AUTOMATED MATCHING AT 1-LOOP FOR EFTS

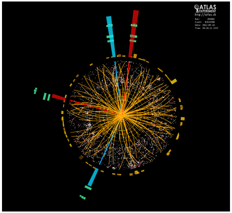
THE 16TH WORKSHOP OF THE LHC HIGGS CROSS SECTION WORKING GROUP

ADRIAN CARMONA BERMUDEZ

October 16, 2019

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 754446 and UGR Research and Knowledge Transfer Found – Athenea3i

EFFECTIVE FIELD THEORY AS A DISCOVERY TOOL



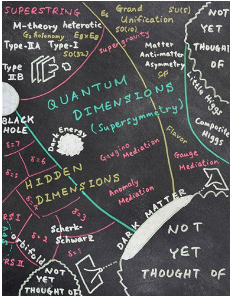
Data

⇔

X^3		φ^6 and $\varphi^4 D^2$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$		
$X^2\varphi^2$		$\psi^2 X\varphi$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}'_p \sigma^{\mu\nu} e'_r)\tau^I \varphi W_{\mu\nu}^I$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}'_p \sigma^{\mu\nu} e'_r)\varphi B_{\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}'_p \sigma^{\mu\nu} T^A u'_r)\widetilde{\varphi}\, G_{\mu\nu}^A$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}'_p \sigma^{\mu\nu} u'_r)\tau^I \widetilde{\varphi}\, W_{\mu\nu}^I$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}'_p \sigma^{\mu\nu} u'_r)\widetilde{\varphi}\, B_{\mu\nu}$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}'_p \sigma^{\mu\nu} T^A d'_r)\varphi\, G_{\mu\nu}^A$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}'_p \sigma^{\mu\nu} d'_r)\tau^I \varphi\, W_{\mu\nu}^I$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}'_p \sigma^{\mu\nu} d'_r)\varphi\, B_{\mu\nu}$

Effective Field Theory

⇔



New Theories

Effective Field Theory (EFT) is THE tool to parametrize in a model-independent way new physics and shed light on what is possible beyond the standard model

Data $\longrightarrow$ EFT   It allows to interpret data with the lens of any new theory

EFT $\longleftarrow$ New Theories   It allows to instantly confront any new theory with data

UNIVERSIDAD DE GRANADA
OFPI Oficina de Proyectos Internacionales
athenea3i
European Commission

BOTTOM - UP EFT

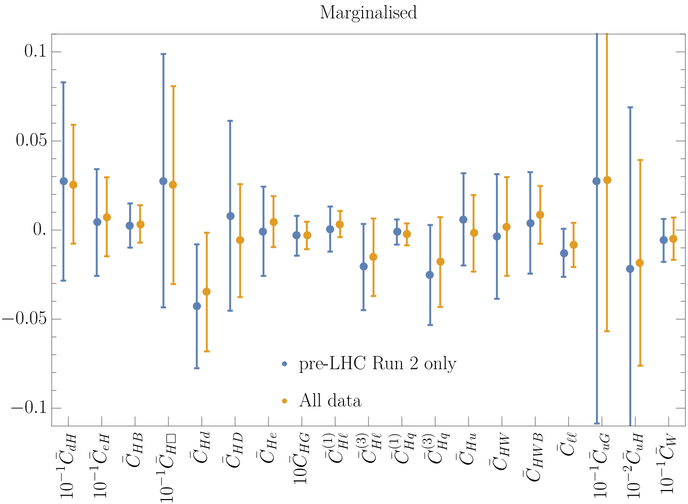
We can write the most general non-renormalizable $\mathcal{L}$ compatible with the observed symmetries and dof and consistently expand in powers of $1/\Lambda$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(4)} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \frac{1}{\Lambda^3}\mathcal{L}^{(7)} + \dots$$

- ⋆ Mapping experimental observables to the Wilson coefficients in $\mathcal{L}_{\text{eff}}$ allows us to search for NP in a model independent way!
- ⋆ We dispose nowadays of an impressive fit of the SM EFT to data

Corbett et al. '12, '12, '13, '14, '15; Ciuchini, Franco, Mishima, Silvestrini '13; de Blas et al. '13, '14, '16, '16, '17; Pomarol, Riva '13; Englert, Freitas, Müllheitner, Plehn, Rauch, Spira, Walz '14; Ellis, Sanz, You '14, '14; Falkowski, Riva '14; Efrati, Falkowski, Soreq '15; Falkowski, Gonzalez-Alonso, Greljo, Marzocca, (Son) '15, '16; Berthier, (Bjørn), Trott '15, '16; Englert, Kogler, Schulz, Spannowsky '15; Buckley, Englert, Ferrando, Miller, Moore, Nördstrom, Russell, White '16; Butter, Éboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, Rauch '16; Freitas, López-Val, Plehn '16; Falkowski, Golzalez-Alonso, Greljo, Marzocca, Son '16; Krauss, Kuttimalai, Plehn '16; Ellis, Murphy, Sanz, You '18;...and many more!!

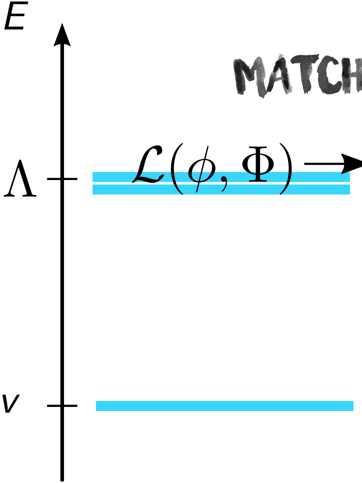
BOTTOM - UP EFT



Ellis, Murphy, Sanz, You ’18

UNIVERSIDAD DE GRANADA OFPI Oficina de Proyectos Internacionales athenea 3i European Commission

TOP - DOWN EFT



MATCHING

$$\mathcal{L}(\phi, \Phi) \longrightarrow \mathcal{L}_{\text{eff}} = \sum_i \frac{c_i(\Lambda)}{\Lambda^{d_i - 4}} \mathcal{O}_i(\phi)$$

RUNNING

$$\downarrow$$

$$c_k(v)$$

TOP - DOWN EFT AT TREE - LEVEL

We already have a tree-level dictionary between (renormalizable) theories with particles with spin $< 3/2$ and the SM EFT at dimension 6

- ✓ New Quarks: del Aguila, Perez-Victoria, Santiago, '00
- ✓ New Leptons: del Aguila, de Blas, Perez-Victoria, '08
- ✓ New Vectors: del Aguila, de Blas, Perez-Victoria, '10
- ✓ New Scalars: de Blas, Chala, Perez-Victoria, Santiago, '15
- ✓ Mixed contributiuons: de Blas, Criado, Perez-Victoria, Santiago, '17

However, loop contributions provide

- the leading effect in certain models/operators
- will be required to have the full NLO when 2-loop anomalous dimensions will be available

One loop matching needs to be automated. Too many possibilities!

RELEVANT EXAMPLES IN HIGGS PHYSICS

Higgs physics provides us with several examples where one loop effects are very important!

- The operators

$$\mathcal{O}_{\varphi G} = \varphi^\dagger \varphi G^A_{\mu\nu} G^{A\mu\nu}, \quad \mathcal{O}_{\varphi W} = \varphi^\dagger \varphi W^I_{\mu\nu} W^{I\mu\nu}, \quad \mathcal{O}_{\varphi B} = \varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu},$$

  can only be generated at one loop, in any renormalizable UV completion

  $\mathcal{O}_{\varphi G}$ is responsible for gluon fusion, and therefore most of the Higgs production, while $\mathcal{O}_{\varphi W}$ and $\mathcal{O}_{\varphi B}$ are the ones leading to $h \to \gamma\gamma, \gamma Z, \ldots$

- Analogously, all the dipole operators ($X\psi^2\varphi$) are loop induced

$$\mathcal{O}_{eB} = (\bar{\ell}_L \sigma^{\mu\nu} e_R) \varphi B_{\mu\nu}, \quad \mathcal{O}_{uG} = (\bar{q}_L \sigma^{\mu\nu} T_A u_R) \tilde{\varphi} G^A_{\mu\nu}, \quad \ldots$$

  with $\mathcal{O}_{uG}$ e.g. contributing to $t\bar{t}h$ production.

ONE LOOP MATCHING

At one loop,

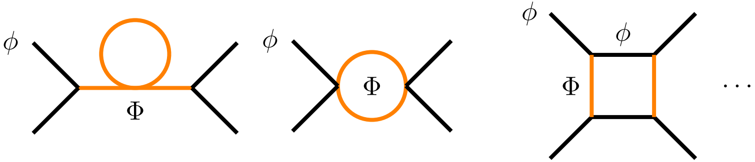
- ⋆ The number of possibilities increases dramatically! → Automation

- ⋆ The matching can be performed

  Diagrammatically Anastasiou, AC, Lazapoulos, Santiago, `MatchMaker`

  By functional methods Henning, Lu & Murayama, '14; Drozd, Ellis, Quevillon, You, '15; Henning, Lu, Murayama, '16; Ellis, Quevillon, You, Zhang, '16; Fuentes-Martin, Portoles, Ruiz-Femenia, '16; Zhang, '16; Ellis, Quevillon, You, Zhang, '17; Krämer, Summ, Voigt, '19

We match 1ℓPI (off-shell) Green functions



ONE LOOP MATCHING

Diagrammatic off-shell 1-loop matching

Choose UV model

Fix Green basis

Fix amplitudes to compute

Compute amplitudes

Solve for WC

Canonically normalize

Eliminate redundancy

ONE LOOP MATCHING

Diagrammatic off-shell 1-loop matching

Choose UV model	user
Fix Green basis	MM ✓
Fix amplitudes to compute	MM ✓
Compute amplitudes	MM ✓
Solve for WC	MM ✓
Canonically normalize	MM ✓
Eliminate redundancy	MM ✓

MATCHMAKER

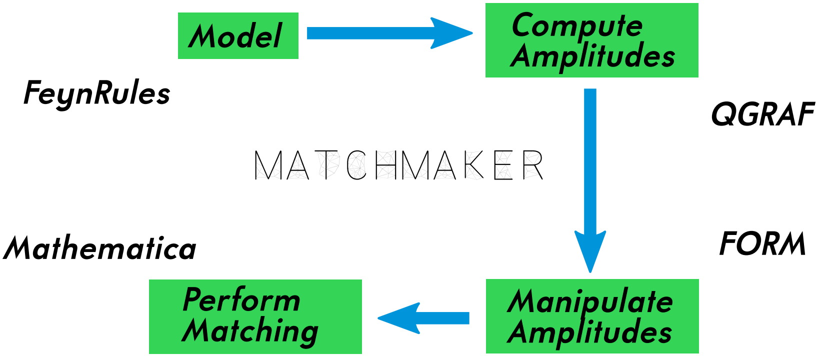
Anastasiou, AC, Lazopoulos, Santiago

`MatchMaker`: automated tree-level and 1-loop matching

- ⋆ Written in python: easy to install, cross-platform
- ⋆ Uses well established techniques and tools: QGRAF, FORM, Mathematica, Feynrules
- ⋆ Off-shell diagrammatic matching of arbitrary models to the SMEFT in the BFM version of the 't Hooft-Feynman gauge (flavor implicit)

MATCHMAKER

Anastasiou, AC, Lazopoulos, Santiago



UNIVERSIDAD DE GRANADA

OFPI Oficina de Proyectos Internacionales

athenea 3i

European Commission

MATCHMAKER

Anastasiou, AC, Lazopoulos, Santiago

The output of `MatchMaker` is `WilsonCoefficients.dat`, a file with all the Wilson Coefficients:

	Tree level	One loop
Green		
Green canon. norm.		
Warsaw		

Here you will find an example: Video

MATCHMAKER: STATUS

Anastasiou, AC, Lazopoulos, Santiago

The code is essentially finished: we just need to: [✓✓✓ ready to go!]

- Polish the output ✓✓
- Finish the documentation ✓
- Perform further cross-checks ✓✓
- Optimize the code ✓✓

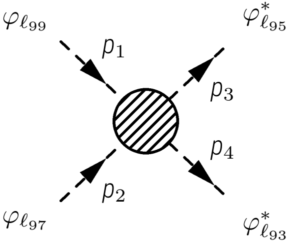
Cross-checks:

- ⋆ Complete off-shell kinematic and gauge structure
- ⋆ Ward identities
- ⋆ Hermiticity and symmetry properties of Wilson coefficients
- ⋆ Comparison with the literature

UNIVERSIDAD DE GRANADA OFPI Oficina de Proyectos Internacionales athenea 3i European Commission

CROSS - CHECKS

FULL OFF - SHELL KINEMATIC AND GAUGE STRUCTURE



$$\mathcal{O}_{\varphi D} = |\varphi^\dagger D_\mu \varphi|^2$$
$$\mathcal{O}_{\varphi\Box} = \varphi^\dagger\varphi\partial^2\varphi^\dagger\varphi$$
$$\mathcal{R}_{\varphi\Box} = \varphi^\dagger\varphi\varphi^\dagger D^2\varphi$$

$$\begin{aligned}
&\phi_{l99}(p1)\ \phi_{l97}(p2)\ \phi^*_{l95}(p3)\ \phi^*_{l93}(p4) = \\
&\mathbf{p3.p4}\ (\delta_{l93,l99}\,\delta_{l95,l97} + \delta_{l93,l97}\,\delta_{l95,l99})\ (\alpha_{\phi D} - 2\,\beta_{\phi\Box}) - \\
&\ 2\,\mathbf{p2.p2}\ (\delta_{l93,l99}\,\delta_{l95,l97} + \delta_{l93,l97}\,\delta_{l95,l99})\ (\alpha_{\phi\Box} + \beta_{\phi\Box}) + \\
&\ \mathbf{p2.p3}\ (-\delta_{l93,l97}\,\delta_{l95,l99}\ (\alpha_{\phi D} + 2\,\beta_{\phi\Box}) + \delta_{l93,l99}\,\delta_{l95,l97}\ (\alpha_{\phi D} - 2\ (2\,\alpha_{\phi\Box} + \beta_{\phi\Box}))) + \\
&\ \mathbf{p2.p4}\ (-\delta_{l93,l99}\,\delta_{l95,l97}\ (\alpha_{\phi D} + 2\,\beta_{\phi\Box}) + \delta_{l93,l97}\,\delta_{l95,l99}\ (\alpha_{\phi D} - 2\ (2\,\alpha_{\phi\Box} + \beta_{\phi\Box}))) + \\
&\ \mathbf{p4.p4}\ \left(\delta_{l93,l97}\,\delta_{l95,l99}\ \left(-2\,\alpha_{\phi\Box} + \alpha_{\phi D} - \beta_{\phi\Box} - \overline{\beta}_{\phi\Box}\right) - \delta_{l93,l99}\,\delta_{l95,l97}\ \left(\beta_{\phi\Box} + \overline{\beta}_{\phi\Box}\right)\right) + \\
&\ \mathbf{p3.p3}\ \left(\delta_{l93,l99}\,\delta_{l95,l97}\ \left(-2\,\alpha_{\phi\Box} + \alpha_{\phi D} - \beta_{\phi\Box} - \overline{\beta}_{\phi\Box}\right) - \delta_{l93,l97}\,\delta_{l95,l99}\ \left(\beta_{\phi\Box} + \overline{\beta}_{\phi\Box}\right)\right)
\end{aligned}$$

12 kinematic & gauge structures for 4 real coefficients

UNIVERSIDAD DE GRANADA
OFPI Oficina de Proyectos Internacionales
athenea 3i
European Commission

CROSS - CHECKS

WARD IDENTITIES

Terminal - adrian@illo: ~/demo_MM

File Edit View Terminal Tabs Help

```
adrian@illo:~/demo_MM > MatchMaker
form properly installed in the system
qgraf properly installed in the system

Welcome to Match-Maker
Please refer to xxx when using this code

MatchMaker> help check_WI
Check Ward Identities for a model that has been already matched
MatchMaker> check_WI MatchMaker/Scalar_Singlet_BFM_MM/
Computing amplitudes to check Ward Identities for model MatchMaker/Scalar_Single
t_BFM_MM. This might take some time depending on the complexity of the model.
Amplitudes to check Ward Identities for model MatchMaker/Scalar_Singlet_BFM_MM c
omputed.
time taken 6 seconds
Checking Ward Identities for model MatchMaker/Scalar_Singlet_BFM_MM. This might
take some time depending on the complexity of the model.
Ward Identities for model MatchMaker/Scalar_Singlet_BFM_MM checked.
time taken 15 seconds
Ward identities satisfied
MatchMaker>
```

CROSS - CHECKS

HERMITICITY AND SYMMETRY PROPERTIES

Hermiticity and symmetry properties of WC. For example,

$$T_{L,R} \sim (3, 1, 2/3)$$
$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \bar{T}\left[i\not{D} - M\right]T - \left[\lambda'_i \bar{q}_{L,i}\tilde{\varphi}T_R + \text{h.c.}\right]$$

$$\left(\mathcal{O}_{qq}^{(1)}\right)_{ijkl} = \left(\bar{q}_{Li}\gamma^\mu q_{Lj}\right)\left(\bar{q}_{Lk}\gamma_\mu q_{Ll}\right) \Rightarrow (\alpha_{qq}^{(1)})^*_{ijkl} = (\alpha_{qq}^{(1)})_{jilk} = (\alpha_{qq}^{(1)})_{lkji}$$

$$\begin{aligned}16\pi^2 M^2(\alpha_{qq}^{(1)})_{ijkl} = &-\frac{g_1^4}{405}\delta_{ij}\delta_{kl} + \frac{g_s^4}{90}\left[2\delta_{ij}\delta_{kl} - 3\delta_{il}\delta_{jk}\right] - \frac{1}{16}\lambda'_i\lambda'^*_j\lambda'_k\lambda'^*_l \\ &+ \left\{\frac{g_1^2}{2592}\left[61 - 18\log\left(\frac{M^2}{\mu^2}\right)\right]\lambda'_i\lambda'^*_j\delta_{kl} - \frac{7g_s^2}{864}\left[2\lambda'_i\lambda'^*_j\delta_{kl} - 3\lambda'_k\lambda'^*_j\delta_{il}\right]\right. \\ &\left.- \frac{1}{32}\left[3 - 2\log\left(\frac{M^2}{\mu^2}\right)\right]\left(Y^dY^{d\dagger} - Y^uY^{u\dagger}\right)_{ij}\lambda'_k\lambda'^*_l + (ij) \leftrightarrow (kl)\right\}\end{aligned}$$

CROSS - CHECKS

COMPARE WITH THE LITERATURE

- ⋆ Not so many complete 1-loop calculations to compare to
- ⋆ Complete 1-loop matching to SM+scalar singlet performed recently [Jiang, Craig, Sutherland '18] Previous partial calculations [Boggia, Gomez-Ambrosio, Passarino '16] [Ellis, Quevillon, You, Zhang '17]
- ⋆ *Work in Progress*

NEXT STEPS

⋆ Make `MatchMaker` public	Soon
⋆ Provide output in WCxf format	Soon
⋆ Include fermion/lepton/baryon violation	V2
⋆ Include parallel/cluster integration	V2/V3
⋆ Extend to other EFTs (WET/LEFT, ...)	V3

SUMMARY

- ⋆ EFTs allow for an efficient 2-step comparison between theory and experiment
- ⋆ Matching is necessary to get physics info on the UV
- ⋆ `MatchMaker` provides a robust and flexible tool to do 1- loop matching to the SMEFT (off-shell, diagrammatic)
- ⋆ Future development of `MatchMaker` will generalize to other EFTs
- ⋆ The final goal is to obtain the 1-loop UV/IR dictionary

THANKS!