Precision Measurement and New Physics at CEPC

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References:
arXiv:1411.1054 and 1412.3107
(JiJi Fan, MR, and Lian-Tao Wang)
also: CEPC pre-CDR (especially Ch. 4)

Precision physics

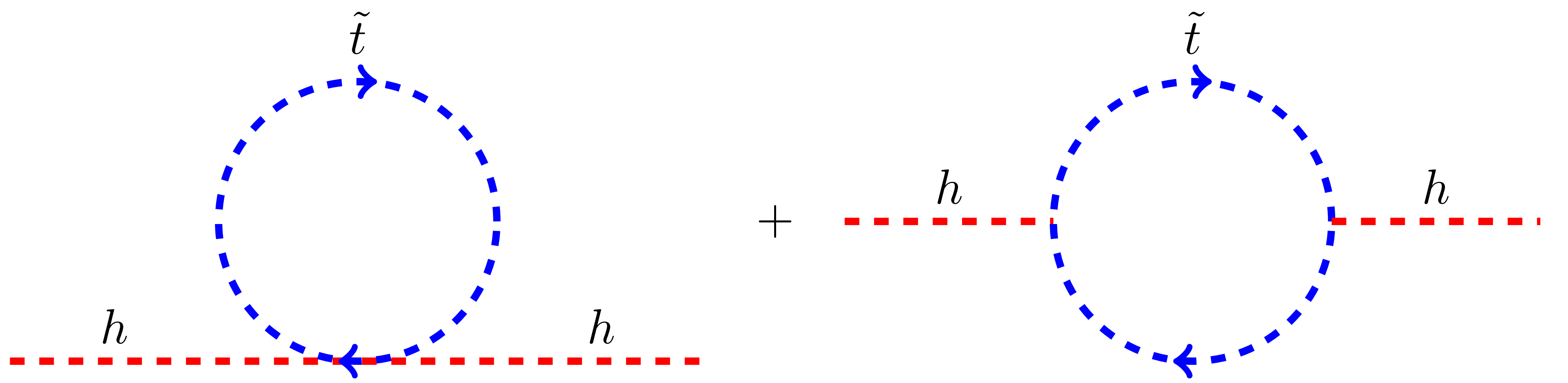
- CEPC will be a precision measurement machine! As a Higgs factory, measuring Higgs couplings precisely is a major goal.

- Several talks at this workshop will cover precision measurements.

- This talk: electroweak precision (S and T parameters), some Higgs physics, but also **context**: what could the measurements tell us about what lies beyond the Standard Model?

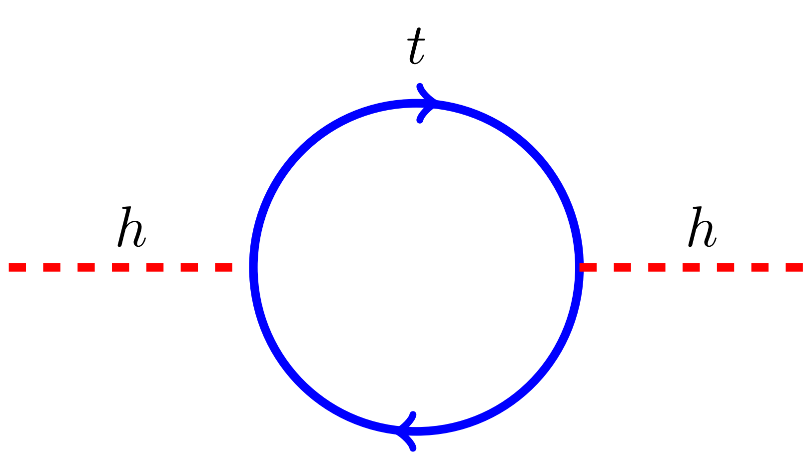
Stops

To contextualize the results, I'll begin by focusing on one illustrative case for what the new physics could be: stops.

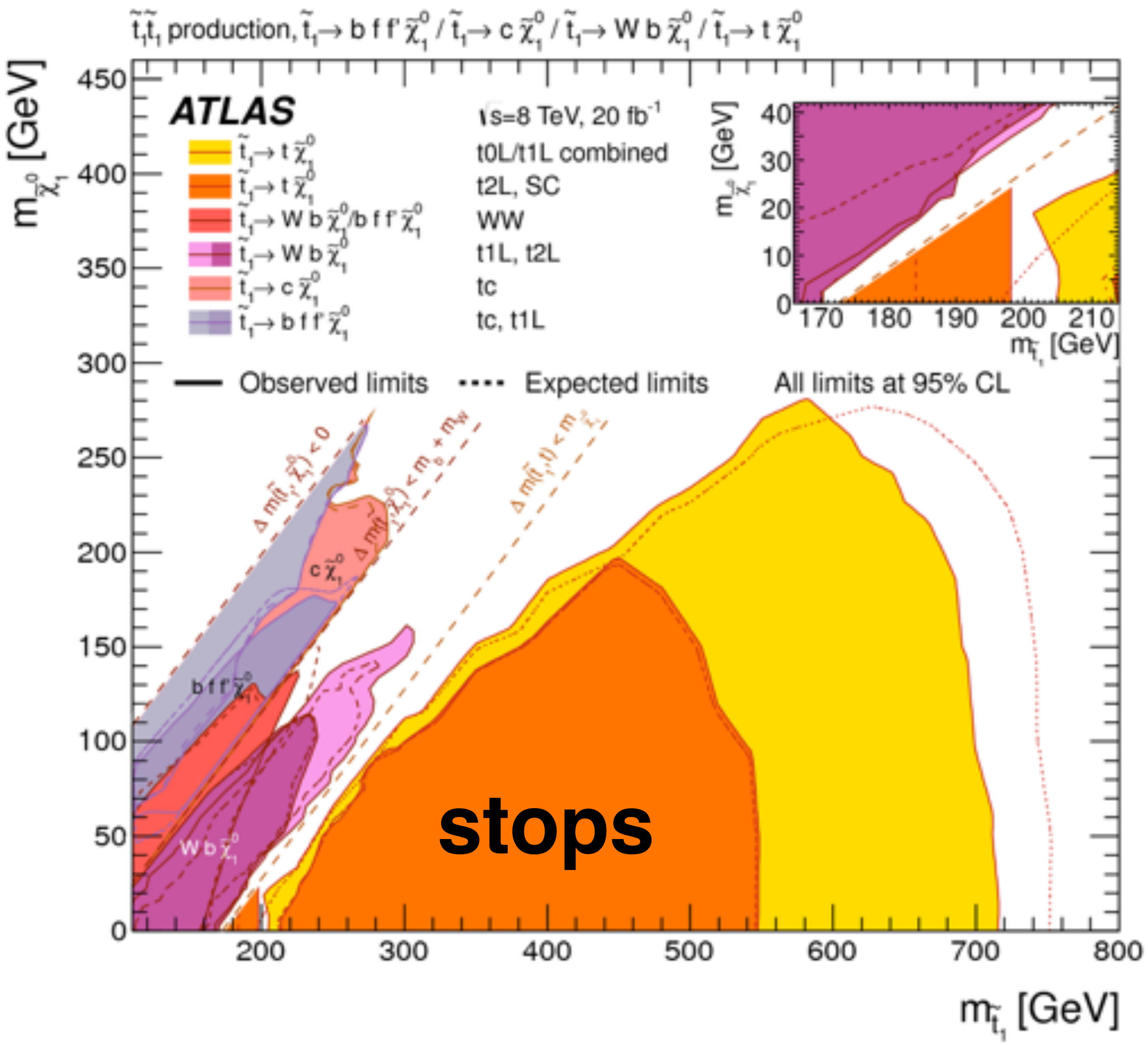


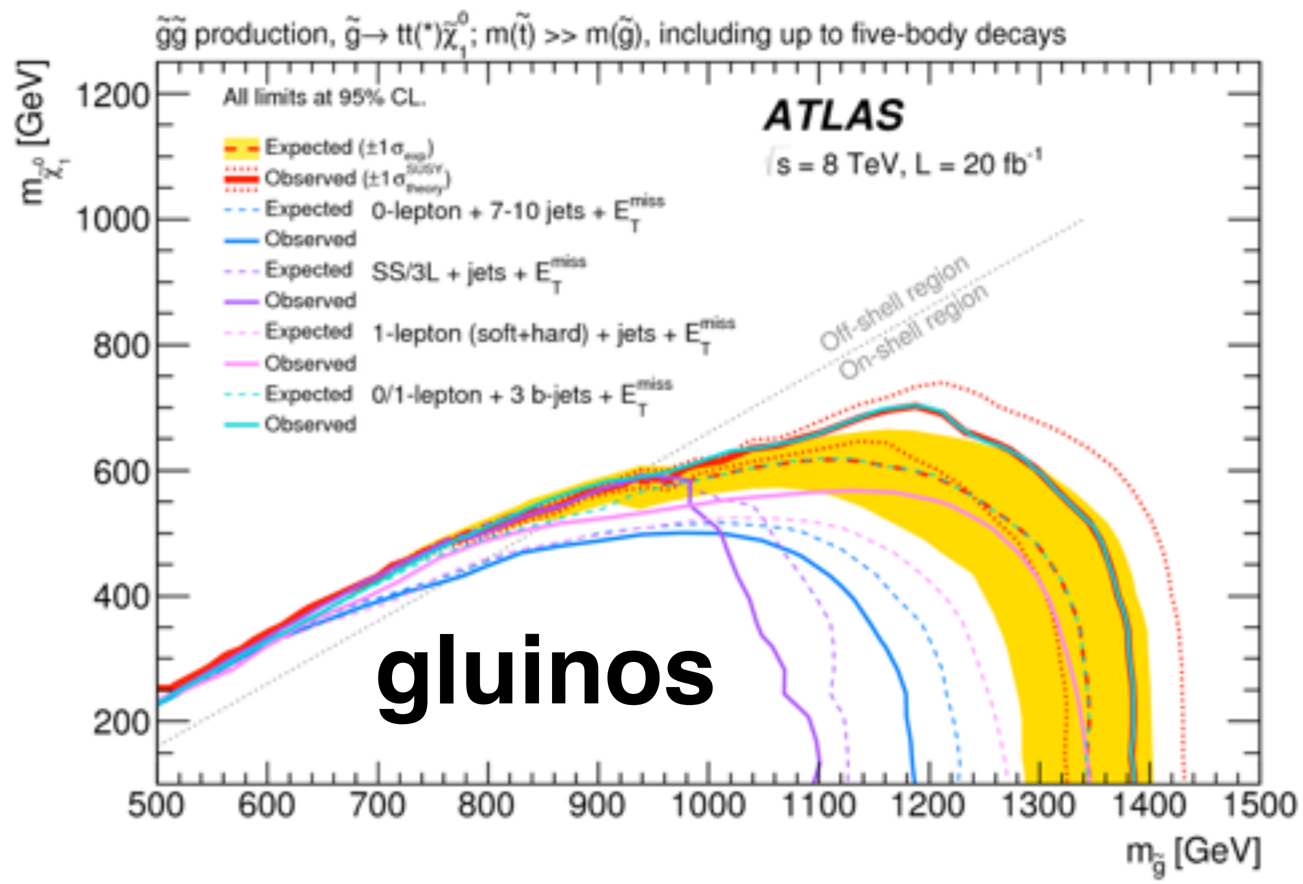
Different-spin pieces combine to cancel large corrections.

"Stop" or "scalar top":
cancels the biggest correction.
~10% tuned if mass ~ 700 GeV.



LHC: Towards Fine-Tuning?





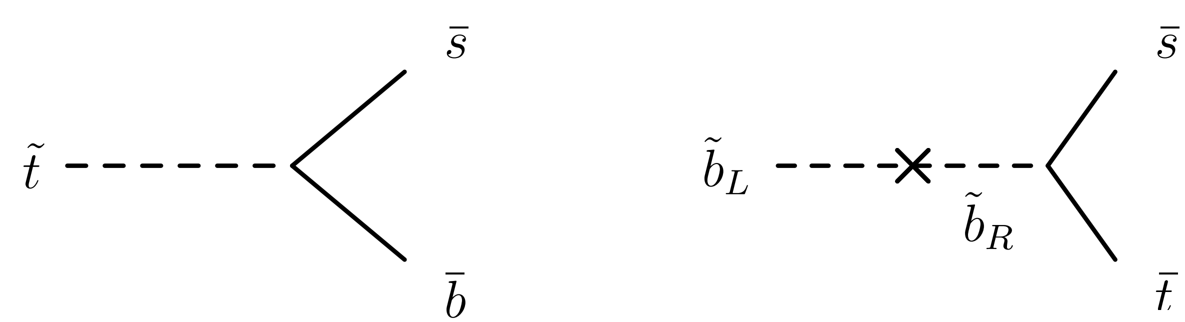
Direct searches for the superpartners are so far coming up empty. But lots of still-uncharted stop territory.

LHC Stop Prospects

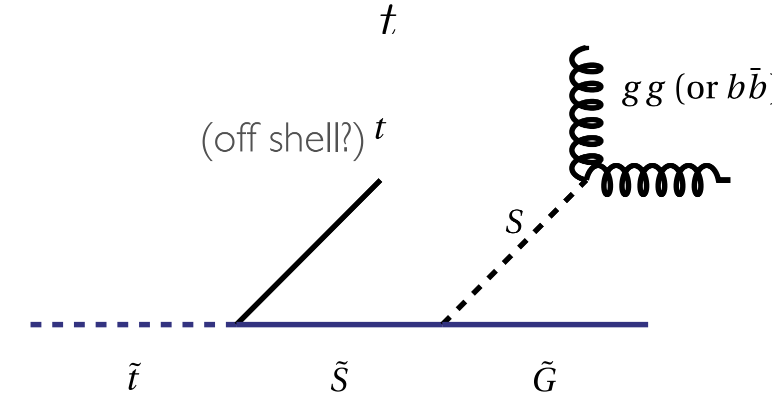
Exhausting all possibilities at the LHC requires a systematic search of many different channels and kinds of physics, e.g.:

Compressed stops (see e.g. Kilic/Tweedie; An/Wang; Macaluso/Park/Shih/Tweedie)

R-parity violating stops:



Decay to hidden sector (e.g. stealth SUSY):
(Fan/Krall/Reece/… to appear)



Despite our best efforts, gaps can and likely will remain in LHC direct search coverage.

Indirect Observables

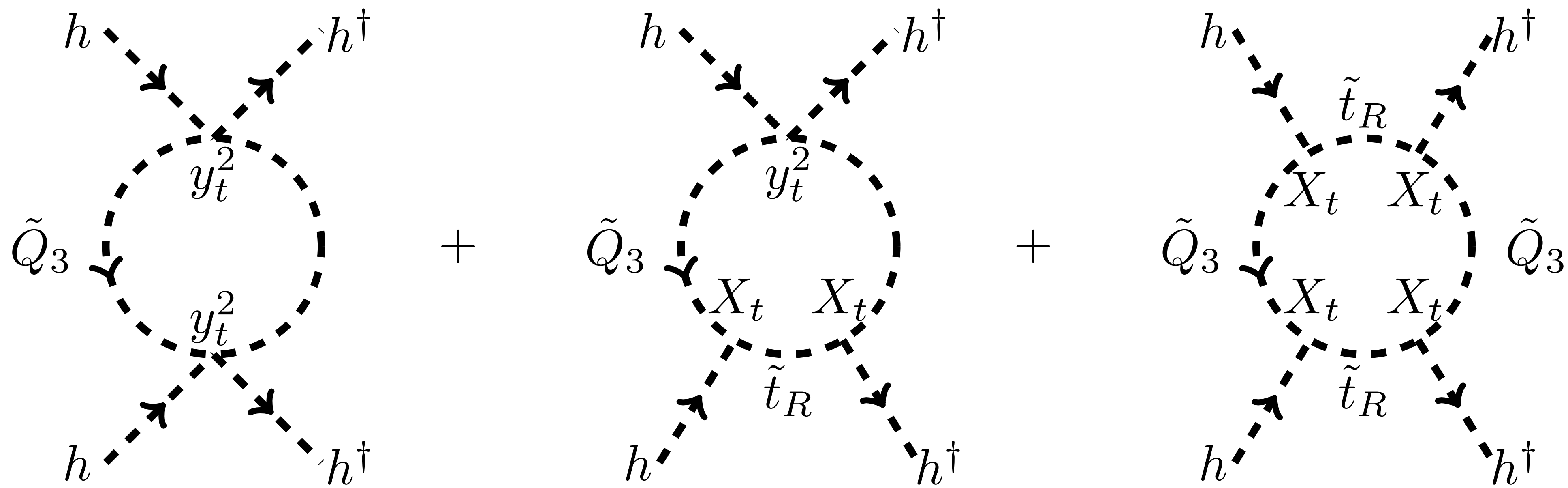
The same physics that is relevant for naturalness—couplings to the Higgs boson—can enter in loops to produce modifications of Standard Model electroweak observables.

S parameter: $$S\left(\frac{\alpha}{4 s_W c_W v^2}\right) h^\dagger \sigma^i h W^i_{\mu\nu} B^{\mu\nu}$$

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

Higgs decays: $$c_{hgg} h^\dagger h G^a_{\mu\nu} G^{a\mu\nu} + c_{h\gamma\gamma} h^\dagger h F_{\mu\nu} F^{\mu\nu}$$

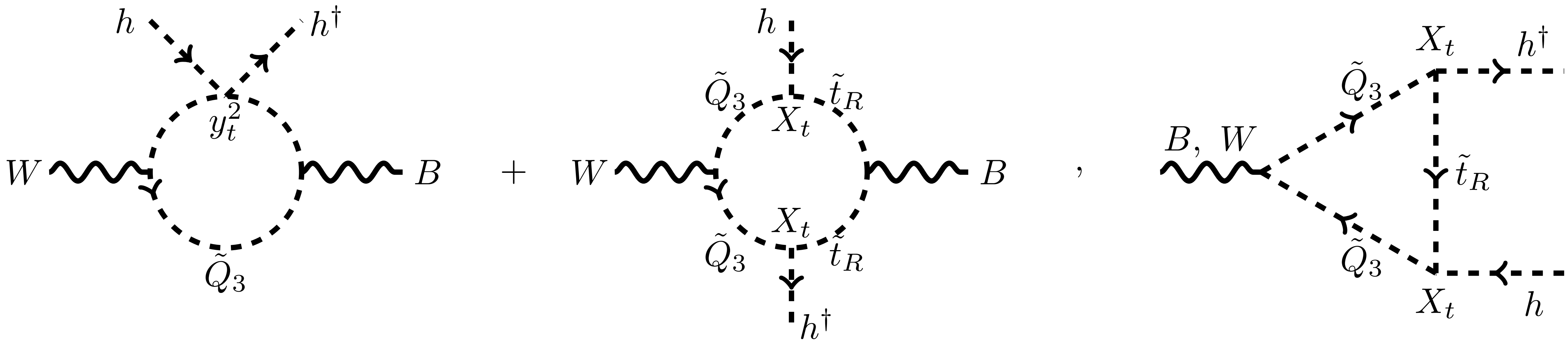
Stops: *T* Parameter



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

A Higgs quartic coupling! These are the same diagrams that lift the Higgs mass in the MSSM, *except* that we are reading off subleading momentum dependence: $D_\mu^2/m_{stop}^2 \sim m_Z^2/m_{stop}^2$.

The S Parameter



The diagram on the right, at first glance, doesn't seem to generate the right operator. In fact, it generates

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

But if we work with a minimal basis of operators, equations of motion turn this into a linear combination including the S parameter.

Why Focus on *S*, *T* ?

Any SU(2)$_L$-charged particles, coupling to the Higgs or not, contribute at one loop to two other dimension-6 operators:

$$c_{WWW}\, g\epsilon_{ijk} W^i_{\mu\nu} W^{j\nu}_{\rho} W^{k\rho\mu}$$

"TGC"

$\lambda_\gamma = \lambda_Z$

$$c_{WWW} = \frac{g^2}{2880\pi^2} \sum_{\text{rep } R,\ \text{mass } M} (-1)^F \frac{T(R)}{M^2},$$

$$c_{JJ} D^\mu W^i_{\mu\nu} D_\lambda W^{i\lambda\nu}$$

"*W* parameter"

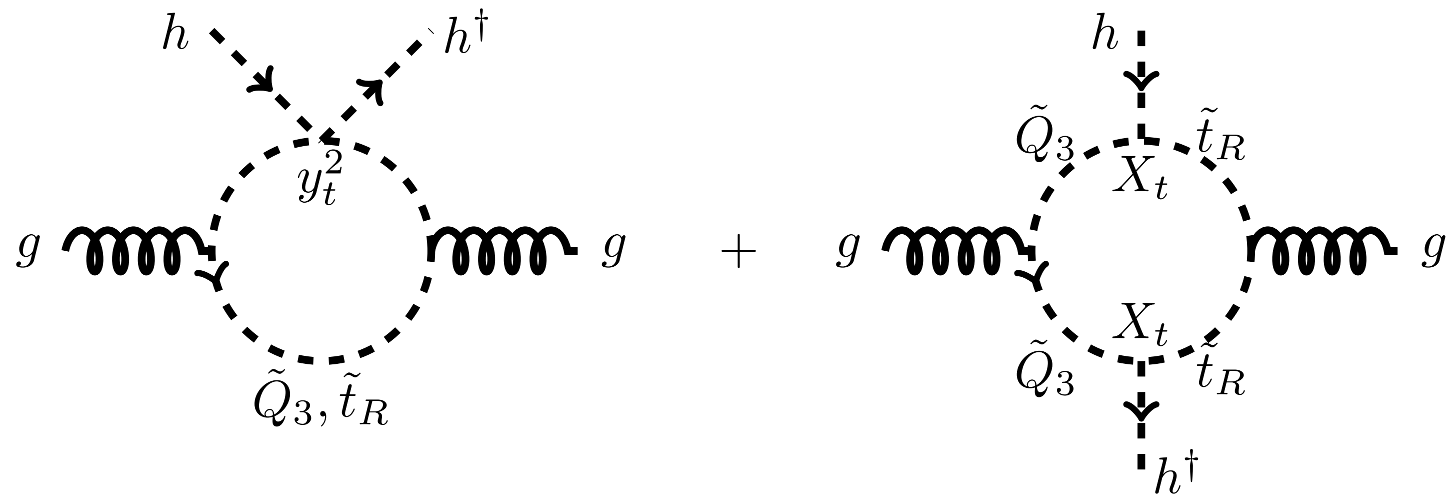
$$c_{JJ} = -\frac{g^2}{960\pi^2} \sum_{\text{rep } R,\ \text{mass } M} a_F \frac{T(R)}{M^2},$$

where $a_F = 4$ for Weyl fermions and 1 for complex scalars.

Unfortunately, their perturbative coefficients are very small. (Could be lucky to have many new degrees of freedom?)

The *U* parameter is dimension 8: $c_U \left(h^\dagger \sigma^i h W^{i\mu\nu}\right)^2$

Higgs Couplings



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

Familiar low-energy theorem: beta function coefficients times $\sum \frac{\partial \log M}{\partial \log v}$

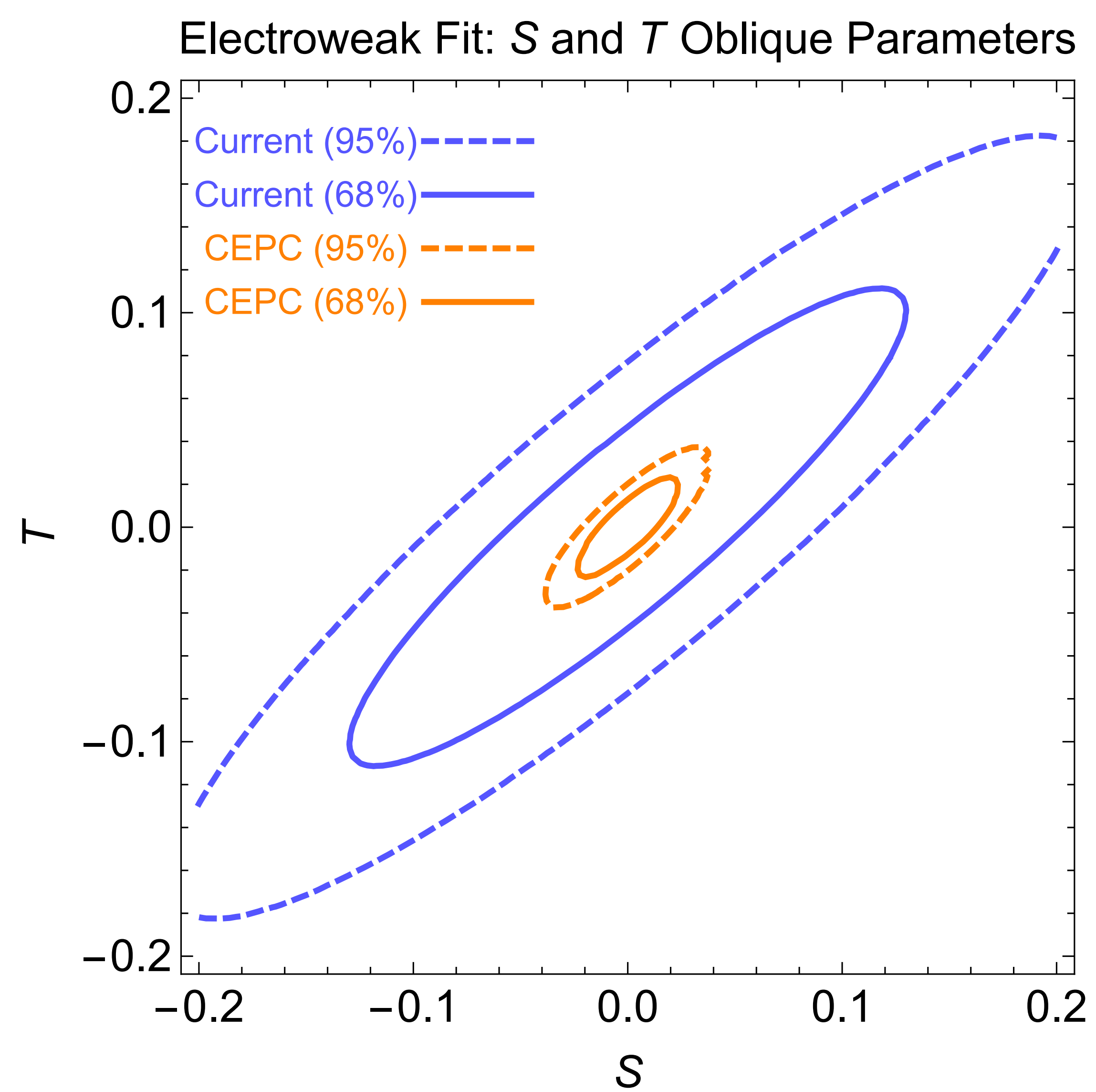
Similar result for photons (except SM contribution dominated by *W* loop)

Electroweak Fit

	Present data	CEPC fit
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [23]	$\pm 1.0 \times 10^{-4}$ [24]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [25]	$\pm 4.7 \times 10^{-5}$ [26]
m_Z [GeV]	91.1875 ± 0.0021 [27]	$\pm \mathbf{0.0005}$
m_t [GeV] (pole)	$173.34 \pm 0.76_{\rm exp}$ [28] $\pm 0.5_{\rm th}$ [26]	$\pm 0.2_{\rm exp} \pm 0.5_{\rm th}$ [29, 30]
m_h [GeV]	125.14 ± 0.24 [26]	$< \pm 0.1$ [26]
m_W [GeV]	$80.385 \pm 0.015_{\rm exp}$ [23] $\pm 0.004_{\rm th}$ [31]	$(\pm \mathbf{3}_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [31]
$\sin^2\theta_{\rm eff}^{\ell}$	$(23153 \pm 16) \times 10^{-5}$ [27]	$(\pm \mathbf{2.3}_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [32]
Γ_Z [GeV]	2.4952 ± 0.0023 [27]	$(\pm \mathbf{5}_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [33]
$R_b \equiv \Gamma_b/\Gamma_{\rm had}$	0.21629 ± 0.00066 [27]	$\pm \mathbf{1.7} \times 10^{-4}$
$R_\ell \equiv \Gamma_{\rm had}/\Gamma_\ell$	20.767 ± 0.025 [27]	$\pm \mathbf{0.007}$

Numbers in **boldface**: major CEPC inputs to the electroweak precision fit.

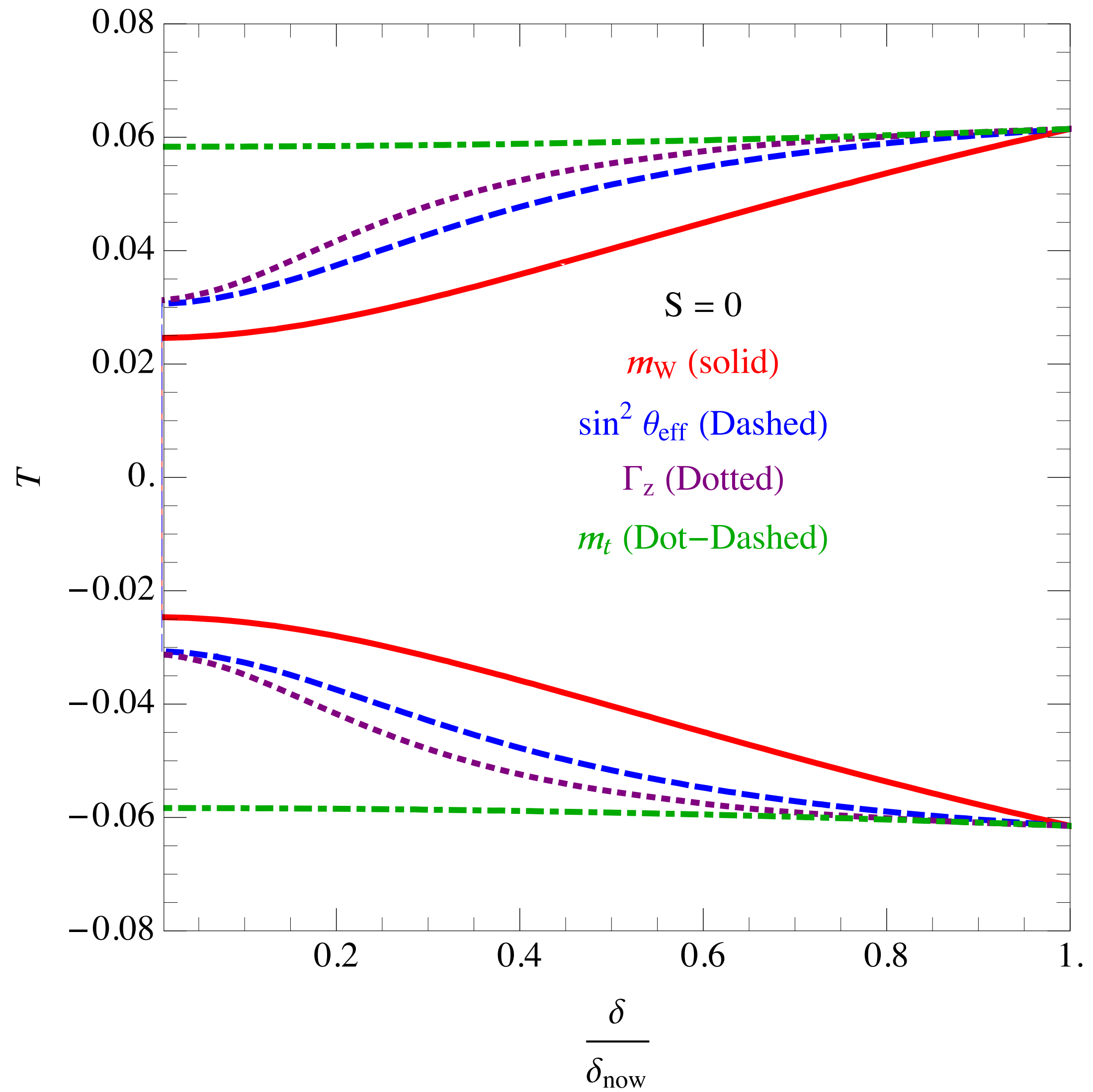
Baseline Fit

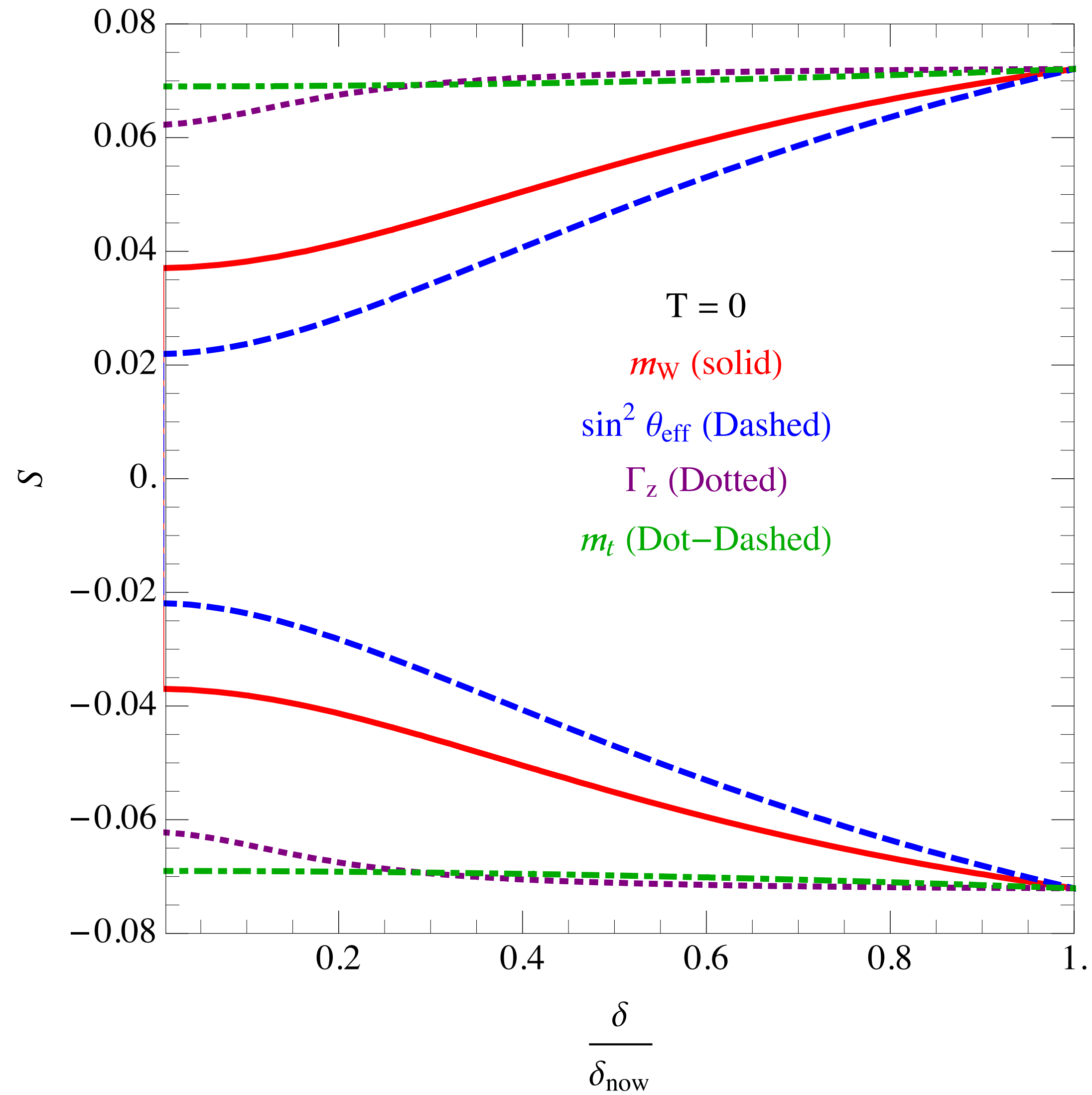


Even with conservative estimates, CEPC will provide a substantial improvement over existing data.

Limiting Measurements

If we only improved one input to fit at a time, hit limits:

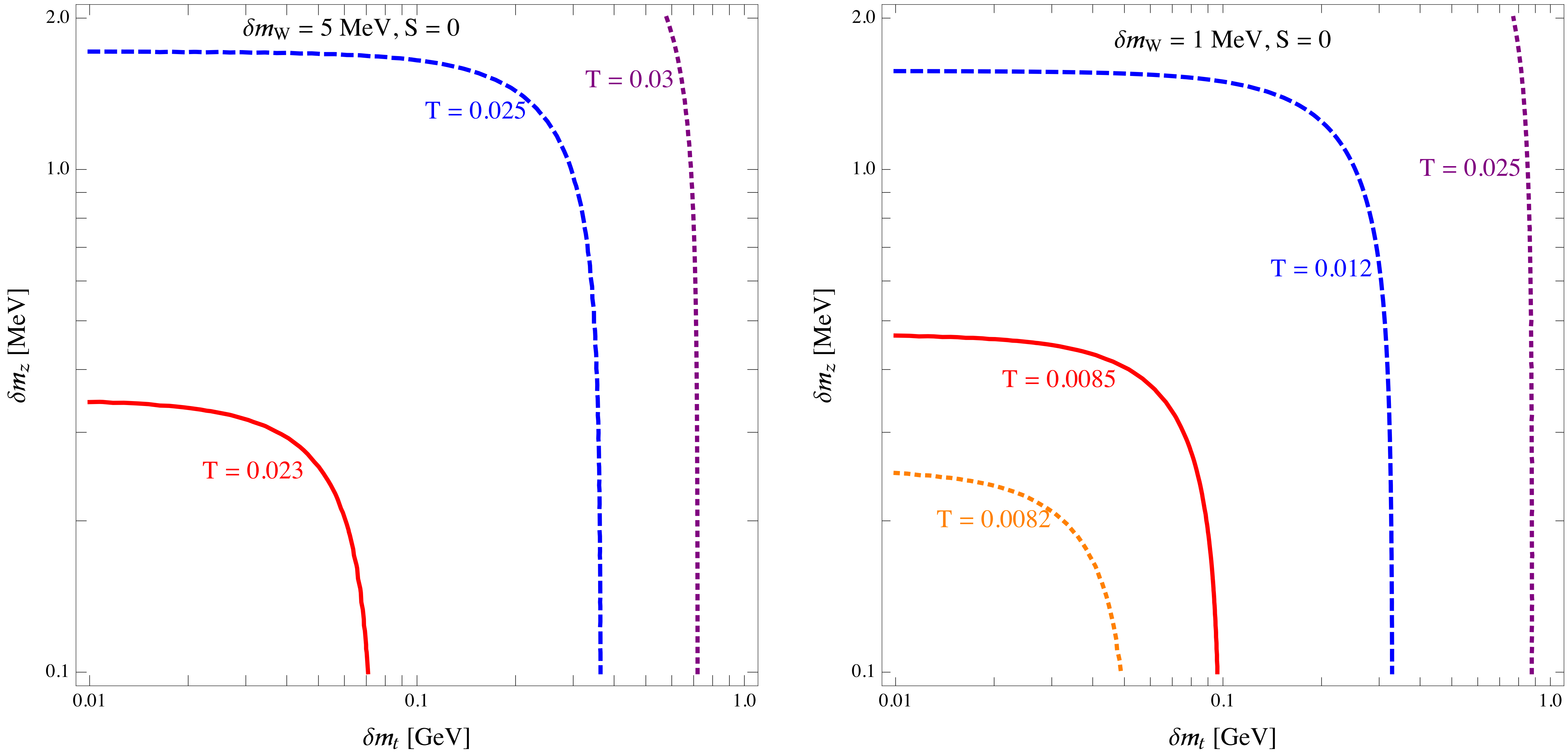




W mass is priority for measuring *T*.

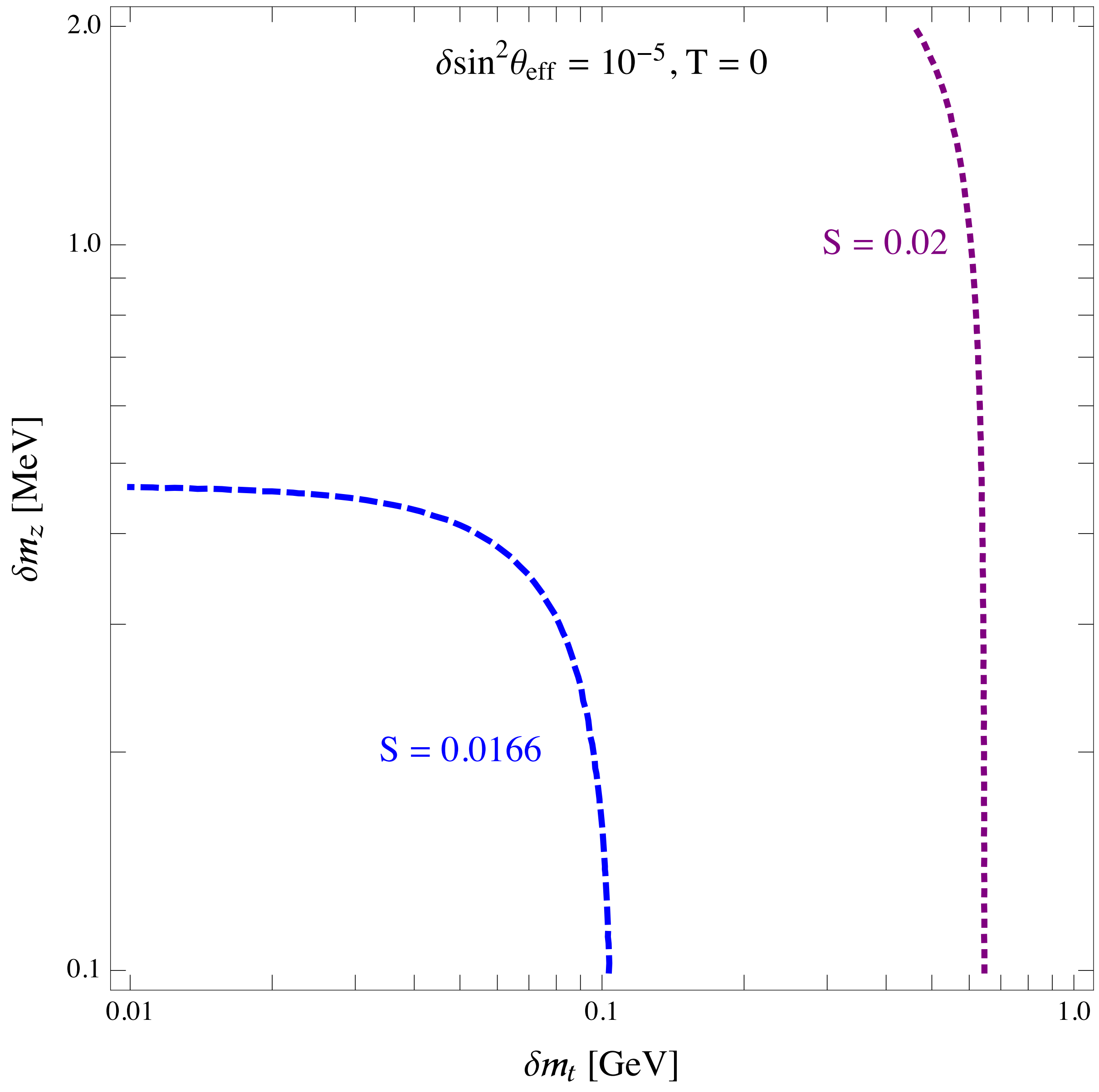
$\sin^2\theta_W$ is priority for measuring *S*

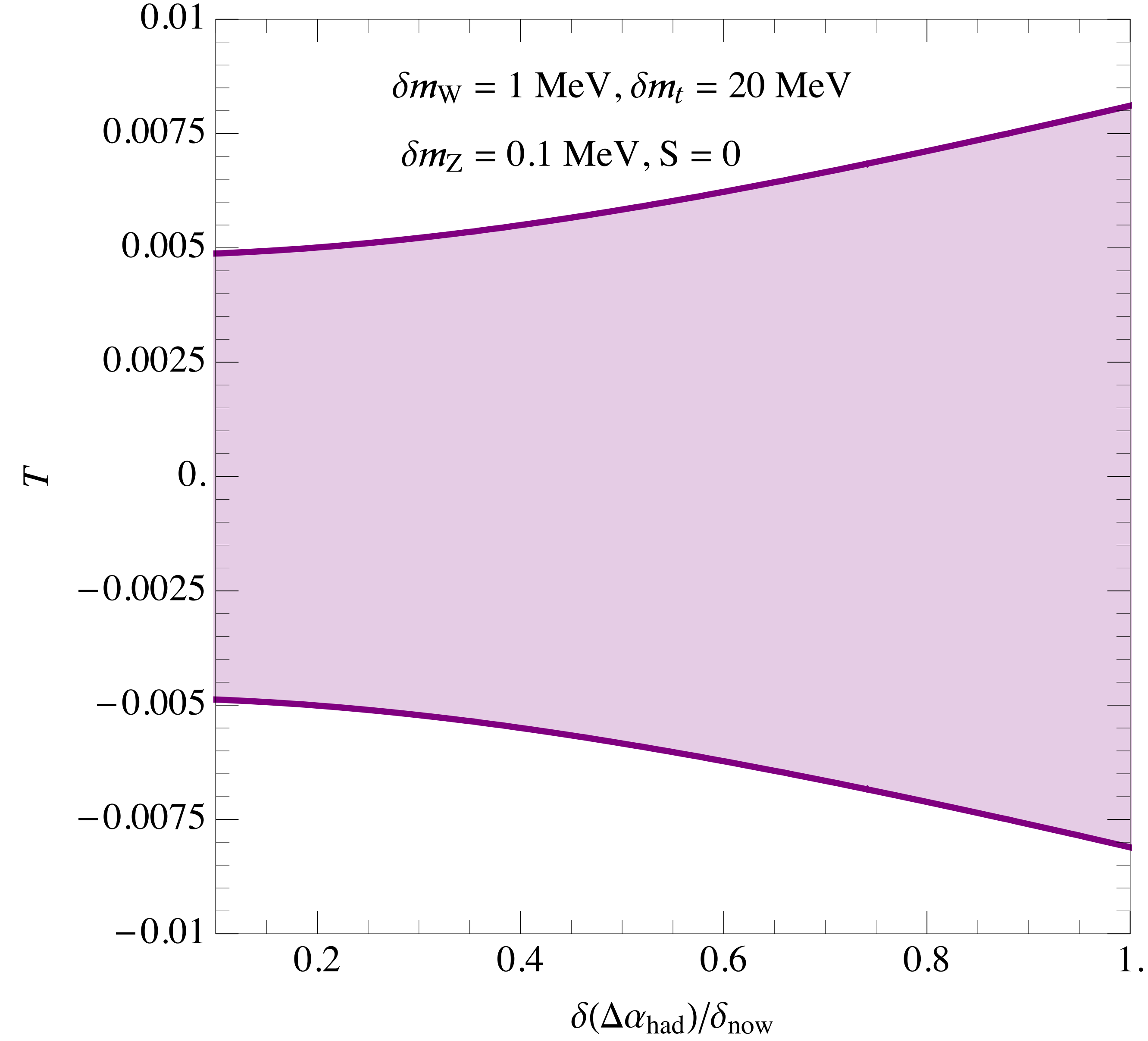
Role of Top and Z Mass for T Parameter



At left: 5 MeV error on W mass. At right: 1 MeV error. Top/Z masses play much larger role once W error is very small. If error stuck at 5 MeV, limited improvement.

Role of Top/Z mass for S Parameter, $\Delta\alpha_{\mathrm{had}}$ for T Parameter





Again, all the ingredients help, but first must achieve sufficient precision on crucial numbers like m_W and $\sin^2\theta_{\mathrm{W}}$.

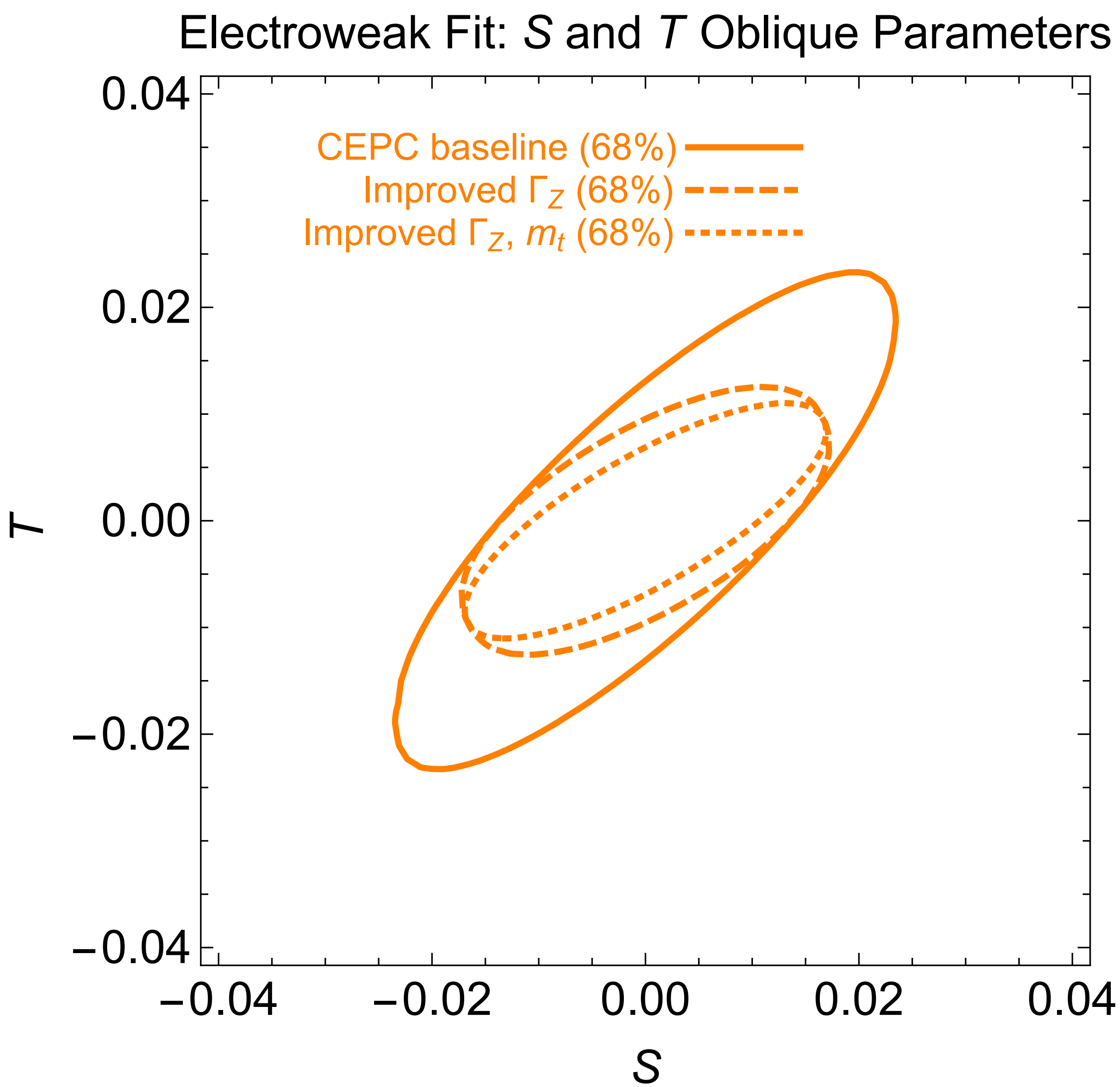
A Wish List

Of course, we want the best measurements possible of many quantities. But here are reasonable goals to probe loops of ~TeV particles. **CEPC will deliver what's in bold.**

- **Measure m_W to better than 5 MeV (now 15 MeV) and $\sin^2\theta_W$ to better than 2×10^{-5} (now 16×10^{-5})**
- **Measure m_Z to 500 keV precision (now 2 MeV)**
- Measure m_t to 100 MeV precision (now ~0.8 GeV*)
- Have precise enough theory to make use of these results: at least 3-loop calculations (Ayres Freitas's talk)

Improving on the Baseline?

CEPC	$\Gamma_Z(m_Z)$ [GeV]	m_t [GeV]
Improved Error	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ (± 0.0001)	$\pm 0.03_{\rm exp} \pm 0.1_{\rm th}$



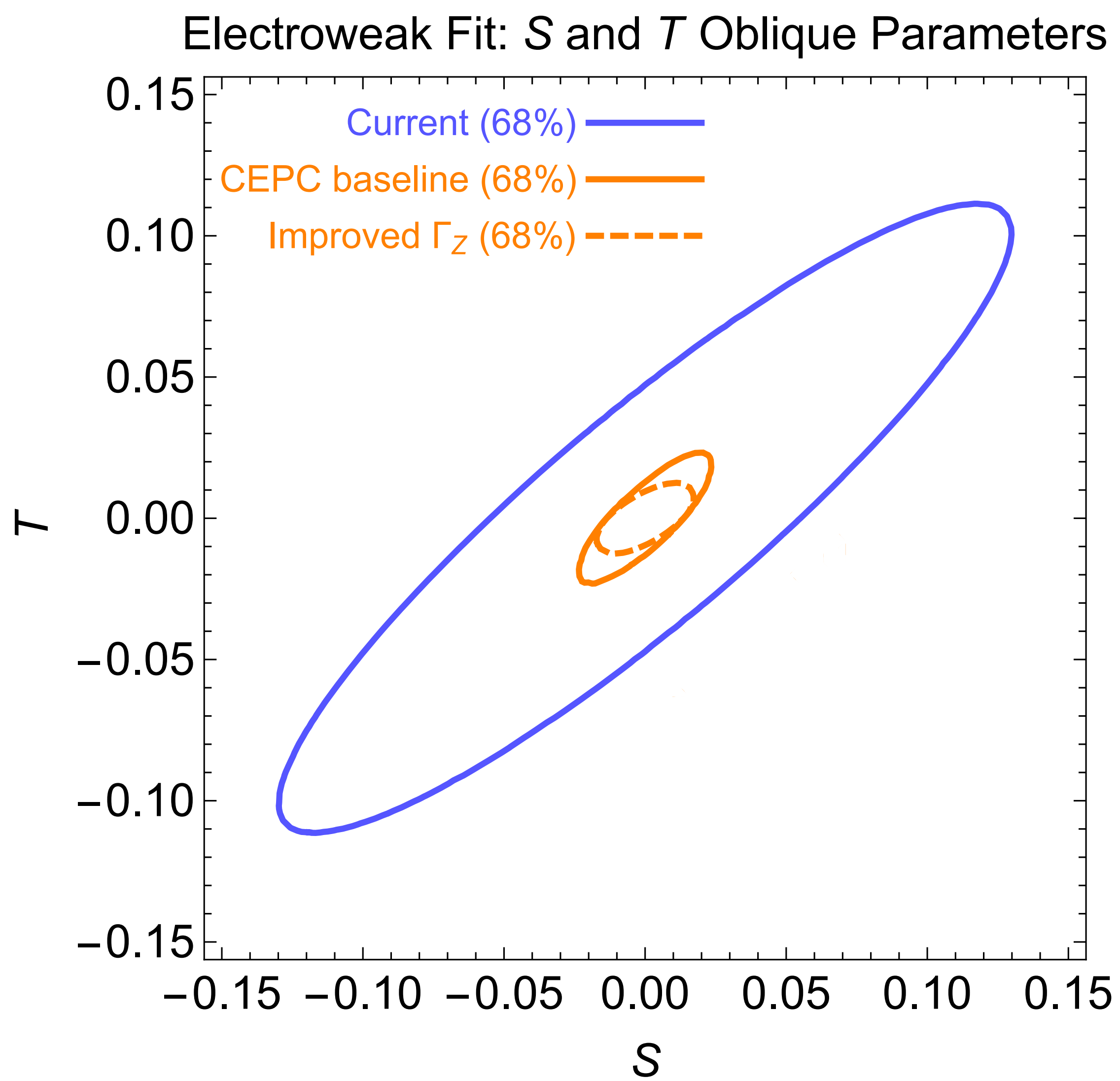
Improving the Z width measurement requires a better energy calibration. Improving the top mass measurement requires an e+e- collider threshold scan. (Beyond CEPC energy plans.)

Summary: CEPC Fit

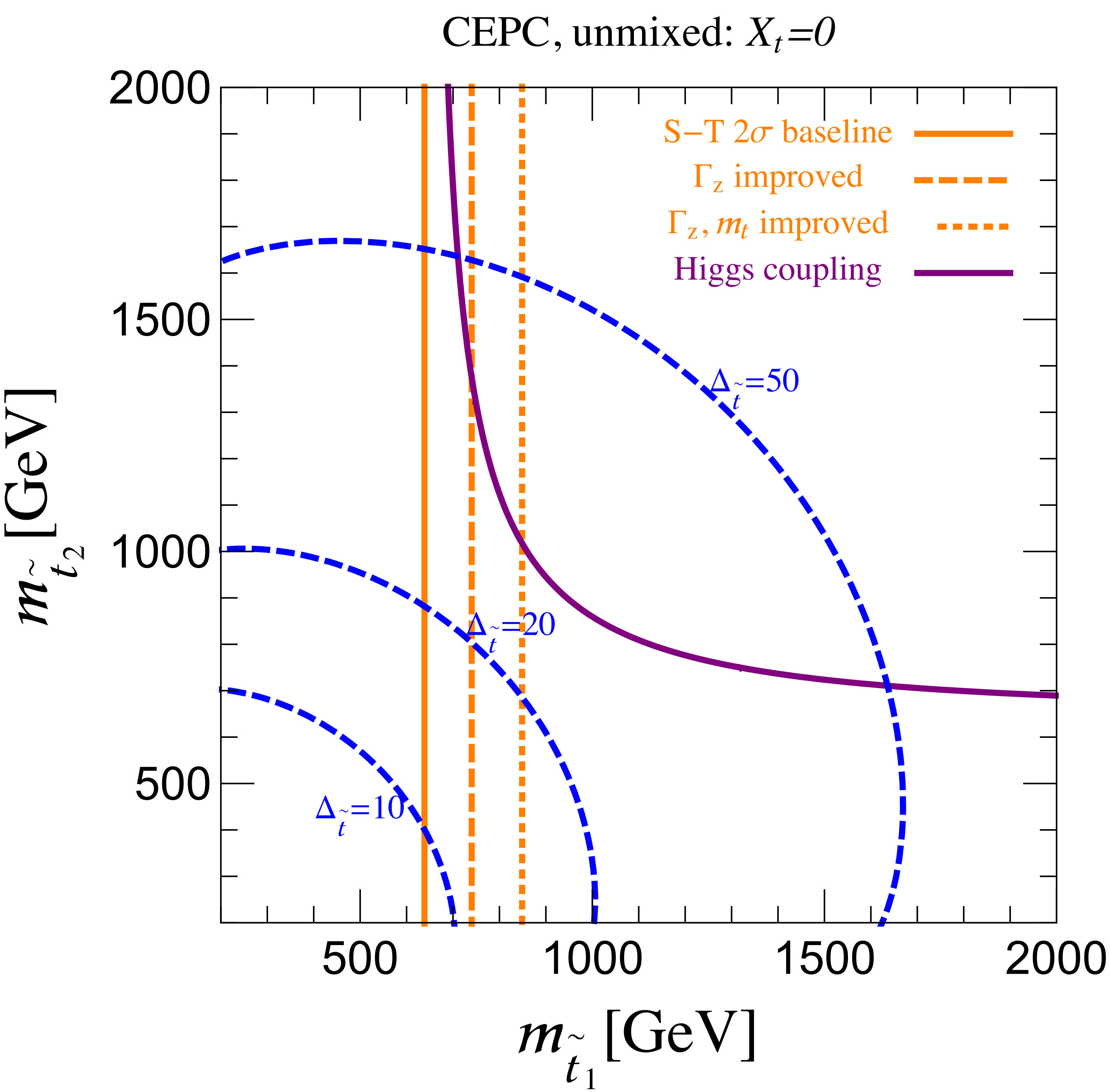
Parameter	Current	CEPC baseline	Improved Γ_Z (and m_Z)	Also improved m_t
S	3.6×10^{-2}	9.3×10^{-3}	9.3×10^{-3}	7.1×10^{-3}
T	3.1×10^{-2}	9.0×10^{-3}	6.7×10^{-3}	4.6×10^{-3}

Results at $\Delta\chi^2 = 1$

The CEPC would provide order-of-magnitude improvement over the current results from LEP, Tevatron, and LHC.



CEPC and Stops

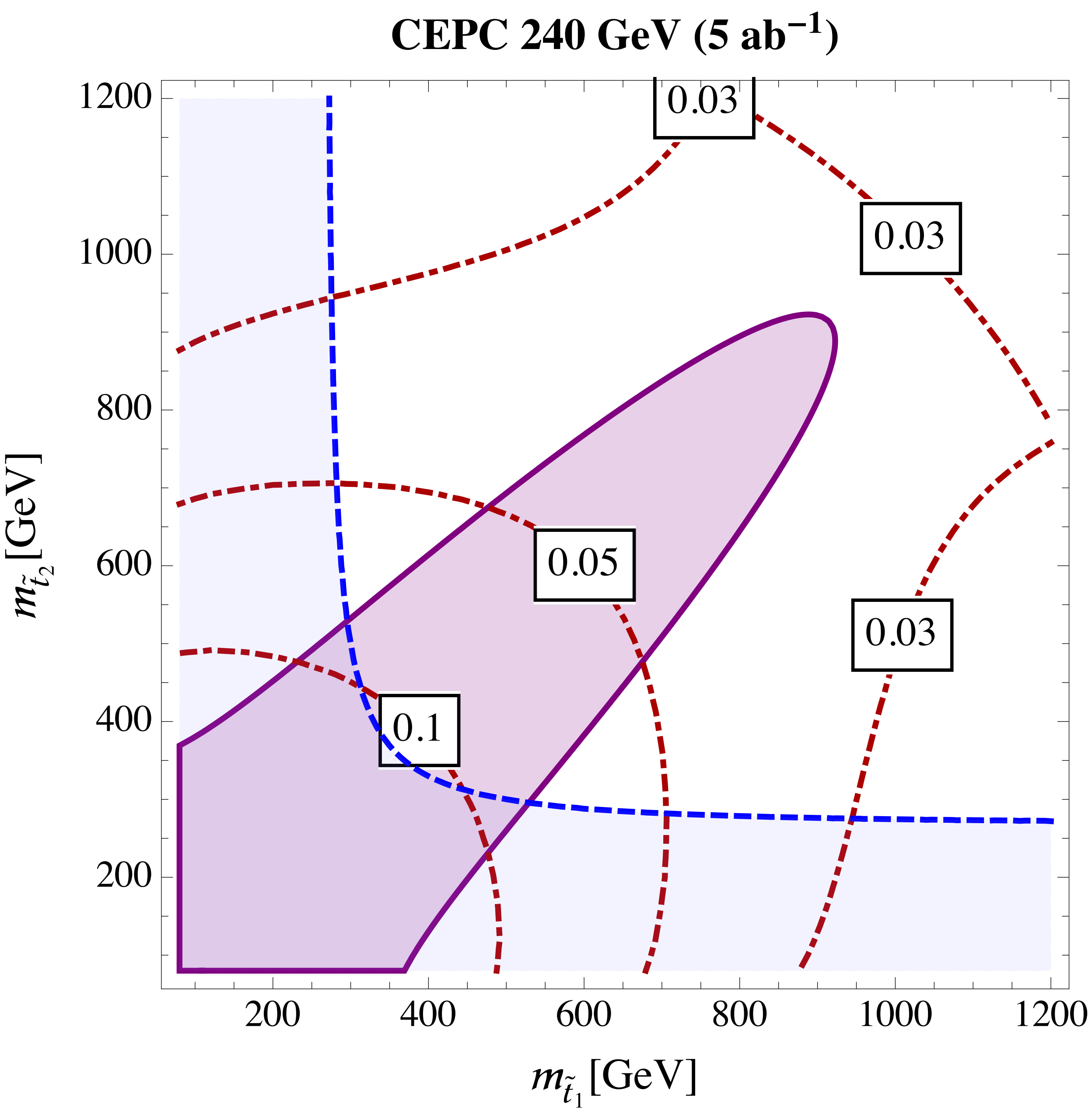


No mixing:

Similar mass reach via *T*-parameter and Higgs couplings. Pushes tuning to the few % level.

Definitively close LHC loopholes (hidden, stealthy, compressed stops).

Higgs Couplings and Stops

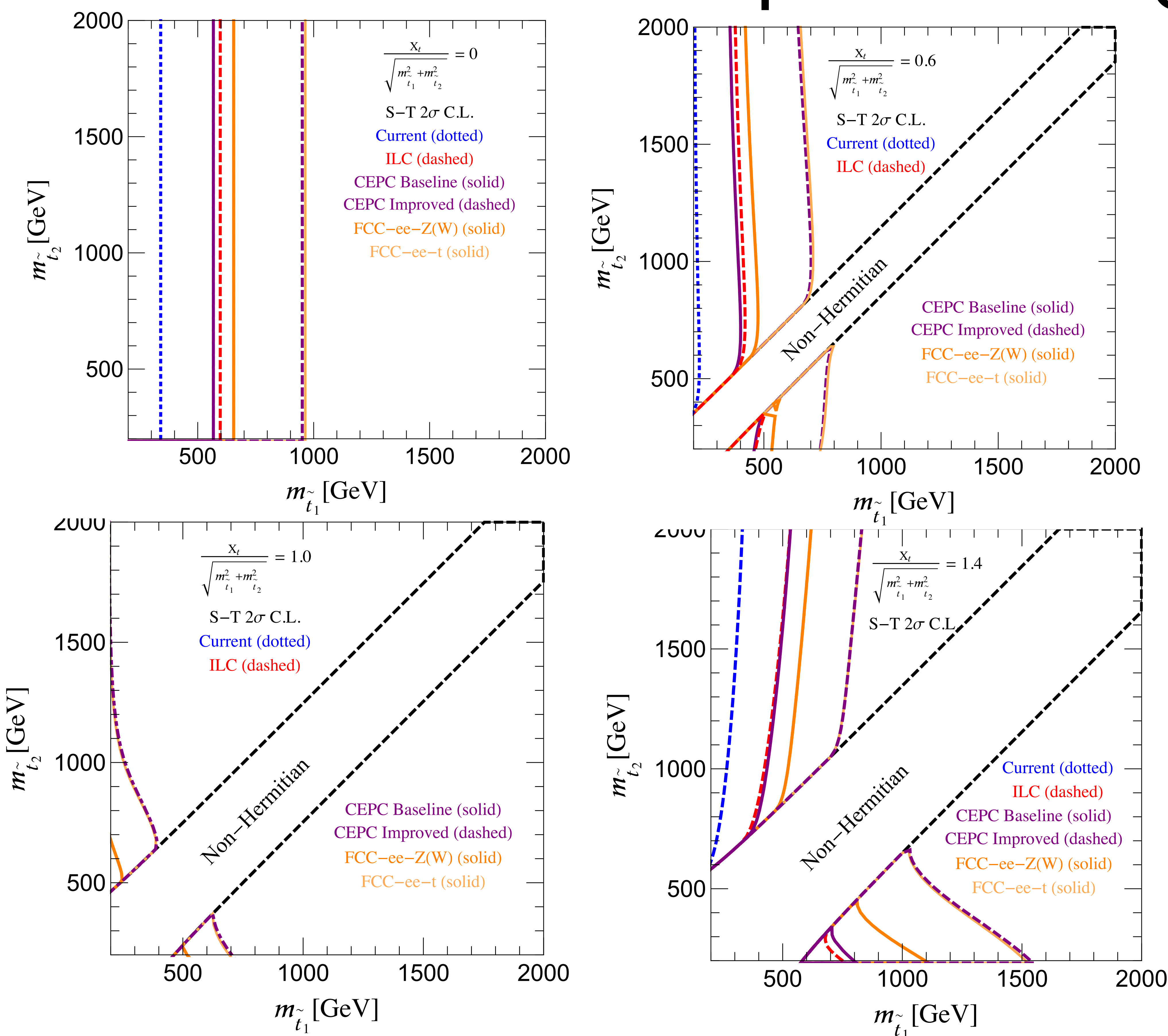


The purple region can be excluded for *any* mixing angle. (Because large mixing forces the mass eigenvalues away from the diagonal.)

Blue region is excluded unless mixing angle is tuned by a factor of 10.

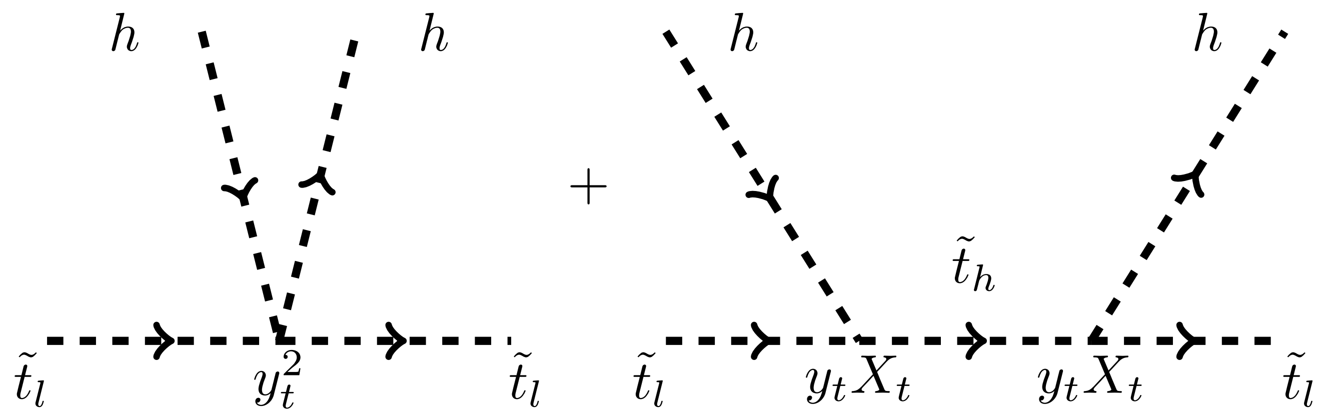
(also see J. Fan, MR arXiv:1401.7671)

EWPT and Stop Mixing

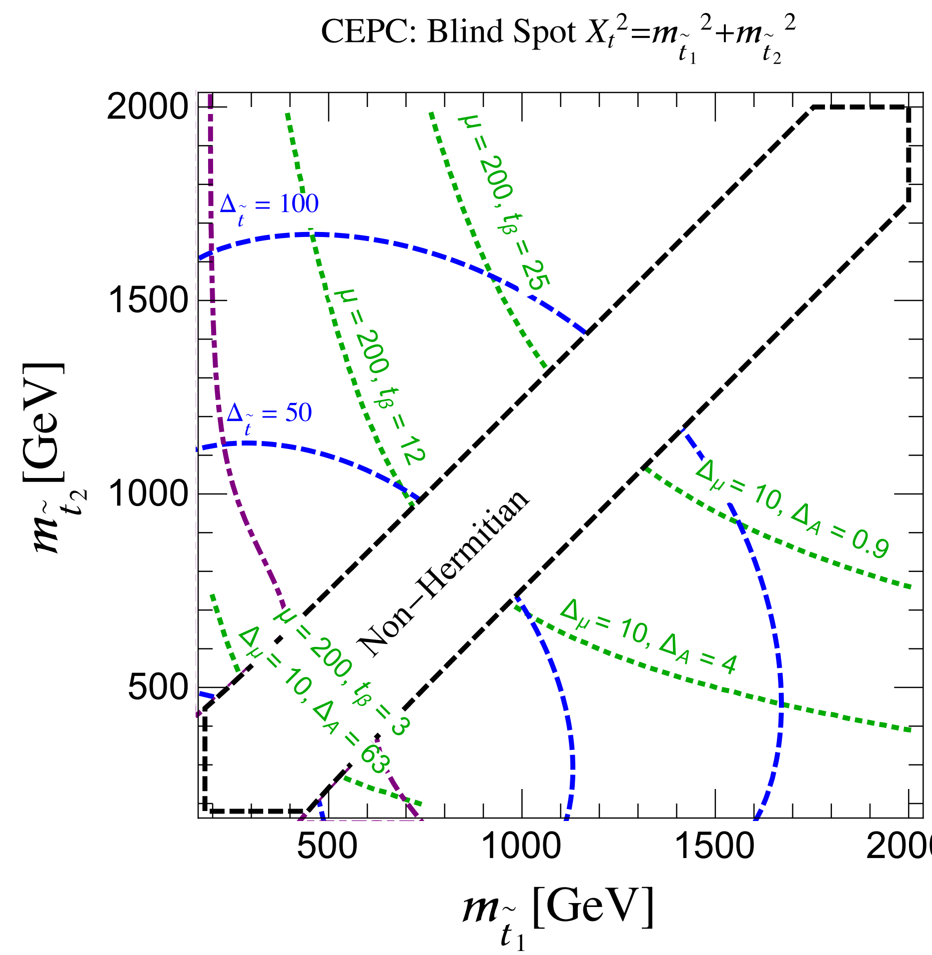


"Blind Spot" for Stops

The light stop mass eigenstate may be decoupled from the Higgs at tree level, at a certain critical mixing angle:



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



If the light stop is decoupled from the Higgs, it's irrelevant for naturalness! Then it's the heavy stop that matters.

Purple: CEPC EWPT
Green: $b \to s\gamma$

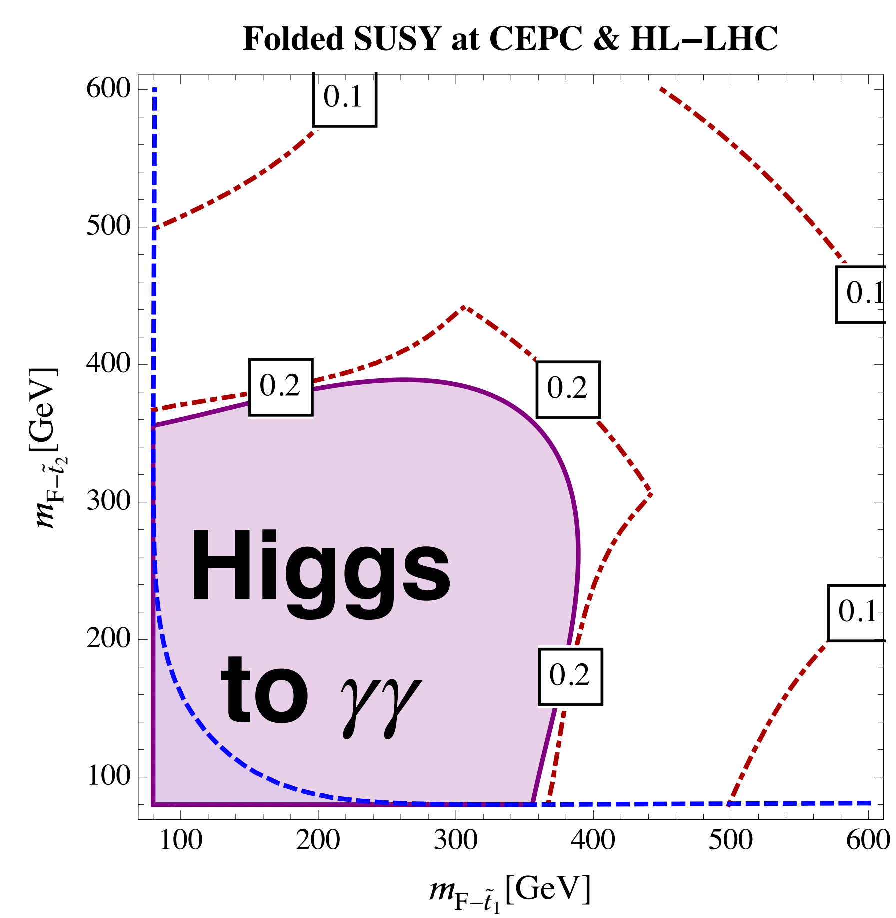
Folded SUSY

In folded SUSY, stops have **no QCD color** (makes life difficult at LHC). But still have electroweak interactions.

Measuring Higgs decays to photons and the *T* parameter can help constrain folded SUSY stops.

The *T*-parameter bounds previously shown for stops are *exactly* the same for folded stops!

Another way the CEPC has exciting potential for uncolored naturalness!



Another Example: W'

There has been a lot of discussion, e.g. at the Summer Institute last week and the TeV workshop over the weekend, of a possible 2 TeV resonance based on hints in LHC Run 1.

Consider a *W'* boson that decays to *WZ* or *Wh*. It could be part of an $SU(2)_L$ triplet with a *Z'*. Or it could be an $SU(2)_L$ singlet that has hypercharge 1, as in $SU(2)_R$ models. In the latter case, it decays through the operator:

$$i g_h W'^{\mu} (h \cdot D_\mu h) + \mathrm{h.c.}$$

Let's see how the EWPT effect of such a state compares to CEPC reach.

W' and CEPC

We're thinking about:

$$i g_h W'^{\mu} (h \cdot D_\mu h) + \text{h.c.}$$

Where the "dot" is the SU(2)$_L$ invariant $a \cdot b \equiv \epsilon^{\alpha\beta} a_\alpha b_\beta$

In unitary gauge, this looks like

$$\frac{g_h g}{2} W'^{\mu} W_\mu \left(v + h^0\right)^2$$

There's a mass mixing between the *W* and the *W'* controlled by the same coupling that gives a diboson decay. This shifts the *W* mass but ***not*** the *Z* mass. In other words,

diboson decay coupling $\longleftrightarrow$ *T*-parameter

W’ and CEPC

You can integrate out the W’ at tree level and read off:

$$\delta m_W = -\frac{g_h^2 m_W v^2}{4m_{W'}^2} \approx -27\ \text{MeV}\left(\frac{g_h}{0.3}\right)^2\left(\frac{2\ \text{TeV}}{m_{W'}}\right)^2$$

(see de Blas, del Aguila, and Perez-Victoria 1005.3998 and also Hisano, Nagata, and Omura 1506.03931 in the context of the recent excess)

So CEPC’s 3 MeV measurement of the W mass can probe this effect (at 2 sigma) up to W’ masses of 4 TeV (for $g_h = 0.3$) or at fixed W’ mass of 2 TeV down to couplings $g_h = 0.15$.

Other Precision Physics

Rare Z decays: Standard Model predicts

$$\begin{aligned}\mathrm{Br}(Z^0 \to J/\psi\, \gamma) &\approx 8 \times 10^{-8} \\ \mathrm{Br}(Z^0 \to \Upsilon(nS)\, \gamma) &\approx 1.0 \times 10^{-7}.\end{aligned}$$

(Grossman, Koenig, Neubert 1501.06569; see also Huang, Petriello 1411.5924)

No current collider has had a large enough Z sample to see them. The CEPC, with 10^{10} Z bosons, can explore a new frontier of the SM.

CEPC could also search for *flavor-violating* processes like Z to electron + muon. Probe of high-scale flavor violation beyond the Standard Model!

Conclusions

The LHC has great potential to study colored particles, but it can miss light uncolored particles or even colored particles that decay in ways that mimic backgrounds.

CEPC can exhaustively probe particles that interact with Higgs bosons, whether or not the LHC can see them.

Both Higgs decays and EWPT on or near the Z-pole can help in this task. Example: the T-parameter could be the strongest constraint on folded stops.

We have exciting times ahead!

Backup

Higgs-Z Interplay

I've shown you results from fits of Higgs properties, and results from Z-pole (and near-Z-pole) physics. But these are not really independent. For instance, the S parameter operator

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

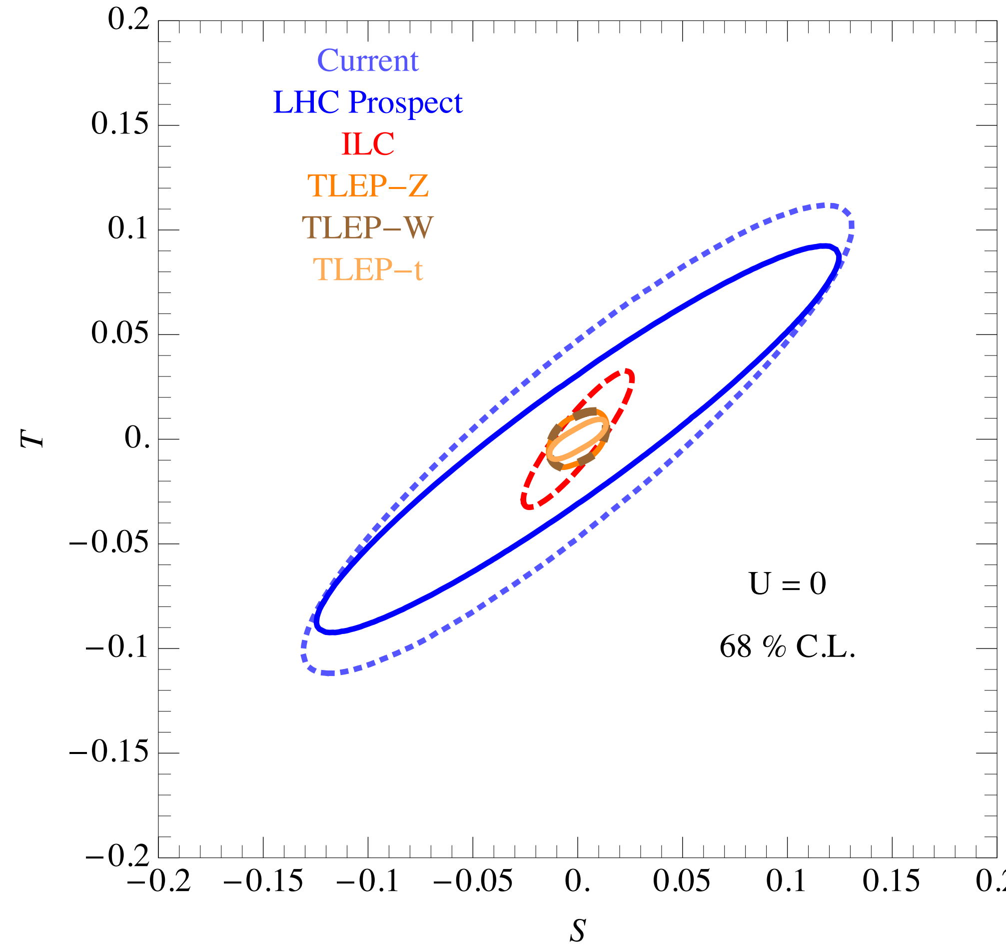
will affect the Higgs decay rate to two neutral gauge bosons (photons or Z bosons)—though other operators do too.

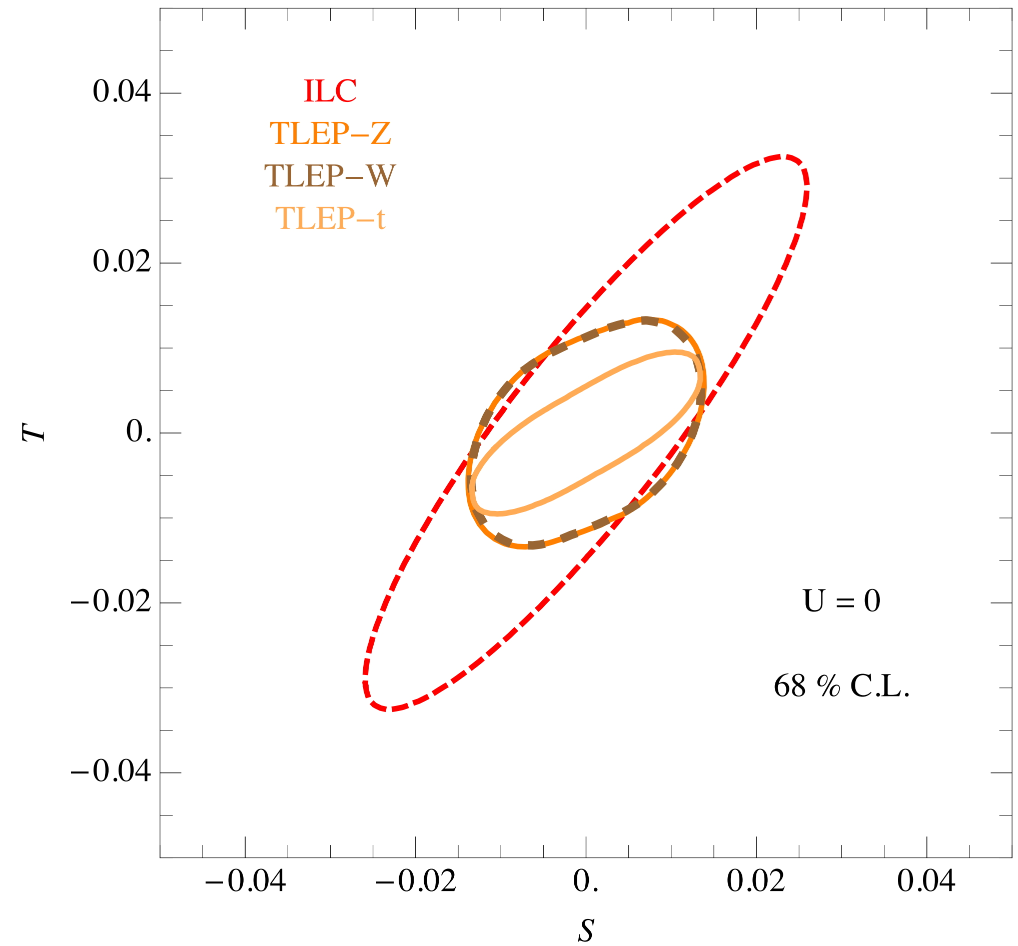
In the end, we should perform a global fit all the data together, including all the electroweak operators. Use all the information. As Nathaniel Craig mentioned, angular observables in Higgs properties can also enhance the physics reach.

Other Colliders

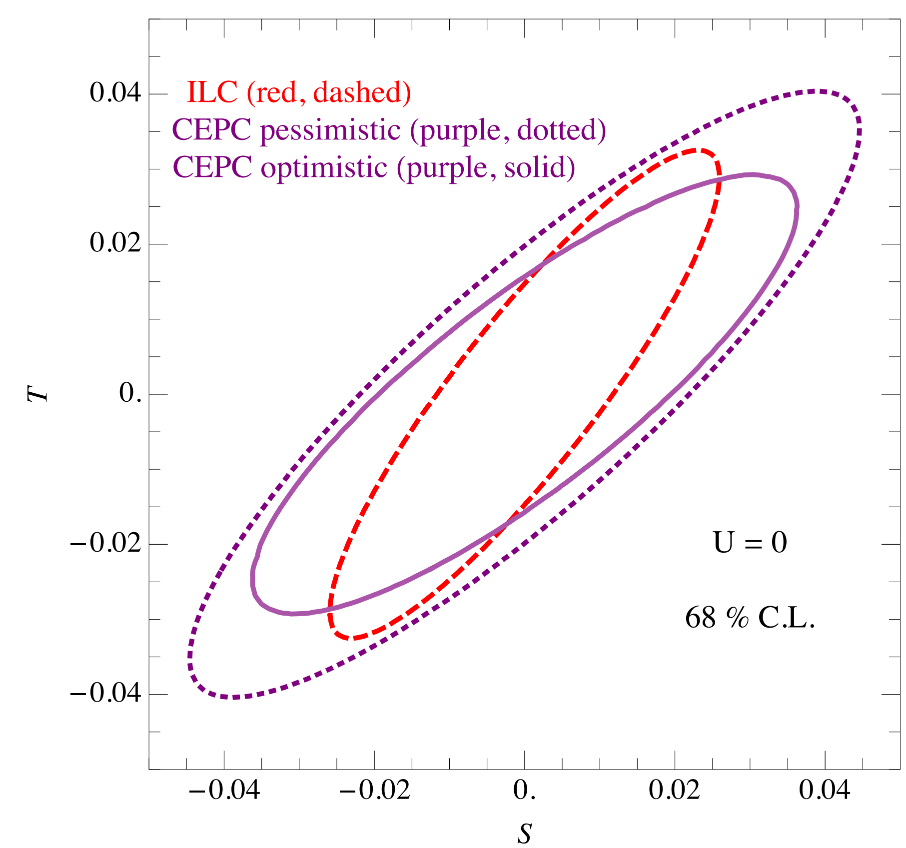
	Present data	LHC14	ILC/GigaZ
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [34]	± 0.0006	$\pm 1.0 \times 10^{-4}$ [35]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [36]	$\pm 4.7 \times 10^{-5}$ [23]	$\pm 4.7 \times 10^{-5}$ [23]
m_Z [GeV]	91.1875 ± 0.0021 [27]	± 0.0021 [23]	± 0.0021 [23]
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]

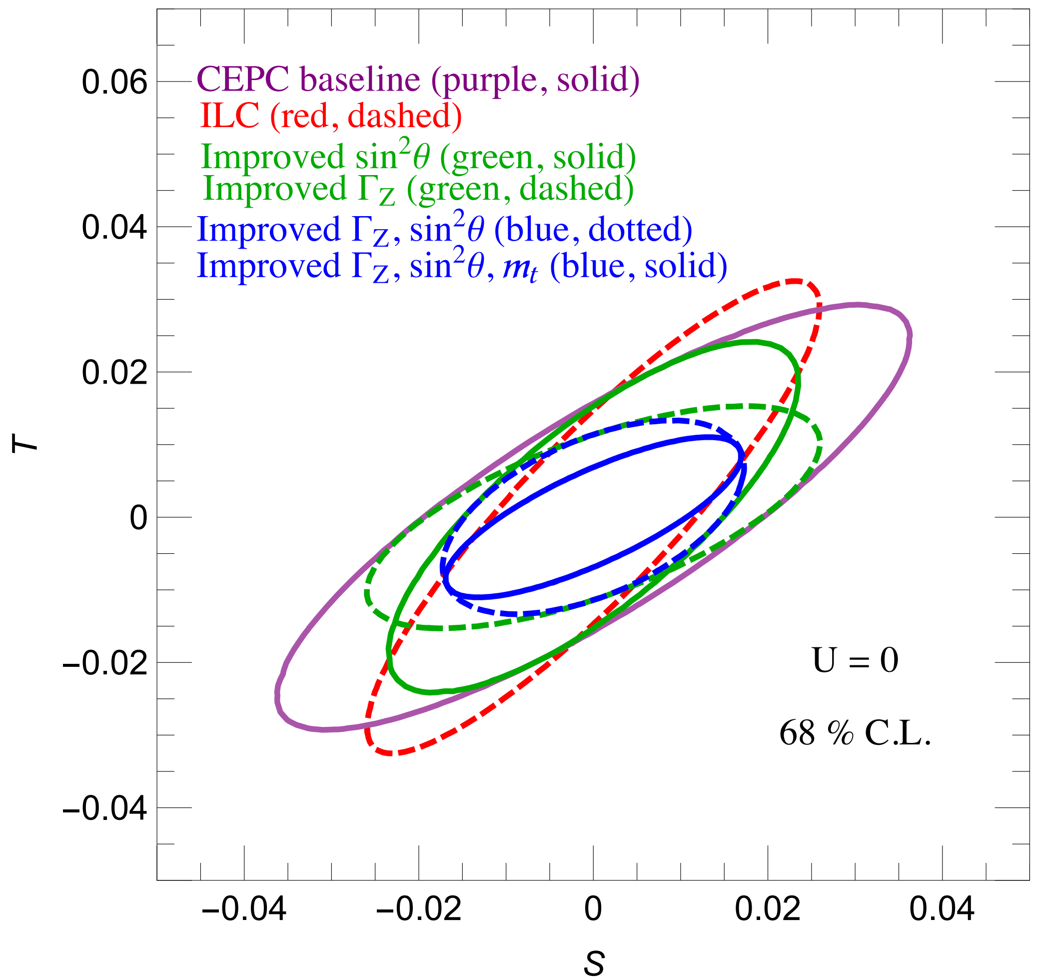
	TLEP-Z	TLEP-W	TLEP-t
$\alpha_s(M_Z^2)$	$\pm 1.0 \times 10^{-4}$ [35]	$\pm 1.0 \times 10^{-4}$ [35]	$\pm 1.0 \times 10^{-4}$ [35]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$	$\pm 4.7 \times 10^{-5}$
m_Z [GeV]	$\pm 0.0001_{\rm exp}$ [2]	$\pm 0.0001_{\rm exp}$ [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]





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





Current	m_t	m_Z	m_h	α_s	$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$
δm_W [MeV]	4.6	2.6	0.1	0.4	1.5
$\delta \sin^2\theta^\ell_{\rm eff}(10^{-5})$	2.4	1.5	0.1	0.2	2.8
$\delta\Gamma_Z$ [MeV]	0.2	0.2	0.004	0.30	0.08

ILC	m_t	m_Z	m_h	α_s	$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$
δm_W [MeV]	0.2	2.6	0.05	0.06	0.9
$\delta \sin^2\theta^\ell_{\rm eff}(10^{-5})$	0.09	1.5	0.04	0.03	1.6
$\delta\Gamma_Z$ [MeV]	0.007	0.2	0.002	0.05	0.04

TLEP-$Z(W)$	m_t	m_Z	m_h	α_s	$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$
δm_W [MeV]	3.6	0.1	0.05	0.06	0.9
$\delta \sin^2\theta^\ell_{\rm eff}(10^{-5})$	1.9	0.07	0.04	0.03	1.6
$\delta\Gamma_Z$ [MeV]	0.1	0.01	0.002	0.05	0.04

TLEP-t	m_t	m_Z	m_h	α_s	$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$
δm_W [MeV]	0.1	0.1	0.05	0.06	0.9
$\delta \sin^2\theta^\ell_{\rm eff}(10^{-5})$	0.06	0.07	0.04	0.03	1.6
$\delta\Gamma_Z$ [MeV]	0.004	0.01	0.002	0.05	0.04

CEPC	m_t	m_Z	m_h	α_s	$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$
δm_W [MeV]	3.6	0.6-1.3	0.05	0.06	0.9
$\delta \sin^2\theta^\ell_{\rm eff}(10^{-5})$	1.9	0.4-0.7	0.04	0.03	1.6
$\delta\Gamma_Z$ [MeV]	0.1	0.05-0.1	0.002	0.05	0.04

Table 5. Parametric errors from each free parameter in the fit for current, ILC, TLEP-Z (TLEP-W), TLEP-t and CEPC scenarios.