# Recent (Copenhagen) developments in the SMEFT

- M. Trott

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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

# 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.)

- All IR assumptions on the EFT limit, not a UV assumption.

- Remember the EFT prime directive★: separate the scales in the problem and calculate with the long distance propagating states. In SMEFT these are still the SM states. Calculate IN the EFT.

★ lingo credit:M.Luke

# 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

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

Does the SMEFT exist as a concept? (as an acronym? :))

Can one constrain and interpret from data in the SMEFT without reference to any UV completion?

View of this talk : YES to all that!

Just irrelevant that the SMEFT is not UV complete. The SM is too.

This is the “the Copenhagen SMEFT interpretation”.
We want to treat SMEFT as a real field theory to interpret the data.

# 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, Melia, Murayama

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

# 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 $\psi^2H^2D$ | 8 | $\frac{1}{2}n_g(9n_g+7)$ | 8 | 51 | $\frac{1}{2}n_g(9n_g-7)$ | 1 | 30 |
| $\psi^4$ | 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 |
| $\psi^4$ | 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 |
| $\psi^4$ | 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 |
| $\psi^4$ | 8 : $(\overline{L}R)(\overline{R}L)$ | 1 | $n_g^4$ | 1 | 81 | $n_g^4$ | 1 | 81 |
| $\psi^4$ | 8 : $(\overline{L}R)(\overline{L}R)$ | 4 | $4n_g^4$ | 4 | 324 | $4n_g^4$ | 4 | 324 |
| $\psi^4$ | 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 $n_g=3$.

Lots of ways to count…for ex at LO:

76 - 9 - 23 - 24 = 20

flavour CP $\psi^4$

arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

# SMEFT has a non-minimal character

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

  Does it make sense to assume away parameters without symmetry assumptions?


- 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 $\Lambda$ has a dynamical origin.

  arXiv:1612.02040 Yun Jiang, MT

# Ex of non-minimal character

- The number of operators allowed is dictated by the SM symmetries,

  Q: How do you reduce the operator profile in a sensible way?

  A: Have non trivial representations under $SU(3) \times SU(2) \times U(1)$

- You can't escape group theory. If you have composites with non trivial reps, then its a package deal,ex: $\bar{3} \times 3 = 8 \times 1$
  $3 \times 3 = 6 \times \bar{3}$

- You can't arbitrarily separate the masses of these states like the $\eta' - \eta$ either

  Instantons can only do so much.

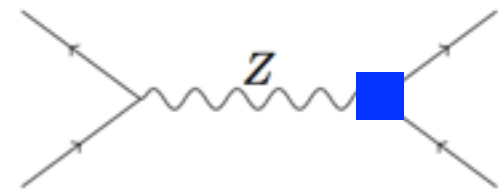
Don't mess with Gell-Mann

arXiv:1612.02040 Yun Jiang, MT

# Ex of non-minimal character

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

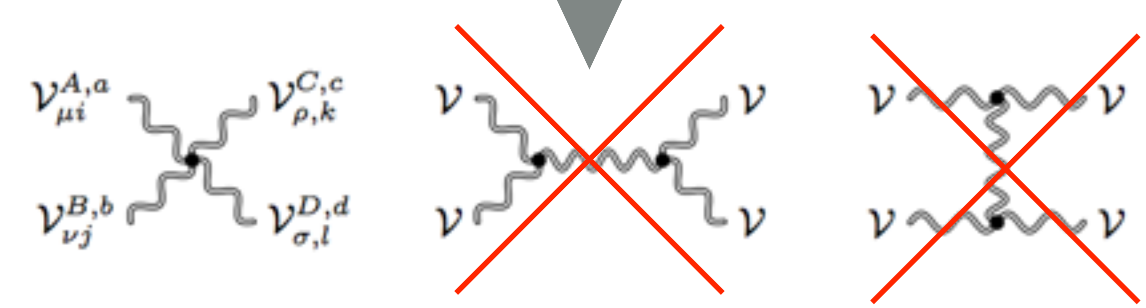
$$\boxed{Q_{H\ell}^{(1)}, Q_{H\ell}^{(3)}, Q_{Hq}^{(1)}, Q_{Hq}^{(3)}, Q_{He}, Q_{Hu}, Q_{Hd}}$$




| $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $G_Q$ | $G_L$ | 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 $\Lambda_V \sim m_V$

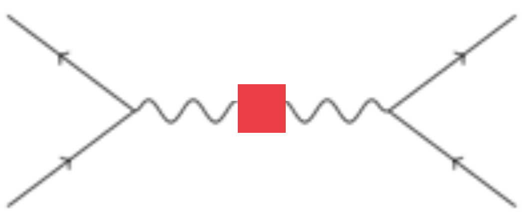
arXiv:1612.02040 Yun Jiang, MT

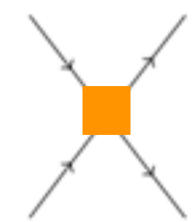
- Minimal benefit to trying UV assumptions if one thinks through consequences of model assumptions carefully

# 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 $\Gamma_{W,Z}/M_{W,Z} \ll 1$

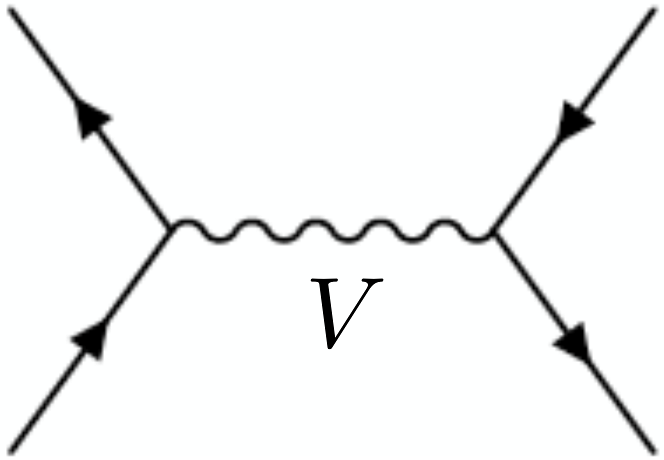
Two core issues:

- What is going on with the different claims and flat directions?
- How do neglected higher order terms effect EWPD?

# The reparameterization invariance

- Recently we have been able to understand the origin of weak constraints when using the Warsaw basis in LEP data. Not a bug - its a physics feature!

arXiv:1701.06424 Reparameterization! Ilaria Brivio, MT




$$(V, g) \leftrightarrow \left(V' \,(1+\epsilon), g' \,(1-\epsilon)\right),$$

$\bar{\psi}\psi \to \bar{\psi}\psi$ scattering has a reparamatrization invariance

$$\mathcal{L}_{V\psi_i} = \frac{1}{2} m_V^2 \, V^\mu \, V_\mu - \frac{1}{4} V^{\mu\nu} V_{\mu\nu} - g \, \bar{\psi}_i \gamma^\mu \psi_j V_\mu - g \, \kappa \, \bar{\psi}_k \gamma^\mu \psi_l V_\mu + \cdots \, .$$

# The reparameterization invariance

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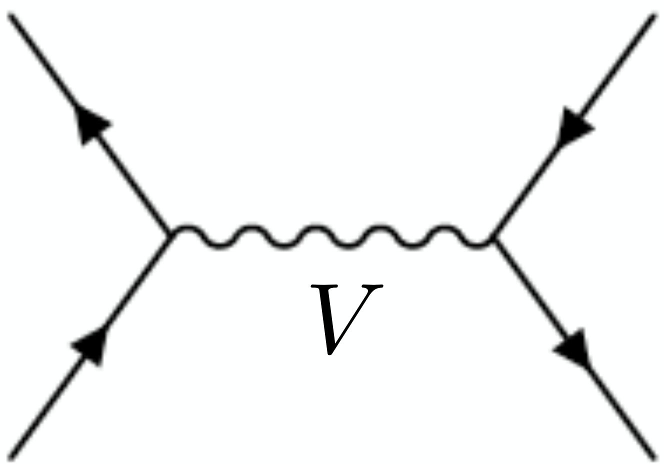



$$(V, g) \leftrightarrow \left(V' \, (1+\epsilon), g' \, (1-\epsilon)\right),$$

$\bar{\psi}\psi \to \bar{\psi}\psi$ scattering has a reparamatrization invariance (RI)

$$\mathcal{L}_{V\psi_i} = \underline{\frac{1}{2} m_V^2 \, V^\mu \, V_\mu} - \boxed{\frac{1}{4} V^{\mu\nu} V_{\mu\nu}} - \underline{g \, \bar{\psi}_i \gamma^\mu \psi_j V_\mu - g \, \kappa \, \bar{\psi}_k \gamma^\mu \psi_l V_\mu} + \cdots .$$

These terms invariant under shift

This term changes!

- BUT! The LSZ formula corrects out the non-normalized kinetic terms, so no physical effect.

# The reparameterization invariance

- This is why at one scale, you can get rid of the effect of the operators

$$H^\dagger H B^{\mu\nu} B_{\mu\nu}, \quad H^\dagger H W^{\mu\nu} W_{\mu\nu}$$

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

$\bar{\psi}\psi \to \bar{\psi}\psi$

- via $B \to \mathcal{B}(1 + C_{HB} v^2), \qquad g_1 \to \bar{g}_1(1 - C_{HB} v^2)$

  Which leaves $B \, g_1 \to \mathcal{B} \, \bar{g}_1$ invariant.

- LEP data also can't see what is EOM equivalent to these operators in $\bar{\psi}\psi \to \bar{\psi}\psi$

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

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

# The reparameterization invariance

- Flat directions discovered in the 2 to 2 scattering data set project onto these EOM equivalent combinations of operators

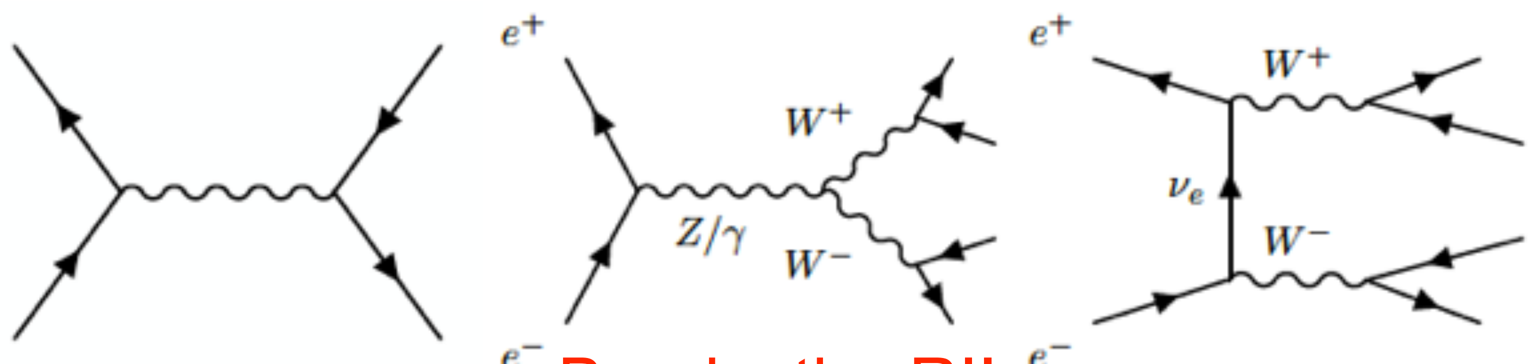
$$w_1^\alpha = -\boxed{w_B} - 2.59\boxed{w_W} \qquad w_2^\alpha = -\boxed{w_B} + 4.31\boxed{w_W}.$$

- We have also confirmed that this is scheme independent.

- The message is not " there are too many parameters" but combine data sets in a well defined SMEFT, as no matter what operator basis you choose you get a consistent results

Not as precisely measured.

So weaker constraints




RI not broken

Breaks the RI!

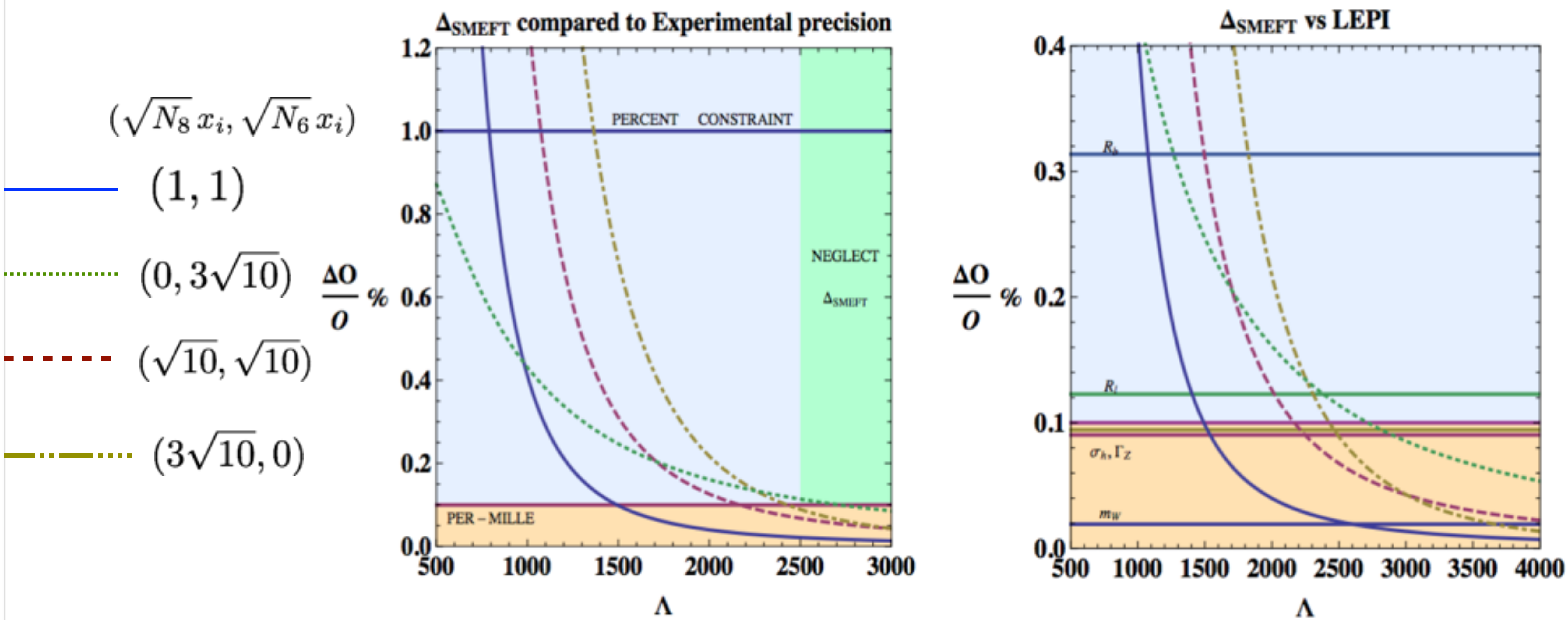
RI not broken

- Can compare to operator basis choice arguments in Grojean et al [hep-ph/0602154 ]. Contino et al arXiv:1303.3876].

# EWPD and neglected higher order

- Need to combine data sets, and for precise observables, neglected higher order terms can affect interpretation/combination

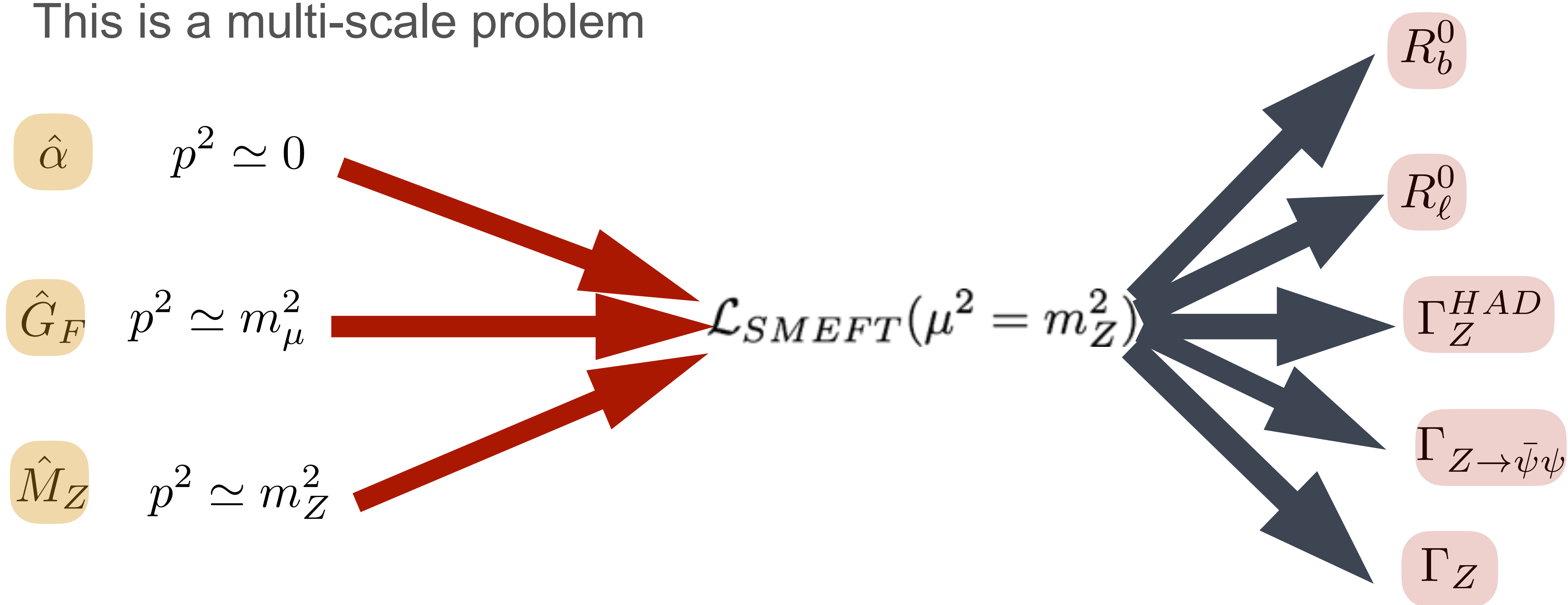
Estimate: $$\Delta^i_{SMEFT}(\Lambda) \simeq \sqrt{N_8}\, x_i \, \frac{\bar{v}_T^4}{\Lambda^4} + \frac{\sqrt{N_6}\, g_2^2}{16\,\pi^2}\, y_i \log\left[\frac{\Lambda^2}{\bar{v}_T^2}\right] \frac{\bar{v}_T^2}{\Lambda^2}.$$ arXiv:1508.05060 Berthier, Trott



# SMEFT decay widths of the Z at one loop

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

- 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)

see also : Passarino et al arXiv:1607.01236 , arXiv:1505.03706

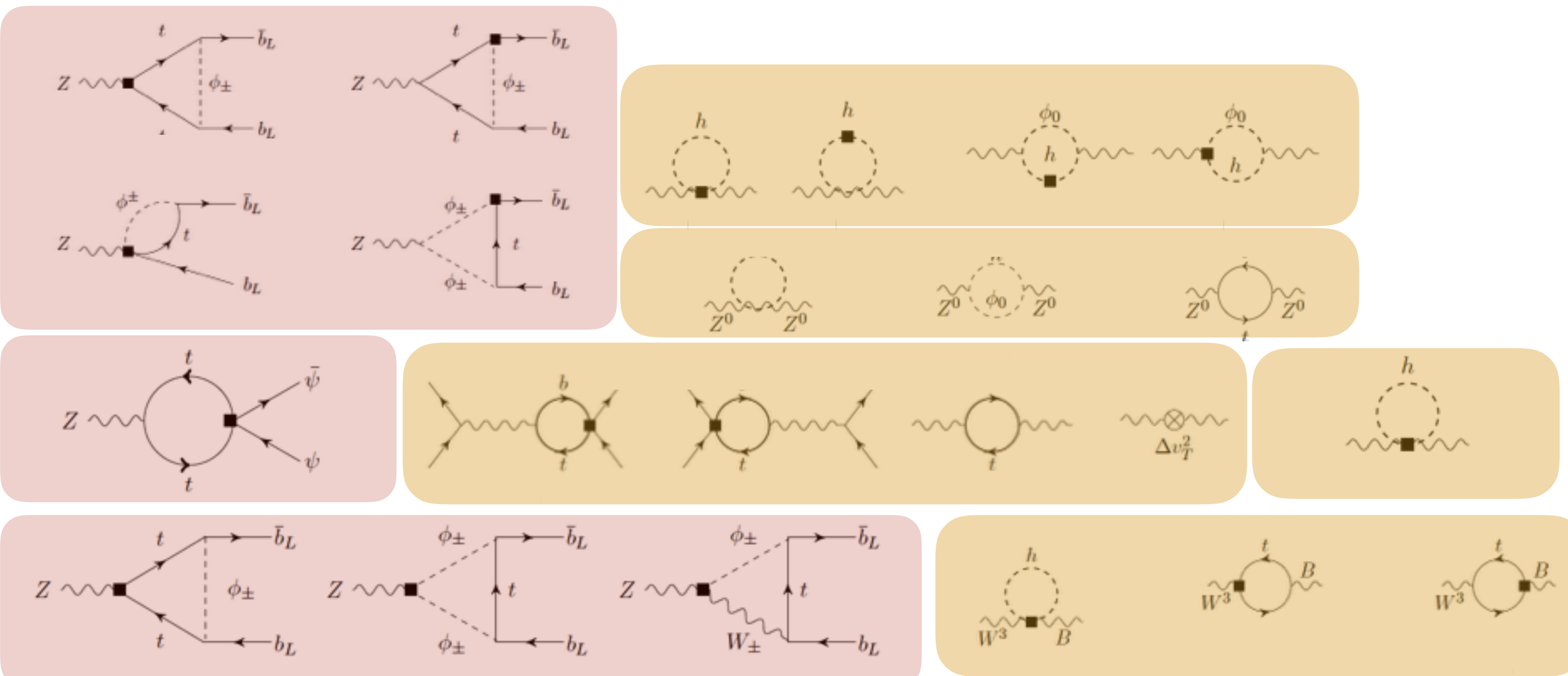
# Loops present

- ~ 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

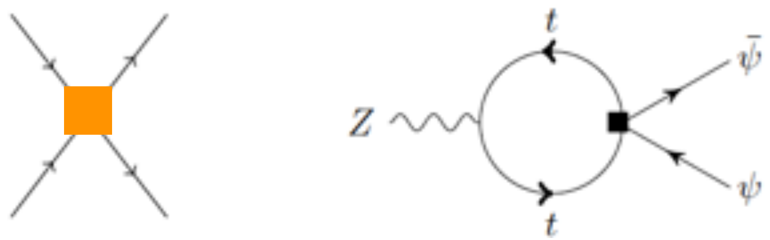


# Again we need to combine data sets!

- (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]

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

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

where

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

while the one loop corrections are

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

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

while

input shifts

decay process

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

# One set of lots o numbers…

- Result for $\Gamma_Z$ in tev units, 10% correction to the leading effects

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

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

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

# Conclusions

- SMEFT is a well defined model independent formalism to use at LO and NLO
- 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 bias (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. FOLLOW THE PRIME DIRECTIVE and treat it consistently!
- 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

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

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:**

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

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

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

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

# LO SMEFT = dim 6 shifts

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

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

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

# 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 $\psi^2H^2D$ | 8 | $\frac{1}{2}n_g(9n_g+7)$ | 8 | 51 | $\frac{1}{2}n_g(9n_g-7)$ | 1 | 30 |
| $\psi^4$ | 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 |
| | 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 |
| | 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 |
| | 8 : $(\overline{L}R)(\overline{R}L)$ | 1 | $n_g^4$ | 1 | 81 | $n_g^4$ | 1 | 81 |
| | 8 : $(\overline{L}R)(\overline{L}R)$ | 4 | $4n_g^4$ | 4 | 324 | $4n_g^4$ | 4 | 324 |
| | 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 due to RI

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

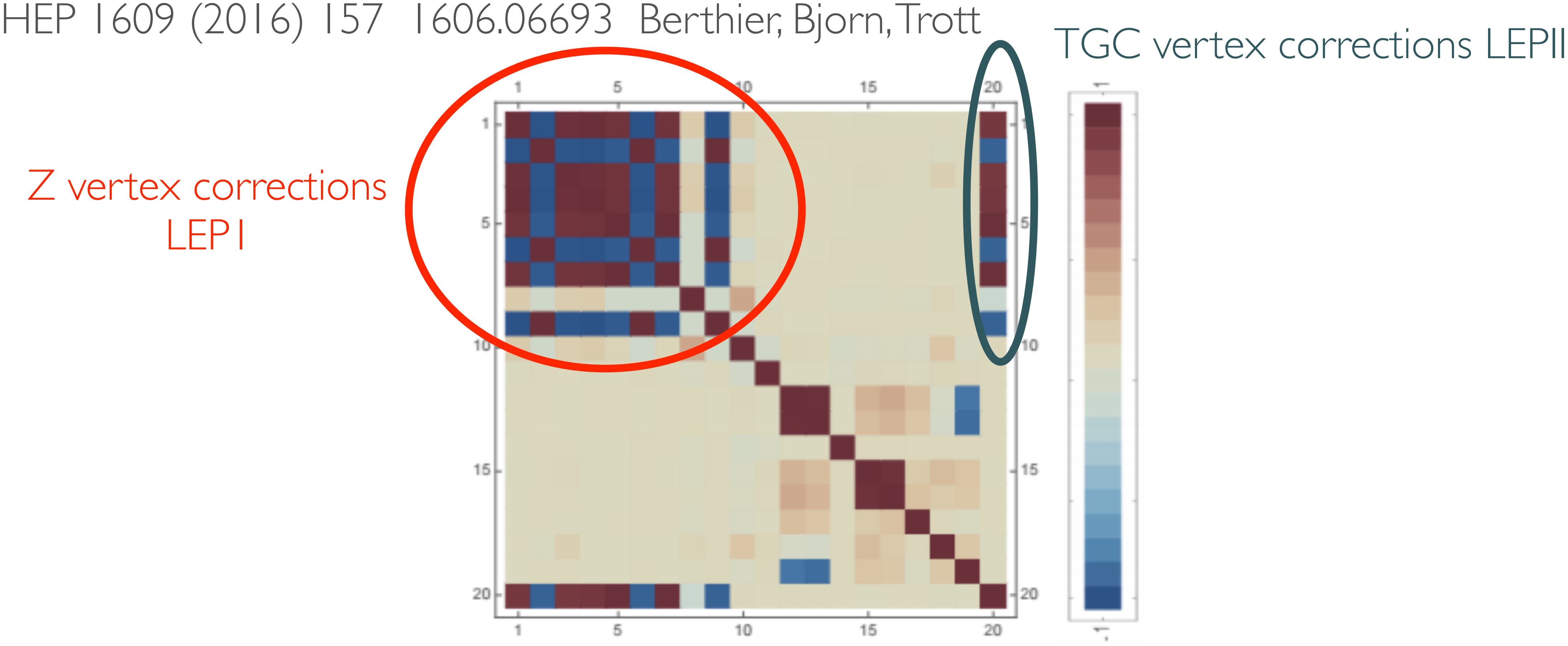
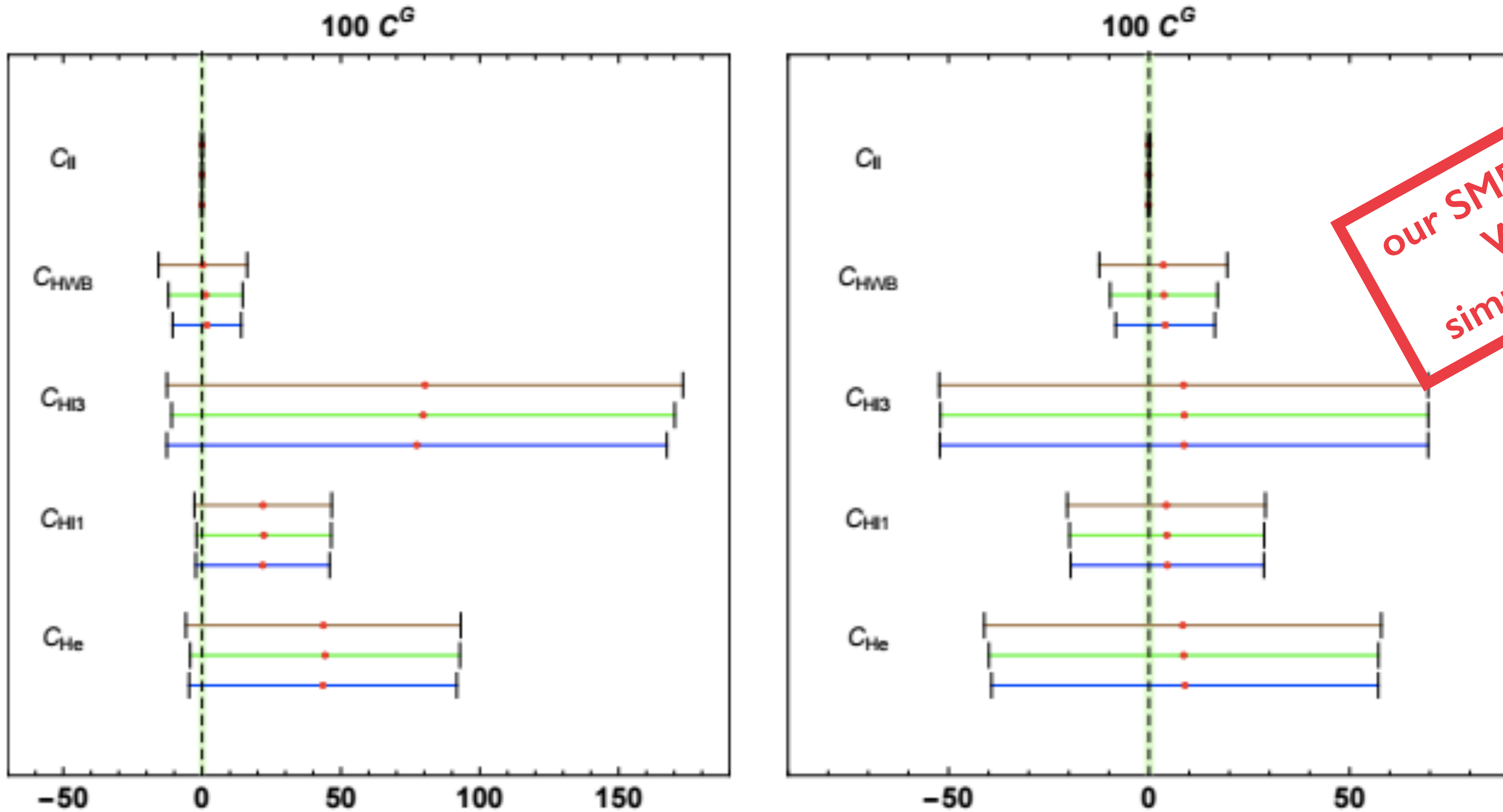



**Figure 5**: Color map of the correlation matrix between the Wilson coefficients when there is no SMEFT error.The Wilson coefficients are ordered as in Eqn.3.6.

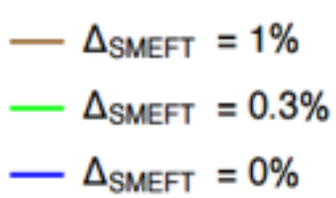
- UV assumptions or sloppy TGC bound treatment can have HUGE effect on the fit space once profiled down.

# Global constraints on dim 6-update

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



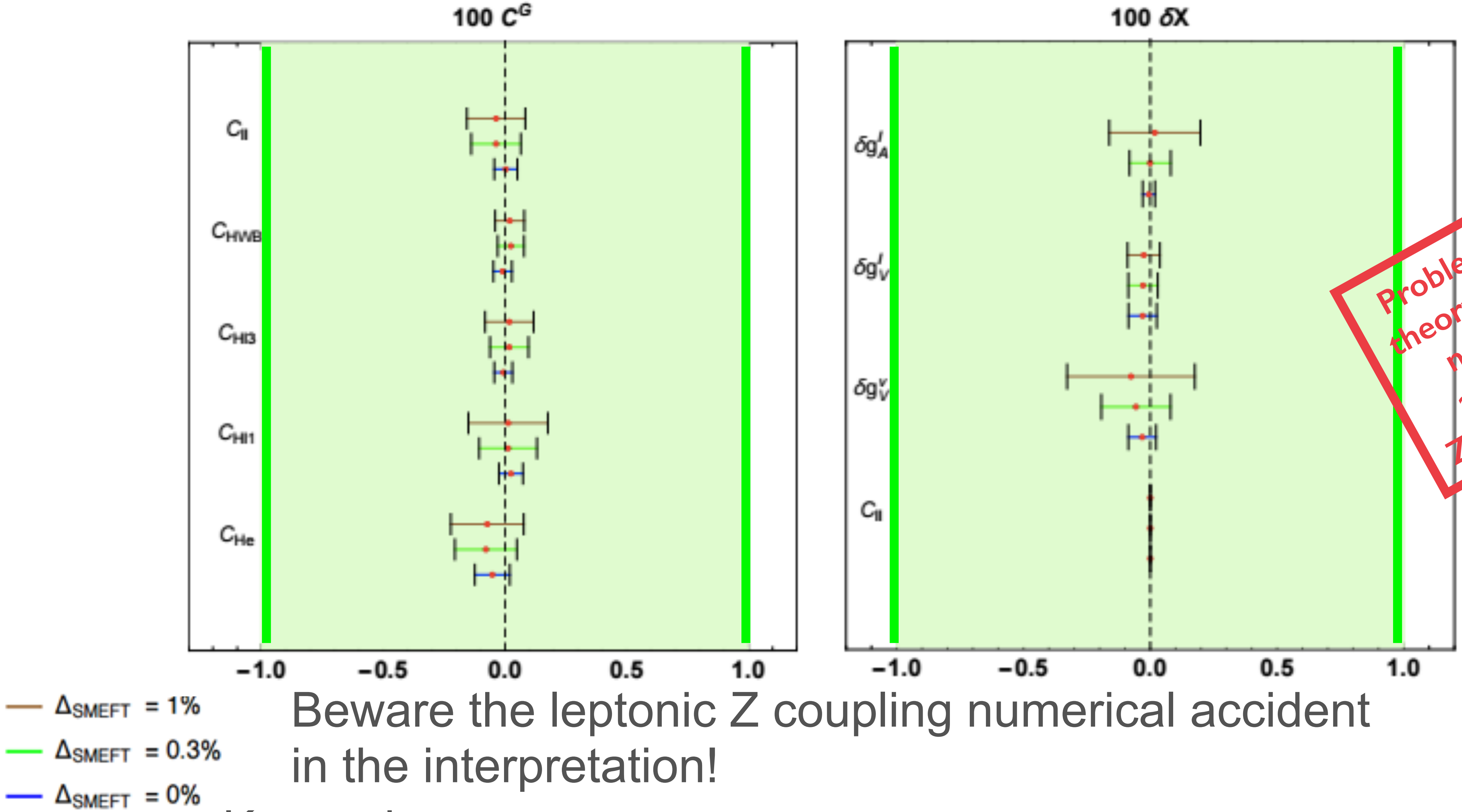

our SMEFT SCORE: 20 of 53 Wilson coefficients simultaneously constrained




- 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.)




Problems here are theory correlations, naive th error, and the leptonic Z coupling accident.

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

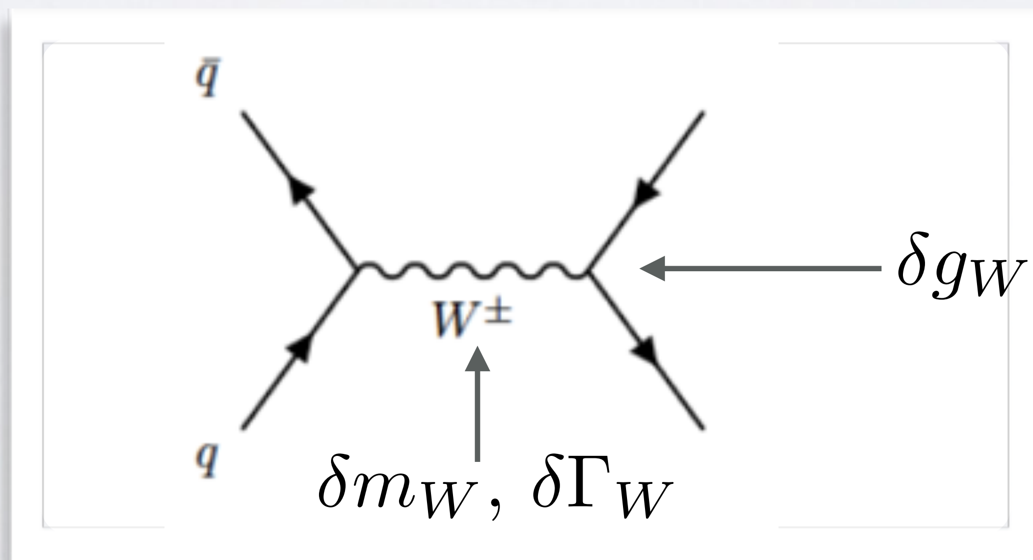
# Ex of measurement bias check

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

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

This is how you want the constraint to act.

*BUT* measurement via transverse variables actually measures a process:



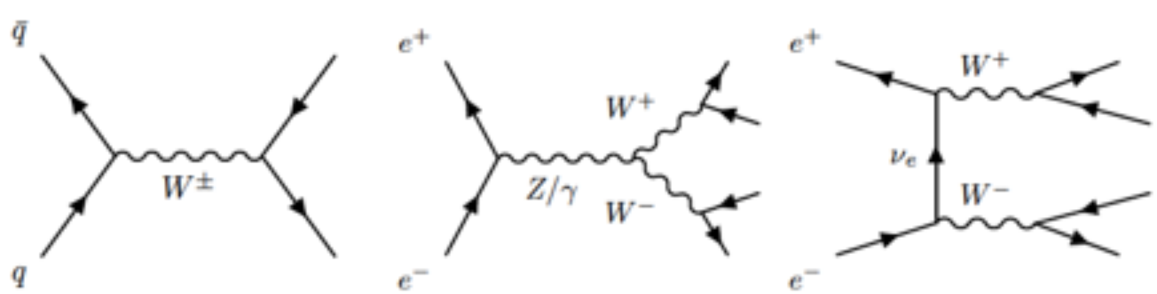

- How wrong is it to just apply the constraint pretending the other shifts not there?

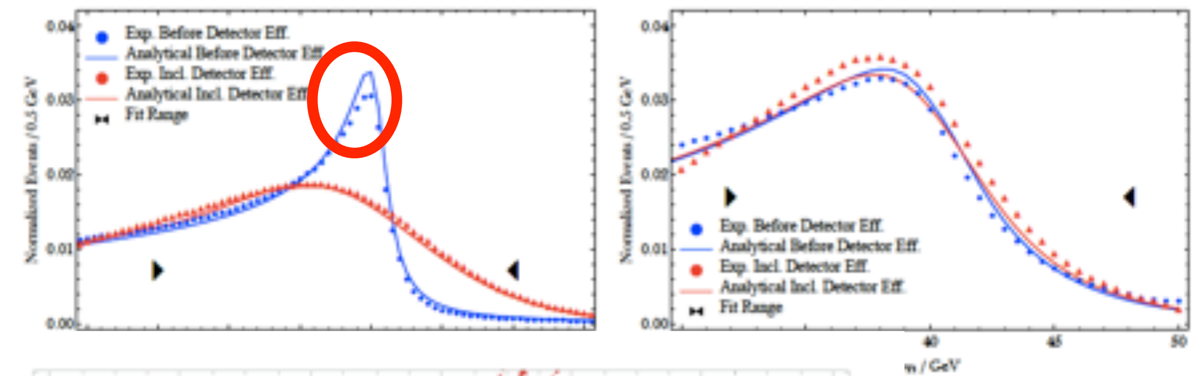
# Mw measurements in SMEFT

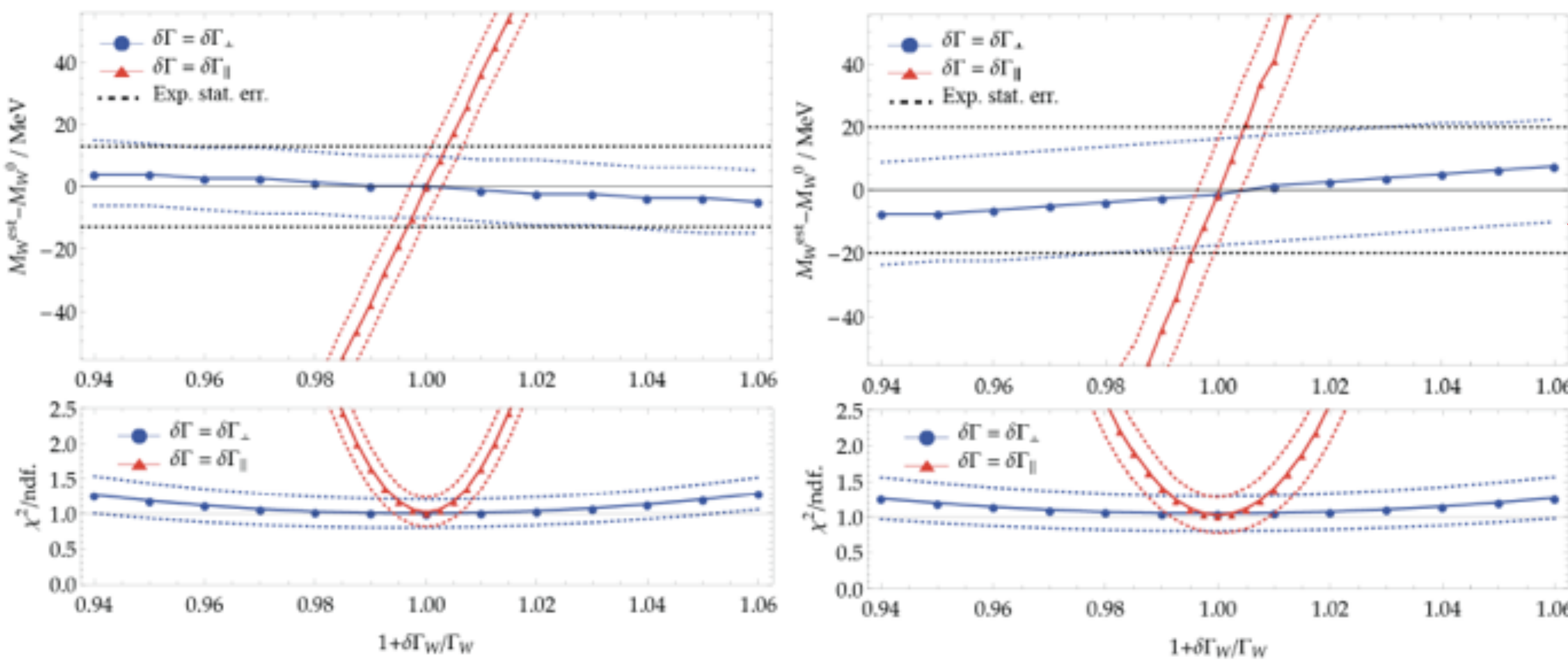
- Mw is a template fit at LEP and at the Tevatron.

1606.06502 Bjorn, Trott

Transverse mass Jacobian peak



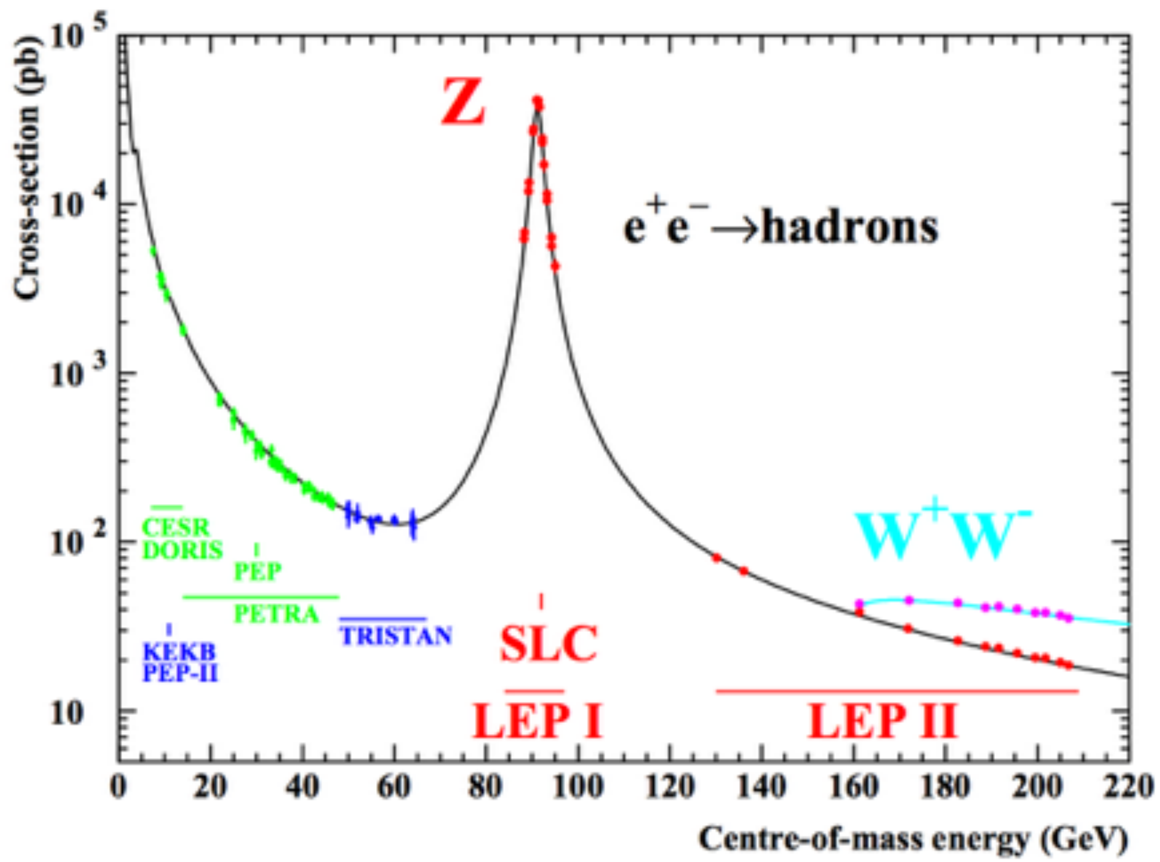




Below percent measurements in SMEFT at colliders possible

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

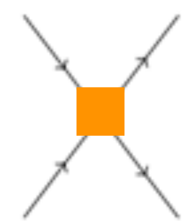
# EWPD measurements in SMEFT




- EWPD is a scan through the Z pole

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

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



- many more $\psi^4$ 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!