Universidad de Granada

High Energy Theory

On-Shell matching in effective field theories

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Why do we need effective field theories?

EFT's are perturbative (Taylor) expansions of a full theory

In QFT's :

Operators of mass dimension $d > 4$ $\quad \mathcal{O}_i^{(d)}$

Useful for finite precision computations

Search for new physics

Green's basis and redundant operators

EFT Lagrangian : $$\mathcal{L} = \mathcal{L}^{(4)} + \sum_{d>4} \sum_{i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Green's basis and redundant operators

EFT Lagrangian : $$\mathcal{L} = \mathcal{L}^{(4)} + \sum_{d>4} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Valid operators

Local operators

Preserve the symmetries of the Lagrangian

Finite number of operators

Integration by parts

Green's basis

Green’s basis and redundant operators

Green’s basis of the bosonic sector of the SMEFT

X^3	
$\mathcal{O}_{3G}$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{3\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{3W}$	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$\mathcal{O}_{3\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

X^2D^2	
$\mathcal{O}_{2G}$	$-\frac{1}{2}(D_\mu G^{A\mu\nu})(D^\rho G^A_{\rho\nu})$
$\mathcal{O}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W^I_{\rho\nu})$
$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$

X^2H^2	
$\mathcal{O}_{HG}$	$G^A_{\mu\nu} G^{A\mu\nu}(H^\dagger H)$
$\mathcal{O}_{H\widetilde{G}}$	$\widetilde{G}^A_{\mu\nu} G^{A\mu\nu}(H^\dagger H)$
$\mathcal{O}_{HW}$	$W^I_{\mu\nu} W^{I\mu\nu}(H^\dagger H)$
$\mathcal{O}_{H\widetilde{W}}$	$\widetilde{W}^I_{\mu\nu} W^{I\mu\nu}(H^\dagger H)$
$\mathcal{O}_{HB}$	$B_{\mu\nu} B^{\mu\nu}(H^\dagger H)$
$\mathcal{O}_{H\widetilde{B}}$	$\widetilde{B}_{\mu\nu} B^{\mu\nu}(H^\dagger H)$
$\mathcal{O}_{HWB}$	$W^I_{\mu\nu} B^{\mu\nu}(H^\dagger \sigma^I H)$
$\mathcal{O}_{H\widetilde{W}B}$	$\widetilde{W}^I_{\mu\nu} B^{\mu\nu}(H^\dagger \sigma^I H)$

H^2XD^2	
$\mathcal{O}_{WDH}$	$D_\nu W^{I\mu\nu}(H^\dagger i \overleftrightarrow{D}^I_\mu H)$
$\mathcal{O}_{BDH}$	$\partial_\nu B^{\mu\nu}(H^\dagger i \overleftrightarrow{D}_\mu H)$

H^2D^4	
$\mathcal{O}_{DH}$	$(D_\mu D^\mu H)^\dagger (D_\nu D^\nu H)$

H^4D^2	
$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\dagger (H^\dagger D_\mu H)$
$\mathcal{O}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger (D^\mu H)$
$\mathcal{O}''_{HD}$	$(H^\dagger H) D_\mu (H^\dagger i \overleftrightarrow{D}^\mu H)$

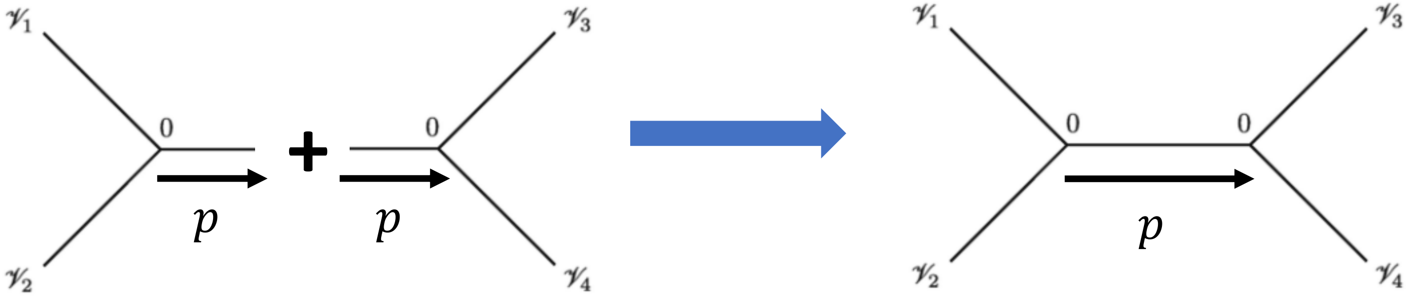
H^6	
$\mathcal{O}_H$	$(H^\dagger H)^3$

V. Gherardi, D. Marzocca y E. Venturini (2021) [2003.12525v5]

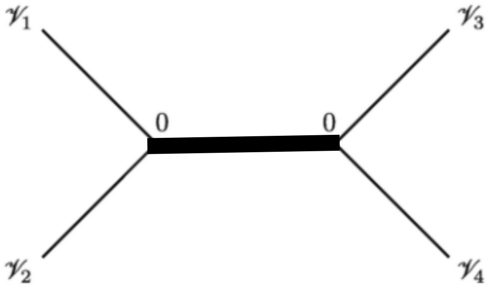
Matching: Off-Shell vs On-shell

Off-Shell matching

- Small number of diagrams (1 lPI)



- Heavy bridges contribution directly local



$p^2 \ll M^2$

$$\sim \frac{1}{p^2 - M^2} = -\frac{1}{M^2}\left(1 + \frac{p^2}{M^2} + \frac{p^4}{M^4} + \cdots\right)$$

- But requires the construction and reduction of the Green's basis

Reduction to the physical basis

Identification of redundant operators

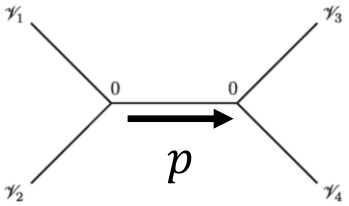
- Field redefinitions
- EOMs (only valid up to linear order)

Non-trivial process

Hard to program it in a systematic way

On-Shell matching

- Huge number of diagrams



- There is delicate cancellation of non-local contributions between between UV and EFT

$$\left.\frac{1}{p^2 - m^2}\right|_{\text{UV}} - \left.\frac{1}{p^2 - m^2}\right|_{\text{EFT}} = Polynomial(p^2)$$

Reduction to the physical basis

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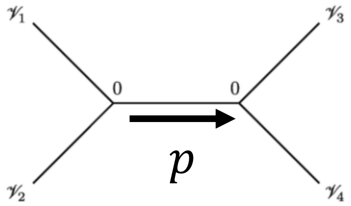

- There is delicate cancellation of non-local contributions between between UV and EFT

Substitution of randomly generated physical momenta

M. Accettulli [2304.01589]

$$\left.\frac{1}{p^2-m^2}\right|_{\text{UV}} - \left.\frac{1}{p^2-m^2}\right|_{\text{EFT}} = Polynomial(p^2)$$

On-Shell matching approach

- Find the Green's basis up to dimension d → $\mathcal{L}_{Green}$
- Find the physical basis

  R. Fonseca [1907.12584]
  J.C. Criado [1901.03501]

  → $\mathcal{L}_{phys}$
- Compute n-points amplitudes with n $\leq d$ **on-shell** → **By the substitution of randomly generated physical momenta**
- Solve the system $\mathcal{M}_{i,Green} = \mathcal{M}_{i,phys}$

Some results in the SMEFT

HIGG'S SECTOR

$$\mathcal{L}_{Green} = \mathcal{L}^{(4)} + \mathcal{L}^{(6)}_{Green} \qquad \mathcal{L}_{phys} = \mathcal{L}^{(4)} + \mathcal{L}^{(6)}_{phys} + \mathcal{L}^{(8)}_{phys}$$

Some results in the SMEFT

HIGG'S SECTOR

$$\mathcal{L}_{Green} = \mathcal{L}^{(4)} + \mathcal{L}^{(6)}_{Green} \qquad \mathcal{L}_{phys} = \mathcal{L}^{(4)} + \mathcal{L}^{(6)}_{phys} + \mathcal{L}^{(8)}_{phys}$$

$$\mathcal{L}^{(4)} = \frac{1}{2}\left(D_\mu H\right)^\dagger \left(D^\mu H\right) - m_0^2 H^\dagger H - \lambda \left(H^\dagger H\right)^2$$

$$\begin{aligned}\mathcal{L}^{(6)}_{Green} = {} & c_H \left(H^\dagger H\right)^3 + c_{H\Box}\left(H^\dagger H\right)\Box\left(H^\dagger H\right) + c_{HD}\left(H^\dagger D^\mu H\right)^\dagger \left(H^\dagger D_\mu H\right) + \\ & r'_{HD}\left(H^\dagger H\right)\left(D_\mu H\right)^\dagger\left(D^\mu H\right) + r''_{HD}\left(H^\dagger H\right) D_\mu \left(H^\dagger i \overleftrightarrow{D}^\mu H\right) + r_{DH}\left(D^2 H\right)^\dagger \left(D^2 H\right)\end{aligned}$$

Some results in the SMEFT

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$$\mathcal{L}^{(6)}_{phys}$$

$$\mathcal{L}^{(6)}_{Green} = c_H\left(H^\dagger H\right)^3 + c_{H\Box}\left(H^\dagger H\right)\Box\left(H^\dagger H\right) + c_{HD}\left(H^\dagger D^\mu H\right)^\dagger\left(H^\dagger D_\mu H\right) +$$
$$r'_{HD}\left(H^\dagger H\right)\left(D_\mu H\right)^\dagger\left(D^\mu H\right) + r''_{HD}\left(H^\dagger H\right)D_\mu\left(H^\dagger i\overleftrightarrow{D}^\mu H\right) + r_{DH}\left(D^2 H\right)^\dagger\left(D^2 H\right)$$

Some results in the SMEFT

HIGG'S SECTOR

$$\mathcal{L}_{Green} = \mathcal{L}^{(4)} + \mathcal{L}^{(6)}_{Green} \qquad \mathcal{L}_{phys} = \mathcal{L}^{(4)} + \mathcal{L}^{(6)}_{phys} + \mathcal{L}^{(8)}_{phys}$$

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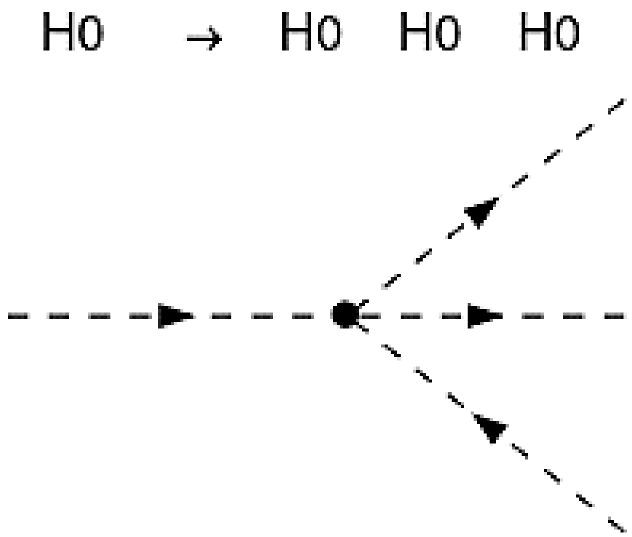
$$\mathcal{L}^{(6)}_{phys}$$

$$\mathcal{L}^{(6)}_{Green} = c_H \left(H^\dagger H\right)^3 + c_{H\Box} \left(H^\dagger H\right) \Box \left(H^\dagger H\right) + c_{HD} \left(H^\dagger D^\mu H\right)^\dagger \left(H^\dagger D_\mu H\right) + r'_{HD} \left(H^\dagger H\right) \left(D_\mu H\right)^\dagger \left(D^\mu H\right) + r''_{HD} \left(H^\dagger H\right) D_\mu \left(H^\dagger i \overleftrightarrow{D}^\mu H\right) + r_{DH} \left(D^2 H\right)^\dagger \left(D^2 H\right)$$

$$\mathcal{L}^{(8)}_{phys} = c_{H^8} \left(H^\dagger H\right)^4 + c^{(1)}_{H^6 D^2} \left(H^\dagger H\right)^2 \left(D_\mu H^\dagger D^\mu H\right) + c^{(2)}_{H^6 D^2} \left(H^\dagger H\right) \left(H^\dagger \sigma^I H\right) \left(D_\mu H^\dagger \sigma^I D^\mu H\right) + c^{(1)}_{H^4 D^4} \left(D_\mu H^\dagger D_\nu H\right) \left(D^\nu H^\dagger D^\mu H\right) + c^{(2)}_{H^4 D^4} \left(D_\mu H^\dagger D_\nu H\right) \left(D^\mu H^\dagger D^\nu H\right) + c^{(3)}_{H^4 D^4} \left(D^\mu H^\dagger D_\mu H\right) \left(D^\nu H^\dagger D_\nu H\right)$$

```
rules12 = Rules[4, 0, 10] /. {rules`k → k, rules`Pair → Pair} // Simplify;
equations = {};
For[j = 1, j ≤ Length[amp1], j ++,
para cada    longitud

    For[i = 1, i ≤ Length[rules12], i++,
    para cada    longitud

      final = amp1[[j]] /. Flatten[rules12[[i]]] // TermCollect;
                           aplana

      final = I Sum[final[[aa]], {aa, 1, Length[final]}] // Expand;
                ·· suma                  longitud          expande factores

      final = final /. Sust;
      final = final /. {x^3 → 0, x^4 → 0, x^5 → 0, x^6 → 0} /. {x → 1};
      ampIR = final /. propEFT /. limitIR;
      ampUV = Z^2 final /. propEFT /. limitUV;
      ampsUV[[i]] = ampsUV[[i]] + ampUV;
      ampsIR[[i]] = ampsIR[[i]] + ampIR;

  ];
  AppendTo[equations, Table[ampsUV[[i]] == ampsIR[[i]], {i, 1, Length[rules12]}]];
  añade al final      tabla                                   longitud
 ];

solution1 = Solve[Flatten[equations], coefsol] /. massPhys // Simplify;
            resuelve aplana                                 simplifica
```



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     ampIR = final /. propEFT /. limitIR;
     ampUV = Z^2 final /. propEFT /. limitUV;
     ampsUV[[i]] = ampsUV[[i]] + ampUV;
     ampsIR[[i]] = ampsIR[[i]] + ampIR;

   ];
   AppendTo[equations, Table[ampsUV[[i]] == ampsIR[[i]], {i, 1, Length[rules12]}]];
   añade al final      tabla                                   longitud
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            resuelve aplana                                  simplifica
```

Replacing momenta by randomly generated values

```
rules12 = Rules[4, 0, 10] /. {rules`k → k, rules`Pair → Pair} // Simplify;
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        final = final /. Sust;
        final = final /. {x^3 → 0, x^4 → 0,  x^5 →  0,  x^6 → 0} /. {x → 1};
        ampIR = final /. propEFT /. limitIR;
        ampUV = Z^2 final /. propEFT /. limitUV;
        ampsUV[[i]] = ampsUV[[i]] + ampUV;
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   ];
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   añade al final        tabla                                    longitud
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```

→ Replacing momenta by randomly generated values

→ Running through every amplitude in the process

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rules12 = Rules[4, 0, 10] /. {rules`k → k, rules`Pair → Pair} // Simplify;
equations = {};
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     final = final /. Sust;
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     ampIR = final /. propEFT /. limitIR;
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     ampsUV[[i]] = ampsUV[[i]] + ampUV;
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```

Replacing momenta by randomly generated values

Running through every amplitude in the process

Setting both theories amplitudes with their propagators and wavefunction renormalizations

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        ampUV = Z^2 final /. propEFT /. limitUV;
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        ampsIR[[i]] = ampsIR[[i]] + ampIR;

  ];
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  añade al final       tabla                                 longitud
 ];

solution1 = Solve[Flatten[equations], coefsol] /. massPhys // Simplify;
            resuelve aplana                                  simplifica
```

Replacing momenta by randomly generated values

Running through every amplitude in the process

Setting both theories amplitudes with their propagators and wavefunction renormalizations

Matching both theories

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|para cada        |longitud

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                             |aplana

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            |resuelve |aplana                              |simplifica
```

Replacing momenta by randomly generated values

Running through every amplitude in the process

Setting both theories amplitudes with their propagators and wavefunction renormalizations

Matching both theories

Solving the system

Some results in the SMEFT

Final solution: redefinition of coefficients

$$\text{cH} \to \text{aH} - \text{lmbd}^2\,\text{rDH} + \text{lmbd rHDp} + \text{m0}^2\left(6\,\text{aH rDH} + \text{aHD lmbd rDH} - 8\,\text{aHDD lmbd rDH} - 11\,\text{lmbd}^2\,\text{rDH}^2 - \frac{\text{aHD rHDp}}{2} + 4\,\text{aHDD rHDp} + 9\,\text{lmbd rDH rHDp} - \frac{\text{rHDp}^2}{4} - \text{rHDpp}^2\right)$$

$$\text{cH41} \to 0$$

$$\text{cH42} \to 0$$

$$\text{cH43} \to 0$$

$$\text{cH61} \to \text{aHD lmbd rDH} + 8\,\text{aHDD lmbd rDH} + \text{lmbd}^2\,\text{rDH}^2 - \frac{\text{aHD rHDp}}{2} - 4\,\text{aHDD rHDp} + 3\,\text{lmbd rDH rHDp} - \frac{7\,\text{rHDp}^2}{4} + \text{rHDpp}^2$$

$$\text{cH62} \to 2\,\text{aHD lmbd rDH} - \text{aHD rHDp}$$

$$\text{cHD} \to \text{aHD} + 4\,\text{aHD m0}^2\,\text{rDH}$$

$$\text{cHDD} \to \frac{1}{2}\left(2\,\text{aHDD} + \text{rHDp}\right) + \text{m0}^2\left(4\,\text{aHDD rDH} + 2\,\text{rDH rHDp}\right)$$

$$\text{mH}^2 \to \text{m0}^2 + \text{m0}^4\,\text{rDH} + 2\,\text{m0}^6\,\text{rDH}^2$$

$$\lambda \to \text{lmbd} + \text{m0}^2\left(4\,\text{lmbd rDH} - 2\,\text{rHDp}\right) + \text{m0}^4\left(16\,\text{lmbd rDH}^2 - 10\,\text{rDH rHDp}\right)$$

J. Aebischer, M. Fael and J. Fuentes-Martín|2023
[2307.08745v1]

V. Gherardi, D. Marzocca and E. Venturini |2021
[2003.12525v5]

Some results in the SMEFT

Final solution: redefinition of coefficients

$$\mathrm{cH} \to \mathrm{aH} - \mathrm{lmbd}^2\,\mathrm{rDH} + \mathrm{lmbd}\,\mathrm{rHDp} + \mathrm{m0}^2 \left(6\,\mathrm{aH}\,\mathrm{rDH} + \mathrm{aHD}\,\mathrm{lmbd}\,\mathrm{rDH} - 8\,\mathrm{aHDD}\,\mathrm{lmbd}\,\mathrm{rDH} - 11\,\mathrm{lmbd}^2\,\mathrm{rDH}^2 - \frac{\mathrm{aHD}\,\mathrm{rHDp}}{2} + 4\,\mathrm{aHDD}\,\mathrm{rHDp} + 9\,\mathrm{lmbd}\,\mathrm{rDH}\,\mathrm{rHDp} - \frac{\mathrm{rHDp}^2}{4} - \mathrm{rHDpp}^2\right)$$

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$$\mathrm{cH62} \to 2\,\mathrm{aHD}\,\mathrm{lmbd}\,\mathrm{rDH} - \mathrm{aHD}\,\mathrm{rHDp}$$

$$\mathrm{cHD} \to \mathrm{aHD} + 4\,\mathrm{aHD}\,\mathrm{m0}^2\,\mathrm{rDH}$$

$$\mathrm{cHDD} \to \frac{1}{2}\left(2\,\mathrm{aHDD} + \mathrm{rHDp}\right) + \mathrm{m0}^2\left(4\,\mathrm{aHDD}\,\mathrm{rDH} + 2\,\mathrm{rDH}\,\mathrm{rHDp}\right)$$

$$\mathrm{mH}^2 \to \mathrm{m0}^2 + \mathrm{m0}^4\,\mathrm{rDH} + 2\,\mathrm{m0}^6\,\mathrm{rDH}^2$$

$$\lambda \to \mathrm{lmbd} + \mathrm{m0}^2\left(4\,\mathrm{lmbd}\,\mathrm{rDH} - 2\,\mathrm{rHDp}\right) + \mathrm{m0}^4\left(16\,\mathrm{lmbd}\,\mathrm{rDH}^2 - 10\,\mathrm{rDH}\,\mathrm{rHDp}\right)$$

J. Aebischer, M. Fael and J. Fuentes-Martín|2023
[2307.08745v1]

V. Gherardi, D. Marzocca and E. Venturini |2021
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Some results in the SMEFT

Final solution: redefinition of coefficients

$$\mathrm{cH} \to \mathrm{aH} - \mathrm{lmbd}^2\,\mathrm{rDH} + \mathrm{lmbd}\,\mathrm{rHDp} + \boxed{\mathrm{m0}^2\left(6\,\mathrm{aH}\,\mathrm{rDH} + \mathrm{aHD}\,\mathrm{lmbd}\,\mathrm{rDH} - 8\,\mathrm{aHDD}\,\mathrm{lmbd}\,\mathrm{rDH} - 11\,\mathrm{lmbd}^2\,\mathrm{rDH}^2 - \frac{\mathrm{aHD}\,\mathrm{rHDp}}{2} + 4\,\mathrm{aHDD}\,\mathrm{rHDp} + 9\,\mathrm{lmbd}\,\mathrm{rDH}\,\mathrm{rHDp} - \frac{\mathrm{rHDp}^2}{4} - \mathrm{rHDpp}^2\right)}$$

$$\mathrm{cH41} \to 0$$

$$\mathrm{cH42} \to 0$$

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$$\mathrm{cH61} \to \boxed{\mathrm{aHD}\,\mathrm{lmbd}\,\mathrm{rDH} + 8\,\mathrm{aHDD}\,\mathrm{lmbd}\,\mathrm{rDH} + \mathrm{lmbd}^2\,\mathrm{rDH}^2} - \frac{\mathrm{aHD}\,\mathrm{rHDp}}{2} - 4\,\mathrm{aHDD}\,\mathrm{rHDp} + \boxed{3\,\mathrm{lmbd}\,\mathrm{rDH}\,\mathrm{rHDp}} - \frac{7\,\mathrm{rHDp}^2}{4} + \mathrm{rHDpp}^2$$

$$\mathrm{cH62} \to \boxed{2\,\mathrm{aHD}\,\mathrm{lmbd}\,\mathrm{rDH}} - \mathrm{aHD}\,\mathrm{rHDp}$$

$$\mathrm{cHD} \to \mathrm{aHD} + \boxed{4\,\mathrm{aHD}\,\mathrm{m0}^2\,\mathrm{rDH}}$$

$$\mathrm{cHDD} \to \frac{1}{2}\left(2\,\mathrm{aHDD} + \mathrm{rHDp}\right) + \boxed{\mathrm{m0}^2\left(4\,\mathrm{aHDD}\,\mathrm{rDH} + 2\,\mathrm{rDH}\,\mathrm{rHDp}\right)}$$

$$\mathrm{mH}^2 \to \mathrm{m0}^2 + \mathrm{m0}^4\,\mathrm{rDH} + \boxed{2\,\mathrm{m0}^6\,\mathrm{rDH}^2}$$

$$\lambda \to \mathrm{lmbd} + \mathrm{m0}^2\left(4\,\mathrm{lmbd}\,\mathrm{rDH} - 2\,\mathrm{rHDp}\right) + \boxed{\mathrm{m0}^4\left(16\,\mathrm{lmbd}\,\mathrm{rDH}^2 - 10\,\mathrm{rDH}\,\mathrm{rHDp}\right)}$$

J. Aebischer, M. Fael and J. Fuentes-Martín|2023
[2307.08745v1]

V. Gherardi, D. Marzocca and E. Venturini |2021
[2003.12525v5]

Future work

BOSONIC SECTOR

$\boldsymbol{X^3}$		$\boldsymbol{X^2H^2}$		$\boldsymbol{H^2D^4}$	
$\mathcal{O}_{3G}$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{HG}$	$G^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$	$\mathcal{O}_{DH}$	$(D_\mu D^\mu H)^\dagger(D_\nu D^\nu H)$
$\mathcal{O}_{3\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\widetilde{G}}$	$\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$	$\boldsymbol{H^4D^2}$	
$\mathcal{O}_{3W}$	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HW}$	$W^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{3\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{H\widetilde{W}}$	$\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\dagger(H^\dagger D_\mu H)$
$\boldsymbol{X^2D^2}$		$\mathcal{O}_{HB}$	$B_{\mu\nu}B^{\mu\nu}(H^\dagger H)$	$\mathcal{O}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger(D^\mu H)$
$\mathcal{O}_{2G}$	$-\frac{1}{2}(D_\mu G^{A\mu\nu})(D^\rho G^A_{\rho\nu})$	$\mathcal{O}_{H\widetilde{B}}$	$\widetilde{B}_{\mu\nu}B^{\mu\nu}(H^\dagger H)$	$\mathcal{O}''_{HD}$	$(H^\dagger H)D_\mu(H^\dagger i\overleftrightarrow{D}^\mu H)$
$\mathcal{O}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W^I_{\rho\nu})$	$\mathcal{O}_{HWB}$	$W^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$	$\boldsymbol{H^6}$	
$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$	$\mathcal{O}_{H\widetilde{W}B}$	$\widetilde{W}^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$	$\mathcal{O}_H$	$(H^\dagger H)^3$
		$\boldsymbol{H^2XD^2}$			
		$\mathcal{O}_{WDH}$	$D_\nu W^{I\mu\nu}(H^\dagger i\overleftrightarrow{D}^I_\mu H)$		
		$\mathcal{O}_{BDH}$	$\partial_\nu B^{\mu\nu}(H^\dagger i\overleftrightarrow{D}_\mu H)$		

Future work

BOSONIC SECTOR

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$\mathcal{O}_{3\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\widetilde{G}}$	$\widetilde{G}_{\mu\nu}^{A}G^{A\mu\nu}(H^\dagger H)$	H^4D^2	
$\mathcal{O}_{3W}$	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HW}$	$W_{\mu\nu}^{I}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{3\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{H\widetilde{W}}$	$\widetilde{W}_{\mu\nu}^{I}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\dagger(H^\dagger D_\mu H)$
X^2D^2		$\mathcal{O}_{HB}$	$B_{\mu\nu}B^{\mu\nu}(H^\dagger H)$	$\mathcal{O}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger(D^\mu H)$
$\mathcal{O}_{2G}$	$-\frac{1}{2}(D_\mu G^{A\mu\nu})(D^\rho G_{\rho\nu}^{A})$	$\mathcal{O}_{H\widetilde{B}}$	$\widetilde{B}_{\mu\nu}B^{\mu\nu}(H^\dagger H)$	$\mathcal{O}''_{HD}$	$(H^\dagger H)D_\mu(H^\dagger i\overleftrightarrow{D}^\mu H)$
$\mathcal{O}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W_{\rho\nu}^{I})$	$\mathcal{O}_{HWB}$	$W_{\mu\nu}^{I}B^{\mu\nu}(H^\dagger\sigma^I H)$	H^6	
$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$	$\mathcal{O}_{H\widetilde{W}B}$	$\widetilde{W}_{\mu\nu}^{I}B^{\mu\nu}(H^\dagger\sigma^I H)$	$\mathcal{O}_H$	$(H^\dagger H)^3$
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Future work

BOSONIC SECTOR

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$\mathcal{O}_{3G}$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{HG}$	$G^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$	$\mathcal{O}_{DH}$	$(D_\mu D^\mu H)^\dagger(D_\nu D^\nu H)$
$\mathcal{O}_{3\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\widetilde{G}}$	$\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$	**H^4D^2**	
$\mathcal{O}_{3W}$	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HW}$	$W^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{3\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{H\widetilde{W}}$	$\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\dagger(H^\dagger D_\mu H)$
X^2D^2		$\mathcal{O}_{HB}$	$B_{\mu\nu}B^{\mu\nu}(H^\dagger H)$	$\mathcal{O}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger(D^\mu H)$
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$\mathcal{O}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W^I_{\rho\nu})$	$\mathcal{O}_{HWB}$	$W^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$	**H^6**	
$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$	$\mathcal{O}_{H\widetilde{W}B}$	$\widetilde{W}^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$	$\mathcal{O}_H$	$(H^\dagger H)^3$
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$$c^{(1)}_{H^4D^4} \to 2r^2_{BDH}$$

$$c^{(2)}_{H^4D^4} \to -2r^2_{BDH}$$

$$c^{(3)}_{H^4D^4} \to 0$$

$$c_{H\Box} \to c_{H\Box} + \frac{1}{2}g' r_{BDH} + \frac{1}{2}r'_{HD}$$

$$c_{HD} \to c_{HD} + 2g' r_{BDH}$$

$$D_\mu = \partial_\mu - ig' B_\mu$$

$$g' \to g'$$

$$c_{HB} \to c_{HB}$$

Future work

BOSONIC SECTOR

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$\mathcal{O}_{3G}$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{HG}$	$G^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$	$\mathcal{O}_{DH}$	$(D_\mu D^\mu H)^\dagger(D_\nu D^\nu H)$
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Fermions ✓

Evanescent operators

Notice that …

Reduction of the Green's basis

- Field redefinitions and EOMs
  - Non-systematic
  - Highly non-lineal
- On-Shell matching approach
  - Systematic
  - Algebraic system of linear equations

Notice that ...

Reduction of the Green's basis

Field redefinitions and EOMs
- Non-systematic
- Highly non-trivial

On-Shell matching approach
- Systematic
- Algebraic system of linear equations

The reduction of **ANY** theory to **ANY** physical basis will be completely **AUTOMATIC**

Universidad de Granada

High Energy Theory

THANKS FOR YOUR ATTENTION !

Generation of random momenta

$$SL(2,\mathbb{C}) \cong SU(2)_L \times SU(2)_R \quad \left\{ \begin{array}{c} \lambda \in SU(2)_L \\ \tilde{\lambda} \in SU(2)_R \end{array} \right\} \quad \begin{array}{l} \lambda^\alpha = \varepsilon^{\alpha\beta}\lambda_\beta \\ \tilde{\lambda}_{\dot{\alpha}} = \varepsilon_{\dot{\alpha}\dot{\beta}}\tilde{\lambda}^{\dot{\beta}} \end{array}$$

Massless momenta : $P_{\alpha\dot{\alpha}} = \lambda_\alpha \tilde{\lambda}_{\dot{\alpha}}$ $\Rightarrow$ $P = p_\mu \sigma^\mu = \begin{pmatrix} p_0 + p_3 & p_1 - ip_2 \\ p_1 + ip_2 & p_0 - p_3 \end{pmatrix}$

Massive momenta : $P^\mu := q^\mu + \dfrac{m^2}{2q \cdot k} k^\mu$

$$\left| \begin{array}{rcl} q^2, k^2 & = & 0 \\ q_{\alpha\dot{\alpha}} & = & \lambda_\alpha \tilde{\lambda}_{\dot{\alpha}} \\ k_{\alpha\dot{\alpha}} & = & \mu_\alpha \tilde{\mu}_{\dot{\alpha}} \end{array} \right.$$

Evanescent operators

$\mathcal{R}=\alpha\,\mathcal{O}$ $\xrightarrow{d=4-2\epsilon}$ $\mathcal{R}=\alpha\mathcal{O}+\mathcal{E}$

$\mathcal{O}(\epsilon)$

Additional finite local contributions in loop amplitudes

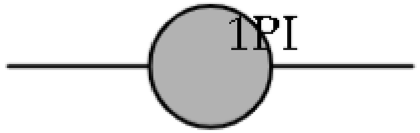
$$\boldsymbol{IR^{(0)}+IR^{(1)}=UV^{(0)}+UV^{(1)}}$$

$$\boldsymbol{IR^{(0)}+\boxed{IR^{(1)}_{soft}}=UV^{(0)}+UV^{(1)}_{hard}+\boxed{UV^{(1)}_{soft}}}$$

We take the hard region

$$\int \mathcal{R}-\mathcal{O}=\frac{1}{\epsilon}(b_{\mathcal{R}}\epsilon-b_{\mathcal{O}}\epsilon)=b$$

$$\int \mathcal{O}=\frac{1}{\epsilon}(a+b_{\mathcal{O}}\epsilon) \qquad \int \mathcal{R}=\frac{1}{\epsilon}(a+b_{\mathcal{R}}\epsilon)$$



$$= \frac{i}{p^2 - m^2 - \Pi(p^2)} = \frac{iZ}{p^2 - m^2_{phys}} + \ldots\,,$$

$$p^2 - m^2 - \Pi(p^2)\Big|_{p^2 = m^2_{phys}} = 0$$

$$\Pi(p^2) = \Pi(m^2_{phys}) + \Pi'(m^2_{phys})(p^2 - m^2_{phys}) + \ldots$$

$$\frac{i}{p^2 - m^2 - \Pi(p^2)} = \frac{i}{p^2 - m^2 - \left(\Pi(m^2_{phys}) + \Pi'(m^2_{phys})(p^2 - m^2_{phys}) + \ldots\right)}$$

$$= \frac{i}{\left(p^2 - m^2_{phys}\right)\left(1 - \Pi'(m^2_{phys}) + \ldots\right)} \sim \frac{i\left(1 - \Pi'(m^2_{phys})\right)^{-1}}{\left(p^2 - m^2_{phys}\right)}$$