General Comments re LO/NLO (perturbative) combinations

Mapping of measurement to SMEFT parameters at LO requires:

- Observable (S matrix element) to Wilson coefficient linear map.

$$\left(\prod_{i=1}^{a}\frac{i\sqrt{Z_i}}{p_i^2-m_i^2+i\epsilon}\right)\left(\prod_{j=1}^{b}\frac{i\sqrt{Z_j}}{k_j^2-m_j^2+i\epsilon}\right)\langle p_1\cdots p_a|S|k_1\cdots k_b\rangle.$$

$$m_i = m_i^{SM} + \sum_j \delta m_i(c_j\, v^2/\Lambda^2)$$

$$\alpha_i = \alpha_i^{SM} + \sum_j \delta\alpha_i(c_j\, v^2/\Lambda^2)$$

$$\langle p_1\cdots p_a|S|k_1\cdots k_b\rangle = \langle p_1\cdots p_a|S|k_1\cdots k_b\rangle^{SM} + \sum_{j,k}\delta\langle S\rangle(c_j v^2/\Lambda^2, c_k P^2/\Lambda^2)$$

- If fields are not redefined by complete set of $1/\Lambda^2$ field redefinitions allowed, then an operator basis is redundant. Redundancies cancel in S matrix. Over-complete basis = a pain, but cures itself in observable.

General Comments re LO/NLO (perturbative) combinations

- Observable to Wilson coefficient incomplete map

$$m_i = m_i^{SM} + \sum_j \delta m_i (c_j \, v^2/\Lambda^2)$$

$$\alpha_i = \alpha_i^{SM} + \sum_j \delta \alpha_i (c_j \, v^2/\Lambda^2)$$

$$\langle p_1 \cdots p_a | S | k_1 \cdots k_b \rangle = \langle p_1 \cdots p_a | S | k_1 \cdots k_b \rangle^{SM} + \sum_{j,k} \delta \langle S \rangle (c_j v^2/\Lambda^2, c_k P^2/\Lambda^2)$$

If you drop some terms in the sums as they are unknown/forgotten. Someone can choose to drop other terms just as well.

As statement in SMEFT an incomplete map leads to numerical differences (ambiguities) the order of the incomplete set of terms.

- To avoid that need all corrections of a certain order in a process

$$\frac{1}{\Lambda^2}, \quad \text{or} \quad \frac{1}{16\pi^2\Lambda^2}$$

Including corrections to input parameters in SMEFT

Do we agree on this?

- To avoid numerical ambiguity need all corrections of a certain order in a process

$$\frac{1}{\Lambda^2}, \quad \text{or} \quad \frac{1}{16\pi^2\Lambda^2}$$

Including corrections to input parameters in SMEFT

The Input parameter challenge.

- Observables use some set of measurement to define Lagrangian parameters numerically: input parameters

Common Choices

$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$	Scheme
$\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$	Scheme

Predictions depend on the input parameter scheme:

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2}\tilde{C}_{HD} + \frac{2^{3/4}\sqrt{\pi\hat{\alpha}}\,\hat{M}_Z}{\hat{G}_F^{1/2}}\tilde{C}_{HWB},$$

$$\frac{\delta\alpha}{2\,\hat{\alpha}} = 0,$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = -\frac{s_{2\hat{\theta}}}{4\,c_{2\hat{\theta}}}\left(\frac{c_{\hat{\theta}}}{s_{\hat{\theta}}}\tilde{C}_{HD} + \frac{s_{\hat{\theta}}}{c_{\hat{\theta}}}2\sqrt{2}\,\delta G_F + 4\tilde{C}_{HWB}\right),$$

$$\delta m_Z^2 = \frac{\hat{M}_Z^2}{2}\tilde{C}_{HD} + 2\,\hat{M}_Z\,\hat{M}_W\sqrt{1-\frac{\hat{M}_W^2}{\hat{M}_Z^2}}\tilde{C}_{HWB},$$

$$\frac{\delta\alpha}{2\,\hat{\alpha}} = -\frac{\delta G_F}{\sqrt{2}} + \frac{\delta m_Z^2}{\hat{M}_Z^2}\frac{\hat{M}_W^2}{2\,(\hat{M}_W^2-\hat{M}_Z^2)} - \tilde{C}_{HWB}\frac{\hat{M}_W}{\hat{M}_Z}\sqrt{1-\frac{\hat{M}_W^2}{\hat{M}_Z^2}},$$

$$\frac{\delta M_W^2}{\hat{M}_W^2} = 0,$$

If one drops these corrections in the predictions, one is also dropping some terms in the sums feeding into the S matrix element.

Vast majority of results are “incomplete” in this way at LO or NLO.

The Input parameter challenge.

- Example of numerical dependence of input scheme at LO in Higgs width:

$\{\hat{\alpha}_{ew}, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\frac{\delta\Gamma^{SMEFT}_{h,full}}{\Gamma^{SM}_h} \simeq 1 - 1.40\,\tilde{C}_{HB} - 1.22\,\tilde{C}_{HW} + 2.89\,\tilde{C}_{HWB} + 50.6\,\tilde{C}_{HG} + 1.83\,\tilde{C}_{H\Box} + 0.34\,\tilde{C}_{HD} + 0.70\,\tilde{C}'_{ll} - 7.85\,\hat{Y}_{\underset{cc}{u}}\,\mathrm{Re}\,\tilde{C}_{uH} - 48.5\,\hat{Y}_{\underset{bb}{d}}\,\mathrm{Re}\,\tilde{C}_{dH} - 12.3\,\hat{Y}_{\underset{\tau\tau}{\ell}}\,\mathrm{Re}\,\tilde{C}_{eH} + 0.002\,\tilde{C}^{(1)}_{Hq} + 0.06\,\tilde{C}^{(3)}_{Hq} + 0.001\,\tilde{C}_{Hu} - 0.0008\,\tilde{C}_{Hd} - 0.0008\,\tilde{C}^{(1)}_{Hl} - 1.38\,\tilde{C}^{(3)}_{Hl} - 0.0007\,\tilde{C}_{He}.$$

$\{\hat{M}_W, \hat{M}_Z, \hat{G}_F, \hat{M}_h\}$ Scheme

$$\frac{\delta\Gamma^{SMEFT}_{h,full}}{\Gamma^{SM}_h} \simeq 1 - 1.50\,\tilde{C}_{HB} - 1.21\,\tilde{C}_{HW} + 1.21\,\tilde{C}_{HWB} + 50.6\,\tilde{C}_{HG} + 1.83\,\tilde{C}_{H\Box} - 0.43\,\tilde{C}_{HD} + 1.17\,\tilde{C}'_{ll} - 7.85\,\hat{Y}_{\underset{cc}{u}}\,\mathrm{Re}\,\tilde{C}_{uH} - 48.5\,\hat{Y}_{\underset{bb}{d}}\,\mathrm{Re}\,\tilde{C}_{dH} - 12.3\,\hat{Y}_{\underset{\tau\tau}{\ell}}\,\mathrm{Re}\,\tilde{C}_{eH} + 0.002\,\tilde{C}^{(1)}_{Hq} + 0.06\,\tilde{C}^{(3)}_{Hq} + 0.001\,\tilde{C}_{Hu} - 0.0007\,\tilde{C}_{Hd} - 0.0009\,\tilde{C}^{(1)}_{Hl} - 2.32\,\tilde{C}^{(3)}_{Hl} - 0.0006\,\tilde{C}_{He},$$

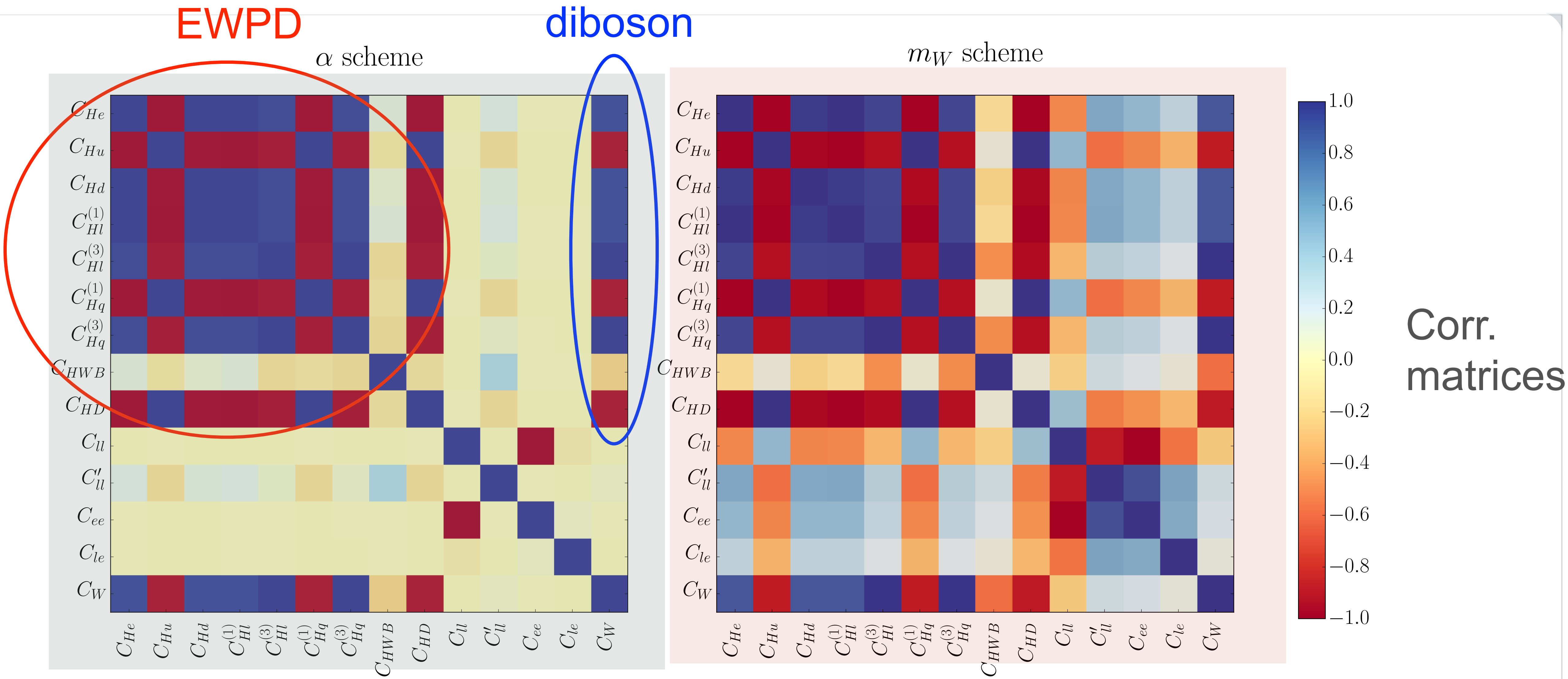
https://arxiv.org/pdf/1906.06949.pdf Brivio, Corbett, Trott

60% 230% 70%

Numerical effect on (ideally) few % perturbation to SM.
Constraint space impacted in order one fashion
for input parameter sensitive parameters.

- What should be the warning to experiment ?
They should be complete at an order! (if possible), and always 2 input schemes?
- What other inputs do we have to worry about at LO?

The Input parameter challenge even at LO

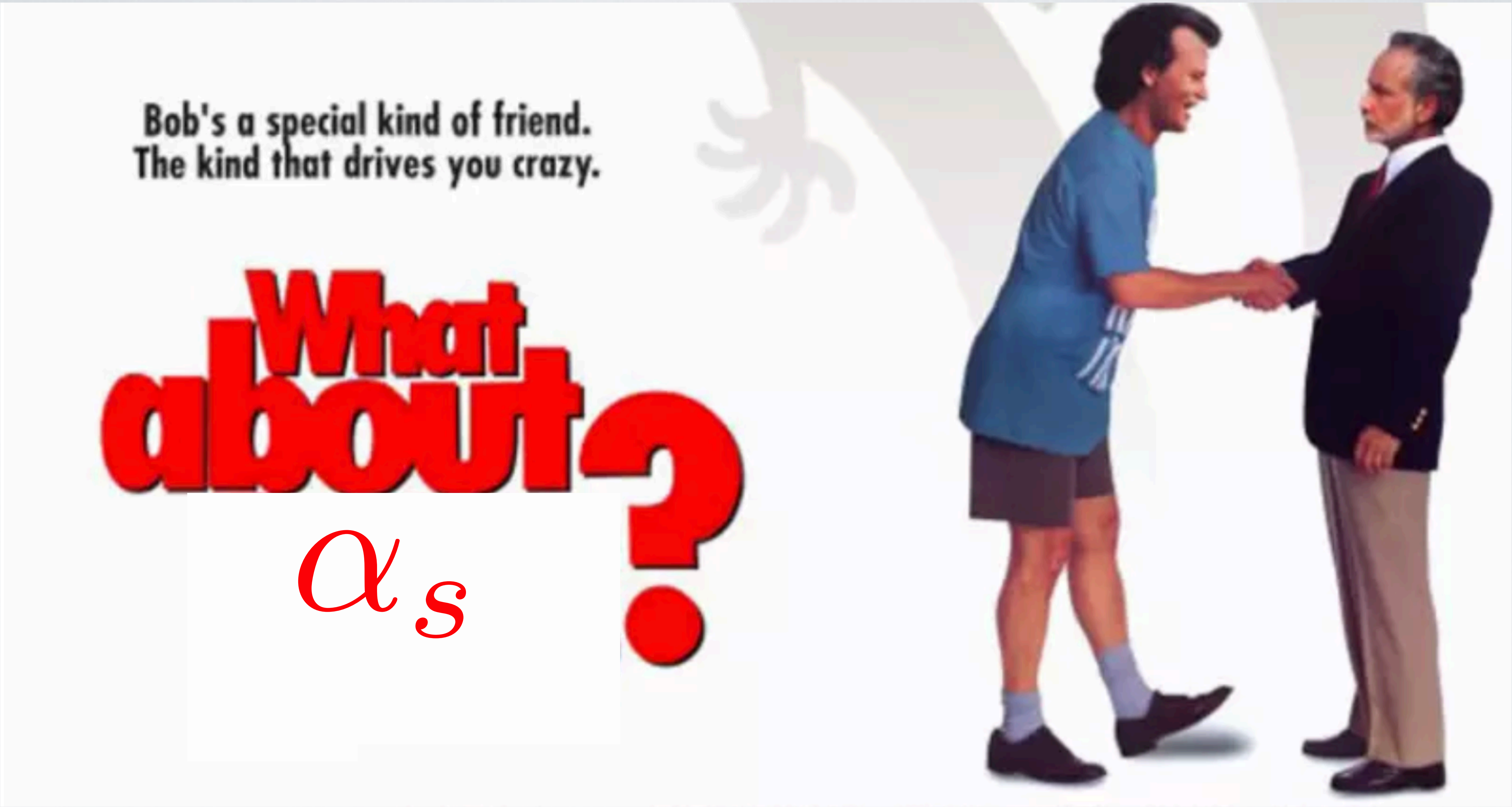


- Global analysis of data from PEP, PETRA, TRISTAN, SpS, Tevatron, SLAC, LEPI and LEP II
- Correlation matrices in a likelihood for the SMEFT (before higgs data)

$$L(C) = \frac{1}{\sqrt{(2\pi)^n |V|}} \exp\left(-\frac{1}{2}\left(\hat{O}-\bar{O}\right)^T V^{-1}\left(\hat{O}-\bar{O}\right)\right),$$

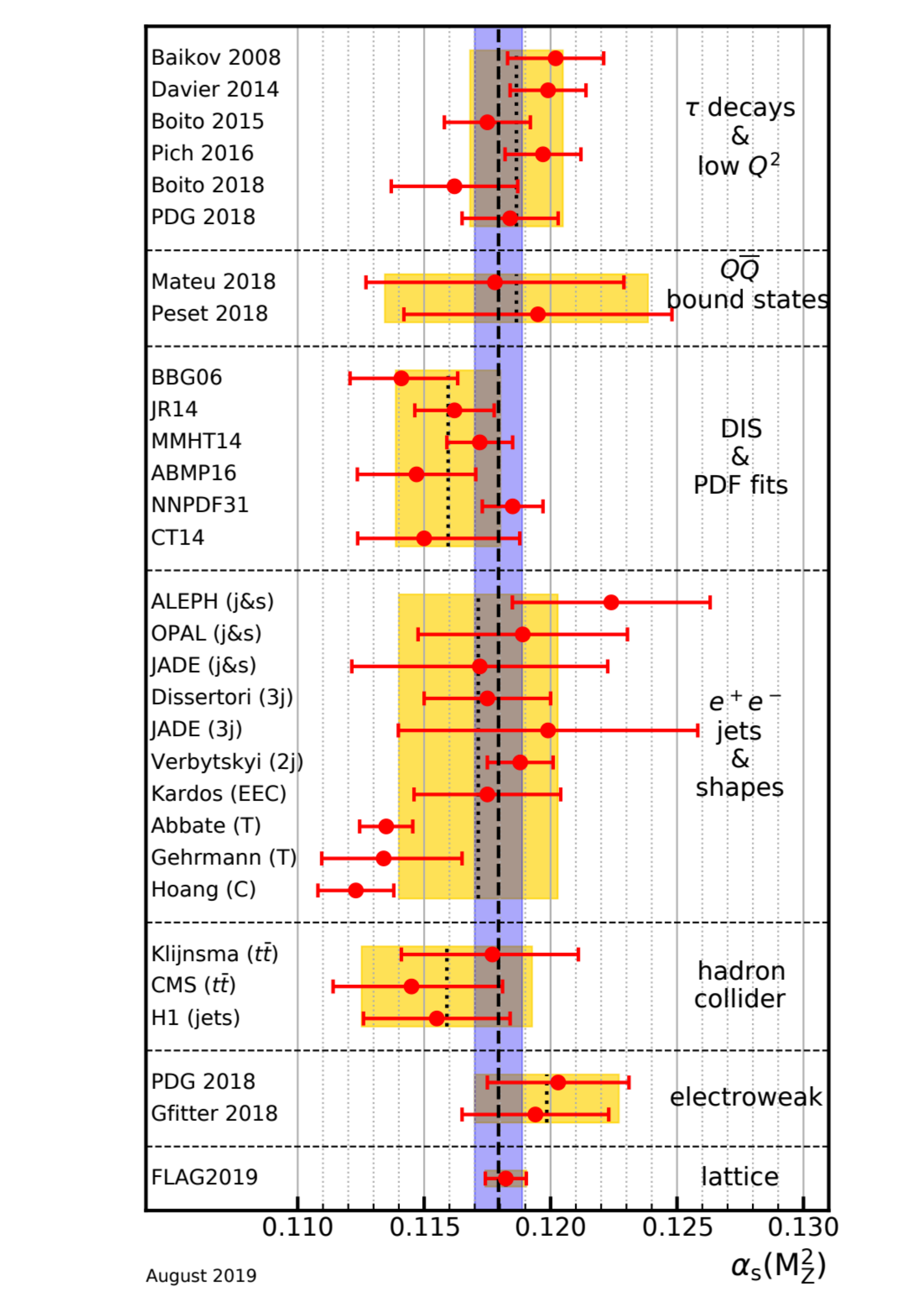
1502.02570, 1508.05060, Berthier, MT ,1606.06693 Berthier, Bjorn, MT , arXiv:1701.06424 Brivio, MT

The Input parameter challenge for higgs NLO



- For higgs production, do we need to specify the SMEFT input parameter dependence of the strong coupling. If so - what is it?

Is this spread in determinations interesting from a SMEFT perspective?



http://pdg.lbl.gov/2019/reviews/rpp2018-rev-qcd.pdf

α_s Unlike the other input parameters is not just dominantly one measurement, its an average. Is the argument that - due to this we neglect SMEFT corrections? Is that at all a sensible claim if so?

NLO (perturbative) combinations vs sensitivity

- All of these statements that hold at LO, also hold at NLO ***even more.***
- Clearly calculations even more incomplete at NLO.

Unfortunately/fortunately: https://cds.cern.ch/record/2694284/files/ATL-PHYS-PUB-2019-042.pdf

Eigenvalue	Eigenvector
241550	$0.24 \cdot c_{HG} - 0.23 \cdot c_{HW} - 0.83 \cdot c_{HB} + 0.45 \cdot c_{HWB}$
147981	$-0.97 \cdot c_{HG} - 0.21 \cdot c_{HB} + 0.11 \cdot c_{HWB}$
6090	$-0.12 \cdot c_{HW} - 0.98 \cdot c_{Hq3} - 0.11 \cdot c_{Hu}$
124	$-0.20 \cdot c_{HWB} + 0.30 \cdot c_{Hq1} + 0.14 \cdot c_{Hq3} - 0.85 \cdot c_{Hu} + 0.29 \cdot c_{Hd}$
34	$-0.21 \cdot c_{Hbox} - 0.56 \cdot c_{HW} - 0.24 \cdot c_{HWB} - 0.11 \cdot c_{Hl1} + 0.51 \cdot c_{Hl3} - 0.16 \cdot c_{Hq1} + 0.17 \cdot c_{Hu} - 0.37 \cdot c_{ll1} - 0.10 \cdot \lvert c_{dH}\rvert + 0.25 \cdot \lvert c_{uG}\rvert - 0.12 \cdot c_{qq3}1$
22	$-0.11 \cdot c_G + 0.60 \cdot c_{HW} - 0.12 \cdot c_{HB} + 0.18 \cdot c_{Hl3} + 0.63 \cdot \lvert c_{uG}\rvert - 0.13 \cdot c_{qq11} - 0.31 \cdot c_{qq31} - 0.13 \cdot c_{uu1}$
16	$-0.48 \cdot c_{HW} + 0.19 \cdot c_{HB} + 0.11 \cdot c_{HWB} + 0.13 \cdot c_{Hl1} - 0.47 \cdot c_{Hl3} - 0.11 \cdot c_{He} + 0.31 \cdot c_{ll1} + 0.14 \cdot \lvert c_{dH}\rvert + 0.49 \cdot \lvert c_{uG}\rvert - 0.24 \cdot c_{qq31} - 0.10 \cdot c_{uu1}$
5	$0.13 \cdot c_{Hbox} - 0.14 \cdot c_{HDD} - 0.33 \cdot c_{HB} - 0.58 \cdot c_{HWB} - 0.42 \cdot c_{Hl1} - 0.34 \cdot c_{Hl3} + 0.33 \cdot c_{He} - 0.24 \cdot c_{Hq1} + 0.11 \cdot c_{ll1} - 0.17 \cdot \lvert c_{eH}\rvert$
0.9	$0.12 \cdot c_{HWB} + 0.26 \cdot c_{Hq1} - 0.21 \cdot c_{ll1} - 0.79 \cdot \lvert c_{eH}\rvert + 0.47 \cdot \lvert c_{dH}\rvert$
0.4	$0.18 \cdot c_{Hbox} - 0.11 \cdot c_{HW} + 0.12 \cdot c_{HWB} - 0.33 \cdot c_{Hl1} - 0.16 \cdot c_{Hl3} + 0.26 \cdot c_{He} + 0.67 \cdot c_{Hq1} + 0.18 \cdot c_{Hu} - 0.20 \cdot c_{Hd} - 0.12 \cdot c_{ll1} - 0.43 \cdot \lvert c_{dH}\rvert$
0.2	$-0.34 \cdot c_{Hbox} - 0.23 \cdot c_{Hl1} + 0.22 \cdot c_{Hl3} + 0.15 \cdot c_{He} + 0.32 \cdot c_{Hq1} + 0.11 \cdot c_{Hu} - 0.11 \cdot c_{Hd} + 0.40 \cdot c_{ll1} + 0.37 \cdot \lvert c_{eH}\rvert + 0.57 \cdot \lvert c_{dH}\rvert$

Table 8: Eigenvectors corresponding to the largest eigenvalues of the Fisher information matrix of the combined measurement of Ref. [5], expressed as a function of Wilson coefficients. The matrix is obtained by the propagation the Fisher information matrix of the STXS measurement to the Wilson coefficients. Both the production cross-sections and decay branching fractions are parametrised as a function of the Wilson coefficients. Only Wilson coefficients with a factor larger than 10% are listed for each eigenvector. The acceptance dependence on the Wilson coefficients is neglected in the parametrisation.

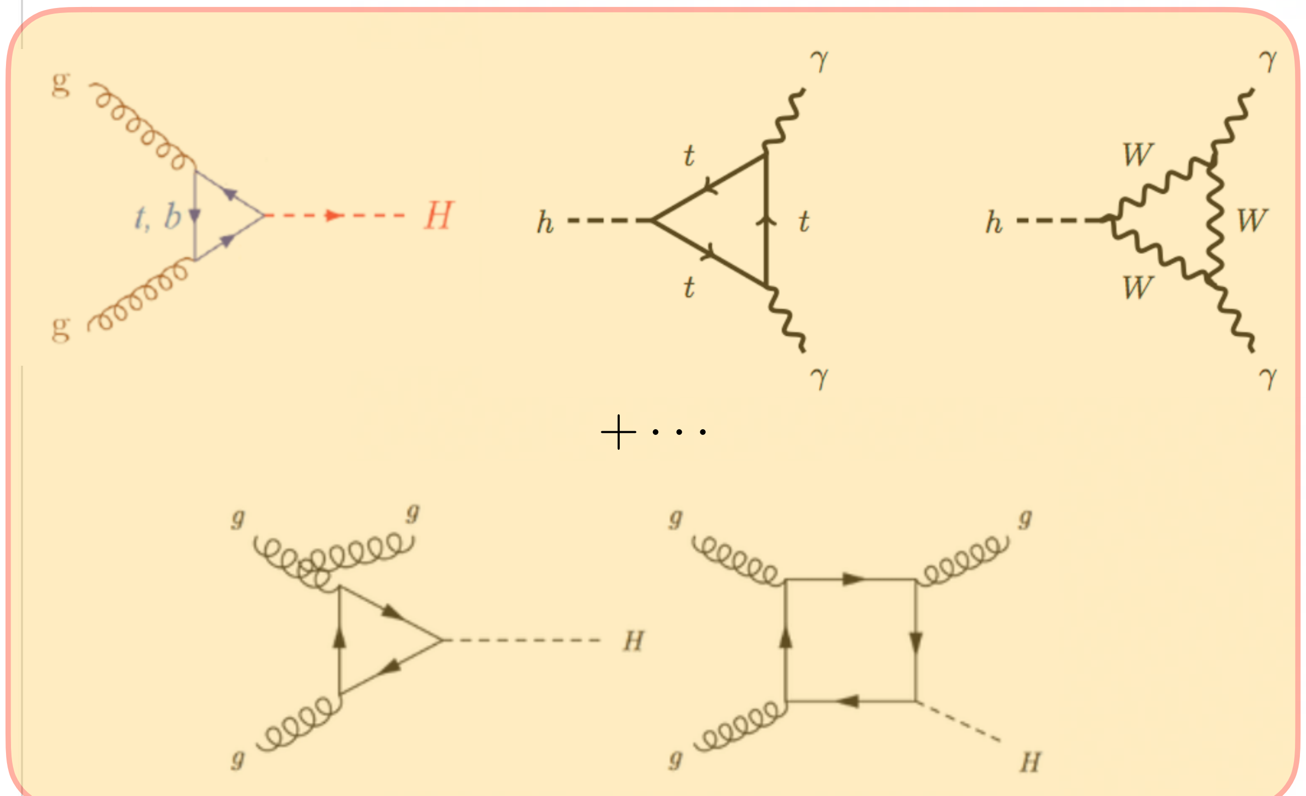
NLO (perturbative) combinations vs sensitivity

- All of these statements that hold at LO, also hold at NLO ***even more.***
- Clearly calculations even more incomplete at NLO.

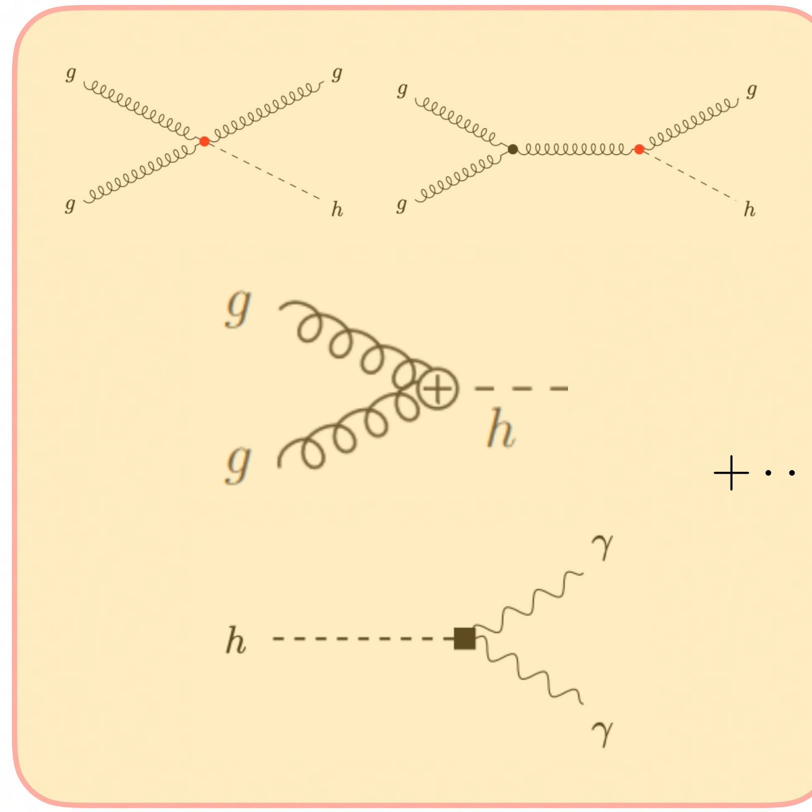
Unfortunately/fortunately: https://cds.cern.ch/record/2694284/files/ATL-PHYS-PUB-2019-042.pdf

Eigenvalue	Eigenvector
241550	$0.24 \cdot c_{HG} - 0.23 \cdot c_{HW} - 0.83 \cdot c_{HB} + 0.45 \cdot c_{HWB}$
147981	$-0.97 \cdot c_{HG} - 0.21 \cdot c_{HB} + 0.11 \cdot c_{HWB}$

Strong hierarchy in experimental sensitivity aligned with



×



NLO (perturbative) combinations vs sensitivity

- Higgs and Higgs+jet production - where are we in SMEFT corrections? What have you calculated?

- EX: $h \to \gamma\gamma$ one loop insertion of SMEFT operators calculated https://arxiv.org/abs/1505.02646, https://arxiv.org/abs/1507.03568

  Using background field method, so $\Pi_{AZ}(0) = 0$

  scheme dependence

  $$\delta R_h = -\frac{\partial \Pi_{hh}(p^2)}{\partial p^2}|_{p^2=m_h^2}.$$

  (see https://arxiv.org/abs/1909.08470)

  Results known to: $\mathcal{A}_{SM} \times \frac{1}{\Lambda^2}$, $\mathcal{A}_{SM} \times \frac{1}{16\pi^2\,\Lambda^2}$

  For complete Warsaw basis (vev SMEFT corrections required at LO). Note scheme dependence comparing to https://arxiv.org/abs/1805.00302 for LO Wilson coefficients C_{HW}, C_{HB}, C_{HWB}

Request:(can you add slides on your calc with this sort of info)

- Can we define and summarise our various results beyond LO.

- What is calculated, to what order in $\frac{1}{\Lambda^2}, \quad \frac{1}{16\pi^2}$

  In what basis is your calc (Warsaw or?) , what operators with what definitions and normalisations? Partial higher orders included?

- Are input parameter redefinitions included in the calc?

- What input scheme is used if any? What scheme is used to define the perturbative corrections?

Possible answers/warnings to give to EXP

- Use best available results for each process (highest order) even if incomplete.

  Very reasonable. Possibly gives misleading numerical results.

- Only use results that are consistent at a certain order and assign a theory error of the order of the incomplete terms.

  Very reasonable. Experimental sensitivity washed out by incomplete theory error, and theory error choice significantly impacts conclusions.

- Should EXP also be warned to only combine (even incomplete results) only in a consistent input parameter and renorm scheme? Probably.

  Can we possibly converge on some hope for a standardisation of what input and renormalisation scheme to prefer to use — going forward? (Probably not, so can we at least summarise what we have done.)

In any case:

Step 1: Can we please summarise at least what is available and calculated beyond LO for experiment? They are asking.
In short summary form with literature ref.

(Priority request for processes with strongest sensitivity in the prelim fits)

https://cds.cern.ch/record/2694284/files/ATL-PHYS-PUB-2019-042.pdf