Computational Tools and Methods in EFT

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YOUNGST@RS — EFTs and Beyond
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b
UNIVERSITÄT
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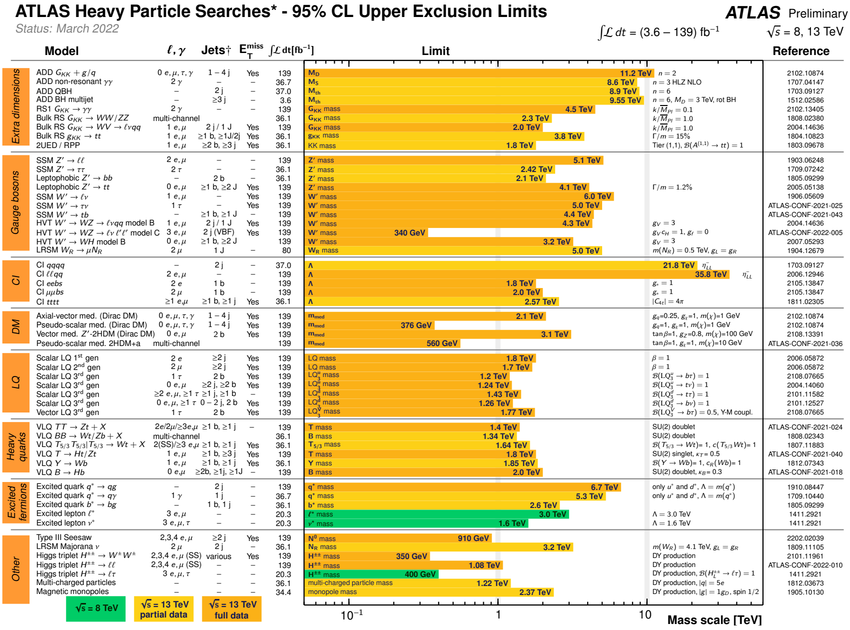
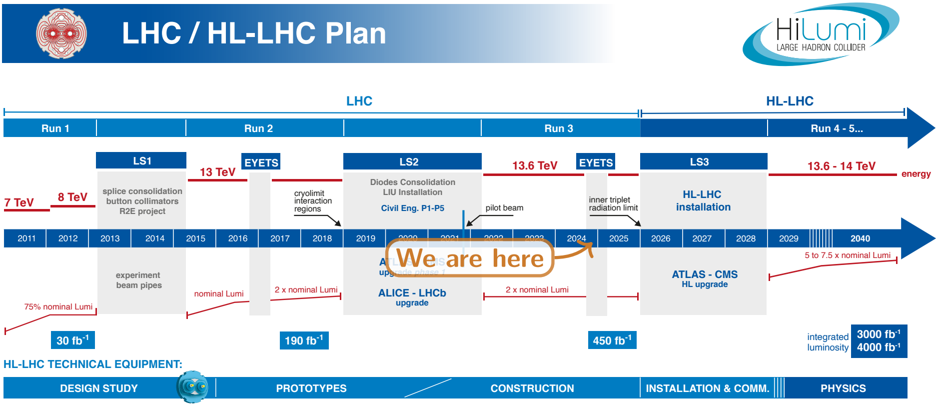
Introduction

EFTs beyond the Standard Model

Direct searches for new physics



Lots of luminosity



- Marginal increase in energy, but **$\sim 20\times$ more int. luminosity!**
- Rather than looking for resonances, we can look for **traces of new physics**

Probing high-scales through precision

W/ U(2)^5 flavor assumption

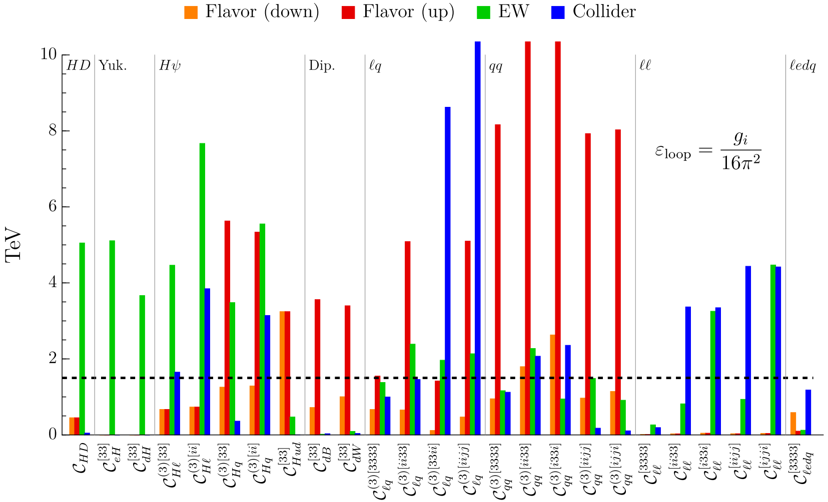
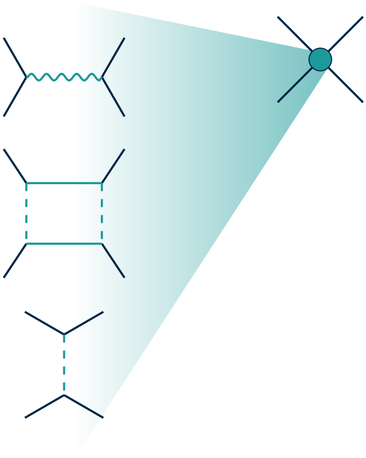


Figure from Allwicher *et al.* [2311.00020]

Effective field theory

High-energy physics manifests as contact interactions in EFTs



UV Physics

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{D=5} \sum_{k} \frac{C_{D,k}}{\Lambda^{D-4}} \mathcal{O}_{D,k}$$

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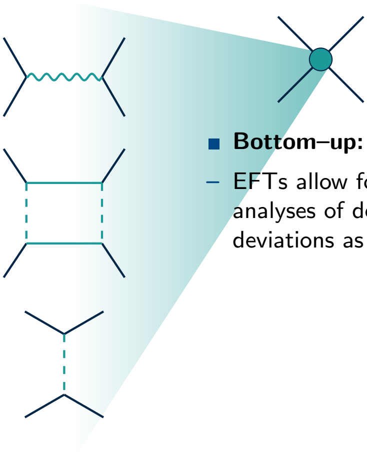

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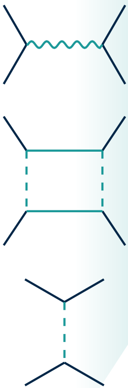

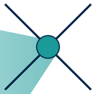

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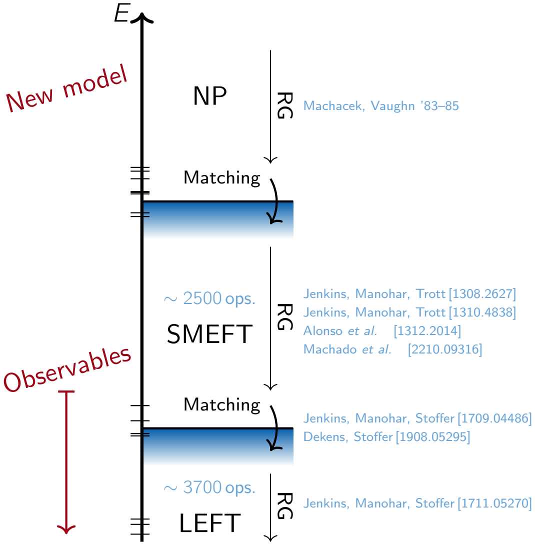
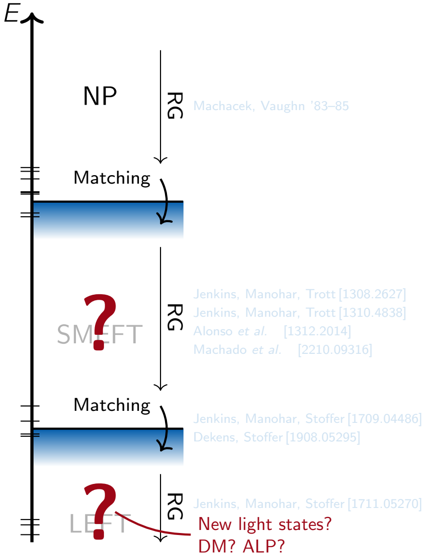
  - EFTs allow for **model-comprehensive** ("model-independent") analyses of deviations from the SM, quantifying possible deviations as an expansion in E/Λ
- **Top–down:**
  - **Precision calculations** necessitates the use of EFTs to separate the large BSM energy scales
  - Many BSM models result in the same EFT and **calculations can be recycled**: you only need to compute once in the EFT

BSM EFT workflow



Operators interfere and mix: it's difficult to confine analyses

BSM EFT workflow



A lot of work must be redone when switching EFT

The case for automation

NASA's human computers

- Proliferation of operators $\implies$ proliferation of work
- Tasks are **repetitive and error prone** and resources are limited

The case for automation

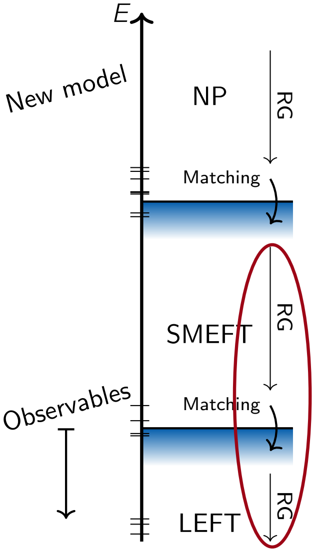
The (SM)EFT software project:

Upgrading from “computers” to computers

Automating EFT calculations

A tool for every occasion

Automating EFT analysis



Evolving SMEFT coefficients:

DsixTools
Fuentes-Martín *et al.* [2010.16341]

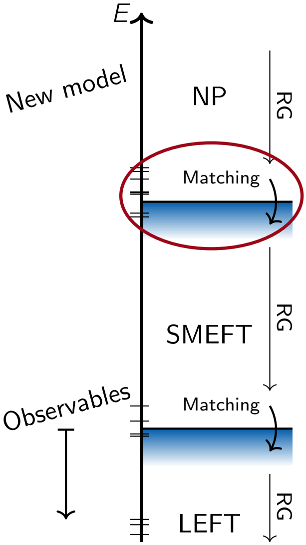
wilson
Aebischer *et al.* [1804.05033]

RGEsolver
Di Noi, Silvestrini [2210.06838]

Common interface format:

WCxf
Aebischer *et al.* [1712.05298]

Automating EFT analysis



One-loop matching tools:

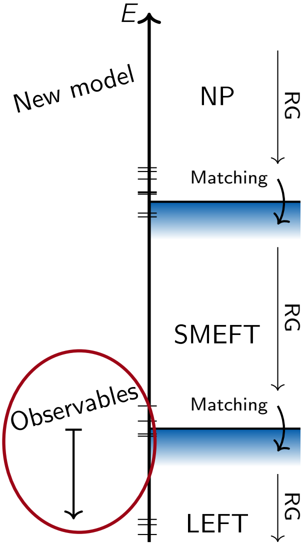
MATCHETE
AET *et al.* [2212.04510]

Carmona *et al.* [2112.10787]

One-loop dictionaries:

Guedes *et al.* [2303.16965]

Automating EFT analysis



SMEFT in event generators:

SMEFT@NLO
Degrande *et al.* [2008.11743]

SmeftFR
Dedes *et al.* [2302.01353]

SMEFTsim
Brivio [2012.11343]

Fitting tools:

Staub [1810.08132]

EOS
van Dyk *et al.* [2111.15428]

Aebischer *et al.* [1810.07698]

HEPfit
de Blas *et al.* [1910.14012]

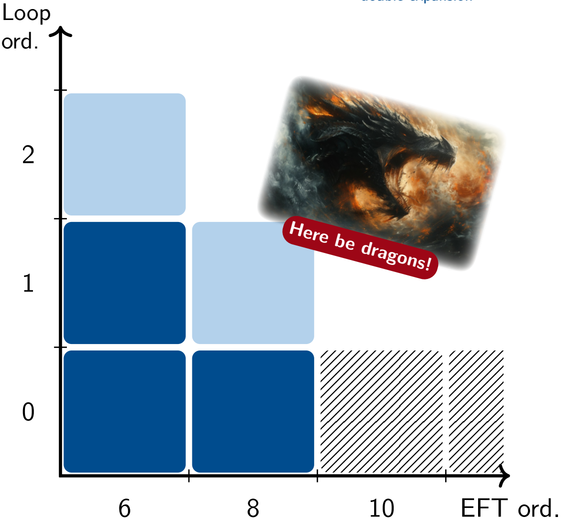
SMEFiT
Ellis *et al.* [2012.02779]

HighPT
Allwicher *et al.* [2207.10756]

Fitmaker
Ellis *et al.* [2012.02779]

SMEFT status

$$\mathcal{L}_{\mathsf{SMEFT}}(\phi) = \mathcal{L}_{d=4}(\phi) + \sum_{d=5}^{\infty}\sum_{\ell=0}^{\infty}\sum_{k} \underbrace{\frac{C_{d,k}^{(\ell)}}{(16\pi^2)^{\ell}\,\Lambda^{d-4}}}_{\text{double expansion}} \mathcal{O}_{d,k}^{(\ell)}(\phi)$$



What EFT?

- Determine what EFT you are working with
  - What are the relevant DOFs?
  - What is the counting? (mass dimension, derivatives, ...)

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- Determine an operator basis
  - Number of SMEFT generators (1 gen., dim. 6):

$$\underset{\text{Buchmüller, Wyler '86}}{80} \; (1986) \quad \longrightarrow \quad \underset{\text{Grzadkowski } et\ al.\ [1008.4884]}{59} \; (2017)$$

  - Counting operator has been “solved” with Hilbert-series techniques

Lehman, Martin [1503.07537]; Henning *et al.* [1507.07240]

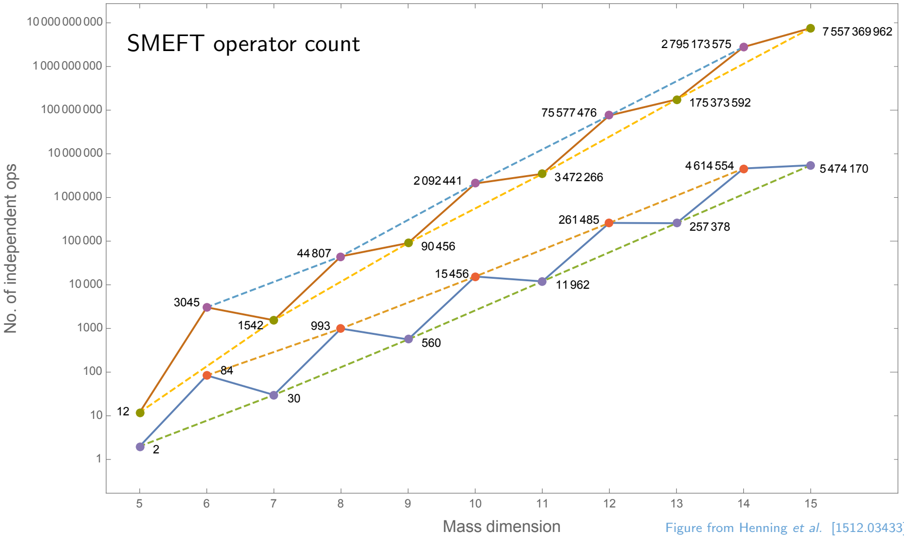

Figure from Henning *et al.* [1512.03433]

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$9: \psi^2 X^2 H + \text{h.c.}$		$9: \psi^2 X^2 H + \text{h.c.}$	
$Q^{(1)}_{leG^2H}$	$(\bar{l}_p e_r) H G^A_{\mu\nu} G^{A\mu\nu}$	$Q^{(1)}_{leWBH}$	$(\bar{l}_p e_r)\tau^I H W^I_{\mu\nu} B^{\mu\nu}$
$Q^{(2)}_{leG^2H}$	$(\bar{l}_p e_r) H \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	$Q^{(2)}_{leWBH}$	$(\bar{l}_p e_r)\tau^I H \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$
$Q^{(1)}_{leW^2H}$	$(\bar{l}_p e_r) H W^I_{\mu\nu} W^{I\mu\nu}$	$Q^{(3)}_{leWBH}$	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\rho} B_\nu{}^\rho$
$Q^{(2)}_{leW^2H}$	$(\bar{l}_p e_r) H \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$	$Q^{(1)}_{leB^2H}$	$(\bar{l}_p e_r) H B_{\mu\nu} B^{\mu\nu}$
$Q^{(3)}_{leW^2H}$	$\epsilon^{IJK}(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W^J_{\mu\rho} W^{K\rho}_\nu$	$Q^{(2)}_{leB^2H}$	$(\bar{l}_p e_r) H \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$Q^{(1)}_{quG^2H}$	$(\bar{q}_p u_r) \widetilde{H} G^A_{\mu\nu} G^{A\mu\nu}$	$Q^{(1)}_{qdG^2H}$	$(\bar{q}_p d_r) H G^A_{\mu\nu} G^{A\mu\nu}$
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$Q^{(3)}_{quG^2H}$	$d^{ABC}(\bar{q}_p T^A u_r) \widetilde{H} G^B_{\mu\nu} G^{C\mu\nu}$	$Q^{(3)}_{qdG^2H}$	$d^{ABC}(\bar{q}_p T^A d_r) H G^B_{\mu\nu} G^{C\mu\nu}$

dim-8 SMEFT basis
Murphy [2005.00059]

Find a basis

Current situation: computer packages to automate the EFT basis construction

Fonseca [1703.05221]

Harlander, Schaad [2309.15783]

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Additional complications

- Green's bases vs. on-shell basis
- Mapping between/reducing to bases (partial + upcoming routines of)

- Evanescent operators: loop calculations required for basis transformations

Simplification and basis reduction

$$\mathcal{L} = -\tfrac{1}{2}\phi\partial^2\phi - \tfrac{1}{2}m^2\phi^2 - \frac{\lambda}{24}\phi^4 + \frac{C_1}{\Lambda^2}\phi^6 + \frac{C_2}{\Lambda^2}\phi^3\partial^2\phi + \frac{C_3}{\Lambda^2}\phi^2(\partial_\mu\phi)^2$$

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Exact simplification (linear):

IBP, Dirac algebra, group identities, commutation relations,...

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On-shell equivalence (non-linear):

Field redefinition: $\phi \longrightarrow \phi + \frac{3C_2 - C_3}{3\Lambda^2}\phi^3$

$$\mathcal{L} \longrightarrow -\tfrac{1}{2}\phi\partial^2\phi - \tfrac{1}{2}m^2\phi^2 - \left(\frac{\lambda}{24} + \frac{(3C_2 - C_3)\, m^2}{3\Lambda^2}\right)\phi^4 + \frac{18C_1 - \lambda(3C_2 - C_3)}{18\Lambda^2}\phi^6$$

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Removal of evanescent operators: complicated but solved

Buras, Weisz '90; Dugan, Grinstein '91; Herrlich, Nierste [hep-ph/9412375]; Aebischer *et al.* [2211.01379]; **AET** *et al.* [2211.09144];...

Linear simplifications (as in Matchete)

Example: Integrating out heavy fermion in the fundamental representation of SU(3)

In[12]:=
```
LEFT // NiceForm
```

Out[12]//NiceForm=

$$\frac{7}{540}\,\hbar\,g^2\,\frac{1}{M\Psi^2}\,\left(D_\rho G^{\mu\nu A}\right)^2 + \frac{1}{40}\,\hbar\,g^2\,\frac{1}{M\Psi^2}\,G^{\mu\nu A}\,D^2 G^{\mu\nu A} + \frac{7}{540}\,\hbar\,g^2\,\frac{1}{M\Psi^2}\,D_\rho G^{\mu\nu A}\,D_\nu G^{\mu\rho A} - \frac{1}{180}\,\hbar\,g^2\,\frac{1}{M\Psi^2}\,D_\nu G^{\mu\nu A}\,D_\rho G^{\mu\rho A} + \frac{1}{40}\,\hbar\,g^2\,\frac{1}{M\Psi^2}\,G^{\mu\nu A}\,D_\nu D_\rho G^{\mu\rho A} + \frac{1}{40}\,\hbar\,g^2\,\frac{1}{M\Psi^2}\,G^{\mu\nu A}\,D_\rho D_\nu G^{\mu\rho A} - \frac{1}{24}\,\hbar\,g^3\,\frac{1}{M\Psi^2}\,G^{\mu\nu A}\,G^{\mu\rho B}\,G^{\nu\rho C}\,f^{ABC}$$

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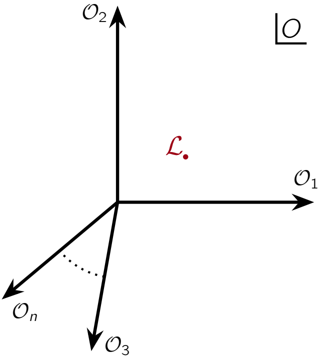

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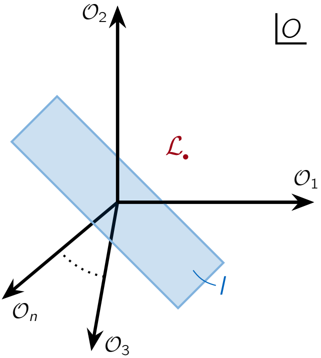

$I \subseteq O$ is the space of all operator identities, e.g., IBP relations such as

$$\mathcal{O}_1 + 2\mathcal{O}_3 = 0$$

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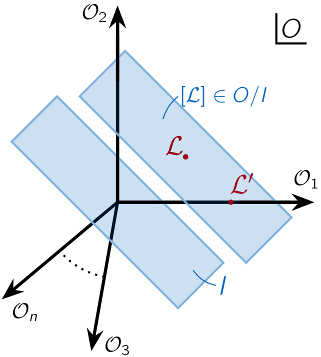

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$$\mathcal{L}_{\text{EFT}} = \sum_i C_i \mathcal{O}_i \in O$$

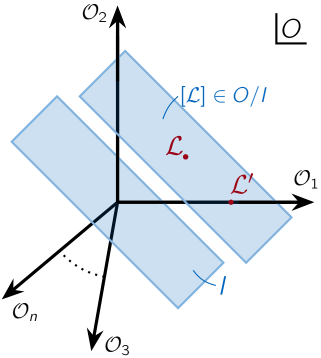
With **linear algebra** on the basis of I we find a simple representative element for $[\mathcal{L}_{\text{EFT}}] \in O/I$:

In[13]:= `LEFT // GreensSimplify // NiceForm`

Out[13]//NiceForm=

$$-\frac{1}{15}\hbar g^2 \frac{1}{M\Psi^2} D_\nu G^{\mu\nu A} D_\rho G^{\mu\rho A} - \frac{1}{180}\hbar g^3 \frac{1}{M\Psi^2} G^{\mu\nu A} G^{\mu\rho B} G^{\nu\rho C} f^{ABC}$$

Green's basis



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EFT fits

Fitmaker

$$-2\ln L \sim \sum_{\text{obs}} \left(\frac{O_{\text{exp}} - O_{\text{th}}(\{C_i\})}{\Delta O} \right)^2$$

- Implementation of 100(0)s of observables: theory prediction + exp. results
- Handling of theoretical and experimental errors (with non-trivial correlations)
- Observables across different energy scales

EFT fits

EOS HEPfit SMEFiT Fitmaker HighPT

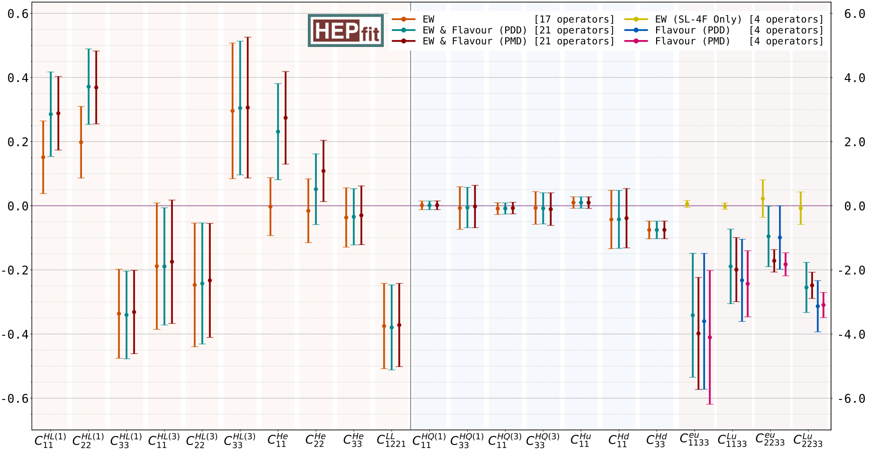


Figure from Alasfar *et al.* [2007.04400]

EFT fits

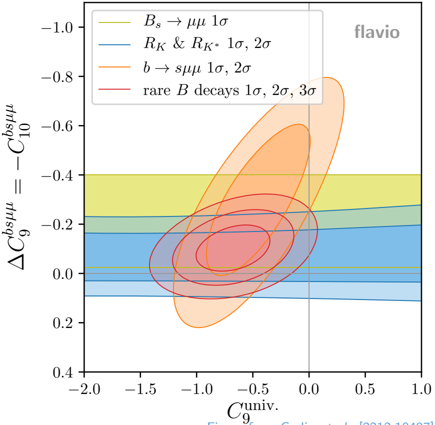
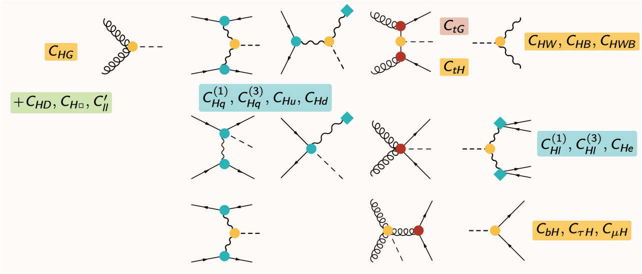


Figure from Greljo *et al.* [2212.10497]

SMEFT in event generators

SMEFT@NLO SMEFTsim SmeftFR

- SMEFT Feynman rules
- Generation of models to MC event generators (e.g. MadGraph5_aMC@NLO)
- Input schemes and flavor structure



Slide from I. Brivio @ Higgs2021

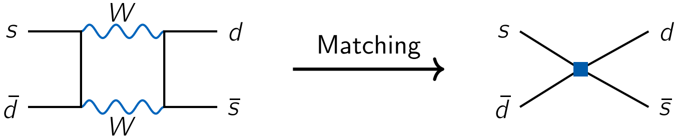
One-Loop Matching

Automation and techniques

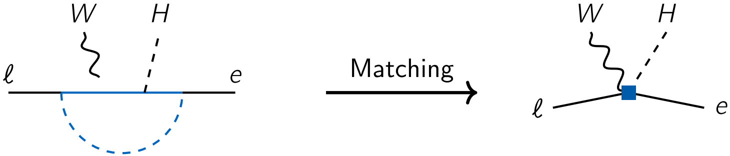
Matching beyond tree level

One-loop matching is often the **leading contribution** from high-scale physics

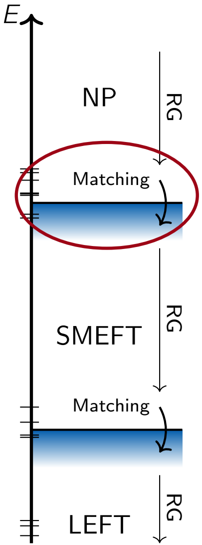
- FCNCs in the SM



- In BSM models: dipoles, FCNCs, EW precision, ...



Matching weakly coupled theories

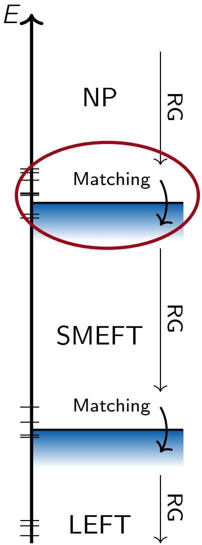


$\mathcal{L}_{\text{EFT}}$ should reproduce the physics of $\mathcal{L}_{\text{UV}}$ at energies $E \ll \Lambda$:

$$\mathcal{L}_{\text{UV}}(\Phi,\, \phi) \xrightarrow{\text{Off-shell matching}} \mathcal{L}_{\text{EFT}}(\phi)$$

$$\mathcal{L}_{\text{EFT}}(\phi) = \mathcal{L}_{d=4}(\phi) + \sum_{d=5}^{\infty} \sum_{\ell=0}^{\infty} \sum_{k} \underbrace{\frac{C_{d,k}^{(\ell)}}{(16\pi^2)^{\ell}\, \Lambda^{d-4}}}_{\text{double expansion}} \mathcal{O}_{d,k}^{(\ell)}(\phi)$$

Matching weakly coupled theories



$\mathcal{L}_{\text{EFT}}$ should reproduce the physics of $\mathcal{L}_{\text{UV}}$ at energies $E \ll \Lambda$:

Off-shell matching: $\mathcal{L}_{\text{UV}}(\Phi,\, \phi) \longrightarrow \mathcal{L}_{\text{EFT}}(\phi)$

$\mathcal{L}_{\text{UV}}(\Phi,\, \phi) \downarrow \Gamma_{\text{UV}}\big[\widehat{\Phi}(\phi),\, \phi\big] \simeq \Gamma_{\text{EFT}}[\phi]$

Diagramatic: $\Gamma_{\text{UV}} \nearrow \mathcal{L}_{\text{EFT}}(\phi)$

$\mathcal{L}_{\text{EFT}}(\phi) \downarrow \Gamma_{\text{EFT}}[\phi]$ (Tree level only)

$$\mathcal{L}_{\text{EFT}}(\phi) = \mathcal{L}_{d=4}(\phi) + \sum_{d=5}^{\infty} \sum_{\ell=0}^{\infty} \sum_{k} \underbrace{\frac{C_{d,k}^{(\ell)}}{(16\pi^2)^\ell\, \Lambda^{d-4}}}_{\text{double expansion}} \mathcal{O}_{d,k}^{(\ell)}(\phi)$$

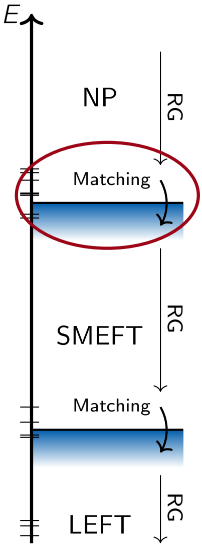
Hard-region matching formula

$$S_{\text{EFT}}[\phi] = \Gamma_{\text{UV}}[\widehat{\Phi},\, \phi]\Big|_{\text{hard}}, \qquad \frac{\delta \Gamma_{\text{UV}}|_{\text{hard}}}{\delta \Phi}[\widehat{\Phi},\, \phi] = 0$$

"hard" denotes the part without *any* soft loop momenta (it includes all tree-level contributions)

Fuentes-Martin *et al.* [1607.02142]; Zhang [1610.00710]; Fuentes-Martin, Palavrić, **AET** [2311.13630]

Matching weakly coupled theories



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Functional

MATCHETE

$$\mathcal{L}_{\text{EFT}}(\phi) = \mathcal{L}_{d=4}(\phi) + \sum_{d=5}^{\infty} \sum_{\ell=0}^{\infty} \sum_{k} \underbrace{\frac{C_{d,k}^{(\ell)}}{(16\pi^2)^{\ell}\, \Lambda^{d-4}}}_{\text{double expansion}} \mathcal{O}_{d,k}^{(\ell)}(\phi)$$

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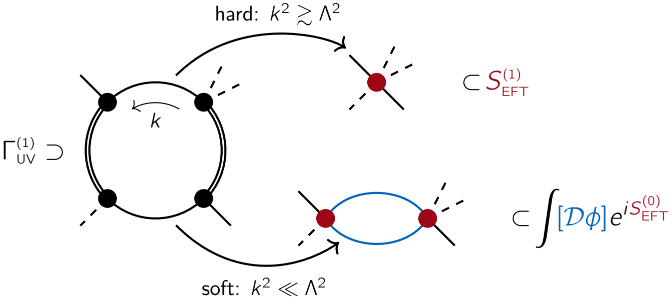
Separation of scales

Mixed (heavy–light) loop example:



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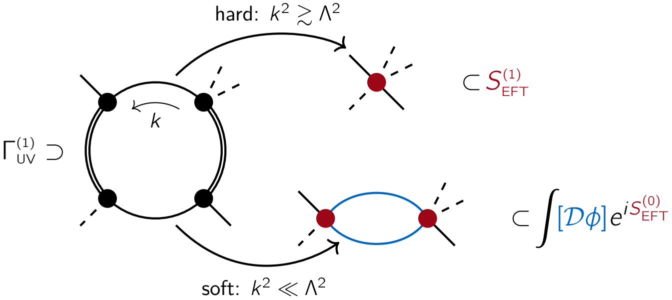


- $\Gamma^{(1)}_{\text{UV}}\big|_{\text{soft}}$: long-distance contributions included in 1-loop matrix elements of tree-level EFT operators

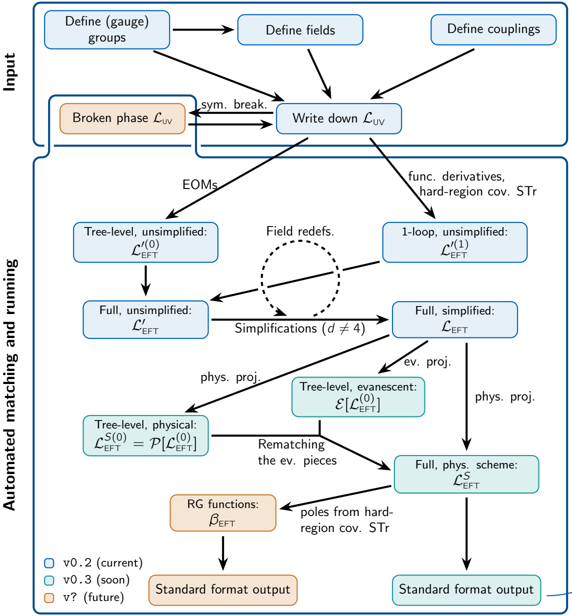
$$\Gamma^{(1)}_{\text{UV}}\big|_{\text{soft}} = \Gamma^{(1)}_{\text{EFT}}$$

- $\Gamma^{(1)}_{\text{UV}}\big|_{\text{hard}}$: short-distance contributions going into the EFT operators

Fuentes-Martin *et al.* [1607.02142]; Zhang [1610.00710]

$$\Gamma^{(1)}_{\text{UV}}\big|_{\text{hard}} = S^{(1)}_{\text{EFT}}$$

MATCHETE



Currently with

Please get in touch!

Example: SM + Vector-like lepton

Setup

SM Lagrangian

In[3]:=
```
LSM = LoadModel["SM"];
```

Define new field

In[4]:=
```
DefineField[EE, Fermion, Charges → {U1Y[-1]}, Mass → {Heavy, ME}]
```

Define new coupling

In[5]:=
```
DefineCoupling[yE, EFTOrder → 0, Indices → {Flavor}]
```

Write interactions

In[6]:=
```
Lint = -yE[p] × Bar@l[i, p] ** PR ** EE[] × H[i] // PlusHc;
Lint // NiceForm
```

Out[7]//NiceForm=

$$-\overline{yE}^{p}\,\bar{H}_{i}\,\left(\overline{EE}\cdot P_{L}\cdot l^{ip}\right)-yE^{p}\,H^{i}\,\left(\bar{l}^{p}_{i}\cdot P_{R}\cdot EE\right)$$

Define full UV Lagrangian

In[8]:=
```
LUV = LSM + FreeLag[EE] + Lint;
LUV // NiceForm
```

Out[9]//NiceForm=

$$-\frac{1}{4}B^{\mu\nu 2}-\frac{1}{4}G^{\mu\nu A2}-\frac{1}{4}W^{\mu\nu I2}+D_{\mu}\bar{H}_{i}\,D_{\mu}H^{i}+\mu^{2}\,\bar{H}_{i}\,H^{i}+i\left(\bar{d}^{p}_{a}\cdot\gamma_{\mu}\,P_{R}\cdot D_{\mu}d^{ap}\right)+i\left(\bar{e}^{p}\cdot\gamma_{\mu}\,P_{R}\cdot D_{\mu}e^{p}\right)+$$
$$i\left(\overline{EE}\cdot\gamma_{\mu}\cdot D_{\mu}EE\right)-ME\left(\overline{EE}\cdot EE\right)+i\left(\bar{l}^{p}_{i}\cdot\gamma_{\mu}\,P_{L}\cdot D_{\mu}l^{ip}\right)+i\left(\bar{q}^{p}_{ai}\cdot\gamma_{\mu}\,P_{L}\cdot D_{\mu}q^{aip}\right)+i\left(\bar{u}^{p}_{a}\cdot\gamma_{\mu}\,P_{R}\cdot D_{\mu}u^{ap}\right)-$$
$$\frac{1}{2}\lambda\,\bar{H}_{i}\,\bar{H}_{j}\,H^{i}\,H^{j}-\overline{Yd}^{pr}\,\bar{H}_{i}\left(\bar{d}^{r}_{a}\cdot P_{L}\cdot q^{aip}\right)-\overline{Ye}^{pr}\,\bar{H}_{i}\left(\bar{e}^{r}\cdot P_{L}\cdot l^{ip}\right)-Ye^{pr}\,H^{i}\left(\bar{l}^{p}_{i}\cdot P_{R}\cdot e^{r}\right)-Yd^{pr}\,H^{i}\left(\bar{q}^{p}_{ai}\cdot P_{R}\cdot d^{ar}\right)-$$
$$Yu^{pr}\,\bar{H}_{i}\left(\bar{q}^{p}_{aj}\cdot P_{R}\cdot u^{ar}\right)\varepsilon^{ji}-\overline{Yu}^{pr}\,H^{j}\left(\bar{u}^{r}_{a}\cdot P_{L}\cdot q^{aip}\right)\bar{\varepsilon}_{ij}-\overline{yE}^{p}\,\bar{H}_{i}\left(\overline{EE}\cdot P_{L}\cdot l^{ip}\right)-yE^{p}\,H^{i}\left(\bar{l}^{p}_{i}\cdot P_{R}\cdot EE\right)$$

Example: SM + Vector-like lepton

Main matching routine

In[9]:=
```
LEFT = Match[LUV, LoopOrder → 1, EFTOrder → 6] /. ϵ^-1 → 0;
```

Simplification to on-shell basis

In[10]:=
```
LEFTOnShell = LEFT // EOMSimplify;
Length@%
```

» The Lagrangian contains terms of lower power than dimension 4. Defining effective couplings and assuming these terms to be dimension 4. Use 'PrintEffectiveCouplings' and 'ReplaceEffectiveCouplings' to recover explicit expressions.

» Added new CG cg1 with indices {Bar[SU2L[fund]], SU2L[adj], Bar[SU2L[fund]]}

Out[11]= 66

Select Higgs-lepton current operator

In[12]:=
```
SelectOperatorClass[LEFTOnShell, {e, Bar@e, H, Bar@H}, 1] // GreensSimplify // NiceForm
```

Out[12]//NiceForm=

$$\frac{i}{360}\hbar\frac{1}{\mathrm{ME}^2}\left(48\,\mathrm{gY}^4\,\delta^{pr}+5\,\overline{\mathrm{yE}}^{s}\left(3\,\mathrm{yE}^{t}\,\overline{\mathrm{Ye}}^{tr}\,\mathrm{Ye}^{sp}\left(1+6\,\mathrm{Log}\left[\frac{\bar{\mu}^2}{\mathrm{ME}^2}\right]\right)-2\,\mathrm{yE}^{s}\,\mathrm{gY}^2\left(13+6\,\mathrm{Log}\left[\frac{\bar{\mu}^2}{\mathrm{ME}^2}\right]\right)\delta^{pr}\right)\right)$$
$$\left(-D_\mu\bar{H}_i\,H^i\left(\bar{e}^r\cdot\gamma_\mu\,P_R\cdot e^p\right)+\bar{H}_i\,D_\mu\,H^i\left(\bar{e}^r\cdot\gamma_\mu\,P_R\cdot e^p\right)\right)$$

$$Q_{He}^{pr}=(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$$

Example: SM + Vector-like lepton

```
LEFTOnShell // NiceForm
```

iceForm=

$$-\frac{1}{4} G^{\mu\nu A2} - \frac{1}{4} W^{\mu\nu I2} + (-\frac{1}{4} - \frac{1}{3}\hbar\, gY^2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])\, B^{\mu\nu 2} + D_\mu\bar{H}_i\, D_\mu H^i + (C_{H2} + \frac{1}{6}\hbar\, \overline{yE}^p\, yE^p\, C_{H2}\, \frac{1}{ME^2}\, (2\, C_{H2} - 3\, ME^2\, (1 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])))\, \bar{H}_i H^i + i\, (\bar{d}^r_a\cdot\gamma_\mu P_R\cdot D_\mu d^{ap})\, \delta^{pr} + i\, (\bar{e}^r\cdot\gamma_\mu P_R\cdot D_\mu e^p)\, \delta^{pr} +$$

$$i\, (\bar{l}^r_i\cdot\gamma_\mu P_L\cdot D_\mu l^{ip})\, \delta^{pr} + i\, (\bar{q}^r_{ai}\cdot\gamma_\mu P_L\cdot D_\mu q^{aip})\, \delta^{pr} + i\, (\bar{u}^r_a\cdot\gamma_\mu P_R\cdot D_\mu u^{ap})\, \delta^{pr} + (-\frac{1}{2}\lambda + \hbar\, (-\frac{1}{2}\overline{yE}^p\, (4\, yE^r\, \overline{Ye}^{rs}\, Ye^{ps}\, (1 + \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])) - yE^p\, (-2\, \overline{yE}^r\, yE^r\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}] + \lambda\, (1 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])))) -$$

$$\frac{1}{180} C_{H2}\, \frac{1}{ME^2}\, (12\, gY^4 - 5\, \overline{yE}^p\, yE^p\, gY^2\, (13 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) + 5\, \overline{yE}^p\, (-12\, (\overline{yE}^r\, yE^p\, yE^r + 6\, yE^r\, \overline{Ye}^{rs}\, Ye^{ps} - 2\, yE^p\, \lambda) + yE^p\, gL^2\, (5 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))))))$$

$$\bar{H}_i \bar{H}_j H^i H^j + (-\overline{Yd}^{pr} + \frac{1}{12}\hbar\, \overline{yE}^s\, yE^s\, \overline{Yd}^{pr}\, \frac{1}{ME^2}\, (-4\, C_{H2} + 3\, ME^2\, (1 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))))\, \bar{H}_i\, (\bar{d}^r_a\cdot P_L\cdot q^{aip}) +$$

$$(-\overline{Ye}^{pr} + \frac{1}{24}\hbar\, yE^s\, \frac{1}{ME^2}\, (-3\, \overline{yE}^p\, \overline{Ye}^{sr}\, (2\, C_{H2} - ME^2)\, (3 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) + 2\, \overline{yE}^s\, \overline{Ye}^{pr}\, (-4\, C_{H2} + 3\, ME^2\, (1 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])))))\, \bar{H}_i\, (\bar{e}^r\cdot P_L\cdot l^{ip}) +$$

$$(-Ye^{rp} + \frac{1}{24}\hbar\, \overline{yE}^s\, \frac{1}{ME^2}\, (3\, ME^2\, (2\, yE^s\, Ye^{rp}\, (1 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) + yE^r\, Ye^{sp}\, (3 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])) - 2\, C_{H2}\, (4\, yE^s\, Ye^{rp} + 3\, yE^r\, Ye^{sp}\, (3 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])))))\, H^i\, (\bar{l}^r_i\cdot P_R\cdot e^p) +$$

$$(-Yd^{rp} + \frac{1}{12}\hbar\, \overline{yE}^s\, yE^s\, Yd^{rp}\, \frac{1}{ME^2}\, (-4\, C_{H2} + 3\, ME^2\, (1 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))))\, H^i\, (\bar{q}^r_{ai}\cdot P_R\cdot d^{ap}) +$$

$$(-Yu^{rp} + \frac{1}{12}\hbar\, \overline{yE}^s\, yE^s\, Yu^{rp}\, \frac{1}{ME^2}\, (-4\, C_{H2} + 3\, ME^2\, (1 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))))\, \bar{H}_i\, (\bar{q}^r_{aj}\cdot P_R\cdot u^{ap})\, \varepsilon^{ji} +$$

$$(-\overline{Yu}^{pr} + \frac{1}{12}\hbar\, \overline{yE}^s\, yE^s\, \overline{Yu}^{pr}\, \frac{1}{ME^2}\, (-4\, C_{H2} + 3\, ME^2\, (1 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))))\, H^j\, (\bar{u}^r_a\cdot P_L\cdot q^{aip})\, \bar{\varepsilon}_{ij} +$$

$$\frac{1}{180}\hbar\, \frac{1}{ME^2}\, (12\, \lambda\, gY^4 + 5\, \overline{yE}^p\, (12\, \overline{yE}^r\, yE^p\, (\overline{yE}^s\, yE^r\, yE^s + 6\, yE^s\, \overline{Ye}^{st}\, Ye^{rt} - yE^r\, \lambda) - 72\, yE^r\, \overline{Ye}^{rs}\, (Ye^{ps}\, \lambda + \overline{Ye}^{tu}\, Ye^{pu}\, Ye^{ts}\, (1 + \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))) + yE^p\, \lambda\, (12\, \lambda + gL^2\, (5 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) - gY^2\, (13 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])))))$$

$$\bar{H}_i \bar{H}_j \bar{H}_k H^i H^j H^k + \frac{1}{90}\hbar\, \frac{1}{ME^2}\, (-12\, gY^4 + 5\, \overline{yE}^p\, yE^p\, gY^2\, (13 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) + 45\, \overline{yE}^p\, yE^r\, (-\overline{yE}^r\, yE^p + \overline{Ye}^{rs}\, Ye^{ps}\, (1 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))))\, \bar{H}_i\, D_\mu\bar{H}_j\, D_\mu H^i H^j +$$

$$\frac{1}{180}\hbar\, \frac{1}{ME^2}\, (-12\, gY^4 + 5\, \overline{yE}^p\, yE^p\, gY^2\, (13 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) - 15\, \overline{yE}^p\, (yE^p\, gL^2\, (5 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) + 4\, yE^r\, (2\, \overline{yE}^r\, yE^p - 3\, \overline{Ye}^{rs}\, Ye^{ps}\, (3 + 2\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])))))\, \bar{H}_i\, D_\mu\bar{H}_j\, H^i\, D_\mu H^j +$$

$$\frac{1}{8}\hbar\, \overline{yE}^p\, yE^p\, gY^2\, \frac{1}{ME^2}\, \bar{H}_i H^i B^{\mu\nu 2} - \frac{1}{3}\hbar\, gL\, gY\, \overline{yE}^p\, yE^p\, \frac{1}{ME^2}\, \bar{H}_i H^j B^{\mu\nu} W^{\mu\nu I} T^{Ii}_j + \frac{1}{24}\hbar\, \overline{yE}^p\, yE^p\, gL^2\, \frac{1}{ME^2}\, \bar{H}_i H^i W^{\mu\nu I2} +$$

$$\frac{1}{360}\hbar\, \overline{Yd}^{pr}\, \frac{1}{ME^2}\, (12\, gY^4 - 5\, \overline{yE}^s\, yE^s\, gY^2\, (13 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) + 5\, \overline{yE}^s\, (-12\, (\overline{yE}^t\, yE^s\, yE^t + 6\, yE^t\, \overline{Ye}^{tu}\, Ye^{su} - 2\, yE^s\, \lambda) + yE^s\, gL^2\, (5 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))))\, \bar{H}_i \bar{H}_j H^j\, (\bar{d}^r_a\cdot P_L\cdot q^{aip}) +$$

$$(\frac{1}{2}\overline{yE}^p\, yE^s\, \overline{Ye}^{sr}\, \frac{1}{ME^2} + \frac{1}{720}\hbar\, \frac{1}{ME^2}\, (30\, \overline{yE}^s\, yE^u\, \overline{Ye}^{pt}\, \overline{Ye}^{ur}\, Ye^{st}\, (37 + 18\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) - 45\, \overline{yE}^p\, (\overline{yE}^s\, yE^s\, yE^t\, \overline{Ye}^{tr}\, (19 + 18\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) + 4\, \overline{Ye}^{sr}\, (yE^t\, \overline{Ye}^{tu}\, Ye^{su} - 2\, yE^s\, \lambda\, (5 + 4\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])))) +$$

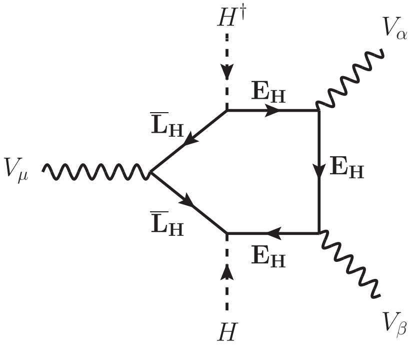
$$2\, \overline{Ye}^{pr}\, (12\, gY^4 - 5\, \overline{yE}^s\, yE^s\, gY^2\, (13 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) + 5\, \overline{yE}^s\, (-12\, (\overline{yE}^t\, yE^s\, yE^t + 6\, yE^t\, \overline{Ye}^{tu}\, Ye^{su} - 2\, yE^s\, \lambda) + yE^s\, gL^2\, (5 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))))))\, \bar{H}_i \bar{H}_j H^i\, (\bar{e}^r\cdot P_L\cdot l^{jp}) +$$

$$(\frac{1}{2}\overline{yE}^s\, yE^r\, Ye^{sp}\, \frac{1}{ME^2} + \frac{1}{720}\hbar\, \frac{1}{ME^2}\, (24\, Ye^{rp}\, gY^4 - 10\, \overline{yE}^s\, yE^s\, Ye^{rp}\, gY^2\, (13 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) + 5\, \overline{yE}^s\, (2\, yE^s\, Ye^{rp}\, gL^2\, (5 + 6\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]) - 3\, \overline{yE}^t\, yE^t\, (8\, yE^s\, Ye^{rp} + 3\, yE^r\, Ye^{sp}\, (19 + 18\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))) +$$

$$6\, (4\, \lambda\, (2\, yE^s\, Ye^{rp} + 3\, yE^r\, Ye^{sp}\, (5 + 4\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}])) + \overline{Ye}^{tu}\, (-6\, yE^r\, Ye^{su}\, Ye^{tp} + yE^t\, (-24\, Ye^{rp}\, Ye^{su} + Ye^{ru}\, Ye^{sp}\, (37 + 18\, \mathrm{Log}[\frac{\bar{\mu}^2}{ME^2}]))))))))\, \bar{H}_i H^i H^j\, (\bar{l}^r_i\cdot P_R\cdot e^p) +$$

Example: neutral triple gauge interactions

New physics in $Z(\gamma, Z)(\gamma^*, Z^*)$?



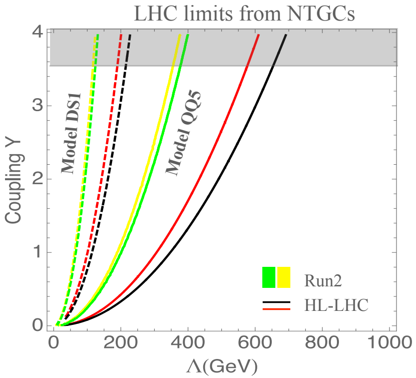


*Diagram and plot from [2402.04306]

22 BSM models with dimension-8 SMEFT contributions to NTG analyzed using **Matchete** by *Cepedello, Esser, Hirsch, and Sanz [2402.04306]*

Summary and outlook

- Broad range of dedicated EFT tools
- Computational tools enables phenomenological EFT analyses
- Software packages $\implies$ new validation possibilities
- Goal: better interfaces between tools
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Thank you!