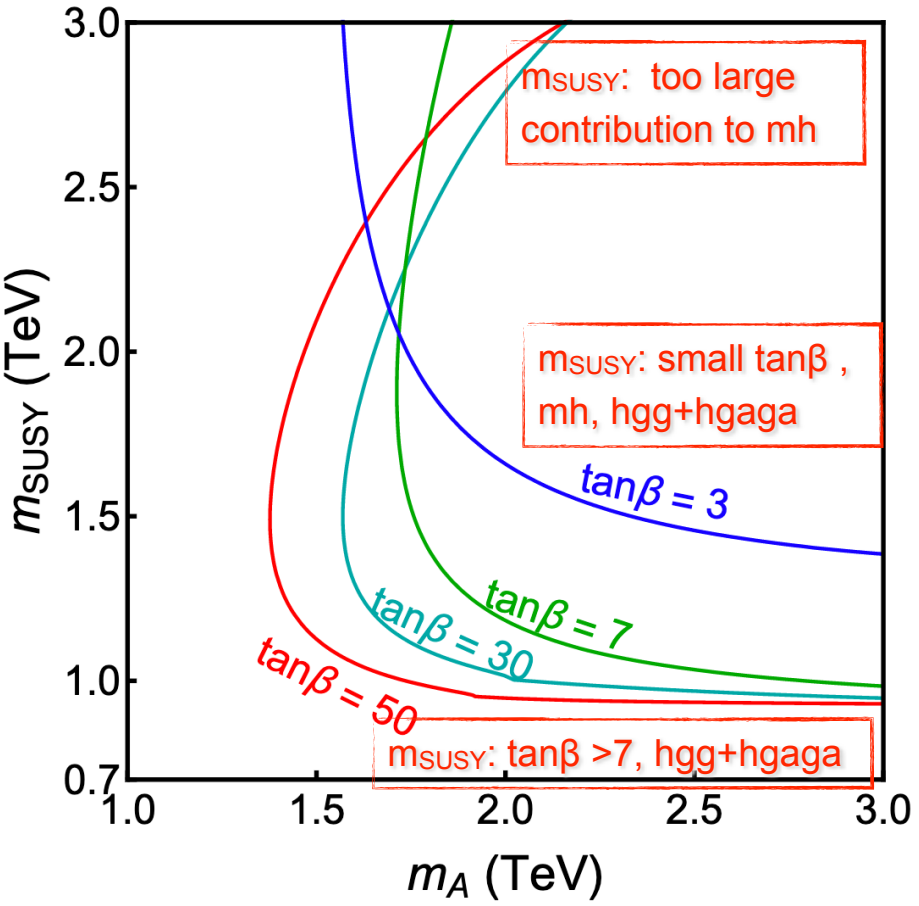
m_{SUSY} vs. X_t


m_A = 1.0 TeV
tanβ = 50
tanβ = 30
Higgs mass
exclude tanβ < 25
X_t (TeV)
m_{SUSY} (TeV)
m_A = 1.5 TeV
tanβ = 50
tanβ = 30
tanβ = 10
X_t (TeV)
m_{SUSY} (TeV)
m_A = 2.0 TeV
tanβ = 50
tanβ = 10
tanβ = 3
X_t (TeV)
m_{SUSY} (TeV)

m_A vs. M_{SUSY}

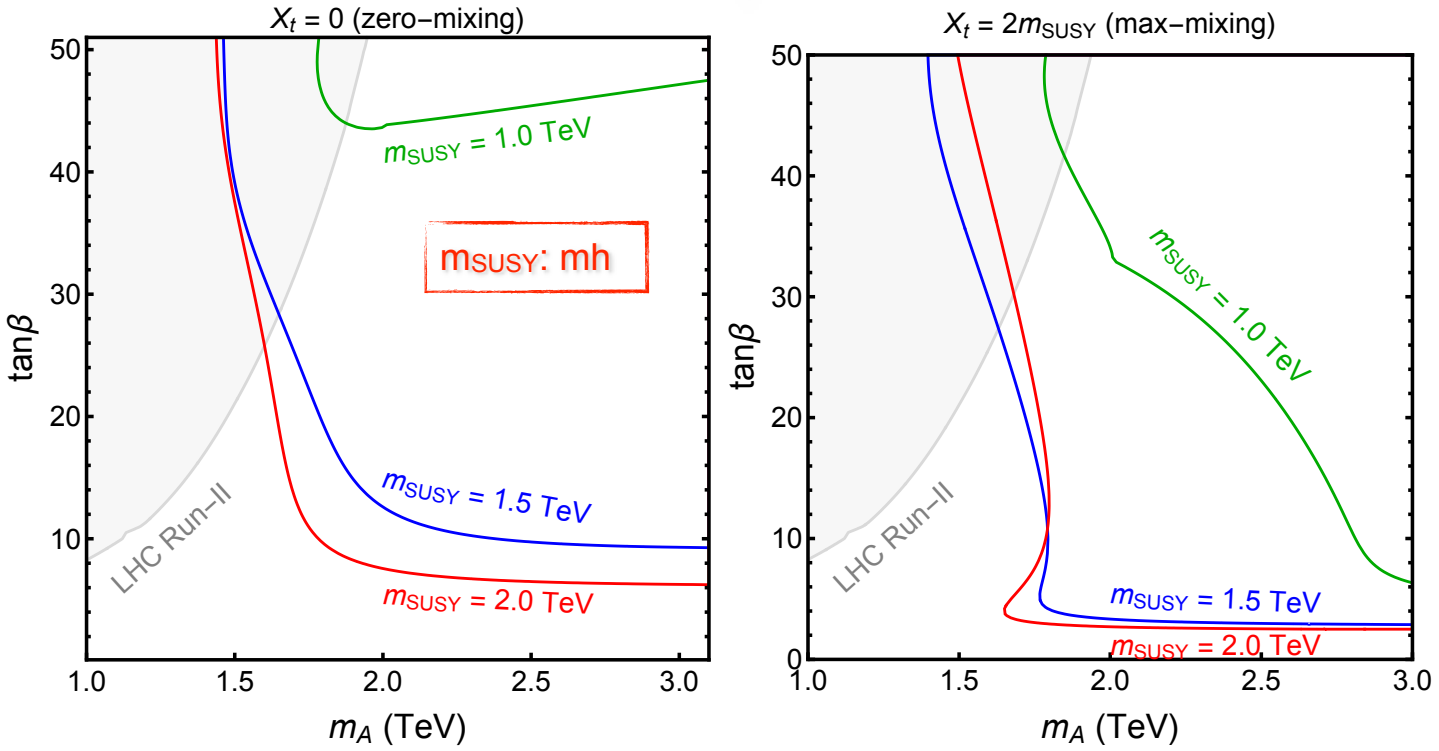
m_A: coupling

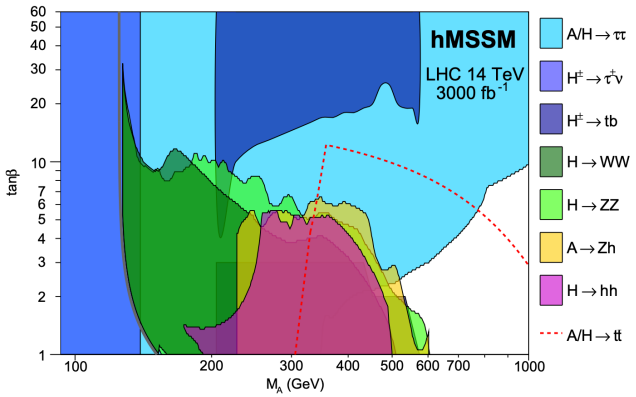




mSUSY
small tanβ, mh
large tanβ, mh+coupling

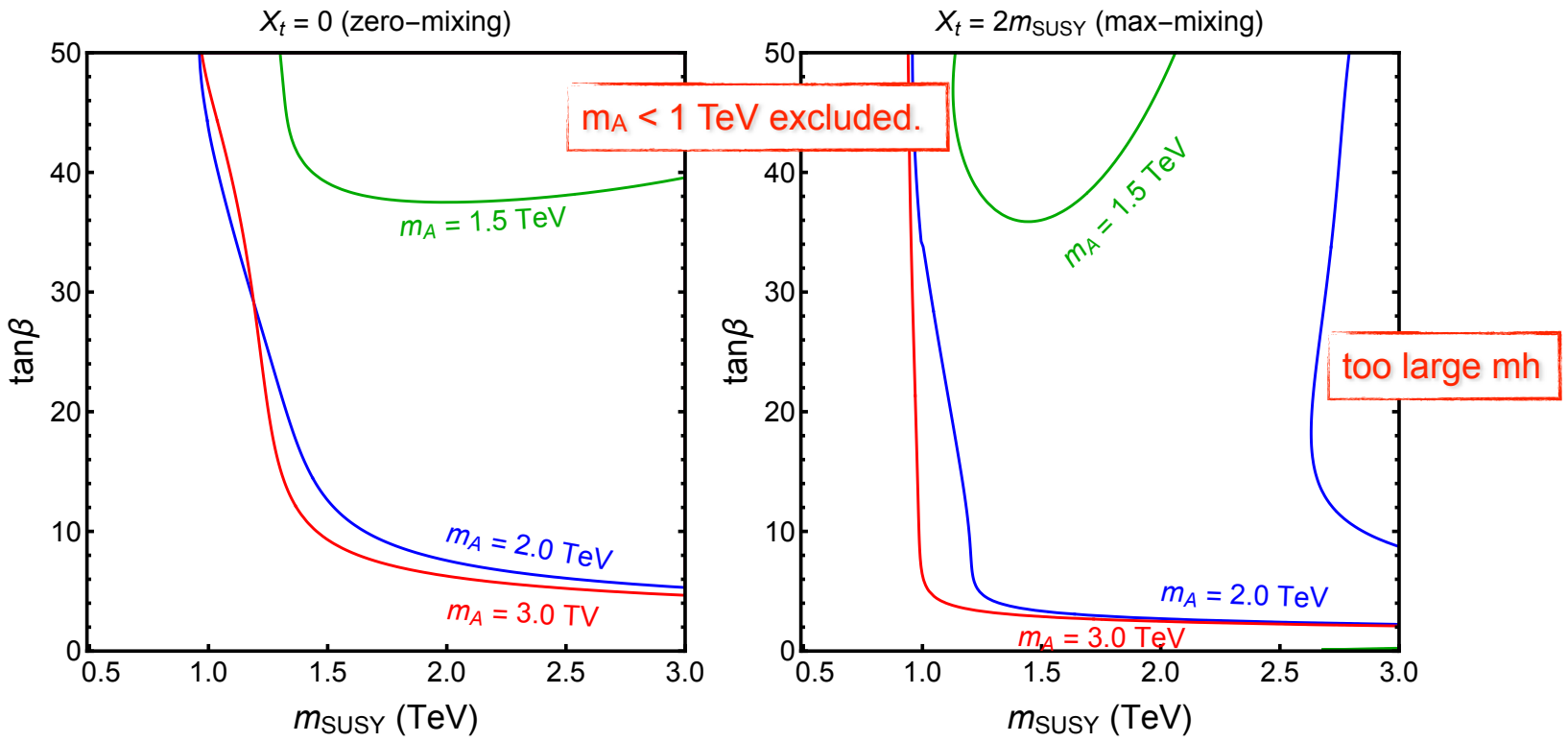
m_A vs. tanβ



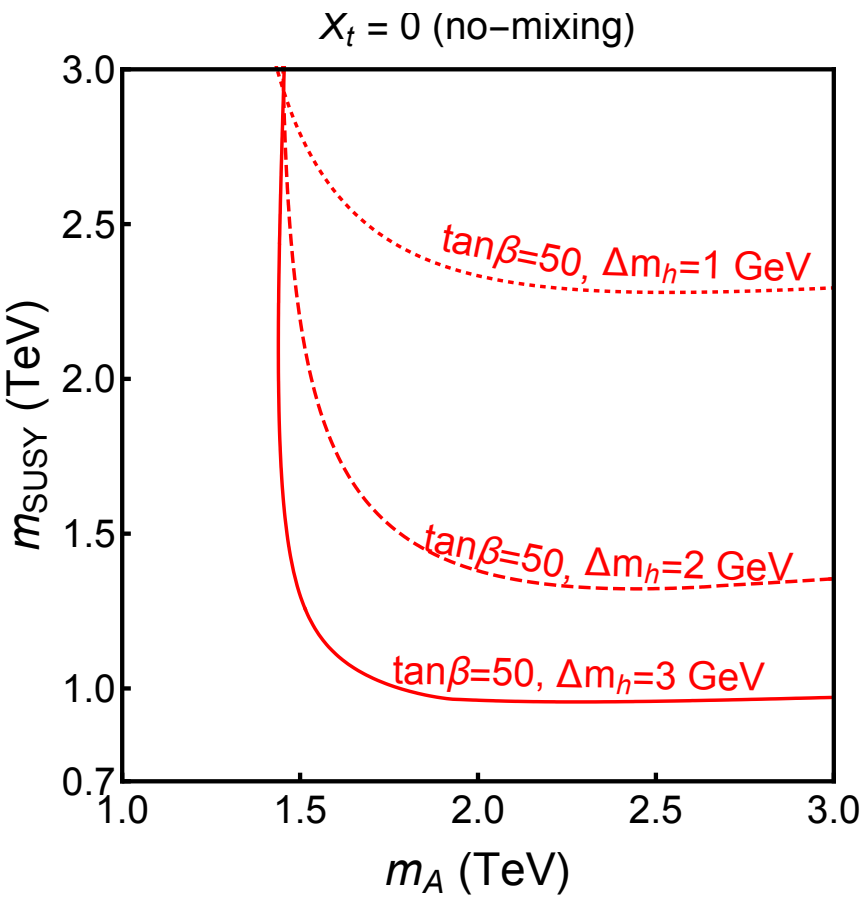


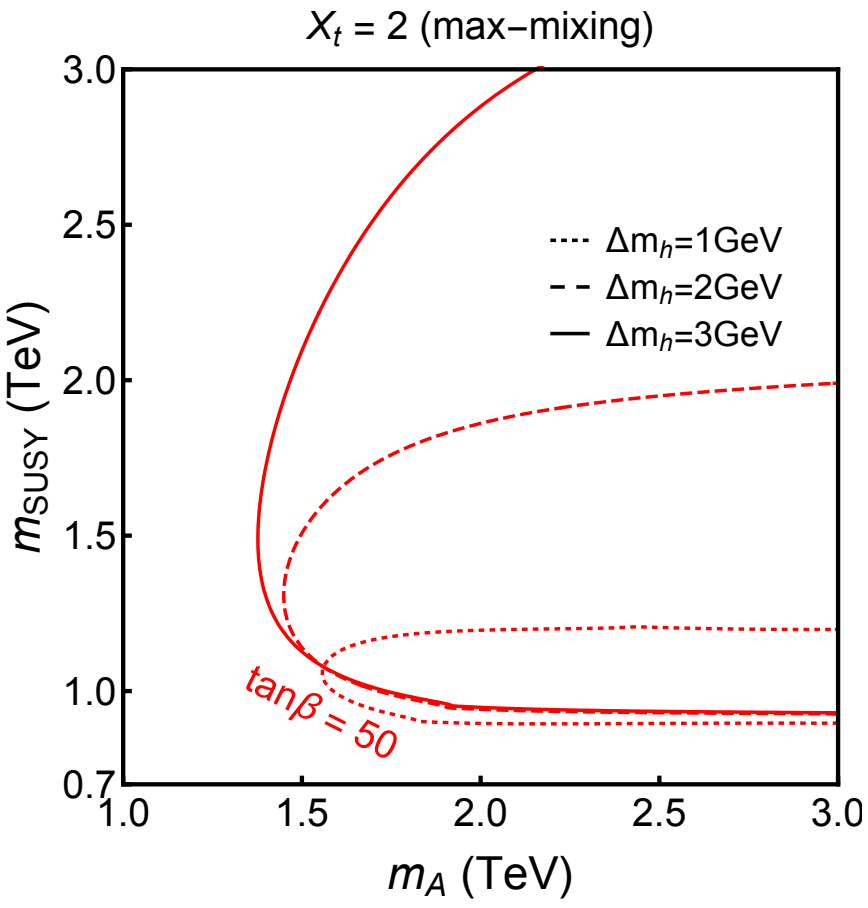
complementary to LHC direct search

m_{SUSY} vs. tanβ



m_A vs. M_S

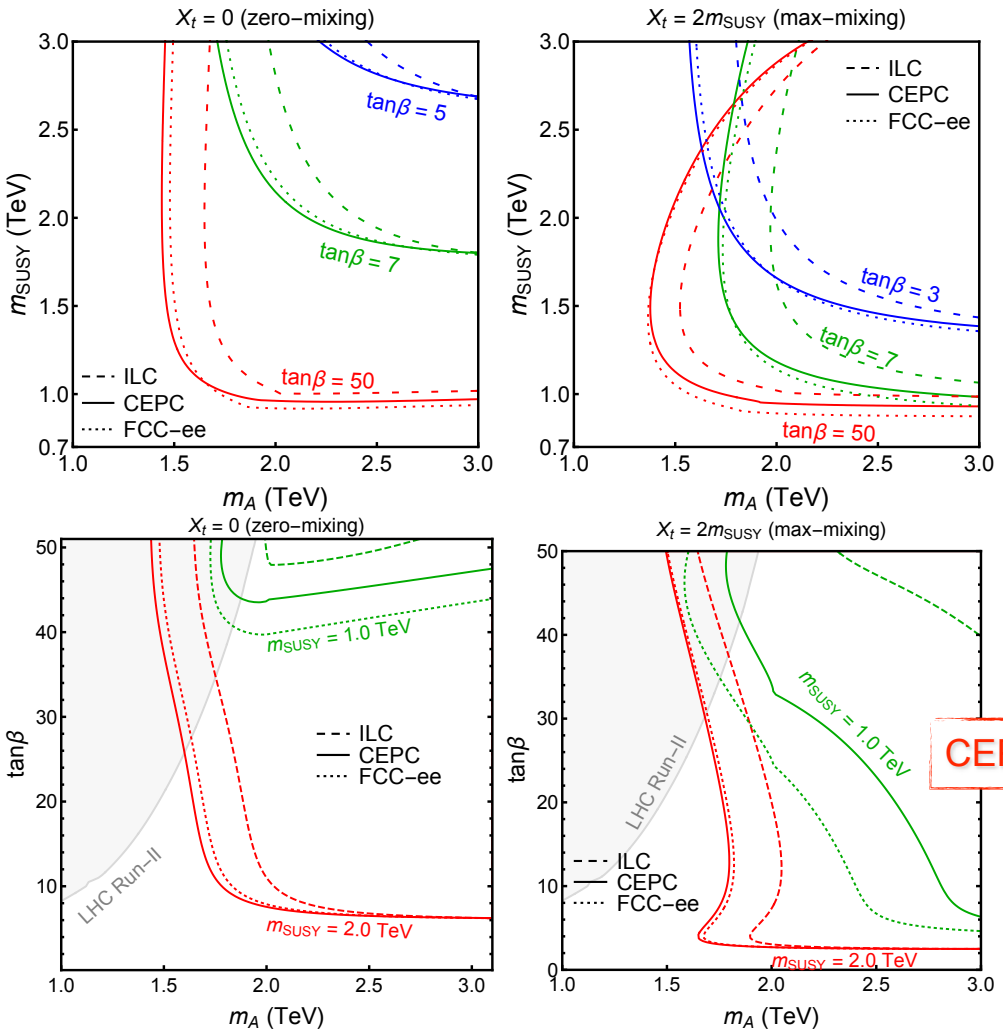




S. Su

Important to improve precision on mh calculation.

CEPC/FCCee/ILC



ILC: better limit on m_A.
Better hbb, hWW.

CEPC: slightly better hgg

Conclusion

- Higgs factory reach impressive precision: mass + couplings
- χ^2_{mh} dominate for small tanβ
- $\chi^2_{couplings}$ (hbb): small to moderate m_A
- hgg,h$\gamma\gamma$: constrain M_{SUSY} for tanβ > 7 (max-mixing)
- m_A: sensitive to Higgs couplings
- tanβ, M_{SUSY}, X_t,: sensitive to Higgs mass
- M_{SUSY} depends sensitively on Δm_h
- CEPC/FCC-ee/ILC: reach comparable
- complementary to direct search @ pp