Probing top-quark couplings indirectly at future Higgs factories

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Based on 1804.09766 with E .Vryonidou
and 1809.03520 with G. Durieux, J. Gu, E. Vryonidou.

Outline

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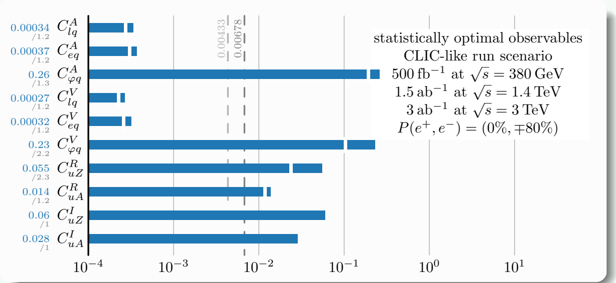
Top couplings at e^+e^- colliders

- Above $t\bar{t}$ or $t\bar{t}H$ threshold, top-gauge couplings / top-Yukawa couplings can be probed by direct production processes.
  - e.g. CLIC [Durieux, Perello, Vos, CZ '18]



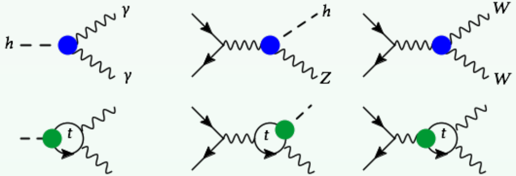
  - e.g. ILC, precision on top-Yukawa can reach $\sim$ 10%. [R. Yonamine et al. '11]

Top couplings at e^+e^- colliders

- What about CEPC 240 GeV (below $t\bar{t}$), or CEPC/FCC-ee 350 GeV (above $t\bar{t}$ but below $t\bar{t}H$)?
  - Recently it is shown that Higgs processes can be sensitive to top-quark couplings, through loop corrections, at HL-LHC.

*[E. Vryonidou, **CZ**, 18]*

- Top is always an important player in Higgs observables: $H \to gg$ and $H \to \gamma\gamma$ are induced by top loops.

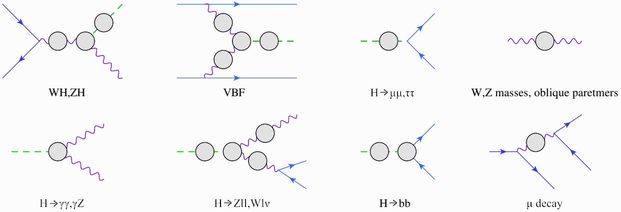


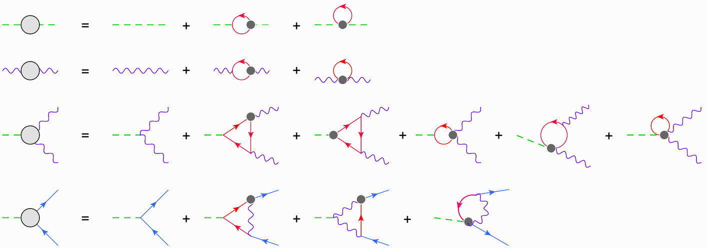
  - However, including only $H\gamma\gamma$, but not the full loop corrections to all measurements, is inconsistent. (e.g. leading to artificially tight bounds on δy_t)

[Durieux, Grojean, Gu, Wang, '17]

Top couplings at e^+e^- colliders

Top loops entering e^+e^- processes

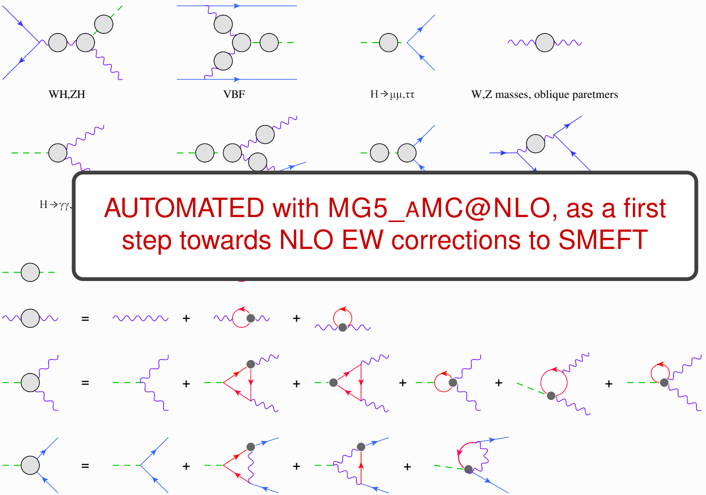




Top couplings at e^+e^- colliders

Top loops entering e^+e^- processes

*[E. Vryonidou, **CZ**, 18]*



AUTOMATED with MG5_aMC@NLO, as a first step towards NLO EW corrections to SMEFT

Probing top-quark indirectly

- If future lepton colliders only run below the $t\bar{t}$ threshold, how can we determine the top-quark-gauge-boson couplings with high precision? (i.e. ttZ, $tt\gamma$, tbW couplings)
- If future lepton colliders only run below the $t\bar{t}H$ threshold, how can we determine the top-Yukawa couplings? (i.e. ttH couplings)
- Does the uncertainty on top-quark couplings affect the reach of future measurements of Higgs couplings?

Top couplings (neglecting four-fermion operators)

- Top Yukawa

$$O_{t\varphi} = \bar{Q}t\tilde{\varphi}\left(\varphi^\dagger\varphi\right) + h.c.$$

- Vector-like coupling $(\bar{f}\gamma^\mu f)V_\mu$

$$O^{(1)}_{\varphi Q} = \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q), \quad O^{(3)}_{\varphi Q} = \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q),$$
$$O_{\varphi t} = \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t), \quad O_{\varphi tb} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{t}\gamma^\mu b) + h.c.$$

  - and redefine: (to separate *ttZ* and *bbZ* couplings)

$$O^{(+)}_{\varphi Q} \equiv \frac{1}{2}\left(O^{(1)}_{\varphi Q} + O^{(3)}_{\varphi Q}\right), \qquad O^{(-)}_{\varphi Q} \equiv \frac{1}{2}\left(O^{(1)}_{\varphi Q} - O^{(3)}_{\varphi Q}\right).$$

- Dipole couplings $(\bar{f}\sigma^{\mu\nu} f)V_{\mu\nu}$

$$O_{tW} = (\bar{Q}\sigma^{\mu\nu}\tau^I t)\,\tilde{\varphi}W^I_{\mu\nu} + h.c., \quad O_{tB} = (\bar{Q}\sigma^{\mu\nu} t)\,\tilde{\varphi}B_{\mu\nu} + h.c.$$

Higgs couplings

- 12 SILH-like basis operators: [Durieux, Grojean, Gu, Wang, '17]

$$
\begin{aligned}
&O_{\varphi W} = \varphi^\dagger\varphi W^I_{\mu\nu}W^{I\mu\nu}, && O_{\varphi B} = \varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu},\\
&O_{\varphi\Box} = \left(\varphi^\dagger\varphi\right)\Box\left(\varphi^\dagger\varphi\right), && O_W = iD^\mu\varphi^\dagger\tau^I D^\nu\varphi W^I_{\mu\nu},\\
&O_B = iD^\mu\varphi^\dagger D^\nu\varphi B_{\mu\nu}, && O_{b\varphi} = (\varphi^\dagger\varphi)\bar{Q}b\varphi + h.c.,\\
&O_{\mu\varphi} = (\varphi^\dagger\varphi)\bar{l}_2 e_2\varphi + h.c., && O_{\tau\varphi} = (\varphi^\dagger\varphi)\bar{l}_3 e_3\varphi + h.c.,\\
&O_{t\varphi} = (\varphi^\dagger\varphi)\bar{Q}t\tilde{\varphi} + h.c., && O_{c\varphi} = (\varphi^\dagger\varphi)\bar{q}_2 u_2\tilde{\varphi} + h.c.,\\
&O_{WWW} = \epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho, && O_{\varphi G} = \varphi^\dagger\varphi G_{\mu\nu}G^{\mu\nu},
\end{aligned}
$$

- Higgs trilinear coupling: [S. Di Vita et al. '17]

$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}}, \qquad \lambda_3^{\rm SM} = \frac{m_h^2}{2v^2}.$$

- Assuming precision EW test is perfect, so

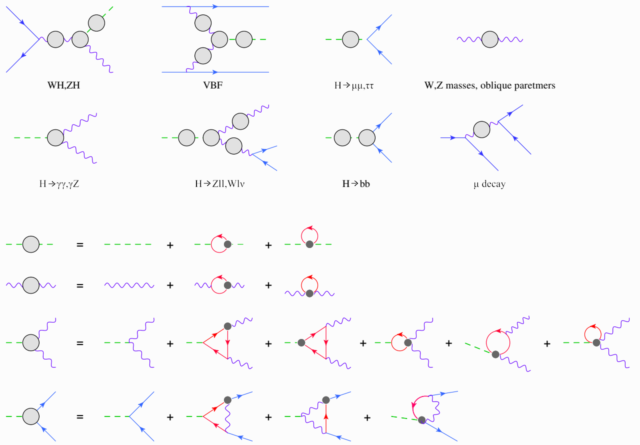
$$O_{\varphi WB} = \varphi^\dagger\tau^I\varphi W^I_{\mu\nu}B^{\mu\nu}, \quad O_{\varphi D} = \left(\varphi^\dagger D^\mu\varphi\right)^*\left(\varphi^\dagger D_\mu\varphi\right).$$

are tuned to minimize deviations from precision EW test.

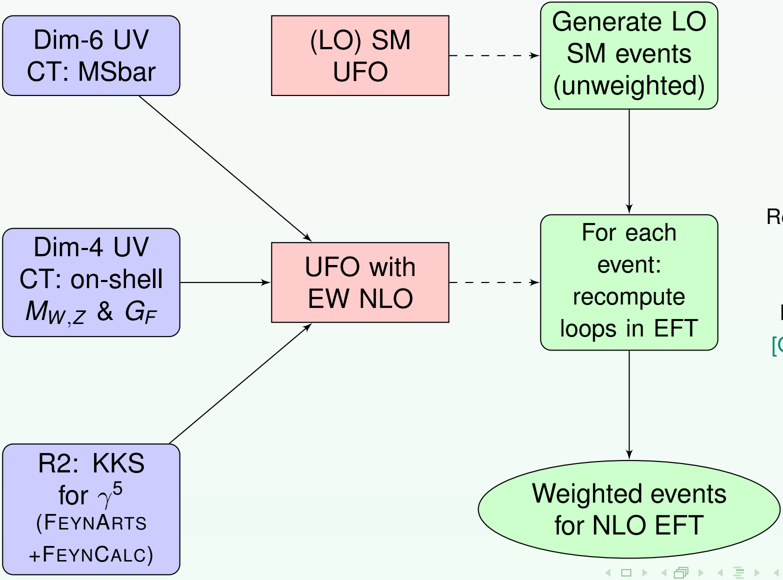
Outline

Dimension-six electroweak top-loop effects in Higgs production and decay

Based on *[E. Vryonidou, **CZ**, 18]*



How it works (for now)



Reweighting module of MG5 based on [Olivier, '16]

RG mixing

	$O_{\varphi t}$	$O^{(+)}_{\varphi Q}$	$O^{(-)}_{\varphi Q}$	$O_{\varphi tb}$	O_{tW}	O_{tB}	$O_{t\varphi}$
$O_{\varphi WB}$	$\frac{1}{3s_W c_W}$	$\frac{1}{3s_W c_W}$	$-\frac{1}{6s_W c_W}$	0	$-\frac{5y_t}{2ec_W}$	$-\frac{3y_t}{2es_W}$	0
$O_{\varphi D}$	$-6\frac{y_t^2}{e^2}$	$3\frac{y_t^2-y_b^2}{e^2}$	$3\frac{y_t^2-y_b^2}{e^2}$	$-6\frac{y_t y_b}{e^2}$	0	0	0
$O_{\varphi\Box}$	$-\frac{3}{2}\frac{y_t^2}{e^2}$	$-\frac{3y_t^2+6y_b^2}{2e^2}$	$\frac{6y_t^2+3y_b^2}{2e^2}$	$3\frac{y_t y_b}{e^2}$	0	0	0
$O_{\varphi W}$	0	$\frac{1}{4s_W^2}$	$-\frac{1}{4s_W^2}$	0	$\frac{3y_t}{2es_W}$	0	0
$O_{\varphi B}$	$\frac{1}{3c_W^2}$	$\frac{1}{12c_W^2}$	$\frac{1}{12c_W^2}$	0	0	$\frac{5y_t}{2ec_W}$	0
O_W	0	$\frac{1}{es_W}$	$-\frac{1}{es_W}$	0	0	0	0
O_B	$\frac{4}{3ec_W}$	$\frac{1}{3ec_W}$	$\frac{1}{3ec_W}$	0	0	0	0
$O_{b\varphi}$	0	$-\frac{y_b}{2c_W^2} + y_b\frac{8\lambda-3y_t^2-5y_b^2}{4e^2}$	$y_b\frac{-4\lambda+3y_t^2+7y_b^2}{4e^2}$	$\frac{3y_t}{4s_W^2} - y_t\frac{2\lambda+y_t^2-6y_b^2}{2e^2}$	$\frac{y_t y_b}{2es_W}$	0	$\frac{3y_t y_b}{4e^2}$
$O_{\mu\varphi}$	0	$-\frac{3y_\mu(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_\mu(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_t y_b y_\mu}{e^2}$	0	0	$\frac{3y_t y_\mu}{2e^2}$
$O_{\tau\varphi}$	0	$-\frac{3y_\tau(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_\tau(y_t^2+y_b^2)}{2e^2}$	$\frac{3y_t y_b y_\tau}{e^2}$	0	0	$\frac{3y_t y_\tau}{2e^2}$

Consistent with [Alonso, Jenkins, Manohar, Trott]

Renormalization

- Dim-6 coefficients are subtracted by MSbar, except for $C_{\varphi WB}$ and $C_{\varphi D}$, which enter precision EW measurements.
- SM is renormalized in the M_W, M_Z and G_F scheme, but dim-6 modifications enter.
  - In particular we want to fix M_W because it enters the phase space.
- "Perfect precision EW measurements" would imply $C_{\varphi WB} = C_{\varphi D} = 0$ in a tree-level analysis.
  - This cannot be done in MSbar scheme at one-loop level, because the top-quark operators will contribute to precision EW tests.

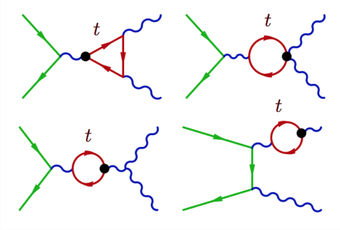
Renormalization

- "On-shell" renormalization using precision EW data, by the following procedures:
  - Add additional counter terms for $C_{\varphi WB}$, $C_{\varphi D}$.
  - Use Z- and W-pole data to perform a global fit, which involves $C_{\varphi WB}$, $C_{\varphi D}$, and all top operators at one loop.
  - In the resulting χ^2, the two tightest constraints are on two linear combinations of $C_{\varphi WB}$, $C_{\varphi D}$ and top-operator coefficients.
  - We adjust the counter terms so that the top-operator couplings drop out from these combinations.
  - **In this specific scheme, "perfect precision measurements" corresponds to exactly** $C_{\varphi WB} = C_{\varphi D} = 0$.
  - One indirect constraint remains and can be combined to our global fit.

Diboson production at one-loop

- $e^+e^- \to W^+W^-$ can be added in the same way.
- Dim-6 contribution to γWW leads to anomaly.
- In our scheme (KKS) this is reflected by the R2 dependence on the "reading point" when tracing the top loop. E.g.

$$O_{\varphi Q}^{(-)}: \quad \frac{e^3 v^2}{48\pi^2 s_W^2 \Lambda^2} \begin{cases} \epsilon^{\mu\nu\rho\sigma}(p_{2\sigma} - p_{3\sigma}) & \gamma \\ \epsilon^{\mu\nu\rho\sigma}(p_{3\sigma} - p_{1\sigma}) & W^+ \\ \epsilon^{\mu\nu\rho\sigma}(p_{1\sigma} - p_{2\sigma}) & W^- \end{cases}$$



- This is fixed by adding a Wess-Zumino-Witten term.

Limitation

- For-fermion *ttll* operators are neglected so far.
- CP conserving only.
- Production + decay not yet available.

Outline

Run scenarios

- Below $t\bar{t}$:
  240 GeV 5 ab^{-1} (CEPC)
- Above $t\bar{t}$:
  350 GeV 0.2 ab^{-1}, and 365 GeV 1.5 ab^{-1} (FCC-ee)

Inputs

Higgs ZH, WW fusion, all decay channels.
Based on [Durieux, Grojean, Gu, Wang, '17], see talk by Jiayin.

Diboson Angular distributions.

Precision EW Assuming a factor of 5 improvements.

Top $t\bar{t}$ with statistical optimal observable.
Based on [Durieux, Perello, Vos, **CZ**, '18]

HL-LHC assumption

Estimates for the precision reachable on key top-quark observables at the HL-LHC.

Channels	Uncertainties without th. unc.	Uncertainties with th. unc.
$t\bar{t}$	4% [1]	7%
Single top (t-ch.)	4% [2]	4%
W-helicity (F_0)	3% [3]	3%
W-helicity (F_L)	5% [3]	5%
$t\bar{t}Z$	10%	15%
$t\bar{t}\gamma$	10%	17%
$t\bar{t}h$	10%	16% [4]
$gg \to h$	4%	11% [4]

[1] A. M. Sirunyan et al. (CMS), Measurement of the $t\bar{t}$ production cross section using events with one lepton and at least one jet in pp collisions at $\sqrt{s}$ = 13 TeV, JHEP 09 (2017) 051
[2] B. Schoenrock, E. Drueke, B. Alvarez Gonzalez, and R. Schwienhorst, Single top quark cross section measurement in the t-channel at the high-luminosity LHC, arXiv:1308.6307 [hep-ex]
[3] M. Aaboud et al. (ATLAS), Measurement of the W boson polarisation in $t\bar{t}$ events from pp collisions at $\sqrt{s}$ = 8 TeV in the lepton + jets channel with ATLAS, Eur. Phys. J. C77 (2017)
[4] ATLAS Collaboration, Projections for measurements of Higgs boson signal strengths and coupling parameters with the ATLAS detector at a HL-LHC, ATL-PHYS-PUB-2014-016 (2014)

Outline

Two types of limits

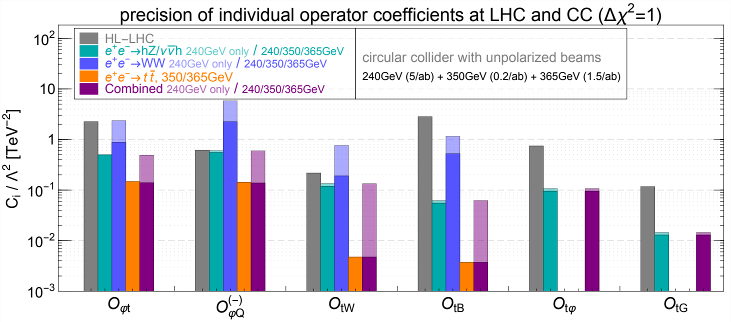
Individual limits One operator at a time. Represents the sensitivity of measurements on a single coefficient.

Marginalized limits All operators are allowed to vary. Conservative constraint on the coefficient, taking into account cancellation effects with others.

Correlation The difference between the above two represents the degree of correlation between different coefficients.

Individual limits

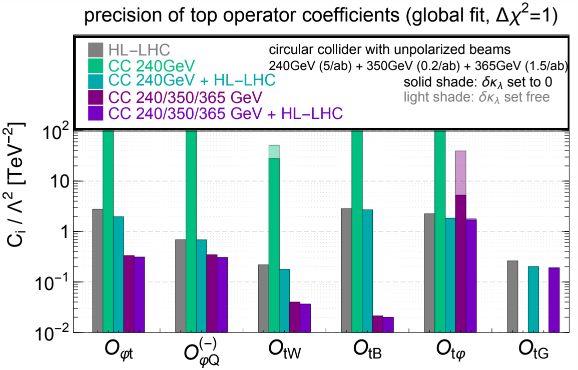
Individual one-sigma reach, one at a time



- Good sensitivity to top couplings below $t\bar{t}$ threshold.
- Loop suppression of top-quark operator contributions is compensated by the high precision of lepton collider.
- Still $ee \to tt$ above 350 GeV provides best sensitivity.
- Diboson sensitivity increases with energy.

Marginalized limits: Top

Global one-sigma precision reach on top-quark operators

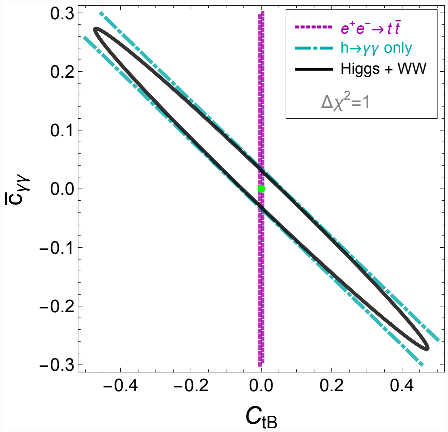


- Indirect bounds are much worse. In particular, large degeneracies if only run at 240 GeV.
- Correlations between Top/Higgs, e.g. $C_{t\varphi}$, C_{tB} and $\bar{c}_{\gamma\gamma}$; $C_{t\varphi}$, C_{tG} and $\bar{c}_{gg}$.

Marginalized limits: Higgs

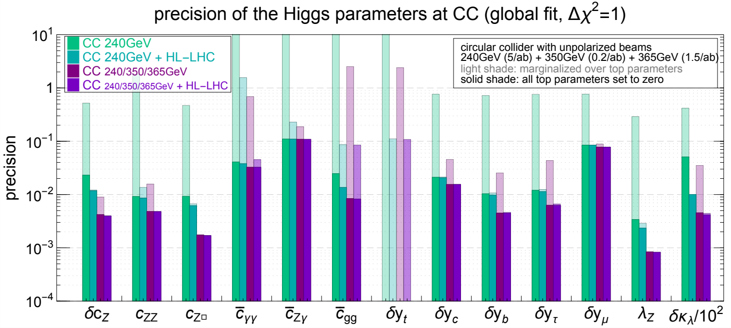
Consider $H \to \gamma\gamma$ on C_{tB} and $\bar{c}_{\gamma\gamma}$

- $H \to \gamma\gamma$ imposes a strong constraint, but also leaves a flat direction.
- Including loop corrections to all other measurements lift this flat direction, but not strong enough to eliminate the degeneracy.
- HL-LHC is too weak.
- $ee \to tt$ at 350/365 will fix C_{tB} which in turn improves $\bar{c}_{\gamma\gamma}$.



Marginalized limits: Higgs

Global one-sigma precision reach on Higgs operators

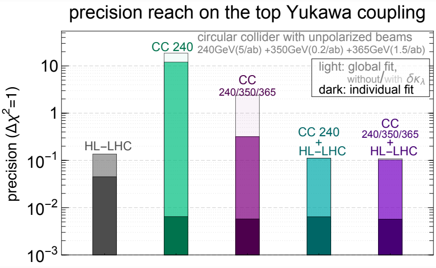


- The difference between bars of lighter and darker shades shows the impact of unknown top-couplings on Higgs couplings.
- At 240 GeV, the inclusion of top-couplings worsen the reach on most Higgs couplings by more than one order of magnitude.
- This effect needs to be solved by 350 GeV run and HL-LHC together.

Top Yukawa

- Large difference between individual/marginalized limits at 240 GeV, due to the same reason.
- Once at 350 GeV, top-gauge couplings will be fixed. Precision on δy_t can reach 32%.
- For comparison:
  - CLIC $t\bar{t}$ threshold scan, 100 fb^{-1} leads to 20% precision, or even better at FCC-ee, see talk by Prof. A. Blondel.
  - ILC 500 GeV, 1 ab^{-1} $ee \to ttH$ leads to 10% precision, assuming SM interactions.

Indirect one-sigma reach on δy_t



Our approach provide a complementary handle on δy_t, with 32% precision, assuming $\delta\kappa_\lambda = 0$ but marginalized over all other top/Higgs couplings.

Outline

Conclusion

- Top quark couplings can be probed indirectly at e^+e^- colliders.
- Below $t\bar{t}$ threshold, individual reach is better than HL-LHC.
- Strong correlation between Top- and Higgs-couplings is present. 350/365 GeV run (plus HL-LHC) is needed to fix Higgs couplings.
- Top-Yukawa can be determined indirectly with 32% precision, marginalized, with 350/365 GeV runs.

Thank you!