New Physics at CEPC: Electroweak Physics, Dark Sectors, etc.

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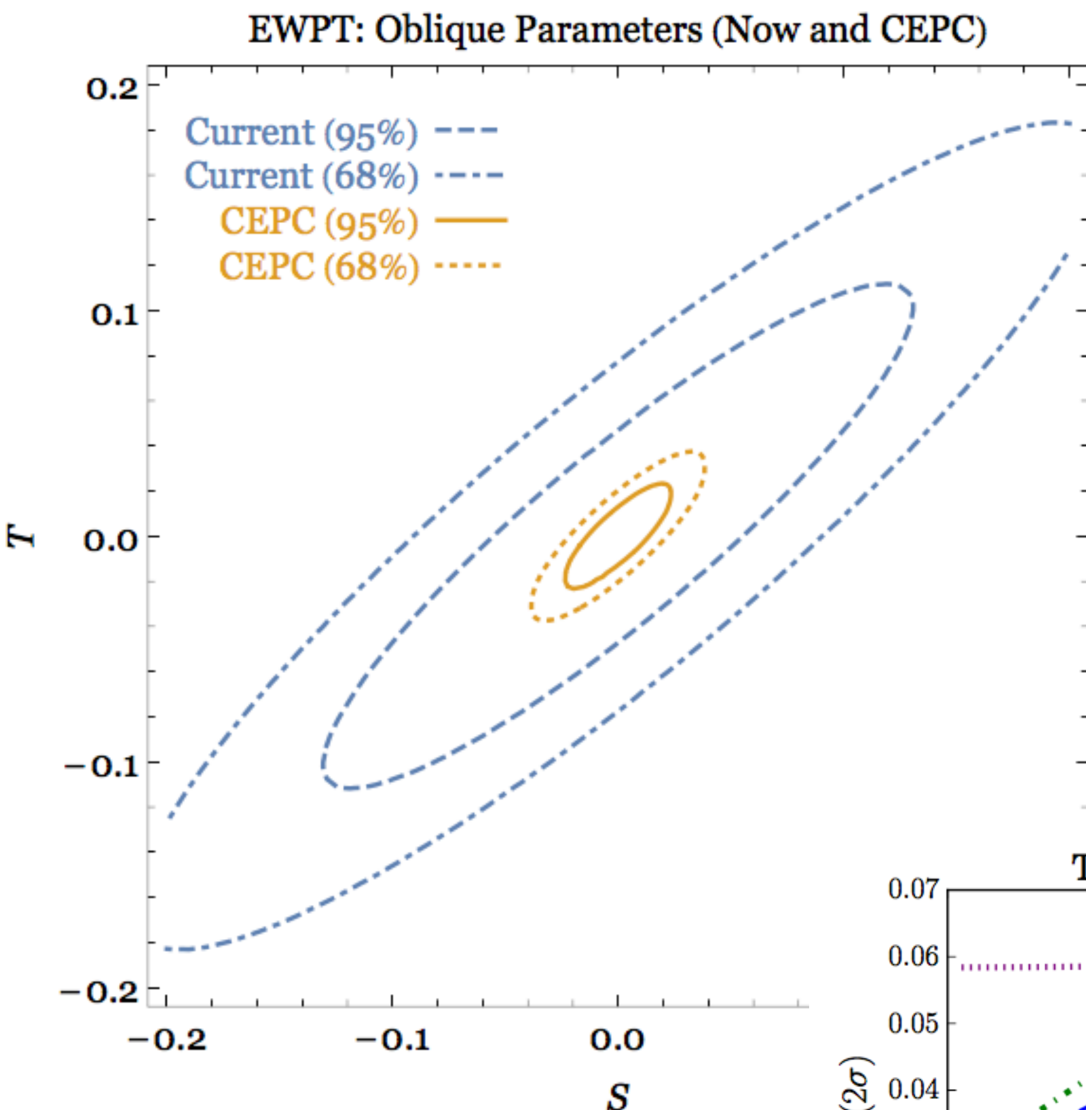
Based on: 1411.1054, 1412.3107 with JiJi Fan, Lian-Tao Wang
Work of various others (cited in context), thoughts while drafting dark matter / dark sector section for the CDR.

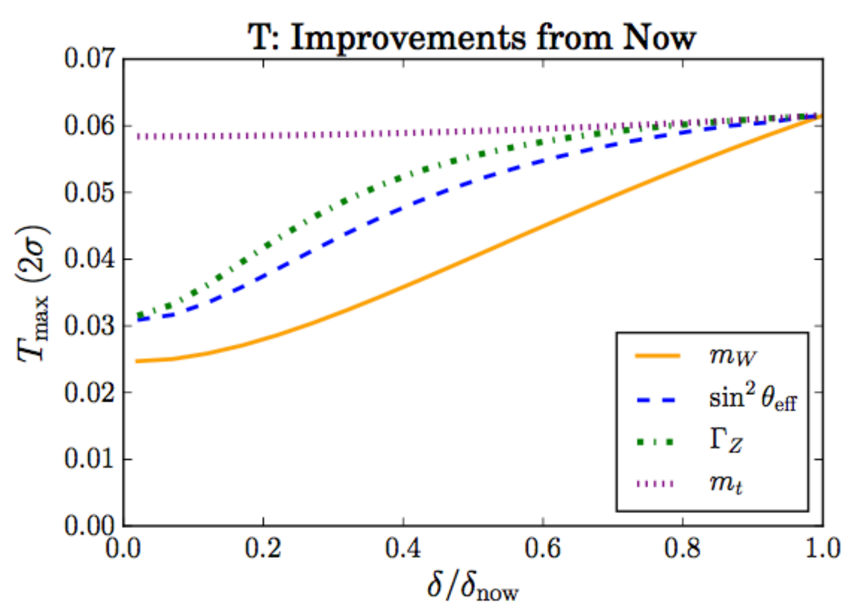
Electroweak Precision at CEPC

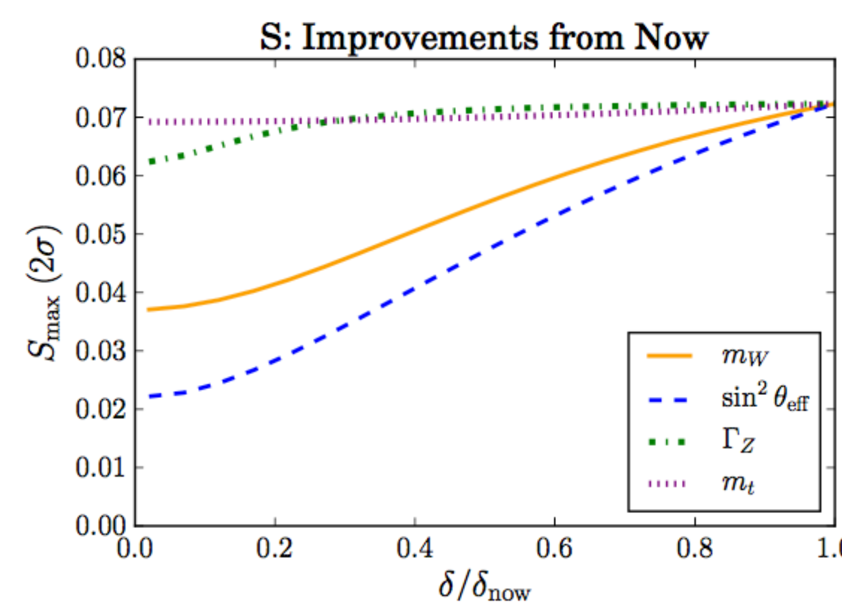


CEPC will significantly improve our knowledge of the S and T parameters. Both probe Higgs-related physics, roughly:

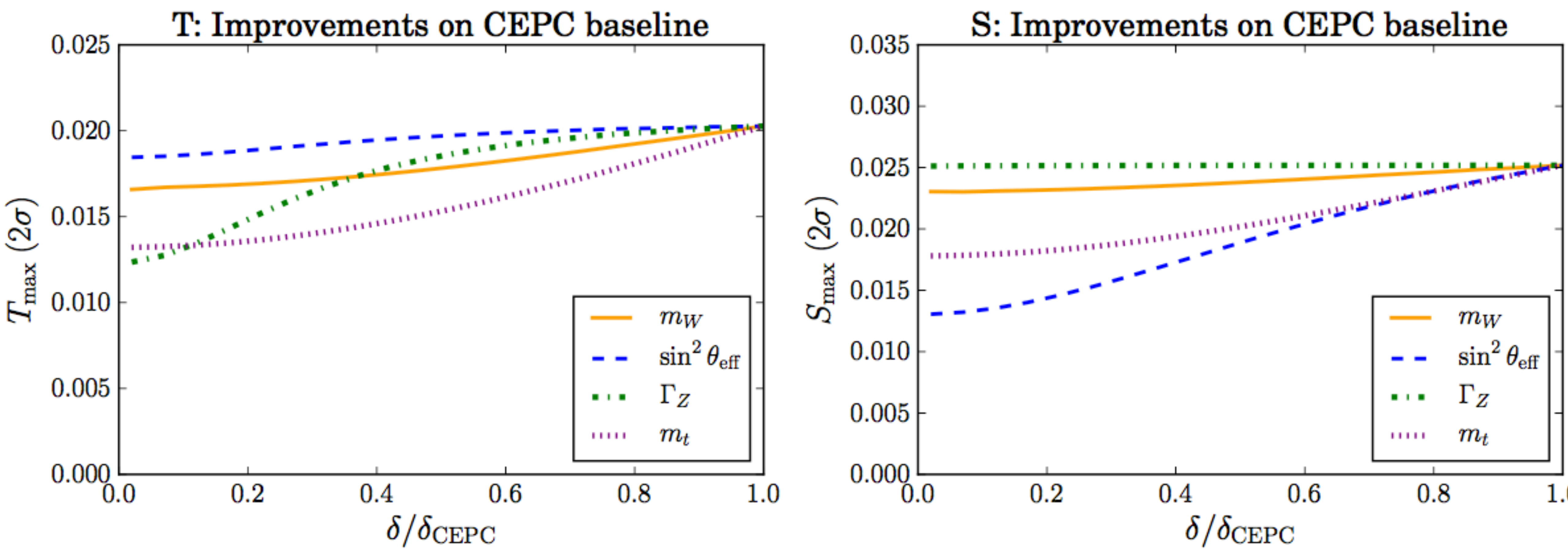
$$S \text{ parameter}: \quad S\left(\frac{\alpha}{4 s_W c_W v^2}\right) h^\dagger \sigma^i h W^i_{\mu\nu} B^{\mu\nu}$$

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





Improving CEPC Baseline

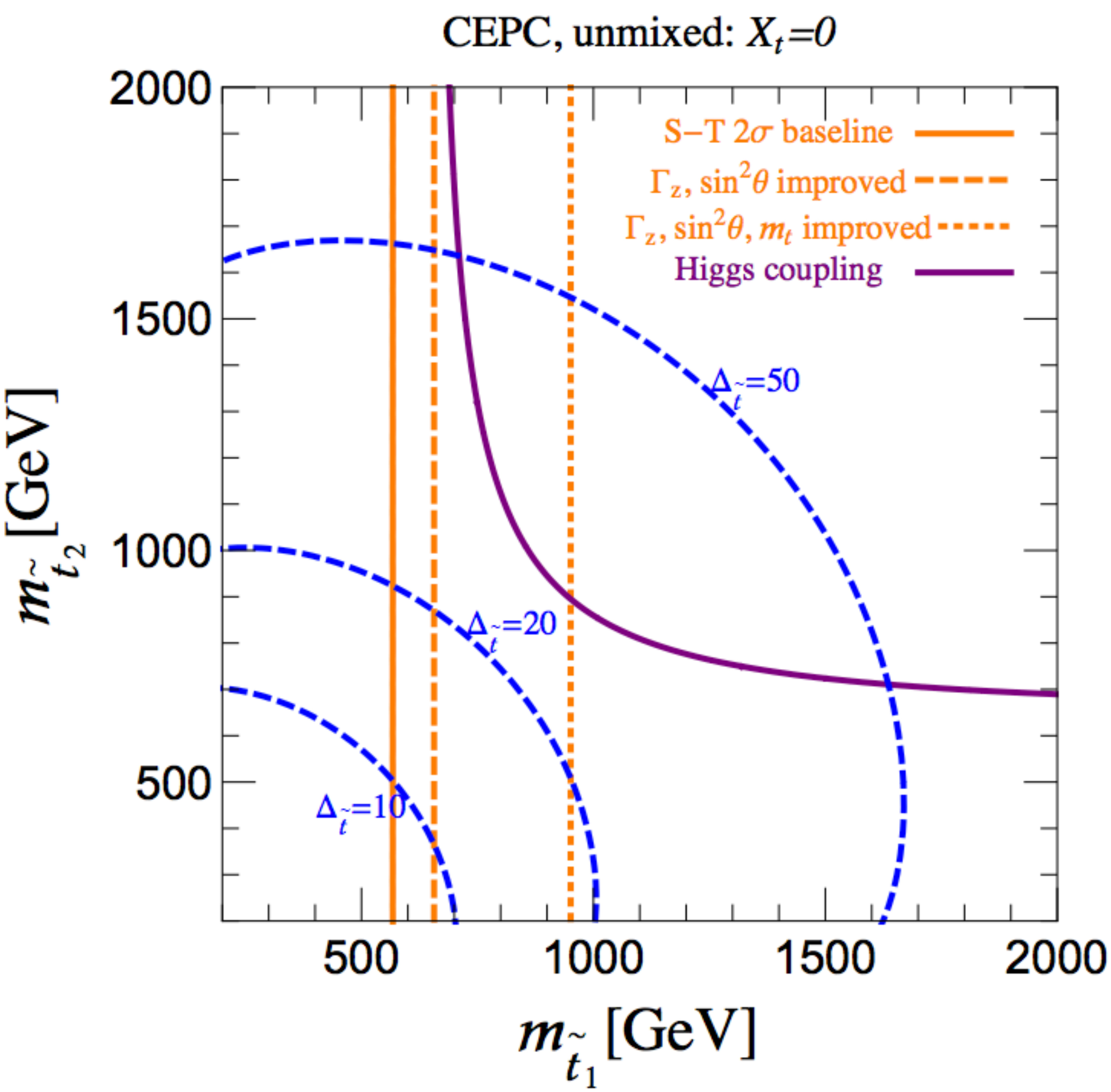


From conference proceedings: MR, 1609.03018

Once the CEPC baseline is reached, improving precision on the top mass and on $\sin^2\boldsymbol{\theta}$ is next priority for (T, S).

Or, improve the Z width *significantly* (plausible!)

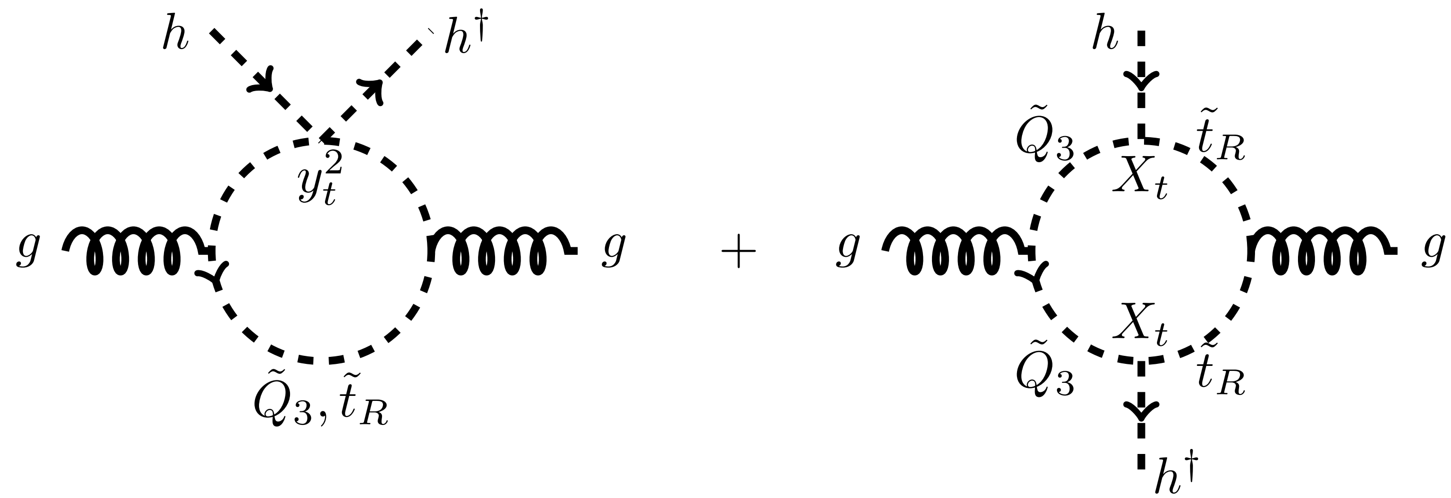
Associated New Physics Reach: Example of Stops



Higgs couplings (gluons and photons) probe left- and right-handed stops roughly equally well.

The *T* parameter probes left-handed stops.

Higgs Couplings

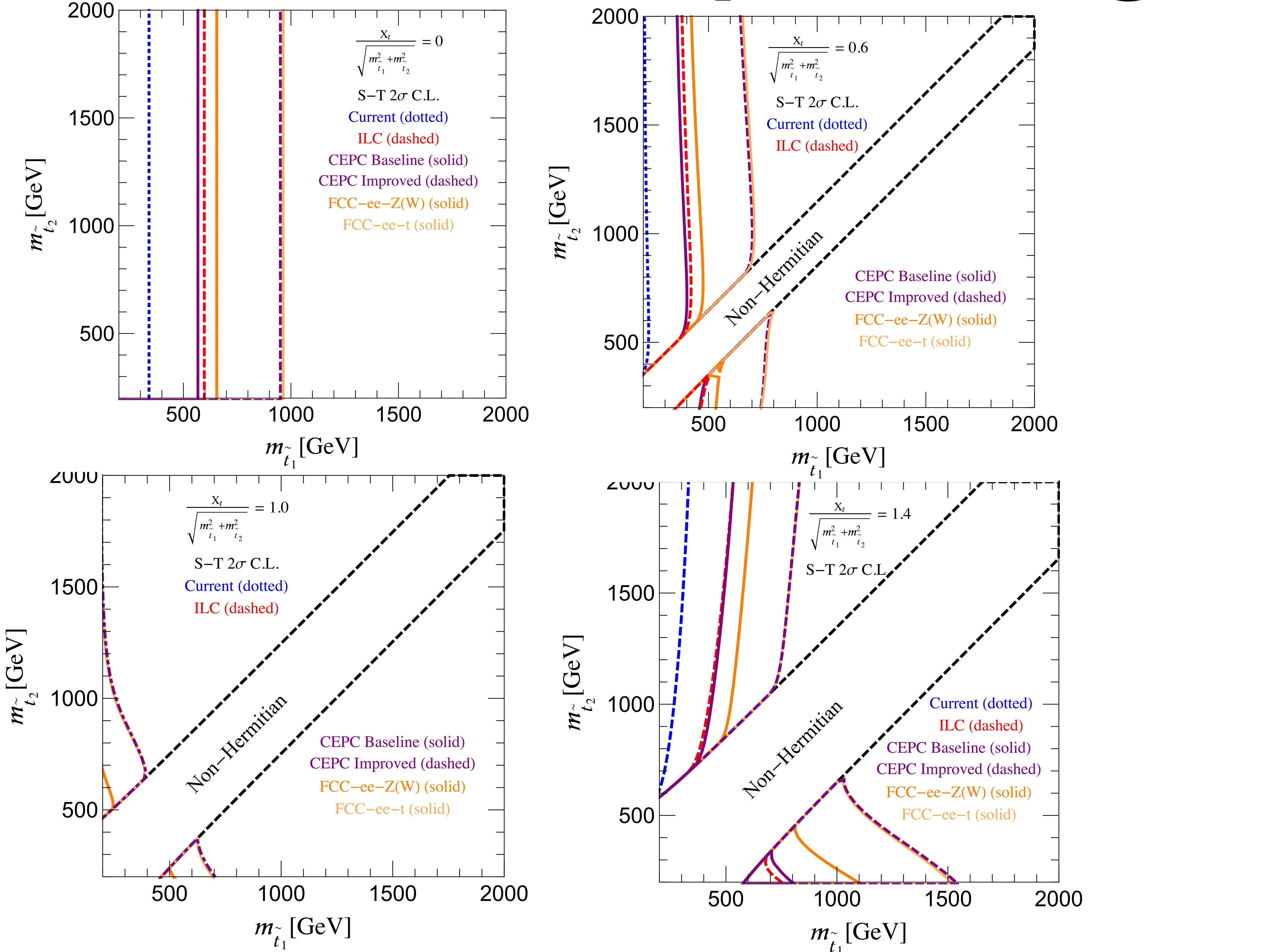


$$r_G^{\tilde{t}} \equiv \frac{c_{hgg}^{\tilde{t}}}{c_{hgg}^{\rm SM}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

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

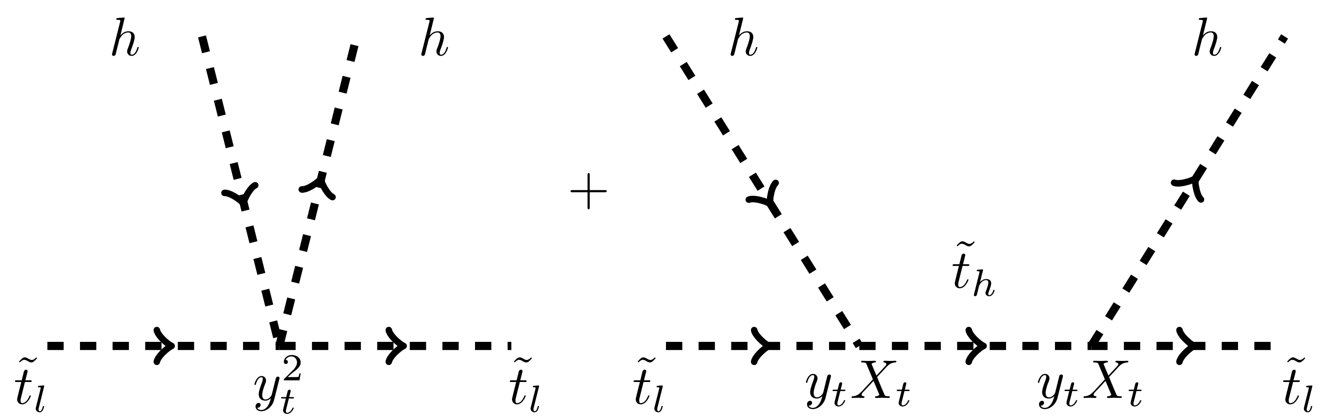
Similar result for photons (except SM contribution dominated by *W* loop)

EWPT and Stop Mixing



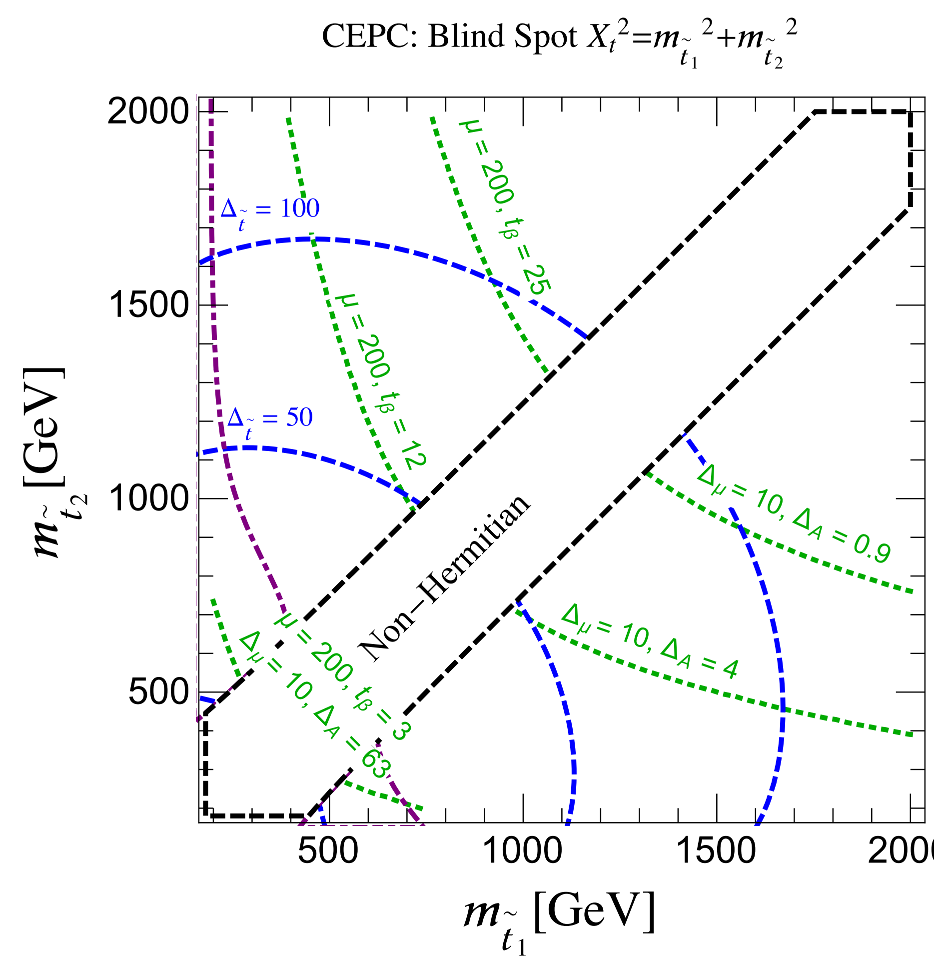
“Blind Spot” for Stops

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: $b \to s\gamma$

(also see Craig, Farina, McCullough, Perelstein 1411.0676)

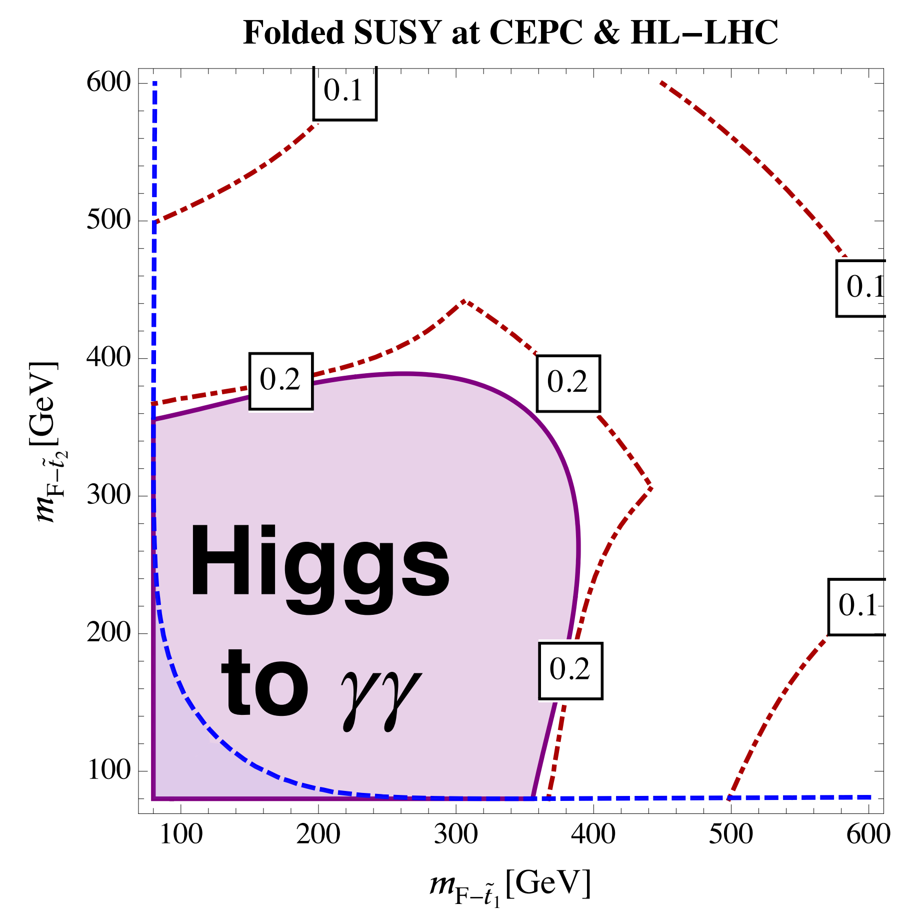
Folded SUSY

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!

Higgs factories have exciting potential for uncolored naturalness!



Dark Matter at CEPC

In drafting a CDR theory section reviewing work on dark matter / dark sectors at CEPC, JiJi Fan and I are classifying models in 4 categories:

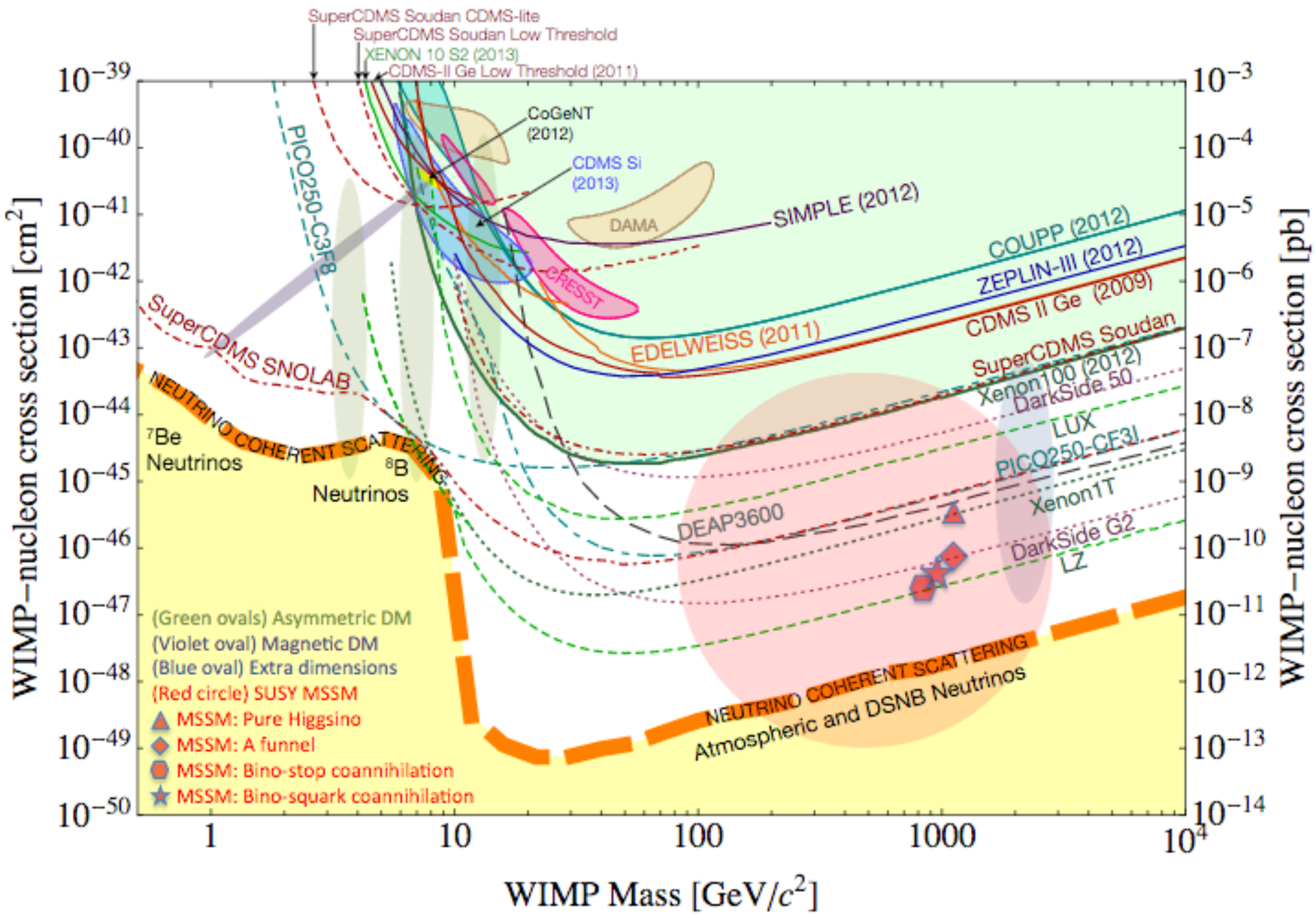
1. Electroweak-interacting particles (e.g., but not limited to, SUSY neutralinos)
2. DM interacting with renormalizable gauge-invariant SM portals, $|H|^2$, $B^{\mu\nu}$, HL
3. DM interacting with BSM portals (e.g. leptonic Higgs portal)
4. Model-agnostic (photon+MET, EFT approach)

I will make a few remarks now about these; definitely not comprehensive.

1. Electroweak DM

Future Direct Detection

Snowmass: Cushman et al. 1310.8327



← Z exchange

← h exchange

← W loop (wino)

← W loop (higgsino)

SU(2) multiplets dominantly scattering through loops are a real challenge, beyond the next generation of experiments.

Tan Beta = 1 Physics

Certain couplings turn off. ("**Blind spot**")

Neutral higgsinos mix; Majorana mass eigenstates

$$\widetilde{H}^0_\pm = \frac{1}{\sqrt{2}}\left(\widetilde{H}^0_u \pm \widetilde{H}^0_d\right)$$. exact at $\tan\beta = 1$

Off-diagonal Z coupling:

$$\frac{g}{2\cos\theta_W} Z_\mu \left(\widetilde{H}^{0\dagger}_+ \overline{\sigma}^\mu \widetilde{H}^0_- + \widetilde{H}^{0\dagger}_- \overline{\sigma}^\mu \widetilde{H}^0_+\right).$$

Higgs coupling (limit of 1 light higgs):

$$\frac{\cos\beta}{2\sqrt{2}}(v+h)\left(g\widetilde{W}^0 - g'\widetilde{B}^0\right)\left[(1-\tan\beta)\widetilde{H}^0_+ - (1+\tan\beta)\widetilde{H}^0_-\right] + \text{h.c.}$$

One mass eigenstate **decouples from higgs** at $\tan\beta = 1$

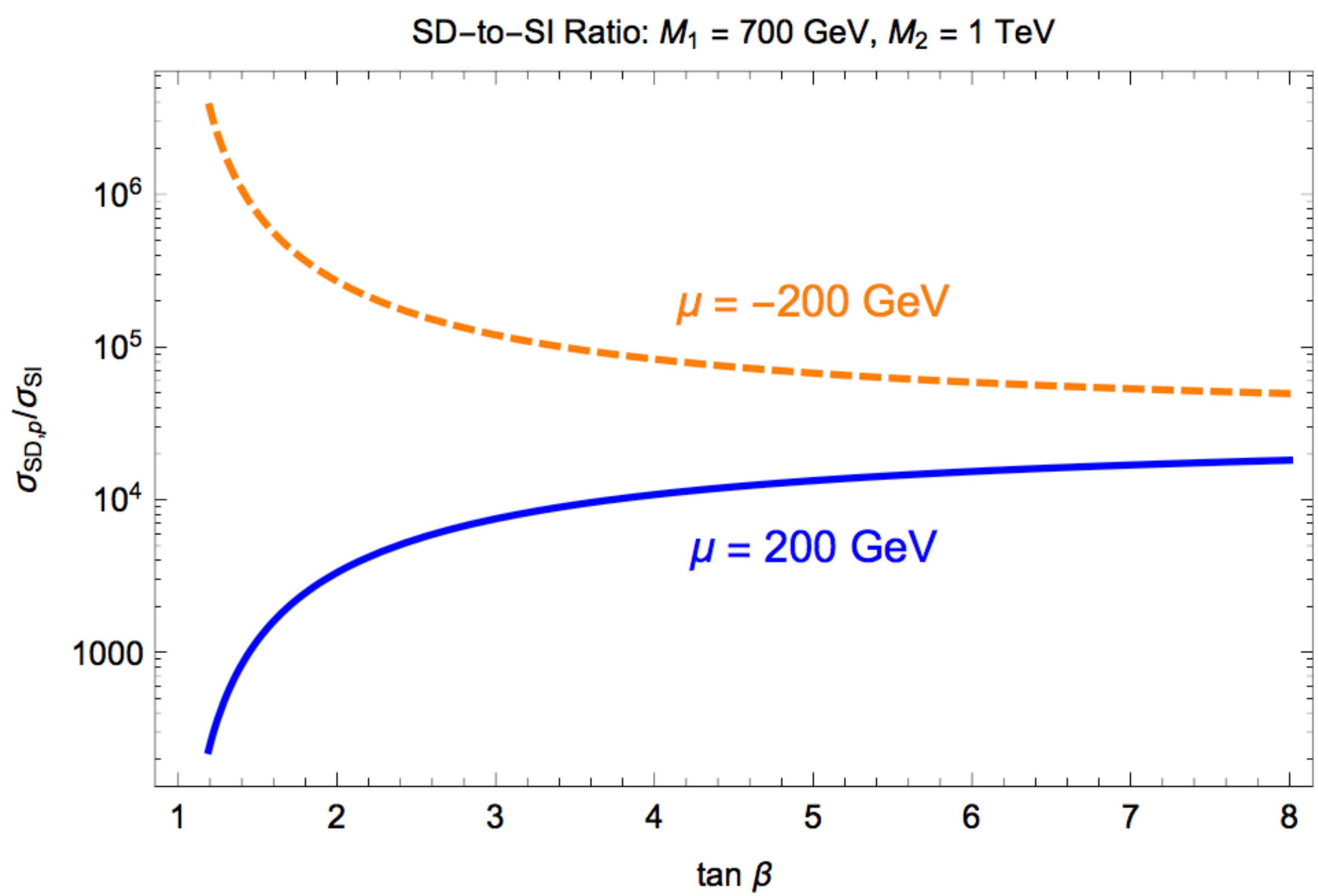
Direct Detection & Tan Beta

Mostly-higgsino dark matter: measuring both spin-dependent and spin-independent scattering.

SI $\longrightarrow$ $$\left[\frac{1}{2}c_{h\chi\chi}h\chi\chi + \mathrm{h.c.}\right] + c_{Z\chi\chi}\chi^\dagger\overline{\sigma}^\mu\chi Z_\mu$$ $\longleftarrow$ SD

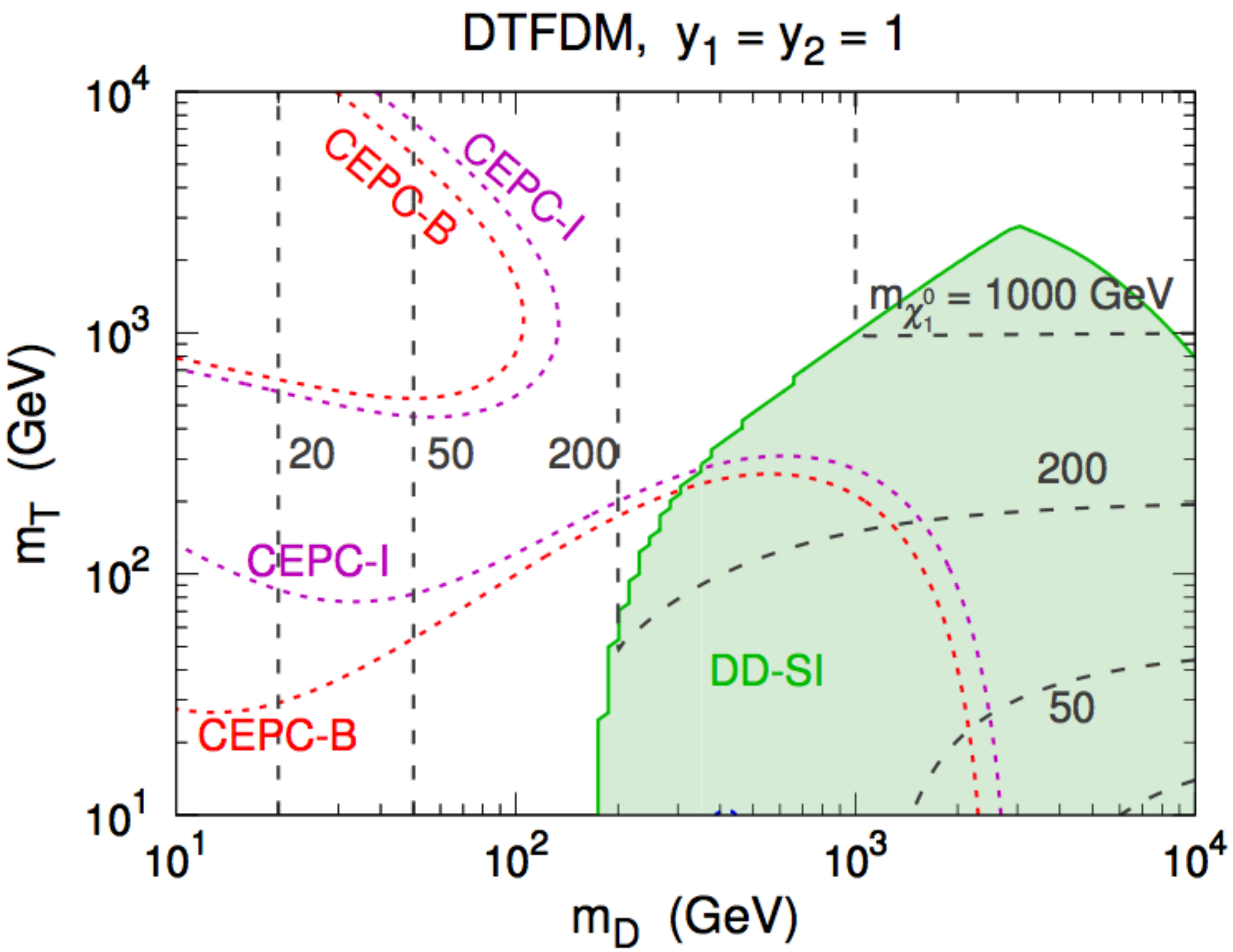
tan $\beta = 1$:
SD vanishes;
SI vanishes faster if $\mu<0$

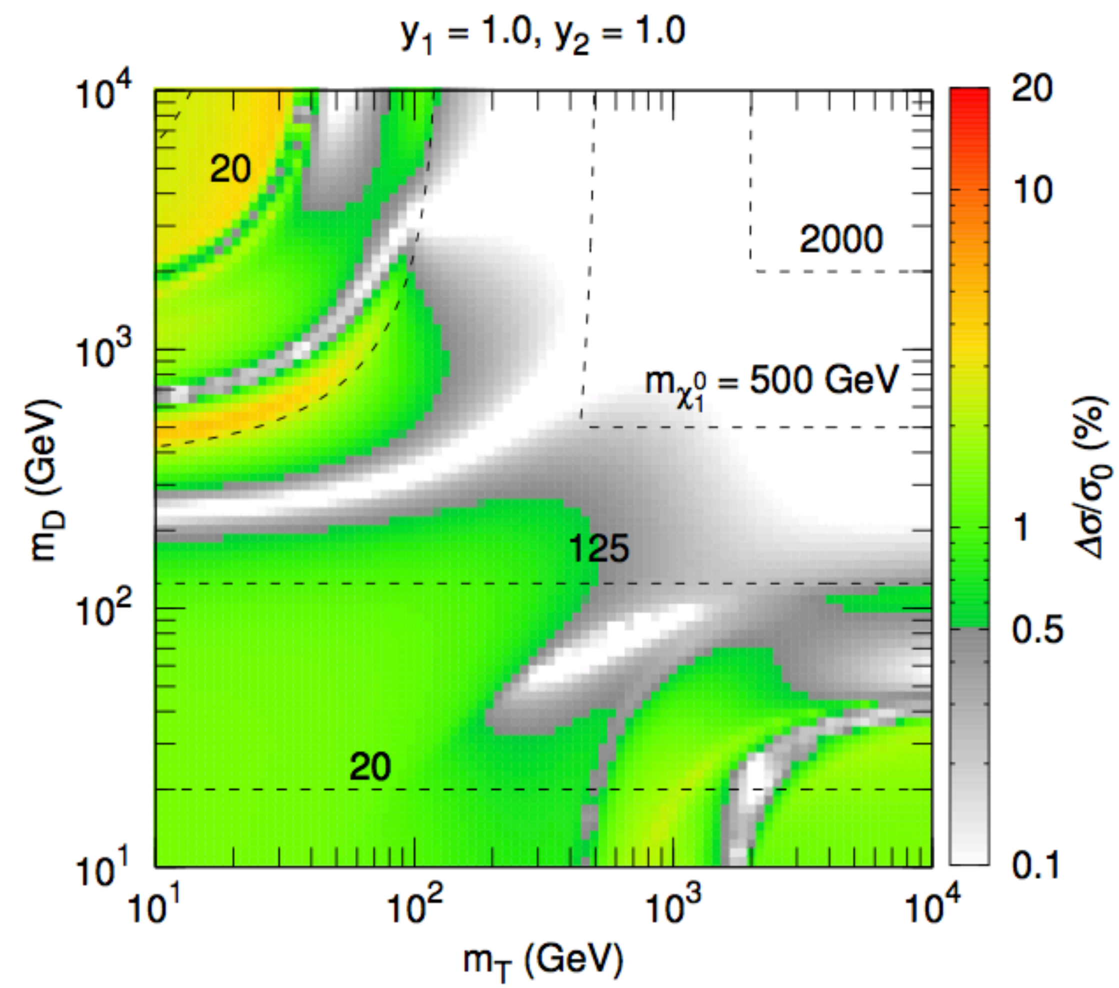
Blind spot where **SI and SD *both* vanish:** understand either as **Z_2** or ***custodial*** symmetry



Doublet/Triplet DM

Like higgsinos and winos, but bigger Yukawas. Custodial symmetry "blind spot" when $y_1 = y_2$. $$y_1(H\sigma^i D_1)T^i - y_2(H^\dagger\sigma^i D_2)T^i + \text{h.c.}$$



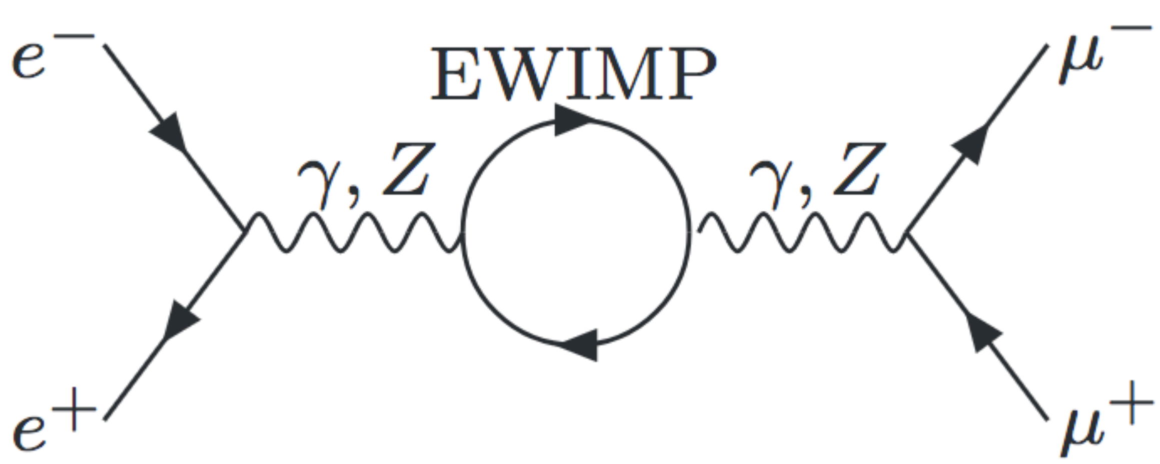


Chengfeng Cai, Zhao-Huan Yu, Hong-Hao Zhang 1611.02186

Qian-Fei Xiang, Xiao-Jun Bi, Peng-Fei Yin, Zhao-Huan Yu 1707.03094

Electroweak precision measurements, especially the *S* parameter, can play a useful role in covering direct detection's blind spot.

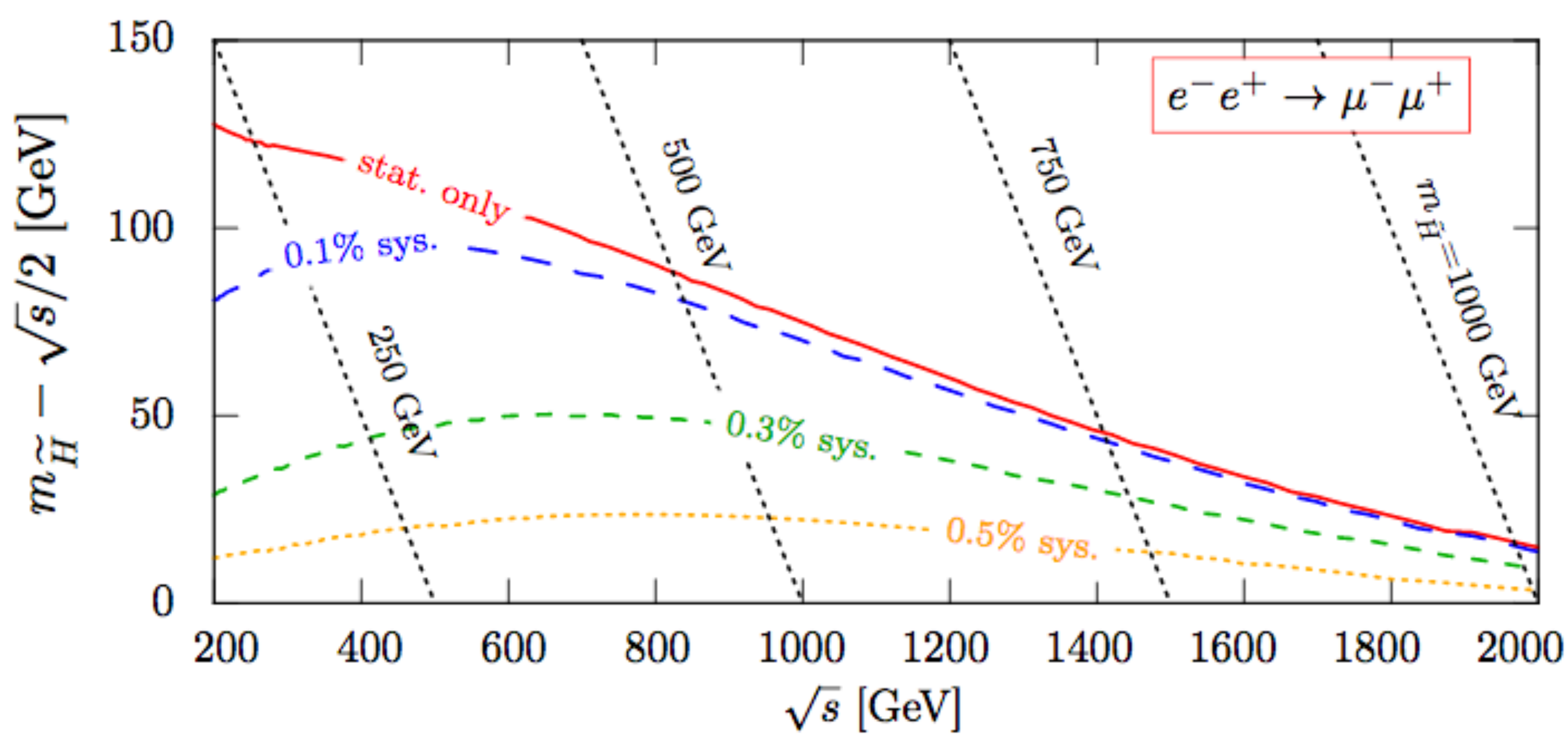
$e^+e^- \to \mu^+\mu^-$



Studied by Keisuke Harigaya, Koji Ichikawa, Anirban Kundu, Shigeki Matsumoto, Satoshi Shirai 1504.03402

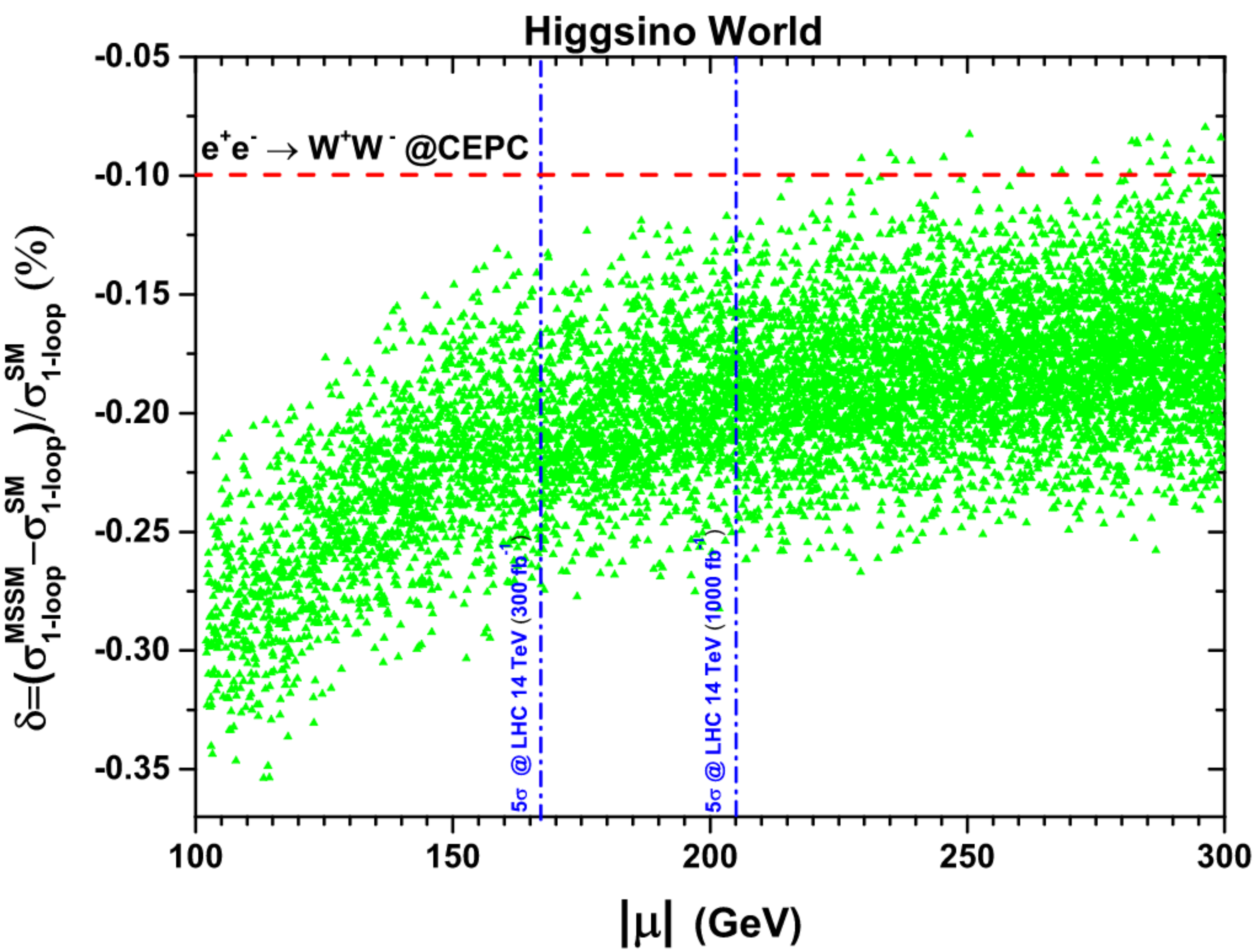
Includes beam polarization; needs an update for CEPC.

Roughly W and Y parameters; potentially beat Z pole due to higher energy



$e^+e^- \rightarrow W^+W^-$

Lei Wu 1705.02534: study the pure (pseudo-Dirac) higgsino



WW process also studied from the viewpoint of TGCs as effective operators, e.g.: Ligong Bian, Jing Shu, Yongchao Zhang 1507.02238

Dashed lines: projected LHC search reach (Baer, Mustafayev, Tata 2014)

2. SM Portals

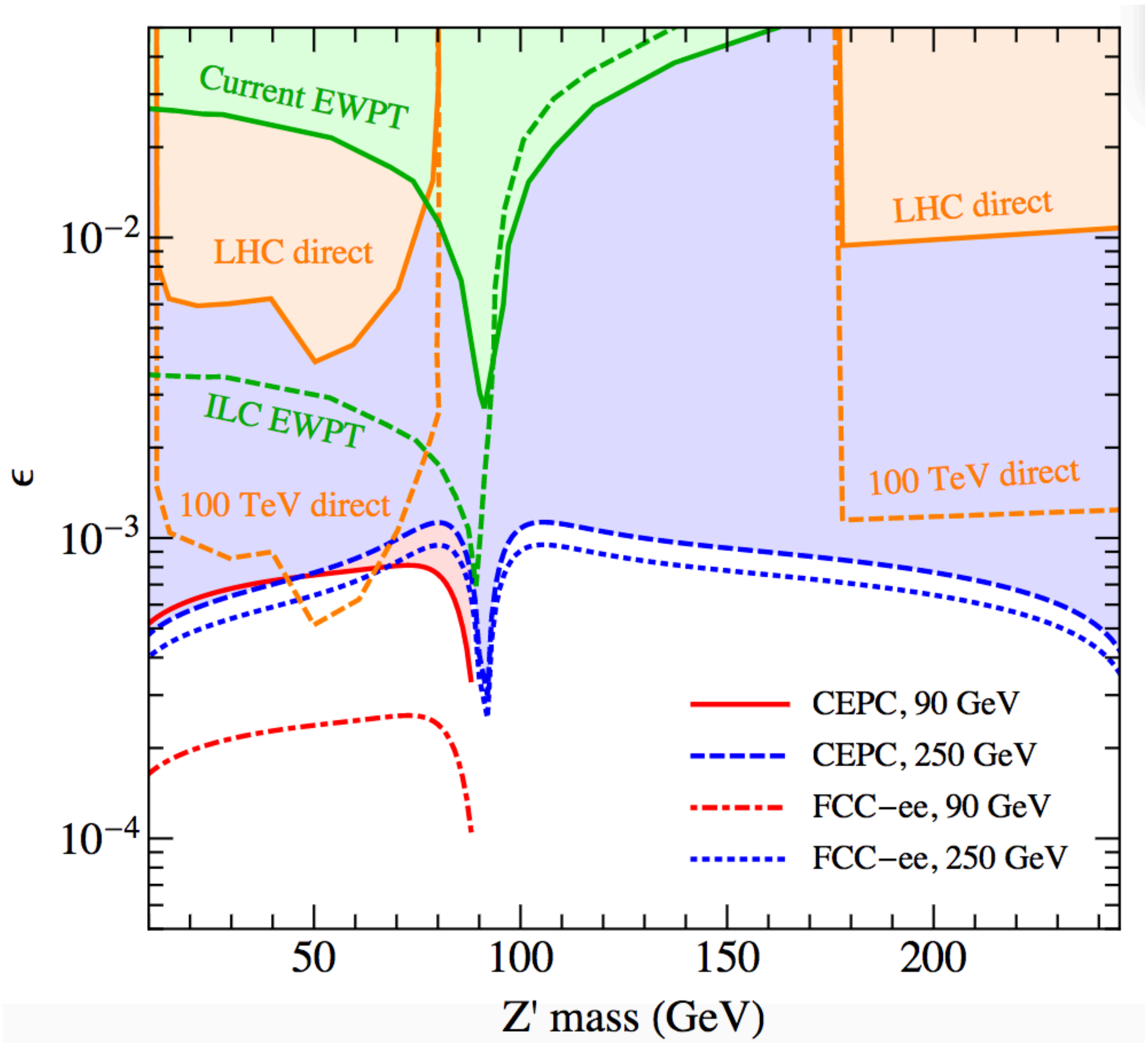
(More in Felix Yu's talk after this)

Dark Photons in Radiative Return

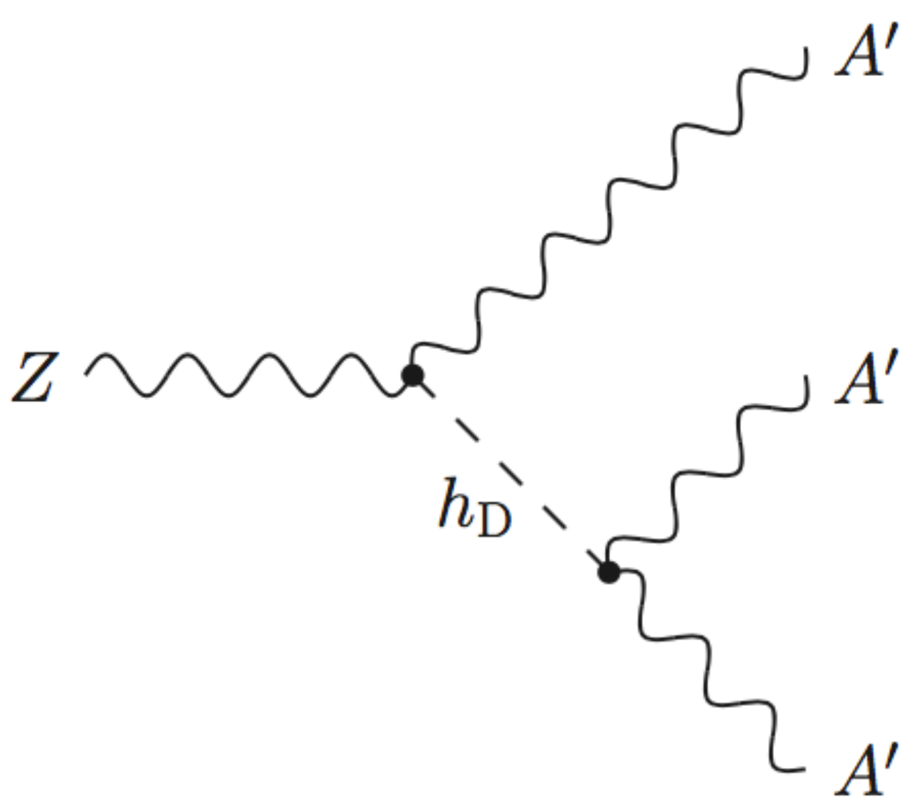
Marek Karliner, Matthew Low, Jonathan L. Rosner, Lian-Tao Wang 1503.07209

Make a dark photon in association with an ordinary photon, and do a resonance search:

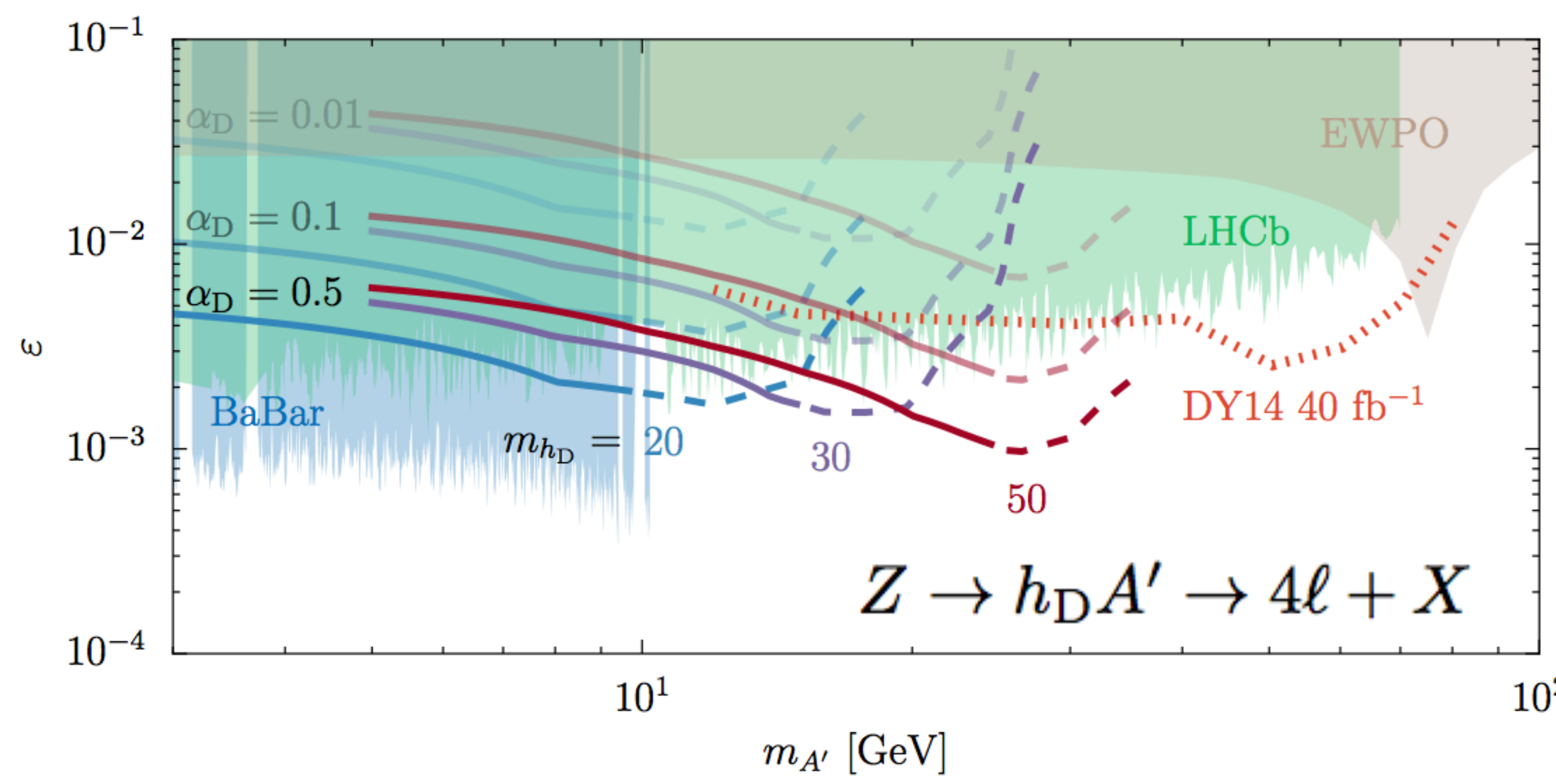
$$e^+e^- \to \gamma Z_D \to \gamma\mu^+\mu^-$$



Dark Photons at CEPC



Blinov, Izaguirre, Shuve 1710.07635
did an **LHC** study



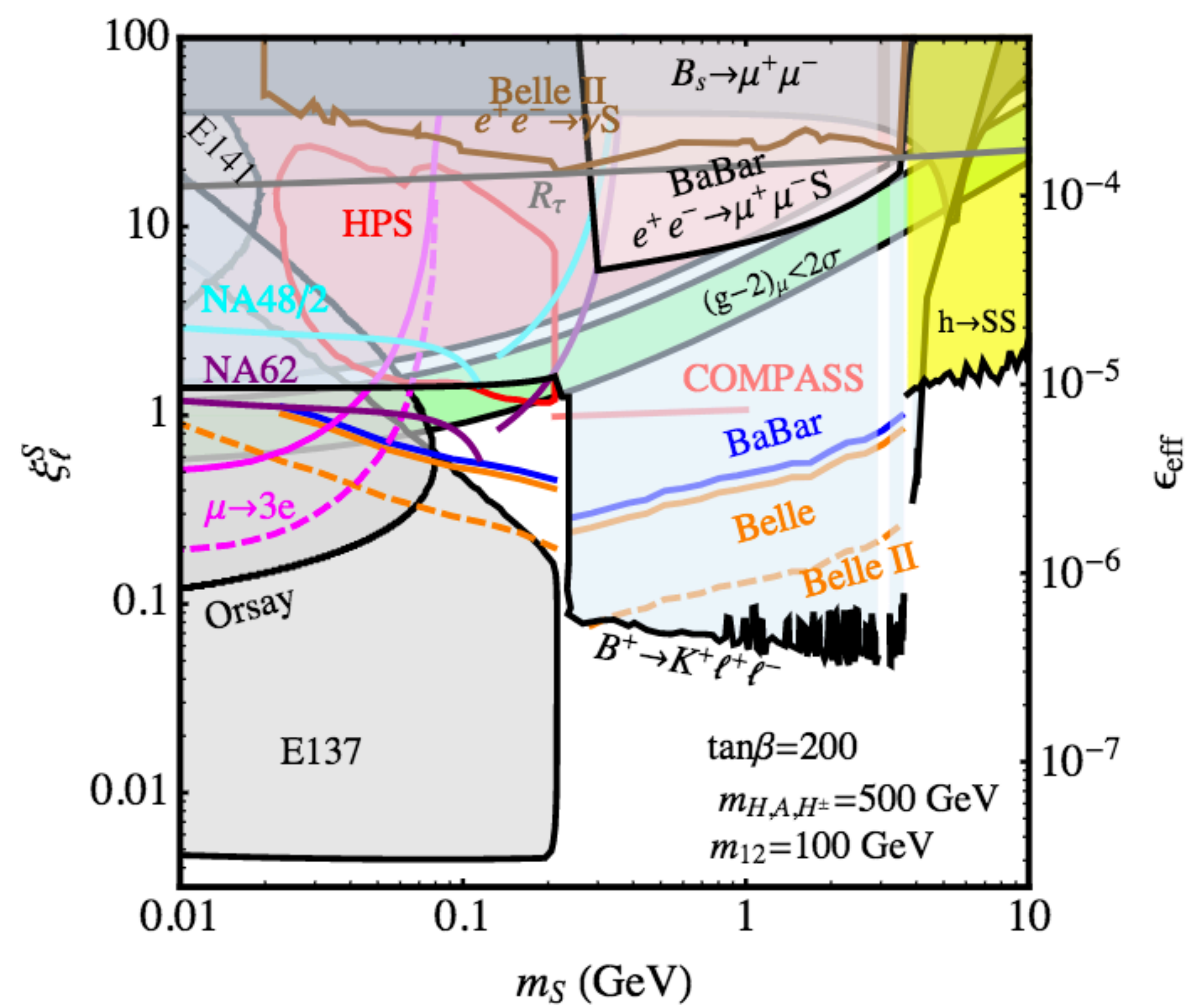
BaBar very constraining for m < 10 GeV. Target higher masses.
Above is a recent LHC study. Would be interesting to do a CEPC study of this rare Z decay. Total number Zs comparable. The cleaner environment at CEPC can help.

3. Beyond-SM Portals

Leptophilic DM

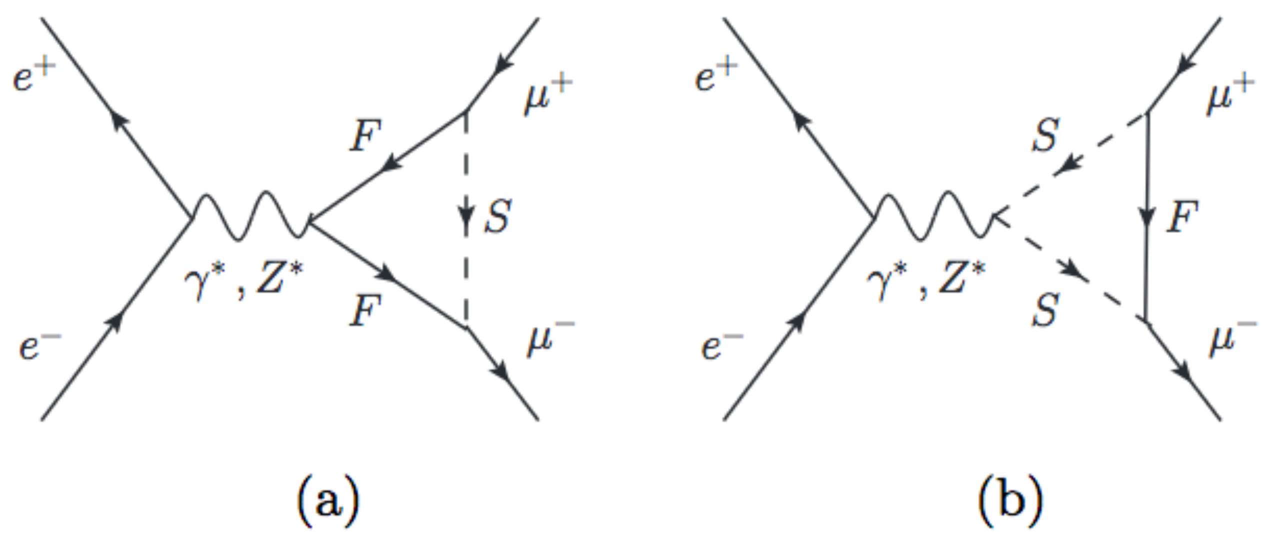
Some portals don't exist in the SM, at least renormalizably: e.g. a scalar coupling preferentially to leptons but not quarks. Can complete into a 2HDM with a leptonic Higgs.
(Brian Batell, Nicholas Lange, David McKeen, Maxim Pospelov, Adam Ritz 1606.04943)

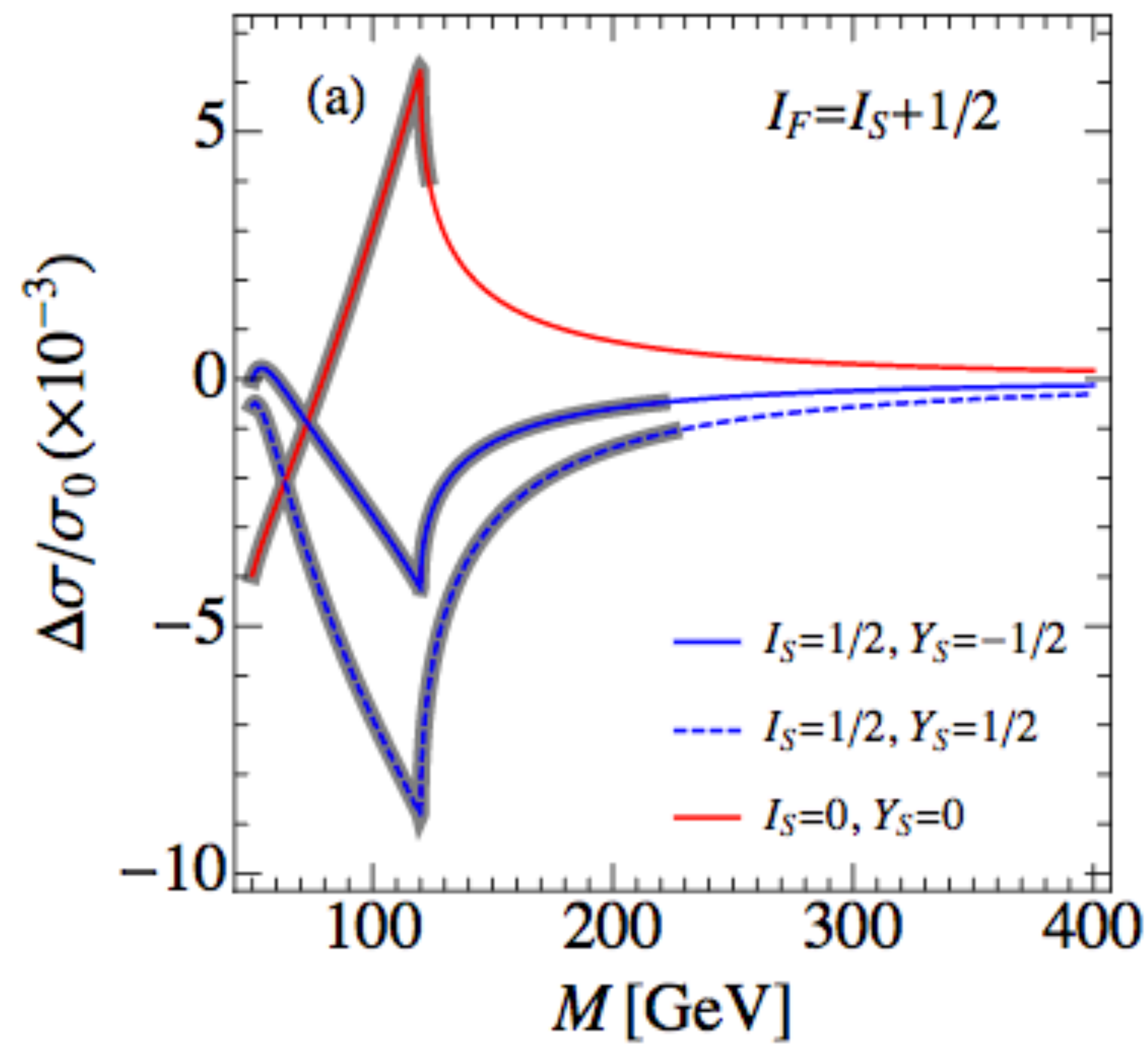
These models can have DM signals but *also* signals from effects of other particles added, like second leptophilic Higgs.



Muon-philic DM

Qing-Hong Cao, Yang Li, Bin Yan, Ya Zhang, Zhen Zhang
1604.07536





Two new fields with Yukawa coupling to muons:

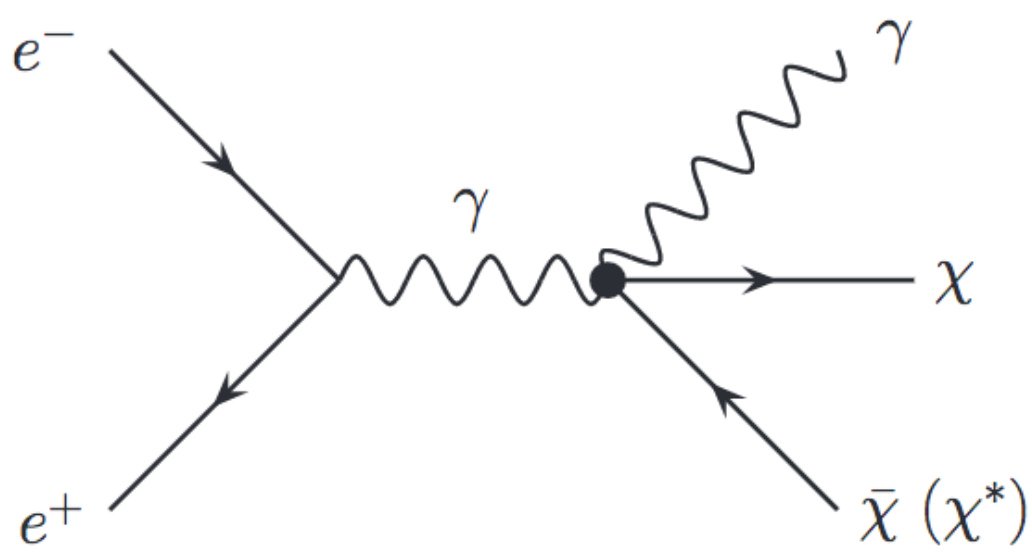
$$S\bar{\mu}_L F$$

Neutral component of S is DM.

Assumes a 0.2% measurement of e+e- → μ+μ- at 240 GeV.

4. Model-Independent

Model-Independent, EFTs



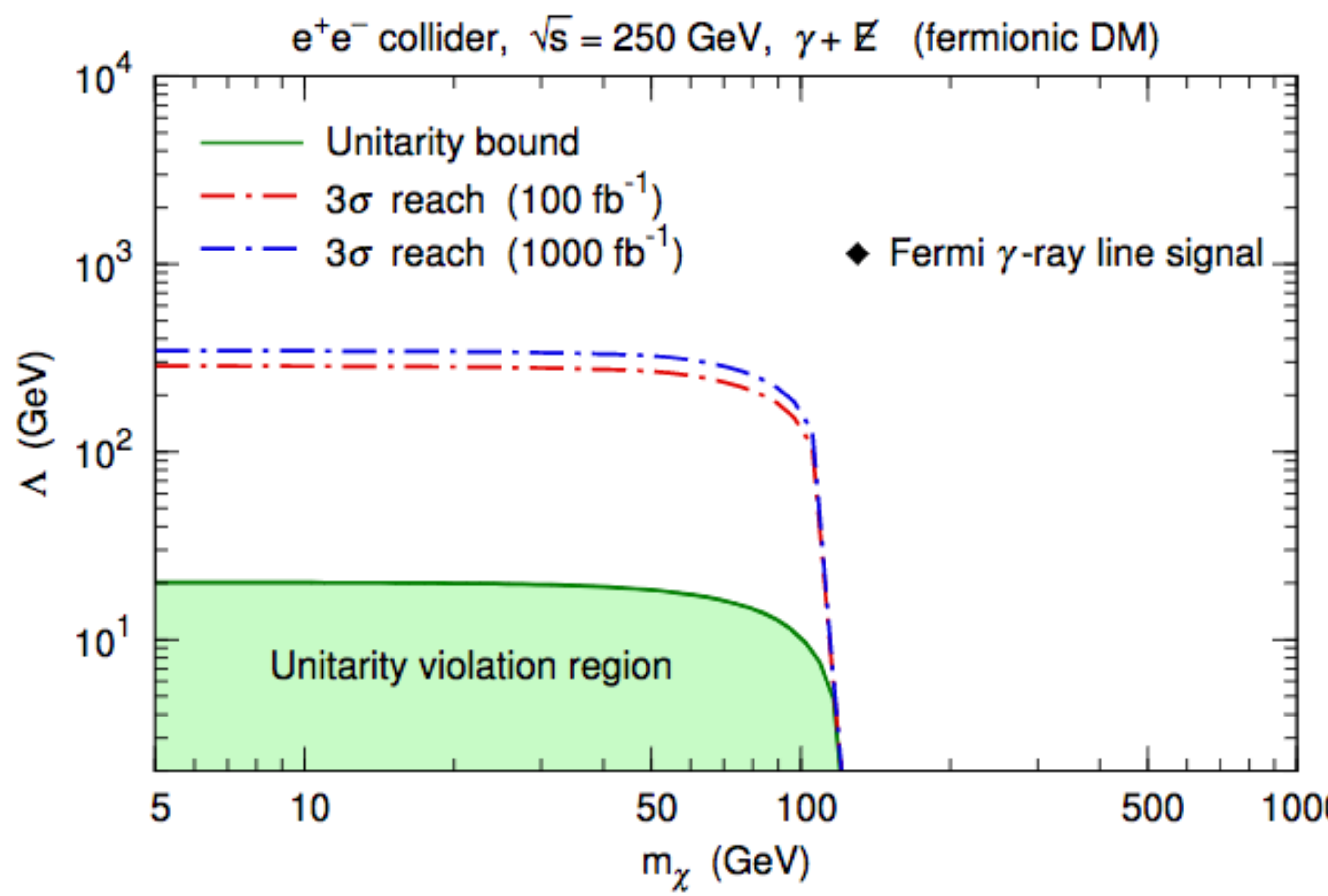
Zhao-Huan Yu, Qi-Shu Yan, Peng-Fei Yin 1307.5740
(Not CEPC-specific)

(Earlier work: Birkedal, Matchev, Perelstein; many others)

"Rayleigh dark matter"

Phrase bound in terms of an operator:

$$\mathcal{O}_F = \frac{1}{\Lambda^3}\bar{\chi}i\gamma_5\chi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



General Thoughts

Lots of nice work being done on EFTs and operators. But, personally, I learn more from “simplified models”—theories with a small number of parameters that you can wrap your head around and understand which measurements to improve.

We’ve heard about some such work here, e.g. Shufang Su’s talk on 2HDMs and Wei Su on MSSM.

The “what is the limiting factor in this measurement” plots are useful guides, for thinking about what to optimize, whether we want to talk about 350, etc.

Concrete things to do:
Incorporate more 240 GeV physics in our thinking about EWPT, like $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to W^+W^-$, and so on.

More work on rare Z decays (but see Jia Liu’s talk, coming up).

Summary

- A variety of studies have been carried out for how CEPC can constrain new physics
- Much more to do. In some cases, studies exist for ILC or “generic” e+e- collider, but not CEPC.
- Dark matter / dark sectors: would like to see more studies that aim to show CEPC can *either* do better than LHC/direct detection/etc at discovery or *complement* their discovery with precision information.
- If you have a key message about DM / dark sectors that you want to go in the CDR, let me know so we can try to integrate with existing draft

Backup

Indirect Observables

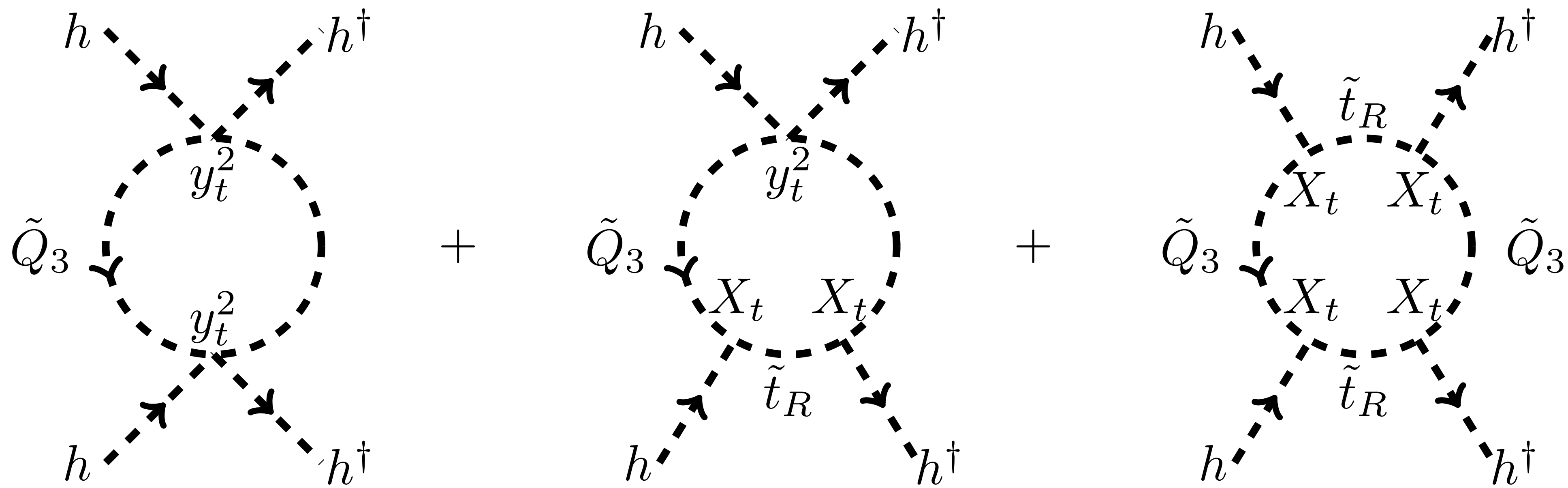
The same physics that is relevant for naturalness—couplings to the Higgs boson—can enter in loops to produce modifications of Standard Model electroweak observables.

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

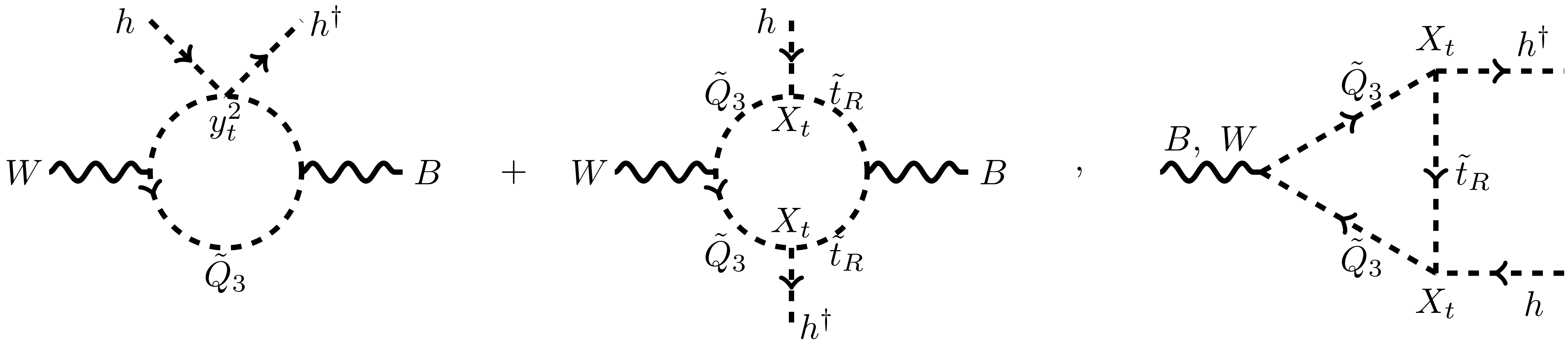
Stops: *T* Parameter



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

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: $D_\mu{}^2/m_{\rm stop}{}^2 \sim m_Z{}^2/m_{\rm stop}{}^2$.

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"

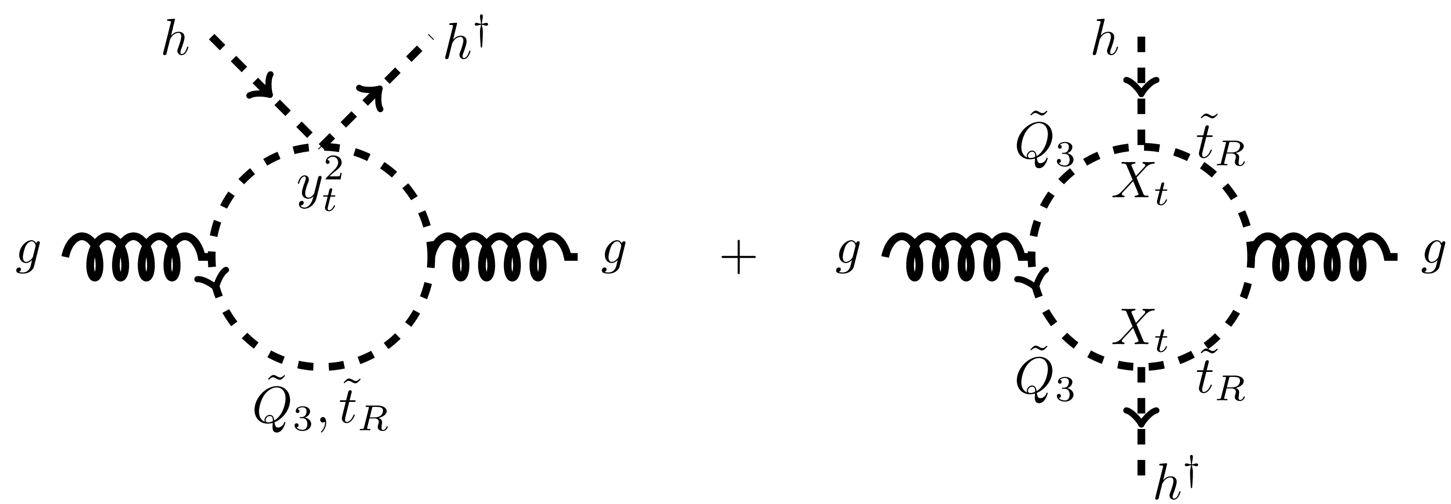
$$c_{JJ} = -\frac{g^2}{960\pi^2} \sum_{\text{rep } R,\ \text{mass } M} a_F \frac{T(R)}{M^2},$$

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



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

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

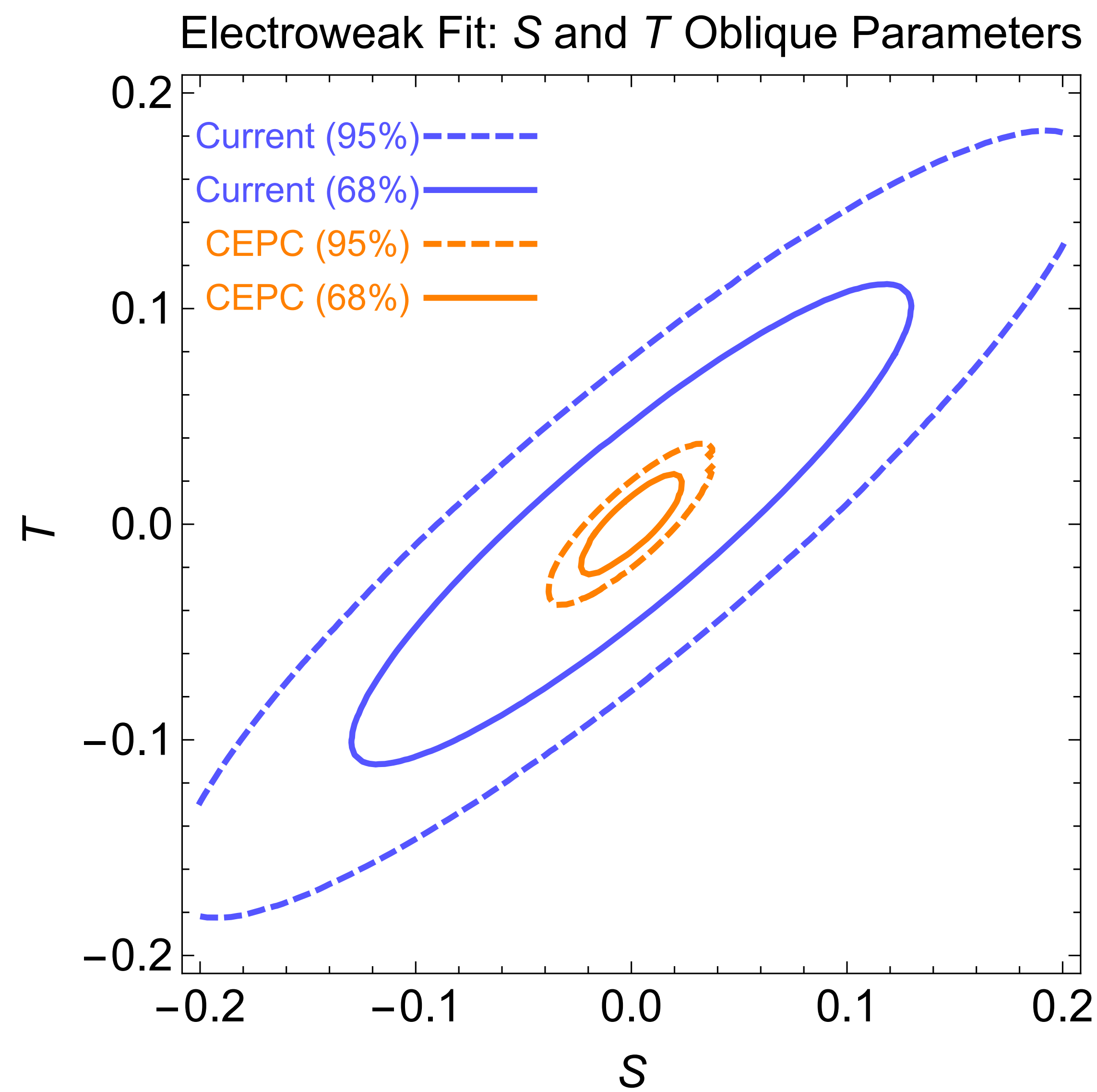
Similar result for photons (except SM contribution dominated by *W* loop)

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.

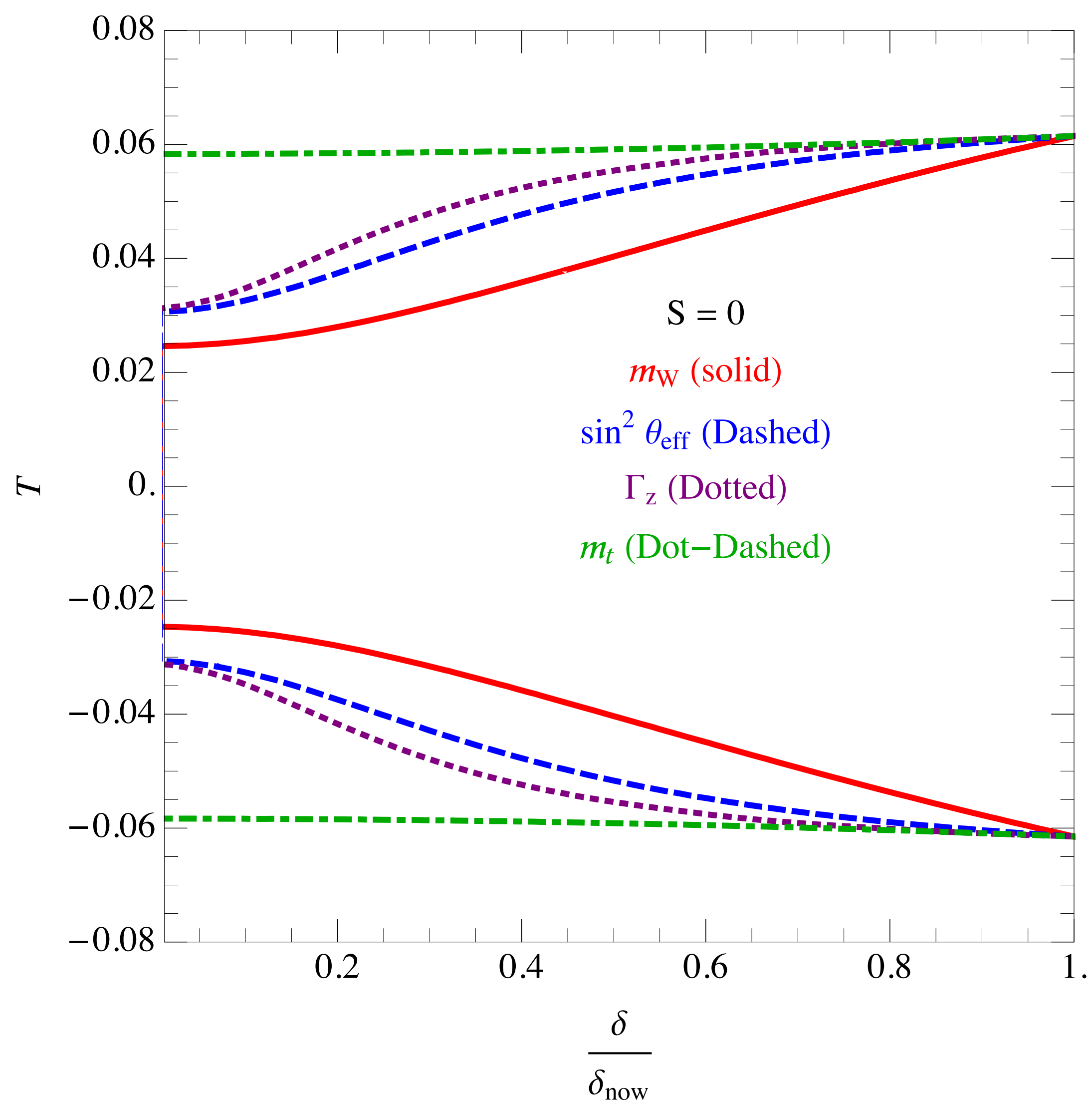
Baseline Fit

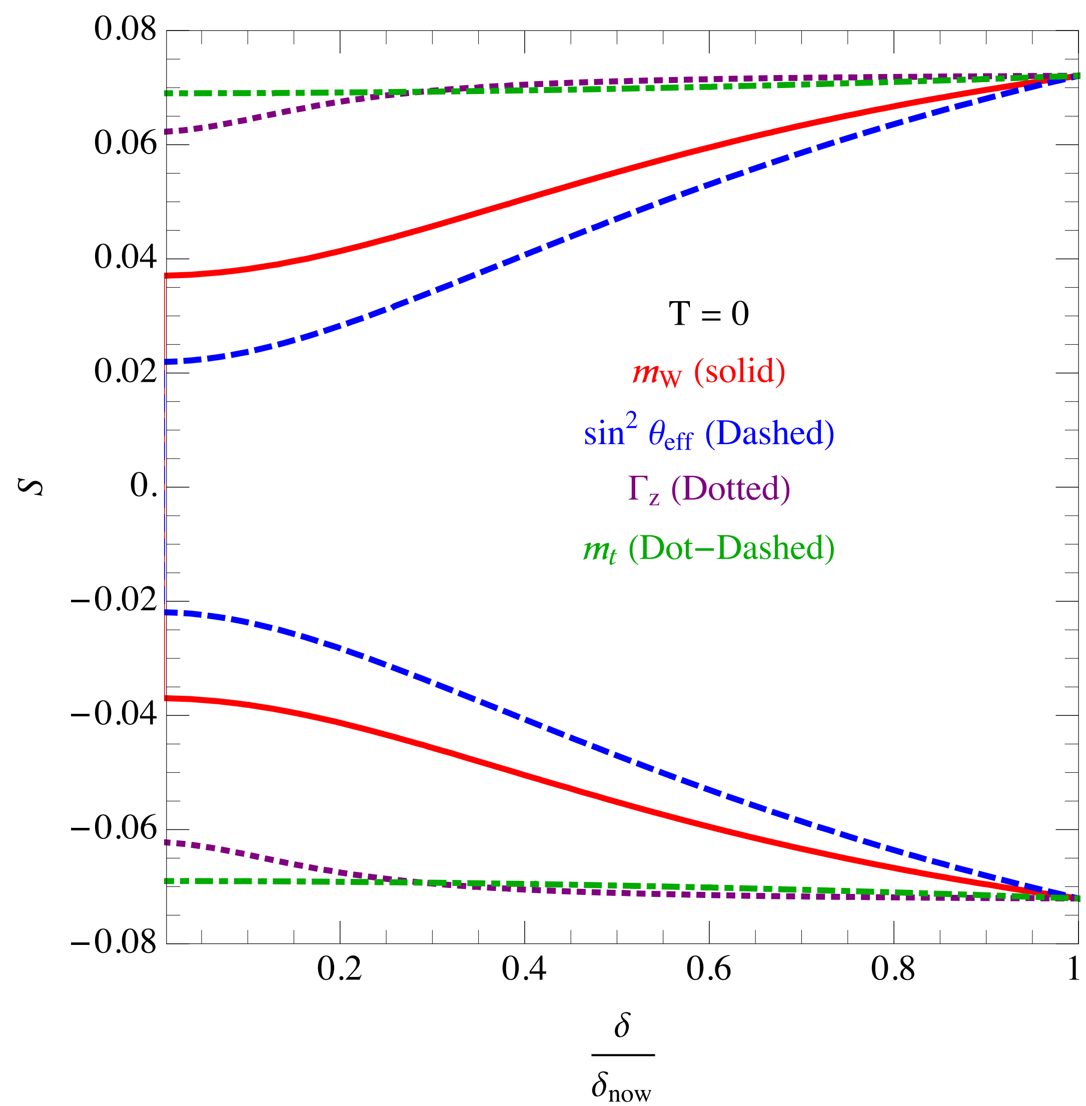


Even with conservative estimates, CEPC will provide a substantial improvement over existing data.

Limiting Measurements

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

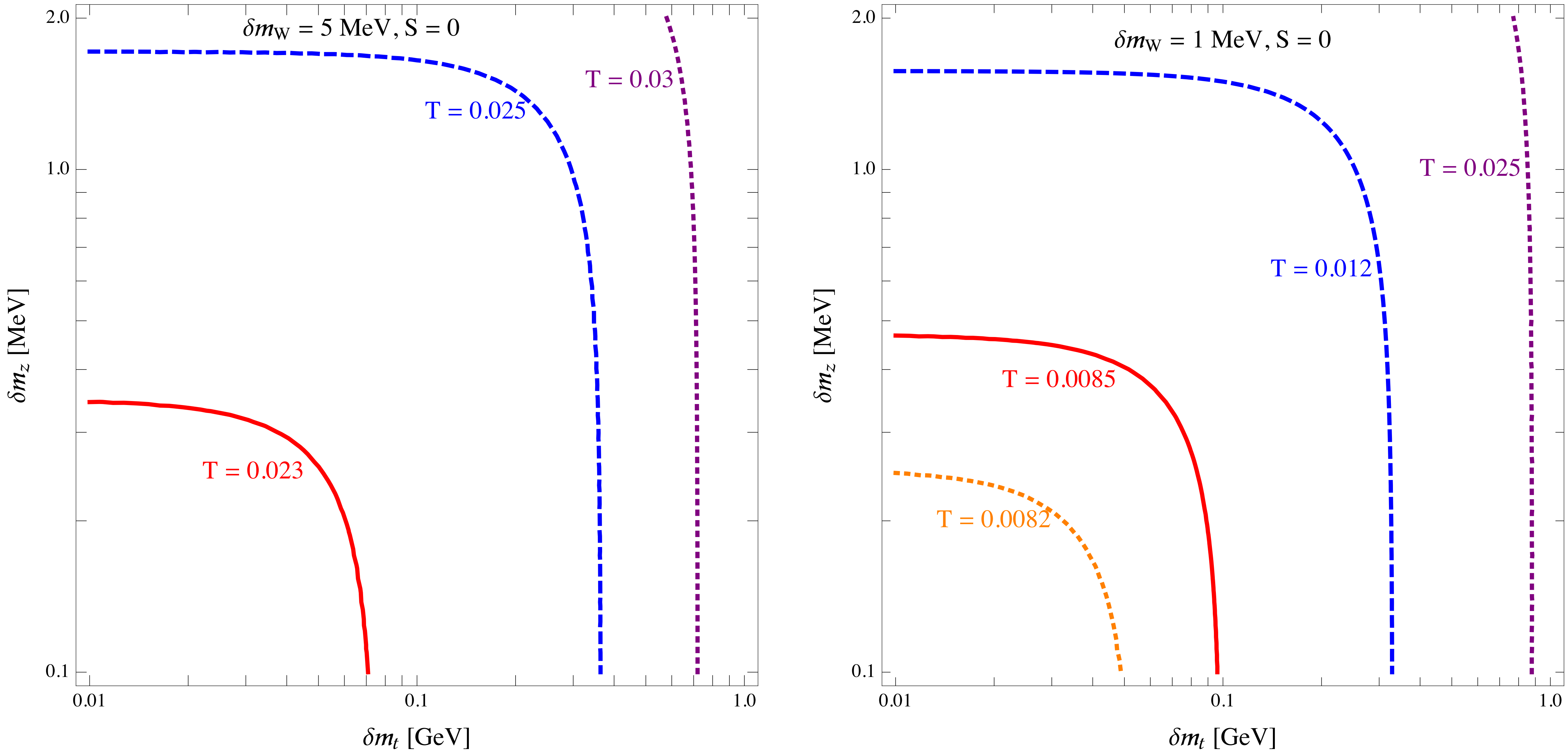




W mass is priority for measuring *T*.

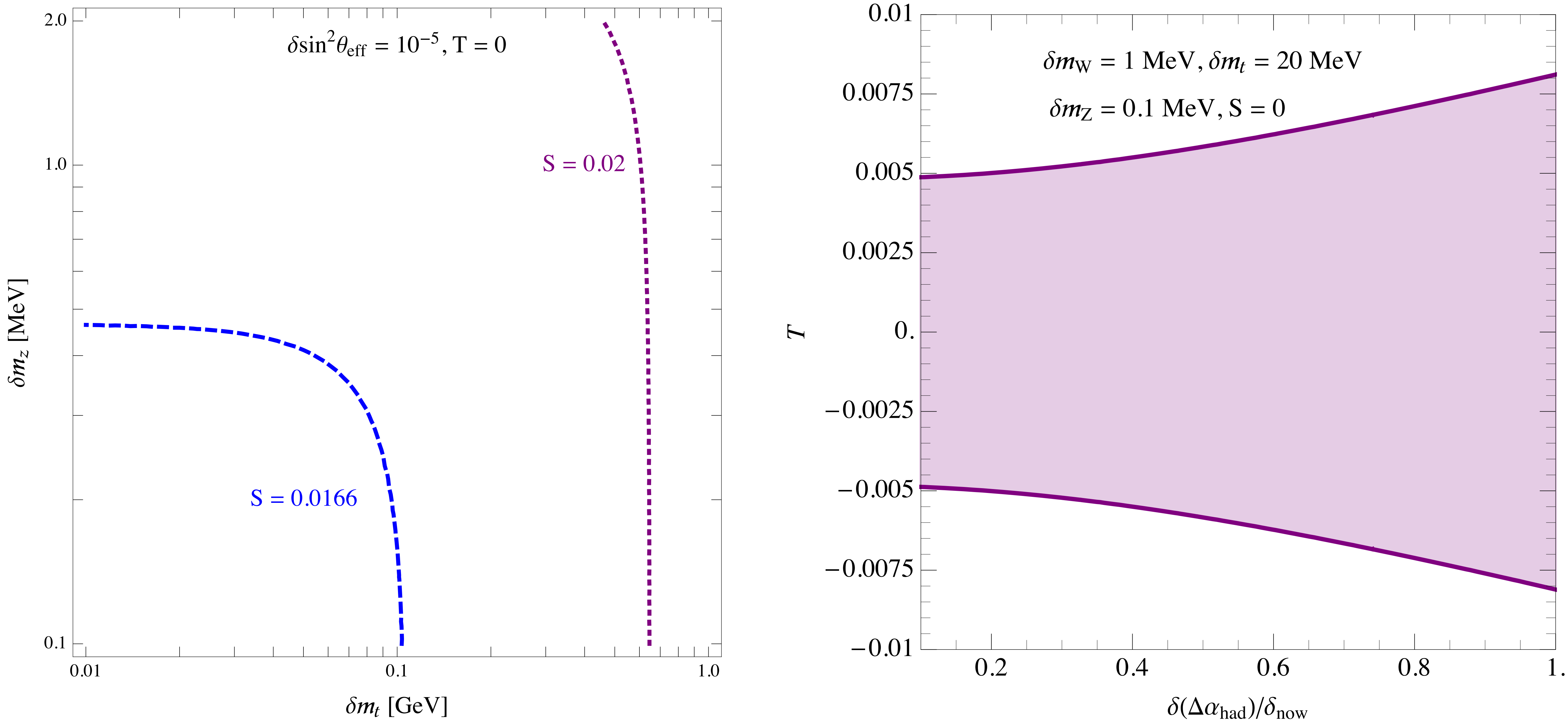
$\sin^2\theta_W$ is priority for measuring *S*

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, $\Delta\alpha_{had}$ for T Parameter



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

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})**

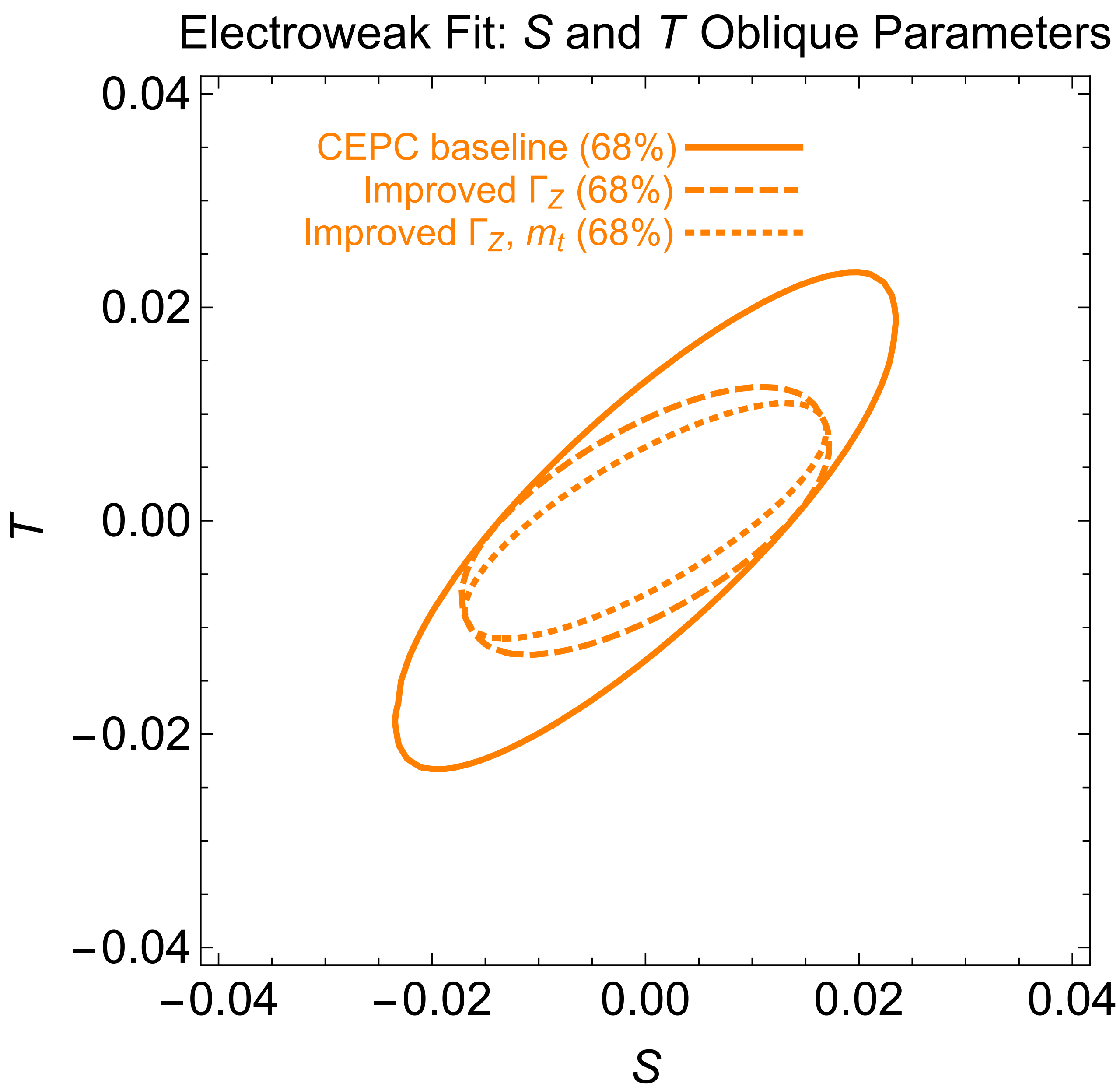
- **Measure m_Z to 500 keV precision (now 2 MeV)**

- 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	$(\pm 1_{\text{exp}} \pm 0.8_{\text{th}}) \times 10^{-4}$ (± 0.0001)	$\pm 0.03_{\text{exp}} \pm 0.1_{\text{th}}$



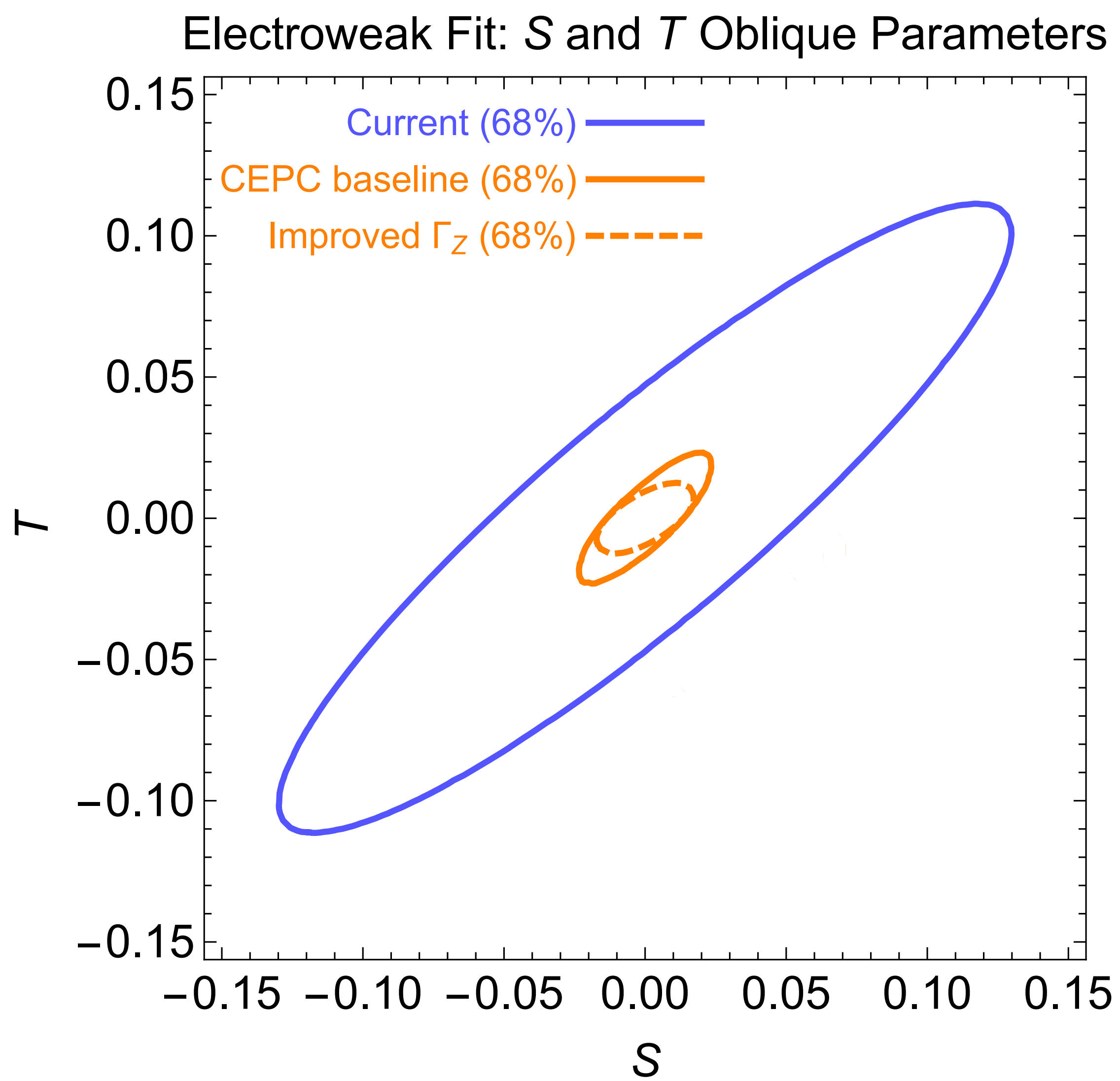
Improving the *Z* width measurement requires a better energy calibration. Improving the top mass measurement requires an e+e- collider threshold scan. (Beyond CEPC energy plans.)

Summary: CEPC Fit

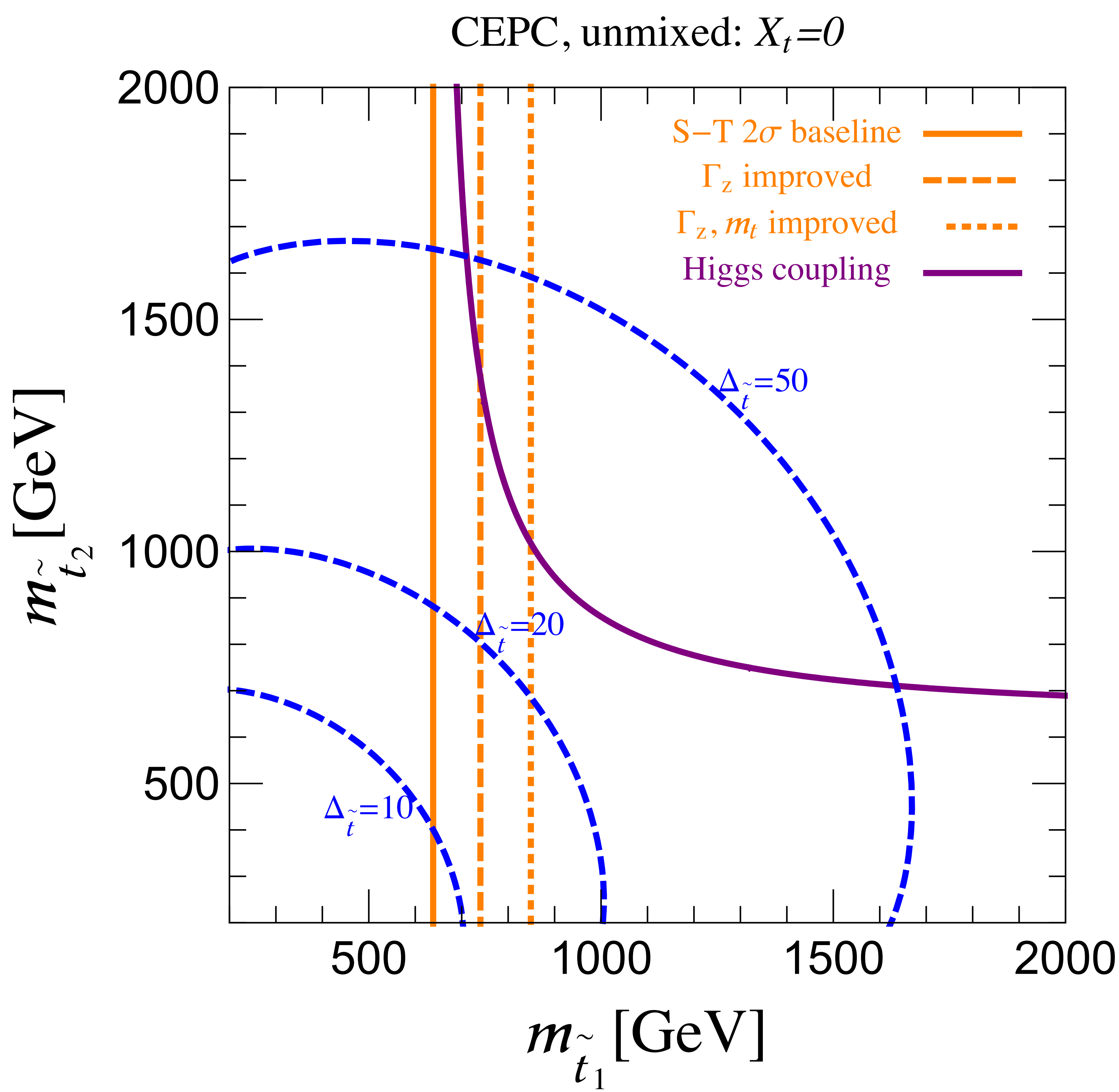
Parameter	Current	CEPC baseline	Improved Γ_Z (and m_Z)	Also improved m_t
S	3.6×10^{-2}	9.3×10^{-3}	9.3×10^{-3}	7.1×10^{-3}
T	3.1×10^{-2}	9.0×10^{-3}	6.7×10^{-3}	4.6×10^{-3}

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

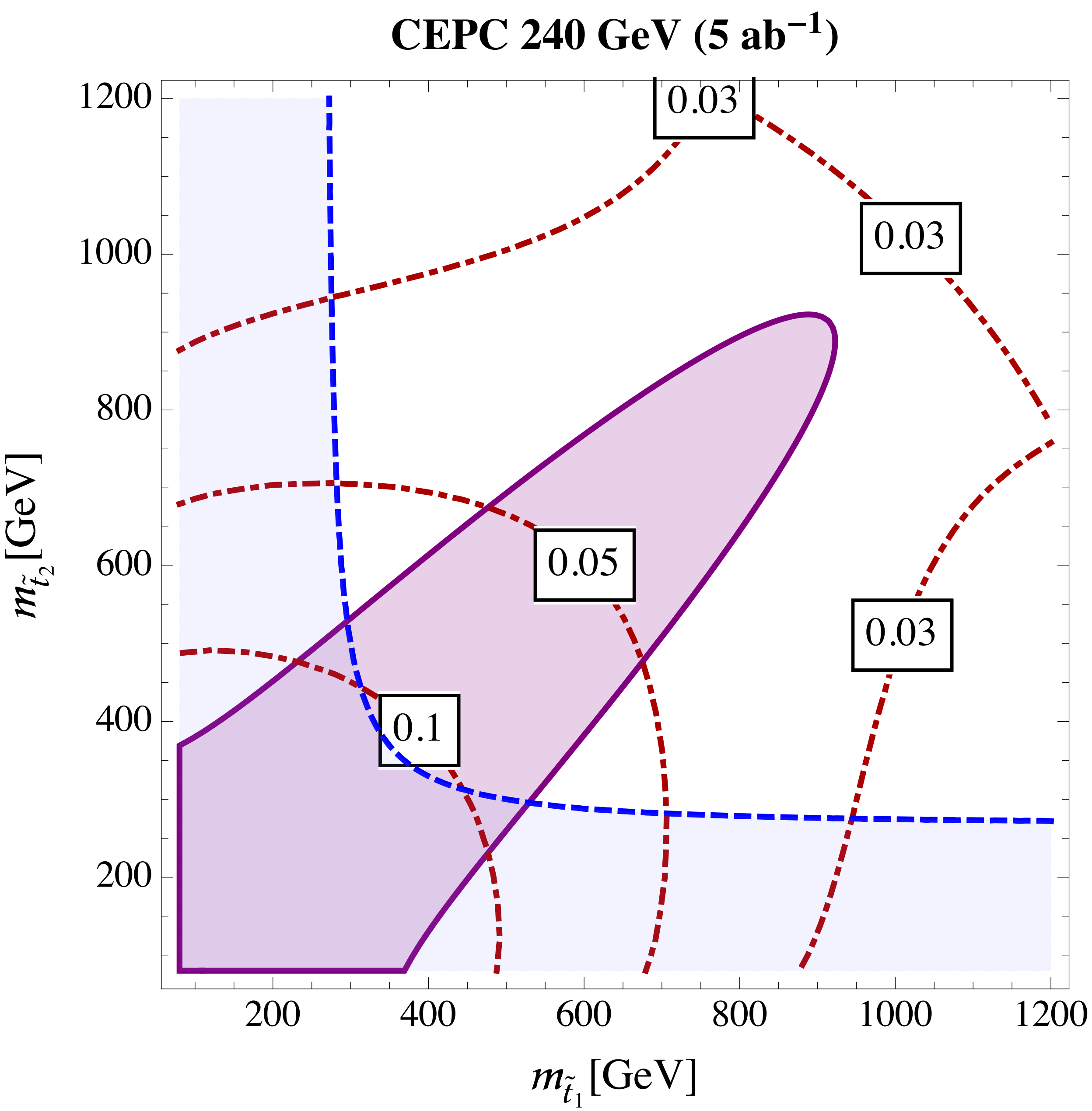


No mixing:

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

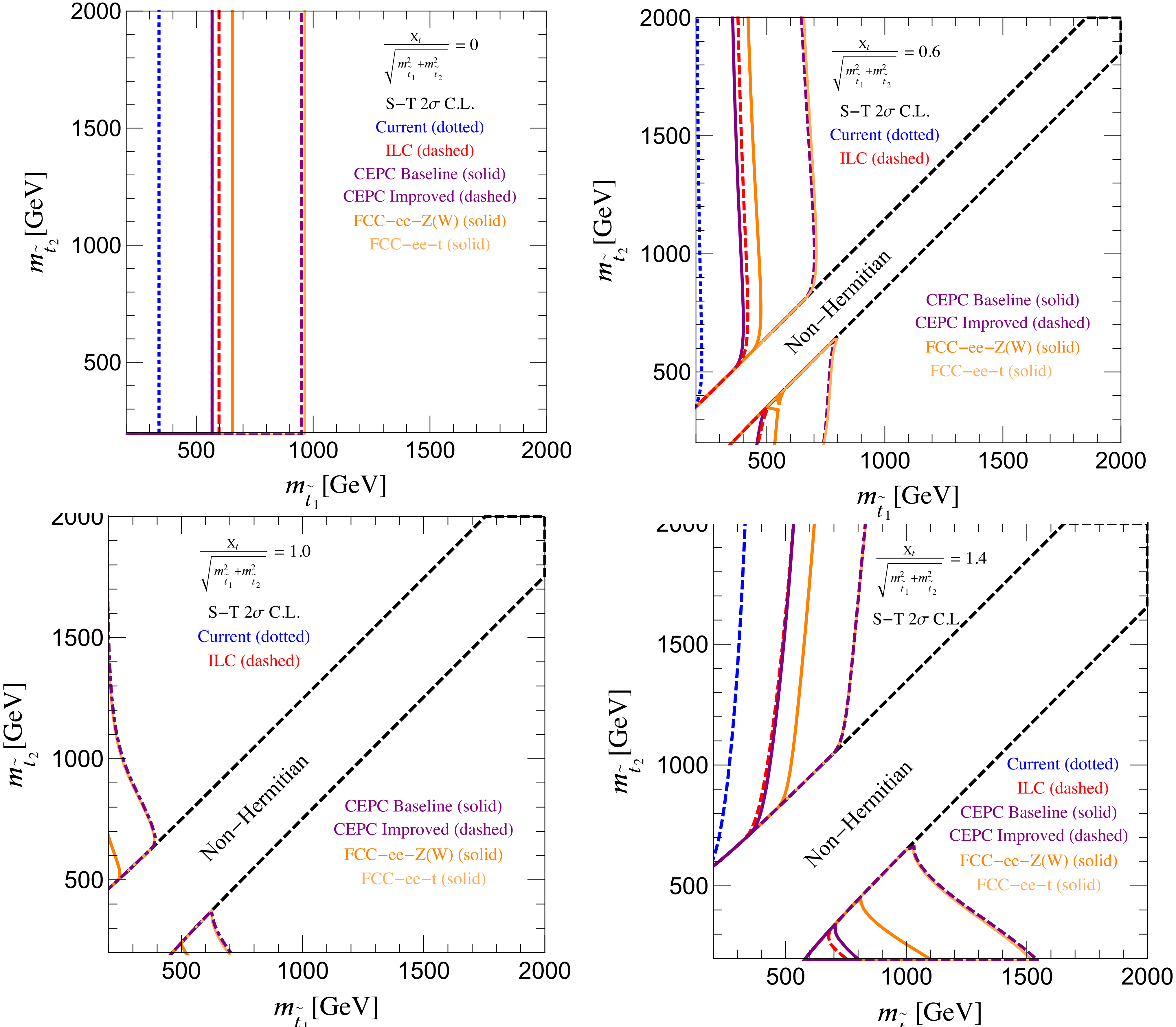


The purple region can be excluded for *any* mixing angle. (Because large mixing forces the mass eigenvalues away from the diagonal.)

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

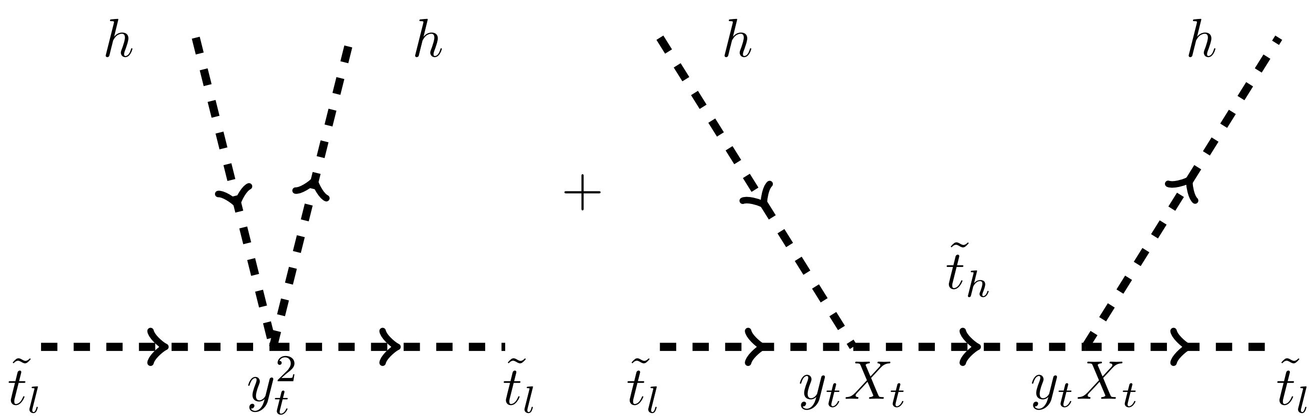
(also see J. Fan, MR arXiv:1401.7671)

EWPT and Stop Mixing

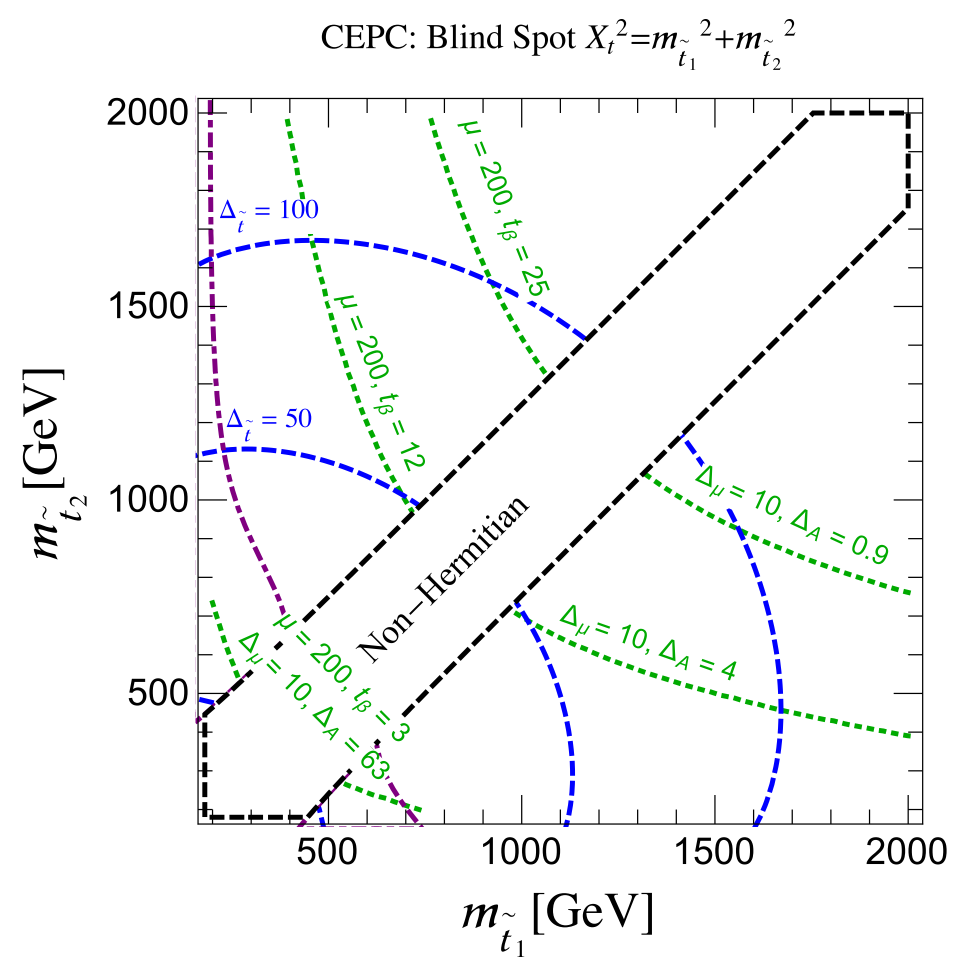


“Blind Spot” for Stops

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: $b \to s\gamma$

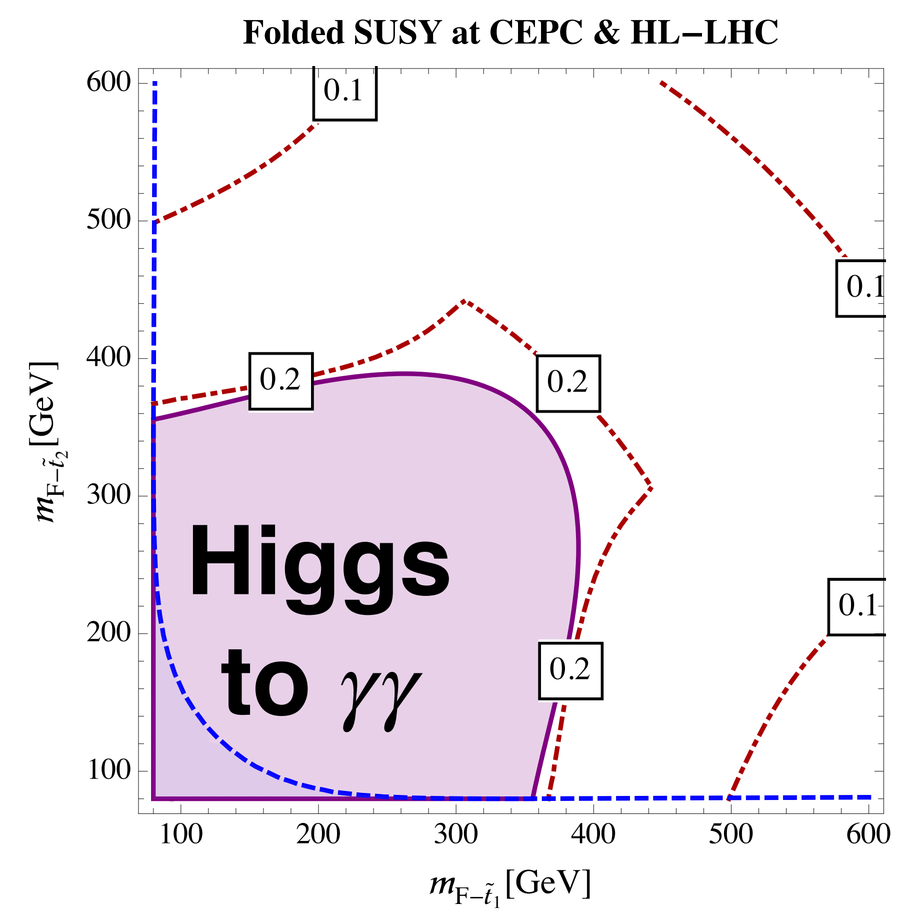
Folded SUSY

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!



Composite Higgs

(see Contino 1005.4269 for a review)

Tuning in Higgs VEV for a light Higgs. Specifically: for Higgs as a pseudo-Goldstone, expect a potential something like

$$V(h) \sim \frac{a\lambda^2}{16\pi^2}\cos(h/f) + \frac{b\lambda^2}{16\pi^2}\sin^2(h/f)$$

This has $v \sim f$ unless:

$$-2\cos(h/f) - (1+\epsilon)\sin^2(h/f) \Rightarrow \langle h\rangle^2 \approx 2\epsilon f^2$$

We tune $v << f$ by making $\epsilon << 1$.

(Exception: “little Higgs” with extended symmetry structure. Pay a big price in complexity.)

Composite Higgs

Constraints: *S*-parameter $S \approx \frac{4\pi v^2}{m_\rho^2}, \quad m_\rho^{(NDA)} \sim \frac{4\pi f}{\sqrt{N}}$

Higgs couplings: $a = \frac{g_{VVH}}{g_{VVh}^{\text{SM}}} = \sqrt{1 - \frac{v^2}{f^2}}$

Currently bounds from *S* and Higgs couplings translate to roughly

$$m_\rho \gtrsim 3 \text{ TeV}, \quad f \gtrsim \max(\sqrt{\frac{N}{3}} \times 400 \text{ GeV}, 550 \text{ GeV})$$

CEPC would bring the *ZZh* coupling measurement to the 0.2% level, probing *f* ~ 4 TeV and achieving **a factor of ~ 300 tuning in the Higgs VEV**

Higgs vs. EWPT

Whether the (S, T) fit or Higgs coupling measurements are more sensitive to new physics depends on the model. Two well-motivated examples:

Composite Higgs: probe scale *f* via ***ZH***, *S*-parameter
Left-handed stops: probe mass via *Hgg*, ***T*-parameter**

Experiment	κ_Z (68%)	f (GeV)	κ_g (68%)	$m_{\tilde{t}_L}$ (GeV)
HL-LHC	3%	1.0 TeV	4%	430 GeV
ILC500	0.3%	3.1 TeV	1.6%	690 GeV
ILC500-up	0.2%	3.9 TeV	0.9%	910 GeV
CEPC	0.2%	3.9 TeV	0.9%	910 GeV
TLEP	0.1%	5.5 TeV	0.6%	1.1 GeV

Experiment	S (68%)	f (GeV)	T (68%)	$m_{\tilde{t}_L}$ (GeV)
ILC	0.012	1.1 TeV	0.015	890 GeV
CEPC (opt.)	0.02	880 GeV	0.016	870 GeV
CEPC (imp.)	0.014	1.0 TeV	0.011	1.1 GeV
TLEP-Z	0.013	1.1 TeV	0.012	1.0 TeV
TLEP-t	0.009	1.3 TeV	0.006	1.5 TeV

(from 1411.1054 Fan, MR, Wang)