SENSITIVITY TO NEW PHYSICS OF PRECISION HIGGS AND EW OBSERVABLES

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FCC week, Washington DC, 3/26/15

OUTLINE

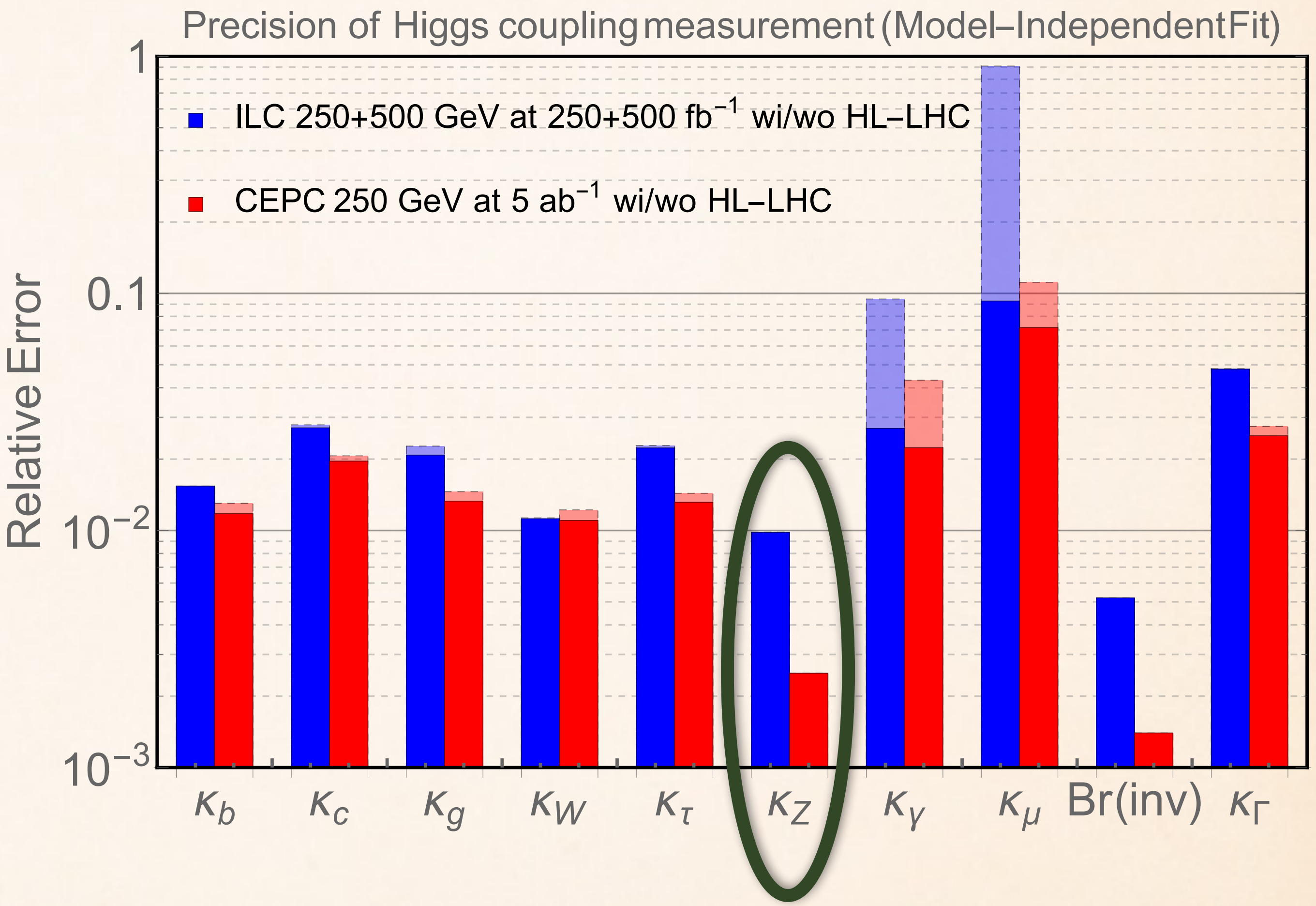
- Higgs Coupling Measurements at Future Colliders
- EWPT at Future Colliders
- New Physics Reach and Complementarity between Different Probes:

1. Supersymmetry
2. Composite Higgs
3. Electroweak phase transition
4. Higgs portal

Higgs Coupling Measurements at Future Colliders

Facility	TLEP (4 IP)	
$\sqrt{s}$ (GeV)	240	350
$\int \mathcal{L}dt$ (fb^{-1})	10000	+2600
$P(e^-, e^+)$	(0, 0)	(0, 0)
Γ_H	1.9%	1.0%
κ_γ	1.7%	1.5%
κ_g	1.1%	0.8%
κ_W	0.85%	0.19%
κ_Z	0.16%	0.15%
κ_μ	6.4%	6.2%
κ_τ	0.94%	0.54%
κ_c	1.0%	0.71%
κ_b	0.88%	0.42%
κ_t	–	13%
BR_{inv}	0.19%	< 0.19%

snowmass Higgs report
1310.8361



CEPC/SppC preCDR

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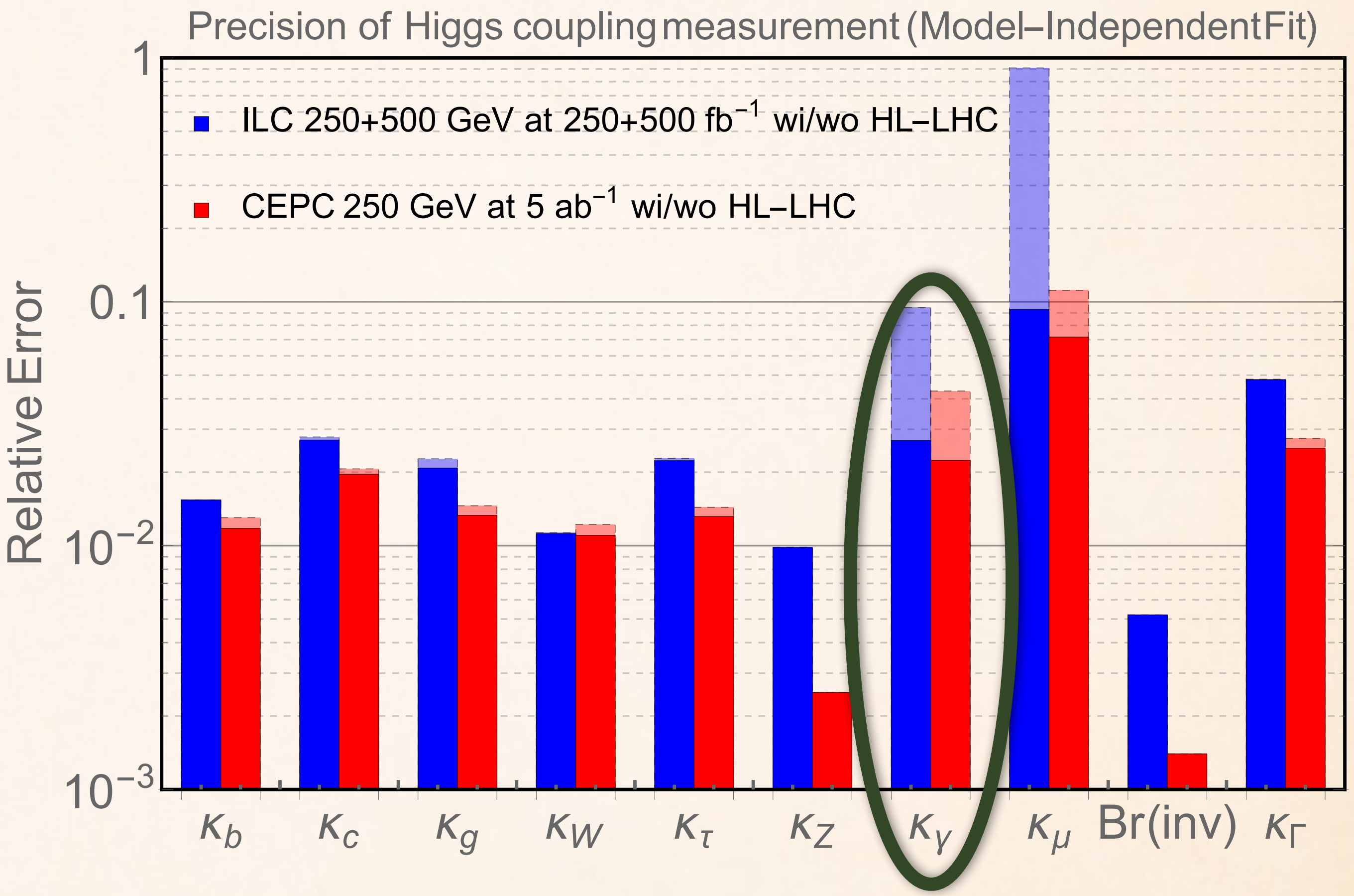
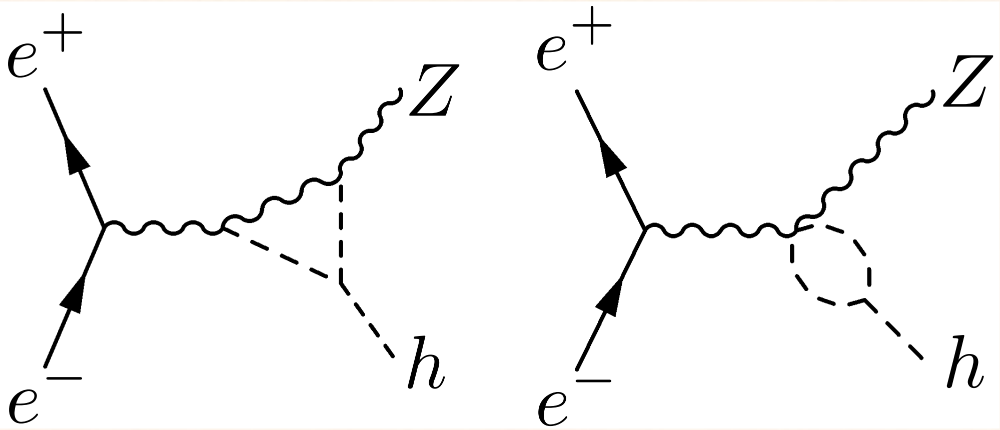
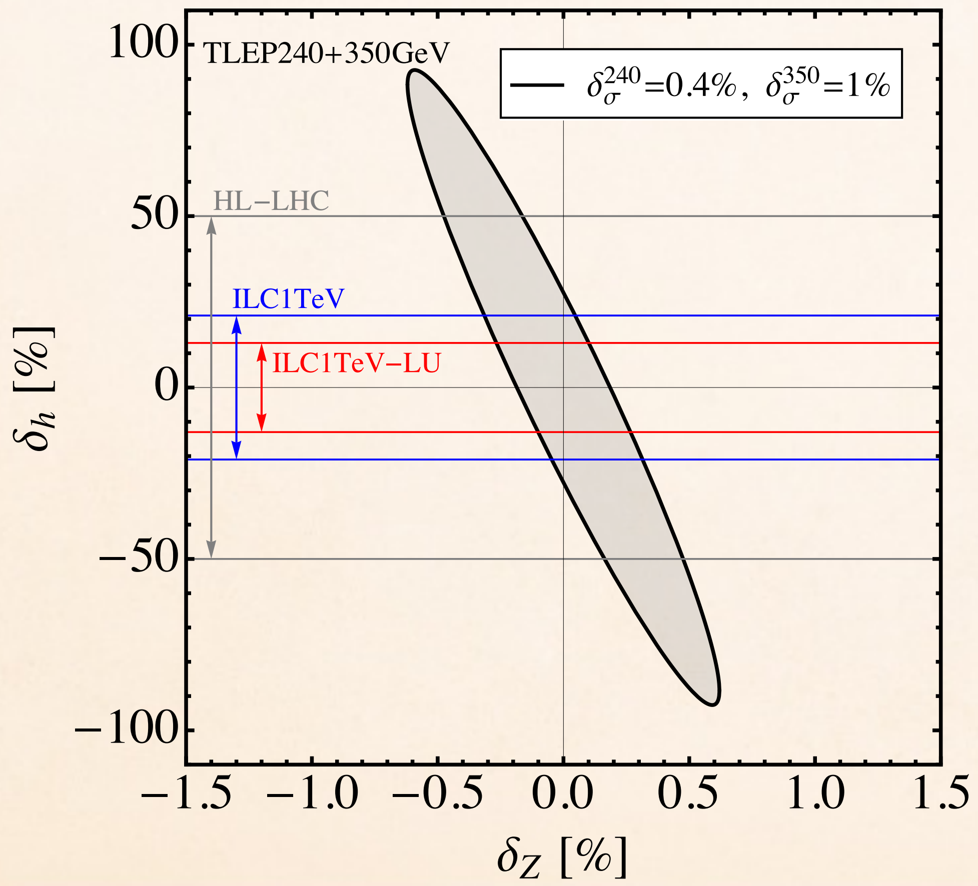


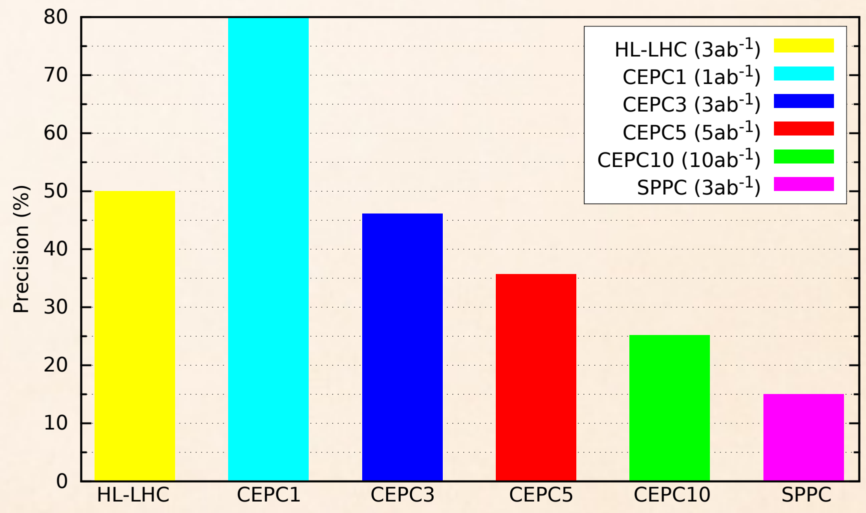
CEPC/SppC preCDR

Higgs self-coupling: indirectly inferred from limit on κ_Z with some assumptions McCullough 2014



$$\Delta\sigma_{Zh} = \frac{\sigma_{Zh}}{\sigma_{Zh}^{\mathrm{SM}}} - 1 = 2\Delta_{\kappa_Z} + 0.014\Delta_{\lambda_{hhh}}.$$





CEPC/SppC preCDR

Direct measurement

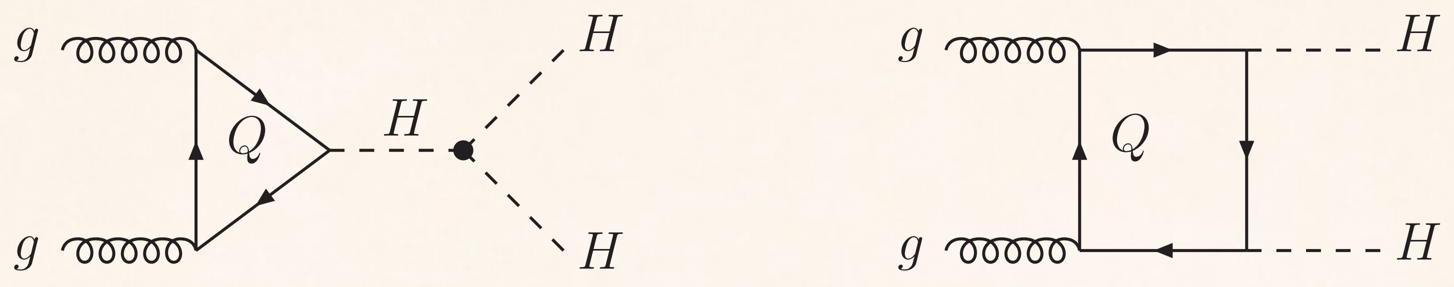


Table 1-24. *Expected per-experiment precision on the triple-Higgs boson coupling. ILC numbers include $bbbb$ and $bbWW^*$ final states and assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 500 GeV and $(-0.8, 0.2)$ at 1000 GeV. ILC500-up is the luminosity upgrade at 500 GeV, not including any 1000 GeV running. ILC1000-up is the luminosity upgrade with a total of 1600 fb^{-1} at 500 GeV and 2500 fb^{-1} at 1000 GeV. CLIC numbers include only the $bbbb$ final state and assume 80% electron beam polarization. HE-LHC and VLHC numbers are from fast simulation [102] and include only the $bb\gamma\gamma$ final state. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to CLIC numbers without accounting for the additional running period.*

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	1600‡	500+1000	1600+2500‡	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

snowmass Higgs report
1310.8361

EWPT at Future Colliders

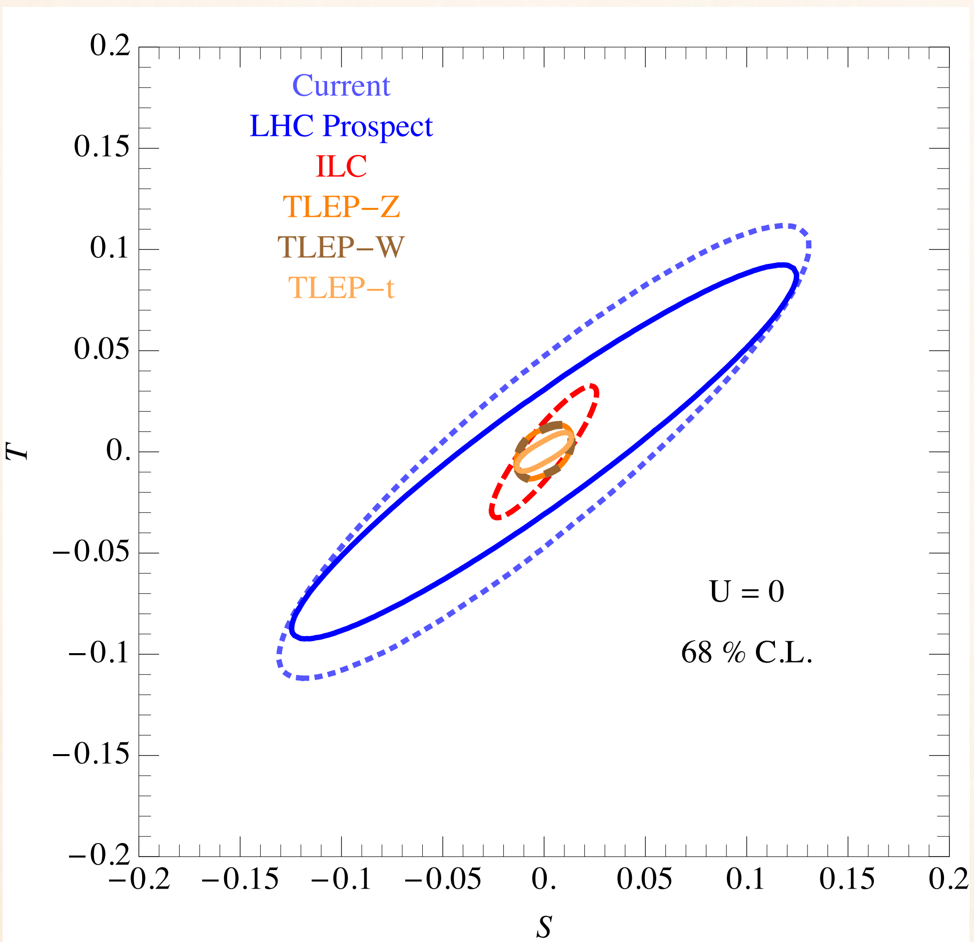
Global Fit of Electroweak Observables with Oblique Corrections

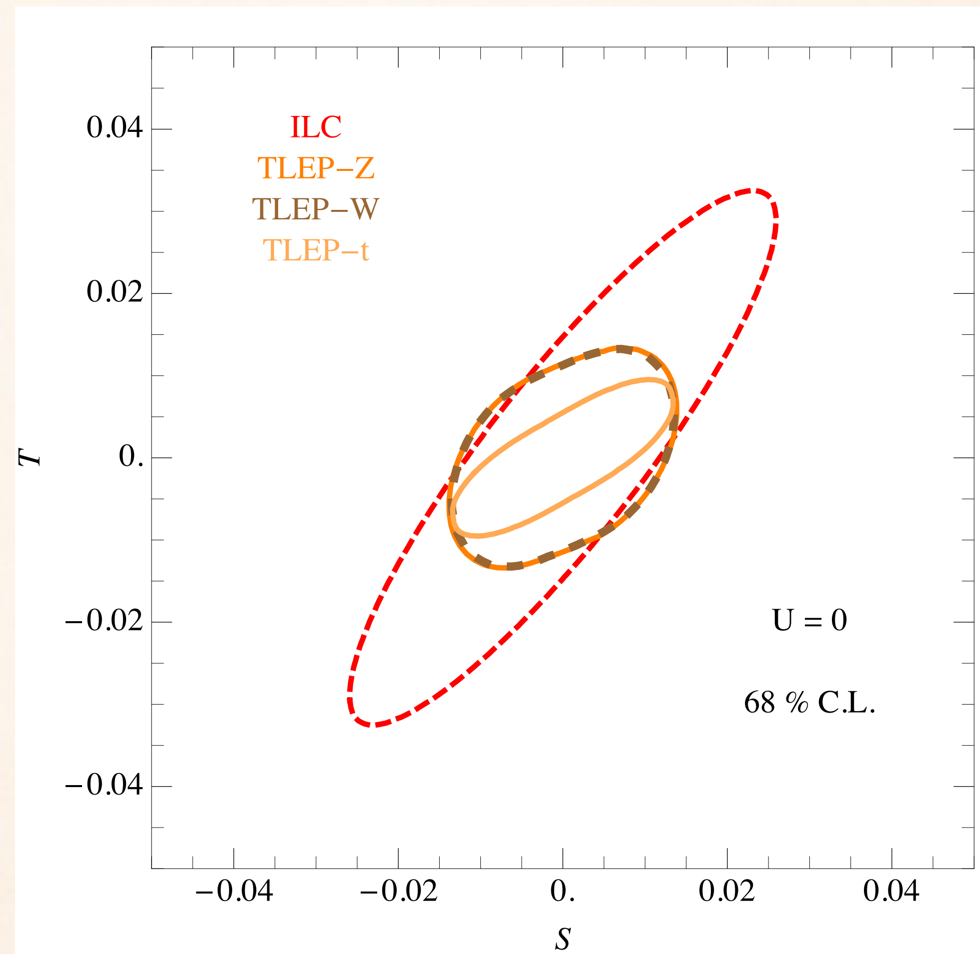
Five observables free to vary in the fit: top mass, Z boson mass, Higgs mass, strong coupling constant at Z pole, hadronic contribution to the running of α;

Three derived observables: W boson mass, effective weak mixing angle, Z boson decay width

Global Fit of Electroweak Observables with Oblique Corrections

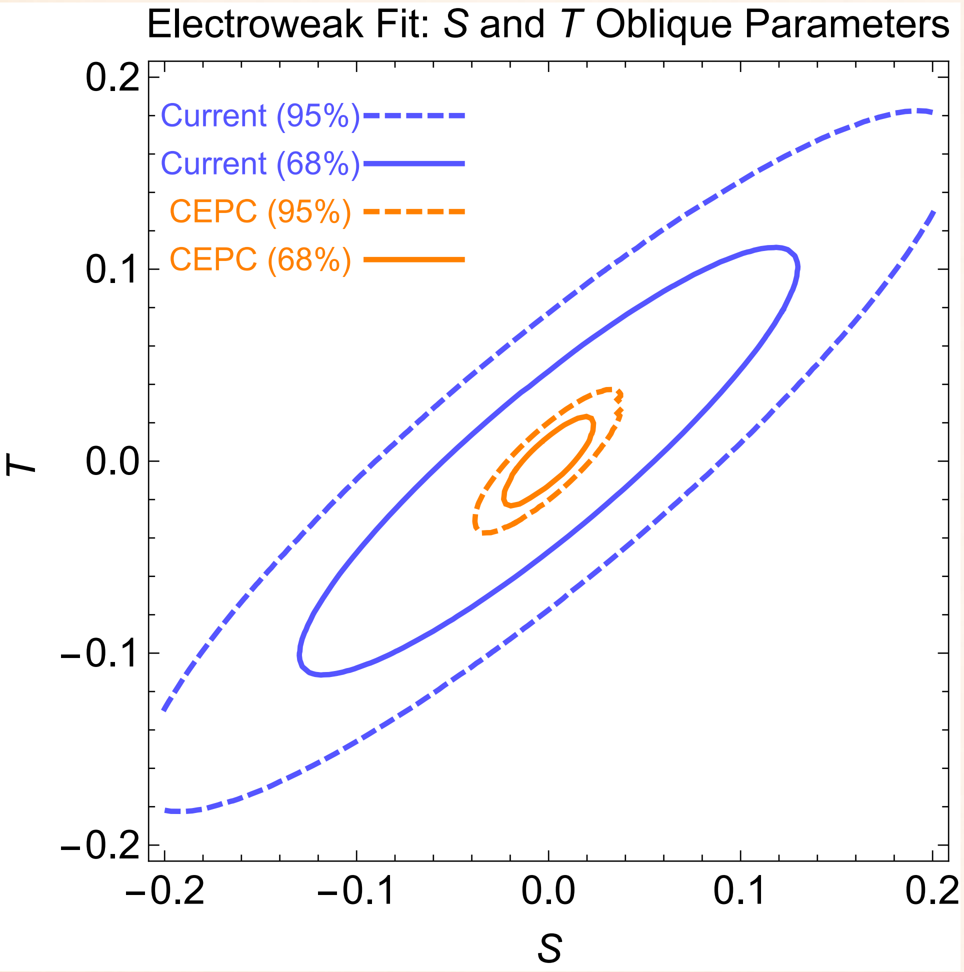
$$\mathcal{L}_{\text{oblique}} = S\left(\frac{\alpha}{4\sin\theta_W\cos\theta_W v^2}\right)h^\dagger W^{i\mu\nu}\sigma^i h B_{\mu\nu} - T\left(\frac{2\alpha}{v^2}\right)\left|h^\dagger D_\mu h\right|^2,$$

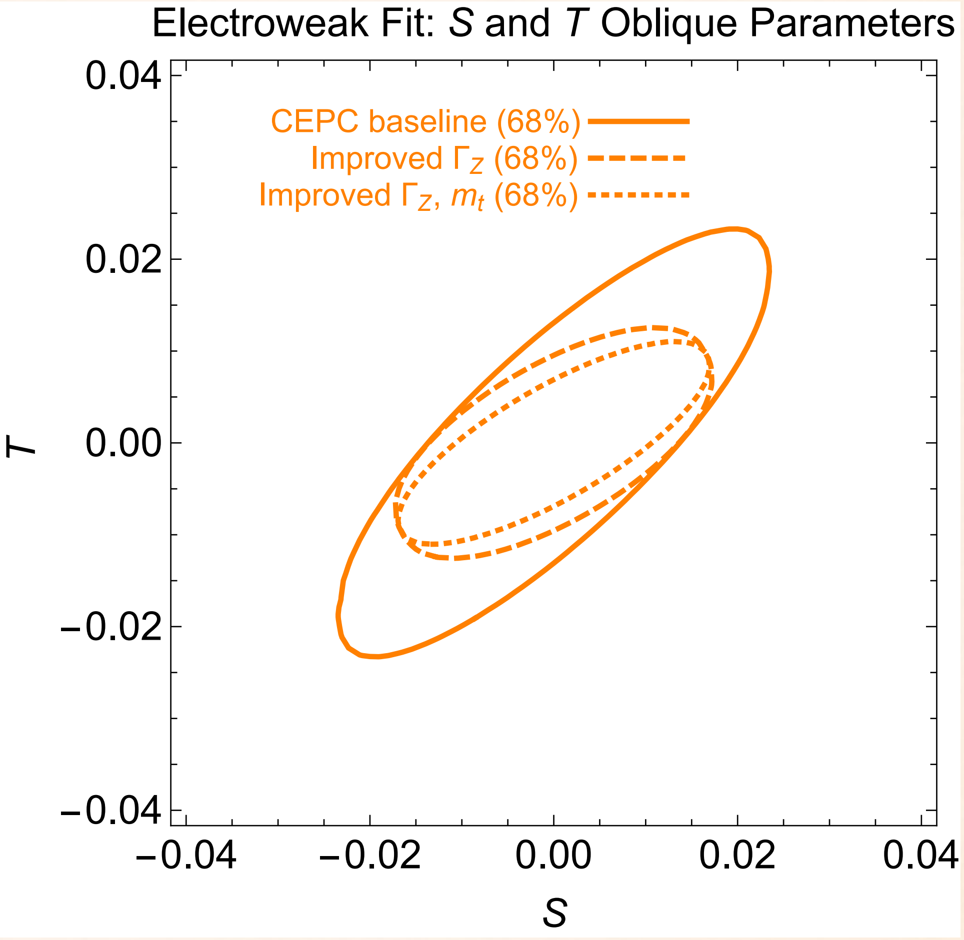




Fan, Reece and Wang 1411.1054

CEPC EWPT



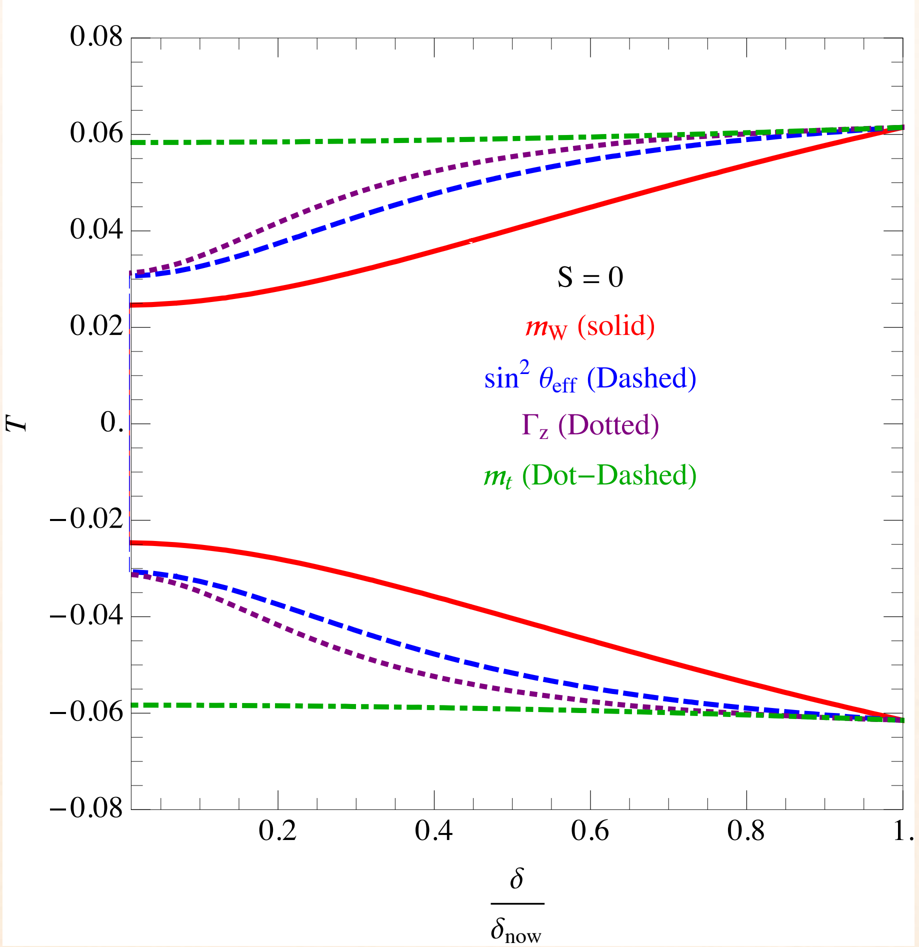


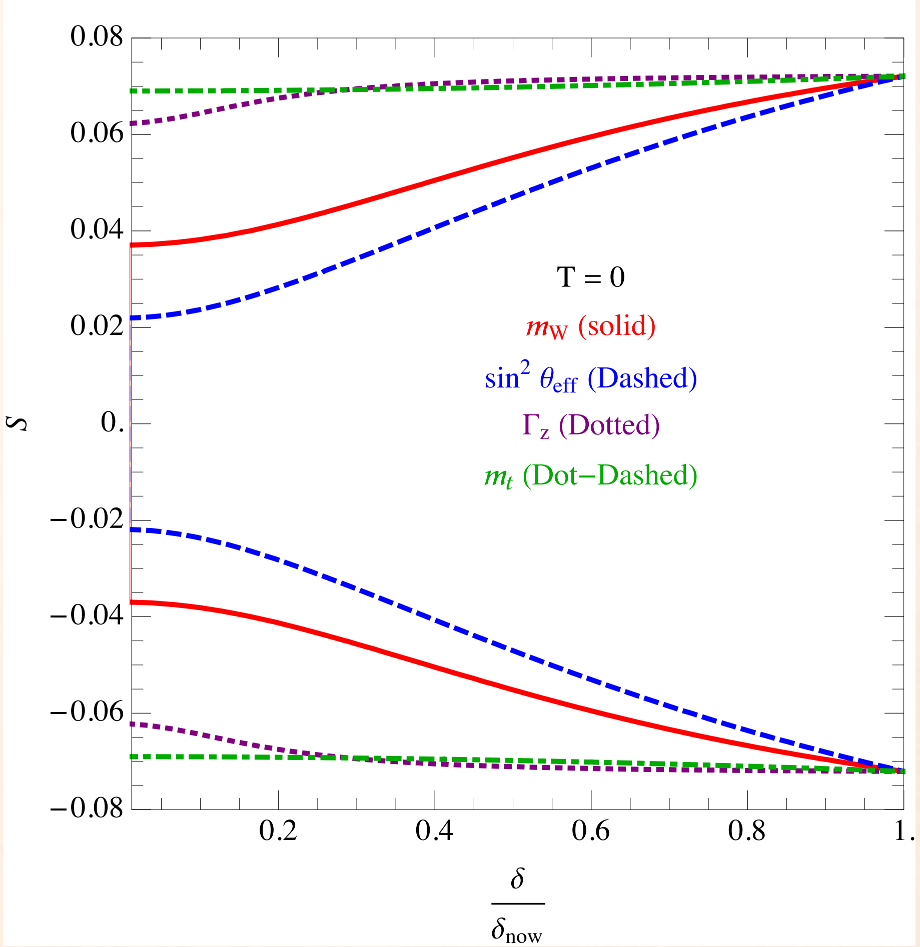
Fan, Reece and Wang 2014; CEPC/SppC preCDR

To do list for a successful electroweak program

What are the most important observables whose precisions need to be improved to achieve the best sensitivity of EWPT?
What levels of precision are desirable for these observables?

Decompose the fits into steps: for example, first vary one parameter at a time





To do list for a successful electroweak program

- Determine m_W to better than 5 MeV precision (15 MeV now) and $\sin^2\theta$ to better than 2×10^{-5} precision (16×10^{-5} now);

- Determine m_t to 100 MeV precision (0.76 GeV now) and m_Z to 500 KeV precision (2.1 MeV now).

- The precision goals apply to both experimental and theory uncertainties. For theory uncertainties, this means for m_W, $\sin^2\theta$, complete three-loop SM electroweak correction computations are desirable (two-loop calculations so far).

New Physics Reach: natural SUSY (stop + Higgsino sector)

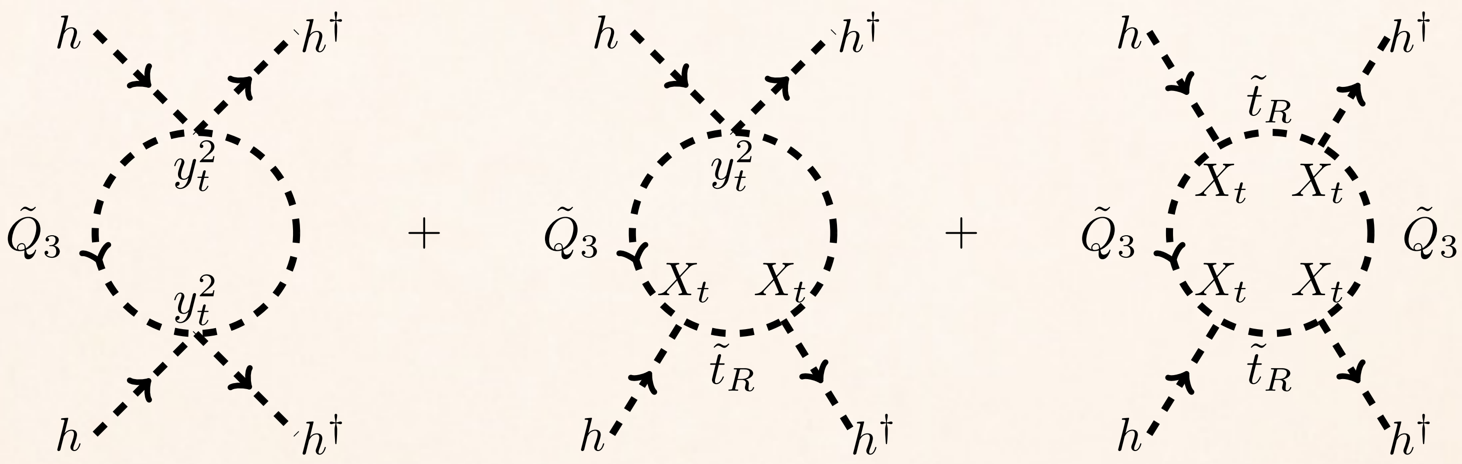
Lepton colliders are limited in kinematic reach of stops compared to proton colliders;

On the other hand, stops can be hidden due to some non-minimal decay modes and/or kinematics of the decay products (RPV, stealth SUSY, folded SUSY…)

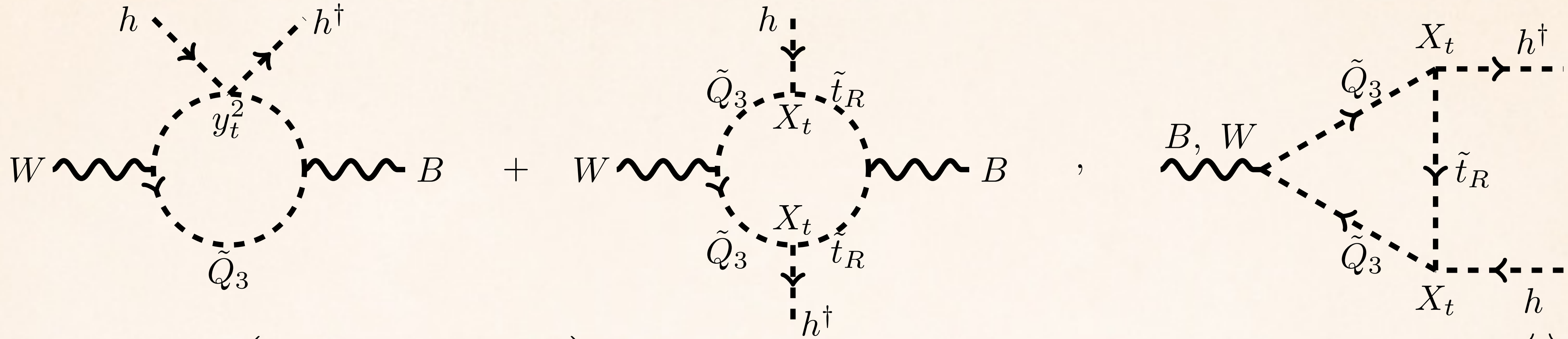
Precision measurements at lepton colliders could provide powerful complementary probes independent of the details of stop decays.

New Physics Reach:
natural SUSY (stop + Higgsino sector)

$$T\left(\frac{2\alpha}{v^2}\right)\left|h^\dagger D_\mu h\right|^2,$$



$$T \approx \frac{m_t^4}{16\pi \sin^2\theta_W m_W^2 m_{\tilde{Q}_3}^2} + \mathcal{O}\left(\frac{m_t^2 X_t^2}{4\pi m_{\tilde{Q}_3}^2 m_{\tilde{u}_3}^2}\right).$$



$$S\left(\frac{\alpha}{4\sin\theta_W\cos\theta_W v^2}\right) h^\dagger W^{i\mu\nu}\sigma^i h B_{\mu\nu}$$

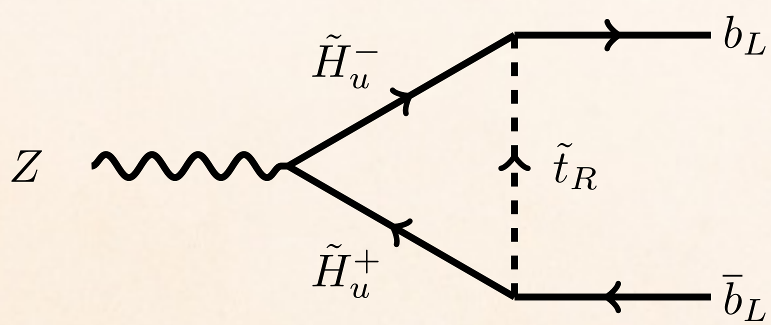
$$i\partial^\nu B_{\mu\nu} h^\dagger \overleftrightarrow{D}^\mu h$$

$$iD^\nu W^i_{\mu\nu} h^\dagger \sigma^i \overleftrightarrow{D}^\mu h$$

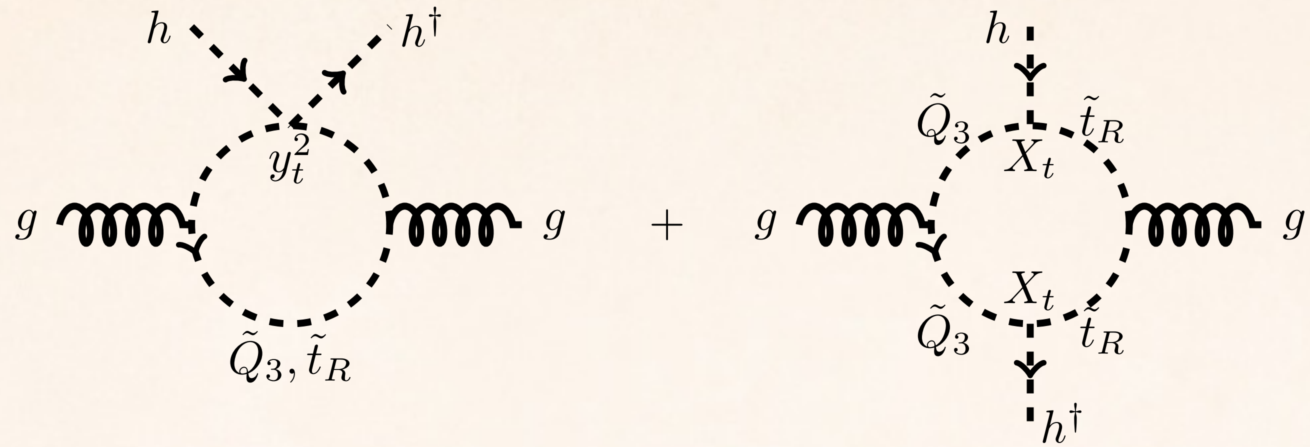
$$S \approx -\frac{1}{6\pi}\frac{m_t^2}{m_{\tilde{Q}_3}^2} + \mathcal{O}\left(\frac{m_t^2 X_t^2}{4\pi m_{\tilde{Q}_3}^2 m_{\tilde{u}_3}^2}\right).$$

Henning, Lu, Murayama 2014

Rb



$$\frac{y_t^2}{m_{\tilde{t}_R}^2} W^i_{\mu\nu} Q_3^\dagger \sigma^i \overline{\sigma}^\mu i D^\nu Q_3 \ \log\frac{m_{\tilde{t}_R}}{\mu}.$$



$H^\dagger H G^2$

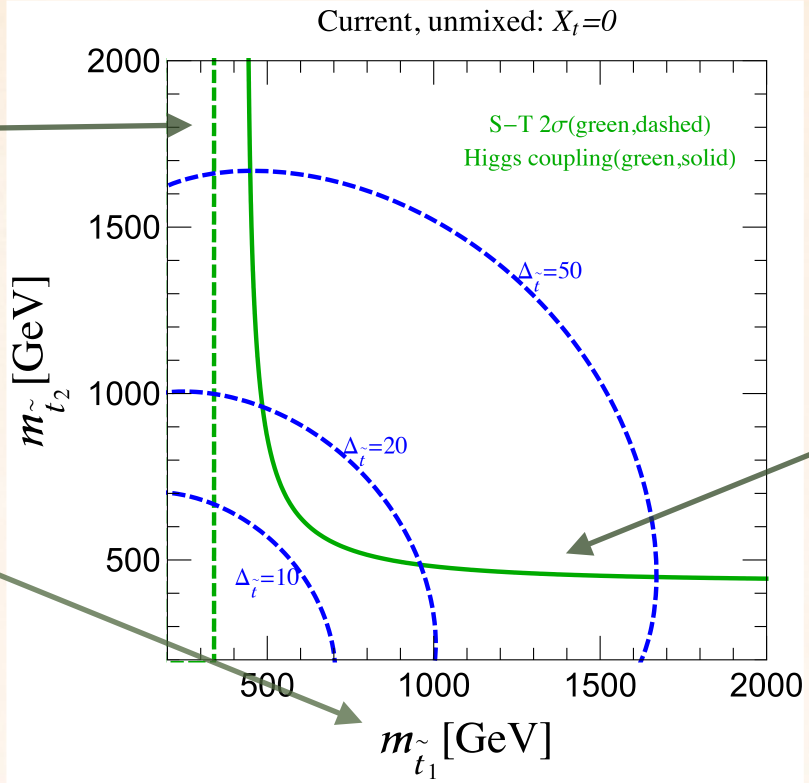
$$r_G^{\tilde{t}} \equiv \frac{c_{hgg}^{\tilde{t}}}{c_{hgg}^{\rm SM}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right), \quad \text{stop contribution to } hgg \text{ coupling}$$

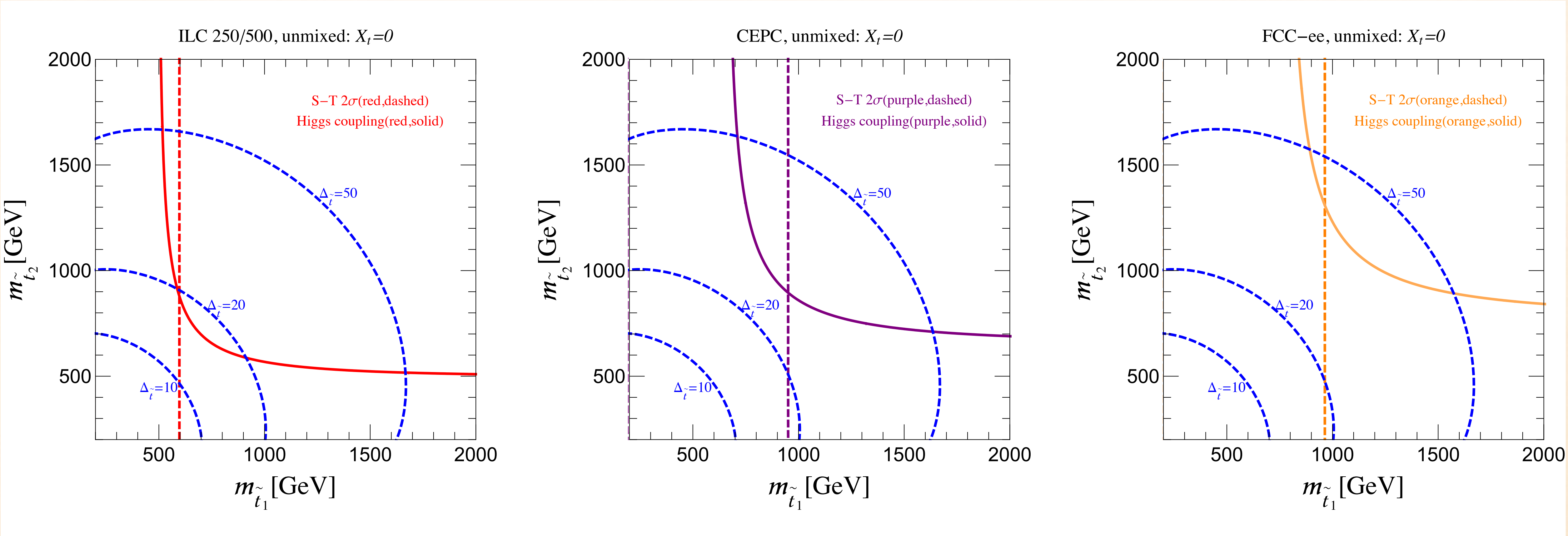
Other corrections to precision observables:
wavefunction renormalization of the Higgs boson
(Craig, Englert, McCullough 2013)
b to s gamma,
triple gauge coupling,
running of the gauge couplings (for hadron collider).
(Alves, Galloway, Ruderman, Walsh 2014)

T parameter

Physical stop masses

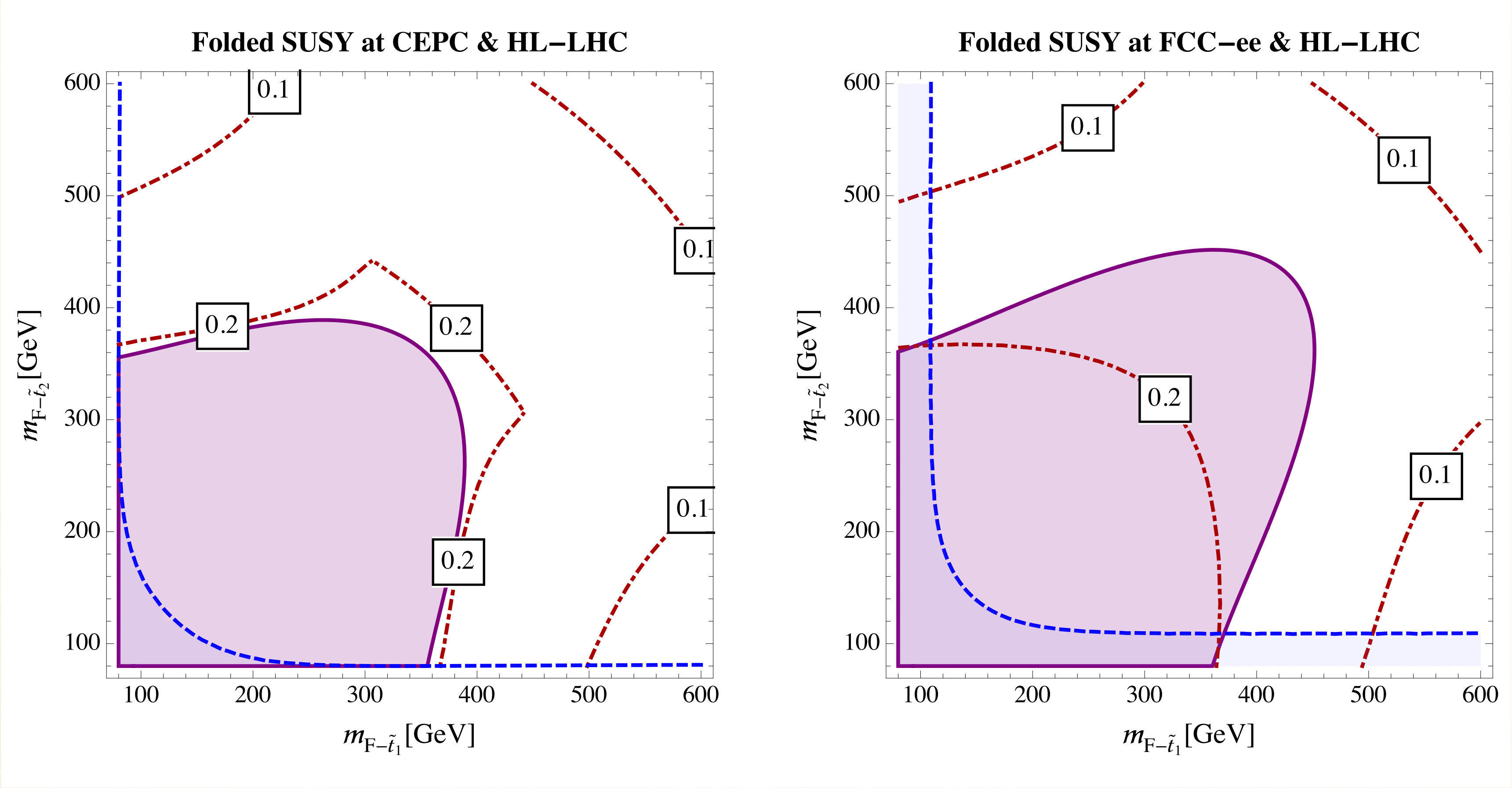
hgg coupling





Fan, Reece, Wang 1412.3107

In certain hidden natural SUSY scenarios with non-colored stops such as folded SUSY (Burdman, Chacko, Goh, Harnik 2006), Higgs-photon coupling have some sensitivity and EWPT could be the most sensitive probe in region away from a blind spot.



To sum up, in natural SUSY, the combined set of precision measurements could probe down to a few percent in fine-tuning and stop mass to about a TeV.

New Physics Reach: composite Higgs scenario

Higgs is a pNGB boson.
It will not completely unitarize the scattering of the longitudinal W and Z bosons (exchange of heavier resonances also play a role).
Failure of the Higgs to unitarize the amplitude is associated with correction to the coupling between the Higgs and the weak gauge bosons.

Minimal composite Higgs scenario: Agashe, Contino, Pomarol 2004

$$\kappa_W = \kappa_Z = \sqrt{1 - \frac{v^2}{f^2}},$$

f: decay constant of PNGB Higgs

Contribution to EWPT is model dependent

$$S \sim \frac{4\pi v^2}{m_\rho^2} \sim \frac{N}{4\pi}\frac{v^2}{f^2},$$

$$m_\rho \sim 4\pi f/\sqrt{N}.$$

Due to Landau pole constraint and cosmology constraint, N cannot be too large

$$S \approx \frac{v^2}{4f^2}.$$

Experiment	κ_Z (68%)	f (GeV)
HL-LHC	3%	1.0 TeV
ILC500	0.3%	3.1 TeV
ILC500-up	0.2%	3.9 TeV
CEPC	0.2%	3.9 TeV
TLEP	0.1%	5.5 TeV

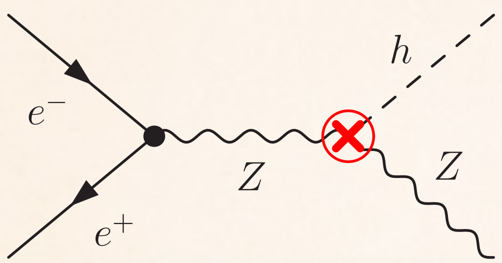
Experiment	S (68%)	f (GeV)
ILC	0.012	1.1 TeV
CEPC (opt.)	0.02	880 GeV
CEPC (imp.)	0.014	1.0 TeV
TLEP-Z	0.013	1.1 TeV
TLEP-t	0.009	1.3 TeV

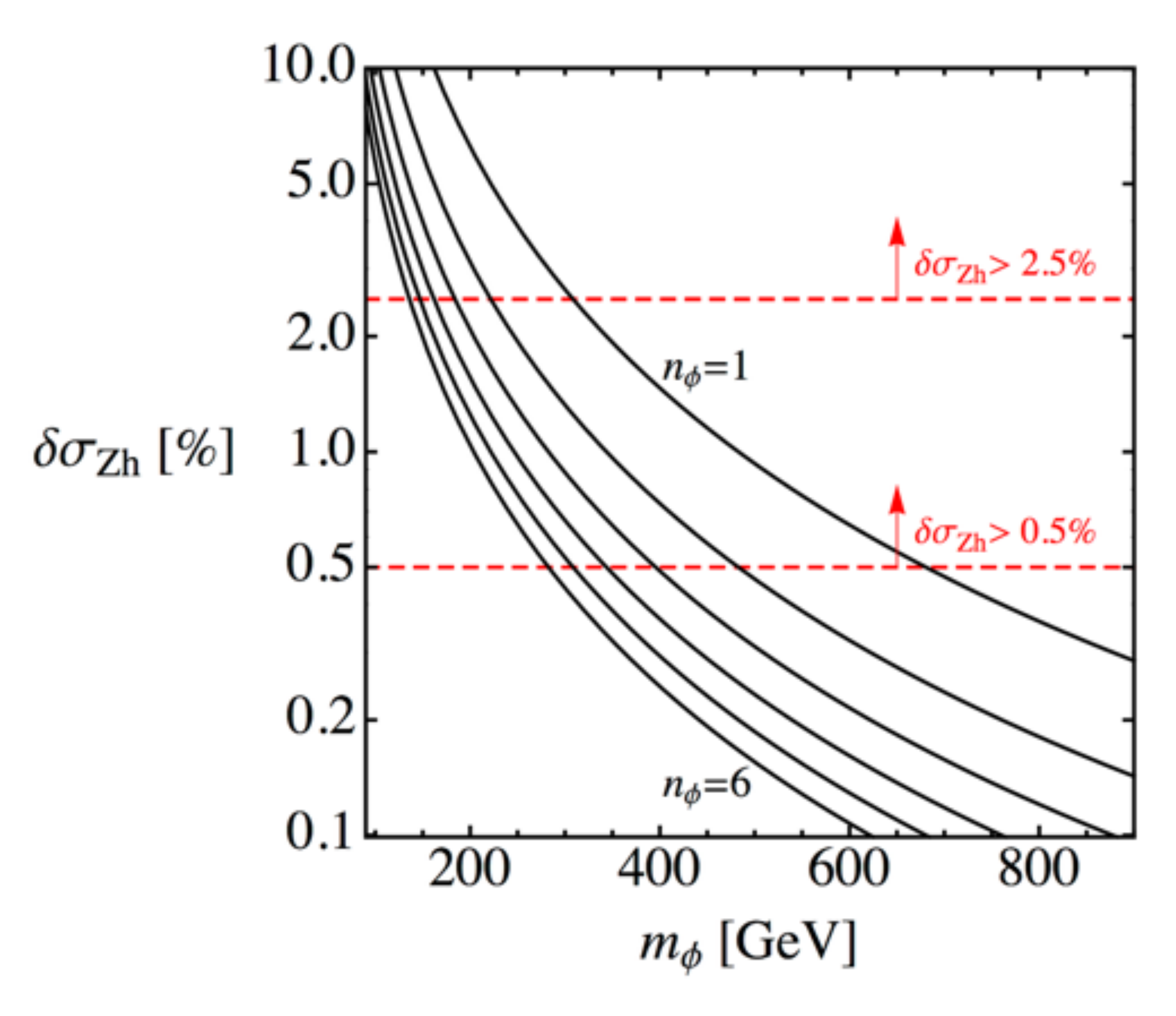
Fan, Reece and Wang 1411.1054

Twin Higgs: Chacko, Goh, Harnik 2006

new light states are not charged under the SM gauge group

$\partial_\mu |H|^2 \partial^\mu |H|^2$





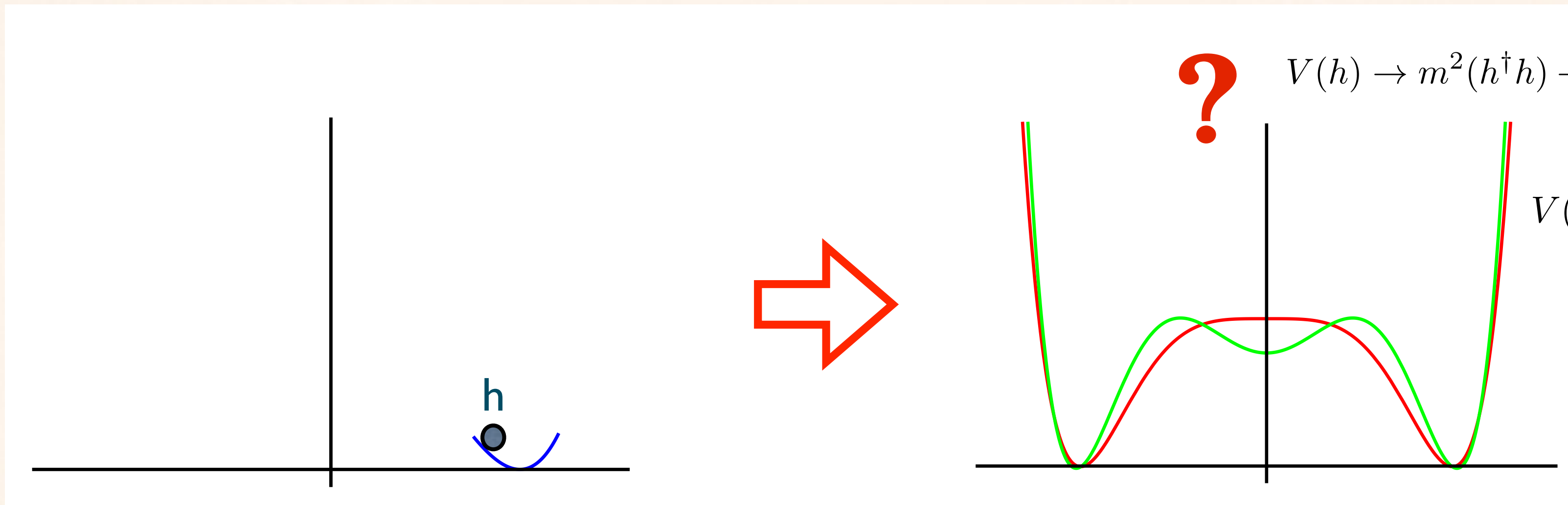
Craig, Englert and McCullough 2013

New Physics Reach: Electroweak Phase Transition

$$V(h) = m^2 h^\dagger h + \frac{1}{2}\lambda(h^\dagger h)^2$$

$$V(h) \to m^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3$$

$$V(h) \to \frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$



$$m^2 h^\dagger h + \frac{\tilde{\lambda}}{2}(h^\dagger h)^2 + \frac{1}{2}m_S^2 S^2 + a m_S S h^\dagger h + \frac{b}{3!}m_S S^3 + \frac{\kappa}{2}S^2 h^\dagger h + \frac{1}{4!}\lambda_S S^4$$

integrate out S → neglect b term

$$m^2 h^\dagger h + \frac{\lambda}{2}(h^\dagger h)^2 + \frac{\kappa a^2}{2m_S^2}(h^\dagger h)^3 \; + \; \frac{a^2}{2m_S^2}(\partial_\mu(h^\dagger h))^2$$

In order to have a first-order phase transition at tree level,

Ignore b term, $\delta Z_h \gtrsim \frac{4}{3}\frac{\sqrt{|\lambda|}}{4\pi} = 0.05, \qquad m_S \lesssim \frac{\sqrt{3}}{2}4\pi v = 2.7\text{TeV}$

Include b term, $\delta Z_h \gtrsim 4\left(\frac{\sqrt{|\lambda|}}{4\pi}\right)^{3/2} = 0.03, \qquad m_S \lesssim 2\pi v\left(\frac{4\pi}{\sqrt{|\lambda|}}\right)^{1/4} = 3.4\ \text{TeV}$

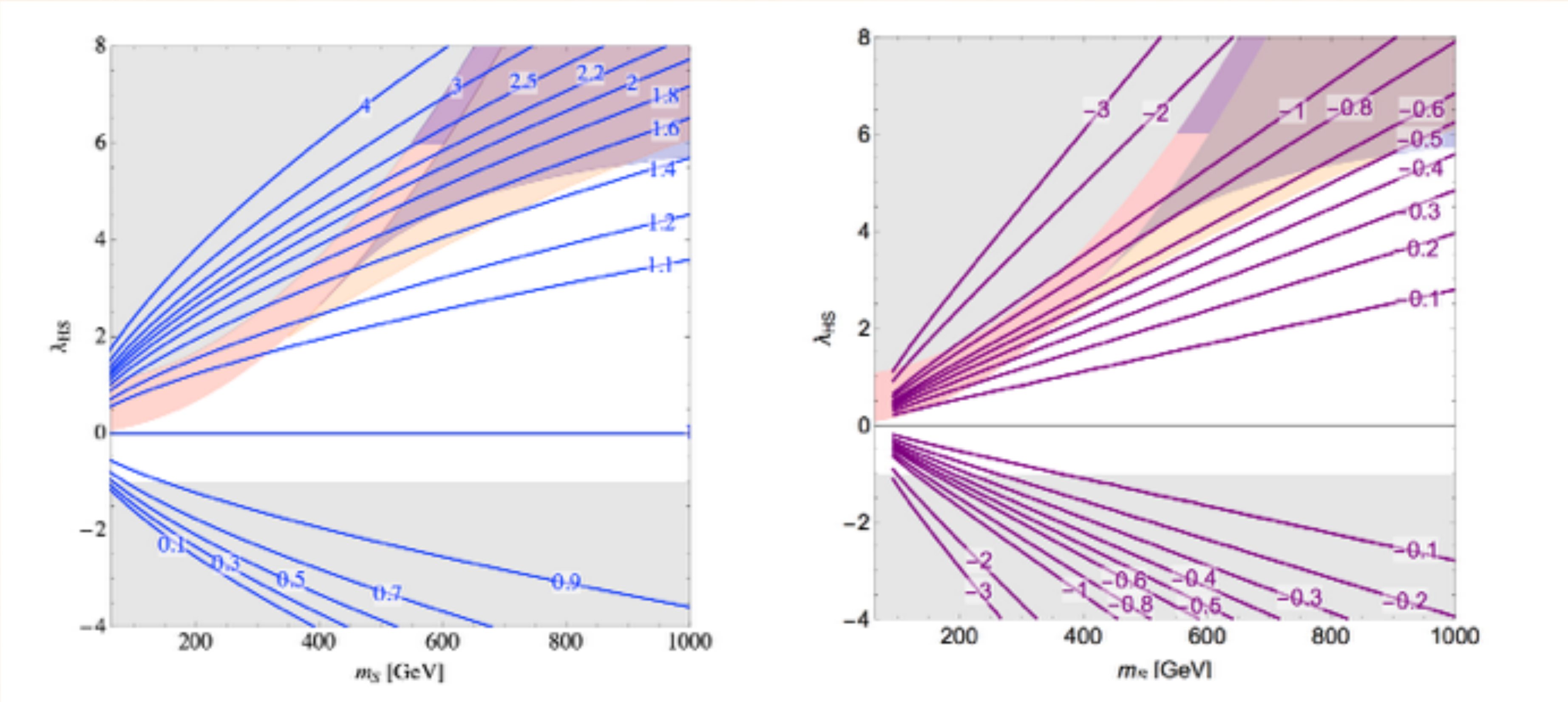
A measurable deviation in Zhh coupling

A not too heavy singlet

Many studies: Profumo, Ramsey-Musolf, Wainwright, Winslow; Katz and Perelstein; Henning, Lu, Murayama 2014...

New Physics Reach:
Electroweak Phase Transition

first-order phase transition at radiative level: Z2 singlet model



shift in Higgs triple coupling

shift in Zh coupling

Curtin, Meade, Yu 2014

New Physics Reach: Fermionic Higgs Portal

$$H^\dagger H \bar{\chi}\chi$$

↑ SM singlet: DM candidate

Lopez-Honorez, Schwetz and Zupan 2012
Fedderke, Chen, Kolb and Wang;
De Simone, Giudice and Strumia 2014

A UV completion $F \sim (\mathbf{1}, \mathbf{2}, +1/2)$

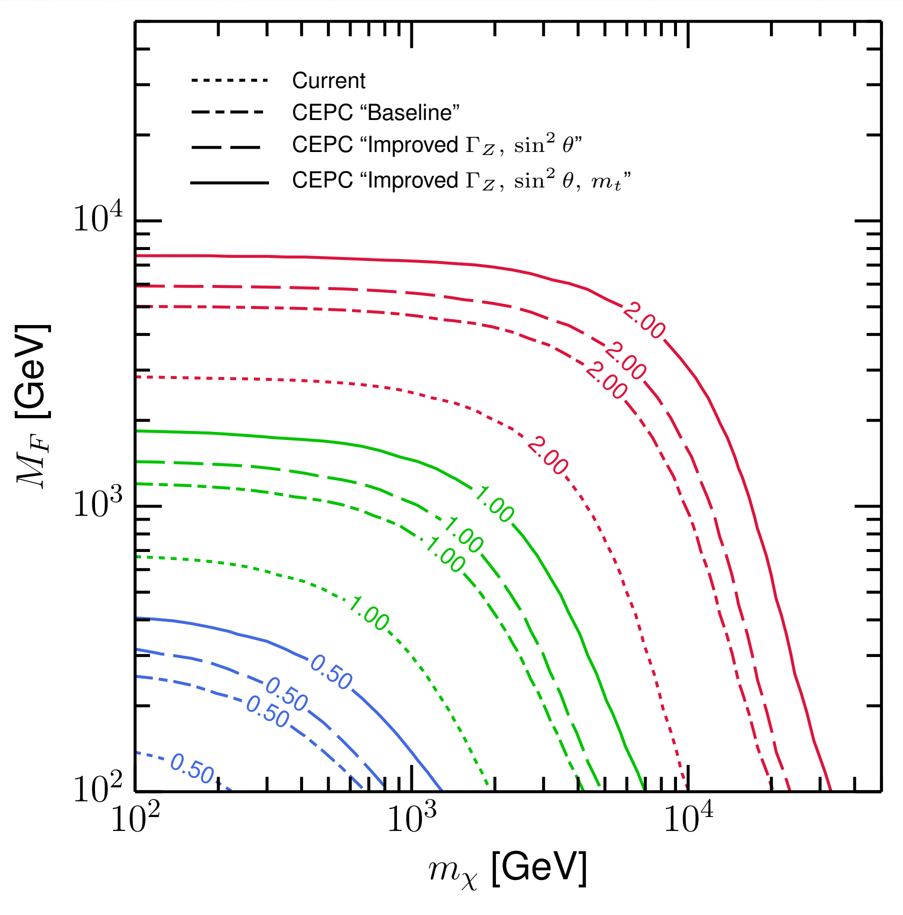
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\bar{\chi}\partial\!\!\!/\chi - m_\chi\bar{\chi}\chi + i\bar{F}D\!\!\!\!/F - M_F\bar{F}F - \kappa\bar{F}H\chi - \kappa\bar{\chi}H^\dagger F.$$

breaks custodial symmetry;
generates mass splitting inside F

$$S \approx \frac{2\kappa^2}{9\pi}\frac{v^2}{M_F^2}\left[1 - \frac{7}{4}\frac{m_\chi}{M_F} - \frac{3}{2}\frac{m_\chi^2}{M_F^2} + \cdots\right]$$

$$T \approx \frac{\alpha_\kappa}{\alpha_e}\frac{5\kappa^2}{24\pi}\frac{v^2}{M_F^2}\left[1 - \frac{2}{5}\frac{m_\chi}{M_F} - 3\frac{m_\chi^2}{M_F^2} + \cdots\right] \quad \text{where} \quad \alpha_\kappa \equiv \frac{\kappa^2}{4\pi}$$

$$U = 0 + (\text{dimension-8}).$$



Fedderke, Lin and Wang, to appear

SUMMARY

- The precisions of Higgs couplings and EWPT could be improved by a factor of 10 or more at future colliders.

- They will provide powerful indirect complementary probes to new physics at or above TeV scale.

Thank you !

ILC: GigaZ, threshold scan at the W pair production threshold, top threshold scan (~ 10^5 top pairs)

FCC-ee: TeraZ, threshold scan at the W pair production threshold (~ 10^8 W's), top threshold scan (~ 10^6 top pairs)

CEPC: GigaZ

In the future, beyond HL-LHC,

Future Circular Collider (FCC-ee, formerly known as TLEP)

International Linear Collider (ILC)

Circular Electron Positron Collider (CEPC)

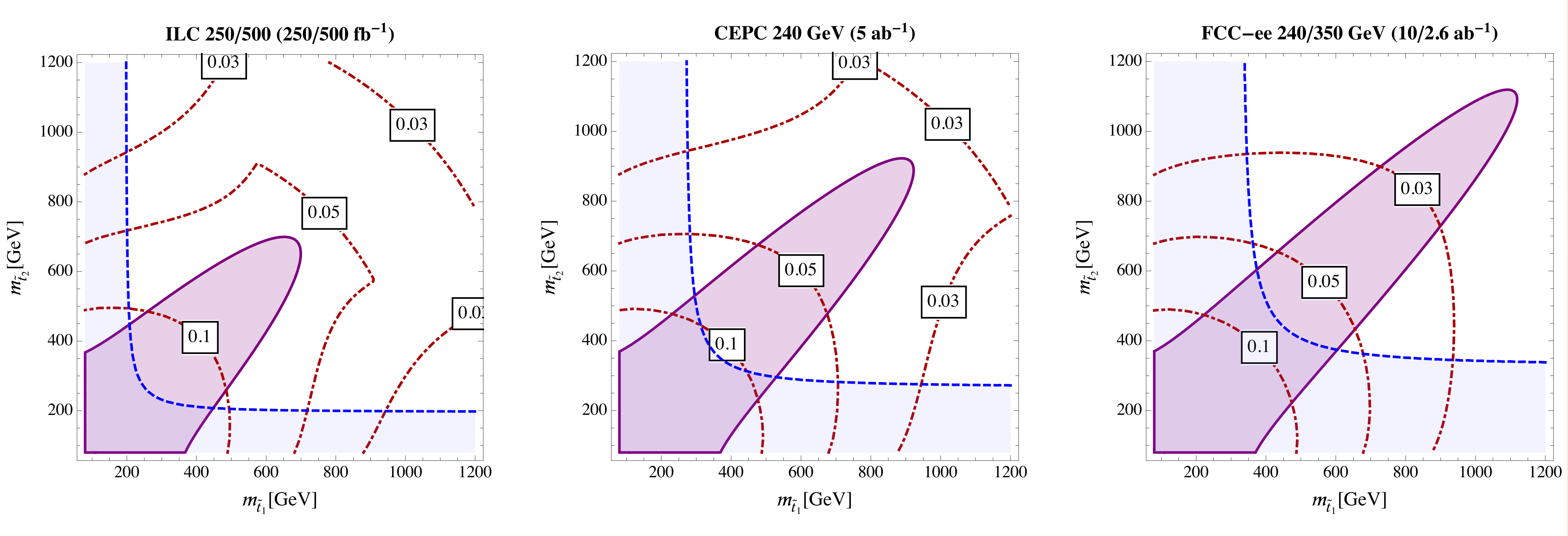
They could measure Higgs properties very well as well as other electroweak observables.

FCC-ee:
Higgs: 240 GeV with 10^4 fb^{-1} , 350 GeV with 2600 fb^{-1}
Z program: TeraZ, threshold scan at the W pair production threshold, top threshold scan

ILC:
Higgs: 250 GeV with 250 fb^{-1} , 500 GeV with 500 fb^{-1}, 1 TeV with 1000 fb^{-1}
Z program: GigaZ, threshold scan at the W pair production threshold, top threshold scan

CEPC:
Higgs: 250 GeV with 5 ab^{-1}
Z program: 10^{10} Z's

Sensitivities of future experiments



Purple: Higgs coupling 2σ sensitive region;

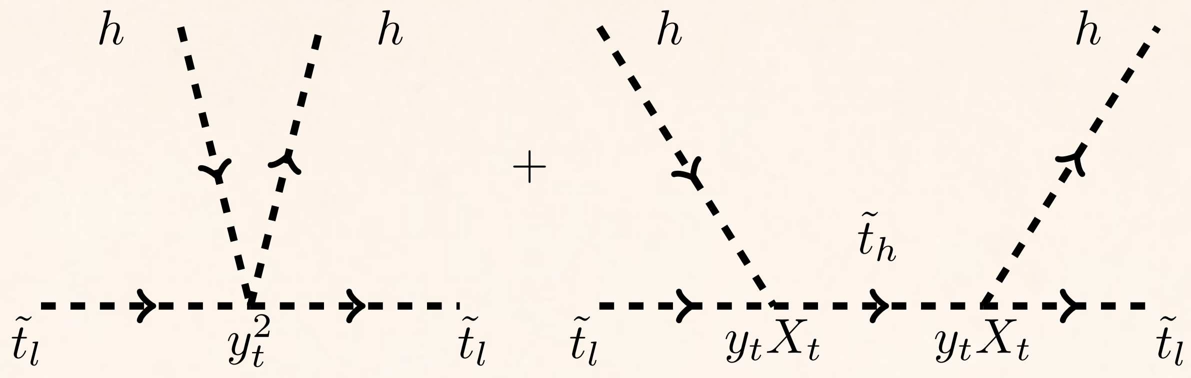
Blue: Higgs coupling fine-tuning worse than 10%;

Red: Higgs mass fine-tuning contours.

	Present data	LHC14	ILC/GigaZ
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [34]	± 0.0006	$\pm 1.0 \times 10^{-4}$ [35]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [36]	$\pm 4.7 \times 10^{-5}$ [23]	$\pm 4.7 \times 10^{-5}$ [23]
m_Z [GeV]	91.1875 ± 0.0021 [27]	± 0.0021 [23]	± 0.0021 [23]
m_t [GeV] (pole)	$173.34 \pm 0.76_{\rm exp}$ [37] $\pm 0.5_{\rm th}$ [23]	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$ [23]	$\pm 0.03_{\rm exp} \pm 0.1_{\rm th}$ [23]
m_h [GeV]	125.14 ± 0.24 [23]	$< \pm 0.1$ [23]	$< \pm 0.1$ [23]
m_W [GeV]	$80.385 \pm 0.015_{\rm exp}$ [34] $\pm 0.004_{\rm th}$ [24]	$(\pm 8_{\rm exp} \pm 4_{\rm th}) \times 10^{-3}$ [23, 24]	$(\pm 5_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [23, 38]
$\sin^2\theta_{\rm eff}^{\ell}$	$(23153 \pm 16) \times 10^{-5}$ [27]	$\pm 16 \times 10^{-5}$	$(\pm 1.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [20, 38]
Γ_Z [GeV]	2.4952 ± 0.0023 [27]	± 0.0023	± 0.001 [39]

	TLEP-Z	TLEP-W	TLEP-t
$\alpha_s(M_Z^2)$	$\pm 1.0 \times 10^{-4}$ [35]	$\pm 1.0 \times 10^{-4}$ [35]	$\pm 1.0 \times 10^{-4}$ [35]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$
m_Z [GeV]	$\pm 0.0001_{\rm exp}$ [2]	$\pm 0.0001_{\rm exp}$ [2]	$\pm 0.0001_{\rm exp}$ [2]
m_t [GeV] (pole)	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$ [23]	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$ [23]	$\pm 0.02_{\rm exp} \pm 0.1_{\rm th}$ [2, 23]
m_h [GeV]	$< \pm 0.1$	$< \pm 0.1$	$< \pm 0.1$
m_W [GeV]	$(\pm 8_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [23, 38]	$(\pm 1.2_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [20, 38]	$(\pm 1.2_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [20, 38]
$\sin^2\theta_{\rm eff}^{\ell}$	$(\pm 0.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [20, 38]	$(\pm 0.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [20, 38]	$(\pm 0.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [20, 38]
Γ_Z [GeV]	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [2, 26]	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [2, 26]	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [2, 26]

“Blind spot” in the stop parameter space



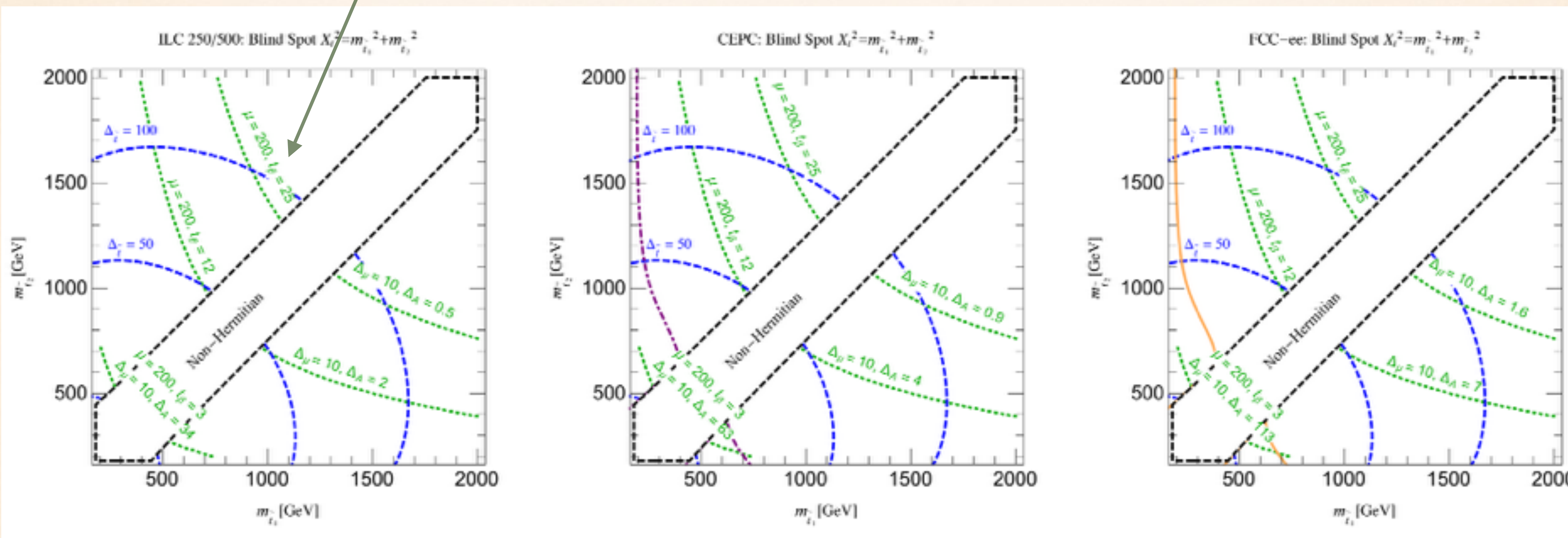
$$\mathcal{L}_{\rm eff} = \left(y_t^2 - \frac{y_t^2 X_t^2}{m_{\tilde{t}_h}^2 - m_{\tilde{t}_l}^2} \right) |H_u|^2 \left|\tilde{t}_l\right|^2 .$$

The coupling of the light stop to Higgs boson vanishes at

$$X_t^* = \left(m_{\tilde{t}_h}^2 - m_{\tilde{t}_l}^2 \right)^{1/2} .$$

T parameter, correction to hgg coupling vanishes;
Also is Rb (most likely an numerical coincidence)

Exclusion of b to s+photon



For small tan beta <~ 3, b to s gamma constraint is weak but from the fine-tuning point of view, heavy CP odd Higgs has to be light and there shall be an associated deviation in the bottom Yukawa

$$\Delta_A \approx \frac{2m_A^2}{m_h^2 \tan^2\beta}. \qquad \kappa_b \equiv \frac{y_{hbb}^{\rm SUSY}}{y_{hbb}^{\rm SM}} \approx 1 + 2\frac{m_h^2}{m_A^2}$$