# *New results in top physics at e+e- colliders*

***Mostly results from ECFA focus topic study, special thanks to:***

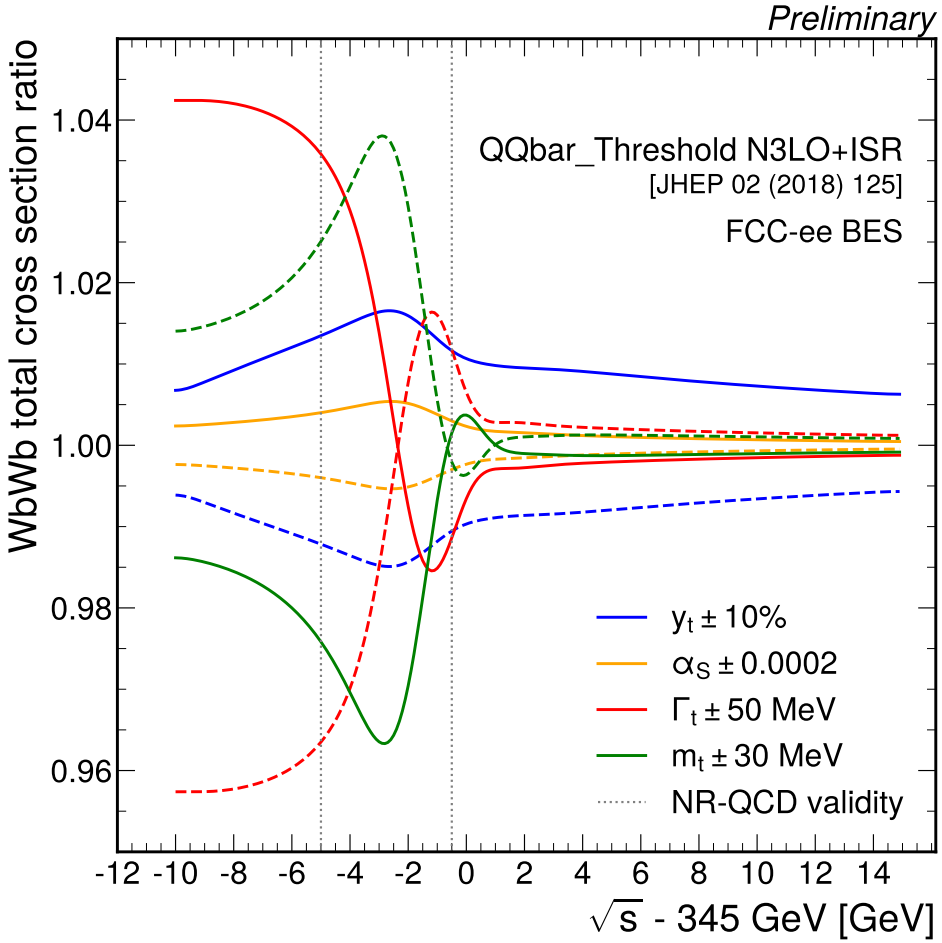
***Matteo Defranchis, Jaco ter Hoeve, Ankita Mehta, Victor Miralles & Fernando Cornet***

*Marcel Vos (IFIC- CSIC/UV, Valencia), on behalf of "tthreshold team"*

**LC Vision meeting, CERN, 08 January 2025**


marcel.vos@ific.uv.es

# Top quark mass from threshold scan




Fast-simulation study in FCCee environment, using state-of-the-art tools

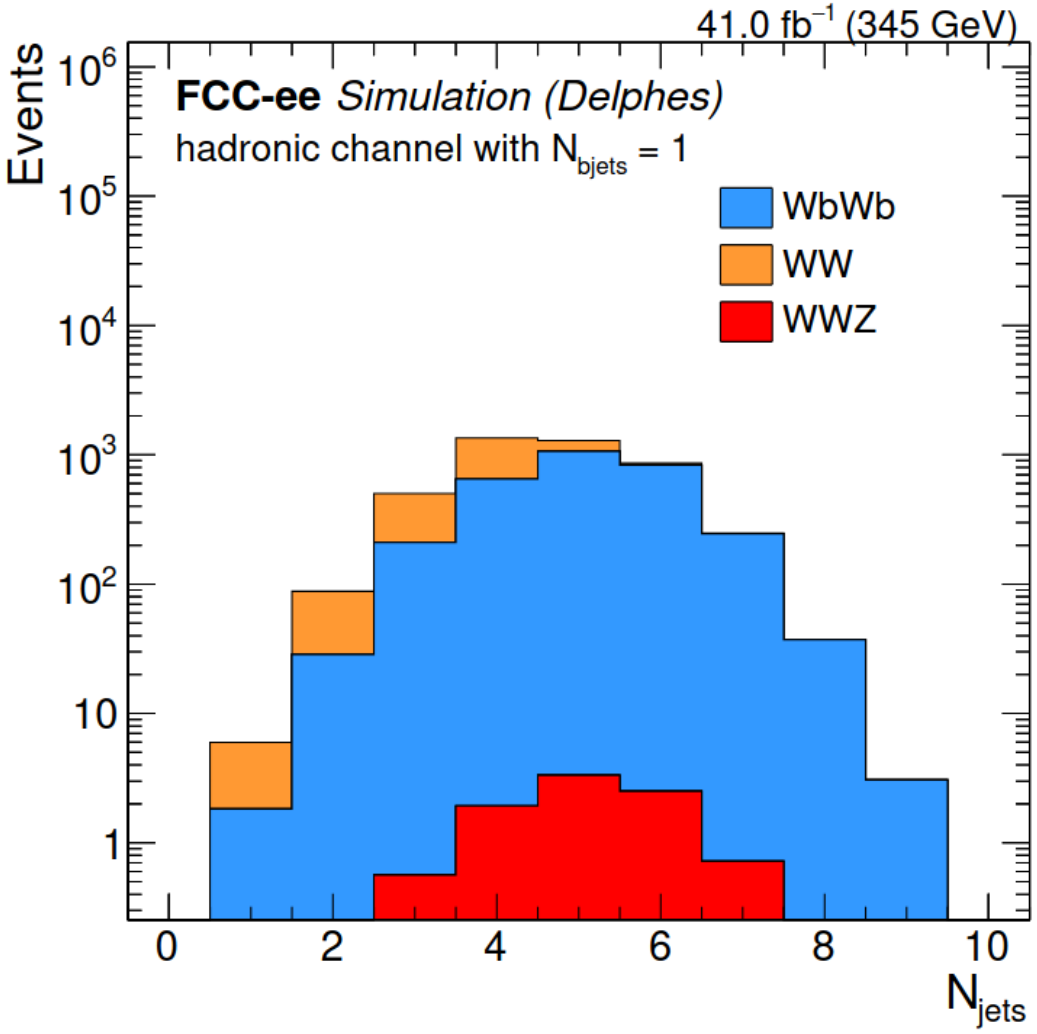
Profile likehood fit, **in-situ control of b-tagging efficiency and background**

Theory & parametric uncertainties from QQThreshold fits to pseudo-data

Assessed machine-related uncertainties
- synchrotron radiation (circular)
- luminosity spectrum (linear)

Matteo Defranchis, Ankita Mehta + Michele Selvaggi & M.V.

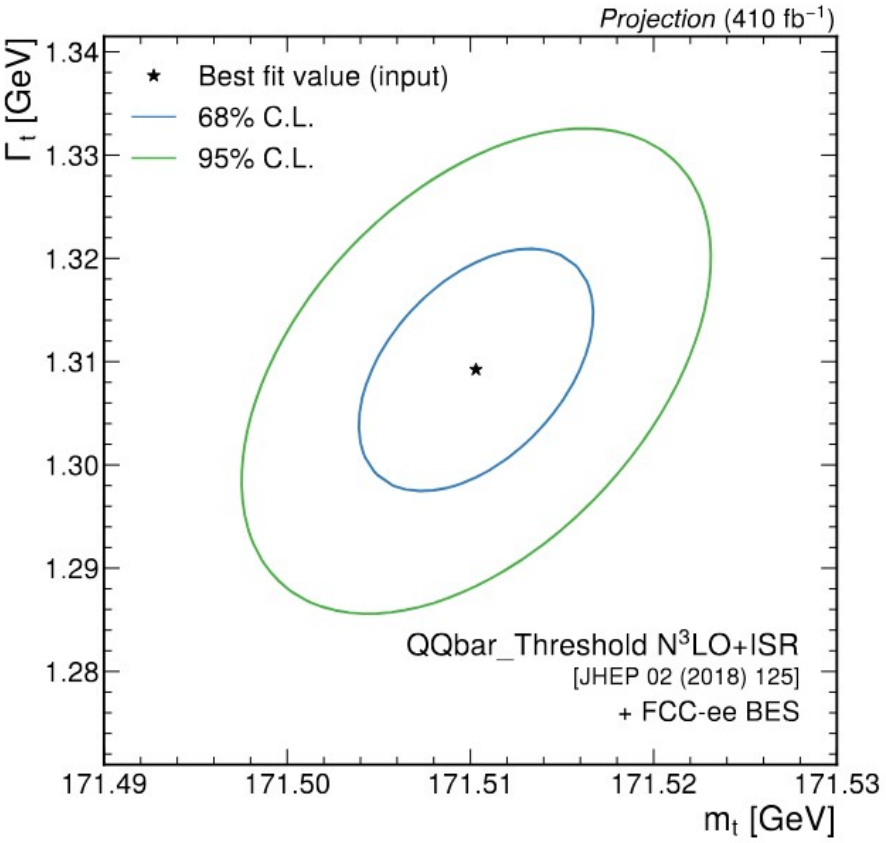
# Top quark pair production cross section




Simultaneous fit to jet multiplicity in 1- and 2-b-jet events to extract signal cross section, background rate and in-situ b-tagging efficiency (modern version of double-tag analysis also used at LEP and in ATLAS/CMS)

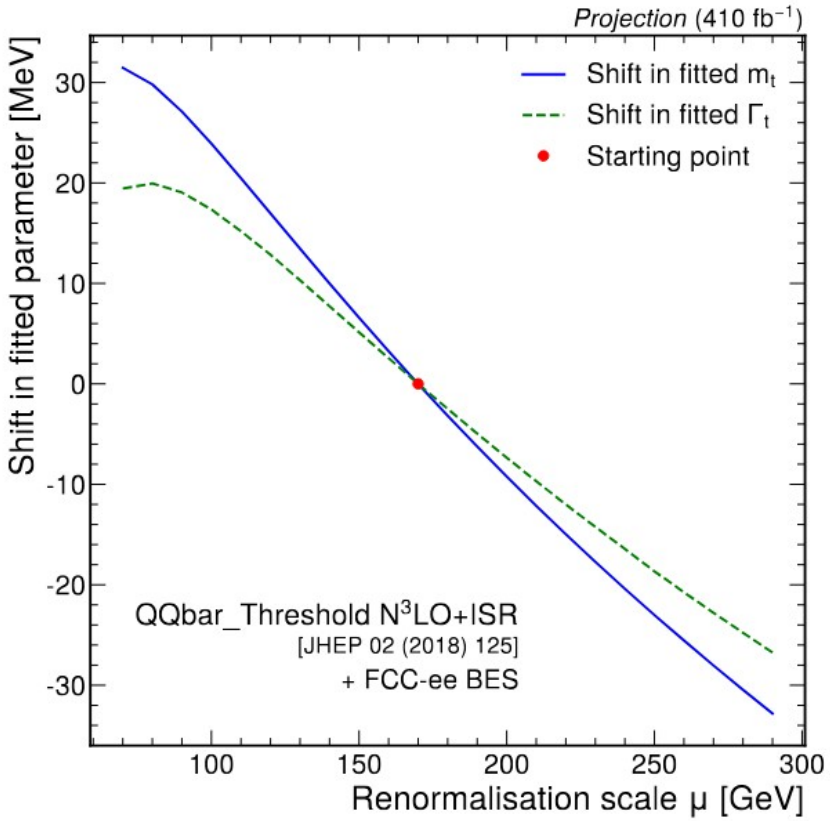
Impact of uncertainty on background normalization and b-tagging efficiency is negligible.

# Uncertainties (I)




Statistical uncertainty on top mass: **4 MeV**
- FCCee statistics of 410 fb$^{-1}$
- external inputs for $\alpha_s$ and $y_t$
- scan configuration: 10 points over 5 GeV

*(less aggressive than Zarnecki et al. or CEPC)*

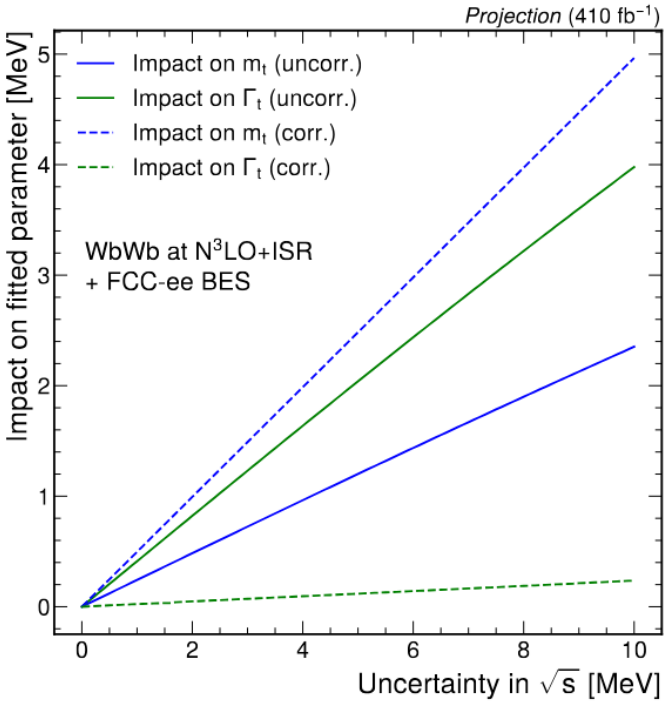


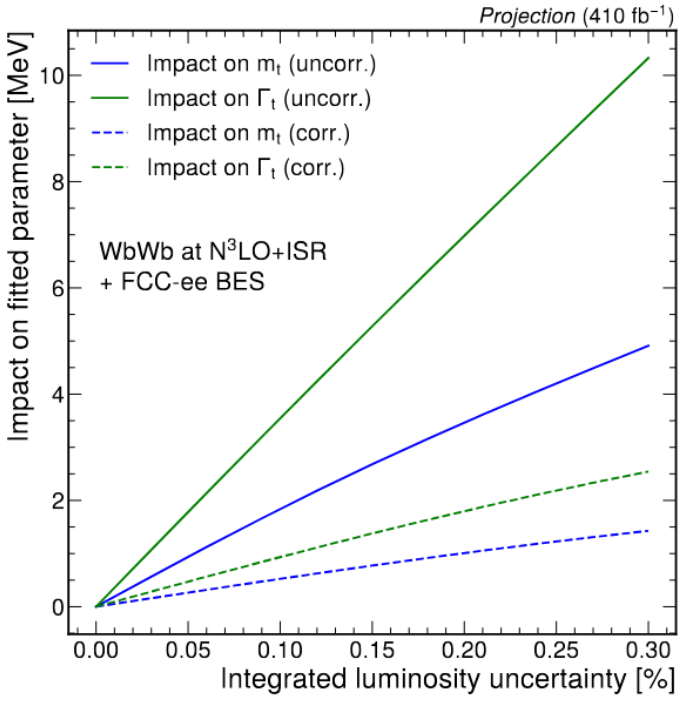

Theory uncertainty is dominant: **35 MeV**
- varying scales in N3LO NRQCD
- multiple scales (hard scale dominates)
- using canonical factors ½ and 2

(this procedure is slightly different from previous studies, e.g. F. Simon, ICHEP2016, but yields similar numbers)

# Uncertainties (II): machine calibration

The machine parameters (cms energy, int. luminosity) must be known precisely to take full advantage of the threshold scan; the input uncertainties may depend on the machine and are not always known; scan uncertainty and register impact on fit




**Distinguish correlated (same for all scan points) and uncorrelated sources**

$\sqrt{s}$ : correlated = input W/Z boson mass ; uncorrelated = W/Z stats in scan point

Lumi : correlated = Bhabha x-sec prediction ; uncorrelated = Bhabha stats

**Need to sit down with LC vision experts on sqrt(s) and luminosity calibration**

# Uncertainties (III): example systematics table (for FCCee)

Statistical uncertainty is non-negligible, but no show-stopper; even with less data than 410/fb
Machine uncertainties are often not documented; can be rescaled as better estimates appear
Parametric uncertainties are non-negligible; from HL-LHC ($y_t$) and lattice/Z-pole ($\alpha_s$)
Theory remains bottle-neck; "no comment" from theorists on N4LO (resummation not too effective)

| uncertainty | $m_t^{PS}$ [MeV] | $\Gamma_t$ [MeV] | comment |
|---|---|---|---|
| statistical | 3.7 | 9.6 | FCC-ee, 410 $fb^{-1}$ |
| b-tagging, background | - | - | controlled in-situ |
| luminosity calibration (uncorr.) | 0.6 | 1.1 | $\delta L/L = 1 \times 10^{-3}$ [928] |
| luminosity calibration (corr.) | 0.3 | 0.5 | $\delta L/L = 0.5 \times 10^{-3}$ |
| beam energy calibration (uncorr.) | 1.2 | 2.0 | $\delta\sqrt{s} = 5$ MeV [926, 927] |
| beam energy calibration (corr.) | 1.2 | 0.1 | $\delta\sqrt{s} = 2.5$ MeV |
| beam energy spread (uncorr.) | 0.6 | 1.1 | $\delta\Delta E = 1\%$ [927] |
| beam energy spread (corr.) | $< 0.1$ | 1.5 | $\delta\Delta E = 0.5\%$ |
| parametric ($\alpha_s$) | 2.0 | 1.9 | $\delta\alpha_s = 1 \times 10^{-4}$ |
| parametric ($y_t$) | 3.8 | 4.5 | $\delta y_t = 3\%$ [846] |
| total profiled | 6.2 | 11.3 | |
| theory, unprofiled (scale) | 35 | 25 | $N^3LO$ NRQCD [918] |

Future direction: define proper theory Nps as per F. Tackmann (see arXiv:2411.18606)

# Uncertainties (III): example systematics table (for FCCee)

Statistical uncertainty is non-negligible, but no show-stopper; even with less data than 410/fb
Machine uncertainties are often not documented; can be rescaled as better estimates appear
Parametric uncertainties are non-negligible; from HL-LHC ($y_t$) and lattice/Z-pole ($\alpha_s$)
Theory remains bottle-neck; "no comment" from theorists on N4LO (resummation not too effective)

| uncertainty | $m_t^{PS}$ [MeV] | $\Gamma_t$ [MeV] | comment |
|---|---|---|---|
| statistical | 3.7 | 9.6 | FCC-ee, 410 $fb^{-1}$ |
| b-tagging, background | - | - | controlled in-situ |
| luminosity calibration (uncorr.) | 0.6 | 1.1 | $\delta L/L = 1 \times 10^{-3}$ [928] |
| luminosity calibration (corr.) | 0.3 | 0.5 | $\delta L/L = 0.5 \times 10^{-3}$ |
| beam energy calibration (uncorr.) | 1.2 | 2.0 | $\delta\sqrt{s} = 5$ MeV [926, 927] |
| beam energy calibration (corr.) | 1.2 | 0.1 | $\delta\sqrt{s} = 2.5$ MeV |
| beam energy spread (uncorr.) | 0.6 | 1.1 | $\delta\Delta E = 1\%$ [927] |
| beam energy spread (corr.) | $< 0.1$ | 1.5 | $\delta\Delta E = 0.5\%$ |
| parametric ($\alpha_s$) | 2.0 | 1.9 | $\delta\alpha_s = 1 \times 10^{-4}$ |
| parametric ($y_t$) | 3.8 | 4.5 | $\delta y_t = 3\%$ [846] |
| total profiled | 6.2 | 11.3 | |
| theory, unprofiled (scale) | 35 | 25 | $N^3LO$ NRQCD [918] |

**That P and S** (for potential-subtracted mass) may seem a detail, but is a big deal!!

# Mass scheme

The mass scheme is all-important in quark mass measurements
- i.e. top quark $\overline{\text{MS}}$ mass is ~10 GeV smaller than pole mass

**The threshold scan yields a well-defined mass** in a scheme of our choice
- typically: threshold masses designed to achieve best convergence

**Conversion between schemes is possible** with near-negligible precision
- 4-loop relation for PS-$\overline{\text{MS}}$ conversion is known

**Quark Mass Relations to Four-Loop Order in Perturbative QCD**

Peter Marquard[1], Alexander V. Smirnov[2], Vladimir A. Smirnov[3], and Matthias Steinhauser[4]

Show more

Phys. Rev. Lett. **114**, 142002 – **Published 7 April, 2015**

DOI: https://doi.org/10.1103/PhysRevLett.114.142002

$$\frac{m_t(m_t)}{\text{GeV}} = 163.643 \pm 0.023 + 0.074\Delta_{\alpha_s} - 0.095\Delta^{\text{PS}}_{m_t},$$

$$\frac{m_t(m_t)}{\text{GeV}} = 163.643 \pm 0.007 + 0.069\Delta_{\alpha_s} - 0.096\Delta^{\text{1S}}_{m_t},$$

$$\frac{m_t(m_t)}{\text{GeV}} = 163.643 \pm 0.011 + 0.067\Delta_{\alpha_s} - 0.095\Delta^{\text{RS}}_{m_t},$$

23 MeV from scale variations in PS mass; 1S mass actually 7 MeV (but why?)
70 MeV x $\Delta\alpha_s/10^{-3}$ from strong coupling; roughly independent of mass scheme
The effect of $\alpha_s$ in conversion is anti-correlated with impact on mass fit (see LCTop15)

# SMEFiT results (Jaco ter Hoeve)

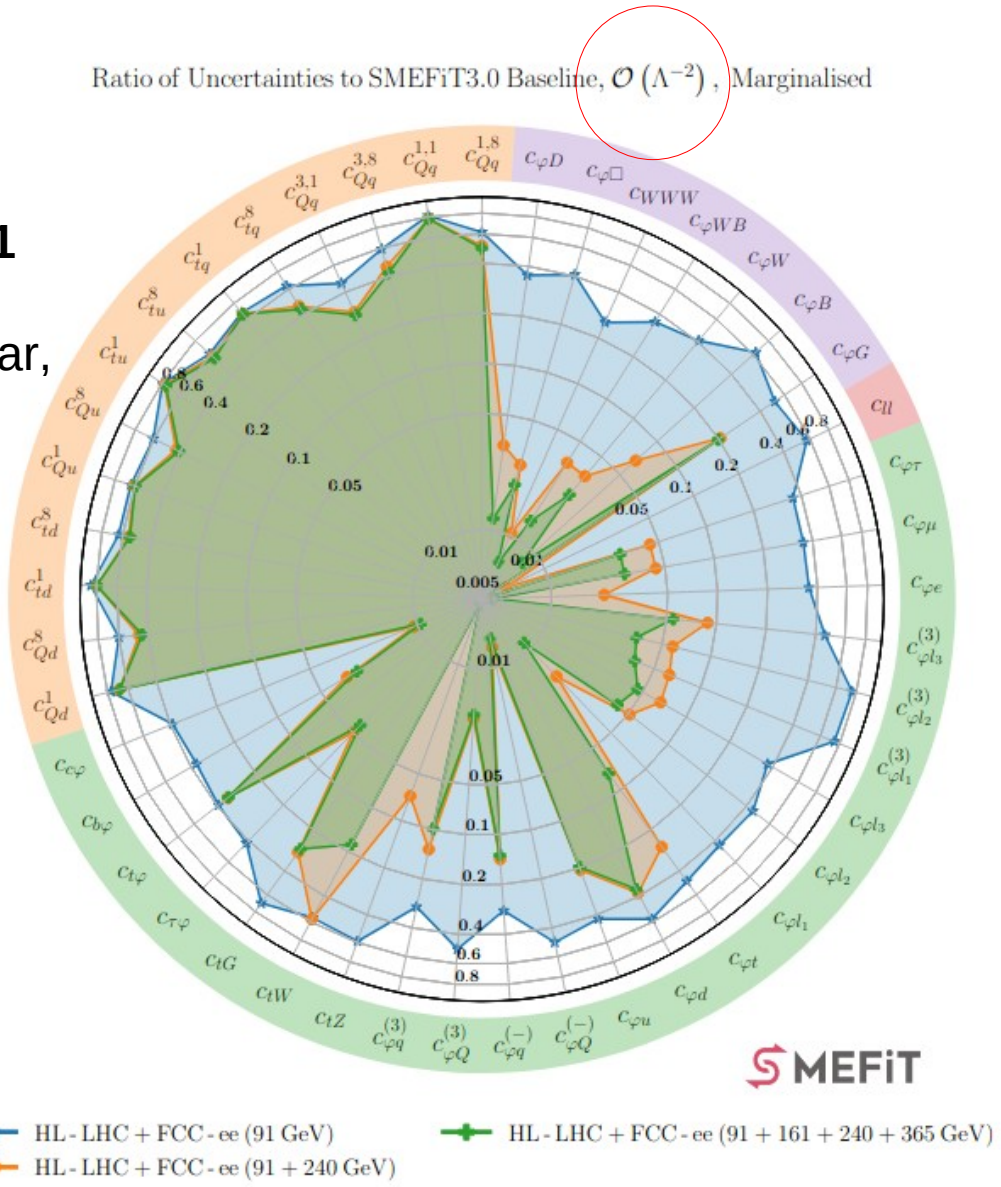
Higgs/EW/top fits on projections

**Results beyond JHEP 09 (2024) 091**

Linear-only bounds: quadratic is similar, except for qqtt operators

RGE evolution: small changes, except tttt operators

**Todo:** eett operators, different collider projects



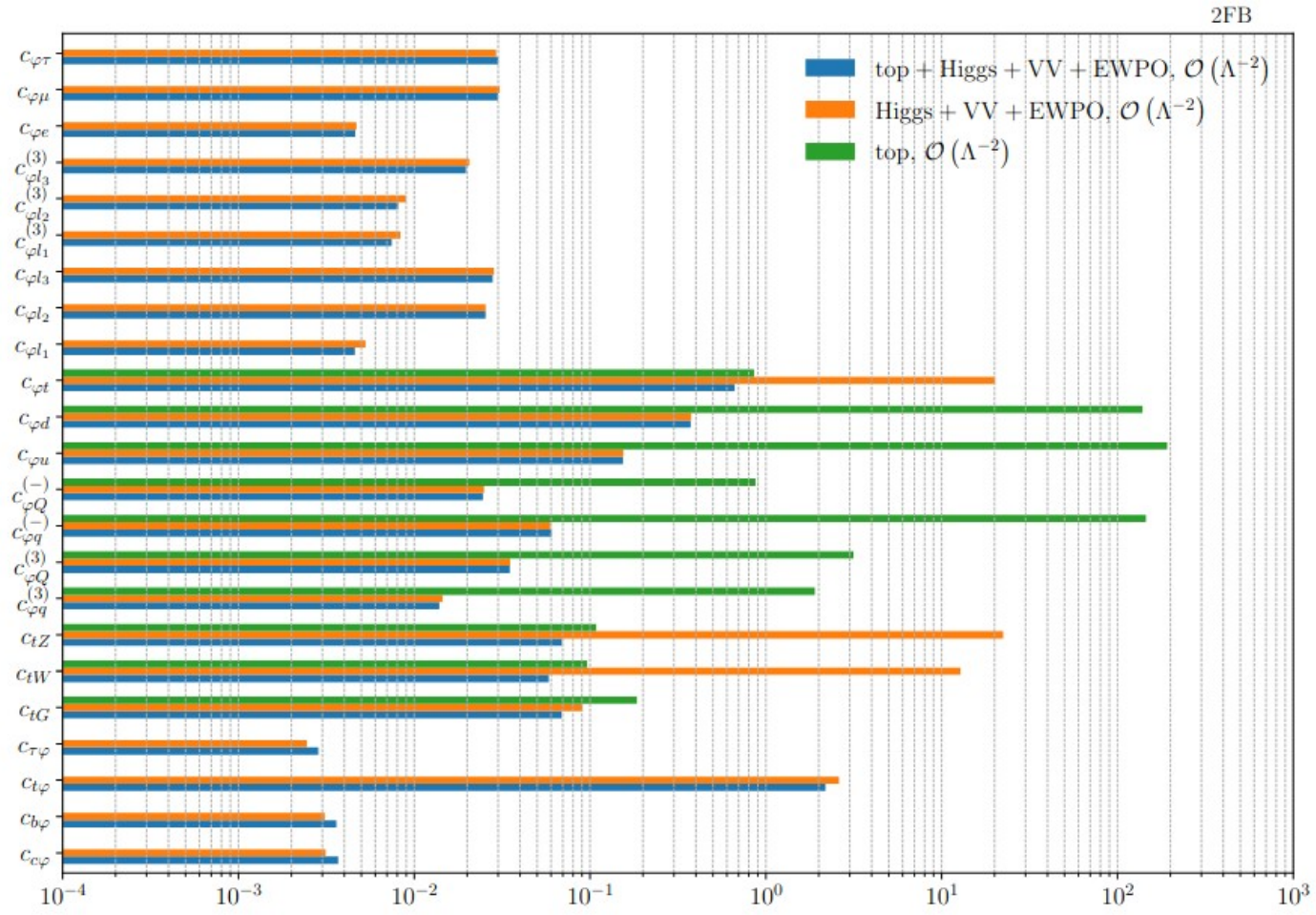

[1804.05033] Aebischer, Kumar, Straub

# SMEFiT results

Higgs/EW/top fits on projections – two-fermion operators
**Results beyond JHEP 09 (2024) 091**

**Higgs operators:** dominated by Higgs data, very small gain from top

**Top operators:** dominated by top data, but some gain from Higgs/EW



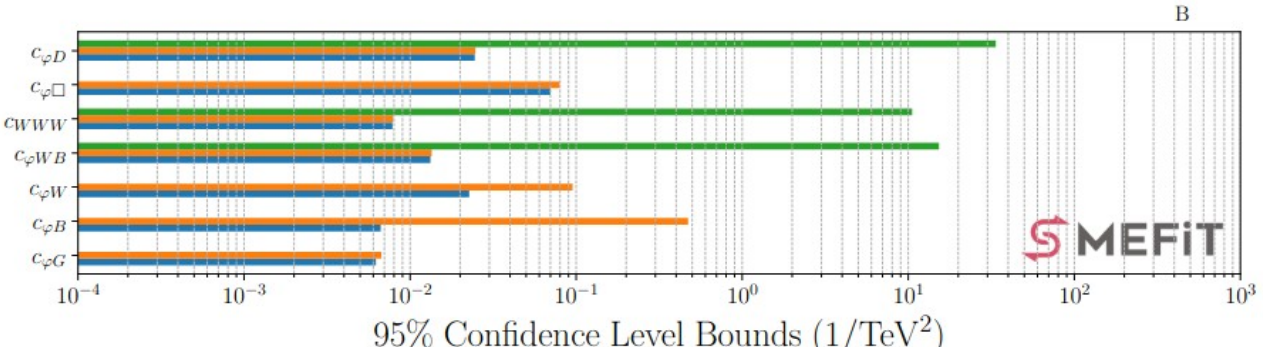
# SMEFiT results

S. Jung et al., *Higgs, top quark, and electroweak precision measurements at future e+e- colliders: A combined effective field theory analysis with renormalization mixing*,
Phys. Rev. D **105** (2022) 016003, DOI: 10.1103/PhysRevD.105.016003,
arXiv: 2006.14631 [hep-ph].

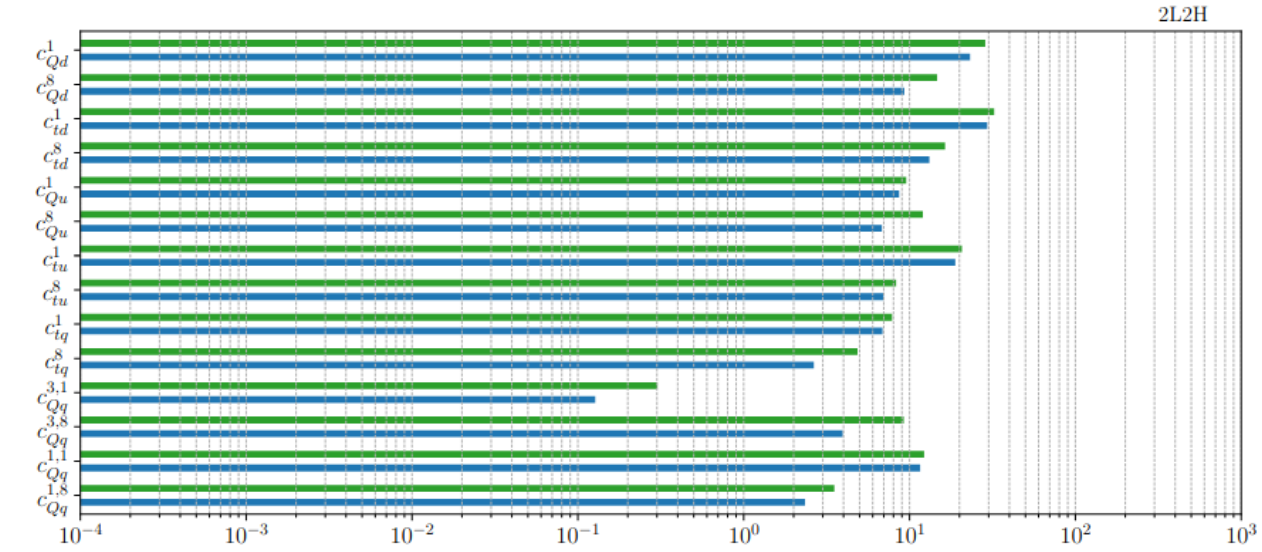
G. Durieux et al., *Probing top-quark couplings indirectly at Higgs factories*,
Chin. Phys. C **42** (2018) 123107, DOI: 10.1088/1674-1137/42/12/123107,
arXiv: 1809.03520 [hep-ph].

Higgs/EW/top fits on projections – bosonic and four-quark operators
**Results beyond JHEP 09 (2024) 091**

**CφW, CφB:**
Big gain from top data, as H→γγ loops are resolved




**qqtt operators:**
dominated by top data, but surprising gain from Higgs/EW in some operators



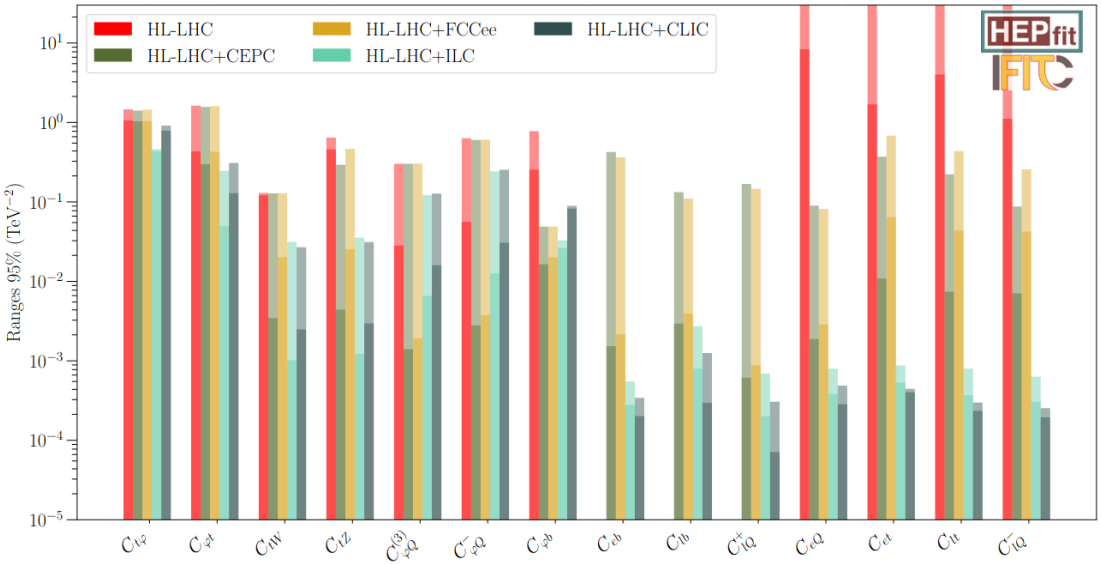
# Fit to the top sector (IFIT/C)

IFIT/C collaboration fits top and bottom operators

Excellent bounds on operators that affect EW interactions of the top quark

**TO DO:** ~~finalize fits~~, ~~compare to SMEFiT~~, write paper

ILC = 250+500+1000
CLIC = 380+1500+3000




eett operators: individual quadratic bounds from CMS exist; see e.g. JHEP 12 (2023)
both experiments have attempted global fits with linear terms only, but found they are underconstrained

HL-LHC on eett operators:
Quadratic global: O(1)
Linear individual: O(1-10 TeV$^{-2}$)
**Linear global: O(100 TeV$^{-2}$)**

e+e- colliders on eett operators:
**Linear fit, circular machine: O(1 TeV$^{-2}$)**
**Linear fit, linear machine@1-3 TeV O(10$^{-2}$ TeV$^{-2}$)**

All e+e- top data is good, high energy data are excellent

# A truly global analysis of Higgs self-coupling from ZH

Indirect model-dependent probe of the Higgs self-coupling

Matthew McCullough

Phys. Rev. D **90**, 015001 – Published 1 July 2014; Erratum Phys. Rev. D **92**, 039903 (2015)

Pier Paolo Giardino: calculation of loop effects of top operators on ZH cross section, arXiv:2406.03557, arXiv:2409.11466

$$\sigma_{\rm EFT,LO}^{(\sqrt{s}=240\ {\rm GeV})}({\rm fb}) = \sigma_{\rm SM,LO}^{(\sqrt{s}=240\ {\rm GeV})} + 25.3\, C_{\phi B} + 4.83\, C_{\phi D} + 29.0\, C_{\phi\Box} + 133\, C_{\phi W} + 64.5 C_{\phi WB} - 177\, C_{\phi e}[1,1] + 220\, C_{\phi l}^{+}[1,1]\,,$$

$$\frac{\sigma_{\rm NLO}}{\sigma_{\rm SM,NLO}} = 1 + \sum_i \frac{C_i(\mu)}{\Lambda^2}\left\{\Delta_i + \bar{\Delta}_i \log\frac{\mu^2}{s}\right\}$$

| | $\sqrt{s} = 240$ GeV | |
|---|---|---|
| | $\Delta_i/\Lambda^2$ | $\bar{\Delta}_i/\Lambda^2$ |
| $C_\phi$ | $-7.22\cdot10^{-3}$ | 0 |
| $C_{uW}[3,3]$ | $-1.63\cdot10^{-3}$ | $4.01\cdot10^{-3}$ |
| $C_{uB}[3,3]$ | $0.15\cdot10^{-3}$ | $-2.22\cdot10^{-3}$ |
| $C_u\phi[3,3]$ | $0.32\cdot10^{-3}$ | 0 |
| $C_{\phi q}^{(1)}[3,3]$ | $-1.34\cdot10^{-3}$ | $-4.10\cdot10^{-3}$ |
| $C_{\phi q}^{(3)}[3,3]$ | $0.51\cdot10^{-3}$ | $4.12\cdot10^{-3}$ |
| $C_{\phi u}[3,3]$ | $-0.54\cdot10^{-3}$ | $3.49\cdot10^{-3}$ |
| $C_{eu}[1,1,3,3]$ | $0.01\cdot10^{-3}$ | $-1.39\cdot10^{-2}$ |
| $C_{lu}[1,1,3,3]$ | $-0.02\cdot10^{-3}$ | $1.73\cdot10^{-2}$ |
| $C_{lq}^{(1)}[1,1,3,3]$ | $-0.37\cdot10^{-2}$ | $-1.80\cdot10^{-2}$ |
| $C_{lq}^{(3)}[1,1,3,3]$ | $-0.37\cdot10^{-2}$ | $1.29\cdot10^{-2}$ |
| $C_{qe}[3,3,1,1]$ | $0.30\cdot10^{-2}$ | $1.45\cdot10^{-2}$ |

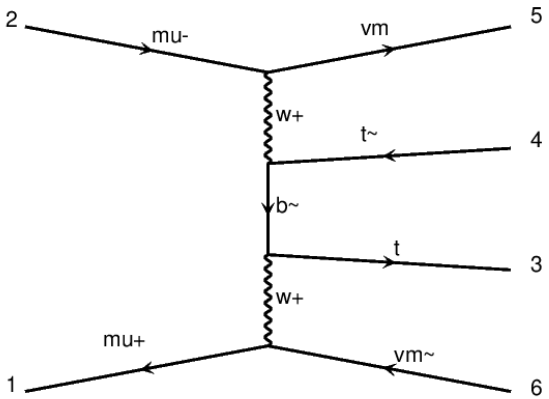
**Impact of self-coupling Cϕ ~ 0.01**

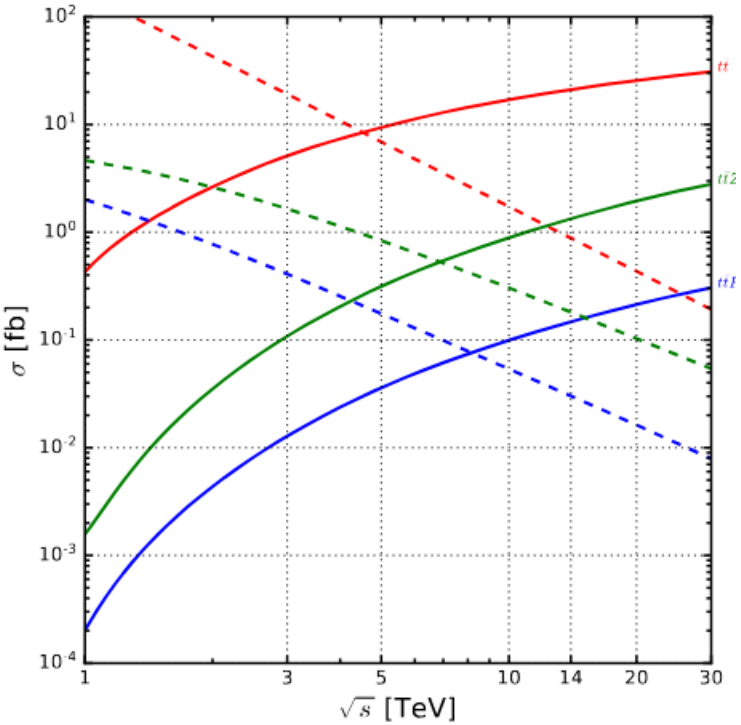
**Impact of top operators is similar;**
need to be constrained with auxiliary data

Complete fit from Jorge & Junping (this week?)

# Ultra-high-energy operation

*Kaufman, hep-ph/9002035*
*Gintner et al., hep-ph/9612342*




At very high energy, VBF production (solid) takes over from the s-channel (dashed)
*Figure from A. Constantini et al, JHEP08 (2022)*

SMEFT contributions grow even faster, especially the quadratic ones (F. Cornet)

$$\sigma_{VBF}(3\ \text{TeV}) = 13\ fb - 0.00036 \times C_{\varphi Q}^{M} + 0.00023 \times (C_{\varphi Q}^{M})^2 - 0.00039 \times C_{\varphi t} + 0.00024 \times (C_{\varphi t})^2 + 0.00007 \times C_{t\varphi} + 0.00002 \times (C_{t\varphi})^2 + 0.019 \times C_{tW} + 0.057 \times (C_{tW})^2 - 0.015 \times C_{tZ} + 0.039 \times (C_{tZ})^2$$

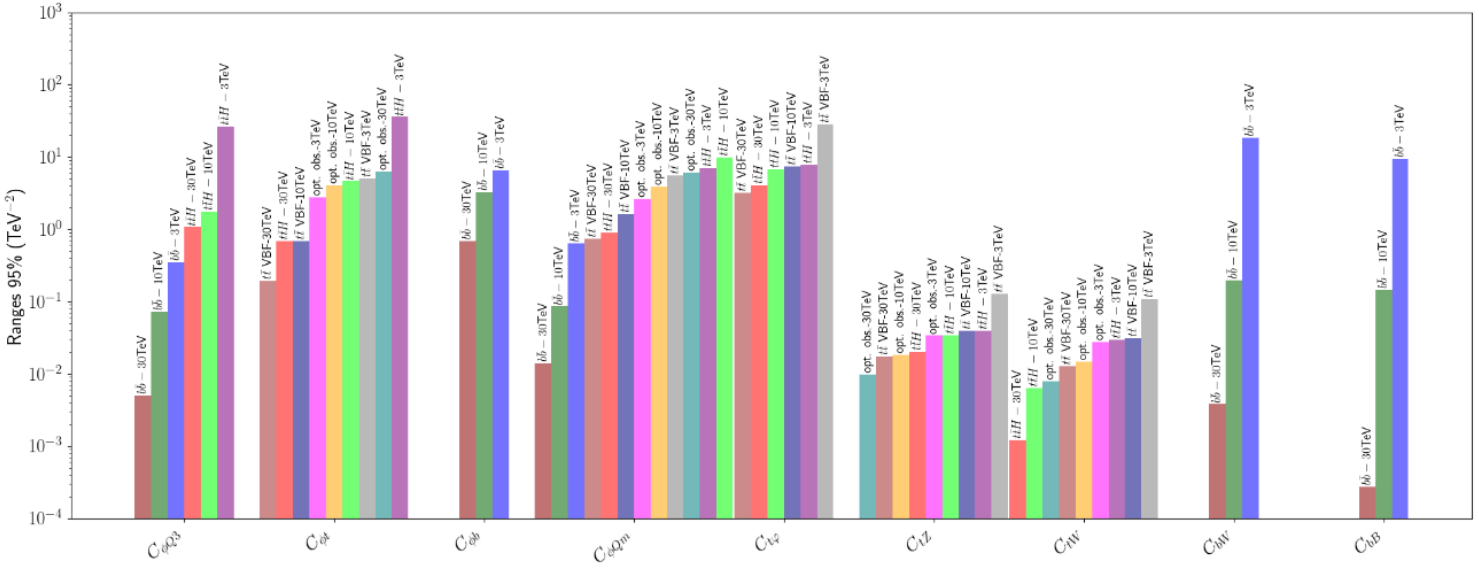
$$\sigma_{VBF}(30\ \text{TeV}) = 61\ fb - 0.0014 \times C_{\varphi Q}^{M} + 0.025 \times (C_{\varphi Q}^{M})^2 - 0.0052 \times C_{\varphi t} + 0.026 \times (C_{\varphi t})^2 + 0.0002 \times C_{t\varphi} + 0.059 \times (C_{t\varphi})^2 + 0.08 \times C_{tW} + 3.7 \times (C_{tW})^2 - 0.06 \times C_{tZ} + 1.7 \times (C_{tZ})^2.$$

# Ultra-high-energy operation

Indeed, individual bounds on Cφt (right-handed top-Z coupling), Ctφ (top Yukawa) and CtW (dipole) are dominated by Vector-Boson-Fusion production

In qualitative agreement with Liu et al., but impact on Yukawa less pronounced

Z. Liu et al., *Top Yukawa coupling determination at high energy muon collider*, Phys. Rev. D **109** (2024) 035021, DOI: 10.1103/PhysRevD.109.035021, arXiv: 2308.06323 [hep-ph].




**Could add a statement to this effect in section on energy upgrade**

# Prospects, projections and targets

LHC experiments are deploying a huge effort to observe Higgs pair production; more aggressive HL-LHC projections are appearing (ESPPU ‘19: 50% precision)
**S2 extrapolations** from existing analyses bank on improving systematics;
these **“targets”** will likely be reached. Some other “targets” have a larger uncertainty.

LC community has published **“prospects”** based on relatively **simple analyses on full simulation**, without systematic jet calibration. These underestimate the sensitivity, especially in complex final states, such as di-Higgs and ttH production.

## Bottlenecks in the ZHH analysis

- jet pairing and jet misclustering: “perfect“ jet clustering → 40% improvement
  improve di-jet mass resolution
- removal of $\gamma\gamma$ overlay: 15% improvement expected
  important to tackle initial state radiation (ISR)
- flavor tagging: 11% improvement expected from 5% eff. increase with newer LCFIPlus
  important as $H \to b\bar{b}$ is the dominant Higgs decay channel
- adding $Z \to \tau\tau$ channel: 8% improvement expected
  include a yet unaccounted decay channel
- more modern ML architectures for signal/background selection
  improvement expected when transitioning from BDTs to (e.g.) transformer-based models etc.
- separation of ZHH diagrams with/without the self-coupling
  would directly improve the sensitivity on $\lambda$ (lower sensitivity factor)

All improvements are relative

Expected improvements from DESY-Thesis-16-027

**<20%!!!**

- **Better than 20% sensitivity on $\lambda$ in reach**
  through demonstrated reconstruction improvements

Higgs factory projections have a lot of room for improvement!!

Talk by Bryan Bliewert on the ZHH analysis at 500/550 GeV

# Associated ttH production revisited

2015 study by Jan Strube and others remains the basis for LC prospects

**Full simulation study of the top Yukawa coupling at the ILC at $\sqrt{s} = 1$ TeV**

Special Article – Tools for Experiment and Theory | Open access | Published: 04 July 2015
Volume 75, article number 309, (2015) Cite this article

Download PDF

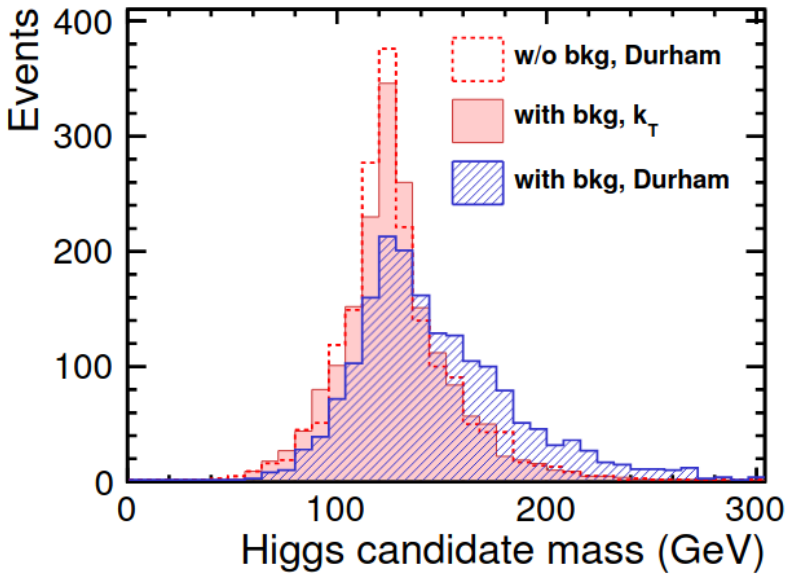
You have full access to this open access article

T. Price, P. Roloff, J. Strube & T. Tanabe

| Type | Final state | P($e^-$) | P($e^+$) | $\sigma$ [$\times$ BR] (fb) |
|---|---|---|---|---|
| Signal | $t\bar{t}H$ (8 jets) | −80% | +20% | 0.87 |
| Signal | $t\bar{t}H$ (8 jets) | +80% | −20% | 0.44 |
| Signal | $t\bar{t}H$ (6 jets) | −80% | +20% | 0.84 |
| Signal | $t\bar{t}H$ (6 jets) | +80% | −20% | 0.42 |
| Background | other $t\bar{t}H$ | −80% | +20% | 1.59 |
| Background | other $t\bar{t}H$ | +80% | −20% | 0.80 |
| Background | $t\bar{t}Z$ | −80% | +20% | 6.92 |
| Background | $t\bar{t}Z$ | +80% | −20% | 2.61 |
| Background | $t\bar{t}g^* \to t\bar{t}b\bar{b}$ | −80% | +20% | 1.72 |
| Background | $t\bar{t}g^* \to t\bar{t}b\bar{b}$ | +80% | −20% | 0.86 |
| Background | $t\bar{t}$ | −80% | +20% | 449 |
| Background | $t\bar{t}$ | +80% | −20% | 170 |

Max. signal yield: few 1000 events

Focus on H→ bb decay; Missing many Higgs decays




Jet clustering and jet pairing in multi-jet final states

$$\chi^2_{6\,\mathrm{jets}} = \frac{(M_{12} - M_W)^2}{\sigma_W^2} + \frac{(M_{123} - M_t)^2}{\sigma_t^2} + \frac{(M_{45} - M_H)^2}{\sigma_H^2}.$$

# Associated ttH production revisited

Multi-variate output (good!) based on 3rd and 4th b-tagged jet, thrust, $Y_{nm}$ splitting scales, and invariant masses of W, H, and top candidates

Signal selected with a cut (to be improved!) that yields selection efficiencies (purities) for signal events of 33.1% (27.7%) and 56.0% (25.2%) for six- and eight-jets events

| Detector | | ILD | | SiD | |
|---|---|---|---|---|---|
| Sample | Before cuts | After Cuts | | | |
| | | 6 jets | 8 jets | 6 jets | 8 jets |
| $t\bar{t}H$ 6 jets | 628.7 | 208.0 | 65.5 | 191.6 | 57.4 |
| $t\bar{t}H$ 8 jets | 652.7 | 2.1 | 365.6 | 1.6 | 299.4 |
| $t\bar{t}H \rightarrow$ other | 1197.5 | 28.8 | 25.3 | 33.0 | 16.6 |
| $t\bar{t}Z$ | 5332.4 | 126.1 | 260.5 | 105.6 | 187.1 |
| $t\bar{t}b\bar{b}$ | 1434.5 | 125.4 | 222.6 | 100.1 | 180.7 |
| $t\bar{t}$ | 308800.9 | 261.2 | 513.6 | 232.0 | 381.6 |
| $y_t$ statistical uncertainty | | 6.9% | 5.4% | 7.0% | 5.8% |
| combined | | 4.3% | | 4.5% | |

Prospect: $\Delta y_t = 1.5\%$ ($\Delta y_t = 4.3\%$, as per the paper, scaled to 8 $ab^{-1}$)
Target: $\Delta y_t < 0.7\%$ (using all channels, fitting full BDT shape)
More room for improvement with improved b-tagging, jet clustering, etc.

Note that signal cross section is maximum at 700-800 GeV and LR ~ 2 x RL

# Top Yukawa coupling comparison

M. L. Mangano et al., *Measuring the Top Yukawa Coupling at 100 TeV*, J. Phys. G **43** (2016) 035001, DOI: 10.1088/0954-3899/43/3/035001, arXiv: 1507.08169 [hep-ph].

Z. Liu et al., *Top Yukawa coupling determination at high energy muon collider*, Phys. Rev. D **109** (2024) 035021, DOI: 10.1103/PhysRevD.109.035021, arXiv: 2308.06323 [hep-ph].

S2 projection: "apples" LC prospects: "oranges" Theory studies: "pears"

| Values in % units | | LHC | HL-LHC | ILC500 | ILC550 | ILC1000 | CLIC | FCChh | $\mu$-coll |
|---|---|---|---|---|---|---|---|---|---|
| $\delta y_t$ | Global fit | 12% | 5.1% | 3.1% | 2.6% | 1.5% | 3.0% | - | - |
| | Indiv. fit | 10% | 3.7% | 2.8% | 2.3% | 1.4% | 2.5% | 1% | 1.5% |

# Top progress

**ECFA Higgs/top/EW factory study yields new results on top mass, top quark EW couplings. I have briefly revisited ttH too.**

**- top mass: more solid foundations for threshold scan**

Detailed experimental study; now more confident about systematics
Machine uncertainties under control (but I need numbers & references)
Parametric uncertainties probably small (but impact $\alpha_s$ is unclear/complicated)
Theory (scale variations) is now more clearly the bottle neck than ever!!

**- top EW couplings: more complete global analyses**

interplay between top and Higgs sector
some advantages; e.g. better individual bounds on top Yukawa
some drawbacks; e.g. indirect bounds on self-coupling from ZH
looking forward to results of a complete fit from Jorge de Blas & Junping Tian

**- top quark Yukawa coupling from ttH production:**

old study from Price et al. is conservative; up to factor 2 gain seems possible
beware of comparisons of “prospects” and “targets”!

**Planning content of LC vision report. New ideas are due now!**