Prospects for determining the top quark Yukawa coupling at future e^+e^- colliders

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Based on: Boselli, Hunter, Mitov arXiv:1805.12027

Intro: why the top-Yukawa coupling?

✓ y_t is a derived parameter in the SM. It is known fairly accurately:

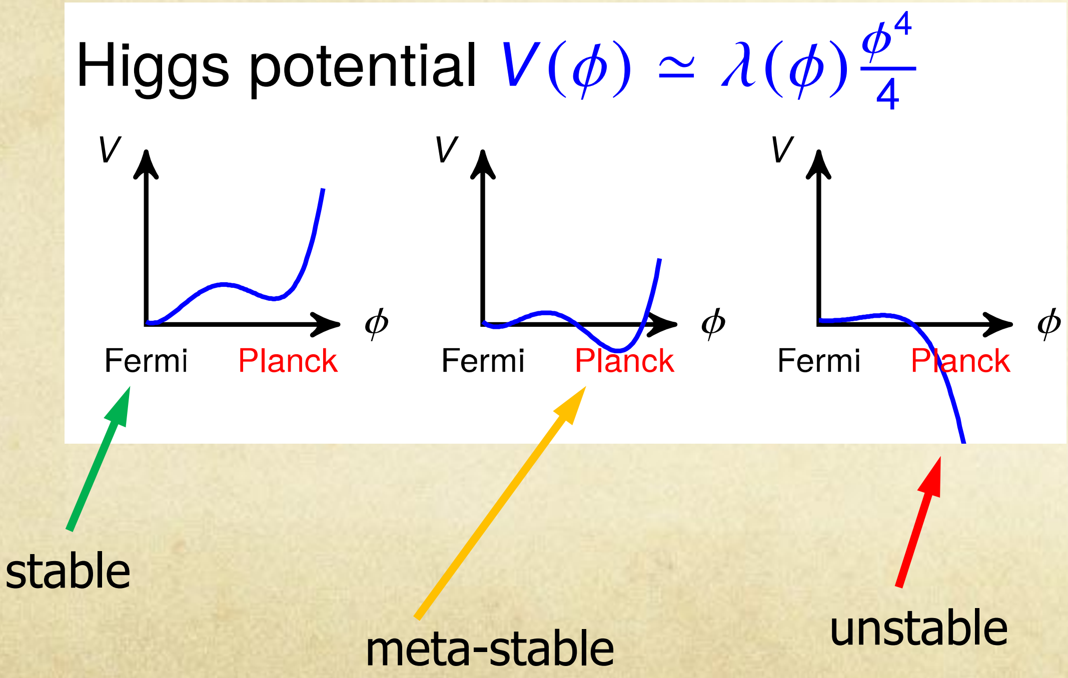
$$y_t(\mu = m_t) \approx 0.9369 + 0.0056\left(\frac{\Delta m_t}{1\mathrm{GeV}}\right) - 0.0006\left(\frac{\Delta\alpha_s}{0.001}\right) \pm \ldots$$

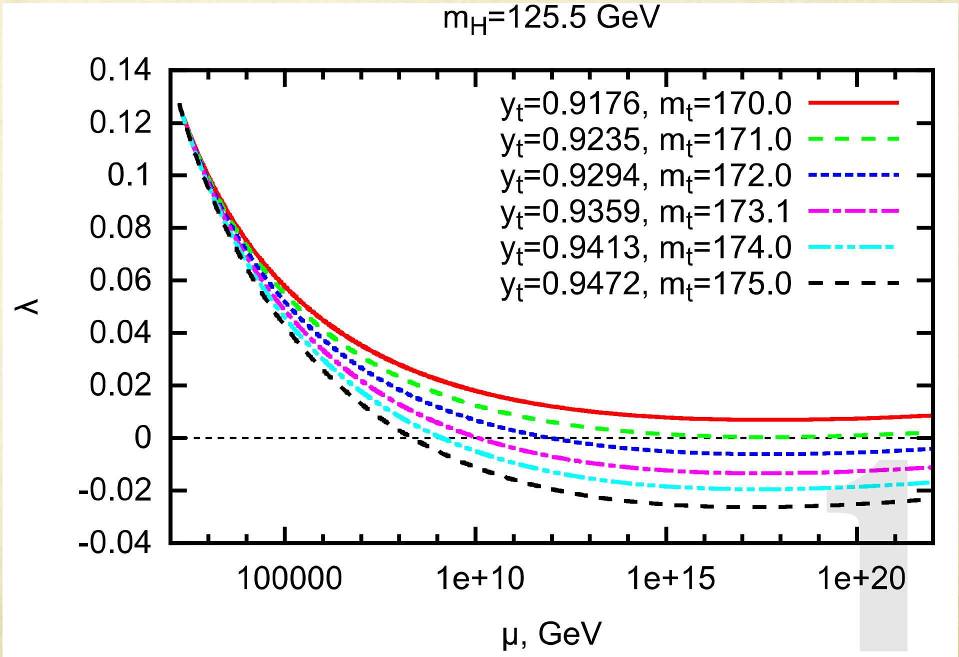
$$y_t(\mu = m_{\mathrm{PL}}) \approx 0.3825 + 0.0051\left(\frac{\Delta m_t}{1\mathrm{GeV}}\right) - 0.003\left(\frac{\Delta\alpha_s}{0.001}\right) \pm \ldots$$

✓ The dominant uncertainty is m_{top} but, currently, only at the sub-percent level!

✓ It is very relevant for understanding the stability of EW vacuum

Plots courtesy of F. Bezrukov





Intro: why the top-Yukawa coupling?

- ✓ We would like to measure y_t directly and verify its SM value
- ✓ It is quite likely that y_t is modified if BSM physics is present

$$y_t = y_t^{\mathrm{SM}} + \Delta y_t$$

- ✓ How to measure Δy_t?
- ✓ And here is the puzzle:
  - ✓ At the LHC we may be able to measure y_t with 10% precision (at HL-LHC)
  - ✓ A 100 TeV hadron collider can measure y_t with 1% precision

Mangano, Plehn, Reimitz, Schell, Shao '15

- ✓ What about e^+e^- colliders?
  - ✓ Usual wisdom: obtain y_t from tth final states.
    - ✓ This offers clean(er) interpretation of the measurement
    - ✓ However, we need a 500GeV c.m. energy to produce tth!
  - ✓ Accessible only at CLIC and ILC (among all proposed colliders)
  - ✓ Existing studies show that y_t can be measured with 4.3% at CLIC and 5% at ILC
  - ✓ Such a prospect is a bit underwhelming, isn't it?

See talk by Yixuan Zhang on Tue

Intro: why the top-Yukawa coupling?

- ✓ Why is the precision from tth so low?
- ✓ Answer: luminosity is low, despite the very good sensitivity of the x-section w/r to y_t.
- ✓ In this work we ask the question: how can one do better (if possible at all)?
- ✓ Clearly, one has to look at different observables; ideally ones with high expected event yields.
- ✓ We consider events with a single Higgs in the final state but no top quarks.
  - ✓ tt final states also have some sensitivity to y_t . It is low; has been studied in the context of m_{top} determination

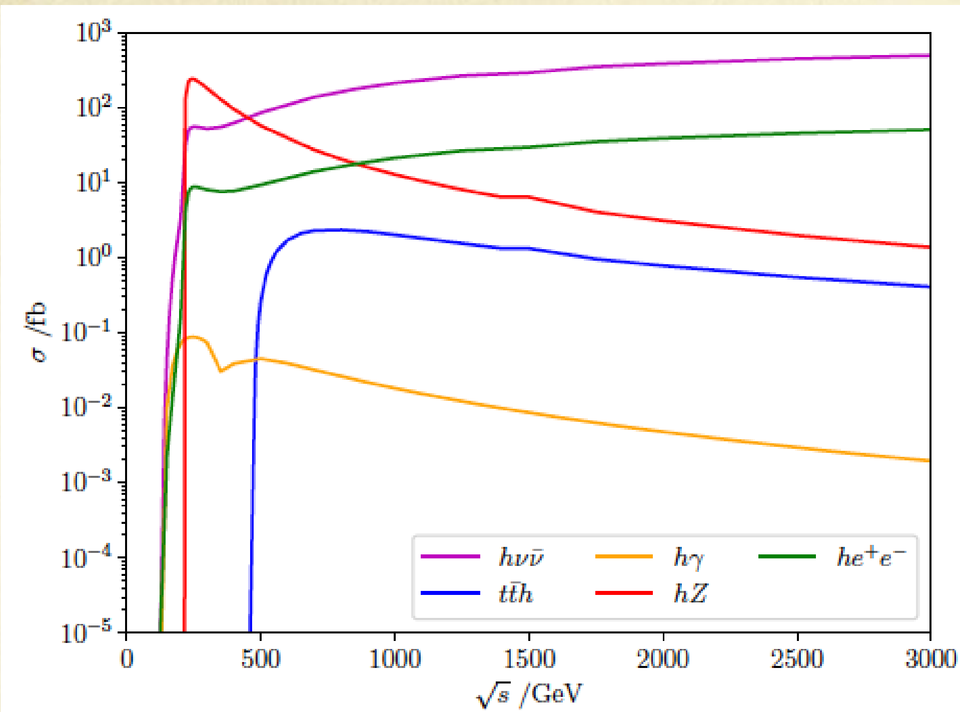
See talks by
Yuichiro Kiyo
Frank Simon
Pablo Lopez

- ✓ We consider all proposed colliders (CEPC, CLIC, FCC-ee, ILC)
- ✓ A great benefit from using single Higgs final states: they can be produced in (relative) abundance at all energies and at all colliders!
- ✓ Where does the y_t sensitivity come from in such processes?
- ✓ From coupling of the Higgs to top quarks in loops (working in the NWA for the Higgs)

Our approach

- ✓ We have identified 3 such loop-induced processes:
  - ✓ $e^+e^- \to h\gamma$ (with $h \to bb$)
  - ✓ $h \to \gamma\,\gamma$ (from $e^+e^- \to hZ/h\nu\nu/hee$)
  - ✓ $h \to g\,g$ (from $e^+e^- \to hZ/h\nu\nu/hee$)
- ✓ Here is a LO estimate of x-sections and event yields

	FCC-ee		CEPC
$\sqrt{s}$ (GeV)	240	350	240
$\mathcal{L}_{\text{int.}}$ (fb^{-1})	$1.0 \cdot 10^4$	$2.6 \cdot 10^3$	$5.0 \cdot 10^3$
σ_{hZ} (fb)	240	130	240
$\mathcal{N}_{hZ}$	$2.4 \cdot 10^6$	$3.38 \cdot 10^5$	$1.2 \cdot 10^6$
$\sigma_{\nu\bar{\nu}h}$ (fb)	54.4	54.7	54.4
$\mathcal{N}_{\nu\bar{\nu}h}$	$5.44 \cdot 10^5$	$1.42 \cdot 10^5$	$2.72 \cdot 10^5$
σ_{eeh} (fb)	7.9	7.13	7.9
$\mathcal{N}_{eeh}$	$7.9 \cdot 10^4$	$1.85 \cdot 10^4$	$3.95 \cdot 10^4$
$\sigma_{h\gamma}$ (fb)	$8.96 \cdot 10^{-2}$	$3.18 \cdot 10^{-2}$	$8.96 \cdot 10^{-2}$
$\mathcal{N}_{h\gamma}$	896	82	448



	CLIC			ILC	
$\sqrt{s}$ (GeV)	350	1400	3000	250	500
$\mathcal{L}_{\text{int.}}$ (fb^{-1})	$5.0 \cdot 10^2$	$1.5 \cdot 10^3$	$2.0 \cdot 10^3$	$2.0 \cdot 10^3$	$4.0 \cdot 10^3$
σ_{hZ} (fb)	130	6.42	1.37	240	57.2
$\mathcal{N}_{hZ}$	$6.50 \cdot 10^4$	$9.6 \cdot 10^3$	$2.74 \cdot 10^3$	$4.80 \cdot 10^5$	$2.29 \cdot 10^5$
$\sigma_{\nu\bar{\nu}h}$ (fb)	54.4	293	498	55.0	85.2
$\mathcal{N}_{\nu\bar{\nu}h}$	$2.73 \cdot 10^4$	$4.39 \cdot 10^5$	$9.96 \cdot 10^5$	$1.10 \cdot 10^5$	$3.41 \cdot 10^5$
σ_{eeh} (fb)	7.13	28.3	49.1	8.2	8.7
$\mathcal{N}_{eeh}$	$3.56 \cdot 10^3$	$4.24 \cdot 10^4$	$9.82 \cdot 10^4$	$1.64 \cdot 10^4$	$3.48 \cdot 10^4$
$\sigma_{t\bar{t}h}$ (fb)	-	1.33	0.41	-	0.27
$\mathcal{N}_{t\bar{t}h}$	-	1995	820	-	$1.08 \cdot 10^3$
$\sigma_{h\gamma}$ (fb)	$3.18 \cdot 10^{-2}$	$1.20 \cdot 10^{-2}$	$3.08 \cdot 10^{-3}$	$8.97 \cdot 10^{-2}$	$4.74 \cdot 10^{-2}$
$\mathcal{N}_{h\gamma}$	16	18	6	179	189

Fit methodology

✓ Extract y_t from a chi^2 fit (assuming this is the only parameter to be fit; more later)

$$\chi^2(\Delta y_t) = \sum_{i=1}^{N_p} \sum_{j=1}^{N_d} \frac{[\mu_{ij}(\Delta y_t) - 1]^2}{\delta_{ij}^2}$$

Sums over these pairs of channels

Collider	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (fb^{-1})	$h \to gg$		$h \to \gamma\gamma$		$h \to b\bar{b}$	
			hZ	$\nu\bar{\nu}h$	hZ	$\nu\bar{\nu}h$	$h\gamma$	$t\bar{t}h$
FCC-ee	240	$1.0 \cdot 10^4$	1.4%	-	3.0%	-	4.4%	-
	350	$2.6 \cdot 10^3$	3.1%	4.7%	14%	21%	14%	-
CEPC	240	$5.0 \cdot 10^3$	1.2%	-	9.0%	-	6.2%	-
CLIC	350	$5.0 \cdot 10^2$	6.1%	10%	-	-	-	-
	1400	$1.5 \cdot 10^3$	-	5.0%	-	15%	-	8.0%
	3000	$2.0 \cdot 10^3$	-	4.3%	-	10%	-	12.5%
ILC	250	$2.0 \cdot 10^3$	2.5%	-	12%	-	10%	-
	500	$4.0 \cdot 10^3$	3.9%	1.4%	12%	6.7%	9.8%	9.9%

where: $$\mu_{ij} = \left(\frac{\sigma_i}{\sigma_i^{\rm SM}}\right)\left(\frac{\Gamma_j}{\Gamma_j^{\rm SM}}\right)\left(\frac{\Gamma_h}{\Gamma_h^{\rm SM}}\right)^{-1}$$

✓ SM above means, basically, that $\Delta y_t=0$

✓ One-sigma uncertainties $\boldsymbol{\delta}_{ij}$ are taken from the literature.

- ✓ An exception is $e^+e^- \to h\gamma$ which is estimated by us based purely on the expected number of events (see previous slide). Likely to be optimistic.

Signal-strengths

✓ Here are the needed signal-strengths

$$\mu_{h\gamma} = \begin{pmatrix} \sqrt{s} = 240\,\mathrm{GeV} \\ \sqrt{s} = 250\,\mathrm{GeV} \\ \sqrt{s} = 350\,\mathrm{GeV} \\ \sqrt{s} = 500\,\mathrm{GeV} \end{pmatrix} = \frac{\sigma_{h\gamma}}{\sigma_{h\gamma}^{\mathrm{SM}}} = 1 - \begin{pmatrix} 0.43 \\ 0.45 \\ 0.73 \\ 0.13 \end{pmatrix} \Delta y_t$$

$$\mu_{t\bar{t}h} \begin{pmatrix} \sqrt{s} = 500\,\mathrm{GeV} \\ \sqrt{s} = 1400\,\mathrm{GeV} \\ \sqrt{s} = 3000\,\mathrm{GeV} \end{pmatrix} = \frac{\sigma_{t\bar{t}h}}{\sigma_{t\bar{t}h}^{\mathrm{SM}}} = 1 + \begin{pmatrix} 1.99 \\ 1.83 \\ 1.71 \end{pmatrix} \Delta y_t,$$

$$\mu_{h\to gg} = \frac{\Gamma_{h\to gg}}{\Gamma_{h\to gg}^{\mathrm{SM}}} = 1 + 2\Delta y_t\,,$$

$$\mu_{h\to\gamma\gamma} = \frac{\Gamma_{h\to\gamma\gamma}}{\Gamma_{h\to\gamma\gamma}^{\mathrm{SM}}} = 1 - 0.56\Delta y_t$$

✓ Derived by us at LO (full one loop):

- ✓ Compute x-sections and decay widths for a number of values of Δy_t ,
- ✓ Fit this with a quadratic polynomial,
- ✓ Take the linear approximation for small Δy_t.
- ✓ Bottom contribution to h ➛ g g neglected.

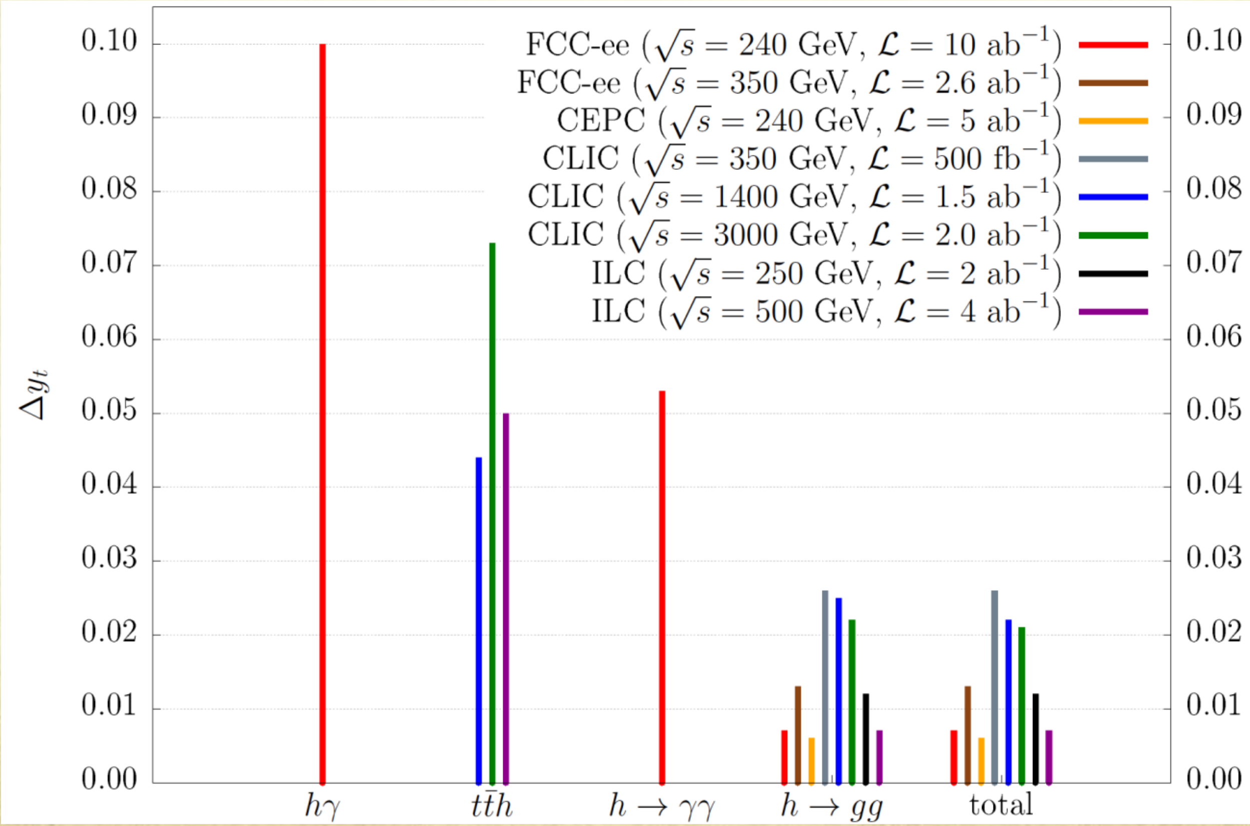
✓ Higher-order corrections in some cases have been included in the literature (CLIC 1.4 TeV).

Abramowicz et al., arXiv:1608.07538

- ✓ Slightly increases the expected precision

Results: top-Yukawa precision prospects

Collider	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (fb^{-1})	$h \to gg$	$h \to \gamma\gamma$	$h\gamma$	$t\bar{t}h$	total
FCC-*ee*	240	$1.0 \cdot 10^4$	0.7%	5.3%	10%	-	0.7%
	350	$2.6 \cdot 10^3$	1.3%	21%	19%	-	1.3%
CEPC	240	$5.0 \cdot 10^3$	0.6%	16%	14%	-	0.6%
CLIC	350	$5.0 \cdot 10^2$	2.6%	-	-	-	2.6%
	1400	$1.5 \cdot 10^3$	2.5%	27%	-	4.4%	2.2%
	3000	$2.0 \cdot 10^3$	2.2%	18%	-	7.3%	2.1%
ILC	250	$2.0 \cdot 10^3$	1.2%	21%	23%	-	1.2%
	500	$4.0 \cdot 10^3$	0.7%	10%	75%	5.0%	0.7%



Top-Yukawa precision prospects: few comments

- ✓ h ➛ g g leads, by far, among all loop-induced processes
- ✓ This process offers potential y_t precision of about 0.6-0.7% at
  - ✓ 240 GeV CEPC and FCC-ee
  - ✓ 500 GeV ILC
- ✓ h ➛ g g is better than tth for all energies and colliders by a factor of at least 2 (CLIC) and up to 7 (ILC)
- ✓ e^+e^- ➛ h**γ** allows 10% determination. It is not great, but is comparable to HL-LHC
- ✓ h ➛ **γ γ** allows about 5-6% precision at FCC-ee 240 GeV
- ✓ CLIC can measure y_t with precision of 2-2.5% (combining loop-induced and tth)
- ✓ ILC can measure y_t with precision of 1% or even better (combining loop-induced and tth)

Limitations, assumptions and possible improvements

- ✓ $e^+e^- \rightarrow h\gamma$: no detector simulation, efficiencies or background estimates. All done at LO.
- ✓ m_{top}: we assume perfect knowledge of the top mass. In reality already after HL-LHC this error will be negligible
- ✓ Lack of proper EFT treatment:
  - ✓ We assume Δy_t is the only source of deviation from SM and so is the only parameter to fit
  - ✓ However, assuming BSM, no reason to have just one source of deviation from SM
  - ✓ Multiple Wilson coefficients will enter. This will dilute the expected precision on y_t.
  - ✓ However, after HL-LHC there will be many constraints on those coefficients.
- ✓ Assumed perfect knowledge of SM predictions.
  - ✓ In reality all is at LO (although fully one loop effects included)
  - ✓ NLO effects can be computed with some effort (2-loop amplitudes)
  - ✓ Realistic cuts imposed, etc.
- ✓ All of the above need to be done but we do not expect to change the picture qualitatively!

Conclusions

- This work tries to address the question: is it really not possible to measure y_t at a future e^+e^- collider with precision better than 4-5%?

- Such a prospect would be disheartening given we expect 10% from HL-LHC and 1% from a 100 TeV hadron collider

- This is an exploratory work. Its precision level is basic; still, we believe it is adequate in order to get a global picture about what is the ultimate possibility for measuring y_t at any one of the future e^+e^- colliders

- We consider *indirect* determination from loop-induced single Higgs processes

- Our findings are very promising. We find y_t can be measured

    - With precision as high as 0.6%

- This is almost an order of magnitude better that from purely tth final states.

- Such precision measurements can be done at any future e+e- colliders, especially at 240 GeV runs with hZ final states.

- Our work is very preliminary and can be made more precise in a number of ways

- We hope it provides useful input to the current discussion about which collider to build!