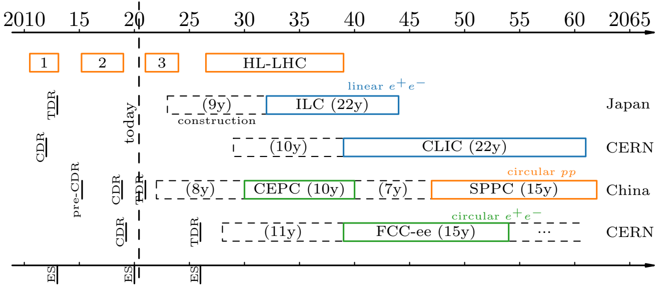
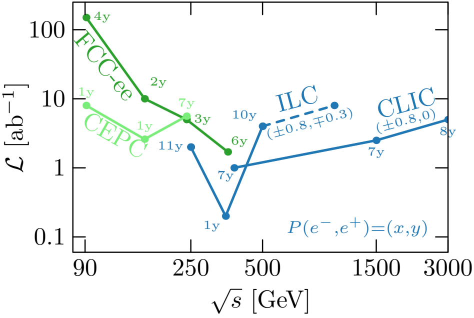
Top-quark precision at lepton colliders

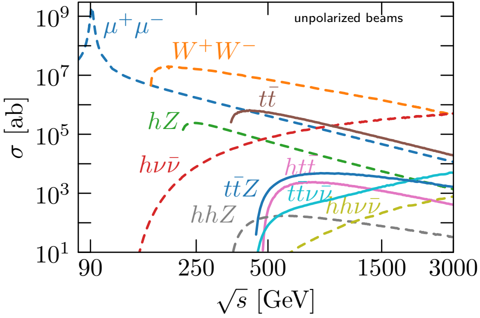
Gauthier Durieux
(Technion)

FCC France workshop
15 May 2020

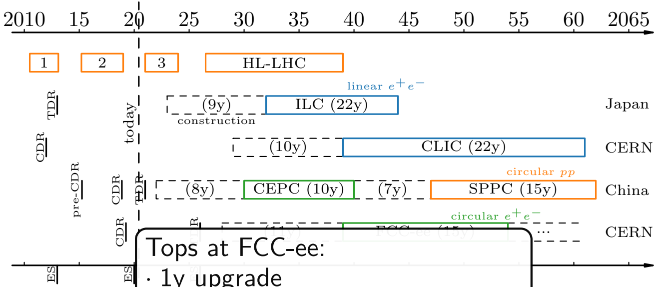
Tops at lepton colliders



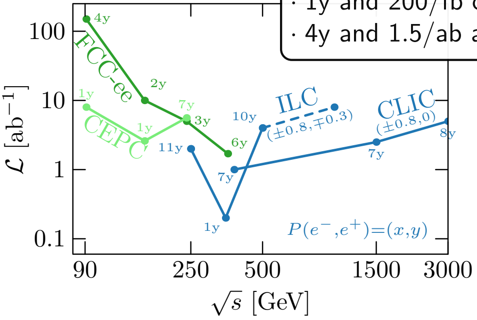


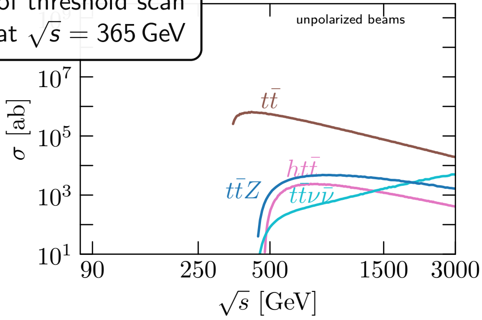


Tops at lepton colliders



Tops at FCC-ee:
- 1y upgrade
- 1y and 200/fb of threshold scan
- 4y and 1.5/ab at $\sqrt{s} = 365$ GeV

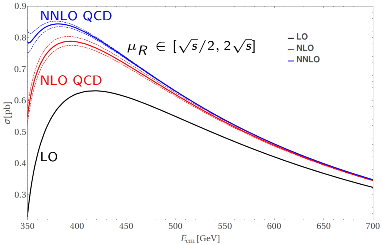




Continuum $t\bar{t}$ production

- NNLO QCD, differential, stable tops

[Gao, Zhu '14]
[Chen, Dekkers, Heisler, Bernreuther, Si '16]



- σ peaked at about 380 GeV
- fall-off as $1/s$
- large corrections near threshold
- (enhanced for a left-handed beam)

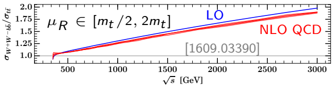
- NLO EW, stable tops

[Beenakker, van der Marck, Hollik '91]
[Fleischer, Leike, Riemann, Werthenbach '93]
[Hahn, Hollik, Lorca, Riemann, Werthenbach '93]

- NLO QCD, unstable tops

[Liebler, Moortgat-Pick, Papanastasiou '15]
[Chokoufé, Kilian, Lindert, Pozzorini, Reuter, Weiss '16]

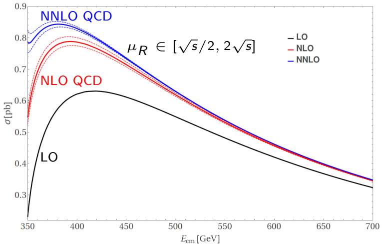
  - single-top increases linearly with $\sqrt{s}$
  - $\sim 5\%$ off-shell effects at $\sqrt{s} = 365$ GeV



Continuum $t\bar{t}$ production

- NNLO QCD, differential, stable tops

[Gao, Zhu '14]
[Chen, Dekkers, Heisler, Bernreuther, Si '16]



- σ peaked at about 380 GeV
- fall-off as $1/s$
- large corrections near threshold
- (enhanced for a left-handed beam)

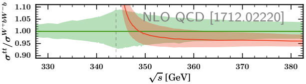
- NLO EW, stable tops

[Beenakker, van der Marck, Hollik '91]
[Fleischer, Leike, Riemann, Werthenbach '93]
[Hahn, Hollik, Lorca, Riemann, Werthenbach '93]

- NLO QCD, unstable tops

[Liebler, Moortgat-Pick, Papanastasiou '15]
[Chokoufé, Kilian, Lindert, Pozzorini, Reuter, Weiss '16]

  - single-top increases linearly with $\sqrt{s}$
  - $\sim 5\%$ off-shell effects at $\sqrt{s} = 365$ GeV



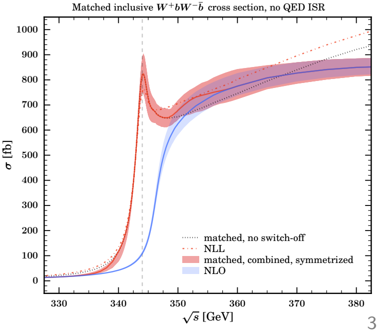
Tools

getting *ee*-ready

Whizard

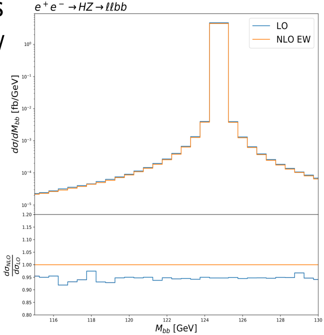
[Reuter @ LCWS '19]

- UFO support for BSM (almost complete)
- automated NLO QCD (FKS, resonance aware) [v3.0.0α from March 3, 2020]
- Powheg matching to Pythia8 shower
- *ee*-ISR & beamstrahlung,
  also for polarized beams
- matched NLO $e^+e^- \to bW^+\bar{b}W^-$
  to threshold NLL [1712.02220]



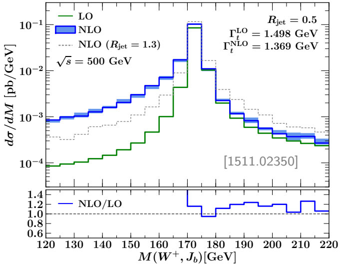
Sherpa

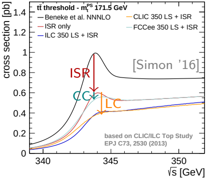
- UFO support for BSM
- automated NLO QCD and EW (CS substraction)
- mc@nlo matching to parton shower
- YFS resummation of soft&collinear photons
  - to be matched to matrix element for NLO EW
  - no ISR/FSR interference yet
- Beamstrahlung being implemented
- Underlying events (e.g. $\gamma\gamma$) planned

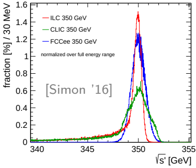


MadGraph

- full UFO support for BSM (also at NLO)
- automated NLO QCD and EW (FKS, resonance aware)
- mc@nlo matching to parton shower
- *ee*-ISR
  - implemented for unpolarized beams [not released]
  - validated against Whizard in $e^+e^- \to t\,\bar{t}$
- beamsstrahlung
  - implemented using parametrizations fitted to GuineaPig
  - no beam energy spread, so far
  - validation ongoing
- NLO+NLL electron PDF [Frixione @ FCC workshop]
  - computed for unpolarized beams
  - only missing piece to be implemented for NLO EW





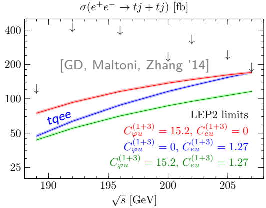


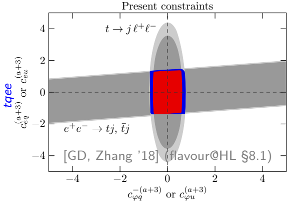
Top EFT at NLO QCD

LHC TOP WG standards [dim6top UFO] [1802.07237]

avoid confusions, facilitate comparisons and combinations

- flavour violating [Zhang '14] [Degrande, Maltoni, Wang, Zhang '14] [GD, Maltoni, Zhang '14]
  - UFO updated to LHC TOP WG standards [to appear] [TopFCNC UFO]
  - automated NLO for four-fermion $tq\ell\ell$ operators [to appear]





- flavour conserving
  - four-quark operators (with evanescent operators) [to appear]
  - all-sector implementation [to appear] [SMEFTatNLO UFO]

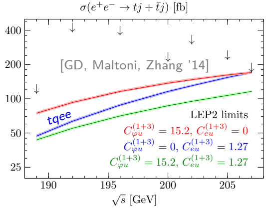
[Degrande, GD, Maltoni, Mimasu, Vryonidou, Zhang]

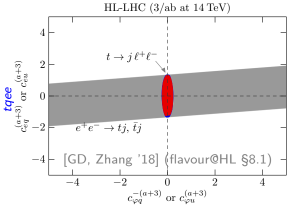
Top EFT at NLO QCD

LHC TOP WG standards [dim6top UFO] [1802.07237]

avoid confusions, facilitate comparisons and combinations

- flavour violating [Zhang '14] [Degrande, Maltoni, Wang, Zhang '14] [GD, Maltoni, Zhang '14]
  - UFO updated to LHC TOP WG standards [to appear] [TopFCNC UFO]
  - automated NLO for four-fermion $tq\ell\ell$ operators [to appear]





- flavour conserving
  - four-quark operators (with evanescent operators) [to appear]
  - all-sector implementation [to appear] [SMEFTatNLO UFO]

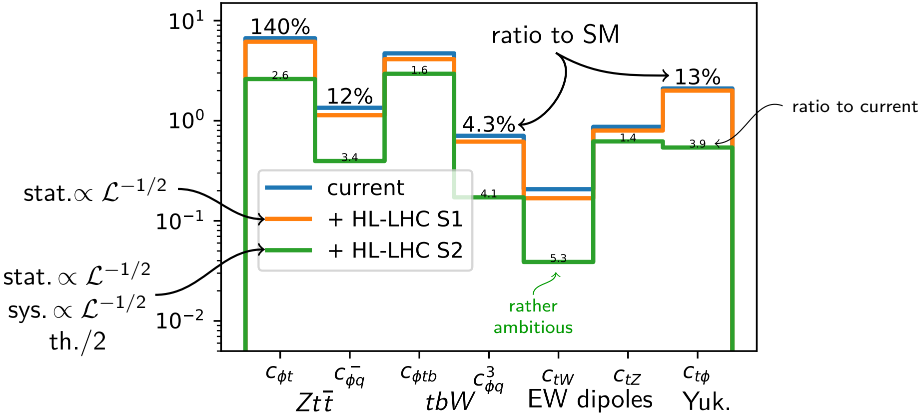
[Degrande, GD, Maltoni, Mimasu, Vryonidou, Zhang]

Electroweak couplings

precise, global and robust

LHC prospects

[projections from 1907.10619]
[TOP WG EFT conventions]

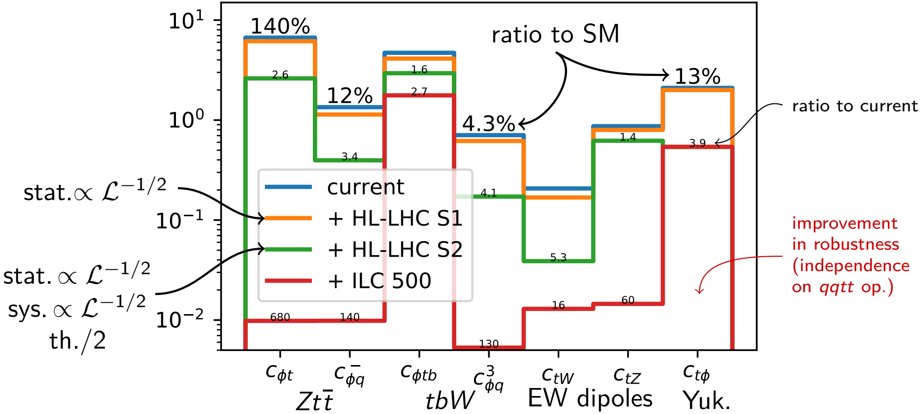


$\rightarrow$ sys. and th. limited reach

$\rightarrow \sim 10\%$ level precision

LHC prospects

[projections from 1907.10619]
[TOP WG EFT conventions]



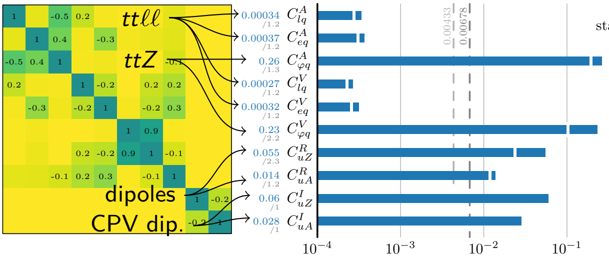
→ sys. and th. limited reach

→ ∼ 10% level precision

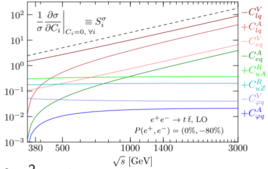
Global $e^+e^- \to t\,\bar{t}$ EFT analysis

[GD, Perelló, Vos, Zhang '18]
[see also Janot '15]

Two centre of mass energies are required to constrain all ten d.o.f. accessible linearly in resonant $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$.



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



statistically optimal observables

resonant $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$
$m_b/m_t \to 0$, analytical LO observable def.

effective stat. efficiencies determined with full sim.
in semi-leptonic final state

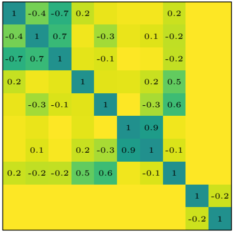
- in TeV^{-2}, $\Delta\chi^2 = 1$
- white marks: individual constraints
- /xx: global/individual ratios

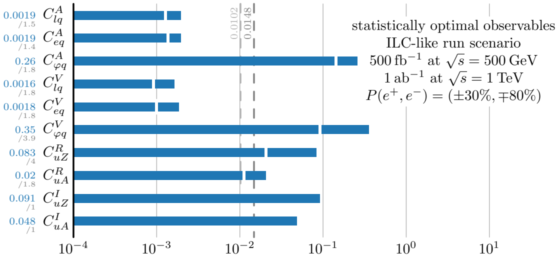
Global $e^+e^- \to t\,\bar{t}$ EFT analysis

[GD, Perelló, Vos, Zhang '18]

[see also Janot '15]

Two centre of mass energies are required to constrain
all ten d.o.f. accessible linearly in resonant $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$.





statistically optimal observables

resonant $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$
$m_b/m_t \to 0$, analytical LO observable def.

effective stat. efficiencies determined with full sim.
in semi-leptonic final state

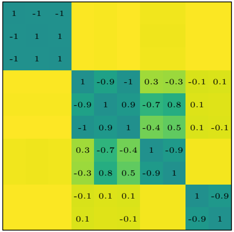
- in TeV^{-2}, $\Delta\chi^2 = 1$
- white marks: individual constraints
- /xx: global/individual ratios

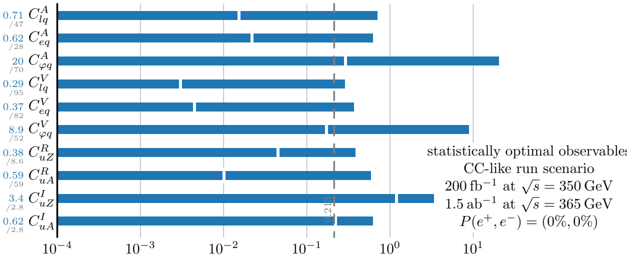
Global $e^+e^- \to t\,\bar{t}$ EFT analysis

[GD, Perelló, Vos, Zhang '18]

[see also Janot '15]

Two centre of mass energies are required to constrain
all ten d.o.f. accessible linearly in resonant $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$.





statistically optimal observables

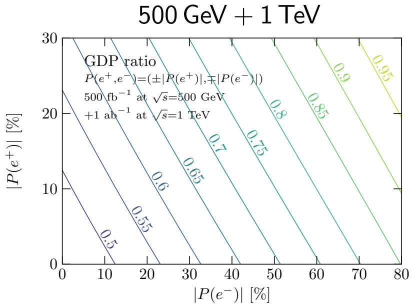
resonant $e^+e^- \to t\,\bar{t} \to bW^+\,\bar{b}W^-$
$m_b/m_t \to 0$, analytical LO observable def.

effective stat. efficiencies determined with full sim.
in semi-leptonic final state

- in TeV^{-2}, $\Delta\chi^2 = 1$
- white marks: individual constraints
- /xx: global/individual ratios

Polarization and energy lever arm

[GD, Perelló, Vos, Zhang '18]



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

'*global determinant parameter*'

geometrical average of constraints

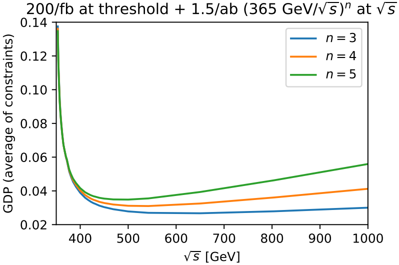
ratios are operator-basis independent

[GD, Grojean, Gu, Wang '17]

10% polarization costs $\sim$ 5% of GDP

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

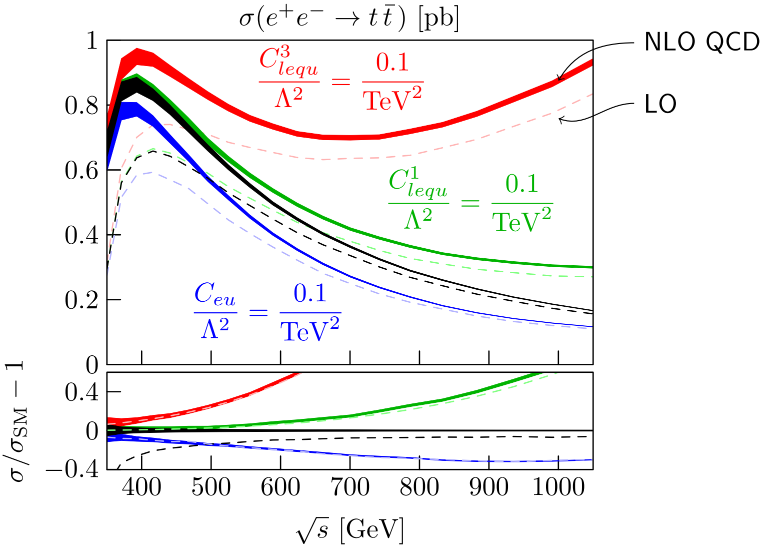
- $P(e^+)$ compensated by 140% lumi
- $P(e^+, e^-)$ 〃 by 460% lumi



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

NLO QCD for $tt\ell\ell$ and CPV dipole operators

In passing: [GD, Perelló, Vos, Zhang '18]

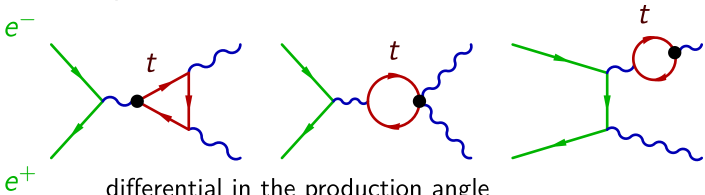


Top/Higgs interplay

at one-loop

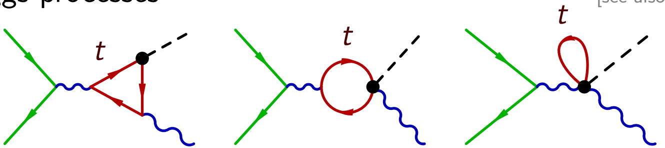
Top electroweak loops

- 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]

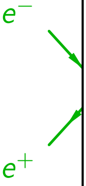


  - Higgsstrahlung and W-fusion through reweighing in MG5/aMC@NLO
  - Higgs decays

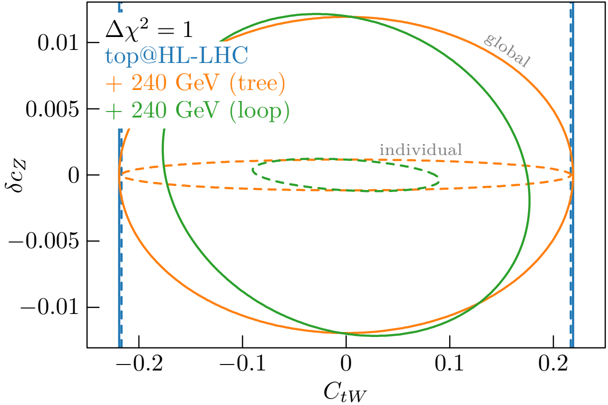
(excluding four-fermion operators, no top loop included in $e^+e^- \to t\bar{t}$)

Top electroweak loops

- At the Z ... lenbrock '12]
- In diboso ... u, Zhang '18]



- In Higgs ... , Zhang, '18] ... selli et al '18]



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

[GD, Gu, Vrionidou, Zhang '18]

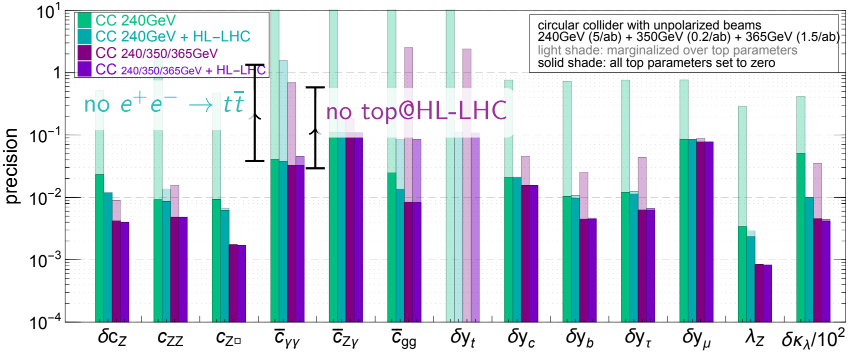
  · Higgs ... NLO
  · Higgs decays

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

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. $\to 0$



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-quark precision at lepton colliders

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

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

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

Tools are getting *ee*-ready!

Backup

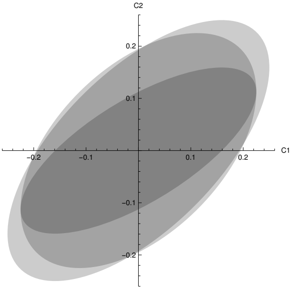
Statistically optimal observables

[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]