The 2021 International Workshop on the High Energy Circular Electron Positron Collider

November 8-12, 2021, Nanjing, China

Consolidate the optimization and design of both accelerator and detectors and aim for a TDR in 2 years

Deepen the cooperation between the industry and high energy physics community

# Top and Higgs Physics Considerations@ CEPC ttbar run

Zhen Liu

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11/08/2021

Material from ongoing studies

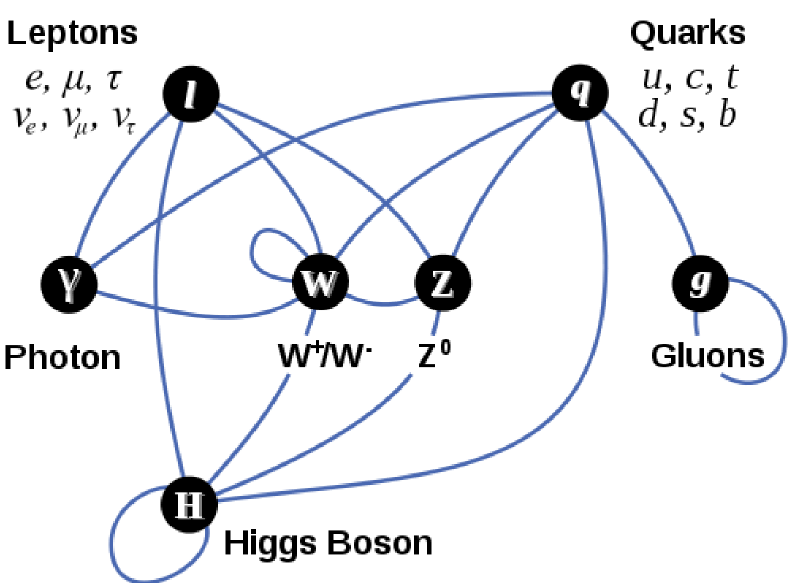
Low, Wang, ZL;

Fang, Wang, ZL; Kaili Zhang; Weimin Song; Xiaohu Sun; Yiwei Wang

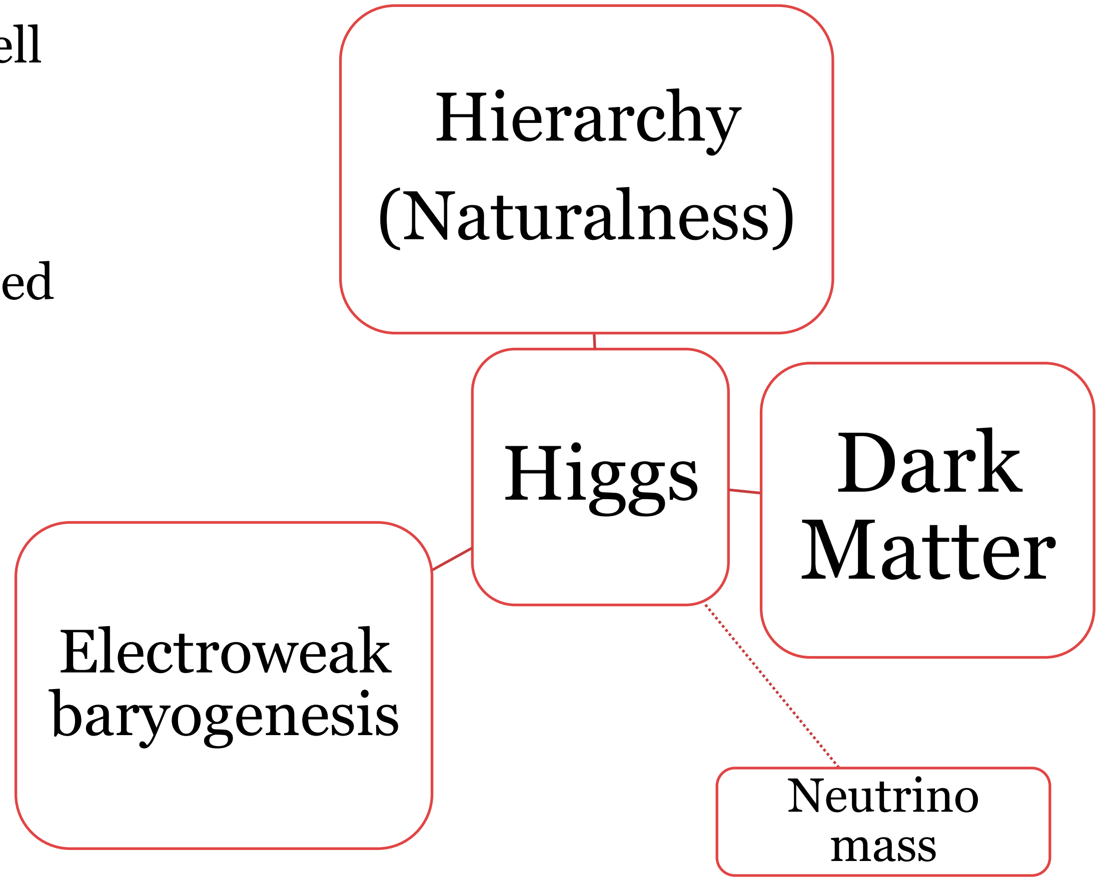
# Why consider ttbar run?

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 plays special roles in Higgs physics**



# Physics outputs from ttbar run

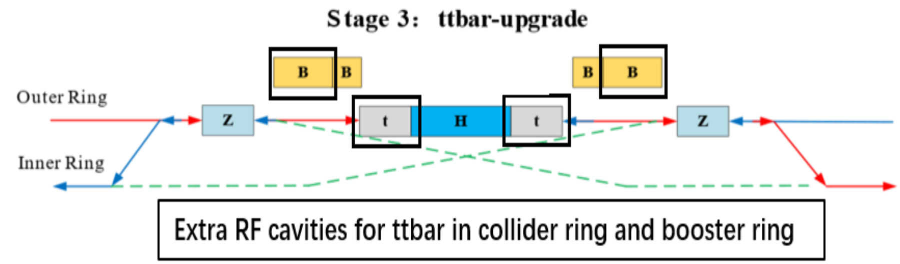
ttbar run defined as O(0.x $ab^{-1}$ ) for the threshold scan near 346 and O(1.x $ab^{-1}$) at 360~365 where ever the maximum amount of ttbar events can be accumulated.

Physics output:

- Precision Top gauge couplings
- Precision Higgs Physics
- Precision Top mass measurement
- Yukawa coupling from the ttbar radiative corrections
- Direct and precision electroweak measurements
- 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 breakthrough.

Inputs from Yiwei Wang team,
CEPC Accelerator Team

# Accelerator at ttbar




- Extra Hardware:
  - ttbar cavities (international sharing): Collider + 7 GV 650 MHz 5-cell cavity, Booster + 6 GV 1.3 GHz 9-cell cavity
  - some septum magnets for beam separation in the RF regions
  - several quadrupole magnets for final focusing
- Accelerator physics design:
  - With SR power limit of 30MW, current design achieved a luminosity of 0.5E34/cm^2/s/IP
  - corresponding to 1ab^-1 for 7.7 years with 1.3 Snowmass units running/year
- To get 2 ab^-1 for 7.7 years
  - reducing the βy*, coupling facto[r] and increasing the synchrotron radiation power limit.

| | ttbar | Higgs | W | Z |
|---|---|---|---|---|
| Number of IPs | 2 | | | |
| Hour glass Factor | 0.89 | 0.9 | 0.9 | 0.97 |
| Luminosity per IP[1e34/cm^2/s] | 0.5 | 5.0 | 16 | 115 |

| Operation mode | | ZH | Z | $W^+W^-$ | ttbar (new) |
|---|---|---|---|---|---|
| $\sqrt{s}$ [GeV] | | ~ 240 | ~ 91.2 | ~ 160 | ~ 360 |
| Run time [years] | | 7 | 2 | 1 | 7.7 |
| CDR | $L$ / IP [$\times10^{34}$ cm$^{-2}$s$^{-1}$] | 3 | 32 | 10 | |
| | $\int L\,dt$ [ab$^{-1}$, 2 IPs] | 5.6 | 16 | 2.6 | |
| | Event yields [2 IPs] | $1\times10^6$ | $7\times10^{11}$ | $2\times10^7$ | |
| Latest | $L$ / IP [$\times10^{34}$ cm$^{-2}$s$^{-1}$] | 5.0 | 115 | 15.4 | 0.5 |
| | $\int L\,dt$ [ab$^{-1}$, 2 IPs] | 9.3 | 57.5 | 4.0 | 1.0 |
| | **Event yields [2 IPs]** | **$1.7\times10^6$** | **$2.5\times10^{12}$** | **$3\times10^7$** | **$3\times10^5$** |

# Physics outputs from ttbar run

ttbar run defined as O(0.1 $ab^{-1}$ ) for the threshold scan near 346 GeV and O(1.0 $ab^{-1}$) at 360 GeV where ever the maximum amount of ttbar events can be accumulated.

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- Precision Top gauge couplings
- Precision Higgs Physics
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# 360GeV: Higher Energy Run

- 350~365GeV $t\bar{t}$ Run:
  - For Higgs: Larger vvH cross section; Benefit width measurement
  - More advantages for EW/Theoretical part;
  - Fcc-ee/ILC/CLIC all have similar plan
- Temporary benchmark: 1 ab^-1 @ 360GeV
  - With current lumi, ~10 (7.7) years to collect 1iab data.
  - 360GeV saves 10% energy with respect to 365 GeV
  - Not determined yet

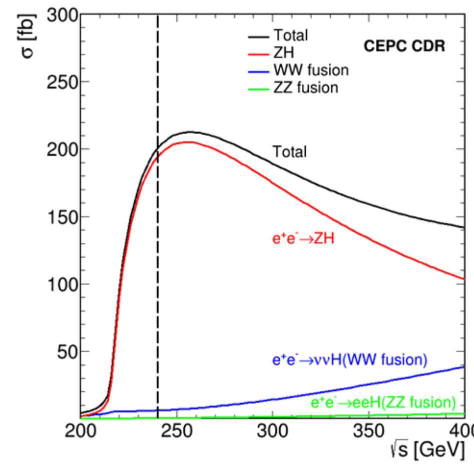
Fcc-ee has the plan for
0.2iab 350GeV Scan + 1.5iab 365GeV

# Signal Cross Sections

ZH/vvH interference already considered.

- 240GeV:
  - ZH: 196.9; vvH: 6.2; interference: ~10% of vvH; about 318:10:1; (Z->vv : vvH = 6.4:1)
- 360GeV: (vvH ~ 117% Z->vv ), (eeH ~ 67% Z->ee)

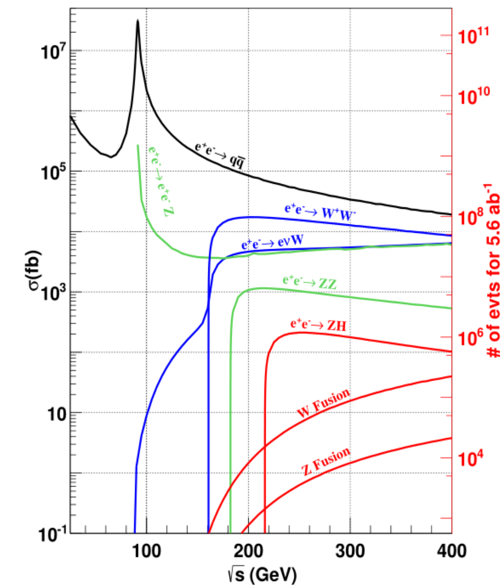
| fb | 240 | 350 | 360 | 365 | 360/240 |
|---|---|---|---|---|---|
| ZH | 196.9 | 133.3 | 126.6 | 123.0 | -36% |
| WW fusion | 6.2 | 26.7 | 29.61 | 31.1 | +377% |
| ZZ fusion | 0.5 | 2.55 | 2.80 | 2.91 | +460% |
| Total | 203.6 | | 159.0 | | |
| Total Events | 1.86M | | 0.16M | | |




In total ~2.0M Higgs would be collected in CEPC 240+360.
More fusion events, also eeH can not be ignored in 360GeV.

# Major background cross sections

| pb | 240 | 350 | 360 | 365 | 360/240 |
|---|---|---|---|---|---|
| ee($\gamma$) | 930 | 336 | 325 | 319 | -65% |
| $\mu\mu$($\gamma$) | 5.3 | 2.2 | 2.1 | 2.1 | -60% |
| qq($\gamma$) | 54.1 | 24.7 | 23.2 | 22.8 | -57% |
| WW | 16.7 | 10.4 | 10.0 | 9.81 | -40% |
| ZZ | 1.1 | 0.66 | 0.63 | 0.62 | -43% |
| tt | \ | 0.155 | 0.317 | 0.369 | |
| sZ | 4.54 | 5.72 | 5.78 | 5.83 | +27% |
| sW | 5.09 | 5.89 | 6.00 | 6.04 | +18% |




While 2fermion bkg and WW, ZZ bkg reduced, W/Z fusion and $t\bar{t}$ raise.

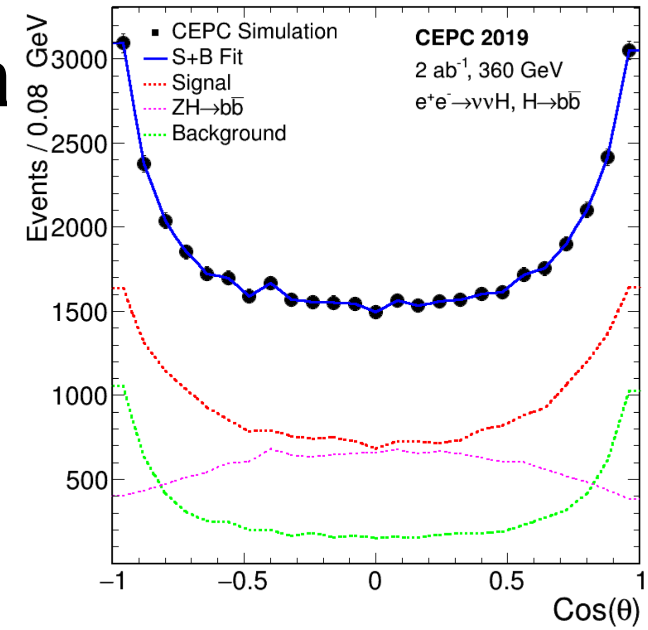
Generally, with larger phase space and smaller bkg cross sections, continuum background would reduce.

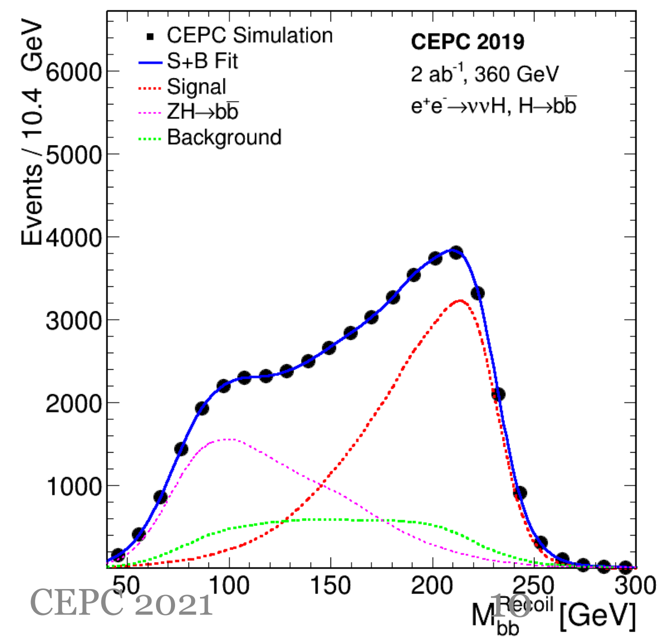
Fast simulation samples are generated to check the shape. Then existing yields are scaled to 360GeV.

Inputs Kaili Zhang team, to be updated to 1 ab^-1 full sim

# vvH->bb : 360 GeV, full sim

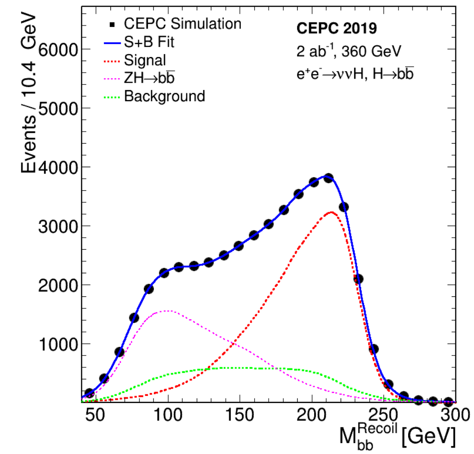
- Clear separation between ZH and vvH.
- Constrain from other ZH->bb($ee, \mu\mu, qq$) considered
  - $\sigma(\text{vv}H) * \text{Br}(\text{H} \to \text{bb})$:0.76%
  - $\sigma(ZH) * \text{Br}(\text{H} \to \text{bb})$: 0.63%
  - share the anti-correlation -15.8%.

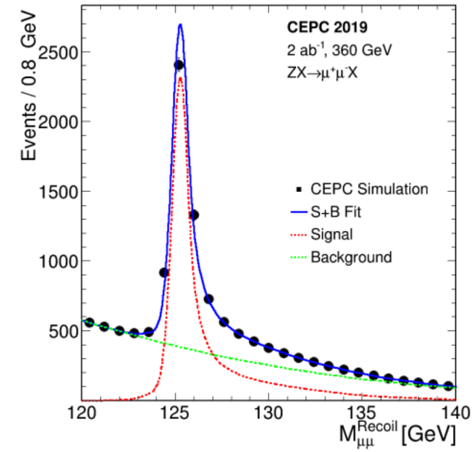


# Higgs Physics Prjection

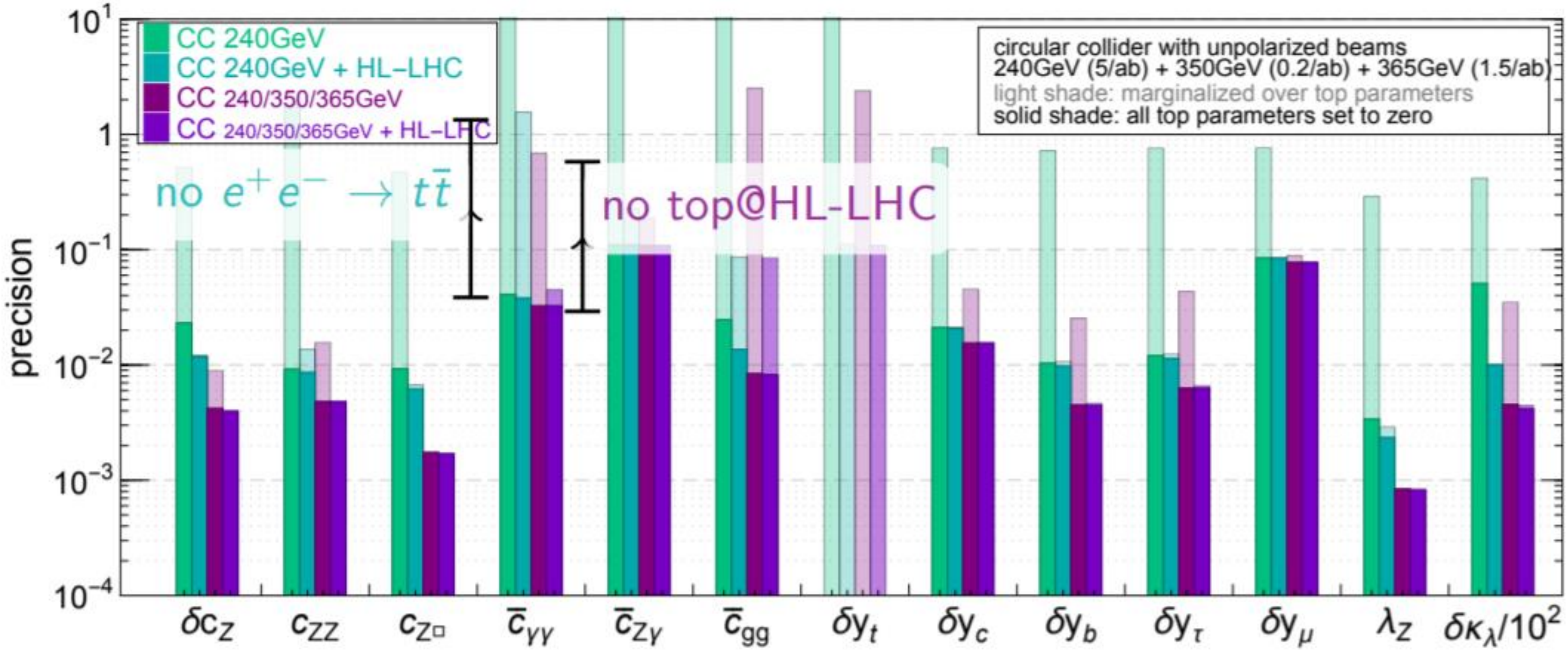
| | 240GeV, 9.3ab$^{-1}$ | 360GeV, 1ab$^{-1}$ | | |
|---|---|---|---|---|
| | ZH | ZH | **vvH** | **eeH** |
| any | 0.40% | 1.4% | \ | \ |
| H→bb | 0.21% | 0.9% | 1.1% | 5.1% |
| H→cc | 2.56% | 8.8% | 15.6% | 41% |
| H→gg | 1.01% | 3.4% | 4.5% | 22% |
| H→WW | 0.78% | 2.8% | 4.4% | 9.3% |
| H→ZZ | 6.13% | 20% | 21% | |
| H→ττ | 0.62% | 2.1% | 4.2% | 9.5% |
| H→γγ | 4.42% | 11% | 16% | |
| H→μμ | 9.31% | 41% | 57% | |
| Br_upper (H→inv.) | 0.16% | | | |
| σ(ZH)∗Br(H→Zγ) | 12% | 35% | | |
| Width | **2.34%** | **1.36%** | | |



# Q2: Contamination in Higgs operators

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. $\rightarrow 0$

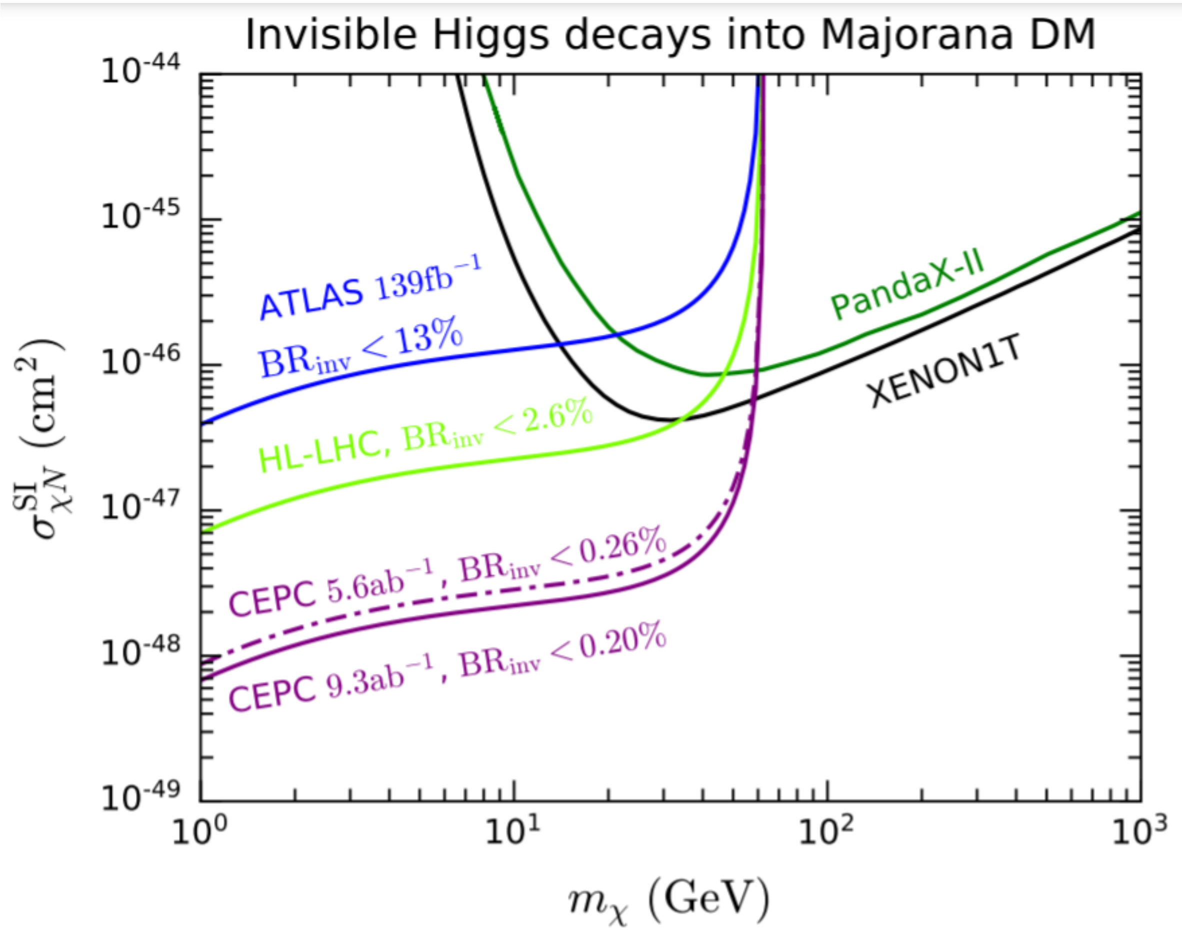



Uncertainties on the top have a big effect on the Higgs

- Higgsstr. run: insufficient
- Higgsstr. run $\oplus$ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run $\oplus$ $e^+e^- \rightarrow t\bar{t}$: large $y_t$ contaminations in various coefficients
- Higgsstr. run $\oplus$ $e^+e^- \rightarrow t\bar{t}$ $\oplus$ top@HL-LHC: top contam. in $\bar{c}_{gg}$ only

# Higgs Invisible

- Higgs invisible will improve statistically
- Helping probe hidden sector physics
- Similarly we will have improvement for the exotic decay program.



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# 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

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

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

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

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

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

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

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

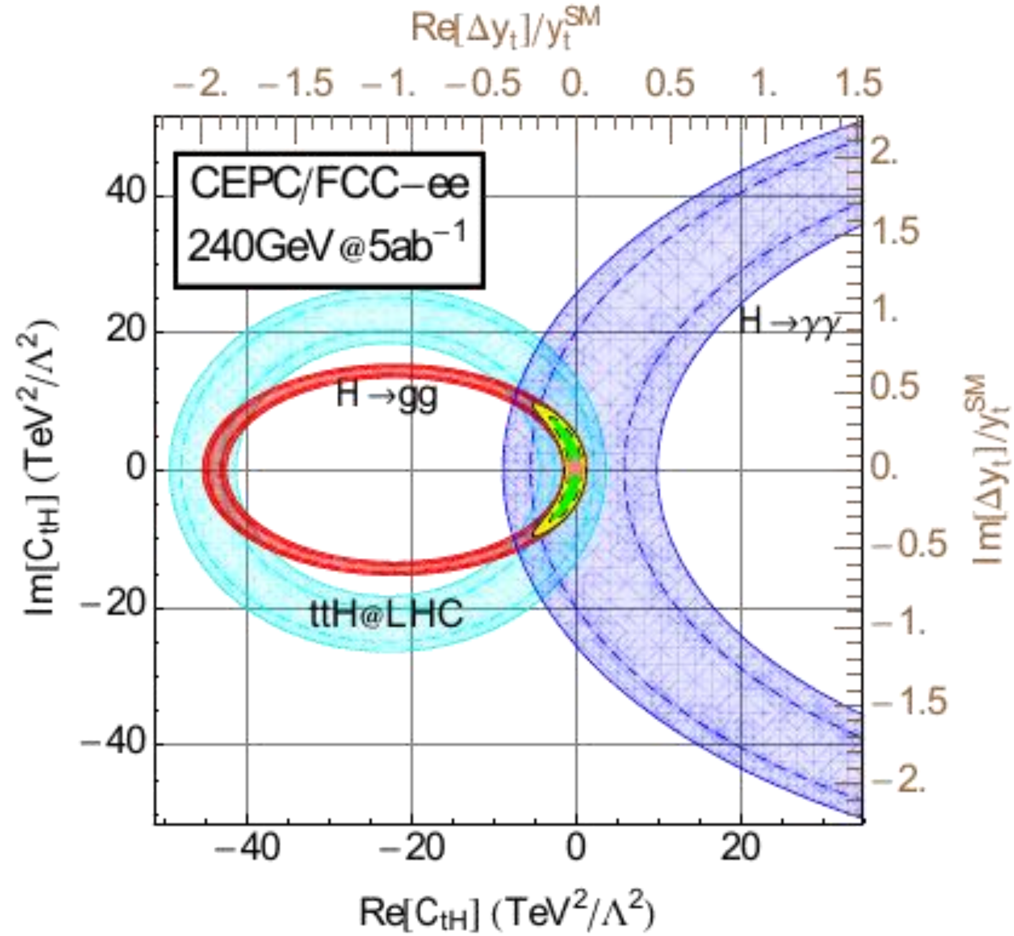
# Top quark and Higgs EFT $O_{tH}$

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

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 $\kappa_Z$ 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 $O_{bH}$

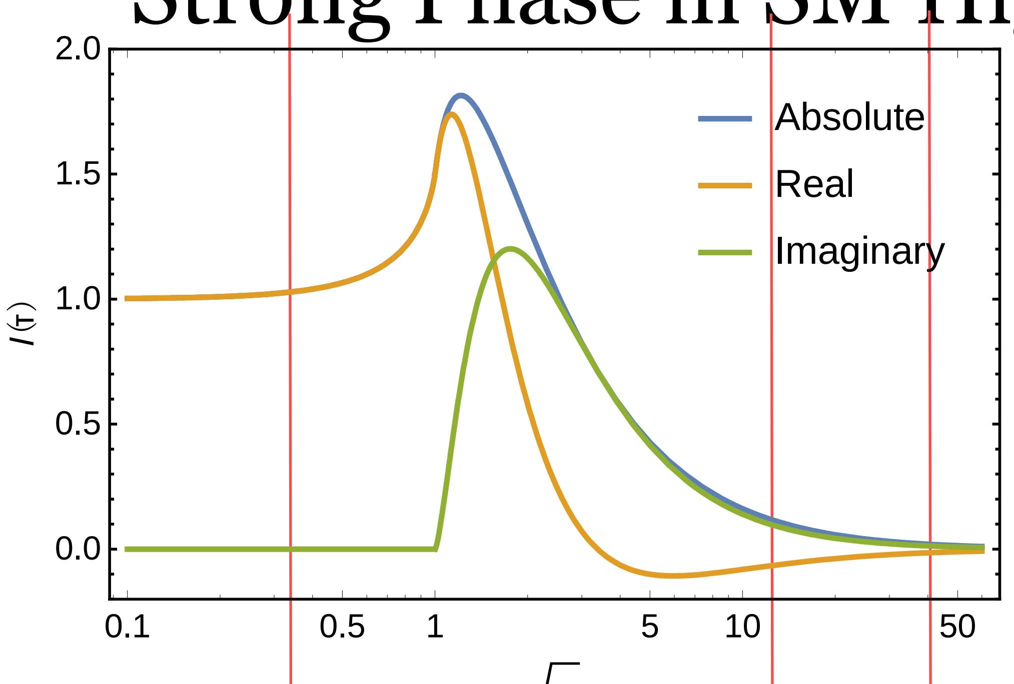
$$\mathcal{O}_{bH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L H b_R),$$

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

CEPC projection of 1.5% on bottom Yukawa~9 TeV on $\Lambda$

But that is not all the story.

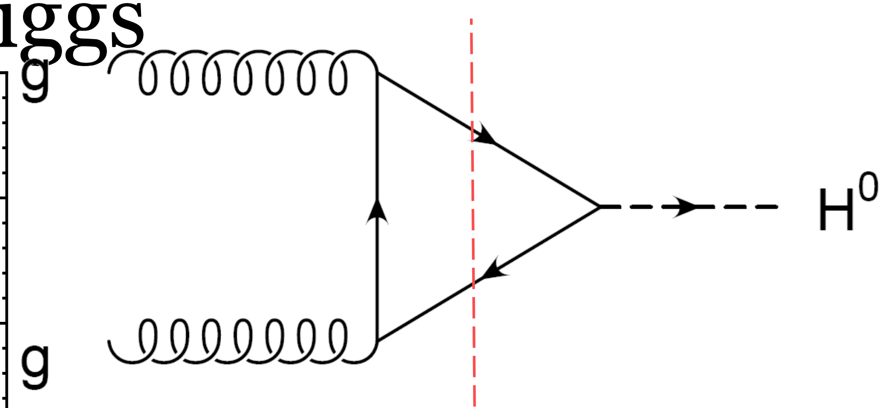
# Strong Phase in SM Higgs




Top loop

Botto m loop

Charm loop




- 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 $-0.004+0.002i$

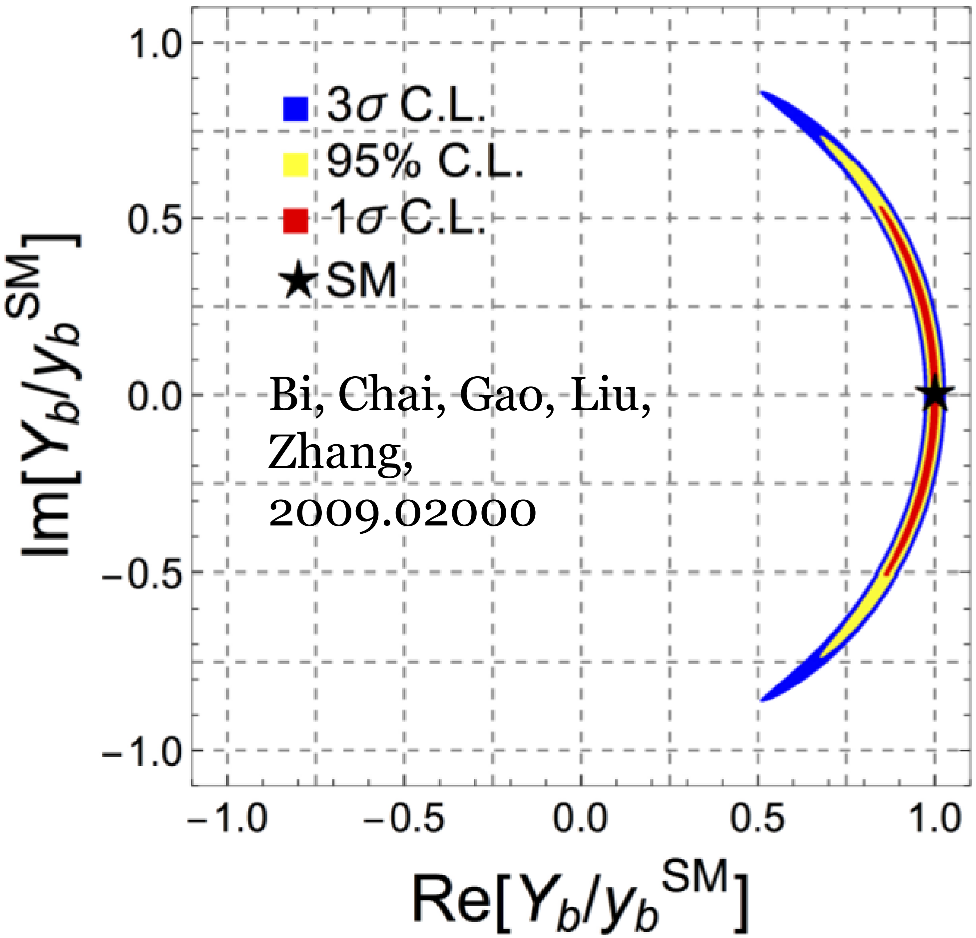
A strong phase in the gluon-gluon fusion production at hadron colliders (imaginary part)

# 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.



# Top quark and Higgs EFT

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

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

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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)

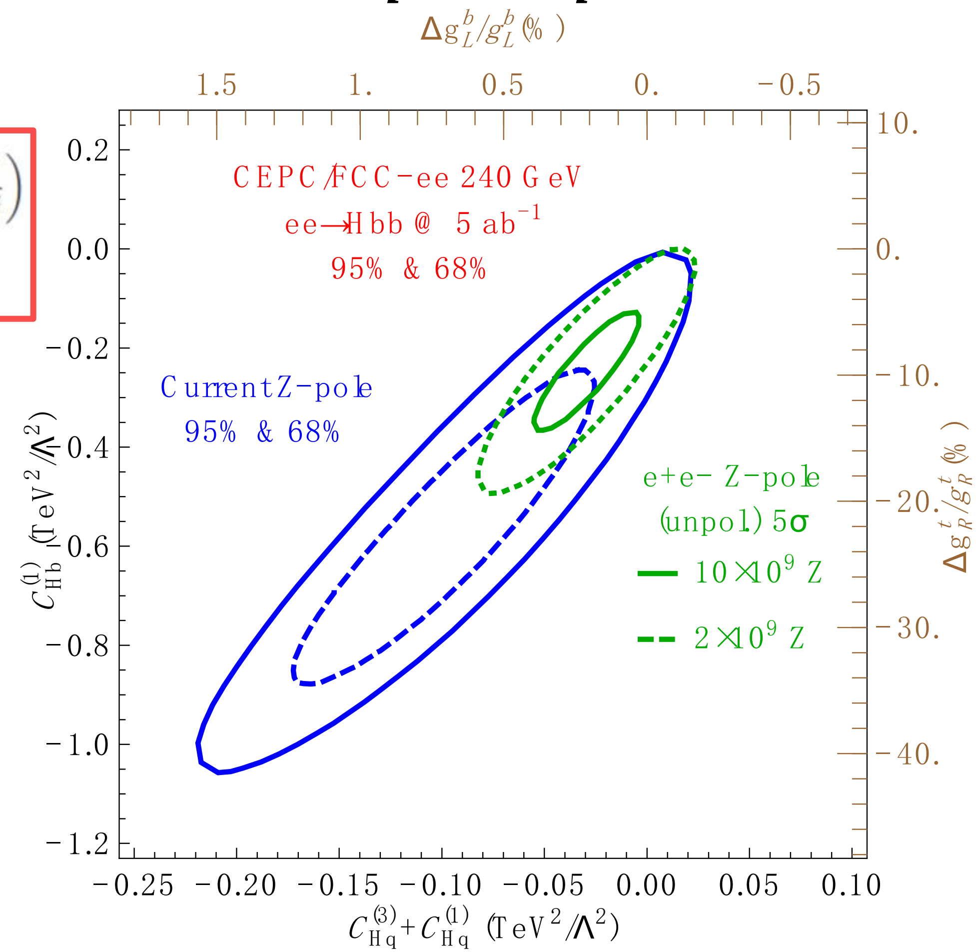
**No photon, only Z and W

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

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

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

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




Z-pole provides very high precision on these coupling.

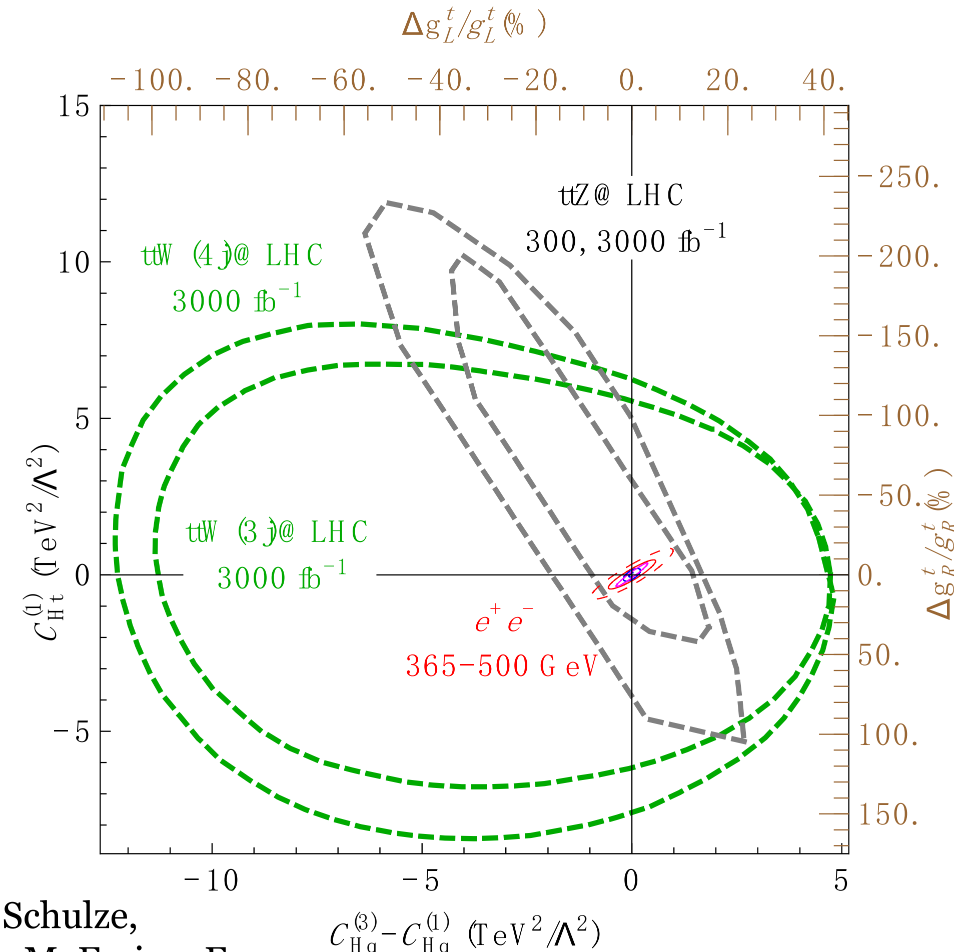


Z-pole result from S. Gori, J. Gu, and L.-T. Wang 1508.07010

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

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

Need ttZ, ttW final states

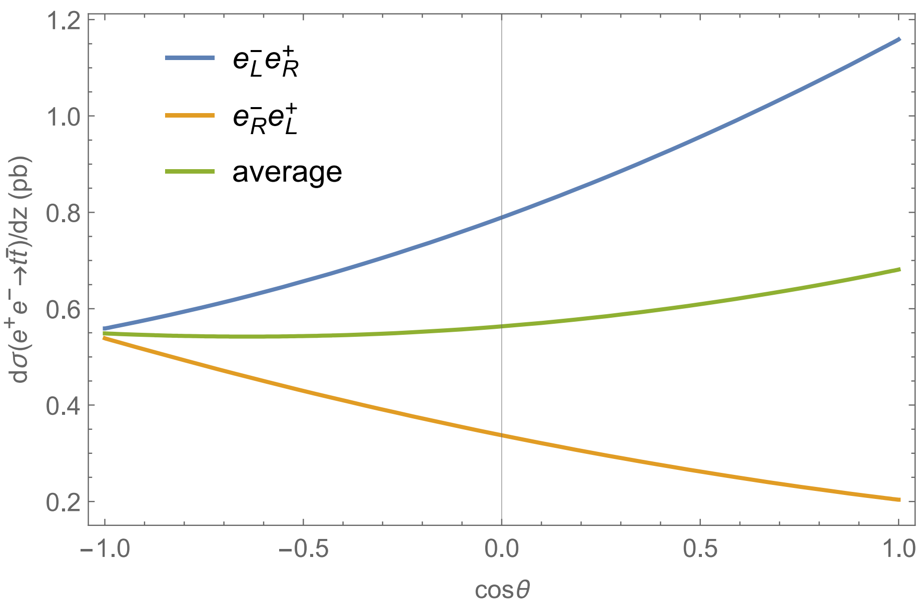


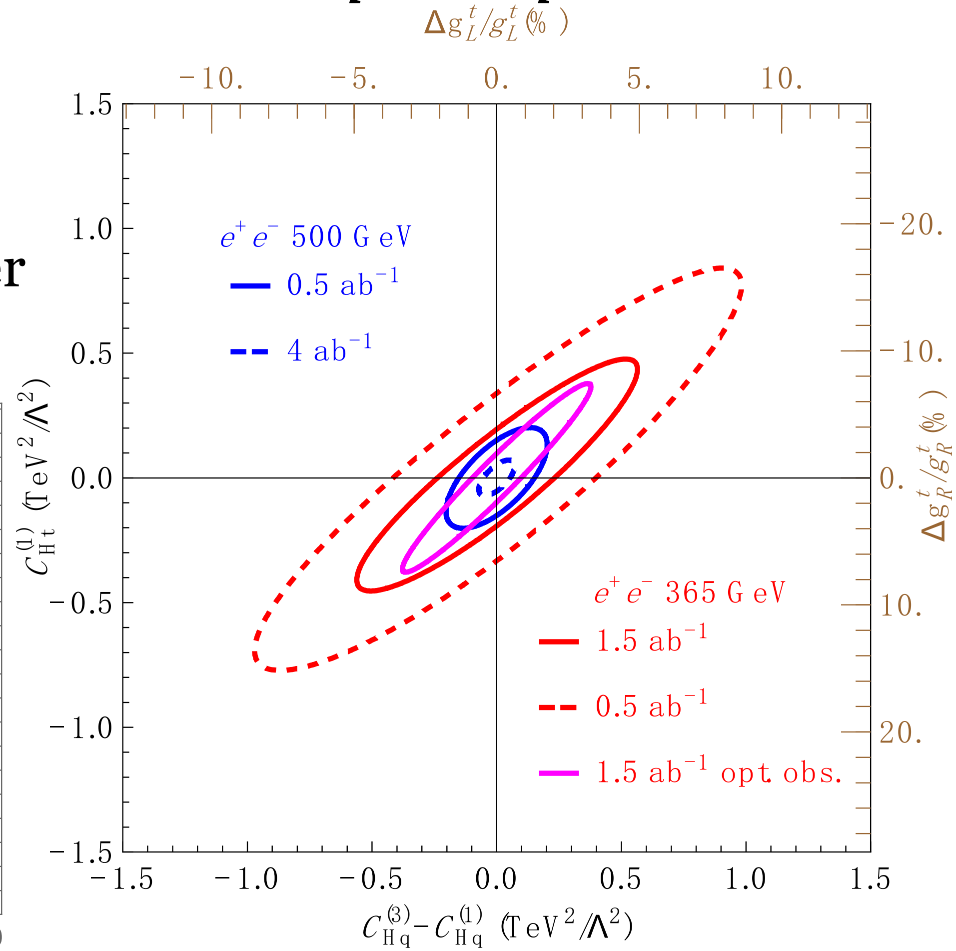

R. Rontsch and M. Schulze, 1404.1005 , J. Dror, M. Farina, E. Salvioni, J. Serra, 1511.03674

# 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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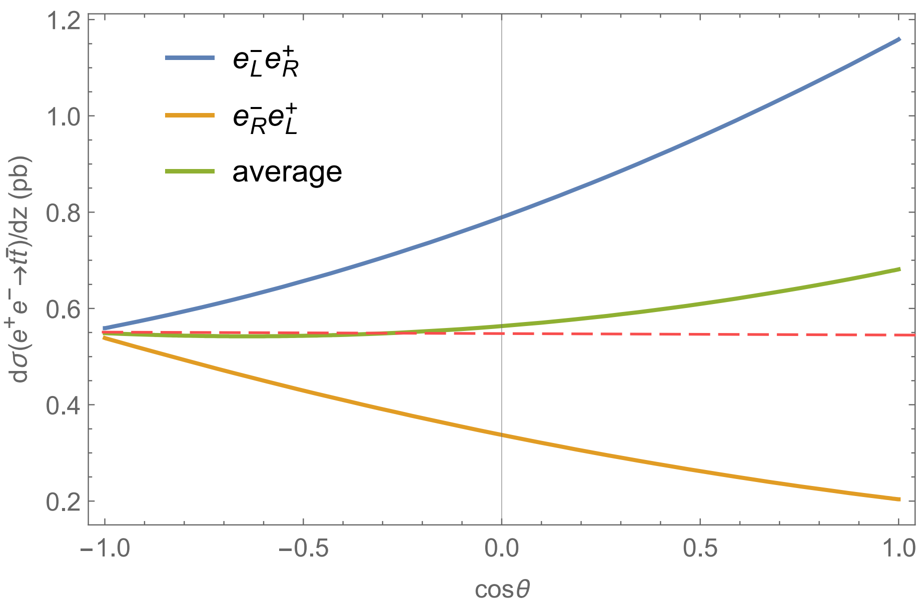
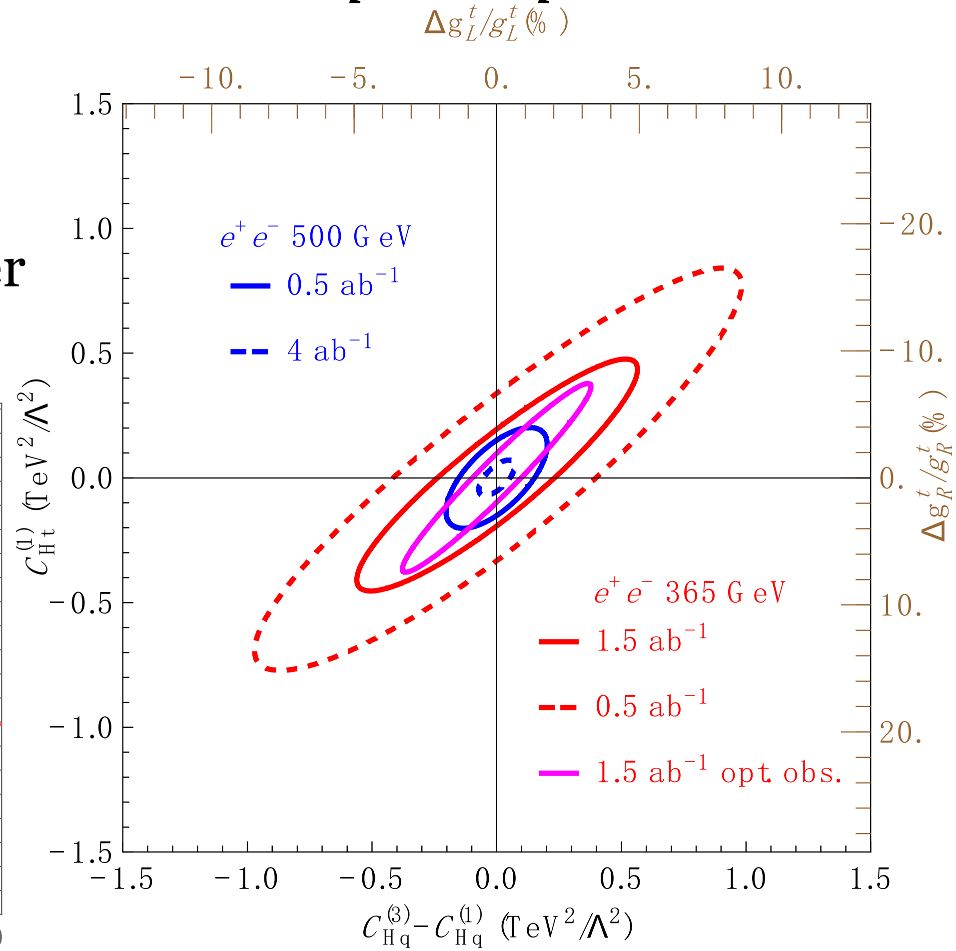
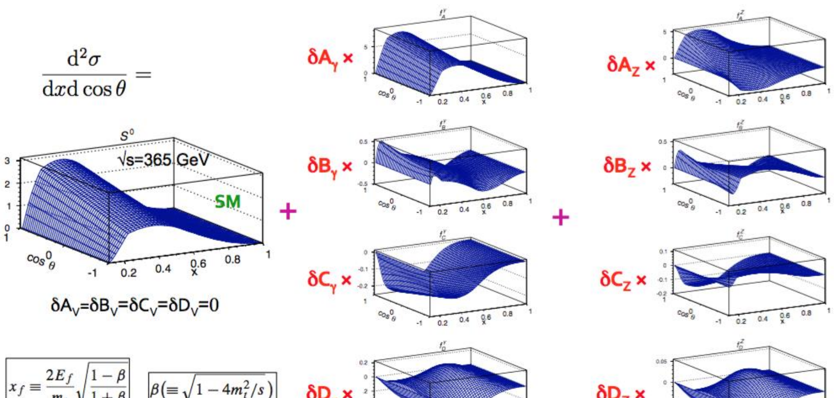


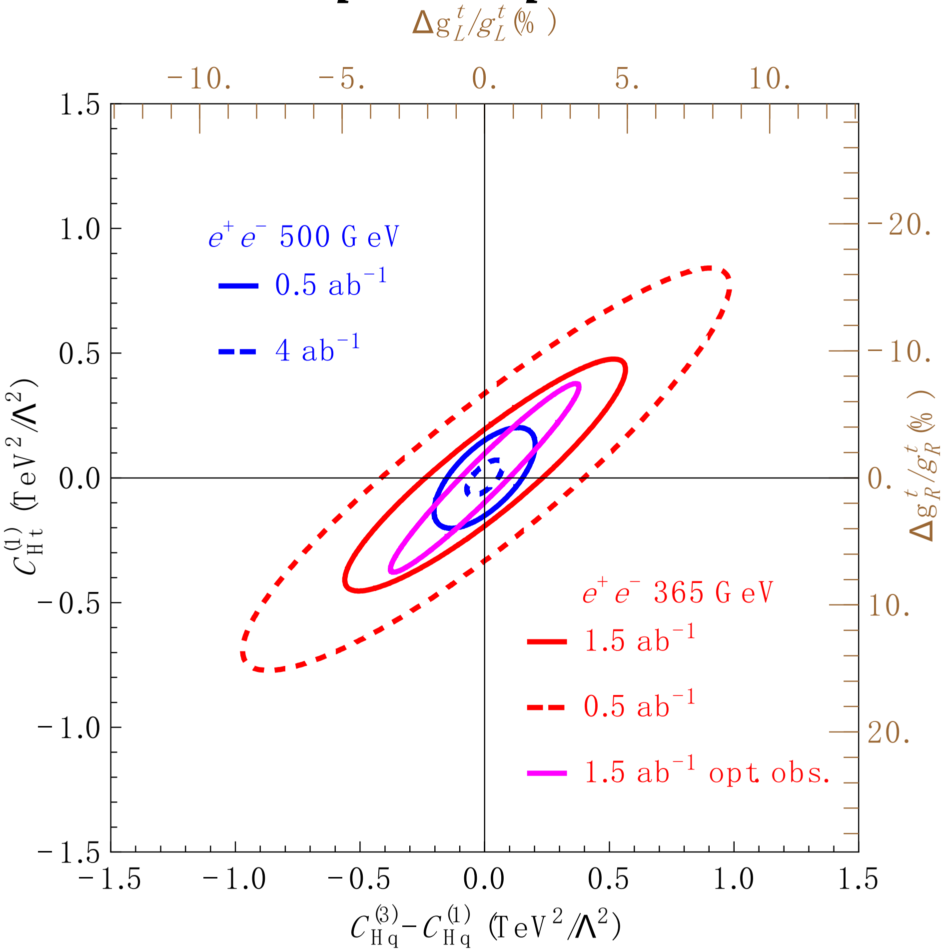

Little asymmetry for unpolarized beam

# 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 the top gauge couplings.

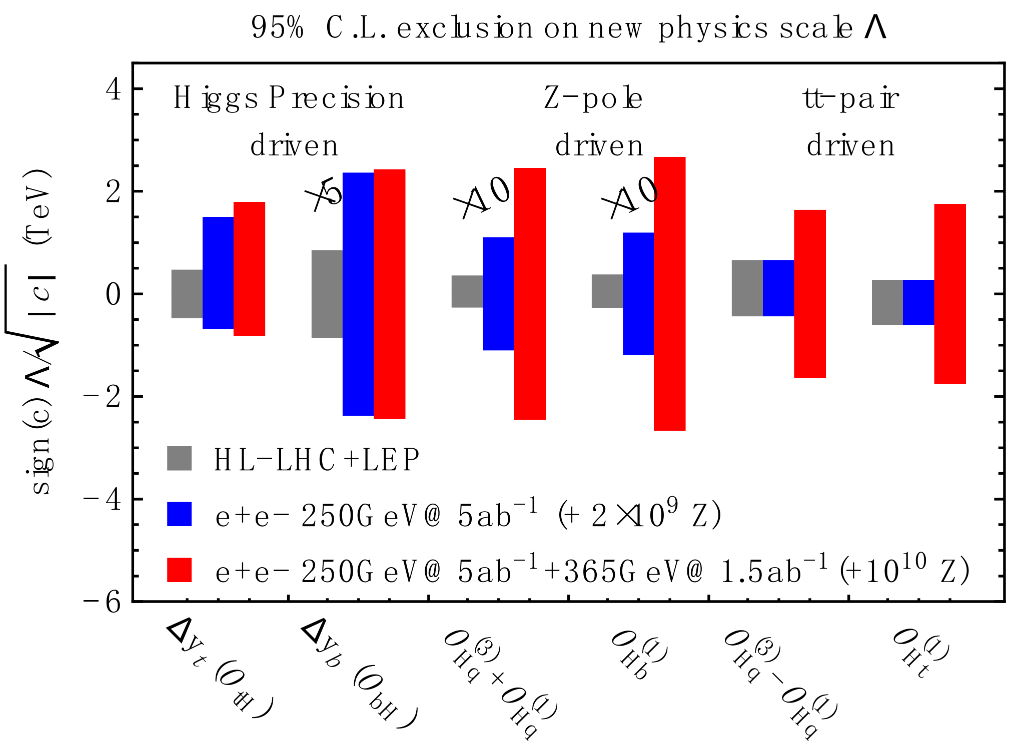



Patrick Janot




Note that the opt. obs. Analysis is a rescaling of Janot's study at 365 GeV, we are performing a CEPC 360 GeV simulation study with Yaquan Fang and Shudong Wang

# Top quark and Higgs EFT summary




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 (360 GeV) all needed to complete the picture.

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

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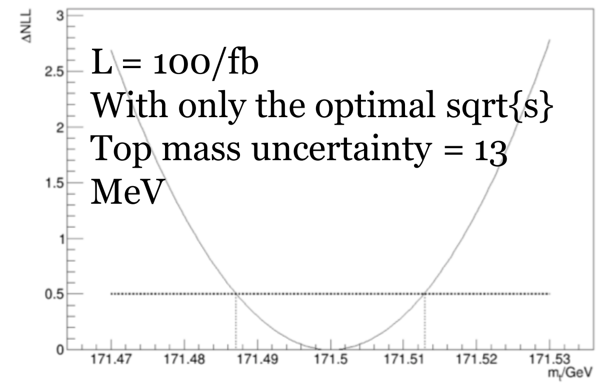
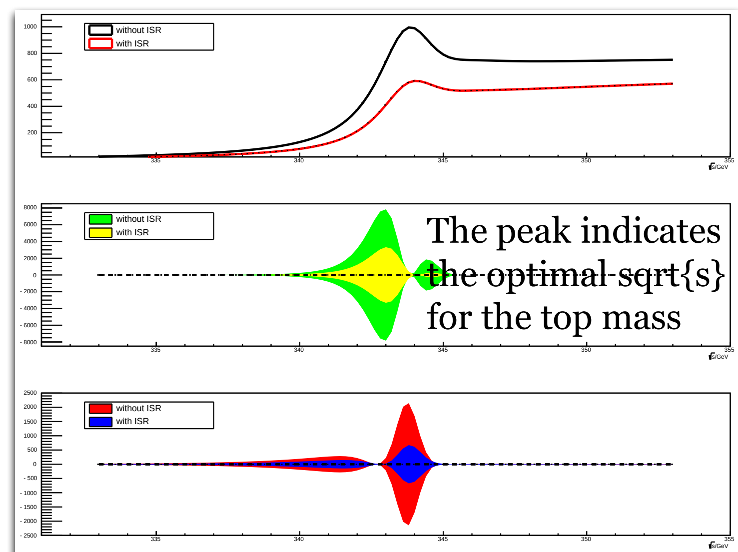
Inputs Xiaohu Sun team,
See Zhan Li's talk next

# Top property measurement

- 360 GeV runs open a door to measure top properties in high precision that hadron colliders cannot reach
- Currently we study the top mass and width measurements using the tt threshold method at ~360 GeV
  - One order of magnitude better precision than the hadron collider is expected
  - A single run at the energy where the tt xsection varies most largely in a given top mass range is found to provide the best performance
  - A quick energy scan with low luminosity to find the optimal energy point before data taking with the full luminosity is proposed
  - More studies are ongoing for the simultaneous measurements of the top mass, width and alpha_S

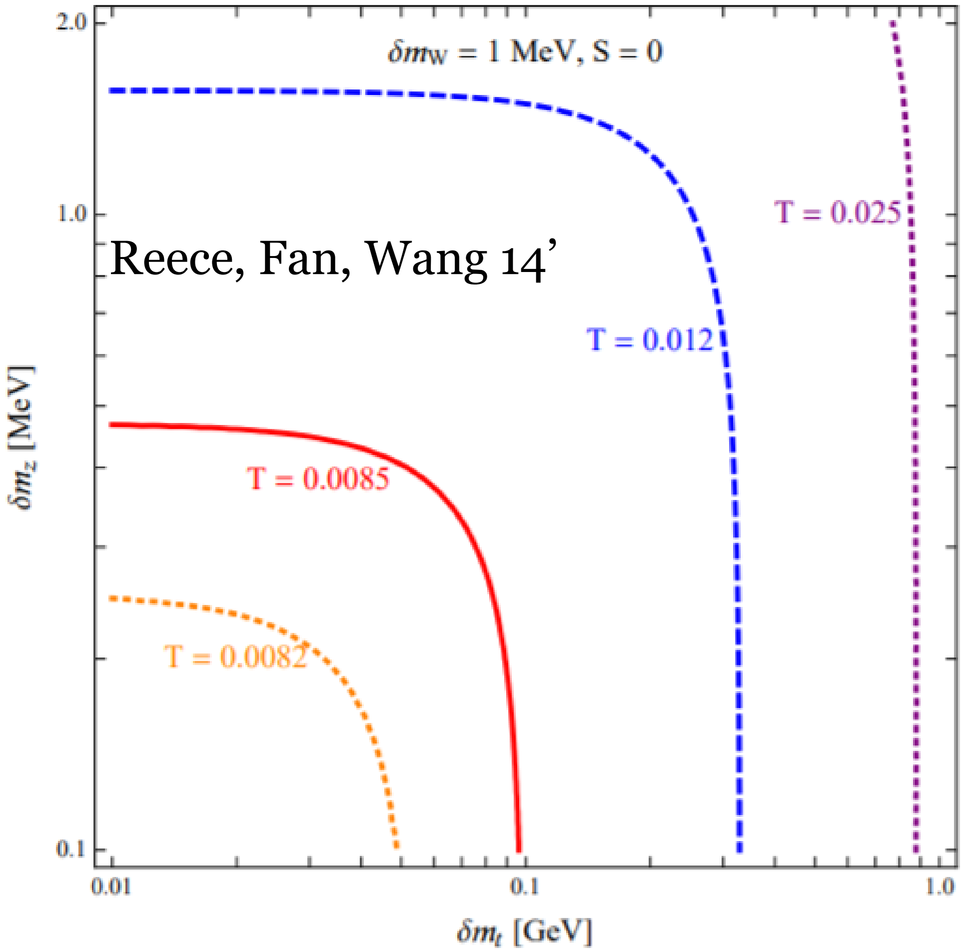


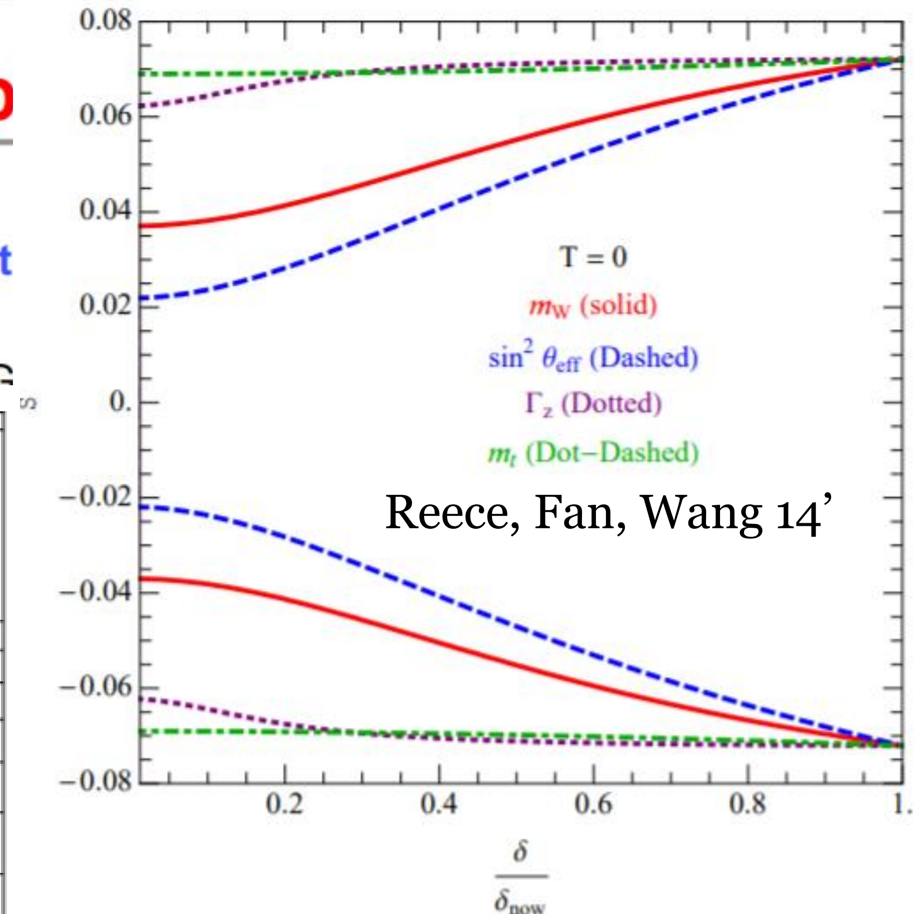



# What can a future lep

**What would a precise measurement of event**

**Exercise:** Make up fictitious ILC data at 500 G



# Physics outputs from ttbar run

ttbar run defined as O(0.1 $ab^{-1}$ ) for the threshold scan near 346 GeV and O(1.0 $ab^{-1}$) at 360 GeV where ever the maximum amount of ttbar events can be accumulated.

**Thank you!**

Physics output:

- Precision Top gauge couplings
- Precision Higgs Physics
- Precision Top mass measurement
- Yukawa coupling from the ttbar radiative corrections
- Direct and precision electroweak measurements
- 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 breakthrough.

With the interests from flavor/muon anomalies, which indicates possible new physics near the weak scale, CEPC 360 GeV run will provide additional added value in probing new these new physics.