POSSIBLE FUTURES OF ELECTROWEAK PRECISION: ILC, FCC-EE AND CEPC

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Aspen, 1/29/15

In the future, beyond HL-LHC,

International Linear Collider (ILC)

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

Circular Electron Positron Collider (CEPC)

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

ILC: GigaZ, threshold scan at the W pair production threshold, top threshold scan

FCC-ee: TeraZ, threshold scan at the W pair production threshold, top threshold scan

CEPC: GigaZ

OUTLINE

- Global Fit of Electroweak Observables with Oblique Corrections (ILC and FCC-ee)
- Prospects for CEPC Electroweak Precision and Higgs measurement
- To Do List for a Successful Electroweak Program
- New Physics Reach and Complementarity

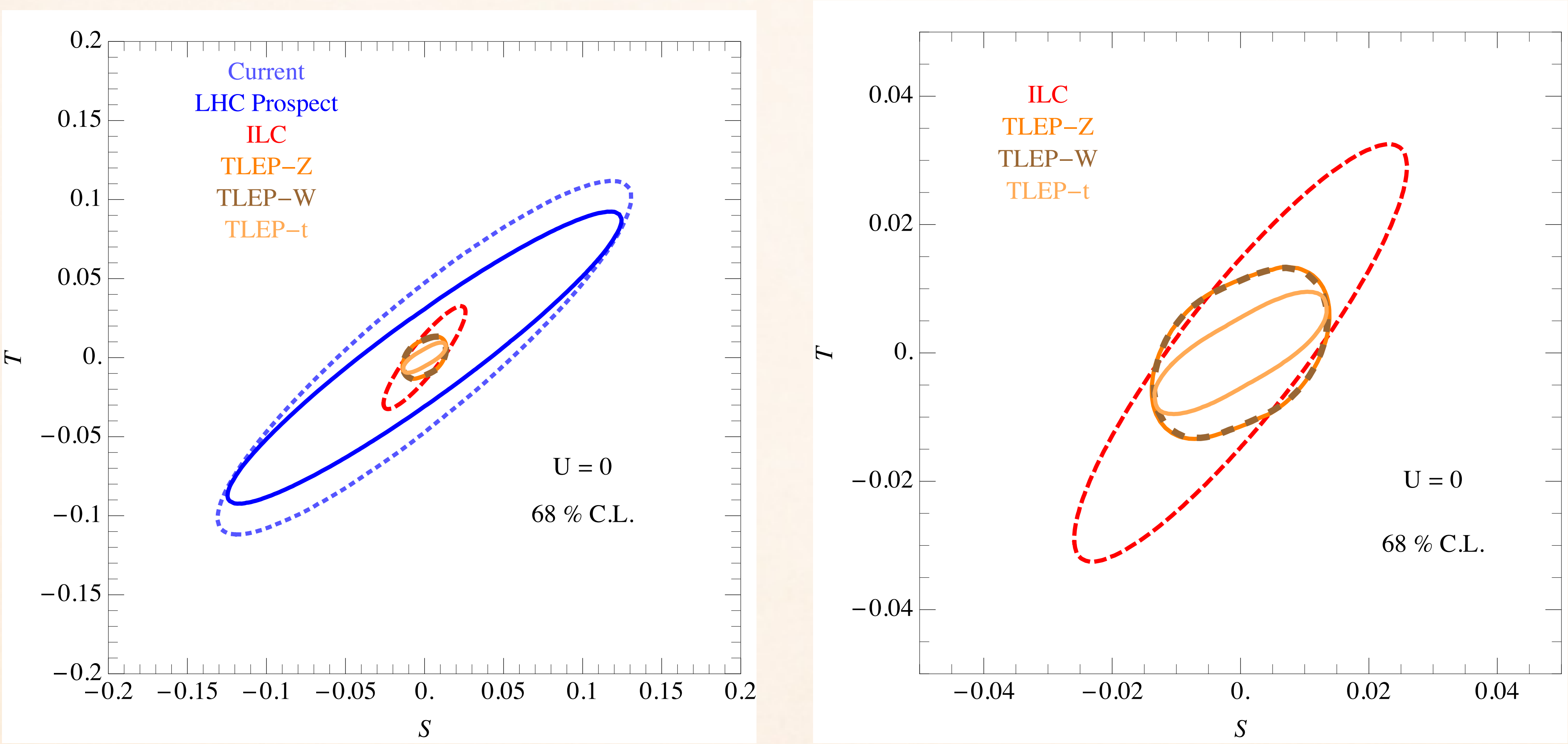
- Global Fit of Electroweak Observables with Oblique Corrections (ILC and FCC-ee)

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 (ILC and FCC-ee)

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



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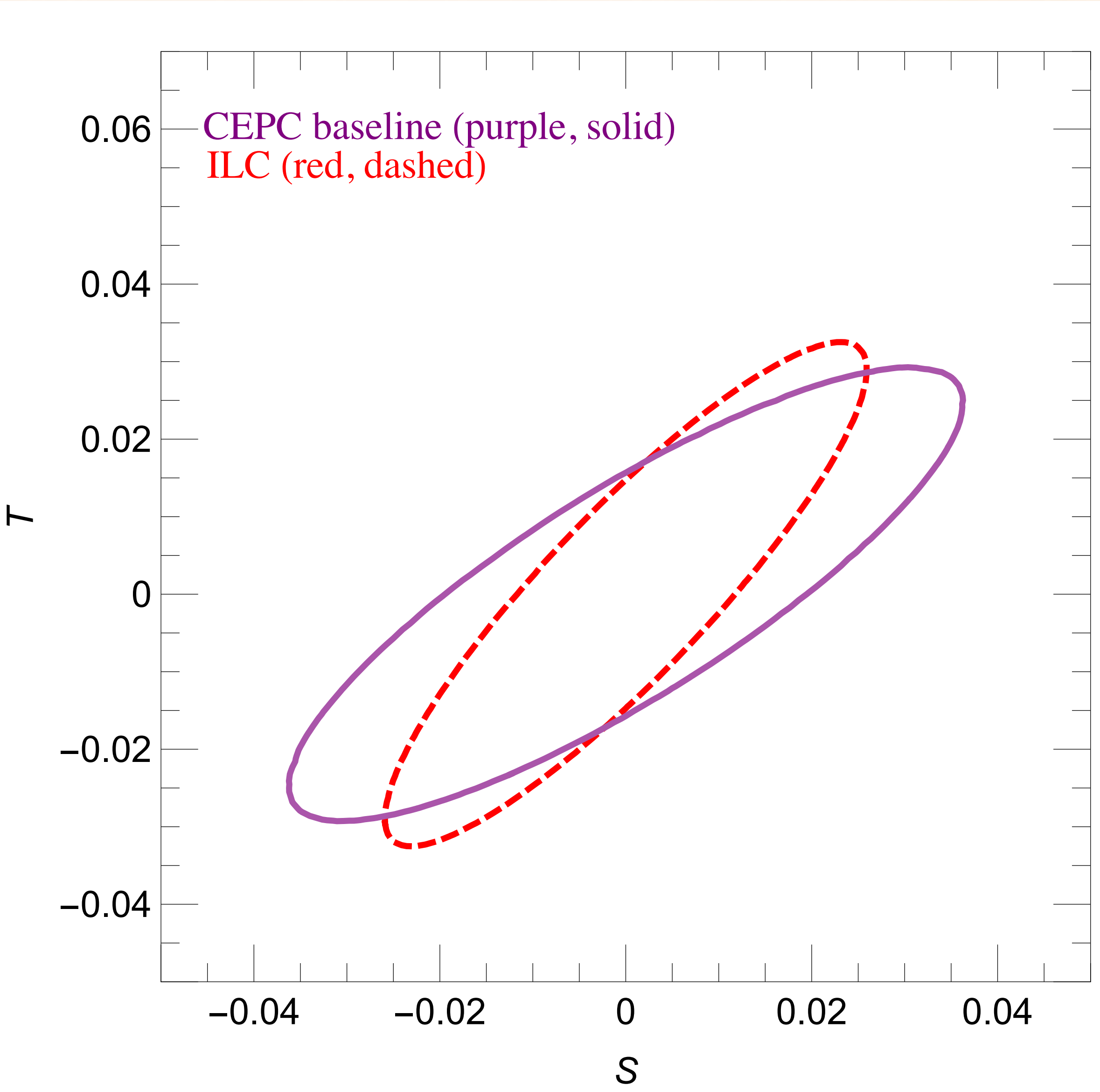
Prospects for CEPC Electroweak Precision

	CEPC
$\alpha_s(M_Z^2)$	$\pm 1.0 \times 10^{-4}$ [35]
$\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z^2)$	$\pm 4.7 \times 10^{-5}$
m_Z [GeV]	$\pm(0.0005 - 0.001)$ [41]
m_t [GeV] (pole)	$\pm 0.6_{\mathrm{exp}} \pm 0.25_{\mathrm{th}}$ [23]
m_h [GeV]	$< \pm 0.1$
m_W [GeV]	$(\pm(3-5)_{\mathrm{exp}} \pm 1_{\mathrm{th}}) \times 10^{-3}$ [24, 38, 41]
$\sin^2\theta_{\mathrm{eff}}^{\ell}$	$(\pm(4.6-5.1)_{\mathrm{exp}} \pm 1.5_{\mathrm{th}}) \times 10^{-5}$ [25, 38, 41]
Γ_Z [GeV]	$(\pm(5-10)_{\mathrm{exp}} \pm 0.8_{\mathrm{th}}) \times 10^{-4}$ [26, 41]

Z. Liang “Z and W physics at CEPC”



Potential Improvements for CEPC Electroweak Precision

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WW threshold scan

better energy calibration using resonant spin depolarization

CEPC	m_t [GeV]	m_W [GeV]	$\sin^2\theta_{\mathrm{eff}}^{\ell}$	Γ_Z [GeV]
Improved Error	$\pm 0.03_{\mathrm{exp}} \pm 0.1_{\mathrm{th}}$	$(\pm 2_{\mathrm{exp}} \pm 1_{\mathrm{th}}) \times 10^{-3}$	$(\pm 2.3_{\mathrm{exp}} \pm 1.5_{\mathrm{th}}) \times 10^{-5}$	$(\pm 1_{\mathrm{exp}} \pm 0.8_{\mathrm{th}}) \times 10^{-4}$

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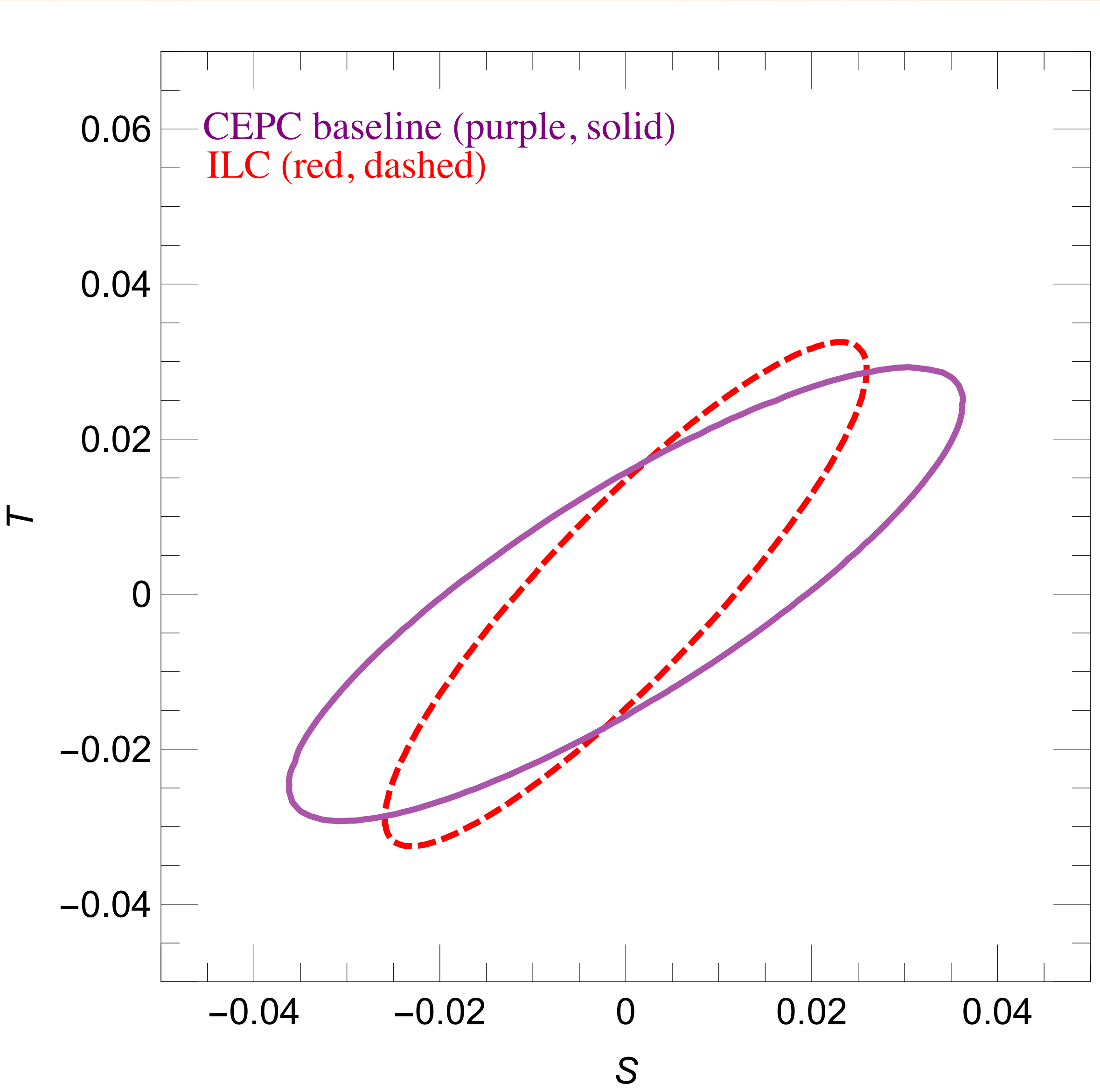

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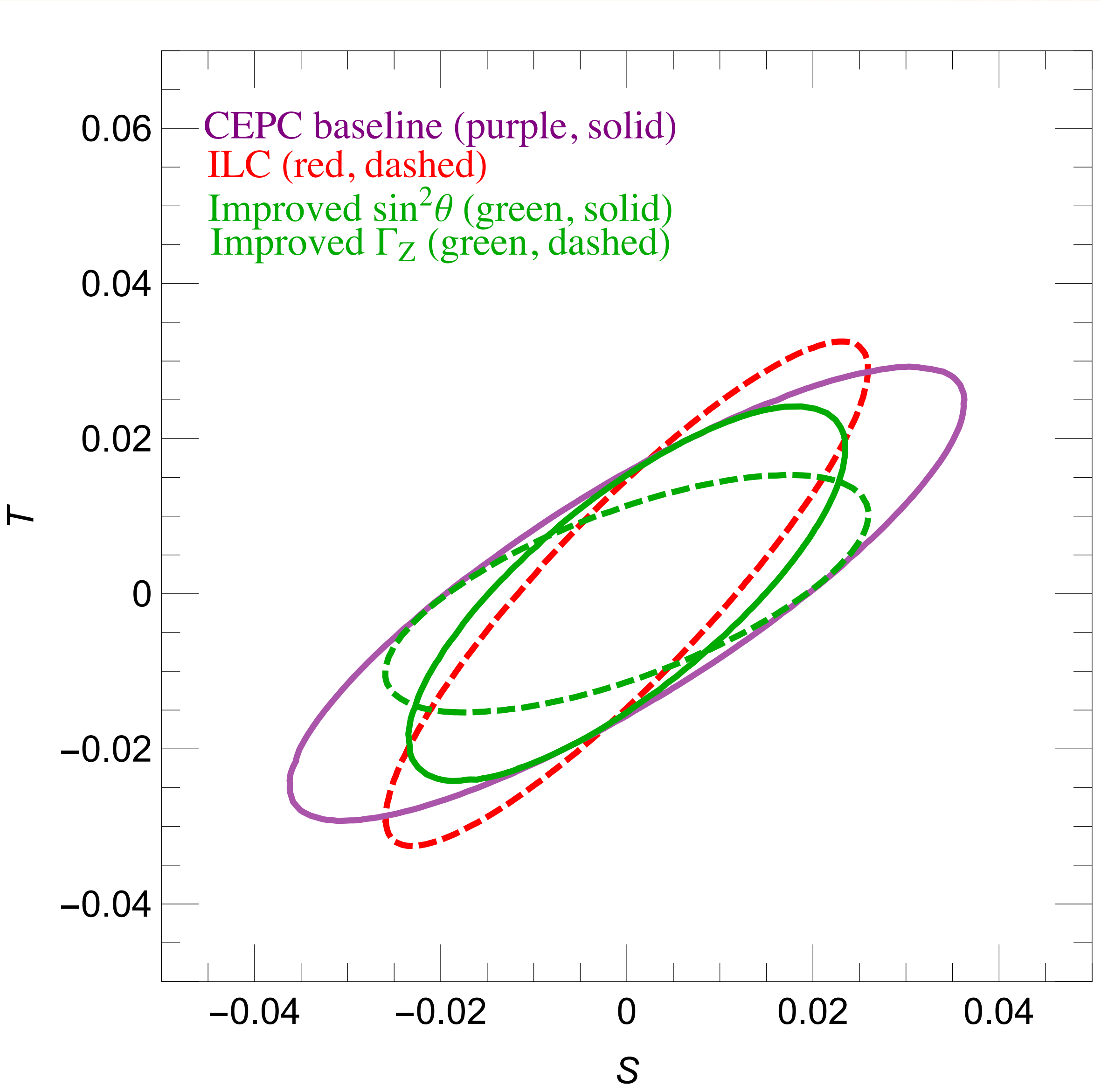

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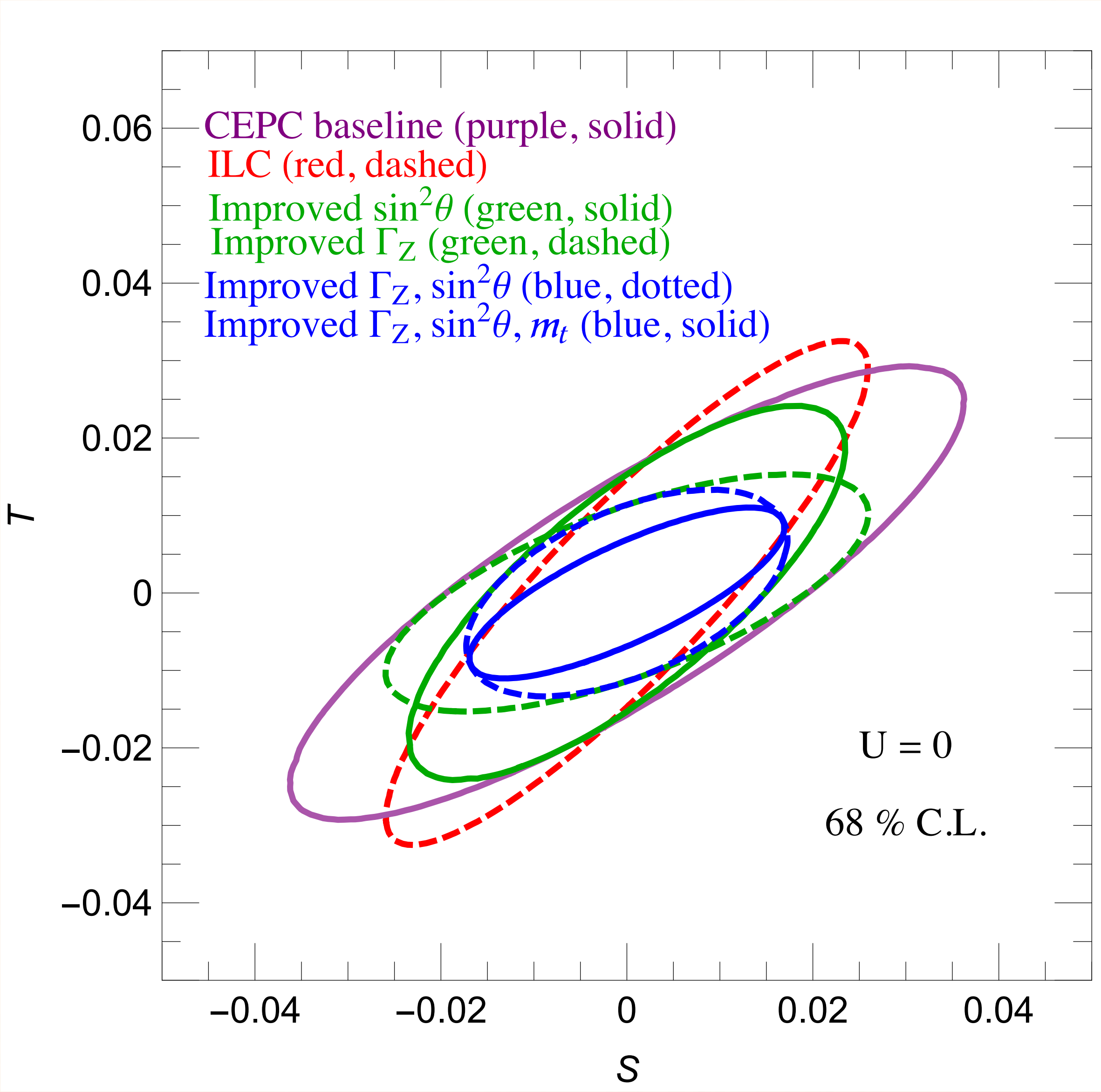

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Potential Improvement for CEPC Electroweak Precision

- WW threshold scan is not necessary;
- Combining possible improvements in weak mixing angle, Z width and/or top threshold scan leads to an improvement of a factor of 2-3, making CEPC EWPT comparable to FCC-ee EWPT

better energy calibration using resonant spin depolarization

WW threshold scan

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ILC top threshold scan

luminosity of off-Z peak running increased by a factor of 10 to 40 fb-1 at each energy point

- # Prospects for CEPC Higgs measurements

$\sqrt{s}$ and $\mathcal{L}$	CEPC: 5 ab^{-1}, 240 GeV	
	Zh	$\nu\bar{\nu}h$
$\Delta\sigma/\sigma$	0.70%	-
mode	$\Delta(\sigma \cdot \mathrm{Br})/(\sigma \cdot \mathrm{Br})$	
$h \to b\bar{b}$	0.32%	4.0%
$h \to c\bar{c}$	2.2 %	-
$h \to gg$	1.9%	-
$h \to WW^*$	1.7%	-
$h \to \tau^+\tau^-$	1.1%	-
$h \to ZZ^*$	4.8%	-
$h \to \gamma\gamma$	9.1%	-
$h \to \mu^+\mu^-$	27%	-

HL-LHC could constrain the ratio of Higgs decay widths to photon and Z's

Coupling	CEPC (5 ab^{-1})	CEPC + HL-LHC
$\gamma\gamma$	4.8%	1.7%
gg	1.9%	1.8%
WW	1.6%	1.6%
ZZ	0.20%	0.20%
$t\bar{t}$	1.9%	1.9%
$b\bar{b}$	1.5%	1.5%
$\tau^+\tau^-$	1.7%	1.6%

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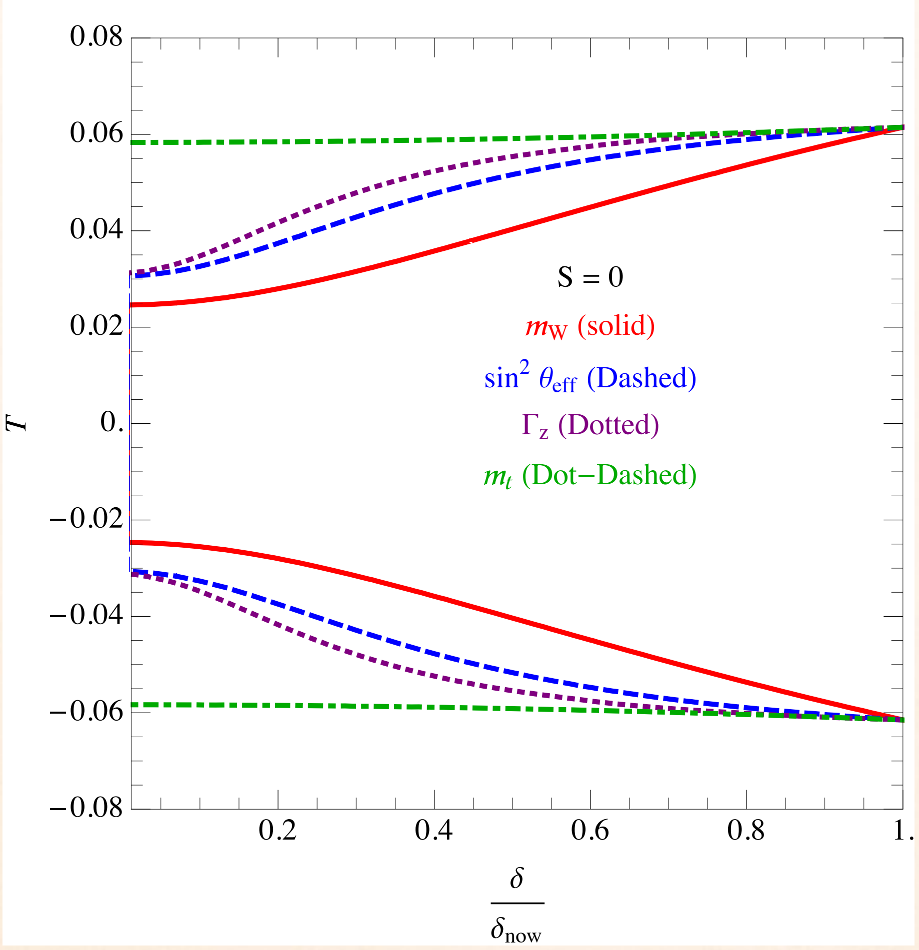
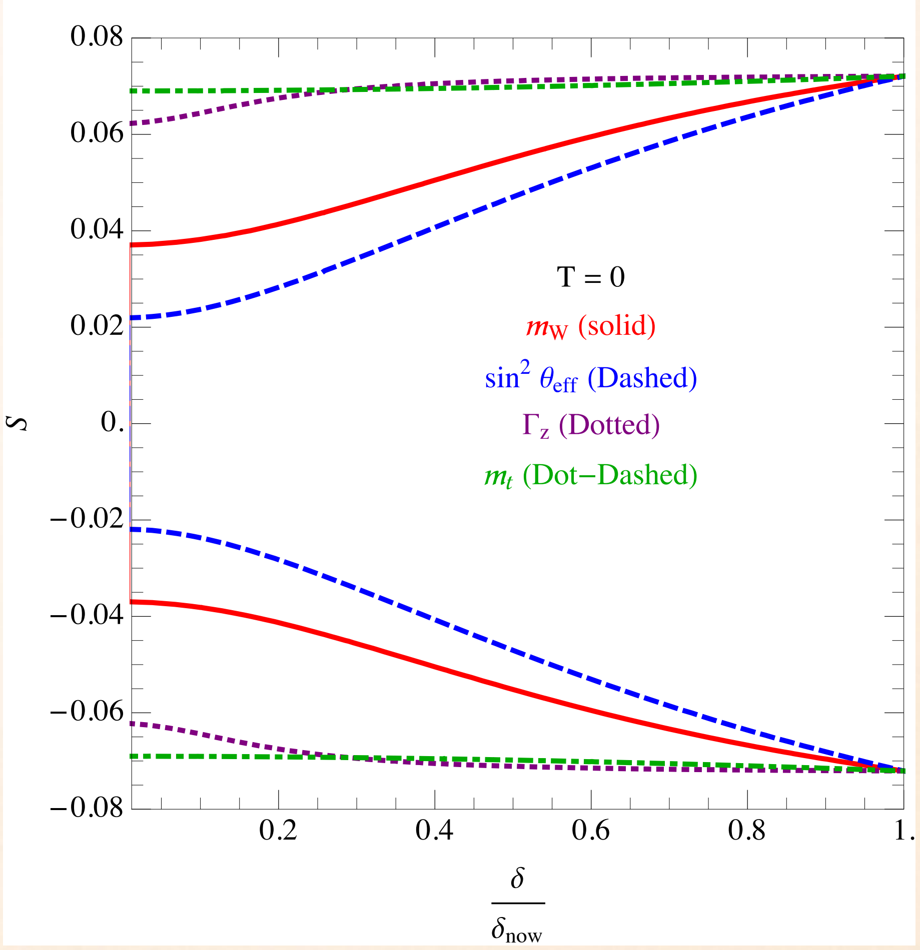
To do list for a successful electroweak program

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





- 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 corrections computations are desirable (two-loop calculations so far).

New Physics Reach: use natural SUSY as an example (stop + Higgsino sector)

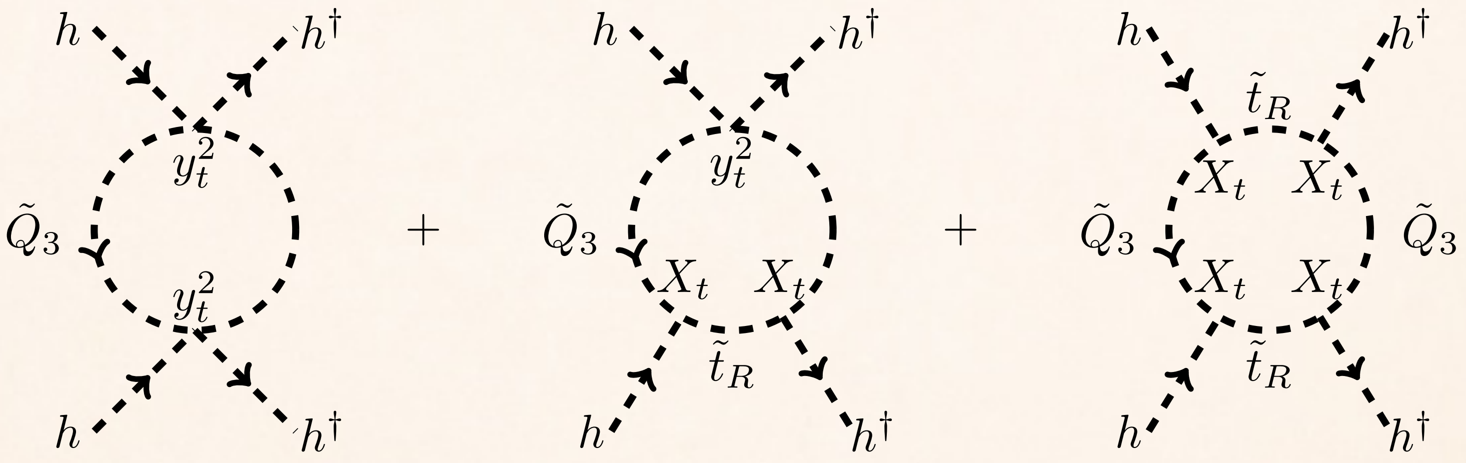
Lepton colliders are limited in kinematic reach of stops compared to proton colliders;

On the other hand, stops can also be hidden due to some non-minimal decay modes and/or kinematics of the decay products.

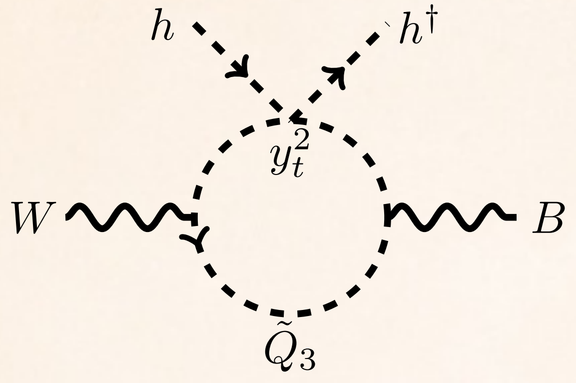
Precision measurements at lepton colliders could provide complementary probes independent of the details of stop decays.

New Physics Reach: use natural SUSY as an example (stop + Higgsino sector)

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



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



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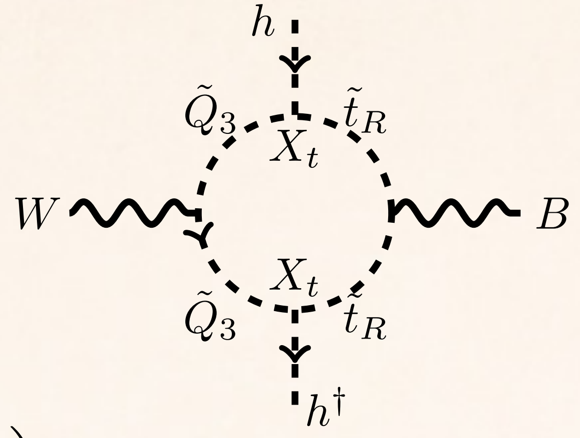

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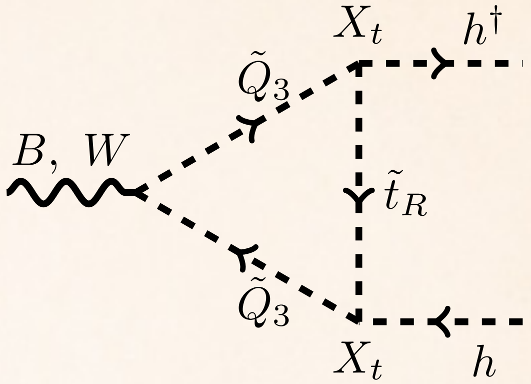


$$S\left(\frac{\alpha}{4\sin\theta_W\cos\theta_W v^2}\right) h^\dagger W^{i\mu\nu}\sigma^i h B_{\mu\nu}$$

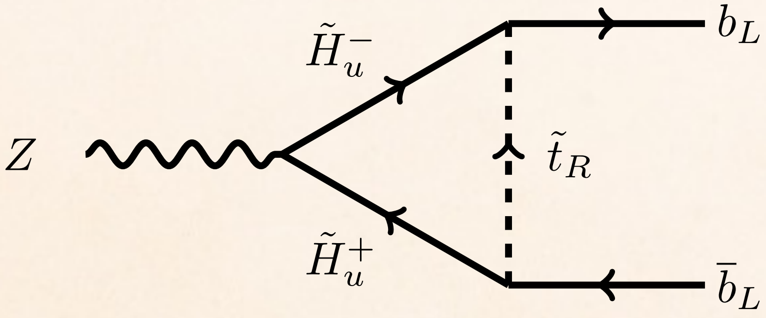
$$i\partial^\nu B_{\mu\nu} h^\dagger \overleftrightarrow{D}^\mu h$$

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

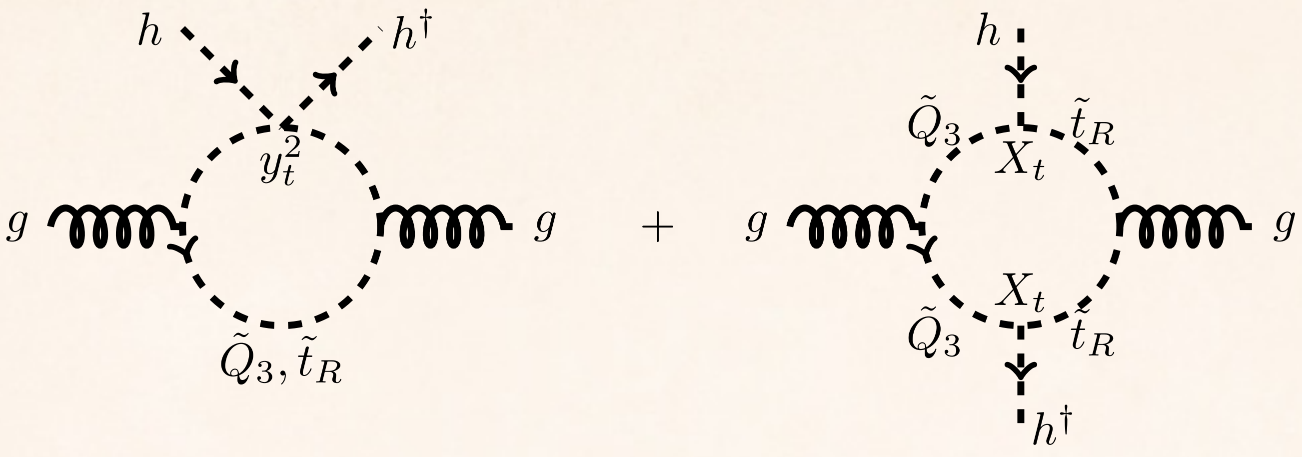
$$S \approx -\frac{1}{6\pi}\frac{m_t^2}{m_{\tilde{Q}_3}^2} + \mathcal{O}\left(\frac{m_t^2 X_t^2}{4\pi m_{\tilde{Q}_3}^2 m_{\tilde{u}_3}^2}\right).$$

Henning, Lu, Murayama
2014

Rb



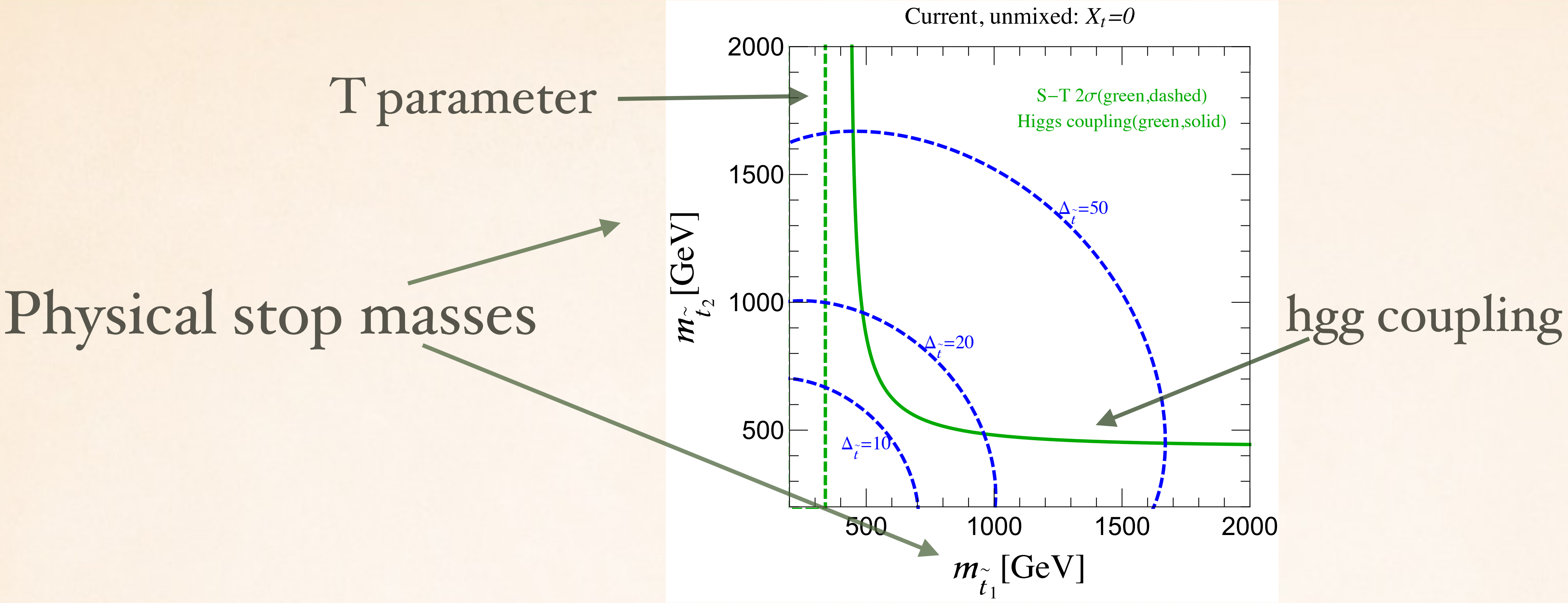
$$\frac{y_t^2}{m_{\tilde{t}_R}^2} W^i_{\mu\nu} Q_3^\dagger \sigma^i \overline{\sigma}^\mu i D^\nu Q_3 \ \log\frac{m_{\tilde{t}_R}}{\mu}.$$



$H^\dagger H G^2$

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

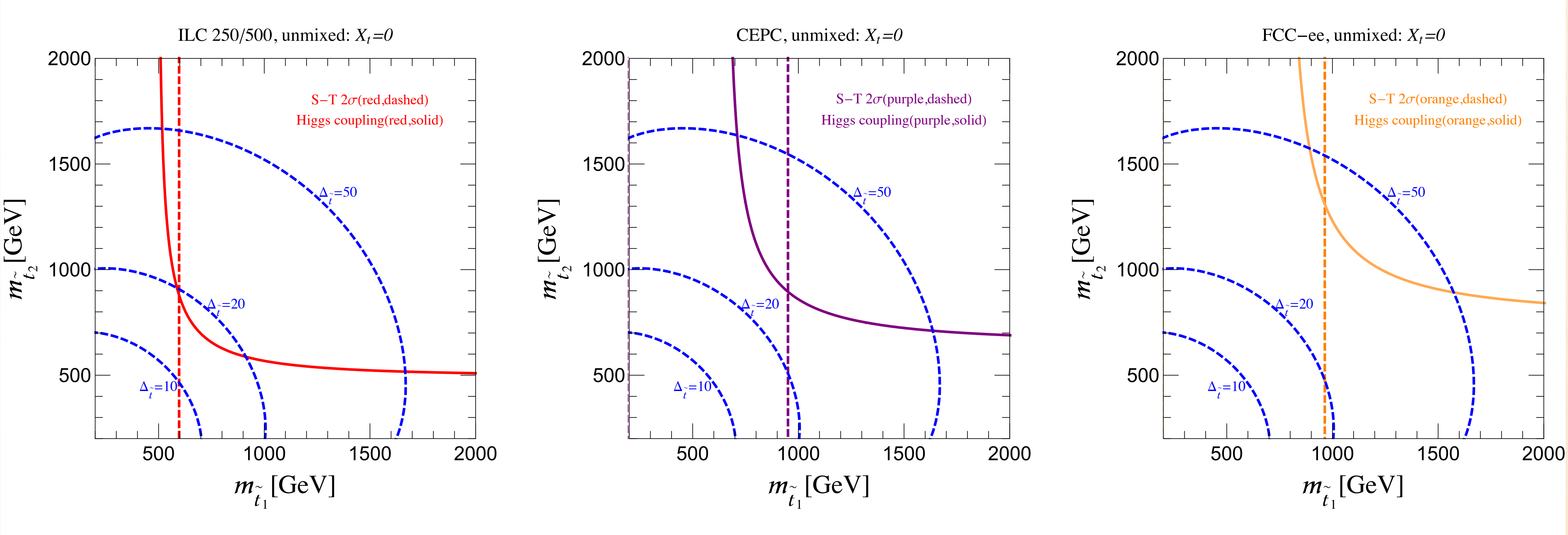
Other corrections to precision observables:
wavefunction renormalization of the Higgs boson
(Craig, Englert, McCullough 2013)
b to s gamma,
triple gauge coupling,
running of the gauge couplings (for hadron collider).



T parameter

Physical stop masses

hgg coupling



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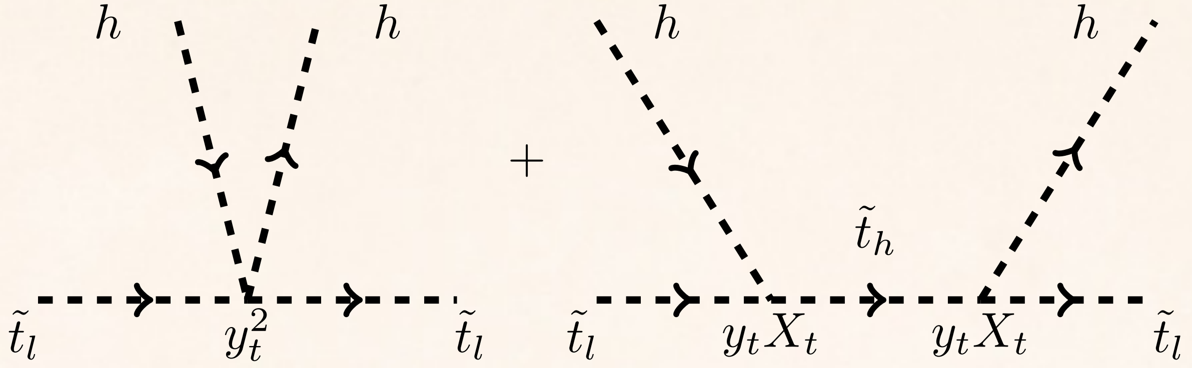
“Blind spot” in the stop parameter space



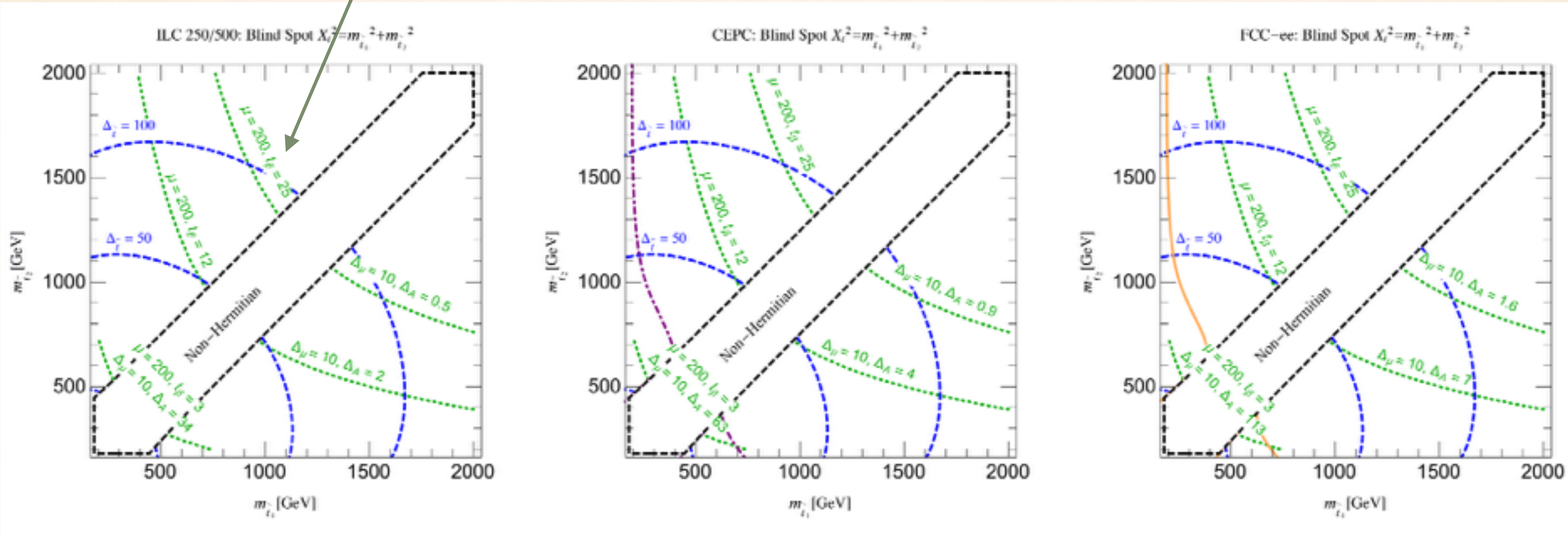
$$\mathcal{L}_{\text{eff}} = \left(y_t^2 - \frac{y_t^2 X_t^2}{m_{\tilde{t}_h}^2 - m_{\tilde{t}_l}^2} \right) |H_u|^2 \left|\tilde{t}_l\right|^2 .$$

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)

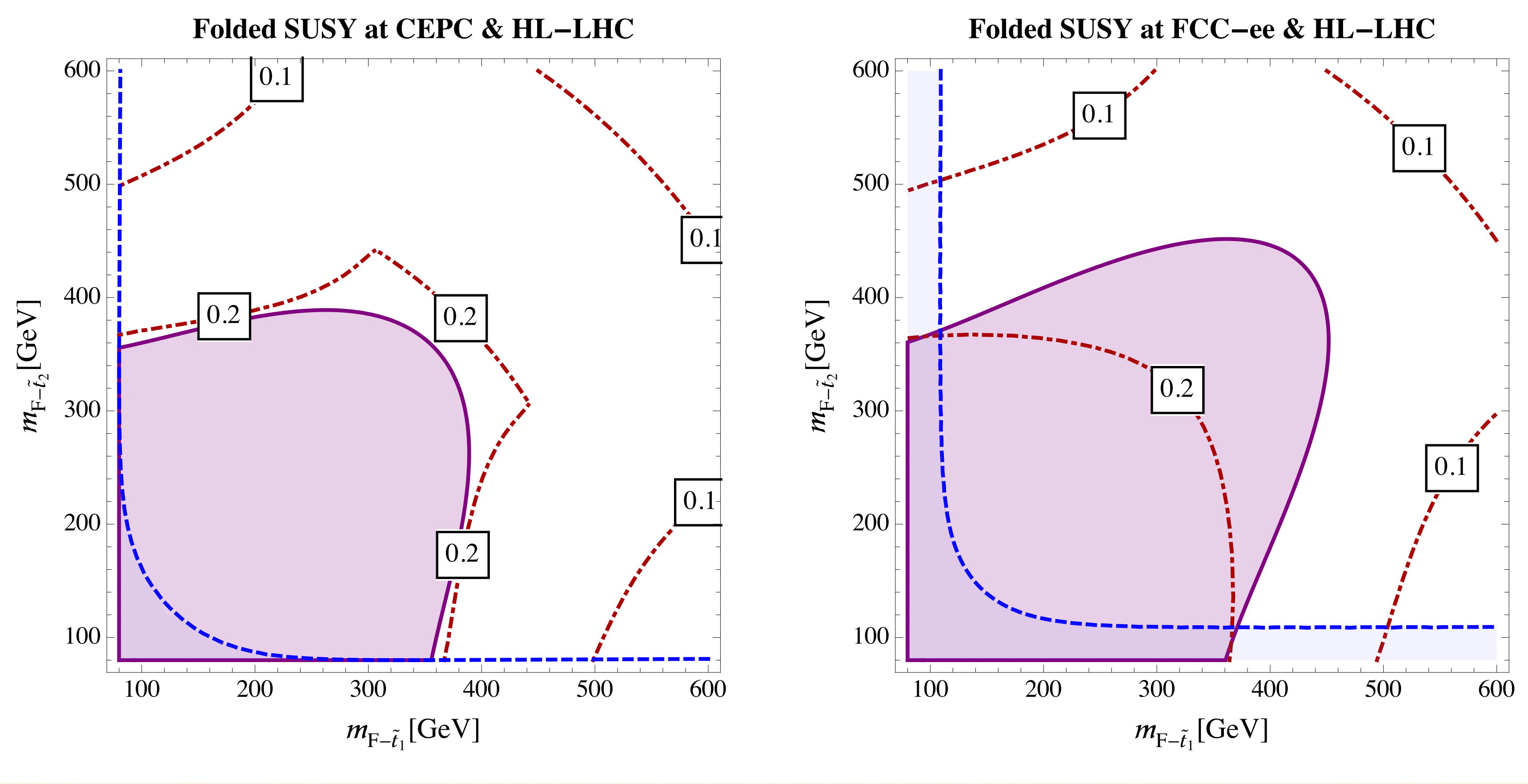
Exclusion of b to s+photon



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

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

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 the blind spot.



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

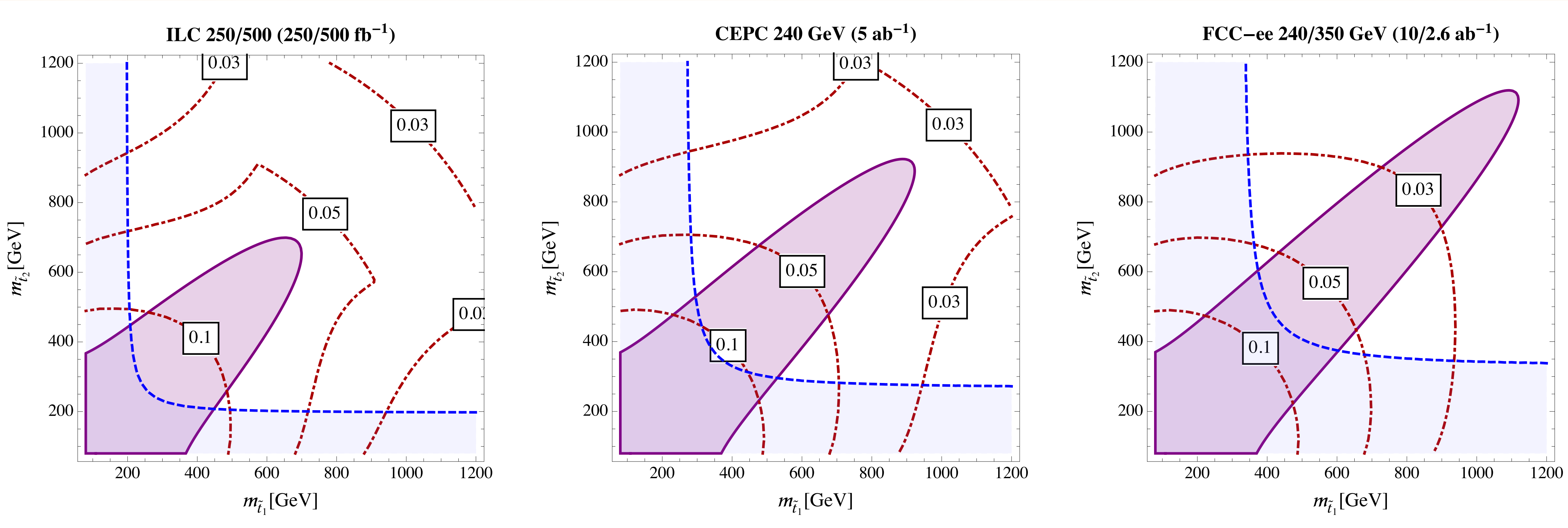
Thank you !

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

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]