top physics opportunities at a new e^+e^- collider

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Top23, Traverse City (MI)

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See also ECFA Higgs/top/EW factory seminar on top physics by Frank Simon and myself and talks in the ECFA session

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Which future collider?

https://cerncourier.com/a/we-cant-wait-for-a-future-collider/

Many ideas and projects (good!), but unclear time lines, opaque strategies, unclear financial and political international situation (not so good!)

The future of the field can be a frustrating area for impatient young particle physicists

We can't wait. Don't wait! Get involved. We'll need to make this happen together!

Which project? Picking the winning horse:

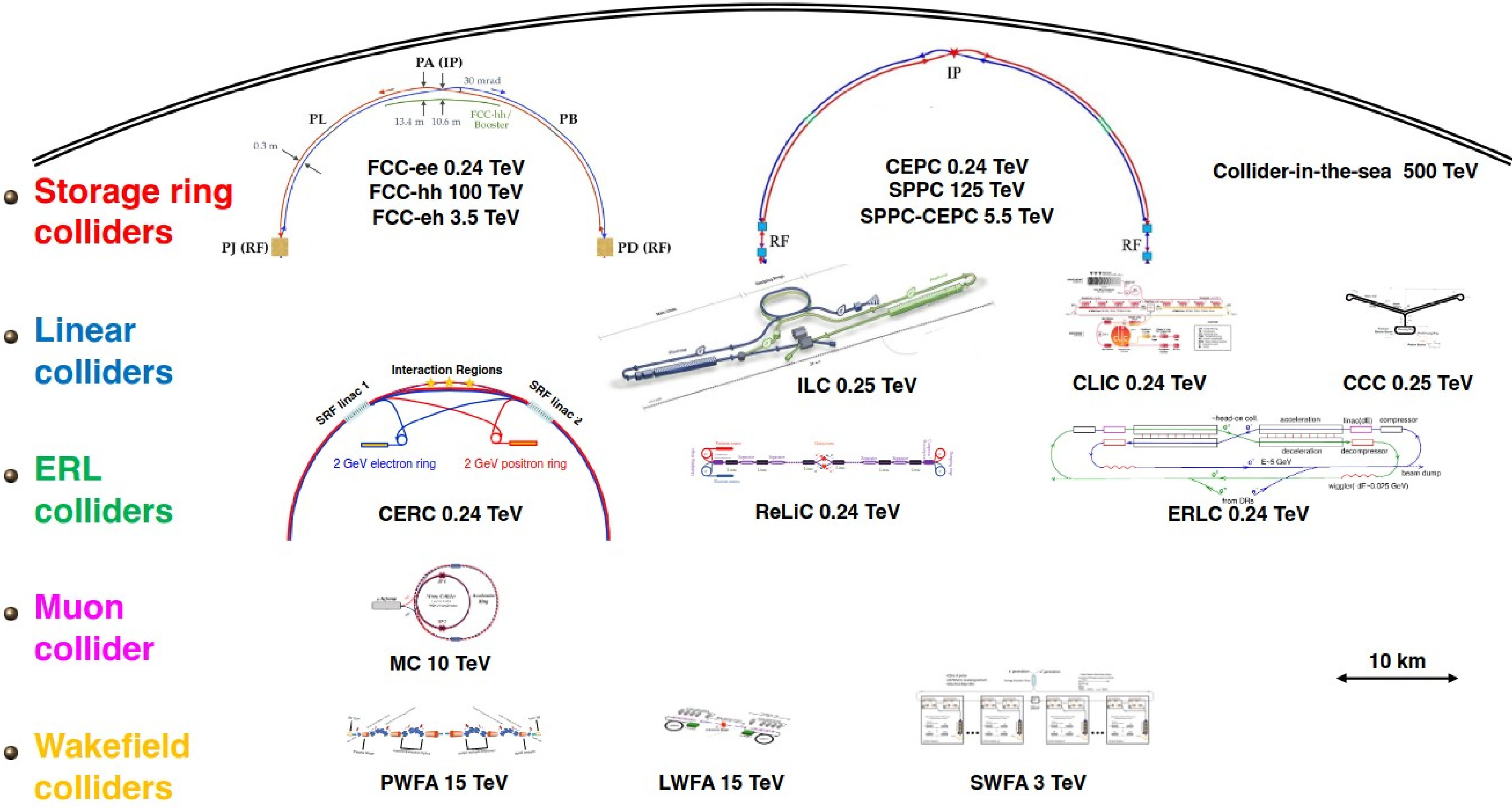
Gambling.com: Learning how to pick a winning horse is a skill honed over a lifetime

Quora: can't you just bet on all horses in a race?
A: technically you can, but you won't make any money.

Good solutions tend to work irrespective of the final choice of technology/location

Possible projects…

Future collider proposals: 0.125 – 500 TeV; e+e-, hh, eh, μμ, γγ, …



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The future collider landscape

European, American and Asian strategies agree on big picture

— e+e- Higgs factory first:

large circular colliders: FCC-ee (CERN) and CEPC (China)
linear colliders: ILC (Japan?), CLIC (CERN), CCC (US)

— exploration of the energy frontier next:

large pp collider: FCC-hh (CERN), SPPC (China)
muon collider: μ-collaboration (CERN+US)
plasma: accelerator R&D (EUPRAXIA, AWAKE), collider studies (i.e. ALEGRO)

Snowmass report

The proposed plans in five-year periods starting in 2025 are given below.

For the five-year period starting in 2025:

1. Prioritize the HL-LHC physics program, including auxiliary experiments,
2. Establish a targeted e^+e^- Higgs Factory Detector R&D program,
3. Develop an initial design for a first-stage TeV-scale Muon Collider in the U.S.,
4. Support critical Detector R&D towards EF multi-TeV colliders.

For the five-year period starting in 2030:

1. Continue strong support for the HL-LHC physics program,
2. Support the construction of an e^+e^- Higgs Factory,
3. Demonstrate principal risk mitigation for a first-stage TeV-scale Muon Collider.

Plan after 2035:

1. Continuing support of the HL-LHC physics program to the conclusion of archival measurements,
2. Support completing construction and establishing the physics program of the Higgs factory,
3. Demonstrate readiness to construct a first-stage TeV-scale Muon Collider,
4. Ramp up funding support for Detector R&D for energy frontier multi-TeV colliders.

European strategy update

3 | High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

Most relevant new developments

Technology progress:
– High-efficiency klystrons (good for all projects): CERN-IHEP project pushes 80%
– High-gradient SCRF cavities: FNAL&IHEP push the envelope > 40 GV/m

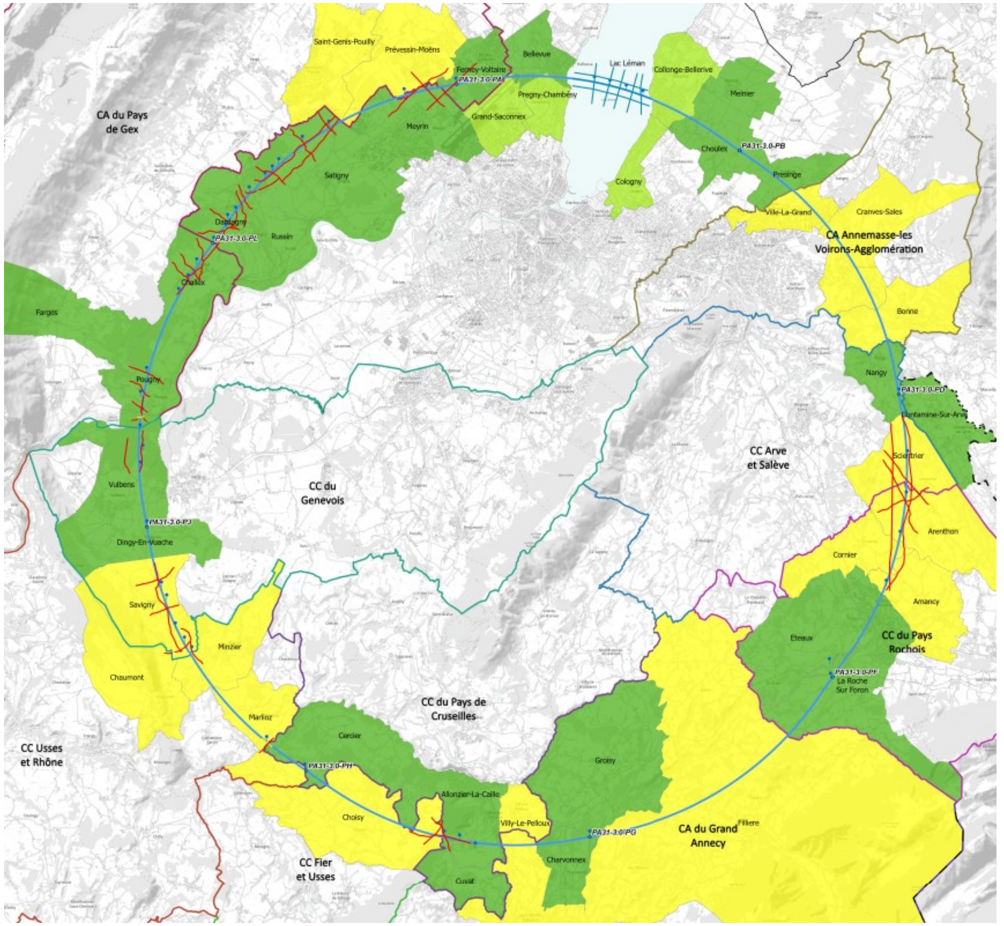
Design studies:
– Energy-recovery LINACs, boost luminosity of e+e- colliders, https://arxiv.org/abs/1909.04437 + first conceptual designs for real machines
– Cool Copper Collider, shrink Higgs factory to 8 km facility, https://arxiv.org/abs/2203.07646
– Hybrid, asymmetric wakefield & RF collider, shrink Higgs factory to 3.3 km facility, https://arxiv.org/abs/2303.10150
– Muon collider (the μC is back!), energy-efficient multi-TeV lepton collisions https://arxiv.org/abs/2209.01318

Global R&D progress is pushing accelerator technology; several new collider concepts have been launched in recent years

Higgs/top/EW factory project progress

Detailed FCC design based on geology and accelerator studies, but also road access, power supply, etc.

Parameter	unit	2018 CDR [1]	2023 Optimised
Total circumference	km	97.75	90.657
Total arc length	km	83.75	76.93
Arc bending radius	km	13.33	12.24
Arc lengths (and number)	km	8.869 (8), 3.2 (4)	9.617 (8)
Number of surface sites	—	12	8
Number of straights	—	8	8
Length (and number) of straights	km	1.4 (6), 2.8 (2)	1.4 (4), 2.031 (4)
superperiodicity	—	2	4



FCC mid-term review end of 2023, CERN council statement Feb. '24

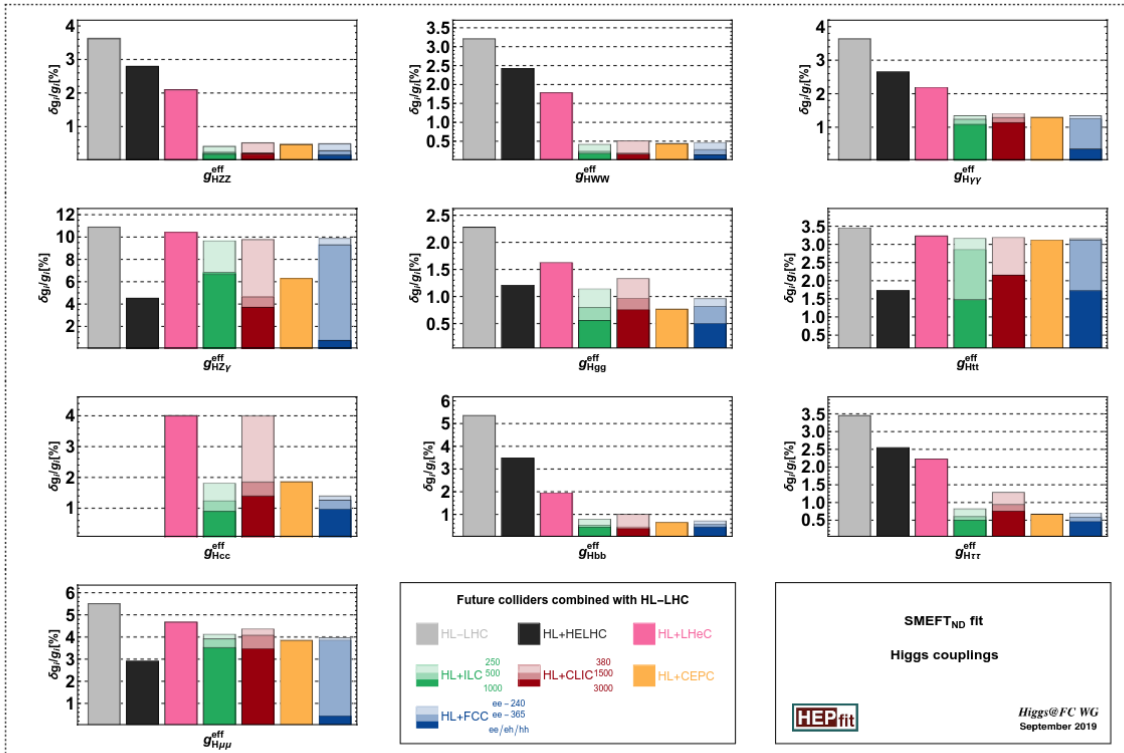
US P5 panel to provide recommendations this year

ILC: signs CERN-KEK agreement for common R&D programme on the accelerator

CEPC: Chinese Academy of Sciences pre-selects CEPC

Circular or linear?

- Circular machines provide superior luminosity at LEP energies (i.e. TeraZ Z-pole run)
- All machines can do excellent Higgs physics and can reach the $t\bar{t}$ threshold
- Upgraded linear colliders access di-Higgs, ttH, and "energy-growth" in new physics



European strategy physics briefing book, https://arxiv.org/pdf/1910.11775.pdf

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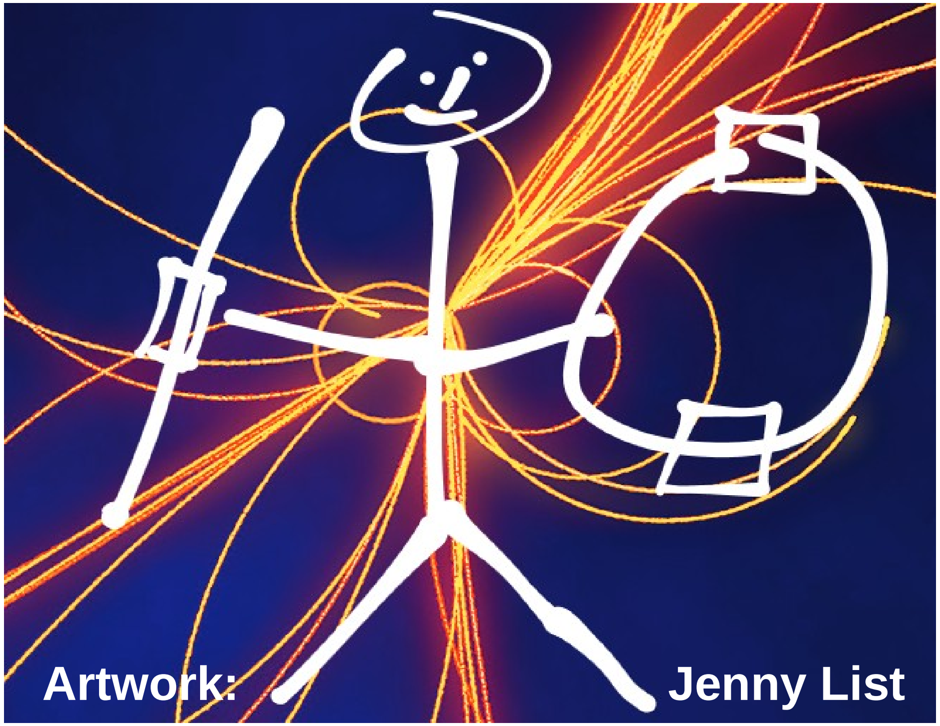

The scientific choice is essentially Z-pole vs. energy upgrade, the rest is "just" politics

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Politics: comparison of main figures of merit

(according to Snowmass Collider Implementation Task Force)

1) for two experiments, 2) accurate beam energy 3) polarized beams enhance cross sections

	Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
Higgs factory	FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
Higgs factory	CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
Higgs factory	ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	$<$12	7-12	140
Higgs factory	CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
Higgs factory	CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
+ERL	CERC[3] (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
+ERL	ReLiC[1,3] (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	$>$25	7-18	315
+ERL	ERLC[3] (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	$>$25	12-18	250
Exotic HF	XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Exotic HF	Muon Collider Higgs Factory[3]	0.13	0.01	$>$10	19-24	4-7	200

More complete report

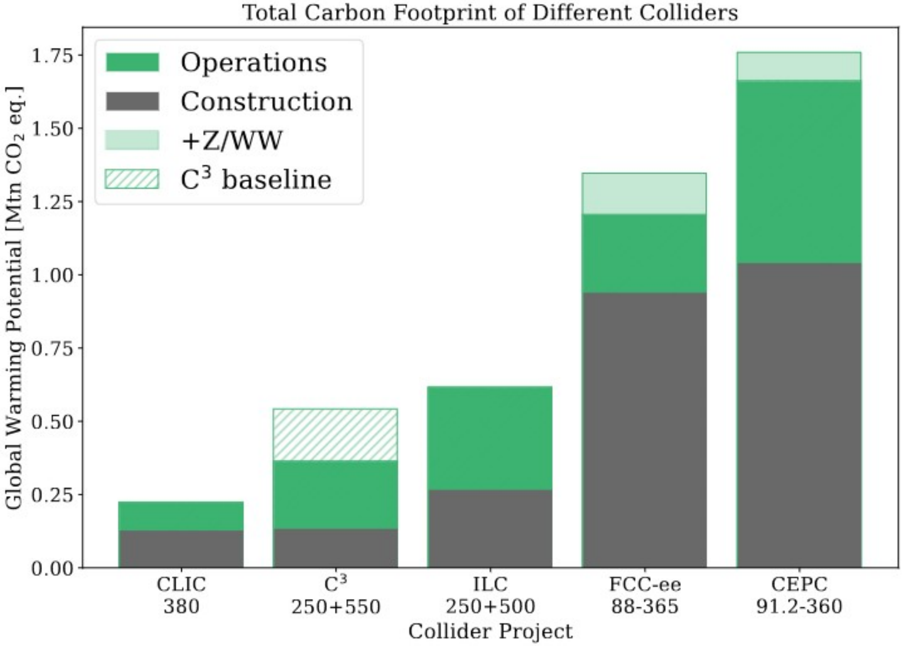
More figures of merit

Carbon footprint of colliders
https://arxiv.org/pdf/2307.04084.pdf

A Sustainability Roadmap for C[3]

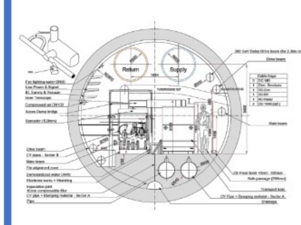
Martin Breidenbach, Brendon Bullard, Emilio Alessandro Nanni, Dimitrios Ntounis[†], Caterina Vernieri
SLAC National Accelerator Laboratory [†] & Stanford University

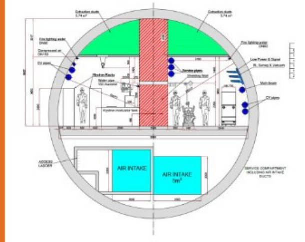
Complete ISO life-cycle assessment ongoing for several projects



Lessons: construction of the facility (boring, concrete+steel for tunnel) has a large impact, exceeding that of energy consumption during operation for most projects.

Optimize design to minimize impact (i.e. CLIC drive beam vs. Klystrons)


CLIC Drive beam, 5.6m dia.


CLIC Klystron, 10m dia.

More figures of merit

Carbon footprint of colliders
https://arxiv.org/pdf/2307.04084.pdf

A Sustainability Roadmap for C^3

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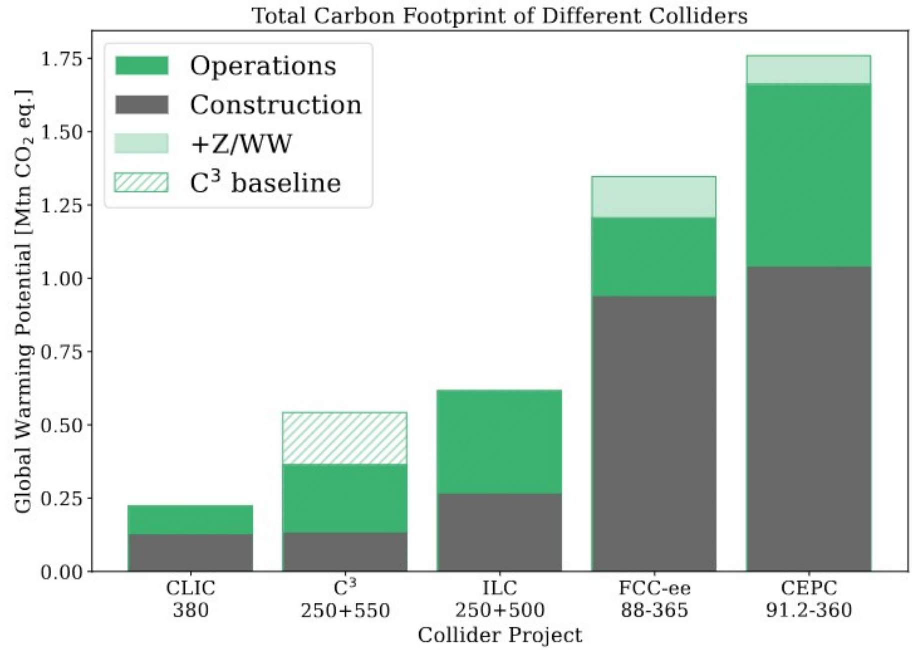
SLAC National Accelerator Laboratory [†] & Stanford University

Complete ISO life-cycle assessment ongoing for several projects



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Optimize design to minimize impact
(i.e. CLIC drive beam vs. Klystrons)

Compare: MAD-ORD return = ~2 tons CO_2

Departure	Arrival
MAD - Adolfo Suárez Madrid–Barajas Air…	ORD - Chicago O'Hare International Airp…

- Distance (each way): **4,196 miles or 6,753 km**
- Round-trip emissions per passenger: **2.4 metric tons CO2 equivalent**
- Avoiding this trip is as climate friendly as being vegetarian for: **4.5 years**
- Avoiding this trip is as climate friendly as carpooling for: **2.4 years**
- This many people in the world emit fewer greenhouse gases in one year: **2.8 billion**
- You could travel this far in an electric train like Eurostar: **10.2 times around the world**
- These emissions melt this much Arctic sea ice: **78.8 square feet or 7.3 square meters**

code & sources

Top physics prospects

t

HL-LHC prospects

Prospect studies have a history of under-selling new facilities

- i.e. LEP prospects without vertex detectors (and precise $Z \rightarrow bb$ studies)
- i.e. ATLAS tttt projection ATL-PHYS-PUB-2022-004

HL-LHC top physics prospects were no exception:

Compare this somewhat gloomy 3-pager in 2005…

> **4.4 Top-quark physics**
>
> Given the large top quark cross-section, most of the top physics programme should be completed during the first few years of LHC operation [32]. In particular, the $t\bar{t}$ and the single-top production cross-sections should be measured more precisely than the expected theoretical uncertainties, and the determination of the top mass should reach an uncertainty (dominated by systematics) of ~ 1 GeV, beyond which more data offer no obvious improvement.

HL-LHC primer, hep-ph/0204087

… with actual LHC results so far (300 MeV on top mass)
… recent prospects (i.e. boosted+rare production, YR arXiv:1902.04070)
… new developments (ATLAS + CMS observation of entangled $t\bar{t}$ pairs)

The LHC programme just got started; plenty of top physics in store!

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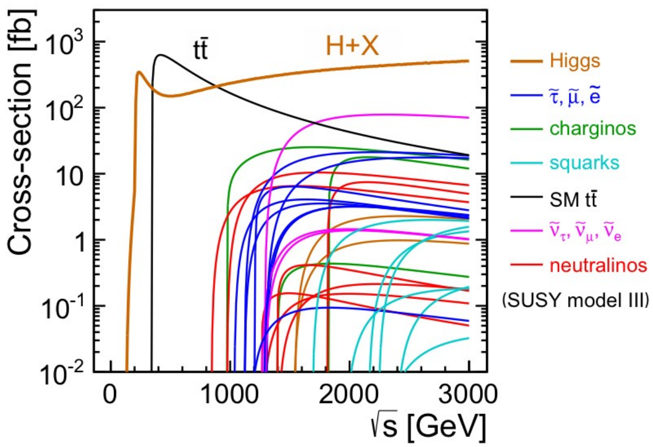
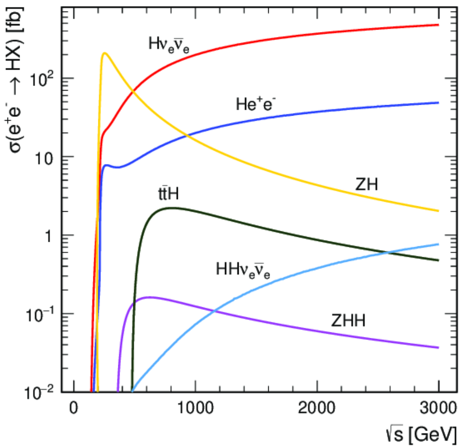
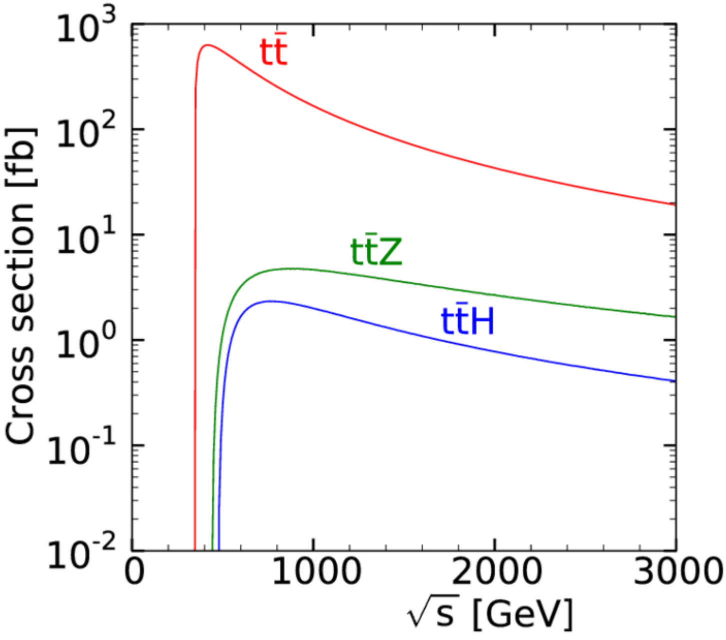
Energy reach: top production thresholds

The ideal facility covers a broad energy range.







Direct BSM searches benefit from high energy

Higgs programme not limited to 250 GeV (VBF, di-Higgs production)

Top physics thresholds: ~ 350 GeV for pair production
~ 550 GeV for ttH
~ few TeV for VBF tt production, single top

Precision

The LHC is a precision machine

Top quark pair production cross section to 2% uncertainty!!

Possible thanks to new luminosity calibration (0.8%!, arXiv:2212.09379)

Main bottle neck: NNLO+NNLL theory (scales, PDFs)

At an e+e- collider realistic statistical uncertainties are O(few ‰)

→ *See e.g. CLIC top paper, arXiv:1807.02441*

Experimental systematic uncertainties can be controlled to that level

→ *requires work on techniques, calibrations and MC*

Theory is already at N3LO for e+e → γ^* → tt

X. Chen et al., Heavy-quark pair production at lepton colliders at NNNLO in QCD, arXiv:2209.14259

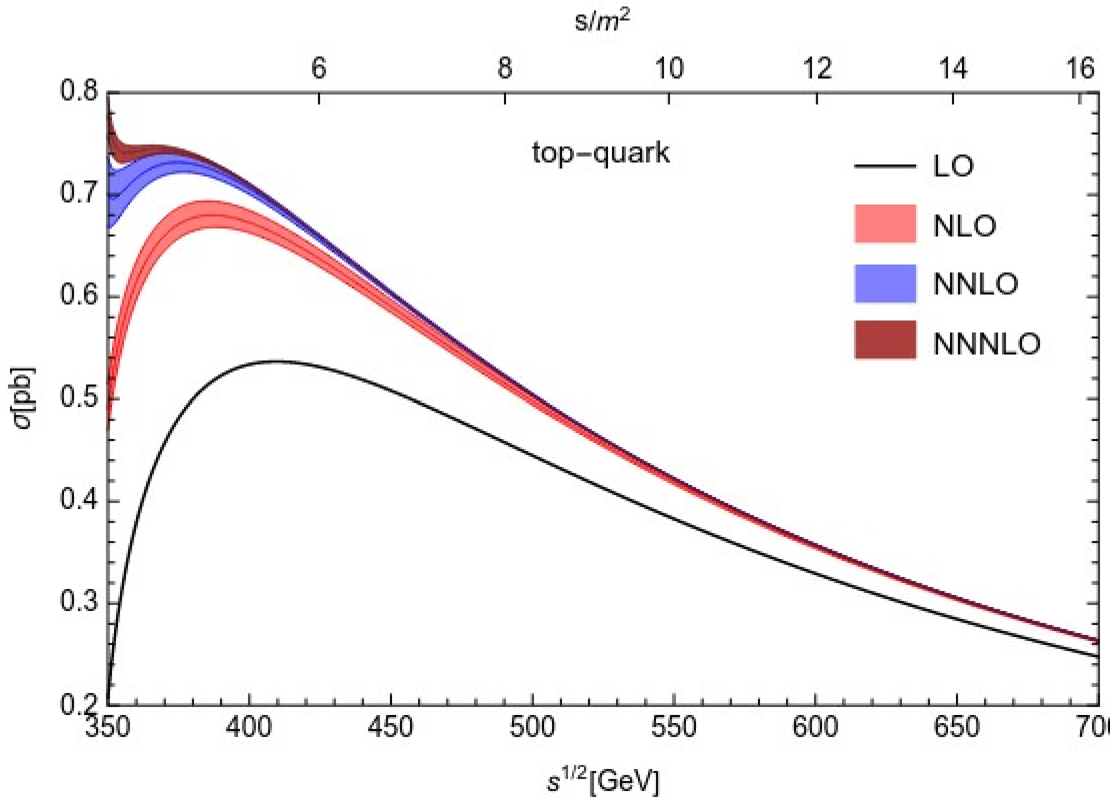
Precision: theory predictions at lepton colliders

X. Chen et al., Heavy-quark pair production at lepton colliders at NNNLO in QCD, arXiv:2209.14259

N^3LO QCD corrections are now available for e+e- → γ* → tt

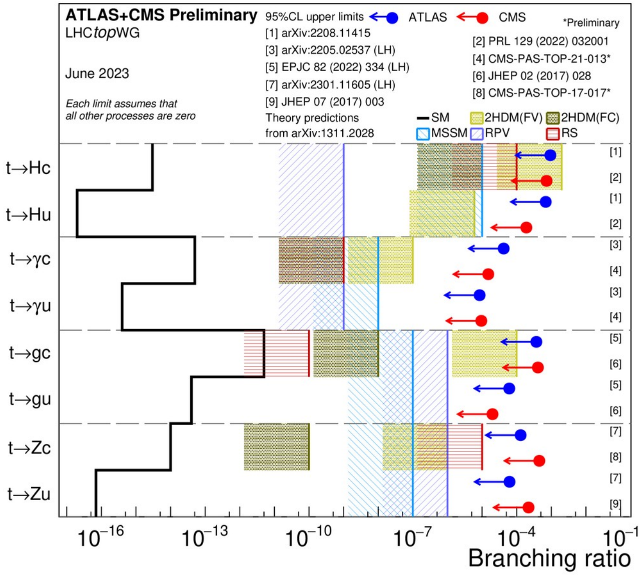
Very good convergence with uncertainty O(‰)

Threshold (<420 GeV) requires resummation



Still need: NNLO EW corrections + ISR + threshold matching + offshell

FCNC interactions:
top physics below the $t\bar{t}$ threshold



FCNC searches are HL-LHC territory, aren't they?

Most recent prospects: CERN YR 7 (2019), arXiv:1902.04070
+ Matteo Defranchis, this morning

LHC: excellent sensitivity. BR(t→qX)@95%CL from 10^{-3} to 10^{-5}

Note: production pp → tX is as important as decay t → qX

HL-LHC: expect to improve more than an order of magnitude

$\mathcal{B}$ limit at 95%C.L.	3 ab^{-1}, 14 TeV	15ab^{-1}, 27 TeV	Ref.
$t \to gu$	3.8×10^{-6}	5.6×10^{-7}	[721]
$t \to gc$	32.1×10^{-6}	19.1×10^{-7}	[721]
$t \to Zq$	$2.4 - 5.8 \times 10^{-5}$		[733]
$t \to \gamma u$	8.6×10^{-6}		[724]
$t \to \gamma c$	7.4×10^{-5}		[724]
$t \to Hq$	10^{-4}		[733]

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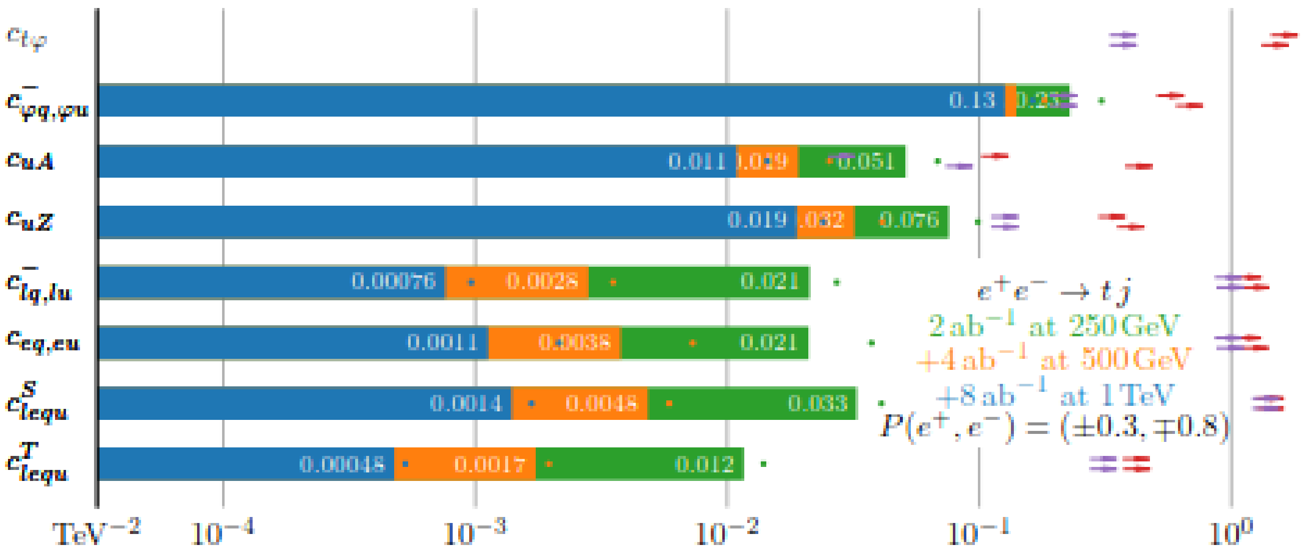
Well, e+e- colliders aren't that bad, either.

Lepton collider is both competitive and complementary

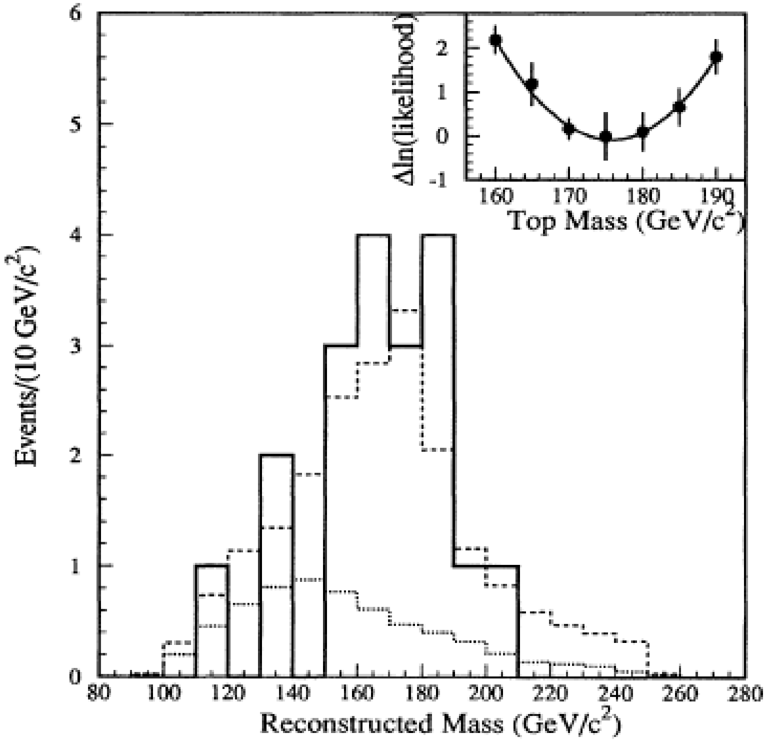
First top physics: e+e- → tj searches at 250 GeV

More full-simulation work needed!

H. Hesari et al., arXiv:1412.8572
G. Durieux et al., arXiv:1412.7166
Shi & Zhang, arXiv:1906.04573
ILC white paper, arXiv:2203.07622
M. Arroyo et al.,arXiv:2202.04572



The $t\bar{t}$ threshold scan: the ultimate top mass measurement



LHC status, HL-LHC prospects, interpretation

+ Snowmass report
arXiv:2209.11267
arXiv:2203.08064

Direct mass measurements are experimentally the most precise

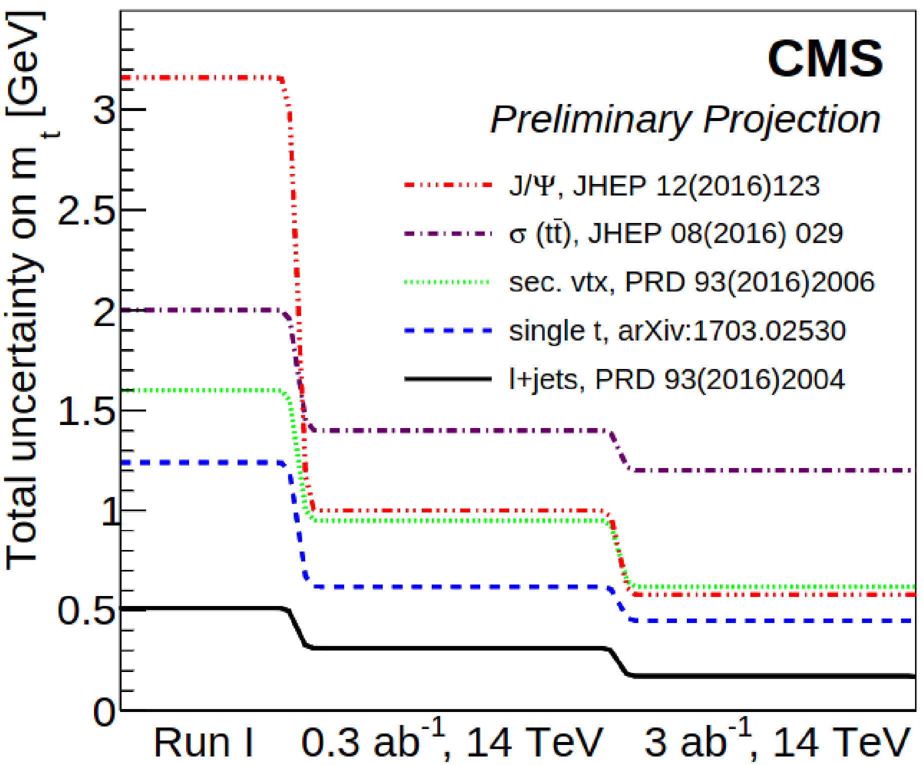
m_t ~ 172.52 ± 0.33 GeV

(ATLAS+CMS run 1 **combination***, see Clara Nellist's presentation at this conference)*

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

Cross-section-based mass extractions achieve O(1 GeV) precision/measurement.
Theorist's combined fit yields 400 MeV (Zenaiev & Moch, preliminary).



Status quo interpretation: "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

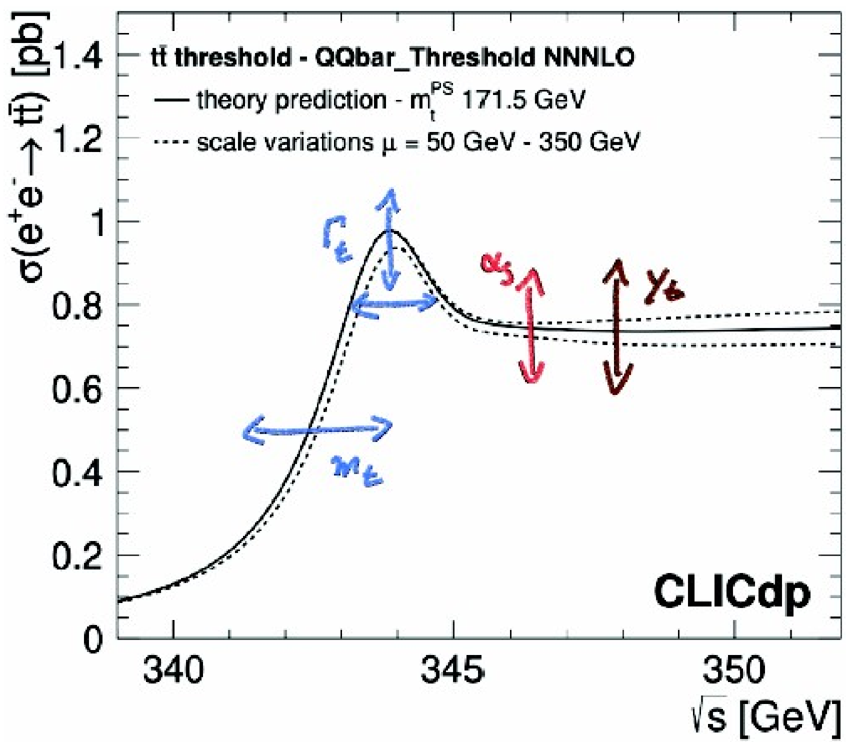
Combination of direct measurements: **200 MeV (exp.) + ?? (theo.)**
Combination of x-sec-based extractions: **500 MeV (theo.+exp.)**

e+e- threshold scan

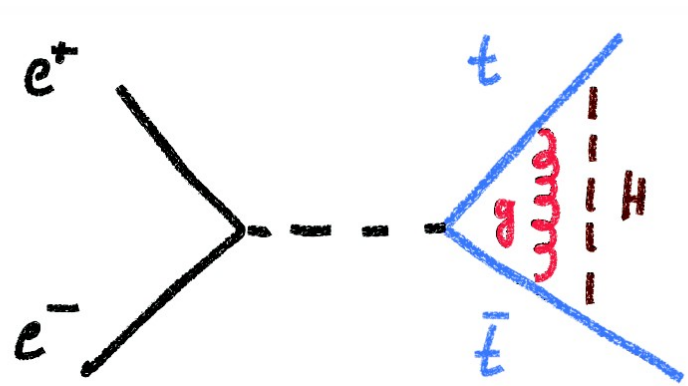
A scan of the e^+e^- center-of-mass energy through the pair production threshold allows for the ultimate mass measurement *(Gusken & Kuhn '85, Peskin & Strassler '91)*

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

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



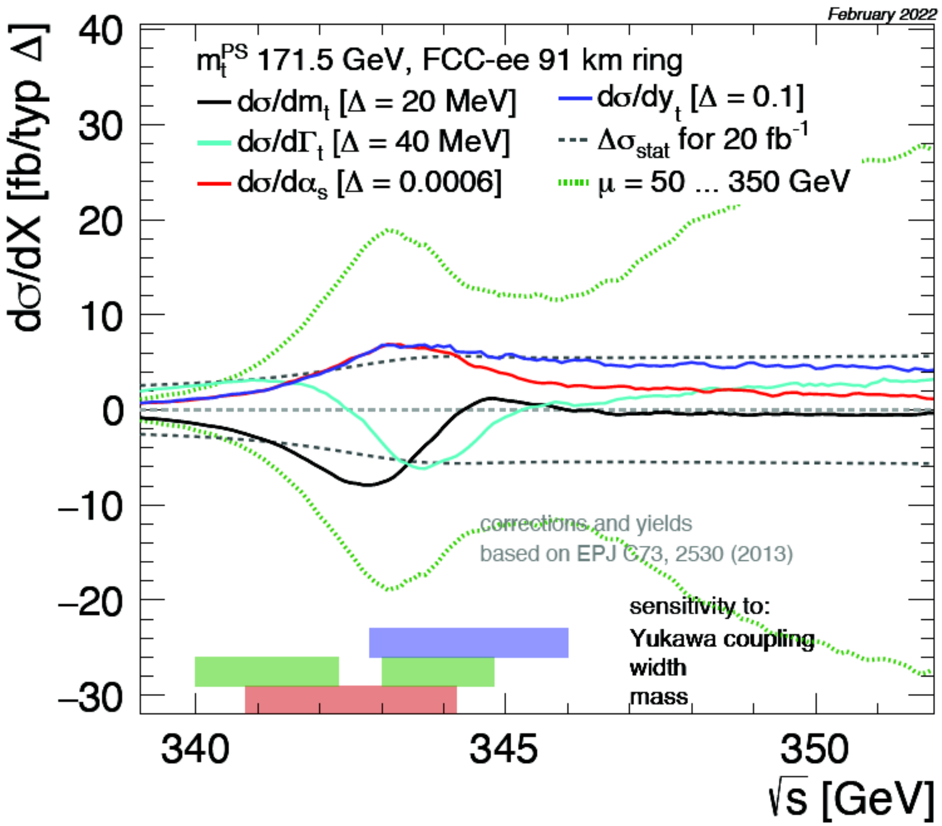
Calculation: Beneke et al.
Art-work: Frank Simon



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.

Top quark mass

Frank Simon's seminar
Snowmass top physics report



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

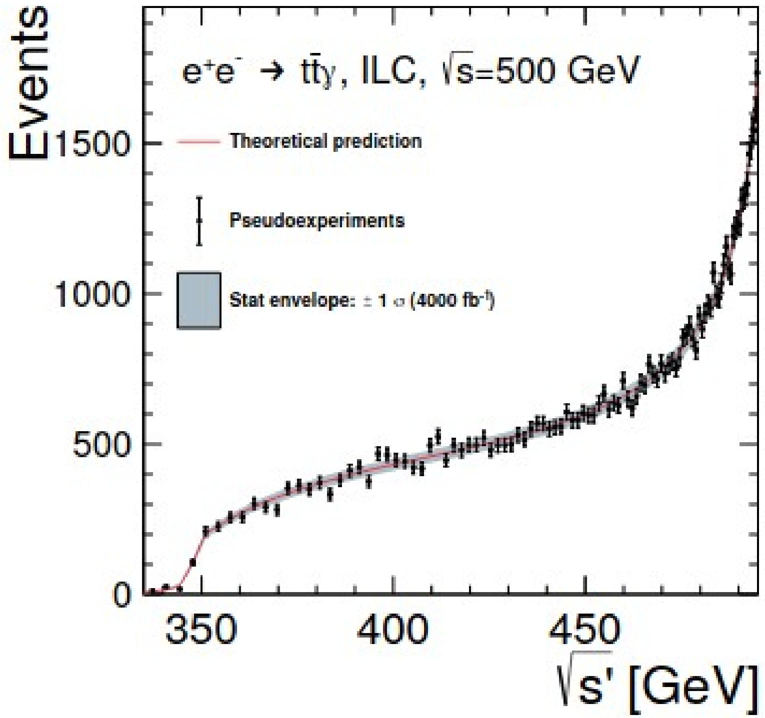
Theory uncertainty …… requires calculation beyond NNNLO (QCD) + NNLO (EW). Resummation is available and can be added.

Note: interpretation unambiguous, translation to MS scheme with O(10 MeV) scale uncertainty, parametric uncertainty due to α_s requires care

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

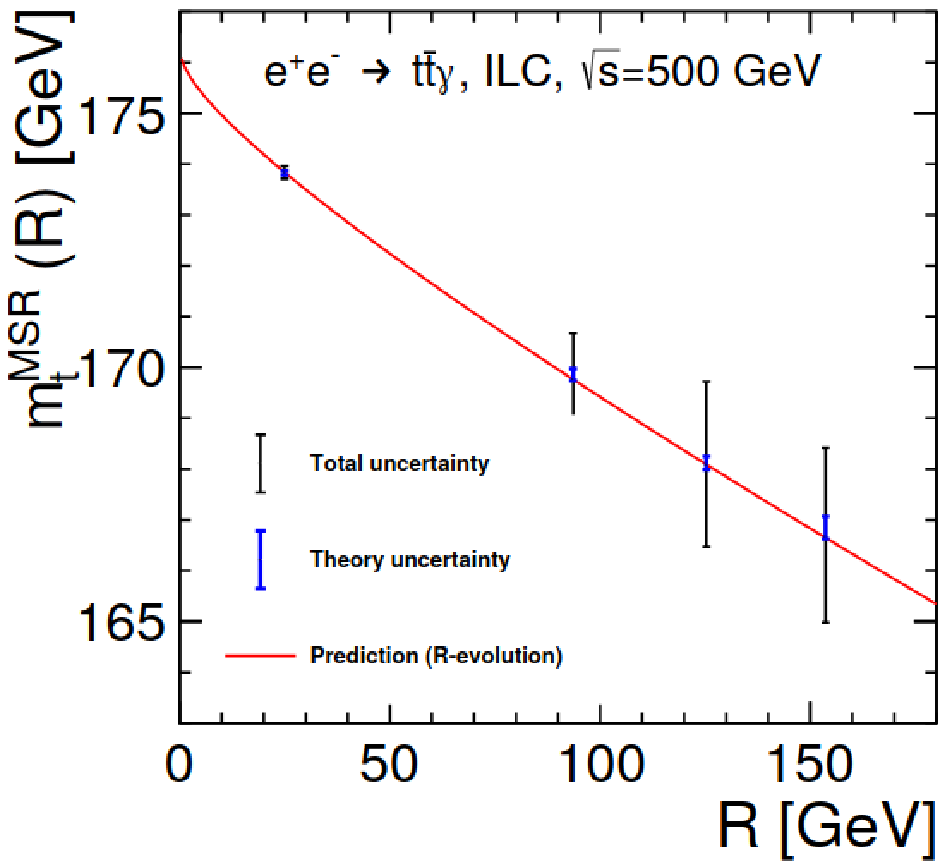
Higher-energy colliders: top quark mass from radiative events



Radiative "return to threshold" in e+e- → ttγ events

Extract short-distance mass with rigorous interpretation and competitive precision:

CLIC380 (1/ab): 50 MeV (theory), 110 MeV total
ILC500 (4/ab): 50 MeV (theory), 150 MeV total

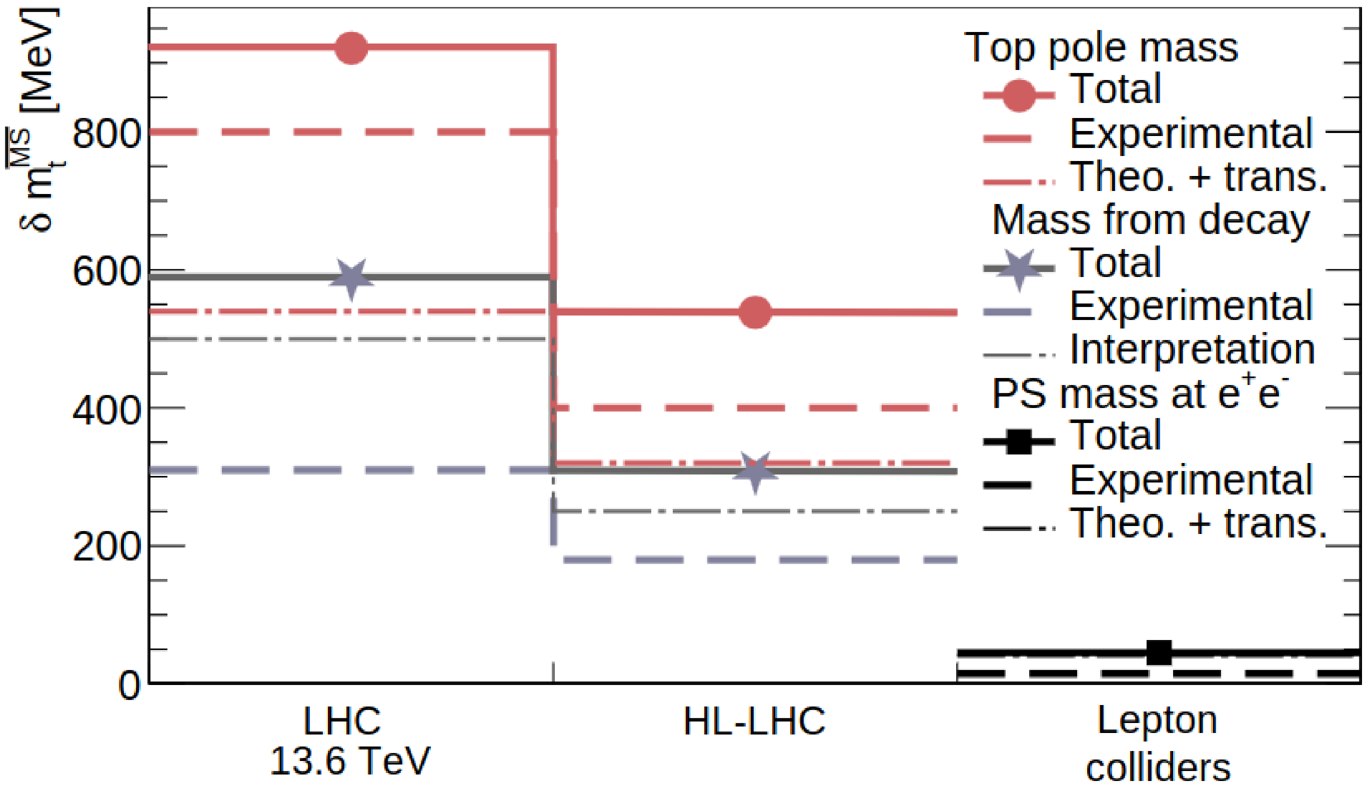


5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone

Boronat et al., arXiv:1912.01275

Top mass summary

Snowmass report, arXiv:2209.11267



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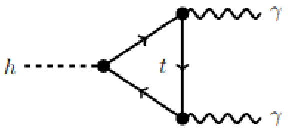
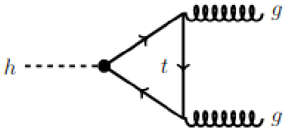
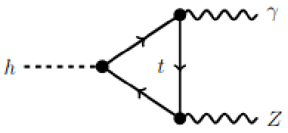
Top and Higgs







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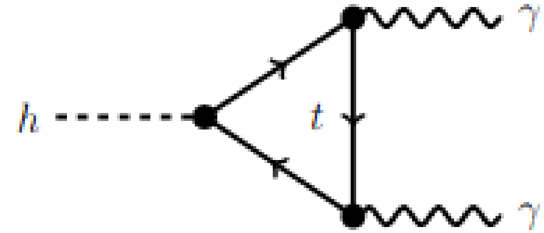
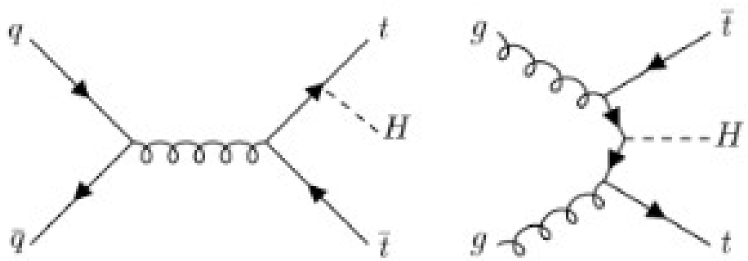
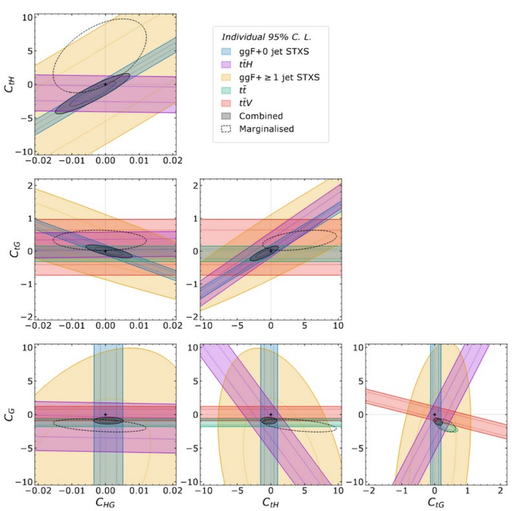
The top Yukwa coupling at the LHC

H(125) observation in **2012** in gg → H, H→ γγ implicitly establishes Higgs-top coupling





Explicit confirmation in **2018** with the observation of pp → ttH production



Global fit to LHC data in **2021** (Ellis et al.) finds correlations among SMEFT coefficients prevent a robust determination of y_t from gg → H or H → γγ.

Global limit on C_phit is dominated by ttH.

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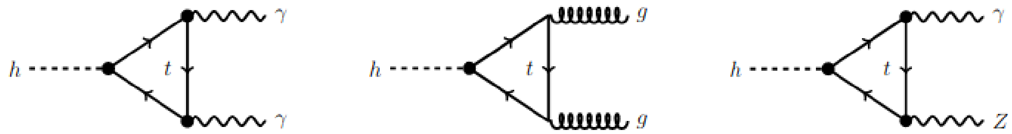
The top Yukawa coupling at a lepton collider



250 GeV run offers "indirect" sensitivity to the top Yukawa

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

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

Assuming the SM for all other couplings

500+ GeV run offers a "direct" measurement in ttH production

1-2% 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

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Above the threshold:
a broad precision programme

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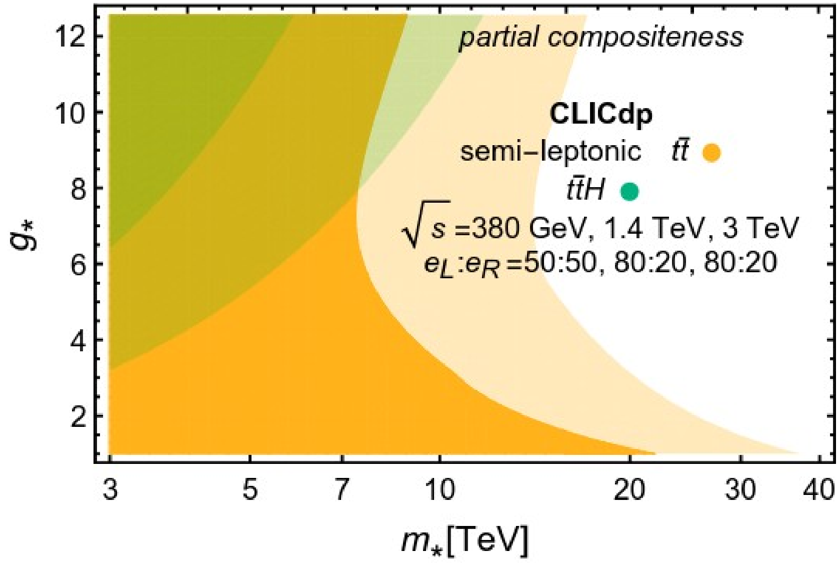
BSM physics and top quark couplings

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

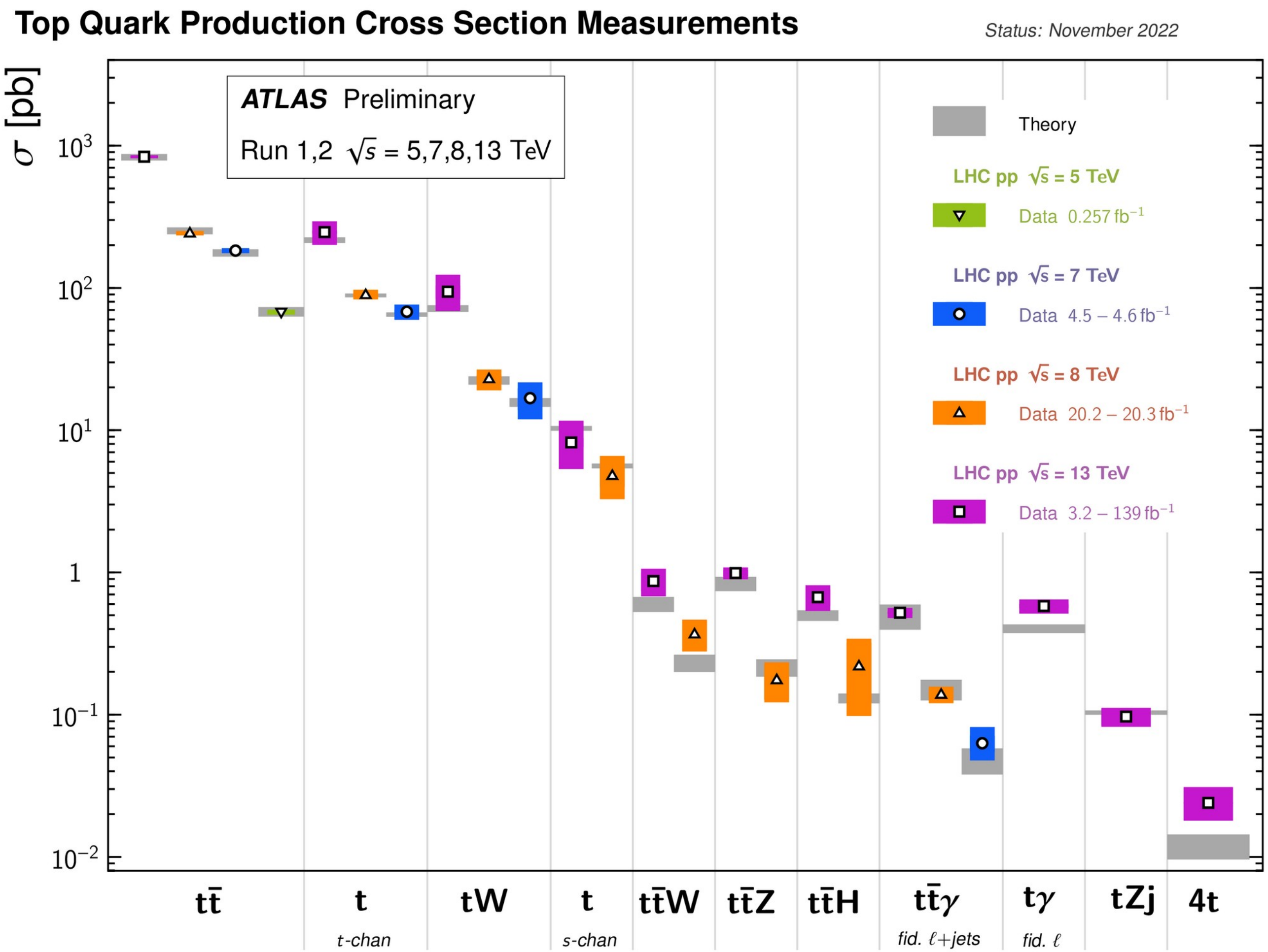
D. Top-quark compositeness

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!

The LHC top couplings programme



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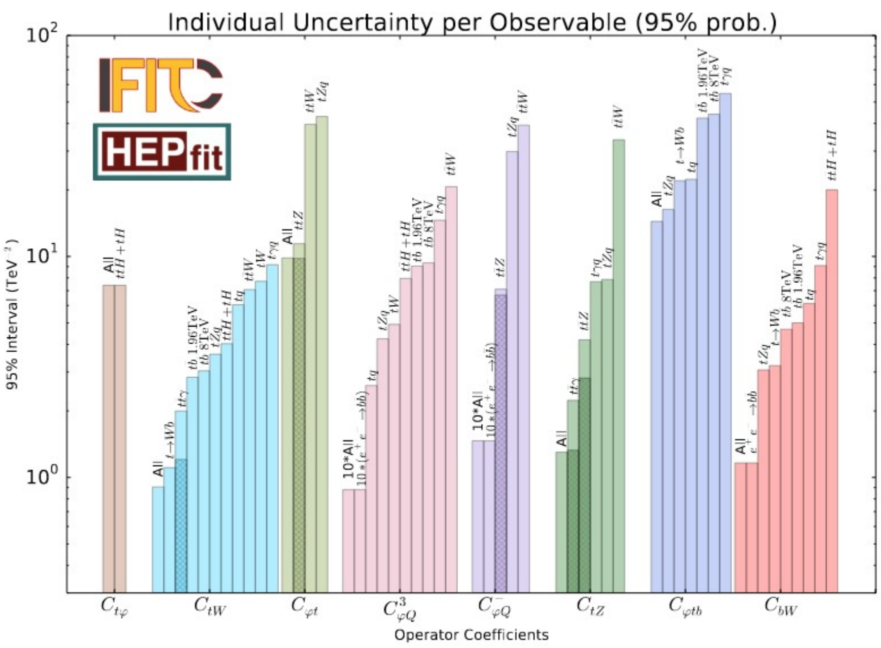
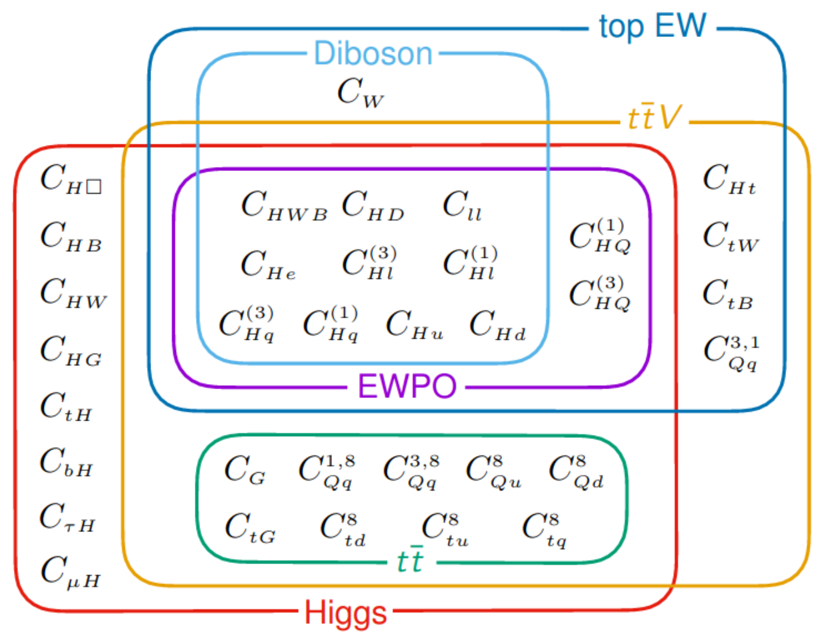
LHC top physics programme

Tevatron+LHC $t\bar{t}$ measurements characterize top QCD couplings precisely
Charged-current tWb interaction constrained by single top and W-helicity
Couplings with γ/Z/H probed in t+X (top quark escaped scrutiny at LEP
Measurements of tttt and ttbb characterize 4-heavy-quark vertices

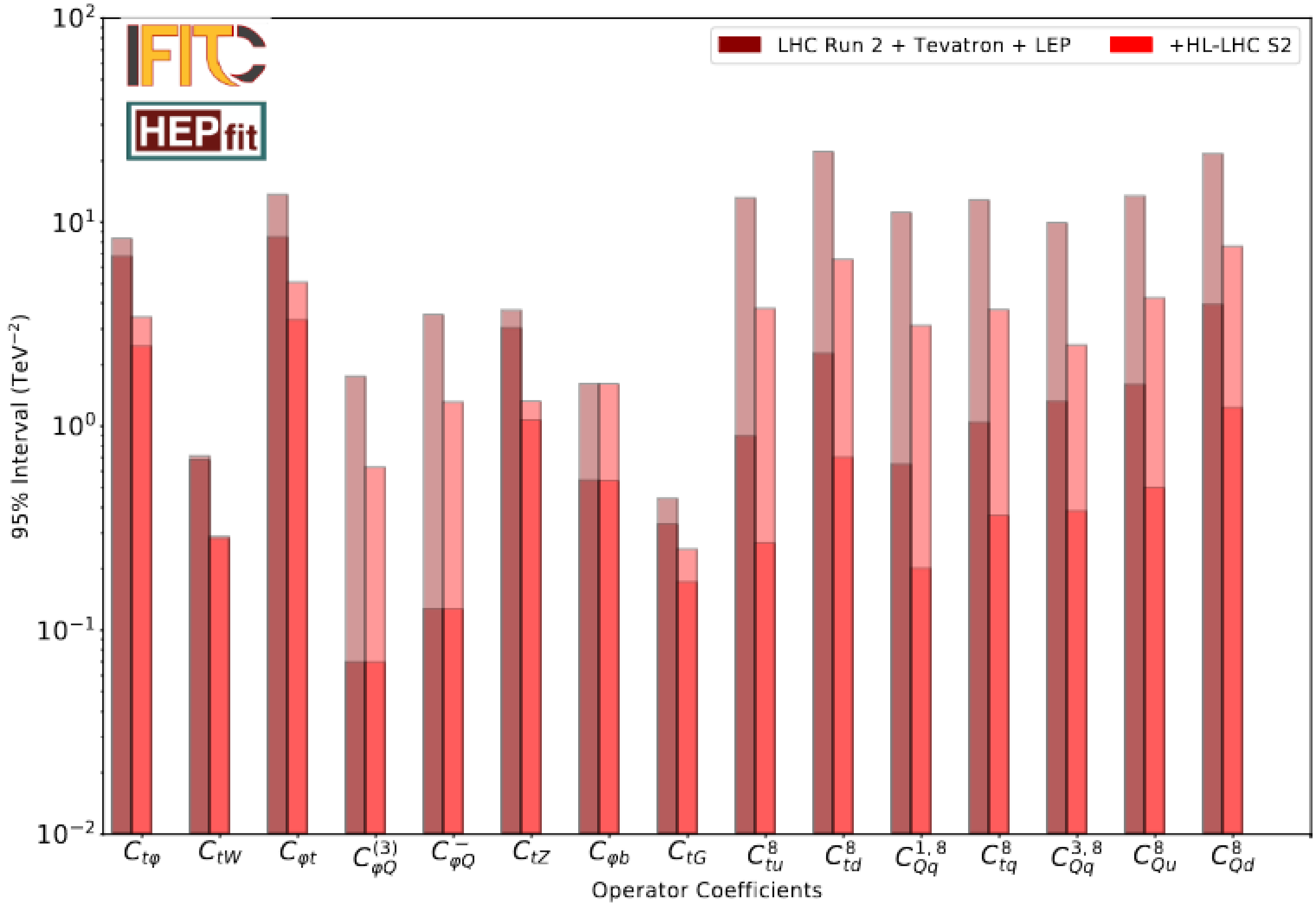




tttt, ttbb

ArXiv:2107.13917

HL-LHC projections



The e+e- programme

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

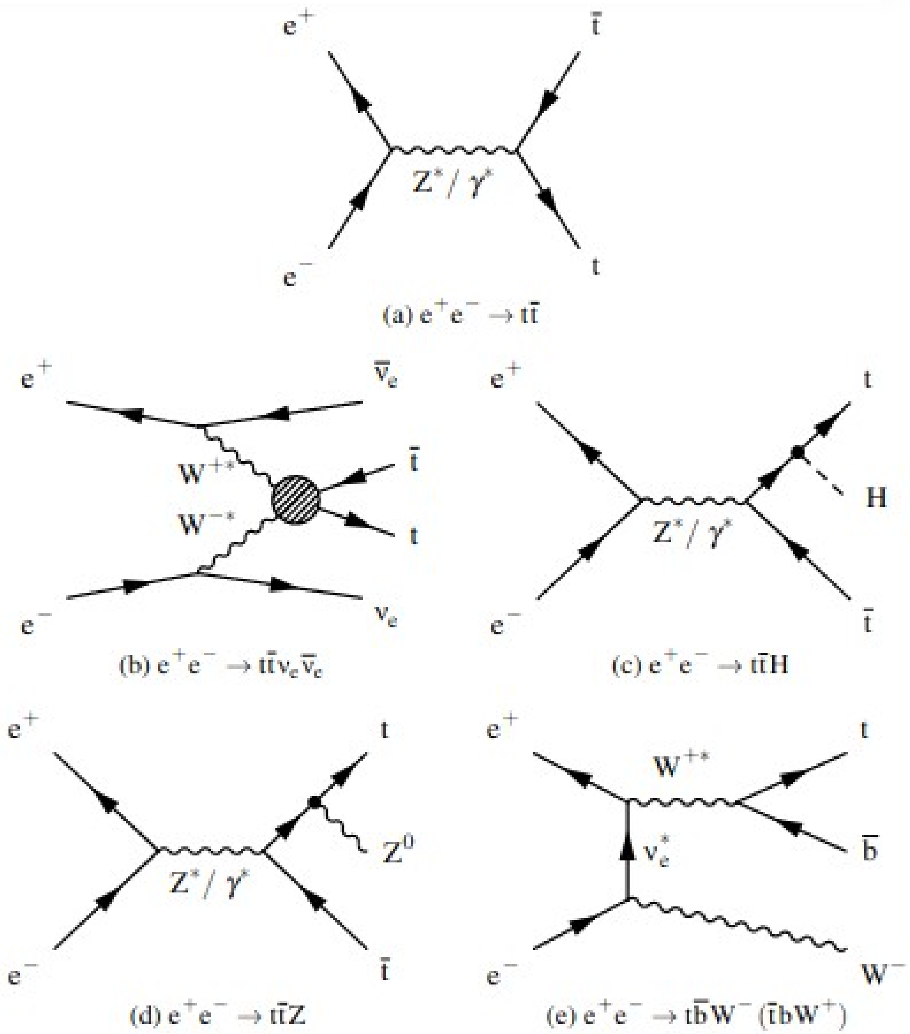
– pair production (a)
– single top production (b)

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



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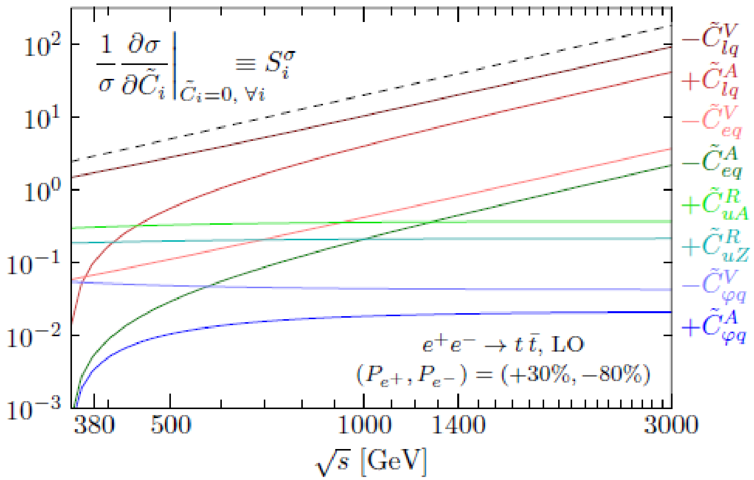
Energy: BSM sensitivity

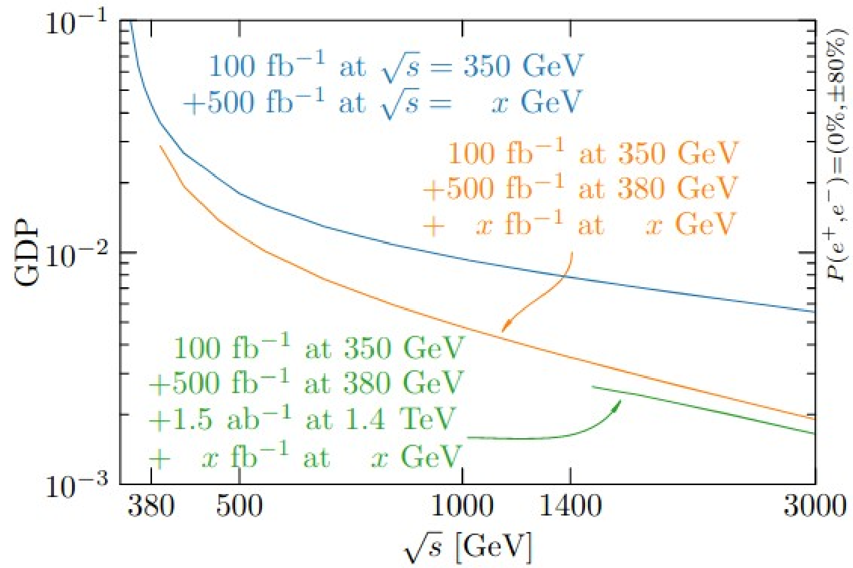
Durieux, Perello, Zhang, Vos, arXiv:1807.02121
CLIC top paper, arXiv:1807.02441
CLIC New Physics paper, arXiv:1812.02093



Effect of four-fermion operators felt most strongly at high energy

Effect of two-fermion operators best probed at ~400-500 GeV

Ideal facility to characterize top EFT:
– take data at two energies
– maximize lever arm of high-energy

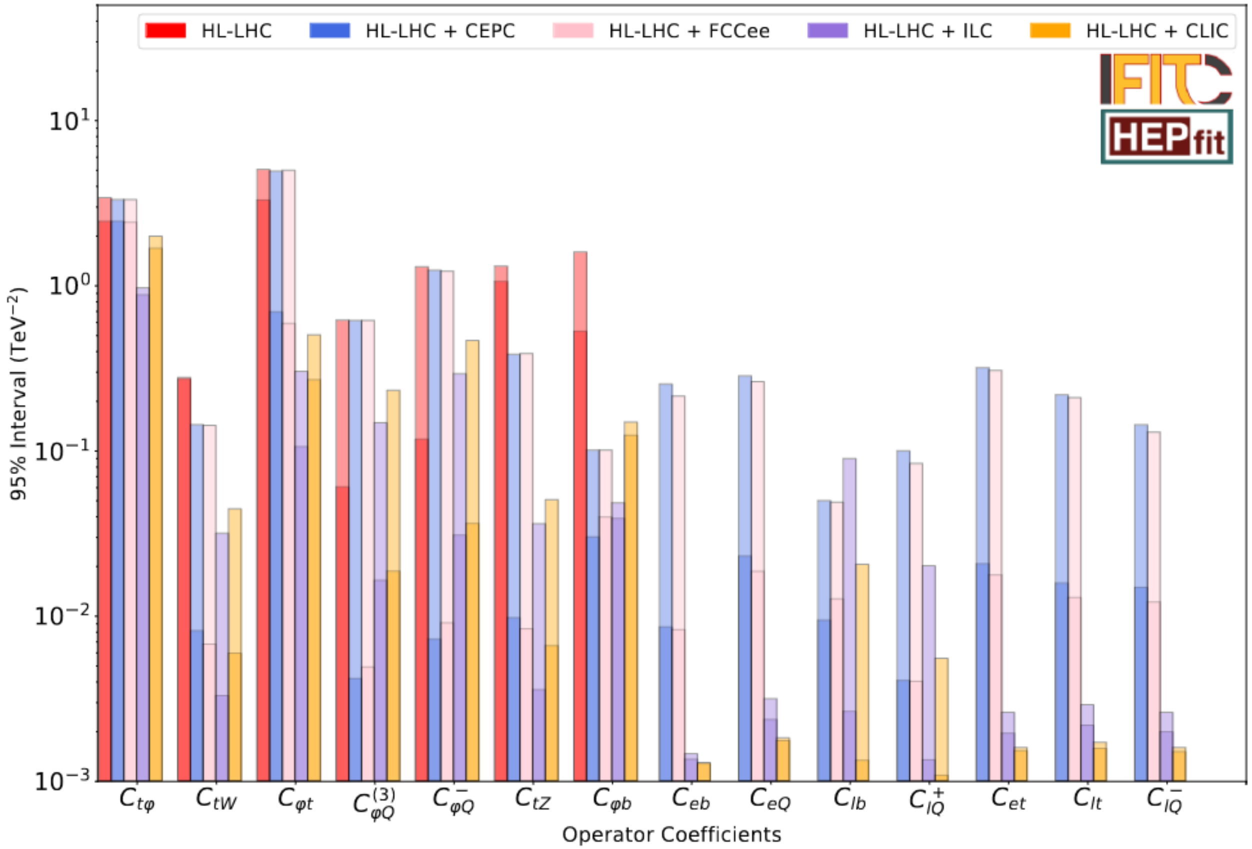


(See also Fiolhiais et al., arXiv:1206.1033)

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})

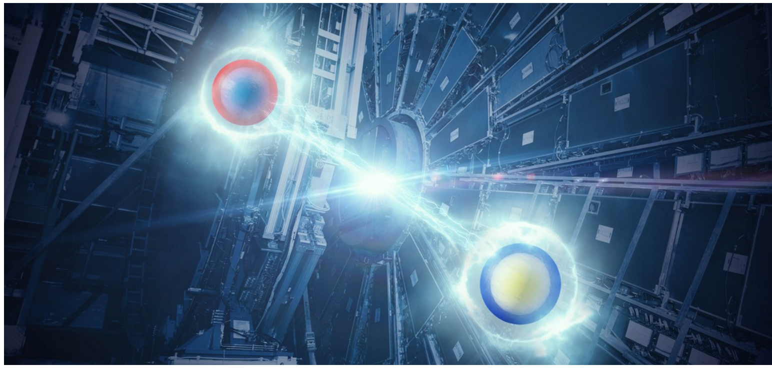


Snowmass SMEFT fit based on Durieux et al., with updated operating scenarios

Entanglement?

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

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



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Summary

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

The Higgs factory run at 250 GeV run already does good indirect top physics (FCNC searches in single top production, indirect top Yukawa from H→gg, gg, Zg)

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, ttγ, ttg, single top, ttZ, ttH, VBF tt production) and many measurements (σ, A_{FB}, polarization, CP-odd observables…).

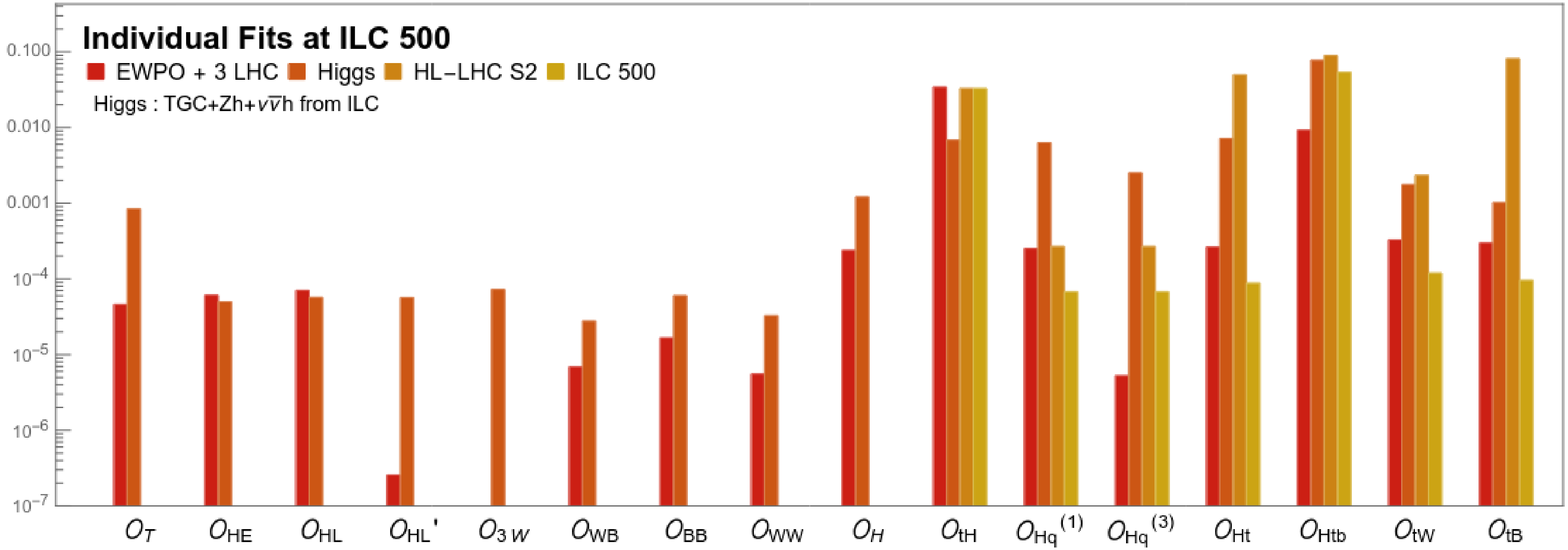
There is a **strong case to reach 500-550 GeV** (direct Yukawa from ttH, running top quark mass, constraints on eett operators) and for beam polarization.

Complementary strengths in comparison to **hadron colliders**

Core potential is clear, but more studies to define the full programme

SMEFT fit – future work

With just the “single” energy (threshold + 360/365 GeV) the challenge is to constrain all directions in SMEFT coefficient space. EWPO and Higgs data have significant constraining power



S. Jung et al., arXiv:2006. (see also work by Vryonidou et al.)

Possible next steps in ECFA Higgs/top/EW factory studies:
– merge Higgs/EW and top EFT fits on prospects
– find further exp. inputs to enable “single-energy” fit