EW precision data and the 1-loop Γ_Z in the SMEFT

- M. Trott

EW Moriond 20th Mar 2017

NBI, NBIA, Copenhagen

VILLUM FONDEN

Mentions from papers:

arXiv:1701.06424 Reparameterization! Ilaria Brivio, MT

arXiv:1612.02040 Non-Minimal Character Yun Jiang, MT

arXiv:1611.09879 One Loop Z C. Hartmann, W. Shepherd, MT

arXiv:1606.06693 EWPD series L. Berthier, M. Bjorn, MT

arXiv:1606.06502 SMEFT W mass, M. Bjorn, MT

arXiv:1502.02570, arXiv:1508.05060 EWPD series, L. Berthier, MT

Basic messages

Using measurements in the SMEFT in a global constraint program need:

- Checks if the measurement assumed the SM in a manner that introduces significant bias for interpretation outside the SM
- Checks if the measurement is precise and accurate enough that one loop corrections projecting this measurement into the SMEFT lead to a gain in its full constraint/discovery power.
- For LEP EWPD, measurement bias is under control, but the LO SMEFT interpretation is insufficient. One loop is on the way. Partial results presented here for $\mathcal{O}(y_t^2), \mathcal{O}(\lambda)$ corrections to $\Gamma_Z,\ R_f^0,\ \Gamma_{Z\to\bar{i},i}$

arXiv:1611.09879 One Loop Z C. Hartmann, W. Shepherd, MT

E.T.A. for full one loop result - this year; multiple groups

SM $\neq$ SMEFT $\neq$ "an extra operator"

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}}\mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B \neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots$$

UV model* $\longrightarrow$ SMEFT $\longrightarrow$ SM

$$\frac{C_i\, v^2}{\Lambda^2}, \frac{C_i\, p^2}{\Lambda^2} < 1 \qquad\qquad \Lambda \to \infty$$

* Assuming no large "nonlinearities/scalar manifold curvatures" (HEFT vs SMEFT as the IR limit assumption.)

SM $\neq$ SMEFT $\neq$ “an operator”

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L \neq 0}} \mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B = 0}} \mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L \neq 0}} \mathcal{L}_7 + \frac{1}{\Lambda^4} \mathcal{L}_8 + \cdots$$

SMEFT is the field theory this talk is focused on… in a symmetric limit:

14 operators, or 18 parameters (+ 1 op and then 19 with strong CP)

1 operator, and 7 extra parameters (dirac) or 9 if Majorana phases

59 + h.c operators, or 2499 parameters (or 76 flavour sym. $U(3)^5$ limit)

$(2499 \ll \infty)$

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

4 operators, or 408 parameters (all violate B number)

arXiv:1405.0486 Alonso, Cheng, Jenkins, Manohar, Shotwell

22 operators or 948 parameters, (all violate L number, B number preserving)

arXiv:1410.4193 L. Lehman

arXiv:1510.00372 L. Lehman and A. Martin,

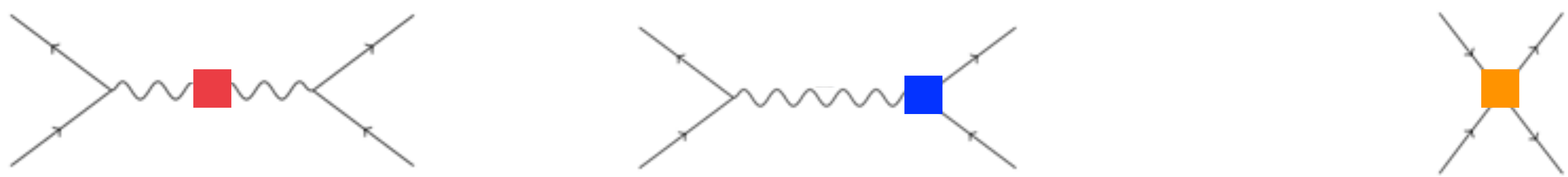
arXiv:1512.03433 Henning, Lu, Meliac, Murayama

Will use Warsaw basis in this talk - see backup slides.

How many parameters in EWPD?

- For measurements of LEPI near Z pole data and W mass at LO:

$$\boxed{Q_{HWB}, Q_{HD}}, \boxed{Q_{H\ell}^{(1)}, Q_{H\ell}^{(3)}, Q_{Hq}^{(1)}, Q_{Hq}^{(3)}, Q_{He}, Q_{Hu}, Q_{Hd}}, \boxed{Q_{\ell\ell}}$$

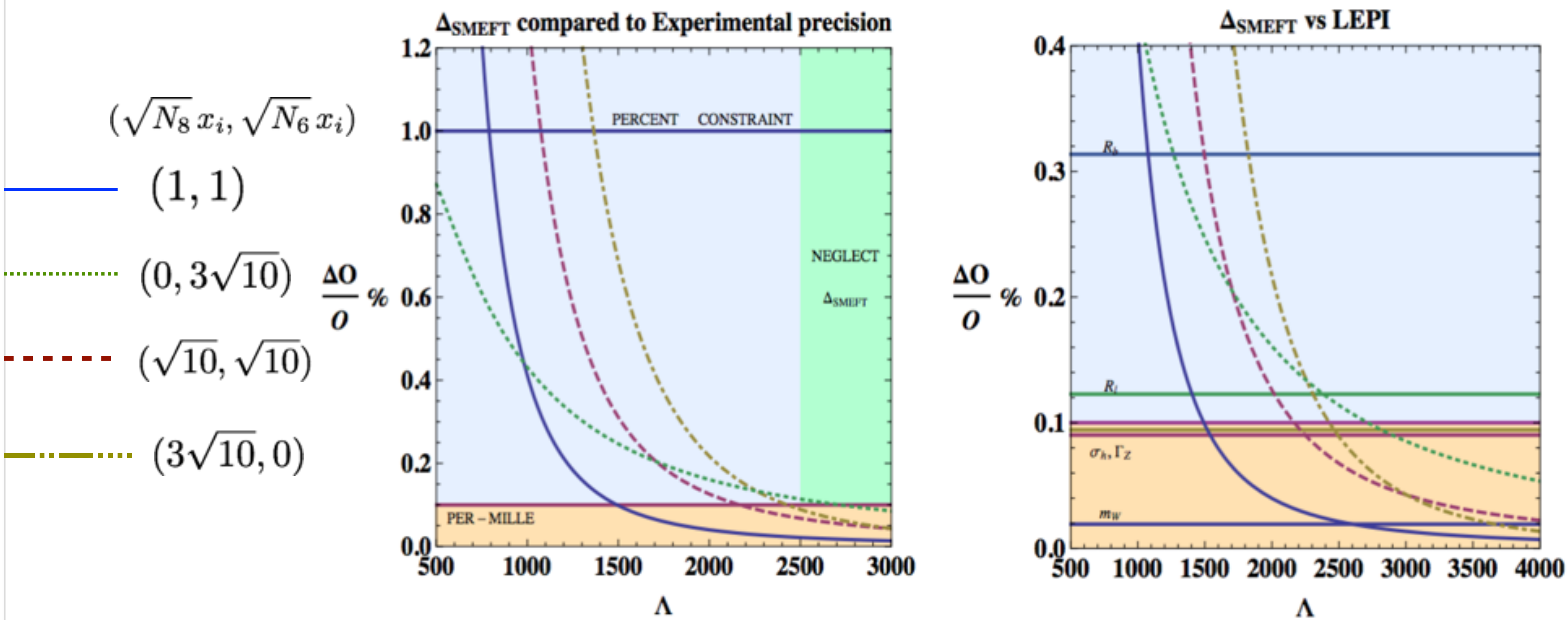


- Relevant four fermion operator at LO is introduced due to $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$ (used to extract G_F)
- Some basis dependence in this, but $\mathcal{O}(10) \ll 76$ as $\Gamma_{W,Z}/M_{W,Z} \ll 1$
- How much do neglected higher order terms effect EWPD?

EWPD and neglected higher order

- For precise observables, neglected higher order terms can affect interpretation.

Estimate: $\Delta^{i}_{SMEFT}(\Lambda) \simeq \sqrt{N_8}\, x_i\, \frac{\bar{v}_T^4}{\Lambda^4} + \frac{\sqrt{N_6}\, g_2^2}{16\, \pi^2}\, y_i \log\left[\frac{\Lambda^2}{\bar{v}_T^2}\right] \frac{\bar{v}_T^2}{\Lambda^2}.$ arXiv:1508.05060 Berthier, Trott



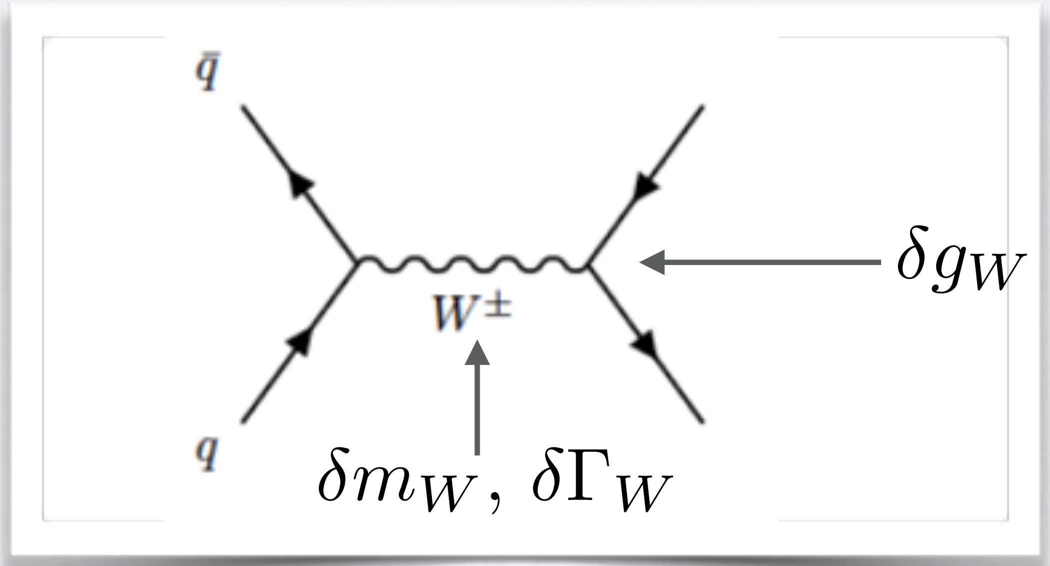
Ex of measurement bias check

- To use a measurement of M_W to constrain the SMEFT: $\{\hat{\alpha}, \hat{G}_F, \hat{m}_Z\}$ inputs

$$\frac{\delta m_W^2}{\hat{m}_W^2} = \frac{c_{\hat{\theta}}\, s_{\hat{\theta}}}{(c_{\hat{\theta}}^2 - s_{\hat{\theta}}^2) 2\sqrt{2}\,\hat{G}_F}\left[4C_{HWB} + \frac{c_{\hat{\theta}}}{s_{\hat{\theta}}}\,C_{HD} + 4\,\frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} C_{H\ell}^{(3)} - 2\frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} C_{\ell\,\ell}\right]$$

This is how you want the constraint to act.

BUT measurement via transverse variables actually measures a process:



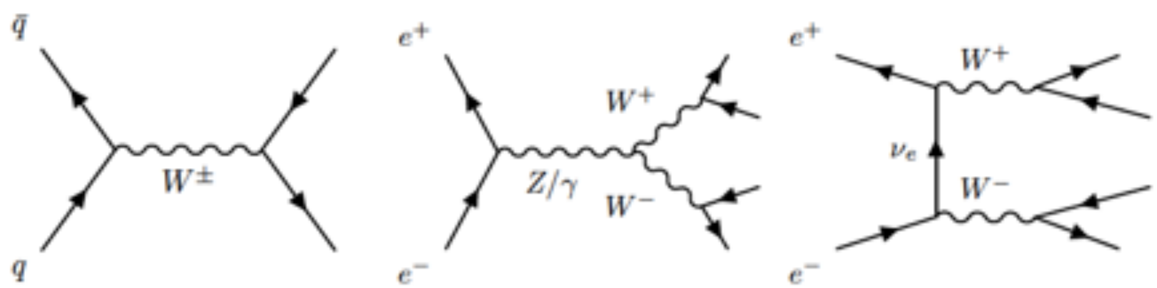
- How wrong is it to just apply the constraint pretending the other shifts not there?

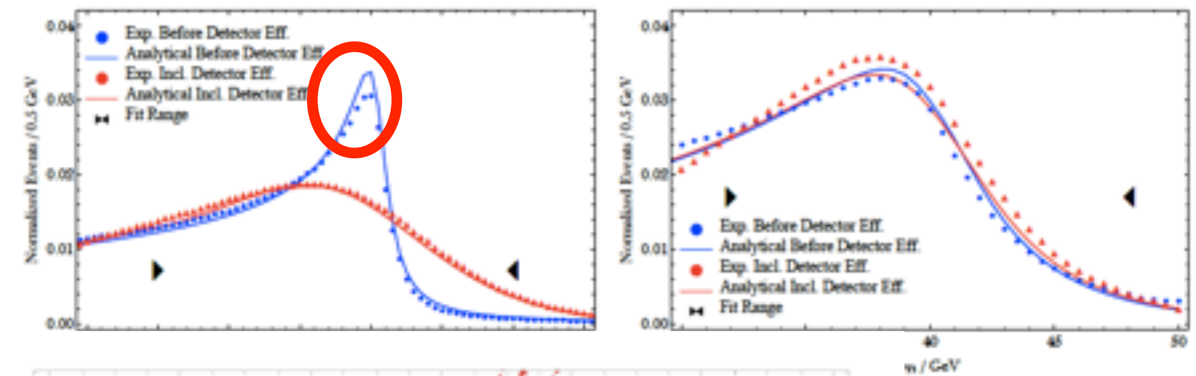
Mw measurements in SMEFT

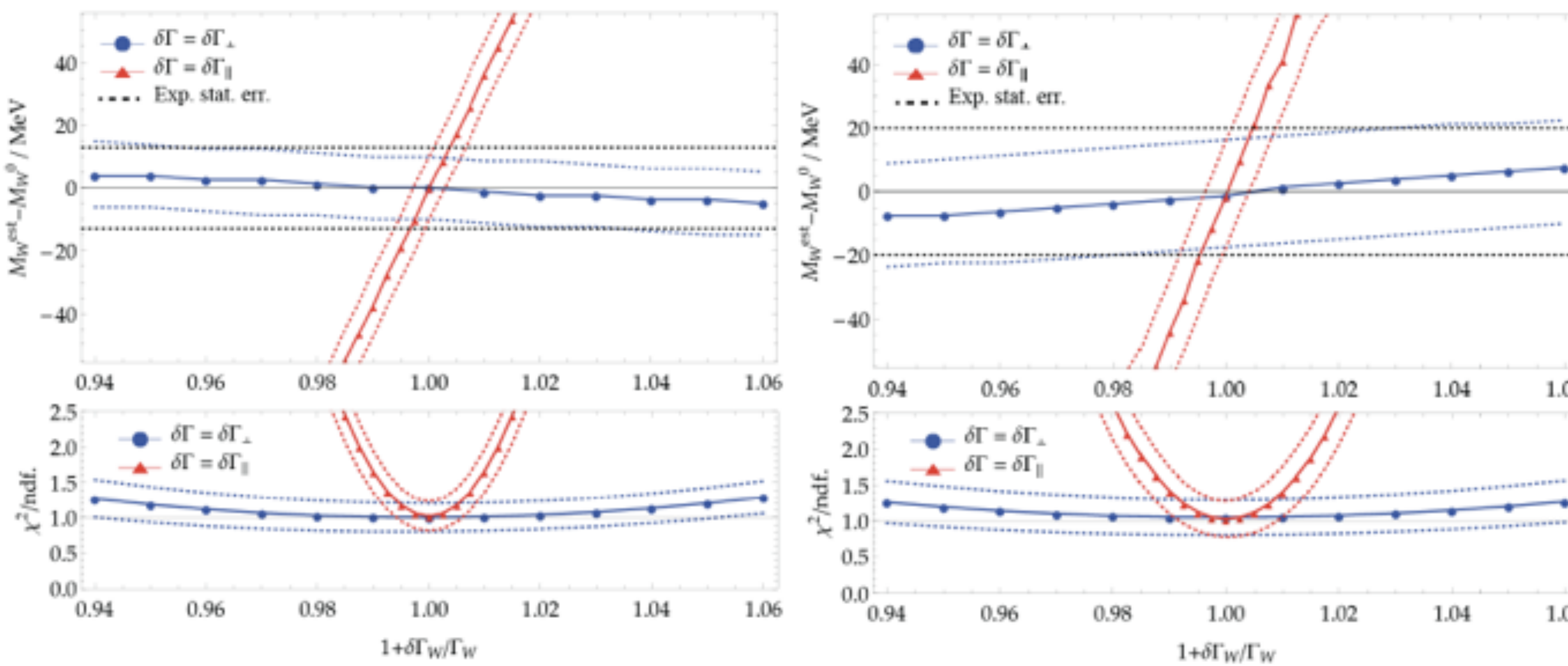
- Mw is a template fit at LEP and at the Tevatron.

1606.06502 Bjorn, Trott

Transverse mass Jacobian peak



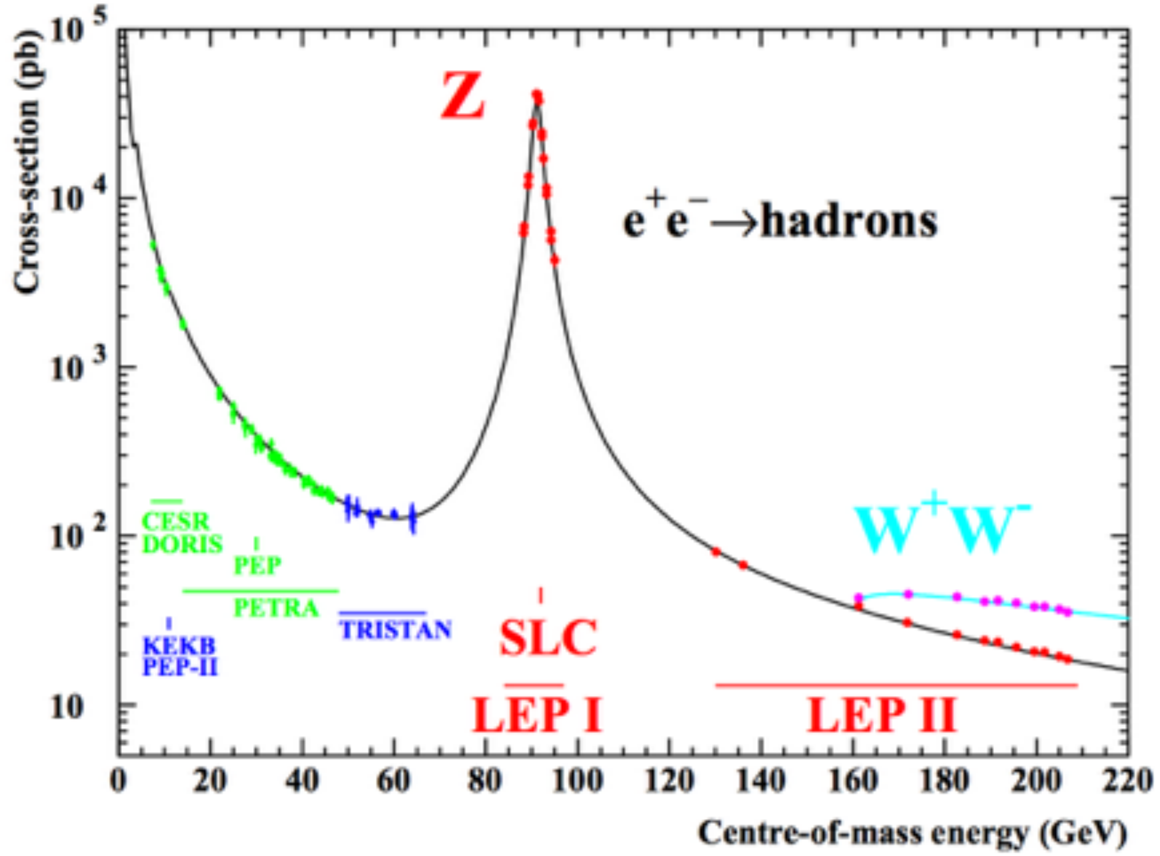




Below percent measurements in SMEFT at colliders possible

- Error quoted on the extraction for the Tevatron is OK in the SMEFT!

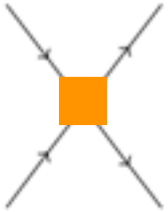
EWPD measurements in SMEFT



- EWPD is a scan through the Z pole

$\sim 40\, pb^{-1}$ off peak data

$\sim 155\, pb^{-1}$ on peak data



- many more ψ^4 ops suppressed by $\dfrac{m_z\,\Gamma_Z}{v^2}$

arXiv:1502.02570 Berthier, MT

- The pseudo-observable LEP data is not subject to large intrinsic measurement bias transitioning from SM to SMEFT, so loops a go!

SMEFT has a non-minimal character

- How many ops induced at tree level or loop level in typical UV sectors?

  Matching at one loop in many models - See Santiago's talk.

- In Warsaw basis, full one loop renormalization of $\mathcal{L}_6$ known.

  arXiv:1301.2588 Grojean, Jenkins, Manohar, Trott
  arXiv:1308.2627, 1309.0819, 1310.4838 Jenkins, Manohar, Trott
  arXiv: 1312.2014 Alonso, Jenkins, Manohar, Trott

  Extensive mixing between operators in most cases.

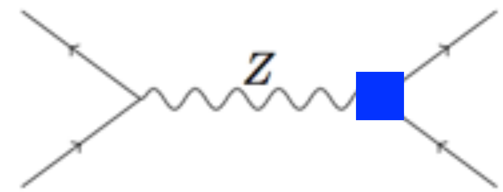
- At tree level, you can prove that multiple operators are induced, so long as you do not explicitly break flavour symmetry and demand that the UV scale Λ has a dynamical origin.

  arXiv:1612.02040 Yun Jiang, MT

Ex of non-minimal character

- To not induce operators that are mixed scalar fermion currents:

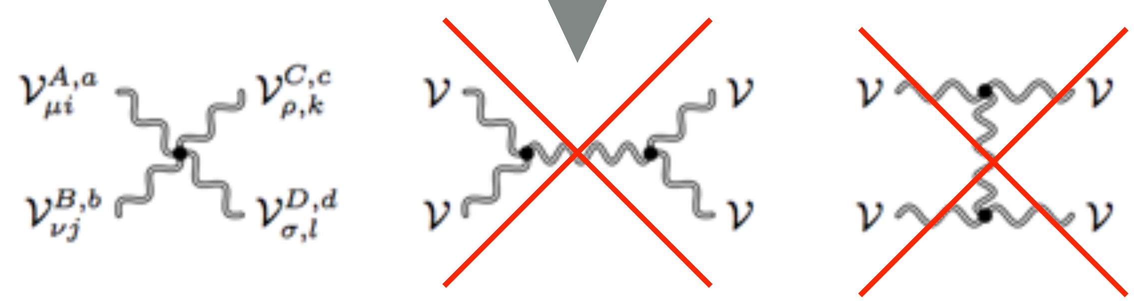
$$\boxed{Q_{H\ell}^{(1)}, Q_{H\ell}^{(3)}, Q_{Hq}^{(1)}, Q_{Hq}^{(3)}, Q_{He}, Q_{Hu}, Q_{Hd}}$$



$\mathrm{SU(3)_C}$	$\mathrm{SU(2)_L}$	$\mathrm{U(1)_Y}$	$\mathrm{G_Q}$	$\mathrm{G_L}$	Couples to
1	1	0	(1,1,1)	(1,1)	$H^\dagger i D^\mu H$
1	3	0	(1,1,1)	(1,1)	$H^\dagger \sigma^I i D^\mu H$

Don't induce the scalar current, so have a non-zero $\mathrm{U}(1)_Y$ charge in new states

But then

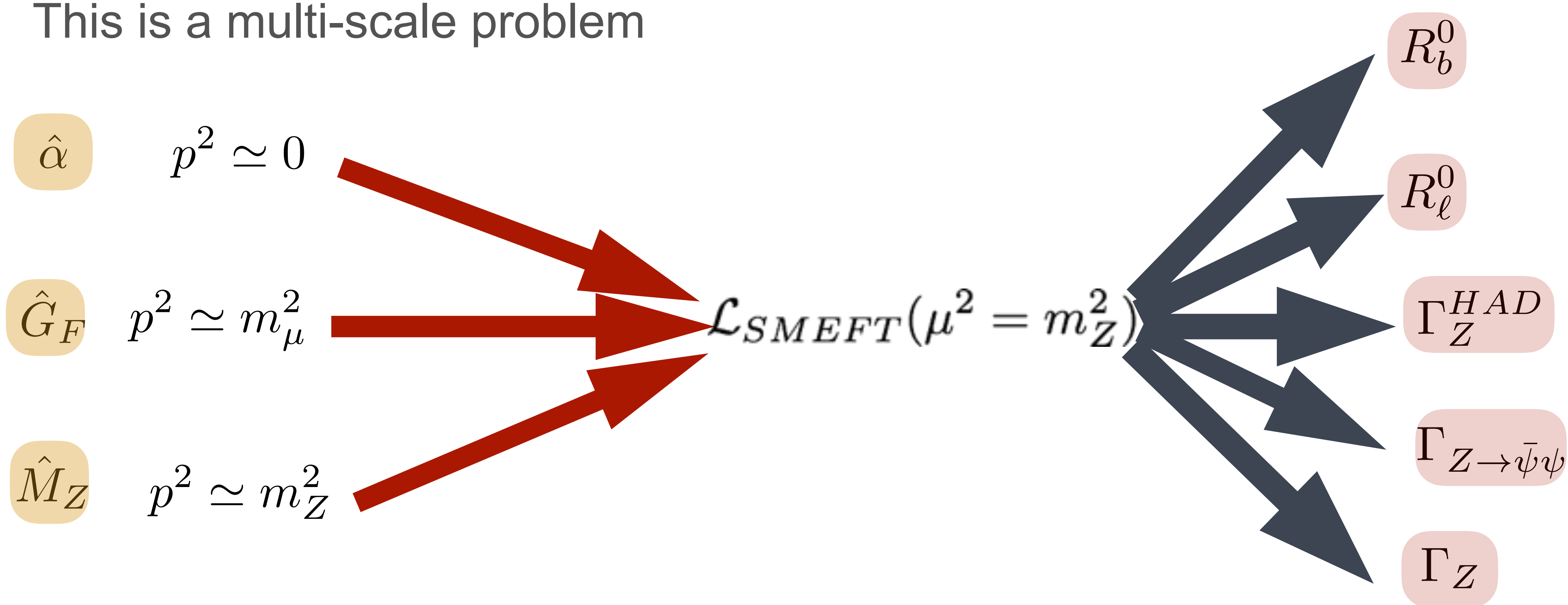


Vector causes unitarity violation $\Lambda_V \sim m_V$

arXiv:1612.02040 Yun Jiang, MT

To predict the decay widths of the Z

- This is a multi-scale problem



- LSZ defn: $\langle Z|S|\bar{\psi}_i \, \psi_i\rangle = (1 + \frac{\Delta R_Z}{2})(1 + \Delta R_{\psi_i})\, i\, \mathcal{A}_{Z\bar{\psi}_i\psi_i}.$

- Need to loop improve the extraction of parameters AND the decay process of interest.

input shifts   decay process (wavefunction&process)

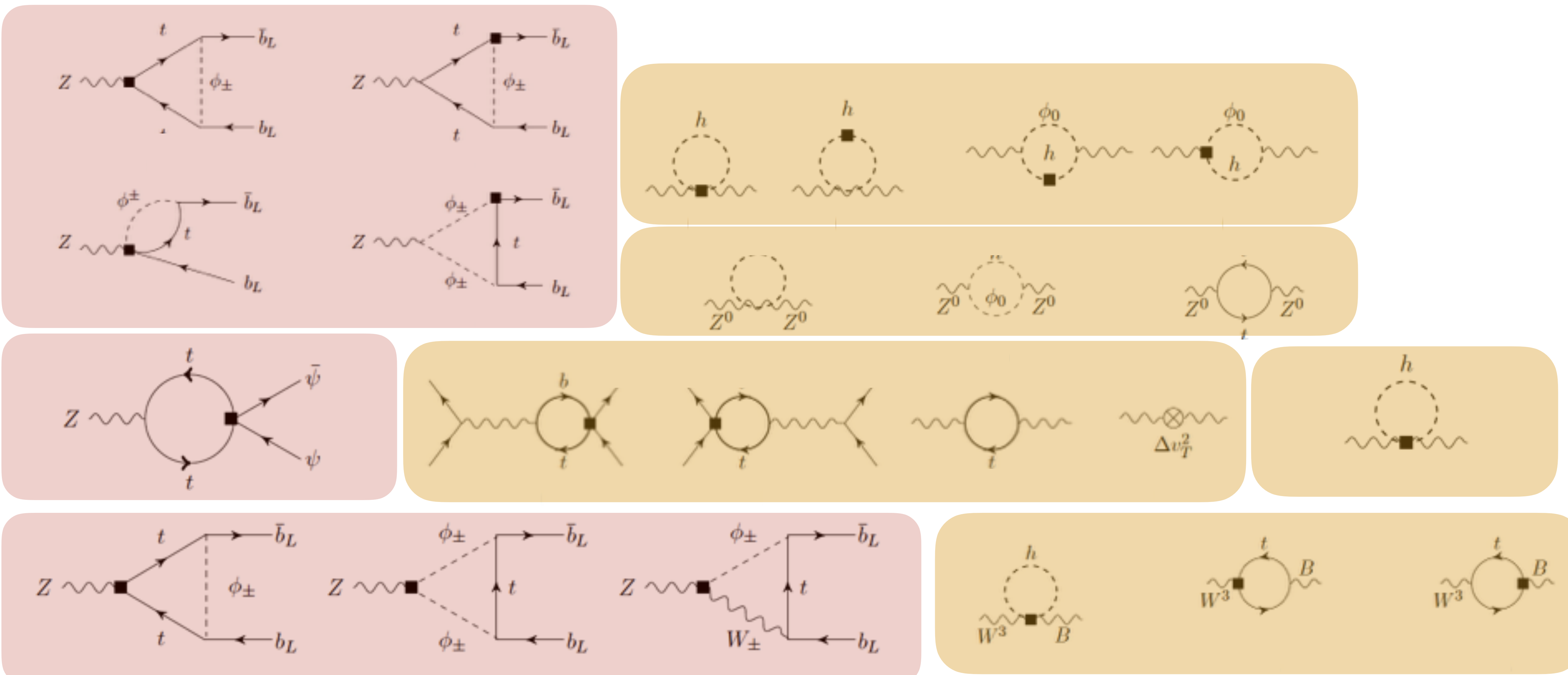
Loops present

- ~ 30 massive loops in addition to the RGE dim reg results of

arXiv:1301.2588 Grojean, Jenkins, Manohar, Trott

arXiv:1308.2627, 1309.0819, 1310.4838 Jenkins, Manohar, Trott

arXiv: 1312.2014 Alonso, Jenkins, Manohar, Trott

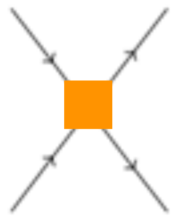


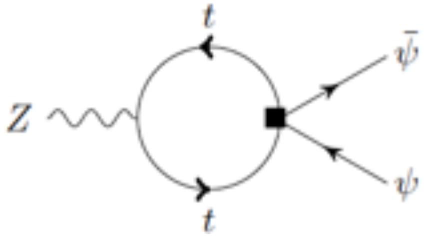
To predict the decay widths of the Z

- (At least) the following operators contribute at one loop to EWPD, that are not present at tree level

$$\{C_{qq}^{(1)}, C_{qq}^{(3)}, C_{qu}^{(1)}, C_{uu}, C_{qd}^{(1)}, C_{ud}^{(1)}, C_{\ell q}^{(1)}, C_{\ell q}^{(3)}, C_{\ell u}, C_{qe}, C_{HB} + C_{HW}, C_{uB}, C_{uW}, C_{uH}\}.$$

- Distinctions between operators made at LO not relevant





- Corrections reported as:

$$\bar{\Gamma}\left(Z \to \psi\bar{\psi}\right) = \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3\, N_c}{6\pi}\left(|\bar{g}_L^{\psi}|^2 + |\bar{g}_R^{\psi}|^2\right),$$

$$\delta\bar{\Gamma}_{Z\to\ell\bar{\ell}} = \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3}{6\pi}\left[2\, g_R^{\ell}\,\delta g_R^{\ell} + 2\, g_L^{\ell}\,\delta g_L^{\ell}\right] + \delta\bar{\Gamma}_{Z\to\bar{\ell}\ell,\psi^4},$$

$$\Delta\bar{\Gamma}_{Z\to\ell\bar{\ell}} = \frac{\sqrt{2}\,\hat{G}_F \hat{m}_Z^3}{6\pi}\left[2\, g_R^{\ell}\,\Delta g_R^{\ell} + 2\, g_L^{\ell}\,\Delta g_L^{\ell} + 2\,\delta g_R^{\ell}\,\Delta g_R^{\ell} + 2\,\delta g_L^{\ell}\,\Delta g_L^{\ell}\right],$$

Parameters exceeds LEP PO at one loop

- Structure of corrections at tree and loop level:

7.2 One loop corrections in the SMEFT

7.2.1 Charged Lepton effective couplings

For charged lepton final states the leading order (flavour symmetric) SMEFT effective coupling shifts are [11]

$$\delta(g_L^\ell)_{ss} = \delta\bar{g}_Z\,(g_L^\ell)_{ss}^{SM} - \frac{1}{2\sqrt{2}\hat{G}_F}\left(C^{(1)}_{\substack{H\ell\\ ss}} + C^{(3)}_{\substack{H\ell\\ ss}}\right) - \delta s_\theta^2, \tag{7.6}$$

$$\delta(g_R^\ell)_{ss} = \delta\bar{g}_Z\,(g_R^\ell)_{ss}^{SM} - \frac{1}{2\sqrt{2}\hat{G}_F} C_{\substack{He\\ ss}} - \delta s_\theta^2, \tag{7.7}$$

where

$$\delta\bar{g}_Z = -\frac{\delta G_F}{\sqrt{2}} - \frac{\delta M_Z^2}{2\hat{m}_Z^2} + s_{\hat\theta}^2\, c_{\hat\theta}^2\, 4\,\hat{m}_Z^2\, C_{HWB}, \tag{7.8}$$

while the one loop corrections are

$$\Delta(g_L^\ell)_{ss} = \Delta\bar{g}_Z\,(g_L^\ell)_{ss}^{SM} + \frac{N_c\,\hat{m}_t^2}{8\,\pi^2}\,\log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\left[C^{(1)}_{\substack{\ell q\\ ss33}} + C^{(3)}_{\substack{\ell q\\ ss33}} - C_{\substack{\ell u\\ ss33}}\right] - \Delta s_\theta^2, \tag{7.9}$$

$$\Delta(g_R^\ell)_{ss} = \Delta\bar{g}_Z\,(g_R^\ell)_{ss}^{SM} + \frac{N_c\,\hat{m}_t^2}{8\,\pi^2}\,\log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right]\left[-C^{(1)}_{\substack{eu\\ ss33}} + C_{\substack{qe\\ 33ss}}\right] - \Delta s_\theta^2, \tag{7.10}$$

input shifts

decay process

One set of lots o numbers…

- Result for Γ_Z in tev units

$$\frac{\delta\bar{\Gamma}_Z}{10^{-2}} = \Big[-2.82\left(C_{Hd}+C_{He}+C^{(1)}_{H\ell}\right) - 9.87\,C_{HD} - 30.2\,C^{(3)}_{H\ell} + 6.97\,C^{(1)}_{Hq} + 23.6\,C^{(3)}_{Hq}, \\ +3.75\,C_{Hu} - 2.80\,C_{HWB} + 19.7\,C_{\ell\ell}\Big]. \tag{A.22}$$

$$\frac{\delta\Delta\bar{\Gamma}_Z}{10^{-3}} = \Big[(0.214\,\Delta\bar{v}_T + 0.603)\left(C_{Hd}+C_{He}+C^{(1)}_{H\ell}\right) - (1.09\,\Delta\bar{v}_T + 1.44)\,C_{HD}, \\ -(9.69\,\Delta\bar{v}_T + 9.11)\,C^{(3)}_{H\ell} + (0.174\,\Delta\bar{v}_T - 0.049)\,C^{(1)}_{Hq} + (1.73\,\Delta\bar{v}_T - 0.406)\,C^{(3)}_{Hq}, \\ -(0.286\,\Delta\bar{v}_T + 0.725)\,C_{Hu} - (0.560\,\Delta\bar{v}_T + 1.00)\,C_{HWB}, \\ +(5.20\,\Delta\bar{v}_T + 4.45)\,C_{\ell\ell} + 3.71\,C^{(3)}_{\ell q} + 1.28\,C^{(3)}_{qq}, \\ +0.101\,C_{uH} + 0.395\,(C_{HB}+C_{HW}) + 26.5\,\Delta\bar{v}_T\Big], \tag{A.23}$$

$$\frac{\delta\Delta\bar{\Gamma}_Z}{10^{-3}} = \Big[1.03\left(C_{Hd}+C_{He}+C^{(1)}_{H\ell}\right) - 2.56\,C_{HD} - 9.66\,C^{(3)}_{H\ell} - 0.749\,C^{(1)}_{Hq} + 0.590\,C^{(3)}_{Hq}, \\ -1.53\,C_{Hu} - 1.71\,C_{HWB} + 8.49\,C_{\ell\ell} - 5.69\,C^{(3)}_{\ell q} + 7.60\,C^{(3)}_{qq}, \\ +0.529\left(C^{(1)}_{\ell q} + C^{(1)}_{qd} + C_{qe} + C^{(1)}_{qd} - C_{\ell u} - C^{(1)}_{ud} - C_{eu}\right) \\ -2.62\,C^{(1)}_{qq} + 0.605\,C^{(1)}_{qu} + 0.067\,C_{uH} + 1.41\,C_{uu} - 0.651\,C_{uW} - 0.391\,C_{uB}\Big]\log\left[\frac{\Lambda^2}{\hat{m}_t^2}\right], \\ +\Big[0.046\left(C_{Hd}+C_{He}+C^{(1)}_{H\ell}\right) + 1.60\times10^{-4}\,C_{HD}, - 0.114\,C^{(1)}_{Hq} - 0.386\,C^{(3)}_{Hq}, \\ -0.061\,C_{Hu} + 0.495\,C^{(3)}_{H\ell} - 0.323\,C_{\ell\ell} - 0.034\,C_{HWB}\Big]\log\left[\frac{\Lambda^2}{\hat{m}_h^2}\right]. \tag{A.24}$$

Conclusions

- One loop results in the SMEFT are becoming increasingly available in well defined formalisms.
- You should check if it matters for the analysis you are working on, and also check if your analysis is constructed to avoid measurement bias generalizing the results into the SMEFT from the SM in the long term
- EWPD is robust against measurement bais (as far as we can tell) and partial one loop results reported for $\mathcal{O}(y_t^2), \mathcal{O}(\lambda)$ corrections to $\Gamma_Z,\, R_f^0,\, \Gamma_{Z\to \bar{i},i}$
- SMEFT has a non-minimal character at one loop and at tree level in matchings.
- LEPI data projects constraints on parameters including the Z vertex corrections in a manner that is UNCONSTRAINED when you hit the loop correction size — when considered alone.

Backup Slides

LO SMEFT = dim 6 shifts

- Warsaw basis: 1008.4884 Grzadkowski, Iskrzynski, Misiak, Rosiek

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

6 gauge dual ops

28 non dual operators

25 four fermi ops

59 + h.c. operators

Notation:

$$\widetilde X_{\mu\nu} = \tfrac{1}{2}\varepsilon_{\mu\nu\rho\sigma} X^{\rho\sigma} \quad (\varepsilon_{0123} = +1)$$

$$\widetilde\varphi^j = \varepsilon_{jk}(\varphi^k)^\star \qquad \varepsilon_{12} = +1$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi \equiv i\varphi^\dagger\left(D_\mu - \overleftarrow{D}_\mu\right)\varphi$$

$$\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi \equiv i\varphi^\dagger\left(\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I\right)\varphi$$

LO SMEFT = dim 6 shifts

- Four fermion operators: 1008.4884 Grzadkowski, Iskrzynski, Misiak,Rosiek

$8:(\bar{L}L)(\bar{L}L)$		$8:(\bar{R}R)(\bar{R}R)$		$8:(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$		$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$	$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Parameter breakdown

Dim 6 counting is a bit non trivial.

Class		N_{op}	CP-even n_g	1	3	CP-odd n_g	1	3
	1 g^3X^3	4	2	2	2	2	2	2
	2 H^6	1	1	1	1	0	0	0
	3 H^4D^2	2	2	2	2	0	0	0
	4 $g^2X^2H^2$	8	4	4	4	4	4	4
	5 $y\psi^2H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
	6 $gy\psi^2XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
	7 ψ^2H^2D	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
ψ^4	8 : $(\overline{L}L)(\overline{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
ψ^4	8 : $(\overline{R}R)(\overline{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
ψ^4	8 : $(\overline{L}L)(\overline{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
ψ^4	8 : $(\overline{L}R)(\overline{R}L)$	1	n_g^4	1	81	n_g^4	1	81
ψ^4	8 : $(\overline{L}R)(\overline{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
ψ^4	8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total		59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

Model independent Global analysis business

- Similar to past work in: Grinstein and Wise Phys.Lett. B265 (1991) 326-334

  Han and Skiba http://arxiv.org/abs/hep-ph/0412166

  Pomarol and Riva https://arxiv.org/abs/1308.2803

  Falkowski and Riva https://arxiv.org/abs/1411.0669

- Key improvements in recent work: Non redundant basis.
  (Han skiba before Warsaw developed)

  Attempt(s) at theory error FOR THE SMEFT included.

  More data, and LEPII done in a more consistent fashion.

- Our conclusions more in line with the less aggressive claims of Han and Skiba despite the basis issues there. Not surprizing. They are careful and the data didn't change for the LEP side of the story in any important manner after that.

Global constraints on dim 6-update

- The Wilson coefficient constraints are highly correlated

JHEP 1609 (2016) 157 1606.06693 Berthier, Bjorn, Trott

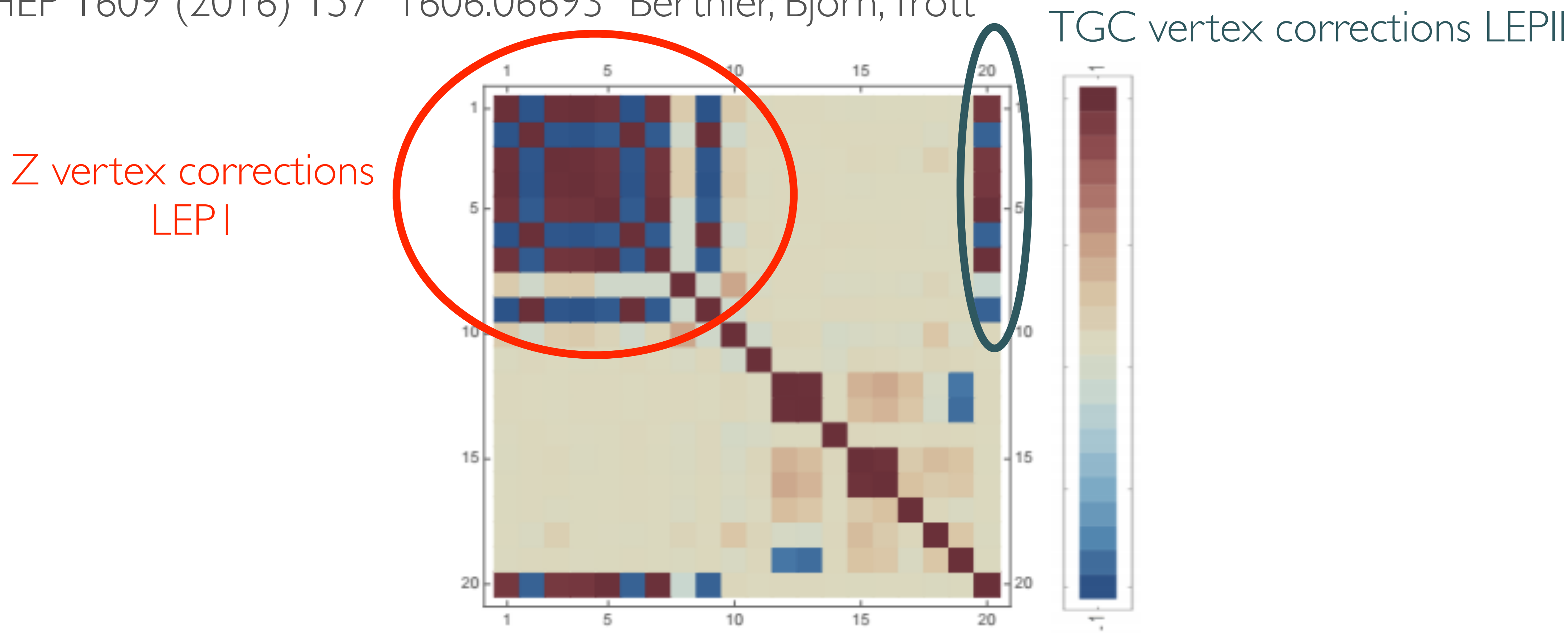
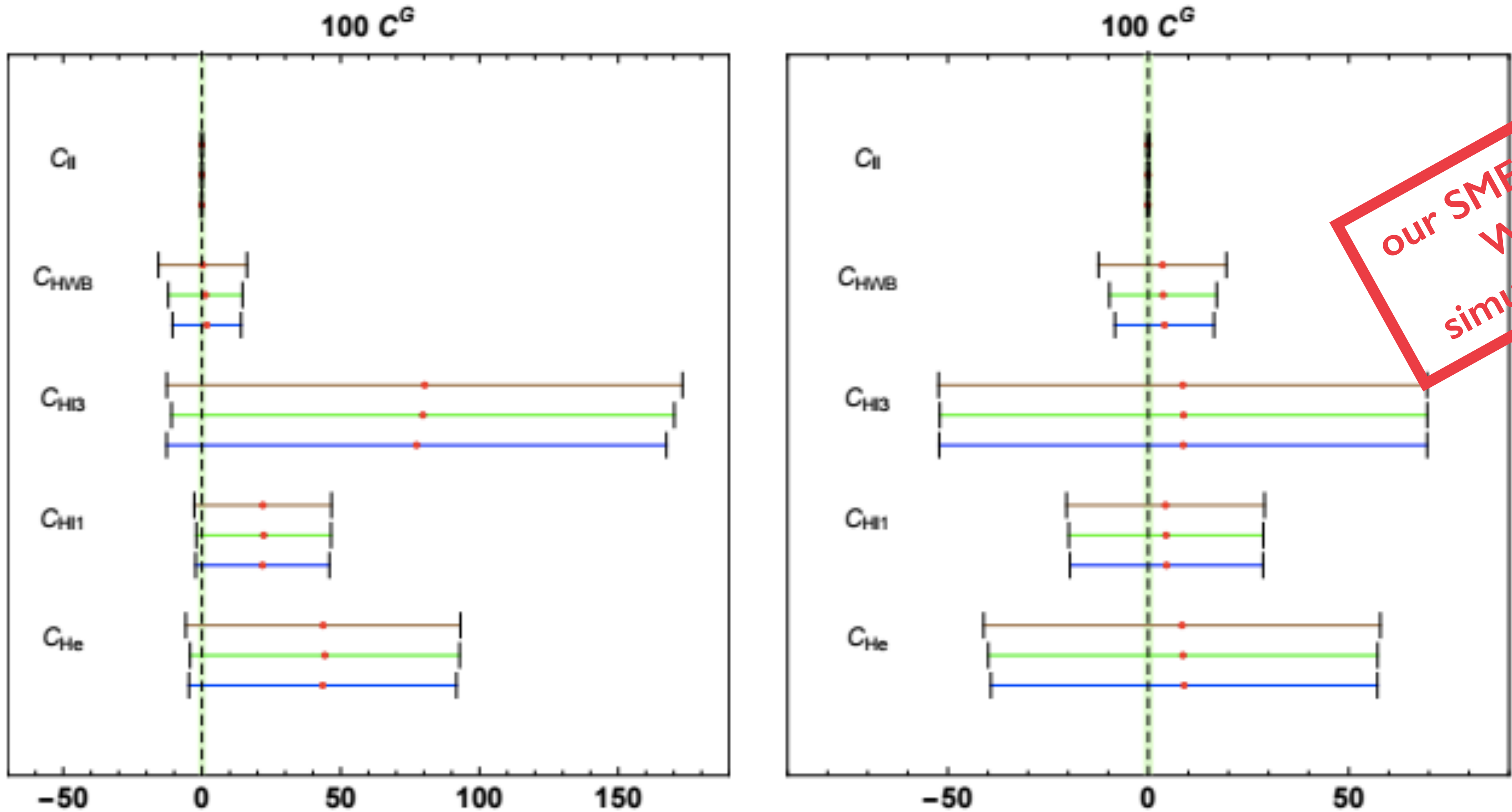


Figure 5: Color map of the correlation matrix between the Wilson coefficients when there is no SMEFT error.The Wilson coefficients are ordered as in Eqn.3.6.

- UV assumptions or sloppy TGC bound treatment can have HUGE effect on the fit space once profiled down.

Global constraints on dim 6-update

- Summary Warsaw basis profiling down to 1 coeff at a time 2 sigma:

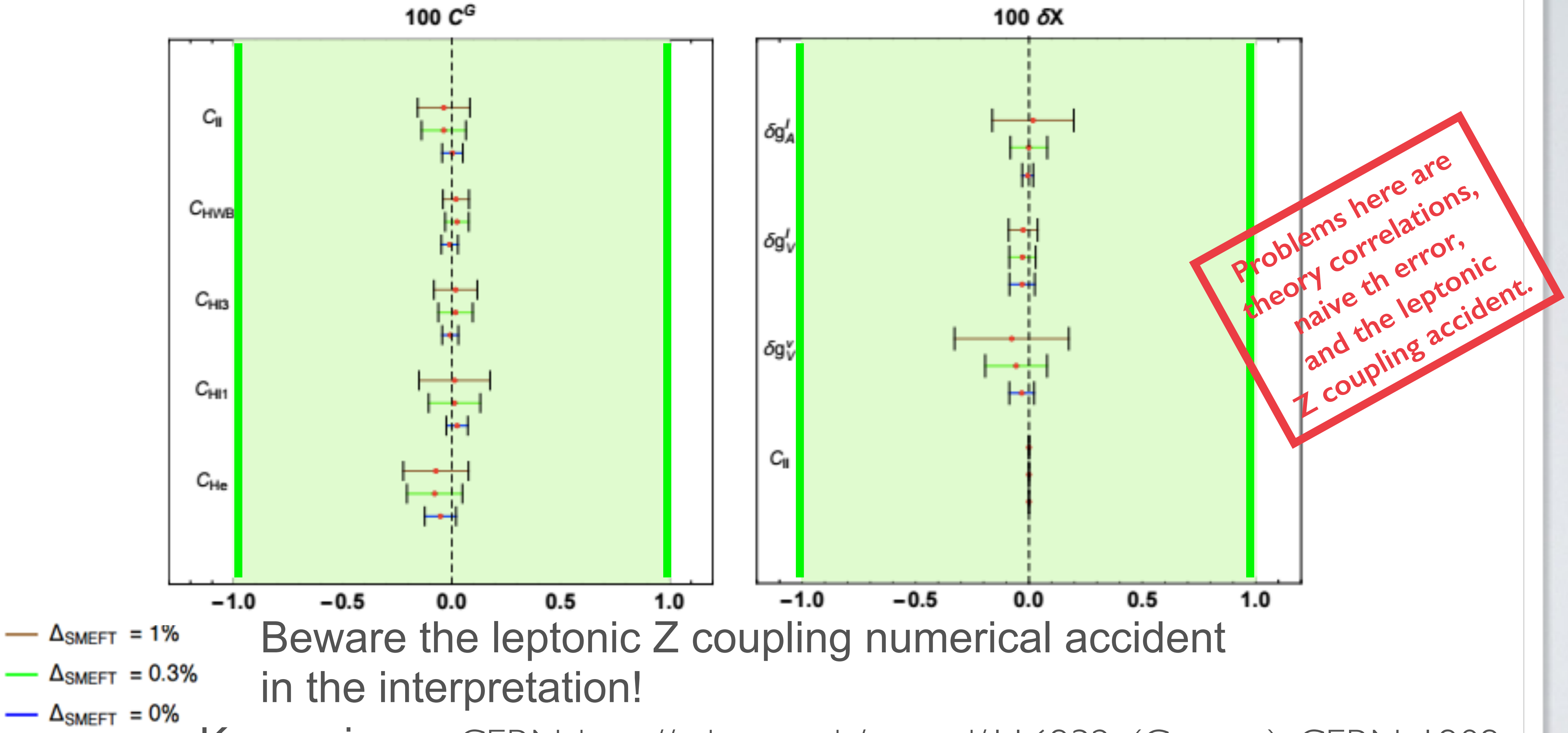


our SMEFT SCORE: 20 of 53 Wilson coefficients simultaneously constrained

- theory error does not impact significantly when cancelations/tunings allowed, very weak constraints

Global constraints on dim 6-update

- When not allowing cancelations (left one at a time, right mass eigen.)



Beware the leptonic Z coupling numerical accident in the interpretation!

Known issue: CERN, http://cds.cern.ch/record/116932, (Geneva), CERN, 1989.

Again same issue in SMEFT JHEP 1602 (2016) 069 arXiv:1508.05060 Berthier, Trott

Percent/per-mille precision need loops

We need loops for the SMEFT for future precision program to reduce theory error. So renormalize SMEFT as first step.

- We know the Warsaw basis is self consistent at one loop as it has been completely renormalized - DONE!

  arXiv:1301.2588 Grojean, Jenkins, Manohar, Trott
  arXiv:1308.2627, 1309.0819, 1310.4838 Jenkins, Manohar, Trott
  arXiv: 1312.2014 Alonso, Jenkins, Manohar, Trott

- Some partial results were also obtained in a "SILH basis"

  arXiv:1302.5661, 1308.1879 Elias-Miro, Espinosa, Masso, Pomarol
  1312.2928 Elias-Miro, Grojean, Gupta, Marzocca

- Recent results obtained in alternate scheme approach:

  arXiv:1505.03706 Ghezzi, Gomez-Ambrosio, Passarino, Uccirati

The reparameterization invariance

- Recently we have been able to understand the origin of weak constraints when using the warsaw basis in LEP data $(V, g) \leftrightarrow (V'(1+\epsilon), g'(1-\epsilon))\,,$

EOM equivalence arXiv:1701.06424 Reparameterization! Ilaria Brivio, MT

$$\langle \mathsf{y}_h\, g_1^2 Q_{HB} \rangle_{S_R} = \langle \sum_{\substack{\psi_\kappa = u,d,\\ q,e,l}} \mathsf{y}_k\, g_1^2\, \overline{\psi}_\kappa\, \gamma_\beta \psi_\kappa\, (H^\dagger\, i \overleftrightarrow{D}_\beta H) + \frac{g_1^2}{2}\,(Q_{H\Box} + 4 Q_{HD}) - \frac{1}{2} g_1\, g_2\, Q_{HWB} \rangle_{S_R}, \tag{2.7a}$$

$$\langle g_2^2 Q_{HW} \rangle_{S_R} = \langle g_2^2\, (\overline{q}\, \tau^I \gamma_\beta q + \overline{l}\, \tau^I \gamma_\beta l)\, (H^\dagger\, i \overleftrightarrow{D}^I_\beta H) + 2\, g_2^2\, Q_{H\Box} - 2\, g_1\, g_2\, \mathsf{y}_h\, Q_{HWB} \rangle_{S_R}. \tag{2.7b}$$

LEP data can't see the kinetic term of the gauge bosons

$$\langle \mathsf{y}_h\, g_1^2 Q_{HB} \rangle_{S_R} \to \frac{g_1^2\, \bar{v}_T^2}{4\, \Lambda^2}\, B^{\mu\nu}\, B_{\mu\nu}, \quad \langle g_2^2 Q_{HW} \rangle_{S_R} \to \frac{g_2^2\, \bar{v}_T^2}{2\, \Lambda^2}\, W_I^{\mu\nu}\, W^I_{\mu\nu}.$$

Or what is EOM equivalent

$$g_1^2\, w_B = g_1^2 \frac{\bar{v}_T^2}{\Lambda^2} \left(-\frac{1}{3} C_{Hd} - C_{He} - \frac{1}{2} C_{Hl}^{(1)} + \frac{1}{6} C_{Hq}^{(1)} + \frac{2}{3} C_{Hu} + 2 C_{HD} - \frac{1}{2 t_{\hat\theta}} C_{HWB} \right),$$

$$g_2^2\, w_W = g_2^2 \frac{\bar{v}_T^2}{\Lambda^2} \left(\frac{C_{Hq}^{(3)} + C_{Hl}^{(3)}}{2} - \frac{t_{\hat\theta}}{2} C_{HWB} \right).$$

This explains the flat directions in LEP data in Warsaw basis

$$w_1^\alpha = -w_B - 2.59\, w_W \qquad w_2^\alpha = -w_B + 4.31\, w_W\,.$$