

# *top physics opportunities at the threshold*

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**ILD meeting, 16 January 2024**

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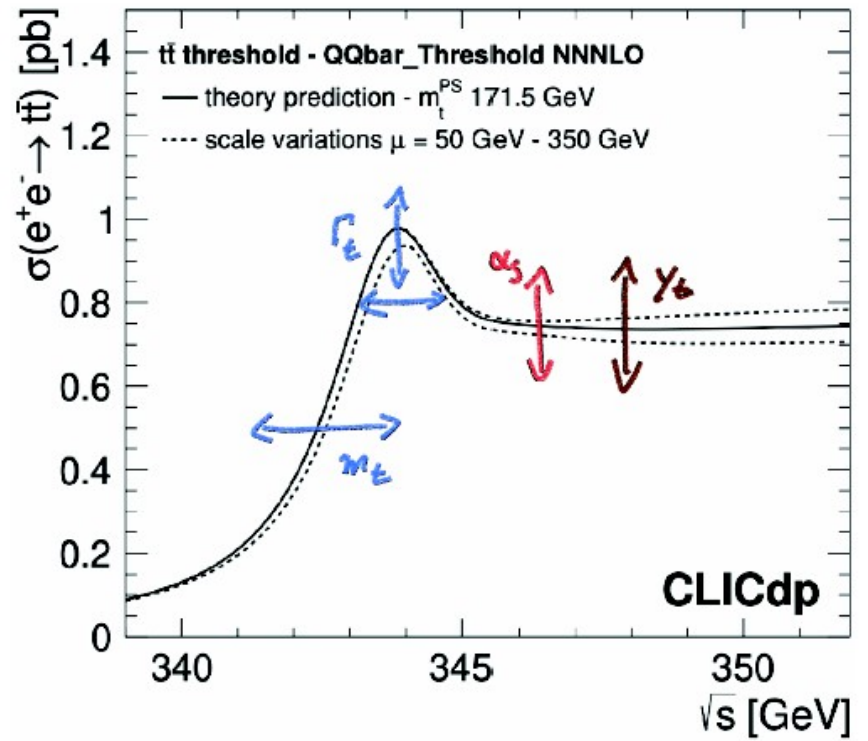
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# The $t\bar{t}$ threshold scan

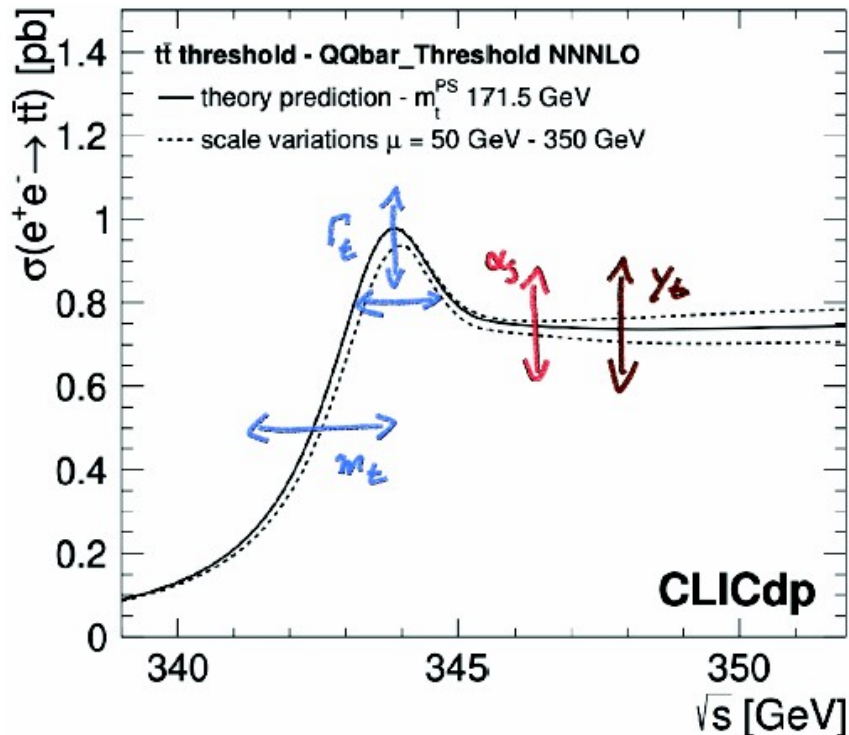


## e+e- threshold scan

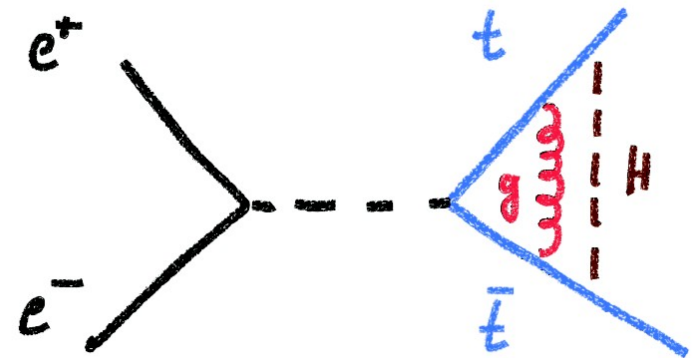
A scan of the  $e^+e^-$  center-of-mass energy through the pair production threshold allows for the ultimate mass measurement (*Gusken & Kuhn '85, Peskin & Strassler '91*)

Experimental studies: Martinez & Miquel, hep-ph/020735, Seidel et al., arXiv:1303.3758

**Part of the operation plan for all e+e- collider projects: Higgs & top factory!**



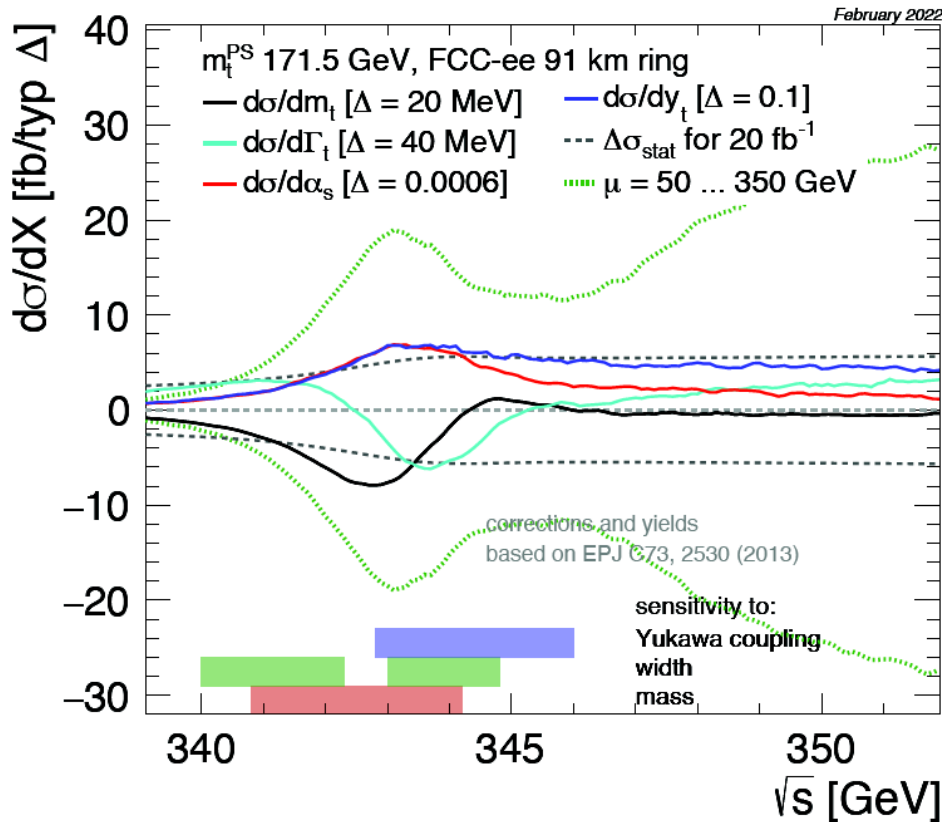
Art-work: Frank Simon



The threshold position is sensitive to the top quark mass, the shape to the width  
 The normalization is sensitive to strong coupling and top quark Yukawa coupling  
 Just measure the cross section vs.  $\sqrt{s}$  shape and derive all parameters

# Top quark mass

Frank Simon's seminar  
Snowmass top physics report



Statistical uncertainty - - - can be made small with 1-2 years of operation

Theory uncertainty ..... requires calculation beyond NNNLO (QCD) + NNLO (EW). Resummation is available and can be added.

Note: interpretation unambiguous, translation to  $\overline{\text{MS}}$  scheme with  $\mathcal{O}(10 \text{ MeV})$  QCD scale uncertainty, parametric uncertainty from  $\alpha_s$  requires care, as well as EW corrections

Top quark mass to **approx. 50 MeV**, limited by theory uncertainty and to first order independent of collider design (luminosity spectrum has 2nd order effect)

Top quark width to 45 MeV → bounds on invisible decays+SMEFT arXiv:1907.00997  
Precision for  $\alpha_s \sim 0.001$  and  $y_t \sim 12\%$  not competitive, but good cross-checks

# Future directions

Exp: Full-simulation study to revisit and harmonize experimental systematic uncertainties

Theo: Fully differential predictions at adequate precision

Specify procedure for comparison of data and theory (i.e. treatment of ISR, off-shell?)

Study width prospects in more detail (i.e. comparison LHC, interpretation in NP scenarios)

Embed top mass prospect in global EW fit environment

Find a way to make top Yukawa and strong coupling results more competitive

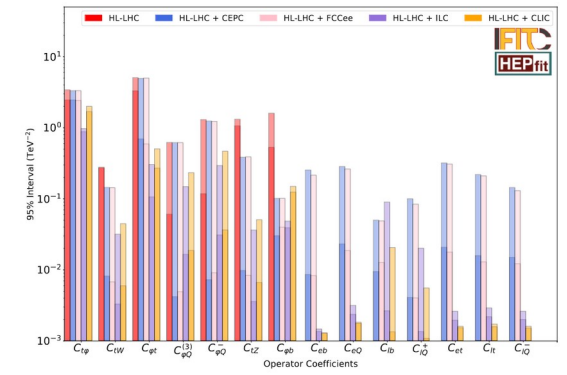
## Concrete decisions:

-- generate ILD samples at threshold?

-- which generator setup should be used?

- WHIZARD  $e+e-$   $\rightarrow$  6 fermions (important for discussion with theory)
- WHIZARD  $e+e-$   $\rightarrow$   $WbWb$  (with threshold model and beam polarization?)
- Something else? (note Pythia8  $e+e-$   $\rightarrow$   $t\bar{t}$  samples produced by FCCee)

# Above the threshold: a broad precision programme

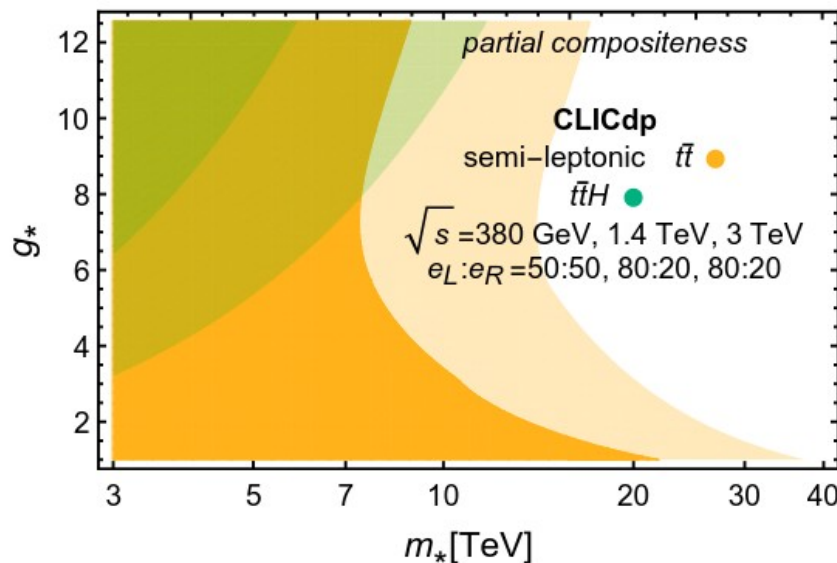


# BSM physics and top quark couplings

**Top (and its couplings) are special in many BSM scenarios**  
**Precision coupling measurements ARE a sensitive BSM search**  
Snowmass top physics report, <https://arxiv.org/pdf/2209.11267.pdf>

## D. Top-quark compositeness

High-energy lepton colliders are sensitive probes of top-quark compositeness. For example, Fig. 30 shows the reach in the composite sector confinement scale  $m_*$  and the composite coupling strength parameter  $g_*$  of a partial top compositeness scenario at a multi-TeV  $e^+e^-$  collider [61] (see also [542]).

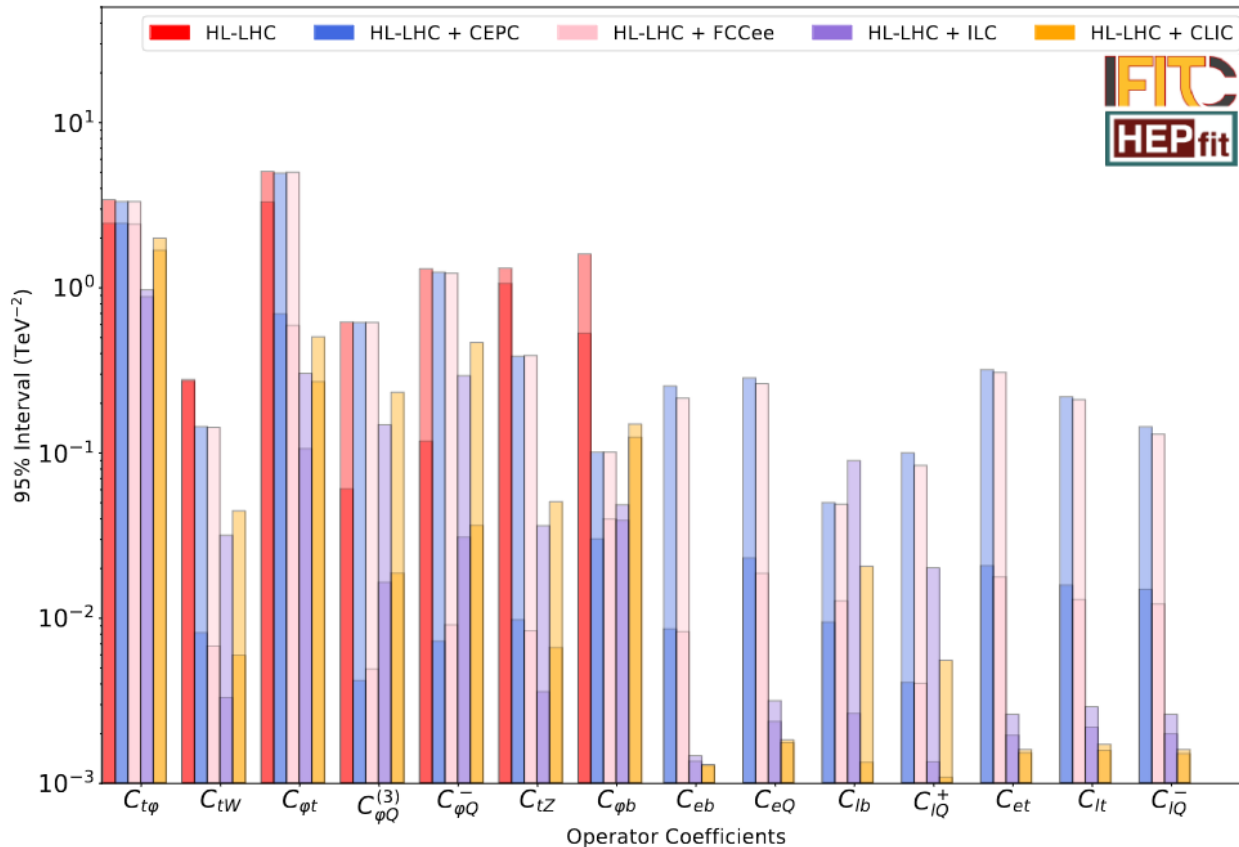


**energy + precision  
= BSM sensitivity**

# SMEFT fit HL-LHC + e+e- collider

EFT for e+e-: Durieux et al. , arXiv:1807.02121  
 top EW fit HL-LHC/e+e-: Durieux et al., arXiv:1907.10619  
 Snowmass top couplings, arXiv:2205.02140  
 Global SMEFT fit, J. De Blas et al., arXiv:2206.08326  
 Snowmass report, Schwienhorst et al., arXiv:2209.11267

four-quark operators (qqtt): no progress  
 two-fermion top-boson:  $O(1) \rightarrow O(0.1)$   
 Two-lepton-two-top (lltt):  $XXX \rightarrow O(10^{-1} - 10^{-3})$



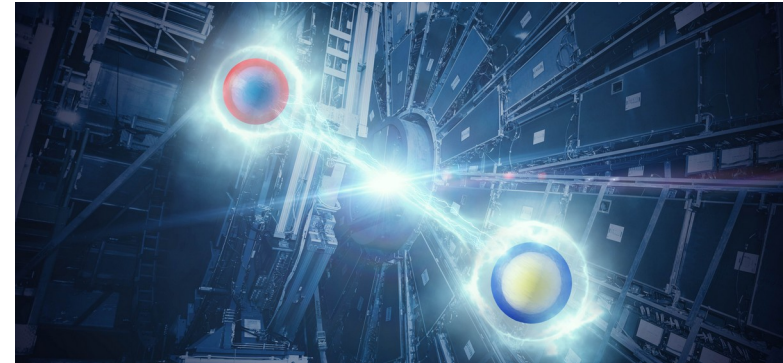
*Snowmass SMEFT fit based on Durieux et al.,  
 with updated operating scenarios*



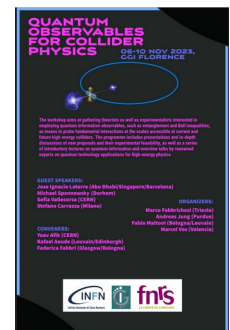
# Quantum information at colliders?

LHC: “an established top QI lab” since Sep. 2023.  
Great statistics; complex “mixed-state” production

Future e+e-: carefully prepared initial state  
(including tunable beam polarization)



Quantum observables for HEP, GGI, Nov. 23



## Future improvements

Complete and update LHC/HL-LHC fit at NLO (work in progress)

Add imaginary parts that are left out (and compare to low-energy observables)

Xunwu@KIT explores FCCee potential following *Janot, JHEP04 (2015)*

Merge top EFT fit with Higgs/EW fit (major project!)

Explore new ideas

## Summary

**The next large-scale e+e- facility in HEP can (should) do a lot of top physics!**

**An energy scan through the pair production threshold** yields the ultimate top quark mass measurement + width, strong coupling, top quark Yukawa

**A broad precision programme of top measurements unfolds above threshold** including many processes (tt, tt $\gamma$ , ttg, single top, ttZ, ttH, VBF tt production) and many measurements ( $\sigma$ ,  $A_{\text{FB}}$ , polarization, CP-odd observables...).

Expert team is in place, with representatives from experiment and theory.  
Long-term goals are clear and several smaller (but very nice) projects are defined.

Looking forward to more ideas and your contributions.