Some recent theory developments related to doubly resonant W boson production

- M. Trott

NBI, 24th Oct. 2016

Let me emphasize what theorists agree on.

Everyone agrees that:

- Experimental results on Multi-boson production is a crucial source of information to consistency test the SM and to search for physics beyond the SM

- Multi-boson production can be predicted in the SM with sufficient accuracy that tests for deviations from the SM are meaningful (due to developments leading up to/during LEPII).

- EFT interpretations are of significant value when studying multi-boson production results from LEP and now LHC.

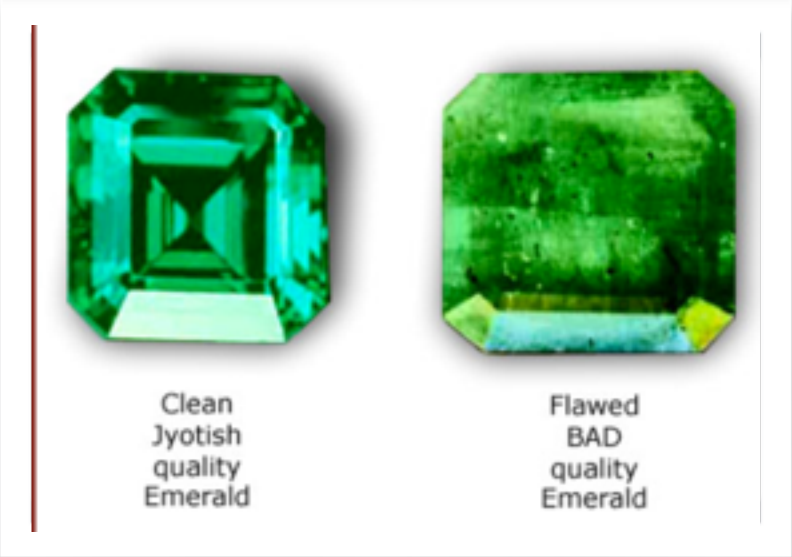
- Significant care must be taken interpreting results measured from the "tails of distributions" (i.e. off resonance) in multi-boson production in general and in the EFT in particular.

- Differences of opinion are in fact small facets of small corrections to this process in the EFT formulations. Nevertheless they matter.

Which EFT interpretation/emerald do you want?

- Differences of opinion are in fact small facets (flaws) of small corrections to this process in the EFT formulations. Nevertheless they matter.

  Which do you want? Both are emeralds. Avoid the small flaws if you can. And you can if you are careful.



- Everyone is happy with parameterizing anomalous TGC couplings Based on Hagiwara et al. Nucl. Phys. B282 1987, 253-307

$$\frac{-\mathcal{L}_{TGC}^{SMEFT}}{g_{VWW}} = i\bar{g}_1^V\left(\mathcal{W}^+_{\mu\nu}\mathcal{W}^{-\mu} - \mathcal{W}^-_{\mu\nu}\mathcal{W}^{+\mu}\right)\mathcal{V}^\nu + i\bar{\kappa}_V\mathcal{W}^+_\mu\mathcal{W}^-_\nu\mathcal{V}^{\mu\nu} + i\frac{\bar{\lambda}_V}{\bar{M}_W^2}\mathcal{V}^{\mu\nu}\mathcal{W}^{+\rho}_\nu\mathcal{W}^-_{\rho\mu},$$

Couplings are related to inputs parameters as:

$$g_{AWW} = \hat{e} = \hat{g}_2 s_{\hat{\theta}} = \sqrt{4\pi\hat{\alpha}},\ g_{ZWW} = \hat{e}\cot\hat{\theta} = \sqrt{4\pi\hat{\alpha}}c_{\hat{\theta}}/s_{\hat{\theta}}$$

Defining coupling shifts as:

$$\bar{g}_1^V = g_1^V + \delta g_1^V,\ \bar{\kappa}_V = \kappa_V + \delta\kappa_V,\ \bar{\lambda}_V = \lambda_V + \delta\lambda_V$$

Mapping a TGC parameterization to operators

- Deviations in the Warsaw basis, with $\{\hat{\alpha}, \hat{G}_F, \hat{m}_Z\}$ inputs

1008.4884 Grzadkowski, Iskrzynski, Misiak, Rosiek

$$\delta g_1^A = 0, \qquad \delta g_1^Z = \frac{1}{2\sqrt{2}\hat{G}_F}\left(\frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} + \frac{c_{\hat{\theta}}}{s_{\hat{\theta}}}\right) C_{HWB} + \frac{1}{2}\delta s_{\hat{\theta}}^2 \left(\frac{1}{s_{\hat{\theta}}^2} + \frac{1}{c_{\hat{\theta}}^2}\right),$$

$$\delta \kappa_A = \frac{1}{\sqrt{2}\hat{G}_F}\frac{c_{\hat{\theta}}}{s_{\hat{\theta}}} C_{HWB}, \qquad \delta \kappa_Z = \frac{1}{2\sqrt{2}\hat{G}_F}\left(-\frac{s_{\hat{\theta}}}{c_{\hat{\theta}}} + \frac{c_{\hat{\theta}}}{s_{\hat{\theta}}}\right) C_{HWB} + \frac{1}{2}\delta s_{\hat{\theta}}^2 \left(\frac{1}{s_{\hat{\theta}}^2} + \frac{1}{c_{\hat{\theta}}^2}\right),$$

$$\delta \lambda_A = 6 s_{\hat{\theta}} \frac{\hat{m}_W^2}{g_{AWW}} C_W, \qquad \delta \lambda_Z = 6 c_{\hat{\theta}} \frac{\hat{m}_W^2}{g_{ZWW}} C_W.$$

$$\delta s_{\hat{\theta}}^2 \equiv \sin^2\hat{\theta} - \sin^2\bar{\theta} = -\frac{s_{\hat{\theta}}\, c_{\hat{\theta}}}{2\sqrt{2}\,\hat{G}_F(1 - 2 s_{\hat{\theta}}^2)}\left[s_{\hat{\theta}}\, c_{\hat{\theta}}\left(C_{HD} + 4\, C_{H\ell}^{(3)} - 2\, C_{ll}\right) + 2\, C_{HWB}\right]$$

(pink)	Effective Lagrangian coupling shifts present in the TCG and SMEFT in general
(grey)	Linearly independent operators in an OPERATOR BASIS.

Shifts vs an Operator Basis

- Not a consensus on the distinction.

- Recently an effort has been made to turn the coupling shifts INTO a basis: arXiv:1405.0181 Gupta, Pomarol, Riva arXiv:1411.0669 Riva, Falkowski
  arXiv:1503.07872 Efrati, Falkowski, Soreq
  arXiv:1508.00581 Falkowski, Gonzalez-Alonso, Greljo, Marzocca
  arXiv:1609.06312 Falkowski, Gonzalez-Alonso, Greljo, Marzocca

- This effort culminated in an attempt to turn such a (manifestly incomplete) construction into a recommendation in WG2, see:

  Higgs Basis: Proposal for an EFT basis choice for LHC HXSWG
  Falkowski: LHCHXSWG-INT-2015-001.

- To clarify the situation. This is not a recommendation for a “preferred basis” formalism to use out of WG2 in the end.

Why is this approach not a Basis?

- Not completely defined at leading order to date.
  Constructed in a gauge dependent manner (unitary gauge) using gauge dependent field redefinitions to arrange the Effective Lagrangian to a certain form.

  see LHCHXSWG-DRAFT-INT-2016-005 Passarino, Trott
  for more discussion on these issues.

- Distinction between a gauge dependent/independent field redefinitions matters. This is due to the fact that the H field has components that define a scalar manifold which has an associated curvature.

- This distinction met before in other contexts and is not a controversial one.
  For example the same mistake was made in unitary Gauge thinking in cosmology, as was explained years ago in:
  Burgess, Lee, Trott JHEP 1007 (2010) 007, 1002.2730 Section II.B.1

- Like any mistake, it can be fixed, but it is irrelevant construction anyway.

Who cares ?!?!?!

- This would just be an uninteresting semantic correction if using only "effective couplings" not a basis was not justifying/related to anything else.

- The issue is tied up into the fact that there is an inequivalent MAPPING of the actual observables to the TGC parameters as defined.

OBSERVABLES should be the focus.

- <u>**Request: have a primary focus on reporting cross section measurements, and differential cross sections with stable final states.**</u>

  <u>***Not***</u> inferred measurements on massive gauge bosons that decay.

  Then all the theorist arguments/issues are irrelevant.

- This request was NOT satisfied at LEP2, where much less information is available on the cross section/diff cross sections compared to extracted

$$\delta g_1^{A,Z}, \delta\lambda_{A,Z}, \delta\kappa_{A,Z}$$

Intrinsically dangerous to model down to these constructed observables arXiv:1409.7605 Trott

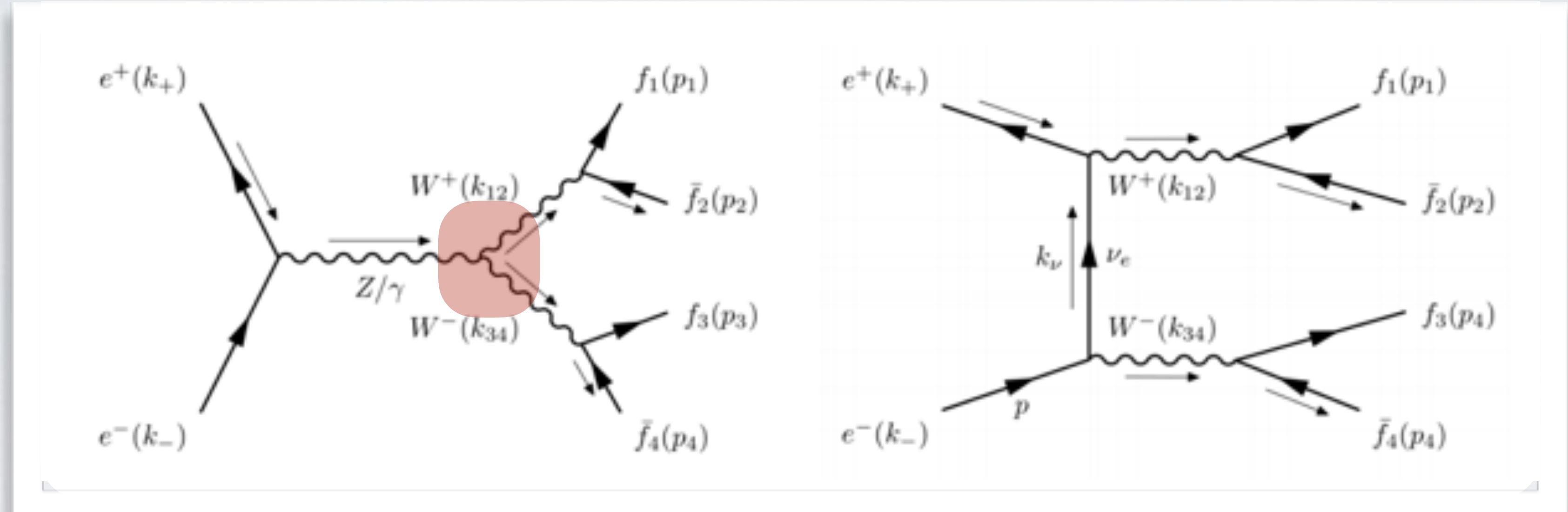
- Relating observables to TGC's follows 2 steps, first the map to PO.

  As far as I know all agree with the PO work in: (but it does not cover this case)

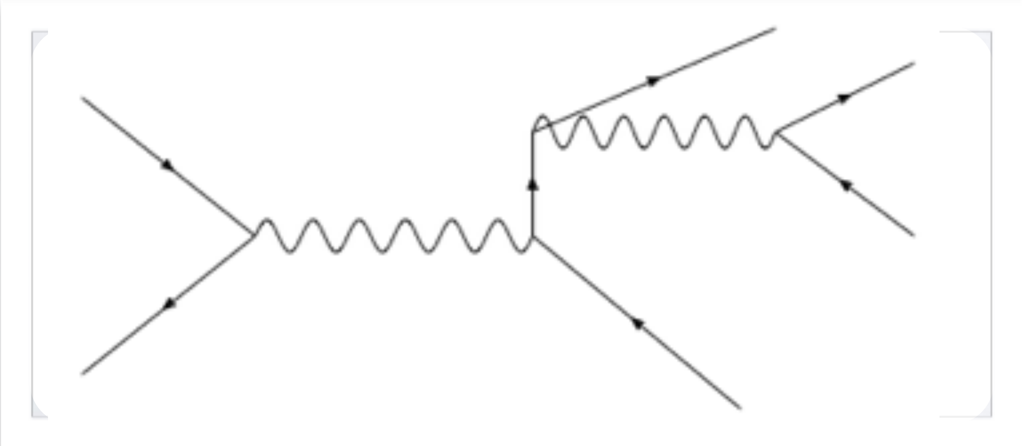
arXiv:1412.6038 Gonzalez-Alonso, Greljo, Marzocca, Isidori
arXiv:1512.06135 Greljo, Marzocca, Isidori, Lindert
YR4 write up A. David, A. Greljo, G. Isidori, J. Lindert, D. Marzocca, G. Passarino

Subtleties due to intermediate unstable states

- It is well known from LEPI/LEPII times that you have to be careful defining the process that involves the off shell TGC verticies



- A difference of gauge fixing terms (axial and feynman gauge) added to the diagrams above generates diagrams like



W. Beenakker and A. Denner, Standard model predictions for W pair production in electron - positron collisions, Int. J. Mod. Phys. A9 (1994) 4837–4920. (and many other refs)

This is the known distinction between “CC03” and “CC11” diagrams.

Subtleties due to intermediate unstable states

- Need a well defined - gauge invariant way - to define the cross section to get down to precision sensitive to off shell effects

  Near resonance pole (relevant for LEPII) scale as and restricted phase space LHC measurements: $\sim \Gamma_Z/m_Z, \Gamma_W/m_W$

  Off resonance pole at LHC in tails these corrections are MUCH larger.

  Aside: in Helicity claims expansion is made in an order one number (near poles) $\sim m_{W,Z}^2/s \sim 1$

  Gauge invariance not addressed in recent Helicity arguments.

  https://arxiv.org/abs/1607.05236 Azatov, Contino, Machado, Riva
  arXiv:1609.06312 Falkowski, Gonzalez-Alonso, Greljo, Marzocca

- Solution for SM was to expand around physical poles to define the off shell process. W. Beenakker and A. Denner, Standard model predictions for W pair production in electron - positron collisions, Int. J. Mod. Phys. A9 (1994) 4837–4920. (and many other refs)

  Suggestion of JHEP 1609 (2016) 157 1606.06693 Berthier, Bjorn, Trott is to do the same thing in the SMEFT.

Defining the Pole decomposition in the SMEFT

- We have performed an analysis of this form. Fit with 177 obs now.
  JHEP 1609 (2016) 157 1606.06693 Berthier, Bjorn, Trott

- The Interesting subtlety is how these processes are defined, in a double pole approximation around the resonances:

$$\mathcal{A}(s_{12}, s_{34}) = \frac{1}{s_{12} - \bar{m}_W^2} \frac{1}{s_{34} - \bar{m}_W^2} \mathrm{DR}[s_{12}, s_{34}, \Omega] + \frac{1}{s_{12} - \bar{m}_W^2} \mathrm{SR}_1[s_{12}, s_{34}, d\Omega], \\ + \frac{1}{s_{34} - \bar{m}_W^2} \mathrm{SR}_2[s_{12}, s_{34}, d\Omega] + \mathrm{NR}[s_{12}, s_{34}, d\Omega].$$

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

when fixing $s_{12} = s_{34} = \bar{m}_W^2$ the shift of the pole in the SMEFT itself.

- As not using Mw as input still not ideal as an expansion in the prop.

My recommendation is simply this.

- Take the Helicity amplitude decompositions of the process in the SMEFT JHEP 1609 (2016) 157 1606.06693 Berthier, Bjorn, Trott

  Which agree with Hagiwara et al. Nucl. Phys. B282 1987, 253-307 in the SM part.

- Fix the pole to the *physical pole in the SMEFT* including contact operator corrections with a chosen input scheme (ideally we would switch to mw as an input here).

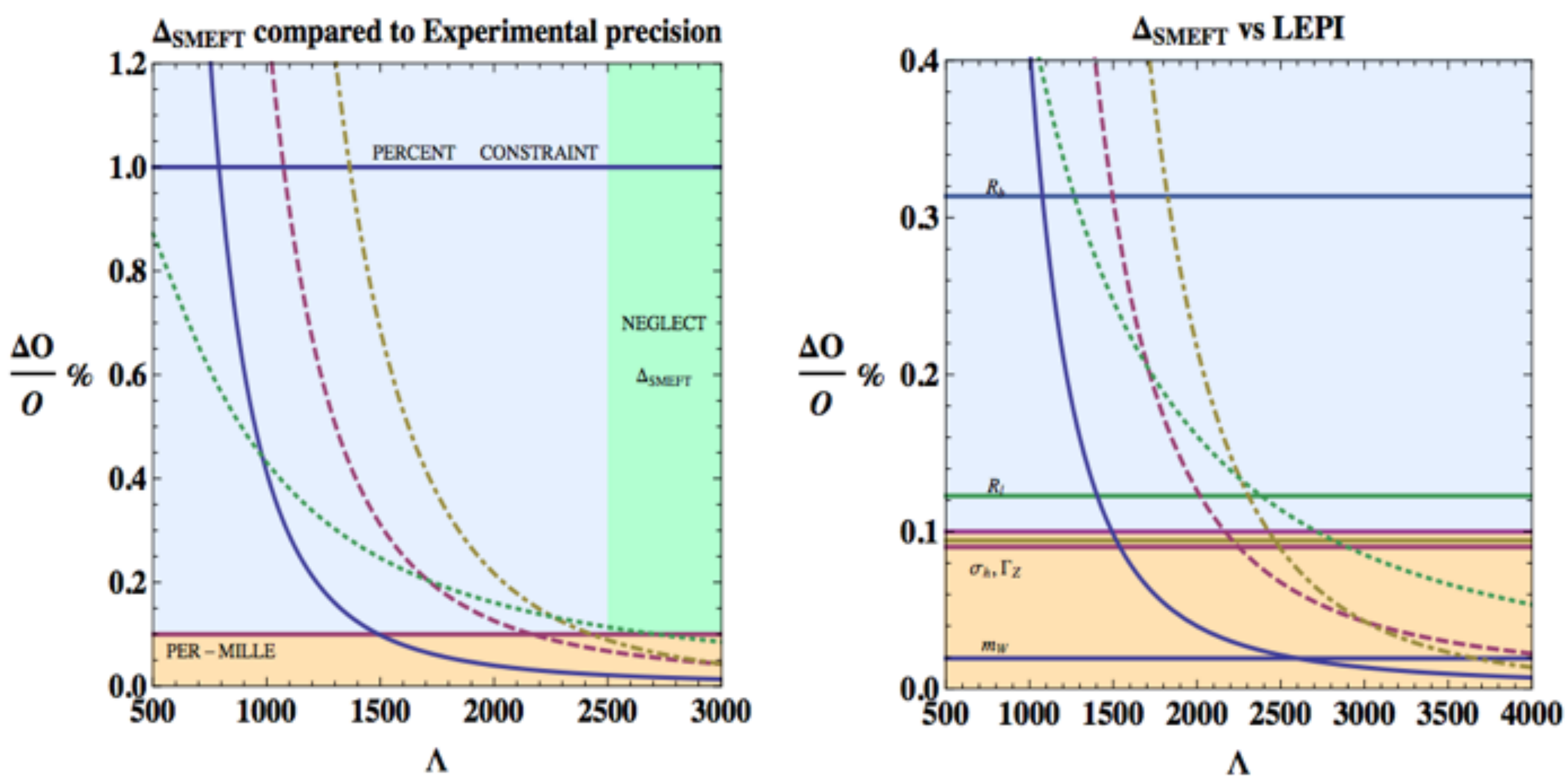
- Convolute with the shifts of the couplings of the W and Z in a consistent manner, and we parameterize the cross sections completely in PO around the pole(s).

- Thats it. I hope we could all agree on that.

To go further - we have to agree on constraints.

- You can avoid that completely, just report your results and actual observables and PO decompositions PLEASE.
- Simplify further requires how constrained are the W, Z coupling shifts and the shift in the W pole are. For precise observables, we can't ignore error in SMEFT itself:

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



JHEP 1602 (2016) 069 arXiv:1508.05060 Berthier, 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.

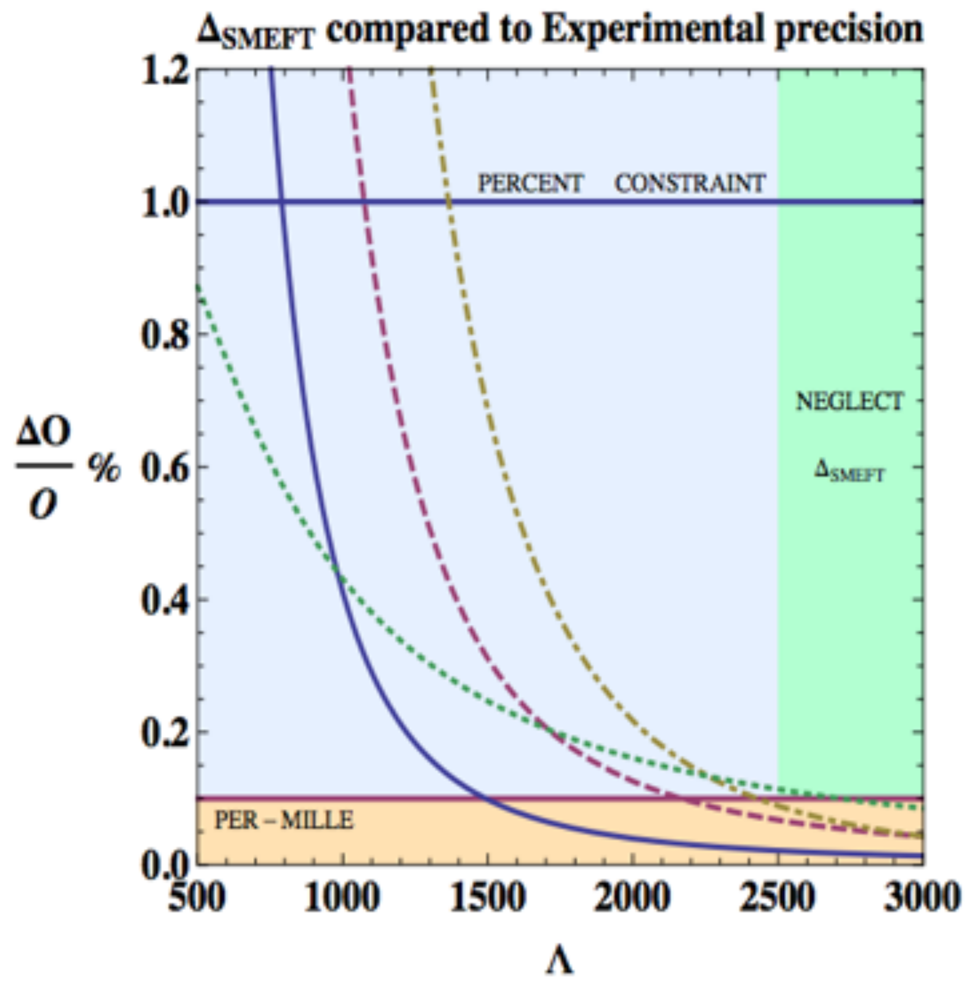
  More data, and LEPII done in a more consistent fashion.

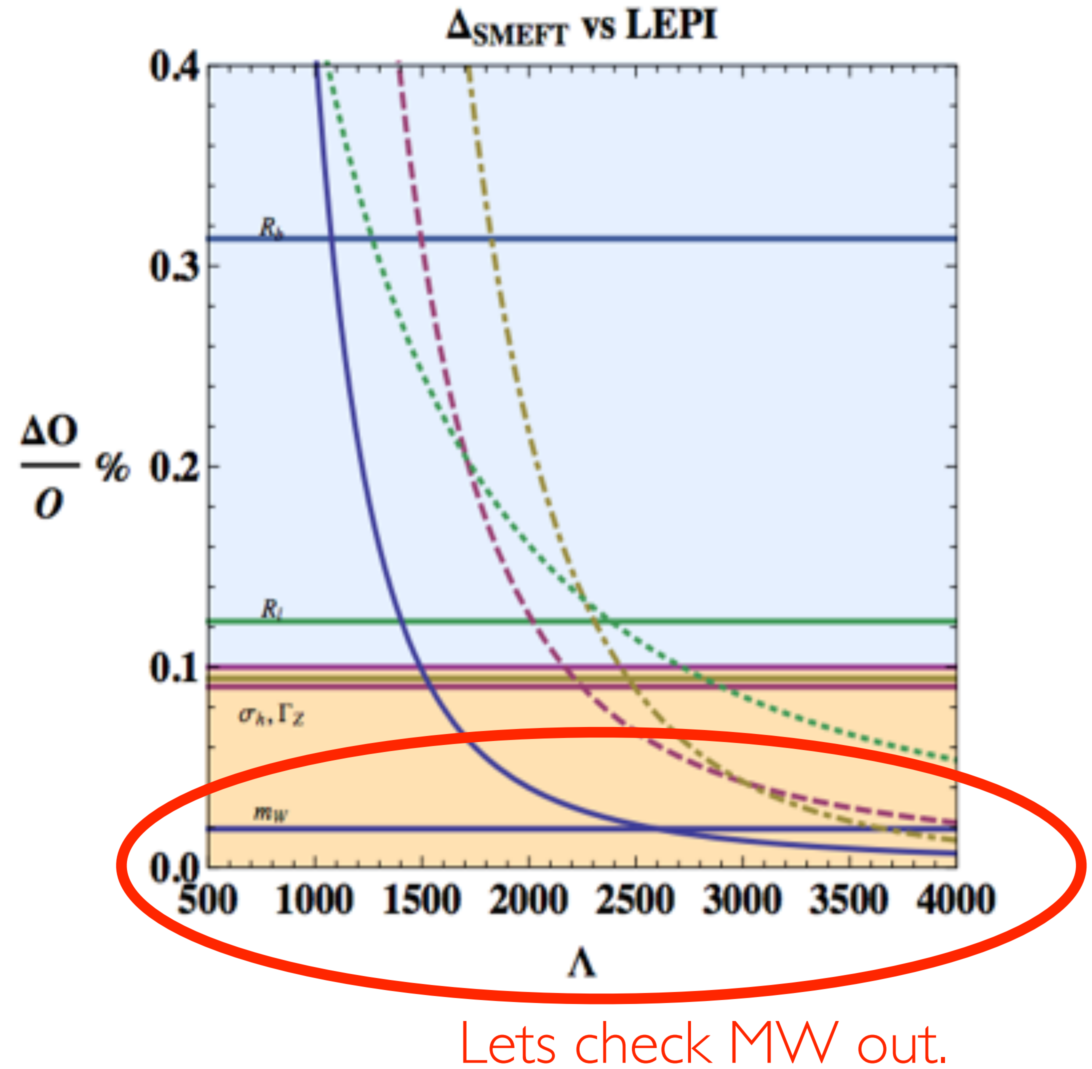
- Our conclusions more in line with the less aggressive claims of Han and Skiba despite the basis issues there. Not surprizing. They are careful and the data didn't change for the LEP side of the story in any important manner after that.

Global constraints on dim 6.

For precise observables, we can't ignore error in SMEFT itself:

JHEP 1602 (2016) 069 arXiv:1508.05060 Berthier, Trott



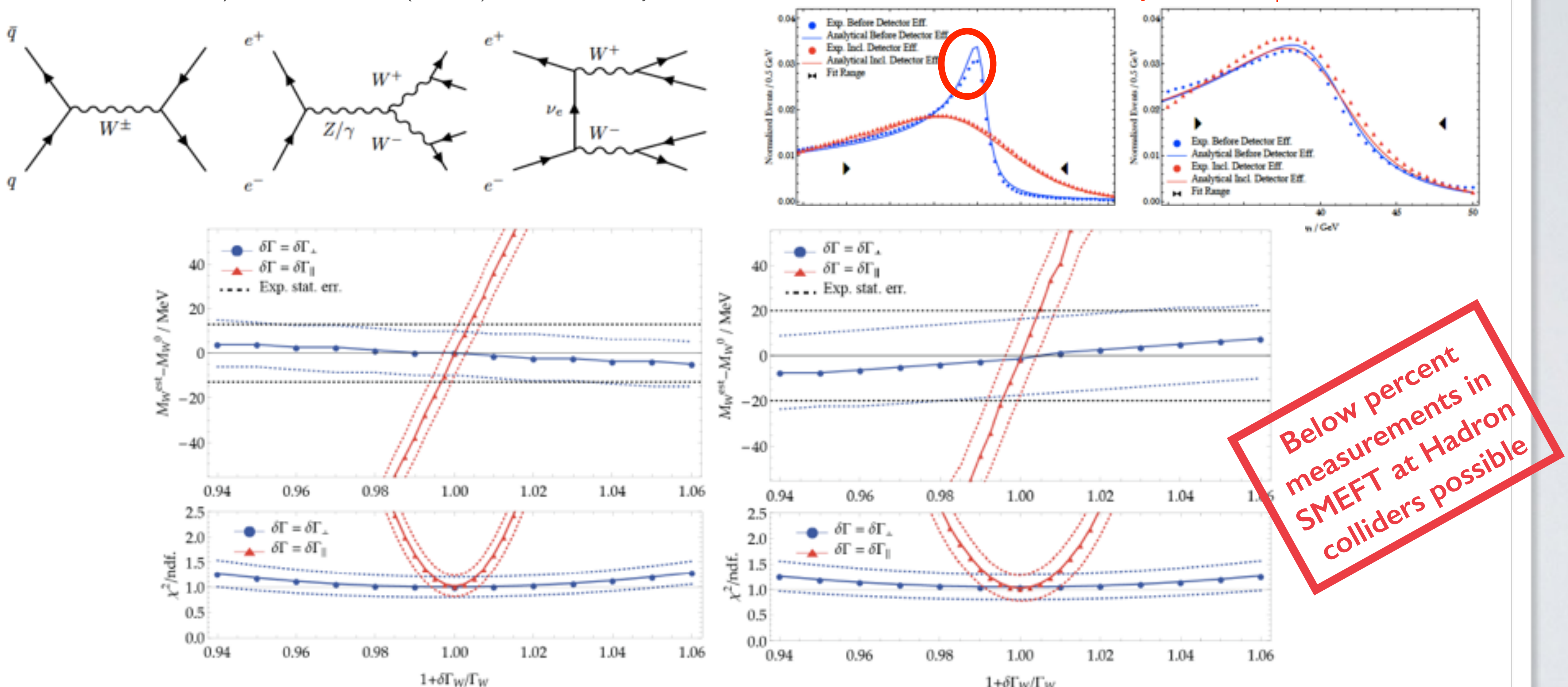


Mw measurements in SMEFT

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

1606.06502 Phys.Lett. B762 (2016) 426-431 Bjorn, Trott

Transverse mass Jacobian peak



Bias on the extraction for the Tevatron is OK in the SMEFT!

Bias on LEPI pseudo-observables due to off-shell effects is also ok

arXiv:1502.02570 JHEP 1505 (2015) 024 Bethier, Trott

Global constraints on dim 6-update

- The Wilson coefficient constraints are highly correlated

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

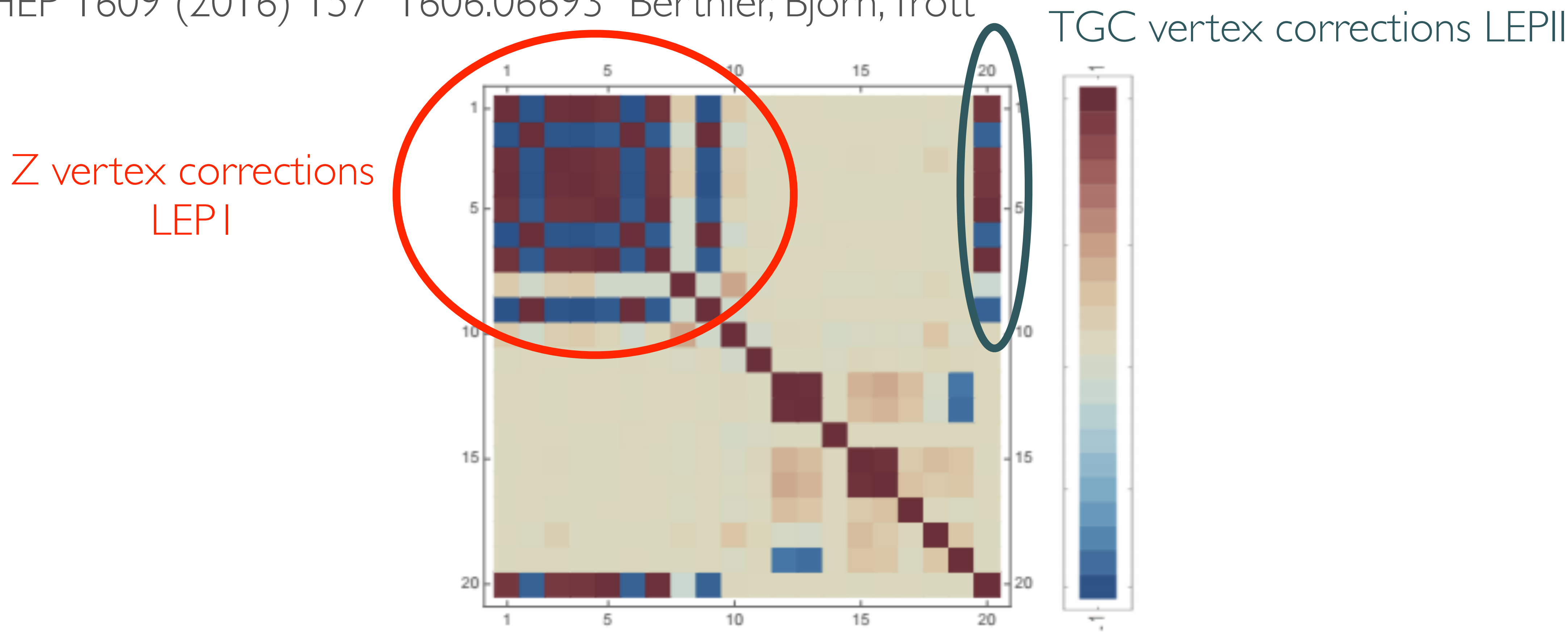
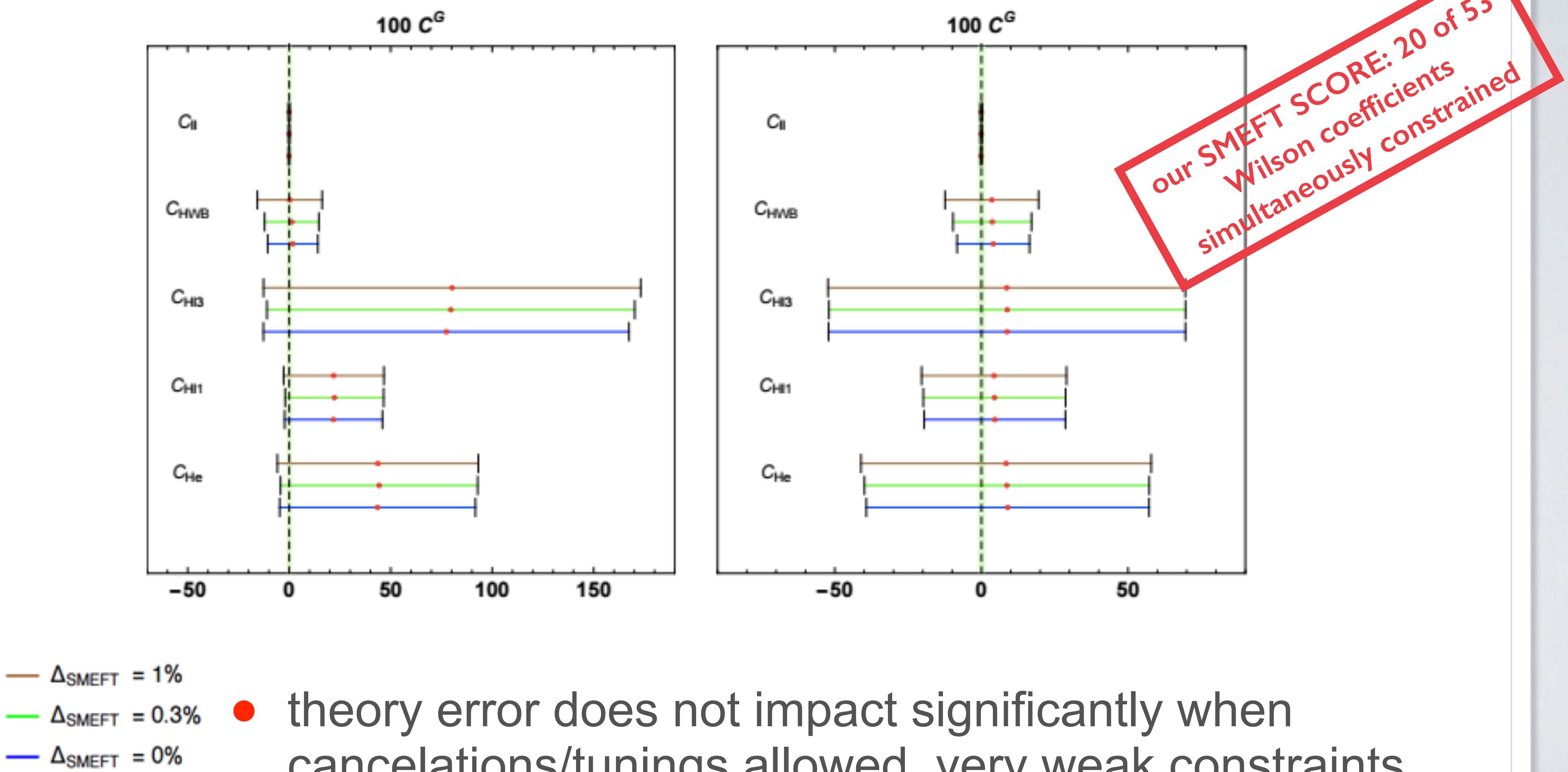


Figure 5: Color map of the correlation matrix between the Wilson coefficients when there is no SMEFT error.The Wilson coefficients are ordered as in Eqn.3.6.

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

Global constraints on dim 6-update

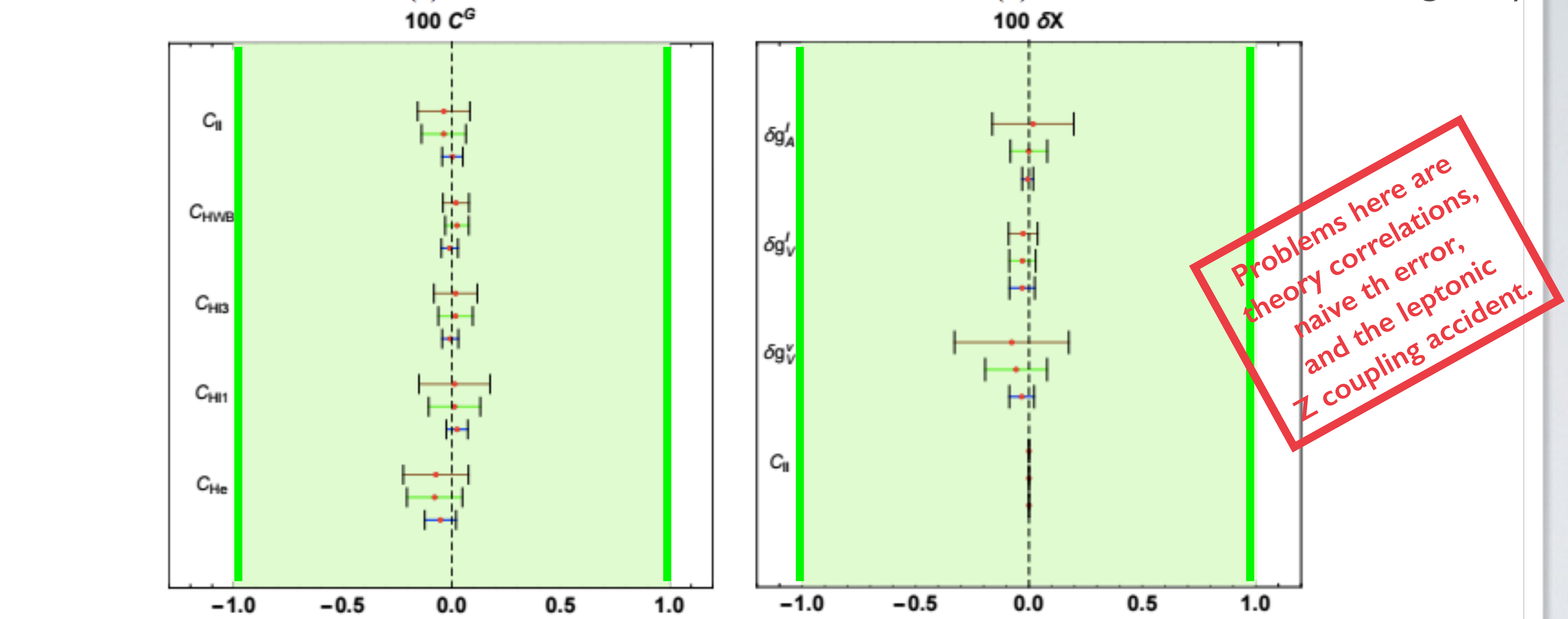
- Summary Warsaw basis profiling down to 1 coeff at a time 2 sigma:



- 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.)

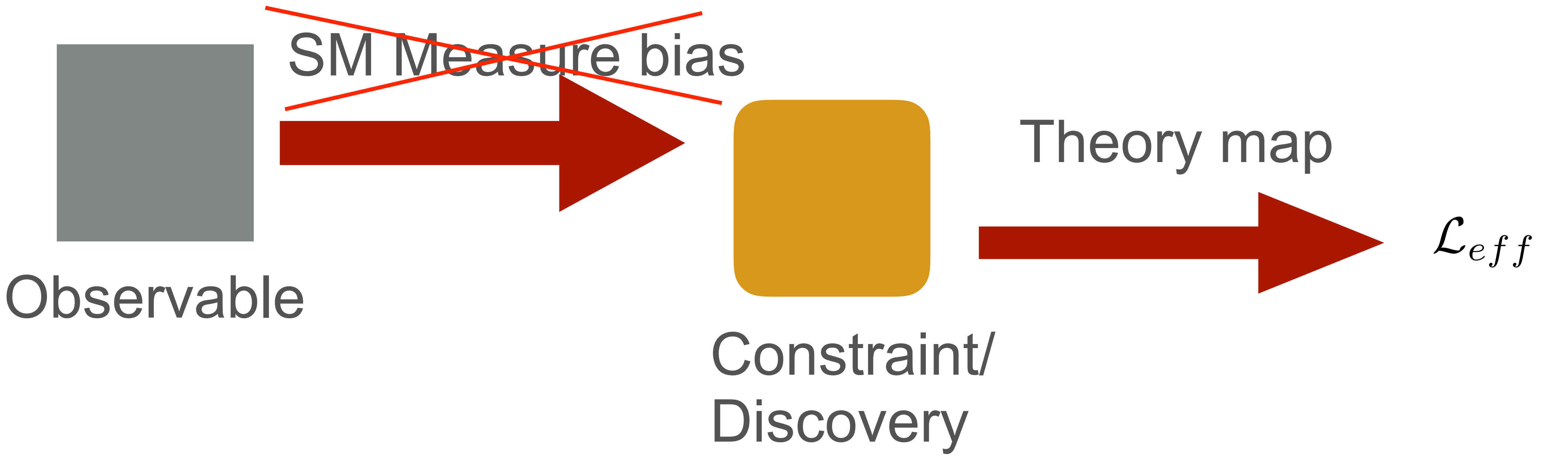


Beware the leptonic Z coupling numerical accident in the interpretation!

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

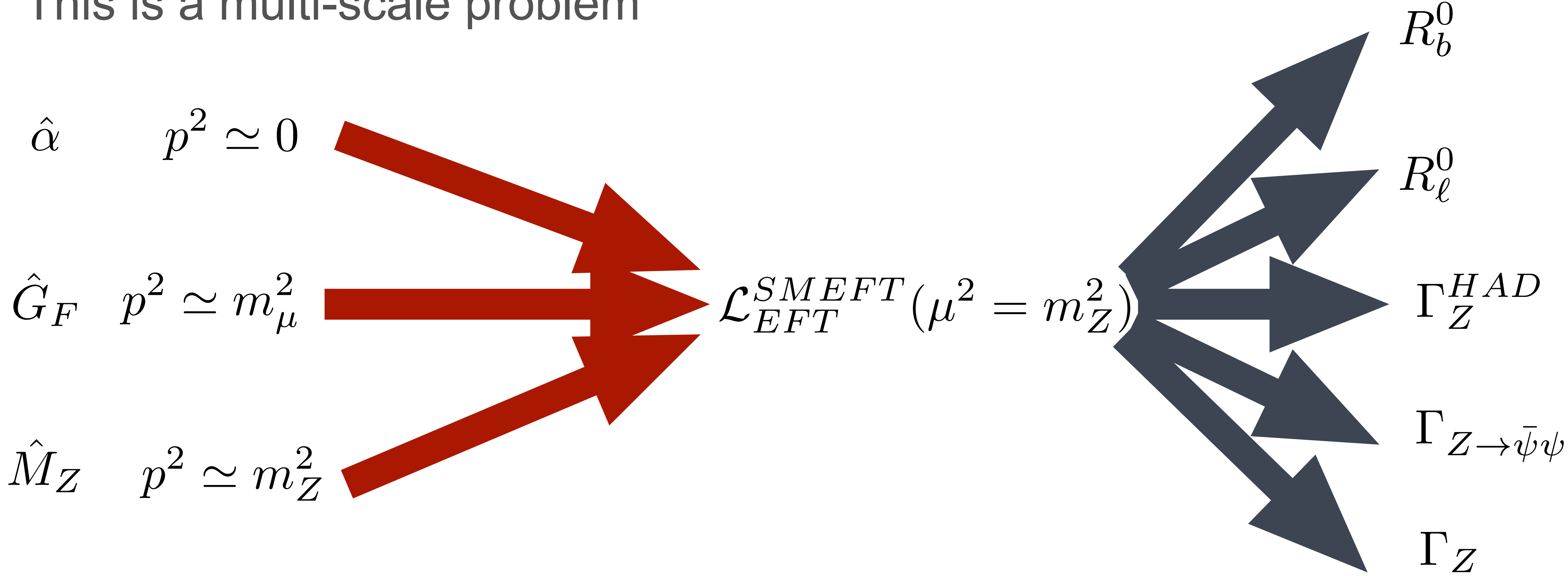
If measure bias is ok how bad is the map?



- It will NEVER be right that the map to $\mathcal{L}_{eff}$ is exactly a LO result. Ever.
- How wrong it is requires a characterization of dim 8 effects and one loop effects. This is now an active industry.
- For (partial) one loop results on MW and EWPD see
  1505.03706 Ghezzi, Gomez-Ambrosio, Passarino, Uccirati
- Here I will just relate some important pheno points on one loop results soon to appear in …Hartmann, Trott, Shepherd (to appear!)…on the Z widths

To predict the decay widths of the Z

- This is a multi-scale problem



- Need to loop improve the extraction of parameters AND the decay process of interest. See discussion in 1505.02646 Hartmann, Trott

see LHCHXSWG-DRAFT-INT-2016-005 Passarino, Trott

1505.03706 Ghezzi, Gomez-Ambrosio, Passarino, Uccirati

1607.01236 Passarino

To predict the decay widths of the Z

- Hartmann, Trott, Shepherd… to appear approximately 30 loops in addition to the RGE 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

  We NOW have some well defined partial results!

- Formally speaking the following parameters are introduced at LEP prevision observables that are not present at tree level

$$Q_{HD}, Q_{H\Box}, Q_{uH}, Q_{HB}, Q_{HW}$$

$$O_{C8} = \{Q_{qq}^{(1)}, Q_{qq}^{(3)}, Q_{lq}^{(1)}, Q_{lq}^{(3)}, Q_{uu}, Q_{eu}, Q_{lu}, Q_{qe}, Q_{ud}^{(1)}, Q_{qu}^{(1)}, Q_{qd}^{(1)}\}.$$

- Dependence at one loop for these operators is not aligned with “flat directions” at tree level $Q_{UH}, Q_{Hq}^{1}, C_{Hq}^{3}$

- Not the case that parameter redefinitions can be done so that observables outnumber the SMEFT parameters at one loop.

Parameters exceeds LEP PO at one loop

- Therefore, formally LEPI alone projects constraints on parameters including the Z vertex corrections in a manner that is UNCONSTRAINED when you hit the loop correction size. (How big is it - consistent with expectations shown)

Hartmann, Trott, Shepherd (to appear!)

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]

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

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

where

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

while the one loop corrections are

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

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

input shifts

decay process

Conclusions

- For multiboson production it would be preferred if measurements of observables instead of the effective aTGC coupling parameters were the priority (in my view)
- There exists a clear and trivial approach to use to parameterize near the poles, building on the SM results that includes the W mass coupling shift and vertex corrections as PO decomposition. In the tails - good luck!
- Going beyond that to further reduce out W/Z coupling dependence and w mass shift dependence means that constraints have to be agreed on.
- Consistent with general expectations, preliminary loop results indicate that current constraint LO claims are subject to substantial theoretical uncertainties.