Standard-model effective field theory at future e^+e^- colliders

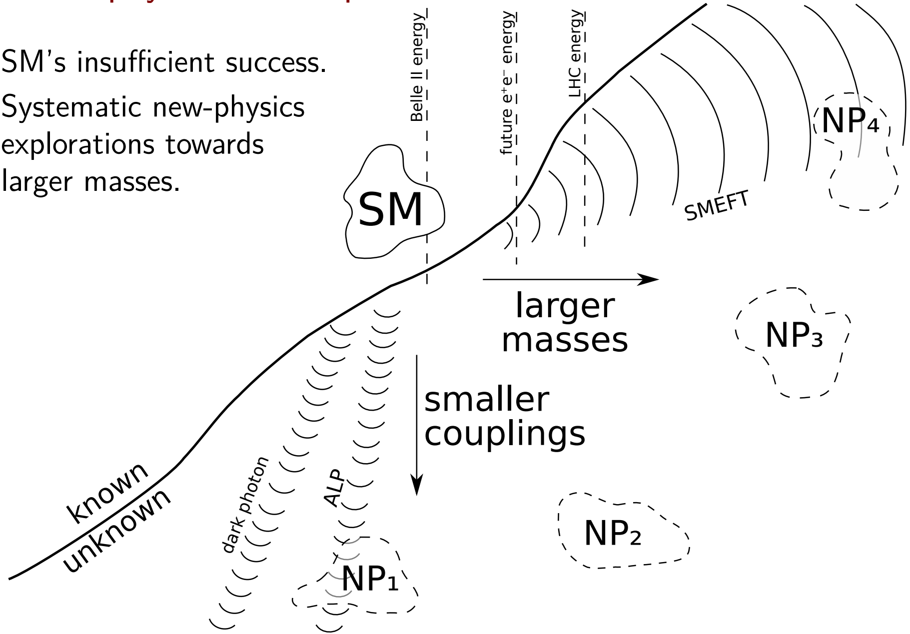
Gauthier Durieux
(CP3 – UCLouvain)

Corfu workshop on future accelerators – 24 May 2024

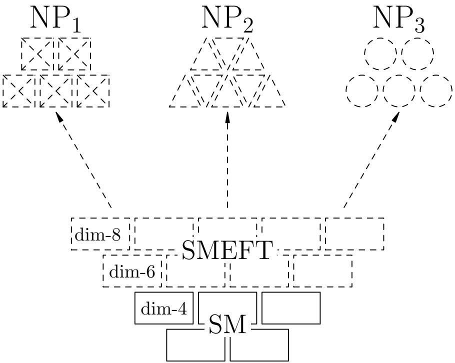
Particle physics landscape

SM's insufficient success.

Systematic new-physics explorations towards larger masses.

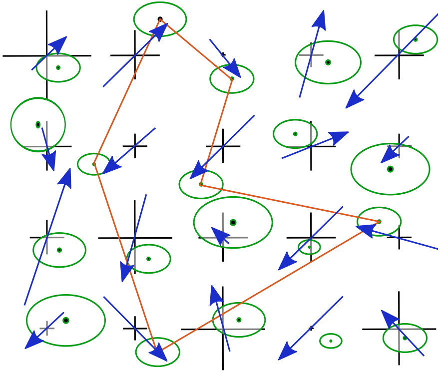


Taking the SM to higher dimensions



- using established bricks (fields and symmetries)
- extension organised by relevance (dimension)
- including all deformations (theory space coverage)

Isolating subtle patterns of new physics



array of sensitive observables

- precise SM&EFT predictions
- precise measurements

→ correlate deviations

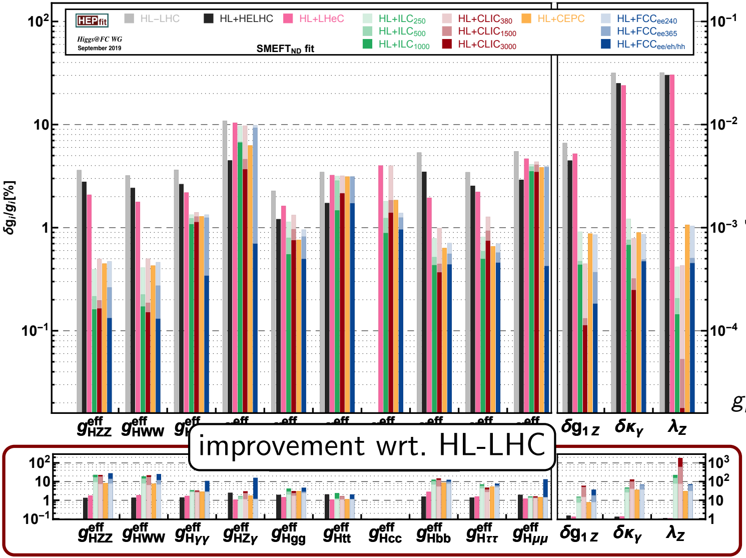
Future e^+e^- colliders provide ideal precision input
at electroweak scales.

Precision further blurs the separation between sectors
rendering a global, consistent QFT, treatment indispensable.

Higgs and weak bosons

Improvement compared to LHC

[Higgs@FC '19]



[Ellis,You '15]
[Ellis et al '17]
[de Blas et al '16]
[GD et al '17]
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[Di Vita et al '17]
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$$g^{eff}_{HXX} \equiv \sqrt{\frac{\Gamma^{SMEFT}_{H\to XX}}{\Gamma^{SM}_{H\to XX}}}$$

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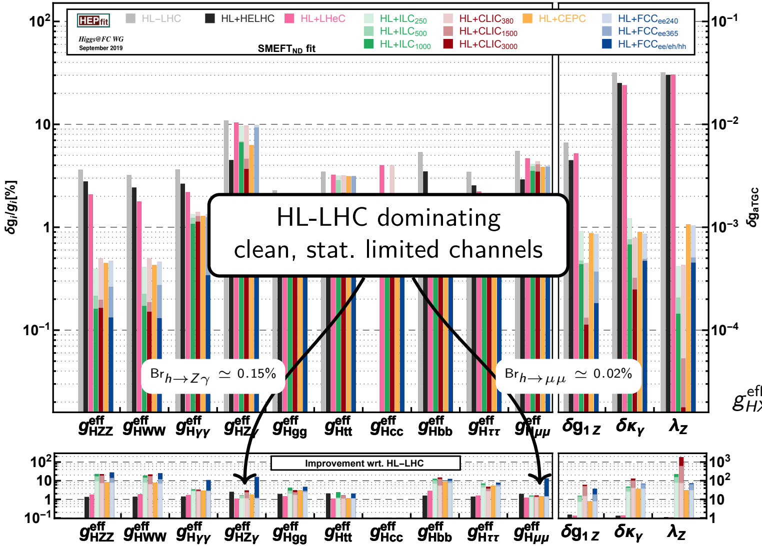

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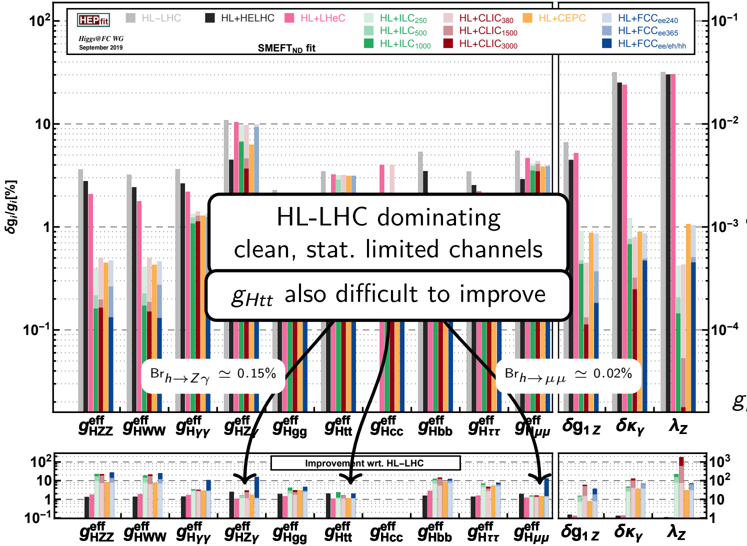

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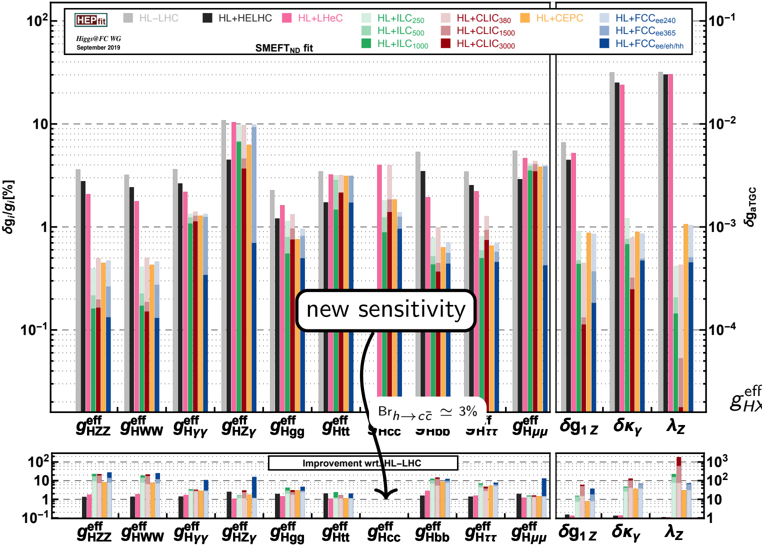

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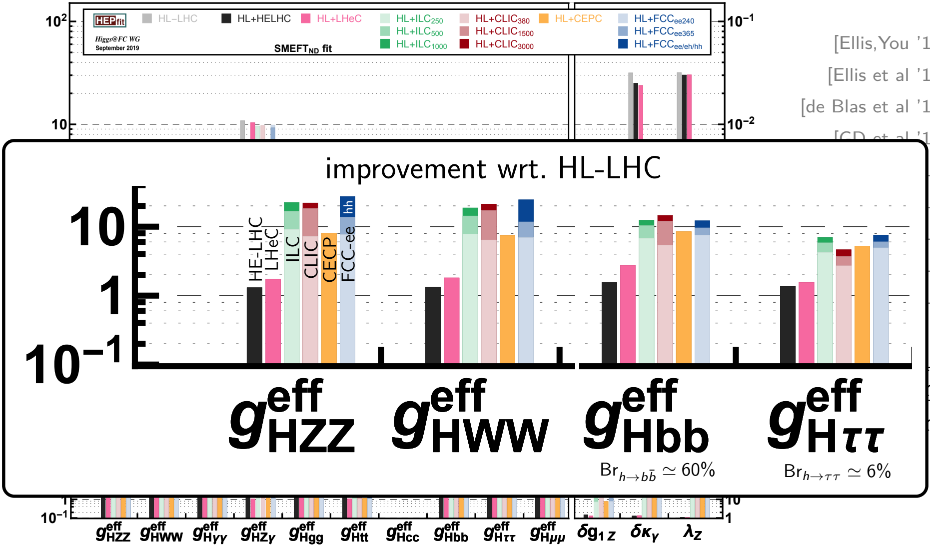


Higgs-diboson interplay

- $e^+e^- \to W^+W^-$ crucial for Higgs precision

- benefiting from optimal observables

  [de Blas, GD, Grojean, Gu, Paul '19]

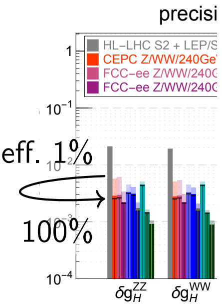
  at LEP already [Opal, L3, ALEPH, DELPHI]

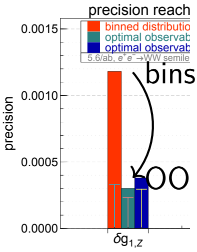
- sensitivity driven by high energies (240, 365 GeV)

  requires good forward detector coverage

- also probes Vff couplings [GD, Grojean, Gu, Wang '17]

  often unduly neglected in diboson

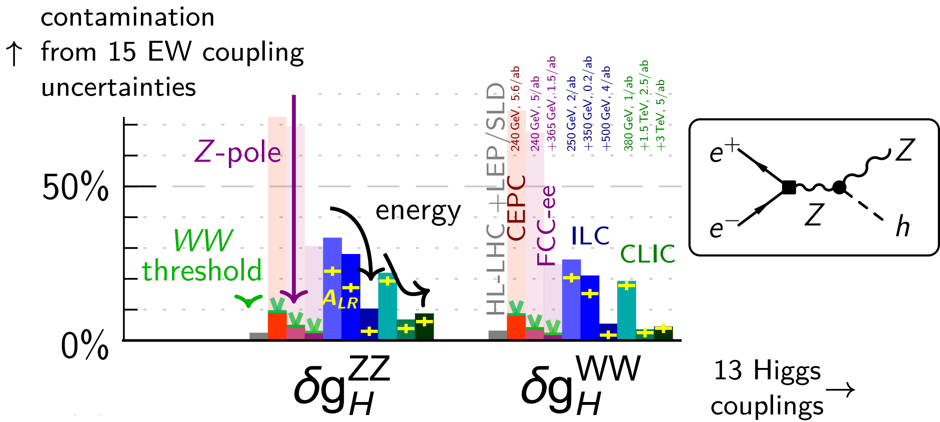




Higgs and electroweak precision

Higgs-electroweak interplay

[de Blas, GD, Grojean, Gu, Paul '19]



New EW measurements required for Higgs coupling extraction.

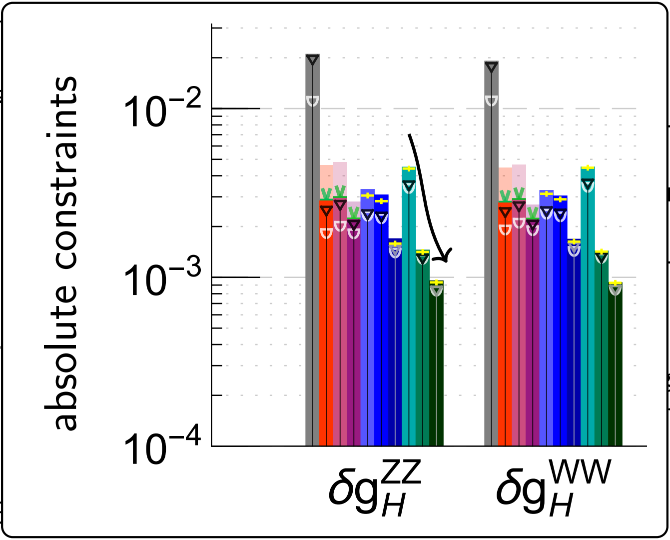
Higgs-electroweak interplay

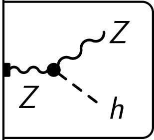
[de Blas, GD, Grojean, Gu, Paul '19]

contam
↑ from 1
uncert

50%

0%



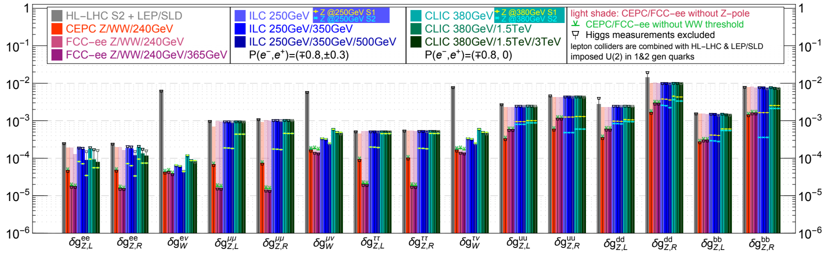


ggs →
ngs

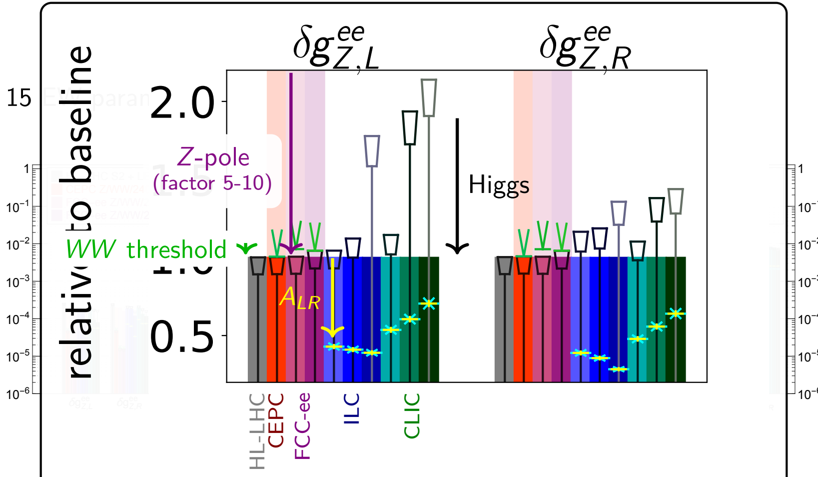
New E … ction.

Electroweak-Higgs interplay

15 EW parameters (13 Higgs-TGC ones also marginalized over)



Electroweak-Higgs interplay



high-energy Higgs measurements help constraining g_Z^{ee}

Electroweak-Higgs interplay

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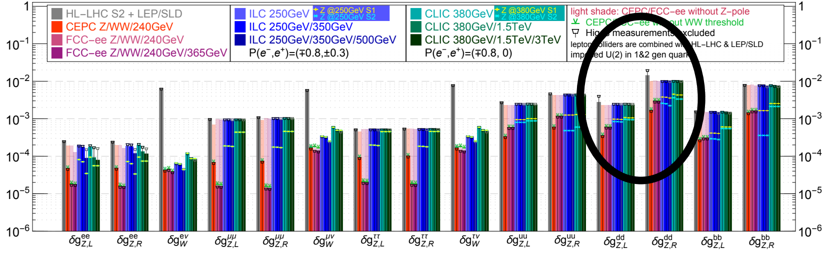
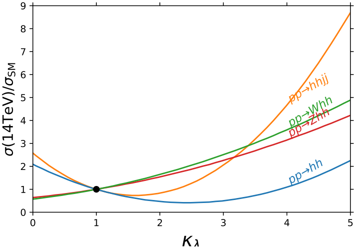


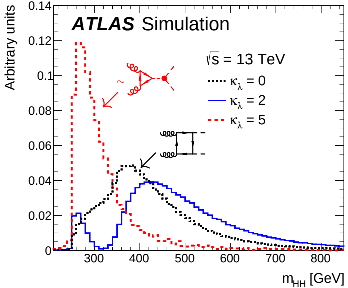
high-energy Higgs measurements help constraining g_Z^{ee}

Single and triple Higgs couplings

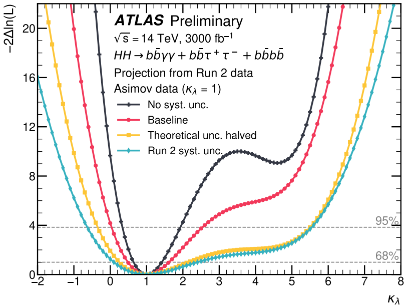
Triple Higgs coupling in proton collisions

SM ratios: 17, 3.7, 1.4





[ATL-PHYS-PUB-2022-053]

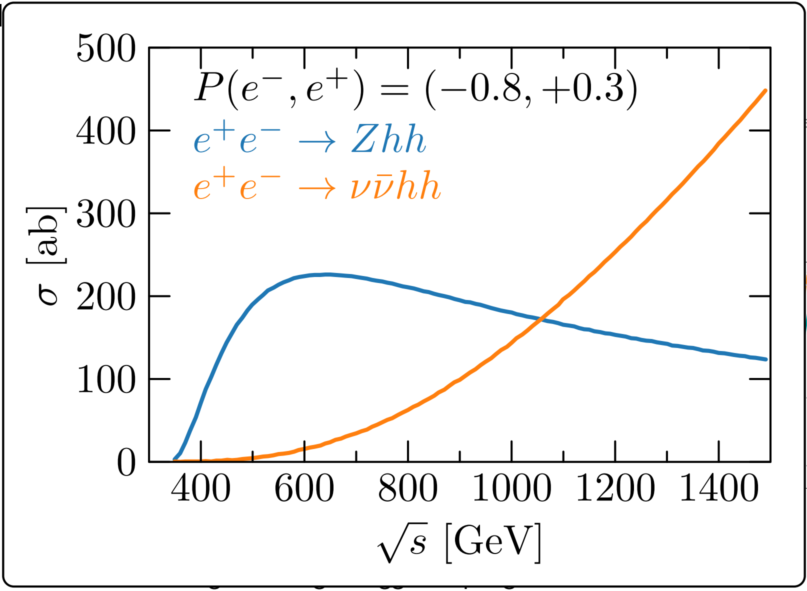


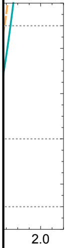
Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

In lepton collisions, above 500 GeV

[Barklow et al. '17]
[Di Vita et al. '17]

et al. '13]





In lepton collisions, above 500 GeV

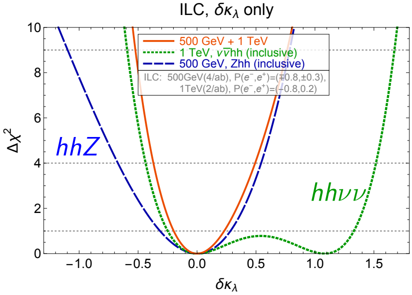
[Barklow et al. '17]
[Di Vita et al. '17]

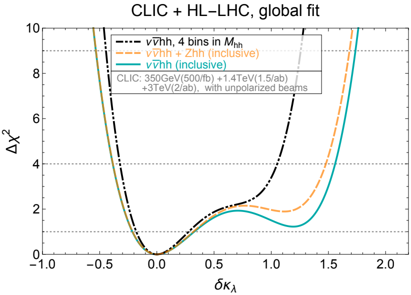
ILC

- perfect complementarity between 500 GeV and 1 TeV
- both individual and global 1σ sensitivity $\sim 10\%$

CLIC

- missing $e^+e^- \to Zhh$ to constrain positive $\delta\kappa_\lambda$
- exploiting m_{hh} instead [Contino et al. '13]
- both individual and global 1σ sensitivity $\sim 10\%$



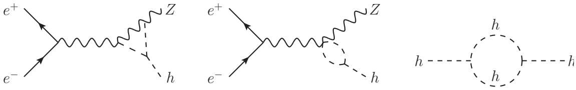


robust against single Higgs couplings modifications

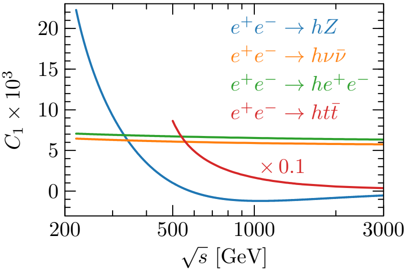
In lepton collisions, below 500 GeV

- NLO sensitivity (finite and gauge-invariant NLO EW subset)
- dominated by $e^+e^- \to hZ$ at threshold

[McCullough '13]
[Gorbahn, Haisch '16]
[Degrassi et al. '16]
[Bizon et al. '16]
[Degrassi et al. '17]
[Kribs et al. '17]
[Maltoni et al. '17]
[Di Vita et al. '17]
[Maltoni et al. '18]
[Gorbahn, Haisch '19]
[Degrassi, Vitti '19]
[Degrassi et al. '21]
[Haisch, Koole '21]



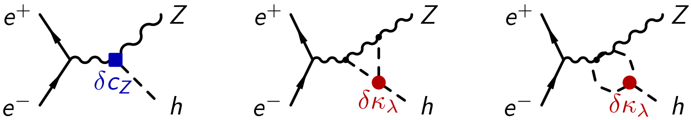
$$\Sigma_{\rm NLO}/\Sigma_{\rm NLO}^{\rm SM} \simeq 1 + (C_1 - 0.0031)\,\delta\kappa_\lambda + \ldots$$

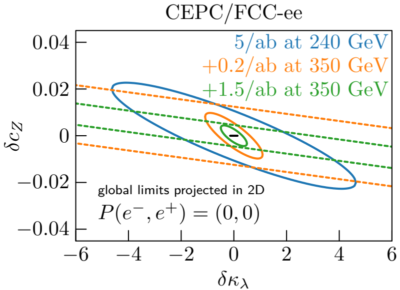


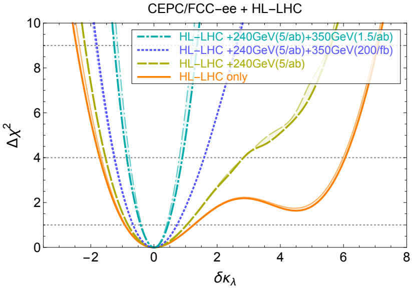
percent effect × permil hZ precision → naive 10% constraint

Single-triple Higgs couplings interplay

[Di Vita et al. '17]







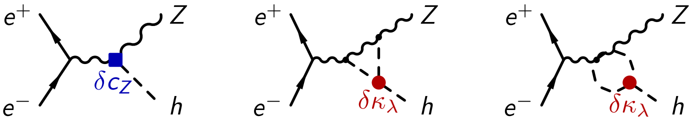
Correlations with single-Higgs couplings require two $\sqrt{s}$.

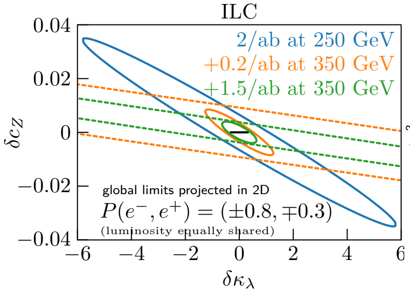
Individual 1σ limit (14%) much tighter than global ones (460, 110, 50%)

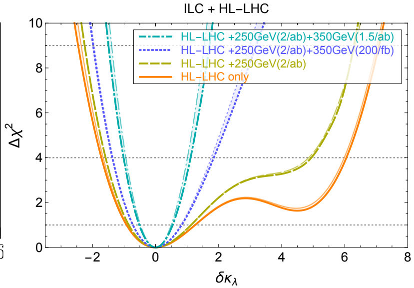
One energy point already help lifting secondary HL-LHC minimum.

[Di Vita et al. '17]

Single-triple Higgs couplings interplay







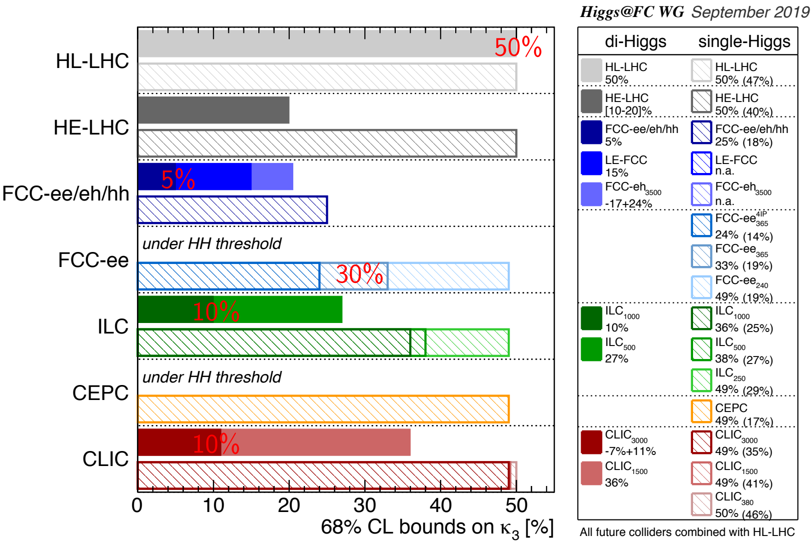
Correlations with single-Higgs couplings require two $\sqrt{s}$.

Individual 1σ limit (30%) much tighter than global ones (580, 130, 60%)

One energy point already help lifting secondary HL-LHC minimum.

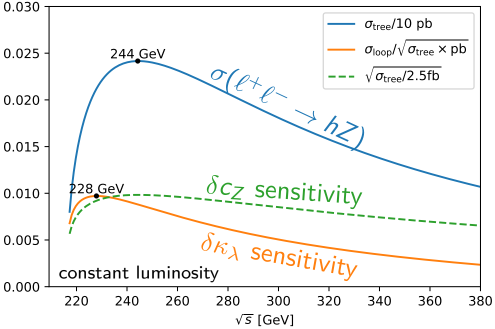
[Higgs@FC '19]

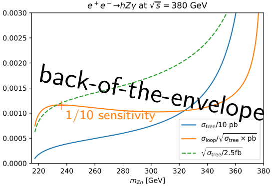
Triple Higgs coupling prospects summary

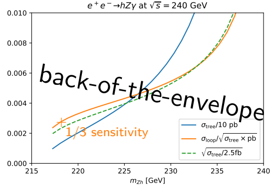


Higgsstrahlung centre-of-mass energy

Back-of-the-envelope calculations!
and discussions with Jenny List
& ECFA self-coupling focus group







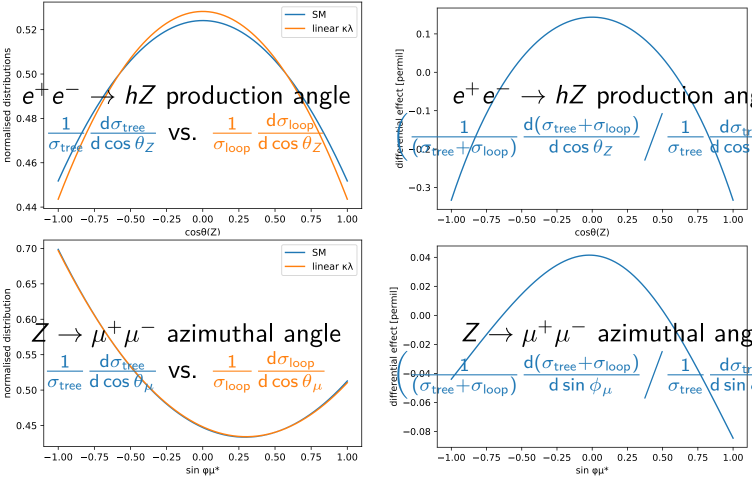
- ¿optimise/split $\sim$ 240 GeV energy/ies?
- ¿radiative return from $\sim$ 365/380 GeV?
- ¿even from $\sim$ 240 GeV downwards?

Differential hZ information

Back-of-the-envelope calculations!
and discussions with Fabio Maltoni
& Xiaoran Zhao

ZZh loop κ_λ vertex: $F_a(p_i^2)\,(\epsilon_1\cdot\epsilon_2) + F_b(p_i^2)\,(p_1\cdot\epsilon_2)(p_2\cdot\epsilon_1)$

with $F_b/F_a \sim 10^{-2}$ so only $\lesssim 10^{-4}$ differential effect



$e^+e^- \to hZ$ production angle

$$\frac{1}{\sigma_{\rm tree}}\frac{d\sigma_{\rm tree}}{d\cos\theta_Z} \text{ vs. } \frac{1}{\sigma_{\rm loop}}\frac{d\sigma_{\rm loop}}{d\cos\theta_Z}$$

$e^+e^- \to hZ$ production angle

$$\left(\frac{1}{(\sigma_{\rm tree}+\sigma_{\rm loop})}\frac{d(\sigma_{\rm tree}+\sigma_{\rm loop})}{d\cos\theta_Z}\Big/\frac{1}{\sigma_{\rm tree}}\frac{d\sigma_{\rm tree}}{d\cos\theta_Z}\right)-1$$

$Z \to \mu^+\mu^-$ azimuthal angle

$$\frac{1}{\sigma_{\rm tree}}\frac{d\sigma_{\rm tree}}{d\cos\theta_\mu} \text{ vs. } \frac{1}{\sigma_{\rm loop}}\frac{d\sigma_{\rm loop}}{d\cos\theta_\mu}$$

$Z \to \mu^+\mu^-$ azimuthal angle

$$\left(\frac{1}{(\sigma_{\rm tree}+\sigma_{\rm loop})}\frac{d(\sigma_{\rm tree}+\sigma_{\rm loop})}{d\sin\phi_\mu}\Big/\frac{1}{\sigma_{\rm tree}}\frac{d\sigma_{\rm tree}}{d\sin\phi_\mu}\right)-1$$

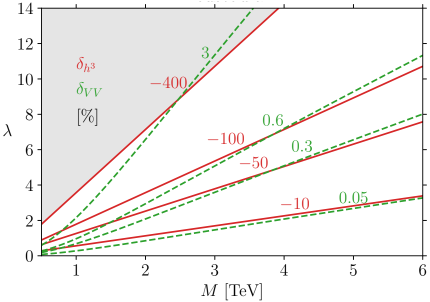
¿exploitable with an optimal discriminant?

Structurally large $\delta\kappa_\lambda/\delta\kappa_V$ in BSM

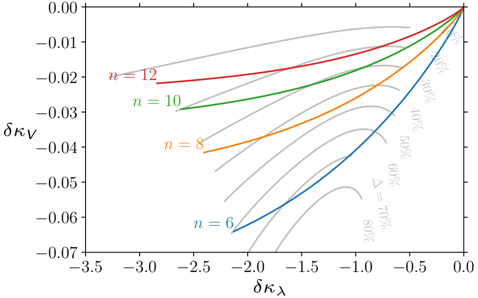
[GD, McCullough, Salvioni '21, '22, '22]
see also: [Di Luzio, Gröber, Spannowsky '17]
[Gupta, Rzehak, Wells '13] [Falkowski, Rattazzi '19]
[Logan, Rentala '15] [Chala, Krause, Nardini '18] [etc.]

loop factor (or v^2/M_X^2) allowed dimensionally btw. H^6 and D^2H^4

custodial weak-quadruplet scalar



Gegenbauer's Twin



$$\lambda\, H^*H^*(\epsilon H)\Phi + \lambda\frac{1}{\sqrt{3}}H^*H^*H^*\widetilde{\Phi}$$

large representations!

- dim≫6 operators may be very relevant
- vacuum stability limiting the $\delta\kappa_\lambda/\delta\kappa_V$ ratio

Structurally large $\delta\kappa_\lambda/\delta\kappa_V$ in BSM

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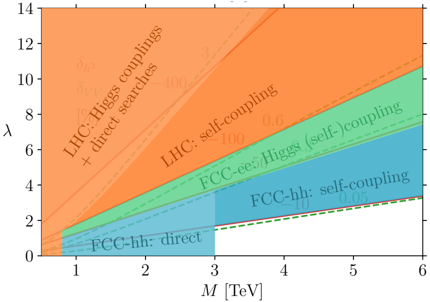

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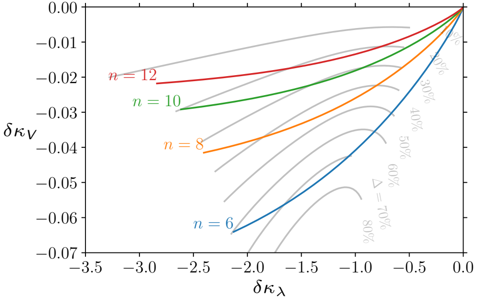

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large representations!

- dim≫6 operators may be very relevant
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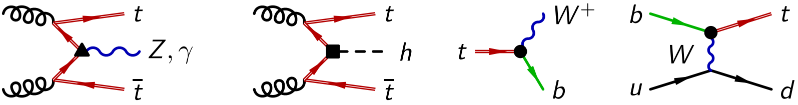
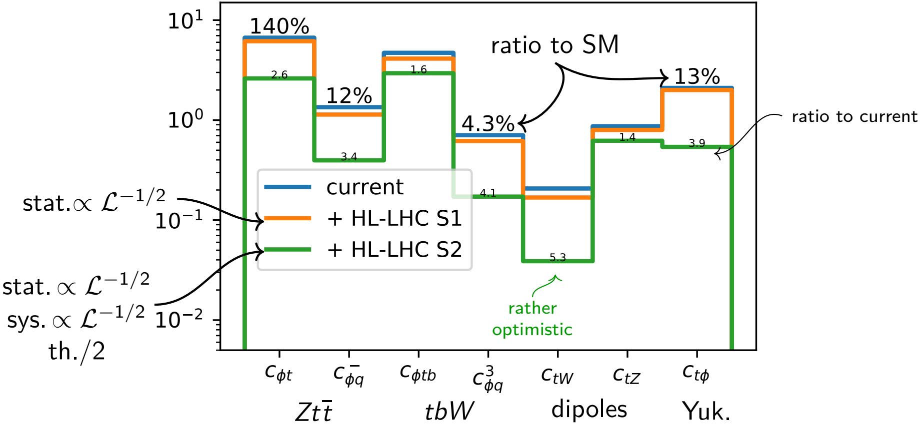
Top quark

Top electroweak interactions

[GD, Irles, Miralles, Peñuelas, Pöschl, Perellò, Vos '19]
[GD, Gutiérrez Camacho, Mantani, Miralles, Miralles López, Moreno Llácer, Poncelet, Vryonidou, Vos '22]

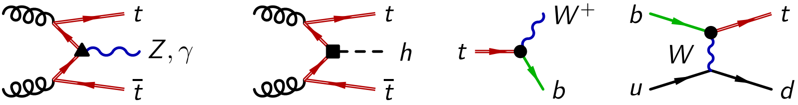


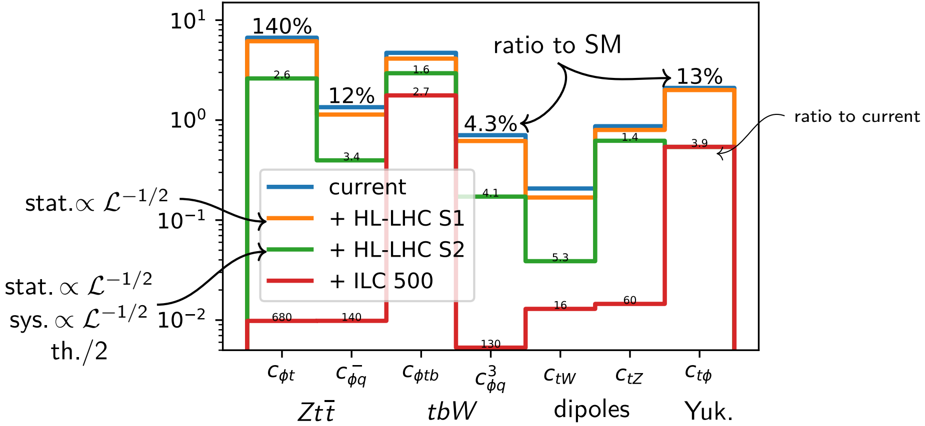


systematics limited, $\sim 10\%$ precision

Top electroweak interactions

[GD, Irles, Miralles, Peñuelas, Pöschl, Perellò, Vos '19]
[GD, Gutiérrez Camacho, Mantani, Miralles, Miralles López, Moreno Llácer, Poncelet, Vryonidou, Vos '22]



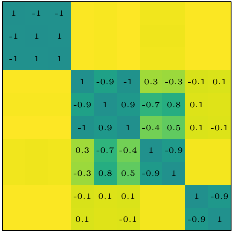


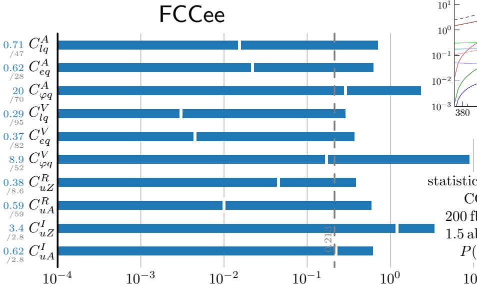
systematics limited, $\sim 10\%$ precision

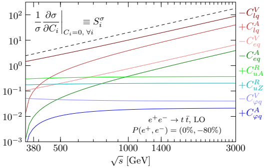
In lepton collisions, above 350 GeV

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

Powerful stat. optimal obs.
Experimentally and theoretically robust.
Two energies required for $ttV + ttll$.





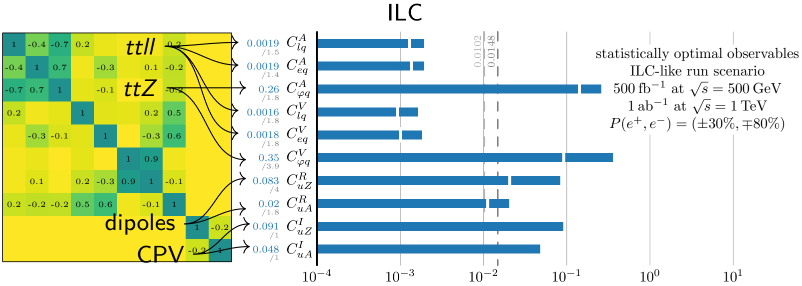


- in TeV^{-2}, $\Delta\chi^2 = 1$
- white marks: individual constraints
- /xx: global/individual ratios

In lepton collisions, above 350 GeV

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

Powerful stat. optimal obs.
Experimentally and theoretically robust.
Two energies required for $ttV + ttll$.



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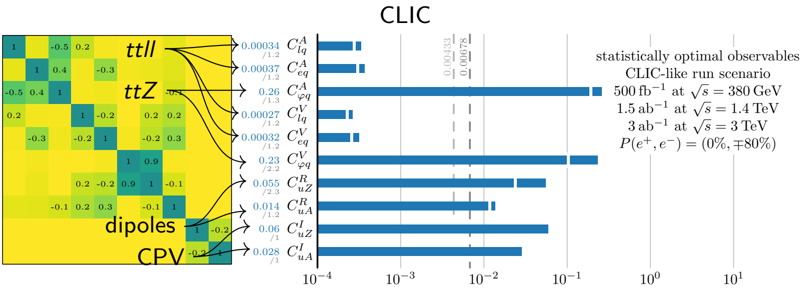

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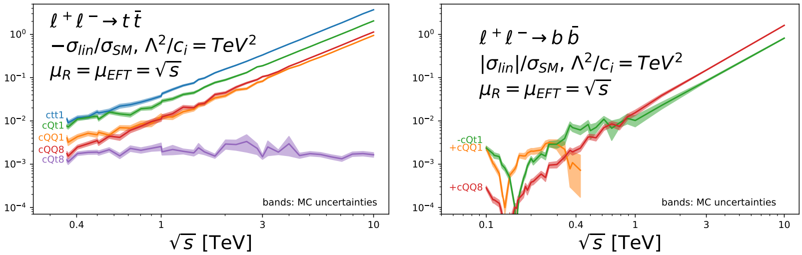
Four tops in pair production

[Degrande, GD, Maltoni, Mimasu, Vryonidou, Zhang '20]
[https://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO]



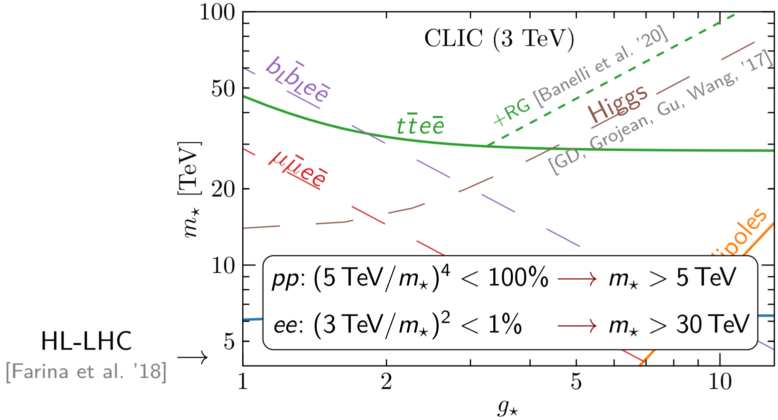
$$\sigma_{SM} \to 1/s, \quad \sigma_{lin} \to \text{cst}$$

c_{Qt}^8 chir.-suppressed
negative

sign flip around 150 GeV
c_{QQ}^1 to ~ 0 above 400 GeV

Composite Higgs scenario

- 1σ sensitivities
- fully composite t_R
- up to $\pm\mathcal{O}(1)$ factors



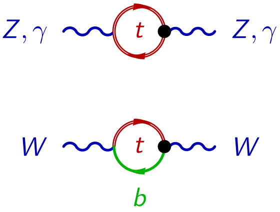
top is complementary to Higgs in probing natural BSM

Top-Higgs interplay

Top electroweak couplings below 350 GeV

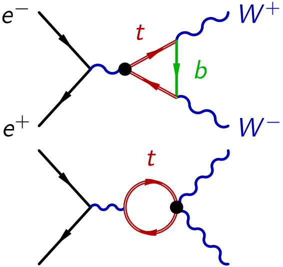
EWPO

[Zhang, Greiner, Willenbrock '12]
[Dawson, Giardino '19, '22, '23]
[Liu et al. '22]



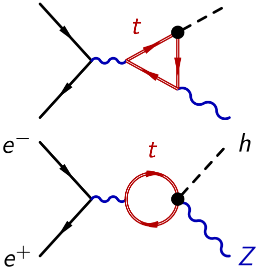
Diboson

[GD, Gu, Vrionidou, Zhang '18]



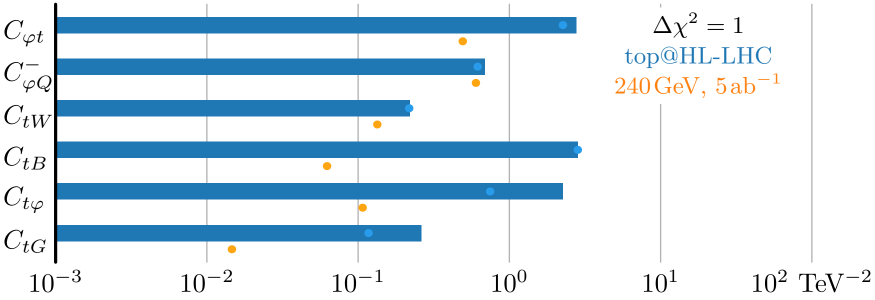
Higgs

[Vrionidou, Zhang, '18]
[see also Boselli et al '18]



Top-Higgs interplay

[GD, Gu, Vrionidou, Zhang '18]
[see also Jung, Lee, Perelló, Tian, Vos '20]



Individual constraints (blobs)

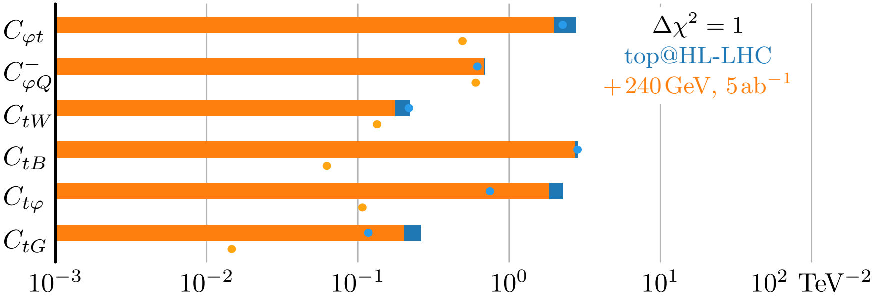
- competitive with the HL-LHC (e.g. on the top Yukawa $C_{t\varphi}$)
- dominated by Higgs measurements (diboson improves with energy)

Global constraints (bars) (12 Higgs + 6 top operators floated)

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

Top-Higgs interplay

[GD, Gu, Vrionidou, Zhang '18]
[see also Jung, Lee, Perelló, Tian, Vos '20]



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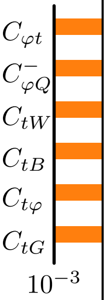
Top-Higgs interplay



TeV^{-2}

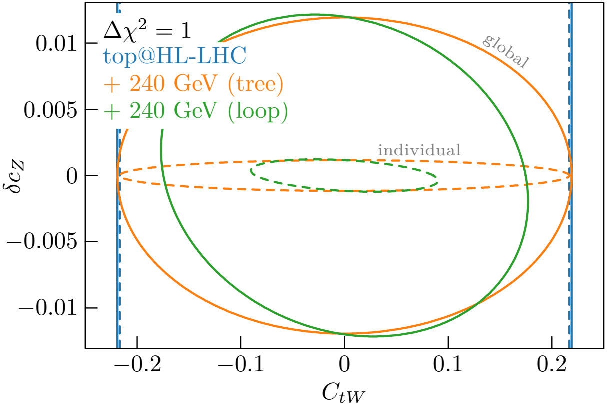
Individu

- com
- dom

Global c

- large
- still
- more differential distributions should help

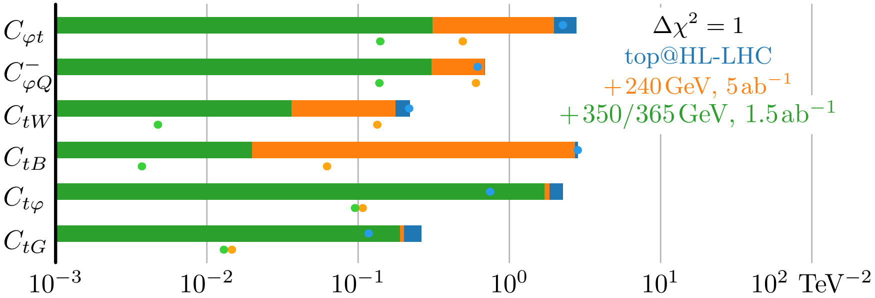
On a linear scale, in the $(C_{tW}, \delta c_Z)$ plane:



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

Top-Higgs interplay

[GD, Gu, Vrionidou, Zhang '18]
[see also Jung, Lee, Perelló, Tian, Vos '20]



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}

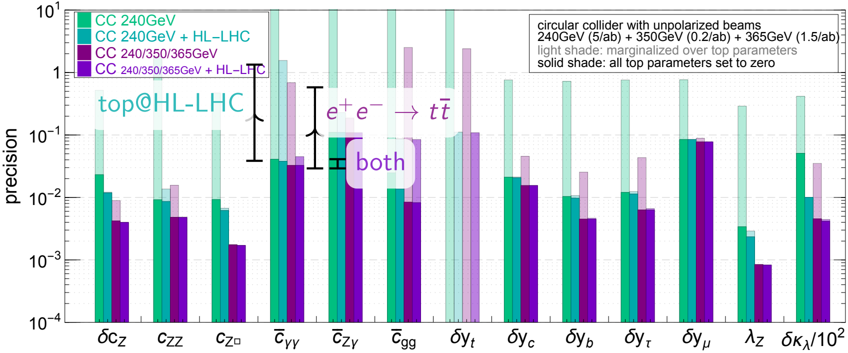
Global constraints (bars) (12 Higgs + 6 top operators floated)

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

Higgs-top interplay

[GD, Gu, Vryonidou, Zhang '18]
[see also Jung, Lee, Perelló, Tian, Vos '20]

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. $\to$ 0

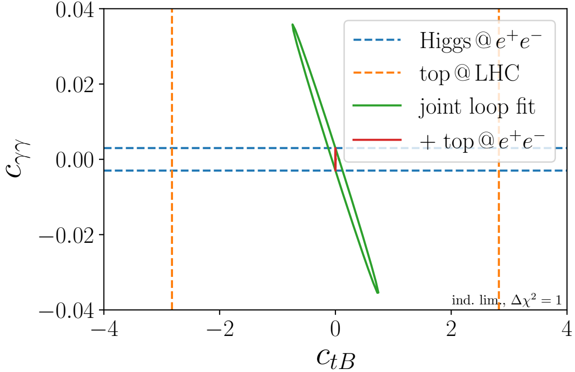


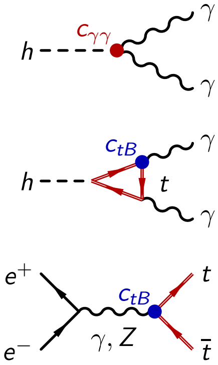
Uncertainties on the top have a big effect on the Higgs

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

Higgs-top interplay

[GD, Gu, Vryonidou, Zhang '18]





Higgs@e^+e^- helps improving top coupling precision.

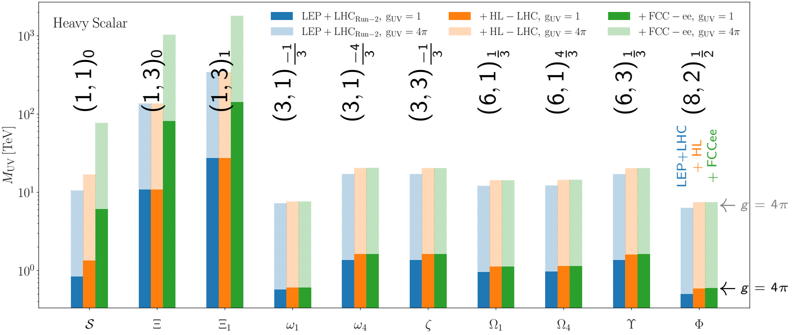
Higgs precision is however contaminated by top uncertainties.

Top@e^+e^- is needed to achieve the full potential of Higgs@e^+e^-.

Toy model interpretations

Toy model interpretations

[Celada, Giani, ter Hoeve, Mantani, Rojo, Rossia, Thomas, Vryonidou '24]



see Christophe Grojean (p.28) and Ben Stefanek's talks
for additional renormalisation-group running effects

SMEFT at future e^+e^- colliders

It encodes the virtual effects of heavy new physics,

in order to systematically probe small correlated deviations.

It is ideally suited for precision measurements at electroweak scales.

It allows to globally combine widely different measurements,

to account for quantum effects,

which further blur the separation between sectors.

Extras

Future lepton colliders