

Matchmakereft

arXiv:2112.10787 A. Carmona, A. Lazopoulos, PO, J. Santiago





An automated tool for EFTs

Pablo Olgoso





• We know (believe) there has to be new physics BSM.

- We know (believe) there has to be new physics BSM.
- This physics is apparently heavy.



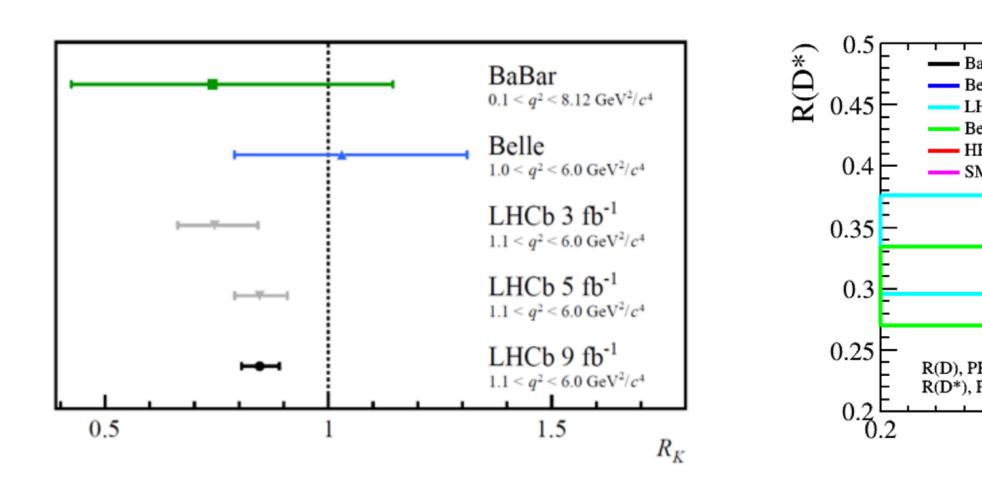
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included)

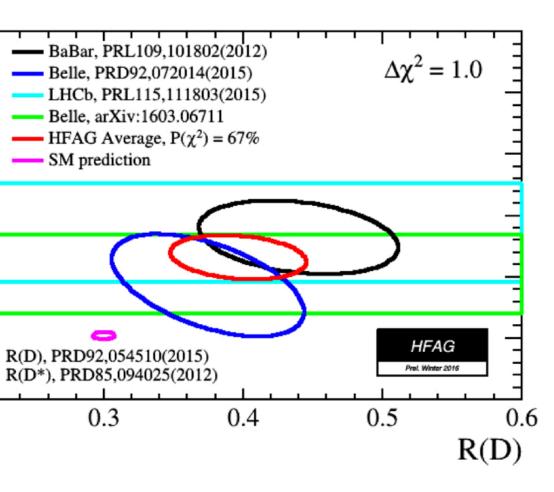
Overview of CMS EXO results

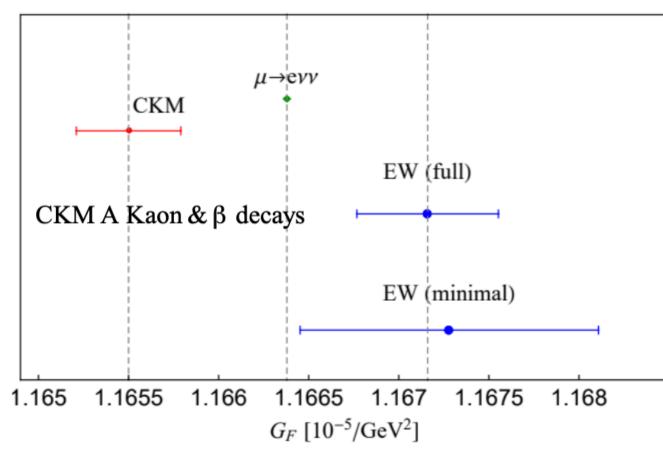
ew of CMS EXU I	esuits	36-140 fb ⁻¹ (13 TeV)		
1911.04968 (3 <i>t</i> , ≥ 4 <i>t</i>)	0.5-8.1 1911. 0.35-4 1712.03143 (2µ + 1γ; 2e + 1γ; 2 0.72-3.25 1808.01257 (1j + 1γ) 0.5-3.7 1911.03947 (2j) 0.5-7.5 1911.03	+ 1y)	137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹	
as tc	DE NEV 02-56 02-57 2001.04521 (2#+ 2 2001.04521 (2#+ 2	<12.8 1803.0803 (2) -17.5 1812/10443 (2/) -17.5 1803.0803 (2) -1812.10443 (2/)	36 fb 36 fb 36 fb 36 fb 36 fb 77 fb 1 77 fb -1	
1901.01553 (0, 1/ + ≥ 3j + E ₇ ^{con}) 1901.01553 (0, 1/ + ≥ 3j + E ₇ ^{con}) 1903.0253 (0, 1/ + ≥ 3j + E ₇ ^{con}) 03-01 = 10113 (1)	<1.8 1712.02345 (\geq 1j + E _T ^{max}) 0.3-2.8 1911.03947 (2j) <1.4 1712.02345 (\geq 1j + E _T ^{max}) <1.54 1810.10069 (4j) <1.9 1908.01713 (h + E _T ^{max}) 0.5-3.2 1908.01713 (h + E _T ^{max}) (\approx 3j7 1j + E _T ^{max})		36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 37 fb ⁻¹	
0 0 0 5 2 1808-531 24 (2) 49 0 1 - 0 7 2 1806.010	(2j) 0.1-1.41 1806.01058 (2j) <1.5 1810.10092 (6j)		36 fb ⁻¹ 38 fb ⁻¹ 38 fb ⁻¹ 36 fb ⁻¹	
	<9.3 <9.9 <8.2 1803 <5.6 1802.01122 (eµ) <4.1 1809.00327 (2γ) <5.9 1803.0803 (2j) <3.6 1802.01122 (eµ) <3.6 1802.01122 (eµ) <9.7 0.4-2.9 1803.11133 (t + Ε ₇ ^(m)) 0.5-2.6 1911.03947 (2j)	<pre><12 1803.0803 (2j) 12.10443 (2γ, 2/) 1712.02345 (≥ 1j + E^{max}) 803 (2j) 805.06013 (≥ 7j(/, γ))</pre>	36 fb ⁻¹ 36 fb ⁻¹ 37 fb ⁻¹	
	1-5.5 1711.04652 (y + j) 1-1.8 1711.04652 (y + j) 0.5-6.3 1911.03947 (2j 0.25-3.9 1811.03052 (y + 2e) 0.25-3.8 1811.03052 (y + 2µ)		36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹	
<0.88 19 0.12-0.79 1905.	$\begin{array}{l} (001-1.43 1802.02965; 1806.10905 \ (3\ell(\mu,e); \ge 1j+2\ell(\mu,e)) \\ 0.02-1.6 1806.10905 \ (\ge 1j+\mu+e) \\ 1.04968 \ (3\ell, \ge 4\ell) \\ 853 \ (3\ell, \ge 4\ell, \ge 1\tau+2\ell) \end{array}$		36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 77 fb ⁻¹	
<1.02 <0.74 1806.03	<1.44 1811.01197 (2e+ 2j) <1.27 1811.01197 (2e+ 2j: e + 2j + E ^{+new}) <1.53 1808.05082 (2µ + 2j) 0.8-1.5 1811.10151 (1µ + 1j + E ^{+new}) <1.29 1808.05082 (2µ + 2j: µ + 2j + E ^{+new}) 1811.00806 (2π + 2j) 2 (2π + b)		36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 77 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹	
5 (2µ) 0 050.45 1909.04114 (2j)	$\begin{array}{cccccccccccccccccccccccccccccccccccc$		137 fb ⁻¹ 137 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 140 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹ 36 fb ⁻¹ 137 fb ⁻¹	
mass scale [TeV] 10 TeV Moriond 2021				

- We know (believe) there has to be new physics BSM.
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Why EFTs?

- EFTs allow us to split the problem in two independent steps:
- Bottom-up: agnostic parametrization of experimental data in terms of WC.
 - The only input is the EFT.
 - Observables are computed just once!
- Top-down: re-introduce dependence with models through matching.



The problem with EFTs UV Theory

- RGE
 - [...]
- RGE
- RGE

 M_1,\ldots,M_n,m

MATCHING $\mu = M_1$

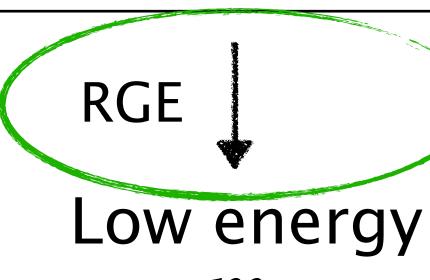
MATCHING $\mu = M_n$

Low energy \mathcal{M}

The problem with EFTs UV Theory M_1,\ldots,M_n,m

- RGE
- RGE

- One-loop running known for LEFT, SMEFT
- This process is automated.



MATCHING $\mu = M_1$

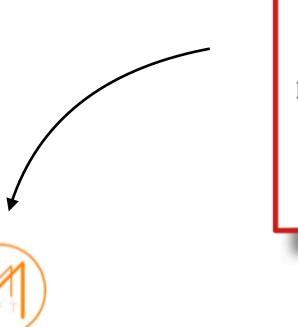
MATCHING $\mu = M_n$

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M

The problem with EFTs UV Theory M_1,\ldots,M_n,m MATCHING $\mu = M_1$ RGE Tree-level matching known and classified. • • • RGE MATCHING $\mu = M_n$ RGE Low energy \mathcal{M}

- One-loop matching highly non-trivial.
- Infinite models can contribute.



Matchmakereft: automated tree-level and one-loop matching

Adrián Carmona $^{a,b},$ Achilleas Lazopoulos b, Pablo Olgoso a and José Santiago a



Adrián Carmona^{*a,b*}, Achilleas Lazopoulos^{*b*}, Pablo Olgoso^{*a*} and José Santiago^{*a*}

^a CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuentenueva, E-18071 Granada, Spain

^b Institute for Theoretical Physics, ETZ Zürich, 8093 Zürich, Switzerland

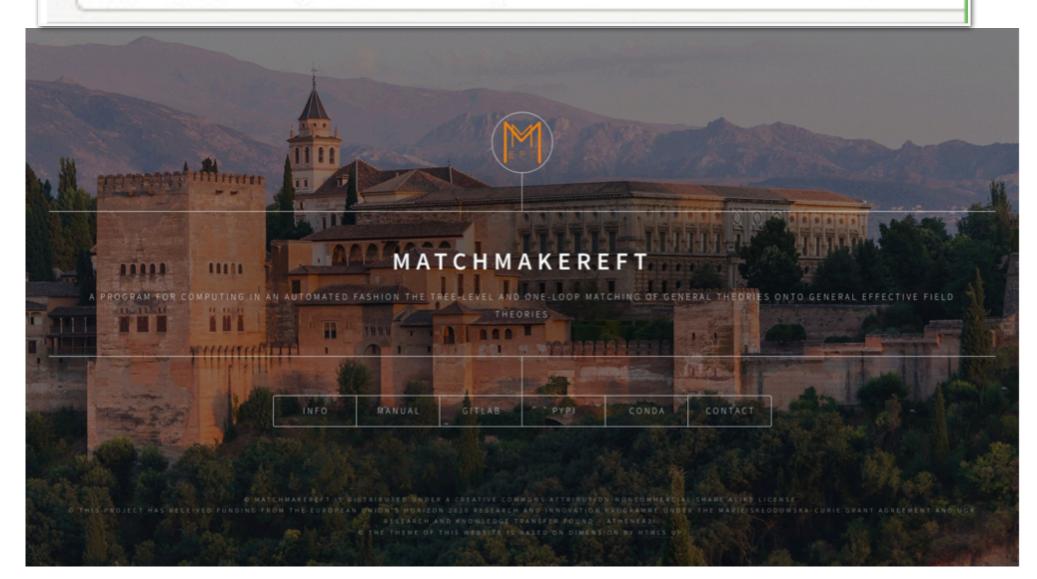
Abstract

We introduce matchmakereft, a fully automated tool to compute the treelevel 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 have many applications beyond the matching between models and effective theories. Some of these applications include the one-loop renormalization of arbitrary theories (including the calculation of the one-loop renormalization group equations for arbitrary theories); the translation between different Green bases for a fixed effective theory or the check of (off-shell) linear independence of the operators in an effective theory. All these applications are performed in a fully automated way by matchmakereft.

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



- [Carmona, Lazopoulos, PO, Santiago '21]
- Flexible, reliable, fast and powerful:
 - Less than 1 minute to compute the one-loop matching of the scalar singlet extension of the SM (which was correctly computed only after some iterations in the literature).

 Matchmakereft is a fully automated tool to perform tree-level and one-loop matching between arbitrary models and arbitrary EFTs.

Matching is performed off-shell, diagrammatically and using BFM.

[Henning, Lu, Murayama '14] [Ellis, Quevillon, You, Zhang '17] [Jiang, Craig, Li, Sutherland '18] [Haisch, Ruhdorfer, Salvioni, Venturini, Weiler '20]



- [Carmona, Lazopoulos, PO, Santiago '21]
- Flexible, reliable, fast and powerful:
 - Already used in several highly nontrivial calculations.

- [Chala, Guedes, Ramos, Santiago '20] (ALPs RGEs)
- [Chala, Guedes, Ramos, Santiago '21] (Dim 8 SMEFT RGEs)
- [Chala, Santiago,'21] (Positivity bounds dim 8)
- [Chala, Díaz-Carmona, Guedes '21] (Green basis dim 8)
- [Bakshi, Chala, Díaz-Carmona, Guedes '22] (Dim 8 SMEFT RGEs)

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- [Carmona, Lazopoulos, PO, Santiago '21]
- Flexible, reliable, fast and powerful:
 - Several cross-checks have been performed.

 Matchmakereft is a fully automated tool to perform tree-level and one-loop matching between arbitrary models and arbitrary EFTs.

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Scalar Singlet [Haisch, Ruhdorfer, Salvioni, Venturini, Weiler '20] SMEFT RGEs [Jenkins, Manohar, Trott '13] Type I Seesaw [Zhang, Zhou '21]

- [Carmona, Lazopoulos, PO, Santiago '21]
- Flexible, reliable, fast and powerful.
- It can also be used to:
 - Compute one-loop RGEs of arbitrary EFTs.
 - Check off-shell (in)dependence of a set of operators. [Chala, Díaz-Carmona, Guedes '21] (Green basis dim 8)

 Matchmakereft is a fully automated tool to perform tree-level and one-loop matching between arbitrary models and arbitrary EFTs.

Matching is performed off-shell, diagrammatically and using BFM.

• FeynRules model.

- FeynRules model.
 - Particle content and masses.

```
F[105] == {
 ClassName -> HL,
Indices -> {Index[SU2D]},
SelfConjugate -> False,
 QuantumNumbers \rightarrow \{Y \rightarrow -1/2\},
 FullName -> "heavy",
                   -> ML,
 Mass
 Width
                   -> 0
},
S[108] == {
 ClassName
                   -> HT,
                   -> {},
 Indices
 SelfConjugate
                   -> True,
 FullName
                   -> "heavy",
 Mass
                   -> MS,
 Width
                   -> 0
```

- FeynRules model.
 - Particle content and masses.
 - Lagrangian.

yuk =
yD[ff1] HLbar[sp1,ii].LR[sp1,ff1] Phi[ii]
+ yT[ff1] HLbar[sp1,ii].LL[sp1,ii,ff1] HT;

yuk2= YHL HLbar[sp1,ii].HL[sp1,ii] HT;

yuk+HC[yuk]+yuk2

• FeynRules model.

qLbar	dR	Phi (-I/2)*deltaF[ll1,ll3]*delt
HLbar	eR	Phi (I/2)*deltaF[ll1,ll3]*gam[
lLbar	eR	Phi (–I/2)*deltaF[ll1,ll3]*gam
HLbar	lL	HT (I/2)*deltaF[ll1,ll2]*gam[yy
gLbar	uR	Phibar (-I/2)*deltaF[mm1,mm2]*e
lLbar	lL	<pre>B (-I/4)*g1*deltaF[flfl1,flfl2]</pre>
lLbar	lL	BQuantum (-I/4)*g1*deltaF[flfl1
lLbar	lL	Wi (I/2)*g2*deltaF[flfl1,flfl2]
lLbar	lL	WiQuantum (I/2)*g2*deltaF[flfl1
gLbar	qL	<pre>B (I/12)*g1*deltaF[flfl1,flfl2]</pre>
gLbar	qL	BQuantum (I/12)*g1*deltaF[flfl1
qLbar	qL	G (I/2)*g3*deltaF[flfl1,flfl2]*
gLbar	qL	GQuantum (I/2)*g3*deltaF[flfl1,
qLbar	qL	Wi (I/2)*g2*deltaF[flfl1,flfl2]
qLbar	qL	WiQuantum (I/2)*g2*deltaF[flfl1
eRbar	eR	<pre>B (-I/2)*g1*deltaF[flfl1,flfl2]</pre>

ltaF[mm1,mm2]*gam[yy1,SIX,yy2]*yd[flfl1,flfl2] [yy1,SIX,yy2]*yD[flfl2] n[yy1,SIX,yy2]*yl[flfl1,flfl2] yy1,SEVEN,yy2]*yT[flfl2] keps[ll1,ll3]*gam[yy1,SIX,yy2]*yu[flfl1,flfl2] 2]*deltaF[ll1,ll2]*gam[yy1,mumu3,SEVEN,yy2] l1,flfl2]*deltaF[ll1,ll2]*gam[yy1,mumu3,SEVEN,yy2] 2]*gam[yy1,mumu3,SEVEN,yy2]*Ta[nn3,ll1,ll2] l1,flfl2]*gam[yy1,mumu3,SEVEN,yy2]*Ta[nn3,ll1,ll2] 2]*deltaF[ll1,ll2]*deltaF[mm1,mm2]*gam[yy1,mumu3,SEVE l1,flfl2]*deltaF[ll1,ll2]*deltaF[mm1,mm2]*gam[yy1,mum]*deltaF[ll1,ll2]*gam[yy1,mumu3,SEVEN,yy2]*T[aa3,mm1, l,flfl2]*deltaF[ll1,ll2]*gam[yy1,mumu3,SEVEN,yy2]*T[a 2]*deltaF[mm1,mm2]*gam[yy1,mumu3,SEVEN,yy2]*T[a 2]*deltaF[mm1,mm2]*gam[yy1,mumu3,SEVEN,yy2]*T[a 2]*deltaF[mm1,mm2]*gam[yy1,mumu3,SEVEN,yy2]*T[a 2]*deltaF[mm1,mm2]*gam[yy1,mumu3,SEVEN,yy2]*Ta[nn3,ll 1,flfl2]*deltaF[mm1,mm2]*gam[yy1,mumu3,SEVEN,yy2]*Ta 2]*gam[yy1,mumu3,SIX,yy2]

• FeynRules model (+ gauge file).

replacegaugedata = {
fsu2 -> SparseArray[Automati
{1, {{0, 2, 4, 6}, {{2, 3},
$\{1, -1, -1, 1, 1, -1\}\}],$
Ta -> SparseArray[Automatic
$\{1, \{\{0, 2, 4, 6\}, \{\{1, 2\}, \}\}$
{1/2, 1/2, -I/2, I/2, 1/2,
Tabar -> SparseArray[Automa
$\{1, \{\{0, 2, 4, 6\}, \{\{1, 2\},$
$\{1/2, 1/2, 1/2, -1/2, 1/2,$
Ta4 -> SparseArray[Automatic,
$\{1, \{\{0, 6, 12, 16\}, \{\{1, 2\}\}$
$\{1, 2\}, \{2, 1\}, \{2, 3\}, \{3, 3\}$
3}, {4, 4}}}, {Sqrt[3]/2,
(-I/2)*Sqrt[3], (I/2)*Sqrt
3/2, 1/2, -1/2, -3/2}}],

ic, {3, 3, 3}, 0, $\{3, 2\}, \{1, 3\}, \{3, 1\}, \{1, 2\}, \{2, 1\}\},\$, {3, 2, 2}, 0, $\{2, 1\}, \{1, 2\}, \{2, 1\}, \{1, 1\}, \{2, 2\}\},\$ -1/2}}], atic, {3, 2, 2}, 0, $\{2, 1\}, \{1, 2\}, \{2, 1\}, \{1, 1\}, \{2, 2\}\},\$ -1/2}}], {3, 4, 4}, 0, $\{2, 1\}, \{2, 3\}, \{3, 2\}, \{3, 4\}, \{4, 3\},$ $\{4, 3\}, \{1, 1\}, \{2, 2\}, \{3,$ 2}, {3, 4}, Sqrt[3]/2, 1, 1, Sqrt[3]/2, Sqrt[3]/2, t[3], -I, I, (-I/2)*Sqrt[3], (I/2)*Sqrt[3],

- FeynRules model.
- QGRAF.
 - Computes all possible diagrams.

```
(-1)*
cpol(lLbar(-1,p1))*
cpol(lL(-3,p2))*
cpol(lL(-5,p3))*
cpol(lLbar(-7,p4))*
```

```
prop(HL(1,-k1),HLbar(2,-k1))*
prop(HT(3,k1-p1),HT(4,k1-p1))*
prop(HT(5,-k1-p2),HT(6,-k1-p2))*
prop(HL(7,-k1+p1+p3),HLbar(8,-k1+p1+p3))*
v3(lLbar(-1,p1),HL(1,-k1),HT(3,k1-p1))*
v3(HLbar(2,k1),lL(-3,p2),HT(5,-k1-p2))*
v3(HLbar(8,k1-p1-p3),lL(-5,p3),HT(4,-k1+p1))*
v3(lLbar(-7,p4),HL(7,-k1+p1+p3),HT(6,k1+p2)),
```

- FeynRules model.
- QGRAF.
- FORM.
 - Expansion by regions.
 - Gamma processing.

- FeynRules model.
- QGRAF.
- FORM.
- Mathematica.
 - Solve for Wilson Coefficients.
 - Canonical Normalization.
 - Redundancies.

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- FeynRules model.
- QGRAF.
- FORM.
- Mathematica.
 - Solve for Wilson Coefficients.
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alphaO3W
$$\rightarrow - rac{g2^3 (MF^2 + 2 ML^2) \text{ onelooporder}}{2880 MF^2 ML^2 \pi^2}$$

Let's see how it works!



Future developments

- Today, the main bottlenecks are:
 - Model generation.
 - Reduction to physical basis (redundancies).
- Both fronts are being already tackled:
 - Interplay with Sym2Int (with R. Fonseca) to automatically generate models.

• On-shell matching (with M. Chala) to compute the redundancies.

Conclusions

- EFTs are a very efficient way to look for new physics.
- Comparing theory vs experiment at one-loop is a highly non-trivial multi-step problem.
- Matchmakereft is an automated tool to overcome this difficulties.
- Its output can be easily combined with other tools to study the low energy phenomenology of any model.
- We encourage you to try!