Stockholm University

Effective field theories in the Higgs sector

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Jörgen Sjölin
Stockholm University

Overview

- Introduction to effective field theories (EFT)
- The Standard Model as EFT (SMEFT)
- Sigma model representations (SMEFT or HEFT)
- Importance of the Higgs sector
- Experimental signatures and observables
- Constraining EFT parameters from experimental data
- Examples of current EFT parameter constraints
- Reflections on the optimal EFT measurement
- Conclusions and outlook

Introduction to EFT

EFT as a common tool in HEP is surprisingly recent (pioneered by Weinberg). However, the fundamental ideas were known already in the 1970s.

1. Appelquist-Carazzone theorem: given two connected systems at different energy scales, there is a renormalization procedure such that actions at the high scale can be included at low scale by changing the parameters at low scale.
2. Wilson renormalization: separates high and low energy modes and integrates out the high energy modes above the decoupling scale (Λ). This is however not how typical EFTs are constructed, usually one just lists the DOF at low energy and match at low energy.

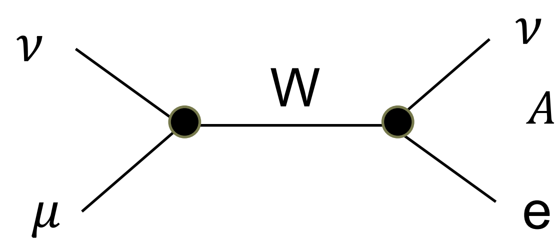
The EFT implementations technically vary a lot but the key point is that there is a defined energy scale that separate the two domains.

EFT cartoon and a classical example

Model UV

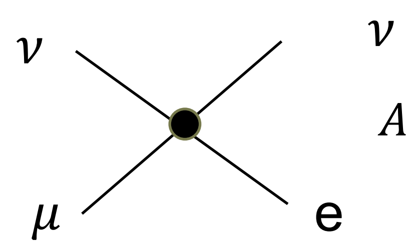
Λ

Model IR (effective)



$$A \sim \frac{1}{q^2 - mW^2}$$

$\Lambda < m_W$



$$A \sim -\frac{1}{{m_W}^2}\left(1 + O\left(\frac{q^2}{{m_W}^2}\right)\right)$$

The W propagator becomes a 4-point vertex at low energy (Fermi theory), and when q is small it is extremely accurate.

E.g. EFT advantages are that we only need the low energy degrees of freedom and the EFT don't have to be cut-off free in UV ("renormalizability") to be fully consistent.

What about the Standard Model (SM)?

- SM encapsulates most our HEP knowledge (except e.g. neutrino masses and the anticipated quantum gravity).
- Can we leverage all the knowledge in the SM and at the same time use it as an EFT to search for new physics?
- In its original form it has the "renormalizability" property, proven by t'Hooft and Veltman. I.e. it has no upper cut-off scale (here leaving out gravity on purpose).
- Clearly with the absence of a cut-off scale it is not an EFT.
- We can turn it into an EFT (SMEFT) by introducing a EFT scale Λ by hand. (Beware, to match the EFT at one loop is non-trivial!)
- OK nice, this means that actions above Λ will alter parameters and induce new operators below Λ where we can observe things.
- And we don't have to worry about "renormalizability" any more.

The Standard Model as an EFT

- **New induced operators are suppressed by mass. Dimension d=5 operators are related to neutrino majorana masses and are not included. Focusing only on d=6 terms conserving baryon number.**
- **First thing to do is to count DOFs (Warsaw basis 2010, parameters). For one generation there are 53 CP-even operators in the complete basis. With 3 generations this becomes 1350. Note that only a small subset of these are relevant for a fixed final state, + e.g. no FCNC.**

The new effective Lagrangian reads: $L_{eff} = L_{d\leq 4}^{SMEFT} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i$

Note that not all the parameters of $L_{d\leq 4}^{SMEFT}$ are the same as in the SM due to d=6 corrections, but just as in the SM fixed from observed data.

Practical UFO implementations: SMEFTsim (LO) and SMEFTatNLO (NLO)

Some details regarding SMEFT

- To remain strict d=6, only single interaction insertions are allowed, and for the same reason EFT cross-sections should be dominated by the interference term SM*EFT in the squared matrix element.
- Only the ratio $\frac{c_i}{\Lambda^2}$ has physical meaning, not c_i and Λ^2 separately.
- The EFT is limited by perturbativity: $A \sim \frac{c_i s}{\Lambda^2}$ breaks perturbativity if $|c_i| < (4\pi)^2$ in the loop expansions. A safer rule of thumb is $|c_i| < 4\pi$.
- Renormalization should be carefully performed using dimensional regularization (DR) or MSbar to be gauge invariant.
- The SM is renormalizable. But in an EFT setting the Higgs is not always protected, even when using DR (Trott). This is a potential real source to hierarchy issues. It does make sense to check that the UV model at hand protects the Higgs, as long as proper renormalization is used.

Another path to include massive fields (HEFT)

- **In the EFT setting, all we care about is to be able to add mass without breaking gauge invariance, i.e. use scalar fields for spontaneous symmetry breaking SSB (the Sigma model).**
- **Putting the scalars into a generic structure Σ (2x2) without specifying the representation, and rewriting the Lagrangian using Σ, one can deduce the required general transformations and constraints.**
- **It turns out that there are actually two valid representations of Σ**
  1. **A linear representation: $\Sigma(x) = (1 - \frac{i}{v}\pi(x)_a\sigma_a)$,**
  2. **and a non-linear representation: $\Sigma(x) = exp(-\frac{i}{v}\pi(x)_a\sigma_a)$.**
- **The linear case leads to the SM Higgs which must be a SU(2) doublet.**
- **The non-linear case (HEFT) forces the Higgs to be a singlet.**
- **HEFT is a more general EFT than SMEFT, but the Higgs potential is not an analytic function, potential breakdown around $\mathcal{O}(4\pi v)\sim$3 TeV.**

SMEFT and HEFT pros and cons

SMEFT

- SMEFT allows to optimally look for deviations from the SM in the Higgs, top and electro-weak sectors as long as the Higgs effectively behaves as a fundamental SU(2) doublet.
- Full strength from SM in combinations, e.g. H, HH and the electroweak sector.
- Works well for weakly coupled UV theories.
- Not suitable for strongly coupled UV.

HEFT

- HEFT expansion powerful when leading effects are Higgs and top.
- Can detect if Higgs is not SM like.
- Works well for strongly coupled UV theories, e.g. composite Higgs.
- Validity for high mass UV unclear.
- Conclusion: at LHC it makes sense to test both SMEFT and HEFT since they in practice focus on different things.
- But strictly physically SMEFT and HEFT are just special cases of a geometric curvature of the scalar fields.

The importance of the Higgs sector

- **New physics can potentially be found as a deviation in any of the EFT parameters. E.g. top EFT is a huge topic on its own.**
- **However, there are several reasons for the Higgs related EFT parameters to be particularly interesting:**
  - ✓ **The mass generation (SSB) is the fabric of the SM, but is Higgs fundamental or part of the Goldstones, if so where do they come from? I.e. is Σ a result from something in the UV?**
  - ✓ **The Higgs sector is new and e.g. the Higgs potential shape is not confirmed to be as predicted by the SM. We currently only constrain the position and the curvature at the VEV.**

Remember: the EFT captures the full theory - it is all there as long as the EFT condition is fulfilled (no new DOF).

Experimental signatures and observables

- **To test if any Higgs sector related $\frac{c_i}{\Lambda^2}$ deviates from 0 one needs experimental data to confront the EFT predictions.**
- **What kind of data?**
- **The starting point is to predict which final states and phase-space (PS) regions that are sensitive to $\frac{c_i}{\Lambda^2}$ using Monte Carlo (MC).**
- **The measurable physical quantities are differential cross-sections.**
- **Measurements can be either binned or un-binned (event based):**
  - ✓ **<u>Discrete PS integrated bins are easier to work with</u> and can be adjusted for the experimental situation, but are not optimal.**
  - ✓ **<u>Un-binnned (event-by-event)</u> measurements are more complicated, but can better <u>allow for close to optimal results</u>.**

Experimental data are folded by detector effects

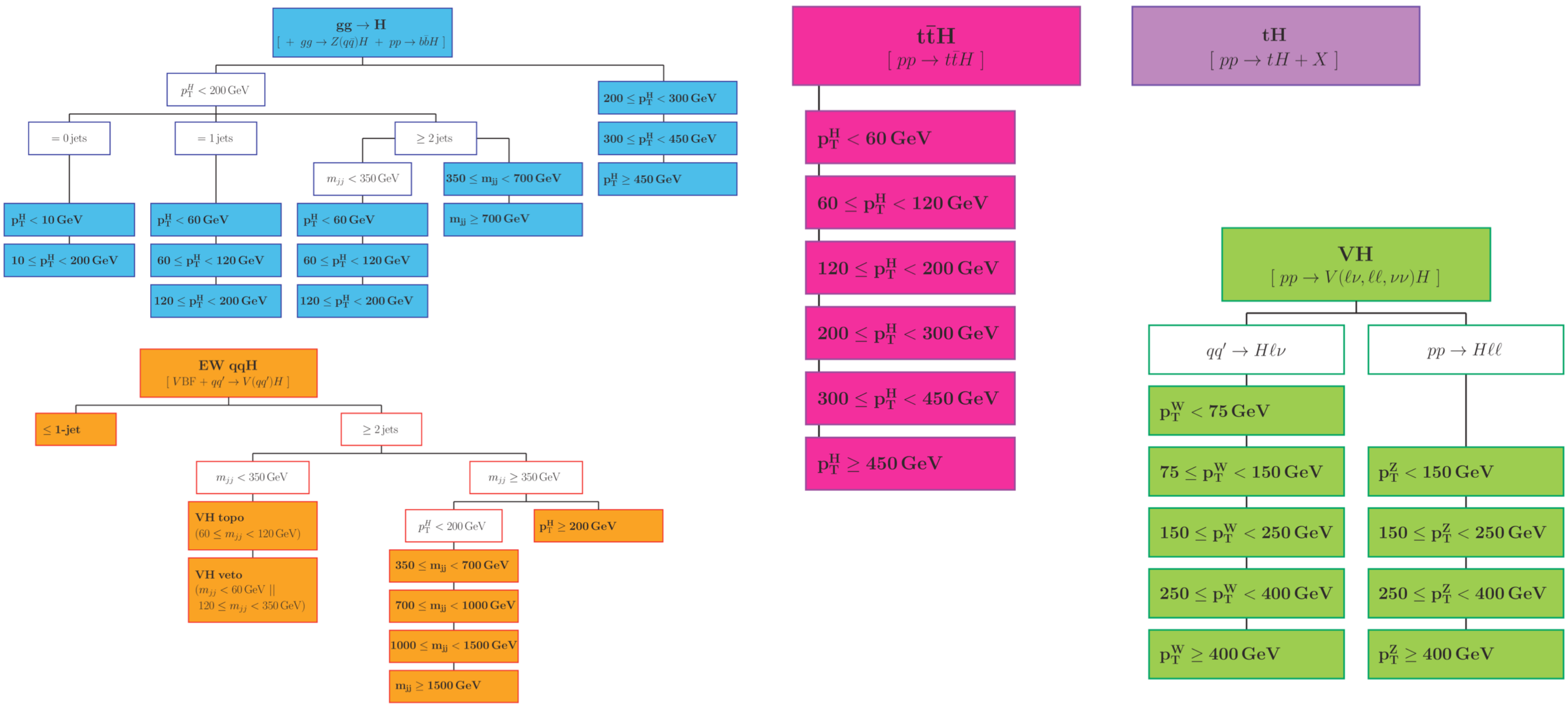
- Experimental data are folded with detector effects. There are two ways out:
  - ✓ Unfold data back to particle level cross-section (PL XS) and compare PL XS data to PL EFT model. The PL XS data is "model independent". Works well when the resolution is sufficiently high (regularization systematics small) and subtracted background has negligible EFT model dependence.
  - ✓ Fold the model and compare folded data to folded model. This is the most accurate method for extracting the output model parameters. Drawback is that the result cannot be repeated for a different model without an accurate public folding prescription and combining to other measurements with correct systematics treatment is difficult.

Constraining EFT parameters from experimental data

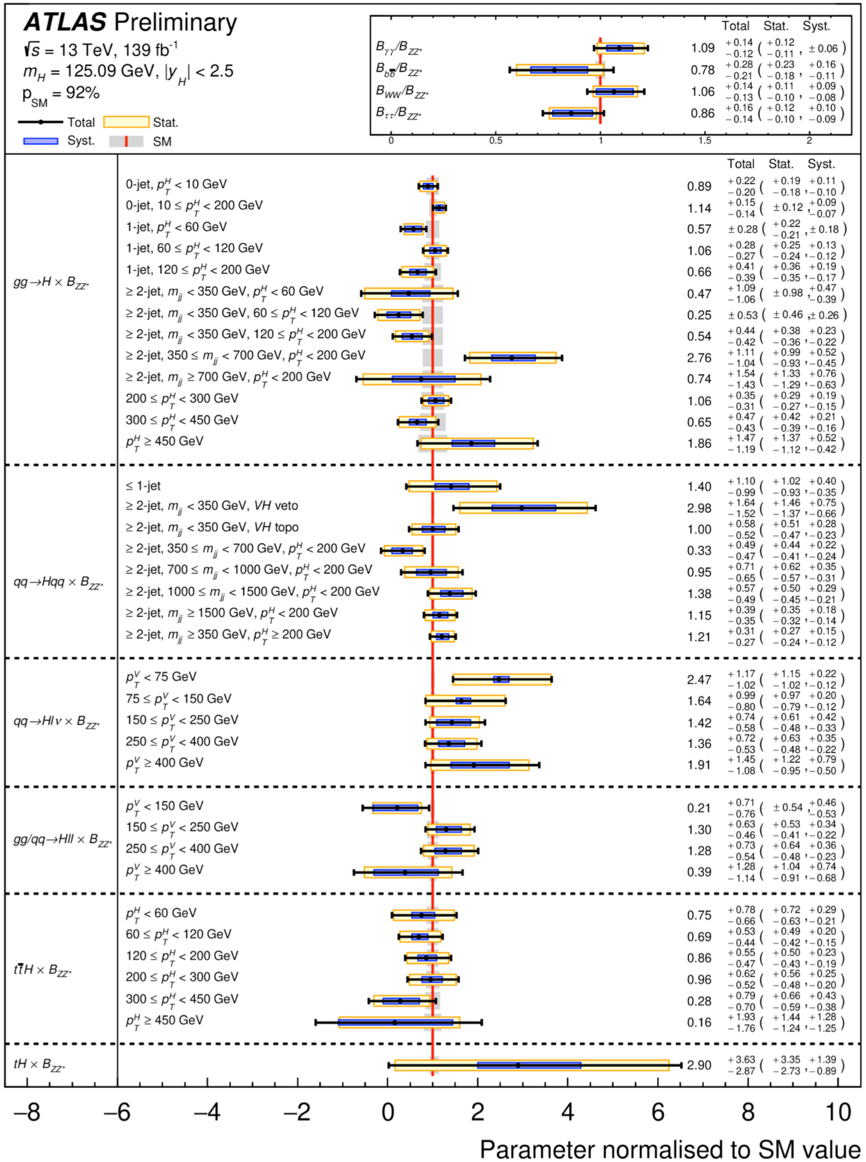
- If we use binned unfolded data, each bin likelihood is $P(N_p|c,\theta)$ where p is each measured bin, c is the EFT parameter vector and θ is a vector of nuisance parameters.
- Bins (measurements) are combined by multiplying the likelihoods.
- In the extreme SMEFT case we will need at least 1350 bins with different EFT parameter dependence to solve the equations and extract the parameters, the more bins the better.
- The other extreme is that we fix all other parameters to 0 except c_i. If we are lucky we might manage to prove it different from 0, in particular if one is dominating. However, we have little knowledge of the actual c_i value until we understand its dependence on all the other parameters. Again, useful to test both scenarios.

Example of binned data, single H templates: STXS

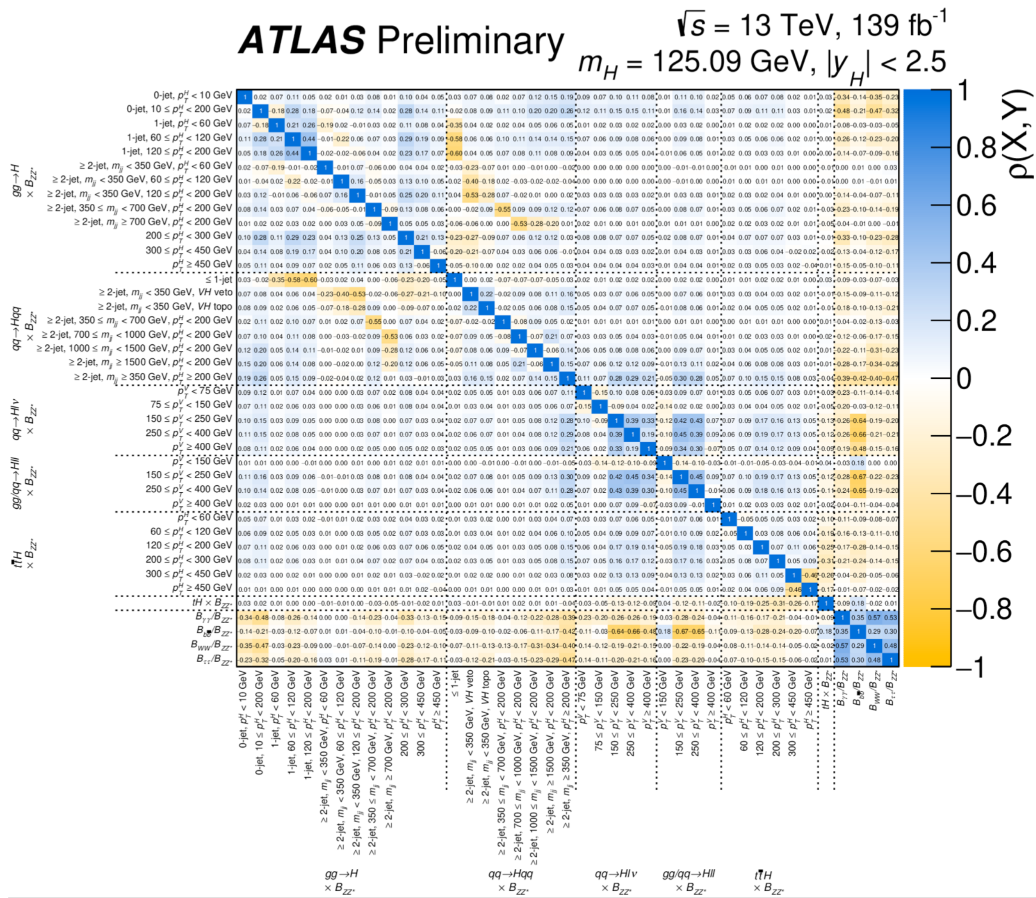
- **"Unfold" data to on-shell H, factorize in production modes.**
- **Aims at good balance between performance and the ability to combine many measurements. This is a [LHC wide approach](#).**
- **Here showing an [ATLAS STXS example](#):**



Example: [ATLAS single H STXS]() SM data



37 data bins



ATLAS single H STXS SMEFT prediction

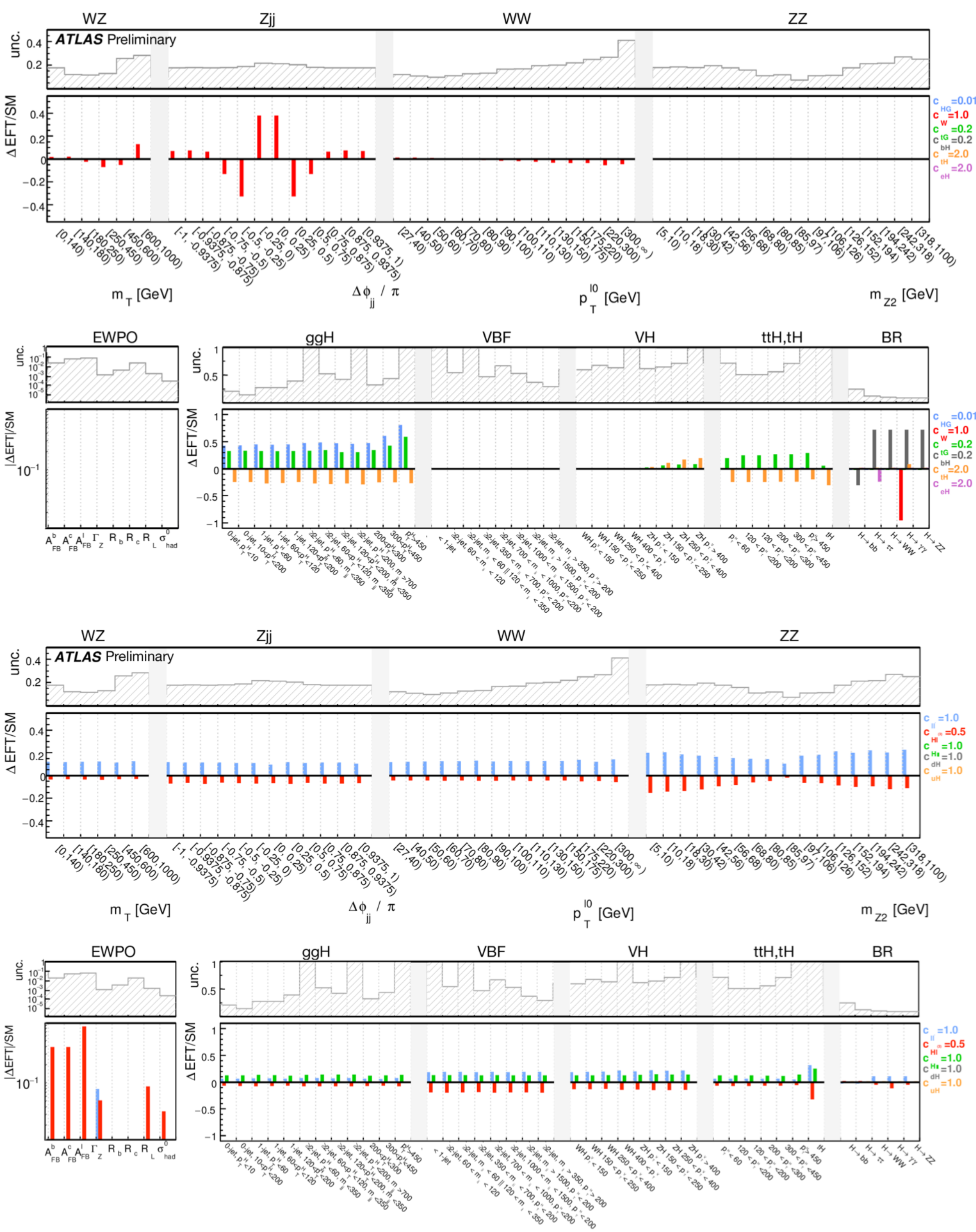
- **Each SM model bin p reweigthed according to SMEFT predictions:**

$$\sigma_p \cdot \mathcal{B}^{H\to f} = \left[\sigma_p \cdot \mathcal{B}^{H\to f}\right]_{\mathrm{SM}} \left(1 + \frac{\sigma_{\mathrm{p,int}}}{\sigma_{p,\mathrm{SM}}} + \frac{\mathcal{B}^{H\to f}_{\mathrm{int}}}{\mathcal{B}^{H\to f}_{\mathrm{SM}}}\right)$$
$$= \left[\sigma_p \cdot \mathcal{B}^{H\to f}\right]_{\mathrm{SM}} \left(1 + \sum_i A_i^{\sigma_p} c_i + \sum_i \left(A_i^{\Gamma_f} - A_i^{\Gamma}\right) c_i\right)$$
$$= \left[\sigma_p \cdot \mathcal{B}^{H\to f}\right]_{\mathrm{SM}} \left(1 + \sum_i A_i^{\sigma_p \cdot \mathcal{B}^{H\to f}} c_i\right).$$

- **Confidence limits from combined likelihood ratio fit.**
- **The EFT precision matrix can be propagated from measured SM STXS data:**

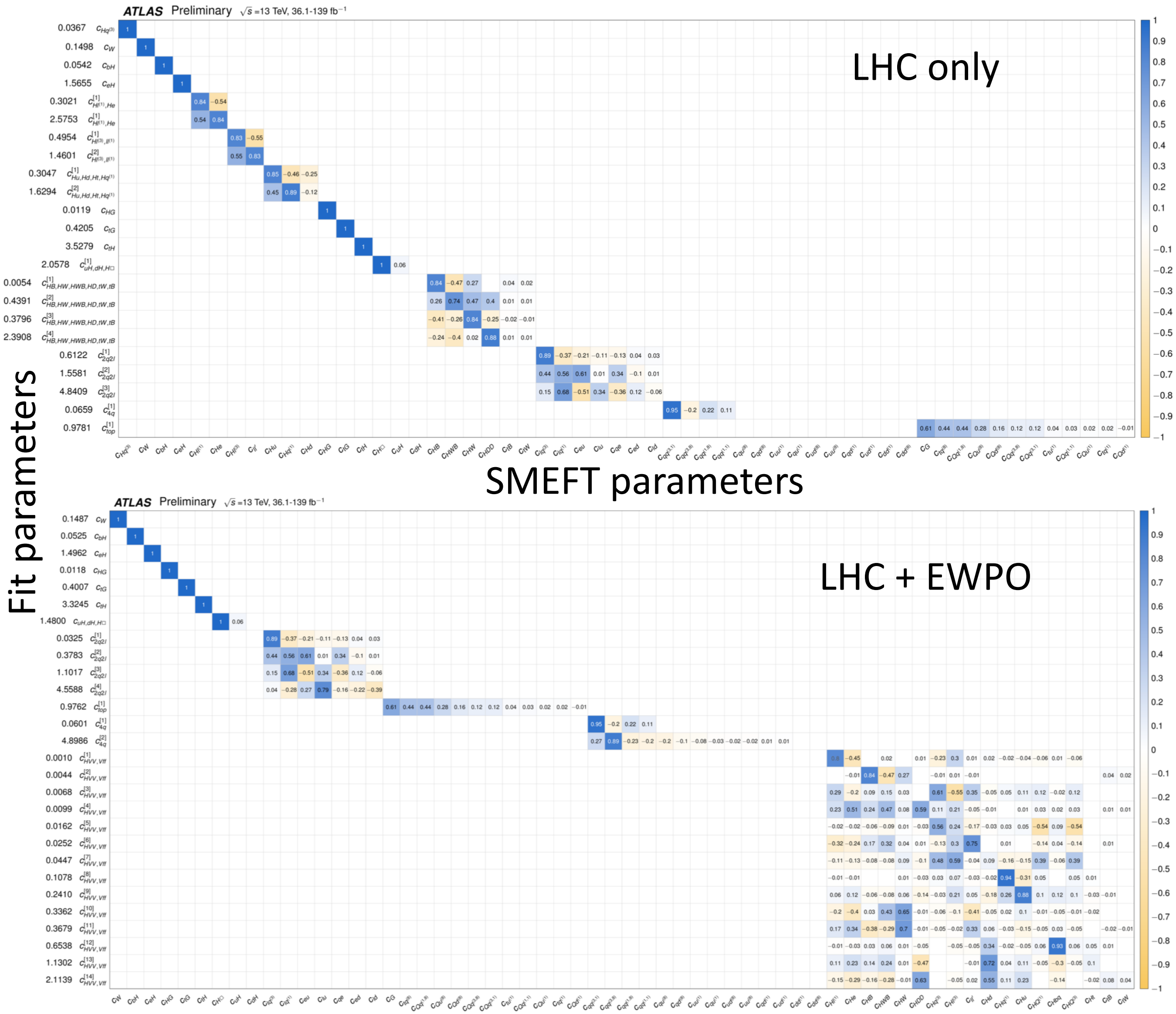
$$C^{-1}_{\mathrm{EFT}} = P^T\, C^{-1}_{\mathrm{STXS}}\, P \qquad P = \begin{pmatrix} A_1^{\sigma_1} & A_2^{\sigma_1} & A_3^{\sigma_1} & \dots \\ A_1^{\sigma_2} & A_2^{\sigma_2} & A_3^{\sigma_2} & \dots \\ A_1^{\sigma_3} & A_2^{\sigma_3} & A_3^{\sigma_3} & \dots \\ \vdots & \vdots & \vdots & \end{pmatrix}$$

ATLAS single H/EW boson/EWPO SMEFT relative impact examples



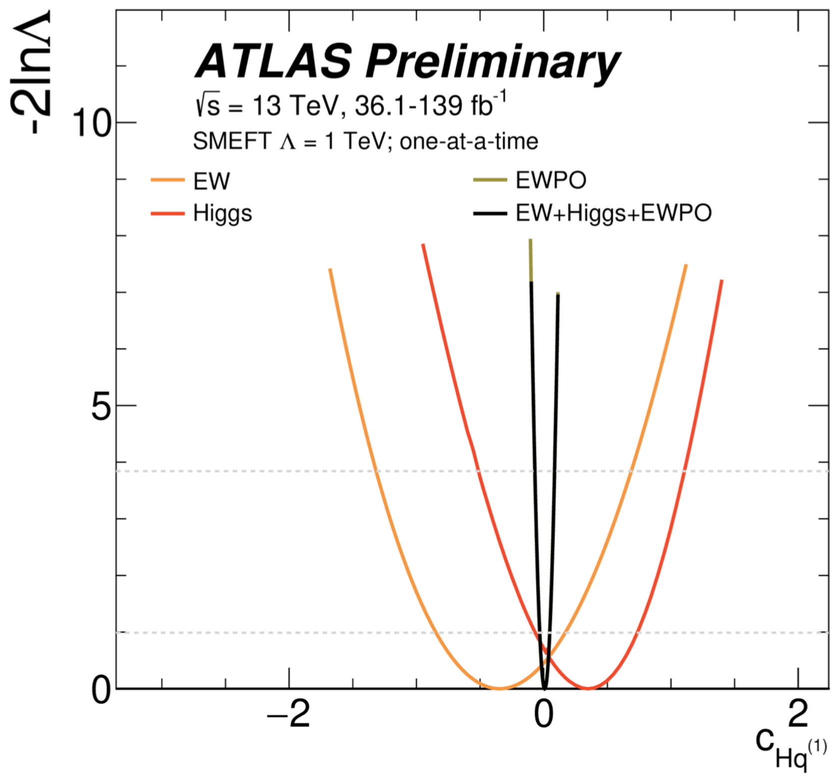
- Latest ATLAS SMEFT limits includes Higgs and EW boson and EW precision observables.
- Here showing examples of the SMEFT impact in the different bins.
- Note that this is just a small example set of the included SMEFT operators.

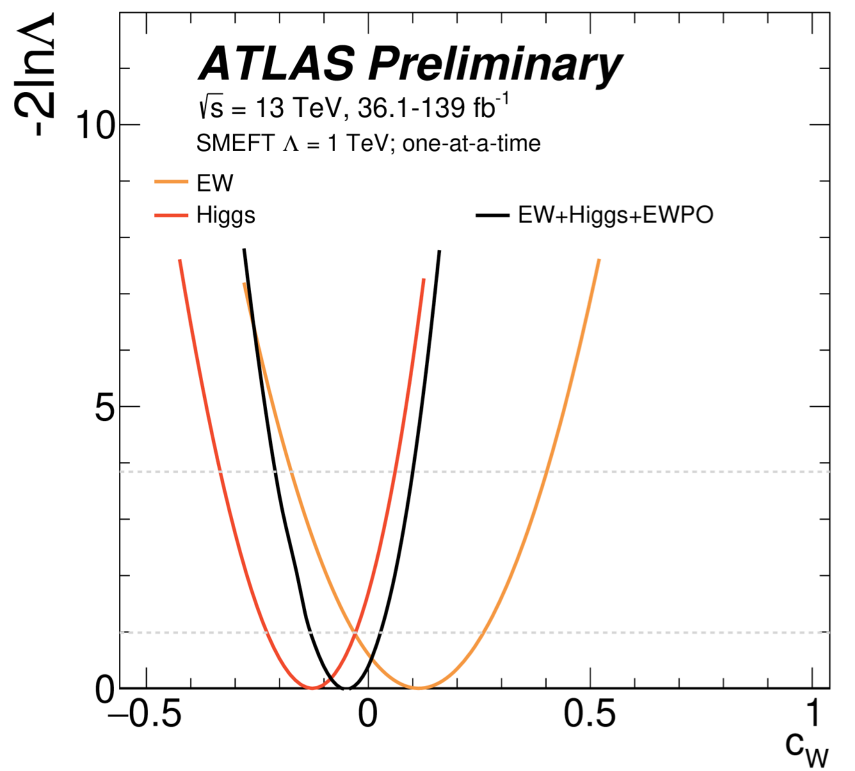
ATLAS single H/EW boson/EWPO SMEFT reducing DOF



- The system is under determined, i.e. lacks measurements to span the EFT space.
- To avoid flat directions in the fit the EFT precision matrix is eigenvector regularized into a new reduced basis.

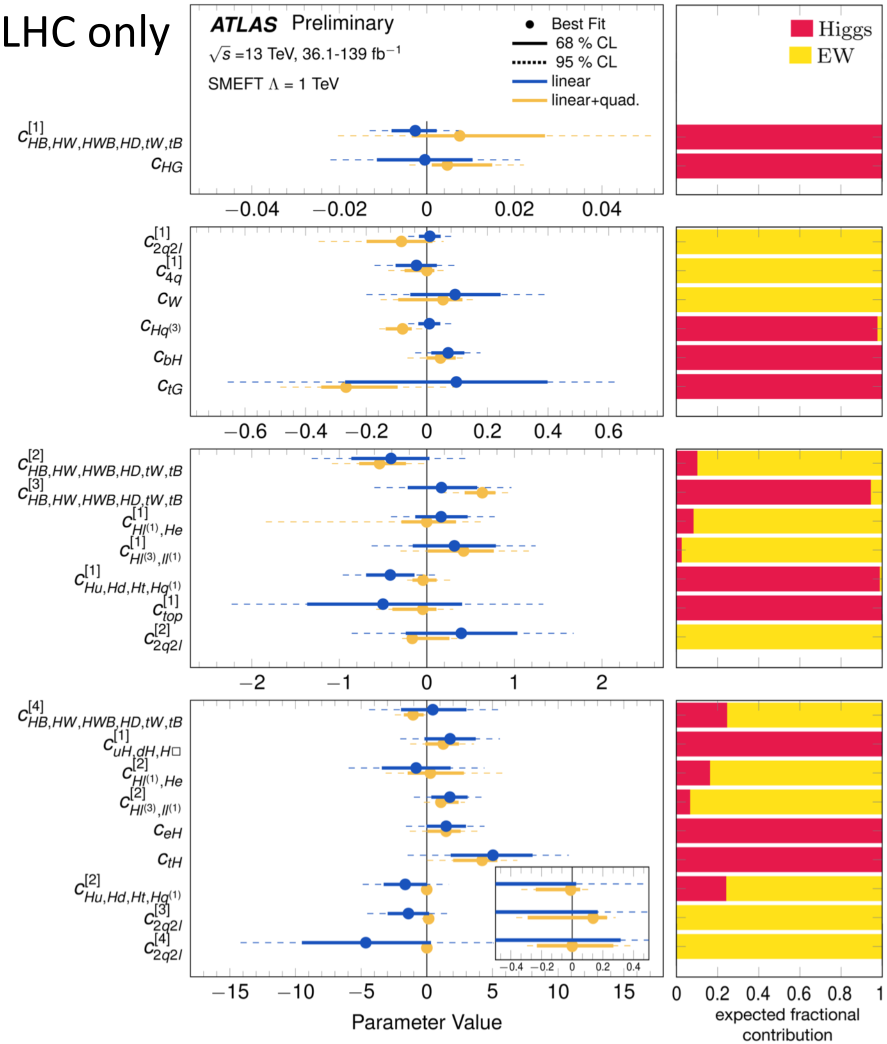
ATLAS single H/EW boson/EWPO SMEFT likelihood examples



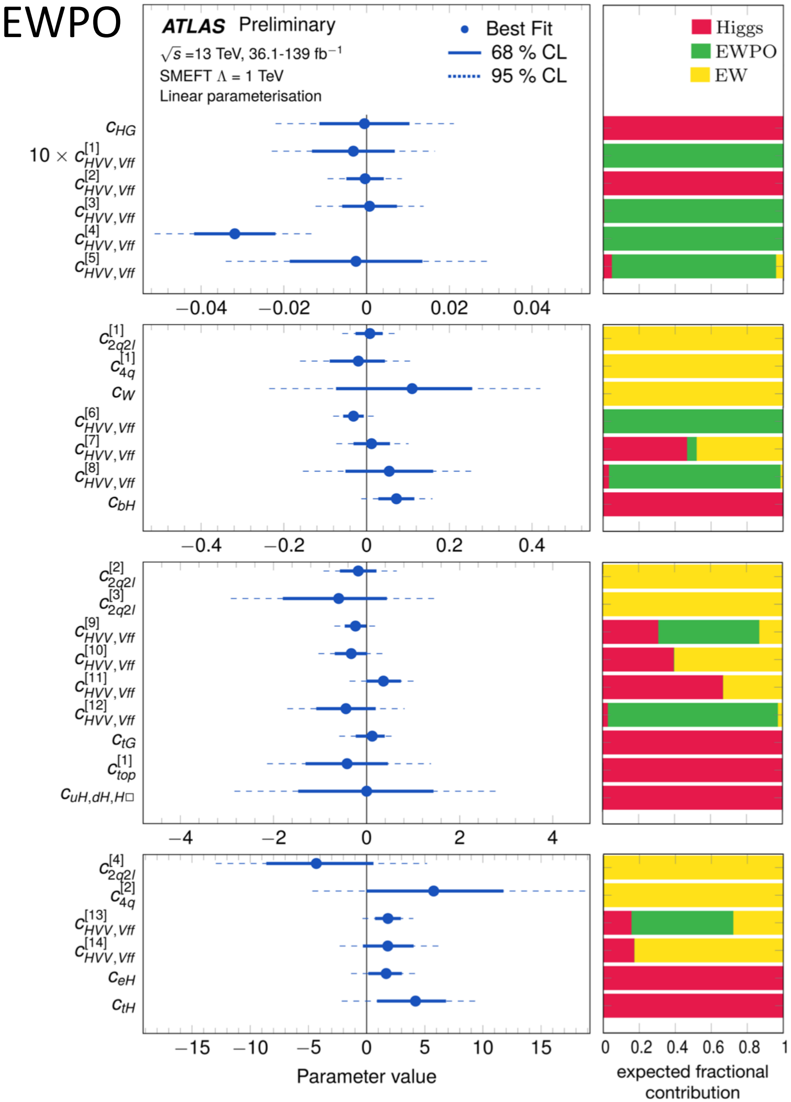


ATLAS single H/EW boson/EWPO SMEFT fit results

LHC only



LHC + EWPO



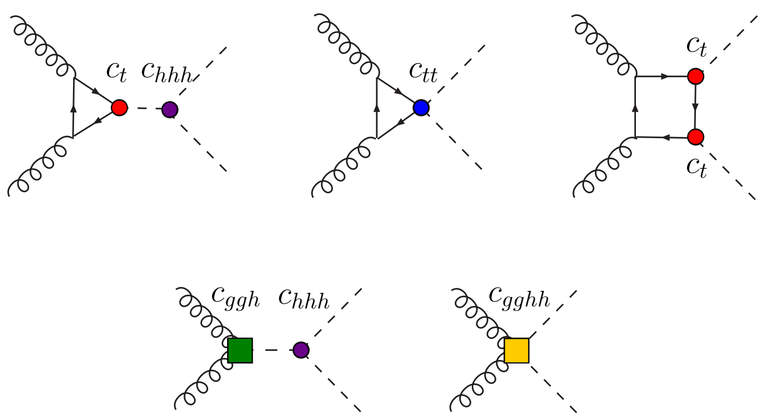
When quadratic terms matter, impact of d=8 should be estimated (or assumed small)

Tree level "intuitive" meaning of the EFT parameters

- We use tree level Feynman diagrams to guide our intuition about different processes.
- Firstly, Feynman diagrams represent series expansions of the Lagrangian. The Lagrangian does not represent physics until gauge fixed and renormalized.
- Different choices gives different Feynman rules for the same physics.
- In the case of HEFT and SMEFT, HEFT can represent physics which is not part of the SMEFT Lagrangian.
- HEFT is expanded in loops in the broken phase, so at tree level it is intuitively close to naïve coupling scaling (κ-framework).
- In weak couplings, a linearized comparison can done (interpreted with care!)

Tree level "intuitive" meaning of the EFT parameters

- To get a feeling for the SMEFT parameters one can linearly expand the HEFT Lagrangian assuming weak couplings.
- However, this is mainly for intuition, in practice better to test both.
- Here an HEFT example from di-Higgs production

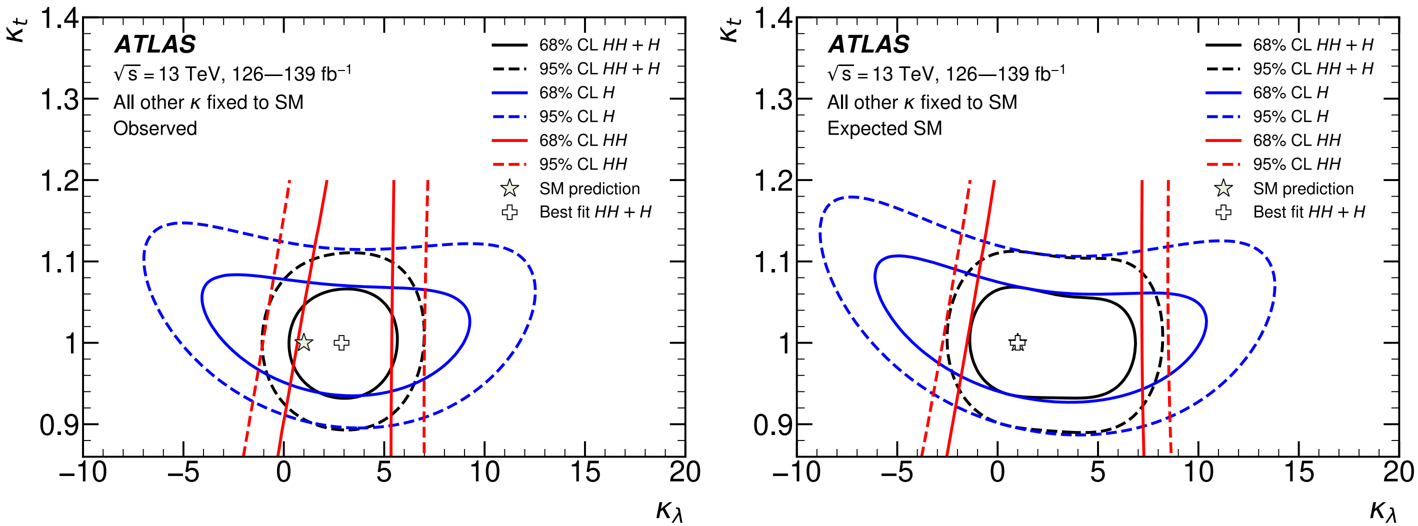


HEFT	Warsaw
c_{hhh}	$1 - 2\frac{v^2}{\Lambda^2}\frac{v^2}{m_h^2}\,C_H + 3\frac{v^2}{\Lambda^2}\,C_{H,\text{kin}}$
c_t	$1 + \frac{v^2}{\Lambda^2}\,C_{H,\text{kin}} - \frac{v^2}{\Lambda^2}\frac{v}{\sqrt{2}m_t}\,C_{uH}$
c_{tt}	$-\frac{v^2}{\Lambda^2}\frac{3v}{2\sqrt{2}m_t}\,C_{uH} + \frac{v^2}{\Lambda^2}\,C_{H,\text{kin}}$
c_{ggh}	$\frac{v^2}{\Lambda^2}\frac{8\pi}{\alpha_s}\,C_{HG}$
c_{gghh}	$\frac{v^2}{\Lambda^2}\frac{4\pi}{\alpha_s}\,C_{HG}$

$$C_{H,\text{kin}} := C_{H,\Box} - \frac{1}{4}\,C_{HD}$$

EFT constraints from di-Higgs production, [ATLAS example]

- **Given the single Higgs constraints, the current di-Higgs dominating contribution is on $c_{hhh} \approx \kappa_\lambda$**



$HH \to b\bar{b}\gamma\gamma$
$HH \to b\bar{b}\tau^+\tau^-$
$HH \to b\bar{b}b\bar{b}$

$H \to \gamma\gamma$
$H \to ZZ^* \to 4\ell$
$H \to \tau^+\tau^-$
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)
$H \to b\bar{b}$ (VH)
$H \to b\bar{b}$ (VBF)
$H \to b\bar{b}$ $(t\bar{t}H)$

- **But as precision increases the κ_λ-framework will not be sufficient and it has to be replaced by a proper EFT model and full model dependence.**
- **Analysis efforts are on-going to transition to di-Higgs EFTs.**

EFT constraints from di-Higgs production

- **EFT Constraints from di-Higgs is not as developed as in single Higgs due to the experimental sensitivity is lower for most EFT parameters.**
- **But, di-Higgs is starting to become very interesting due to several reasons:**
  1. **its unique sensitivity already at tree level to the triple Higgs coupling which is related to the Higgs potential shape.**
  2. **Ability to disentangle SMEFT from HEFT if e.g. $c_{ggh} \neq c_{gghh}$.**
- **A summary of the current status of NLO codes where finite top mass effect are included, and how they can be used at LHC is given here.**

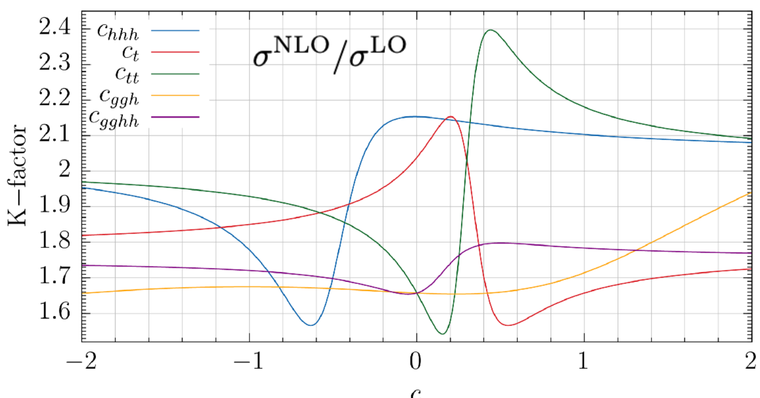
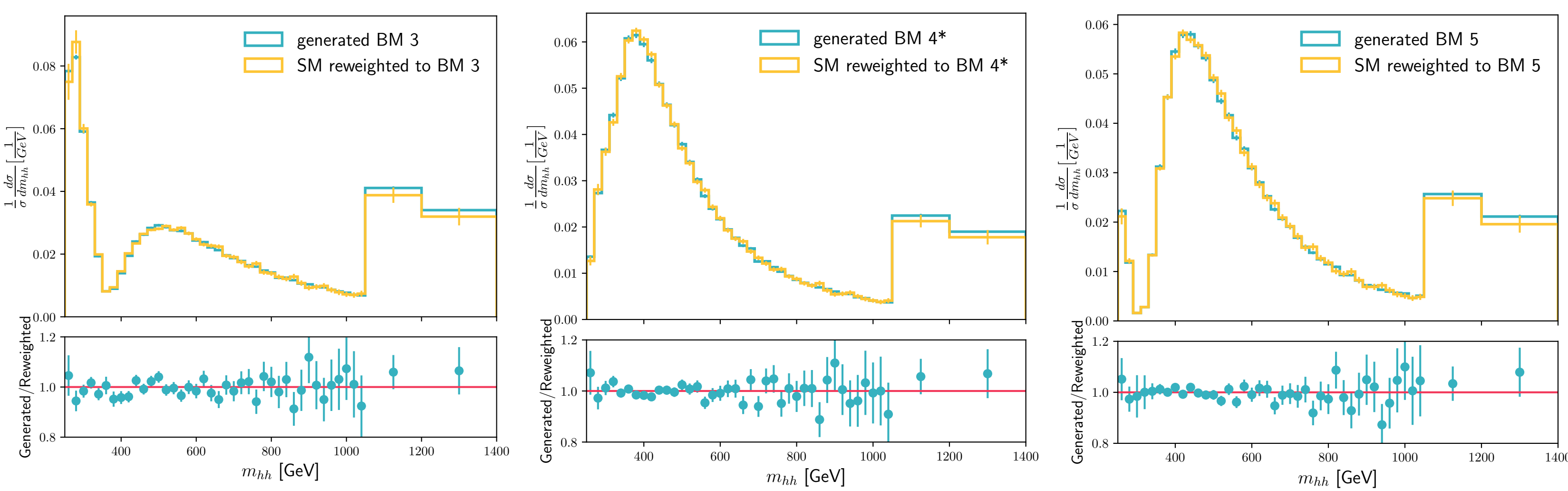


figure: L.Scyboz

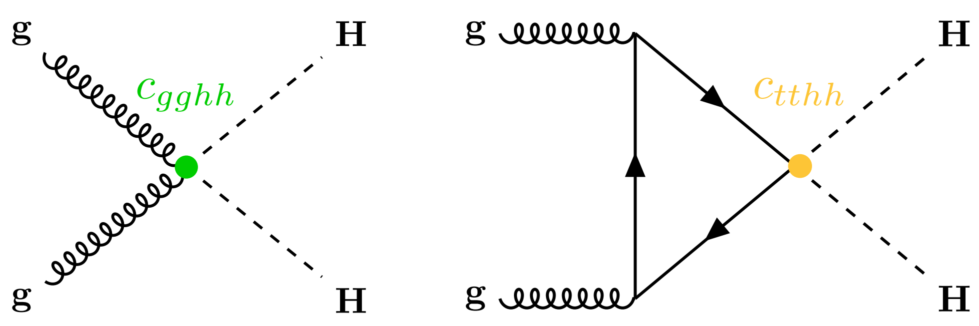
Contrary to single Higgs, the di-Higgs leading theory systematic is expected to be finite top mass effects. Available in POWHEG-BOX.

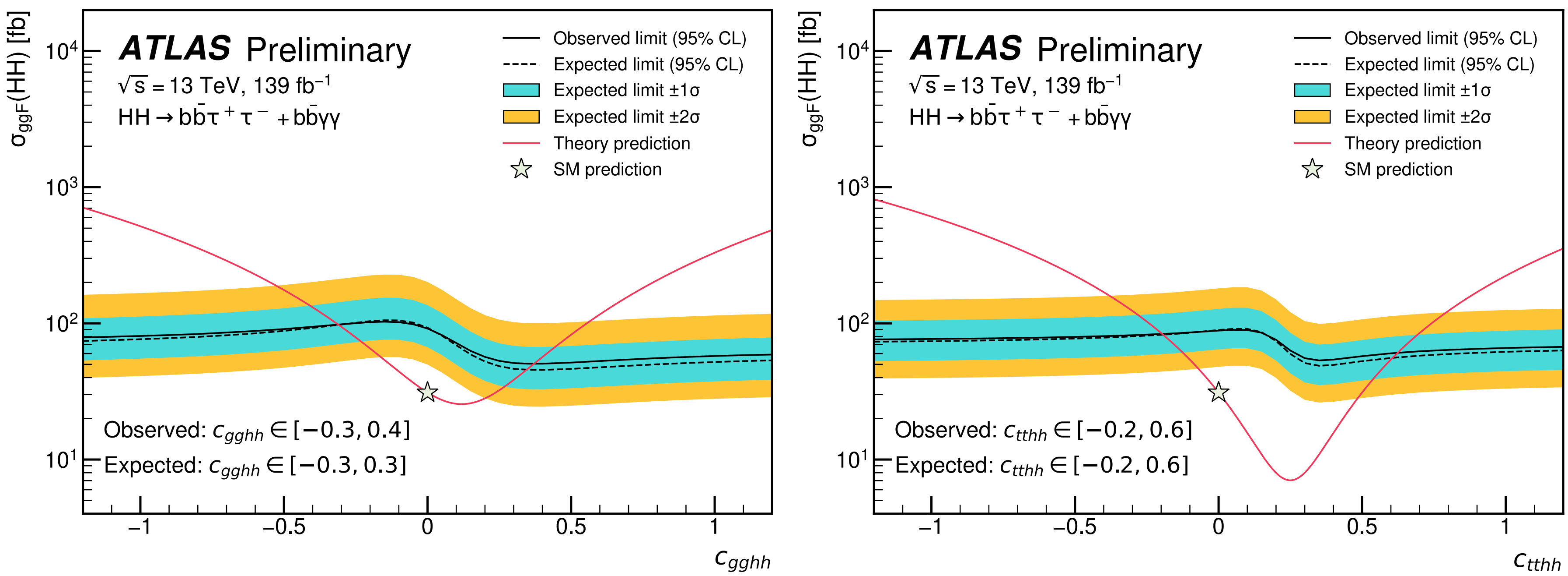
EFT event re-weighting

- As shown already for single Higgs, a very nice property of EFTs is that they allow for re-weighting since no new particles are created.
- As long as the density is known at each phase-space point and non-zero, events can be re-weighted. This allows also for fully differential analyses, even un-binned versions, given just the SM detector simulated sample.
- Here are examples of a few HEFT binned benchmark points of m_{hh}



HEFT constraints from di-Higgs production: ATLAS example





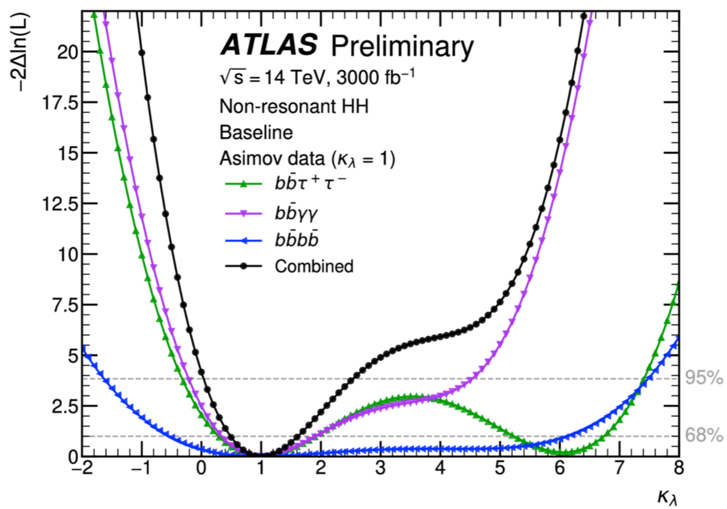
Towards precision EFT analyses

As always, as precision increases many new issues become important that previously were sub-dominant:

- **Complete understanding of all relevant EFT parameters on observables.**
- **QCD NLO in general, and EWK NLO in distributions.**
- **Treatment of EFT effects on the propagators.**
- **EFT effects on the backgrounds.**
- **EFT effects on signal efficiencies.**
- **EFT effects from d=8 operators.**
- **How to handle parameters and distributions in higher dimensions in the likelihood fits and simultaneously include systematics in a consistent way.**

HL-LHC projections

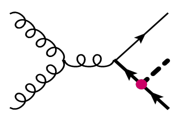
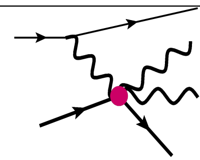
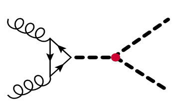
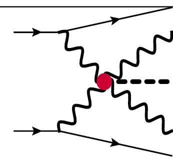
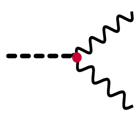
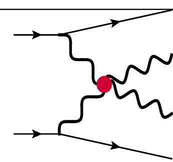
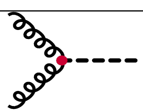
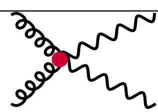
- **Remaining in the κ_λ-framework there are projections available for HL-LHC (again an ATLAS example)**

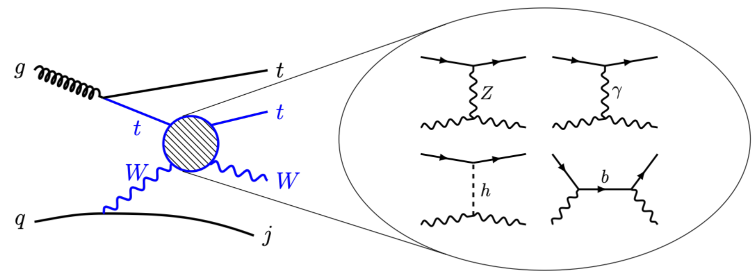


Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

Strong scattering (SS), an alternative probe via the goldstones

- **Away from the SM Higgs, the scalar goldstones (Sigma model) hiding in the longitudinal modes of the gauge bosons can pick up a strong E or E^2 dependence (e.g. is explicit using the goldstone boson equivalence theorem). Examples are tW scattering and HwH**

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

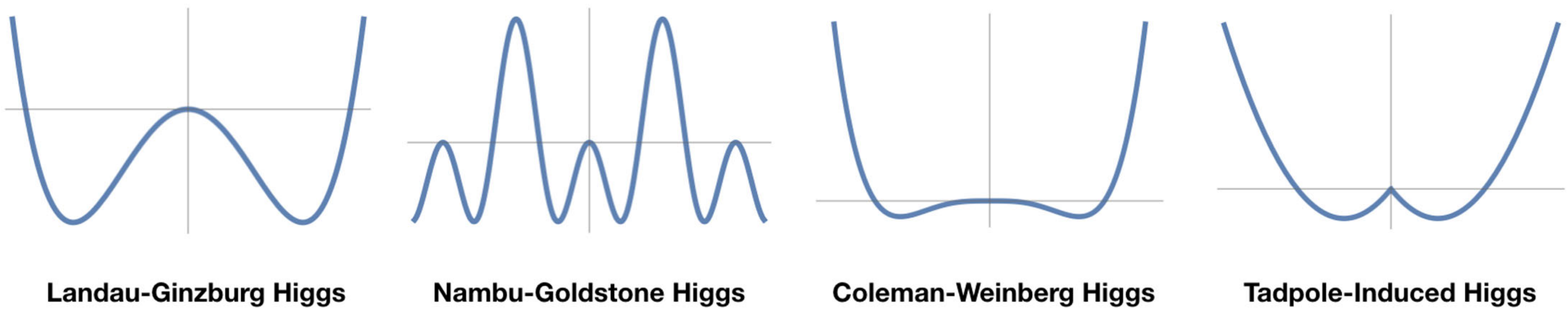


$$\kappa_t : pp \to jt + V_L V'_L$$
$$(e^+e^- \to ll + \{tbW_L, tbZ_L, ttW_L, ttZ_L\})$$
$$\kappa_\lambda : pp \to jjh + V_L V'_L, \; (e^+e^- \to llhV_L V'_L)$$
$$pp \to jj + 4V_L, \; (e^+e^- \to ll\, 4V_L)$$
$$\kappa_{\gamma\gamma, Z\gamma} : pp \to jj + V'V, \; (e^+e^- \to llV'V)$$
$$\kappa_V : pp \to jj + V_L V'_L, \; (e^+e^- \to llV_L V'_L)$$
$$\kappa_g : pp \to W_L^+ W_L^-, Z_L Z_L, \; (e^+e^- \to lljj)$$

- **For LHC not clear if SS competitive, but definitely for future machines**

Regarding the Higgs potential shape

- **If we are lucky, the LHC might find a significant deviation in the EFT operator related to the Higgs potential.**
- **But to actually interpret its value requires precision from future colliders.**
- **It is interesting to note that not all potentials are properly described by SMEFT, in some cases HEFT is required (Phys. Rev. D 101, 075023)**



$$V(H) \simeq \begin{cases} -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{c_6 \lambda}{\Lambda^2} (H^\dagger H)^3, & \text{Elementary Higgs} \\ -a \sin^2(\sqrt{H^\dagger H}/f) + b \sin^4(\sqrt{H^\dagger H}/f), & \text{Nambu-Goldstone Higgs} \\ \lambda (H^\dagger H)^2 + \epsilon (H^\dagger H)^2 \log \frac{H^\dagger H}{\mu^2}, & \text{Coleman-Weinberg Higgs} \\ -\kappa^3 \sqrt{H^\dagger H} + m^2 H^\dagger H, & \text{Tadpole-induced Higgs} \end{cases}$$

Coleman-Weinberg Higgs: **Requires HEFT**

Tadpole-induced Higgs: **Requires HEFT**

Brainstorming on the optimal EFT analysis

- **The EFT analyses done so far are mainly interpretation, not designed from scratch aiming for optimal EFT parameter exclusions.**
- **An asymptotically optimal (efficient) observable of the EFT parameters can be formulated as an un-binned extended maximum likelihood**

$$\max_{n_s, n_b, \mathbf{c}} l(n_s, n_b, \mathbf{c}) = \sum_{i=1}^{N} \ln \left(n_s p_s(\mathbf{x}_i, \mathbf{c}) + n_b p_b(\mathbf{x}_i) \right) - n_s - n_b$$

- **The deep problem is that the probabilities are high dimensional, both in phase-space and in the EFT parameters.**
- **Here one can try density estimation with machine learning or perhaps try more analytic and transparent methods e.g. sparse Fourier approximation techniques that can go a bit up in dimensions and easier allow for systematics treatment?**

Conclusions

- Effective field theories are very powerful “UV agnostic” tools to search for new physics, and physics in general.
- The SM as EFT is an ongoing development progressing step by step along with the increasing precision of the data.
- But, much work remains in both the theory and experimental communities to develop the required tools to take advantage of the full EFT power in LHC analyses.

Stockholm University

Backup

ATLAS STXS operators

Wilson coefficient and operator		Affected process group: LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		✓	
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$		✓	✓
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$		✓	✓
c_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$		✓	✓
c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$		✓	
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		✓	
c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$		✓	
c_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	✓	✓	✓
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$		✓	
c_{uH}	$(H^\dagger H)(\bar{q} Y_u^\dagger u \widetilde{H})$		✓	
c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H} t)$		✓	
c_{bH}	$(H^\dagger H)(\bar{Q} H b)$		✓	
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	✓	✓	✓
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	✓	✓	
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$	✓	✓	
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	✓		
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	✓	✓	
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\, G_{\mu\nu}^A$		✓	
c_{tW}	$(\bar{Q}\sigma^{\mu\nu} t)\tau^I \widetilde{H}\, W_{\mu\nu}^I$		✓	
c_{tB}	$(\bar{Q}\sigma^{\mu\nu} t)\widetilde{H}\, B_{\mu\nu}$		✓	
c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓		✓

Wilson coefficient and operator		Affected process group: LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$			✓
$c_{lq}^{(3)}$	$(\bar{l}\gamma_\mu \tau^I l)(\bar{q}\gamma^\mu \tau^I q)$			✓
c_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$			✓
c_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$			✓
c_{lu}	$(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$			✓
c_{ld}	$(\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)$			✓
c_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$			✓
$c_{qq}^{(1,1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$			✓
$c_{qq}^{(1,8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$			✓
$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$			✓
$c_{qq}^{(3,8)}$	$(\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$			✓
$c_{uu}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$			✓
$c_{uu}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$			✓
$c_{dd}^{(1)}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$			✓
$c_{dd}^{(8)}$	$(\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$			✓
$c_{ud}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$			✓
$c_{qu}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$			✓
$c_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$			✓
$c_{qd}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$		✓	
$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$		✓	
$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$		✓	
$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$		✓	
$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$		✓	
$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$		✓	
$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$		✓	
$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$		✓	
$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$		✓	
$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$		✓	
$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$		✓	

di-Higgs Lagrangians

$$\Delta\mathcal{L}_{\text{Warsaw}} = \frac{C_{H,\Box}}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \frac{C_{HD}}{\Lambda^2}(\phi^\dagger D_\mu\phi)^*(\phi^\dagger D^\mu\phi) + \frac{C_H}{\Lambda^2}(\phi^\dagger\phi)^3$$
$$+ \left(\frac{C_{uH}}{\Lambda^2}\phi^\dagger\phi\bar{q}_L\tilde{\phi}\,t_R + h.c.\right) + \frac{C_{HG}}{\Lambda^2}\phi^\dagger\phi G^a_{\mu\nu}G^{\mu\nu,a}$$
$$+ \frac{C_{uG}}{\Lambda^2}(\bar{q}_L\sigma^{\mu\nu}T^aG^a_{\mu\nu}\tilde{\phi}\,t_R + \text{h.c.})\,.$$

$$\Delta\mathcal{L}_{\text{HEFT}} = -m_t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{v^2}\right)\bar{t}\,t - c_{hhh}\frac{m_h^2}{2v}h^3$$
$$+ \frac{\alpha_s}{8\pi}\left(c_{ggh}\frac{h}{v} + c_{gghh}\frac{h^2}{v^2}\right)G^a_{\mu\nu}G^{a,\mu\nu}\ .$$

Reference information

Warsaw: https://arxiv.org/abs/1008.4884v3
Parameters: https://arxiv.org/abs/1312.2014v4
SMEFTsim: https://smeftsim.github.io/
SMEFTatNLO: https://smeftsim.github.io/
Trott: https://arxiv.org/abs/1706.08945
Sigma model: https://arxiv.org/abs/0910.4182v6
HEFT breakdown: arxiv:1902.05936v2
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STXS LHC: https://cds.cern.ch/record/2669925
STXS ATLAS 2021: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-053/
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ML EFT: https://arxiv.org/abs/1805.00020
Fourier methods: https://arxiv.org/abs/2202.13801