EWPO in the SMEFT at NLO

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S. Dawson, PPG, *Phys.Rev.D* 101 (2020) 1, 013001

EWPO in the SM depend on a small set of parameters

"Tree-level" parameters

α $\Delta\alpha^{(5)}_{\rm had}(M_Z)$

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

$$M_W, \Gamma_W, \Gamma_Z, \sigma_h, R_l, R_b, R_c, A_{l,FB}, A_{b,FB}, A_{c,FB}, A_l, A_b, A_c$$

W mass as an example:

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

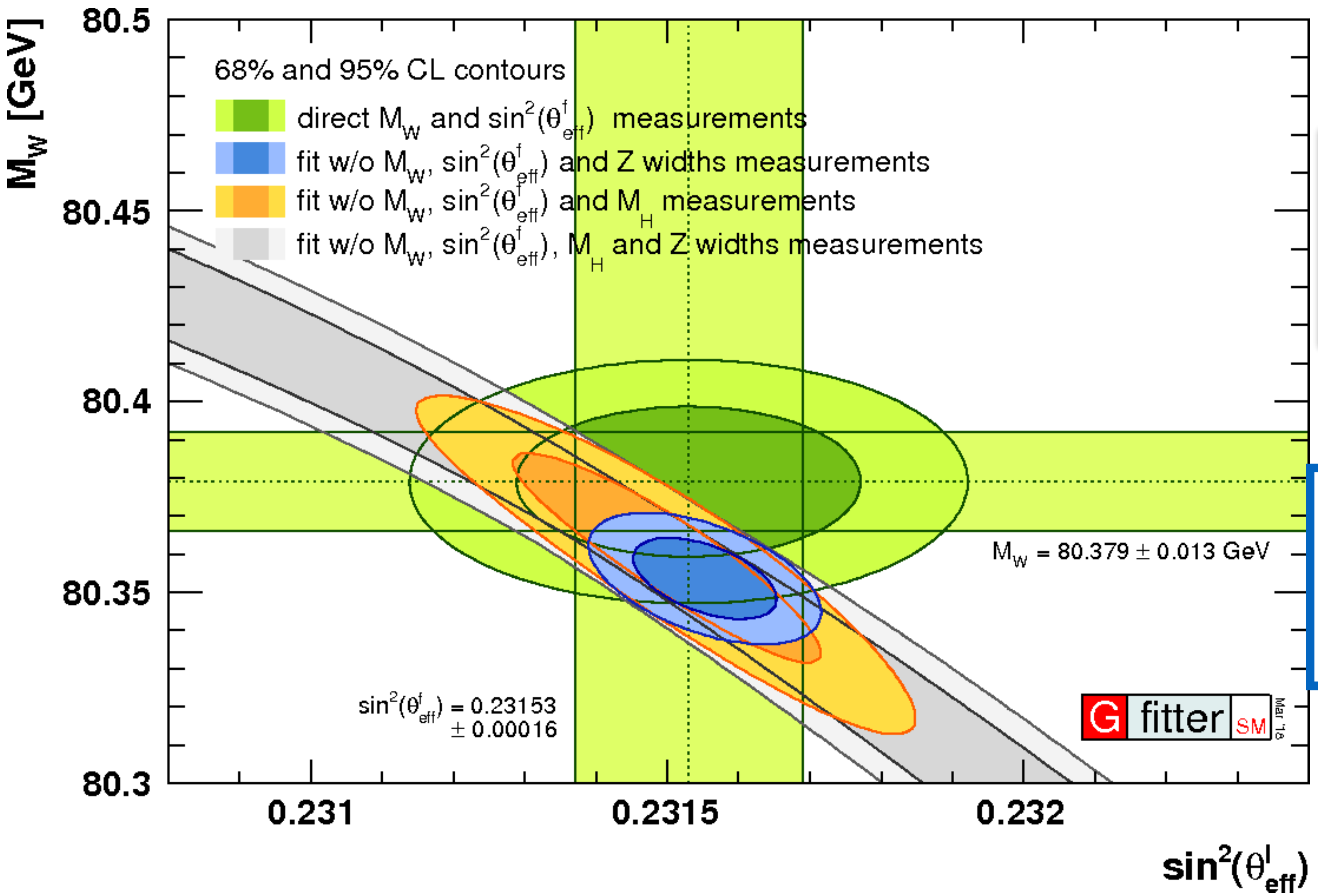
$$M_W^2 = \frac{M_z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1 + \Delta r)}{G_\mu M_z^2}}\right)$$

Quantum corrections

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

A small set of inputs can describe a large number of observables.

Precision physics can give information on new physics



Anything that can modify a PO will do it.

Any inconsistency could be an indication of NP

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

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

Do not interfere with SM

Not independent at LO due to SU(2)

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

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)

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

At NLO 10 combinations but 32 operators

NLO corrections are computed at order $\mathcal{O}(\frac{v^2}{\Lambda^2})$

SM is renormalized in OS

Operators are treated as $\overline{\text{MS}}$

$$\mathscr{C}_i(\mu) = \mathscr{C}_{0,i} - \frac{1}{2\epsilon}\frac{1}{16\pi^2}\gamma_{i,j}\mathscr{C}_j$$

RGE mixing: new operators enter here

E. Jenkins, A. Manohar, M. Trott JHEP 1310 (2013) 087, JHEP 1401 (2014) 035;
R. Alonso, E. Jenkins, A. Manohar, M. Trott JHEP 1404 (2014) 159

Input scheme α, G_μ, M_Z

$$G_\mu = \frac{1}{\sqrt{2}v^2}\left(1 + \frac{v^2}{\Lambda^2}(2\mathscr{C}^{(3)}_{\phi l} - \mathscr{C}_{ll}) + \Delta_r\right)$$

Relationship between parameters changed at tree level

SM and SMEFT at NLO $\Delta_r = \Delta_{r,SM} + \frac{v^2}{\Lambda^2}\Delta_{r,EFT}$

S. Dawson, PPG, PRD 97 (2018) no.9, 093003

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

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

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

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

Single parameter fits at 95% CL

with Λ=1 TeV

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

5-10% effects from NLO

Fits to other coefficients that do not appear at LO not particularly informative

Marginalized fits at 95% CL

with Λ=1 TeV

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

All NLO coefficients put to 0

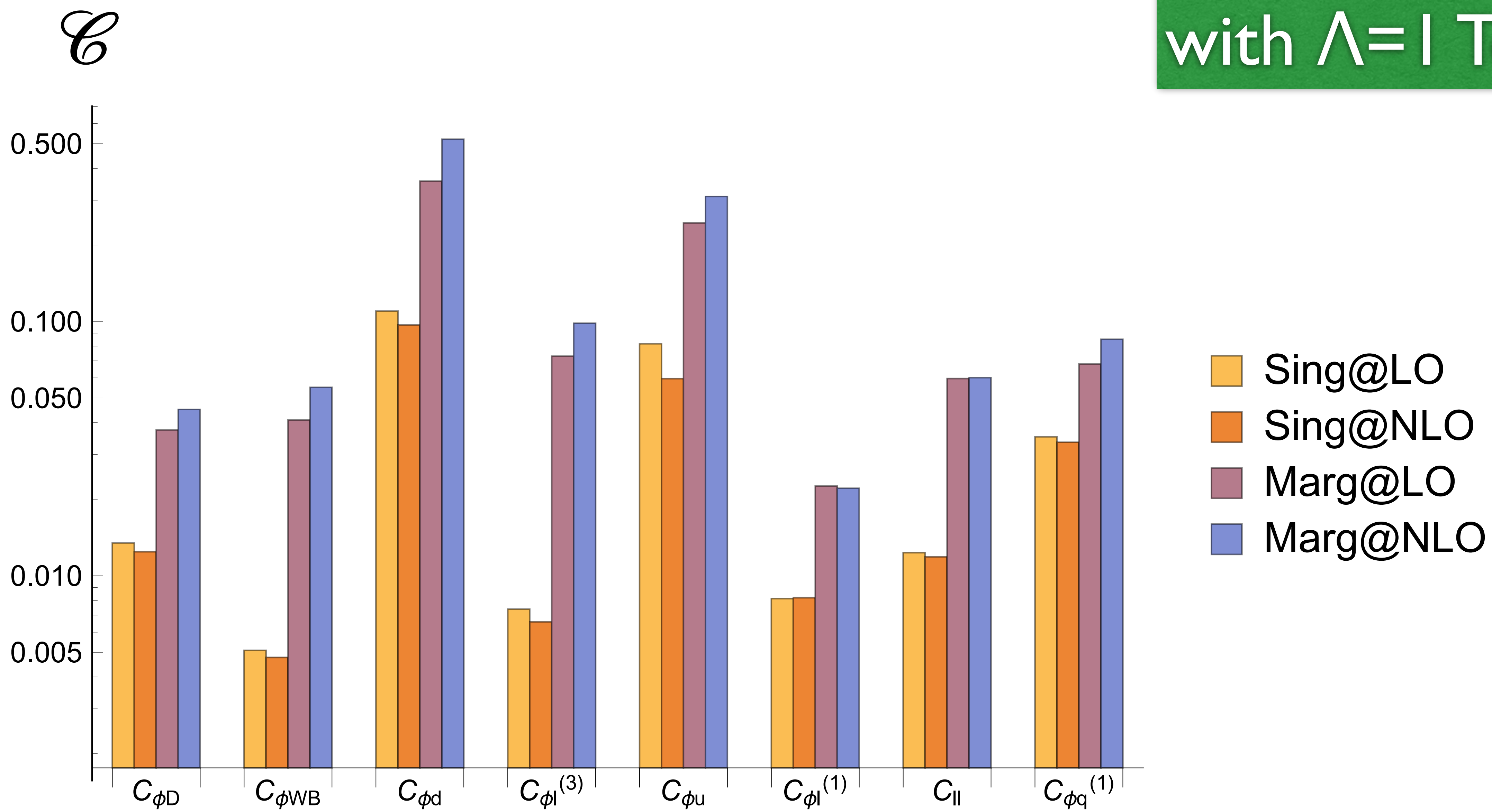
$$\mathscr{C}_{\phi e} = 0, \mathscr{C}_{\phi q}^{(3)} = 0$$

Fits done marginalizing over 7 parameters

Large 20-30% effects.

Single fit vs. Marginalized fit at LEP

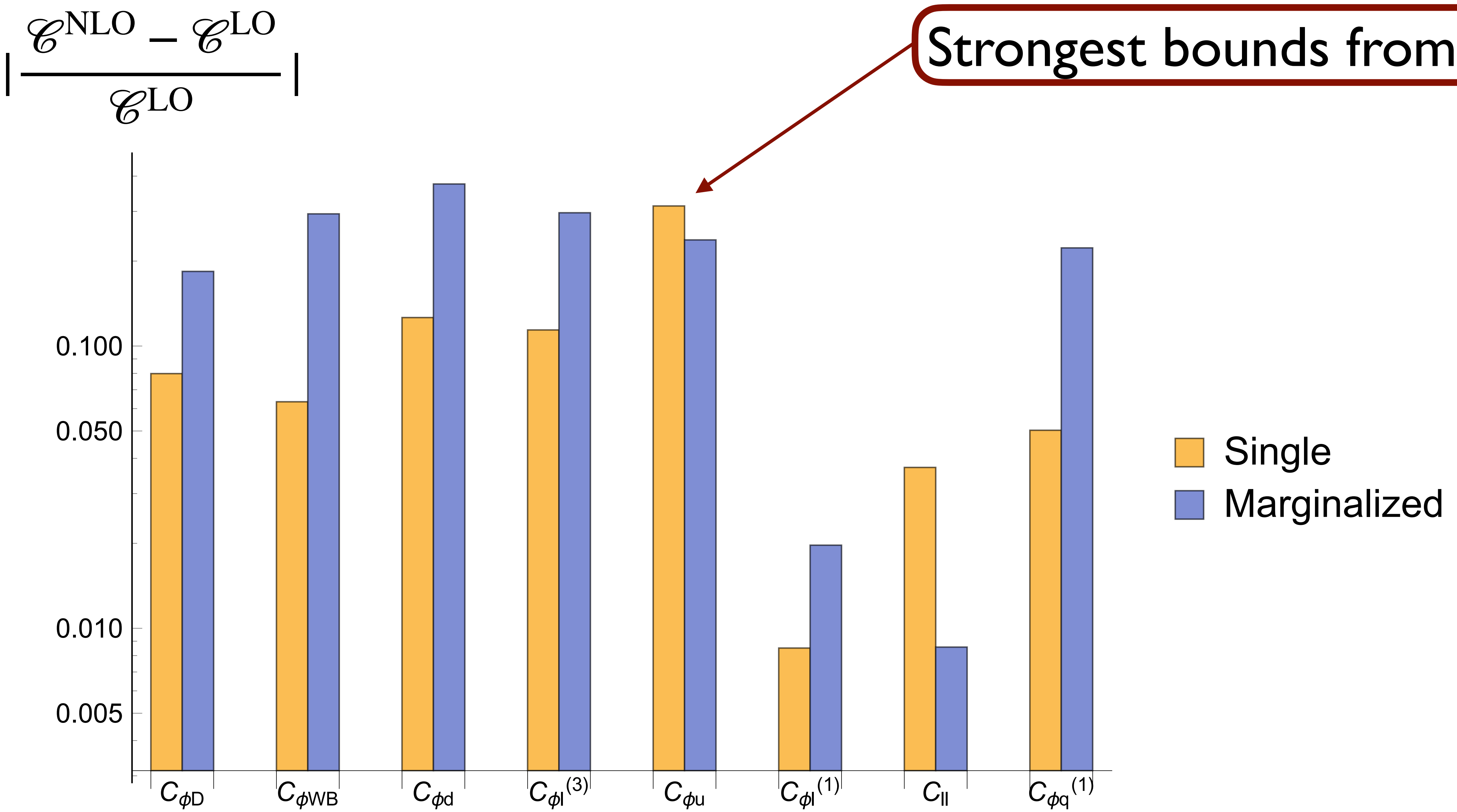
with Λ=1 TeV



Small effects for single fit vs. large effects for marginalized fit

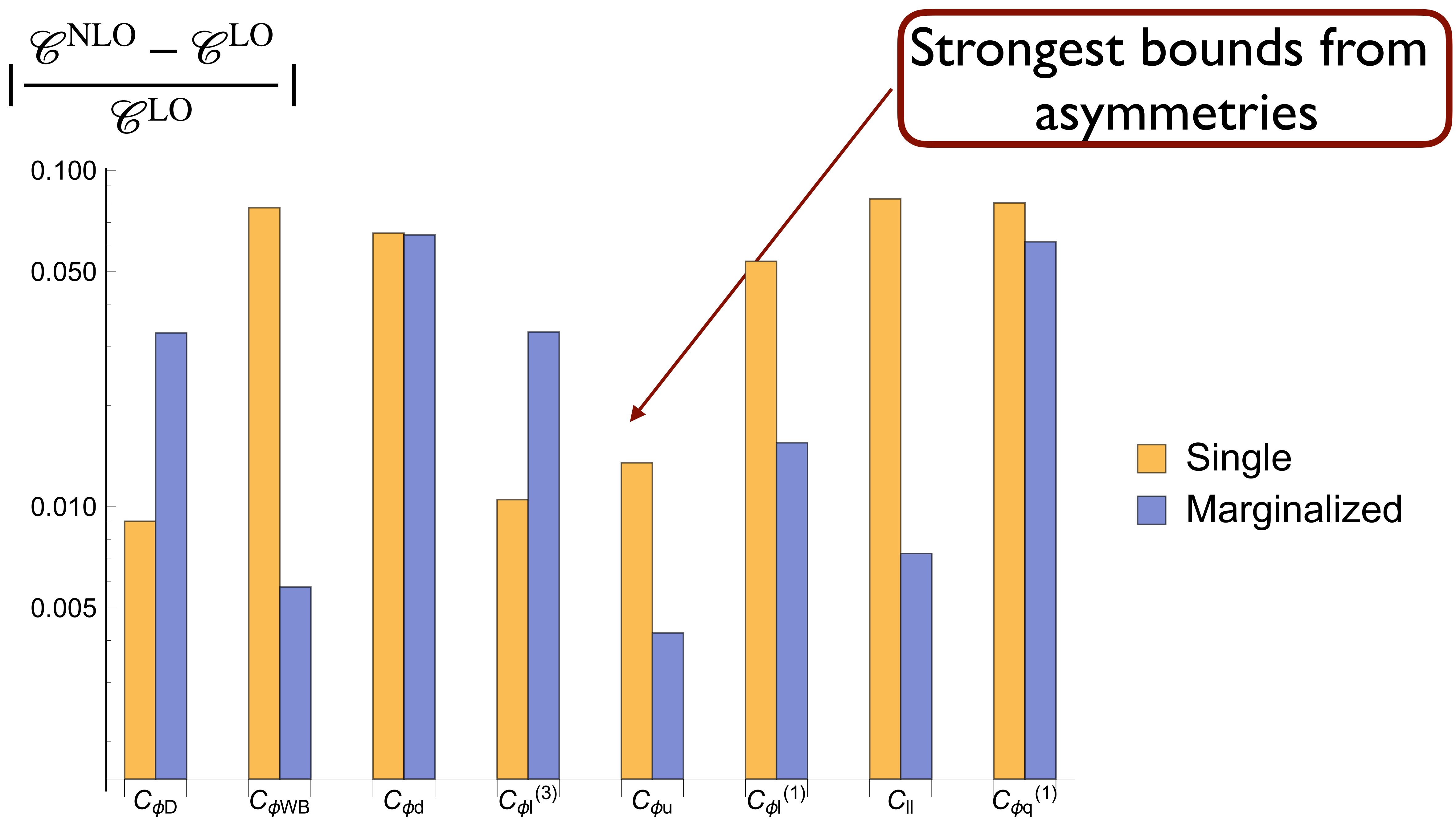
Size of NLO corrections

Strongest bounds from Γz



Large NLO corrections seem to propagate

Size of NLO corrections at ILC



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.
- NLO effects are possibly large and should be taken into account.
- I considered only EWPO, similar studies for Higgs and Top data are necessary.
- A more general fit, that uses Higgs and Top results and measurements at other regimes could include omitted (NLO) operators.