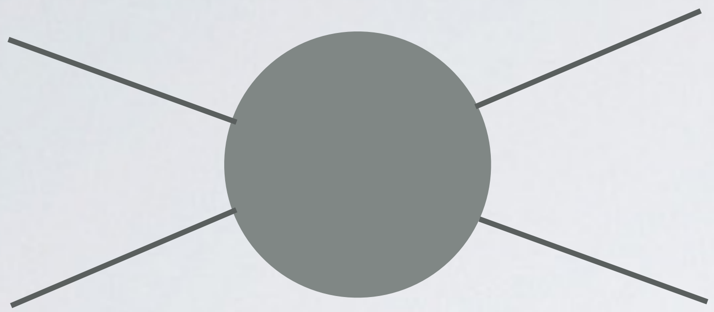
Overview of low energy/precision in SMEFT

- M. Trott

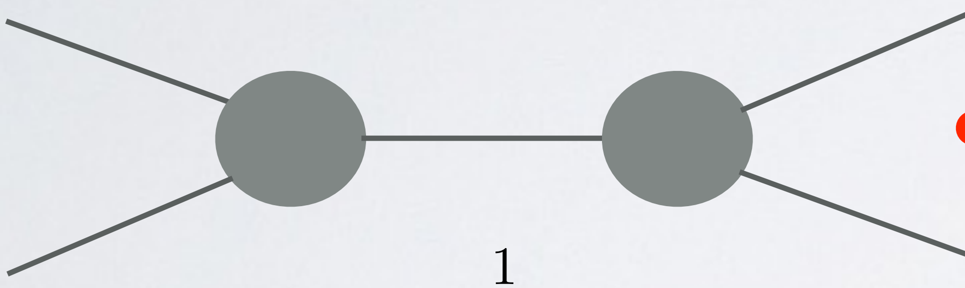
Durham, 7th Sept. 2017

Niels Bohr Institute, Copenhagen, Denmark.

Probing an S-matrix below a particle threshold



- The observable is a function of the external Lorentz invariants: $f(s,t,u)$
- The observable is an analytic function of these invariants except in special regions of phase space where an internal state goes on-shell. This is the "Landau Principle".



$$\sim \frac{1}{s - m^2 + i\Gamma(s)\, m}$$

- IF the collision probe can never reach the $\sim m^2_{heavy}$ THEN the observable's dependence on that scale is DRAMATICALLY, practically, (wonderfully!) simplified
- No non-analytic behavior due to that state, and you can Taylor expand in LOCAL functions

$$\langle\rangle \sim O^0_{SM} + \frac{f_1(s,t,u)}{M^2_{heavy}} + \frac{f_2(s,t,u)}{M^4_{heavy}} + \cdots$$

- The locality is due to the uncertainty principle

See the review for the basics (1706.08945 Brivio,MT)

We should take advantage of this simplification

- When you don't rely on a resonance discovery the SM interactions are perturbed by local interactions

Unknown UV: M_i , g_j $\;\Rightarrow\;$ $\sum_{i,j} \frac{g_i^2 M_j^2}{16\,\pi^2} h^2$

- We now have a scalar with mass $m_h \sim 125\,\mathrm{GeV}$ reasonable to expect $g_i\, M_j \sim few\,\mathrm{TeV}$

- LHC reach limited $\lesssim 14/6 \sim 2\,\mathrm{TeV}$ (rule of thumb due to PDF suppression)

- Corrections expected on the order of

$$\langle H|\mathcal{L}_{SM}|H\rangle \Rightarrow \frac{v^2}{\Lambda^2} \sim few\,\% \qquad \frac{E^2}{\Lambda^2} \sim few - tens\%$$

$\Lambda \sim M/\sqrt{g}$ in this talk

(LEP data few % to 0.1 % precise)

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 → SMEFT[★] → ~~SM~~

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

★ 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 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:

- (red) 14 operators, or 18 parameters (+ 1 op and then 19 with strong CP)
- (blue) 1 operator, and 7 extra parameters (dirac) or 9 if Majorana phases
- (green) 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
- (cyan) 4 operators, or 408 parameters (all violate B number)

  arXiv:1405.0486 Alonso, Cheng, Jenkins, Manohar, Shotwell
- (black) 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.

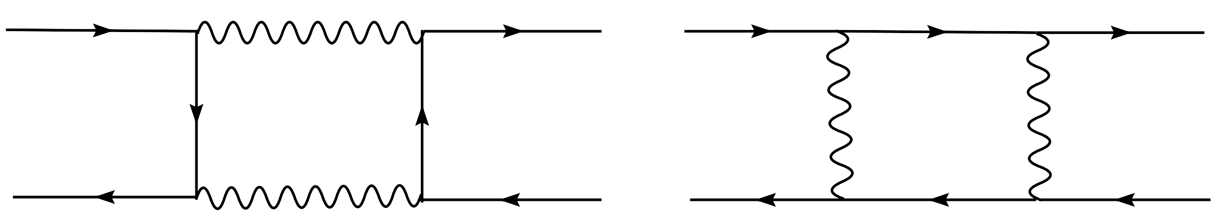
Class		N_{op}	CP-even n_g	1	3	CP-odd n_g	1	3
	1 g^3X^3	4	2	2	2	2	2	2
	2 H^6	1	1	1	1	0	0	0
	3 H^4D^2	2	2	2	2	0	0	0
	4 $g^2X^2H^2$	8	4	4	4	4	4	4
	5 $y\psi^2H^3$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
	6 $gy\psi^2XH$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
	7 ψ^2H^2D	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
ψ^4	8 : $(\overline{L}L)(LL)$	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 $n_g=3$.

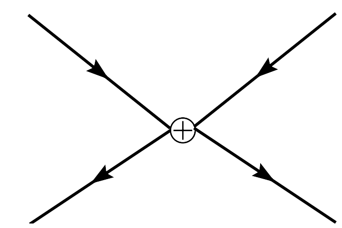
arXiv:1312.2014 Alonso, Jenkins, Manohar, Trott

Precision constraints that VIOLATE symmetries

Flavour and CP assumptions



VS



Recall SM contribution to meson mixing:

$$\mathcal{A}_{SM} \sim \frac{m_t^2}{16\,\pi^2 v^4}\,(V_{3i}^\star\,V_{3j})^2 \langle \bar{M}|(\bar{d}_L^i\,\gamma^\mu\,d_L^j)^2|M\rangle$$

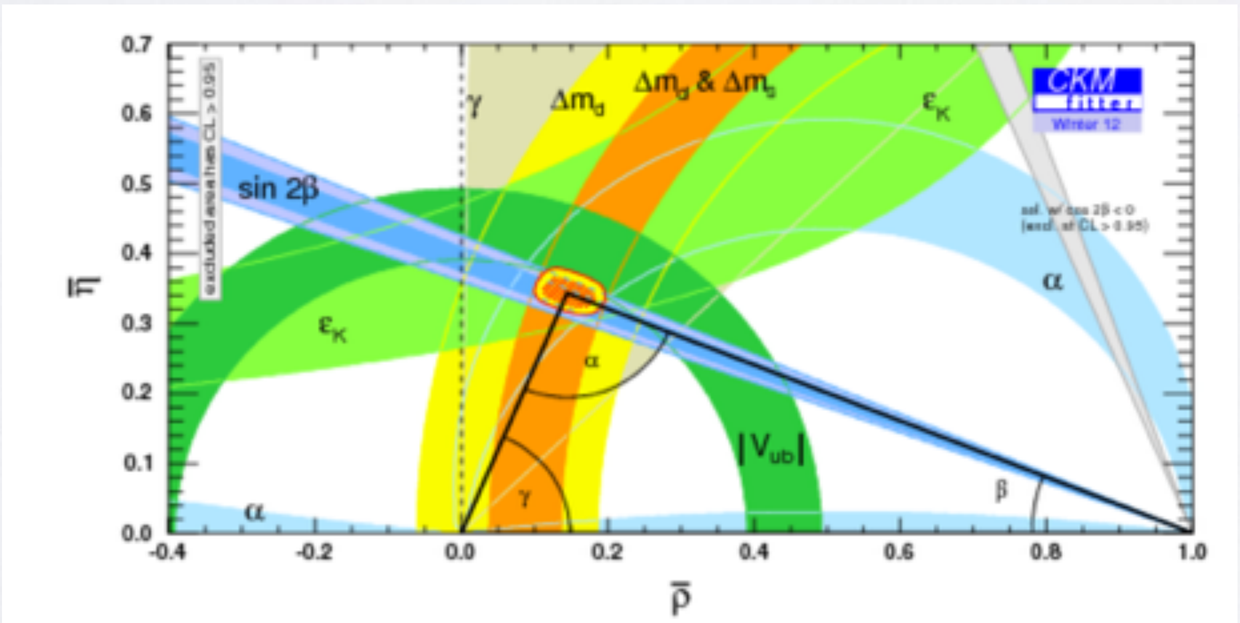
SM PATTERN has GIM suppression, CKM suppression , and loop suppression

$\lambda \sim 0.2$ so $\lambda^8 \sim 10^{-6}$ $\quad \lambda^4 \sim 10^{-3}$

Integrate out your desired NP states/sector

$$O_{ij} = \frac{c_{ij}}{\Lambda^2}\,(\bar{Q}_L^i\,\gamma^\mu\,Q_L^j)^2$$

We assume MFV for TeV new physics to be robust (for now).



- SM flavour violating pattern validated

Flavour and CP assumptions

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

- CP violating effects strongest constraints

$$\Lambda < \frac{3.4\ \text{TeV}}{|V_{3i}^* V_{3j}|/|c_{ij}|^{1/2}} < \begin{cases} 9\times10^3\ \text{TeV}\times|c_{21}|^{1/2} & \text{from}\quad K^0-\bar{K}^0 \\ 4\times10^2\ \text{TeV}\times|c_{31}|^{1/2} & \text{from}\quad B_d-\bar{B}_d \\ 7\times10^1\ \text{TeV}\times|c_{32}|^{1/2} & \text{from}\quad B_s-\bar{B}_s \end{cases}$$

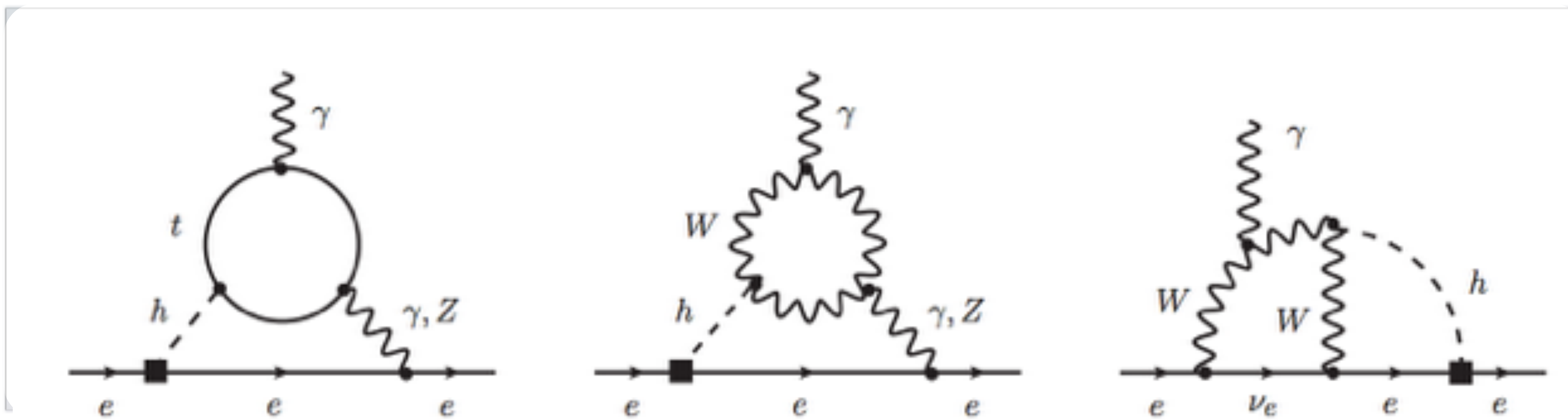
- Need the ops to carry the CKM factors (MFV)

Operator	Bound on Λ	Observables
$\phi^\dagger\left(\overline{D}_R Y_d^\dagger Y_u Y_u^\dagger \sigma_{\mu\nu} Q_L\right)(eF_{\mu\nu})$	6.1 TeV	$B\to X_s\gamma,\ B\to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L)^2$	5.9 TeV	$\epsilon_K,\ \Delta m_{B_d},\ \Delta m_{B_s}$
$\phi^\dagger\left(\overline{D}_R Y_d^\dagger Y_u Y_u^\dagger \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B\to X_s\gamma,\ B\to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right)(\overline{E}_R\gamma_\mu E_R)$	5.7 TeV	$B_s\to\mu^+\mu^-,\ B\to K^*\mu^+\mu^-$
$i\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right)\phi^\dagger D_\mu\phi$	4.1 TeV	$B_s\to\mu^+\mu^-,\ B\to K^*\mu^+\mu^-$
$\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right)(\overline{L}_L\gamma_\mu L_L)$	5.7 TeV	$B_s\to\mu^+\mu^-,\ B\to K^*\mu^+\mu^-$
$\left(\overline{Q}_L Y_u Y_u^\dagger \gamma_\mu Q_L\right)(eD_\mu F_{\mu\nu})$	1.7 TeV	$B\to K^*\mu^+\mu^-$

- In the MFV case, still flavour violation, but TeV sectors viable

Charts all from Isidori 1302.0661

Flavour and CP assumptions



See: Altmannshofer, Brod, Schmaltz, 1503.04830, Brod, Haisch, JZ, 1310.1385, Cirigliano, de Vries, Dekens, Mereghetti, 1603.03049

- Direct (2 loop) EDM contributions
  Still matter!

- One loop mixing effects of electroweak CP violating ops into EDMs

Operator		Coupling
$-\sqrt{2}\varphi^\dagger\varphi\, \bar{q}_L Y'_u u_R \tilde{\varphi}$	O_Y	$y_t C_Y = [Y'_u]_{33}$
$-\frac{g_s}{\sqrt{2}}\, \bar{q}_L \sigma\cdot G\, \Gamma^u_g\, u_R \tilde{\varphi}$	O_g	$y_t C_g = [\Gamma^u_g]_{33}$
$-\frac{g'}{\sqrt{2}}\, \bar{q}_L \sigma\cdot B\, \Gamma^u_B\, u_R \tilde{\varphi}$ $-\frac{g}{\sqrt{2}}\, \bar{q}_L \sigma\cdot W^a \tau^a\, \Gamma^u_W\, u_R \tilde{\varphi}$	$O_{\gamma,Wt}$	$y_t Q_t C_\gamma = -[\Gamma^u_B + \Gamma^u_W]_{33}$ $y_t C_{Wt} = [\Gamma^u_W]_{33}$
$-\frac{g}{\sqrt{2}}\, \bar{q}_L \sigma\cdot W^a \tau^a\, \Gamma^d_W\, d_R \varphi$	O_{Wb}	$y_b C_{Wb} = [\Gamma^d_W]_{33}$

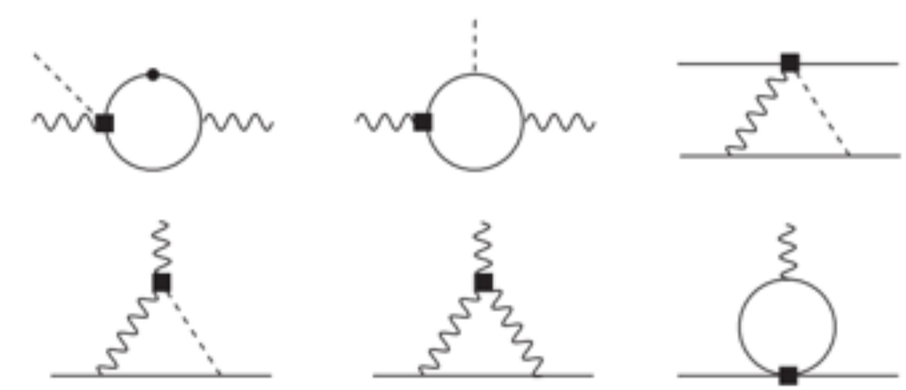


FIG. 1: Representative diagrams contributing to the mixing of C_γ into $C_{\varphi\tilde{W},\varphi\tilde{B},\varphi\tilde{W}B,quqd,lequ}$ (top panel), and the mixing of the latter into light fermion electroweak dipoles (bottom panel). The square (circle) represents an operator (quark mass) insertion. Solid, wavy, and dotted lines represent fermions, electroweak gauge bosons, and the Higgs, respectively.

Cirigliano, de Vries, Dekens, Mereghetti, 1603.03049

Flavour and CP assumptions

https://arxiv.org/pdf/1603.03049.pdf V. Cirigliano, I W. Dekens, J. de Vries, and E. Mereghetti

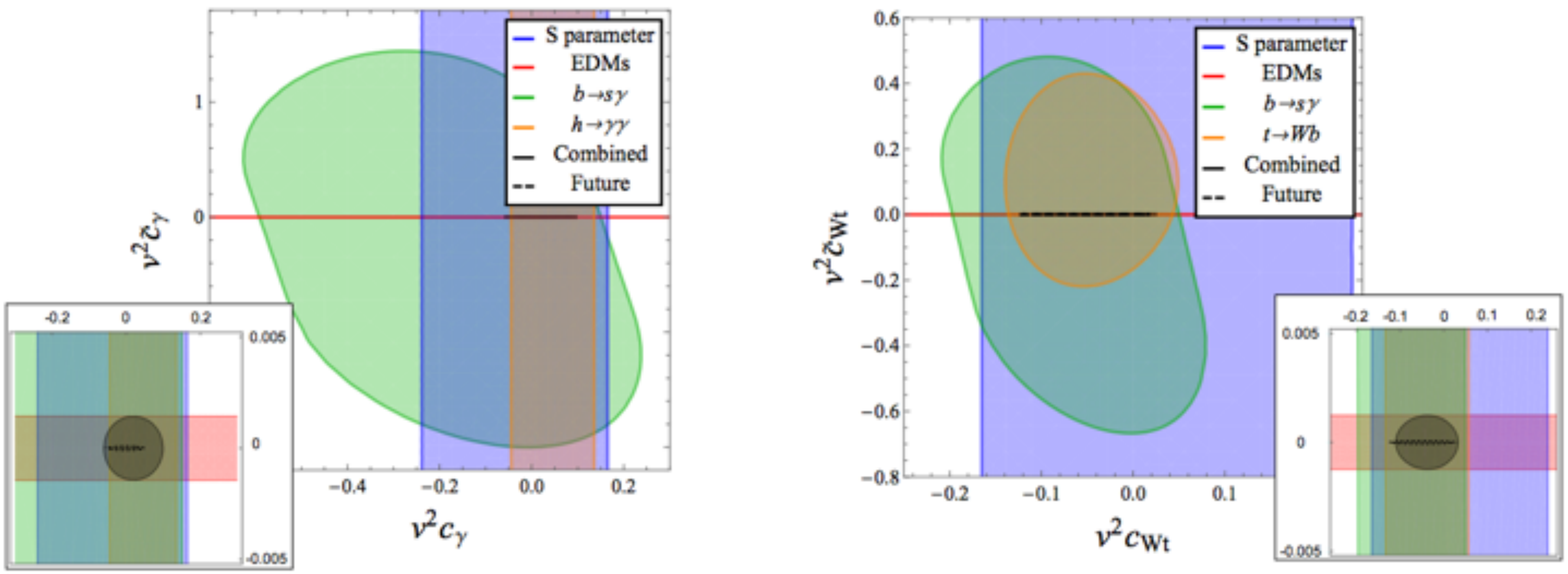


FIG. 2: 90% CL allowed regions in the $v^2c_\gamma - v^2\tilde{c}_\gamma$ (left panel) and $v^2c_{Wt} - v^2\tilde{c}_{Wt}$ planes (right panel), with couplings evaluated at $\Lambda = 1$ TeV. In both cases, the inset zooms into the current combined allowed region and shows projected future sensitivities. Future EDM searches will probe $v^2\tilde{c}_\gamma \sim 8 \cdot 10^{-5}$ and $v^2\tilde{c}_{Wt} \sim 7 \cdot 10^{-5}$.

- "The overarching message emerging from our single-operator analysis is that the CPV couplings (top-higgs) are very tightly constrained, and out of reach of direct collider searches."

- One operator at a time. But symmetry violation constraint leads to symmetry conclusions.

Summary

- Beyond the general SMEFT, if is of interest to examine the following cases

  Respect the SM flavour symmetry that exists in the $Y_U, Y_D \rightarrow 0$ limit in a new sector.

$$\mathrm{G_F} = \mathrm{U(3)}^5 = \mathrm{S_Q} \otimes \mathrm{S_L} \otimes \mathrm{U(1)}^5$$

where $S_Q = \mathrm{SU(3)_{Q_L}} \otimes \mathrm{SU(3)_{U_R}} \otimes \mathrm{SU(3)_{D_R}}$ $\quad S_L = \mathrm{SU(3)_{L_L}} \otimes \mathrm{SU(3)_{E_R}}$

  Technically the Yukawas act as spurions: $Y_U \sim (\overline{3}, 3, 1)\,, Y_D \sim (\overline{3}, 1, 3)$

- U(3)^5 SMEFT with possible CP violating phases beyond the SM

- MFV SMEFT with NO possible CP violating phases beyond the SM

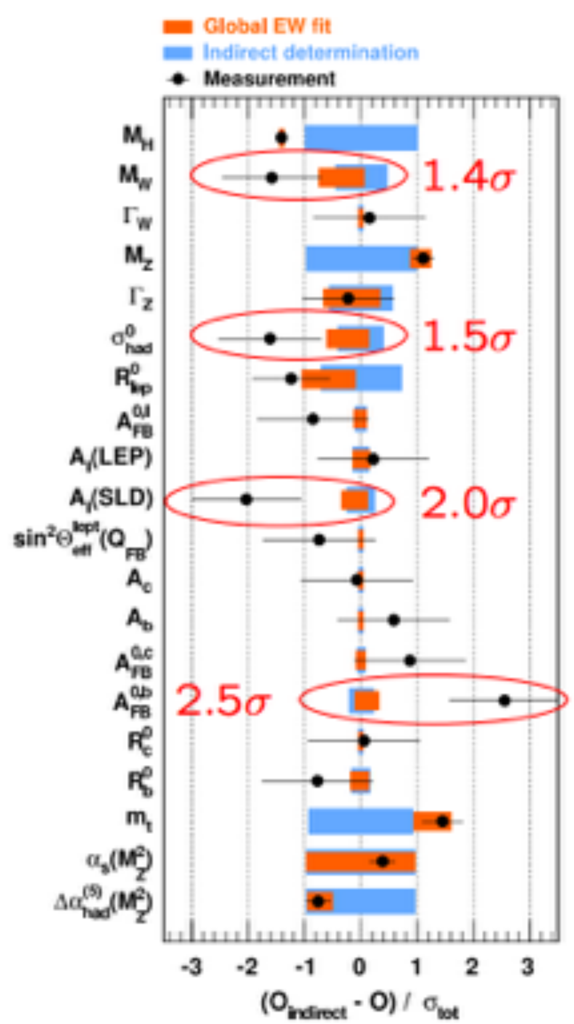
AGAIN: One operator at a time analysis does not matter so much for SYMMETRY violation tests

Precision constraints that DO NOT violate symmetries

How many parameters in EWPD?

Current status of electroweak precision tests

A. Freitas
University of Pittsburgh
HEFT 2017



Surprisingly good agreement:
$\chi^2/\text{d.o.f.} = 18.1/14$ ($p = 20\%$)

Most quantities measured with
1%–0.1% precision

A few interesting deviations:

M_W	$(\sim 1.4\sigma)$
σ^0_{had}	$(\sim 1.5\sigma)$
A_ℓ(SLD)	$(\sim 2\sigma)$
A^b_{FB}	$(\sim 2.5\sigma)$
$(g_\mu - 2)$	$(\sim 3\sigma)$

GFitter coll. '14

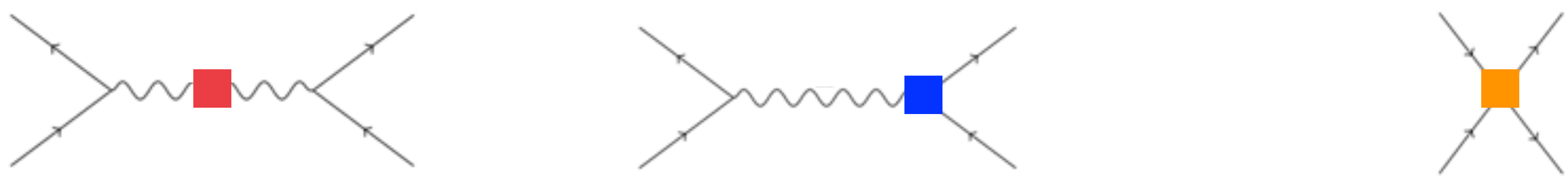
https://conference.ippp.dur.ac.uk/event/590/session/8/contribution/24/material/slides/0.pdf

- No discovery of new physics - but exactly SM like?!?!??!?!? Nope.

How many parameters in EWPD?

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

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



- 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?

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 Λ 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.

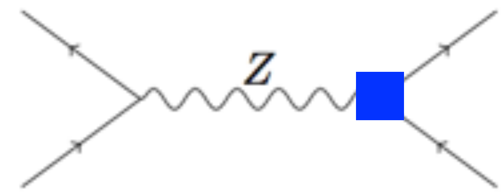
Don't mess with Gell-Mann

arXiv:1612.02040 Yun Jiang, MT

Ex of non-minimal character

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

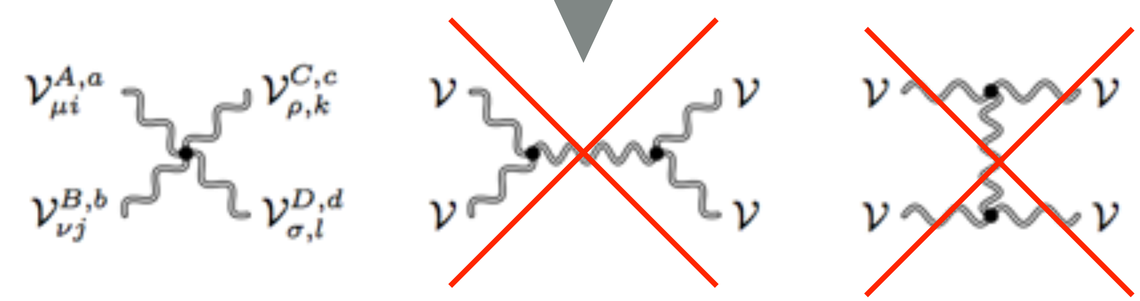
$$Q_{H\ell}^{(1)}, Q_{H\ell}^{(3)}, Q_{Hq}^{(1)}, Q_{Hq}^{(3)}, Q_{He}, Q_{Hu}, Q_{Hd}$$



$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	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 $U(1)_Y$ charge in new states

But then



Vector causes unitarity violation $\Lambda_V \sim m_V$

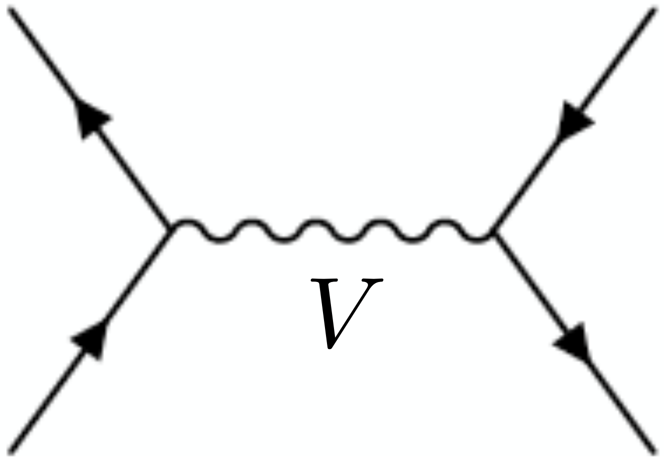
arXiv:1612.02040 Yun Jiang, MT

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

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



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

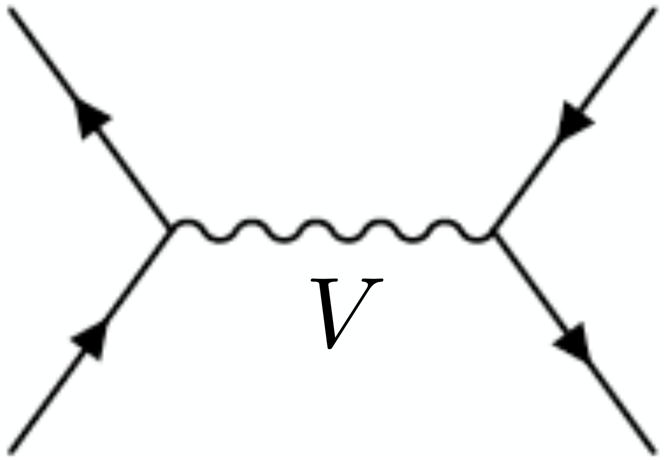
$\bar{\psi}\psi \to \bar{\psi}\psi$ scattering has a reparamatrization invariance

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

The reparameterization invariance

- 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 (RI)

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

This term changes!

These terms invariant under shift

- 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

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

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

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

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

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

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

The reparameterization invariance

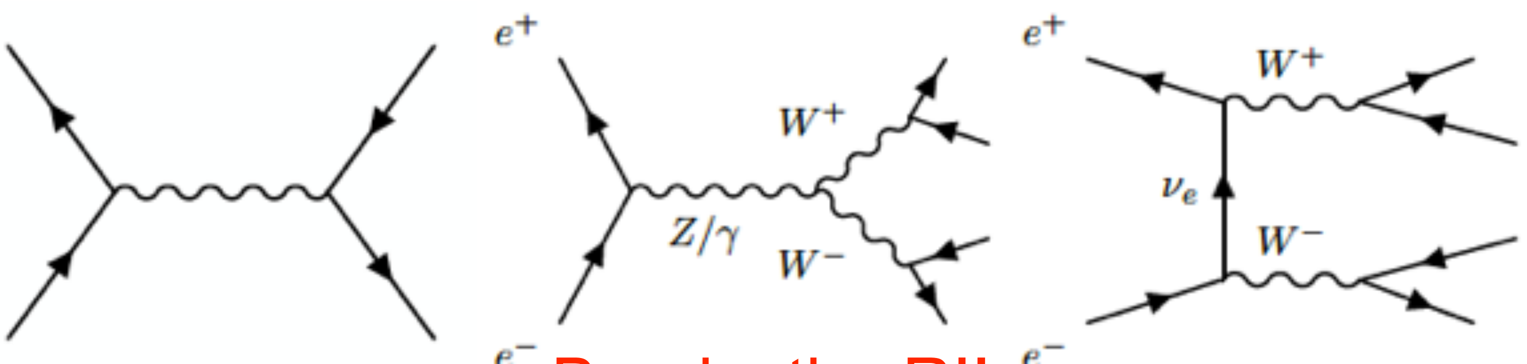
- Flat directions discovered in the 2 to 2 scattering data set project onto these EOM equivalent combinations of operators

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

- 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].

Interlude: note the recurring theme of Pole parameters

- Operators of the form $\langle H|\mathcal{L}_{SM}|H\rangle$

  These can contribute to resonance features of the SM in an unsuppressed fashion and resonant regions of phase space are critical for precision measurements. The W,Z,H pole parameters are critical for the EW tests of the SMEFT.

- Wrinkle, in $\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ need to expand the W propagator, formally messing with gauge invariance in the double resonant calculation of $\bar{\psi}\psi \rightarrow \bar{\psi}\psi\bar{\psi}\psi$

$$\bar{\chi}(s_{ij}) = \bar{D}^W(s_{ij})\,\bar{D}^{*W}(s_{ij}) = \frac{1}{(s_{ij}-\bar{m}_W^2)^2 + (\bar{\Gamma}_W \bar{m}_W)^2} = \frac{1}{(s_{ij}-\hat{m}_W^2)^2 + \left(\hat{\Gamma}_W \hat{m}_W\right)^2}\left[1+\delta\chi(s_{ij})\right],$$

$$\delta\chi(s_{ij}) = \frac{\left[-2\left(s_{ij}-\hat{m}_W^2\right)+\hat{\Gamma}_W^2\right]\delta m_W^2 - 2\hat{\Gamma}_W \hat{m}_W^2 \delta\Gamma_W}{(s_{ij}-\hat{m}_W^2)^2 + \left(\hat{m}_W \hat{\Gamma}_W\right)^2},$$

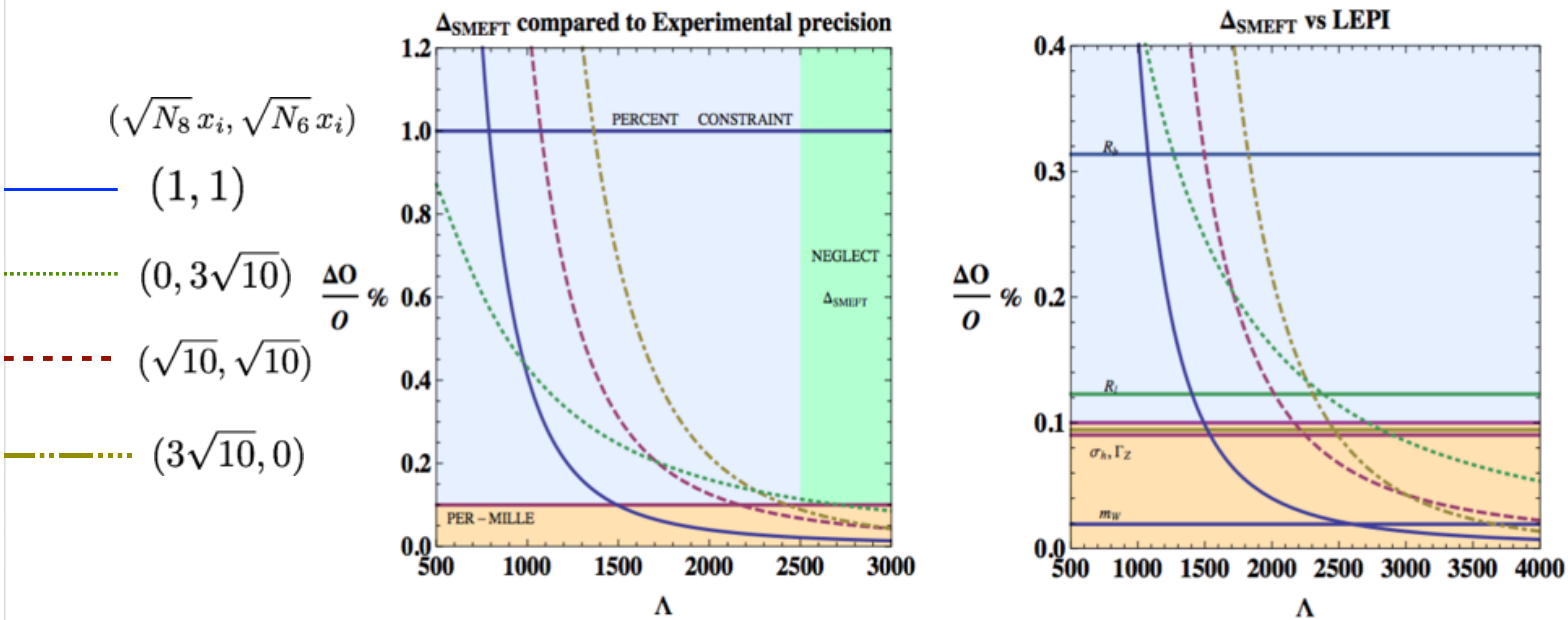
- Near on shell region of phase space $s_{ij} - m_W^2 \sim \Gamma_W$ then $\delta m_W^2 \dfrac{m_W}{\Gamma_W}$

- The $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ scheme is better for this reason and others!

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

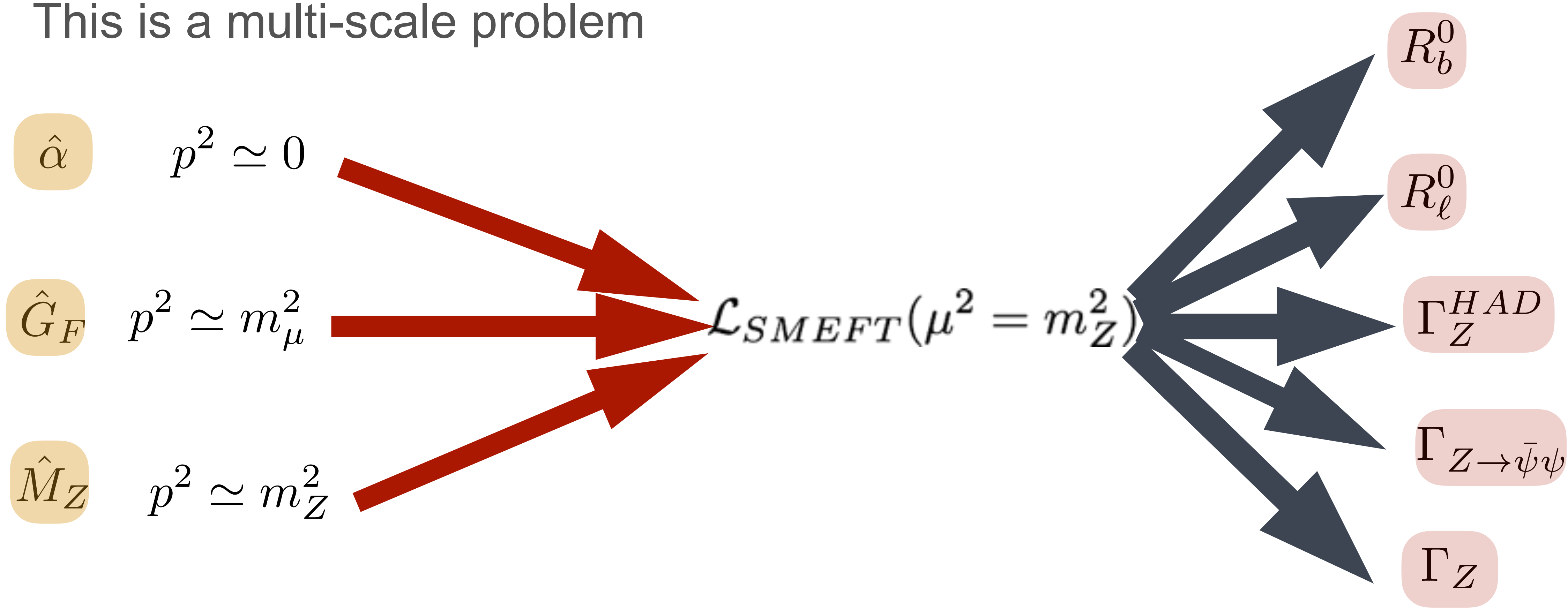


- Need to work harder as these observables DO NOT violate symmetries.

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

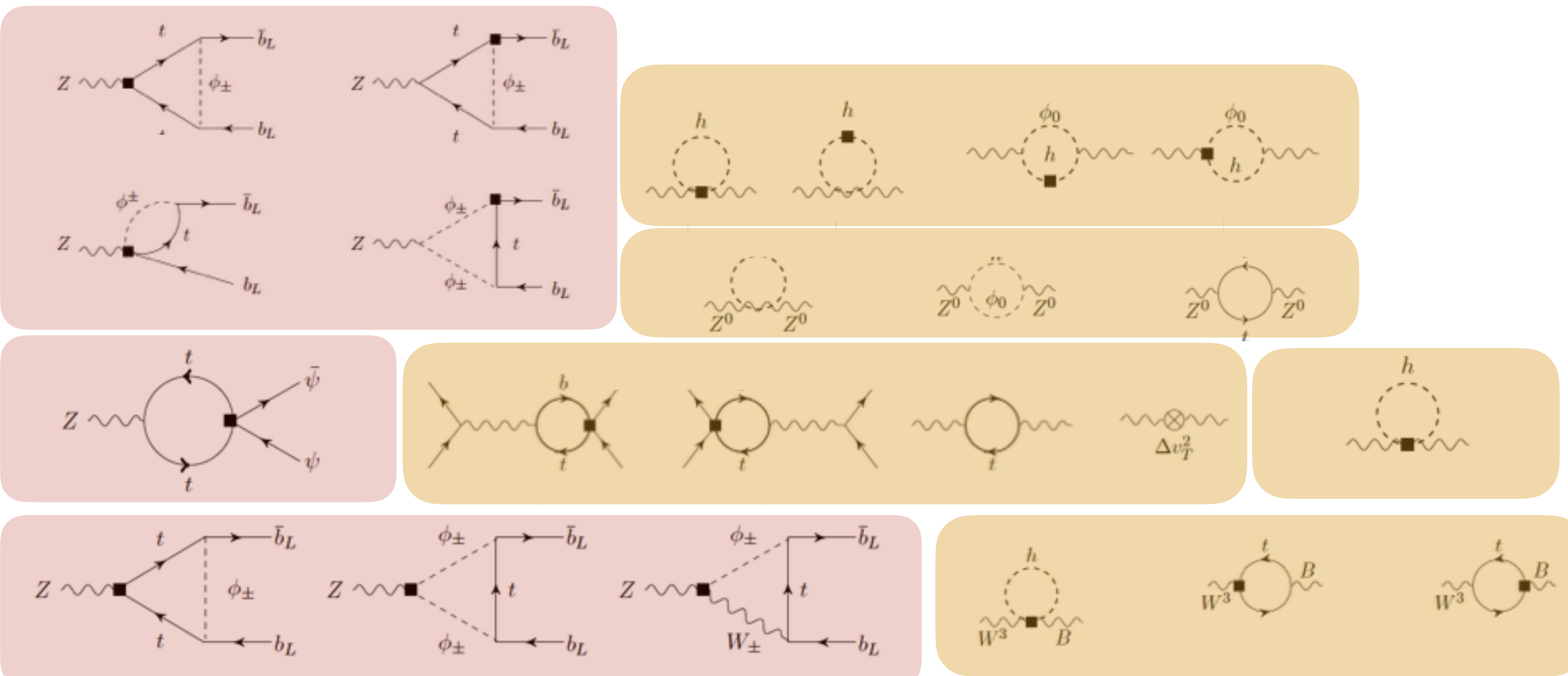
Loops present

- ~ 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

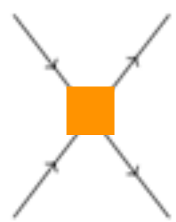


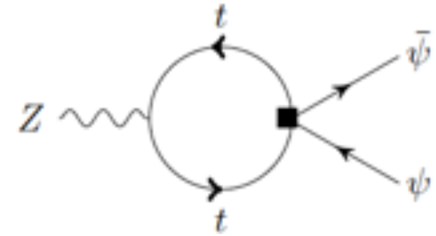
Again we need to combine data sets!

- (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]

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

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

where

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

while the one loop corrections are

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

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

input shifts

decay process

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

One set of lots o numbers…

- Result for Γ_Z in tev units, 10% correction to the leading effects

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

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

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

Wouldn't it be great if….

- We had the ability to study the cases:

    General flavour SMEFT

    MFV SMEFT no CP violating phase beyond the SM

    U(3)^5 SMEFT with CP violating phases

  in numerical tools?

- We had the ability to use the $\{\hat{\alpha}, \hat{m}_Z, \hat{G}_F\}$ OR $\{\hat{m}_W, \hat{m}_Z, \hat{G}_F\}$ scheme easily in some code?
- Had a systematic program of the pole parameters $\langle H|\mathcal{L}_{SM}|H\rangle$ sorted
- Foreshadowing….See Ilaria's talk.

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$		$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
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 due to RI

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

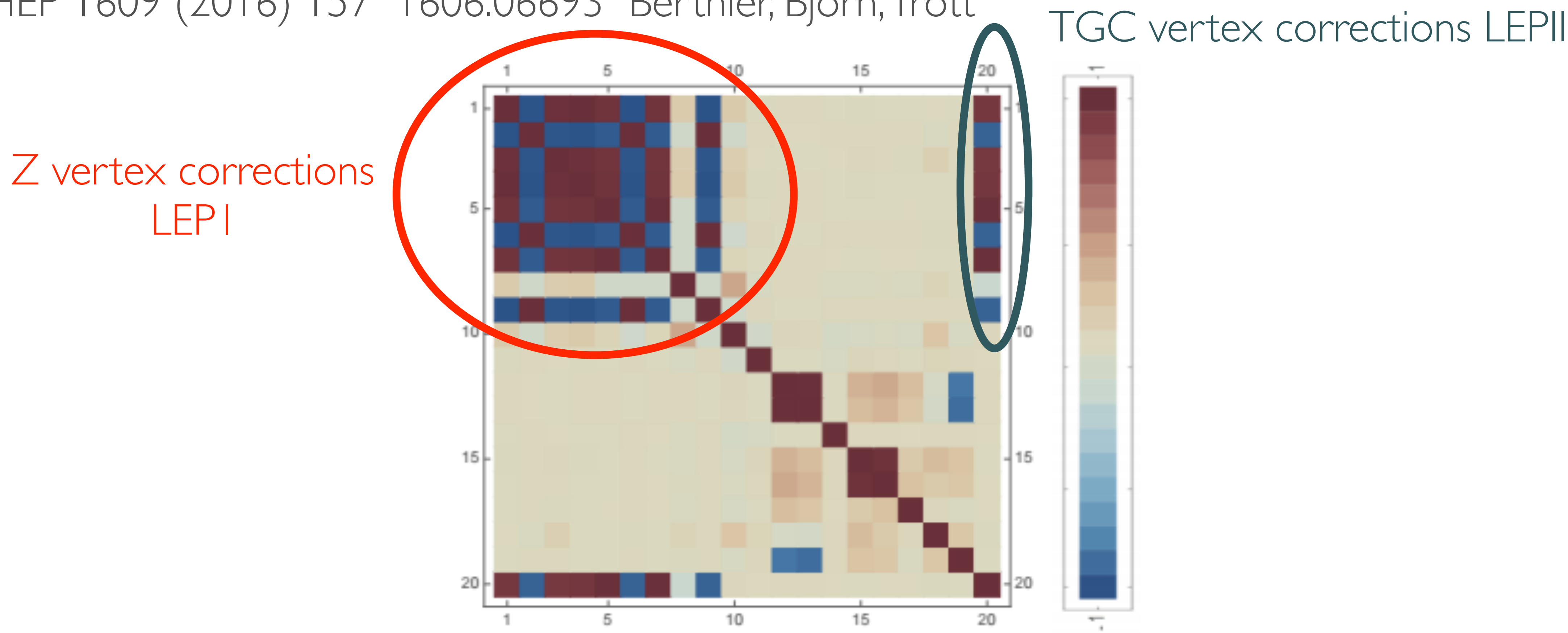
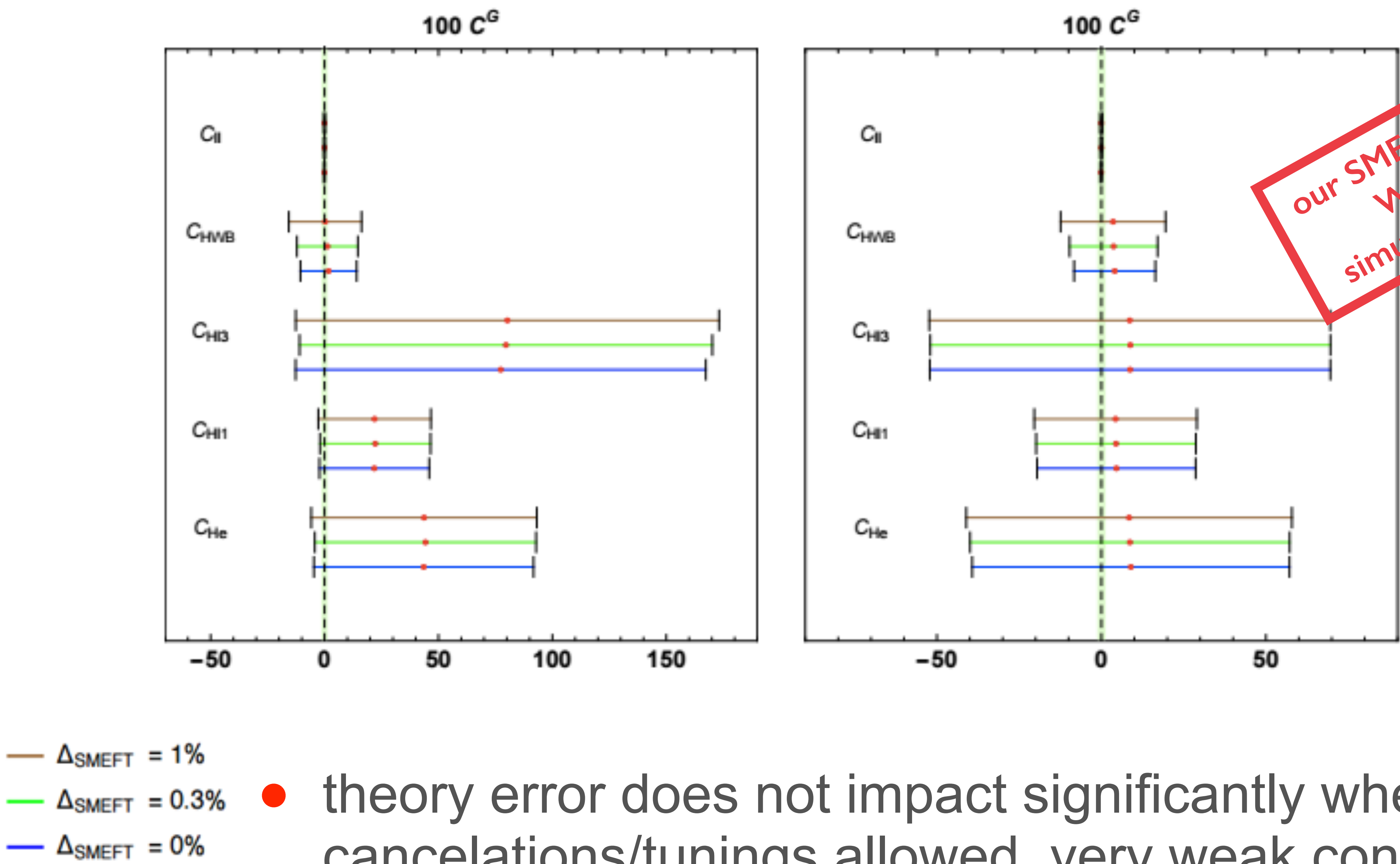


Figure 5: Color map of the correlation matrix between the Wilson coefficients when there is no SMEFT error.The Wilson coefficients are ordered as in Eqn.3.6.

- 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:

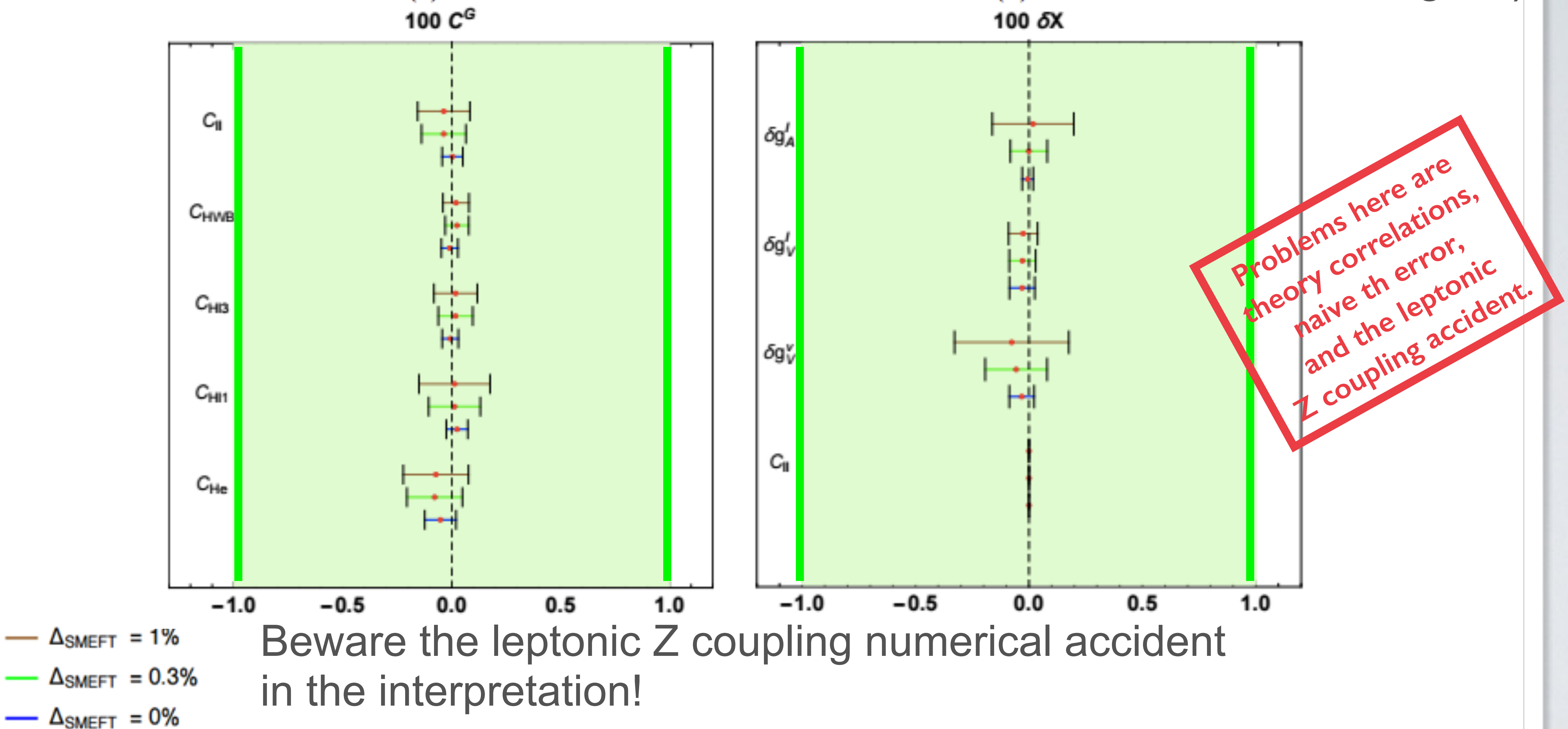


our SMEFT SCORE: 20 of 53 Wilson coefficients simultaneously constrained

- 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.)



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

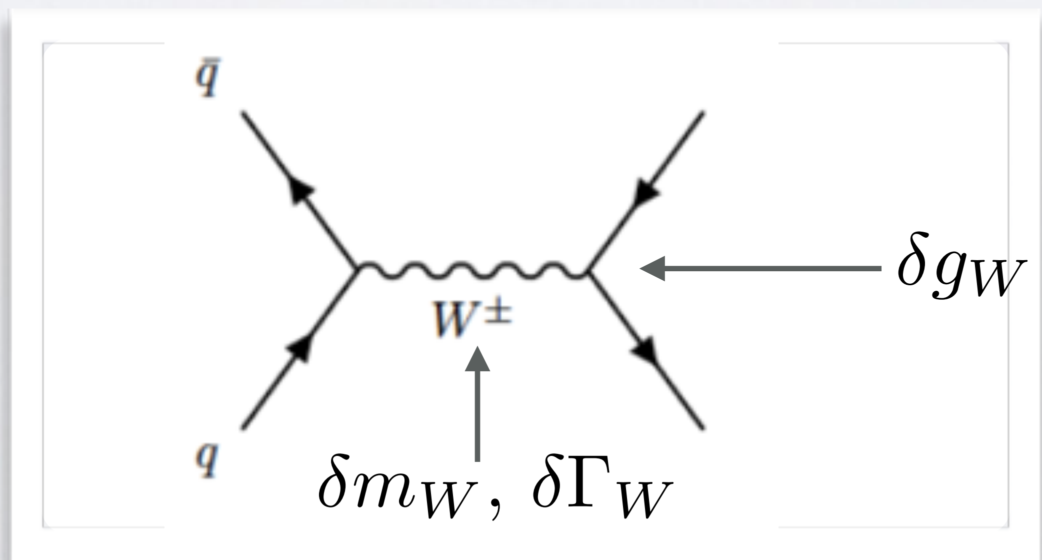
Ex of measurement bias check

- 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:



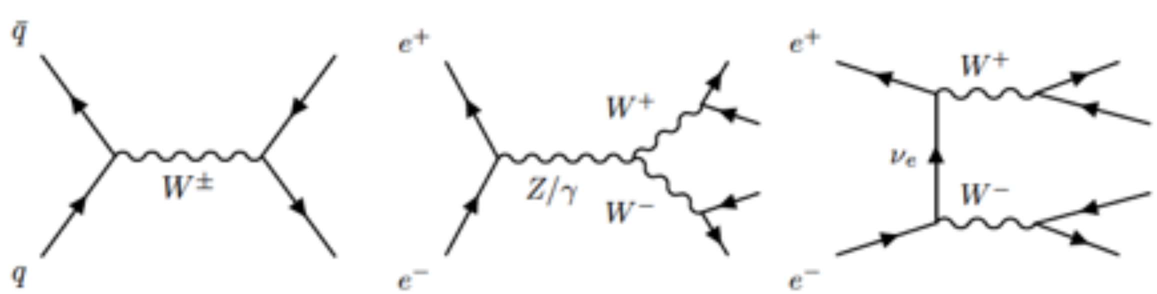
- How wrong is it to just apply the constraint pretending the other shifts not there?

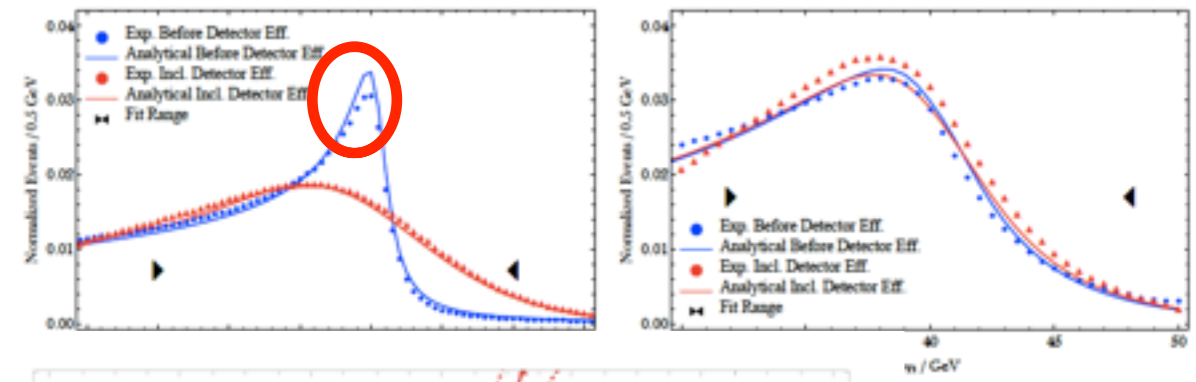
Mw measurements in SMEFT

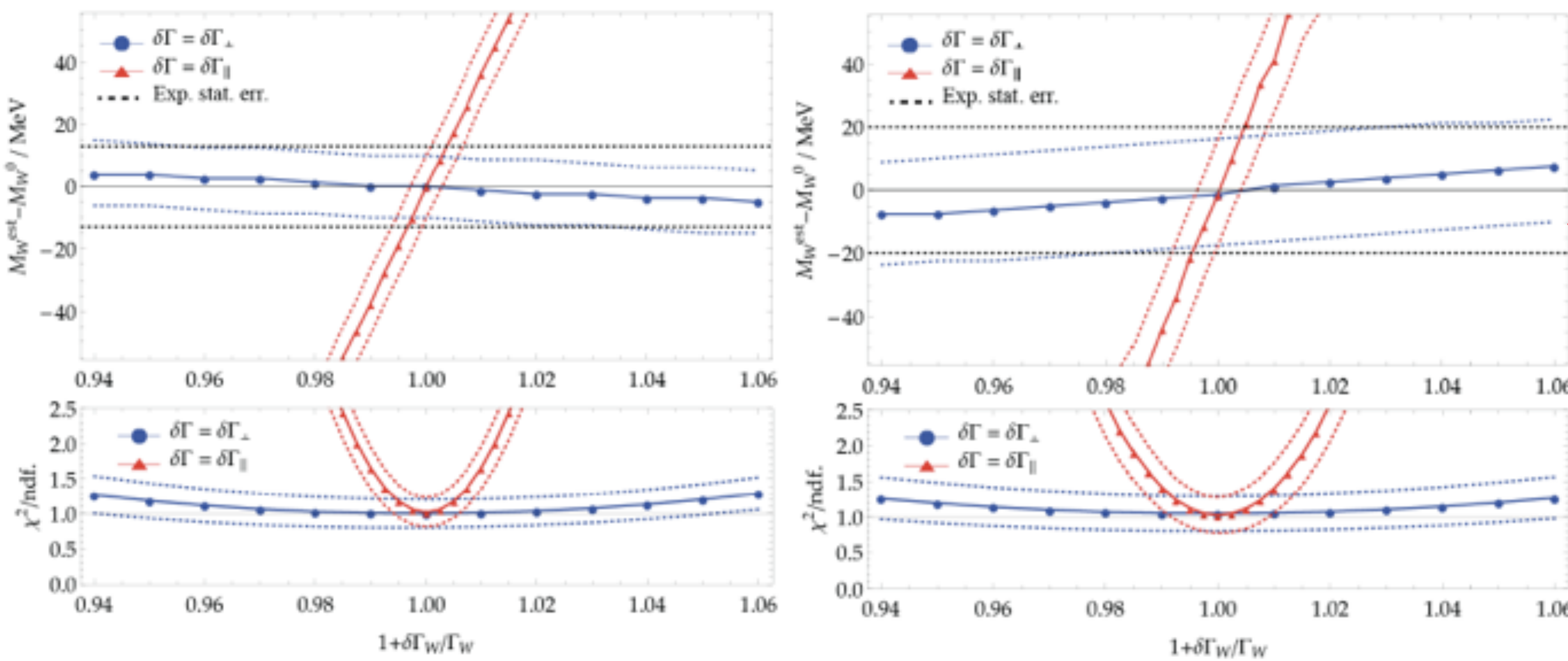
- Mw is a template fit at LEP and at the Tevatron.

1606.06502 Bjorn, Trott

Transverse mass Jacobian peak



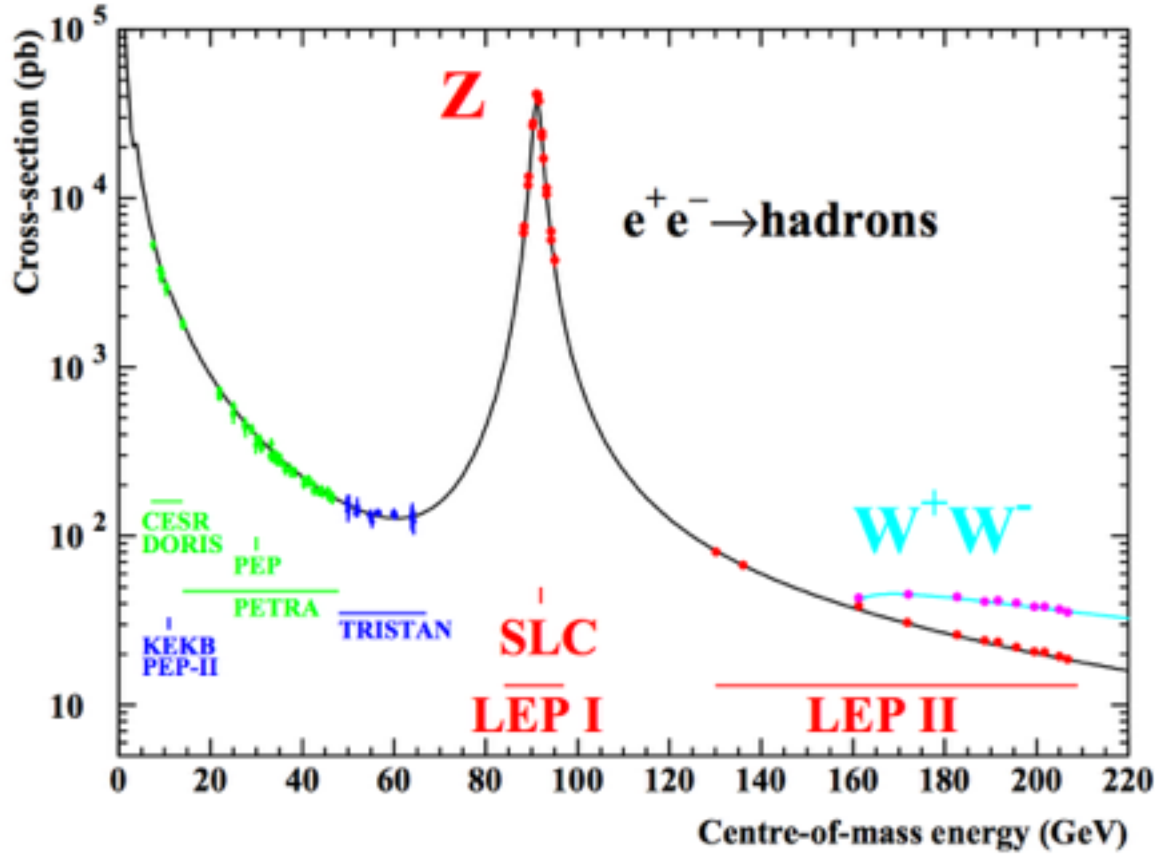




Below percent measurements in SMEFT at colliders possible

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

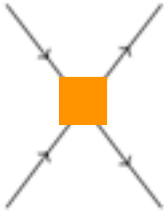
EWPD measurements in SMEFT



- EWPD is a scan through the Z pole

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

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



- many more 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!