ZPW2023: Recent highlights across phenomenology

Jan 11 – 13, 2023
University of Zurich

Recent progress in one-loop matching

José Santiago

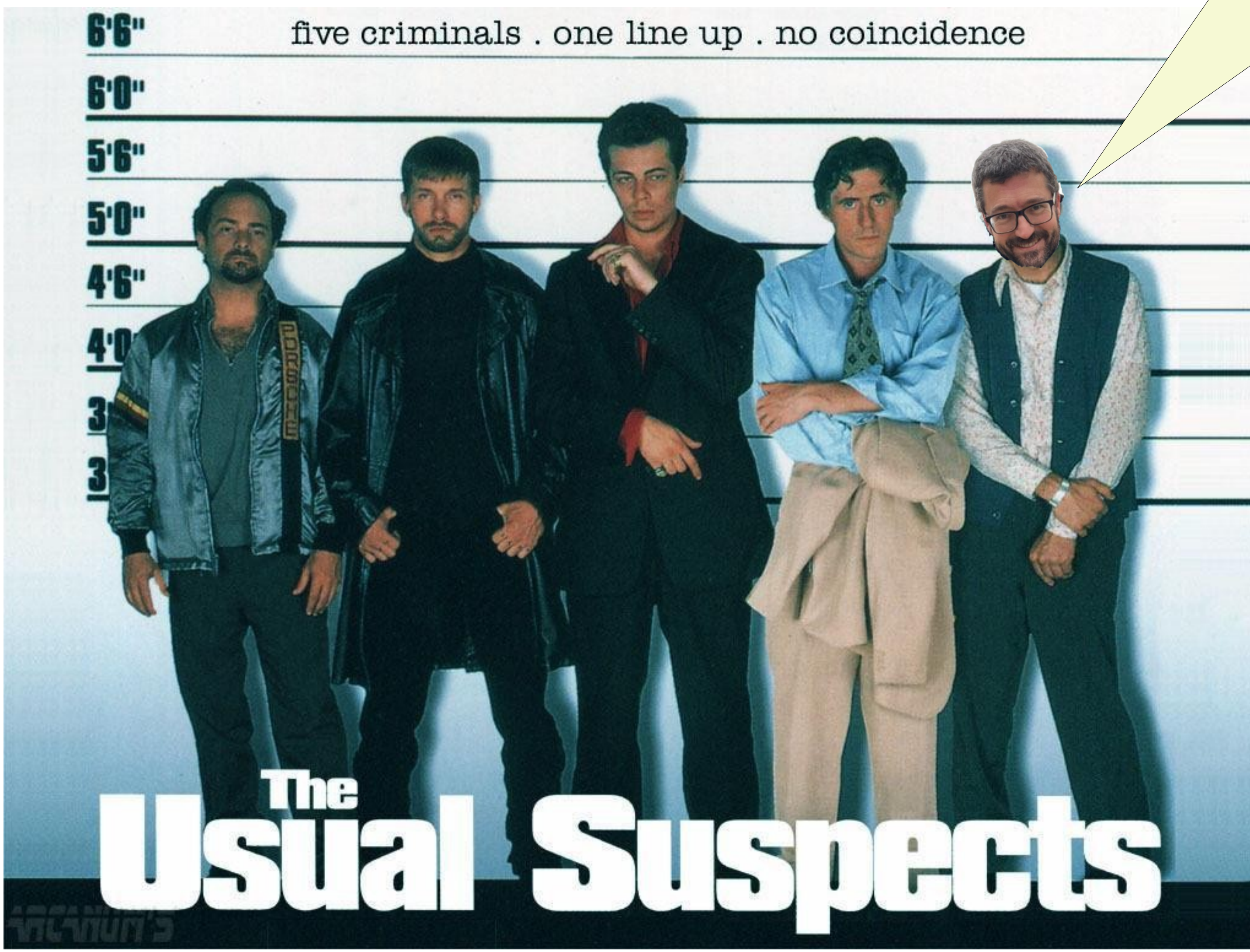
High Energy Theory

Universidad de Granada

In collaboration with: A. Carmona, M. Chala, J.C. Criado, R. Fonseca, G. Guedes, A. Lazopoulos, P. Olgoso

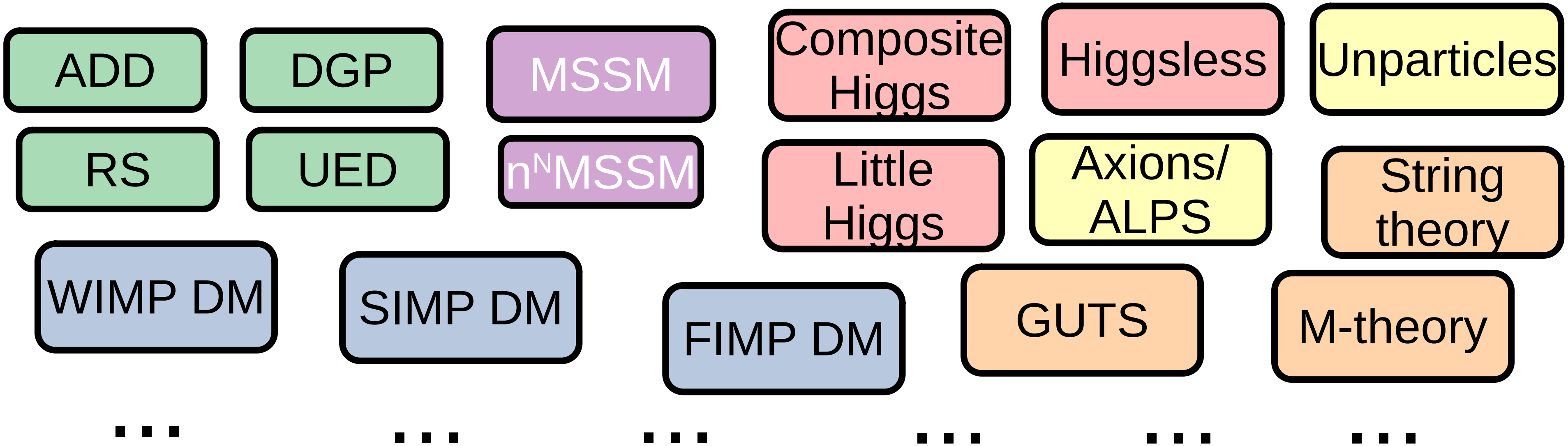
Confession

I'm (still)
a BSM guy



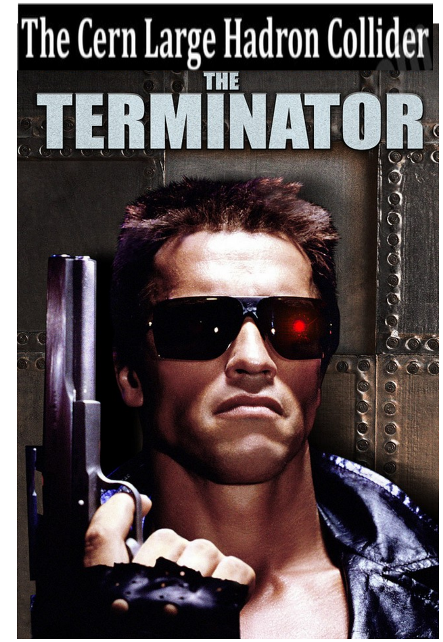
The good old times ...

- Model building (without experimental data) lead to an ever growing number of new physics models.

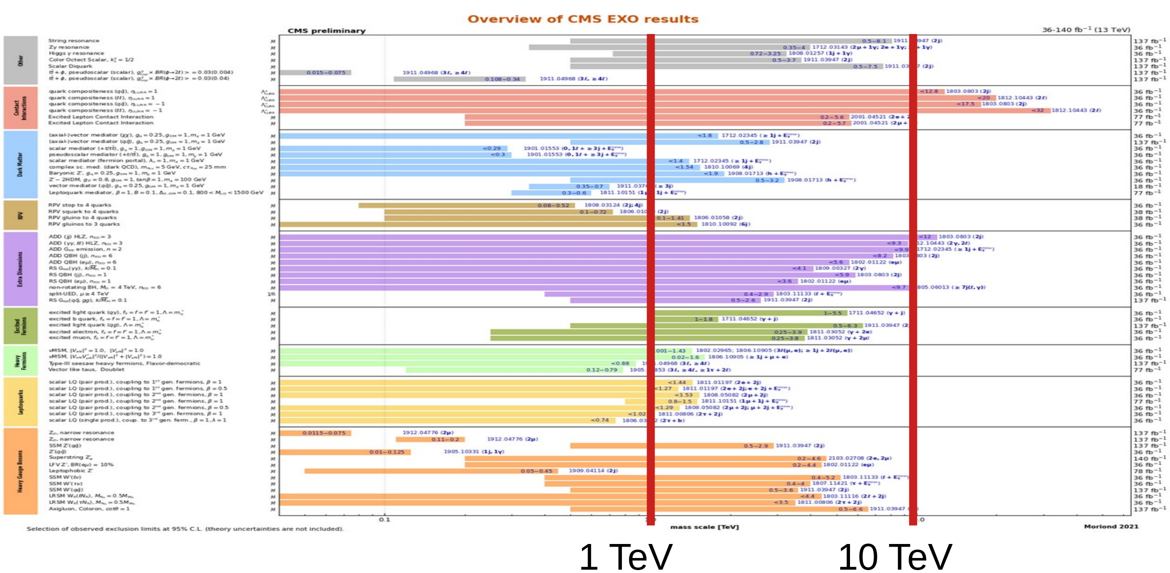


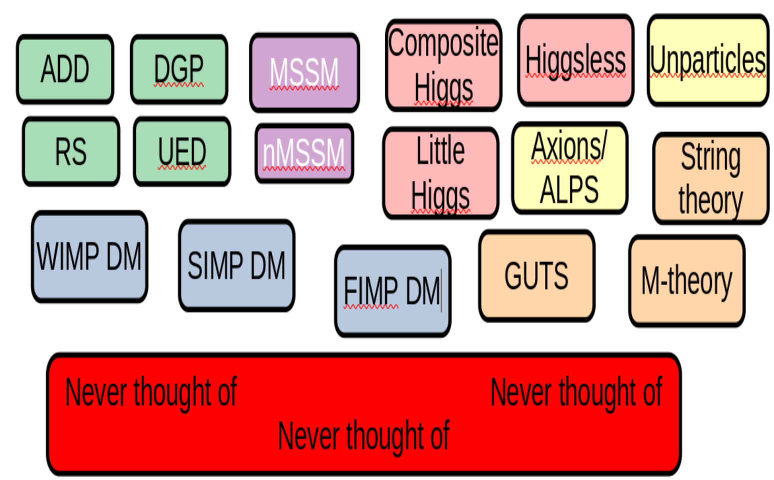
- Tree-level calculations (and MC simulations) were enough to get a state of the art estimate of their phenomenology.
- Naturalness "guaranteed" one of these models (or yet another one) would be discovered at the LHC.

An then came the LHC …



- The experimental effort (from the LHC and other experiments) has not found new physics so far.
- A multitude of experimental data puts stringent constraints on models of new physics.
- Getting the implications of experimental data on new physics models is highly non-trivial.
- And the number of new physics models is huge!





Listing new physics models

Briefing book for 2020 update of European Strategy for Particle Physics

The newly published book distils inputs from Europe's particle physics community

2 OCTOBER, 2019 | By Matthew Chalmers

Chapter 8

Beyond the Standard Model

8.1 Introduction

The search for physics Beyond the SM (BSM) is the main driver of the exploration programme in particle physics. The initial results from the LHC are already starting to mould the strategies and priorities of these searches and, as a result, the scope of the experimental programme is broadening. Growing emphasis is given to alternative scenarios and more unconventional experimental signatures where new physics could hide, having escaped traditional searches. This broader approach towards BSM physics also influences the projections for discoveries at future colliders. Rather than focusing only on a restricted number of theoretically motivated models, future prospects are studied with a signal-oriented strategy. In this chapter an attempt to reflect both viewpoints and to present a variety of possible searches is made. Since it is impossible (and probably not very useful) to give a comprehensive classification of all existing models for new physics, the choice is made to consider some representative cases which satisfy the following criteria: *(i)* they have valid theoretical motivations, *(ii)* their experimental signatures are characteristic of large classes of models, *(iii)* they allow for informative comparisons between the reach of different proposed experimental projects.

In considering the physics reach of any experimental programme, there are two key ques-

future prospects are studied with a signal-oriented strategy. In this chapter an attempt to reflect both viewpoints and to present a variety of possible searches is made. Since it is impossible (and probably not very useful) to give a comprehensive classification of all existing models for new physics, the choice is made to consider some representative cases which satisfy the following criteria: *(i)* they have valid theoretical motivations, *(ii)* their experimental signatures are

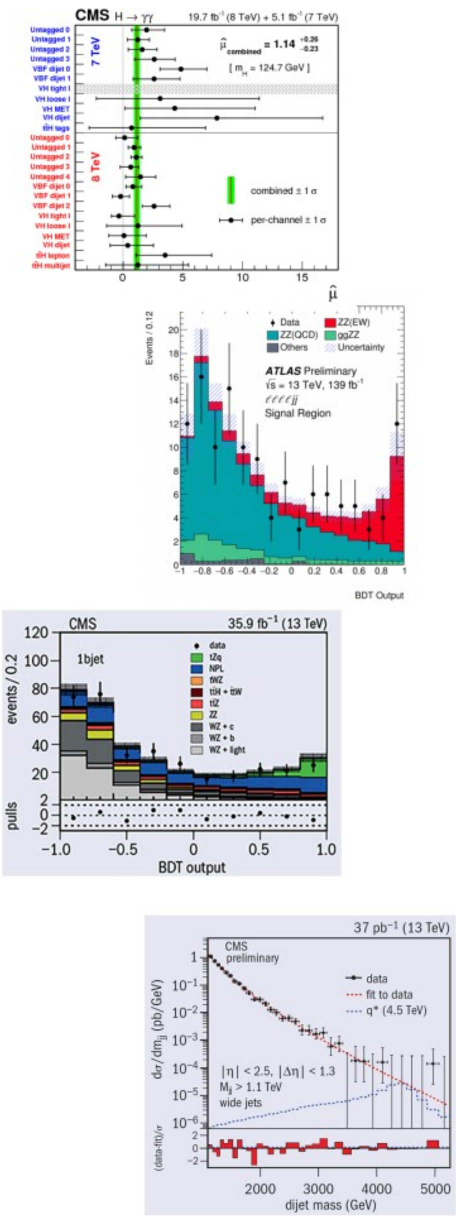
It is actually possible … using EFTs!*

*Within **weakly-coupled** theories of local fields with a **mass gap**

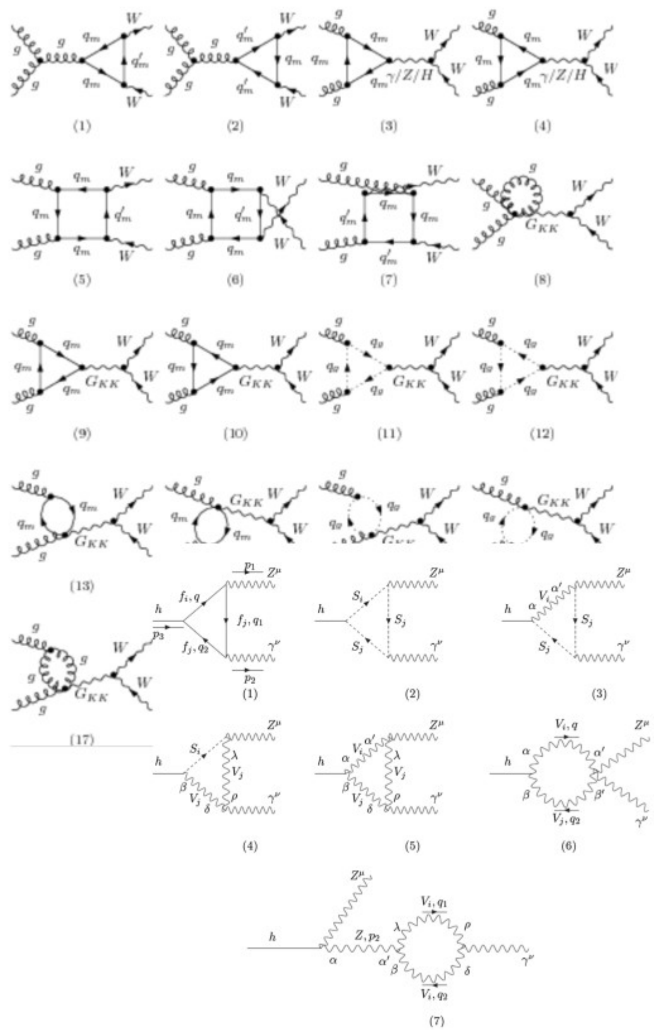
Outline

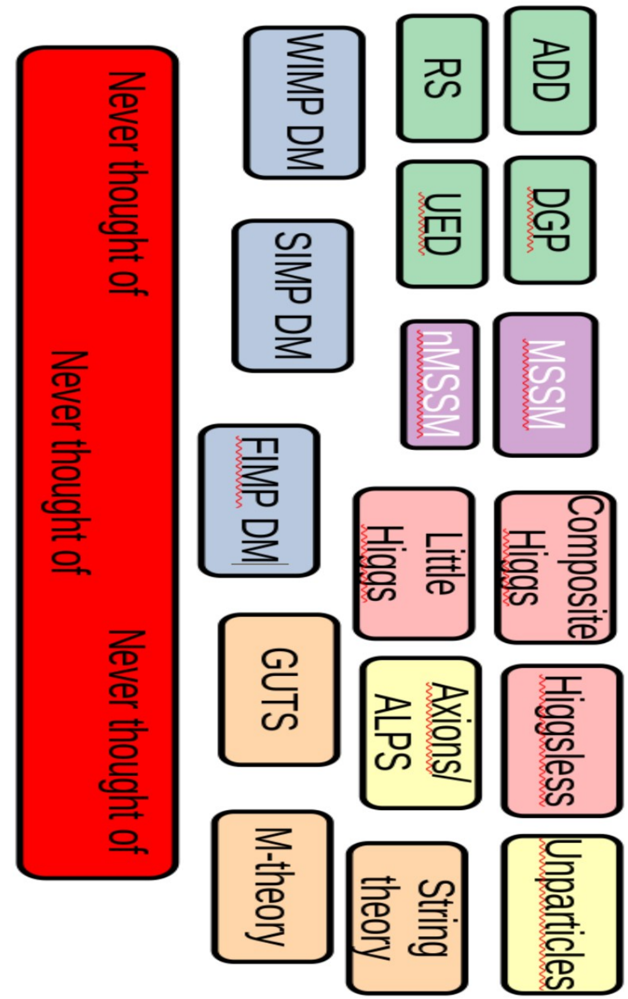
- The effective way beyond the Standard Model.
- IR/UV dictionaries to connect theory and experiment.
  - Towards the next IR/UV dictionaries.
- Recent developments:
  - On-shell matching.
  - Generation of arbitrary models.
  - Renormalization and matching of general theories.
- Conclusions and outlook.

Connecting theory and experiment

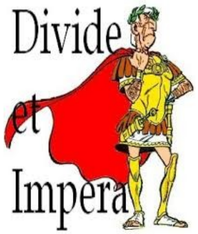


Getting implications of experimental data on new physics models is highly non trivial!





The effective way beyond the SM



EFTs allow for an efficient two-step comparison between theory and experiment:

Bottom-up: model-independent parametrization of experimental data in the form of global fits.

- Small number of models (EFTs).
- Observables computed just once.

Top-down: model discrimination (matching).

- Has to be done on a model-by-model basis.
- Can be automated and fully classified.

Top-down: connecting NP to EFTs

- The top-down approach consists on matching specific NP models to the EFT: computing the EFT Wilson coefficients in terms of the parameters of the NP model.
- We sacrifice model independence in favor of model discrimination (physics) and model completeness.
  - Computer techniques allow us to automate the matching calculations.
  - Power counting+topology makes the problem of classifying the models that contribute at a certain order solvable.
- IR/UV dictionaries tell us all possible models that can contribute to a specific experimental observable at certain order in the EFT expansion: A new, alternative guiding principle beyond naturalness.

IR/UV dictionaries

- The leading IR/UV dictionary (tree-level, dimension 6 SMEFT) was computed a few years ago. [Blas, Criado, Pérez-Victoria, Santiago '18]

Effective description of general extensions of the Standard Model: the complete tree-level dictionary

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[b] *INFN, Sezione di Padova, Via Marzolo 8, I-35131 Padova, Italy*
[c] *CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuentenueva, E-18071, Granada, Spain*
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Abstract: We compute all the tree-level contributions to the Wilson coefficients of the dimension-six Standard-Model effective theory in ultraviolet completions with general scalar, spinor and vector field content and arbitrary interactions. No assumption about the renormalizability of the high-energy theory is made. This provides a complete ultraviolet/infrared dictionary at the classical level, which can be used to study the low-energy implications of any model of interest, and also to look for explicit completions consistent with low-energy data.

JHEP03(2018)109

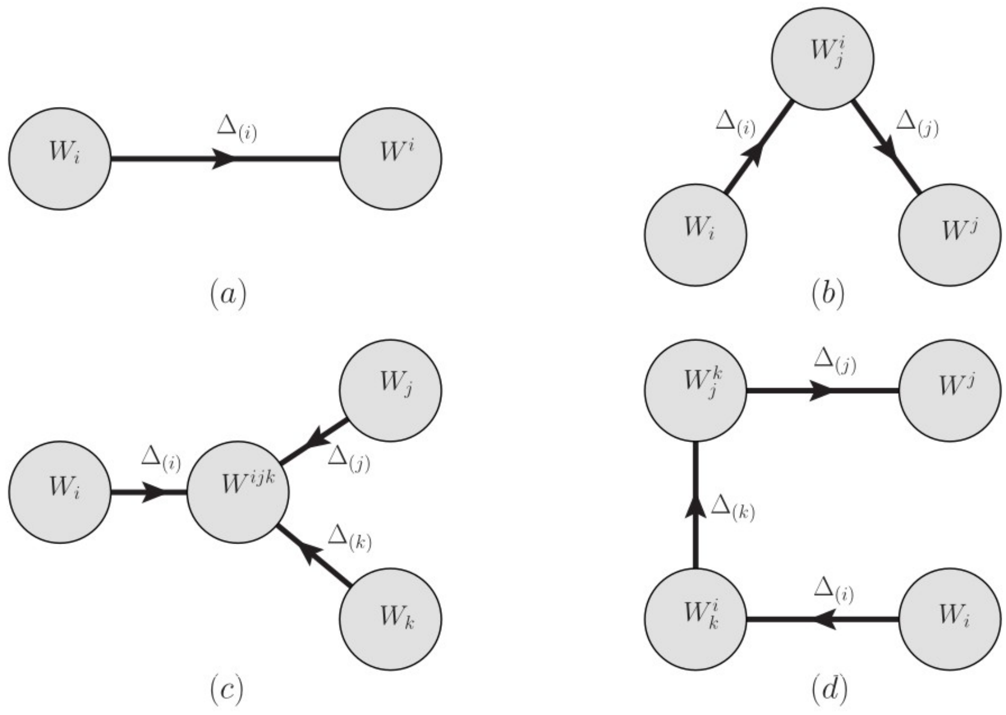
Building on previous results

Blas, Chala, Pérez-Victoria, JS '14;
Águila, Blas, Pérez-Victoria '08, '10;
Águila, Pérez-Victoria, JS '00

Results given in Warsaw basis

IR/UV dictionaries

- The leading IR/UV dictionary (tree-level, dimension 6 SMEFT) was computed a few years ago. [Blas, Criado, Pérez-Victoria, Santiago '18]
- Complete list of all possible models that contribute to experiment at tree-level and dim 6 (and their contributions).



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19 scalars

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

13 fermions

Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Table 2. New vector-like fermions contributing to the dimension-six SMEFT at tree level.

16 vectors

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Table 3. New vector bosons contributing to the dimension-six SMEFT at tree level.

48 new fields

IR/UV dictionaries

- The leading IR/UV dictionary (tree-level, dimension 6 SMEFT) was computed a few years ago. [Blas, Criado, Pérez-Victoria, Santiago '18]
- Complete list of all possible models that contribute to experiment at tree-level and dim 6 (and their contributions).

6 pages

where

$$
\begin{aligned}
-\mathcal{L}_{\rm S}^{(\leq 4)} = {} & (\kappa_{\mathcal{S}})_r \mathcal{S}_r \phi^\dagger \phi + (\lambda_{\mathcal{S}})_{rs} \mathcal{S}_r \mathcal{S}_s \phi^\dagger \phi + (\kappa_{\mathcal{S}^3})_{rst} \mathcal{S}_r \mathcal{S}_s \mathcal{S}_t \\
& + \left\{ (y_{\mathcal{S}_1})_{rij} \mathcal{S}_{1r}^\dagger \bar{l}_{Li} i\sigma_2 l^c_{Lj} + \text{h.c.} \right\} \\
& + \left\{ (y_{\mathcal{S}_2})_{rij} \mathcal{S}_{2k}^\dagger \bar{e}_{Ri} e^c_{Rj} + \text{h.c.} \right\} \\
& + \left\{ (y^e_\varphi)_{rij} \varphi_r^\dagger \bar{e}_{Ri} l_{Lj} + (y^d_\varphi)_{rij} \varphi_r^\dagger \bar{d}_{Ri} q_{Lj} + (y^u_\varphi)_{rij} \varphi_r^\dagger i\sigma_2 \bar{q}^T_{Li} u_{Rj} \right. \\
& \quad \left. + (\lambda_\varphi)_r \left(\varphi_r^\dagger \phi \right) \left(\phi^\dagger \phi \right) + \text{h.c.} \right\} \\
& + (\kappa_\Xi)_r \phi^\dagger \Xi^a_r \sigma^a \phi + (\lambda_\Xi)_{rs} \left(\Xi^a_r \Xi^a_s \right) \left(\phi^\dagger \phi \right) \\
& + \frac{1}{2} (\lambda_{\Xi_1})_{rs} \left(\Xi^{a\dagger}_{1r} \Xi^a_{1s} \right) \left(\phi^\dagger \phi \right) + \frac{1}{2} (\lambda'_{\Xi_1})_{rs} f_{abc} \left(\Xi^{a\dagger}_{1r} \Xi^b_{1s} \right) \left(\phi^\dagger \sigma^c \phi \right) \\
& + \left\{ (y_{\Xi_1})_{rij} \Xi^{a\dagger}_{1r} \bar{l}_{Li} \sigma^a i\sigma_2 l^c_{Lj} + (\kappa_{\Xi_1})_r \Xi^{a\dagger}_{1r} \left(\tilde{\phi}^\dagger \sigma^a \phi \right) + \text{h.c.} \right\} \\
& + \left\{ (\lambda_{\Theta_1})_r \left(\phi^\dagger \sigma^a \phi \right) C^I_{a\beta} \tilde{\phi}_\beta \epsilon_{IJ} \Theta^J_{1r} + \text{h.c.} \right\} \\
& + \left\{ (\lambda_{\Theta_3})_r \left(\phi^\dagger \sigma^a \tilde{\phi} \right) C^I_{a\beta} \tilde{\phi}_\beta \epsilon_{IJ} \Theta^J_{3r} + \text{h.c.} \right\} \\
& + \left\{ (y^{ql}_{\omega_1})_{rij} \omega^\dagger_{1r} \bar{q}^c_{Li} i\sigma_2 l_{Lj} + (y^{qq}_{\omega_1})_{rij} \omega^{A\dagger}_{1r} \epsilon_{ABC} \bar{q}^B_{Li} i\sigma_2 q^{cC}_{Lj} \right. \\
& \quad \left. + (y^{eu}_{\omega_1})_{rij} \omega^\dagger_{1r} \bar{e}^c_{Ri} u_{Rj} + (y^{du}_{\omega_1})_{rij} \omega^{A\dagger}_{1r} \epsilon_{ABC} \bar{d}^B_{Ri} u^{cC}_{Rj} + \text{h.c.} \right\} \\
& + \left\{ (y_{\omega_2})_{rij} \omega^{A\dagger}_{2r} \epsilon_{ABC} \bar{d}^B_{Ri} d^{cC}_{Rj} + \text{h.c.} \right\} \\
& + \left\{ (y^{ed}_{\omega_4})_{rij} \omega^{A\dagger}_{4r} \bar{e}^c_{Ri} d_{Rj} + (y^{uu}_{\omega_4})_{rij} \omega^{A\dagger}_{4r} \epsilon_{ABC} \bar{u}^B_{Ri} u^{cC}_{Rj} + \text{h.c.} \right\} \\
& + \left\{ (y_{\Pi_1})_{rij} \Pi^\dagger_{1r} i\sigma_2 \bar{l}^T_{Li} d_{Rj} + \text{h.c.} \right\} \\
& + \left\{ (y^{lu}_{\Pi_7})_{rij} \Pi^\dagger_{7r} i\sigma_2 \bar{l}^T_{Li} u_{Rj} + (y^{eq}_{\Pi_7})_{rij} \Pi^\dagger_{7r} \bar{e}_{Ri} q_{Lj} + \text{h.c.} \right\} \\
& + \left\{ (y^{ql}_\zeta)_{rij} \zeta^{a\dagger}_r \bar{q}^c_{Li} i\sigma_2 \sigma^a l_{Lj} + (y^{qq}_\zeta)_{rij} \zeta^{a\dagger}_r \epsilon_{ABC} \bar{q}^B_{Li} \sigma^a i\sigma_2 q^{cC}_{Lj} + \text{h.c.} \right\} \\
& + \left\{ (y^{ud}_{\Omega_1})_{rij} \Omega^{AB\dagger}_{1r} \bar{u}^{c(A|}_{Ri} d^{|B)}_{Rj} + (y^{qq}_{\Omega_1})_{rij} \Omega^{AB\dagger}_{1r} \bar{q}^{c(A|}_{Li} i\sigma_2 q^{|B)}_{Lj} + \text{h.c.} \right\} \\
& + \left\{ (y_{\Omega_2})_{rij} \Omega^{AB\dagger}_{2r} \bar{d}^{c(A|}_{Ri} d^{|B)}_{Rj} + \text{h.c.} \right\} \\
& + \left\{ (y_{\Omega_4})_{rij} \Omega^{AB\dagger}_{4r} \bar{u}^{c(A|}_{Ri} u^{|B)}_{Rj} + \text{h.c.} \right\} \\
& + \left\{ (y_\Upsilon)_{rij} \Upsilon^{AB\dagger}_r \bar{q}^{c(A|}_{Li} i\sigma_2 \sigma^a q^{|B)}_{Lj} + \text{h.c.} \right\} \\
& + \left\{ (y^{qu}_\Phi)_{rij} \Phi^{A\dagger}_r i\sigma_2 \bar{q}^T_{Li} T_A u_{Rj} + (y^{dq}_\Phi)_{rij} \Phi^{A\dagger}_r \bar{d}_{Ri} T_A q_{Lj} + \text{h.c.} \right\} \\
& + (\lambda_{\mathcal{S}\Xi})_{rs} \mathcal{S}_r \Xi^a_s \left(\phi^\dagger \sigma^a \phi \right) + (\kappa_{\mathcal{S}\Xi})_{rst} \mathcal{S}_r \Xi^a_s \Xi^a_t \\
& + (\kappa_{\mathcal{S}\Xi_1})_{rst} \mathcal{S}_r \Xi^{a\dagger}_{1s} \Xi^a_{1t} + \left\{ (\lambda_{\mathcal{S}\Xi_1})_{rs} \mathcal{S}_r \Xi^{a\dagger}_{1s} \left(\tilde{\phi}^\dagger \sigma^a \phi \right) + \text{h.c.} \right\} \\
& + \left\{ (\kappa_{\mathcal{S}\varphi})_{rs} \mathcal{S}_r \varphi^\dagger_s \phi + (\kappa_{\Xi\varphi})_{rs} \Xi^a_r (\varphi^\dagger_s \sigma^a \phi) + (\kappa_{\Xi_1\varphi})_{rs} \Xi^{a\dagger}_{1r} \left(\tilde{\varphi}^\dagger_s \sigma^a \phi \right) + \text{h.c.} \right\} \\
& + (\kappa_{\Xi\Xi_1})_{rst} f_{abc} \Xi^a_r \Xi^{b\dagger}_{1s} \Xi^b_{1t} + \left\{ (\lambda_{\Xi_1\Xi})_{rs} f_{abc} \Xi^{a\dagger}_{1r} \Xi^b_s \left(\tilde{\phi}^\dagger \sigma^c \phi \right) + \text{h.c.} \right\} \\
& + \left\{ (\kappa_{\Xi\Theta_1})_{rs} \Xi^a_r C^I_{a\beta} \tilde{\phi}_\beta \epsilon_{IJ} \Theta^J_{1s} + (\kappa_{\Xi_1\Theta_1})_{rs} \Xi^{a\dagger}_{1r} C^I_{a\beta} \phi_\beta \epsilon_{IJ} \Theta^J_{1s} \right. \\
& \quad \left. + (\kappa_{\Xi_1\Theta_3})_{rs} \Xi^{a\dagger}_{1r} C^I_{a\beta} \tilde{\phi}_\beta \epsilon_{IJ} \Theta^J_{3s} + \text{h.c.} \right\},
\end{aligned}
\tag{A.7}
$$

28 pages

D.4.2 $X^2\phi^2$

$$
Z_\phi C_{\phi B} = -\frac{(g_1)^2 (\gamma_{\mathcal{L}_1})^*_r (\gamma_{\mathcal{L}_1})_r}{8 M^4_{\mathcal{L}_{1r}}} - \frac{g_1 (g^B_{\mathcal{L}_1})_{rs} (\gamma_{\mathcal{L}_1})^*_r (\gamma_{\mathcal{L}_1})_s}{4 M^2_{\mathcal{L}_{1r}} M^2_{\mathcal{L}_{1s}}} + \frac{1}{f} \left\{ \frac{(\tilde{k}^B_{\mathcal{S}})_r (\kappa_{\mathcal{S}})_r}{M^2_{\mathcal{S}_r}} - \frac{\text{Im}\left((\tilde{\gamma}^B_{\mathcal{L}_1})_r (\gamma_{\mathcal{L}_1})^*_r \right) g_1}{2 M^2_{\mathcal{L}_{1r}}} \right\}, \tag{D.46}
$$

$$
Z_\phi C_{\phi \tilde{B}} = -\frac{g_1 (g^{\tilde{B}}_{\mathcal{L}_1})_{rs} (\gamma_{\mathcal{L}_1})^*_r (\gamma_{\mathcal{L}_1})_s}{4 M^2_{\mathcal{L}_{1r}} M^2_{\mathcal{L}_{1s}}} + \frac{1}{f} \left\{ \frac{(\tilde{k}^{\tilde{B}}_{\mathcal{S}})_r (\kappa_{\mathcal{S}})_r}{M^2_{\mathcal{S}_r}} - \frac{\text{Im}\left((\tilde{\gamma}^{\tilde{B}}_{\mathcal{L}_1})_r (\gamma_{\mathcal{L}_1})^*_r \right) g_1}{2 M^2_{\mathcal{L}_{1r}}} \right\}, \tag{D.47}
$$

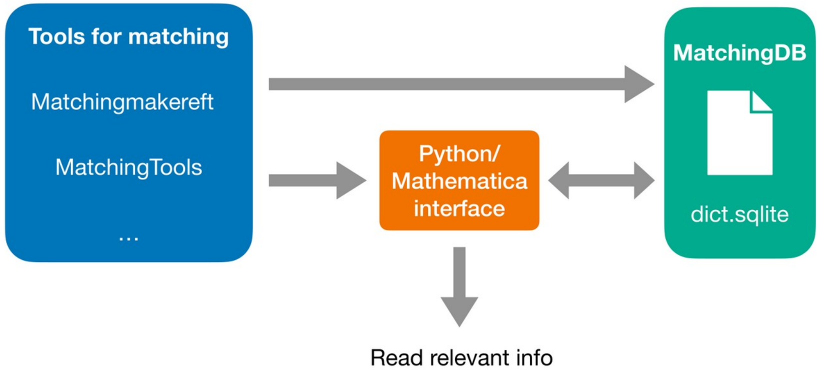
$$
Z_\phi C_{\phi W} = -\frac{(g_2)^2 (\gamma_{\mathcal{L}_1})^*_r (\gamma_{\mathcal{L}_1})_r}{8 M^4_{\mathcal{L}_{1r}}} - \frac{g_2 (g^W_{\mathcal{L}_1})_{rs} (\gamma_{\mathcal{L}_1})^*_r (\gamma_{\mathcal{L}_1})_s}{4 M^2_{\mathcal{L}_{1r}} M^2_{\mathcal{L}_{1s}}} + \frac{1}{f} \left\{ \frac{(\tilde{k}^W_{\mathcal{S}})_r (\kappa_{\mathcal{S}})_r}{M^2_{\mathcal{S}_r}} - \frac{\text{Im}\left((\tilde{\gamma}^W_{\mathcal{L}_1})_r (\gamma_{\mathcal{L}_1})^*_r \right) g_2}{2 M^2_{\mathcal{L}_{1r}}} \right\}, \tag{D.48}
$$

$$
Z_\phi C_{\phi \tilde{W}} = -\frac{g_2 (g^{\tilde{W}}_{\mathcal{L}_1})_{rs} (\gamma_{\mathcal{L}_1})^*_r (\gamma_{\mathcal{L}_1})_s}{4 M^2_{\mathcal{L}_{1r}} M^2_{\mathcal{L}_{1s}}} + \frac{1}{f} \left\{ \frac{(\tilde{k}^{\tilde{W}}_{\mathcal{S}})_r (\kappa_{\mathcal{S}})_r}{M^2_{\mathcal{S}_r}} - \frac{\text{Im}\left((\tilde{\gamma}^{\tilde{W}}_{\mathcal{L}_1})_r (\gamma_{\mathcal{L}_1})^*_r \right) g_2}{2 M^2_{\mathcal{L}_{1r}}} \right\}, \tag{D.49}
$$

$$
Z_\phi C_{\phi WB} = -\frac{g_1 g_2 (\gamma_{\mathcal{L}_1})^*_r (\gamma_{\mathcal{L}_1})_r}{4 M^4_{\mathcal{L}_{1r}}} - \frac{g_2 (g^B_{\mathcal{L}_1})_{rs} (\gamma_{\mathcal{L}_1})^*_r (\gamma_{\mathcal{L}_1})_s}{4 M^2_{\mathcal{L}_{1r}} M^2_{\mathcal{L}_{1s}}} - \frac{g_1 (g^W_{\mathcal{L}_1})_{rs} (\gamma_{\mathcal{L}_1})^*_r (\gamma_{\mathcal{L}_1})_s}{4 M^2_{\mathcal{L}_{1r}} M^2_{\mathcal{L}_{1s}}} + \frac{1}{f} \left\{ \frac{(\tilde{k}^{WB}_{\Xi})_r (\kappa_{\Xi})_r}{M^2_{\Xi_r}} - \frac{\text{Im}\left((\tilde{\gamma}^B_{\mathcal{L}_1})_r (\gamma_{\mathcal{L}_1})^*_r \right) g_2}{2 M^2_{\mathcal{L}_{1r}}} - \frac{\text{Im}\left((\tilde{\gamma}^W_{\mathcal{L}_1})_r (\gamma_{\mathcal{L}_1})^*_r \right) g_1}{2 M^2_{\mathcal{L}_{1r}}} \right\}, \tag{D.50}
$$

IR/UV dictionaries

- The leading IR/UV dictionary (tree-level, dimension 6 SMEFT) was computed a few years ago. [Blas, Criado, Pérez-Victoria, Santiago '18]
- Complete list of all possible models that contribute to experiment at tree-level and dim 6 (and their contributions).
- Tree-level and dimension 6 is not enough for current experimental precision. Going beyond requires automation.
- The next (tree-level dimension 8 or 1-loop dimension 6) dictionaries will need to be published in electronic form. We are working on a standard database format to store them [with J.C. Criado]



gitlab.com/jccriado/matchingdb

Automated matching with MME

The Zürich Precision Workshop 2016: Higgs Physics at the LHC

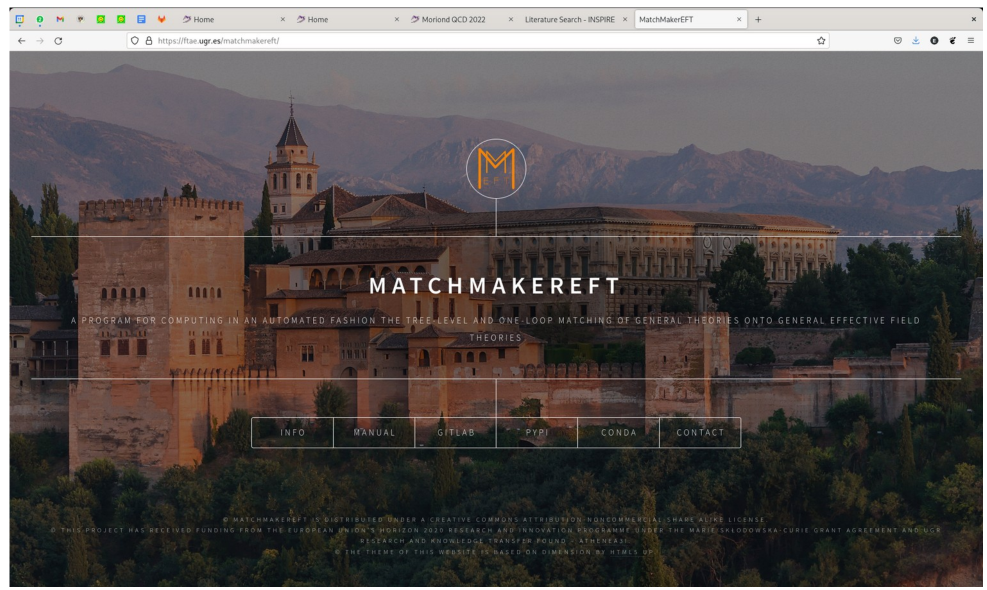
MatchMaker: automated matching in effective theories C. Anastasiou, A. Lazopoulos, J.S., in progress

- Status:
  - First version: SM effective Lagrangian
    - Bosonic operators: finished
    - Two-fermion operators: almost finished
    - Four-fermion operators: in progress
- Expected time-line:
  - First complete version: spring 2016
  - First public version: summer 2016
  - Second version with extended matching: end 2016

Matchmakereft: automated tree-level and one-loop matching

Adrián Carmona[a,b], Achilleas Lazopoulos[b], Pablo Olgoso[a] and José Santiago[a]

https://ftae.ugr.es/matchmakereft/



Xiv:2112.10787v1 [hep-ph] 20 Dec 2021

Matchmakereft: automated tree-level and one-loop matching

Adrián Carmona[a,b], Achilleas Lazopoulos[b], Pablo Olgoso[a] and José Santiago[a]

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Abstract

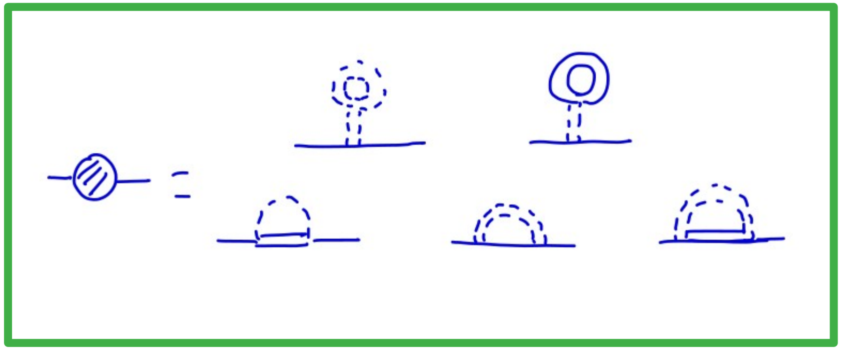
We introduce matchmakereft, a fully automated tool to compute the tree-level and one-loop matching of arbitrary models onto arbitrary effective theories. Matchmakereft performs an off-shell matching, using diagrammatic methods and the BFM when gauge theories are involved. The large redundancy inherent to the off-shell matching together with explicit gauge invariance offers a significant number of non-trivial checks of the results provided. These results are given in the physical basis but several intermediate results, including the matching in the Green basis before and after canonical normalization, are given for flexibility and the possibility of further cross-checks. As a non-trivial example we provide the complete matching in the Warsaw basis up to one loop of an extension of the Standard Model with a charge −1 vector-like lepton singlet. Matchmakereft has been built with generality, flexibility and efficiency in mind. These ingredients allow matchmakereft to

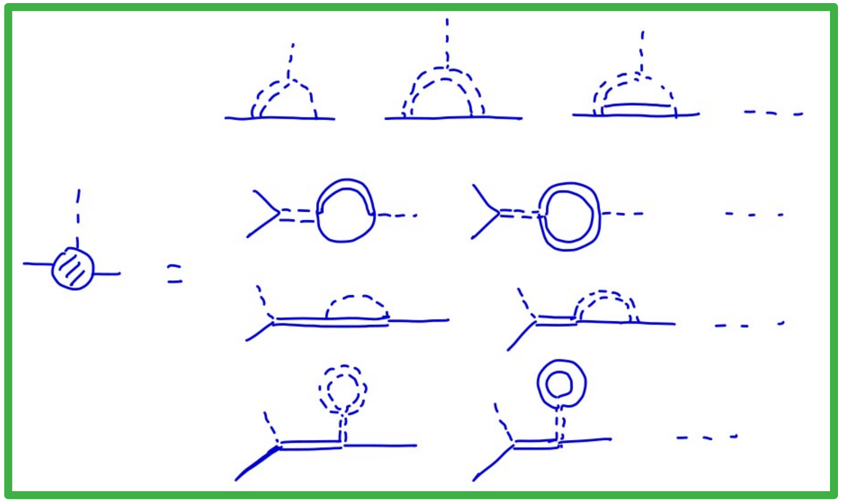
– Also RGEs, operator independence, ...

Towards the next IR/UV dictionaries

Preliminary!

- We are working on the one-loop, dimension-6 IR/UV dictionary [with G. Guedes and P. Olgoso]. see also [Cepedello, Esser, Hirsch, Sanz 2207.13714]
  - We have started with operators that cannot be generated at tree level in weakly-coupled extensions $[X^3, X^2\phi^2, \psi^2 X\phi]$, with heavy scalars and fermions [heavy vectors currently under study with J. Fuentes-Martín, P. Olgoso, A.E. Thomsen] and renormalizable interactions.
    - Extend the SMEFT with heavy fields in arbitrary gauge configurations.
    - Just need 2 and 3 point functions (plus gauge boson insertions).





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    - Extend the SMEFT with heavy fields in arbitrary gauge configurations.
    - Just need 2 and 3 point functions (plus gauge boson insertions).
    - Perform the matching with MME using the kinematics but leave gauge directions general [MME is very well suited for this task: matching from EFT, gauge numerics replaced only at the end of the calculation].
    - Result for specific models can be obtained doing a simple group-theoretical calculation [we use GroupMath by R. Fonseca].

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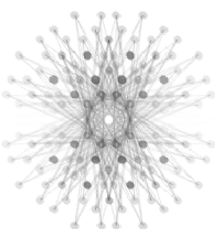
In[∘]:= << OneLoopDictionary`

One Loop Dictionary loaded
Version: 0.0.1
Authors: Guilherme Guedes, Pablo Olgoso, José Santiago
Reference: _____



```
XXXXXXXXXXXXXXXXXXXXXXXXXXX GroupMath XXXXXXXXXXXXXXXXXXXXXXXXXXX
Version: 1.1.2 (6/May/2020)
Author: Renato Fonseca
Reference: 2011.01764 [hep-th]
Website: renatofonseca.net/groupmath
Built-in documentation: here
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

In[∘]:= OneLoopOperatorsGrid

Out[∘]=

$\mathcal{O}_{3G}$	$\mathcal{O}_{3\widetilde{G}}$	$\mathcal{O}_{3W}$	$\mathcal{O}_{3\widetilde{W}}$	$\mathcal{O}_{HG}$
$\mathcal{O}_{H\widetilde{G}}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{H\widetilde{W}}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{H\widetilde{B}}$
$\mathcal{O}_{HWB}$	$\mathcal{O}_{H\widetilde{W}B}$	$\mathcal{O}_{uG}$	$\mathcal{O}_{uW}$	$\mathcal{O}_{uB}$
$\mathcal{O}_{dG}$	$\mathcal{O}_{dW}$	$\mathcal{O}_{dB}$	$\mathcal{O}_{eW}$	$\mathcal{O}_{eB}$

$\widetilde{B}_{\mu\nu}B^{\mu\nu}(H^\dagger H)$

In[34]:=

ListModelsWarsaw[alphaOeW[i, j]] // TableForm

Out[34]//TableForm=

$\phi1 \to \mathbf{1}\otimes\mathbf{2}$	$\psi1 \to \mathbf{1}\otimes\mathbf{1}$	$Y_{\phi1} \to \frac{1}{2}$, $Y_{\psi1} \to 0$		
$\phi1 \to \mathbf{1}\otimes\mathbf{2}$	$\psi1 \to \mathbf{1}\otimes\mathbf{3}$	$Y_{\phi1} \to \frac{1}{2}$, $Y_{\psi1} \to 0$		
$\psi2 == \phi1$	$\phi1\otimes\overline{\phi1} \supset \mathbf{1}\otimes\mathbf{3}$	$\psi1\otimes\phi1 \supset \mathbf{1}\otimes\mathbf{2}$	$\psi1\otimes\overline{\phi1} \supset \mathbf{1}\otimes\mathbf{2}$	$Y_{\psi1} \to -\frac{1}{2} + Y_{\phi1}$, $Y_{\psi2} \to -1 + Y_{\phi1}$
$\phi1 \to \mathbf{1}\otimes\mathbf{2}$	$\psi1 \to \overline{\mathbf{3}}\otimes\mathbf{1}$	$Y_{\phi1} \to -\frac{1}{2}$, $Y_{\psi1} \to \frac{2}{3}$		
$\phi1 \to \mathbf{1}\otimes\mathbf{2}$	$\psi1 \to \overline{\mathbf{3}}\otimes\mathbf{3}$	$Y_{\phi1} \to -\frac{1}{2}$, $Y_{\psi1} \to \frac{2}{3}$		
$\phi1 \to \mathbf{1}\otimes\mathbf{2}$	$\psi1 \to \overline{\mathbf{3}}\otimes\mathbf{1}$	$Y_{\phi1} \to -\frac{1}{2}$, $Y_{\psi1} \to -\frac{1}{3}$		
$\phi1 \to \mathbf{1}\otimes\mathbf{2}$	$\psi1 \to \overline{\mathbf{3}}\otimes\mathbf{3}$	$Y_{\phi1} \to -\frac{1}{2}$		

ListValidQNs[{ψ2 == ϕ1, ϕ1⊗$\overline{\phi1}$ ⊃ "1"⊗"3", ψ1⊗ϕ1 ⊃ "1"⊗"2", ψ1⊗$\overline{\phi1}$ ⊃ "1"⊗"2", {$Y_{\psi1} \to -\frac{1}{2} + Y_{\phi1}$, $Y_{\psi2} \to -1 + Y_{\phi1}$}}]

{{$\phi1 \to \mathbf{1}\otimes\mathbf{2}$, $\psi1 \to \mathbf{1}\otimes\mathbf{1}$}, {$\phi1 \to \mathbf{1}\otimes\mathbf{2}$, $\psi1 \to \mathbf{1}\otimes\mathbf{3}$},
{$\phi1 \to \mathbf{1}\otimes\mathbf{3}$, $\psi1 \to \mathbf{1}\otimes\mathbf{2}$}, {$\phi1 \to \mathbf{1}\otimes\mathbf{3}$, $\psi1 \to \mathbf{1}\otimes\mathbf{4}$},
{$\phi1 \to \mathbf{1}\otimes\mathbf{4}$, $\psi1 \to \mathbf{1}\otimes\mathbf{3}$}, {$\phi1 \to \mathbf{1}\otimes\mathbf{4}$, $\psi1 \to \mathbf{1}\otimes\mathbf{5}$},
{$\phi1 \to \mathbf{1}\otimes\mathbf{5}$, $\psi1 \to \mathbf{1}\otimes\mathbf{4}$}, {$\phi1 \to \mathbf{8}\otimes\mathbf{2}$, $\psi1 \to \mathbf{8}\otimes\mathbf{1}$},
{$\phi1 \to \mathbf{8}\otimes\mathbf{2}$, $\psi1 \to \mathbf{8}\otimes\mathbf{3}$}, {$\phi1 \to \mathbf{8}\otimes\mathbf{3}$, $\psi1 \to \mathbf{8}\otimes\mathbf{2}$},
{$\phi1 \to \mathbf{8}\otimes\mathbf{3}$, $\psi1 \to \mathbf{8}\otimes\mathbf{4}$}, {$\phi1 \to \mathbf{8}\otimes\mathbf{4}$, $\psi1 \to \mathbf{8}\otimes\mathbf{3}$},
{$\phi1 \to \mathbf{8}\otimes\mathbf{4}$, $\psi1 \to \mathbf{8}\otimes\mathbf{5}$}, {$\phi1 \to \mathbf{8}\otimes\mathbf{5}$, $\psi1 \to \mathbf{8}\otimes\mathbf{4}$}}

Towards the next IR/UV dictionaries

Preliminary!

- We are working on the one-loop, dimension-6 IR/UV dictionary [with G. Guedes and P. Olgoso].

```
Print["αeB[i,j]=",
 Simplify[
  Match2Warsaw[alphaOeB[i, j], {Fa → {1, 1, -1}, Sa → {1, 1, 0}}] /.
     Log[a_] → Log[a / μ^2] /. μ → MSa /. iCPV^2 → 1 /. FourPi → 4 Pi]]
```

$$\alpha_{eB}[i,j]=\frac{1}{384\,\mathrm{MFa}^3\,\pi^2}\,\mathrm{g1}\left(\frac{1}{(\mathrm{MFa}^2-\mathrm{MSa}^2)^4}\mathrm{L1}[\mathrm{eR},\mathrm{minus},\mathrm{Fa},\mathrm{Sa}][\mathrm{j}]\right.$$
$$\left(\mathrm{MFa}^3\left(\mathrm{MFa}^6-6\,\mathrm{MFa}^4\,\mathrm{MSa}^2+3\,\mathrm{MFa}^2\,\mathrm{MSa}^4+2\,\mathrm{MSa}^6+6\,\mathrm{MFa}^2\,\mathrm{MSa}^4\,\mathrm{Log}\left[\frac{\mathrm{MFa}^2}{\mathrm{MSa}^2}\right]\right)\right.$$
$$\mathrm{L1}[\mathrm{minus},\mathrm{eR},\mathrm{Fa},\mathrm{Sa}][\mathrm{mif3}]\times\mathrm{L1}[\mathrm{minus},\mathrm{lL},\mathrm{eR},\mathrm{phi}][\mathrm{i},\mathrm{mif3}]-$$
$$3\left(\mathrm{MFa}^2-\mathrm{MSa}^2\right)\left(-12\left(\mathrm{MFa}^2-\mathrm{MSa}^2\right)^3\mathrm{L1}[\mathrm{Sa},\mathrm{Sa},\mathrm{Sa}]+\mathrm{MFa}^2\right.$$
$$\left(2\,\mathrm{MFa}\,\mathrm{L1}[\mathrm{minus},\mathrm{Fa},\mathrm{Fa},\mathrm{Sa},\mathrm{SIX}]\left(\mathrm{MFa}^4-4\,\mathrm{MFa}^2\,\mathrm{MSa}^2+3\,\mathrm{MSa}^4+2\,\mathrm{MSa}^4\,\mathrm{Log}\left[\frac{\mathrm{MFa}^2}{\mathrm{MSa}^2}\right]\right)+\right.$$
$$\mathrm{L1}[\mathrm{phi},\mathrm{minus},\mathrm{phi},\mathrm{Sa}]\left(\mathrm{MFa}^4+2\,\mathrm{MFa}^2\,\mathrm{MSa}^2-3\,\mathrm{MSa}^4+\right.$$
$$\left.\left.\left.\left(\mathrm{MFa}^4-5\,\mathrm{MFa}^2\,\mathrm{MSa}^2\right)\mathrm{Log}\left[\frac{\mathrm{MFa}^2}{\mathrm{MSa}^2}\right]\right)\right)\right)\mathrm{L1}[\mathrm{minus},\mathrm{lL},\mathrm{Fa},\mathrm{phi}][\mathrm{i}]\Big)+$$
$$2\,\mathrm{MFa}\,\mathrm{L1}[\mathrm{minus},\mathrm{lL},\mathrm{eR},\mathrm{phi}][\mathrm{mif3},\mathrm{j}]\times\mathrm{L1}[\mathrm{minus},\mathrm{lL},\mathrm{Fa},\mathrm{phi}][\mathrm{i}]\times$$
$$\left.\mathrm{L1}[\mathrm{minus},\mathrm{Fa},\mathrm{lL},\mathrm{minus},\mathrm{phi}][\mathrm{mif3}]\right)$$

Towards the next IR/UV dictionaries

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- We are working on the one-loop, dimension-6 IR/UV dictionary [with G. Guedes and P. Olgoso].

```
αeB[i,j]->{Sa.Sa.Sa L1[Sa, Sa, Sa] × T[1][Sa, Sa, Sa] +
   eR.F̄a.Sa L1[eR, minus, Fa, Sa] × T[1][eR, minus, Fa, Sa] +
   F̄a.PL.Fa.Sa L1[minus, Fa, Fa, Sa, SEVEN] × T[1][minus, Fa, Fa, Sa] +
   F̄a.PR.Fa.Sa L1[minus, Fa, Fa, Sa, SIX] × T[1][minus, Fa, Fa, Sa] +
   phi.phi†.Sa L1[phi, minus, phi, Sa] × T[1][phi, minus, phi, Sa],
  {T[1][Sa, Sa, Sa] → {{{{1}}}, {{{1}}}}, T[1][phi, minus, phi, Sa] →
    {{{{1}}}, {{{1}, {0}}, {{0}, {1}}}}, T[1][minus, Fa, Fa, Sa] → {{{{1}}}, {{{1}}}},
   T[1][minus, Fa, Fa, Sa] → {{{{1}}}, {{{1}}}}, T[1][eR, minus, Fa, Sa] → {{{{1}}}, {{{1}}}}}}
```

- We will also provide a function to automatically generate Matchmakereft models for specific choices of field quantum numbers to perform the complete one-loop matching.

On-shell matching

Preliminary!

- Off-shell matching is very efficient:
  - Small(ish) number of diagrams (1lPI).
  - Hard region contribution directly local, many cross-checks.
- But requires the construction and reduction of a Green basis.
- On-shell matching can be done in terms of a Physical basis but:
  - There are many diagrams contributing (light bridges have to be included).
  - There is a delicate cancellation of non-local contributions between UV and EFT that is non-trivial to follow analytically.
- Our solution [with M. Chala]:
  - We rely on QGRAF (very efficient even for a large number of diagrams).
  - We do kinematics numerically (trivial cancellation of non-local terms).
  - We stick to tree level.

On-shell matching

Preliminary!

- Tree level on-shell matching of the Green basis to the physical basis provides a simple reduction (which has to be done only once, for the EFT at the end of the chain of EFTs across thresholds), including higher order terms.

- Simplest example: a real scalar to dimension 8 (Z2 symmetric)

$$\mathcal{L}_{IR} = -\frac{1}{2}s(\partial^2 + m^2)s - \lambda s^4 + \alpha_{61}s^6 + \alpha_{81}s^8 + \alpha_{82}s^2(\partial_\mu\partial_\nu s)^2$$

$$\mathcal{L}_{UV} = -\frac{1}{2}s(\partial^2 + m^2)s - \lambda s^4 + \alpha_{61}s^6 + \beta_{61}(\partial^2 s)^2 + \beta_{62}s^3\partial^2 s$$

$$+\alpha_{81}s^8 + \alpha_{82}s^2(\partial_\mu\partial_\nu s)^2 + \beta_{81}s\partial^2\partial^2\partial^2 s + \beta_{82}s^3\partial^2\partial^2 s$$

$$+\beta_{83}s^2(\partial^2 s)^2 + \beta_{84}s^5\partial^2 s$$

On-shell matching

Preliminary!

- Simplest example: a real scalar to dimension 8 (Z2 symmetric)
  - Corrections to the 2-point function have to be carefully included in the UV theory

$$m_{\text{phys}}^2 = m^2 - 2\beta_{61}m^4 + 2(\beta_{81} + 4\beta_{61}^2)m^6 + \dots$$

$$\sqrt{Z} = 1 - 2\beta_{12}m^2 + (3\beta_{81} + 10\beta_{61}^2)m^4 + \dots$$

  - Connected, amputated amplitudes have to be computed with full propagators, $\sqrt{Z}$ factors and $p_i^2 = m_{\text{phys}}^2$

$$\alpha_{61} \to \alpha_{61} + 16\lambda^2\beta_{61} - 4\lambda\beta_{62} + m^2\Big[-\frac{304}{5}\lambda^4\beta_{81} + \frac{65}{5}\lambda\beta_{82} + 8\lambda\beta_{83} - \beta_{84} - 12\alpha_{61}\beta_{61} - \frac{1728}{5}\lambda^2\beta_{61}^2 - \frac{22}{5}\beta_{62}^2 + \frac{512}{5}\lambda\beta_{61}\beta_{62}\Big]$$

$$\alpha_{81} \to \alpha_{81} - \frac{576}{2}\lambda^3\beta_{81} + 6\alpha_{61}\beta_{62} + \dots$$

Automatic basis generation

Preliminary!

- Producing a Green basis is non-trivial.

  [Buchmuller, Wyller '86]
  [Grzadkowski, Iskrzynski, Misiak, Rosiek 1008.4884]
  [Gherardi, Marzocca, Venturini 2003.12525]

  } SMEFT at dim 6

- Tools can help us do that in an automated (and error-free) way.
- Why not do the calculation once and for all? [with R. Fonseca, P. Olgoso].
  - Write down a generic EFT up to dimension 6 [with Sym2Int].
  - Compute its RGEs [using Matchmakereft].
  - The result is valid for arbitrary EFTs (only the group theory remains to be done).

- The next step is to compute the finite matching [with R. Fonseca, G. Guedes and P. Olgoso].

RGEs of general EFTs

Preliminary!

- Build the most general EFT using Sym2Int.

$$\mathscr{L}_{d\leq 4} = -\frac{1}{4}(a_{KF})_{AB}F^A_{\mu\nu}F^{B\,\mu\nu} + \frac{1}{2}(a_{K\phi})_{ab}D_\mu\phi_a D^\mu\phi_b + (a_{K\psi})_{ij}\bar{\psi}_i \mathrm{i}\not{D}\psi_j - \frac{1}{2}\Big[(m_f)_{ij}\psi_i^T C\psi_j + \text{h.c.}\Big]$$
$$- \frac{1}{2}(m_\phi^2)_{ab}\phi_a\phi_b - \frac{1}{2}\Big[Y_{ija}\psi_i^T C\psi_j + \text{h.c.}\Big]\phi_a - \frac{\kappa_{abc}}{3!}\phi_a\phi_b\phi_c - \frac{\lambda_{abcd}}{4!}\phi_a\phi_b\phi_c\phi_d,$$

$$\mathscr{L}_5^{\text{phys}} = \Big[\frac{1}{2}\big(a^{(5)}_{\psi F}\big)_{Aij}\psi_i^T C\sigma^{\mu\nu}\psi_j F^A_{\mu\nu} + \frac{1}{4}\big(a^{(5)}_{\psi\phi^2}\big)_{ijab}\psi_i^T C\psi_j\phi_a\phi_b + \text{h.c.}\Big]$$
$$+ \frac{1}{2}\big(a^{(5)}_{\phi F}\big)_{ABa}F^{A\,\mu\nu}F^B_{\mu\nu}\phi_a + \frac{1}{2}\big(a^{(5)}_{\phi\widetilde{F}}\big)_{ABa}F^{A\,\mu\nu}\widetilde{F}^B_{\mu\nu}\phi_a + \frac{1}{5!}\big(a^{(5)}_{\phi}\big)_{abcde}\phi_a\phi_b\phi_c\phi_d\phi_e,$$
$$\mathscr{L}_5^{\text{red}} = \frac{1}{2}\big(r^{(5)}_{\phi\Box}\big)_{abc}(D_\mu D^\mu\phi_a)\phi_b\phi_c + \Big[\frac{1}{2}\big(r^{(5)}_{\psi}\big)_{ij}(D_\mu\psi_i)^T C D^\mu\psi_j + \big(r^{(5)}_{\psi\phi}\big)_{ija}\bar{\psi}_i\mathrm{i}\not{D}\psi_j\phi_a + \text{h.c.}\Big],$$

- Compute its beta functions using MME.

$$\big(\dot{a}^{(5)}_{\phi\widetilde{F}}\big)_{ABa} = -2g^2\theta^C_{ab}\theta^C_{bc}\big(a^{(5)}_{\phi\widetilde{F}}\big)_{ABc} - 2g^2\Big\{\Big[\frac{11}{6}f^{CDB}f^{CDE} - \frac{1}{12}\theta^B_{bc}\theta^E_{cb} - \frac{1}{3}t^B_{ij}t^E_{ji}\Big]\big(a^{(5)}_{\phi\widetilde{F}}\big)_{AEa} + (A\leftrightarrow B)\Big\}$$
$$+ 2\mathrm{i}g\Big[\big(a^{(5)}_{\psi F}\big)_{Aij}t^B_{jk}\bar{Y}^a_{ki} - \big[\big(a^{(5)}_{\psi F}\big)_{Aij}\big]^* t^B_{kj}Y^a_{ki} + (A\leftrightarrow B)\Big] + \frac{1}{2}\big(a^{(5)}_{\phi\widetilde{F}}\big)_{ABc}\mathrm{Tr}[Y^c\bar{Y}^a + Y^a\bar{Y}^c],$$

- Only a straight-forward group theory calculation remains for any specific model.

Conclusions and outlook

- The effective approach is well supported by experimental data and extremely powerful:
  - IR/UV dictionaries allow us to study new physics in a systematic and comprehensive way.
  - Automated generation of models, on-shell matching, automated finite matching and RGE calculation, global likelihoods, ... all make the dream of a one-keystroke calculation of phenomenological implications of any new physics model feasible.
- The way ahead: renormalization and matching of arbitrary (effective) theories.
  - Do all calculations for a generic gauge configuration.
  - Results for specific models require just a simple group-theoretical calculation.

Zurich, a great place to do physics … and good friends

ETHZ Postdoc (2007-2009)

Visit to Granada (2011)

Sabbatical at ETHZ (2015)

Big thanks to the organizers!

keep up the amazing work!