La Thuile 2023 - Les Rencontres de Physique de la Vallée d'Aoste

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Planibel Hotel
Europe/Rome timezone

Automated one-loop matching for physics beyond the Standard Model

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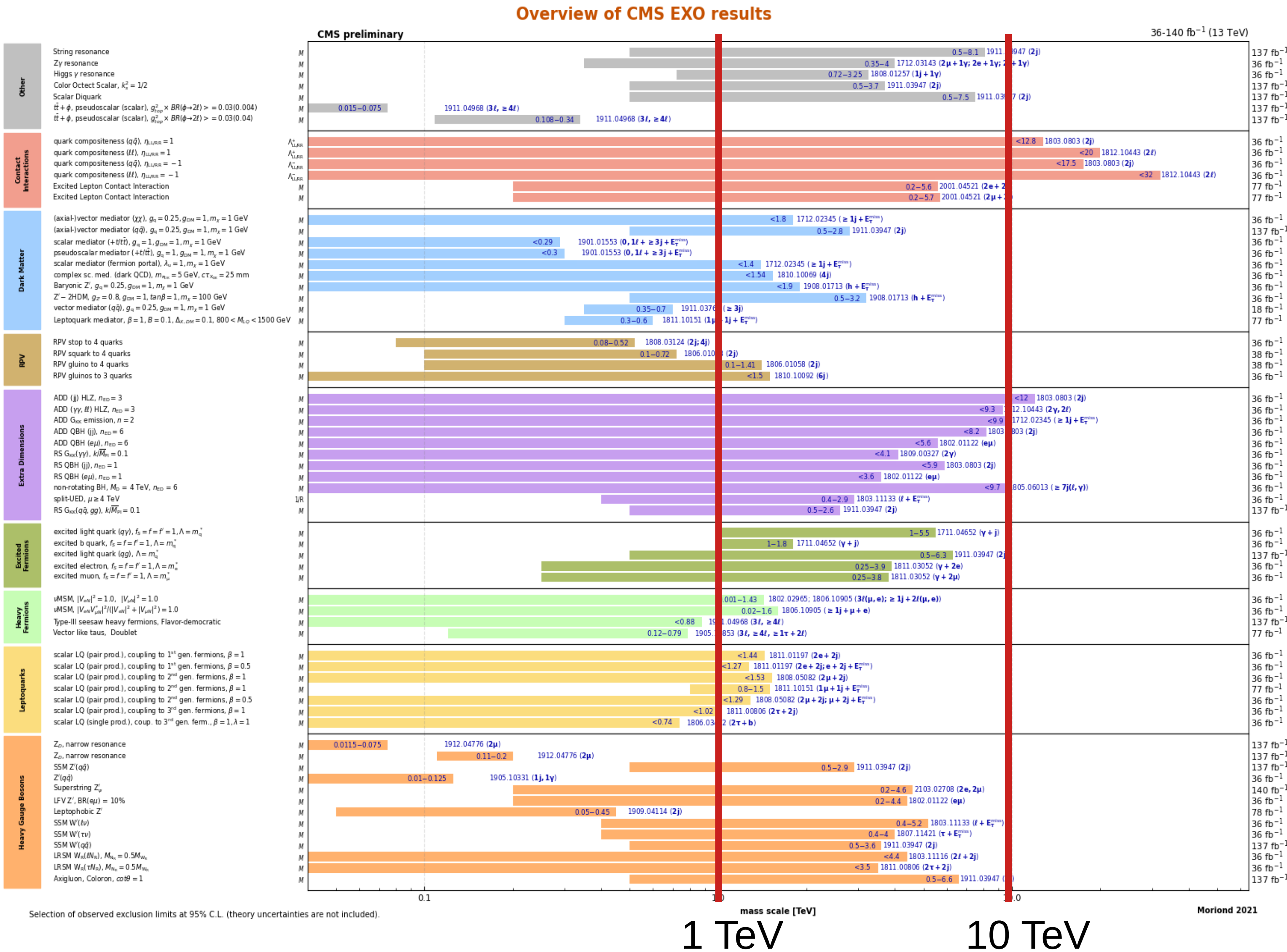
FTAE High Energy Theory

ugr Universidad de Granada

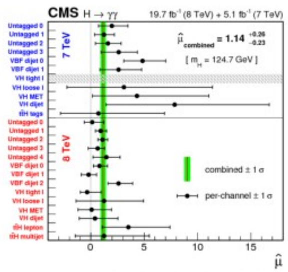
Based on: G. Guedes, P. Olgoso, J.S., arXiv:2303.XXXXX

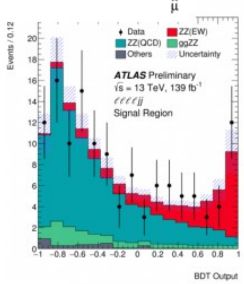
What is experiment telling us?

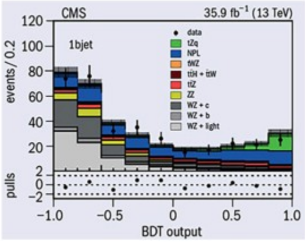


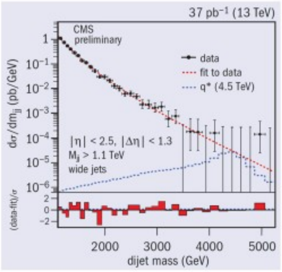
Turning all the stones! NP seems to be relatively heavy

Connecting theory and experiment

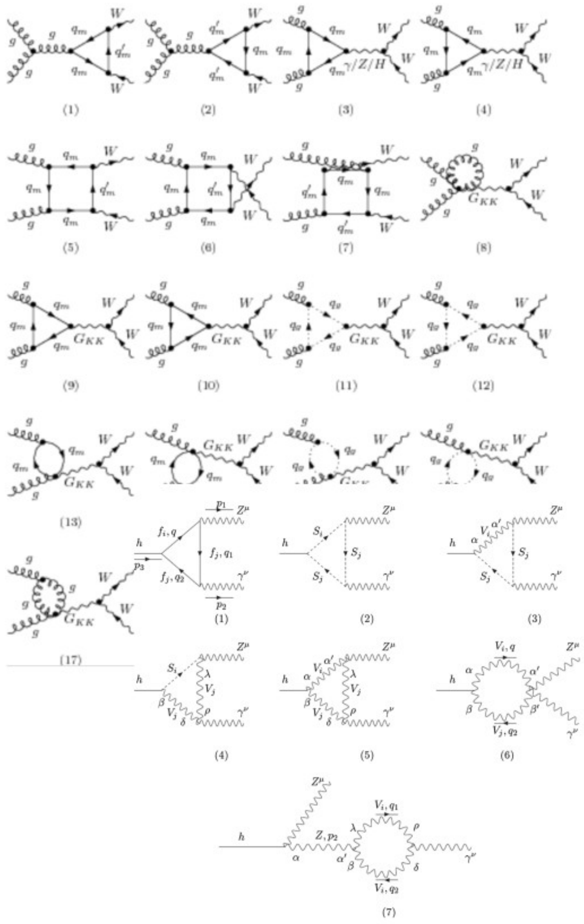


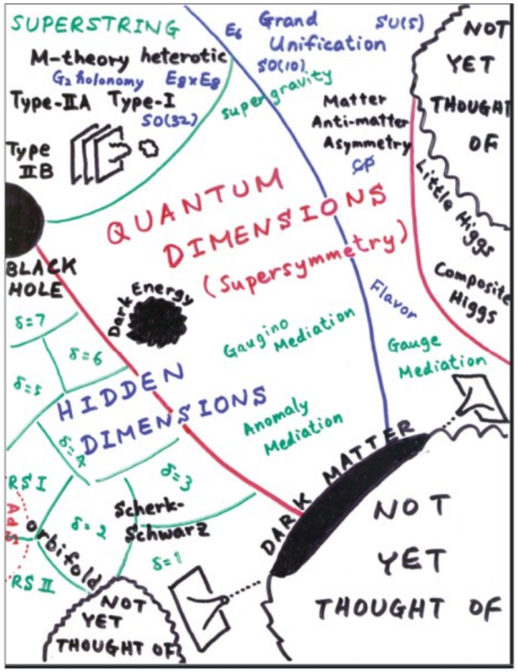






Getting implications of experimental data on new physics models is highly non trivial!





We need a more efficient approach!!

Effective Field Theories!

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**

The EFT approach to BSM

- Effective Lagrangians parametrise the low-energy effects of arbitrary new physics models

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

- It is a double expansion in mass dimension and loops

$$\begin{aligned}\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} &+ \frac{1}{\Lambda}\sum_i \left(c_{5,i}^{(0)} + \frac{c_{5,i}^{(1)}}{16\pi^2} + \ldots \right) \mathcal{O}_i^{(5)} \\ &+ \frac{1}{\Lambda^2}\sum_i \left(c_{6,i}^{(0)} + \frac{c_{6,i}^{(1)}}{16\pi^2} + \ldots \right) \mathcal{O}_i^{(6)} + \ldots\end{aligned}$$

- In weakly coupled extensions this expansion is well behaved

The EFT approach to BSM

- It is a double expansion in mass dimension and loops

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_i \left(c^{(0)}_{5,i} + \frac{c^{(1)}_{5,i}}{16\pi^2} + \dots \right) \mathcal{O}^{(5)}_i + \frac{1}{\Lambda^2}\sum_i \left(c^{(0)}_{5,i} + \frac{c^{(1)}_{5,i}}{16\pi^2} + \dots \right) \mathcal{O}^{(6)}_i + \dots$$

- Their effect at lower energies is hierarchical

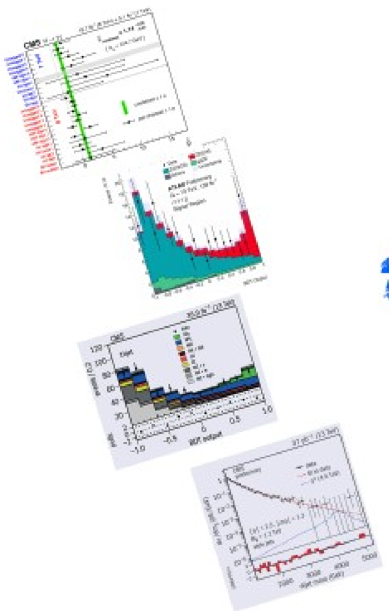
$$\mathcal{M} \sim \mathcal{M}_{\rm SM} + c_{5,i}\left(\frac{E}{\Lambda}\right) + [c_{6,i} + c^2_{5,i}]\left(\frac{E}{\Lambda}\right)^2 + \dots$$

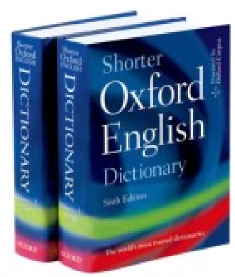
- In the SM EFT odd-dimension operators are associated to (tiny) lepton-number violating physics

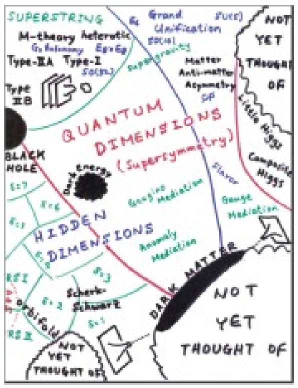
$$\mathcal{L}_{\rm SMEFT} \sim \mathcal{L}_{\rm SM} + \frac{\mathcal{L}_6}{\Lambda^2} + \frac{\mathcal{L}_8}{\Lambda^4} + \dots$$

IR/UV dictionaries

- Given a **fixed order** in this expansion we can **list all models** that generate the EFT at this order and compute their contribution.
- This provides true **IR/UV dictionaries** that **connect experiment with** all possible **models of new physics**.







Let's get to it!

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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[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

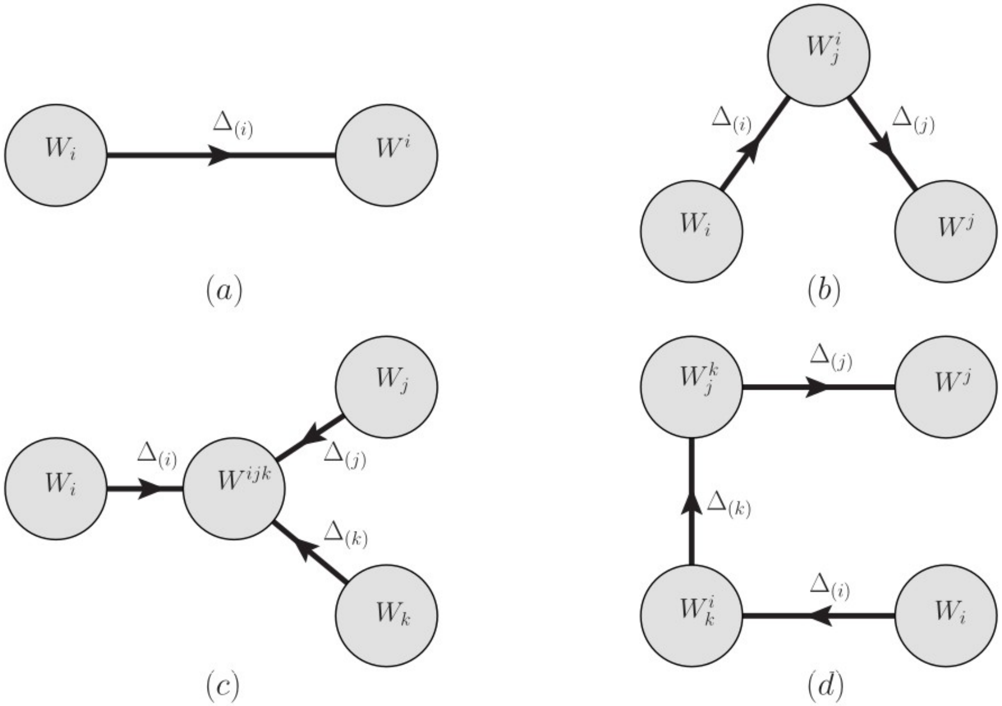
Building on previous results

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

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- Complete list of all possible models that contribute to experiment at tree-level and dim 6 (and their contributions).

where

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{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_{Lj}^c + \mathrm{h.c.} \right\} \\
& + \left\{ (y_{\mathcal{S}_2})_{rij} \mathcal{S}_{2k}^\dagger \bar{e}_{Ri} e_{Rj}^c + \mathrm{h.c.} \right\} \\
& + \left\{ (y_\varphi^e)_{rij} \varphi_r^\dagger \bar{e}_{Ri} l_{Lj} + (y_\varphi^d)_{rij} \varphi_r^\dagger \bar{d}_{Ri} q_{Lj} + (y_\varphi^u)_{rij} \varphi_r^\dagger i\sigma_2 \bar{q}_{Li}^T u_{Rj} \right. \\
& \quad \left. + (\lambda_\varphi)_r \left(\varphi_r^\dagger \phi \right) \left(\phi^\dagger \phi \right) + \mathrm{h.c.} \right\} \\
& + (\kappa_\Xi)_r \phi^\dagger \Xi_r^a \sigma^a \phi + (\lambda_\Xi)_{rs} \left(\Xi_r^a \Xi_s^a \right) \left(\phi^\dagger \phi \right) \\
& + \frac{1}{2} (\lambda_{\Xi_1})_{rs} \left(\Xi_{1r}^{a\dagger} \Xi_{1s}^a \right) \left(\phi^\dagger \phi \right) + \frac{1}{2} (\lambda'_{\Xi_1})_{rs} f_{abc} \left(\Xi_{1r}^{a\dagger} \Xi_{1s}^b \right) \left(\phi^\dagger \sigma^c \phi \right) \\
& + \left\{ (y_{\Xi_1})_{rij} \Xi_{1r}^{a\dagger} \bar{l}_{Li} \sigma^a i\sigma_2 l_{Lj}^c + (\kappa_{\Xi_1})_r \Xi_{1r}^{a\dagger} \left(\tilde{\phi}^\dagger \sigma^a \phi \right) + \mathrm{h.c.} \right\} \\
& + \left\{ (\lambda_{\Theta_1})_r \left(\phi^\dagger \sigma^a \phi \right) C_{a\beta}^I \tilde{\phi}_\beta \epsilon_{IJ} \Theta_{1r}^J + \mathrm{h.c.} \right\} \\
& + \left\{ (\lambda_{\Theta_3})_r \left(\phi^\dagger \sigma^a \tilde{\phi} \right) C_{a\beta}^I \tilde{\phi}_\beta \epsilon_{IJ} \Theta_{3r}^J + \mathrm{h.c.} \right\} \\
& + \left\{ (y_{\omega_1}^{ql})_{rij} \omega_{1r}^\dagger \bar{q}_{Li}^c i\sigma_2 l_{Lj} + (y_{\omega_1}^{qq})_{rij} \omega_{1r}^{A\dagger} \epsilon_{ABC} \bar{q}_{Li}^B i\sigma_2 q_{Lj}^{cC} \right. \\
& \quad \left. + (y_{\omega_1}^{eu})_{rij} \omega_{1r}^\dagger \bar{e}_{Ri}^c u_{Rj} + (y_{\omega_1}^{du})_{rij} \omega_{1r}^{A\dagger} \epsilon_{ABC} \bar{d}_{Ri}^B u_{Rj}^{cC} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_{\omega_2})_{rij} \omega_{2r}^{A\dagger} \epsilon_{ABC} \bar{d}_{Ri}^B d_{Rj}^{cC} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_{\omega_4}^{ed})_{rij} \omega_{4r}^{A\dagger} \bar{e}_{Ri}^c d_{Rj} + (y_{\omega_4}^{uu})_{rij} \omega_{4r}^{A\dagger} \epsilon_{ABC} \bar{u}_{Ri}^B u_{Rj}^{cC} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_{\Pi_1})_{rij} \Pi_{1r}^\dagger i\sigma_2 \bar{l}_{Li}^T d_{Rj} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_{\Pi_7}^{lu})_{rij} \Pi_{7r}^\dagger i\sigma_2 \bar{l}_{Li}^T u_{Rj} + (y_{\Pi_7}^{eq})_{rij} \Pi_{7r}^\dagger \bar{e}_{Ri} q_{Lj} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_\zeta^{ql})_{rij} \zeta_r^{a\dagger} \bar{q}_{Li}^c i\sigma_2 \sigma^a l_{Lj} + (y_\zeta^{qq})_{rij} \zeta_r^{a\dagger} \epsilon_{ABC} \bar{q}_{Li}^B \sigma^a i\sigma_2 q_{Lj}^{cC} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_{\Omega_1}^{ud})_{rij} \Omega_{1r}^{AB\dagger} \bar{u}_{Ri}^{c(A|} d_{Rj}^{|B)} + (y_{\Omega_1}^{qq})_{rij} \Omega_{1r}^{AB\dagger} \bar{q}_{Li}^{c(A|} i\sigma_2 q_{Lj}^{|B)} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_{\Omega_2})_{rij} \Omega_{2r}^{AB\dagger} \bar{d}_{Ri}^{c(A|} d_{Rj}^{|B)} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_{\Omega_4})_{rij} \Omega_{4r}^{AB\dagger} \bar{u}_{Ri}^{c(A|} u_{Rj}^{|B)} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_\Upsilon)_{rij} \Upsilon_r^{AB\dagger} \bar{q}_{Li}^{c(A|} i\sigma_2 \sigma^a q_{Lj}^{|B)} + \mathrm{h.c.} \right\} \\
& + \left\{ (y_\Phi^{qu})_{rij} \Phi_r^{A\dagger} i\sigma_2 \bar{q}_{Li}^T T_A u_{Rj} + (y_\Phi^{dq})_{rij} \Phi_r^{A\dagger} \bar{d}_{Ri} T_A q_{Lj} + \mathrm{h.c.} \right\} \\
& + (\lambda_{\mathcal{S}\Xi})_{rs} \mathcal{S}_r \Xi_s^a \left(\phi^\dagger \sigma^a \phi \right) + (\kappa_{\mathcal{S}\Xi})_{rst} \mathcal{S}_r \Xi_s^a \Xi_t^a \\
& + (\kappa_{\mathcal{S}\Xi_1})_{rst} \mathcal{S}_r \Xi_{1s}^{a\dagger} \Xi_{1t}^a + \left\{ (\lambda_{\mathcal{S}\Xi_1})_{rs} \mathcal{S}_r \Xi_{1s}^{a\dagger} \left(\tilde{\phi}^\dagger \sigma^a \phi \right) + \mathrm{h.c.} \right\} \\
& + \left\{ (\kappa_{\mathcal{S}\varphi})_{rs} \mathcal{S}_r \varphi_s^\dagger \phi + (\kappa_{\Xi\varphi})_{rs} \Xi_r^a (\varphi_s^\dagger \sigma^a \phi) + (\kappa_{\Xi_1\varphi})_{rs} \Xi_{1r}^{a\dagger} \left(\tilde{\varphi}_s^\dagger \sigma^a \phi \right) + \mathrm{h.c.} \right\} \\
& + (\kappa_{\Xi\Xi_1})_{rst} f_{abc} \Xi_r^a \Xi_{1s}^{b\dagger} \Xi_{1t}^b + \left\{ (\lambda_{\Xi_1\Xi})_{rs} f_{abc} \Xi_{1r}^{a\dagger} \Xi_s^b \left(\tilde{\phi}^\dagger \sigma^c \phi \right) + \mathrm{h.c.} \right\} \\
& + \left\{ (\kappa_{\Xi\Theta_1})_{rs} \Xi_r^a C_{a\beta}^I \tilde{\phi}_\beta \epsilon_{IJ} \Theta_{1s}^J + (\kappa_{\Xi_1\Theta_1})_{rs} \Xi_{1r}^{a\dagger} C_{a\beta}^I \phi_\beta \epsilon_{IJ} \Theta_{1s}^J \right. \\
& \quad \left. + (\kappa_{\Xi_1\Theta_3})_{rs} \Xi_{1r}^{a\dagger} C_{a\beta}^I \tilde{\phi}_\beta \epsilon_{IJ} \Theta_{3s}^J + \mathrm{h.c.} \right\},
\end{aligned}
\tag{A.7}
$$

6 pages

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

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

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

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

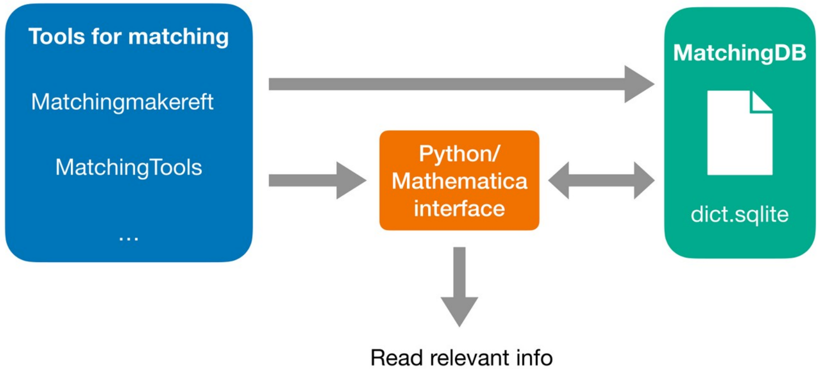
$$
Z_\phi \, C_{\phi \tilde{W}} = - \frac{g_2 (g_{\mathcal{L}_1}^{\tilde{W}})_{rs} (\gamma_{\mathcal{L}_1})_r^* (\gamma_{\mathcal{L}_1})_s}{4 M_{\mathcal{L}_{1r}}^2 M_{\mathcal{L}_{1s}}^2} + \frac{1}{f} \left\{ \frac{(\tilde{k}_{\mathcal{S}}^{\tilde{W}})_r (\kappa_{\mathcal{S}})_r}{M_{\mathcal{S}_r}^2}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

$$
\begin{aligned}
Z_\phi \, C_{\phi W B} = {} & - \frac{g_1 g_2 (\gamma_{\mathcal{L}_1})_r^* (\gamma_{\mathcal{L}_1})_r}{4 M_{\mathcal{L}_{1r}}^4} - \frac{g_2 (g_{\mathcal{L}_1}^B)_{rs} (\gamma_{\mathcal{L}_1})_r^* (\gamma_{\mathcal{L}_1})_s}{4 M_{\mathcal{L}_{1r}}^2 M_{\mathcal{L}_{1s}}^2} - \frac{g_1 (g_{\mathcal{L}_1}^W)_{rs} (\gamma_{\mathcal{L}_1})_r^* (\gamma_{\mathcal{L}_1})_s}{4 M_{\mathcal{L}_{1r}}^2 M_{\mathcal{L}_{1s}}^2} \\
& + \frac{1}{f} \left\{ \frac{(\tilde{k}_\Xi^{WB})_r (\kappa_\Xi)_r}{M_{\Xi_r}^2} - \frac{\mathrm{Im}\left((\tilde{\gamma}_{\mathcal{L}_1}^B)_r (\gamma_{\mathcal{L}_1})_r^* \right) g_2}{2 M_{\mathcal{L}_{1r}}^2} - \frac{\mathrm{Im}\left((\tilde{\gamma}_{\mathcal{L}_1}^W)_r (\gamma_{\mathcal{L}_1})_r^* \right) g_1}{2 M_{\mathcal{L}_{1r}}^2} \right\},
\end{aligned}
\tag{D.50}
$$

28 pages

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

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/

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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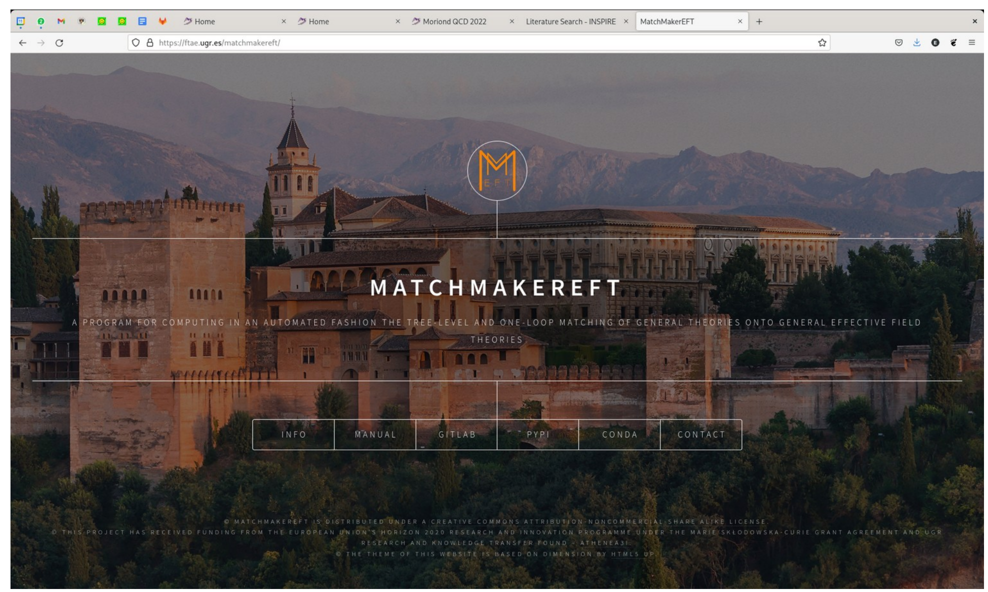
Abstract

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

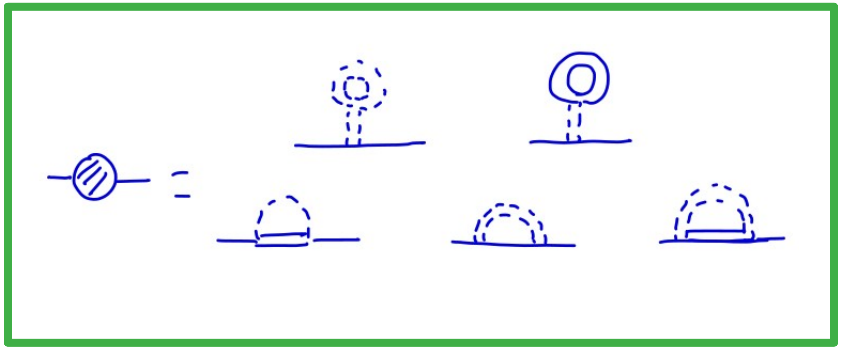


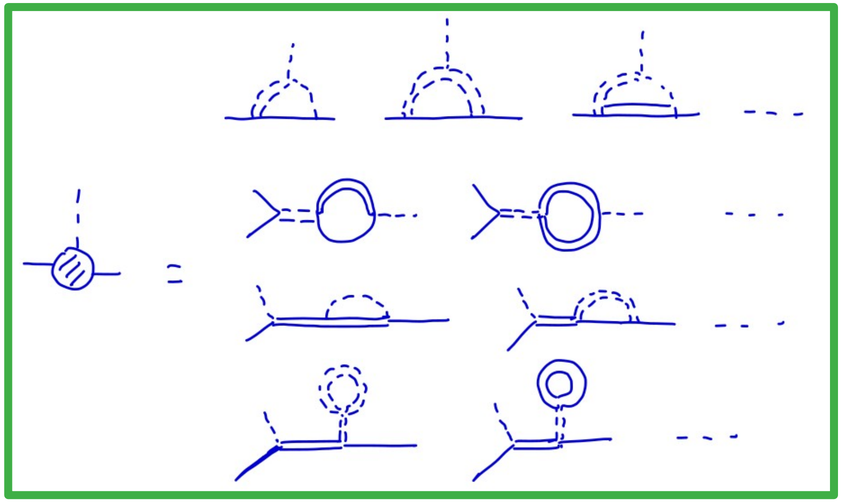
– Also RGEs, operator independence, ...

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, 2302.03485]
  - 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).





Towards the next IR/UV dictionaries

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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.
    - Result for specific models can be obtained doing a simple group-theoretical calculation [we use GroupMath by R. Fonseca].

SOLD

https://gitlab.com/jsantiago_ugr/sold

S

SOLD

Project ID: 42493139

32 Commits 1 Branch 1 Tag 69.1 MB Project Storage 1 Release

Smeft **O**ne **L**oop **D**ictionary (**SOLD**)

Towards the next IR/UV dictionaries

SOLD

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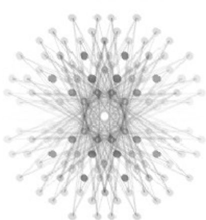
```
In[1]:= Import["https://gitlab.com/jsantiago_ugr/sold/-/raw/main/install.m"]
Installing SOLD
Installation completed.
In[2]:= << SOLD`
```

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



```
XXXXXXXXXXXXXXXXXXXXXXXXXX GroupMath XXXXXXXXXXXXXXXXXXXXXXXXXX
Version: 1.1.2 (6/May/2020)
Author: Renato Fonseca
Reference: 2011.01764 [hep-th]
Website: renatofonseca.net/groupmath
Built-in documentation: here
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
In[3]:= OneLoopOperatorsGrid
```

Out[3]=

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

```
ListModelsWarsaw[alphaOeW[i, j]]
```

atrixForm=

Field Content	SU(3) ⊗ SU(2)	U(1)
$\{\phi1\}$	$\{\phi1 \to \overline{\mathbf{3}} \otimes \mathbf{3}\}$	$\{Y_{\phi1} \to \frac{1}{3}\}$
$\{\phi1\}$	$\{\phi1 \to \mathbf{1} \otimes \mathbf{1}\}$	$\{Y_{\phi1} \to -1\}$
$\{\phi1\}$	$\{\phi1 \to \mathbf{1} \otimes \mathbf{2}\}$	$\{Y_{\phi1} \to -\frac{1}{2}\}$
$\{\phi1\}$	$\{\phi1 \to \mathbf{1} \otimes \mathbf{3}\}$	$\{Y_{\phi1} \to 1\}$
$\{\phi1\}$	$\{\phi1 \to \mathbf{3} \otimes \mathbf{1}\}$	$\{Y_{\phi1} \to -\frac{1}{3}\}$
$\{\phi1\}$	$\{\phi1 \to \mathbf{3} \otimes \mathbf{2}\}$	$\{Y_{\phi1} \to \frac{1}{6}\}$
$\{\phi1\}$	$\{\phi1 \to \mathbf{3} \otimes \mathbf{2}\}$	$\{Y_{\phi1} \to \frac{7}{6}\}$
$\{\psi1\}$	$\{\psi1 \to \mathbf{1} \otimes \mathbf{1}\}$	$\{Y_{\psi1} \to 0\}$
$\{\psi1\}$	$\{\psi1 \to \mathbf{1} \otimes \mathbf{1}\}$	$\{Y_{\psi1} \to 1\}$
$\{\psi1\}$	$\{\psi1 \to \mathbf{1} \otimes \mathbf{2}\}$	$\{Y_{\psi1} \to -\frac{3}{2}\}$
$\{\psi1\}$	$\{\psi1 \to \mathbf{1} \otimes \mathbf{3}\}$	$\{Y_{\psi1} \to 0\}$
$\{\psi1\}$	$\{\psi1 \to \mathbf{1} \otimes \mathbf{3}\}$	$\{Y_{\psi1} \to 1\}$
$\{\phi1, \phi2\}$	$\{\phi1 \to \mathbf{1} \otimes \mathbf{2}, \phi2 \to \mathbf{1} \otimes \mathbf{1}\}$	$\{Y_{\phi1} \to -\frac{1}{2}, Y_{\phi2} \to -1\}$
$\{\phi1, \phi2\}$	$\{\phi1 \to \mathbf{1} \otimes \mathbf{2}, \phi2 \to \mathbf{1} \otimes \mathbf{1}\}$	$\{Y_{\phi1} \to -\frac{1}{2}, Y_{\phi2} \to 0\}$

ListValidQNs$\left[\{\phi1, \psi1\}\ \{\phi1 \otimes \overline{\phi1} \supset \text{"1"} \otimes \text{"3"}, \psi1 \otimes \overline{\phi1} \supset \text{"1"} \otimes \text{"2"}\}\ \{Y_{\psi1} \to -\frac{1}{2} + Y_{\phi1}\}\right]$[[1]]

$$\left\{\left\{\phi1 \to \mathbf{1}\otimes\mathbf{2}\otimes Y_{\phi1},\ \psi1 \to \mathbf{1}\otimes\mathbf{1}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},\ \left\{\phi1 \to \mathbf{1}\otimes\mathbf{2}\otimes Y_{\phi1},\ \psi1 \to \mathbf{1}\otimes\mathbf{3}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},\right.$$

$$\left\{\phi1 \to \mathbf{1}\otimes\mathbf{3}\otimes Y_{\phi1},\ \psi1 \to \mathbf{1}\otimes\mathbf{2}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},\ \left\{\phi1 \to \mathbf{1}\otimes\mathbf{3}\otimes Y_{\phi1},\ \psi1 \to \mathbf{1}\otimes\mathbf{4}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},$$

$$\left\{\phi1 \to \mathbf{1}\otimes\mathbf{4}\otimes Y_{\phi1},\ \psi1 \to \mathbf{1}\otimes\mathbf{3}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},\ \left\{\phi1 \to \mathbf{1}\otimes\mathbf{4}\otimes Y_{\phi1},\ \psi1 \to \mathbf{1}\otimes\mathbf{5}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},$$

$$\left\{\phi1 \to \mathbf{1}\otimes\mathbf{5}\otimes Y_{\phi1},\ \psi1 \to \mathbf{1}\otimes\mathbf{4}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},\ \left\{\phi1 \to \mathbf{3}\otimes\mathbf{2}\otimes Y_{\phi1},\ \psi1 \to \mathbf{3}\otimes\mathbf{1}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},$$

$$\left\{\phi1 \to \mathbf{3}\otimes\mathbf{2}\otimes Y_{\phi1},\ \psi1 \to \mathbf{3}\otimes\mathbf{3}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},\ \left\{\phi1 \to \mathbf{3}\otimes\mathbf{3}\otimes Y_{\phi1},\ \psi1 \to \mathbf{3}\otimes\mathbf{2}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},$$

$$\left\{\phi1 \to \mathbf{3}\otimes\mathbf{3}\otimes Y_{\phi1},\ \psi1 \to \mathbf{3}\otimes\mathbf{4}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},\ \left\{\phi1 \to \mathbf{3}\otimes\mathbf{4}\otimes Y_{\phi1},\ \psi1 \to \mathbf{3}\otimes\mathbf{3}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},$$

$$\left\{\phi1 \to \mathbf{3}\otimes\mathbf{4}\otimes Y_{\phi1},\ \psi1 \to \mathbf{3}\otimes\mathbf{5}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},\ \left\{\phi1 \to \mathbf{3}\otimes\mathbf{5}\otimes Y_{\phi1},\ \psi1 \to \mathbf{3}\otimes\mathbf{4}\otimes\left(-\frac{1}{2}+Y_{\phi1}\right)\right\},$$

Towards the next IR/UV dictionaries

SOLD

- 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], iCPV ^ 2 → 1, FourPi → 4 Pi} /. μ → MSa] // NiceOutput]
```

$$
\begin{aligned}
\alpha_{eB}[i,j] = {} & \frac{1}{384\,\pi^2\,M_{Fa}^2\,\left(M_{Fa}^2 - M_{Sa}^2\right)^4}\, g_1 \\
& \Bigg(-M_{Fa}^2 \left(M_{Fa}^6 - 6\,M_{Fa}^4\,M_{Sa}^2 + 3\,M_{Fa}^2\,M_{Sa}^4 + 6\,\mathrm{Log}\left[\frac{M_{Fa}^2}{M_{Sa}^2}\right] M_{Fa}^2\,M_{Sa}^4 + 2\,M_{Sa}^6\right) y_e{}^{[i,mif3]}\, \lambda_{\overline{eR},Fa,Sa}{}^{[mif3]}\, \lambda_{\overline{Fa},eR,Sa}{}^{[j]} - \\
& \left(M_{Fa}^2 - M_{Sa}^2\right) \Bigg(3\,M_{Fa} \left(M_{Fa}^4 + 2\,M_{Fa}^2\,M_{Sa}^2 - 3\,M_{Sa}^4 + \mathrm{Log}\left[\frac{M_{Fa}^2}{M_{Sa}^2}\right] \left(M_{Fa}^4 - 5\,M_{Fa}^2\,M_{Sa}^2\right)\right) \lambda_{\phi,\overline{\phi},Sa}\, \lambda_{\overline{Fa},eR,Sa}{}^{[j]} + \\
& \quad 6\,M_{Fa}^2 \left(M_{Fa}^4 - 4\,M_{Fa}^2\,M_{Sa}^2 + 3\,M_{Sa}^4 + 2\,\mathrm{Log}\left[\frac{M_{Fa}^2}{M_{Sa}^2}\right] M_{Sa}^4\right) \lambda^{[R]}{}_{\overline{Fa},Fa,Sa}\, \lambda_{\overline{Fa},eR,Sa}{}^{[j]} + \\
& \quad 2\,\left(M_{Fa}^2 - M_{Sa}^2\right)^3 y_e{}^{[mif3,j]}\, \lambda_{\overline{Fa},lL,\overline{\phi}}{}^{[mif3]}\Bigg)\, \lambda_{\overline{lL},Fa,\phi}{}^{[i]}\Bigg)
\end{aligned}
$$

Towards the next IR/UV dictionaries

SOLD

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```
createLagQuick[{Fa → {1, 1, -1}, Sa → {1, 1, 0}}]

New Physics Lagrangian:

 L1 [Fa, Sa, Fabar] Fabar[sp1].left[Fa[sp1]] Sa+Fabar[sp1].right[Fa[sp1]] Sa + L1 [Sa, Sa, Sa]
   Sa Sa Sa + L1 [Sa, Sa, Sa, Sa] Sa Sa Sa Sa + L1[LL, Fabar, Phibar][ff0]
   Fabar[sp1].LL[sp1,ss0,ff0] Phibar[ss2] TS71[ss0, ss2] + L1[LR, Sa, Fabar][ff0]
   Fabar[sp1].LR[sp1,ff0] Sa + L1 [Phi, Sa, Sa, Phibar] Phi[ss0] Sa Sa Phibar[ss3]
   TS31[ss0, ss3] + L1 [Phi, Sa, Phibar] Phi[ss0] Sa Phibar[ss2] TS11[ss0, ss2]
 Numerical Clebsch-Gordan coefficients:
 {TS11 → {{1, 0}, {0, 1}}, TS11bar → {{1, 0}, {0, 1}}, TS31 → {{1, 0}, {0, 1}},
  TS31bar → {{1, 0}, {0, 1}}, TS71 → {{1, 0}, {0, 1}}, TS71bar → {{1, 0}, {0, 1}}}
```

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

```
CompleteOneLoopMatching[extension, modelname, <EFTname>,<outputdirectory>]
```

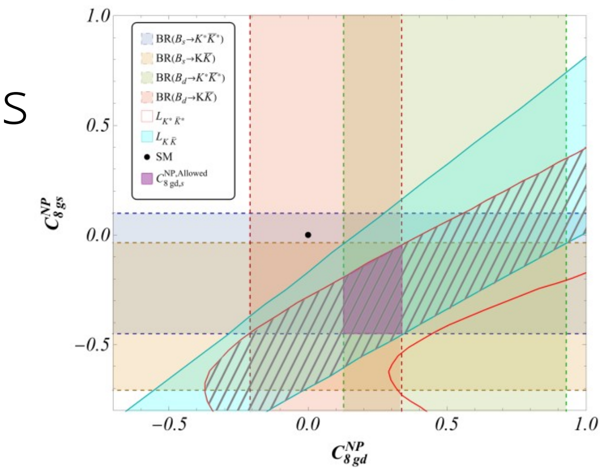
Towards the next IR/UV dictionaries

SOLD

- Can be used for phenomenological analyses

A new puzzle in non-leptonic B decays

Aritra Biswas,[a] Sébastien Descotes-Genon,[b] Joaquim Matias,[a] Gilberto Tetlalmatzi-Xolocotzi[b,c]



- Can be explained by dipole operators.
  - Run to EW scale, match at one loop to SMEFT and run up to matching scale (all known and in codes), then use the dictionary.

$$
\begin{aligned}
C_{8gq}\frac{g_s}{F_q}\Big|_{\mu=m_b} = & -\frac{g_s}{32\pi^2}\sum_{q_u=u,c} m_{q_u}\left[(C^{(1)}_{quqd})_{qq_uq_ub} - \frac{1}{6}(C^{(8)}_{quqd})_{qq_uq_ub}\right]\log\left(\frac{m_b^2}{m_t^2}\right) \\
& + \frac{v_T}{\sqrt{2}}V^\dagger_{qk}(C_{dG})_{kb} - \frac{g_3}{64\pi^2}F_1(x_W)V^\dagger_{qt}V_{tb}m_b\Delta G_F \\
& - \frac{g_3}{36\pi^2}\left(1-\frac{m_W^2}{m_Z^2}\right)m_q(C_{Hd})_{qb} - \frac{g_3}{64\pi^2}F_2(x_W)m_tV^\dagger_{qt}(C_{Hud})_{tb} \\
& + \frac{g_3}{72\pi^2}\left(1+\frac{2m_W^2}{m_Z^2}\right)m_bV^\dagger_{qk}(C^{(1)}_{Hq})_{kl}V_{lb} \\
& + \frac{g_3}{576\pi^2}m_b\left\{8\left(7+2\frac{m_W^2}{m_Z^2}\right)V^\dagger_{qk}(C^{(3)}_{Hq})_{kl}V_{lb} - 9F_1(x_W)[V^\dagger_{qt}(C^{(3)}_{Hq})_{tk}V_{kb} + V^\dagger_{qk}(C^{(3)}_{Hq})_{kt}V_{tb}]\right\} \\
& - V^\dagger_{qk}\left[\frac{g_3}{32\pi^2}\left(C^{(1)}_{quqd} - \frac{1}{6}C^{(8)}_{quqd}\right)_{qkkb}(m_u)_k\log\left(\frac{m_t^2}{\Lambda^2}\right)\right] + \dots, \qquad (5.19)
\end{aligned}
$$

Towards the next IR/UV dictionaries

SOLD

- Can be used for phenomenological analyses

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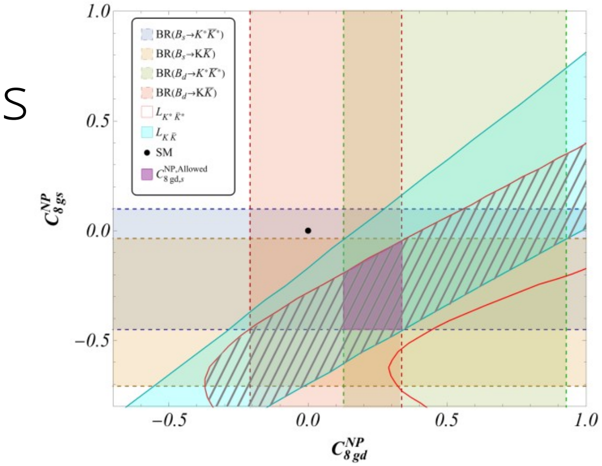

- Can be explained by dipole operators.
  - Run to EW scale, match at one loop to SMEFT and run up to matching scale (all known and in codes), then use the dictionary.
  - One viable possibility: $\Phi \sim (1,1)_{Y_\Phi}, \quad \Psi_1 \sim (3,2)_{\frac{1}{6}-Y_\Phi}, \quad \Psi_2 \sim (3,1)_{-\frac{1}{3}-Y_\Phi}$

$$
\begin{aligned}
(C_{dG})_{ij} = &-\frac{g_3}{64\pi^2}\frac{1}{M_\Phi^2(M_a^2-M_b^2)}\Bigg[2M_aM_b\log\left(\frac{M_a^2}{M_b^2}\right)\lambda^R_{ab} \\
&+\left(2M_b^2\log\left(\frac{M_a^2}{M_b^2}\right)+(M_a^2-M_b^2)\left(3+2\log\left(\frac{M_a^2}{M_\Phi^2}\right)\right)\right)\lambda^L_{ab}\Bigg](\lambda_{qa})_i(\lambda_{bd})_j+\mathcal{O}\left(\frac{M_{a,b}^2}{M_\Phi^4}\right)
\end{aligned}
$$

$$M_{\Psi_a} \approx 1.5 \text{ TeV}, \quad M_{\Psi_b} \approx 2.0 \text{ TeV}, \quad M_\Phi \approx 4 \text{ TeV},$$

Conclusions and outlook

- The effective approach is well supported by experimental data and extremely powerful.
- It allows us to exhaustively list all observable models and compute their phenomenological information.
- IR/UV dictionaries connect directly experiment to all observable new physics models:
  - Perfect guiding principle to pin-point new physics if anomalies found.
  - Optimal framework to interpret bounds if no new physics is found.
- The leading order dictionary was computed a few years back, the **S**meft **O**ne **L**oop **D**ictionary (**SOLD**) is currently being computed, thanks to recent progress in automated matching calculations.


Thank you!!!
Lo Ratrak
ATOMIC