Effective Field Theories for HEP: The different approaches and applications

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This part is divided in 5 sections:

1. The Kappa framework *(presented by Giulia)*
2. Fiducial and Template cross sections *(presented by Davide)*
3. Computational Tools for New Physics searches *(presented by Michele)*
4. **Effective Field Theories**
5. Pseudo Observables *(presented by Agniezska)*

The aim of this talk is to present the content of section 4. Namely, a broad introduction to EFTs, and a review of the state of the art. Our main goal is to make clear the connection between EFTs, κ-framework and pseudo-observables, and to show how the former are used for New Physics searches.

Outline

Motivation

After the success of RUN-I of LHC, with the Higgs boson discovery, the door is open to search for new physics. During RUN-II the pheno community needs to move forward too, and define tools and strategies to follow.

Moreover, there are strong hints that "New Physics" will only show small effects at the energies accessible to us → **Need alternatives to direct searches**

Motivation

EFTs are the main tool used nowadays by the theory community, it is the most powerful alternative to direct searches for new physics. Motivations for the use of EFT are several

- We are looking for small deviations, not big ones (i.e. no resonances)
- EFTs are the natural substitute for the kappa framework → Solid QFTs
- EFT predictions can be systematically improved → Higher order corrections
- EFTs have many historical precedents of success

Search for BSM physics: The kappa framework

The simplest example: Gamma-Gamma state originated from Gluon-Gluon fusion

$$(\sigma \cdot BR)_{(gg \to H \to \gamma\gamma)} = (\sigma_{ggH})^{SM} \cdot (BR_{H\gamma\gamma})^{SM} \cdot \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

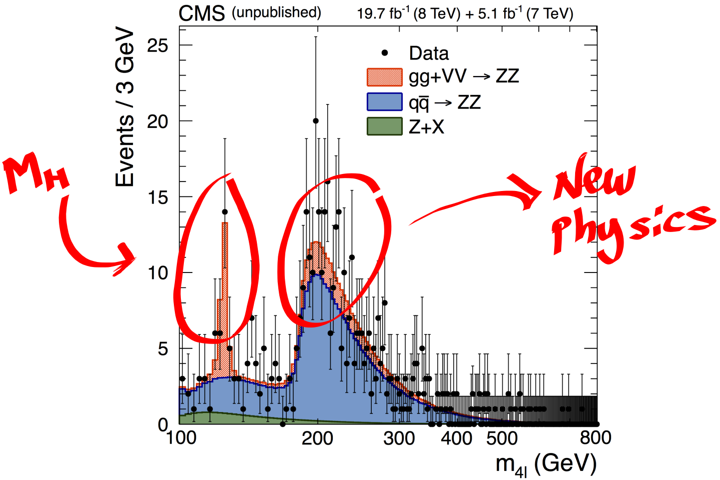
$$\kappa_g^2 = \frac{\sigma_{ggH}}{(\sigma_{ggH})^{SM}}, \quad \kappa_\gamma^2 = \frac{\Gamma_{\gamma\gamma}}{(\Gamma_{\gamma\gamma})^{SM}}, \quad \kappa_H^2 = \frac{\Gamma_H}{(\Gamma_H)^{SM}}$$

Disadvantages . . .

- The κ's don't have a direct physical interpretation
- Only valid for total xsec, not for kinematic studies
- Ad-hoc deviations are not compatible with QFT (they break gauge invariance)
- With the available amount of data and theoretical predictions, no deviation has been found: $\rightarrow$ Need to go to NLO for signal AND background processes

Searches for New Physics: Tails of kinematic distributions

M_H can be extracted from the peak, for Γ_H we have to look at the off-shell region:



CMS results, May 2014

Searches for New Physics: Tails of kinematic distributions

On the peak:

$$\delta_{\text{on-shell}} \approx \frac{g_{UV}^2 M_H^2}{\Lambda^2} \gtrsim \underbrace{0.001}_{\substack{\text{exp. resolution}\\ \text{on the peak}}} \qquad \Rightarrow \qquad \underbrace{\Lambda \gtrsim 3\,TeV}_{g_{UV}=1}$$

On the tail:

$$\delta_{\text{off-shell}} \approx \frac{g_{UV}^2 p_T^2}{\Lambda^2} \gtrsim \underbrace{0.1}_{\substack{\text{exp. resolution}\\ \text{on the tail}}} \qquad \Rightarrow \qquad \Lambda \gtrsim \underbrace{3\,TeV}_{\substack{g_{UV}=1\\ p_T=1\,TeV}},\ \underbrace{7\,TeV}_{\substack{g_{UV}=1\\ p_T=2\,TeV}}$$

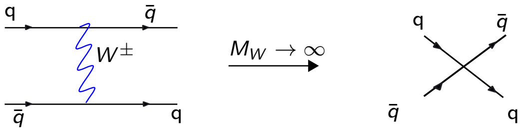
The measurements off-shell can also be used to probe relatively low energy scales

The paradigmatic example: Fermi Theory

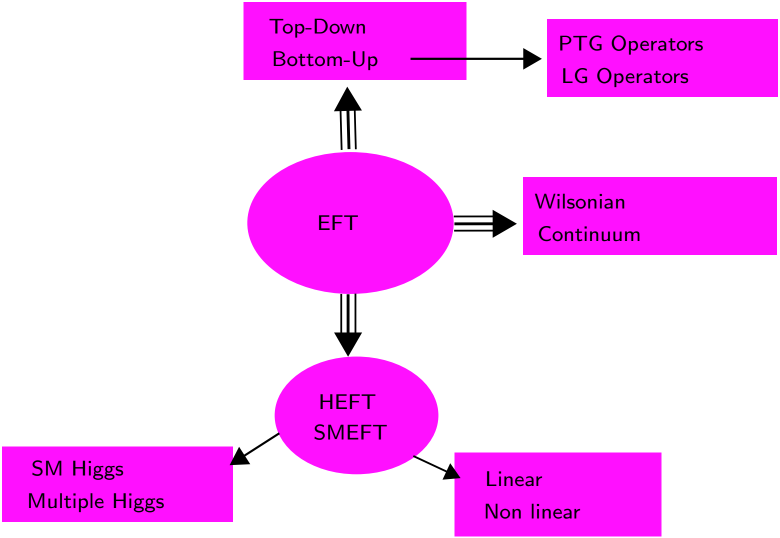
1 $\mathcal{A} = \left(\frac{ig}{\sqrt{2}}\right)^2 \mathrm{V_{us}V^*_{ud}}(\bar{\mathrm{u}}\gamma^\mu \mathrm{P_L s})(\bar{\mathrm{d}}\gamma^\nu \mathrm{P_L u}) \left(\frac{-\mathrm{i}g_{\mu\nu}}{\mathrm{p^2 - M_w^2}}\right)$

2 $p^2 << M_W^2 \quad \Rightarrow \quad \frac{1}{p^2 - M_W^2} \approx \left(\frac{-1}{M_W^2}\right)\left(1 + \frac{p^2}{M_W^2} + \frac{p^4}{M_W^4} + \dots\right)$

3 $\mathcal{A}_{Eff} = \left(\frac{i}{M_w^2}\right)\left(\frac{ig}{\sqrt{2}}\right)^2 \mathrm{V_{us}V^*_{ud}} \underbrace{(\bar{u}\gamma^\mu \mathrm{P_L s})(\bar{\mathrm{d}}\gamma_\mu \mathrm{P_L u})}_{\text{four-fermion operator}}$

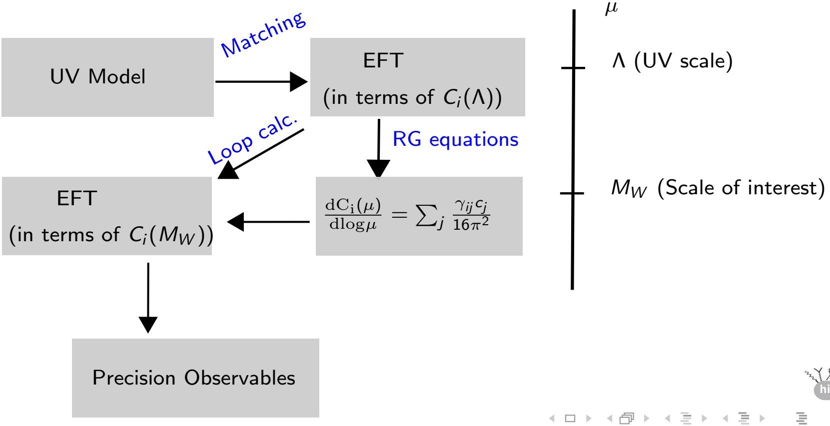


Effective Field Theory: Different aspects



Effective Field Theory: General considerations

1. There is an effective Lagrangian
   (which we build using the top-down or bottom-up approaches)
2. This $\mathcal{L}_{Eff}$ has to be renormalized
   (the UV or SM renormalization is not valid anymore)
3. After it is renormalized we have to match the Wilson coefficients at the scale Λ to the SM ones (at the scale where we are working)



Effective Field Theory: The bottom-up approach

There is an effective Lagrangian:

$$\mathcal{L}_{eff} = \underbrace{\mathcal{L}_{SM}}_{\text{dim 4}} + \underbrace{\frac{1}{\Lambda^2}\sum_k \alpha_k \mathcal{O}_k^{(6)}}_{\text{dim 6}} + \underbrace{\frac{1}{\Lambda^4}\sum_k \alpha_k \mathcal{O}_k^{(8)}}_{\text{dim 8}} + \underbrace{\cdots}_{\text{higher dim. operators}}$$

Model independent, up to some (reasonable) assumptions:

- There is one Higgs doublet with a linear representation
- The EFT does not add new light degrees of freedom
- The heavy degrees of freedom of the EFT decouple
- The heavy degrees of freedom do not mix with the Higgs doublet
- The UV completion is weakly coupled and renormalizable

Effective Field Theory: The bottom-up approach

Augment the SM with operators of dim > 4, suppressed by factors of a new scale Λ^{d-4}

$$\mathcal{L}_{eff} = \underbrace{\mathcal{L}_{SM}}_{\text{dim 4}} + \underbrace{\frac{1}{\Lambda^2}\sum_k \alpha_k \mathcal{O}_k^{(6)}}_{\text{dim 6}} + \underbrace{\frac{1}{\Lambda^4}\sum_k \alpha_k \mathcal{O}_k^{(8)}}_{\text{dim 8}} + \underbrace{\cdots}_{\text{higher dim. operators}}$$

- α_k is the Wilson coefficient of the k^{th} operator.
- For the current experimental resolution we can truncate this expansion at $d = 6$
- Choose a basis of dim-6 operators, with $SU(2) \times SU(3) \times U(1)$ and lepton/baryon conservation, **and** assuming flavor universality.
- We chose the "Warsaw Basis" $\rightarrow$ arXiv: 1008.4884 $\rightarrow$ containing 59 operators.

Operator Set Vs. Operator Basis

Three types of operator sets

- A complete set: a Basis
  - (+) All the possible independent operators are included
  - (+) The γ_{ij} matrix is known
- An overcomplete set: Some operators are redundant
  - (+) Physics is more transparent, γ_{ij} might be simpler (although bigger)
  - (−) Ward and WST identitites cannot be applied, and you "carry around" more operators
- An undercomplete set:
  - (+) Take only the interesting operators for the problem
  - (−) Is not closed under the renormalization group

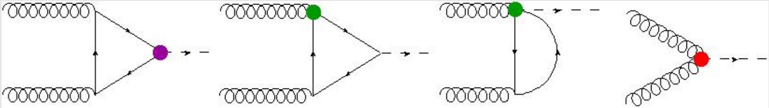
The most popular dimension 6 bases are:

1. *The Warsaw Basis:* the standard basis, γ_{ij} is known
2. *The SILH Basis:* "Strongly Interacting Light Higgs"

One of the main challenges for the EFT community is that of building bases for $dim > 6$ and eventually finding a systematic procedure to do it.

Using bottom-up (LO) EFT for phenomenological predictions

SMEFT

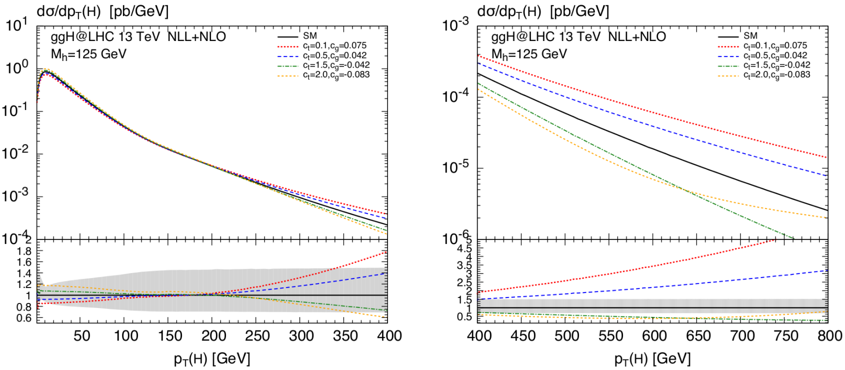


In the mass eigenstates:

- $\frac{c_1}{\Lambda^2}\mathcal{O}_1 \sim \frac{\alpha_s}{\pi v} c_g h G^a_{\mu\nu} G^{\mu\nu a}$ $\rightarrow$ Higgs-Gluon-Gluon coupling
- $\frac{c_2}{\Lambda^2}\mathcal{O}_2 \sim \frac{m_t}{v} c_t t\bar{t}h$ $\rightarrow$ Higgs-t-tbar coupling
- $\frac{c_3}{\Lambda^2}\mathcal{O}_3 \sim \frac{m_b}{v} c_b b\bar{b}h$ $\rightarrow$ Higgs-b-bbar coupling
- $\frac{c_4}{\Lambda^2}\mathcal{O}_4 \sim \frac{g_s m_t}{2v^3} c_{tg}(v+h)G^a_{\mu\nu}(\bar{t}_L \sigma^{\mu\nu} \mathrm{T^a t_R} + \mathrm{h.c.})$ $\rightarrow$ chromomagnetic op.

Grazzini, Ilnicka, Spira, Wiesemann (1612.00283)

Using bottom-up (LO) EFT for phenomenological predictions: More tails

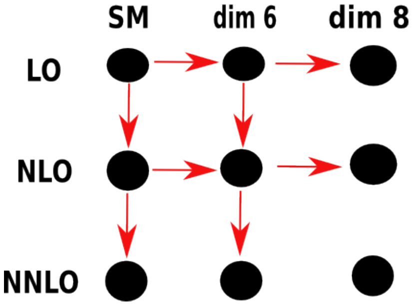


Higgs p_T distribution compared to variations of c_t and c_g, peak vs. tail. $\rightarrow$ **This kind of analysis is not possible within the κ framework**

Grazzini, Ilnicka, Spira, Wiesemann (1612.00283)

Just like with SM calculations, if we want to improve our prediction and/or estimate theoretical uncertainties, we have to look at higher perturbative orders.

Unlike in the SM, here we have a double expansion:



Beyond Leading Order: NLO EFT

There are plenty of reasons to go beyond LO: Since Λ is not known, we cannot know if NLO SMEFT corrections are comparable NLO SM ones.

Example: Correction to the running of α_s (from $p^2 \sim 1\mathrm{GeV}$ to m_h)

$$\left[\frac{(\Delta\alpha_{ew})_{\mathrm{SMEFT}}}{(\Delta\alpha_{ew})_{\mathrm{SM}}}\right] \approx -250\left(\frac{1\mathrm{TeV}}{\Lambda}\right)^2 \tilde{C}_{HB} - 80\left(\frac{1\mathrm{TeV}}{\Lambda}\right)^2 \tilde{C}_{HW}$$

Jenkins, Manohar, Trott (arXiv:1308.2627); *Passarino, Trott* (arXiv:1610.08356)

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NLO SMEFT: Renormalization

The Standard Model renormalization can not be "recycled", there are new divergences introduced by the higher dim operators that need to be solved. However the renormalization procedure is the same:

Fields, parameters, Self Energies, Propagators

$$\Phi = Z_\Phi \Phi_{ren} \qquad p = Z_p p_{ren}$$

$$Z_i = 1 + \frac{g^2}{16\pi^2}\left(\mathrm{dZ}_\mathrm{i}^{(4)} + \mathrm{g}_6 \mathrm{dZ}_\mathrm{i}^{(6)}\right)\Delta_\mathrm{UV}$$

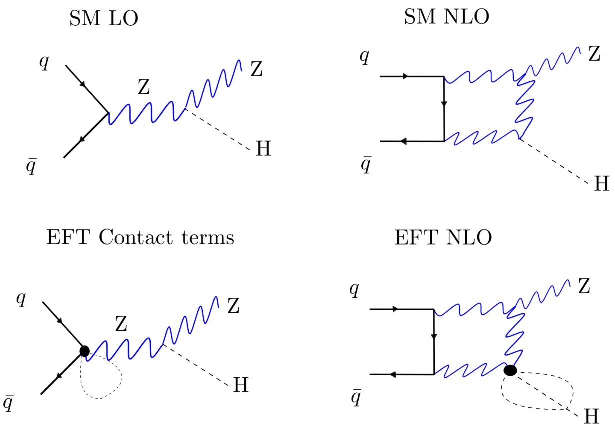
For $n > 2$ point Green's functions, we need an additional constraint:

In order to remove the $\mathcal{O}^{(6)}$ divergences, the Wilson coefficients have to get mixed

$$C_i = \sum_j Z_{ij}^W C_j^{ren} \qquad Z_{ij}^W = \delta_{ij} + \frac{g^2}{16\pi^2}\mathrm{dZ}_\mathrm{ij}^\mathrm{W}\Delta_\mathrm{UV}$$

NLO SMEFT Example:

some diagrams for $pp \to ZH$, contributing up to $\mathcal{O}(\frac{1}{\Lambda^2})$



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Amplitudes

EFT Amplitudes

$$\mathcal{A} = \sum_{n=N}^{\infty} g^n \mathcal{A}_n^{(4)} + \sum_{n=N_6}^{\infty} \sum_{\ell=0}^{n} \sum_{k=\ell}^{\infty} g^n g_{4+2k}^{\ell} \mathcal{A}_{n\ell k}^{(4+2k)}, \qquad g_{4+2k} = \frac{1}{(\sqrt{2} G_F \Lambda^2)^k}$$

More concretely:

$$|\mathcal{A}|^2 = |\mathcal{A}_{SM}|^2 + \underbrace{|\mathcal{A}_{SM} \times \mathcal{A}^{(6)}|}_{\mathcal{O}(\frac{1}{\Lambda^2})} + \underbrace{|\mathcal{A}^{(6)}|^2}_{\mathcal{O}(\frac{1}{\Lambda^4})} + \underbrace{|\mathcal{A}_{SM} \times \mathcal{A}^{(8)}|}_{\mathcal{O}(\frac{1}{\Lambda^4})} + \dots$$

Where do we truncate the amplitude expansion?
How do we estimate theoretical uncertainties?

Amplitudes

EFT Amplitudes

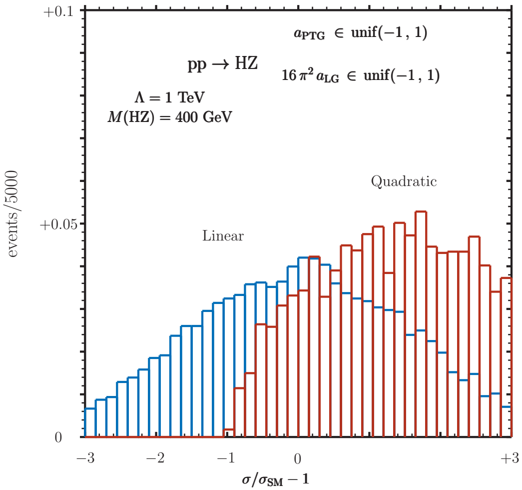
$$\mathcal{A} = \sum_{n=N}^{\infty} g^n \mathcal{A}_n^{(4)} + \sum_{n=N_6}^{\infty} \sum_{\ell=0}^{n} \sum_{k=\ell}^{\infty} g^n g_{4+2k}^{\ell} \mathcal{A}_{n\ell k}^{(4+2k)}, \qquad g_{4+2k} = \frac{1}{(\sqrt{2} G_F \Lambda^2)^k}$$

More concretely:

$$|\mathcal{A}|^2 = |\mathcal{A}_{SM}|^2 + \underbrace{|\mathcal{A}_{SM} \times \mathcal{A}^{(6)}|}_{\text{“linear EFT”}} + \underbrace{|\mathcal{A}^{(6)}|^2}_{\text{“quadratic EFT”}} + \underbrace{|\mathcal{A}_{SM} \times \mathcal{A}^{(8)}|}_{\text{not available (th.uncertainty)}} + \ldots$$

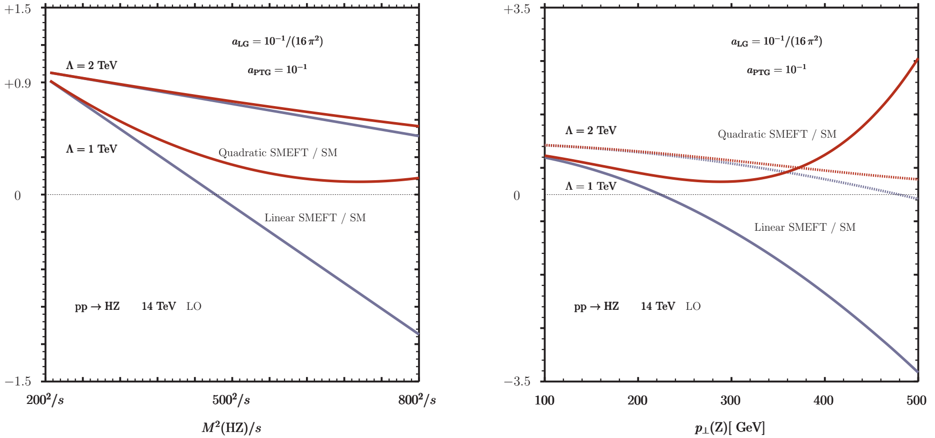
Where do we truncate the amplitude expansion?
How do we estimate theoretical uncertainties?

Some results: Tails of kinematic distributions



- Sigma goes negative if we only include linear
- The quadratic corrections are apparently bigger than the linear
- A study of partial waves (perturbative unitarity) can help us understand the validity of the theory.

Some results: Tails of kinematic distributions



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Top-Down EFT

General considerations:

- Start from a UV theory: identify the heavy fields that have to be removed and the scale of the theory (**non trivial!**) and derive $\mathcal{L}_{eff}$
- Therefore: model dependent

From the UV theory to the EFT (Top-down approach)

- Integrate out the heavy fields of the UV theory

$$e^{iS_{eff}[\phi](\mu)} = \int \mathcal{D}\Phi \, e^{iS_{UV}[\phi,\Phi](\mu)}$$

- Using the saddle point approximation, follows straightforwardly:

$$S_{eff} \approx \underbrace{S[\Phi_C]}_{\text{tree-level}} + \underbrace{\frac{i}{2}\mathrm{Tr}\log\left(-\frac{\delta^2 S}{\delta\Phi^2}\bigg|_{\Phi_C}\right)}_{\text{one-loop}}$$

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Diagrammatic interpretation

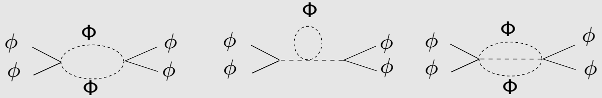
- Clear form the path integral point of view: Only Φ is “dynamical” (ϕ is fixed)

$$\int \mathcal{D}\Phi \; e^{iS_{UV}[\phi,\Phi](\mu)} \neq \int \mathcal{D}\Phi\mathcal{D}\phi \; e^{iS_{UV}[\phi,\Phi](\mu)}$$

- Recall the background field method: $\phi \to \phi + \tilde{\phi}$

$$\mathcal{L}(\phi) \to \mathcal{L}(\phi_i + \tilde{\phi}_i) = \mathcal{L}(\phi_i) + \underbrace{\mathcal{L}_1}_{=0} + \underbrace{\frac{1}{2}\frac{\delta^2\mathcal{L}}{\delta\phi_i\phi_j}\bigg|_{\tilde{\phi}=\phi}\phi_i\phi_j}_{\text{1-loop}} + \dots$$

ϕ is taken as a background field:



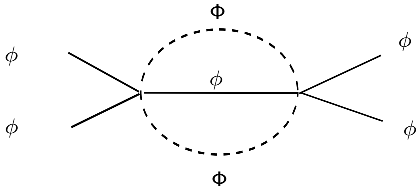
Diagrammatic interpretation

There is a caveat to this procedure:

- Only Φ is "dynamical" (ϕ is fixed)

$$\int \mathcal{D}\Phi \; e^{iS_{UV}[\phi,\Phi](\mu)} \neq \int \mathcal{D}\Phi\mathcal{D}\phi \; e^{iS_{UV}[\phi,\Phi](\mu)}$$

- But if we leave ϕ fixed, we are neglecting some diagrams!



"improved" CDE

The previous formula for the 1-loop effective action,

$$S_{eff} \approx \underbrace{S\left[\Phi_C\right]}_{\text{tree-level}} + \underbrace{\frac{i}{2}\mathrm{Tr}\log\left(-\frac{\delta^2 S}{\delta\Phi^2}\bigg|_{\Phi_C}\right)}_{\text{one-loop}}$$

has to be corrected, namely adding a non-local term:

$$\Gamma[\phi] = S_{eff}[\phi] + \underbrace{\frac{i}{2}\log\,\det\left(\frac{-\delta^2 \mathrm{S}}{\delta\phi^2}\right)}_{\text{non-local term}}$$

This term accounts for such heavy-light loop diagrams, and it is strongly model dependent, not possible to infer a universal formula from it. However, this "mixed" contributions are generally small compared with the purely heavy ones.

The difference between the $\mathcal{L}_{eff}$ in the bottom-up approach and the $\mathcal{L}_{eff}$ in the top-down, is that the latter is calculated at the scale Λ, so we need to evolve its couplings (Wilson coeffs) from that scale to the scale of interest to us (M_W, $2M_W$. M_b, M_{ZZ}...)

In order to do so we have two options:

1. use the **Renormalization Group** equations:

$$\frac{\mathrm{dC_i}(\mu)}{\mathrm{dlog}\mu} = \sum_j \frac{1}{16\pi^2}\gamma_{ij} C_j(\mu)$$

   For this, we need to know the anomalous dimension matrix γ_{ij}, known at dimension 6 for the Warsaw basis, but more challenging as we go to higher dimensions or bigger sets of operators.

2. Renormalize the theory by doing a loop calculation, like in the bottom-up approach (and the SM) $\rightarrow$ after finite renormalization we get the C_i's at the scale of interest.

Applications of EFT

The applications of EFT for indirect searches of New Physics are several. The main ones are:

1. Search for deviations in Higgs Production/Decay cross-sections
2. Search for deviations in kinematic distributions
3. Search for deviations in EWPD: S, T, U, V, W, X , Y
4. Search for deviations in Pseudo Observables (eg. couplings: TGCs, QGCs)

ElectroWeak Precision Data (EWPD)

- Oblique corrections to the propagators of electroweak gauge bosons.
- Transverse vacuum polarization functions:

$$\Pi_{ZZ}(p^2), \Pi_{WW}(p^2), \Pi_{\gamma\gamma}(p^2), \Pi_{\gamma Z}(p^2)$$

- with:

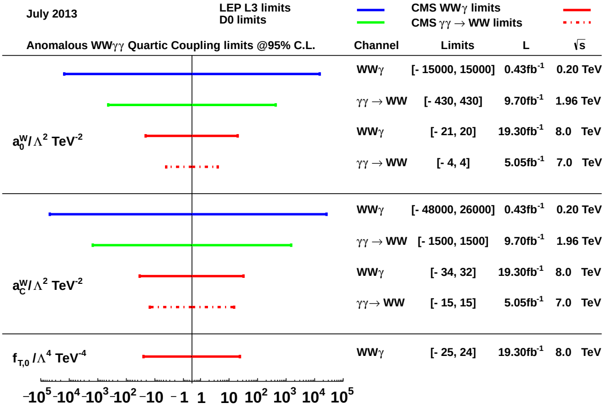
$$\Pi(p^2) = a_0 + a_2 p^2 + a_4 p^4 + \dots$$

- 7 Free parameters: 3 up to $\mathcal{O}(p^2)$: S,T,U and 4 of $\mathcal{O}(p^4)$: V, W, X, Y

These variables have been measured very precisely by the experiment. They are the most sensitive portal to see small deviations.

EFT in the experiments: EFT applications in CMS

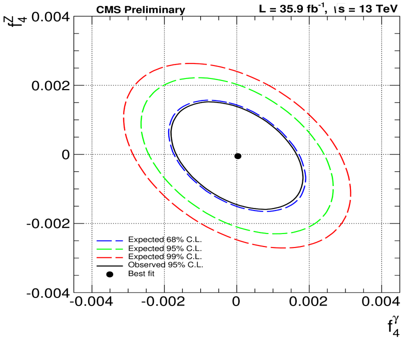
"EFT" studies have been in the LHC programme for a while:

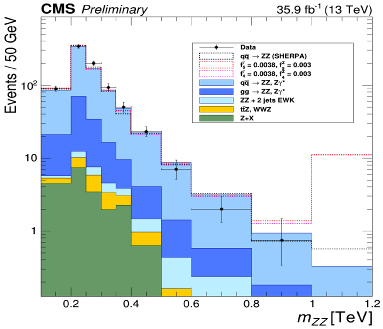


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

In *CMS-PAS-SMP-16-017*, some constraints on aTGCs were calculated using SHERPA in the $Z \to 4\ell$ channel at LO (i.e. κ-framework) $\to$ a full EFT analysis could improve this result.

$$-0.00117 \leq f^{4Z} \leq 0.00110 \qquad -0.00100 \leq f^{5Z} \leq 0.00125$$
$$-0.00133 \leq f^{4\gamma} \leq 0.00132 \qquad -0.00123 \leq f^{5\gamma} \leq 0.00130$$





Similarly in *CMS-PAS-SMP-16-019* (**in approval stage**), some constraints on aQGCs were calculated, using EFT:

"The ZZjj channel is sensitive to the operators T0, T1, and T2, as well as the neutral current operators T8 and T9"
Eboli, Gonzalez-Garcia, Mizukoshi (arXiv:hep-ph/0606118)

- $T_0 = \mathrm{Tr}\left[\hat{\mathrm{W}}_{\mu\nu}\hat{\mathrm{W}^{\mu\nu}}\right] \times \mathrm{Tr}\left[\hat{\mathrm{W}}_{\alpha\beta}\hat{\mathrm{W}^{\alpha\beta}}\right]$
- $T_1 = \mathrm{Tr}\left[\hat{\mathrm{W}}_{\alpha\nu}\hat{\mathrm{W}^{\mu\beta}}\right] \times \mathrm{Tr}\left[\hat{\mathrm{W}}_{\mu\beta}\hat{\mathrm{W}^{\alpha\nu}}\right]$
- $T_2 = \mathrm{Tr}\left[\hat{\mathrm{W}}_{\alpha\mu}\hat{\mathrm{W}^{\mu\beta}}\right] \times \mathrm{Tr}\left[\hat{\mathrm{W}}_{\beta\nu}\hat{\mathrm{W}^{\nu\alpha}}\right]$
- $T_8 = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$
- $T_9 = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$

Further, unitarity bounds are derived using VBFNLO $\rightarrow$ find Λ for which unitarity is violated.

Summary & Open Questions

- For the handbook, we prepared a broad review on Effective Field Theories
- The first level of the chapter is intended to be pedagogic
  (Fermi theory, examples of integration of heavy modes and functional integrals)
- In a second stage we present more advanced topics, like the state of the art, the calculation of dim > 6 bases of operators, calculation of NLO EFT amplitudes
- In the last level, we discuss open questions like: what is the range of validity of the EFT?, how do we chose the scale Λ?, where should we truncate the amplitude expansion?, how can EFT be used in the experiments?

Thank you for your attention

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