DISCOVERY POTENTIAL OF A HIGH-LUMINOSITY Z/W/H/T FACTORY

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Future Lepton Collider Physics

Future Circular Collider - ee (formerly known as TLEP) will be a precision measurement machine!

As a Higgs factory, the major goal is to measure the Higgs couplings precisely.

It could also do precision Z pole, W and top threshold physics.

There are other proposals of lepton colliders such as International Linear Collider, Compact Linear Collider and Circular Electron-Positron Collider.

The focus of the talk will be:
What could all these precision measurements tell us about what lies beyond the Standard Model?

Electroweak Precision Measurements

Systematic uncertainty dominates in most observables

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Key	Challenge
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6) keV	< 100 keV	$E_{\rm beam}$ calibration	QED corrections
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{\rm had}$)	2495200 ± 2300	Z Line shape scan	8 (10) keV	< 100 keV	$E_{\rm beam}$ calibration	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	Statistics	QED corrections
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004		Bhabha scat.
N_ν	... and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001	Statistics	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	Statistics, small IP	Hemisphere correlations
$A_{\rm LR}$	$\Delta\rho$, ϵ_3, $\Delta\alpha_{\rm had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	4 bunch scheme, 2exp	Design experiment
m_W (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{\rm had}$	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV	$E_{\rm beam}$, Statistics	QED corrections
$m_{\rm top}$ (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12) MeV	< 10 MeV	Statistics	Theory interpretation

A multi-parameter fit of m_{top}, Γ_{top}, y_{top} and α_s to top cross section, momentum distribution and forward-backward asymmetry

At Least a factor of 10 improvement in all measurements

TLEP "first look" report: 1308.6176; in parallel talks by Blekman and Antonelli

In addition, there are theory uncertainties with current values from two-loop calculations much larger than the future experimental uncertainties.

We need at least a complete three loop SM electroweak correction computation to fully explore the power of future precision measurements.

Indirect Observables

New physics could enter in loops to produce modifications of the Standard Model electroweak observables. One model independent way is to parametrize the modifications by high-dimensional operators such as

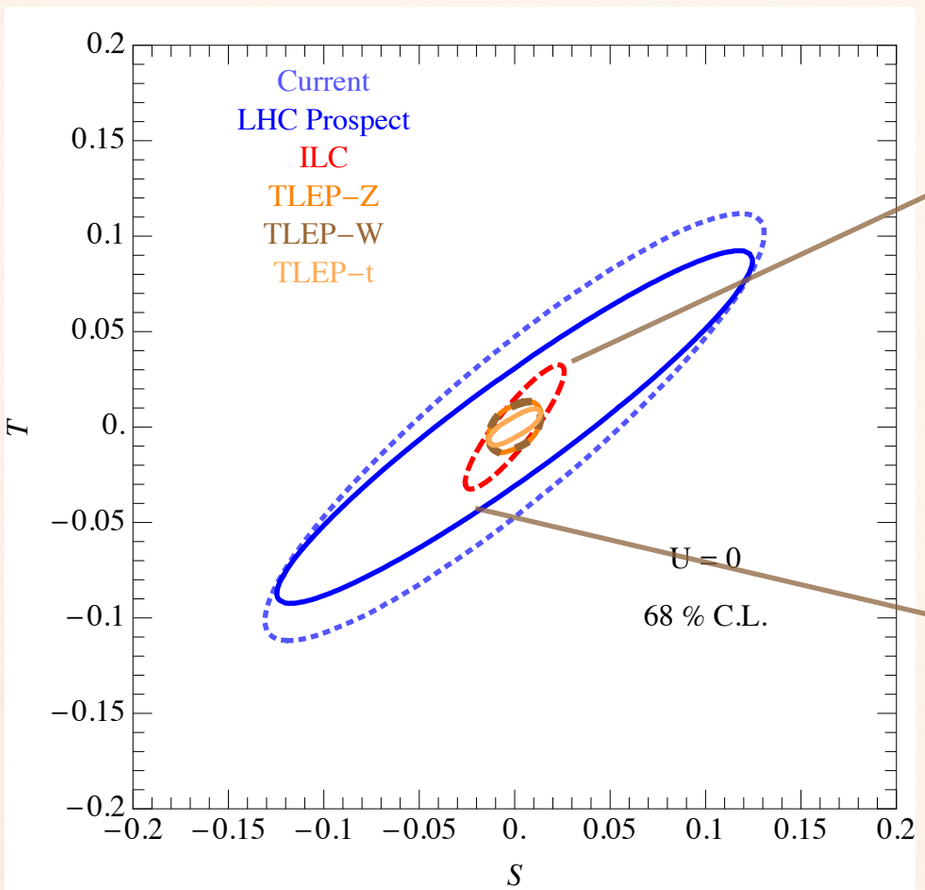
S parameter: $$S\left(\frac{\alpha}{4s_W c_W v^2}\right) h^\dagger \sigma^i h W^i_{\mu\nu} B^{\mu\nu}$$

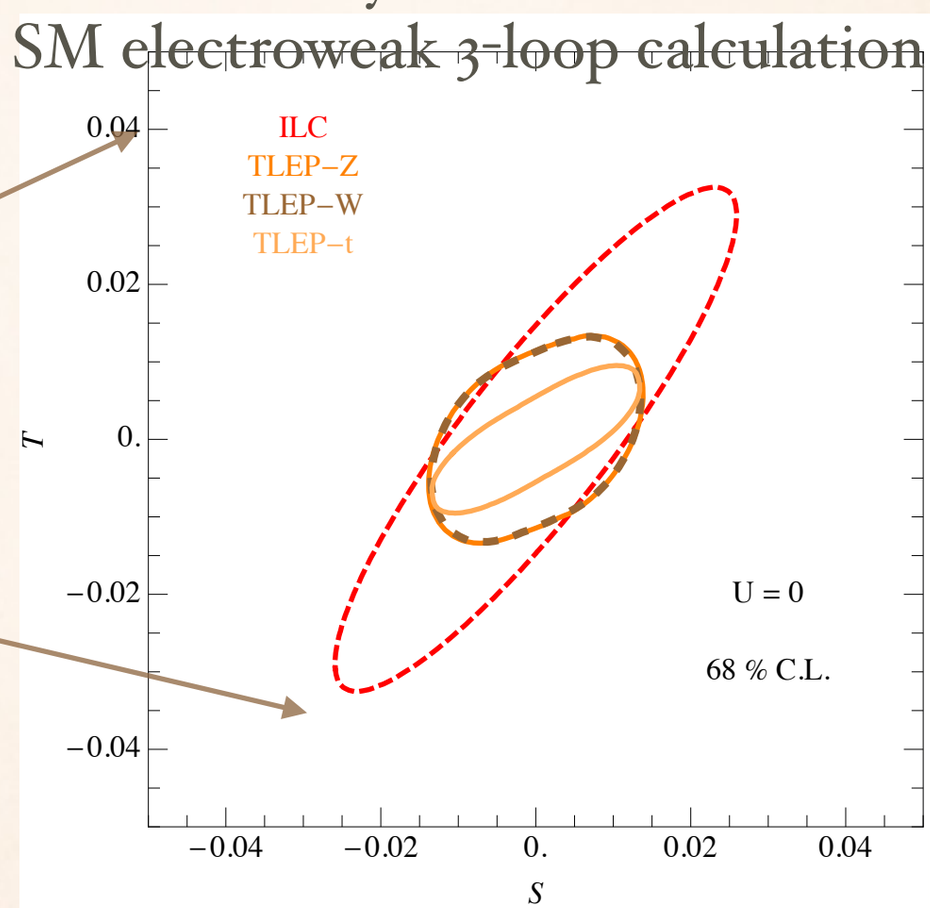
T parameter: $$-T\left(\frac{2\alpha}{v^2}\right) \left|h^\dagger D_\mu h\right|^2$$

Global Fit of Electroweak Observables with Oblique Corrections

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

assume theory uncertainties from a future SM electroweak 3-loop calculation





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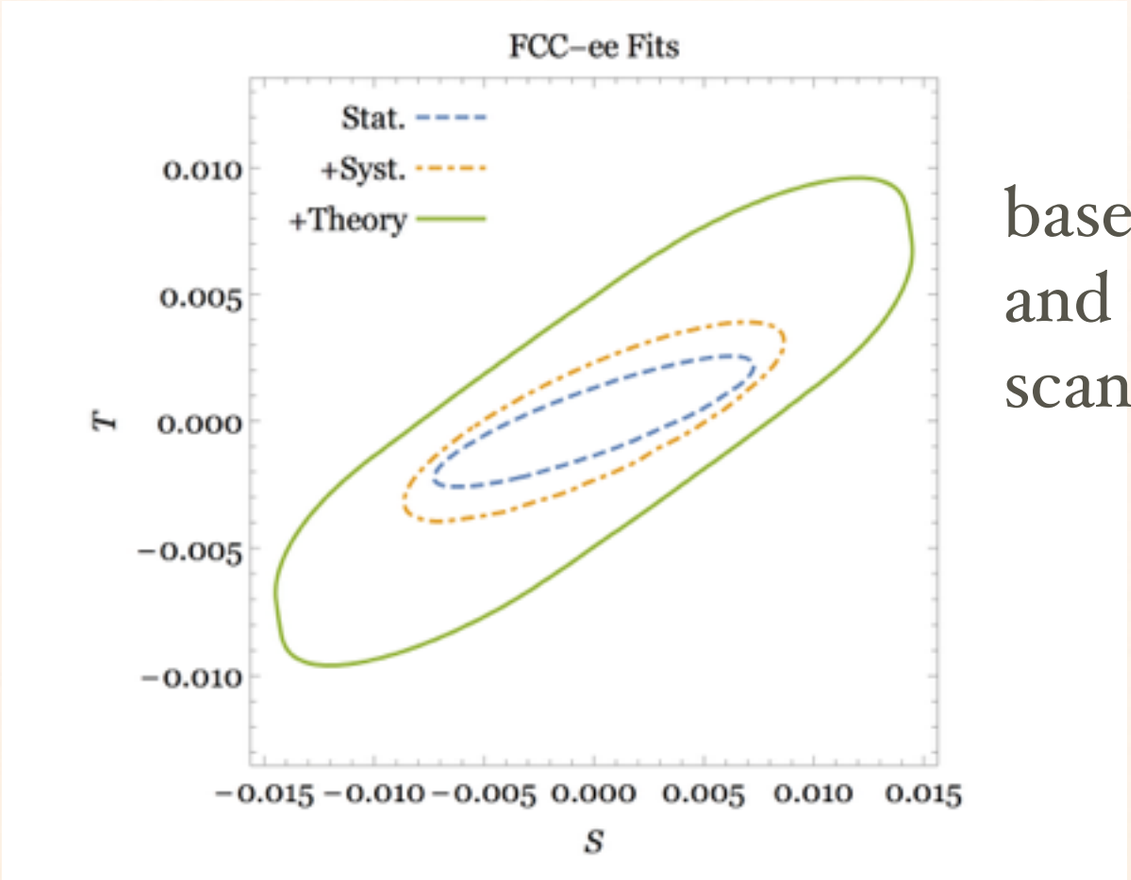
At FCC-ee, we could get a factor of 10 improvement in (S,T) sensitivities considering the theory uncertainties of a 3-loop calculation. If the theory uncertainty could be reduced further, we could get another factor of 2 improvement.

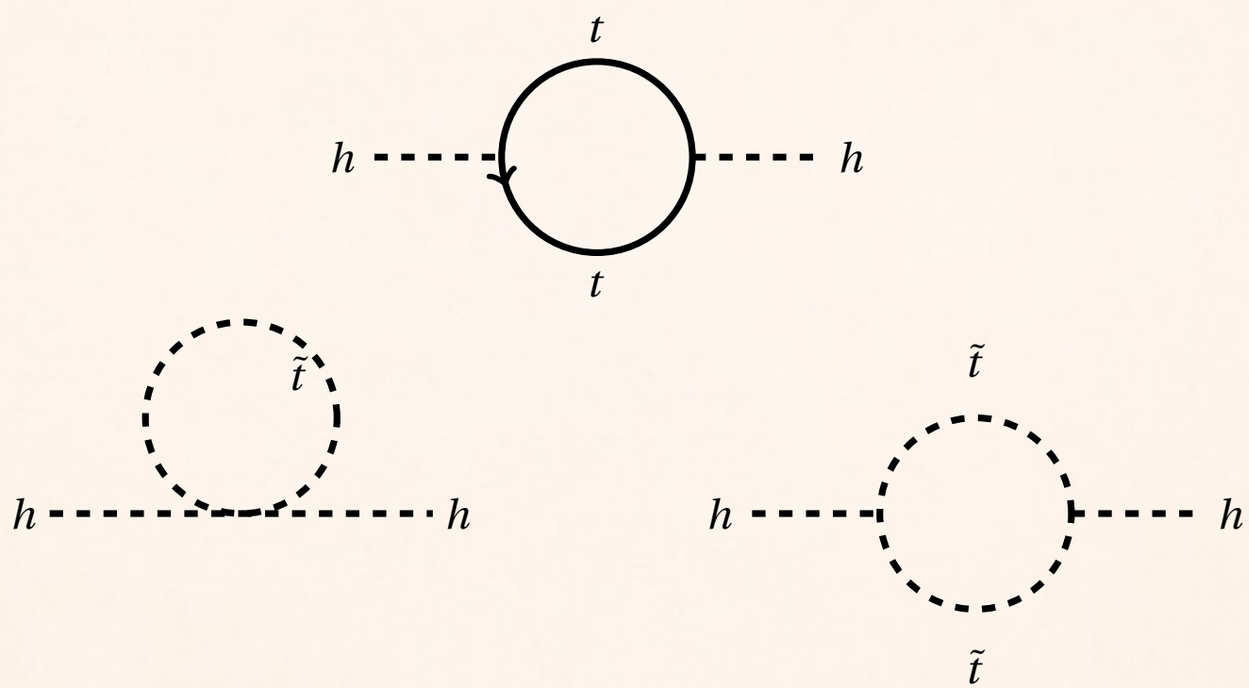


based on Z-pole and top threshold scan

Reece, proceeding of Hong Kong IAS high energy meeting 2016

Example what new physics could be relevant

Natural supersymmetry with light scalar tops at ~TeV



Different-spin pieces combine to cancel the large quantum correction to the Higgs potential and stabilize it.

At the LHC, stops with simple decay chains are strongly constrained already.

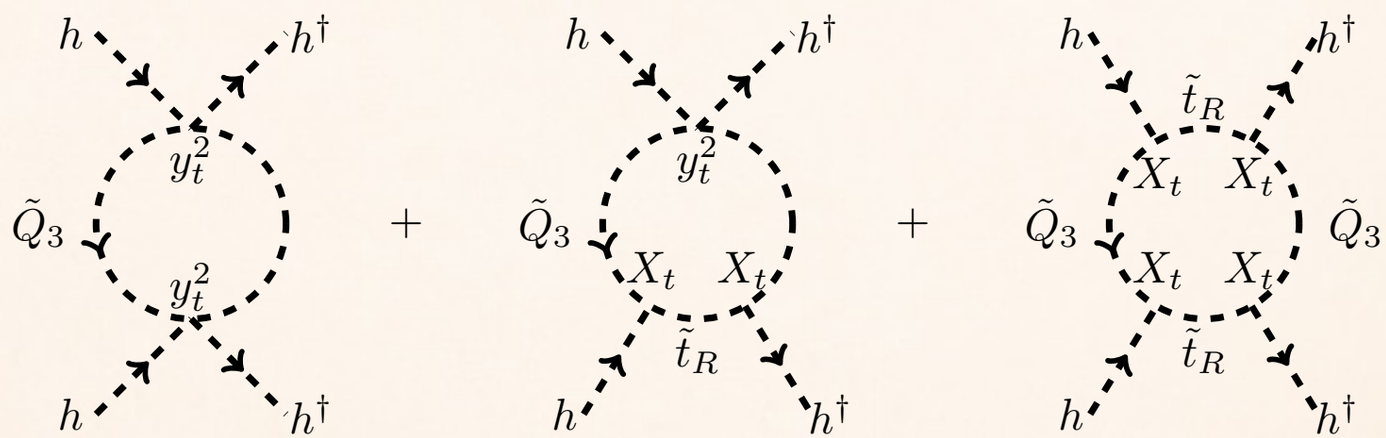
Yet they can be hidden at hadron collider due to some non-minimal decay modes and/or kinematics of the decay products (examples: R-parity violation, stealth SUSY, ...).

Or they could only carry electroweak charges but no colors (folded SUSY) and thus much weakly constrained.

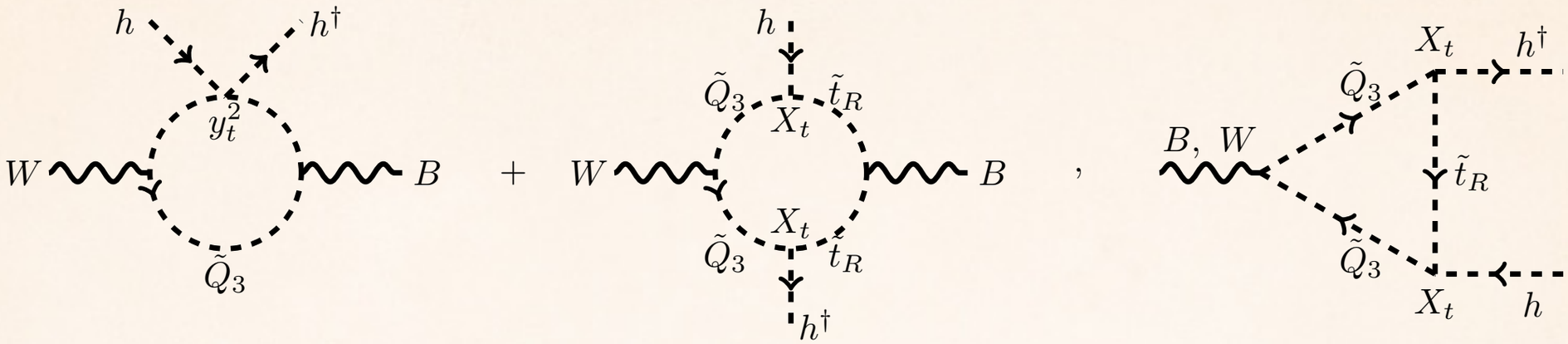
These loopholes could be filled in at future lepton colliders!

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

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

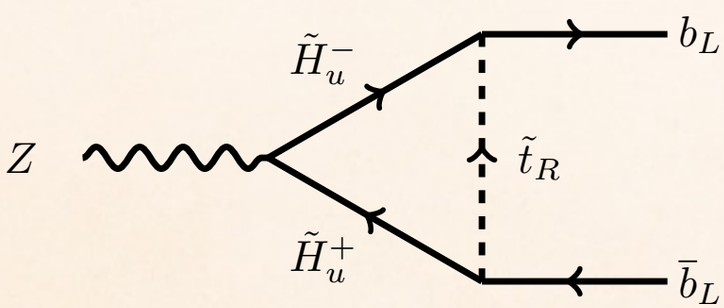


$$T \approx \frac{m_t^4}{16\pi \sin^2\theta_W m_W^2 m_{\tilde{Q}_3}^2} + \mathcal{O}\left(\frac{m_t^2 X_t^2}{4\pi m_{\tilde{Q}_3}^2 m_{\tilde{u}_3}^2}\right).$$

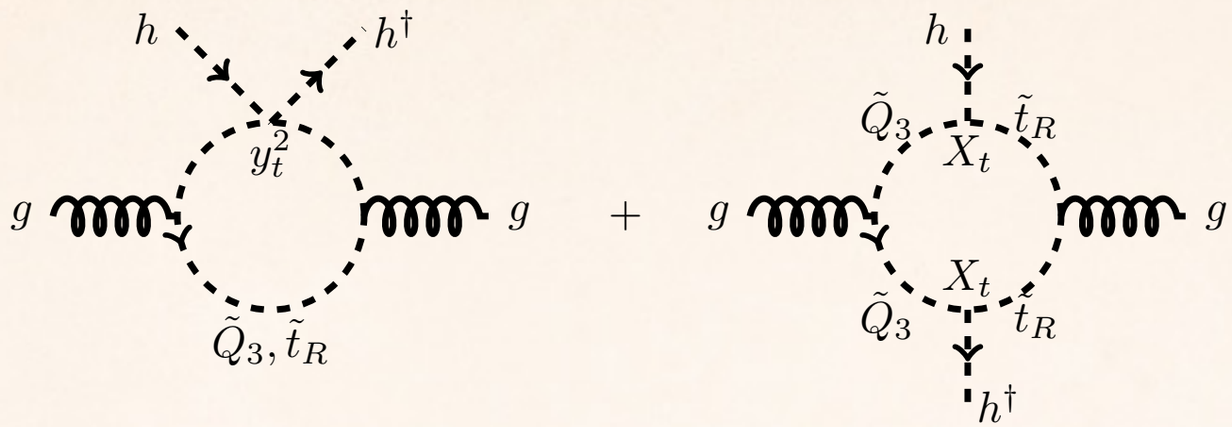


$$S \approx -\frac{1}{6\pi}\frac{m_t^2}{m_{\tilde{Q}_3}^2} + \mathcal{O}\left(\frac{m_t^2 X_t^2}{4\pi m_{\tilde{Q}_3}^2 m_{\tilde{u}_3}^2}\right).$$

Rb



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



$H^\dagger H G^2$

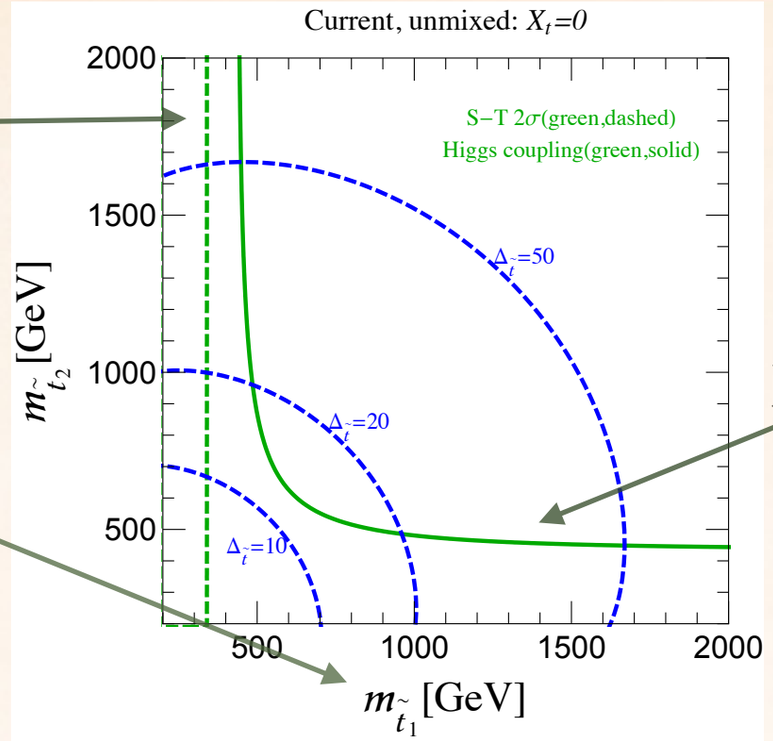
$$r_G^{\tilde{t}} \equiv \frac{c_{hgg}^{\tilde{t}}}{c_{hgg}^{\rm SM}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right),$$ stop contribution to hgg coupling

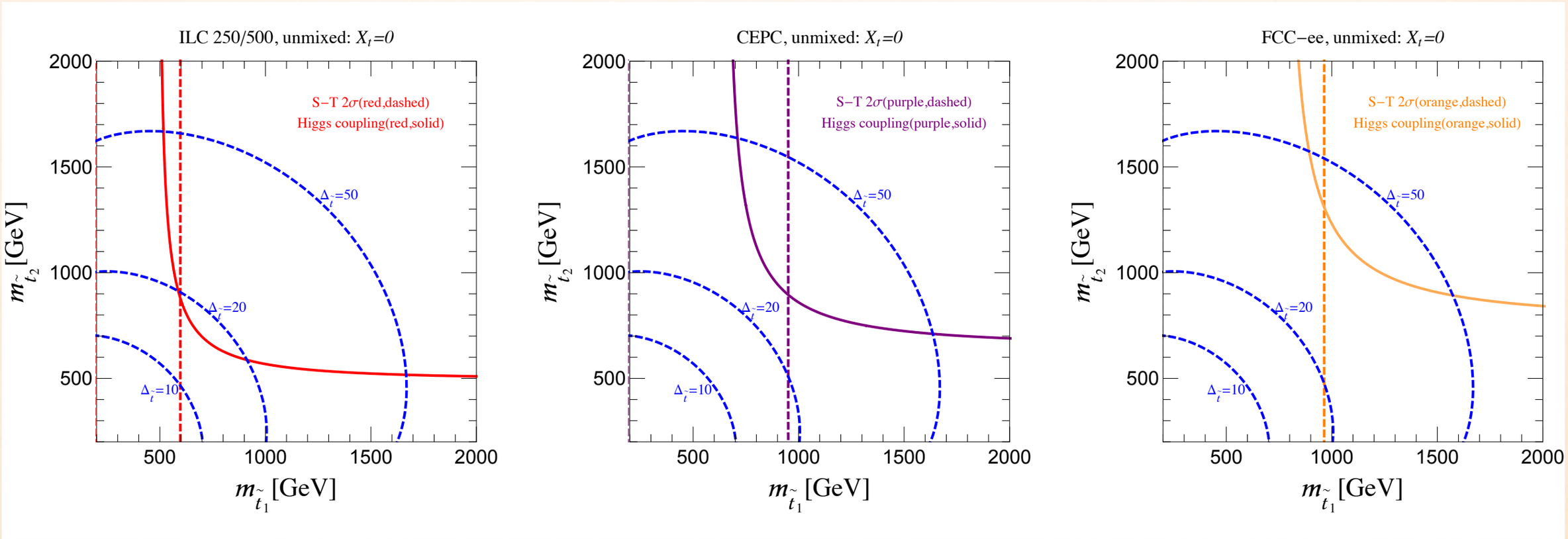
Other corrections to precision observables:
wavefunction renormalization of the Higgs boson
(Craig, Englert, McCullough 2013)
b to s gamma,
triple gauge coupling,
running of the gauge couplings (for hadron collider).
(Alves, Galloway, Ruderman, Walsh 2014)

T parameter

Physical stop masses

hgg coupling





Fan, Reece, Wang 1412.3107

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**. They will fill in the potential loopholes of the direct searches at hadron colliders!

Discovery Potential of Higgs Coupling Measurements

Use results of 7-parameter fit as a benchmark

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%
$BR_{\rm inv}$	0.19%	$< 0.19\%$

almost all couplings could be measured with percentage level precisions;

in particular, Zh coupling with 0.1% level precision.

snowmass Higgs report 1310.8361

Composite Higgs

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

Higgs coupling measurement is the most sensitive probe and probe the decay constant up to ~ 6 TeV

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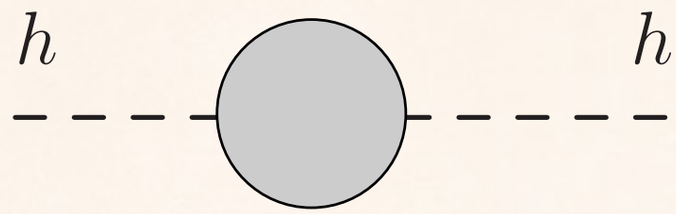
Higgs Wave function renormalization
Craig, Englert, McCullough 2013

$\delta Z_h, \delta m_h^2 \sim$ 

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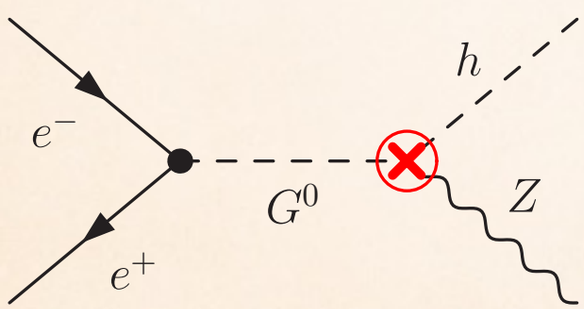
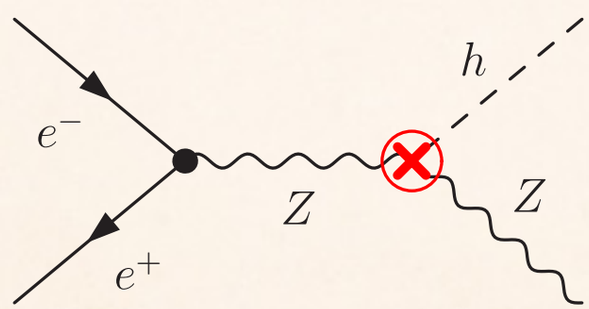
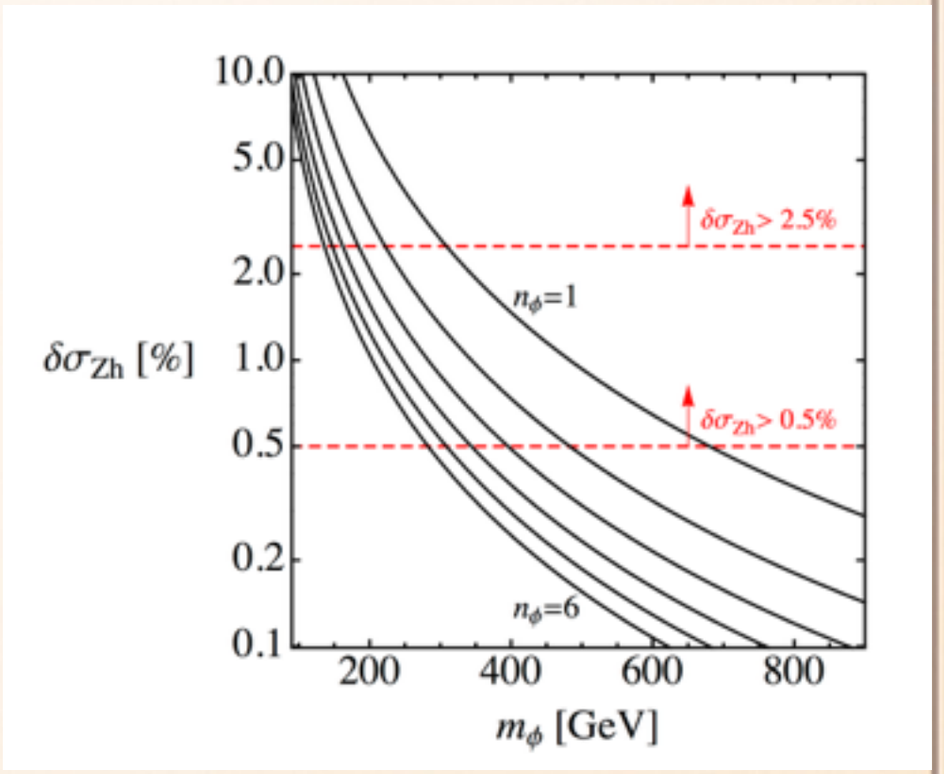
probe completely neutral top partner (e.g: twin Higgs)

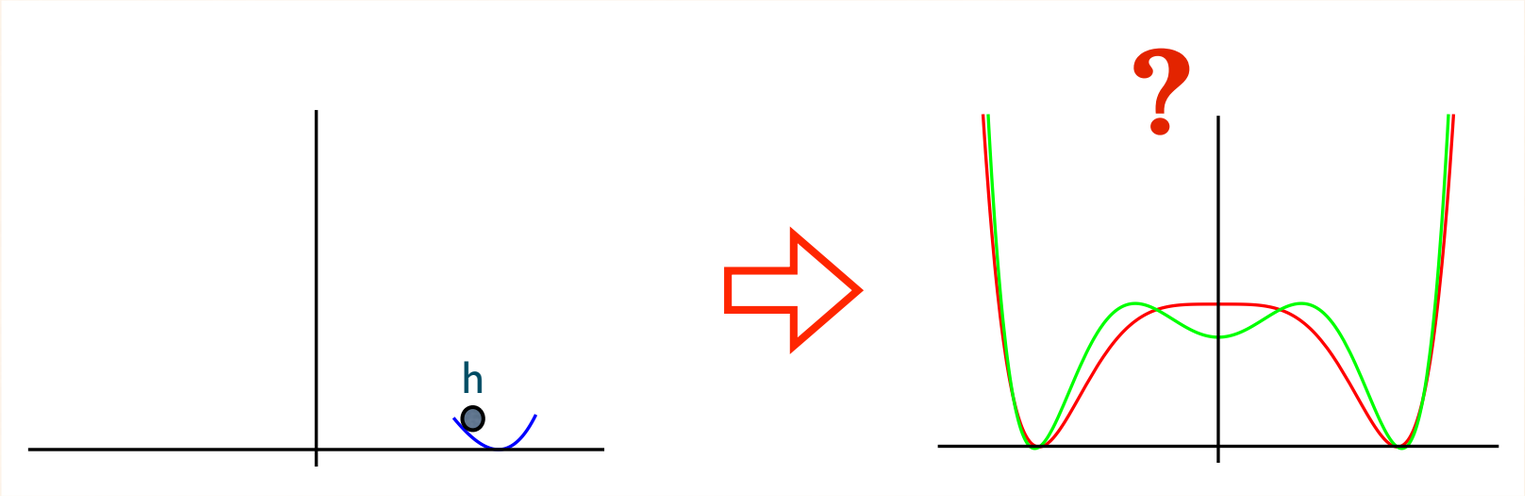
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_H}{m_\phi^2}\left(\frac{1}{2}\partial_\mu |H|^2 \partial^\mu |H|^2\right) + \ldots$$







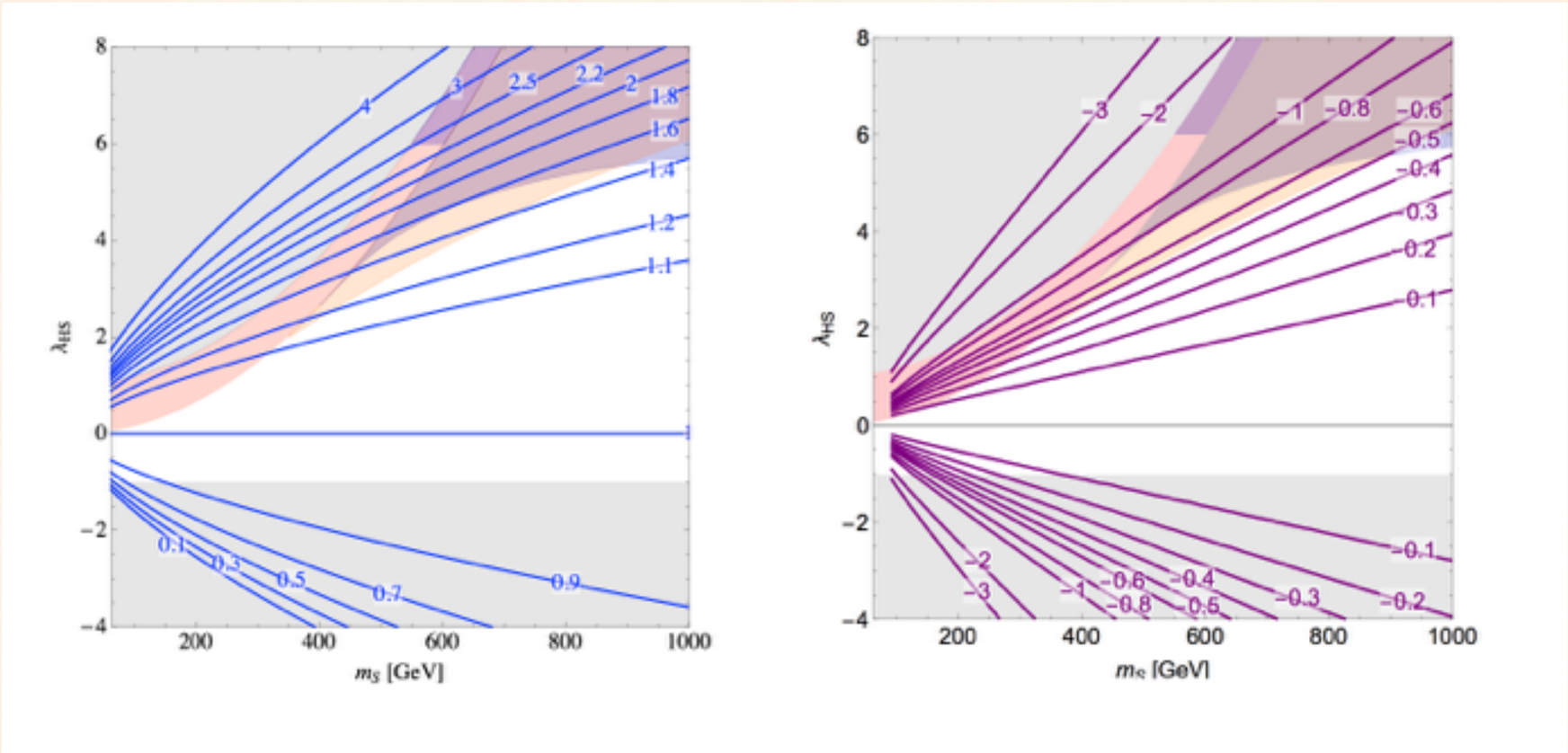
Other physics reach: Electroweak Phase Transition and Baryogenesis



If the Higgs potential allows for a first-order phase transition in the early Universe, that opens up the possibility of electroweak baryogenesis.

The simplest way to extend the Higgs sector and open up the possibility of a first-order phase transition is to add a singlet

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



contours: Higgs triple coupling (normalized by the SM value)

contours: Zh coupling (normalized by the SM value)

Curtin, Meade, Yu 2014

Complementarity between Precision Measurements and Direct Searches at Hadron Colliders

Observables at Current + Future Colliders	100 TeV	ILC/TLEP
producing extra higgs states (incl. superpartners)	✓	
Exotic Higgs Decays	✓	✓
Electroweak Precision Observables		✓
Higgs coupling measurements	✓	✓
Higgs portal direct production of new states	✓	
Higgs self coupling measurements	✓	✓
Zh cross section measurements		✓

Curtin's talk at FCC-week 2015

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 (naturalness, electroweak baryogengesis) at or above TeV scale.

- More studies need to be done to fully explore the power of precision measurements at future colliders!

Thank you !