Many aspects are mentioned at different levels from the talks today, like Higgs from Jin and Kaili, the EFT fits from Zhijun, Cen and Jiayin, the BSM fits from Shufang and Yongcheng. I will give this topic in my own setup and simplification.

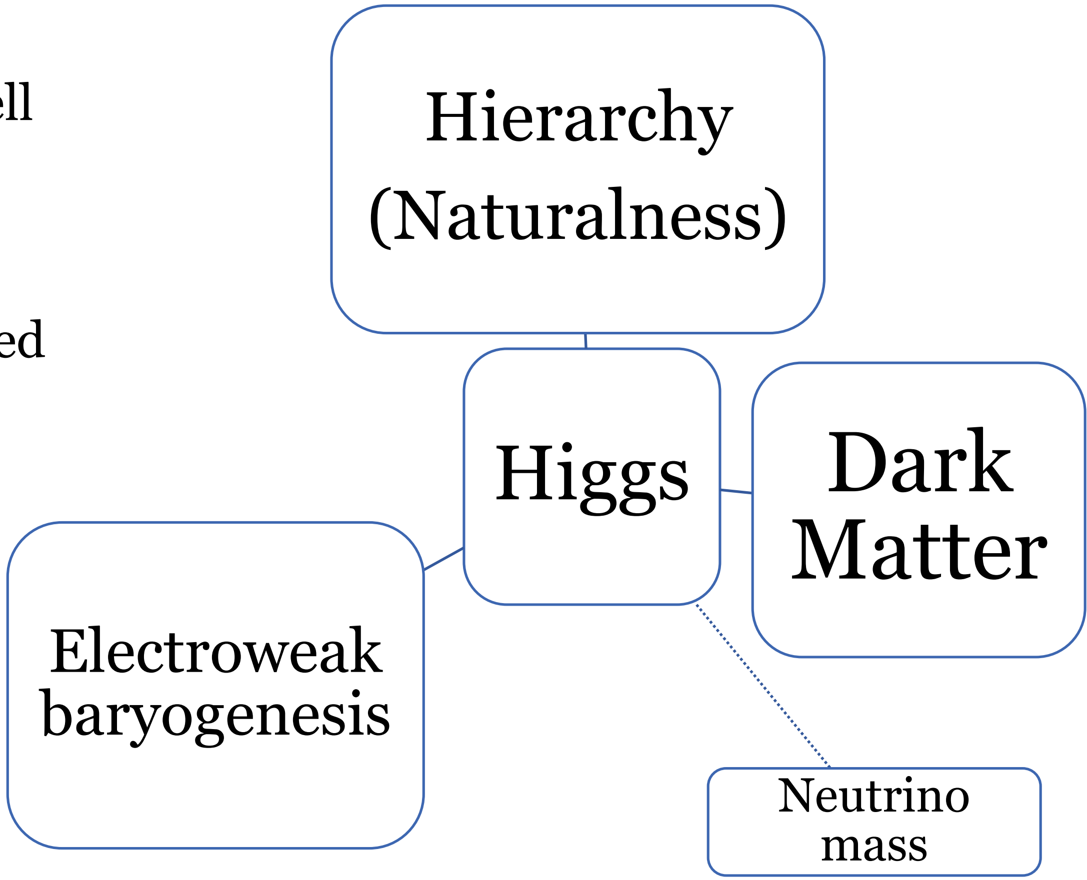
Higgs–Top couplings

Zhen Liu
University of Maryland
12/17/2019

Mainly based upon my work with Lian-Tao Wang and Ian Low;
My talk 1/12/2018 at HKIAS and 11/06/2017 at IHEP

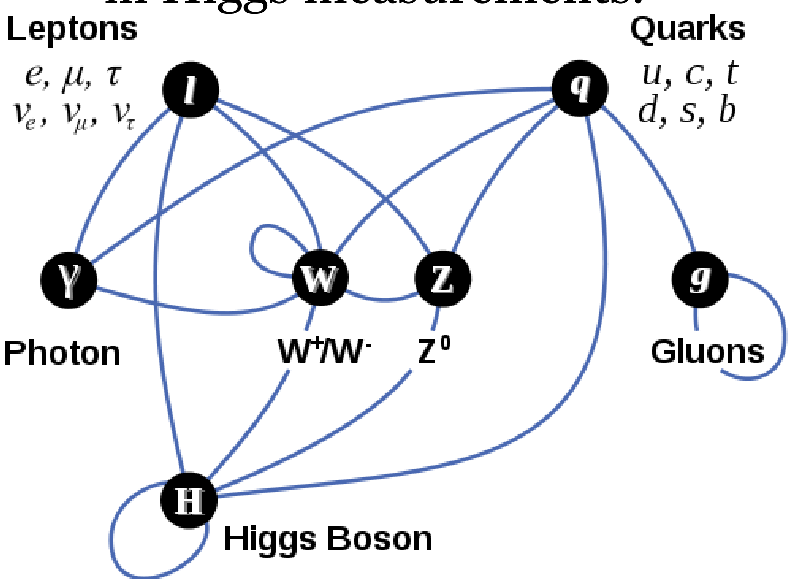
Key to many Puzzles

Top quark plays special roles in Higgs physics



Higgs boson discovery substantiates (more) many big questions in nature. It could well be the key to unlock some of nature's secrets.

All connections could be revealed in Higgs measurements.



Top quark and Higgs EFT Overview

Top-quark and Higgs couplings are the key driver of the hierarchy problem (and subsequent naturalness problem). Solutions to such problem are likely to induce corrections to these couplings.

Important to consider the CEPC sensitivity to Higgs and top EFT, even though the operational energy is below ttbar+Higgs threshold.

Top quark and Higgs EFT Overview

$$\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R),$$

$$\mathcal{O}_{bH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L H b_R),$$

$$\mathcal{O}_{Hq}^{(1)} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L),$$

$$\mathcal{O}_{Hq}^{(3)} = \frac{i}{\Lambda^2}(H^\dagger \tau^I \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu \tau^I q_L)$$

$$\mathcal{O}_{Ht} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R),$$

$$\mathcal{O}_{Hb} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{b}_R \gamma^\mu b_R),$$

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Here we choose a (minimal-)complete set of relevant operators, can be obtain by integrating out heavy particles and EOM.
J. Aguilar-Saavedra, arXiv:0811.3842, arXiv:0904.2387

C. Degrande, J. Gerard, C. Grojean, F. Maltoni, and G. Servant arXiv:1205.1065, B. A. Kniehl and O. L. Veretin arXiv:1206.7110, A. Hayreter and G. Valencia arXiv:1304.6976

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Top-quark and Higgs couplings are the key driver of the hierarchy problem (and subsequent naturalness problem). Solutions to such problem are likely to induce corrections to these couplings.

Important to consider the CEPC sensitivity to Higgs and top EFT, even though the operational energy is far below ttbar+Higgs threshold.

I will go through the physics probes for these operators individually and by groups

Here we choose a (minimal-)complete set of relevant operators, can be obtain by integrating out heavy particles and EOM.
J. Aguilar-Saavedra, arXiv:0811.3842, arXiv:0904.2387

C. Degrande, J. Gerard, C. Grojean, F. Maltoni, and G. Servant arXiv:1205.1065, B. A. Kniehl and O. L. Veretin arXiv:1206.7110, A. Hayreter and G. Valencia arXiv:1304.6976

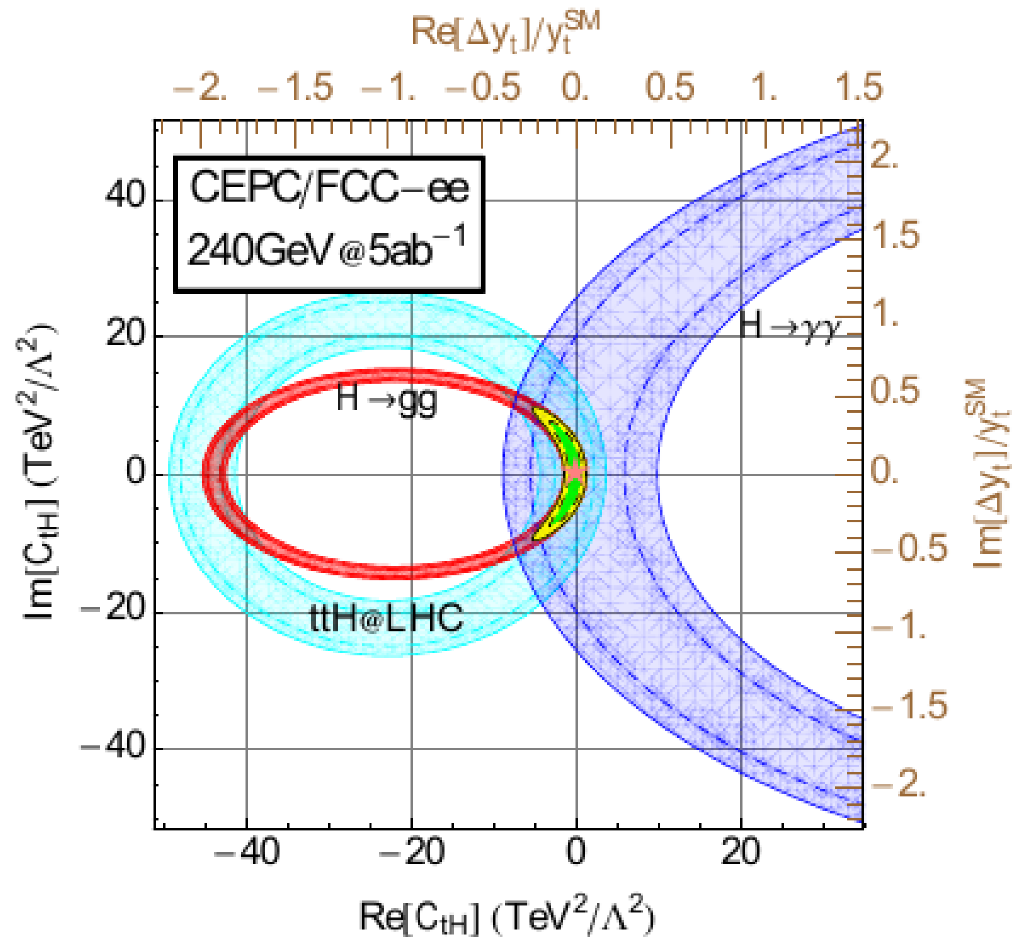
Top quark and Higgs EFT O_{tH}

$$\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R),$$

CP-even and CP-odd type of Yukawas, asymmetries too tiny below ttbar threshold.

Sensitivity from loop process. Gluon-gluon and diphoton drives the limits, though the precision of corresponding coupling is worse than κ_Z measurement.

Better than HL-LHC tth direct production.



Assuming no new HGG and HFF operators;
In cases where HGG and HFF are of the same order, e.g., top partners with mixing, a correlation presents and the constraints on new physics scales are generically still be the same order

$$\Delta y_t \approx \mathrm{Re}[C_{tH}]\frac{v^2}{\Lambda^2} + i\,\mathrm{Im}[C_{tH}]\frac{v^2}{\Lambda^2} + \mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$$

Top quark and Higgs EFT O_{bH}

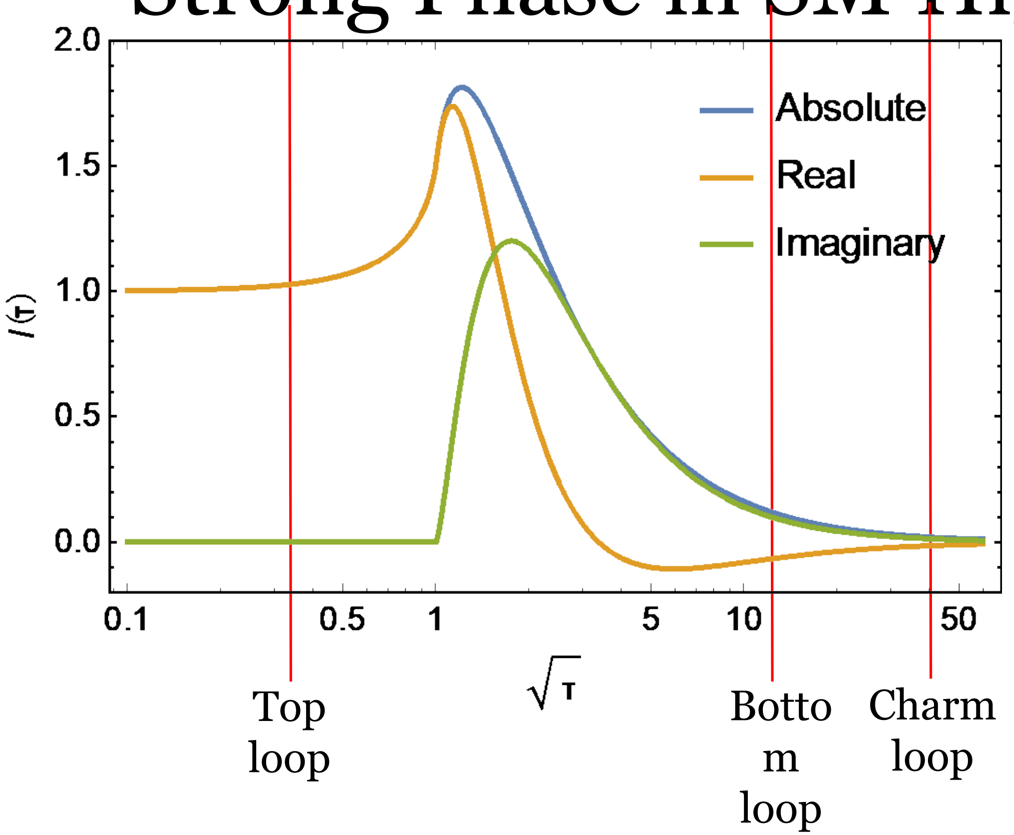
$$\mathcal{O}_{bH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L H b_R),$$

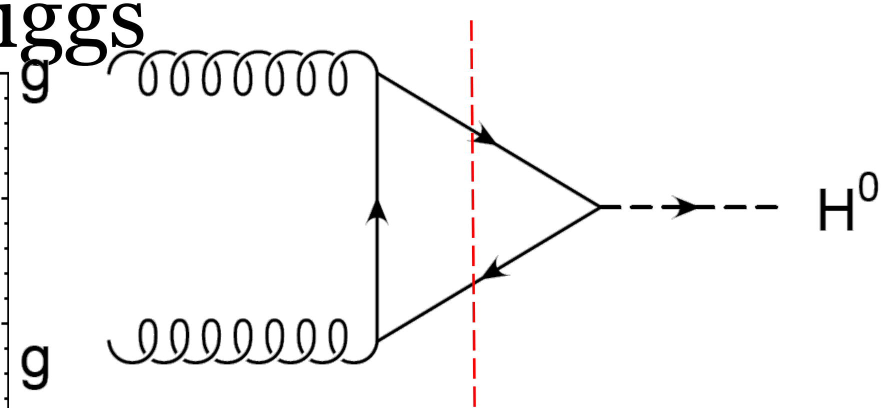
Direct constraints from $H \rightarrow \bar{b}b$ precision.

CEPC projection of 1.5% on bottom Yukawa~9 TeV on Λ

But that is not all the story.

Strong Phase in SM Higgs





- All quark contributions normalized the same way, the plot represents the relative contributions
- Numerically:
  - t-loop $+1.034$
  - b-loop $-0.035 + 0.039i$
  - c-loop $-0.004 + 0.002i$

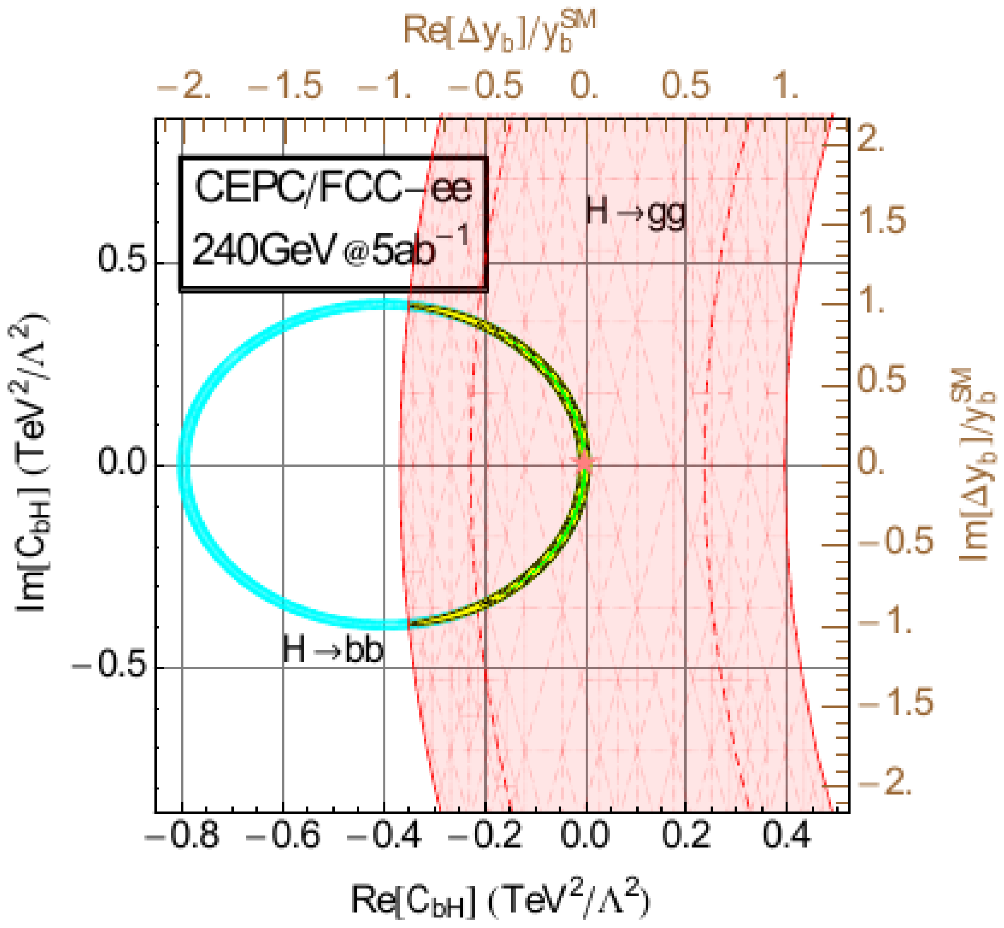
A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part)

Top quark and Higgs EFT O_{bH}

$$\mathcal{O}_{bH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L H b_R),$$

Direct constraints from $H \to \bar{b}b$ precision.

Sensitivity to CP-phase phase through interference with top loop for the gluon-gluon-Higgs coupling.



Joint Analysis
O_{bH} and O_{tH}

Key measurements (CEPC):
Higgs to diphoton
Higgs to digluon
Higgs to bb
(ttH@LHC)

Four d.o.f., bottom and top Yukawa:
Strengths (x-axes) and phases (y-axes)

Joint Analysis O_{bH} and O_{tH}

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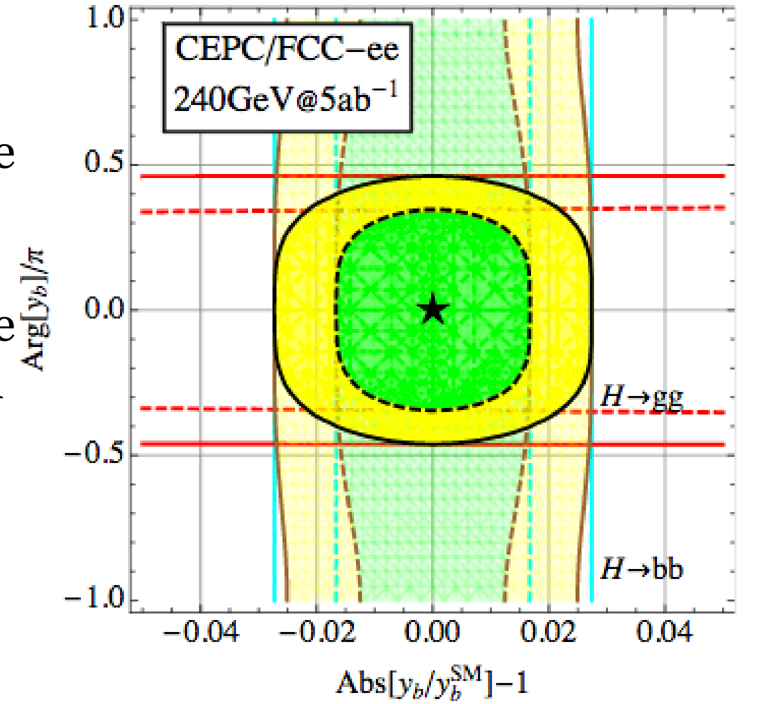
Four d.o.f., bottom and top Yukawa:
Strengths (x-axes) and phases (y-axes)

Bottom Yukawa:

- H to bb constraints the strength
- H to digluon constraints the phase through interference



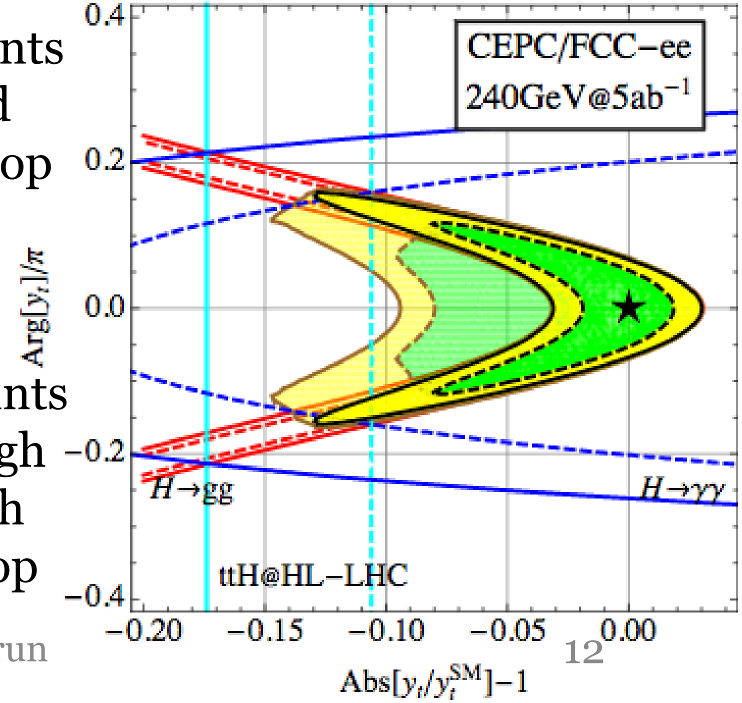
Joint Analysis O_{bH} and O_{tH}

Key measurements (CEPC):
Higgs to diphoton
Higgs to digluon
Higgs to bb
(ttH@LHC)

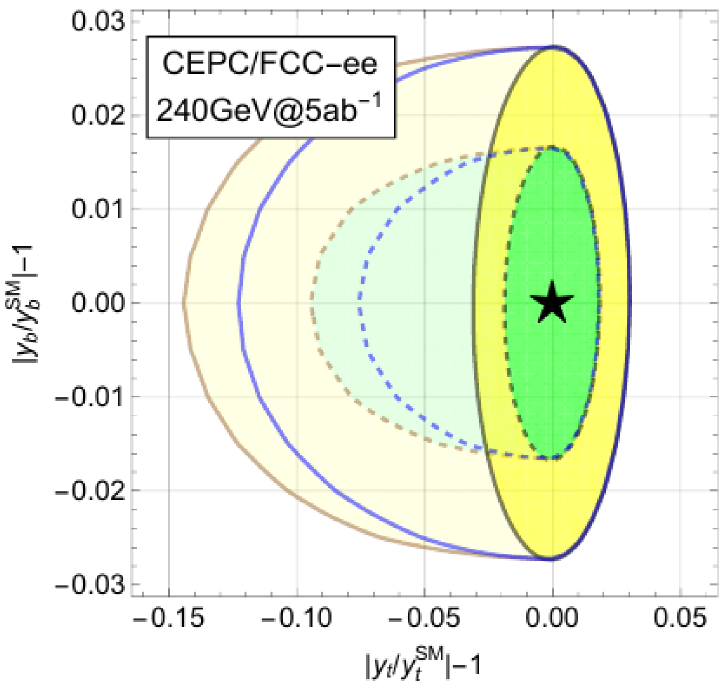
Four d.o.f., bottom and top Yukawa:
Strengths (x-axes) and phases (y-axes)

Top Yukawa:

- H to gg constraints the strength and phase (due to loop function differences)
- H to gamma gamma constraints the phase through interference with dominant W-loop



Joint Analysis O_{bH} and O_{tH}



Bottom Yukawa and top Yukawa:
Black: no CP violation;
Essentially independent determination of top and bottom Yukawa from H->gg and H->bb process;

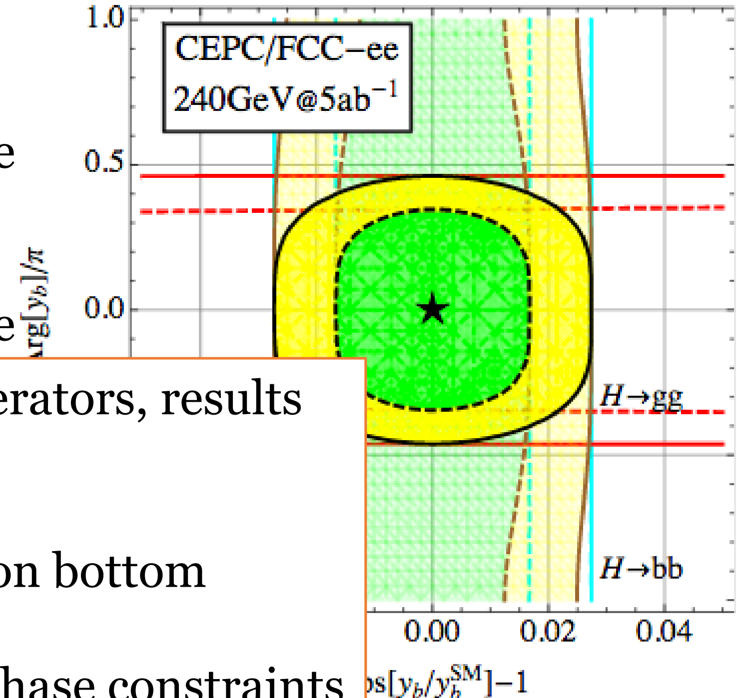
Blue: common CP phase for top and bottom Yukawa;
Having top CP phase allows for a same H->gg a smaller top Yukawa due to loop function differences and less destructive interference between top-loop and W-loop.

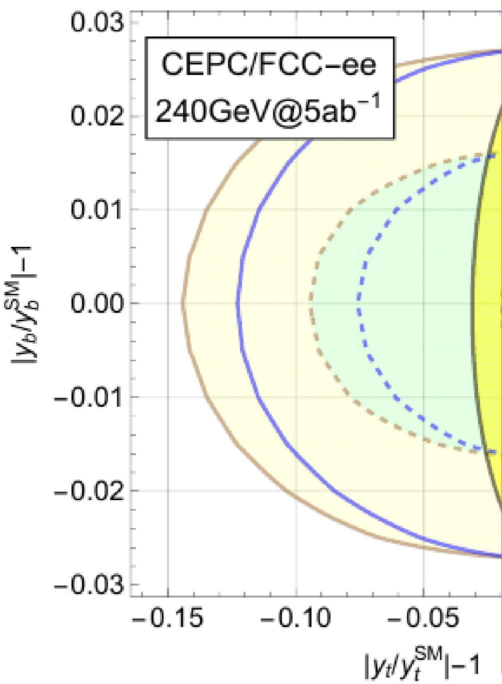
Brown: general CP phase
Allows one to turn destructive interference between top and bottom for H->gg process to constructive. Allows for lower top Yukawa.

Joint Analysis O_{bH} and O_{tH}

Bottom Yukawa:

- H to bb constraints the strength
- H to digluon constraints the

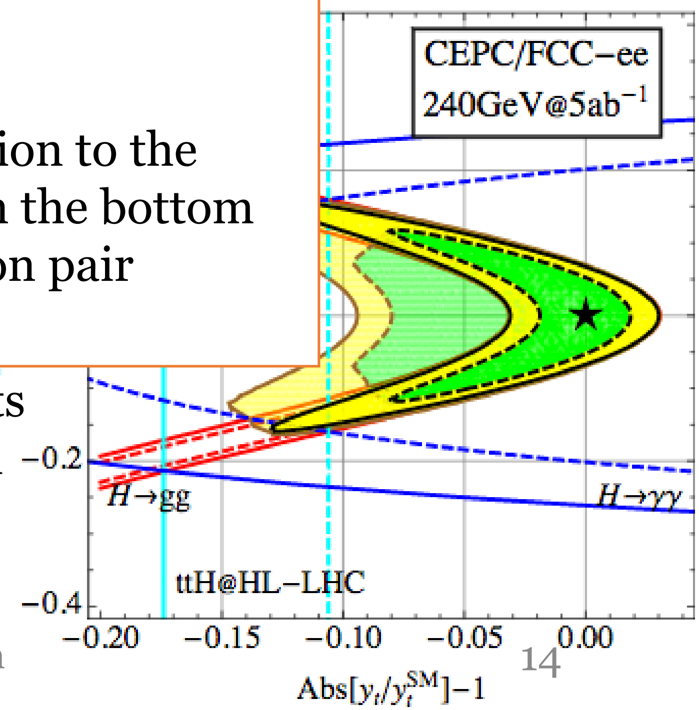




Joint analysis of these two operators, results in faint shaded regions:

Relaxing the phase constrain on bottom Yukawa;
Relaxing the magnitude and phase constraints on top Yukawa.

These are through the modification to the destructive interference between the bottom and top loop to the Higgs to gluon pair couplings.



gamma constraints the phase through interference with dominant W-loop

Top quark and Higgs EFT

$$O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Ht}, O_{Hb}$$

$$\mathcal{O}_{Hq}^{(1)} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L),$$

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$q_L = (t_L, b_L)$, $H^\dagger \overleftrightarrow{D}_\mu H = H^\dagger (D_\mu H) - (D_\mu H)^\dagger H$, and $\tilde{H} = i\sigma^2 H$.

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$$\mathcal{O}_{Hb} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{b}_R \gamma^\mu b_R),$$

Three-point functions only qqV

$$Z_\mu \bar{b}_R \gamma^\mu b_R : \quad -g_Z \frac{v^2}{2\Lambda^2} C_{Hb}^{(1)}$$

$$Z_\mu \bar{b}_L \gamma^\mu b_L : \quad -g_Z \frac{v^2}{2\Lambda^2} (C_{Hq}^{(1)} + C_{Hq}^{(3)})$$

$$Z_\mu \bar{t}_R \gamma^\mu t_R : \quad -g_Z \frac{v^2}{2\Lambda^2} C_{Ht}^{(1)}$$

$$Z_\mu \bar{t}_L \gamma^\mu t_L : \quad -g_Z \frac{v^2}{2\Lambda^2} (C_{Hq}^{(1)} - C_{Hq}^{(3)})$$

$$W_\mu^+ \bar{t}_L \gamma^\mu b_L : \quad g_2 \frac{v^2}{\sqrt{2}\Lambda^2} C_{Hq}^{(3)},$$

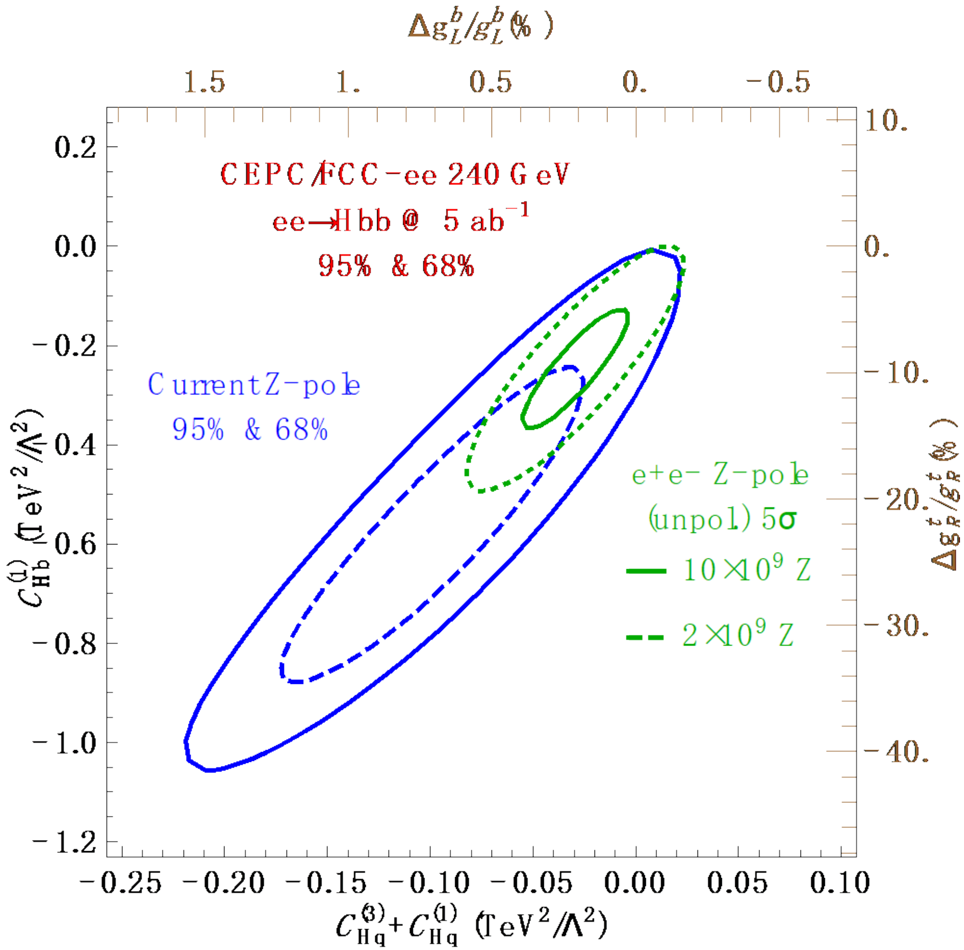
Higgs modification starting at the four-point function qqVH

*little impact on the Higgs coupling precision fits at tree-level (since most Higgs decay are two-body)

**No photon, only Z and W

$q_L = (t_L, b_L)$, $H^\dagger \overleftrightarrow{D}_\mu H = H^\dagger (D_\mu H) - (D_\mu H)^\dagger H$, and $\tilde{H} = i\sigma^2 H$.

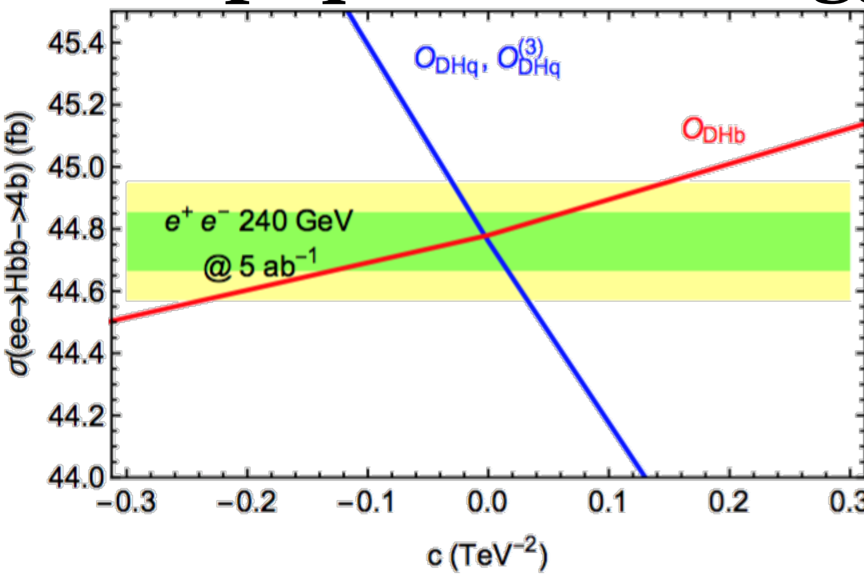
Top quark and Higgs EFT $O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Hb}$



Z-pole provides very high precision on these coupling.

Z-pole result from S. Gori, J. Gu, and L.-T. Wang 1508.07010

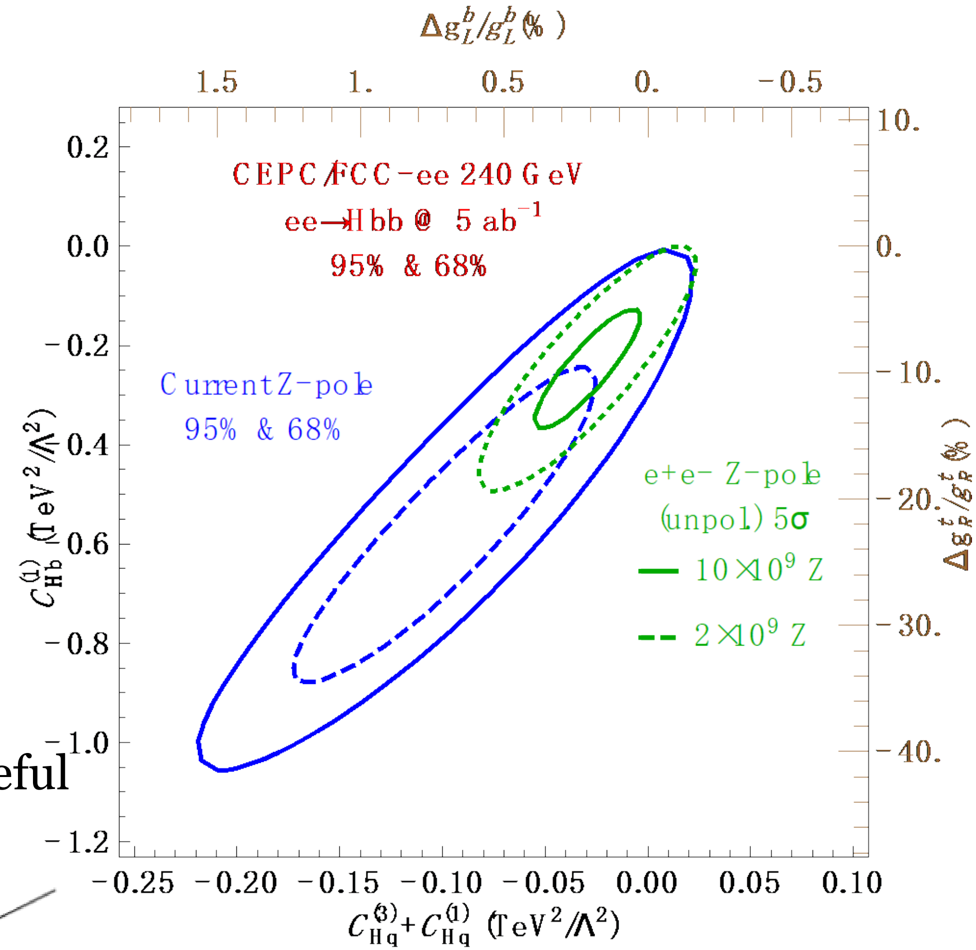
Top quark and Higgs EFT $O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Hb}$

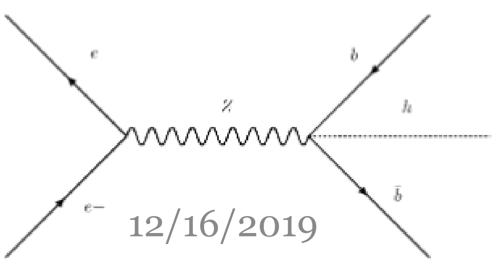


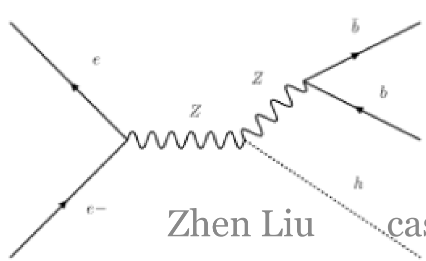
HVbb vertex

$$ee \to Z^* \to b\bar{b}h$$
$$h \to Zbb$$

Exotic production might provide us useful information about these operators.







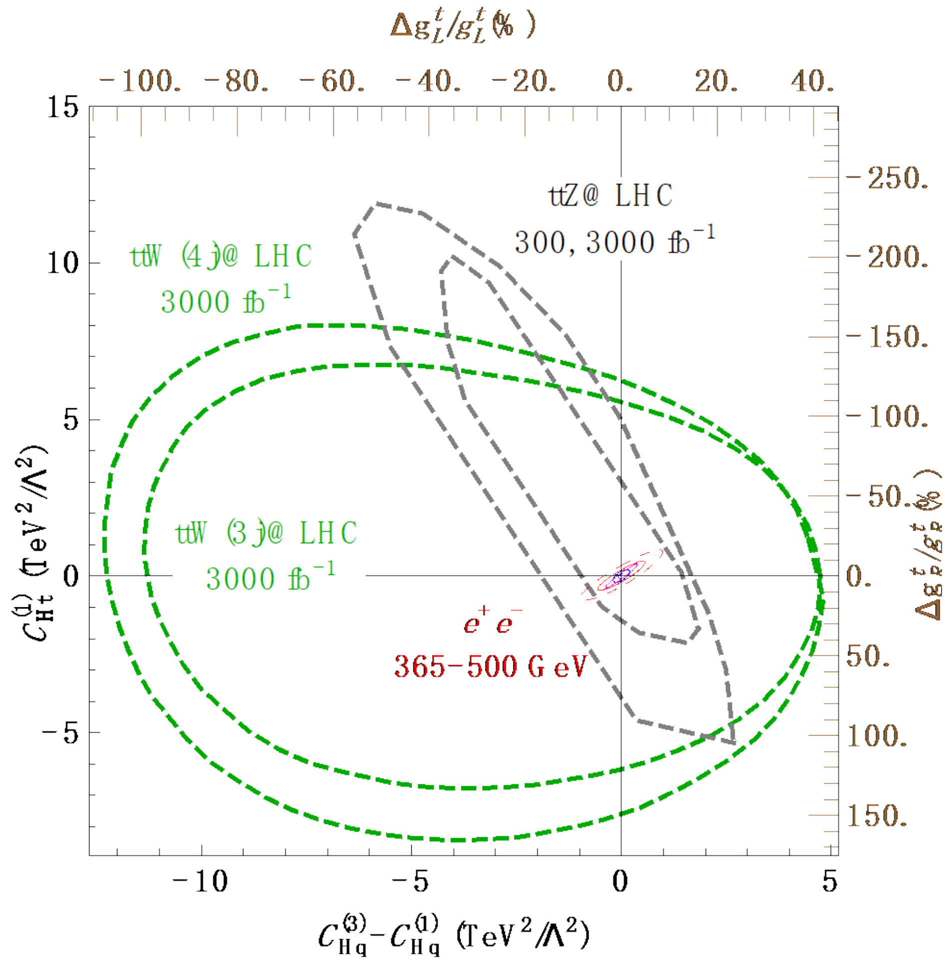
Z-pole provides very high precision on these coupling.

Z-pole result from S. Gori, J. Gu, and L.-T. Wang 1508.070

Top quark and Higgs EFT $O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Ht}$

LHC-DY-ttbar is buried under the QCD ttbar production

Need ttZ, ttW final states



R. Rontsch and M. Schulze, 1404.1005 , J. Dror, M. Farina, E. Salvioni, J. Serra, 1511.03674

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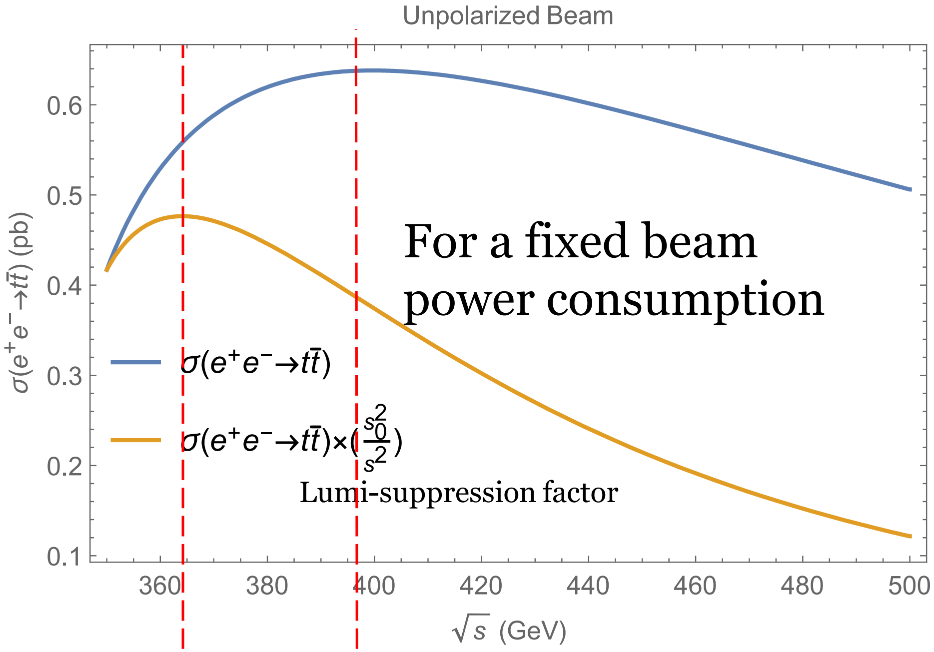
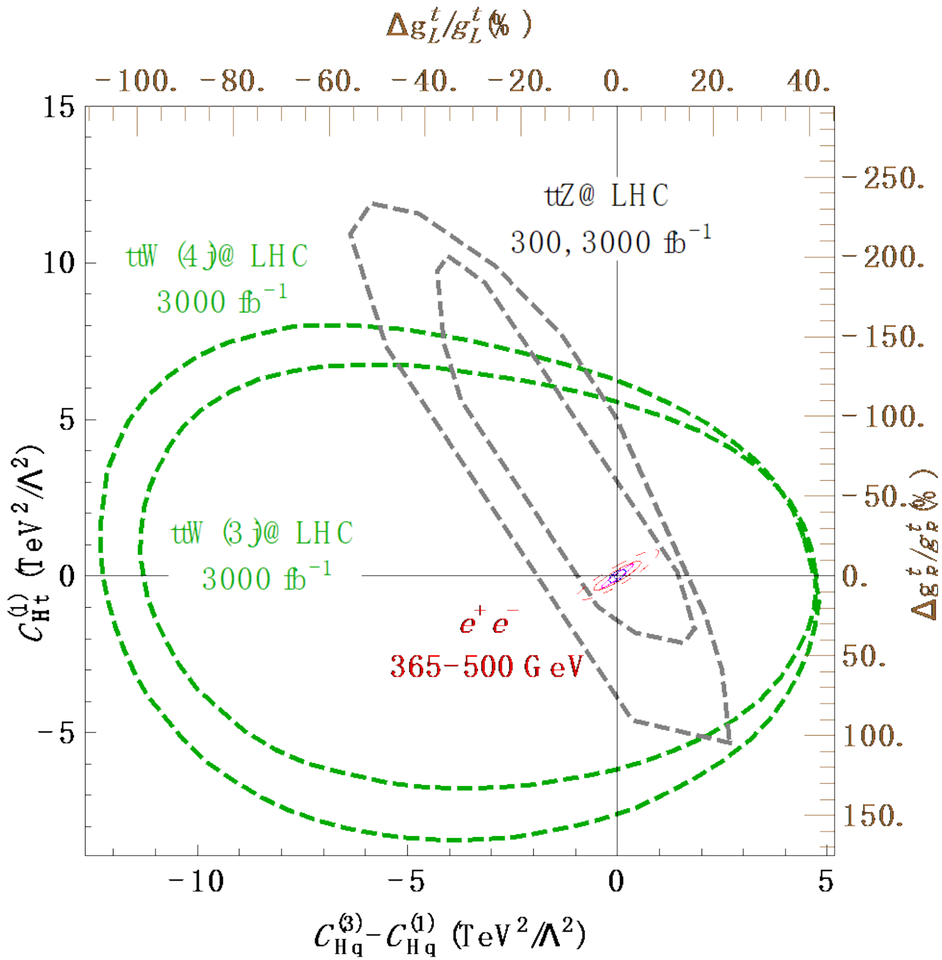
LHC-DY-ttbar is buried under the QCD ttbar production

Why 365 GeV?





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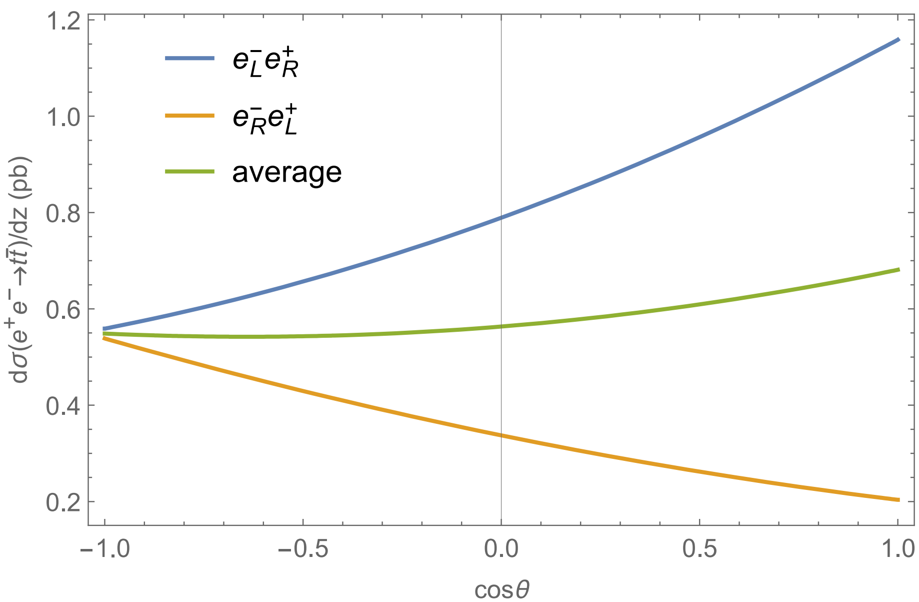
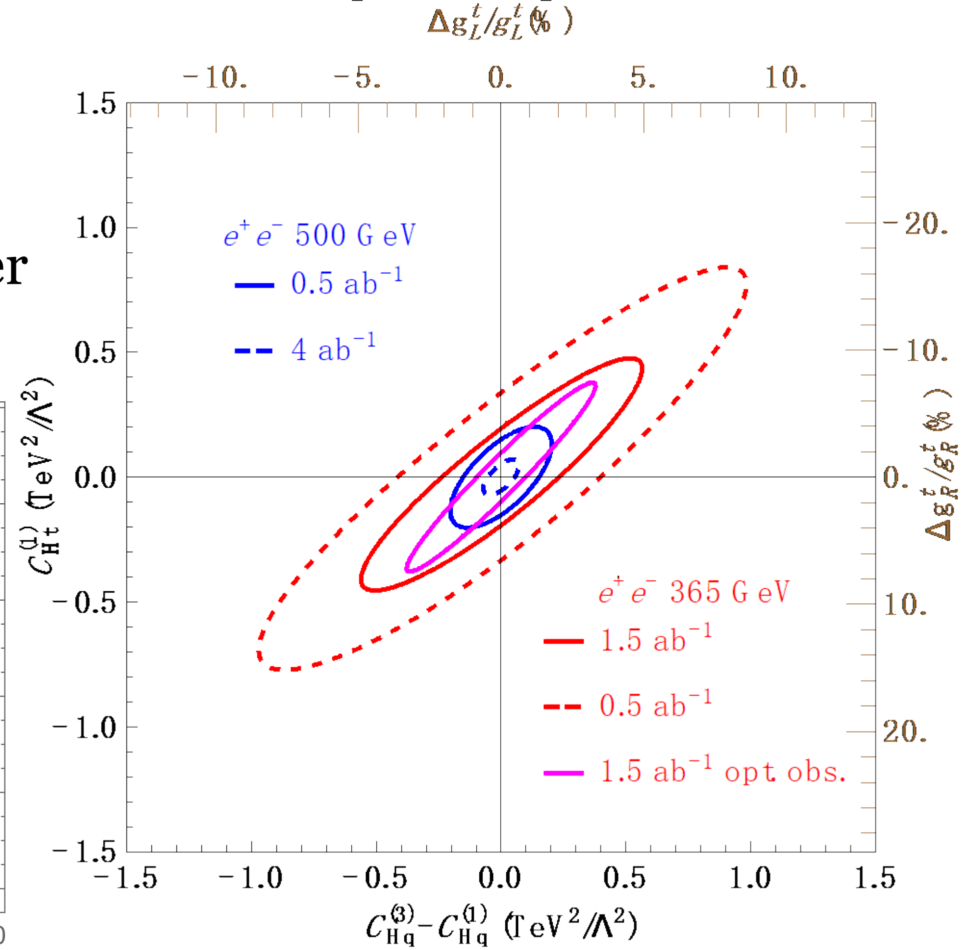
Top quark and Higgs EFT $O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Ht}$

Cross section and forward-backward asymmetry

ILC 0.5 ab^{-1} with polarization better than 1.5 ab^{-1} unpolarized





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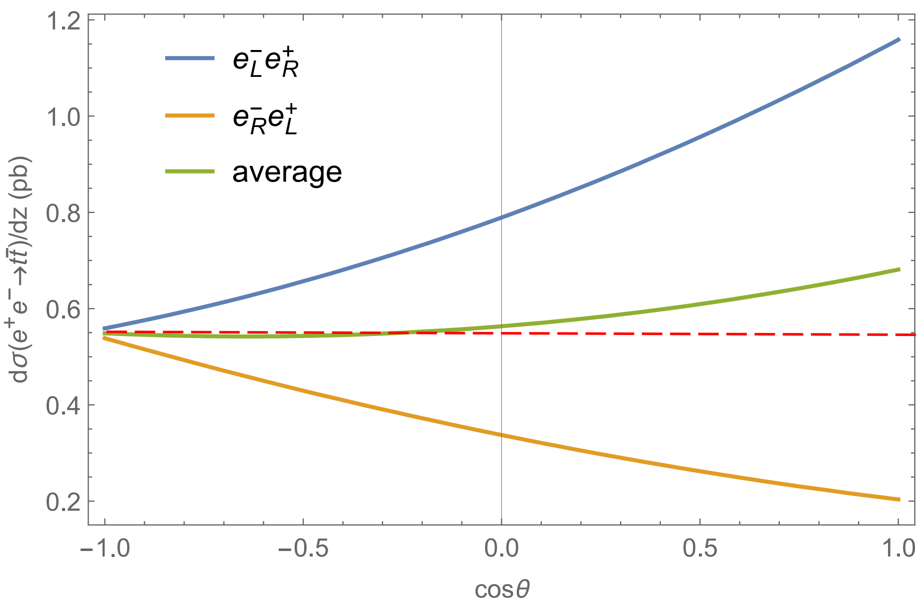
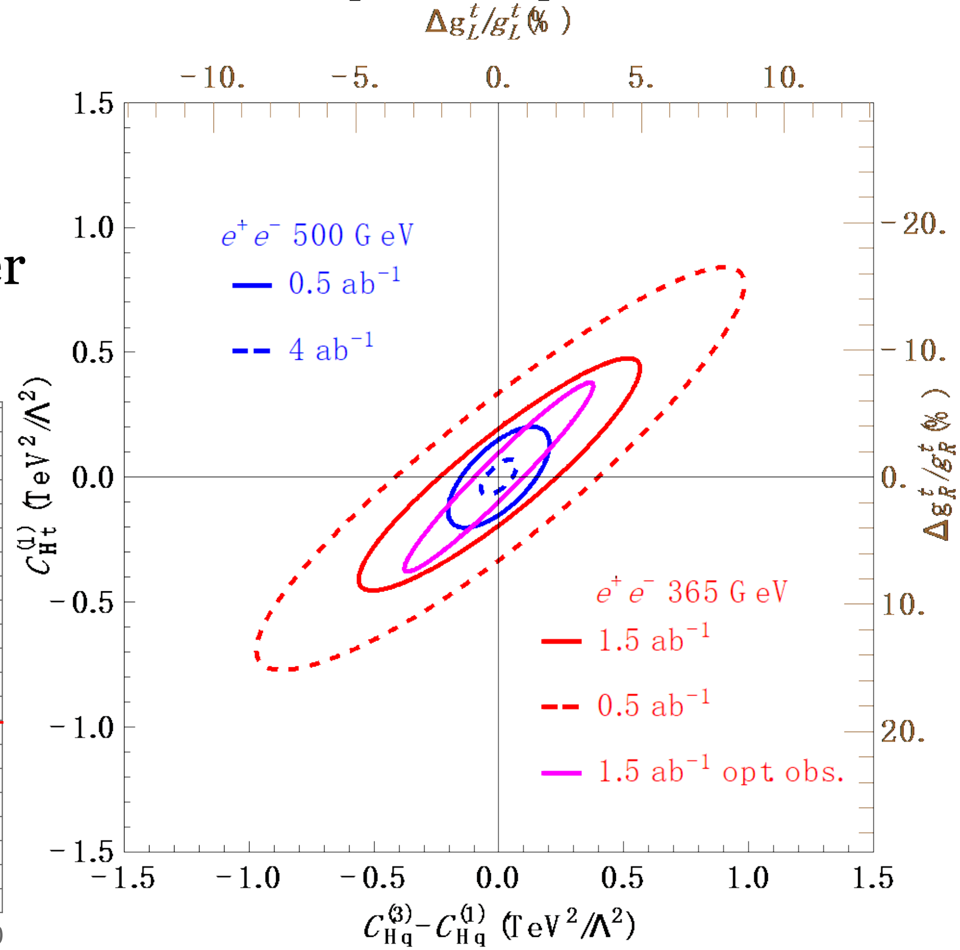


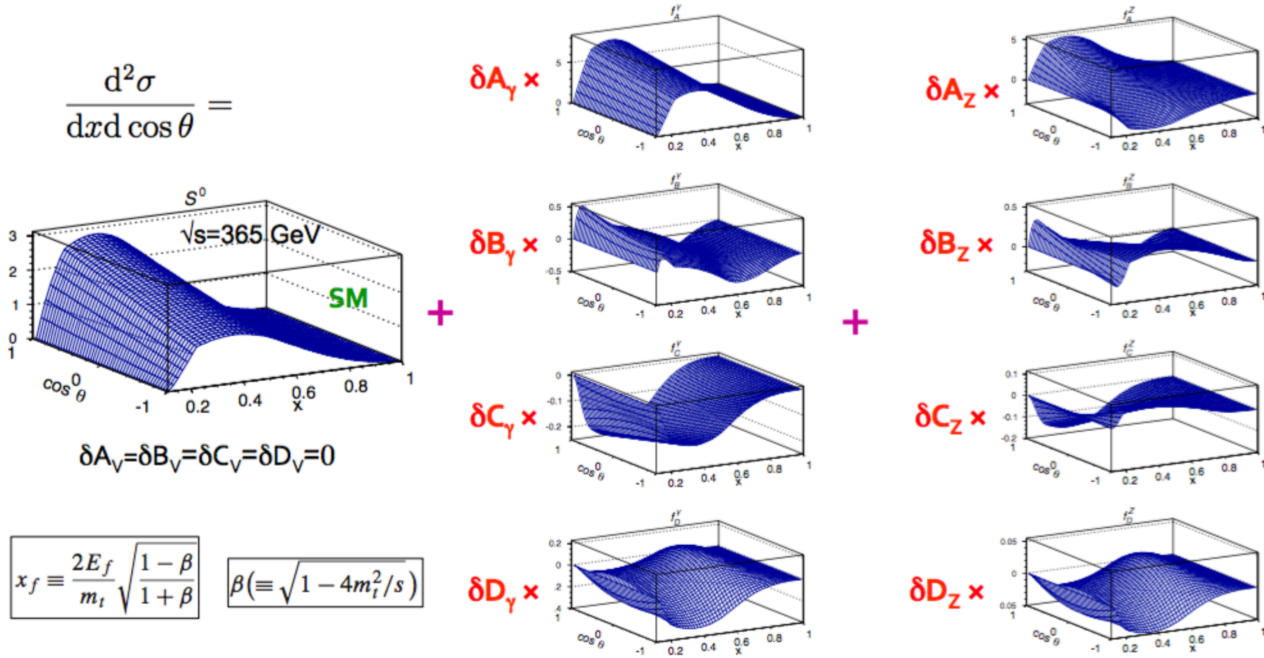


Little asymmetry for unpolarized beam

Top quark and Higgs EFT $O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Ht}$

At or above $t\bar{t}$ threshold at lepton colliders, one immediately again great sensitivities to tl couplings.

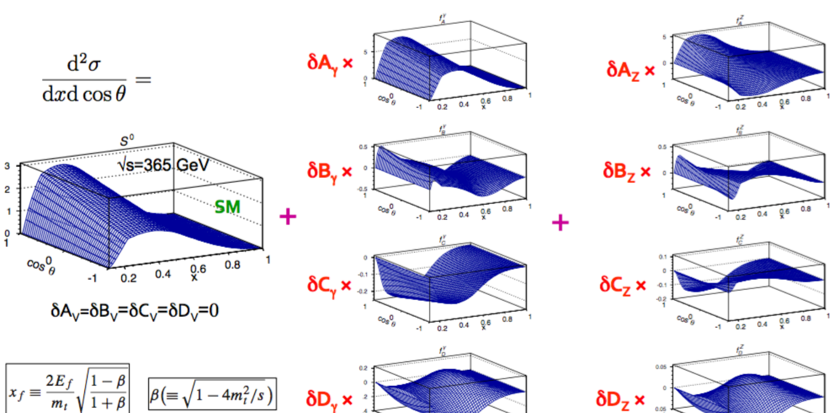
Optimal observable estimates:
P. Janot 15'



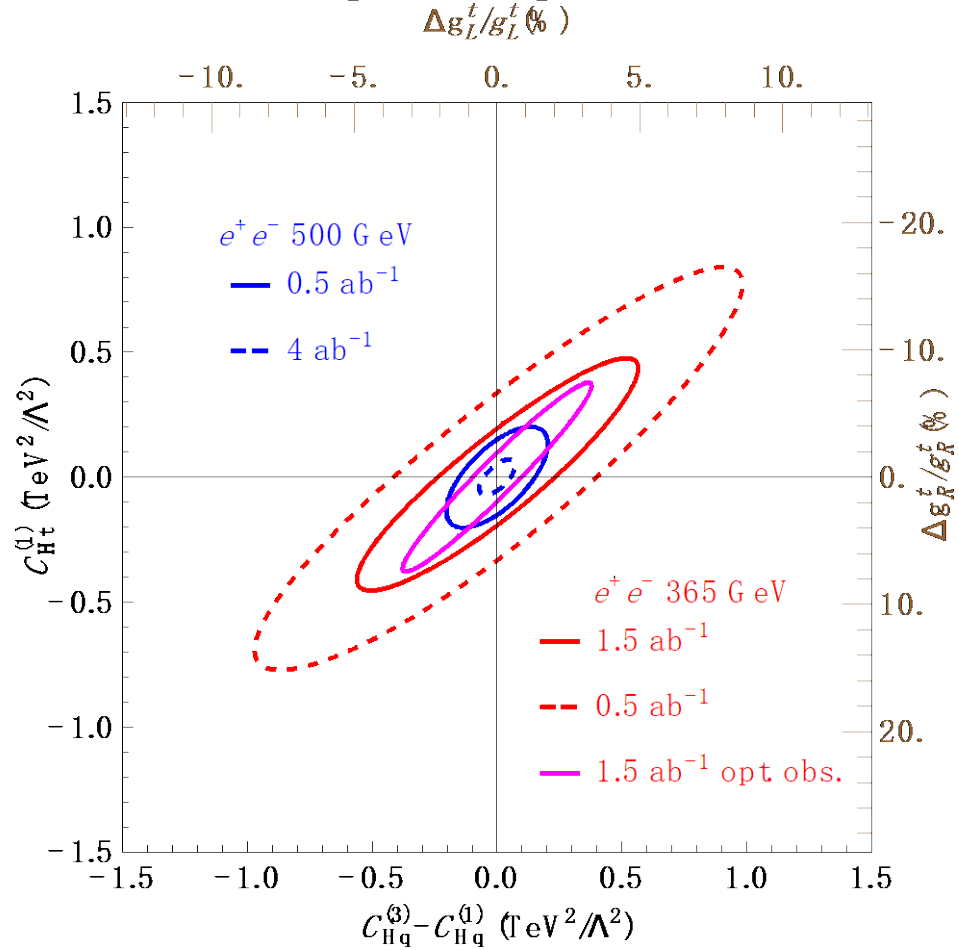
Patrick Janot

Top quark and Higgs EFT $O_{Hq}^{(1)}, O_{Hq}^{(3)}, O_{Ht}$

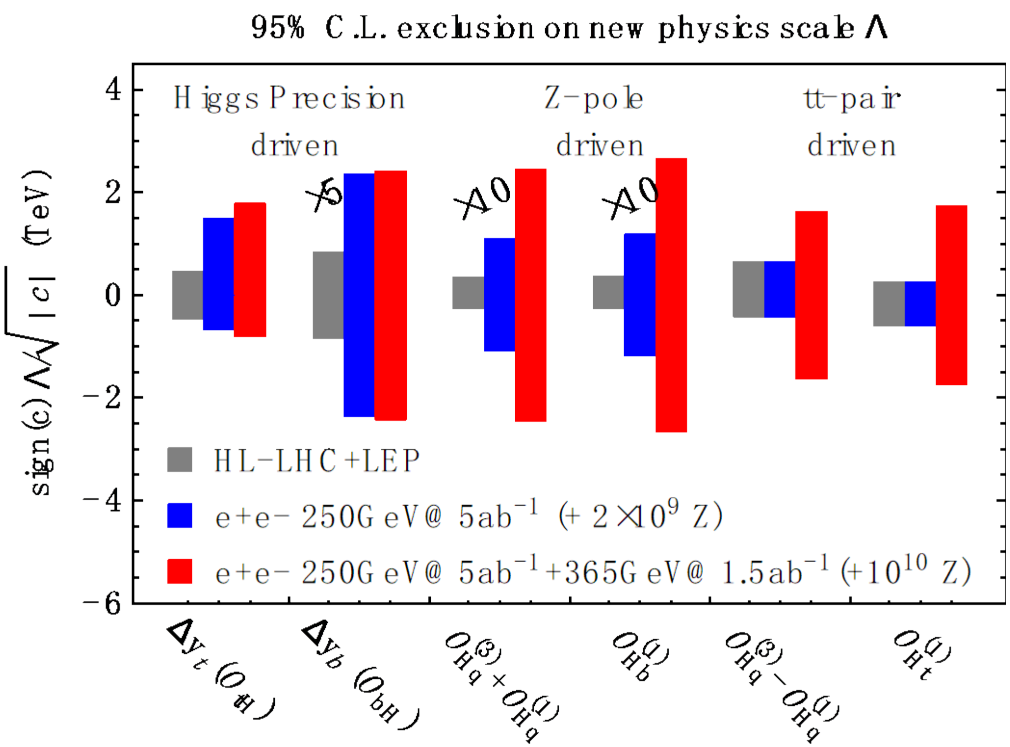
At or above $t\bar{t}$ threshold at lepton colliders, one immediately again great sensitivities to the top gauge couplings.



Patrick Janot

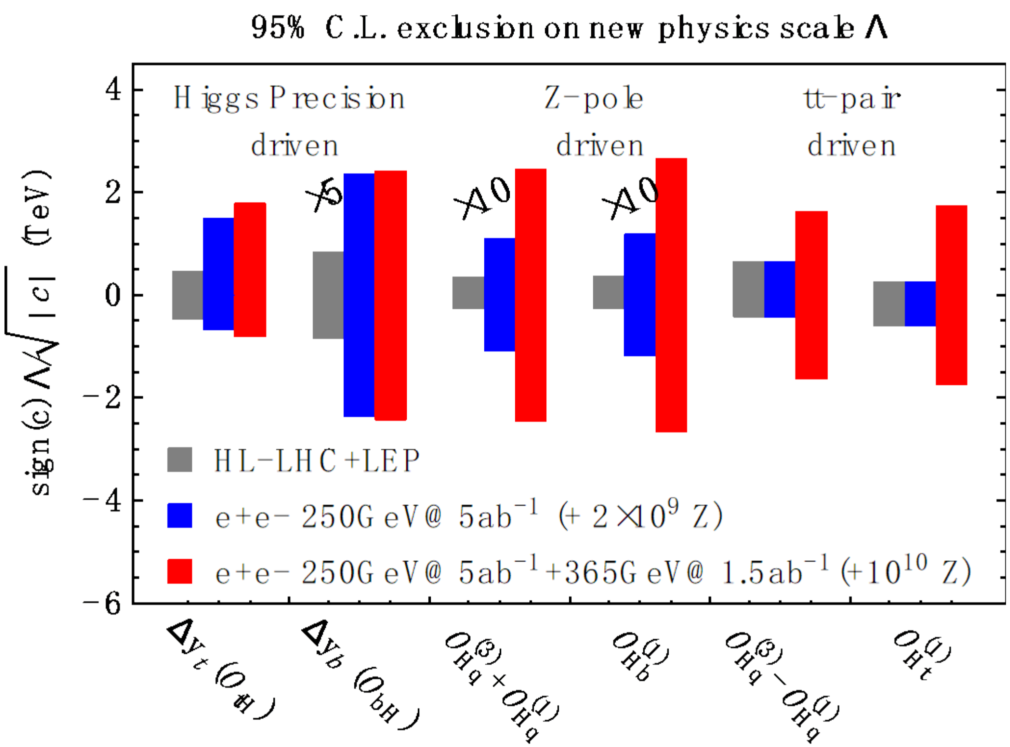


Top quark and Higgs EFT summary



Naturally divide into groups, where the correlations between the measurements are not large at linear level.

Top quark and Higgs EFT summary



Naturally divide into groups, where the correlations between the measurements are not large at linear level.

Higgs-Top couplings important and interesting.

We try to develop some comprehensive understanding of the minimal Higgs Top anomalous coupling EFT set.

Higgs precision, Z-pole precision, ttbar (365 GeV) all needed to complete the picture.

Might be interesting to consider the synergy and physics outcome of larger ring (100 km) and larger energy (350~400 GeV).

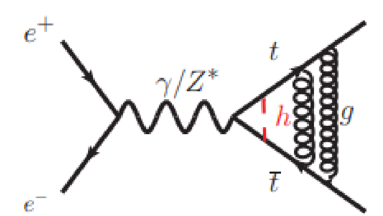
Disclaimer: the following discussion is beyond my paygrade

Physics outputs from ttbar run

ttbar run defined as O(0.x fb^{-1})(run1) for the threshold scan near 346 and O(1.x fb^{-1})(run2) at 360~365 where ever the maximum amount of ttbar events can be accumulated.

Physics output (in order) and my personal evaluations:

1. Precision Top gauge couplings (run2)
   - For ttZ couplings alone, cross section plus asymmetry;
   - For top EFT, optimal observable (or Matrix Element Method) needed;
2. Precision Higgs Physics (run2)
   - Leading order study with 360 statistics (even plus 346) well underway;
   - Higher order fit needs more theorists for consistency;
3. Precision Top mass measurement (run1)
   - Physics case: help with EWPO interpretation (under universal theory);
   - Non-Universal case, worthies a consistent theory study;
4. Get Yukawa coupling from the ttbar radiative corrections (run1+run2)
   - There is 4.2% projection from 1310.0563, but later on the theory uncertainties is estimated to be ~30% by 1506.06865
5. Get a bit constraint on the double Higgs production (run2+, 400 GeV needed)…
   - Far fetching, leave this in the back of our mind if our accelerator friends make some breal



Disclaimer: the following discussion is beyond my paygrade but here are my two cents

Physics outputs from ttbar run

1)+2)+3) is sufficient for a ttbar whitepaper, ideally we perform a simulation for 1);
Nice to mention 1) (which ~4% for g_L and ~8% for g_R) in EW whitepaper;
Simulation priority: 2>1>3~4, as 3 and 4 has too much theory intervened;
Pheno/Theory priority: 1), 2), 3), 4) are all interesting, no rank can be provided;

Physics output (in order) and my personal evaluations:

1. Precision Top gauge couplings (run2)
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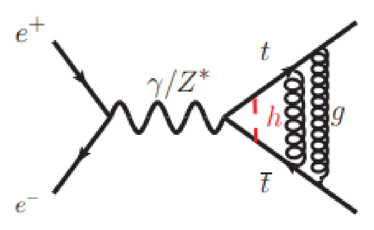

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$$hGG(\pm\pm): \quad +1.035\,\mathrm{Re}\left[\frac{y_t}{y_t^{\mathrm{SM}}}\right] + 0.053 e^{i0.732\pi}\,\mathrm{Re}\left[\frac{y_b}{y_b^{\mathrm{SM}}}\right]$$

$$hG\tilde{G}(\pm\pm): \quad \pm 1.575\,\mathrm{Im}\left[\frac{y_t}{y_t^{\mathrm{SM}}}\right] \pm 0.055 e^{i0.747\pi}\,\mathrm{Im}\left[\frac{y_b}{y_b^{\mathrm{SM}}}\right], \tag{3.5}$$

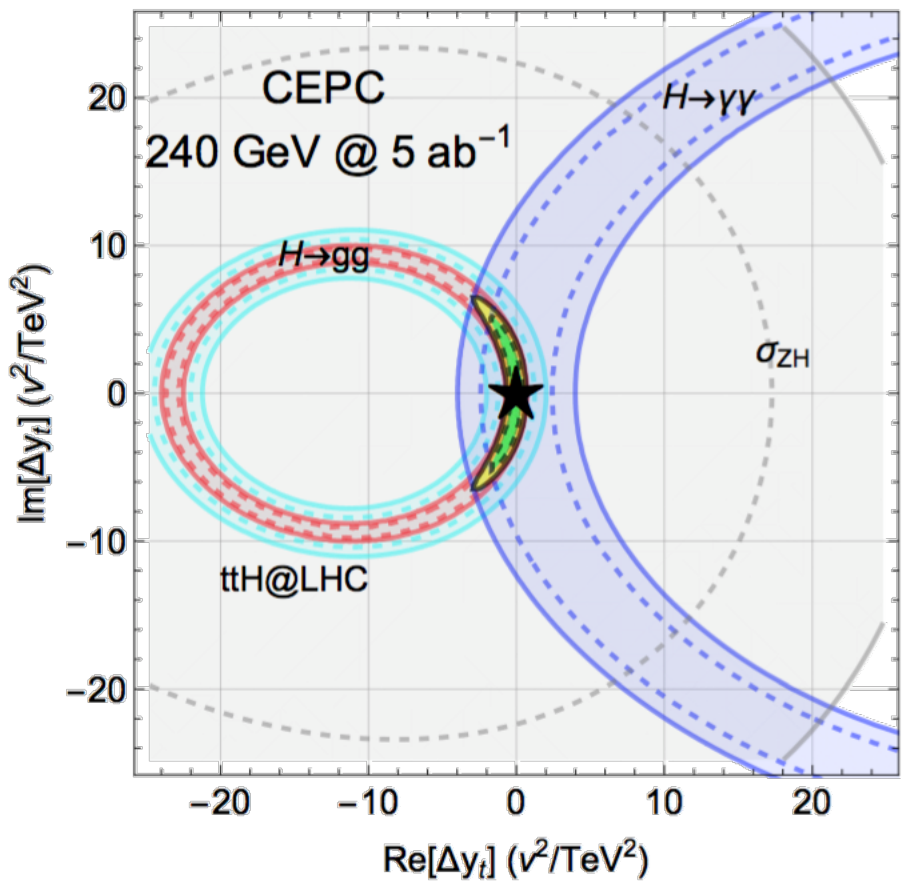
where θ_t and θ_b are the CP phases (weak phase) for the top Yukawa and bottom Yukawa, respectively, and the phase $\sim 0.7\pi$ is the phase of the bottom loop-function evaluate for an on-shell Higgs. The analytic expressions are listed in the Appendix. After squaring and averaging over helicity states, we can obtain the parametric dependence of the $H \to gg$ partial width (which is directly related to measurements) to be,

$$\begin{aligned}\frac{\Gamma(h\to gg)}{\Gamma(h\to gg)^{\mathrm{SM}}} = \; & 1.070\left|\frac{y_t}{y_t^{\mathrm{SM}}}\right|^2 - 0.073\left|\frac{y_t}{y_t^{\mathrm{SM}}}\frac{y_b}{y_b^{\mathrm{SM}}}\right|\cos\theta_t^{\mathrm{CP}}\cos\theta_b^{\mathrm{CP}} + 0.03\left|\frac{y_b}{y_b^{\mathrm{SM}}}\right|^2 \\ & +1.410\left|\frac{y_t}{y_t^{\mathrm{SM}}}\right|^2\sin^2\theta_t^{\mathrm{CP}} - 0.122\left|\frac{y_t}{y_t^{\mathrm{SM}}}\frac{y_b}{y_b^{\mathrm{SM}}}\right|\sin\theta_t^{\mathrm{CP}}\sin\theta_b^{\mathrm{CP}} \\ & +O(0.0001;\left|\frac{y_t}{y_t^{\mathrm{SM}}}\right|,\left|\frac{y_b}{y_b^{\mathrm{SM}}}\right|),\end{aligned} \tag{3.6}$$

where θ_t^{CP} is the CP angle in the top Yukawa, relating to the Yukawa modifications and thus Wilson coefficients of operator $\mathcal{O}_{tH}$ as shown in Eq. 3.3,

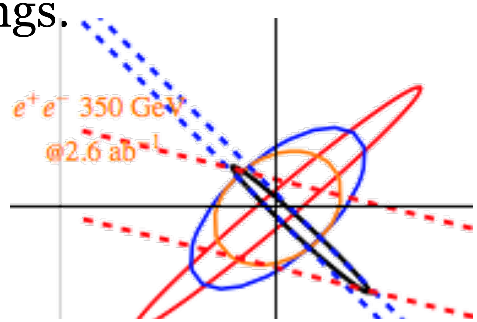
$$\mathrm{Re}\left[\frac{\Delta y_t}{y_t^{\mathrm{SM}}}\right] = \left|\frac{y_t}{y_t^{\mathrm{SM}}}\right|\cos\theta_t^{CP} \quad \text{and} \quad \mathrm{Im}\left[\frac{\Delta y_t}{y_t^{\mathrm{SM}}}\right] = \left|\frac{y_t}{y_t^{\mathrm{SM}}}\right|\sin\theta_t^{CP}, \tag{3.7}$$

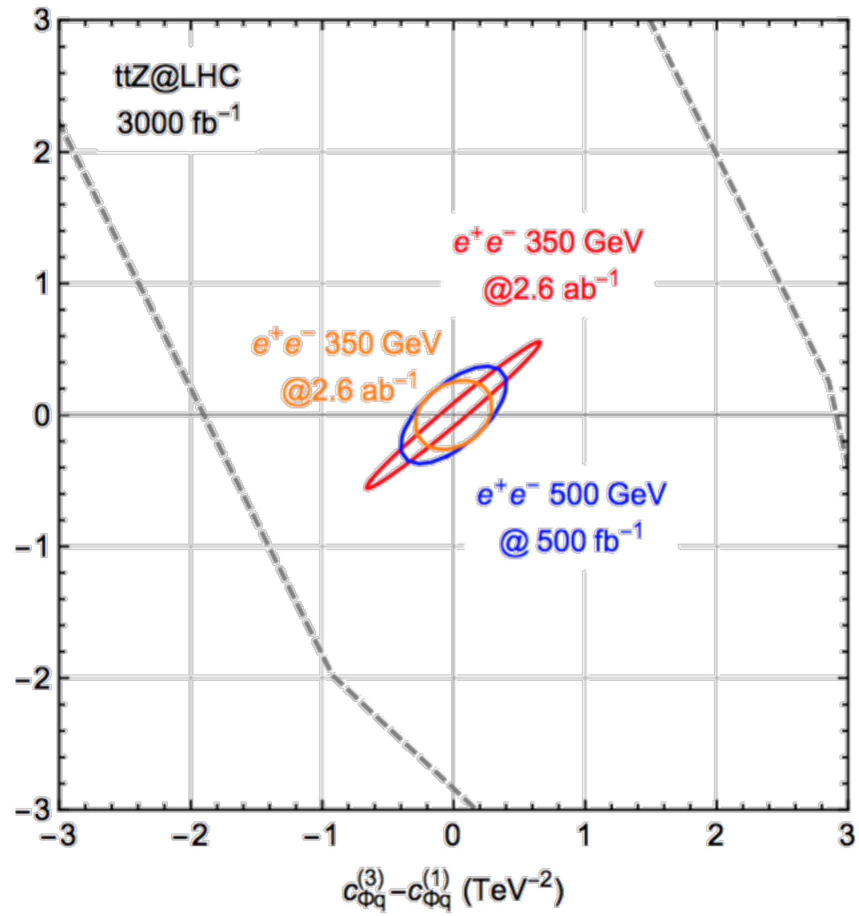
Loop-level constraints from precision Zh measurements



Top quark and Higgs EFT DHq-DHq(3), DHt

At or above $t\bar{t}$ threshold at lepton colliders, one immediately again huge sensitivities to the top gauge couplings.





Top quark loop can also induce some operator mixing and enter the Z-pole precisions (Altarelli, Barbieri, Caravaglios, 93') ϵ_1, ϵ_b

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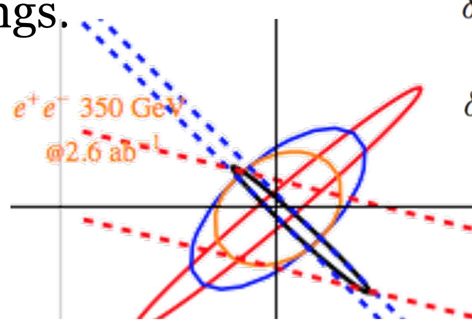

$$\delta\varepsilon_1 = \frac{3m_t^2 G_F}{2\sqrt{2}\pi^2}\,\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} + C_{\phi u}^{33} + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right]\left(\frac{v^2}{\Lambda^2}\right)\log\left(\frac{\Lambda^2}{m_t^2}\right)$$

$$\delta\varepsilon_b = -\frac{m_t^2 G_F}{2\sqrt{2}\pi^2}\,\mathrm{Re}\left[C_{\phi q}^{(3,33)} - C_{\phi q}^{(1,33)} + \frac{1}{4}C_{\phi u}^{33}\right]\left(\frac{v^2}{\Lambda^2}\right)\log\left(\frac{\Lambda^2}{m_t^2}\right).$$

Top quark loop can also induce some operator mixing and enter the Z-pole precisions (Altarelli, Barbieri, Caravaglios, 93') ϵ_1, ϵ_b

However, these are essentially R_b and A_{FB} . To use them, one have to assume extreme cases of DHq+DHq(3) and DHb both are zero at the same time. Only known example is custodial Zbb Agashe, Contino, De Rold, Pomarol, 06'.

In addition, there are some controversies about finite pieces in these relations.