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Addendum: Scheming in the SMEFT... and a reparameterization invariance!

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Abstract: We allow two independent flavor contractions for the operator $\mathcal{Q}_{ll}$ in the $\mathrm{U}(3)^5$ flavor symmetric limit and report modified fit results in this limit.

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The original paper adopted an overly restrictive form of a U(3)^5 limit by not allowing two independent flavor contractions admitted by the operator $\mathcal{Q}_{ll}$ in the U(3)^5 flavor symmetric limit [2]. Defining

$$\mathcal{L}_{\rm SMEFT} \supset \left[C_{ll}\,\delta_{mn}\delta_{op} + C'_{ll}\,\delta_{mp}\delta_{no}\right](\bar{l}_m\gamma_\mu l_n)(\bar{l}_o\gamma^\mu l_p),$$

both C_{ll} and C'_{ll} are allowed to be independent parameters in the U(3)^5 flavour symmetric limit. The original paper used the same parameter C_{ll} in both terms, which is overly restrictive. This leads to $C_{ll} \to C'_{ll}$ in the expressions:

$$\delta G_F = \frac{1}{\sqrt{2}\,\hat{G}_F}\left(\sqrt{2}C^{(3)}_{H\ell} - \frac{1}{\sqrt{2}}C'_{ll}\right), \tag{4}$$

$$\delta\bar{g}_Z = -\frac{1}{\sqrt{2}}\,\delta G_F - \frac{1}{2}\frac{\delta m_Z^2}{\hat{m}_Z^2} + \frac{s_{\hat\theta}c_{\hat\theta}}{\sqrt{2}\hat{G}_F}C_{HWB} = -\frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{HD} + 4\,C^{(3)}_{H\ell} - 2C'_{ll}\right), \tag{15}$$

$$\delta g_1^\gamma = \frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{HD}\frac{\hat{m}_W^2}{\hat{m}_W^2 - \hat{m}_Z^2} - 4C^{(3)}_{H\ell} + 2C'_{ll} - C_{HWB}\frac{4\hat{m}_W}{\sqrt{\hat{m}_Z^2 - \hat{m}_W^2}}\right), \tag{22}$$

$$\delta g_1^Z = \frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{HD} - 4C^{(3)}_{H\ell} + 2C'_{ll} + 4\frac{\hat{m}_Z}{\hat{m}_W}\sqrt{1 - \frac{\hat{m}_W^2}{\hat{m}_Z^2}}C_{HWB}\right), \tag{23}$$

$$\delta\kappa_\gamma = \frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{HD}\frac{\hat{m}_W^2}{\hat{m}_W^2 - \hat{m}_Z^2} - 4C^{(3)}_{H\ell} + 2C'_{ll}\right), \tag{24}$$

$$\delta\kappa_Z = \frac{1}{4\sqrt{2}\hat{G}_F}\left(C_{HD} - 4C^{(3)}_{H\ell} + 2C'_{ll}\right), \tag{25}$$

The list in eq. (3.37) should also include C'_{ll}:

$$\tilde{C}_i \equiv \frac{\bar{v}_T^2}{\Lambda^2}\{C_{He}, C_{Hu}, C_{Hd}, C^{(1)}_{Hl}, C^{(3)}_{Hl}, C^{(1)}_{Hq}, C^{(3)}_{Hq}, C_{HWB}, C_{HD}, C_{ll}, C'_{ll}, C_{ee}, C_{le}\}, \tag{37}$$

and the number of Wilson coefficients in the text after eq. (3.45) is then 21.

The fit results in this case are shown in figures 3, 4, 5 and tables 5, 6. The limits obtained minimizing the coefficients one-at-a-time are largely unchanged, while the fit results that marginalize over the larger set of parameters are modified. A significant scheme dependence is found for C'_{ll} in this case. This coefficient enters the considered observables via shift parameters. In the $\{\hat\alpha, \hat{m}_Z, \hat{G}_F\}$-scheme it impacts most LEPI data, and in particular $\hat{m}_W$. In the $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$-scheme it affects dominantly bhabha scattering via $\delta\alpha$, that is less constraining. C_{ll} and C_{ee} are poorly constrained and strongly anti-correlated as they both contribute to bhabha scattering only, where they enter in a linear combination of the form[1] $[C_{ee} + (1 + \Delta(s, c_\theta))C_{ll}]$ where $0 < \Delta(s, c_\theta) < 0.1$ at the LEP2 c.m.s. energy. The direction $C_{ll} - C_{ee}$ is nearly unconstrained and this degeneracy is weakly broken by the kinematic dependence. The correlations are larger in the $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ scheme for the observables considered. C'_{ll} is more correlated with C_{ll}, C_{ee}, C_{le} as bhabha scattering provides the dominant constraint on C'_{ll} in this scheme increasing correlations. In the $\{\hat\alpha_W, \hat{m}_Z, \hat{G}_F\}$ scheme, C'_{ll} is primarily bounded by the m_W measurement, and this allows the parameters to split in less correlated blocks, one constrained by LEPI + WW production data and one by bhabha scattering.

[1]Here c_θ is the cosine of the angle between the incoming e^- and the outgoing e^+ in bhabha scattering.

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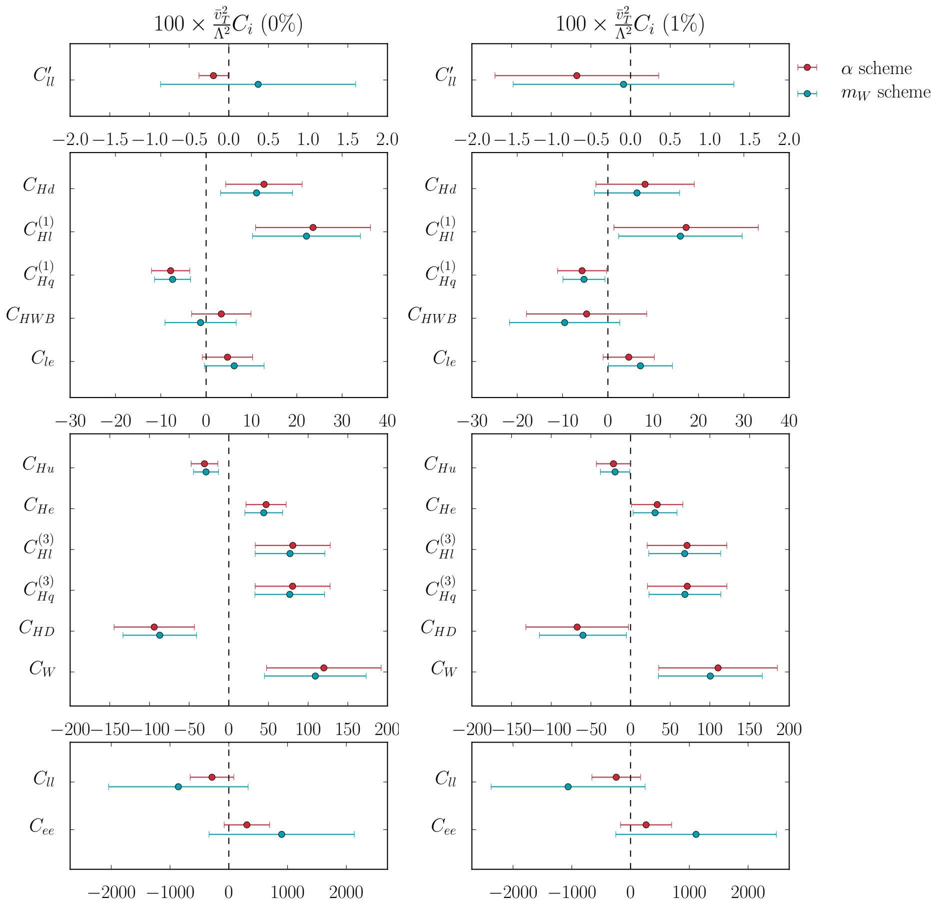

Figure 3. Best fit values of the Wilson coefficients (scaled by a factor 100) and corresponding $\pm 1\sigma$ confidence regions obtained after profiling away the other parameters. Red (blue) points were obtained in the $\{\hat{\alpha}\,(\hat{m}_W), \hat{m}_Z, \hat{G}_F\}$ input parameter scheme. The plot to the left has been obtained assuming $\Delta_{\rm SMEFT} = 0$, while the one to the right includes a theoretical error $\Delta_{\rm SMEFT} = 0.01$.

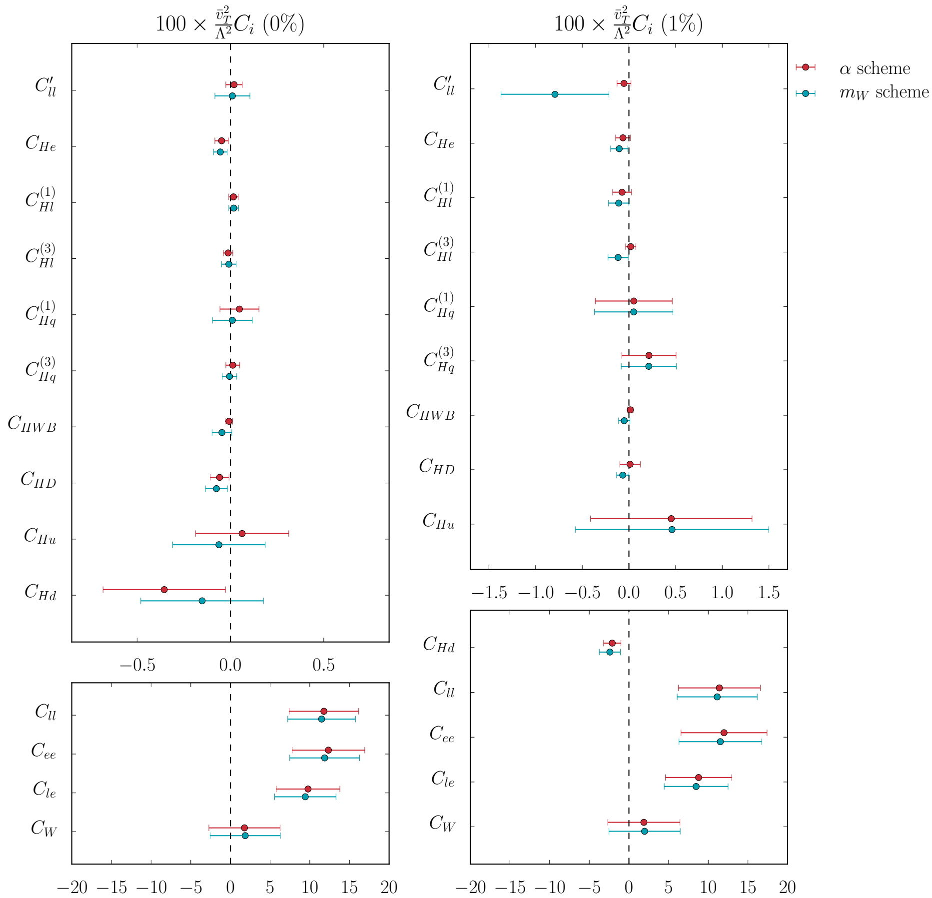

Figure 4. Best fit values of the Wilson coefficients (scaled by a factor 100) and corresponding $\pm 1\sigma$ confidence regions obtained minimizing the $\Delta\chi^2$ with one parameter at a time. Red (blue) points were obtained in the $\{\hat{\alpha}(\hat{m}_W), \hat{m}_Z, \hat{G}_F\}$ input parameter scheme. The plot to the left has been obtained assuming $\Delta_{\rm SMEFT} = 0$, while the one to the right includes a theoretical error $\Delta_{\rm SMEFT} = 0.01$. Note that in the right plot the x axis has been scaled by a factor 2 and the coefficient C_{Hd} has been moved to the lower panel: increasing the theoretical error enhances the pull of the $\mathcal{A}_{FB}^{0,b}$ anomaly compared to Z width data, and this relaxes by one order of magnitude the bound on this parameter.

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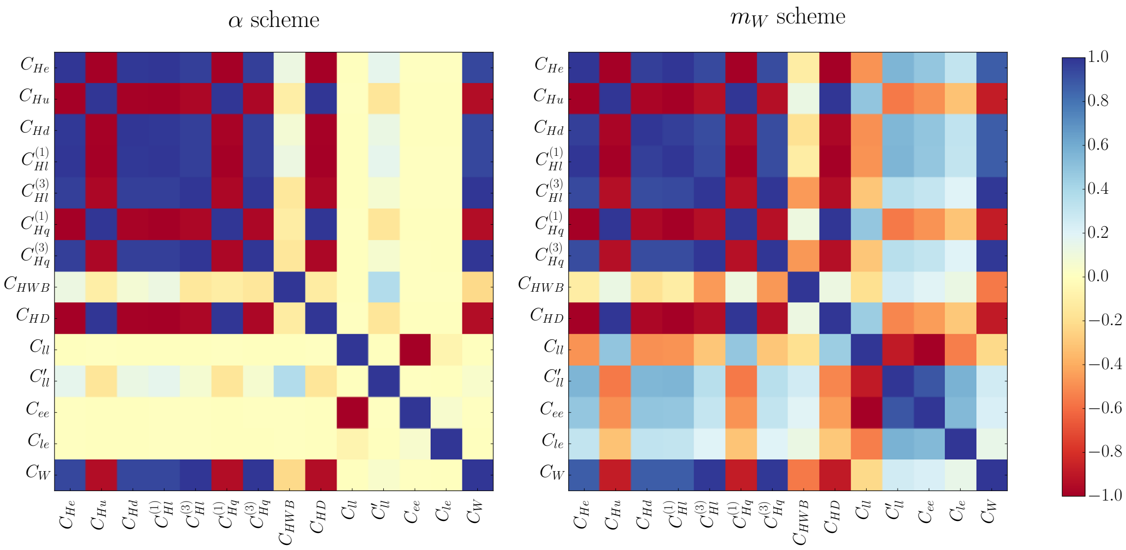

Figure 5. Color map of the correlation matrix among the Wilson coefficients, obtained assuming zero SMEFT error, for the $\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ input scheme (left) and for the $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ input scheme (right).

$C_i \times \frac{\bar{v}_T^2}{\Lambda^2}$	$\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme (0%)	(1%)	$\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ scheme (0%)	(1%)
C_{He}	$47. \pm 25.$	$34. \pm 32.$	$44. \pm 24.$	$31. \pm 28.$
C_{Hu}	$-31. \pm 17.$	$-22. \pm 22.$	$-29. \pm 16.$	$-20. \pm 18.$
C_{Hd}	12.8 ± 8.4	$8. \pm 11.$	$11. \pm 7.9$	6.4 ± 9.4
$C_{Hl}^{(1)}$	$24. \pm 13.$	$17. \pm 16.$	$22. \pm 12.$	$16. \pm 14.$
$C_{Hl}^{(3)}$	$81. \pm 47.$	$71. \pm 50.$	$77. \pm 44.$	$68. \pm 45.$
$C_{Hq}^{(1)}$	-7.8 ± 4.2	-5.7 ± 5.4	-7.4 ± 4.0	-5.2 ± 4.6
$C_{Hq}^{(3)}$	$80. \pm 47.$	$71. \pm 50.$	$77. \pm 44.$	$69. \pm 45.$
C_{HWB}	3.4 ± 6.5	$-5. \pm 13.$	-1.2 ± 7.9	$-10. \pm 12.$
C_{HD}	$-94. \pm 51.$	$-67. \pm 65.$	$-87. \pm 46.$	$-60. \pm 55.$
C_{ll}	$-286. \pm 371.$	$-244. \pm 414.$	$-859. \pm 1190.$	$-1062. \pm 1310.$
C'_{ll}	-0.19 ± 0.18	-0.7 ± 1.0	-0.37 ± 1.2	-0.08 ± 1.4
C_{ee}	$308. \pm 388.$	$264. \pm 434.$	$890. \pm 1240.$	$1114. \pm 1366.$
C_{le}	4.7 ± 5.5	4.6 ± 5.6	6.2 ± 6.6	7.1 ± 7.1
C_W	$120. \pm 72.$	$110. \pm 75.$	$109. \pm 64.$	$101. \pm 65.$

Table 5. Best fit values and corresponding 1σ confidence regions for $\Delta_{\rm SMEFT} = \{0\%, 1\%\}$ and for the two input parameter schemes considered in this work. The numbers have been obtaining after profiling the χ^2 over the other parameters and they have been multiplied by a factor 100.

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$C_i \times \frac{\bar{v}_T^2}{\Lambda^2}$	$\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ scheme (0%)	(1%)	$\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ scheme (0%)	(1%)
C_{He}	-0.047 ± 0.036	-0.064 ± 0.079	-0.054 ± 0.037	-0.104 ± 0.092
C_{Hu}	0.06 ± 0.25	0.45 ± 0.87	-0.06 ± 0.25	0.462 ± 1.036
C_{Hd}	-0.35 ± 0.33	-2.1 ± 1.1	-0.152 ± 0.33	-2.4 ± 1.3
$C_{Hl}^{(1)}$	0.016 ± 0.025	-0.07 ± 0.10	0.018 ± 0.026	-0.109 ± 0.11
$C_{Hl}^{(3)}$	-0.013 ± 0.025	0.019 ± 0.054	-0.009 ± 0.039	-0.12 ± 0.11
$C_{Hq}^{(1)}$	0.05 ± 0.10	0.05 ± 0.41	0.01 ± 0.11	0.05 ± 0.42
$C_{Hq}^{(3)}$	0.013 ± 0.037	0.21 ± 0.29	-0.005 ± 0.039	0.21 ± 0.30
C_{HWB}	-0.008 ± 0.020	0.015 ± 0.029	-0.046 ± 0.053	-0.050 ± 0.061
C_{HD}	-0.058 ± 0.051	0.01 ± 0.11	-0.075 ± 0.059	-0.066 ± 0.066
C_{ll}	11.8 ± 4.4	11.4 ± 5.2	11.9 ± 4.4	11.1 ± 5.0
C'_{ll}	0.019 ± 0.044	-0.053 ± 0.074	0.011 ± 0.094	-0.79 ± 0.58
C_{ee}	12.4 ± 4.6	12.0 ± 5.4	11.9 ± 4.4	11.5 ± 5.2
C_{le}	9.8 ± 4.0	8.8 ± 4.2	9.4 ± 3.9	8.5 ± 4.0
C_W	1.8 ± 4.5	1.9 ± 4.5	1.9 ± 4.4	2.0 ± 4.5

Table 6. Best fit values and corresponding 1σ confidence regions for $\Delta_{\rm SMEFT} = \{0\%, 1\%\}$ and for the two input parameter schemes considered in this work. These numbers have been obtained minimizing the χ^2 with one parameter at a time (despite the non-minimal character of the SMEFT [1]), and they have been multiplied by a factor 100.

References

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[2] V. Cirigliano, J. Jenkins and M. Gonzalez-Alonso, *Semileptonic decays of light quarks beyond the standard model*, Nucl. Phys **B 830** (2010) 95 [arXiv:0908.1754].

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