EWPO with dim-6 operators

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Sendai, LCWS2019

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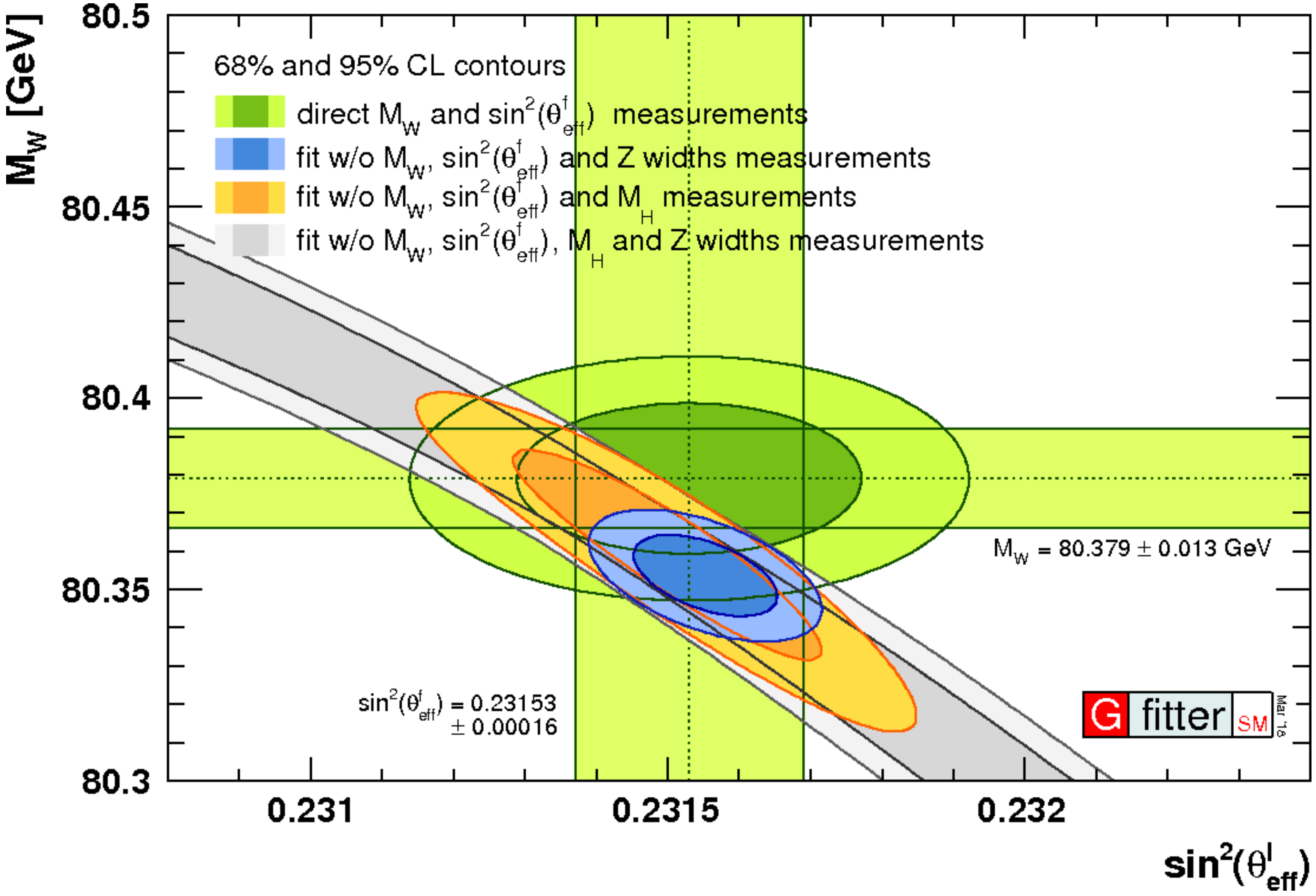
S. Dawson, PPG, arXiv:1909.02000

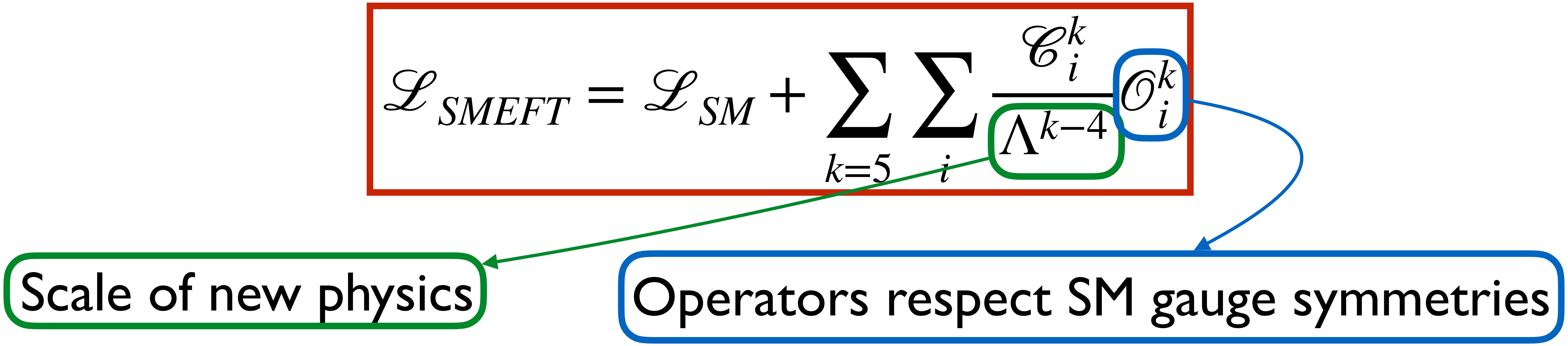
Precision physics can give information on new physics



- At LEP it predicted the Higgs mass.
- Now it shows a small inconsistency for the W mass.

How can we systematically look for new physics?

Assume the SM is low energy limit of an EFT



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

Scale of new physics

Operators respect SM gauge symmetries

Assumptions: no “light” particles; Higgs is part of a SU(2) doublet

The theory is renormalizable order by order in Λ

We are interested only for dimension-6 operators

EWPO in the SMEFT

Effective Z and W couplings

Induced effective couplings

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

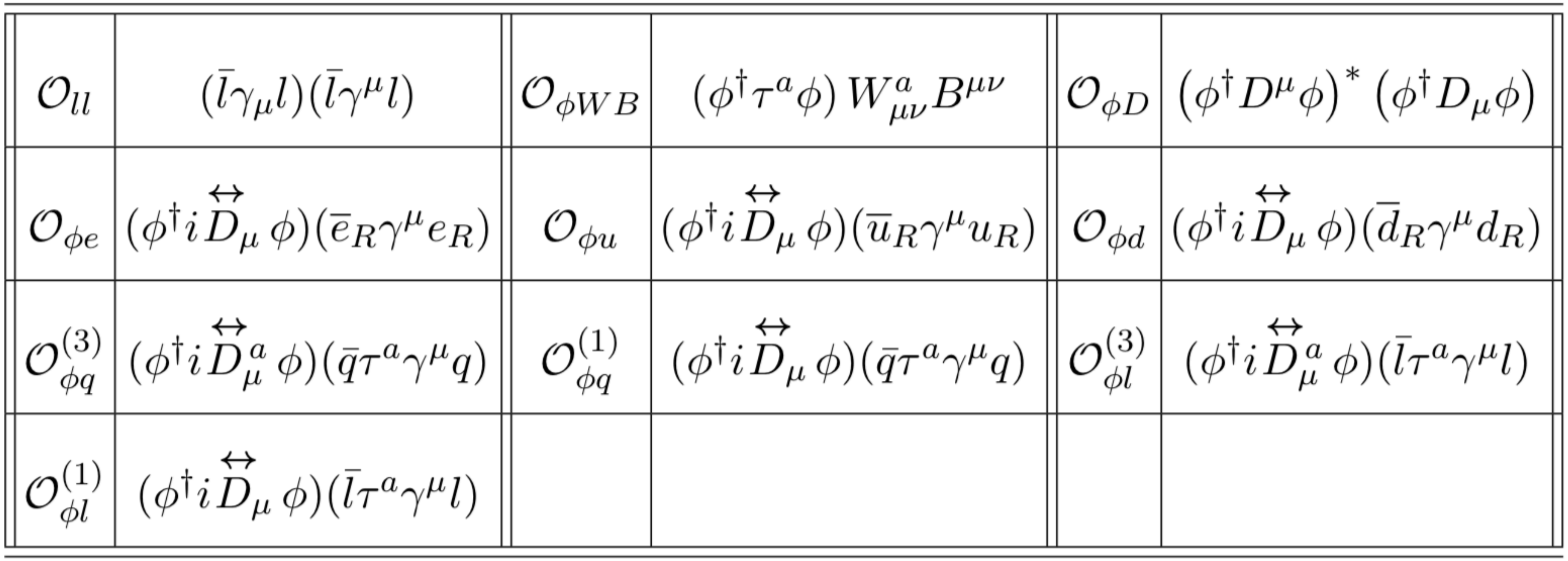
Do not interfere with SM

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)

At LO effective couplings depend on (Warsaw basis)



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

Only 8 combinations can be proved 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 NLO 10 combinations but 32 operators

Input scheme α, G_μ, M_Z

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

Relationship between parameters changed at tree level

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

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

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

SM is renormalized in OS

Operators are treated as 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

EWPO in the SMEFT

SMEFT @ NLO

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

Quantum corrections

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

EFT corrections

Many new operators at NLO

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

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

Fit at LEP

χ^2 at LO vs. NLO

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

Using LEP results

$$\delta\chi^2_{LO} = \left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)\Big\{32\mathscr{C}_{\phi d} + 105\mathscr{C}_{\phi e} - 445\mathscr{C}^{(1)}_{\phi l} + 639\mathscr{C}^{(3)}_{\phi l} - 49\mathscr{C}^{(1)}_{\phi q} - 60\mathscr{C}^{(3)}_{\phi q} - 11\mathscr{C}_{\phi u} - 424\mathscr{C}_{ll} + 491\mathscr{C}_{\phi D} + 1114\mathscr{C}_{\phi WB}\Big\} + \mathrm{quad\,.\,terms}$$

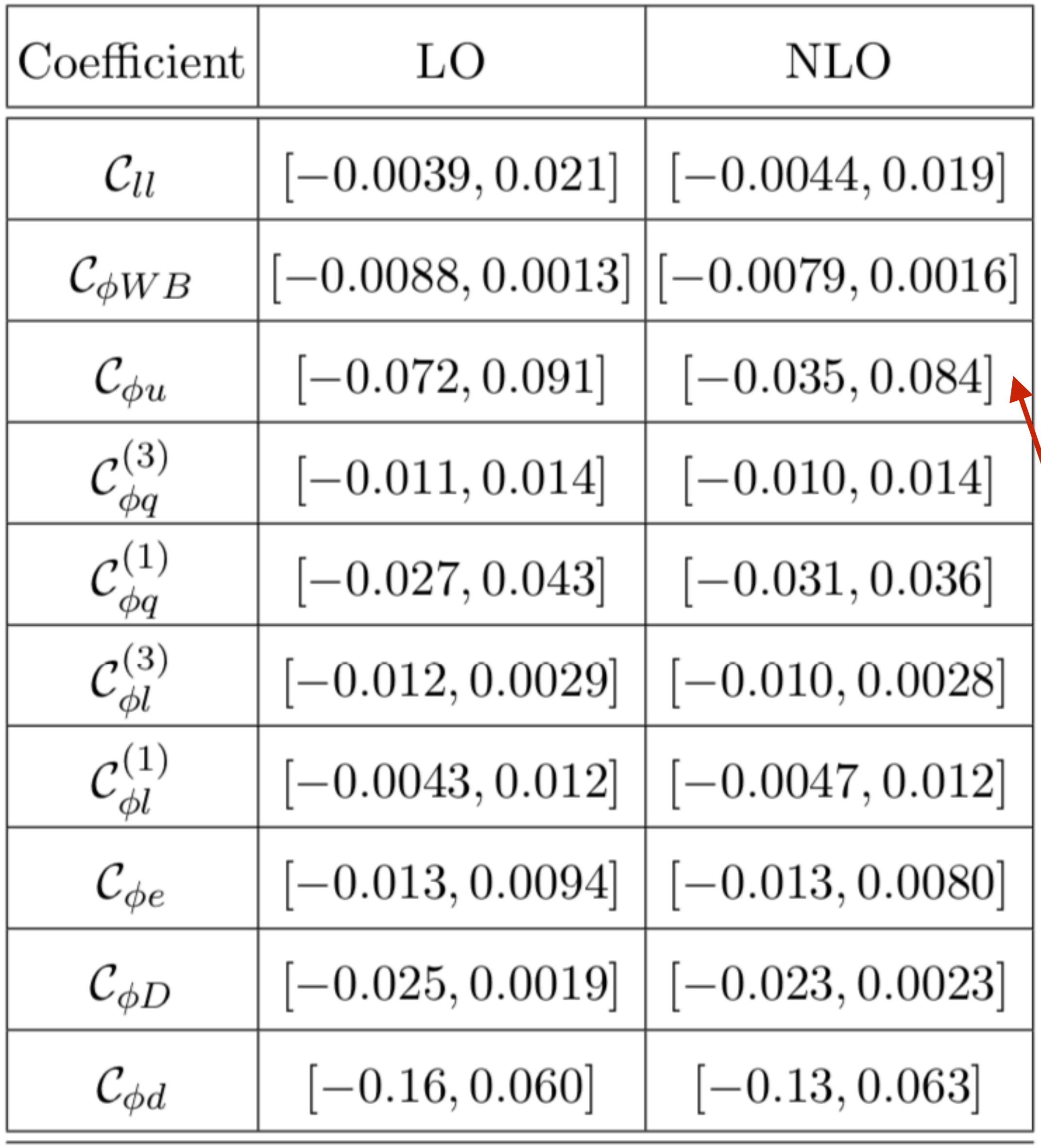
$$\delta\chi^2_{NLO} = \left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)\Big\{27\mathscr{C}_{\phi d} + 176\mathscr{C}_{\phi e} - 402\mathscr{C}^{(1)}_{\phi l} + 667\mathscr{C}^{(3)}_{\phi l} - 19\mathscr{C}^{(1)}_{\phi q} - 93\mathscr{C}^{(3)}_{\phi q} - 53\mathscr{C}_{\phi u} - 403\mathscr{C}_{ll} + 503\mathscr{C}_{\phi D} + 1070\mathscr{C}_{\phi WB} + 22\,\text{other terms}\Big\} + \mathrm{quad\,.\,terms}$$

EWPO in the SMEFT

Fit at LEP

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

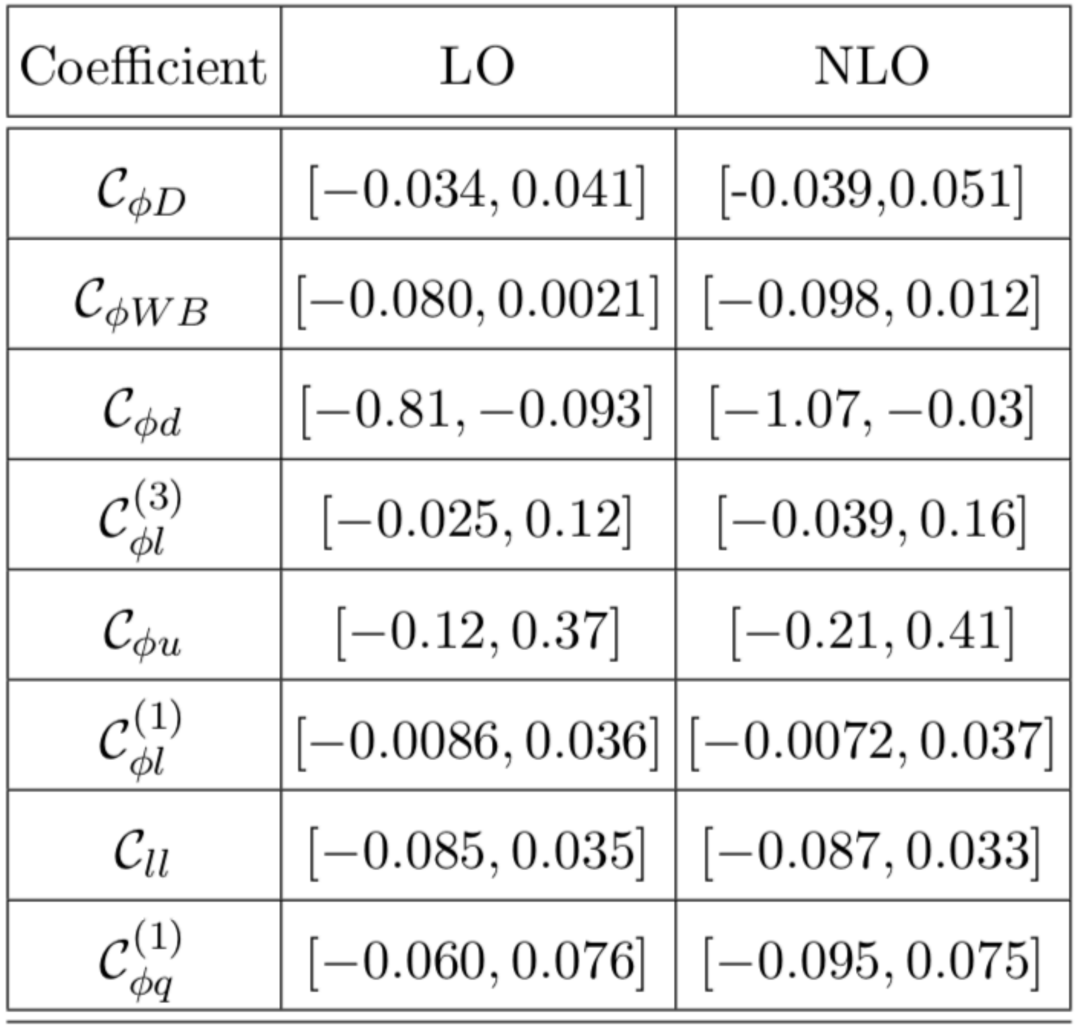
Fits to other coefficients that do not appear at LO not particularly informative

Contribution from Top important

Fit at LEP

Marginalized fits at 95% CL

with Λ=1 TeV



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

All NLO coefficients put to 0

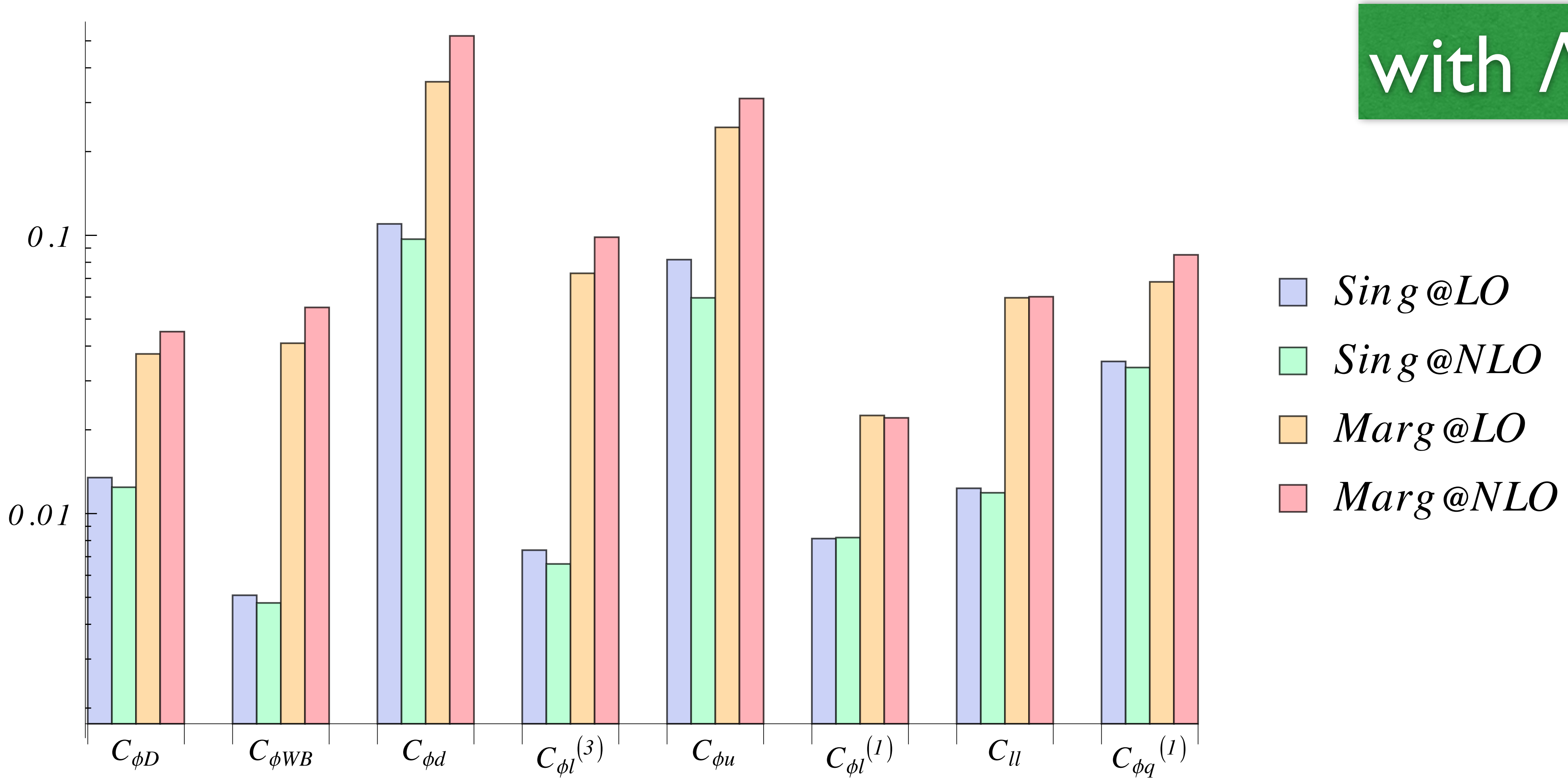
$$\mathscr{C}_{\phi e} = 0, \mathscr{C}^{(3)}_{\phi q} = 0$$

Fits done marginalizing over 7 parameters

Large 20-30% effects.

Single fit vs. Marginalized fit at LEP

with Λ=1 TeV



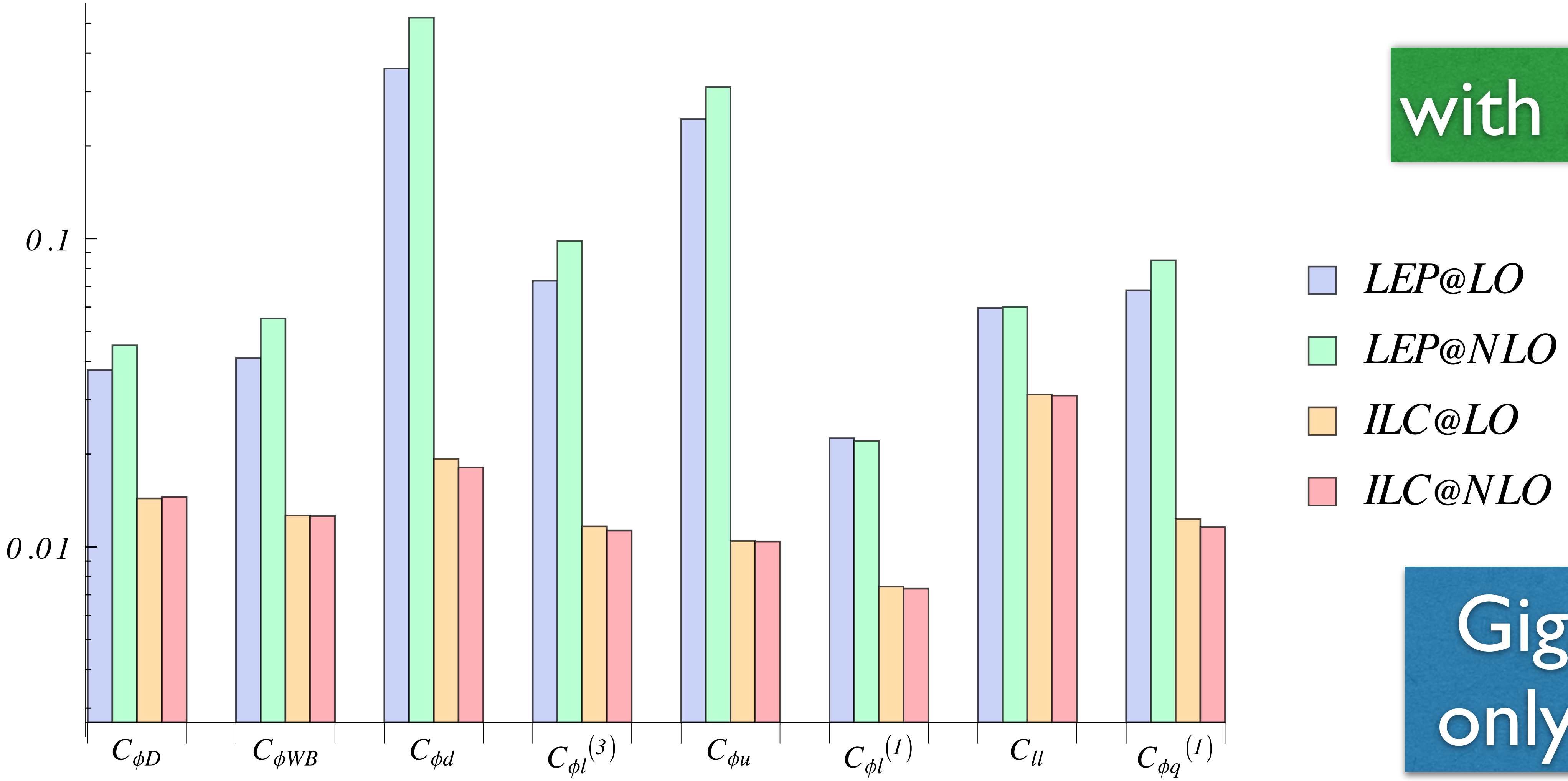
Small effects for single fit vs. large effects for marginalized fit

Large uncertainties not taken in account at LO

Fit at ILC

Marginalized LEP vs. ILC fit

Tests of the Standard Model at the International Linear Collider, LCC Physics Working Group: arXiv:1908.11299



with Λ=1 TeV

GigaZ run
only EWPO

Input scheme uncertainties under control

Conclusions

- I have presented a calculation of the complete NLO EW and QCD corrections to the EWPO in the SMEFT.
- These results were used in a fit using the LEP data.
- Large uncertainties in the input parameter scheme result in large NLO effects in the marginalized fit.
- Effects due to the NLO corrections are smaller for the ILC. Input parameter scheme uncertainties are under control.
- For the ILC I considered only EWPO from the GigaZ run.
- Higgs and Top results, and measurements at other regimes will improve the fit and allow for a more general fit.

Thank you!

Olena Shmahalo/Quanta Magazine