Top quarks at next-generation lepton colliders

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TOP 2019
Beijing, 27 Sept.

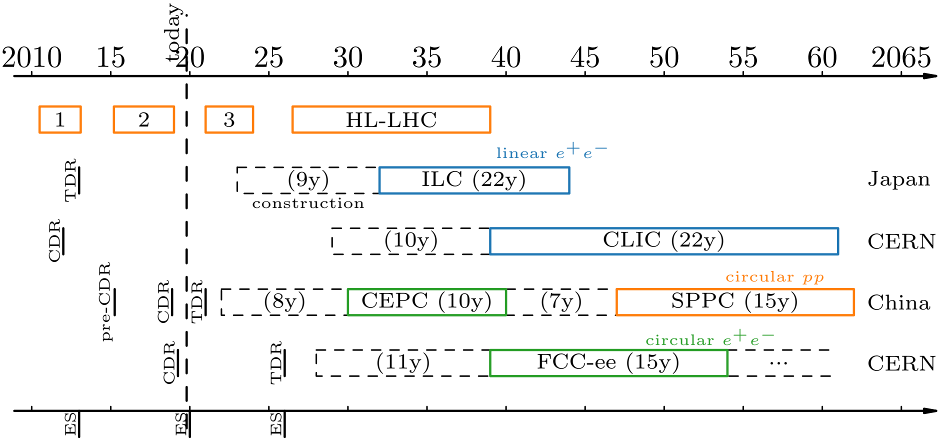
The top-quark escaped scrutiny
at the previous generation of lepton colliders.

At hadron colliders:

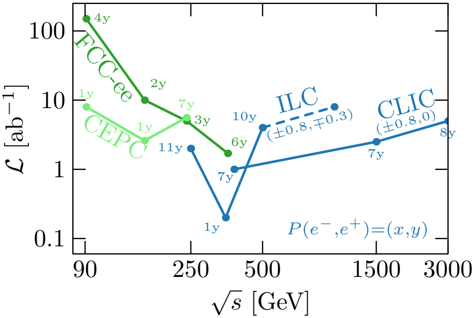
- top mass measurements are not theoretically clean,
- top electroweak couplings are difficult to access.

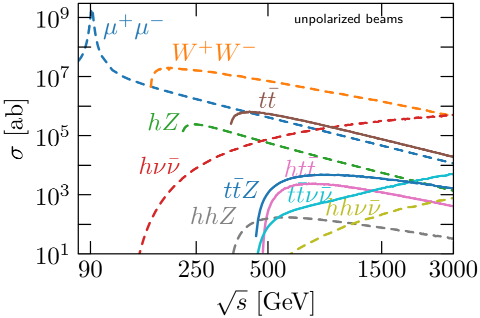
Leap into the future

Optimistic and speculative timelines:



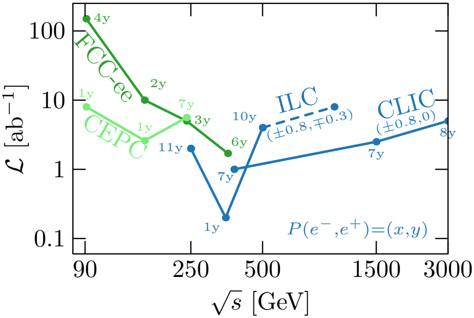
Circular vs. linear

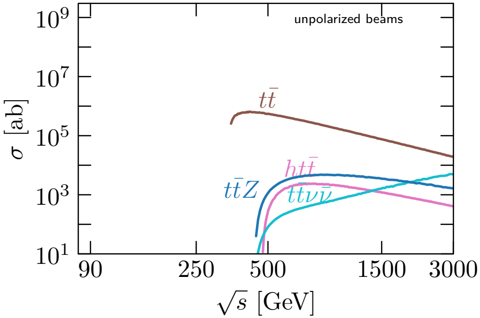




luminosity (on Z and W) vs. energy (for $t\bar{t}h$, hhX, etc.)
upgradable to pp vs. stageable in energy
higher beam quality vs. beam polarization

Circular vs. linear



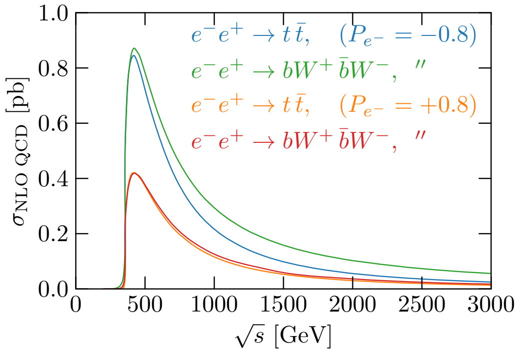


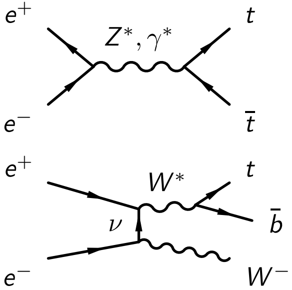
luminosity (on Z and W) vs. energy (for $t\bar{t}h$, hhX, etc.)

upgradable to pp vs. stageable in energy

higher beam quality vs. beam polarization

Top-quark pair production





$+ \, W^+W^- \to t\,\bar{t}$
catching up at multi-TeV
w/ unitarity breaking effects
[Grojean, Wulzer, You, Zhang]

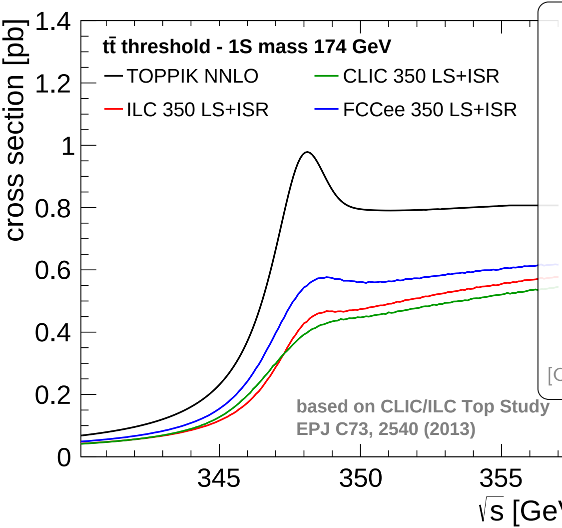
- σ peaked at about 380 GeV
- enhanced for a left-handed beam
- fall-off as $1/s$
- single-top contribution increasingly important

Top mass

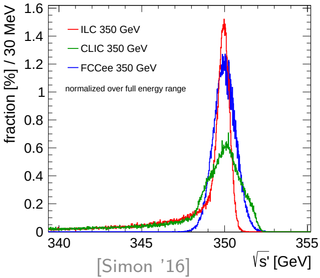
as clean as it gets

Threshold

NNLL [Hoang Stahlhofen '13], $\mathrm{N^3LO}$ in NRQCD [Beneke et al. '15] ,
matching with continuum NLO in Whizard [Bach et al. '17]



based on CLIC/ILC Top Study
EPJ C73, 2540 (2013)



[Simon '16]

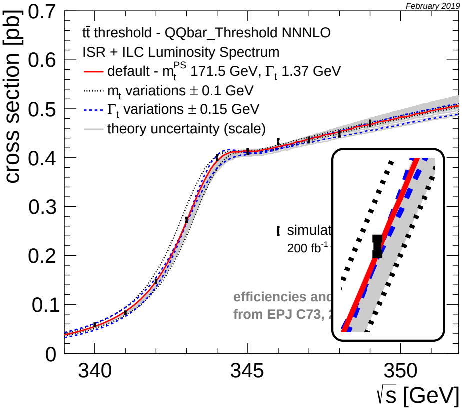
better with reduced bunch charge or focusing

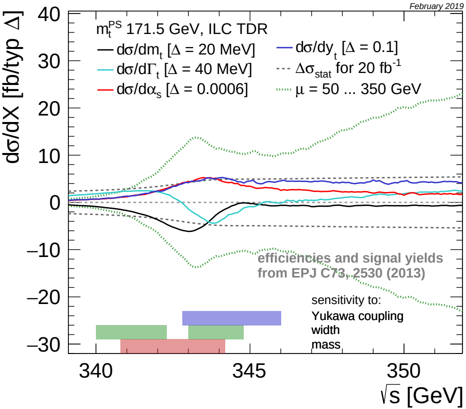
[CLIC Top Paper '18] [Simon@LCWS '18]

[Vos et al. '16]

Mass extraction

[Simon '19]





stat.: $\sim$ 20 MeV (with 100–200 fb^{-1})

sys.: up to 50 MeV (beam energy, lumi. spectrum, sel. eff., bkg's, non-resonant contrib.)

scales: $\sim$ 40 MeV

α_S: $\sim$ 5–30 MeV

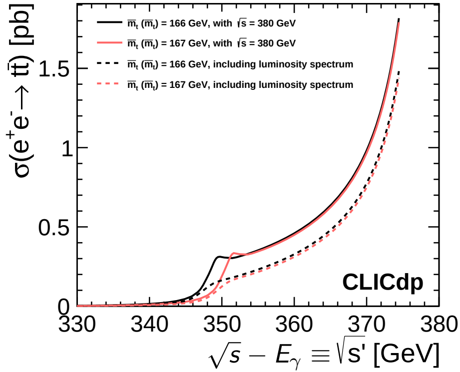
+ sensitivity to/contamination from:

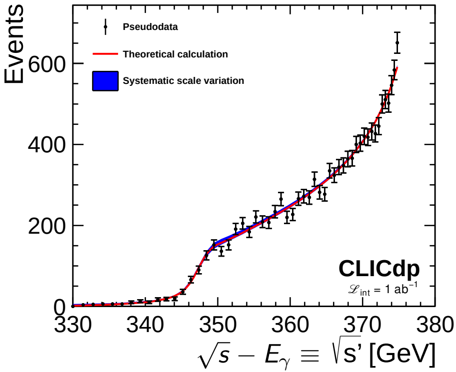
Γ_t: $\sim$ 70 MeV from 2D fit
y_t: $\sim$ 20% from 2D fit
α_S : $\sim$ few 10^{-4}
EW couplings: ??!!

Radiative return ($e^+e^- \to t\bar{t}\gamma$)

from $\sqrt{s} = 500$ GeV, $4\,\mathrm{ab}^{-1}$ [ILC '19]

from $\sqrt{s} = 380$ GeV, $1\,\mathrm{ab}^{-1}$ [CLIC Top Paper '18]





stat.: ~ 100 MeV

scales: ~ 100 MeV

tot.: ~ 100–200 MeV

+ comparison with kin. reco.: ~ 100 MeV

Electroweak couplings

precise, global and robust

LHC TOP WG EFT standards

[1802.07237]

Joint theory effort under the auspices of the LHC TOP WG, with extensive feedback from experimentalists.

Make reasonable assumptions

- focus a priori on processes and operators involving top quarks
- determine which contributions are relevant
- prioritize the study of flavour structures

Fix notation

- define d.o.f. natural for top physics at the LHC
- fix notation, normalization, and indicative allowed ranges
- provide simulation tools as TH/EXP interface [UFO model]

Translate your results in these standards
to ease comparisons and combinations!

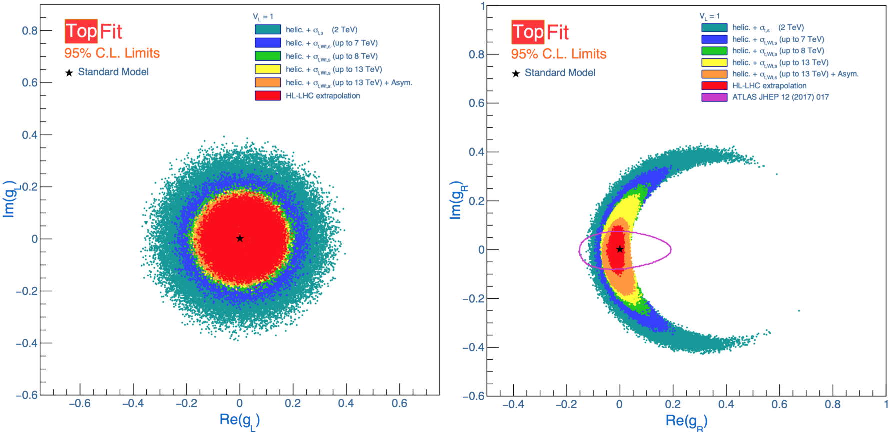
Discuss analysis strategies (one example)

- address the challenges of a global EFT
- highlight useful experimental outputs

[see also *Recasting through reweighting*, Cranmer Heinrich '17]

tbW coupling at the HL-LHC

W-helicity fractions, single top production, $t\bar{t}$ asymmetries: [Déliot et al. '18]



$g_L \equiv \frac{v^2}{\Lambda^2} c^*_{bW}$, $g_R \equiv \frac{v^2}{\Lambda^2} c_{tW}$ in LHC TOP WG conventions,

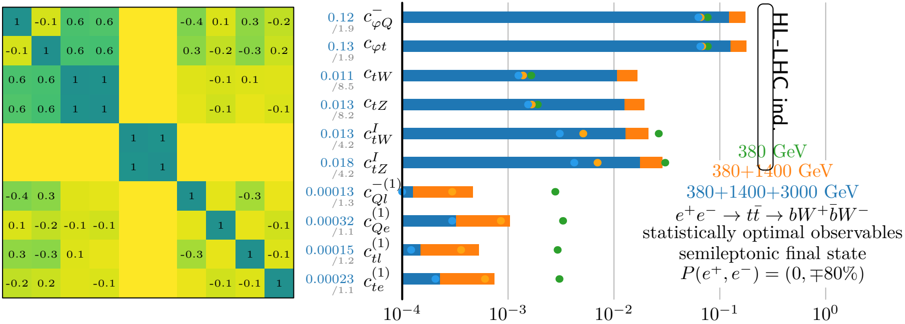
→ limited improvement between current and HL-LHC

→ $\sim$ 10% level precision

Future lepton colliders

[GD et al. '18]
[CLIC Top paper '18]

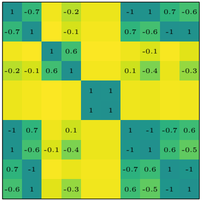
CLIC scenario (1, 2.5, and 5 ab^{-1}), 1σ, in TeV^{-2}
bars: global, blobs: individual



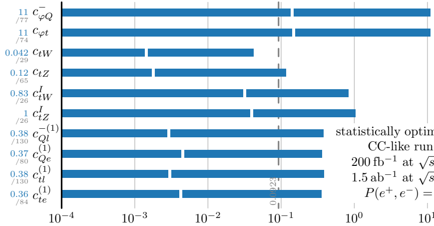
1	-0.1	0.6	0.6			-0.4	0.1	0.3	-0.2
-0.1	1	0.6	0.6			0.3	-0.2	-0.3	0.2
0.6	0.6	1	1				-0.1	0.1	
0.6	0.6	1	1				-0.1		-0.1
				1	1				
				1	1				
-0.4	0.3					1		-0.3	
0.1	-0.2	-0.1	-0.1				1		-0.1
0.3	-0.3	0.1				-0.3		1	-0.1
-0.2	0.2		-0.1				-0.1	-0.1	1

→ clean and robust global analysis (very hard at hadron colliders)

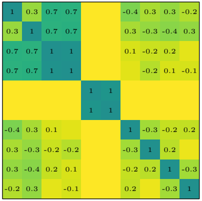
[see also Janot '15]



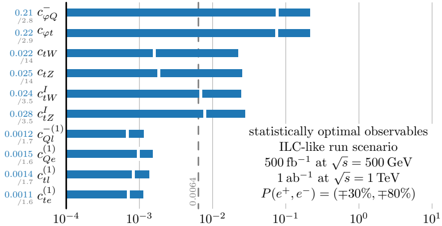
1	-0.7		-0.2			-1	1	0.7	-0.6
-0.7	1		-0.1			0.7	-0.6	-1	1
		1	0.6				-0.1		
-0.2	-0.1	0.6	1			0.1	-0.4		-0.3
				1	1				
				1	1				
-1	0.7		0.1			1	-1	-0.7	0.6
1	-0.6	-0.1	-0.4			-1	1	0.6	-0.5
0.7	-1					-0.7	0.6	1	-1
-0.6	1		-0.3			0.6	-0.5	-1	1



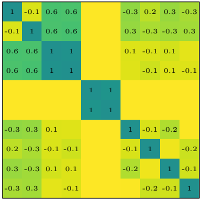
statistically optimal observables
CC-like run scenario
200 fb^{-1} at $\sqrt{s} = 350$ GeV
1.5 ab^{-1} at $\sqrt{s} = 365$ GeV
$P(e^+, e^-) = (0\%, 0\%)$



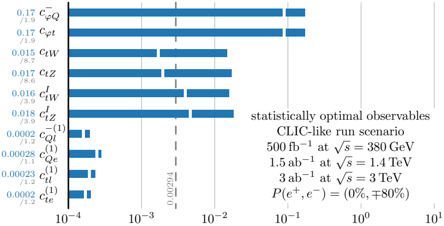
1	0.3	0.7	0.7			-0.4	0.3	0.3	-0.2
0.3	1	0.7	0.7			0.3	-0.3	-0.4	0.3
0.7	0.7	1	1			0.1	-0.2	0.2	
0.7	0.7	1	1				-0.2	0.1	-0.1
				1	1				
				1	1				
-0.4	0.3	0.1				1	-0.3	-0.2	0.2
0.3	-0.3	-0.2	-0.2			-0.3	1	0.2	
0.3	-0.4	0.2	0.1			-0.2	0.2	1	-0.3
-0.2	0.3		-0.1			0.2		-0.3	1



statistically optimal observables
ILC-like run scenario
500 fb^{-1} at $\sqrt{s} = 500$ GeV
1 ab^{-1} at $\sqrt{s} = 1$ TeV
$P(e^+, e^-) = (\mp 30\%, \pm 80\%)$



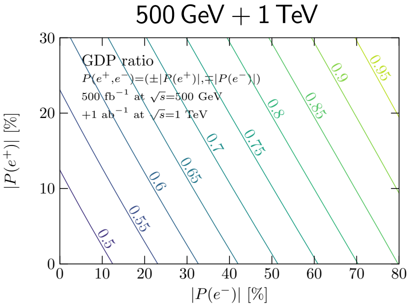
1	-0.1	0.6	0.6			-0.3	0.2	0.3	-0.3
-0.1	1	0.6	0.6			0.3	-0.3	-0.3	0.3
0.6	0.6	1	1			0.1	-0.1	0.1	
0.6	0.6	1	1				-0.1	0.1	-0.1
				1	1				
				1	1				
-0.3	0.3	0.1				1	-0.1	-0.2	
0.2	-0.3	-0.1	-0.1			-0.1	1		-0.2
0.3	-0.3	0.1	0.1			-0.2		1	-0.1
-0.3	0.3		-0.1				-0.2	-0.1	1



statistically optimal observables
CLIC-like run scenario
500 fb^{-1} at $\sqrt{s} = 380$ GeV
1.5 ab^{-1} at $\sqrt{s} = 1.4$ TeV
3 ab^{-1} at $\sqrt{s} = 3$ TeV
$P(e^+, e^-) = (0\%, \mp 80\%)$

Polarization and energy lever arm

[GD et al. '18]



10% polarization costs ∼ 5% of GDP

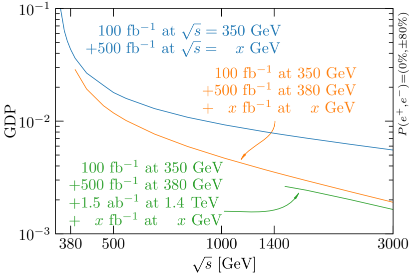
w.r.t. $P(e^+, e^-) = (\pm 30\%, \mp 80\%)$:

- $P(e^+)$ compensated by 140% lumi
- $P(e^+, e^-)$ 〃 by 460% lumi

$$\text{GDP} \equiv \left[\det \text{cov}(C_i, C_j)\right]^{1/n}$$

'*global determinant parameter*'
geometrical average of constraints
ratios are operator-basis independent

[GD et al. '17]

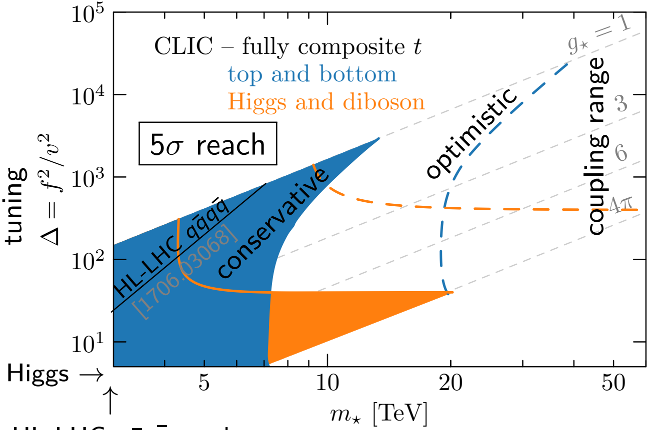


$\sqrt{s}$ lever arm disentangles 2f/4f

Compositeness

[GD, Matsedonskyi '18]

high-energy top measurements are very sensitive to compositeness



HL-LHC Higgs →

↑

HL-LHC $q\bar{q}t\bar{t}$ reach

Farina et al. [1811.04084]

→ Higgs probes fine tuning

→ top probes composite partner masses

Composite

D, Matsedonskyi '18]

high-e

teness

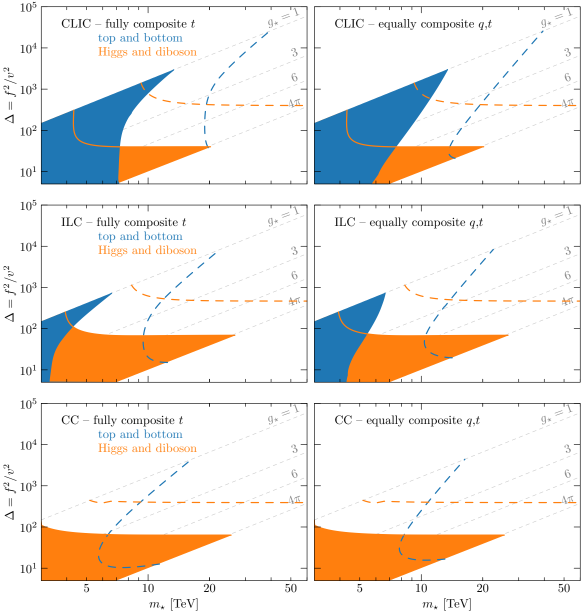
tuning

$\Delta = f^2/v^2$

HL-LHC Higg

HL-

Farina



$\epsilon_t = 1 \qquad (y_t = \epsilon_t \epsilon_q g_\star) \qquad \epsilon_t = \epsilon_q$

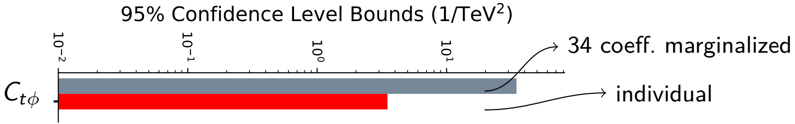
Top Yukawa

$qqtt$ insensitive

Top Yukawa

At the LHC $pp \to t\bar{t}h$

[SMEFiT '19]



- contaminations from poorly constrained *qqtt* operators
- $\sim 15\%$ individual, $\sim 150\%$ global

HL-LHC prospect

- $\sim 3\%$ individual, ?? global

At lepton colliders $e^+e^- \to t\bar{t}h$

- robust against $eett$, ttZ, $tt\gamma$ modifications [1907.10619]
- $\sim 3\,\%$ at $550\,\text{GeV}/4\,\text{ab}^{-1}$ or $1\,\text{TeV}/2.5\,\text{ab}^{-1}$ or $1.5\,\text{TeV}/2.5\,\text{ab}^{-1}$

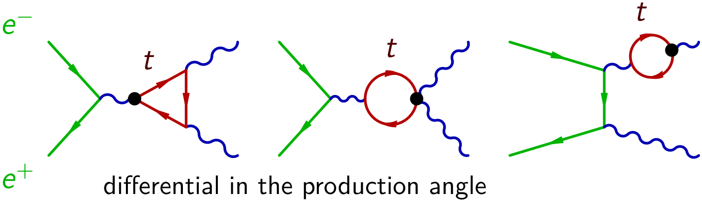
[Fujii et al. '15] [Asner et al. '13] [CLIC top paper '18]

Top electroweak loops

top/Higgs interplay

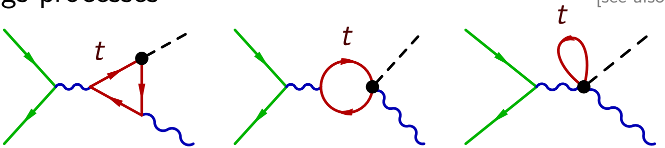
Top electroweak loops

- At the Z pole [Zhang, Greiner, Willenbrock '12]
- In diboson production [GD, Gu, Vrionidou, Zhang '18]



differential in the production angle

- In Higgs processes [Vrionidou, Zhang, '18] [see also Boselli et al '18]

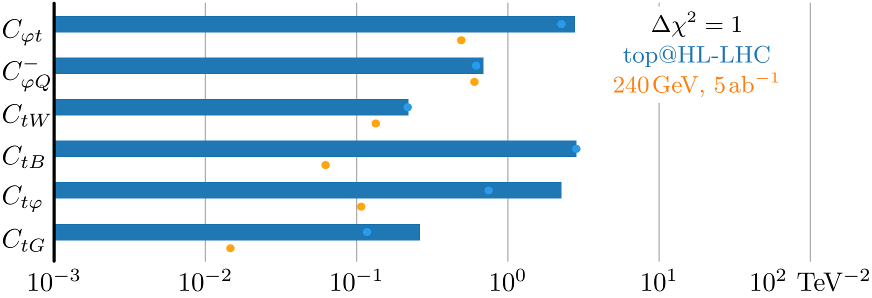


  - Higgsstrahlung and W-fusion through reweighing in MG5/aMC@NLO
  - Higgs decays

(excluding four-fermion operators, no top loop included in $e^+e^- \to t\bar{t}$)

Improvement on top operators

[GD, Gu, Vrionidou, Zhang '18]



Individual constraints (blobs)

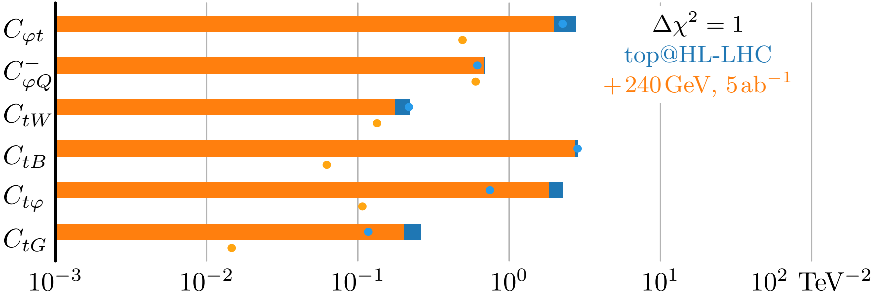
- competitive with the HL-LHC (e.g. on the top Yukawa $C_{t\varphi}$)
- dominated by Higgs measurements (diboson improves with energy)

Global constraints (bars) (12 Higgs + 6 top op. floated)

- large flat directions with 240 GeV run alone (not shown)
- still improves the HL-LHC combination
- more differential distributions would help further

Improvement on top operators

[GD, Gu, Vrionidou, Zhang '18]



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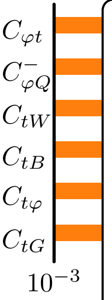
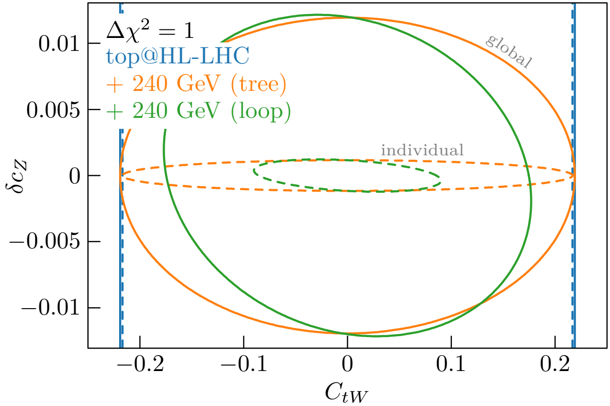


On a linear scale, in the $(C_{tW}, \delta c_Z)$ plane:



- extra parameter space covered thanks to loop sensitivity
- room for improvement between glo. and ind. constraints

Individu

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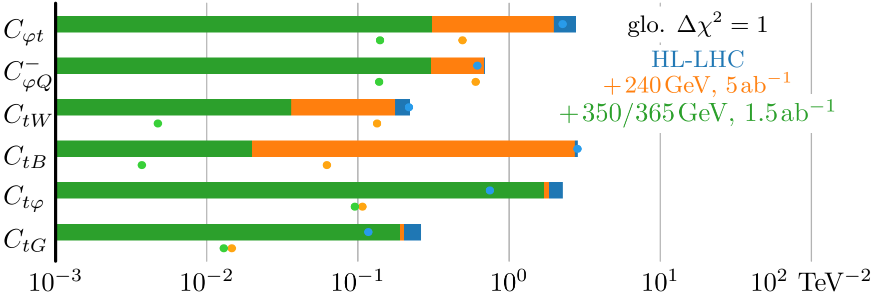
- dom

Global c

- large
- still
- more differential distributions would help further

Improvement on top operators

[GD, Gu, Vrionidou, Zhang '18]



Individual constraints (blobs)

- competitive with the HL-LHC (e.g. on the top Yukawa $C_{t\varphi}$)
- dominated by Higgs measurements (diboson improves with energy)
- loops in $e^+e^- \to t\bar{t}$ would improve its impact on $C_{t\varphi}$ and C_{tG}

Global constraints (bars) (12 Higgs + 6 top op. floated)

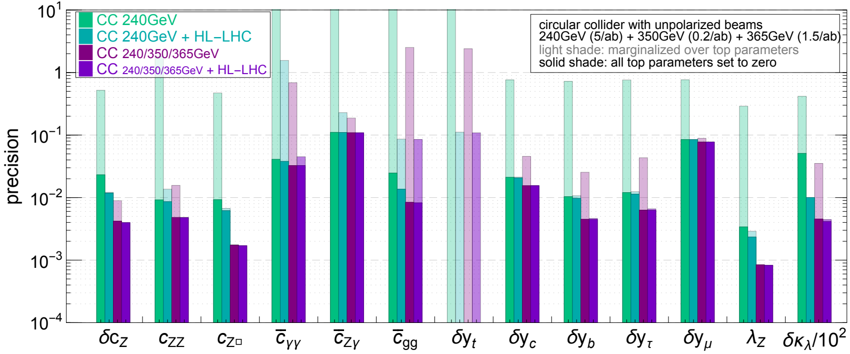
- large flat directions with 240 GeV run alone (not shown)
- still improves the HL-LHC combination
- more differential distributions would help further

Contamination in Higgs operators

[GD, Gu, Vrionidou, Zhang '18]

light shades: 12 Higgs op. floated + 6 top op. floated

dark shades: 12 Higgs op. floated + 6 top op. → 0



Uncertainties on the top have a big effect on the Higgs

- Higgsstr. run: insufficient
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run $\oplus$ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run $\oplus$ $e^+e^- \to t\bar{t}$ $\oplus$ top@HL-LHC: top contam. in $\bar{c}_{gg}$ only

Top FCNC

from below the $t\bar{t}$ theshold

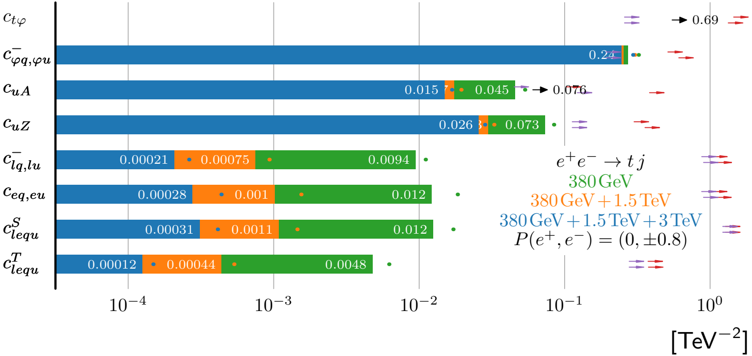
$e^+e^- \to t\,j$ at 380 GeV/1 ab^{-1} and above

[CLIC BSM YR '18]
[HL-LHC Flavour YR '18]

Marginalized 95% CL constraints

efficiencies extrapolated from TESLA & FCC studies

[hep-ph/0102197]
[1408.2090]



- compared to decay: black arrows
- compared to current limits $^{\text{up}}_{\text{charm}}$
- compared to HL-LHC estimates $^{\text{up}}_{\text{charm}}$
- without beam polarization: blobs

quadratic optimal observables
semileptonic final state, *WW* bkg

$e^+e^- \to t\, j$ at 380 GeV/1 ab^{-1} and above

M YR '18]

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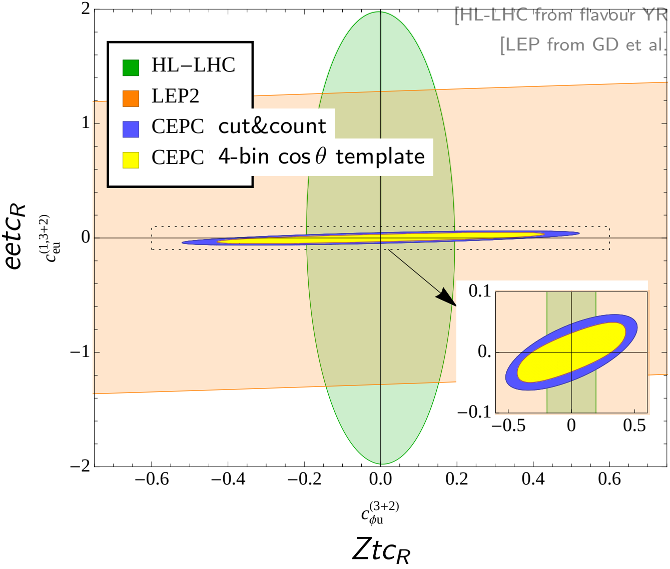
At 240 GeV/5.6 ab^{-1}:

[L. Shi's poster]

[Shi, Zhang '19]

[HL-LHC from flavour YR '18]

[LEP from GD et al. '14]



Top quarks at next-generation lepton colliders

The top quark so far escaped the scrutiny of lepton colliders.

They offer a unique opportunity for precise and robust determination of the top electroweak couplings and mass.

In new-physics parameter space, high-energy top-quark measurements are very complementary to Higgs ones.

Knowing top-quark couplings precisely is also indispensable for the Higgs precision program.

Searches for exotic top-quark interactions have outstanding reaches.

Extras

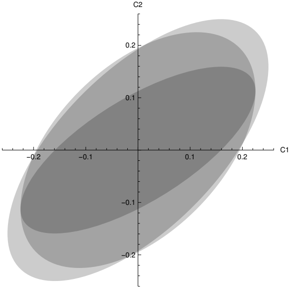
Statistically optimal observables

[Atwood,Soni '92]
[Diehl,Nachtmann '94]

minimize the one-sigma ellipsoid in EFT parameter space

(*joint efficient* set of estimators, saturating the Cramér-Rao bound: $V^{-1} = I$,like MEM)

For small C_i, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\,\sigma_i(\Phi)$, the stat. opt. obs. are the average values of $O_i(\Phi) = n\,\sigma_i(\Phi)/\sigma_0(\Phi)$.



e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1+\cos\phi}$

$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

Previous applications in $e^+e^- \to t\,\bar{t}$, on different distributions:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

Statistically optimal observables

- answer statistically the question “What observable?”
  - for linear(ized) parameter dependences (EFT!)
  - easiest when kinematics are fully determined
  - ideal for clean environments
- exploit our physical understanding
  - need modelling, no blind and expensive training
  - extend to detector level with machine-learning techniques [1805.00020]
- scale well with parameter-space dimensionality
  - need no scan (unlike MEM)
  - require only one discrete observable per d.o.f.
  - cover efficiently all directions
- facilitate ideal theory estimates
  - $\text{cov}(C_i, C_j)^{-1} = \epsilon \mathcal{L} \int d\Phi \, \frac{\sigma_i(\Phi)\sigma_j(\Phi)}{\sigma_0(\Phi)} + \mathcal{O}(C_i)$ (incl. total rate information)

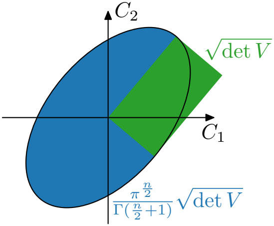
Global determinant parameter

[GD, Grojean, Gu, Wang, '17]

In a n-dimensional Gaussian fit, with covariance matrix V,

$$\text{GDP} \equiv \sqrt[2n]{\det V}$$

provides a geometric average of the constraints strengths.



Interestingly, GDP ratios are operator-basis independent!

- as the volume scales linearly with coefficient normalization
- as the volume is invariant under rotations

$\Longrightarrow$ conveniently assess constraint strengthening.