High-Energy Physics Tools for Effective Field Theories

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Effective field theories for new physics

✦ The effective field theory (EFT) approach for new physics

- All new phenomena are assumed to appear at a large energy scale Λ
- Departures from the Standard Model expressed as a series in 1/Λ
  - In terms of the SM fields (no assumption on the form of new physics)
  - Addition of higher-dimensional operators
  - Leading effects usually assumed to be of dimension six
  - Sometimes dimension-eight operators are relevant as well
- Not predictive at scales larger than Λ (loss of unitarity)

✦ The EFT parameter space is large

- One parameter for each new operator (large number of parameters)
  - A basis can be defined at a given order in 1/Λ (equations of motion, integration by parts)
  - The number of operator is finite (e.g.: dimension six: 76 BNC + 8 BNV for $n_F=1$)
- Observables usually depend on specific linear combinations of coefficients
  - A much smaller subset of parameters is relevant with respect to data
  - EFT are testable

The development of tools dedicated to EFT calculations
has been very intense during the last decades

Tools for effective field theories

✦ Tools dedicated to effective field theories

- ✤ Precision calculations
  - ★ Higgs single-production in the gluon fusion mode: HIGLU [Spira]
  - ★ Higgs pair-production in the gluon fusion mode: HPAIR [Gröber, Mühlleitner, Spira & Streicher]
  - ★ Higgs decays: eHDECAY [Contino, Ghezzi, Grojean, Mühlleitner & Spira]
- ✤ Machineries for the characterization of the Higgs
  - ★ Using pseudo-observables: HIGGSPO [Greljo, Isidori & Marzocca]
  - ★ The Higgs / BSM characterisation framework [Demartin, Mawatari & Zaro; BF & Mawatari]
- ✤ Monte Carlo event generators
  - ★ MADGRAPH5_aMC@NLO (HC/BSMC, SILH) [Alwall *et al.*]
  - ★ VBFNLO [Campanario, Rauch, Perez, Roth & Zeppenfeld]
  - ★ WHIZARD [Chokoufe, Kilian, Ohl, Reuter, Sekulla, Shim, Speckner & Weiss]
- ✤ Translator linking different operator basis languages
  - ★ ROSETTA [Falkowski, BF, Mawatari, Mimasu, Riva & Sanz]

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Single Higgs production with HIGLU

[http://tiger.web.psi.ch/higlu/]

✦ Precision of the calculation

- ✤ NNLO accuracy in QCD (SM and MSSM)
- ✤ Quark mass effects (top, bottom and charm) included at the NLO
- ✤ NLO accuracy for the electroweak corrections (SM only)
- ✤ EFT contributions at the NNLO accuracy in QCD

✦ The EFT contributions are based on (in terms of mass-eigenstates):

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{\pi}\left[\frac{c_t}{12}(1+\delta)+c_g\right] G_a^{\mu\nu} G^a_{\mu\nu} \frac{H}{v}$$

- ✤ c_t (=1 in the SM): rescaling factor of the top Yukawa
- ✤ c_g (=0 in the SM):
  - ★ Pure dimension-six origin
  - ★ No QCD corrections but scale dependence included (NNLL)
- ✤ δ: contains NNLO QCD corrections

$$\delta = \delta_1 \frac{\alpha_s}{\pi} + \delta_2 \left(\frac{\alpha_s}{\pi}\right)^2 + \delta_3 \left(\frac{\alpha_s}{\pi}\right)^3$$

✦ Cross section results

- ✤ Either in the SILH case or the non-linear case
- ✤ Inputs: SM parameters and the Wilson coefficients

Higgs pair-production with HPAIR

[http://tiger.web.psi.ch/hpair/]

✦ Precision of the calculation

- ✤ NLO accuracy in QCD, in the heavy top quark limit (SM and MSSM)
- ✤ EFT contributions at the NLO accuracy in QCD

✦ The EFT contributions are based on (in terms of mass-eigenstates):

$$\mathcal{L}_{\rm eff} = -m_t \bar{t} t \left[c_t \frac{H}{v} + c_{tt} \frac{H^2}{2v^2} \right] - \frac{1}{6} c_3 \left[\frac{3m_h^2}{v} \right] H^3 + \frac{\alpha_s}{\pi} G_a^{\mu\nu} G_{\mu\nu}^a \left[c_g \frac{H}{v} + c_{gg} \frac{H^2}{2v^2} \right]$$

that gives, after integrating out the top quark

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{\pi} G_a^{\mu\nu} G_{\mu\nu}^a \left\{ \frac{H}{v} \left[\frac{c_t}{12} \left(1 + \frac{11}{4} \frac{\alpha_s}{\pi} \right) + c_g \right] + \frac{H^2}{v^2} \left[\frac{c_{tt} - c_t^2}{24} \left(1 + \frac{11}{4} \frac{\alpha_s}{\pi} \right) + \frac{c_{gg}}{2} \right] \right\}$$

✦ The EFT contributions can also be derived from the SILH basis

$$\Delta\mathcal{L}_6^{\rm SILH} \supset \frac{\bar{c}_H}{2v^2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi) + \frac{\bar{c}_u}{v^2} y_t \left(\Phi^\dagger \Phi \bar{q}_L \Phi^c t_R + {\rm h.c.} \right) - \frac{\bar{c}_6}{6v^2} \frac{3m_h^2}{v^2} \left(\Phi^\dagger \Phi \right)^3 + \bar{c}_g \frac{g_s^2}{m_W^2} \Phi^\dagger \Phi G_{\mu\nu}^a G_a^{\mu\nu}$$

that gives, after integrating out the top quark

$$c_t = 1 - \frac{\bar{c}_H}{2} - \bar{c}_u \,, \qquad c_{tt} = -\frac{1}{2} (\bar{c}_H + 3\bar{c}_u) \,, \qquad c_3 = 1 - \frac{3}{2} \bar{c}_H + \bar{c}_6 \,, \qquad c_g = c_{gg} = \bar{c}_g \frac{4\pi}{\alpha_2}$$

✦ User inputs

- ✤ SM parameters and the Wilson coefficients in one of the two basis choices

Higgs decays with eHDECAY

[http://www.itp.kit.edu/~maggie/eHDECAY/]

✦ Precision of the calculations

- QCD corrections and mass effects included in the relevant decay channels
- Electroweak corrections included in the linear case (unknown otherwise)
- EFT contributions stemming from all bosonic operators implemented

✦ Example of the H → gg decay mode in the SILH case

$$
\begin{aligned}
\Gamma^{\rm SILH}_{gg} = \frac{G_F \alpha_s^2 m_h^3}{4\sqrt{2}\pi^3} \Bigg[& \frac{1}{9} \sum_{q,q'=t,b,c} (1 - \bar{c}_H - \bar{c}_q - \bar{c}_{q'}) A^*_{1/2}(\tau_{q'}) A_{1/2}(\tau_q) c^2_{\rm eff} \boxed{\kappa_{\rm soft}} \\
& + 2\,{\rm Re}\Bigg\{ \sum_{q=t,b,c} \frac{1}{3} A^*_{1/2}(\tau_q) \frac{16\pi \bar{c}_g}{\alpha_2} \Bigg\} \boxed{c_{\rm eff}} \kappa_{\rm soft} + \Bigg| \sum_{q=t,b,c} \frac{1}{3} A_{1/2}(\tau_q) \Bigg|^2 c^2_{\rm eff} \boxed{\kappa_{\rm ew}} \kappa_{\rm soft} \\
& + \frac{1}{9} \sum_{q,q'=t,b} (1 - \bar{c}_H - \bar{c}_q - \bar{c}_{q'}) A^*_{1/2}(\tau_q) A_{1/2}(\tau_{q'}) \boxed{\kappa^{\rm NLO}(\tau_q, \tau_{q'})} \Bigg]
\end{aligned}
$$

N^{3}LO QCD in the heavy top quark limit

Electroweak corrections

High-energy gluon and quark exchange (N^{3}LO in QCD)

Quark mass effects (at NLO)

✦ Results

- Either in the linear or the non-linear case (no electroweak corrections here)
- Inputs: SM parameters and the Wilson coefficients
- Future developments: implementation of the Higgs basis and the $\overline{\rm MS}$ scheme

Characterizing the Higgs with pseudo-observables

[http://www.physik.uzh.ch/data/HiggsPO/]

✦ The pseudo-observable framework

- Extension of the κ-framework to account for differential distributions
- Finite set of experimentally accessible parameters that are well defined in QFT
- Characterize the Higgs properties

✦ Technicalities

- Decomposition of the on-shell amplitudes involving the Higgs
- Momentum expansion
- Assumption: the Higgs is a scalar with a narrow width

✦ A HIGGSPO model is implemented in FEYNRULES

- The values of the pseudo-observables can be fixed (externally derived)
- Specific processes can be computed in this framework (but not any process)
- Currently: Higgs decays are implemented and publicly available
  - ★ The model can be used, *e.g.*, to decay the Higgs boson in a Monte Carlo framework
  - ★ The HIGGSPO model is only used for the decay (and nothing else)
- Supported decays:
  - ★ Higgs into two fermions, two bosons, four leptons, photon/Z+two leptons

Higgs and new physics characterization

[http://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation; http://feynrules.irmp.ucl.ac.be/wiki/BSMCharacterisation; http://feynrules.irmp.ucl.ac.be/wiki/HEL]

✦ HC: study of the Higgs properties in a systematic way

- ✤ Based on an EFT description
  - ★ Implementation of the Lagrangian in the mass basis into FEYNRULES
  - ★ All couplings are taken independent (more free parameters)
- ✤ Strategy: implementation within a full simulation chain (Lagrangian to events)
  - ★ Predictions at the NLO accuracy in QCD available
  - ★ Full automation (in particular within the MADGRAPH5_aMC@NLO framework)
- ✤ No assumption on the Higgs quantum numbers (spin, parity)

✦Spin-0 example:

$$
\begin{aligned}
\mathcal{L}_0 = \Big\{ & -\sum_{f=t,b,\tau} \bar\psi_f \big(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att}\,\gamma_5\big)\psi_f + c_\alpha \kappa_{\rm SM}\big[\frac{1}{2} g_{HZZ}\, Z_\mu Z^\mu + g_{HWW}\, W^+_\mu W^{-\mu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma}\, A_{\mu\nu} \widetilde{A}^{\mu\nu}\big] - \frac{1}{2}\big[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma}\, Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma}\, Z_{\mu\nu} \widetilde{A}^{\mu\nu}\big] \\
& - \frac{1}{4}\big[c_\alpha \kappa_{Hgg} g_{Hgg}\, G^a_{\mu\nu} G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg}\, G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}\big] - \frac{1}{4}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ}\, Z_{\mu\nu} \widetilde{Z}^{\mu\nu}\big] \\
& - \frac{1}{2}\frac{1}{\Lambda}\big[c_\alpha \kappa_{HWW}\, W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW}\, W^+_{\mu\nu} \widetilde{W}^{-\mu\nu}\big] \\
& - \frac{1}{\Lambda} c_\alpha \big[\kappa_{H\partial\gamma}\, Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + \kappa_{H\partial W}\big(W^+_\nu \partial_\mu W^{-\mu\nu} + h.c.\big)\big] \Big\} X_0\,,
\end{aligned}
$$

✦ BSMC: extension to all interactions arising from the SM EFT

✦ An implementation in the SILH basis is also available

Anomalous couplings in VBFNLO

[https://www.itp.kit.edu/vbfnlo]

- NLO QCD computations including EFT effects can be studied for:
  - VBF processes: Higgs, single and double vector boson production (plus jets)
  - WH, double and triple boson production (plus jets), Hjj production (via gluon fusion)
- Technicalities
  - *K*-matrix unitarization procedure implemented for two dimension-eight operators
    - ★ EFT contributions frozen to a fixed value in the regime where unitarity is lost

$$\mathcal{O}_{S,0} + \mathcal{O}_{S,2} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]\left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] + \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right]\left[(D^\nu\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{O}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right]\left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

  - Form factors can also be included to avoid unitarity violation

- EFT contributions
  - Dimension-six operators (plus the CP-odd counterparts)

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger \widehat{W}^{\mu\nu}(D_\nu\Phi), \qquad \mathcal{O}_B = (D_\mu\Phi)^\dagger \widehat{B}^{\mu\nu}(D_\nu\Phi), \qquad \mathcal{O}_{WWW} = \mathrm{Tr}\left[\widehat{W}_{\mu\nu}\widehat{W}^{\nu\rho}\widehat{W}_\rho{}^\mu\right]$$

$$\mathcal{O}_{WW} = \Phi^\dagger \widehat{W}_{\mu\nu}\widehat{W}^{\mu\nu}\Phi, \qquad \mathcal{O}_{BB} = \Phi^\dagger \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\Phi.$$

    - ★ Inputs: the L3 and mass-basis parameterization are also available
  - A set of dimension-eight operators are also available (see the manual)

The WHIZARD event generator

[https://whizard.hepforge.org/]

✦ Technicalities

- ✤ Internal matrix element generator: O'MEGA
  - ★ Recursive computations of tree-level amplitudes
- ✤ Internal parton shower (p_T-ordered and analytic)
- ✤ NLO: FKS subtraction and POWHEG matching available (external virtual calculator)
- ✤ BSM: SARAH and FEYNRULES interfaces

✦ EFT contributions

- ✤ Bosonic dimension-six operators (in the Warsaw basis)
- ✤ Fermionic dimension-six operators involving top quarks
  - ★ Using anomalous couplings
- ✤ A set of dimension-eight operators (involving gauge and Higgs bosons)
- ✤ *K*-matrix unitarization procedure implemented for two dimension-eight operators
  - ★ EFT contributions frozen to a fixed value in the regime where unitarity is lost

The ROSETTA package

[http://rosetta.hepforge.org/]

✦ Aims of the program

- ✤ Translation of the coefficients in a given EFT basis to another one
- ✤ Link to the BSMC implementation in FEYNRULES
  - ★ Event generation in the context of all implemented EFT bases is possible

✦ Special features

- ✤ Core bases: Higgs, Warsaw, SILH (and the BSMC basis)
- ✤ Several options for flavor violation (MFV, general)
- ✤ New bases can easily be added
  - ★ Translation to one of the three core bases allows for an indirect translation to any basis
- ✤ Interface to eHDECAY (that can now work in any basis)
- ✤ Flexible package
  - ★ Easily extendable for interfacing it to future tools (NLO effects, RGEs, *etc.*)

Summary

✦ Several tools have been developed for calculations in the EFT framework

- Precision calculations
  - ★ Single Higgs production in the gluon fusion mode: HIGLU [Spira]
  - ★ Higgs pair-production in the gluon fusion mode: HPAIR [Gröber, Mühlleitner, Spira & Streicher]
  - ★ Higgs decays: eHDECAY [Contino, Ghezzi, Grojean, Mühlleitner & Spira]
- Machineries for the characterization of the Higgs
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