Higgs physics at future lepton colliders

theory progress from and after the ESU

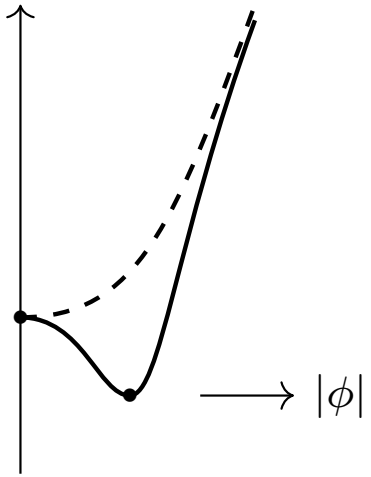
Gauthier Durieux
(CERN)

Higgs Hunting – Paris – 14 Sept 2022

The Higgs at 10

Is it elementary? Is its mass protected by a symmetry?

Phenomenological description of a more microscopic dynamics like the Ginzburg-Landau theory of superconductivity?



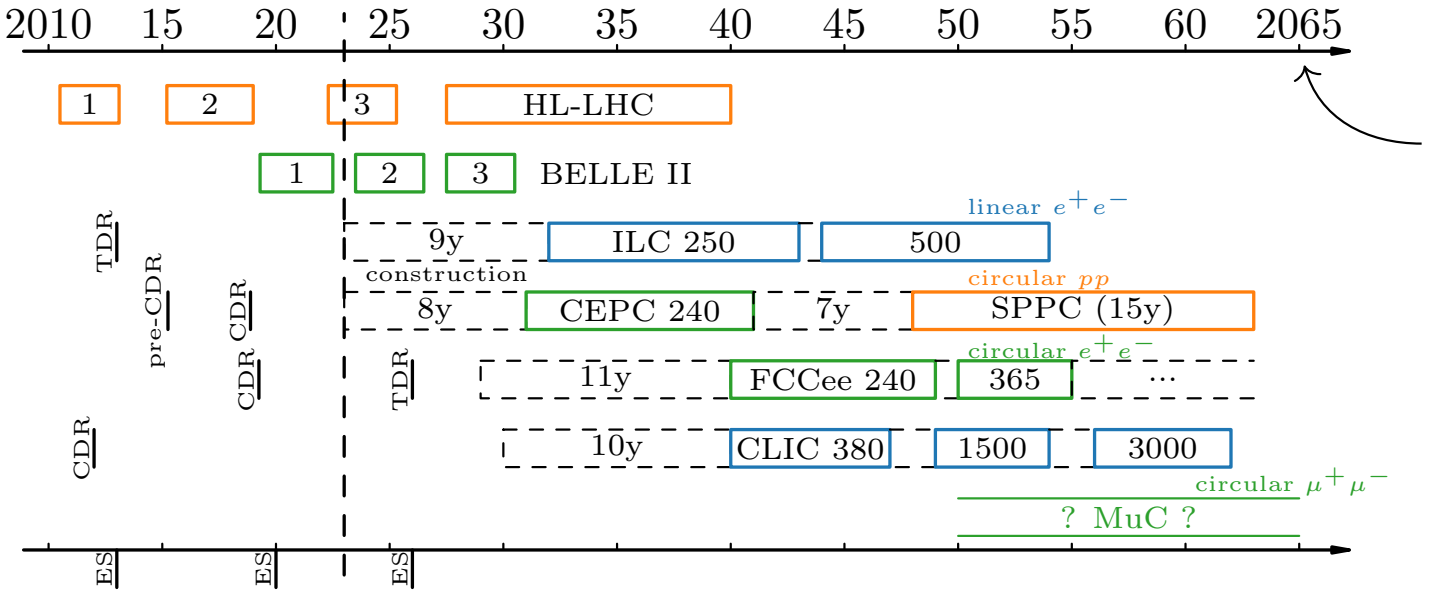
$$V(\phi) = \pm\mu^2|\phi|^2 + \lambda|\phi|^4$$

European Strategy Update 2020 [https://europeanstrategyupdate.web.cern.ch]

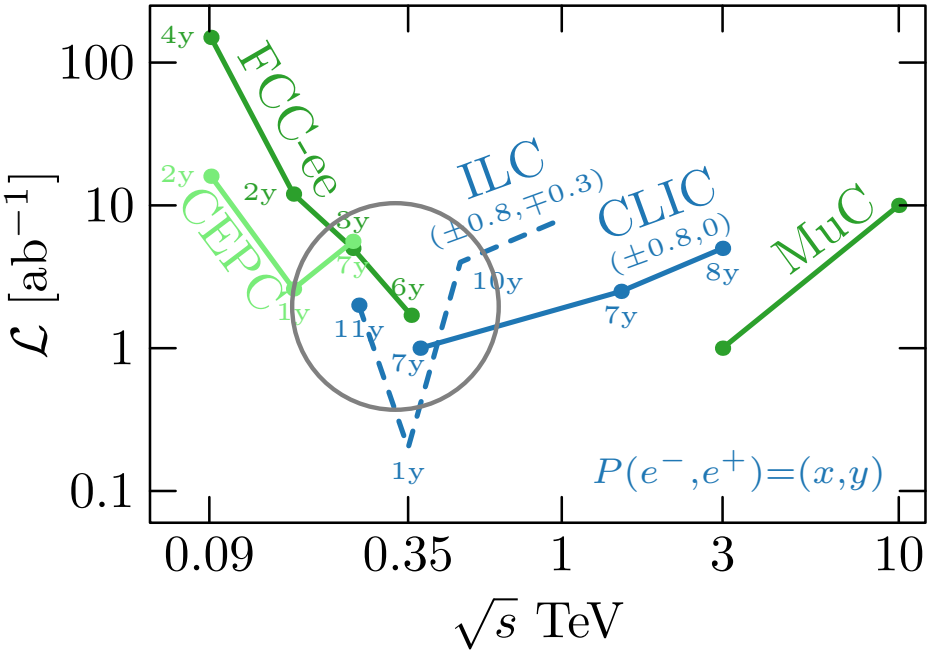
1. Major developments from the 2013 Strategy
   a) (...) The successful completion of the **high-luminosity upgrade** of the machine and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. (...)

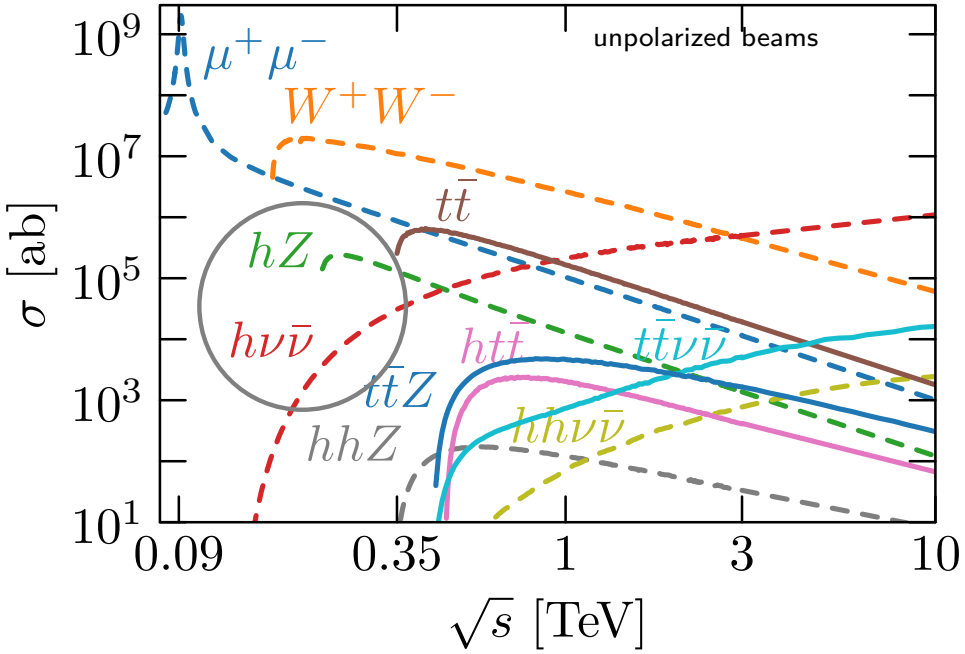
3. High-priority future initiatives
   a) An **electron-positron Higgs factory** is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. (...)
   b) Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders (...) high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, **bright muon beams**, energy recovery linacs.

Future lepton colliders

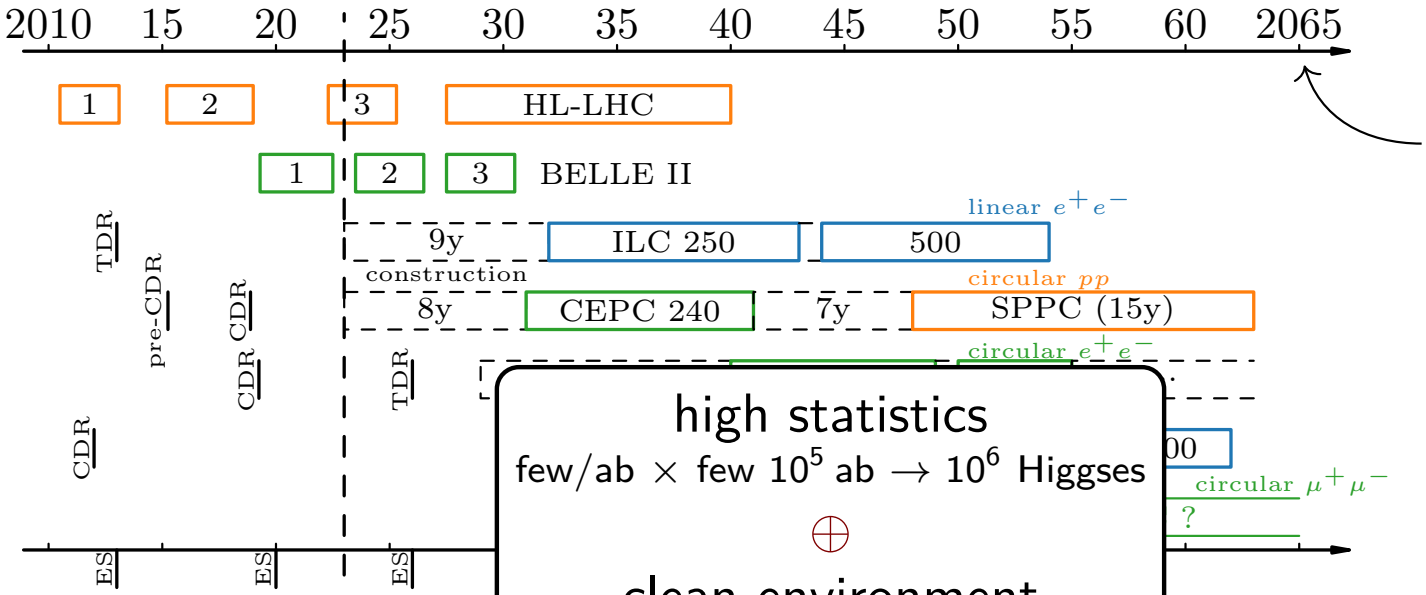


Happy 400th birthday!





Future lepton colliders



Happy 400th birthday!

high statistics

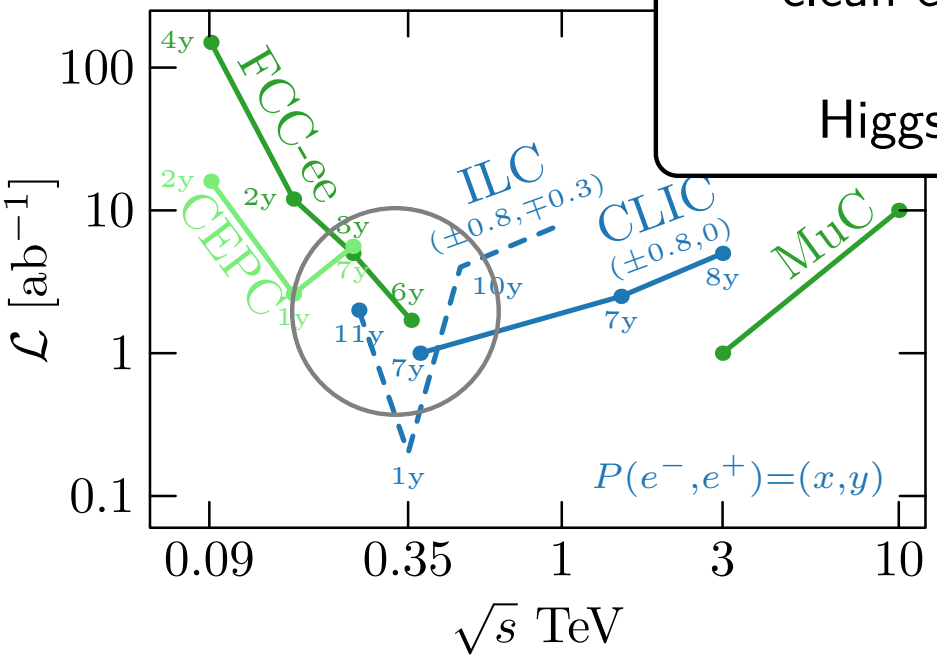
few/ab × few 10^5 ab → 10^6 Higgses

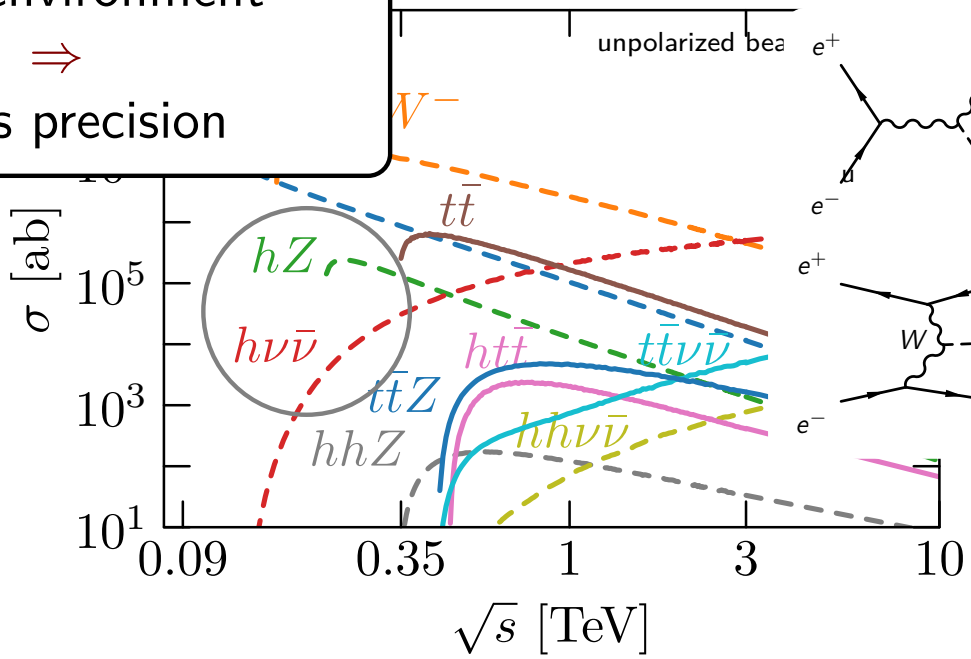
⊕

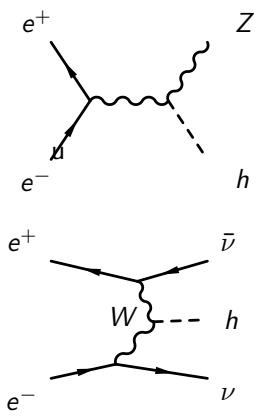
clean environment

⇒

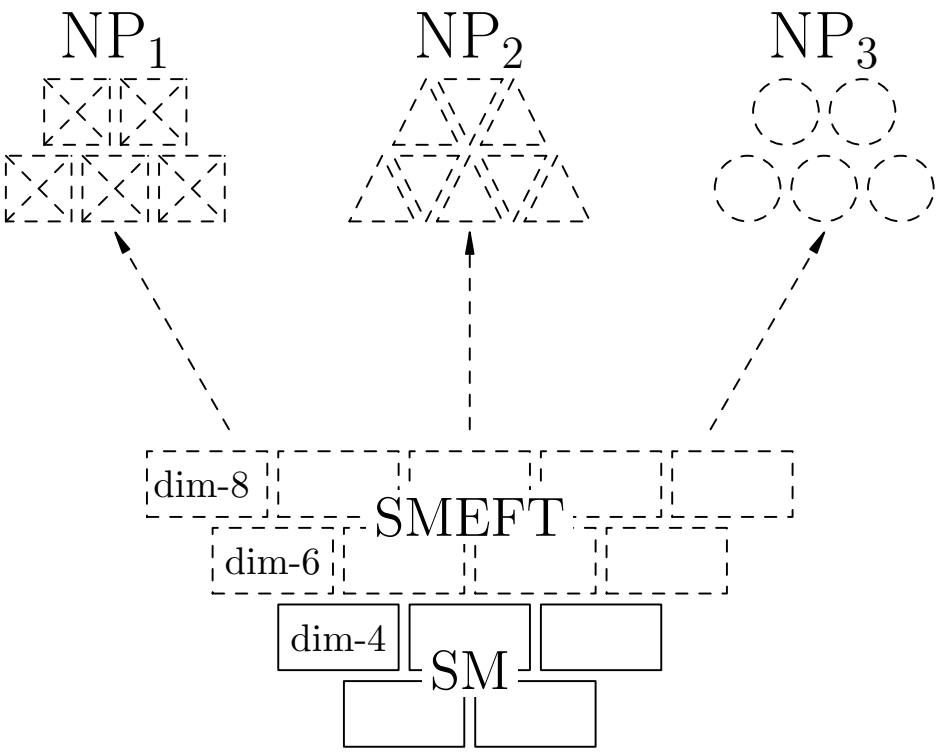
Higgs precision







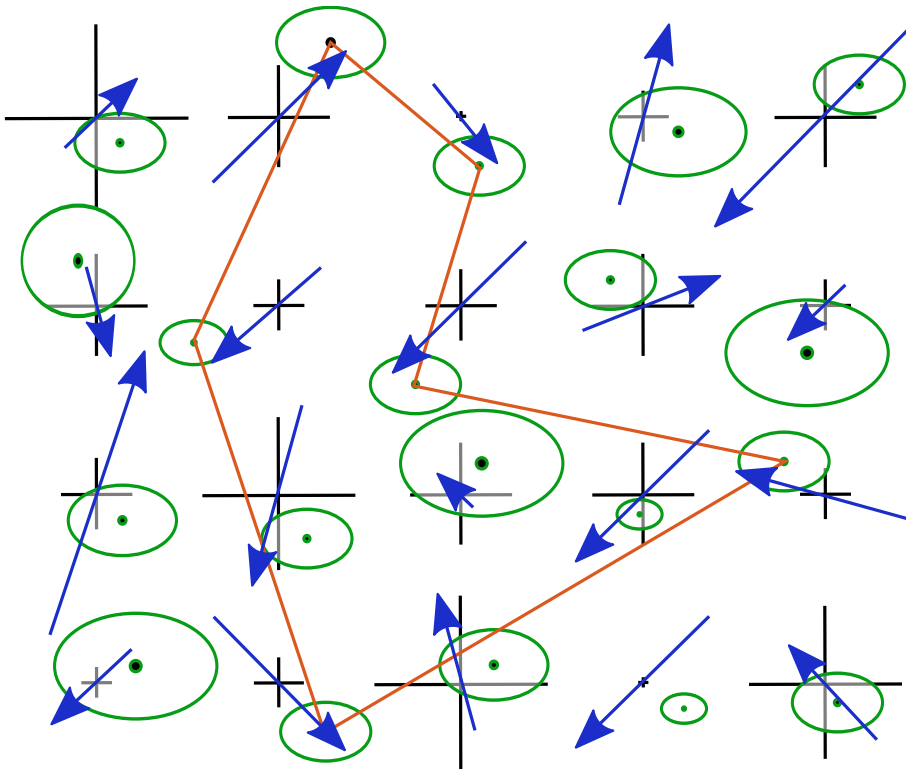
Taking the SM to higher dimensions



- using established bricks (fields and symmetries)
- organised by relevance (operator dimension)
- full coverage of heavy new physics (finite operator set)

systematic strategy through a global approach

Isolating patterns of new physics



array of sensitive observables

precise measurements

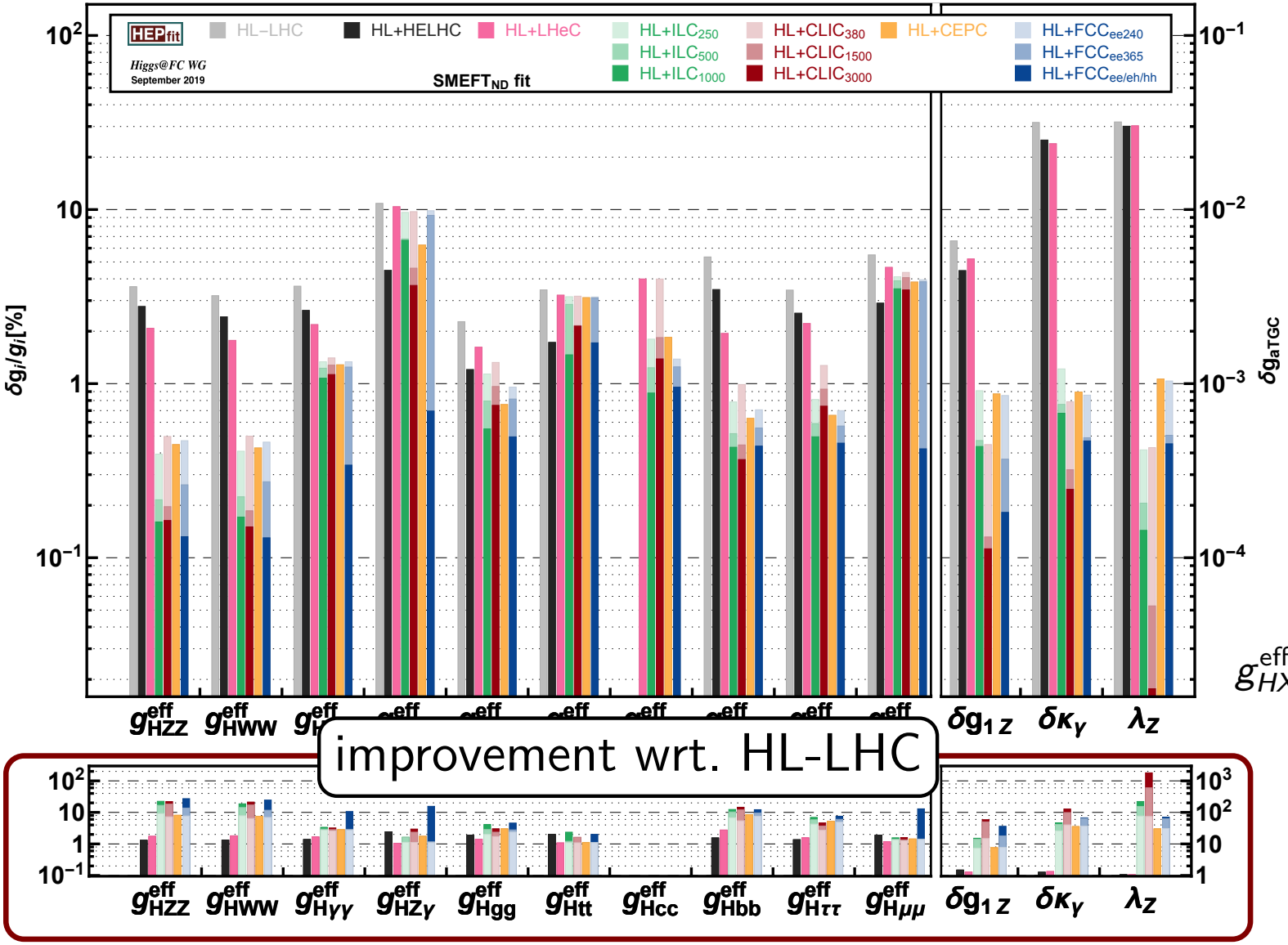
precise SMEFT predictions

→ correlate deviations

Global Higgs prospects

An order of magnitude improvement

[Higgs@FC '19]



[Ellis, You '15]

[Ellis et al '17]

[de Blas et al '16]

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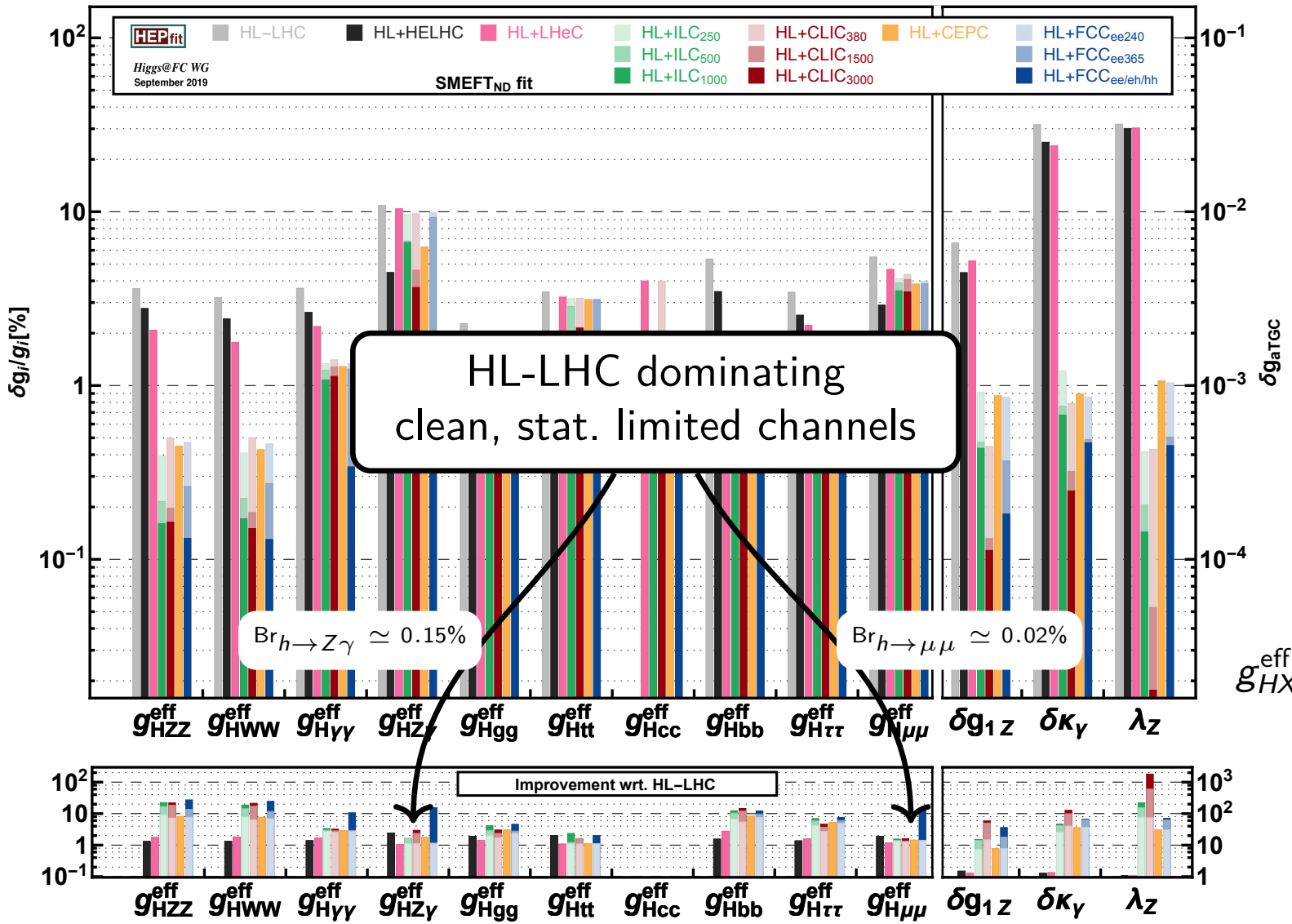
$$g^{\rm eff}_{HXX} \equiv \sqrt{\frac{\Gamma_{H\to XX}}{\Gamma^{\rm SM}_{H\to XX}}}$$

An order of magnitude improvement

[Higgs@FC '19]



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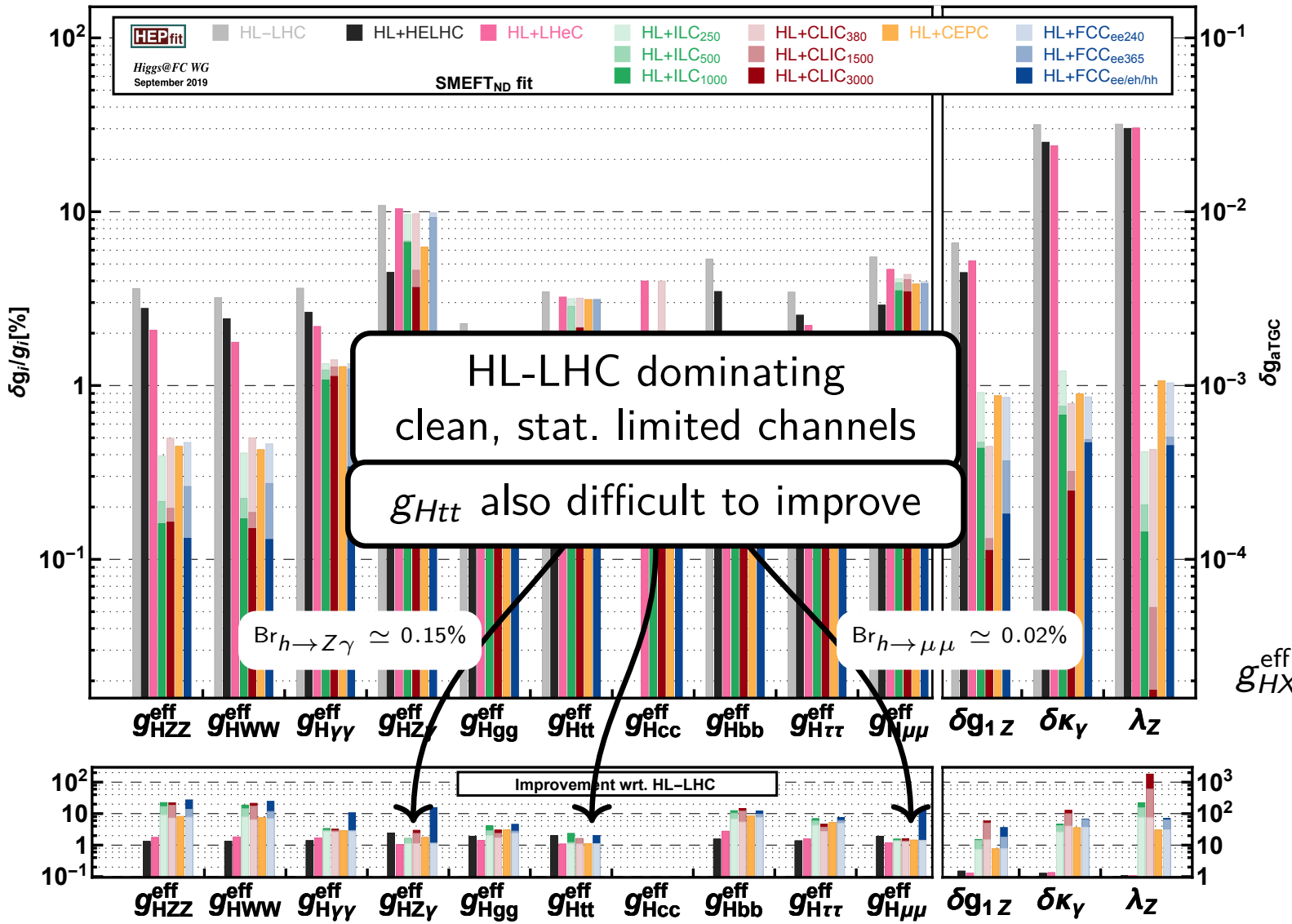

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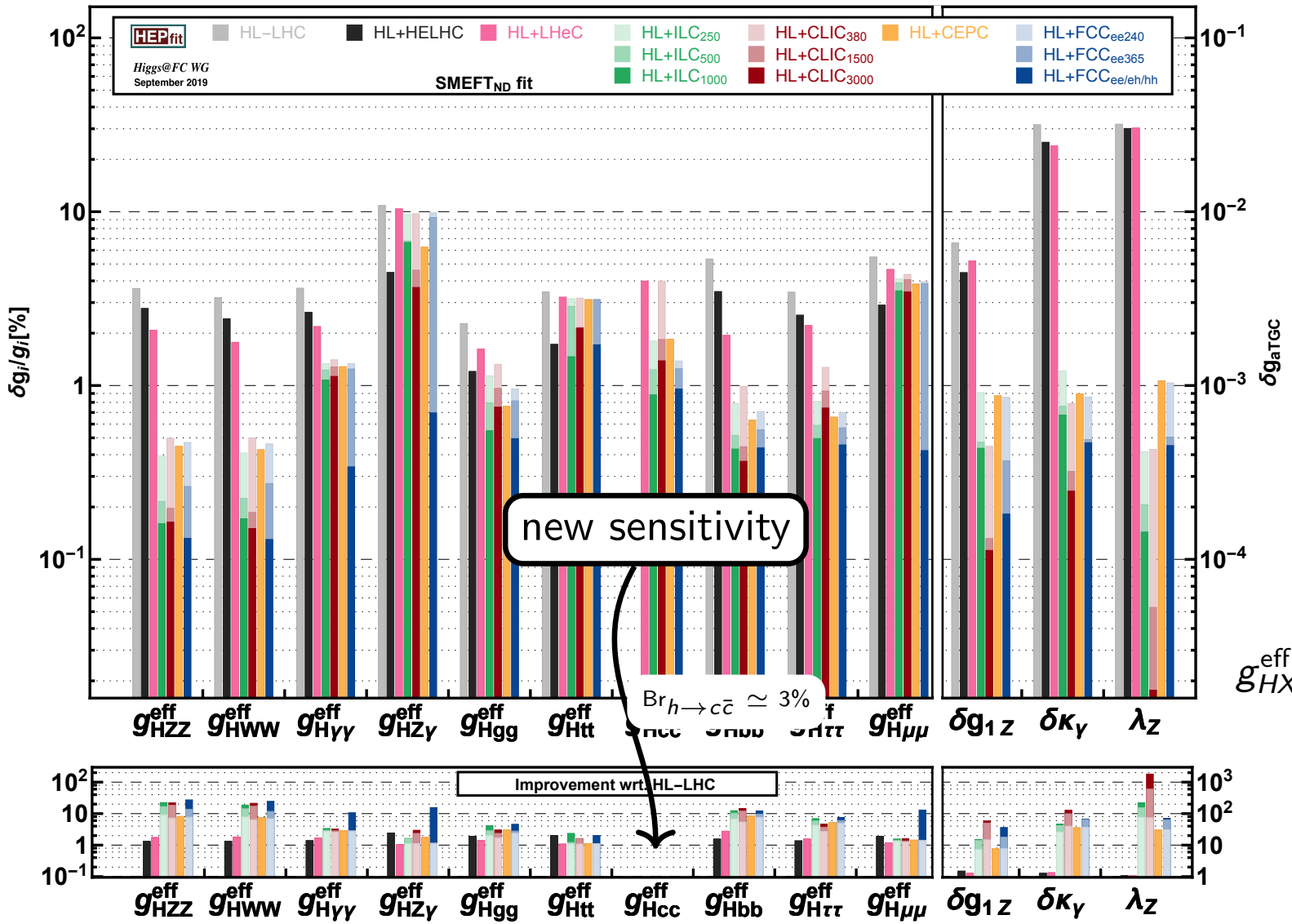

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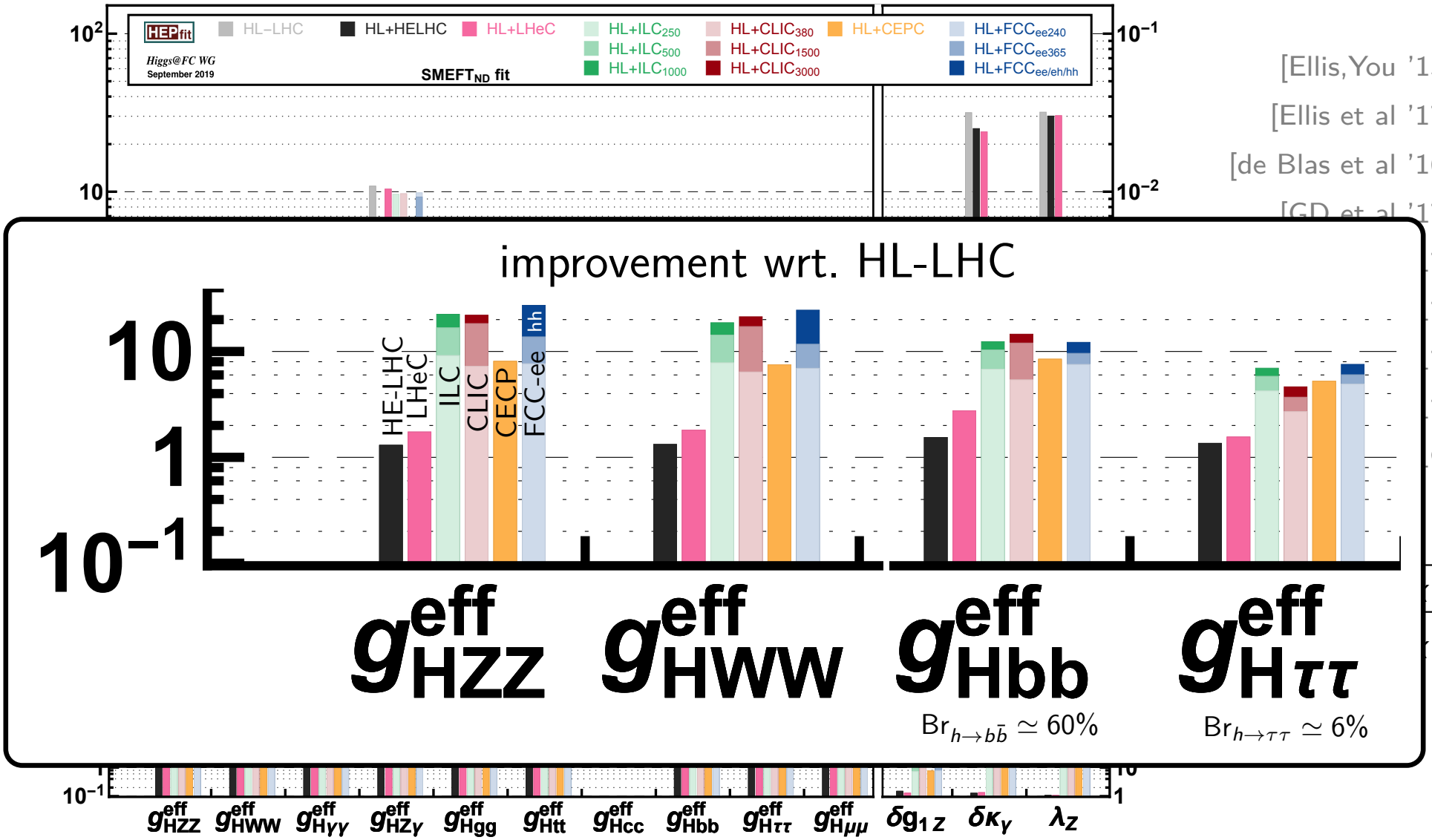
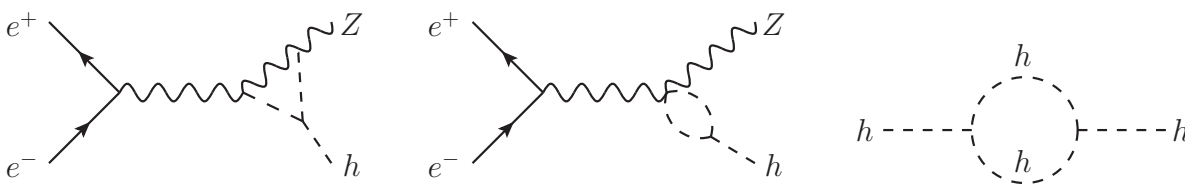


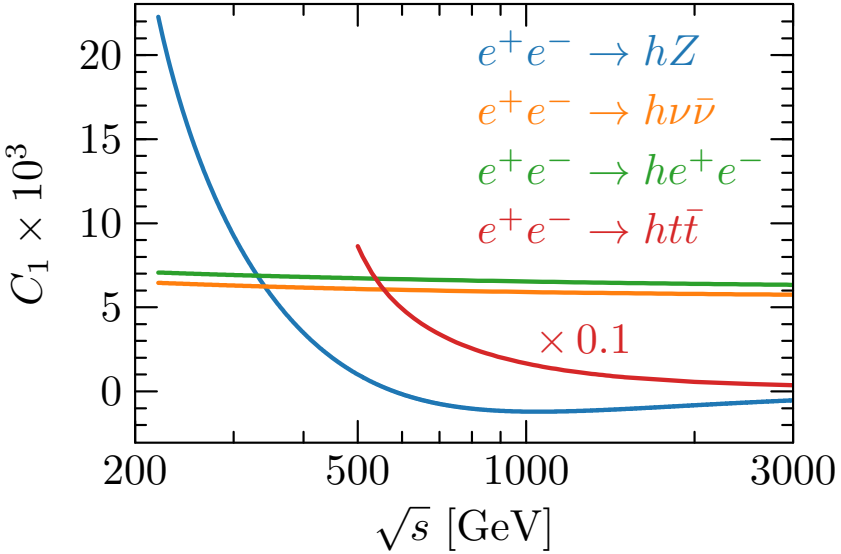
Higgs trilinear loops

- 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]



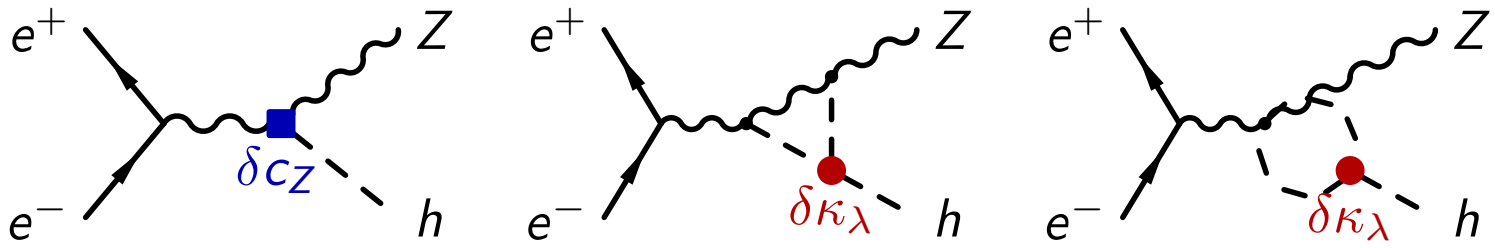
$$\Sigma_{\rm NLO}/\Sigma_{\rm NLO}^{\rm SM} \simeq 1 + (C_1 - 0.0031)\,\delta\kappa_\lambda + \ldots$$

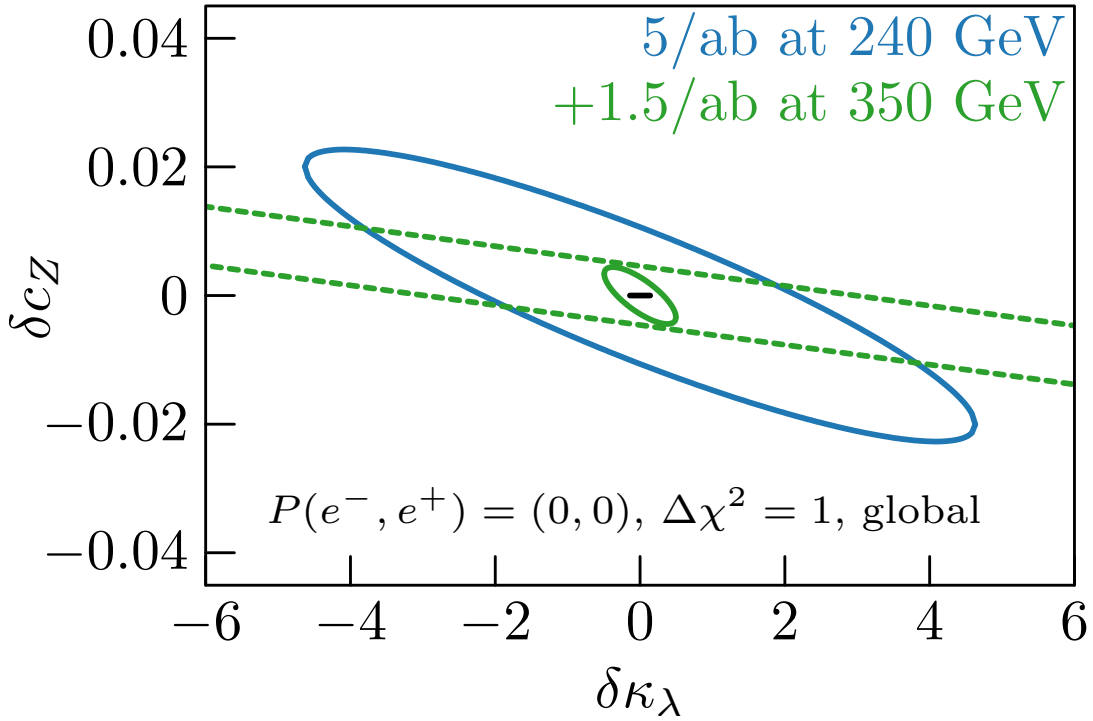


percent sensitivity $\times$ permil hZ precision $\to$ naive 10% constraint

Higgs trilinear loops

[Di Vita, GD, Grojean, Gu, Liu, et al. '17]



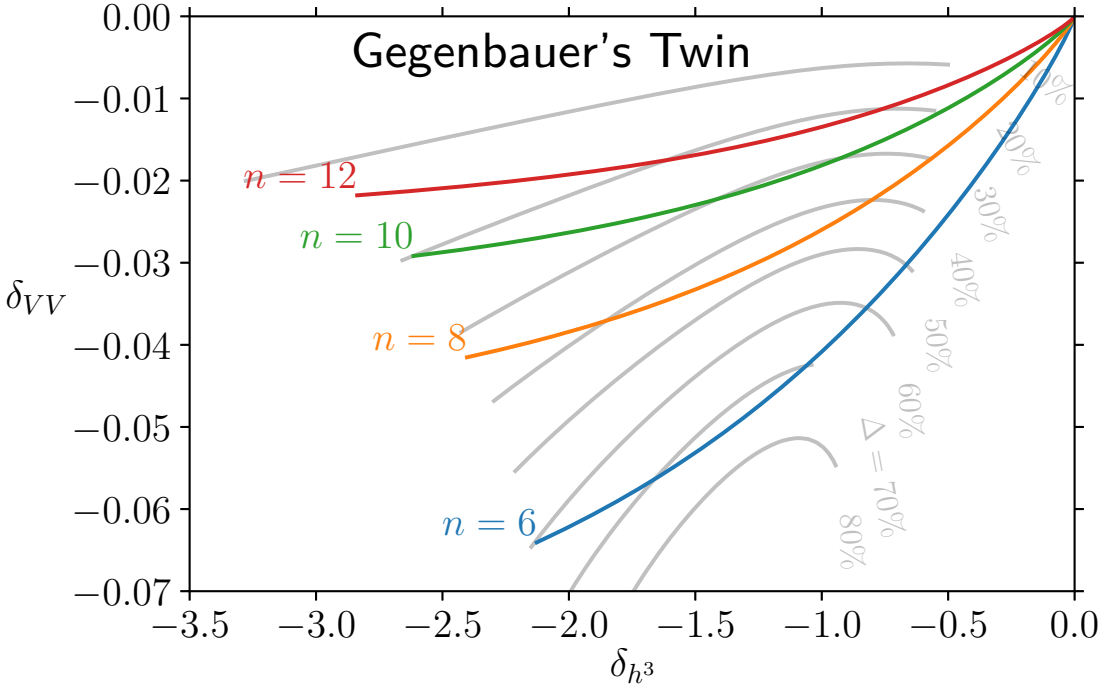


Correlations with single-Higgs couplings require two $\sqrt{s}$.

Models with large δ_{h^3}/δ_{VV} ?

[GD, McCullough, Salvioni '21, '22, '22]

Gegenbauer potentials $G_n^{(N-1)/2}(\cos\frac{h}{f})$ are radiatively stable for pseudo-Nambu-Goldstone bosons of $\mathrm{SO}(N+1) \to \mathrm{SO}(N)$.



Naturally features $\mathcal{O}(1\%)$ Higgs deviations,

but yields $\mathcal{O}(100\%)$ self-coupling modifications.

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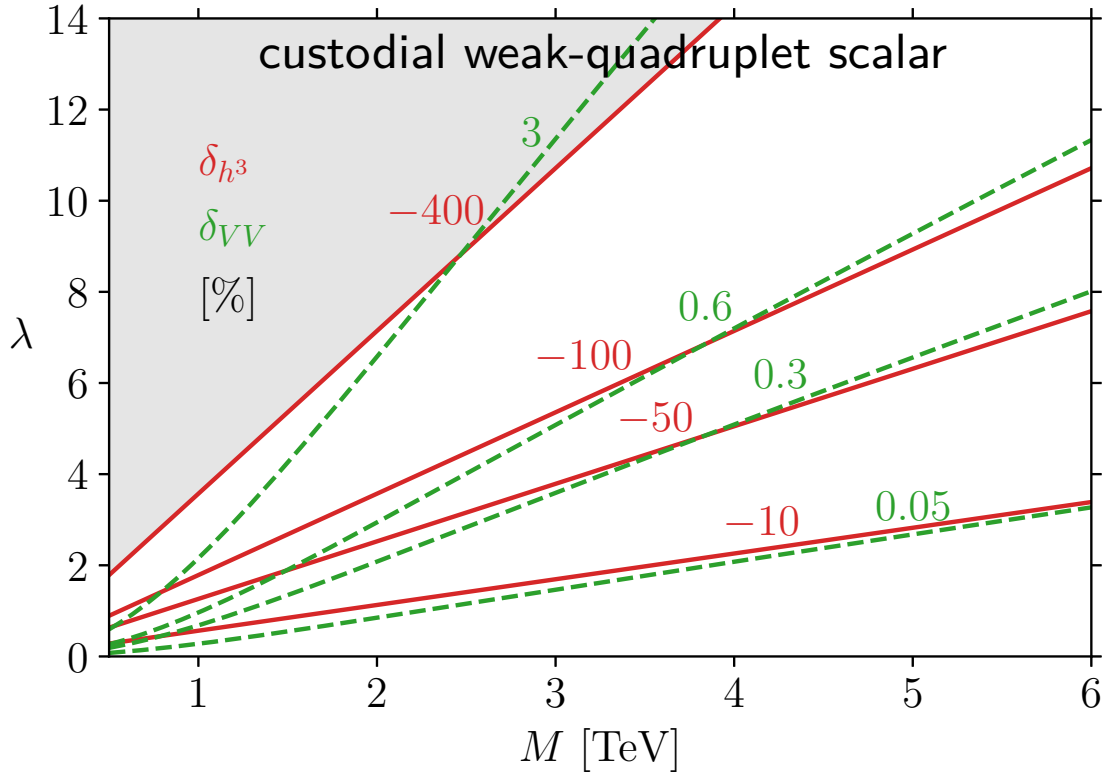

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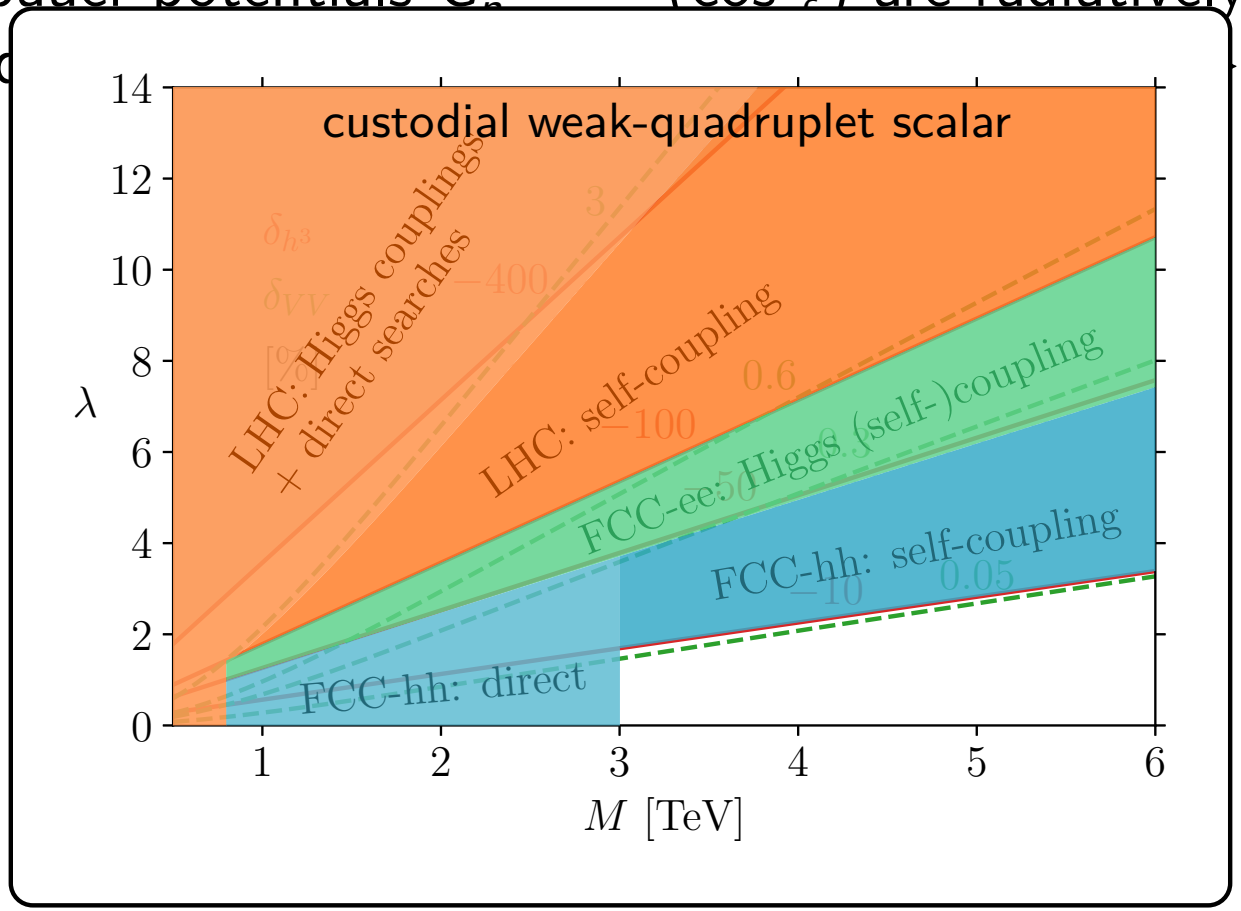

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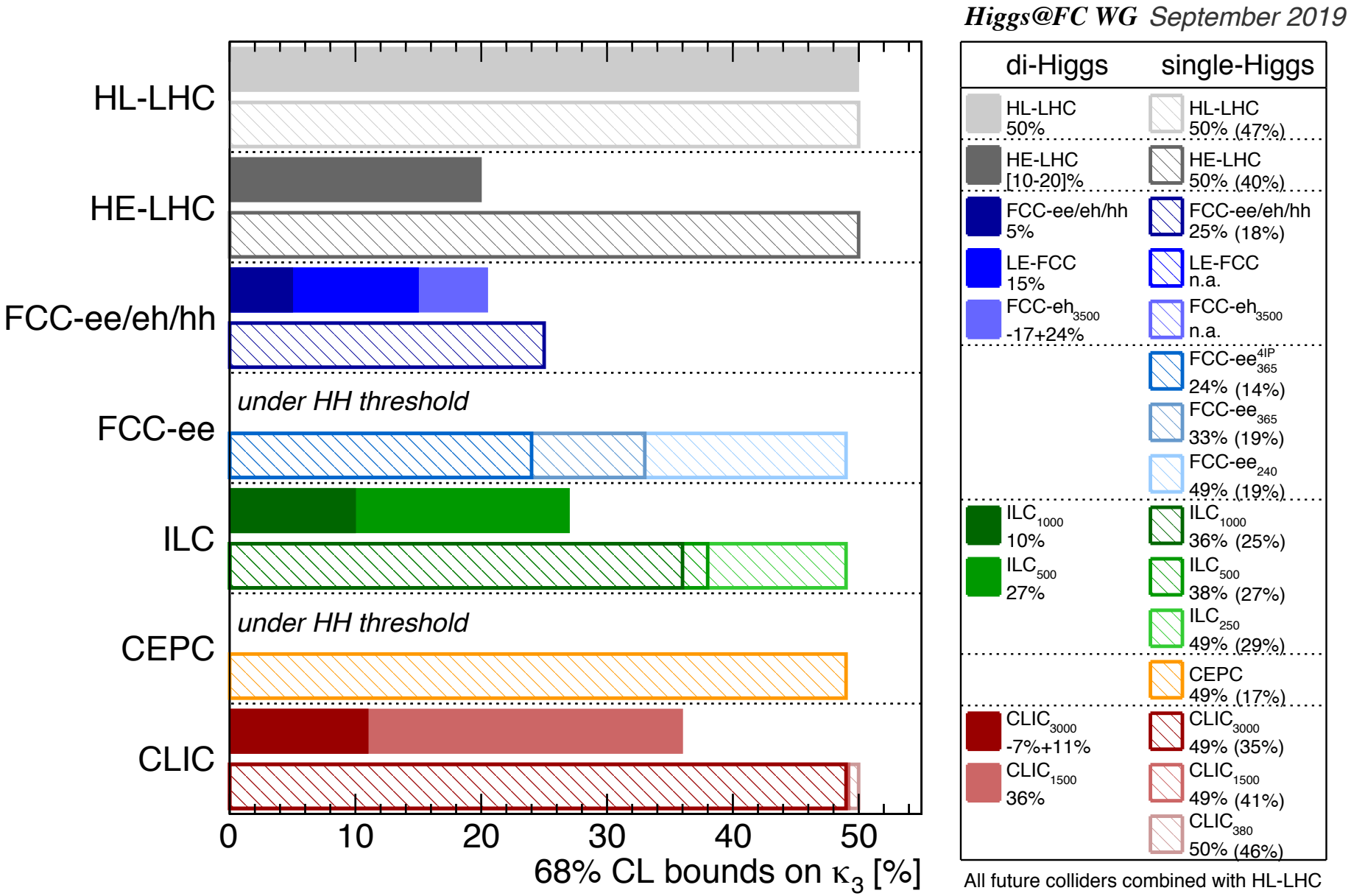
Higgs trilinear self-coupling

[Higgs@FC '19]



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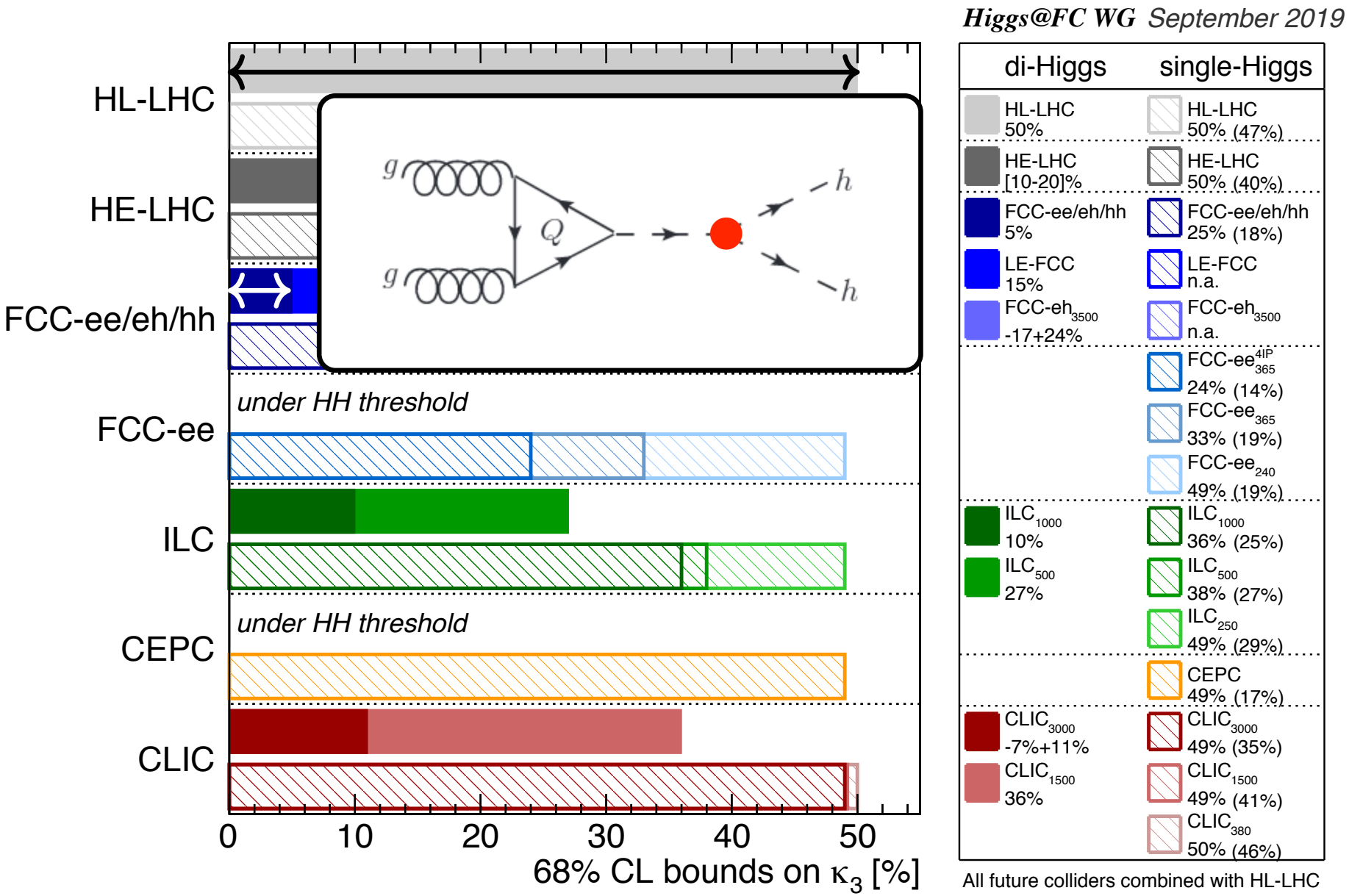

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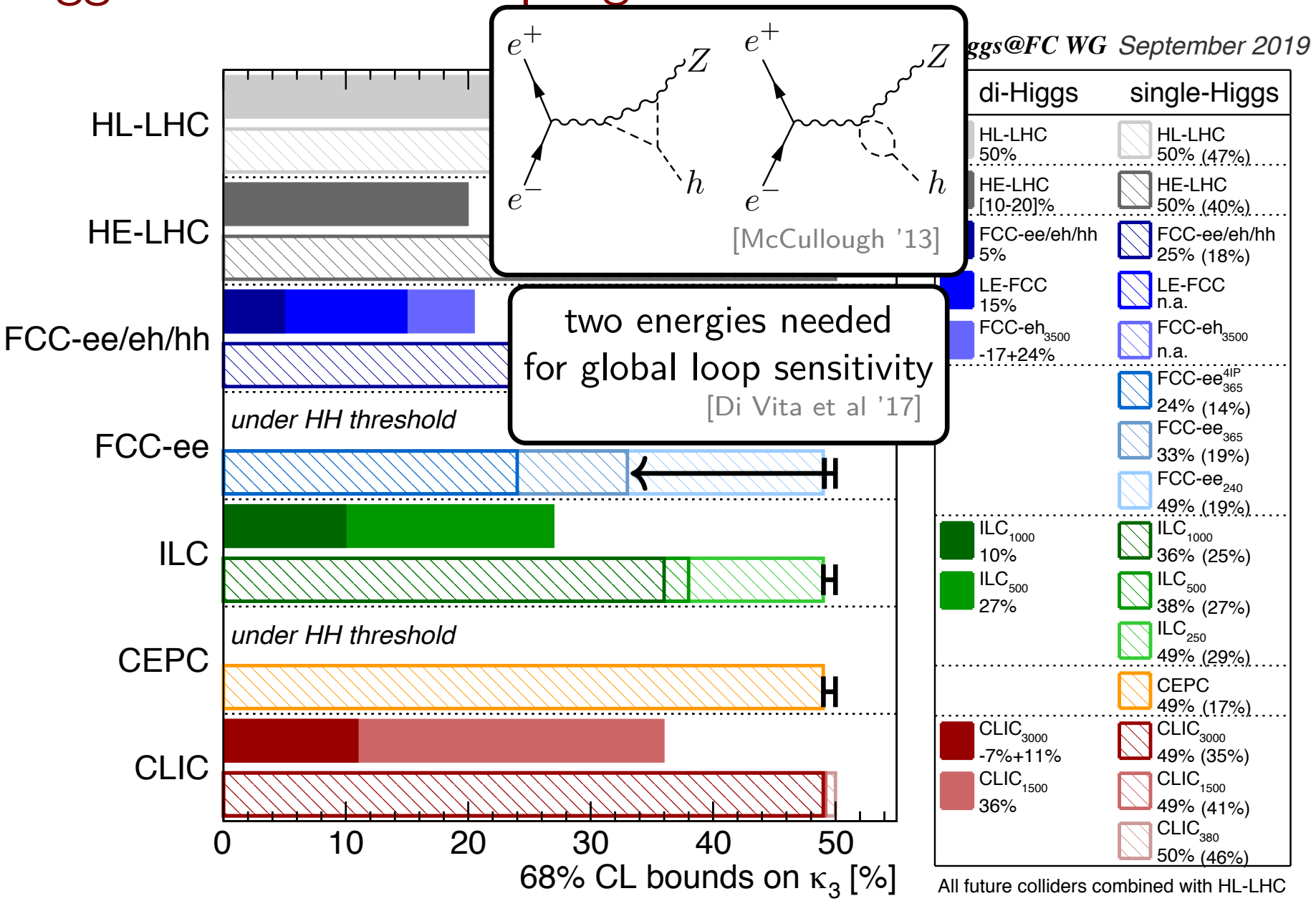

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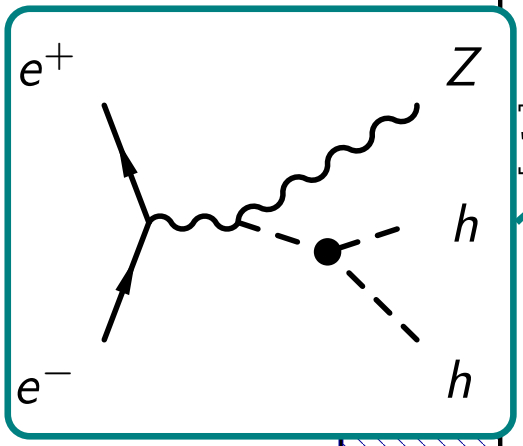

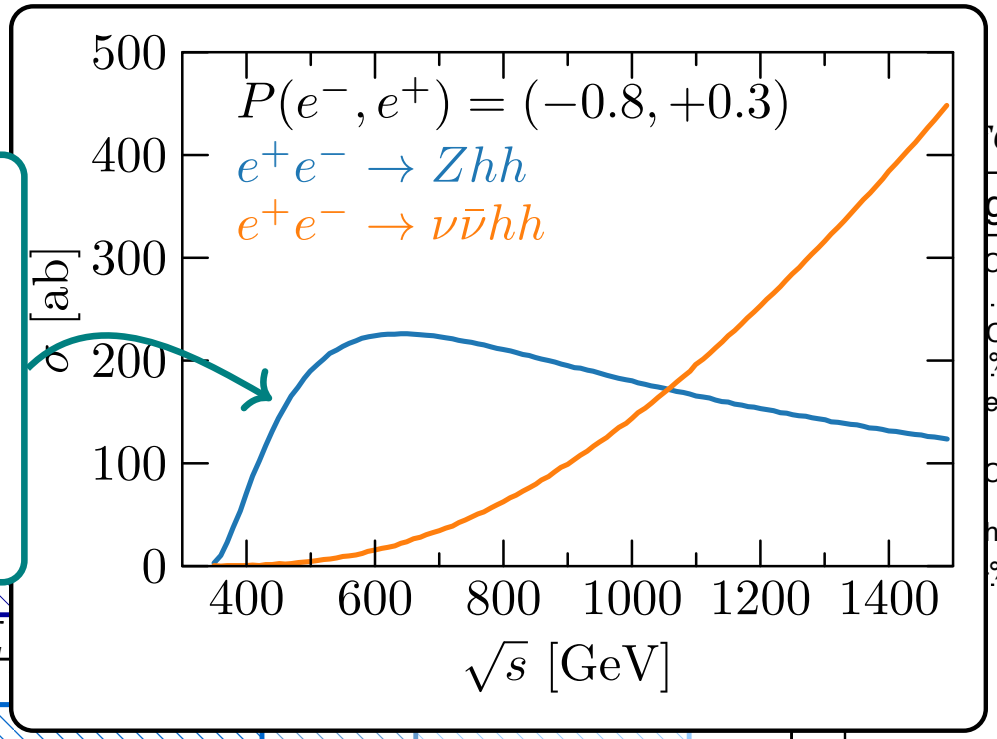

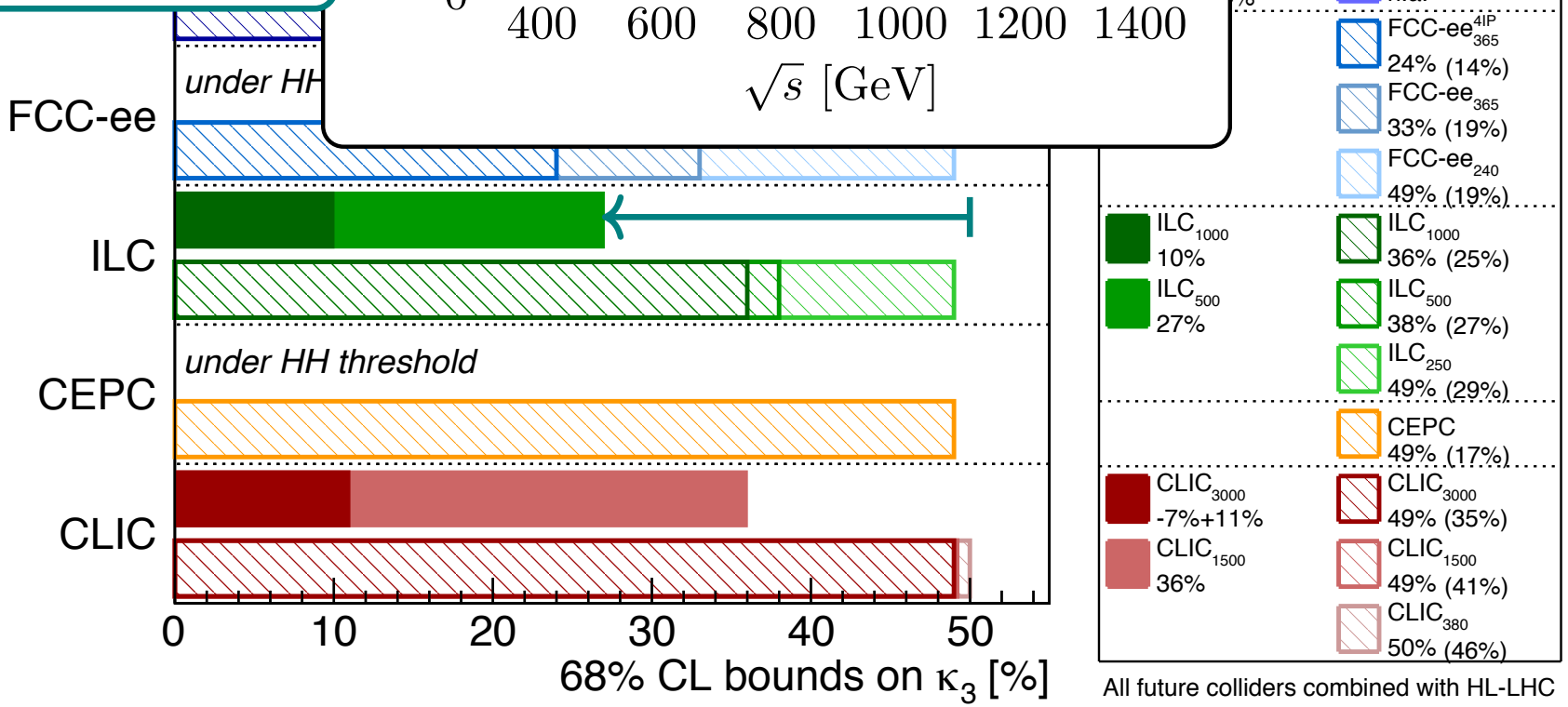

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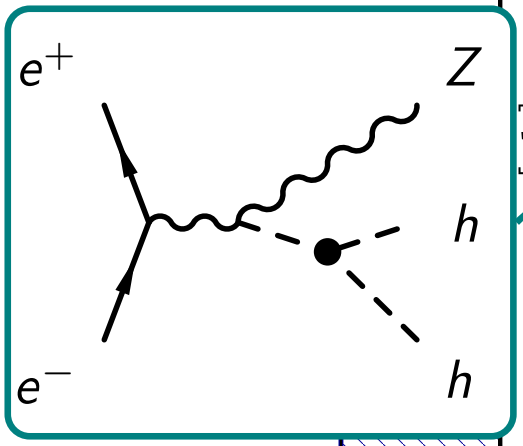
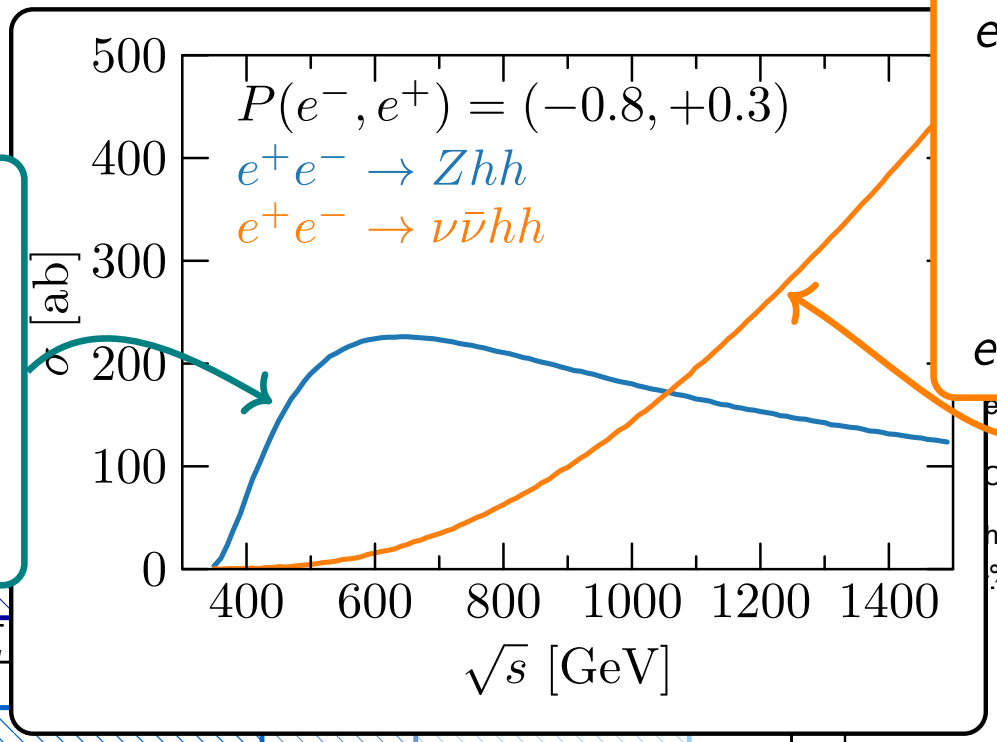
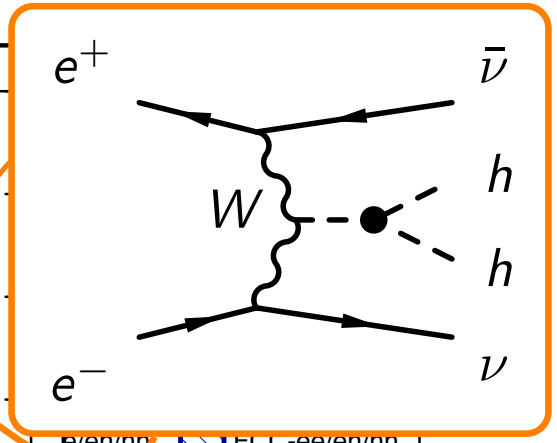
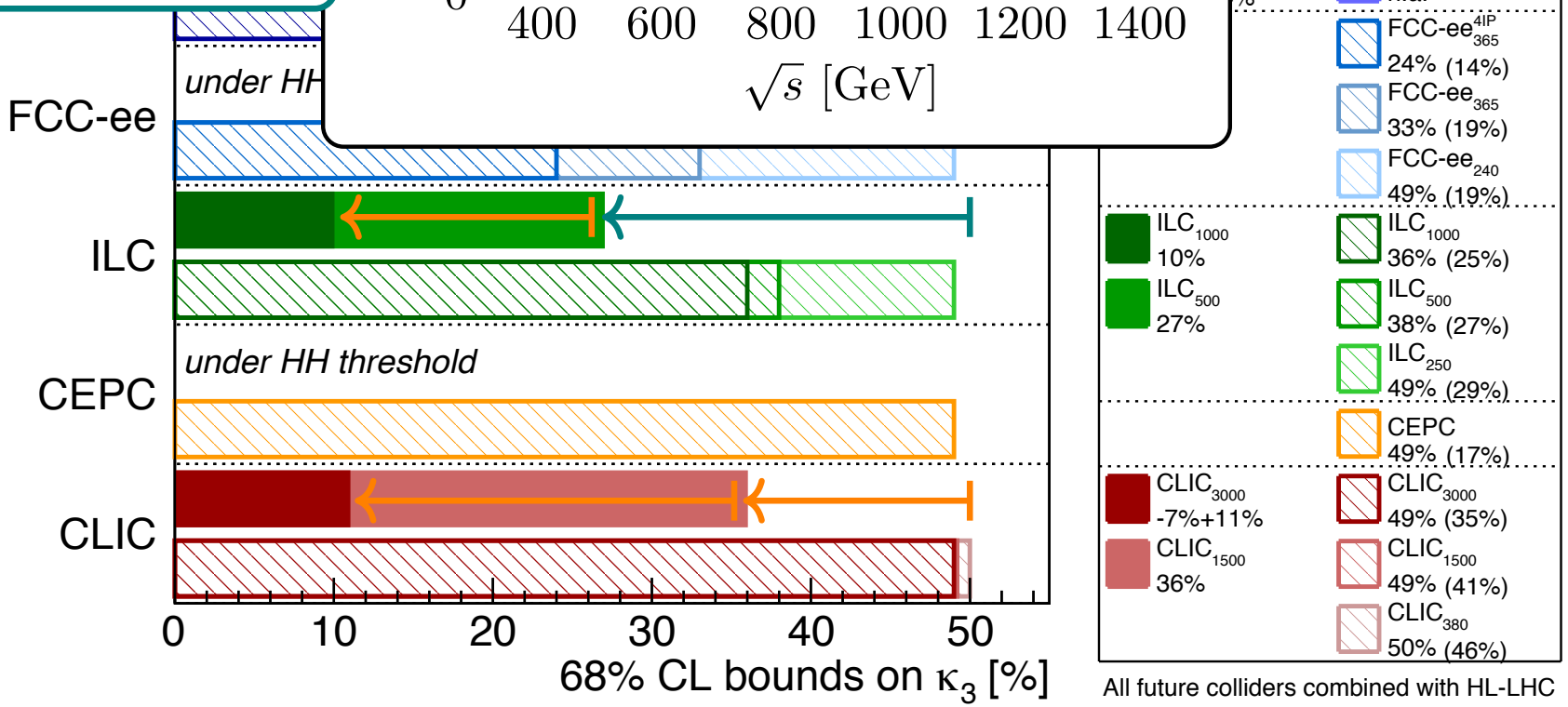








Cross-sector interplay

Higgs-diboson interplay

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

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

- Benefiting from optimal observables
  - used at LEP already [Opal, L3, ALEPH, DELPHI]
  - ILC studies ongoing [Karl PhD Thesis '19] [sec. 10.2 of Snowmass input]

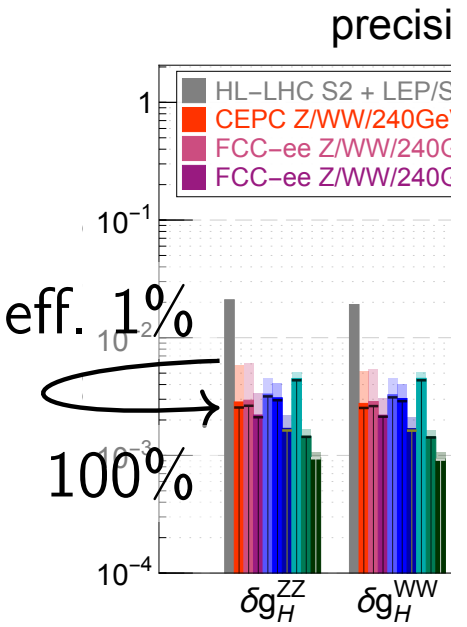
- Sensitivity driven by high energies (240, 365 GeV)

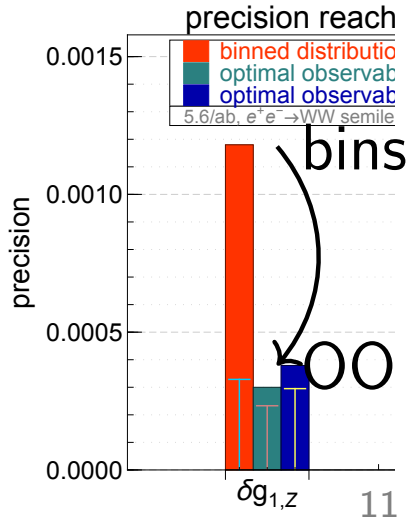
  requires good forward detector coverage

- Also sensitive to Vff couplings

  dependence often unduly neglected

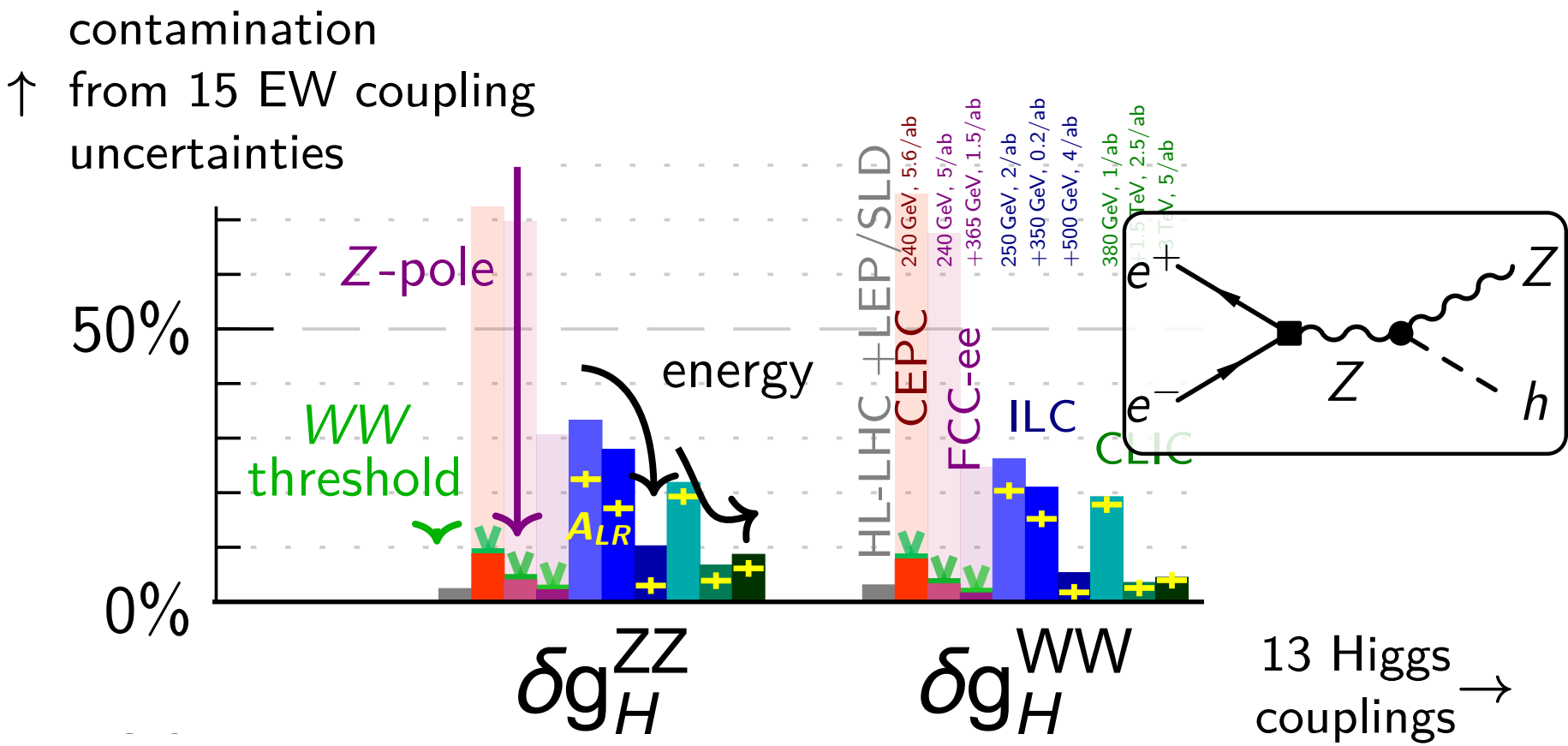
  [GD, Grojean, Gu, Wang '17]





Higgs-EW interplay

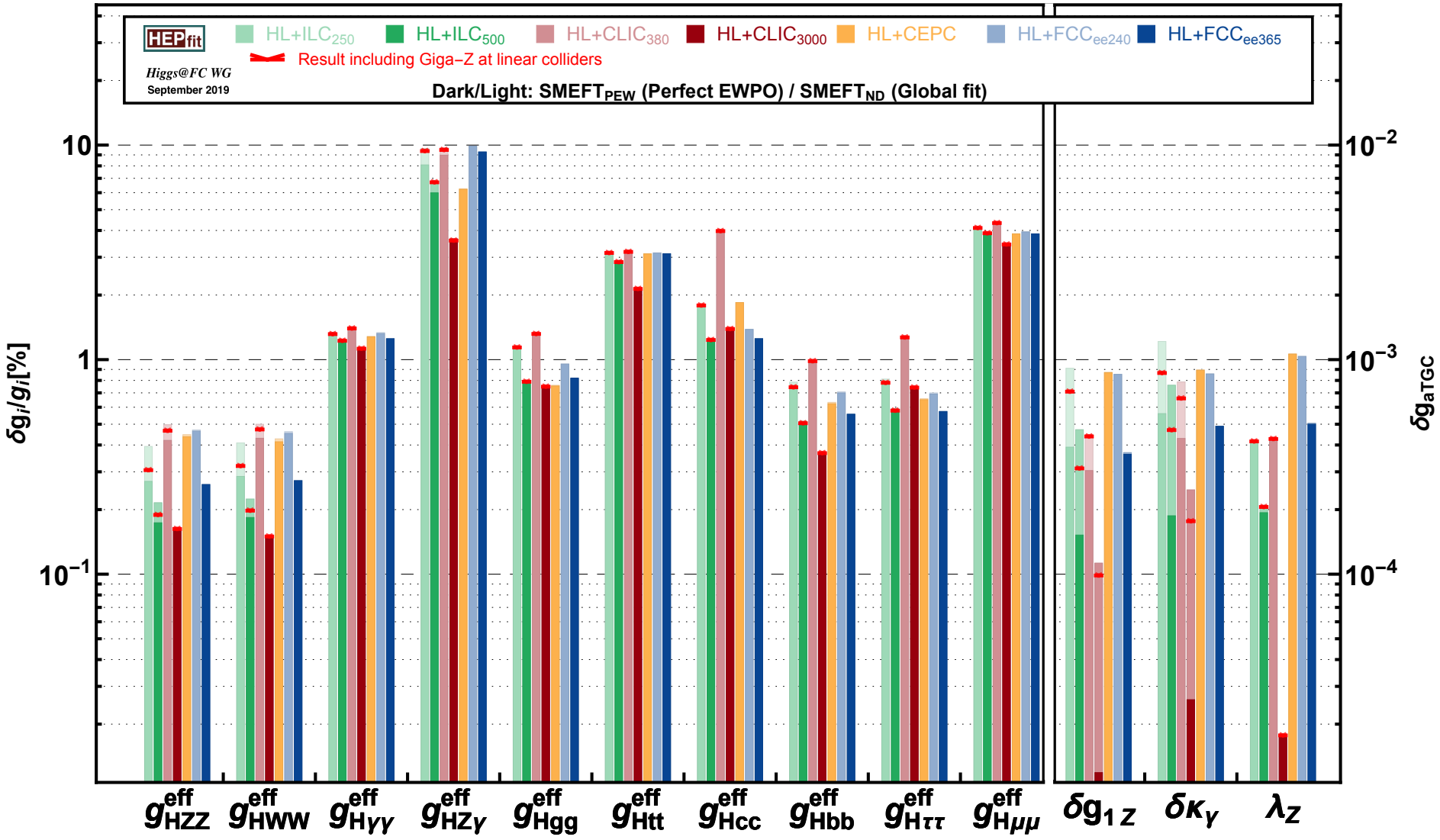
[de Blas, GD, Grojean, Gu, Paul '19]



New EW measurements required for Higgs precision.

Higgs-EW interplay

[de Blas et al '19]
[Higgs@FC '19]



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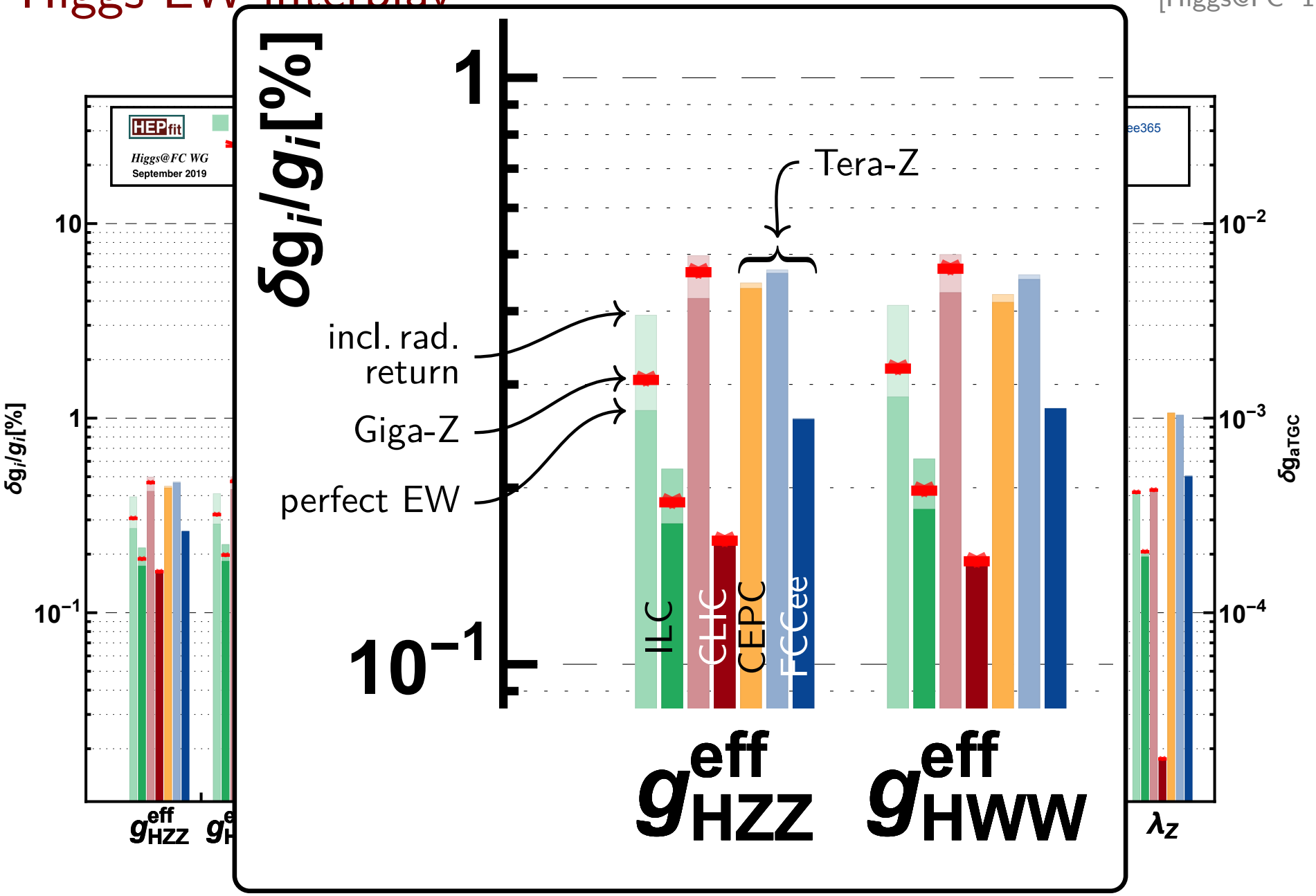
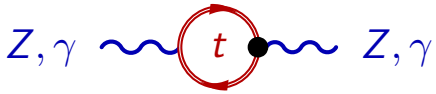


Higgs-top interplay

[Vryonidou, Zhang '18; + GD, Gu '18]
[Jung, Lee, Perelló, Tian, Vos '20]

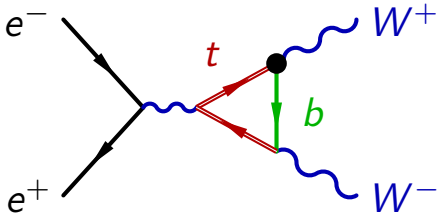
EWPO

[Zhang, Greiner, Willenbrock '12]



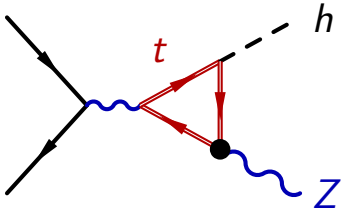
Diboson

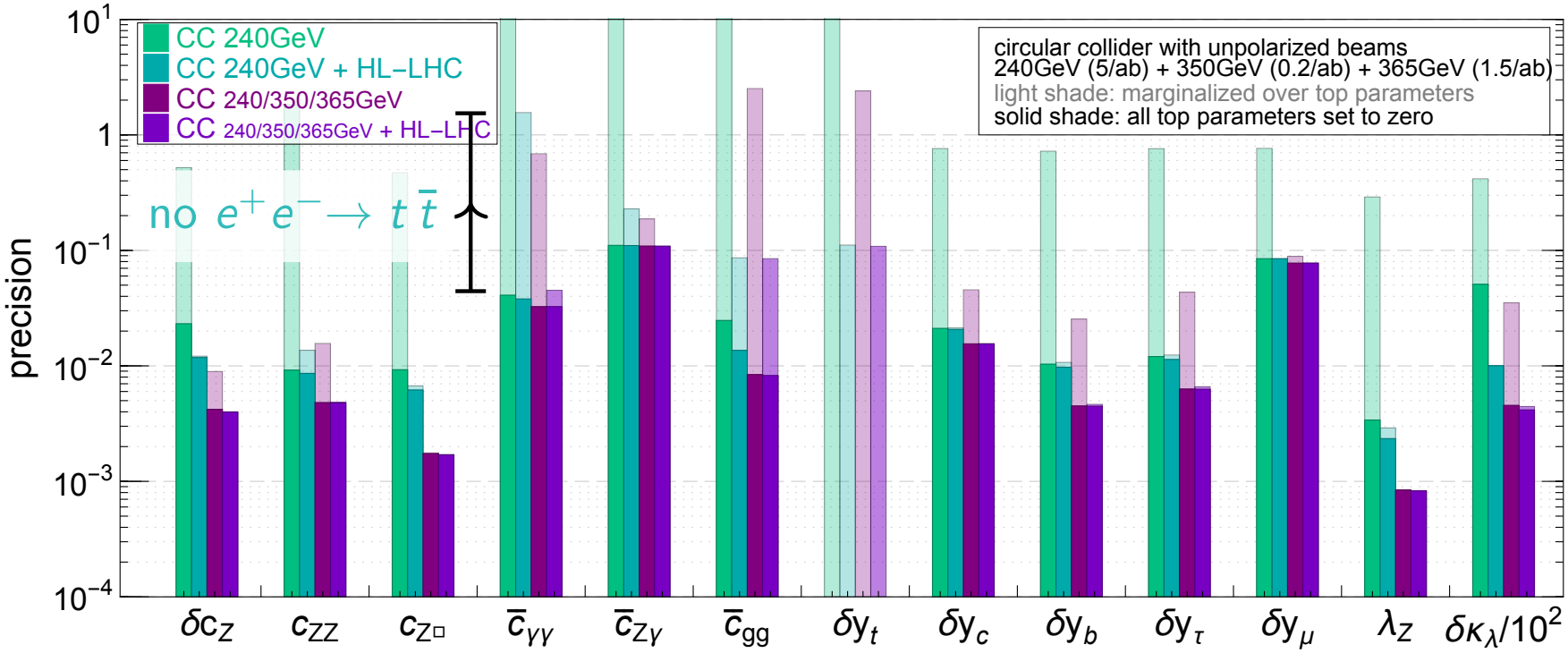
[GD, Gu, Vrionidou, Zhang '18]



Higgs

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



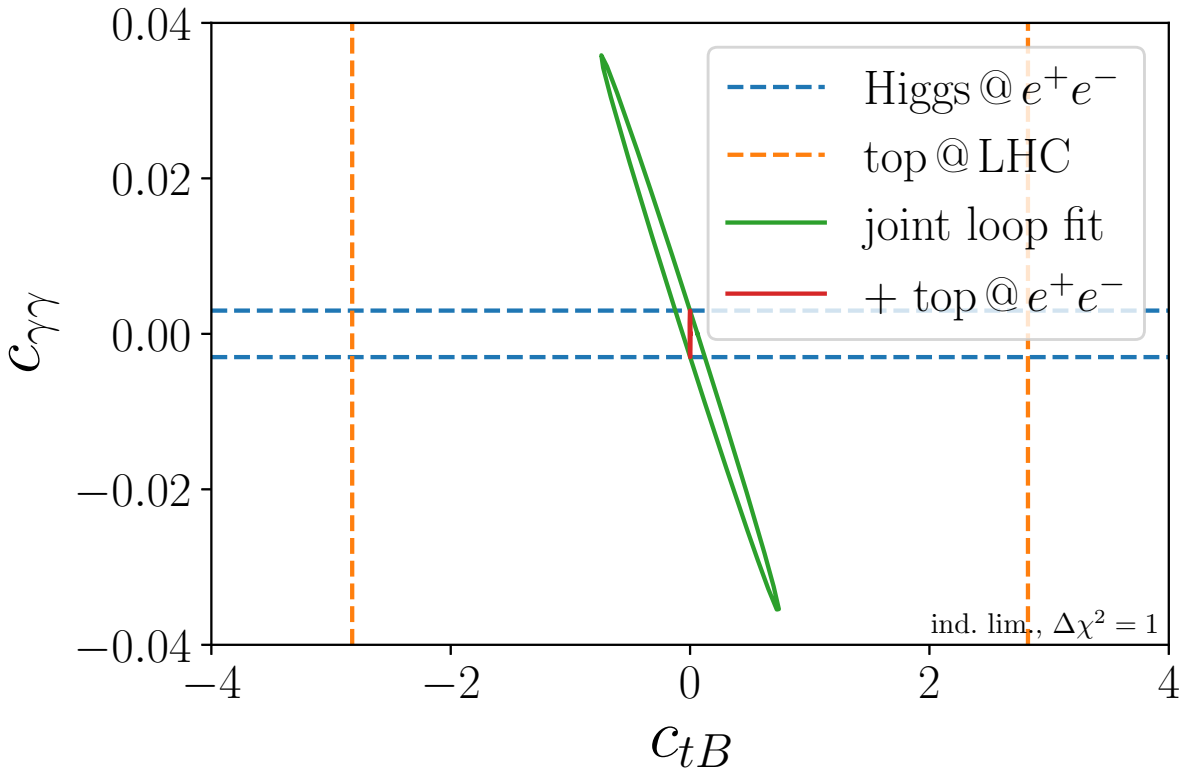


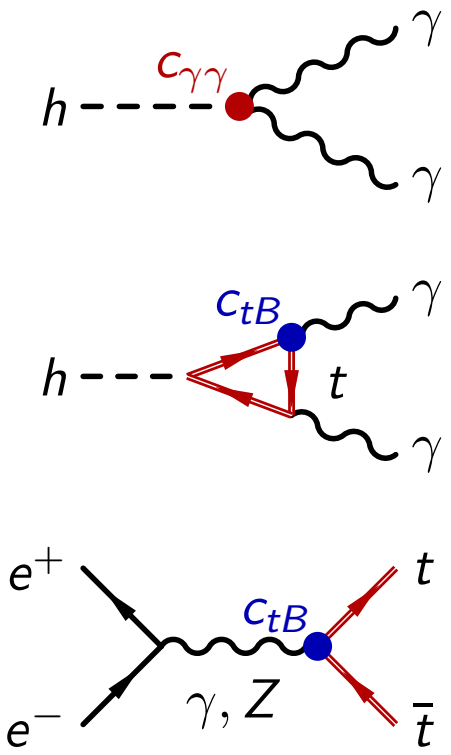
Top-quark uncertainties can impede Higgs precision!

$e^+e^- \to t\,\bar{t}$ measurements required at two c.o.m. energies!

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^-.

Theory predictions

SMEFT at one loop

- $pp \to jj$ ($q\bar{q}q\bar{q}$) [Gao, Li, Wang, Zhu, Yuan '11]
- $pp \to t\bar{t}$ ($q\bar{q}t\bar{t}$) [Shao, Li, Wang, Gao, Zhang, Zhu '11]
- $pp \to VV$ [Dixon, Kunszt, Signer '99] [Melia, Nason, Röntsch, Zanderighi '11] [Baglio, Dawson, Lewis '17, '18, '19] [Chiesa, Denner, Lang '18]
- EWPO (top) [Zhang, Greiner, Willenbrock '12]
- top decays [Zhang '14] [Boughezal, Chen, Petriello, Wiegand '19]
- top FCNCs UFO [Degrande, Maltoni, Wang, Zhang '14] [GD, Maltoni, Zhang '14]
- $pp \to t\bar{t}$ (chromo-dipole) [Franzosi, Zhang '15]
- $h \to \gamma\gamma$, VV, γZ [Hartmann, Trott '15] [Ghezzi, Gomez-Ambrosio, Passarino, Uccirati '15] [Dawson, Giardino '18] [Dedes, Paraskevas, Rosiek, Suxho, Trifyllis '18] [Dawson, Giardino '18] [Dedes, Suxho, Trifyllis '19]
- $h \to f\bar{f}$ [Gauld, Pecjak, Scott '15, '16] [Cullen, Pecjak, Scott '19, '20]
- $pp \to tj$ [Zhang '16] [de Beurs, Laenen, Vreeswijk, Vryonidou '18]
- $pp \to t\bar{t}Z$, $gg \to ZH$ [Röntsch, Markus Schulze '14] [Bylund, Maltoni, Vryonidou, Zhang '16]
- $pp \to t\bar{t}H$, $gg \to Hj, HH$ [Maltoni, Vryonidou, Zhang '16]
- $pp \to HV$ [Degrande, Fuks, Mawatari, Mimasu, Sanz '16] [Alioli, Dekens, Girard, Mereghetti '18]
- Z, W poles [Hartmann, Shepherd, Trott '16] [Dawson, Ismail, Giardino '18, '18, '19]
- $pp \to h$ [Grazzini, Ilnicka, Spira, Wiesemann '16] [Deutschmann, Duhr, Maltoni, Vryonidou '17]
- $pp \to tjZ, tjh$ [Degrande, Maltoni, Mimasu, Vryonidou, Zhang '18]
- $pp \to$ jets (triple gluon) UFO [Hirshi, Maltoni, Tsinikos, Vryonidou '18]
- Higgs self-coupling [McCullough '13] [Gorbahn, Haisch '16] [Degrassi et al. '16, '17] [Bizon et al. '16] [Kribs et al. '16] [Maltoni, Pagani, Shivaji, Zhao '17] [Di Vita, GD, Grojean, Gu, Liu, Panico, Riembau, Vantalon '17]
- EW Higgs & WW (top) [Vryonidou, Zhang '18] [GD, Gu, Vryonidou, Zhang '18] [Boselli, Hunter, Mitov '18]
- EW $pp \to t\bar{t}$ (ttZ,tth) [Martini, Schulze '19] [Martini, Pan, Schulze, Xiao '21]
- all QCD and four-quarks UFO [Degrande, GD, Maltoni, Mimasu, Vryonidou, Zhang '20]
- EW $pp \to \ell^+\ell^-$ [Dawson, Giardino '21, '22]
- EW $QQQQ$ in $gg \to h$, $h \to bb$, $pp \to tth$ [Alasfar, de Blas, Gröber '22]

SM at two-loop and beyond

[Freitas, Heinemeyer, et al. '19]

- 2-loop ZH needed for $< 1\%$ unc. and possibly achievable
- Partial 2-loop VBF possibly achievable and sufficient
- Off-shell WW production at 2-loop requiring significant effort
- Factorisable NNLO QCD to $H \to VV^* \to 4f$ decay achievable
- $\mathrm{N^4LO}$ $H \to gg$ and m_b dependence at $\mathrm{N^3LO}$ needed for $< 1\%$ unc. and possibly reachable

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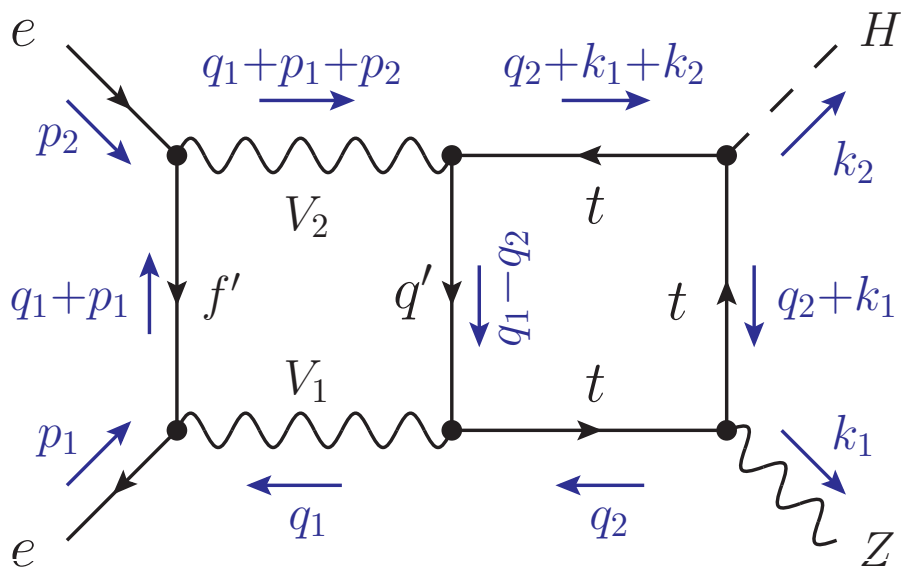
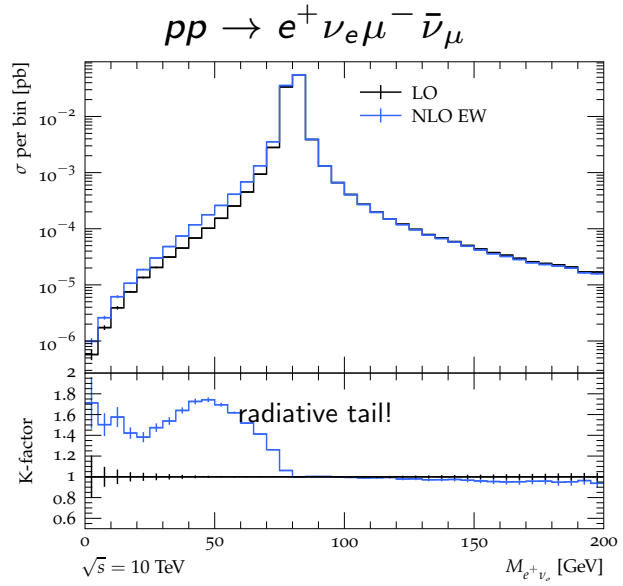


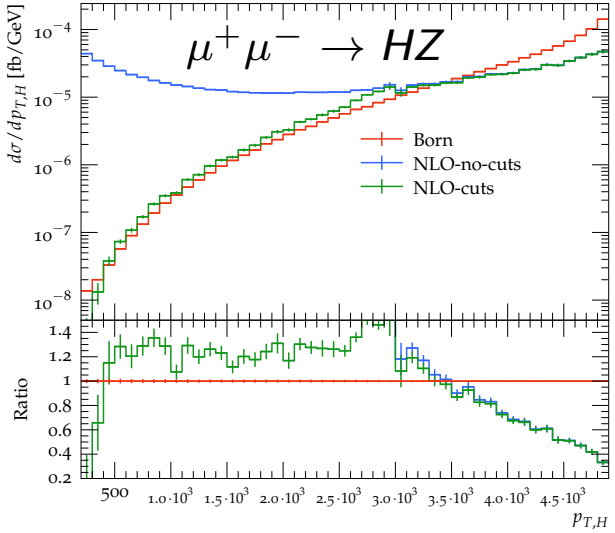
[Song, Freitas '21]

Whizard

[Stienemeier, March '21]

- UFO support for BSM completed
- ISR & beamsstrahlung,
  also for polarized beams
- automated NLO QCD
  (FKS subtraction, resonance aware)
- Powheg matching to Pythia8 shower
- NLO EW developments ongoing
  implementing NLL electron PDFs



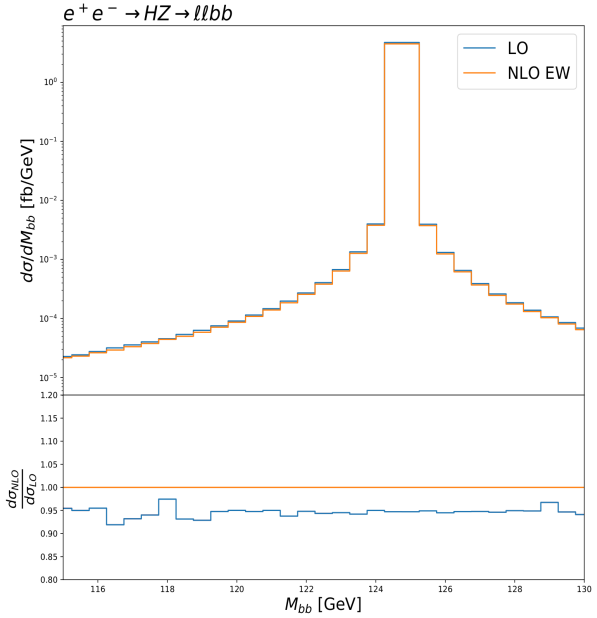


[Bredt et al. '22]

[Frixione et al. '19, '19]

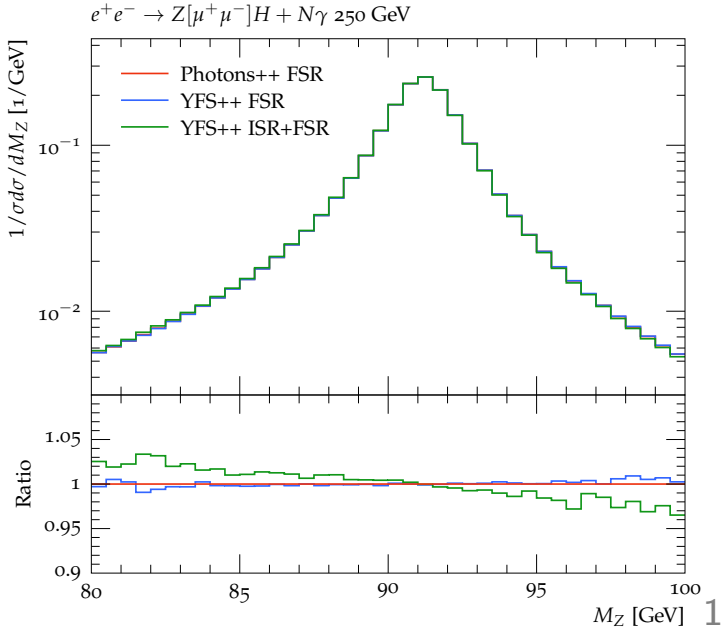
Sherpa

[Price, March '21]



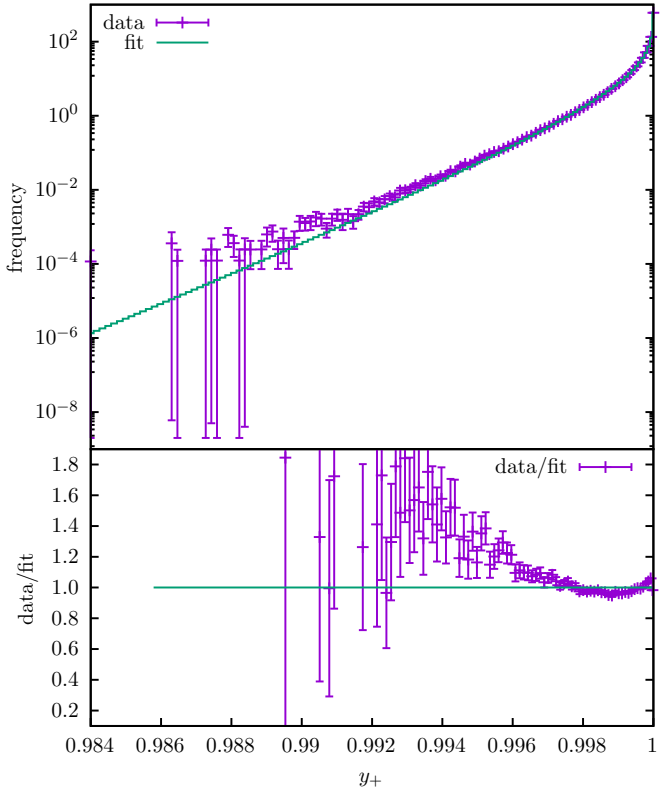
- UFO support for BSM
- automated NLO QCD and EW (CS subtraction)
- mc@nlo matching to parton shower
- YFS resummation of soft&collinear photons
  - to be matched to NLO EW
  - ISR/FSR interference planned
- Beamsstrahlung being implemented
- Underlying events (e.g. $\gamma\gamma$) planned

[Krauss, Price, Schönherr '22]



MadGraph

- UFO support for BSM (also at NLO)
- automated NLO QCD and EW (FKS, resonance aware)
- mc@nlo matching to parton shower
- ISR and beamsstrahlung (from v3.2.0)
  - for unpolarised beams
  - no spread above partonic beam energy
- NLL electron PDFs
  - computed for unpolarised beams
  - NLO EW being finalised



[Frixione, Mattelaer, Zaro, Zhao '21]

[Bertone, Cacciari, Frixione, Stagnitto '19, '19]

Higgs at future lepton colliders

After a decade of measurements,
the nature of the Higgs keeps puzzling theorists.

Future lepton colliders would bring an order of magnitude
improvement on Higgs coupling precision.

The Higgs precision programme requires
diboson, electroweak, and top-quark measurements.

SM(EFT) loops become very relevant.

Not covered: exciting challenges and reach of a muon collider.