Top physics opportunities at and e+e- collider – focus topic “ttbar threshold”

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R. Franceschini, A. Irles J. de Blas (related focus topics), P. Azzi (liaison FCCee)

Practical

The ECFA focus topics document:

https://arxiv.org/abs/2401.07564

Focus topics for the ECFA study on Higgs / Top / EW factories

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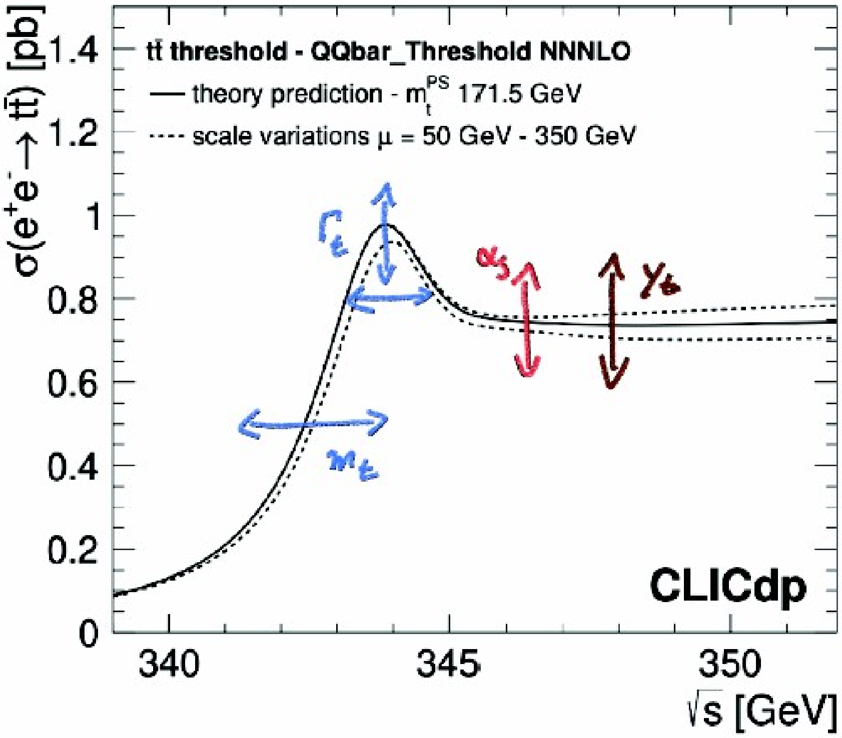
The mailing list:

https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics/TTthresh

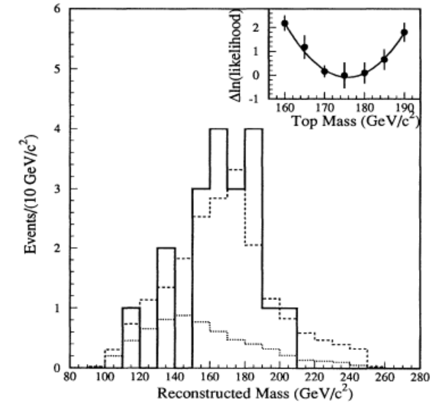
The $t\bar{t}$ threshold scan

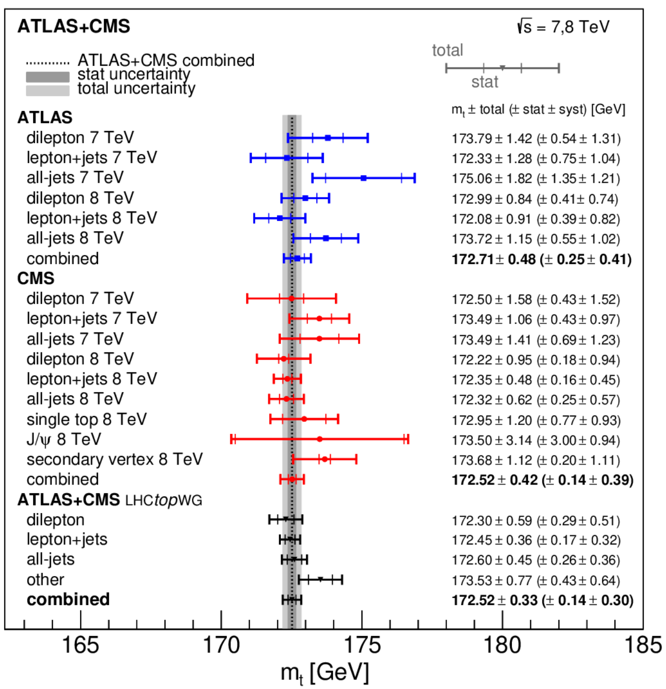


The top quark mass

The top quark mass is a key parameter of the SM that must be determined experimentally

Direct measurements at hadron collider determine the best-fit mass parameter of the workhorse Powheg+Pythia8 Monte Carlo generator





Experiment is extremely precise:

- 600 MeV for single measurements
  see also CMS, arXiv:2302.1967
- 330 MeV for LHC run 1 combination
  arXiv:2402.08713 (PRL soon)

More work is needed to bring interpretation to the same level

(André Hoang, What is the top quark mass? Ann. Rev. Nucl. Part. Sci. 70 (2020)

Status quo: “the difference between the top mass in direct measurements and the top pole mass is of the order of few hundred MeV”, Corcella, Nason, Hoang, Yokoya, arXiv:1902.04070

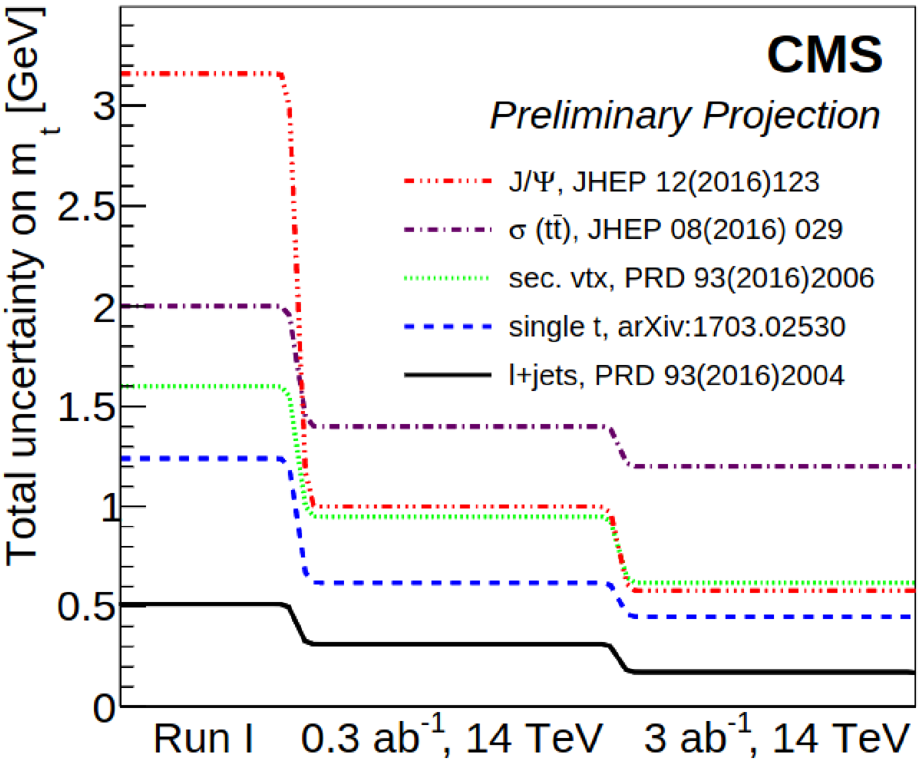
Top mass at LHC & HL-LHC, interpretation

+ Snowmass report
arXiv:2209.11267
arXiv:2203.08064

J/psi and sec. vertex methods are starting to deliver (CMS sec. Vtx., ATLAS soft-muon)

Boosted top mass improving rapidly
CMS 2.5 GeV in 2020 → 0.8 GeV in 2023
Connects direct results with "calibration"
Butenschoen et al., PRL 117 (2016),
Hoang et al. PRD100 (2019)

Cross-section-based mass extractions achieve O(1 GeV) precision/measurement.
Theorist's combined fit yields 300 MeV (Zenaiev & Moch, arXiv:).

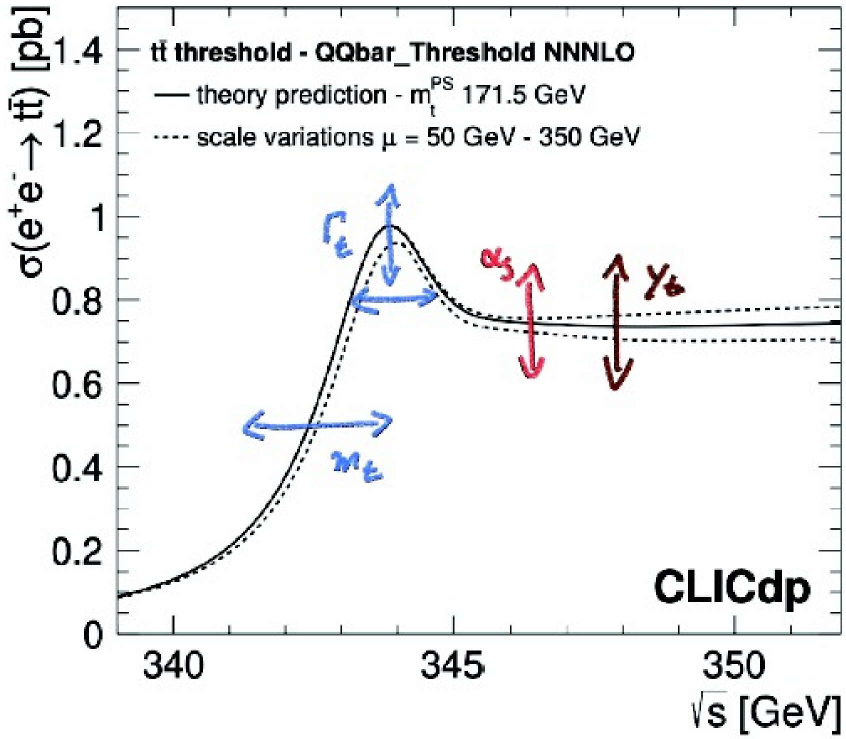


Variety of methods yields important test of internal consistency

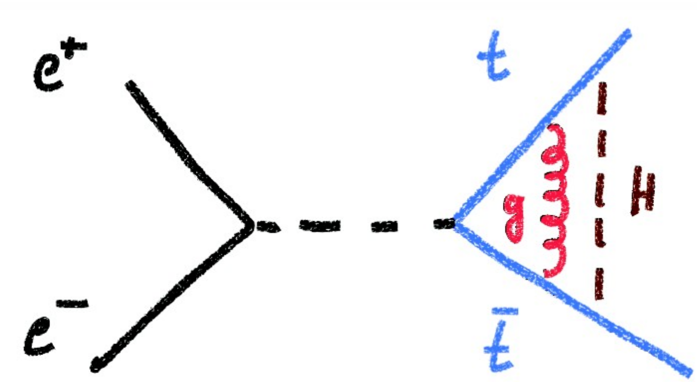
Even with the most conservative interpretation we're well beyond 1 GeV expectation!!!
(HL-LHC primer, hep-ph/0204087)

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!



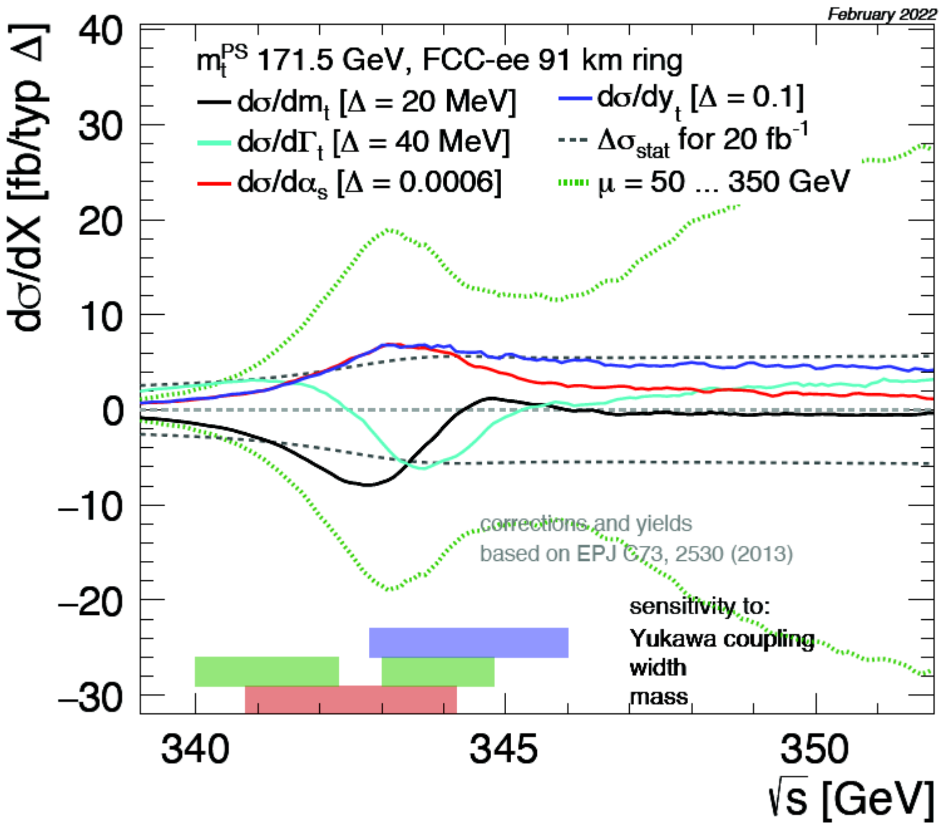
Art-work: Frank Simon



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 MS scheme with O(10 MeV) QCD scale uncertainty, parametric uncertainty from α_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 α_s ~ 0.001 and y_t ~ 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?)

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

Theoretical and phenomenological targets

- Complete and harmonised assessment of systematic uncertainties on SM parameters extracted from the threshold scan.
- Degeneracies in a EFT analysis including only "one" energy point. How to disentangle effects combining with other (non-top-quark) measurements. Indirect constraints on top Yukawa.

MC samples needed

Basic samples available as listed in the Motivation Section, dedicated samples for threshold scan are needed.

Existing tools / examples

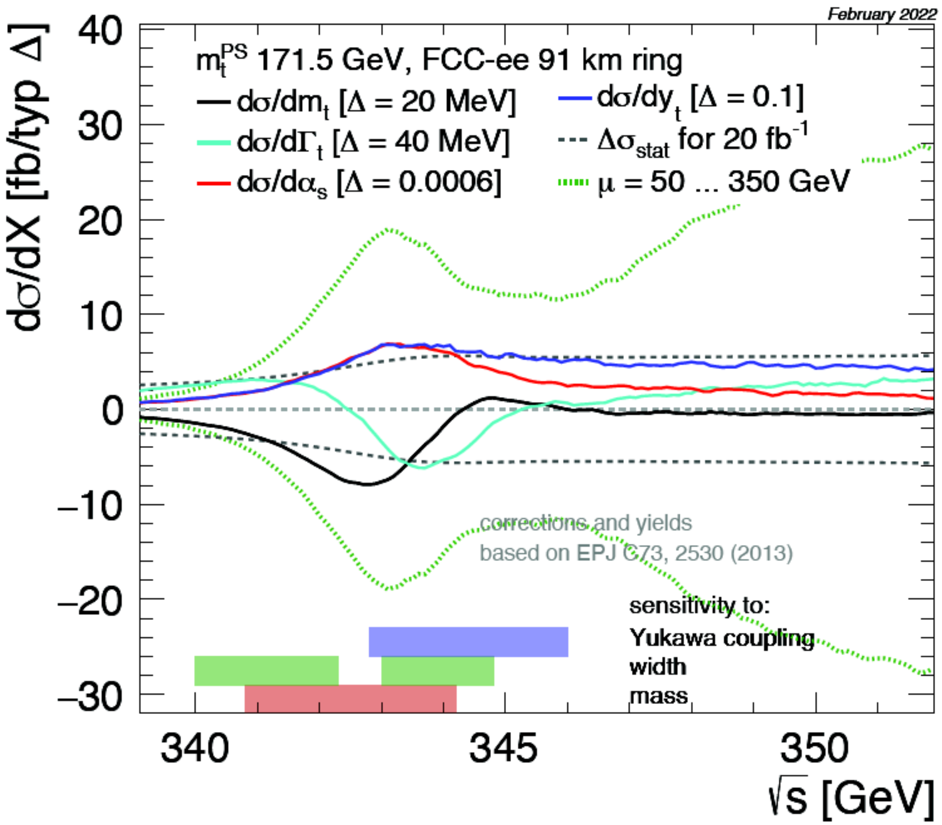
- ILD $t\bar{t}$ analysis https://github.com/ILDAnaSoft/ILDbench_QQbar

Contact & Further Information

- Gitlab wiki: https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics/TTthresh
- Sign up for egroup: ECFA-WHF-FT-TTthres@cern.ch via http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=ecfa-whf-ft-tthres
- and/or email the conveners of ECFA WG1 GLOBal group: mailto:ecfa-whf-wg1-glob-conveners@cern.ch

New results

The top Yukawa coupling affects the overall cross section and is nearly degenerate with the strong coupling constant.

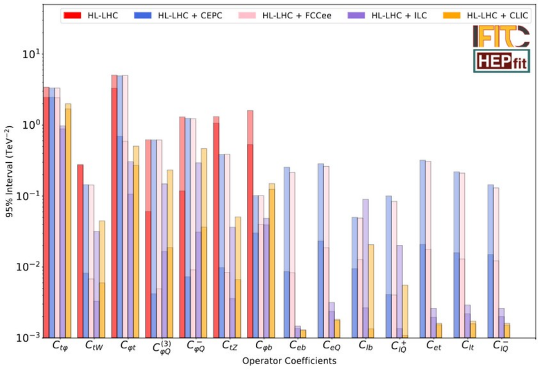


Ankita Mehta & Matteo Defranchis (preliminary):
A shape analysis may benefit from a point well above threshold, where the Yukawa coupling still has an effect, while α_s doesn't (leading Yukawa effect is virtual correction, not the potential generated by Higgs exchange)

Potential issues: validity of the calculation, correlation of scale uncertainties…

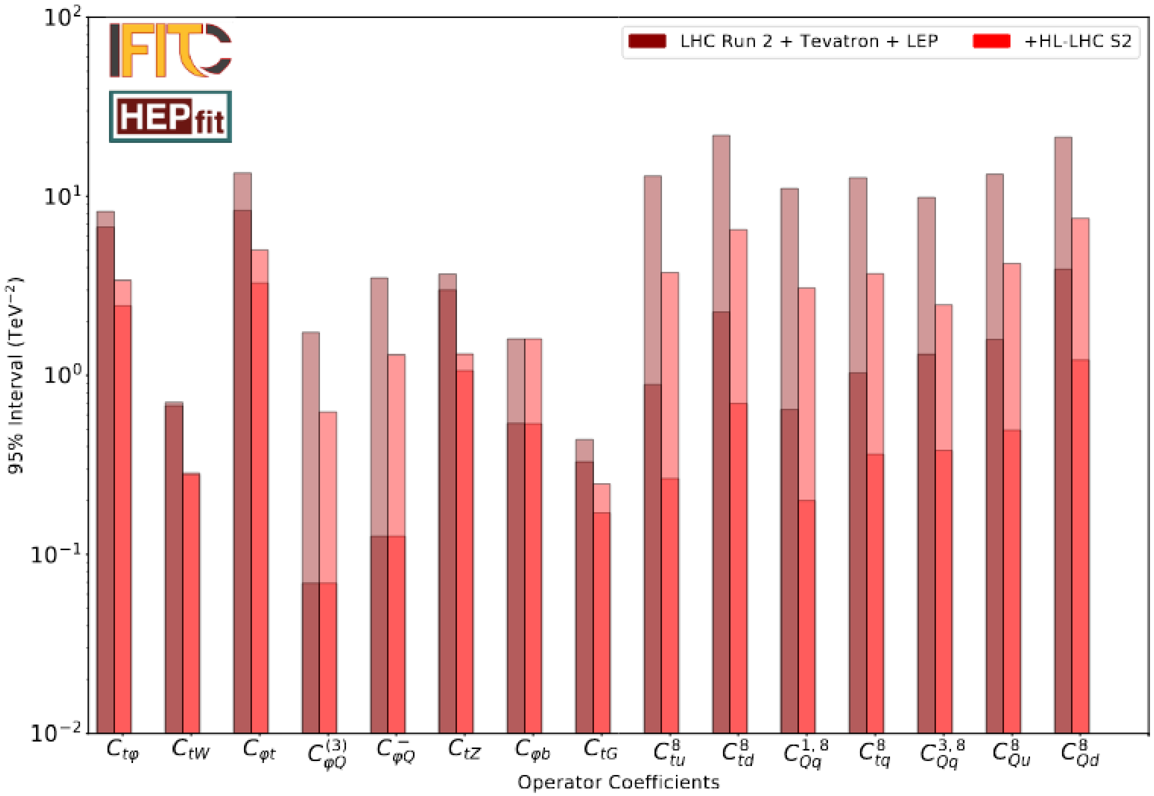
Above the threshold:
a broad precision programme

Top EW couplings
Top quark Yukawa
Quantum information
...



Current SMEFT bounds from top program

Bounds on SMEFT Wilson coefficients still O(1) to O(10) for many operators
Still large correlations and many blind directions: add more measurements



From: arXiv:2206.08326

Based on JHEP12(2019)098

Individual bounds
Global bounds

HL-LHC to gain factor 2-5 in all coefficients, with reasonable assumptions:

- *NNLO calculations appear for ttX and tqX production*
- *Modelling uncertainties improve by factor 2*
- *Progress in top quark pair production driven by boosted production*
- *Measurements improve as 1/sqrt(L_{int}): O(10%) now → O(few %) in 2037*

The e+e- programme

A broad programme above the $t\bar{t}$ threshold

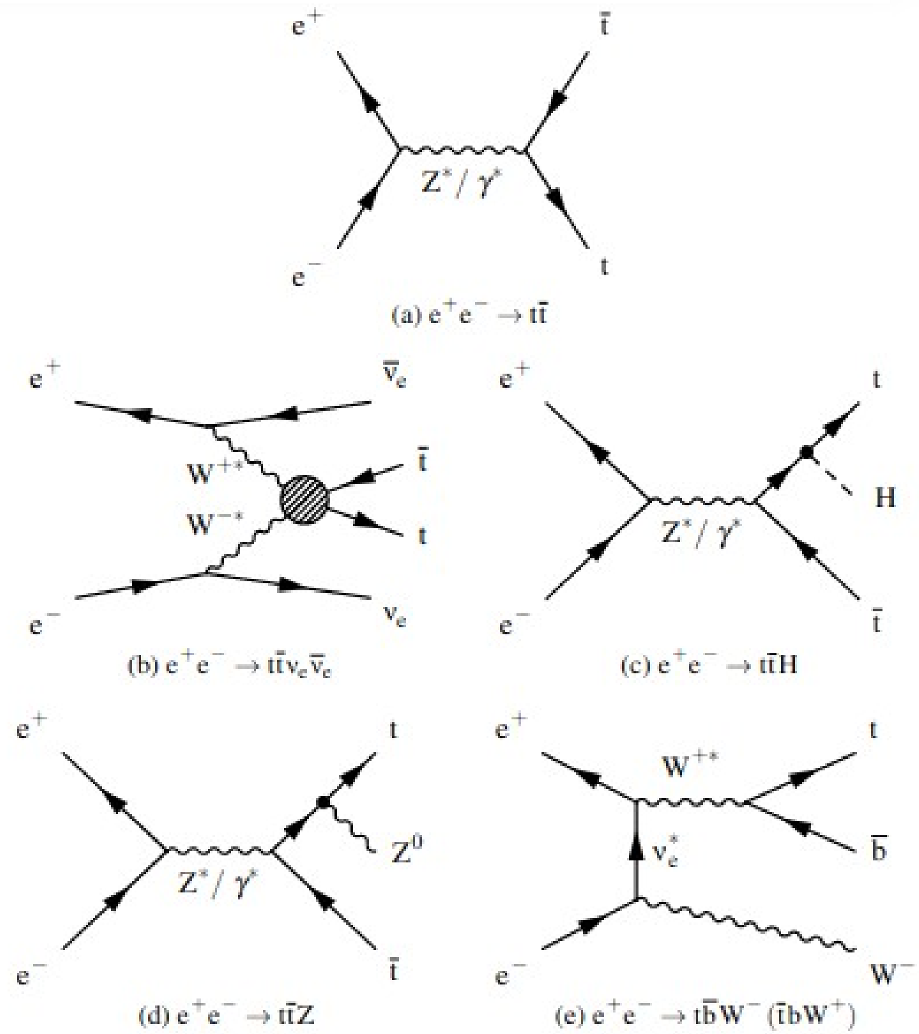
– pair production (a)
– single top production (e)

High energy enables further processes

– ttZ & ttH (c,d)
– VBF top production (b)

Measurements of cross section, forward-backward asymmetry, polarization, CP-odd observables

Durieux et al. (arXiv:1807.02121) define **optimal observables** *on e+e- → WbWb production*



top SMEFT fit

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

Circular Collider 350+365

Sensitivity to four-fermion operators increases strongly with energy

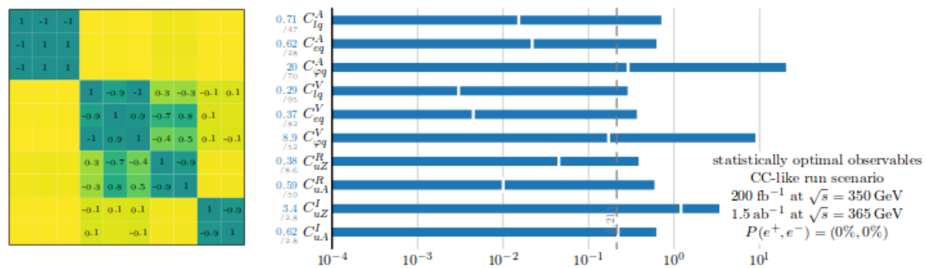


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

ILC500+ ILC1000

Ultimate precision in global EFT fit requires a collider with two energy stages and polarization

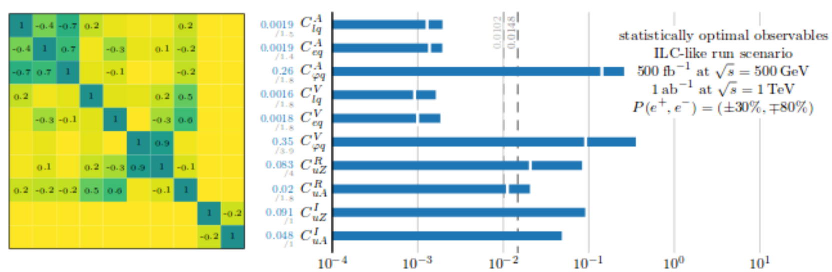


Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.

CLIC380+ CLIC1500+ CLIC3000

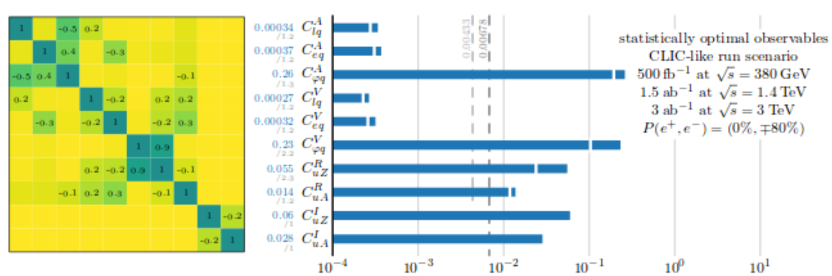


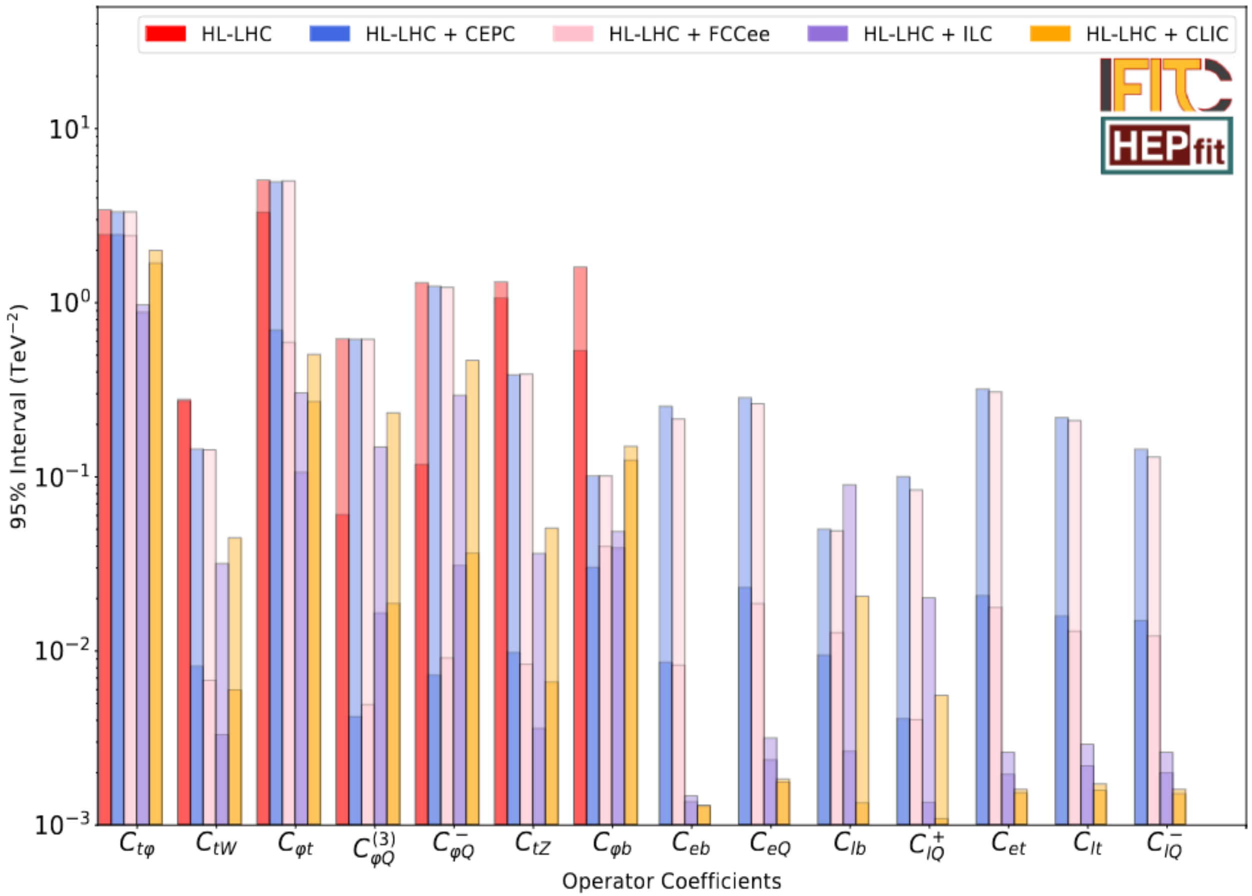
Figure 25. Global one-sigma constraints and correlation matrix arising from the measurement of statistically optimal observables in a CLIC-like benchmark run scenario.

Warning: versions with old luminosity

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) → O(0.1)
Two-lepton-two-top (lltt):	XXX → $O(10^{-1} - 10^{-3})$



Snowmass SMEFT fit based on Durieux et al., with updated operating scenarios, see talk by F. Cornet

SMEFT fit HL-LHC + e+e- collider

Mapping the SMEFT at High-Energy Colliders: from LEP and the (HL-)LHC to the FCC-ee

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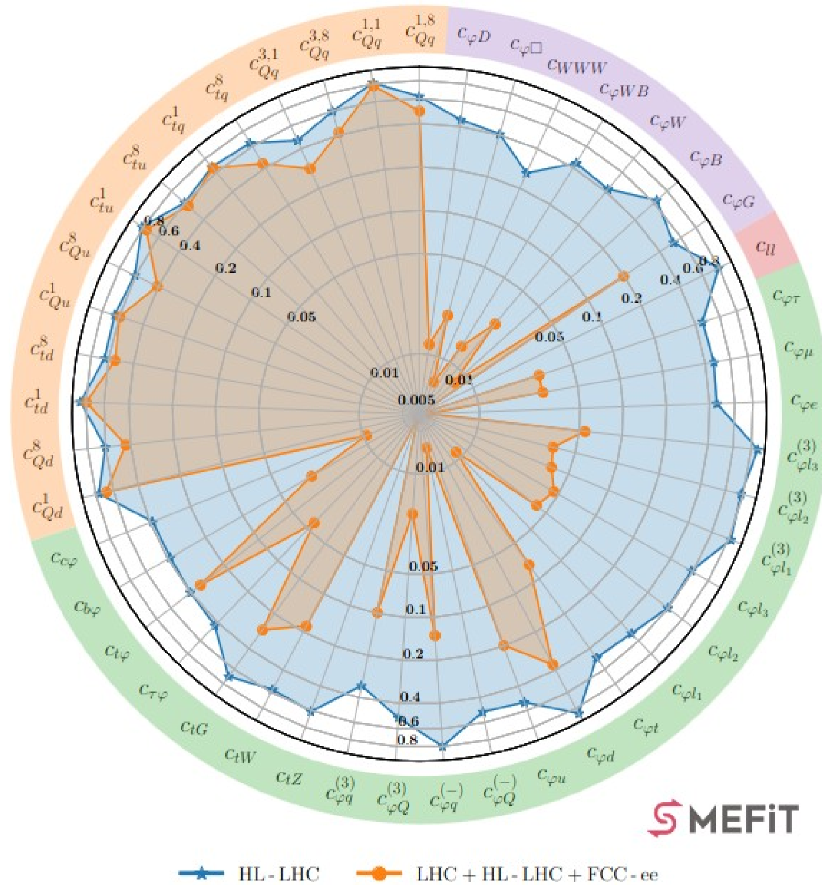
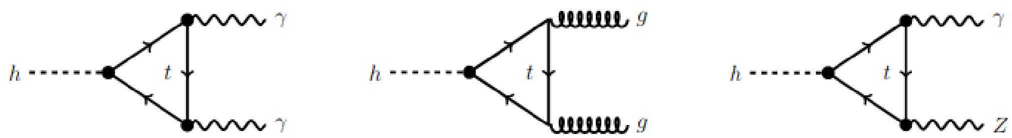
Abstract: We present SMEFiT3.0, an updated global SMEFT analysis of Higgs, top quark, and diboson production data from the LHC complemented by electroweak precision observables (EWPOs) from LEP and SLD. We consider recent inclusive and differential measurements from the LHC Run II, alongside with a novel implementation of the EWPOs based on independent calculations of the relevant EFT contributions. We estimate the impact of HL-LHC measurements on the SMEFT parameter space when added on top of SMEFiT3.0, through dedicated projections extrapolating from Run II data. We quantify the significant constraints that measurements from two proposed high-energy circular e^+e^- colliders, the FCC-ee and the

Celada et al., arXiv:2404.12809

Fit includes Higgs, top and EW sectors



The top Yukawa coupling at a lepton collider



250 GeV run offers “indirect” sensitivity to the top Yukawa

$\Delta y/y < 1\%$ from $H \rightarrow gg$ *Mitov et al., arXiv:1805.12027*

$\Delta y/y < 1\%$ from $H \rightarrow \gamma\gamma$ *Jung et al., arXiv:2006.14631*

Assuming the SM for all other couplings

500+ GeV run offers a “direct” measurement in ttH production

<3% precision *Price et al., arXiv:1409.7157*

robust in global analysis *Jung et al.,arXiv:2006.14631*

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	12.2	5.06	3.14	2.60	1.48	2.96
	Indiv. fit	10.2	3.70	2.82	2.34	1.41	2.52

Top-SMEFT fit on prospects, de Blas et al., 2206.08326

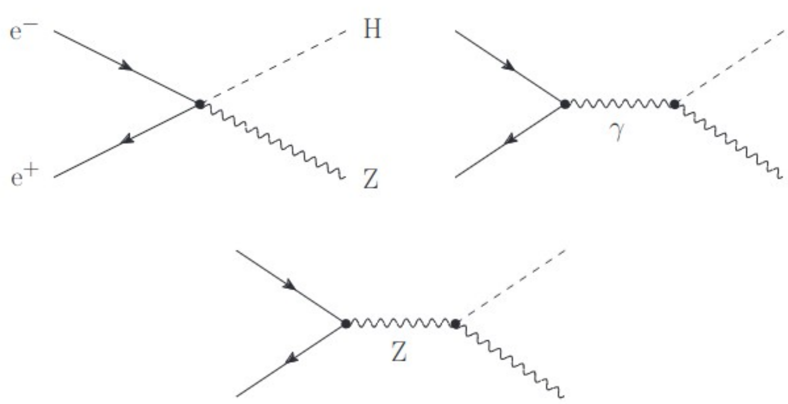
Top operators and loop contributions

Clear complementarity between hadron and lepton colliders: constrain qqtt operators at LHC; eett operators in e+e-; two-fermion operators benefit from both data sets

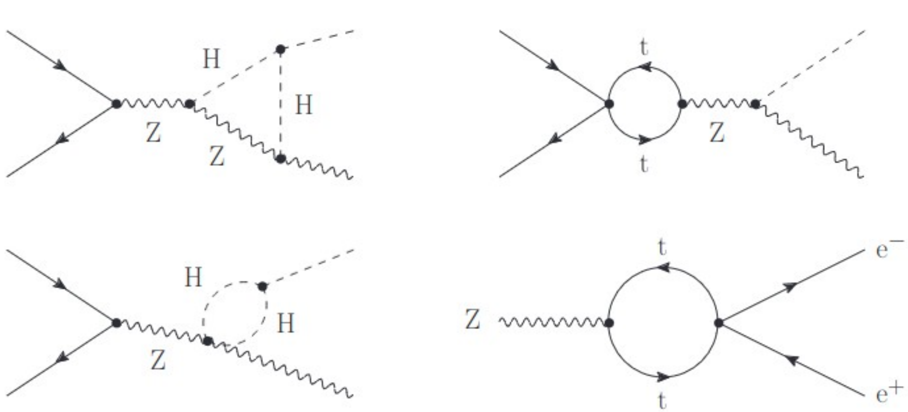
However, eett operators have an important impact on e+e- → ZH cross section

(see Asteriadis, Dawson, Giardino, Szafron, arXiv:2406.03557)

Leading order



Loop effects:
Higgs self-coupling top operators

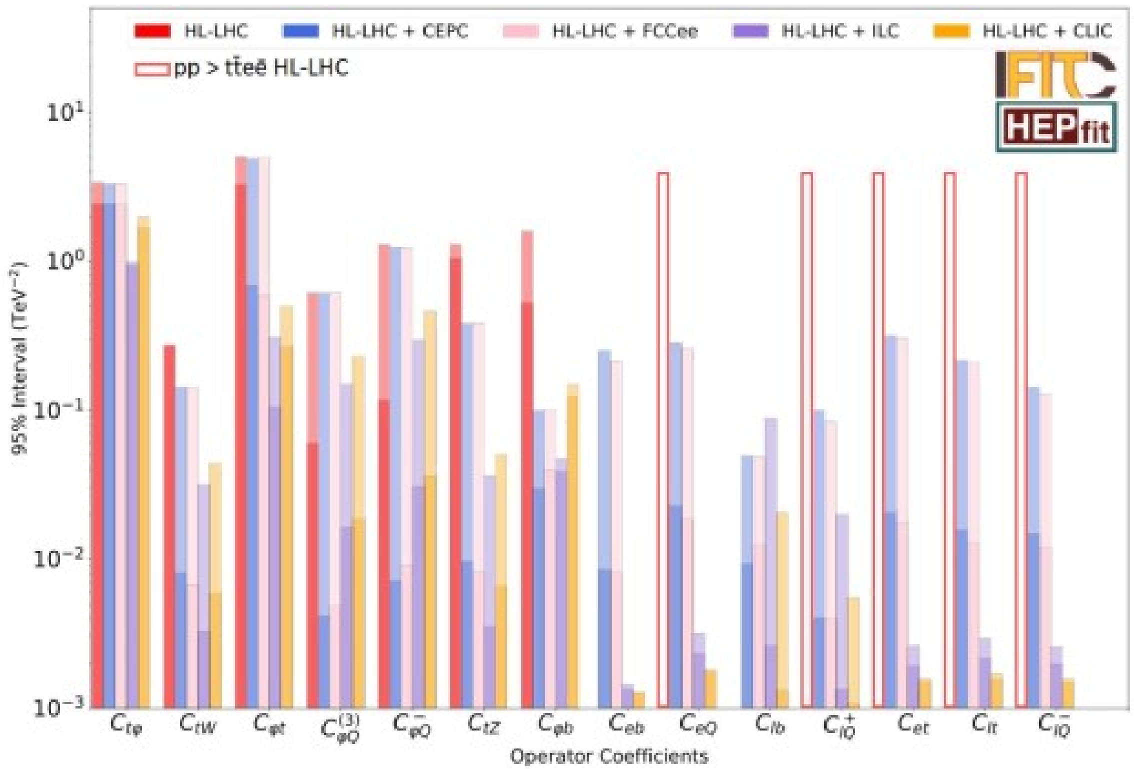


Numerically, coefficients are similar. Threat to indirect self-coupling extraction, or opportunity to constrain top operators with 250 GeV data!!

What about HL-LHC?

LHC and HL-LHC can access ttee operators in off-shell ttee analysis

Extrapolation from ATLAS work space: weak O(1-10 TeV-2) bounds are possible

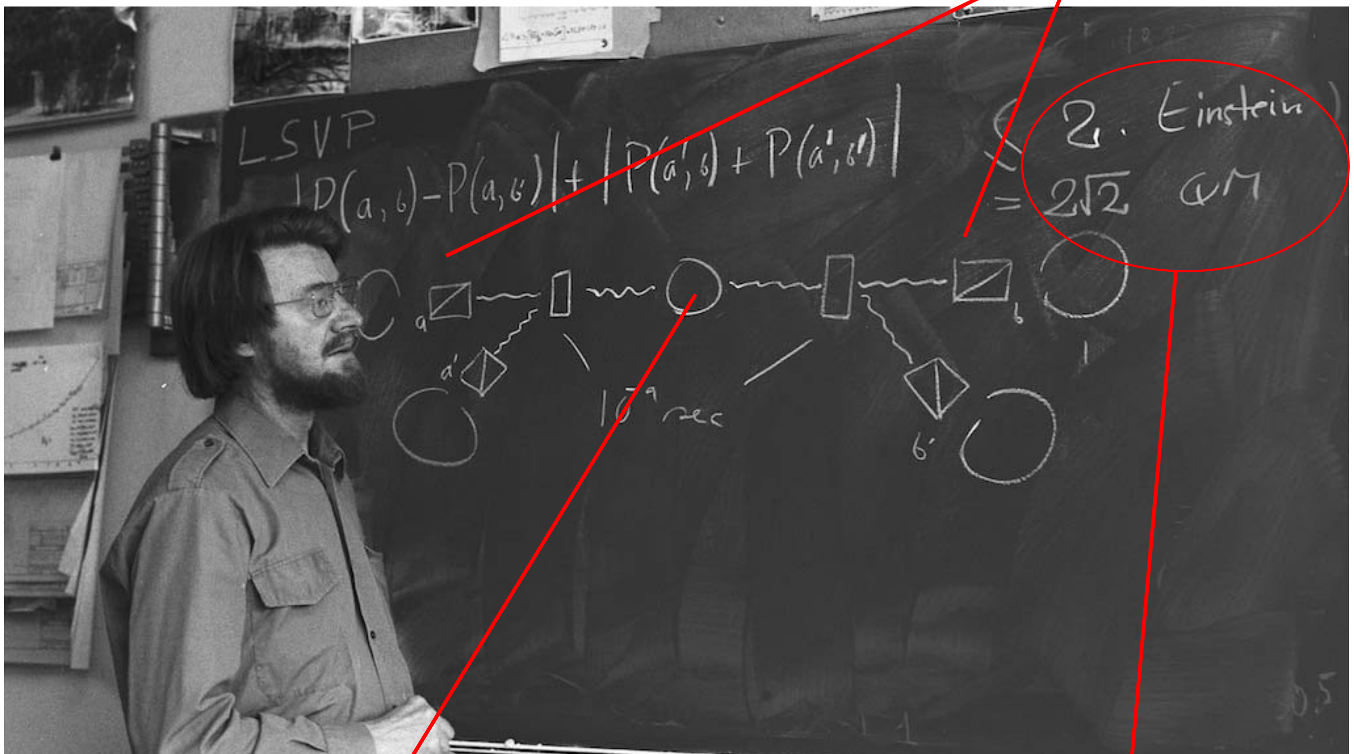


From Maria Moreno, ECFA Higgs/top/EW factory study conveners meeting

Bell-style experiments

Afik & de Nova, EPJPlus

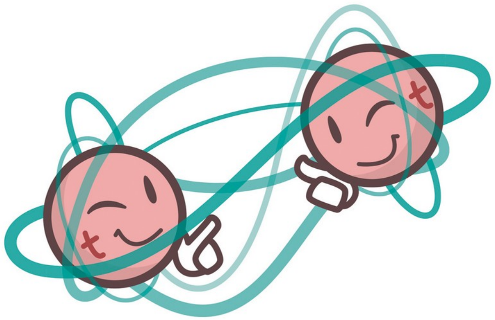
Two well-separated & independent detectors



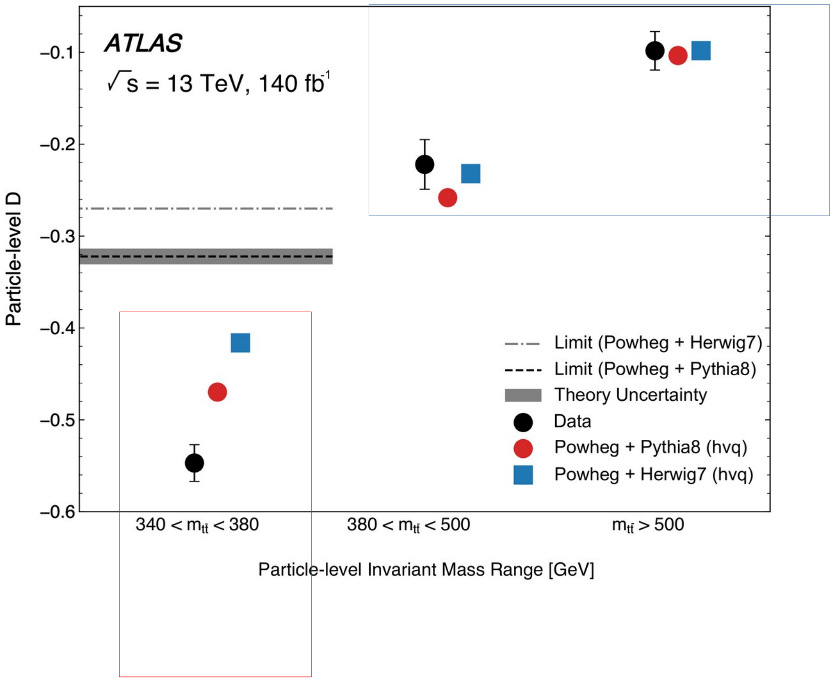
Source of quantum-correlated "entangled" photons

Outcome of the Bell tests decides between "Einstein" (local realistic theory with hidden variables) and "Bohr" (probablistic interpretation of QM)

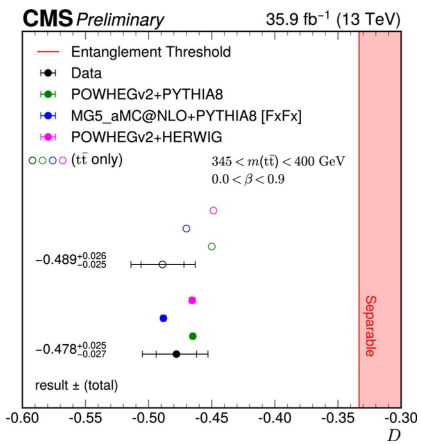
Observation of entanglement



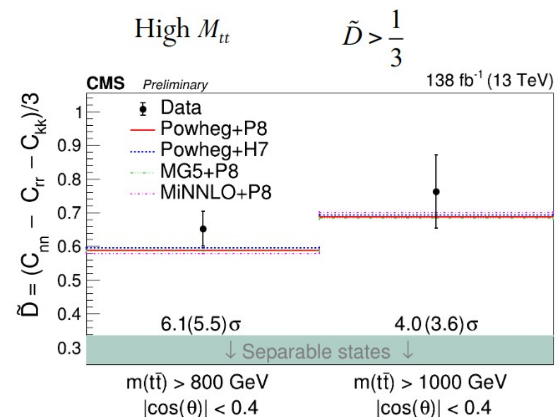
ATLAS, TOP '23, *arXiv:2311.07288*



D != 0 top spins are correlated
(nice, but known since 2013)



CMS at Moriond24



CMS at LHCp24

D < -1/3 top spin correlations are "quantum"
(new! Opens the door to QI@LHC)

Quantum entanglement observed in top quark pair production

Quantum information at lepton colliders?

v:2404.08049v1 [hep-ph] 11 Apr 2024

Quantum tops at circular lepton colliders

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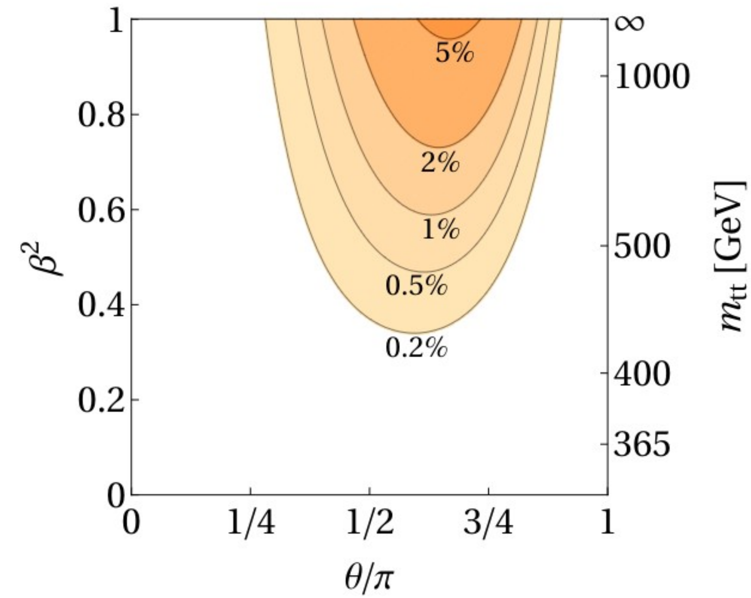
E-mail: fabio.maltoni@unibo.it, claudio.severi@manchester.ac.uk, simone.tentori@uclouvain.be, eleni.vryonidou@manchester.ac.uk

Abstract: We study the quantum properties of top quark pairs in lepton colliders with unpolarised beams, including spin correlations, entanglement, and violation of Bell inequalities. We present analytical results in the SM and in the SMEFT and discuss several practical aspects, like the choice of quantisation axes and $t\bar{t}$ threshold effects. We also note a correspondence between parity symmetry and entanglement. We find that quantum observables exhibit a rich phenomenology in the SM, and can also provide additional leverage in detecting new physics residing at higher scales.



"the entanglement presence criterion is always satisfied for colliders running above the tt threshold. For Bell violation we showed that prospects for observing it improve at larger centre-of-mass energies and in specific phase space regions but would still require percent level experimental precision."

Study at moderate-to-high-energy lepton colliders, including beam polarization?

Summary

Top quark properties from threshold scan:

- motivation from EW fit anno 2050
- new fast-sim samples are being analyzed
- assessing FCCee environment with significant synchrotron losses
- revisiting selection: high and robust efficiency seems feasible
- using shape information for Yukawa extraction

Top quark couplings:

Several groups have public results for SMEFT fits of the top sector, including e+e- prospects for different colliders from Durieux et al.

Next step: include loop effects and study top physics below threshold, interplay with Higgs/EW sector in detail

Entanglement & quantum information

Plenty of room for contributions!!

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