Interplay between Higgs and top-quark loops in $e^+e^- \to hZ$

Gauthier Durieux
(CP3 – UCLouvain)

Bottom line: The sizeable uncertainties resulting from top-quark couplings in the trilinear extraction are mitigated by $pp \to t\bar{t}h$ measurements.
More differential $e^+e^- \to hZ$ measurements could maybe be investigated too.

Probing top-quark couplings indirectly at Higgs factories,
GD, J.Gu, E.Vryonidou, C.Zhang,
Chin.Phys.C 42 (2018) 123107, [1809.03520]

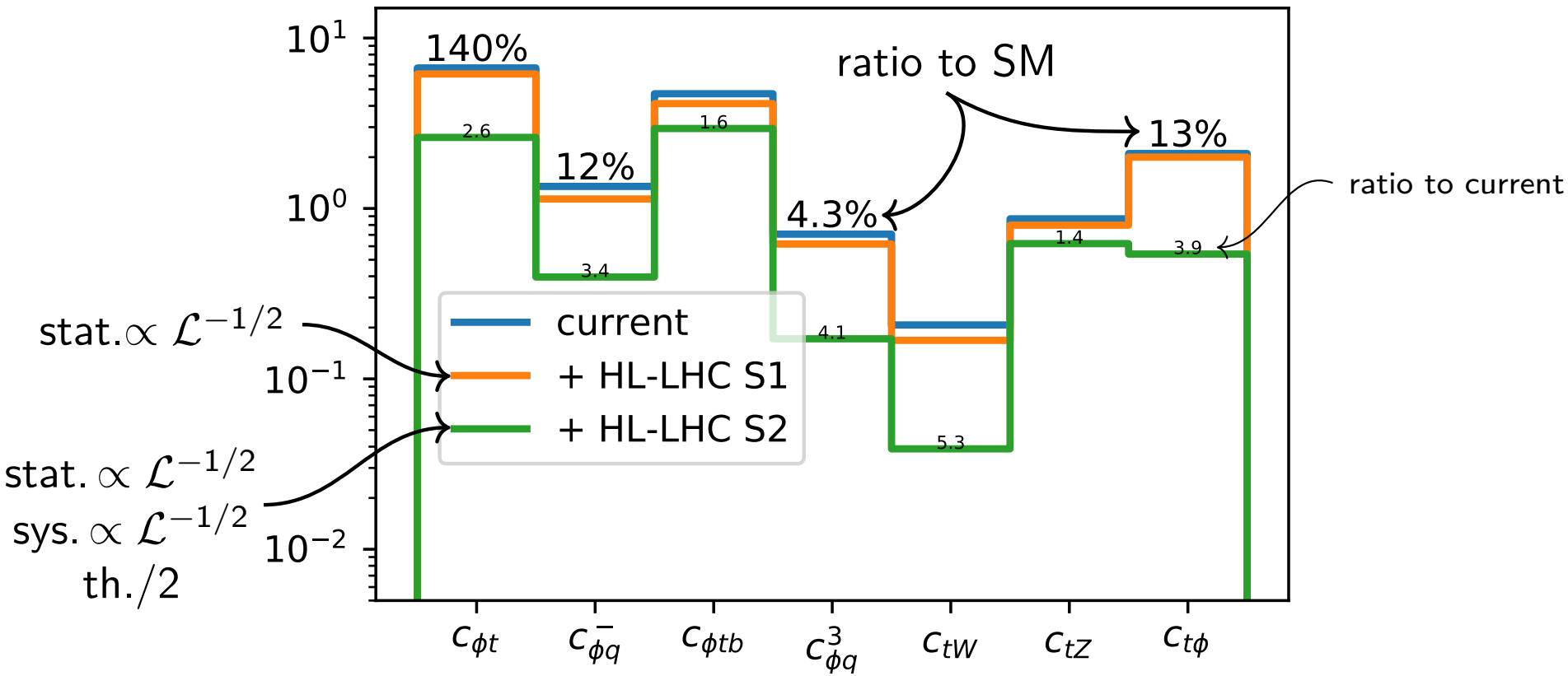
ECFA mini-workshop – Higgs self-coupling – 15 May 2024

Top-quark electroweak couplings

In proton collisions

[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

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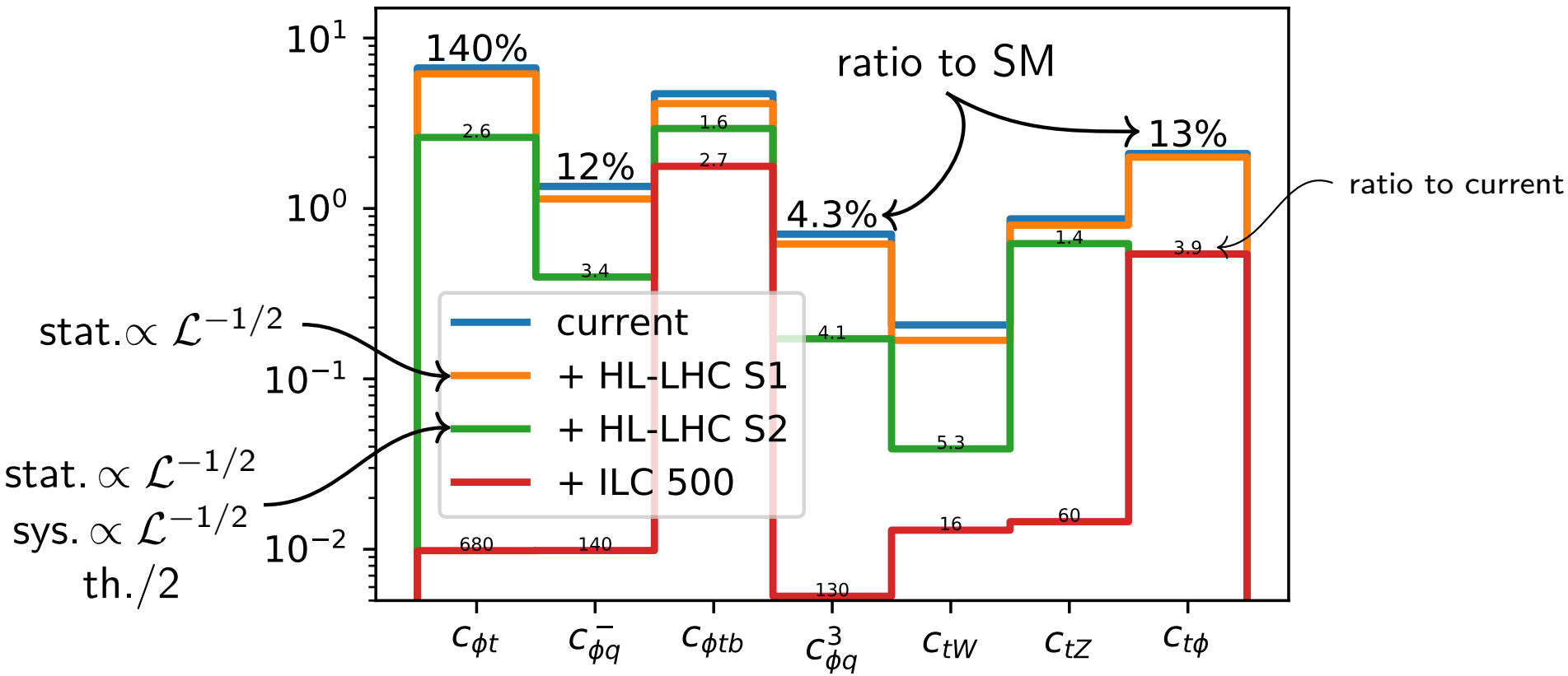


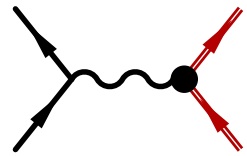
systematics limited

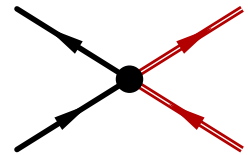
$\sim$ 10% precision

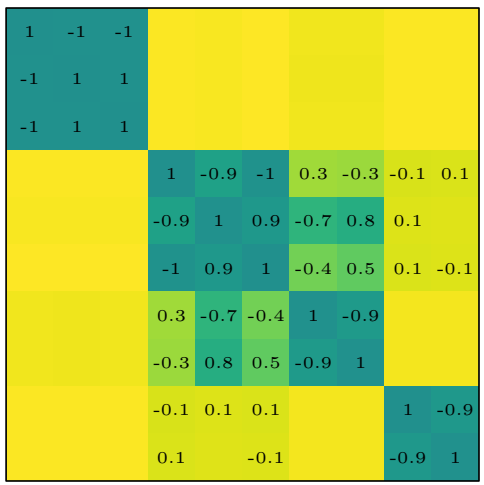
In lepton collisions, above 350 GeV

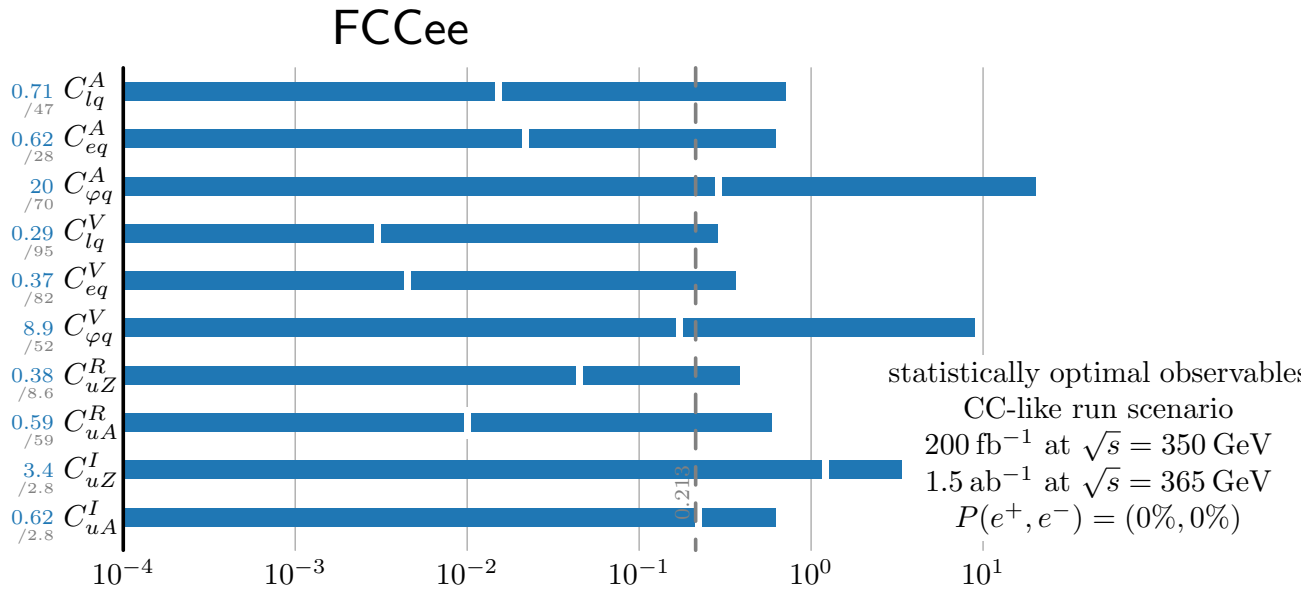
[GD, Perelló, Vos, Zhang '18]
[CLICdp '18]
[see also Janot '15]

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

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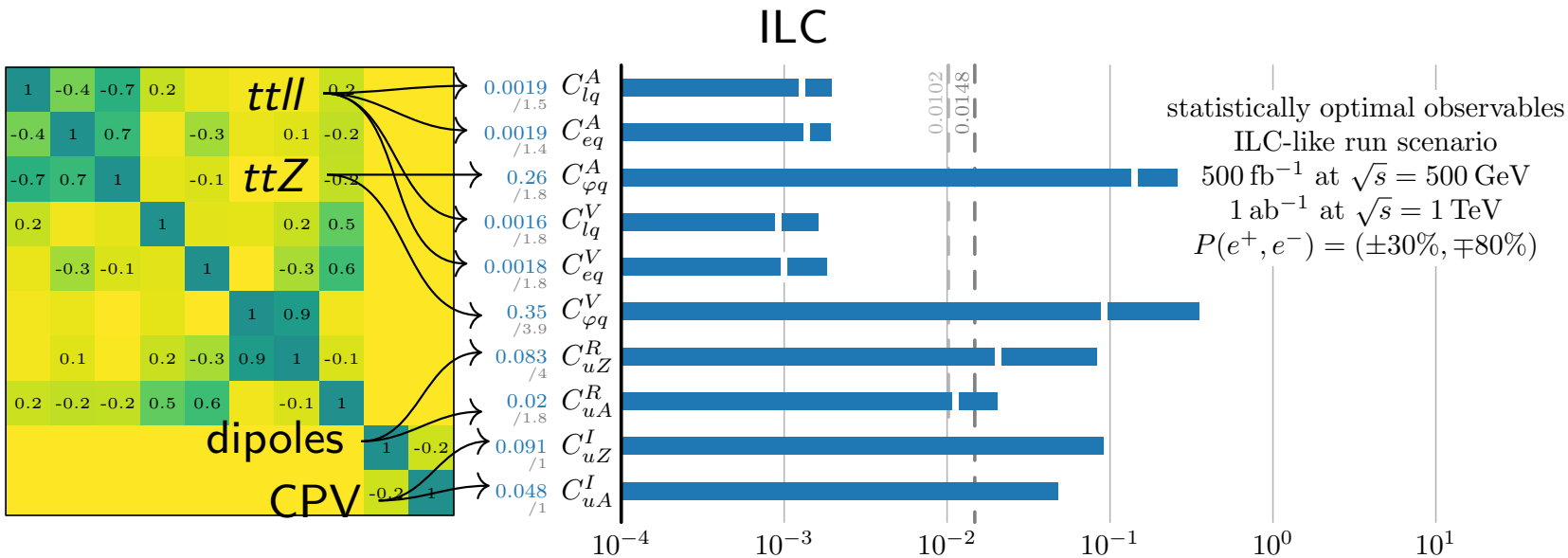

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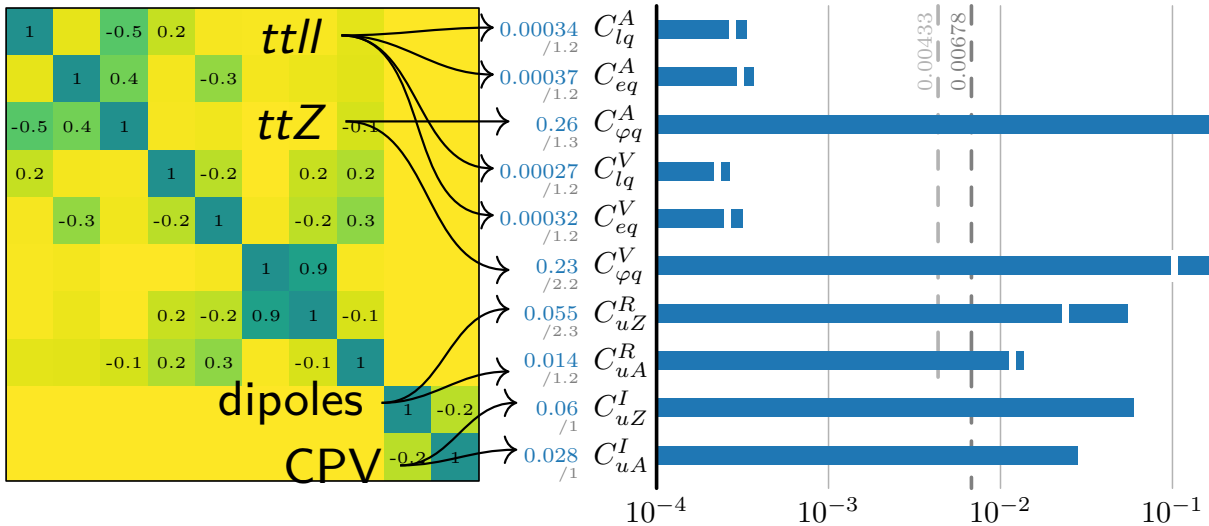
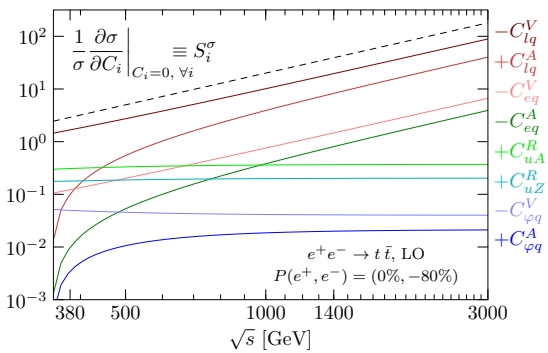


statistically optimal observables
CLIC-like run scenario
$500\,\text{fb}^{-1}$ at $\sqrt{s} = 380\,\text{GeV}$
$1.5\,\text{ab}^{-1}$ at $\sqrt{s} = 1.4\,\text{TeV}$
$3\,\text{ab}^{-1}$ at $\sqrt{s} = 3\,\text{TeV}$
$P(e^+, e^-) = (0\%, \mp 80\%)$



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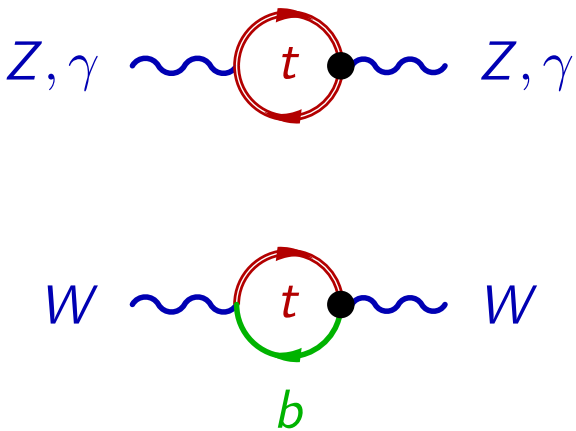
In lepton collisions, below 350 GeV

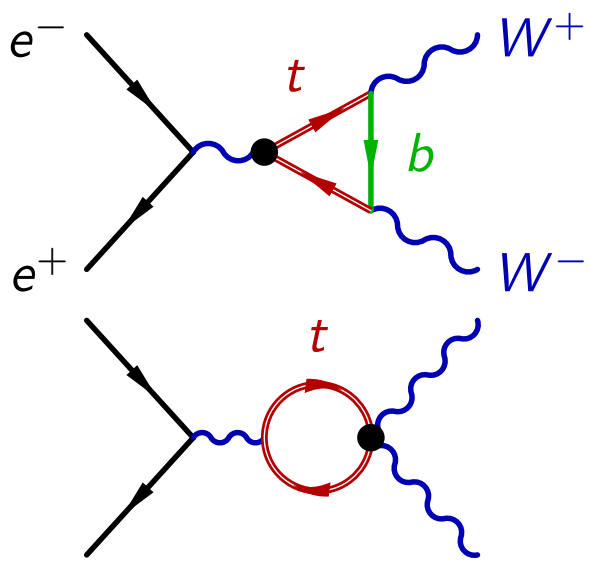
EWPO

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



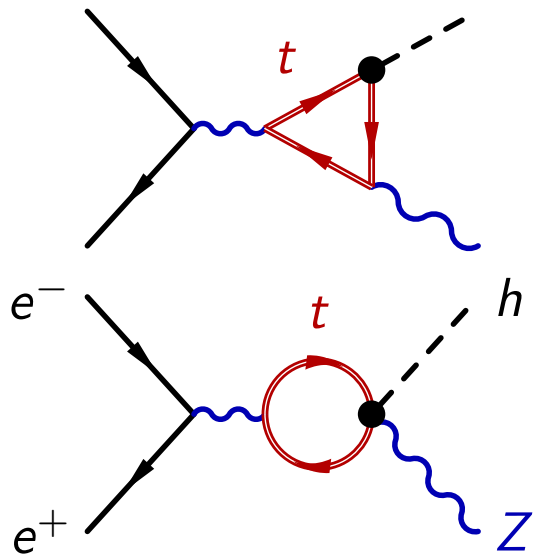
Diboson

[GD, Gu, Vrionidou, Zhang '18]



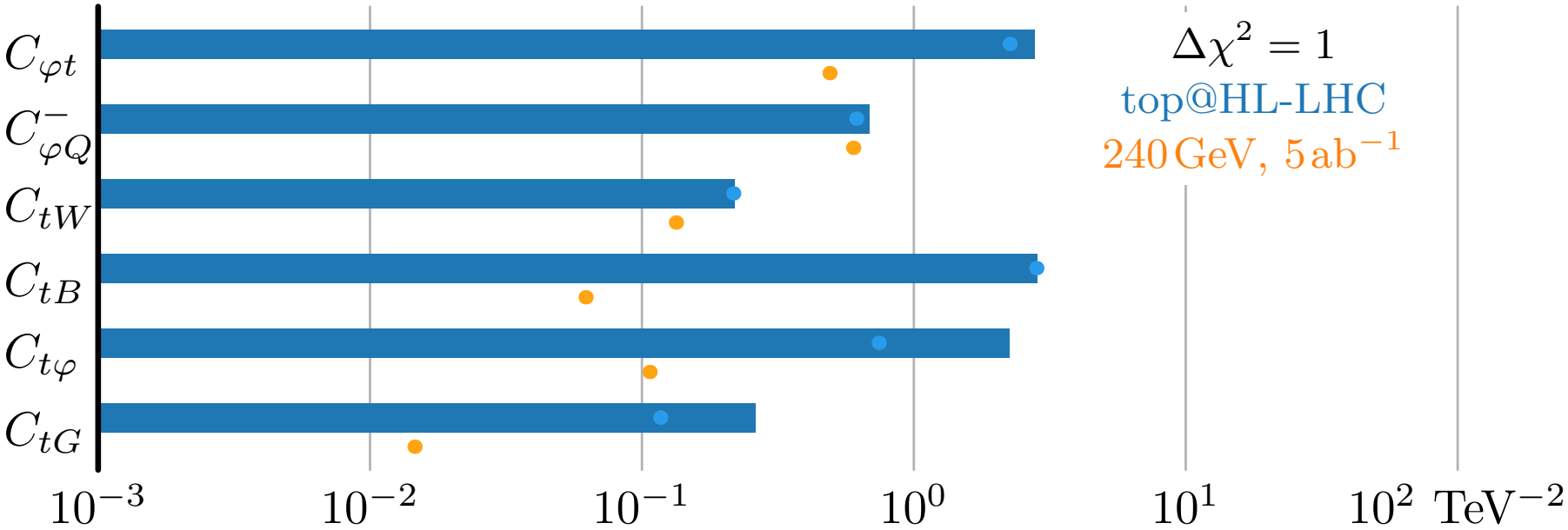
Higgs

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



Degeneracies

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



Individual constraints (blobs)

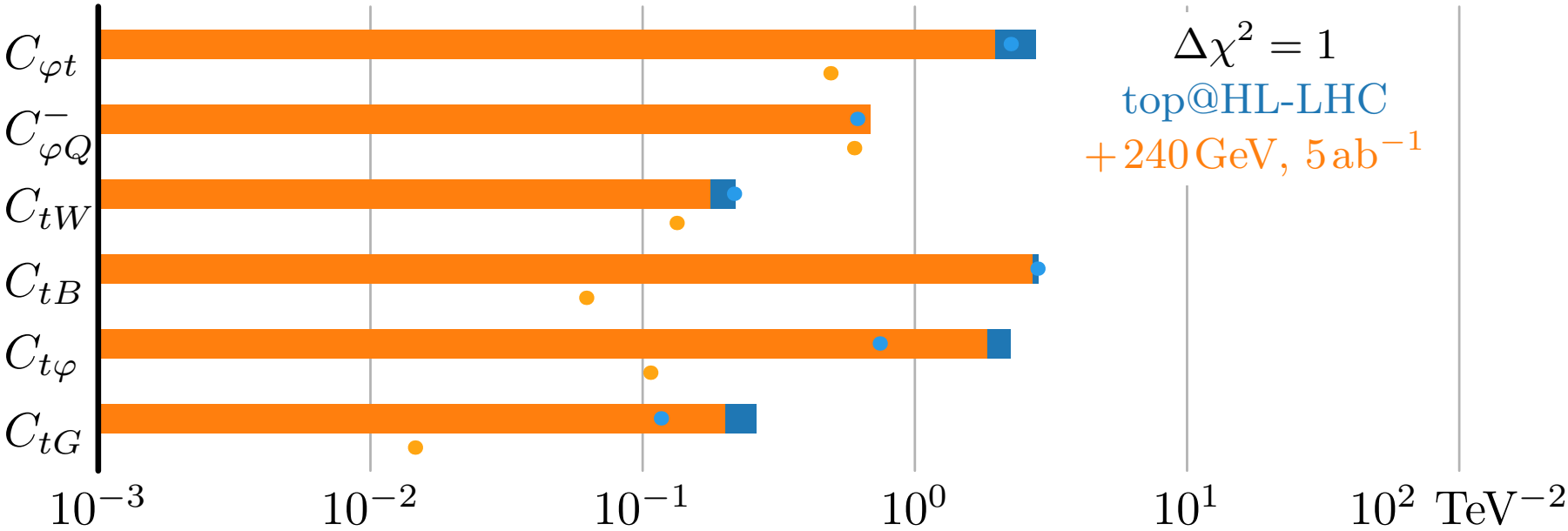
- competitive with the HL-LHC (e.g. on the top Yukawa $C_{t\varphi}$)
- dominated by Higgs measurements (diboson improves with energy)

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

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

Degeneracies

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



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Degeneracies

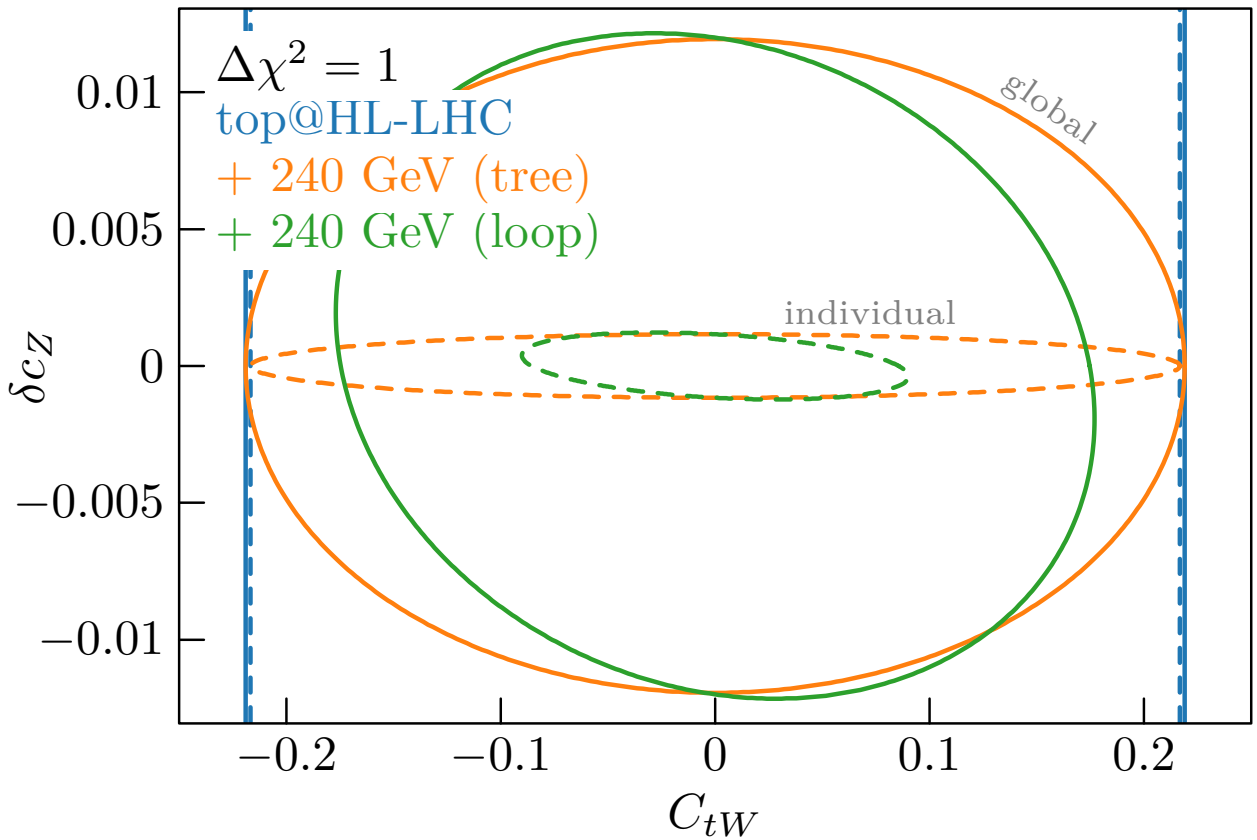
[GD, Gu, Vrionidou, Zhang '18]
[see also Jung, Lee, Perelló, Tian, Vos '20]

$C_{\varphi t}$
$C^{-}_{\varphi Q}$
C_{tW}
C_{tB}
$C_{t\varphi}$
C_{tG}

10^{-3}

TeV^{-2}

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



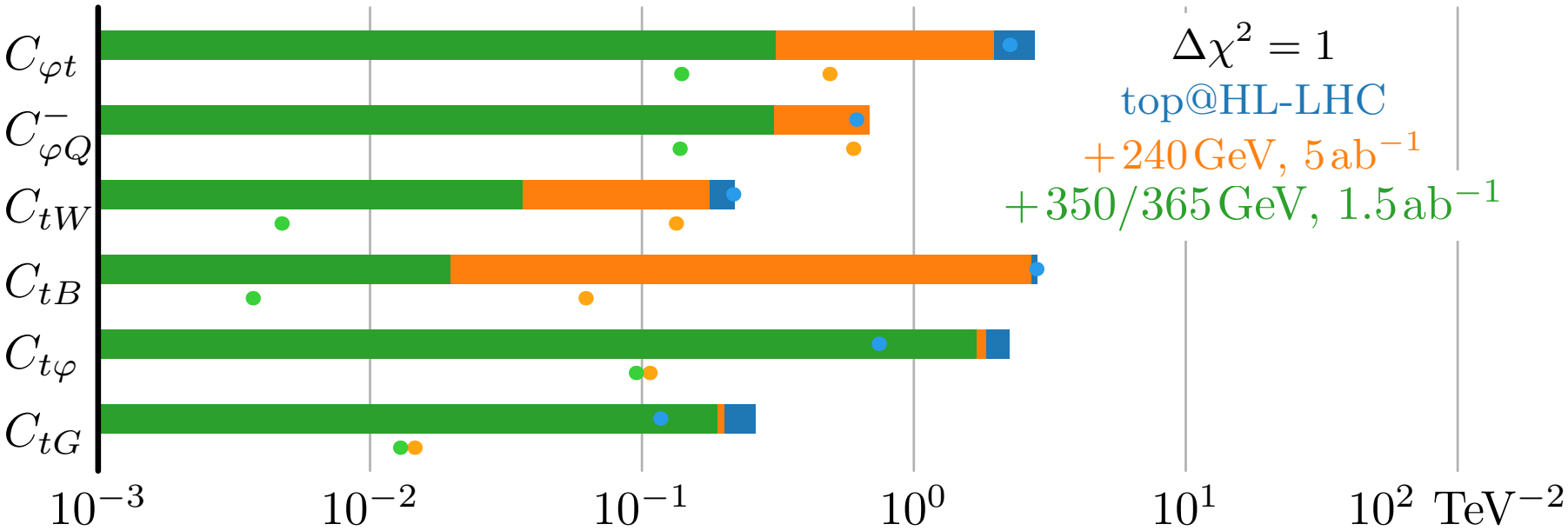
Individu
- com
- dom

Global c
- large
- still
- more differential distributions should help

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

Degeneracies

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



Individual constraints (blobs)

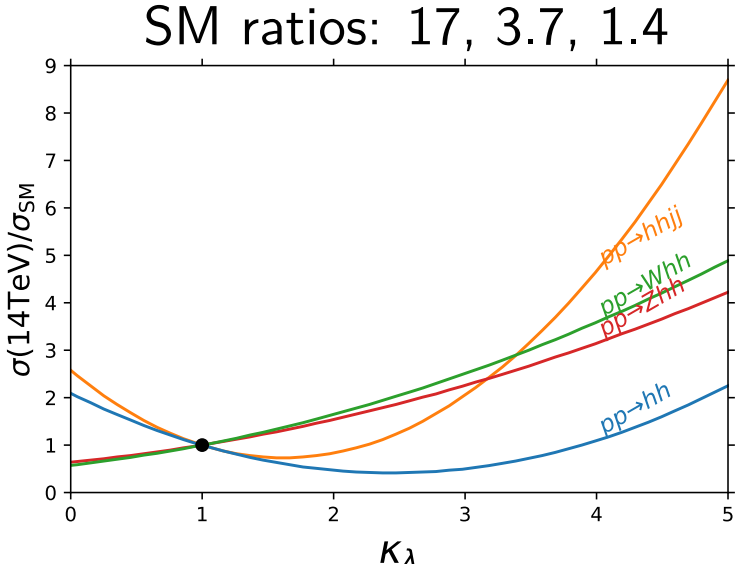
- competitive with the HL-LHC (e.g. on the top Yukawa $C_{t\varphi}$)
- dominated by Higgs measurements (diboson improves with energy)
- loops in $e^+e^- \to t\bar{t}$ would improve its impact on $C_{t\varphi}$ and C_{tG}

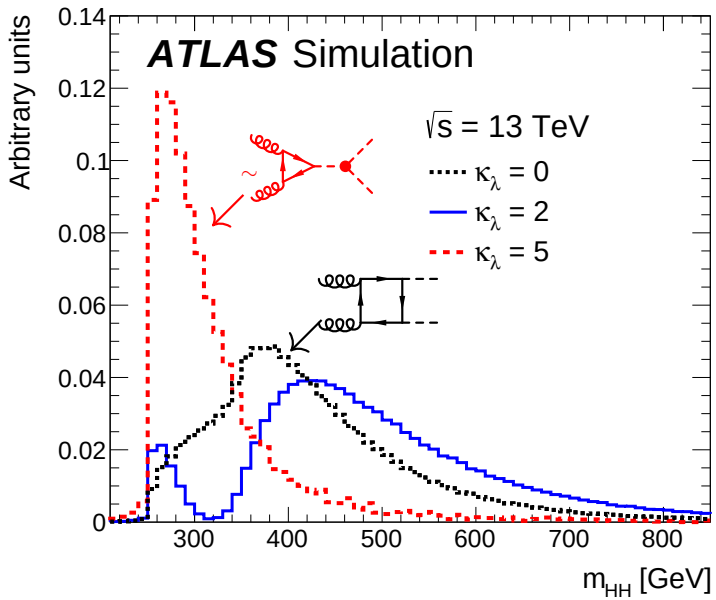
Global constraints (bars) (12 Higgs + 6 top op. floated)

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

Higgs trilinear self-coupling

In proton collisions





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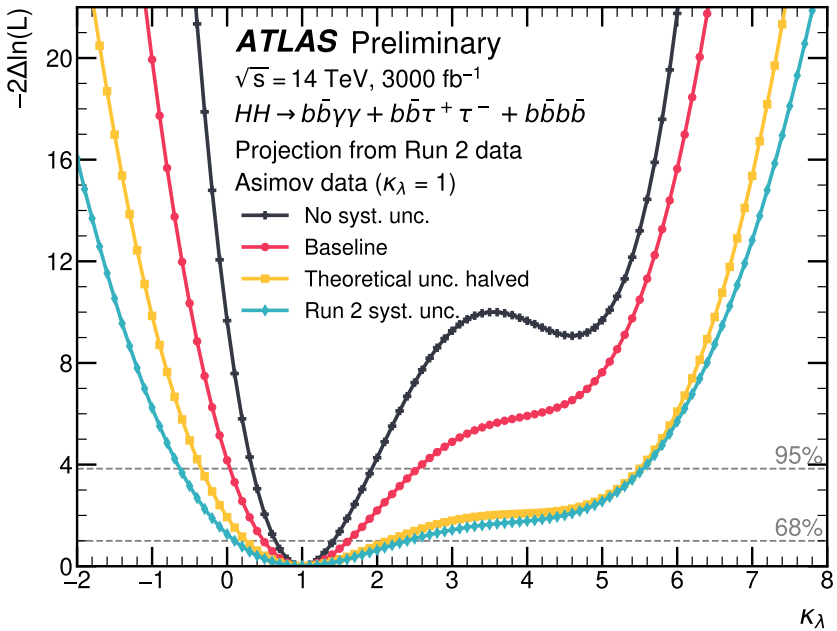
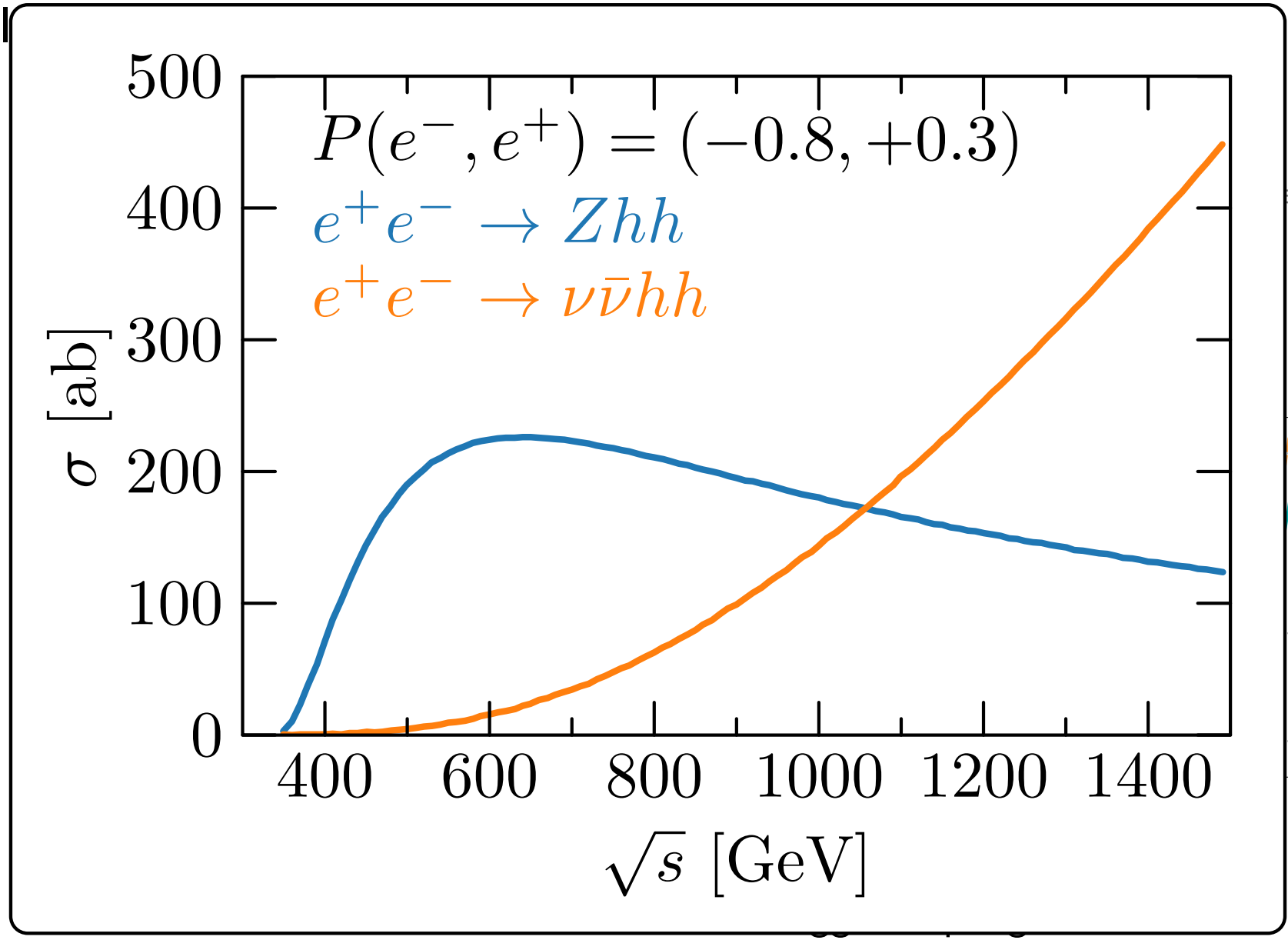


Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

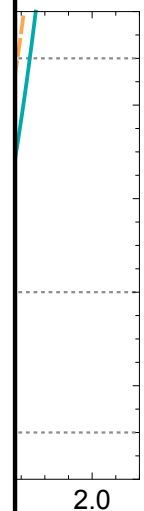
ATLAS [−0.4, 6.3] (obs)
run 2 [−1.9, 7.6] (exp)

In lepton collisions, above 500 GeV

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



et al. '13]



In lepton collisions, above 500 GeV

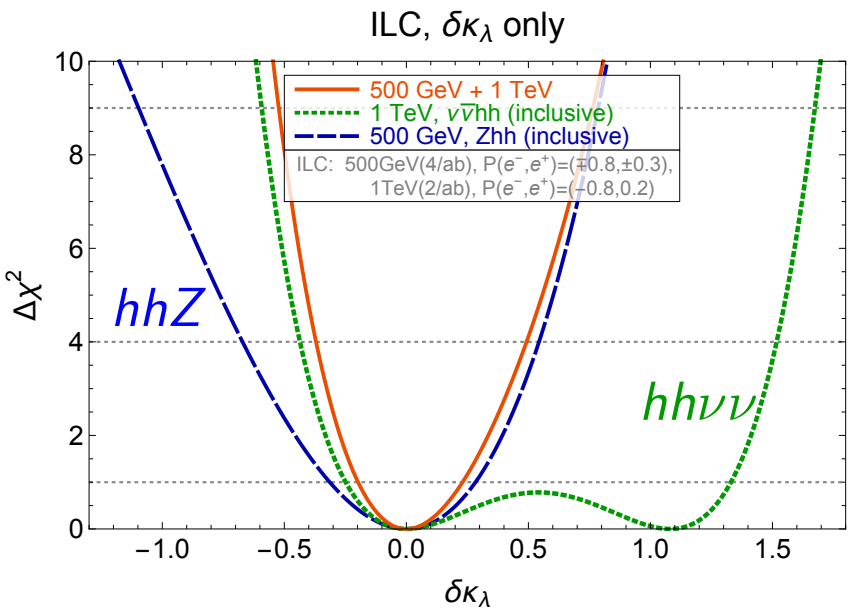
[Barklow et al. '17]
[Di Vita et al. '17]

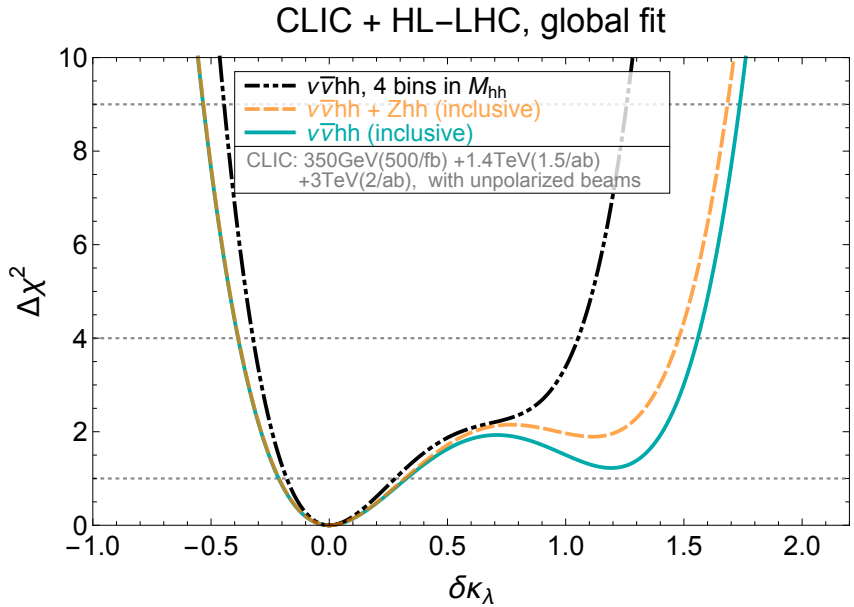
ILC

- perfect complementarity between 500 GeV and 1 TeV
- both individual and global 1σ sensitivity $\sim 20\%$

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 $\sim -20, +30\%$

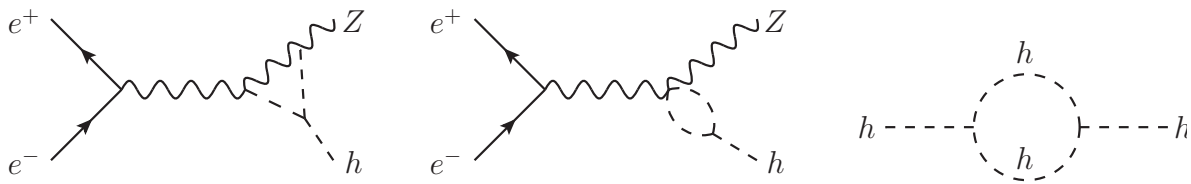




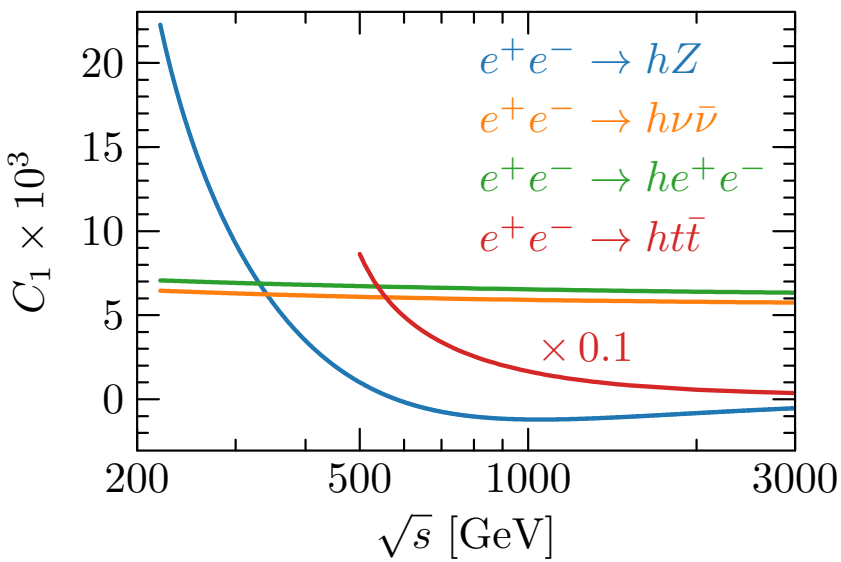
No contamination from other Higgs couplings

In lepton collisions, below 500 GeV

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



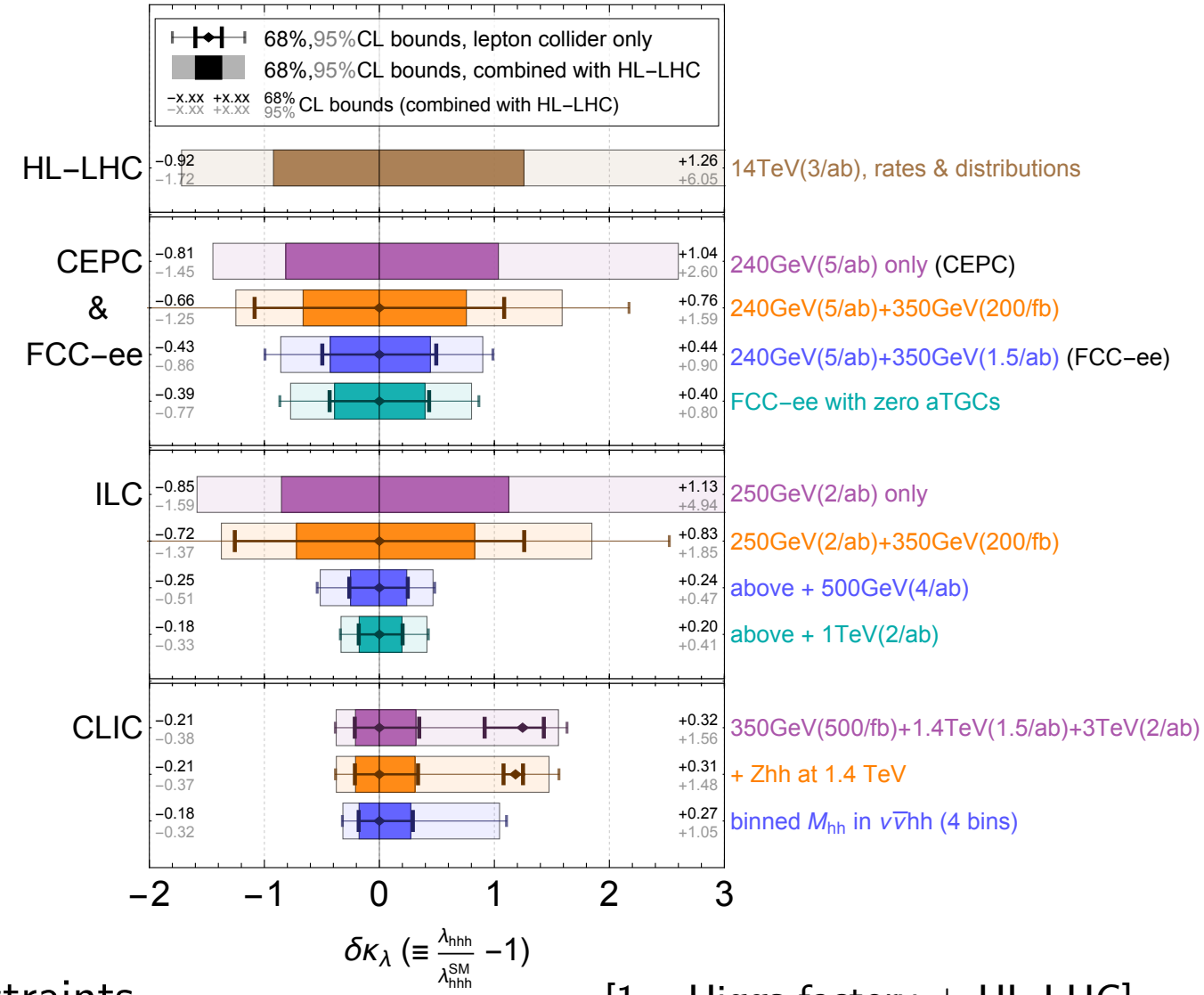
$$\Sigma_{\rm NLO}/\Sigma_{\rm NLO}^{\rm SM} \simeq 1 + (C_1 - 0.0031)\,\delta\kappa_\lambda + \ldots$$



[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]

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

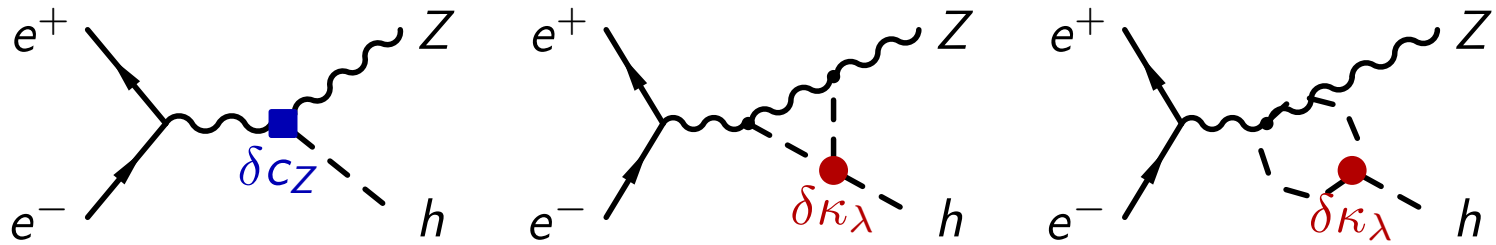
Trilinear prospects summary

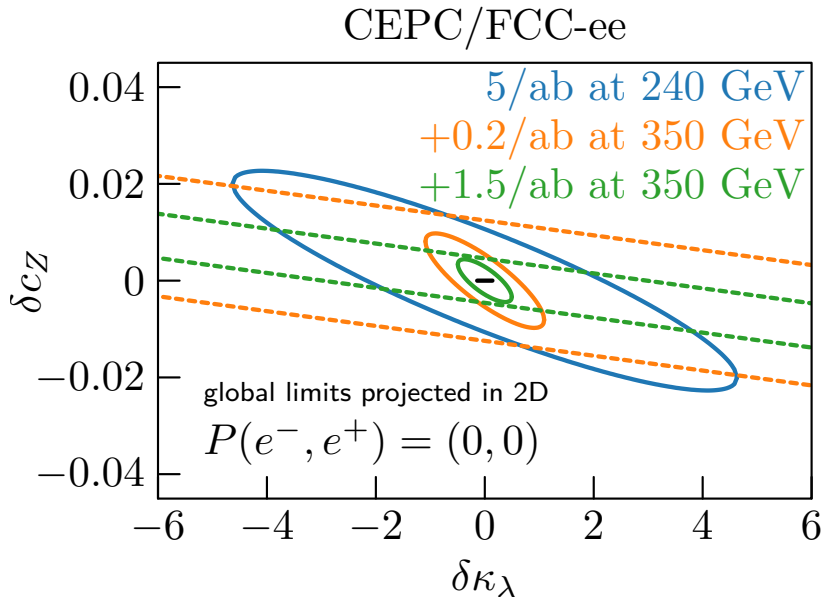


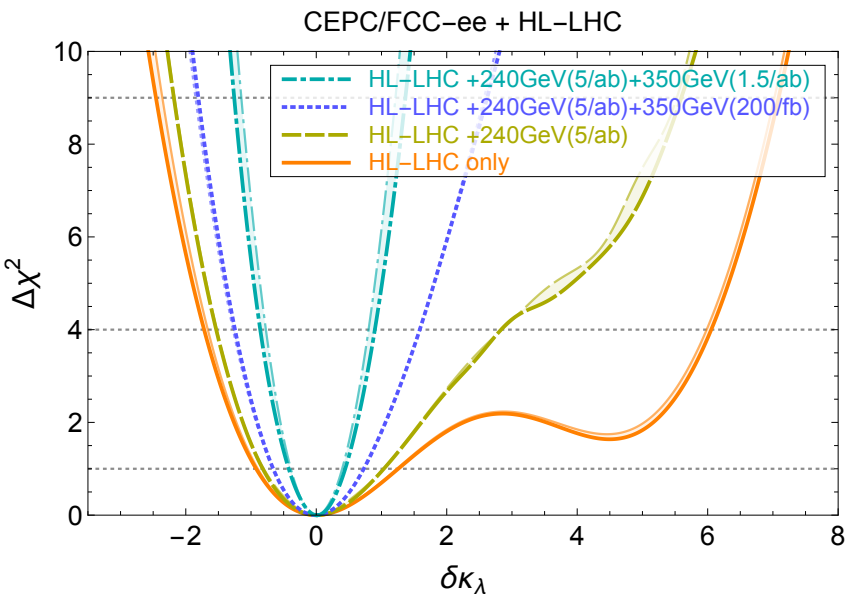
- indirect constraints [1σ, Higgs factory + HL-LHC]
  - $\sim 90\%$ with 240 GeV run only
  - $\sim 70\%$ with $0.2\,\text{ab}^{-1}$ at 350 GeV
  - $\sim 40\%$ with $1.5\,\text{ab}^{-1}$
- direct constraints are $\sim 20\%$

Degeneracies

[Di Vita et al. '17]







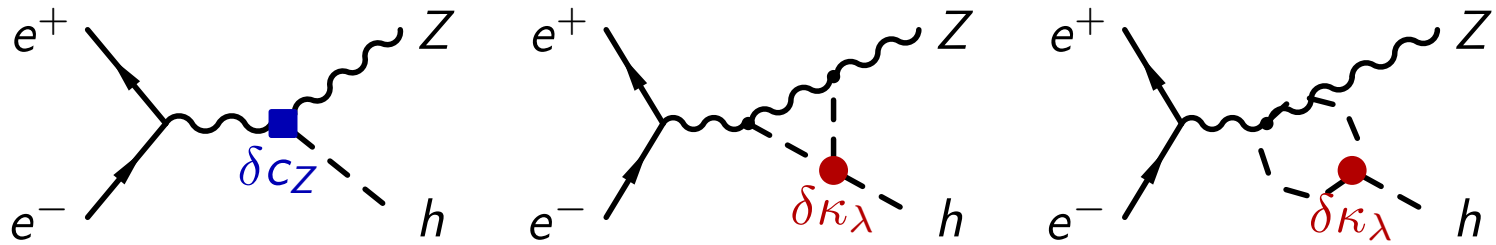
Correlations with single-Higgs couplings require two $\sqrt{s}$.

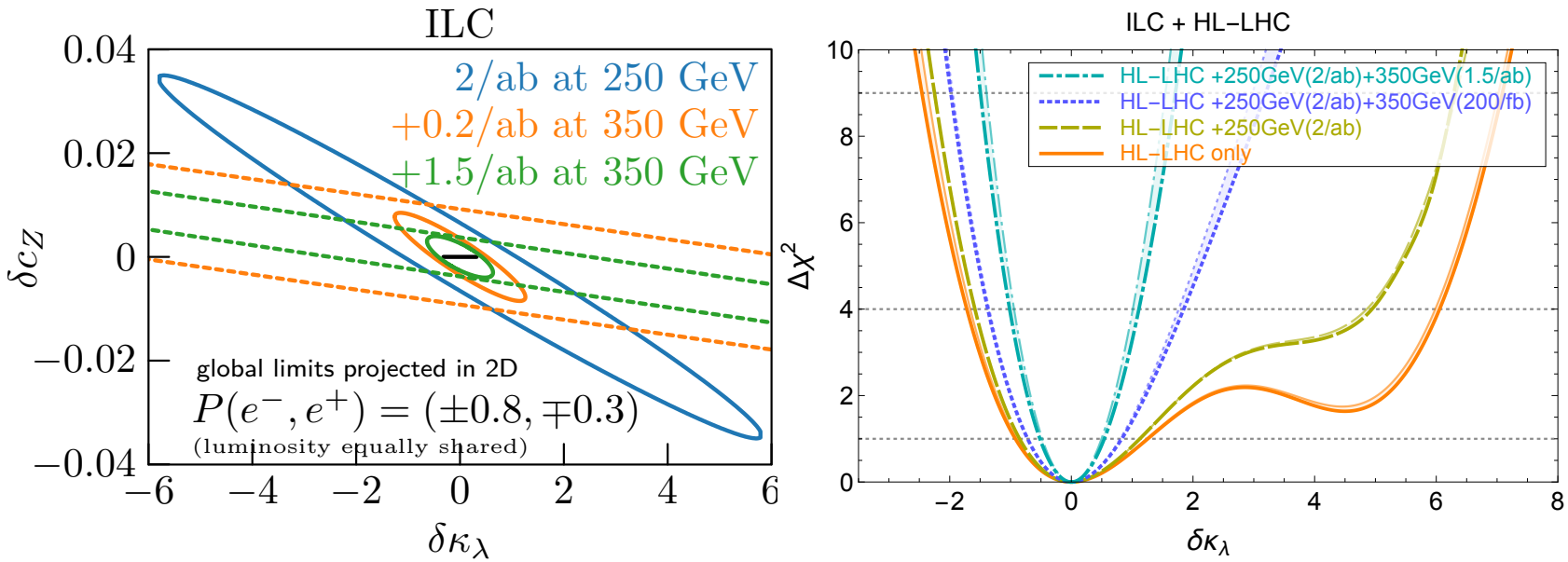
Individual 1σ limit (14%) much tighter than global ones (460, 110, 50%)

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

Degeneracies

[Di Vita et al. '17]





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

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

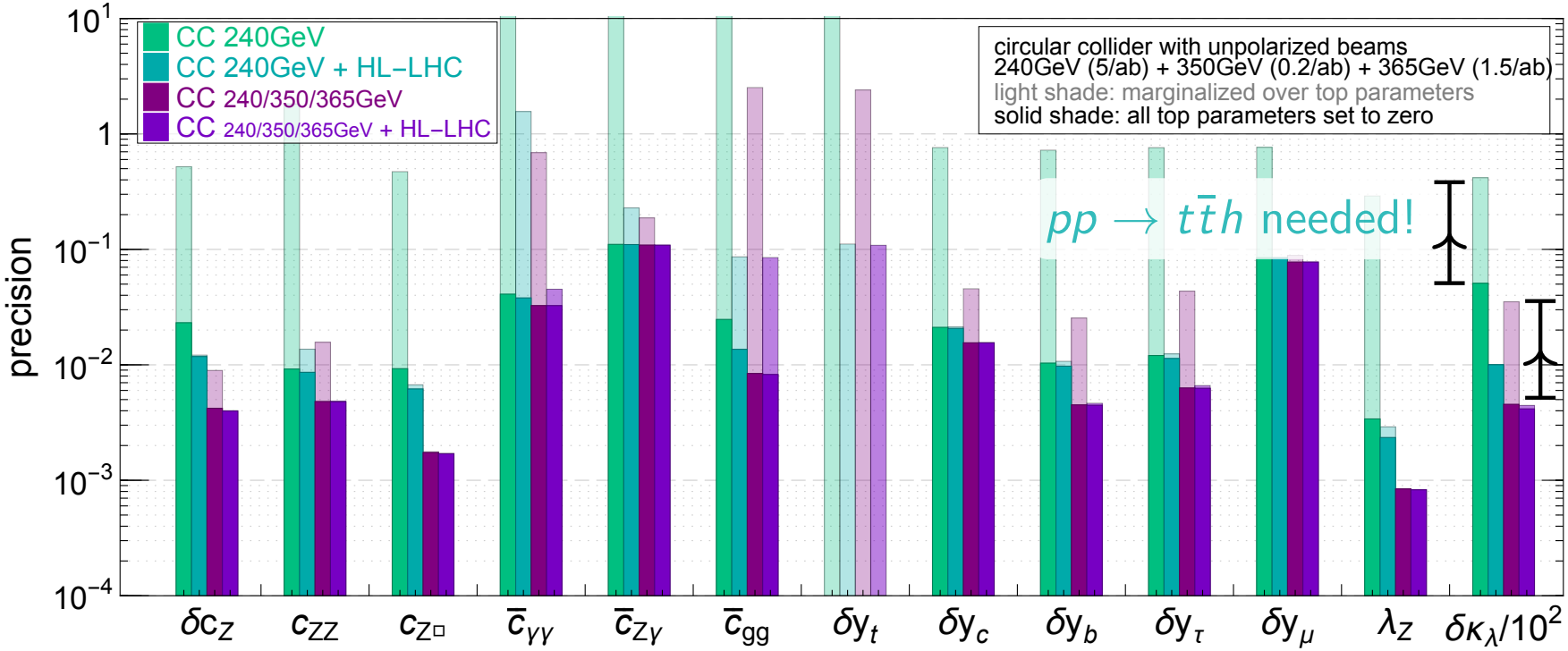
One energy point already help lifting secondary HL-LHC minimum.

Top and trilinear

Top and trilinear

[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. → 0



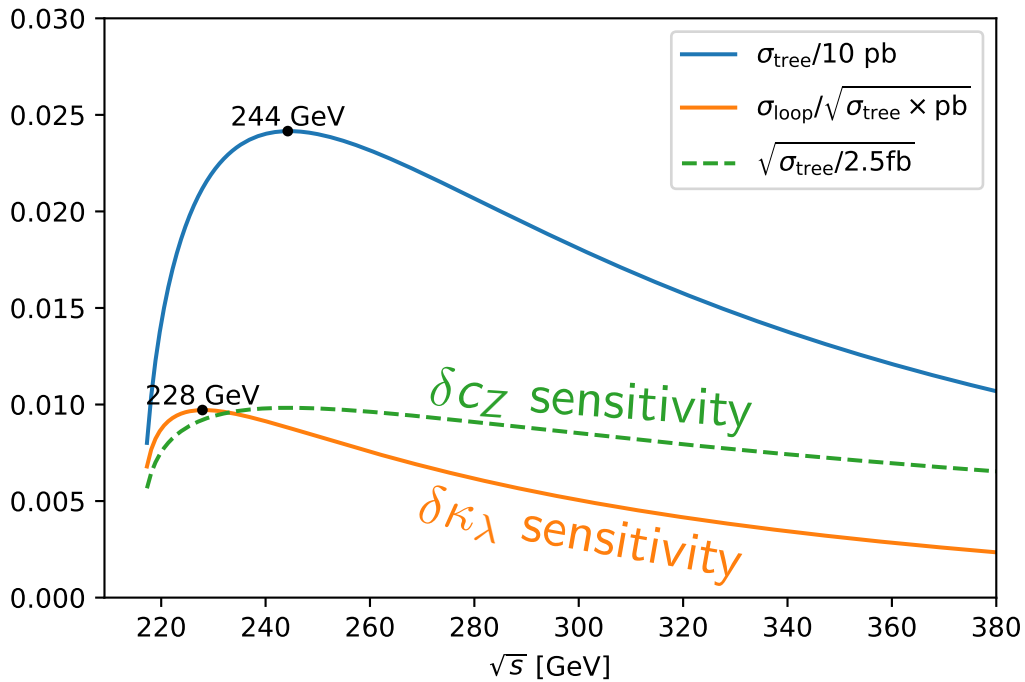
Uncertainties on the top have a big effect on the Higgs

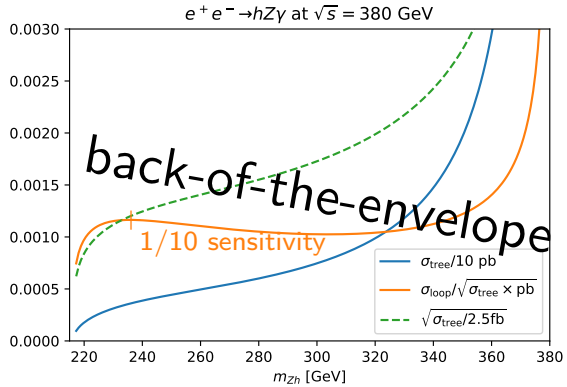
- Higgsstr. run: insufficient
- Higgsstr. run ⊕ top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma,gg,Z\gamma,ZZ}$
- Higgsstr. run ⊕ $e^+e^- \to t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run ⊕ $e^+e^- \to t\bar{t}$ ⊕ top@HL-LHC: top contam. in $\bar{c}_{gg}$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

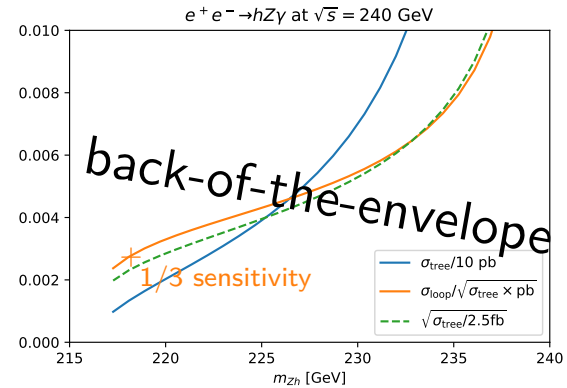
¿More handles?

hZ run energy/ies and radiative return

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





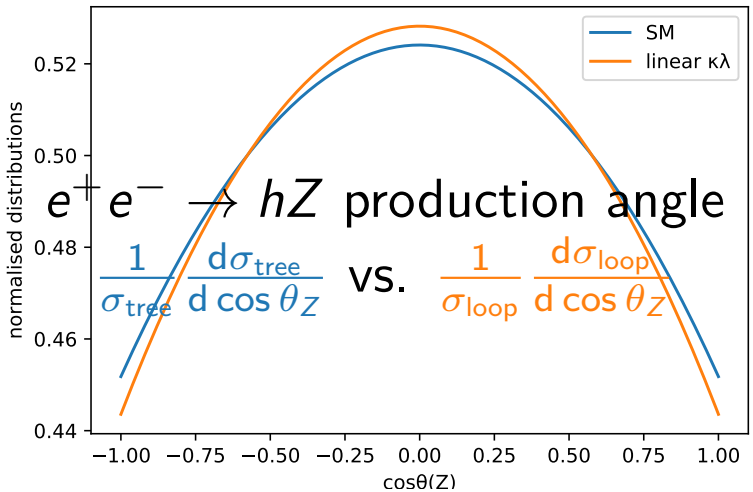


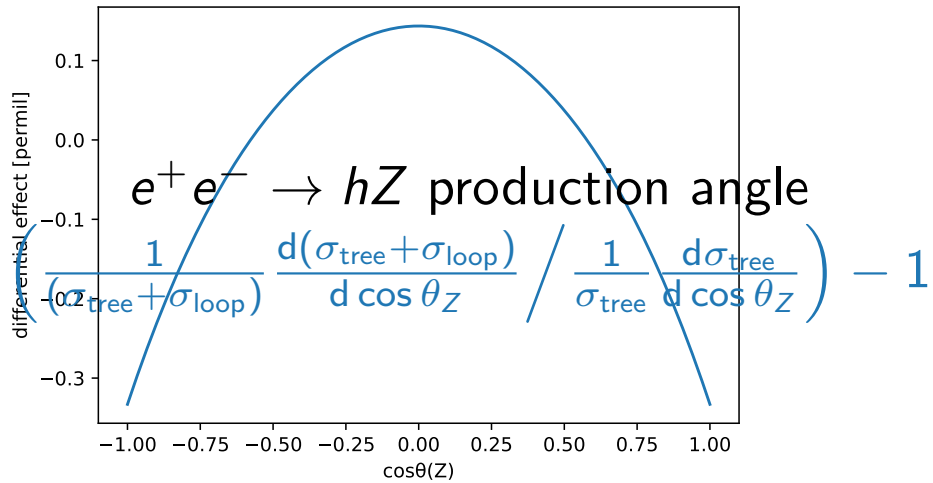
- ¿optimise/split $\sim$ 240 GeV energy/ies?
- ¿radiative return from $\sim$ 365/380 GeV?
- ¿even from $\sim$ 240 GeV downwards?

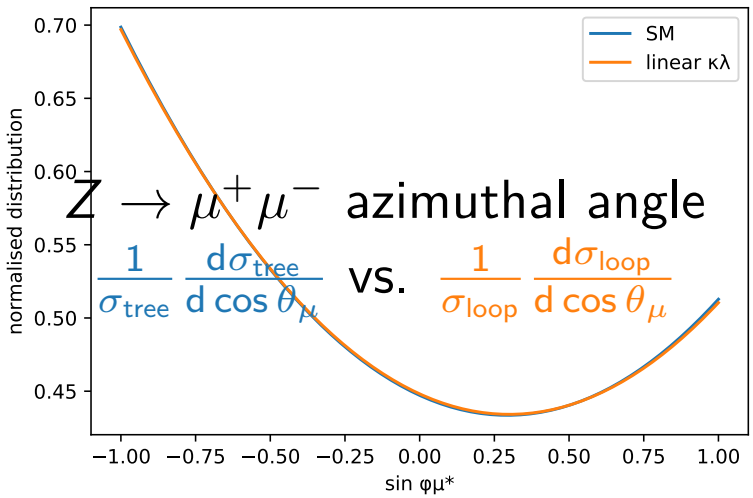
Differential hZ information

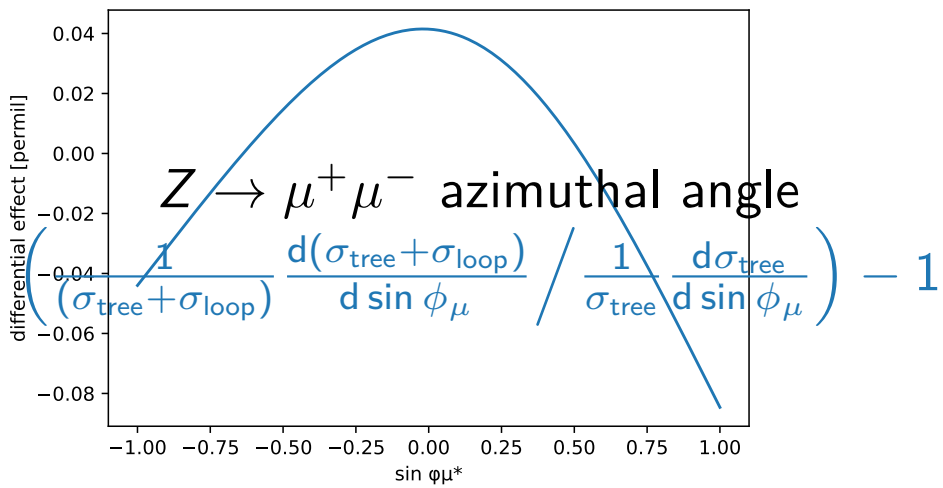
[Back-of-the-envelope calculations!!]
and discussions with Fabio Maltoni
& Xiaoran Zhao

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









¿exploitable with an optimal discriminant?

Interplay between Higgs and top-quark loops in hZ

Higgsstrahlung has sizeable tree and loop dependences
on Higgs and top-quark couplings.

Single Higgs coupling contaminations in the trilinear extraction
can be mitigated with different centre-of-mass energies.

Top-quark coupling contaminations to the trilinear extraction
can be mitigated with $pp \to t\bar{t}h$ measurements.

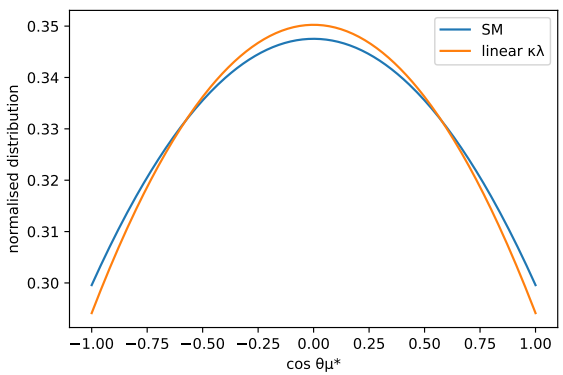
Are there more handles to lift degeneracies at e^+e^- machines?

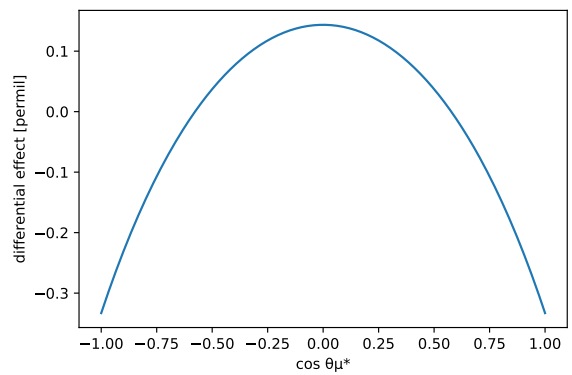
- hZ run optimisation and radiative return could be explored
- differential trilinear effects look small; top effects are unexplored

Extras

Questions and comments from the audience

- Marcel Vos: $e\bar{e}t\bar{t}$ operators are even harder to constrain at the LHC and could induce additional degeneracies. GD: Maybe these would have a distinctive centre-of-mass-energy dependence. The corresponding loops have not been computed, afaik.
- Junping Tian: The differential impact of trilinear loops is maybe captured by SMEFT modifications of the ZZh vertex. GD: This would also mean they are degenerate with these other SMEFT effects.
- Jenny List: Is the different sensitivity tilt in the single/triple Higgs coupling plane for linear and circular colliders due to beam polarisation? GD: Probably.
- Sven Heinemeyer, Jenny List: Can BSM discovery be obtained instead of SM precision/BSM exclusion? GD: Probably.
- Jürgen Reuter: Is the Z polarisation a good probe for trilinear modifications? GD: The polar angle of the Z decay products is not more sensitive than the 10^{-4} value advertised. Here are the corresponding (back-of-the-envelope!!) plots:





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