NLO EWPO in SMEFT and Higgs trilinear coupling determination

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S. Dawson, PPG, *Phys.Rev.D* 101 (2020) 1, 013001;
G. Degrassi, M. Fedele, PPG, JHEP 1704 (2017) 155

Characteristics of the EW sector of the SM

- (Relatively) Large number of observables,
- (Relatively) Small set of inputs.
- EW observables are (in general) extremely well measured quantities.

The difference between observables and inputs is somewhat arbitrary.

Our set of inputs is given by the set of most precise observables.

"Tree-level" parameters

α $\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z)$

Fine structure constant

G_μ

Fermi constant

M_Z

Z mass

"Loop-level" parameters

$\alpha_s(M_Z)$

Strong coupling

M_H

Higgs mass

m_t

Top mass

parameter	measurement	full EWK fit without m_H	full EWK fit with m_H
M_H [GeV]	125.09 ± 0.15	91 ± 19	125.09 ± 0.15
M_W [GeV]	80.380 ± 0.013	80.374 ± 0.01	80.360 ± 0.006
Γ_W [GeV]	2.085 ± 0.042	2.092 ± 0.001	2.091 ± 0.001
m_t [GeV]	172.9 ± 0.5	172.9 ± 0.5	173.1 ± 0.5
$\sin^2\theta^l_{\text{eff}}$	0.2314 ± 0.00023	0.2314 ± 0.00009	0.23152 ± 0.00006
M_Z [GeV]	91.188 ± 0.002	91.188 ± 0.002	91.188 ± 0.002
σ^0_{had} [nb]	41.54 ± 0.037	41.482 ± 0.015	41.483 ± 0.015
Γ_Z [GeV]	2.495 ± 0.002	2.495 ± 0.001	2.495 ± 0.001
A_c	0.67 ± 0.027	0.6683 ± 0.0003	0.6679 ± 0.0002
A_b	0.923 ± 0.02	0.9347 ± 0.00006	0.93462 ± 0.00004
A_l (SLD)	0.1513 ± 0.00207	0.14797 ± 0.00073	0.14707 ± 0.00044
A_l (LEP)	0.1465 ± 0.0033	0.14797 ± 0.00073	0.14707 ± 0.00044
A^l_{FB}	0.0171 ± 0.001	0.01642 ± 0.00016	0.01622 ± 0.0001
A^c_{FB}	0.0707 ± 0.0035	0.0742 ± 0.0004	0.0737 ± 0.0002
A^b_{FB}	0.0992 ± 0.0016	0.1037 ± 0.0005	0.1031 ± 0.0003
R^0_l	20.767 ± 0.025	20.747 ± 0.018	20.744 ± 0.018
R^0_c	0.1721 ± 0.003	0.17226 ± 0.00008	0.17225 ± 0.00008
R^0_b	0.21629 ± 0.00066	0.2158 ± 0.00011	0.21581 ± 0.00011
$\Delta\alpha^{(5)}_{\text{had}}$ [10^{-5}]	2760 ± 9	0.02761 ± 9	2757 ± 9
$\alpha_s(M_Z)$	0.1181 ± 0.0011	0.1198 ± 0.003	0.1197 ± 0.003

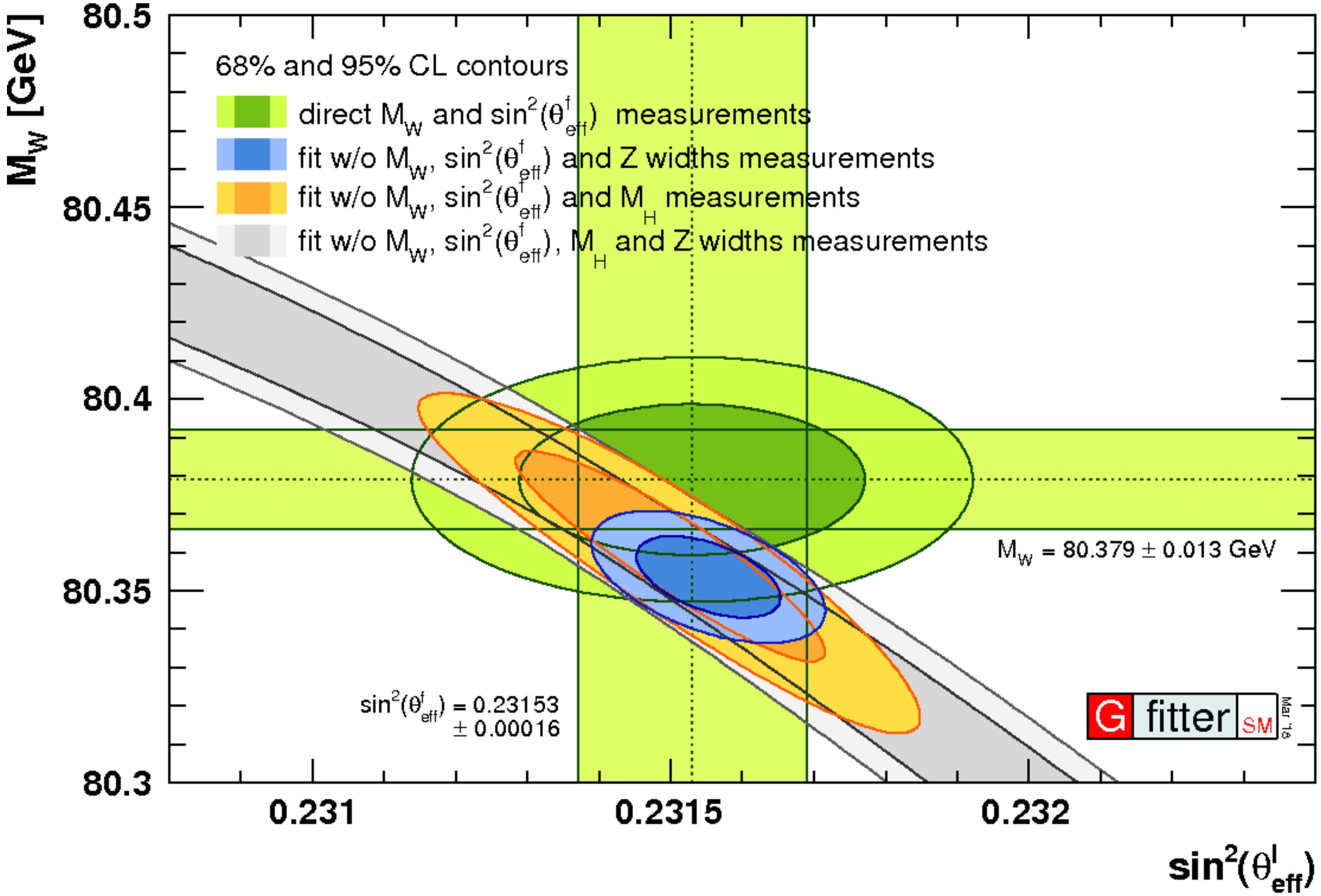
Observables

W mass and width
Effective EW sine
Z pole observables:

- Z width
- Hadronic cross section
- LR and FB asymmetries
- Ratios of partial Γ_Z

J. Erler and M. Schott Prog.Part.Nucl.Phys. 106 (2019) 68-119 using GFitter J. Haller et al., Eur. Phys. J. **C78**, 675 (2018)

Any inconsistency in EWPO could be an indication of NP



If precision physics is the road to the discovery of NP, the EW is a very good starting point

How can we systematically look for new physics?

Assume the SM is low energy limit of an EFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{k=5} \sum_{i} \frac{\mathscr{C}_i^k}{\Lambda^{k-4}} \mathscr{O}_i^k$$

Scale of new physics

Operators respect SM gauge symmetries

The theory is renormalizable order by order in powers of Λ

We consider only Dimension-6 operators

We use EWPO to study the effects of NLO corrections on SMEFT

Induced effective couplings

$$L \equiv 2M_Z\sqrt{\sqrt{2}G_\mu}Z_\mu\left[g_L^{Zq}+\delta g_L^{Zq}\right]\bar{q}\gamma_\mu q + 2M_Z\sqrt{\sqrt{2}G_\mu}Z_\mu\left[g_R^{Zu}+\delta g_R^{Zu}\right]\bar{u}_R\gamma_\mu u_R$$
$$+2M_Z\sqrt{\sqrt{2}G_\mu}Z_\mu\left[g_R^{Zd}+\delta g_R^{Zd}\right]\bar{d}_R\gamma_\mu d_R + 2M_Z\sqrt{\sqrt{2}G_\mu}Z_\mu\left[g_L^{Zl}+\delta g_L^{Zl}\right]\bar{l}\gamma_\mu l$$
$$+2M_Z\sqrt{\sqrt{2}G_\mu}Z_\mu\left[g_R^{Ze}+\delta g_R^{Ze}\right]\bar{e}_R\gamma_\mu e_R + 2M_Z\sqrt{\sqrt{2}G_\mu}\left(\delta g_R^{Z\nu}\right)\bar{\nu}_R\gamma_\mu\nu_R$$
$$+\frac{\bar{g}_2}{\sqrt{2}}\Big\{W_\mu\left[(1+\delta g_L^{Wq})\bar{u}_L\gamma_\mu d_L + \left(\delta g_R^{Wq}\right)\bar{u}_R\gamma_\mu d_R\right]$$
$$+W_\mu\left[(1+\delta g_L^{Wl})\bar{\nu}_L\gamma_\mu e_L + \left(\delta g_R^{W\nu}\right)\bar{\nu}_R\gamma_\mu e_R\right] + h.c.\Big\}.$$

Do not interfere with SM

Not independent at LO due to SU(2)

$$\delta g_L^{Wq} = \delta g_L^{Zu} - \delta g_L^{Zd}$$
$$\delta g_L^{Wl} = \delta g_L^{Z\nu} - \delta g_L^{Ze}.$$

7 new parameters (3+2*2)

Only 8 combinations can be probed at a time

$$M_W, g_L^{zu}, g_L^{zd}, g_L^{ze}, g_L^{z\nu}, g_R^{zu}, g_R^{zd}, g_R^{ze}$$

At LO effective couplings depend on (Warsaw basis)

$\mathcal{O}_{ll}$	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	$\mathcal{O}_{\phi WB}$	$(\phi^\dagger \tau^a \phi)\, W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{\phi D}$	$(\phi^\dagger D^\mu \phi)^* \, (\phi^\dagger D_\mu \phi)$
$\mathcal{O}_{\phi e}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{e}_R \gamma^\mu e_R)$	$\mathcal{O}_{\phi u}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}_{\phi d}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{d}_R \gamma^\mu d_R)$
$\mathcal{O}_{\phi q}^{(3)}$	$(\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{q}\tau^a \gamma^\mu q)$	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{q}\tau^a \gamma^\mu q)$	$\mathcal{O}_{\phi l}^{(3)}$	$(\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{l}\tau^a \gamma^\mu l)$
$\mathcal{O}_{\phi l}^{(1)}$	$(\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{l}\tau^a \gamma^\mu l)$				

At NLO 10 combinations but 32 operators

$$M_W^2 = \frac{M_z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_\mu M_z^2}}\right) + \delta M_W^{SMEFT}$$

SM Quantum corrections (known)

$\Delta r \rightarrow \Delta r(M_Z, G_\mu, \alpha, M_h, m_t, \alpha_s)$

Dubovyk, A. Freitas, J. Gluza, T. Riemann, and J. Usovitsch: arXiv:1906.08815; A. Fritas: arXiv: 1401.2447; M. Awramik, M. Czakon, A. Freitas, and G. Weiglein; arXiv: arXiv:hep-ph/0311148

EFT corrections

Many new operators at NLO

$$\delta M_W^{LO} = \frac{v^2}{\Lambda^2}\left\{-29.827\mathcal{C}_{\phi l}^{(3)} + 14.914\mathcal{C}_{ll} - 27.691\mathcal{C}_{\phi D} - 57.479\mathcal{C}_{\phi WB}\right\}$$

$$\delta M_W^{NLO} = \frac{v^2}{\Lambda^2}\left\{-35.666\mathcal{C}_{\phi l}^{(3)} + 17.243\mathcal{C}_{ll} - 30.272\mathcal{C}_{\phi D} - 64.019\mathcal{C}_{\phi WB}\right.$$
$$-0.137\mathcal{C}_{\phi d} - 0.137\mathcal{C}_{\phi e} - 0.166\mathcal{C}_{\phi l}^{(1)} - 2.032\mathcal{C}_{\phi q}^{(1)} + 1.409\mathcal{C}_{\phi q}^{(3)} + 2.684\mathcal{C}_{\phi u}$$
$$\left.+0.438\mathcal{C}_{lq}^{(3)} - 0.027\mathcal{C}_{\phi B} - 0.033\mathcal{C}_{\phi\Box} - 0.035\mathcal{C}_{\phi W} - 0.902\mathcal{C}_{uB} - 0.239\mathcal{C}_{uW} - 0.15\mathcal{C}_{W}\right\}$$

Fit to SMEFT operators NLO operators are put to 0

Λ=1 TeV

Single parameter fits at 95% CL

Coefficient	LO	NLO
C_{ll}	$[-0.0039, 0.021]$	$[-0.0044, 0.019]$
$C_{\phi WB}$	$[-0.0088, 0.0013]$	$[-0.0079, 0.0016]$
$C_{\phi u}$	$[-0.072, 0.091]$	$[-0.035, 0.084]$
$C_{\phi q}^{(3)}$	$[-0.011, 0.014]$	$[-0.010, 0.014]$
$C_{\phi q}^{(1)}$	$[-0.027, 0.043]$	$[-0.031, 0.036]$
$C_{\phi l}^{(3)}$	$[-0.012, 0.0029]$	$[-0.010, 0.0028]$
$C_{\phi l}^{(1)}$	$[-0.0043, 0.012]$	$[-0.0047, 0.012]$
$C_{\phi e}$	$[-0.013, 0.0094]$	$[-0.013, 0.0080]$
$C_{\phi D}$	$[-0.025, 0.0019]$	$[-0.023, 0.0023]$
$C_{\phi d}$	$[-0.16, 0.060]$	$[-0.13, 0.063]$

Marginalized fits at 95% CL

Coefficient	LO	NLO
$C_{\phi D}$	$[-0.034, 0.041]$	[-0.039,0.051]
$C_{\phi WB}$	$[-0.080, 0.0021]$	$[-0.098, 0.012]$
$C_{\phi d}$	$[-0.81, -0.093]$	$[-1.07, -0.03]$
$C_{\phi l}^{(3)}$	$[-0.025, 0.12]$	$[-0.039, 0.16]$
$C_{\phi u}$	$[-0.12, 0.37]$	$[-0.21, 0.41]$
$C_{\phi l}^{(1)}$	$[-0.0086, 0.036]$	$[-0.0072, 0.037]$
C_{ll}	$[-0.085, 0.035]$	$[-0.087, 0.033]$
$C_{\phi q}^{(1)}$	$[-0.060, 0.076]$	$[-0.095, 0.075]$

Fit to SMEFT operators **NLO operators are put to 0** **Λ=1 TeV**

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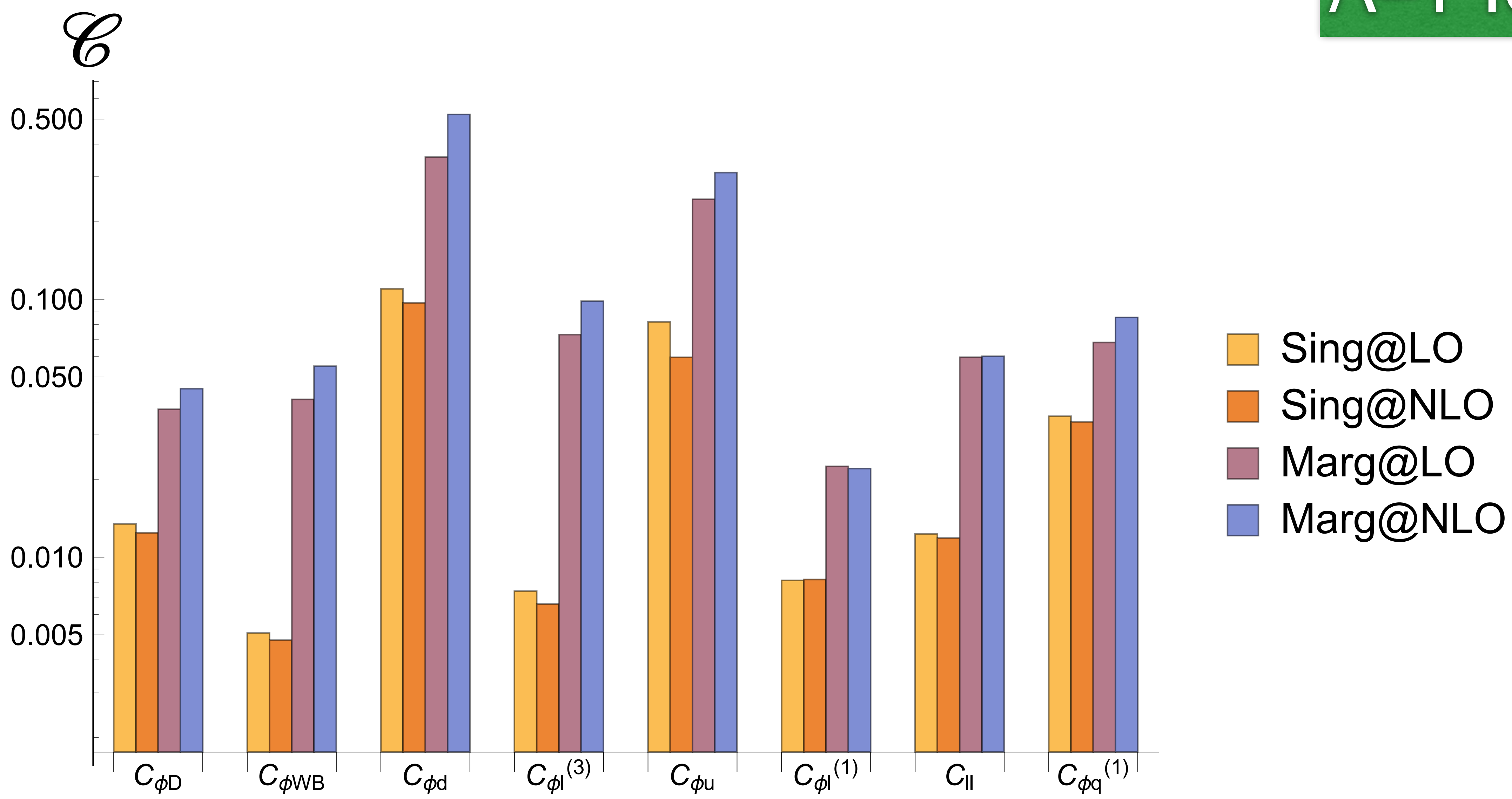
0 in the marginalized fit (arrows pointing to $C_{\phi q}^{(3)}$ and $C_{\phi e}$)

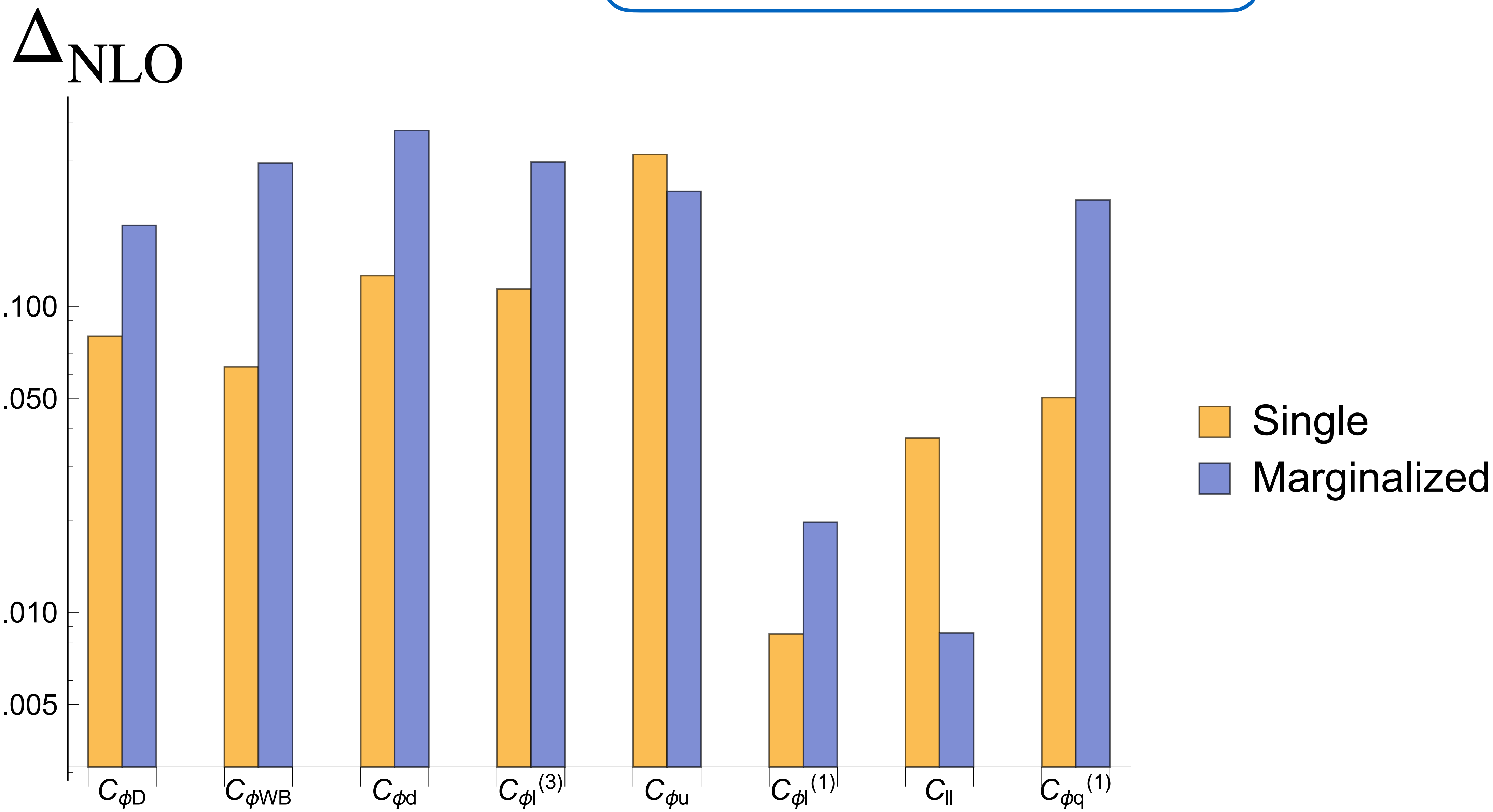
Result of the fit to LEP

Λ=1 TeV



NLO corrections have different effects depend on how the fit is done

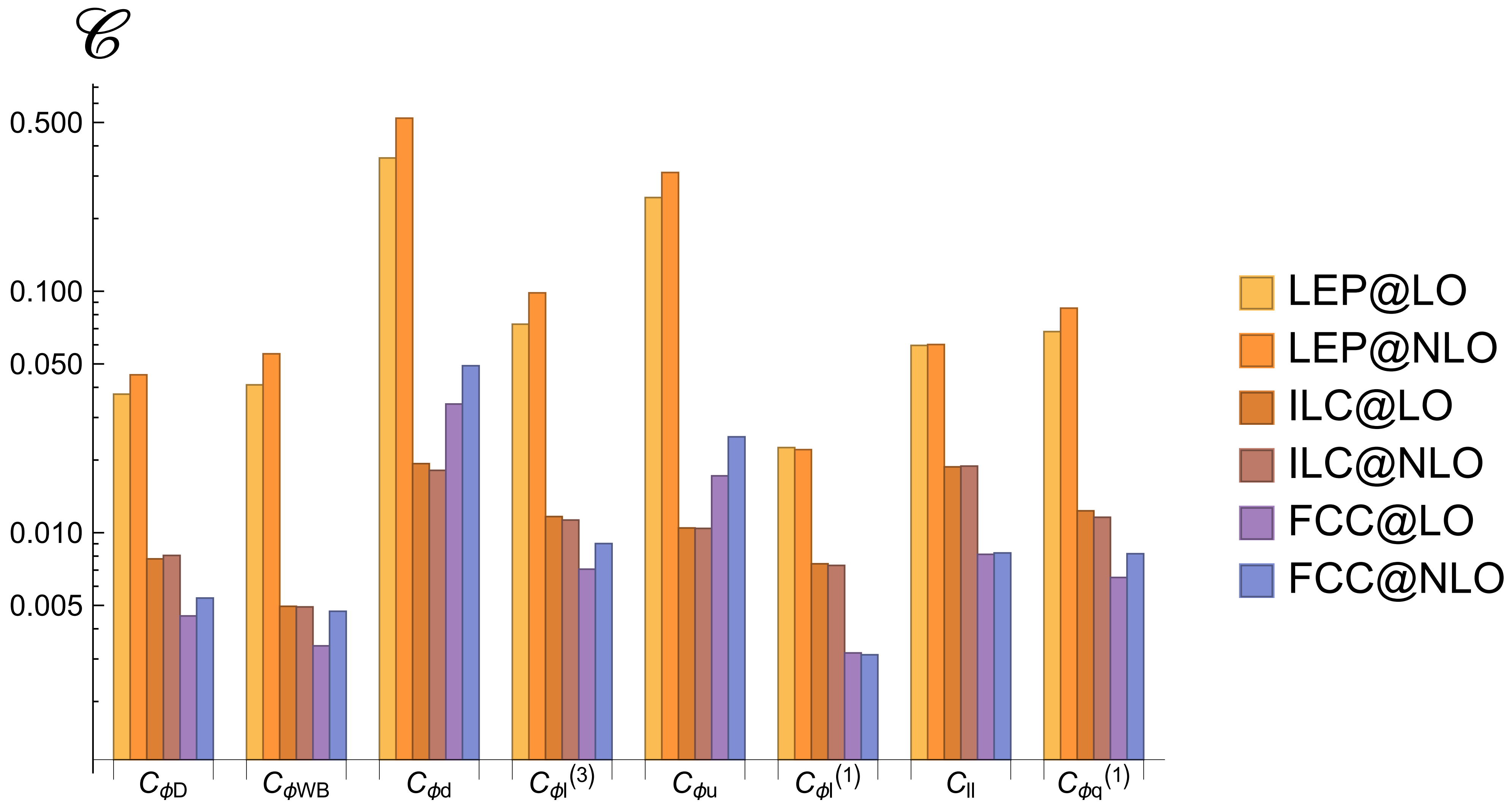
Let me define $\Delta_{\text{NLO}} \equiv \left| \frac{\mathscr{C}^{\text{NLO}} - \mathscr{C}^{\text{LO}}}{\mathscr{C}^{\text{LO}}} \right|$



Large (up to ~30%) corrections

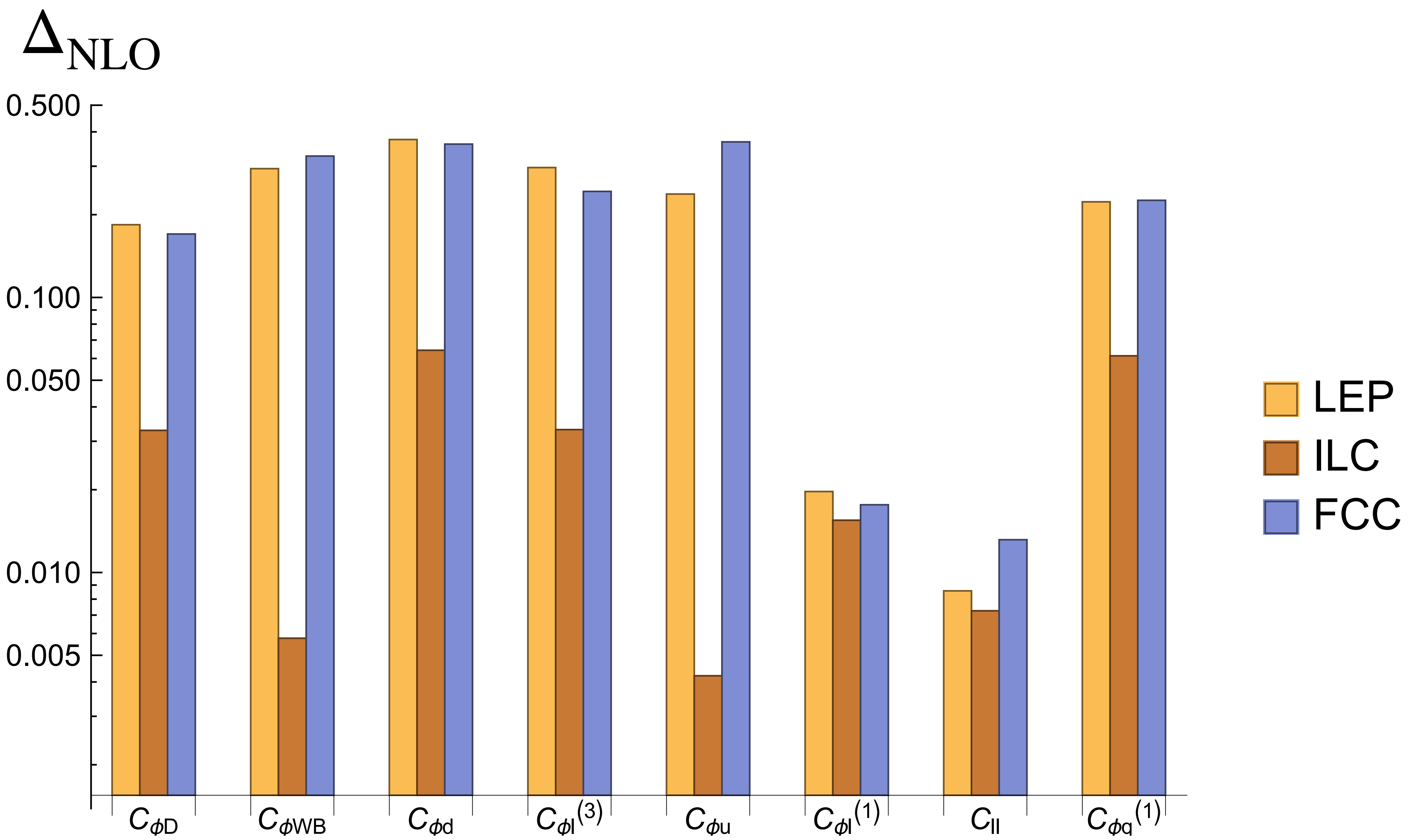
Marginalized fit LEP vs ILC vs FCC-ee

arXiv:1809.01830v3; arXiv:1908.11299



Similar behavior (better reach)

Size of NLO corrections at LEP, ILC and Fcc



Δ_{NLO} at ILC is smaller due to polarized beams

The Higgs sector

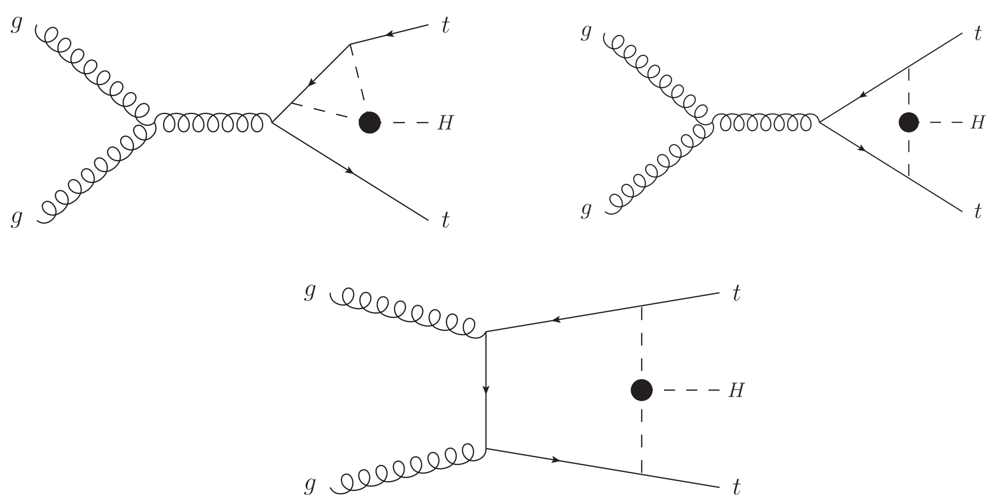
- EWPO are sensitive to modifications of the Higgs couplings (w.r.t. SM) only when NLO corrections are considered.
- In general, EWPO cannot compete with the direct measurements of the Higgs couplings at LHC.
- One exception is the Higgs trilinear, since its direct measurement at LHC is hindered by a very small cross-section

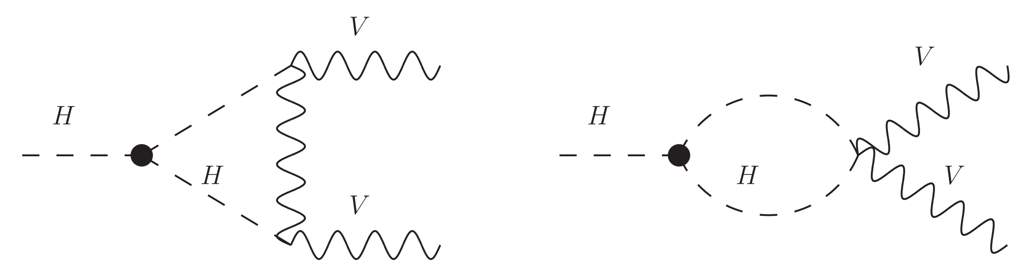
In order to study the Higgs trilinear is convenient to consider a general anomalous coupling instead of a proper EFT

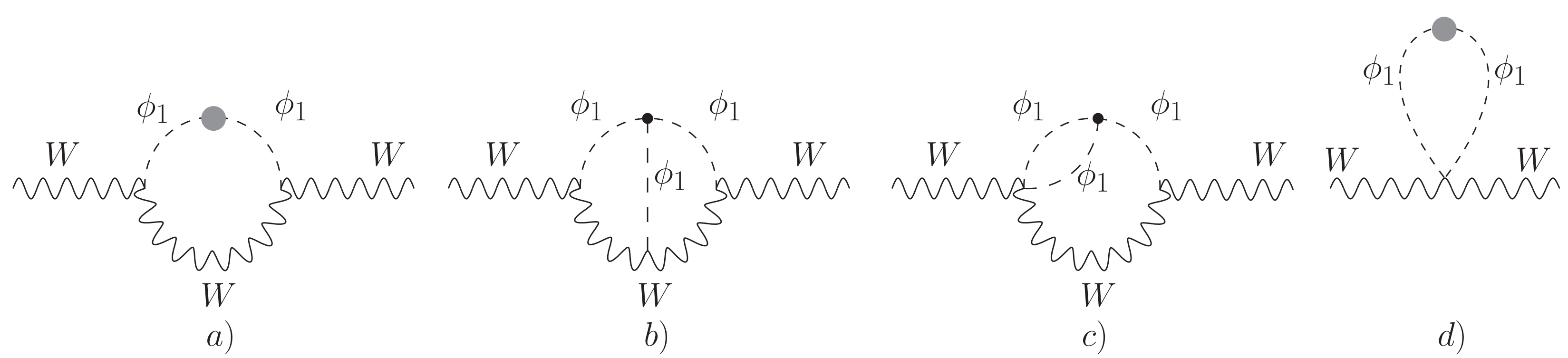
$$V_{H^3} = \lambda_3 v H^3 \equiv \kappa_\lambda \lambda_3^{\mathrm{SM}} v H^3$$

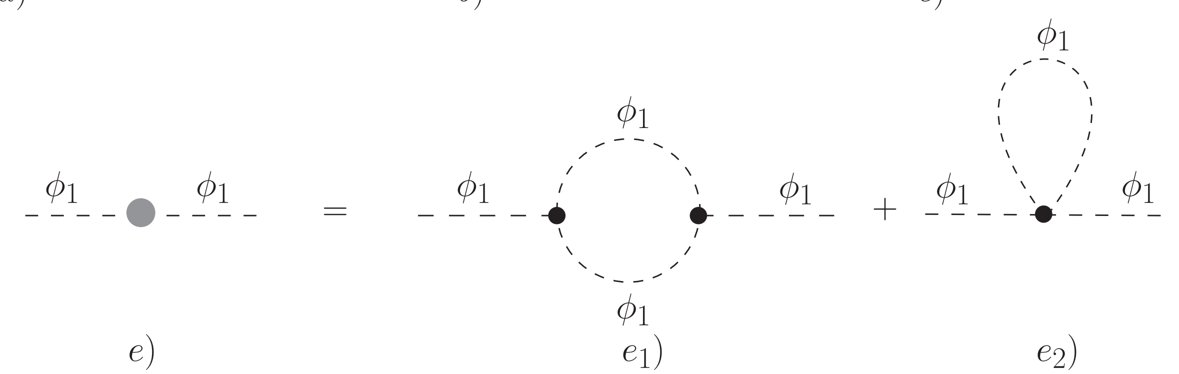
G. Degrassi, PPG, F. Maltoni, D. Pagani, JHEP 1612 (2016) 080
M. McCullough Phys. Rev. D90 (2014), no. 1 015001

Best limits obtained in combination with single Higgs processes.



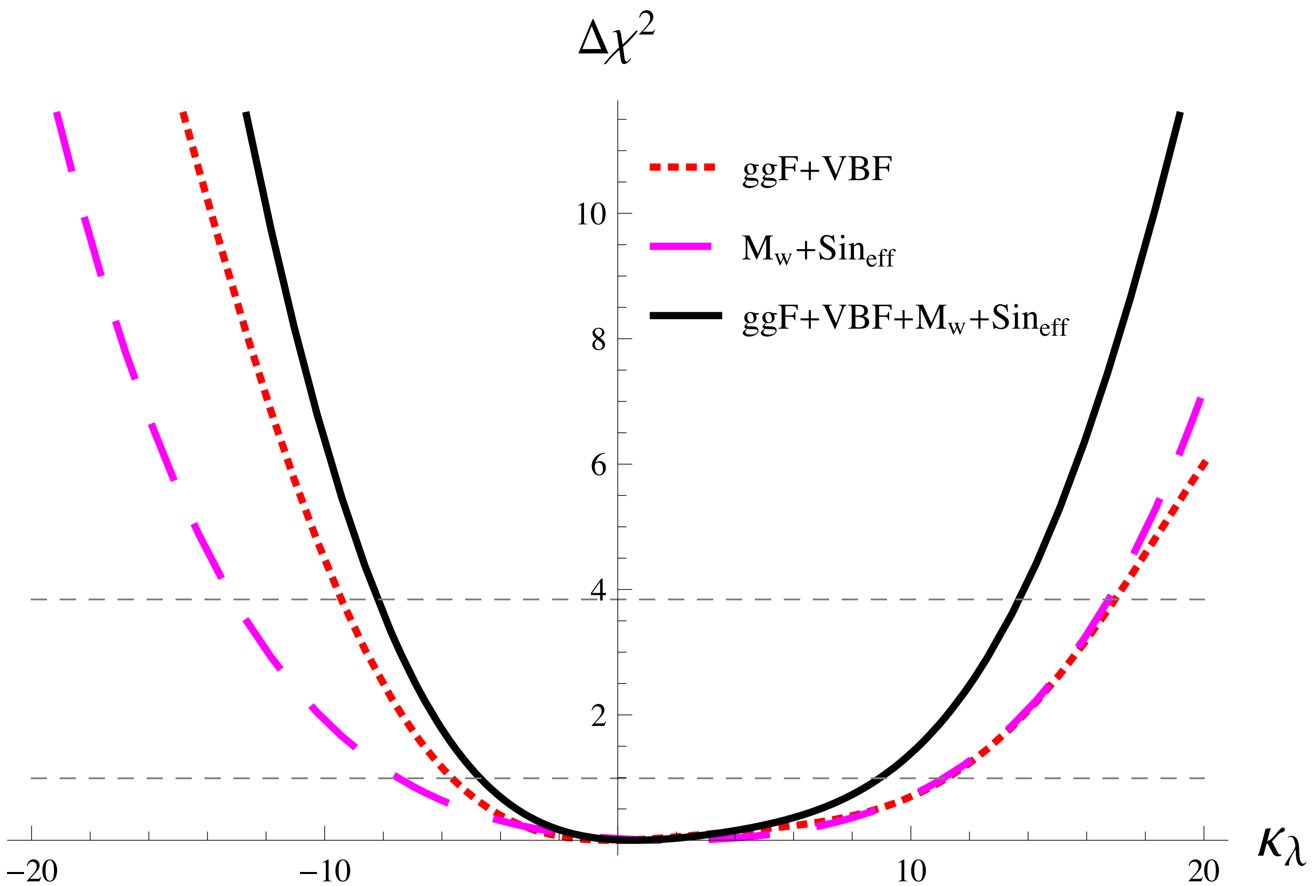






We consider only M_W and sine eff.

EWPO vs λ3



From Run I data

- ATLAS and CMS: $\mathcal{O}(\pm(15-20))$
- Our constraint using ggF+VBF: $\kappa_\lambda > -14.3$
- Our constraint using ggF+VBF+EW: $-13.3 < \kappa_\lambda < 20.0$

An update of this result is coming

G. Degrassi, B. Di Micco, PPG, E. Rossi

Conclusions

- I have presented a calculation of the complete NLO EW and QCD corrections to the EWPO in the SMEFT.
- and used it to test their effects on the EFT fits.
- The size of the NLO corrections seems to depend more on the details of the fit rather than the precision of the measurement.
- Tread carefully!
- EWPO can also be useful to help constrain the Higgs trilinear. New results are coming!