Automating Matching to the SMEFT

Anders Eller Thomsen

With J. Fuentes-Martín, M. König, J. Pagès, and F. Wilsch

MATCHETE

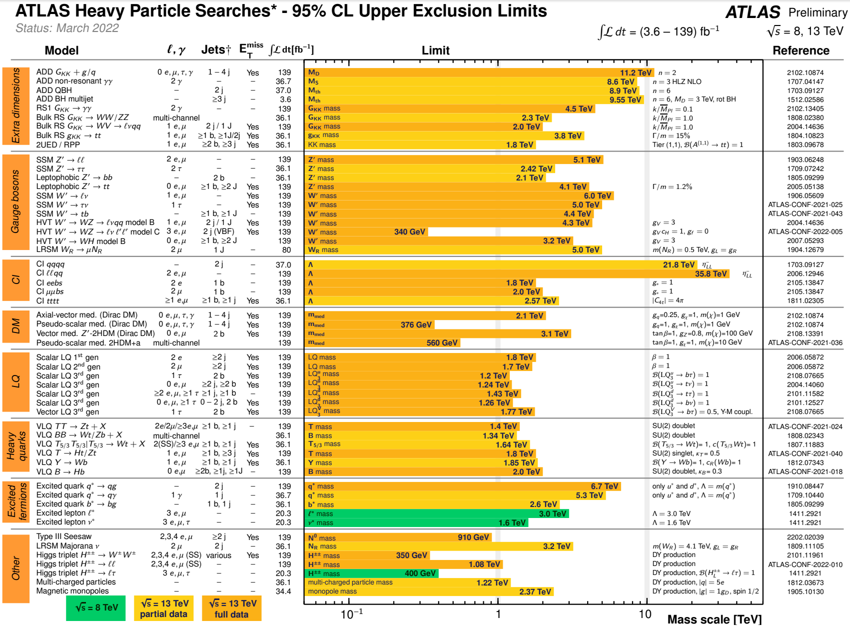
12th Edition of the Large Hadron Collider Physics Conference
3–7 June 2024, Boston

UNIVERSITÄT
BERN

AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

Swiss National
Science Foundation

Direct searches for new physics



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2022

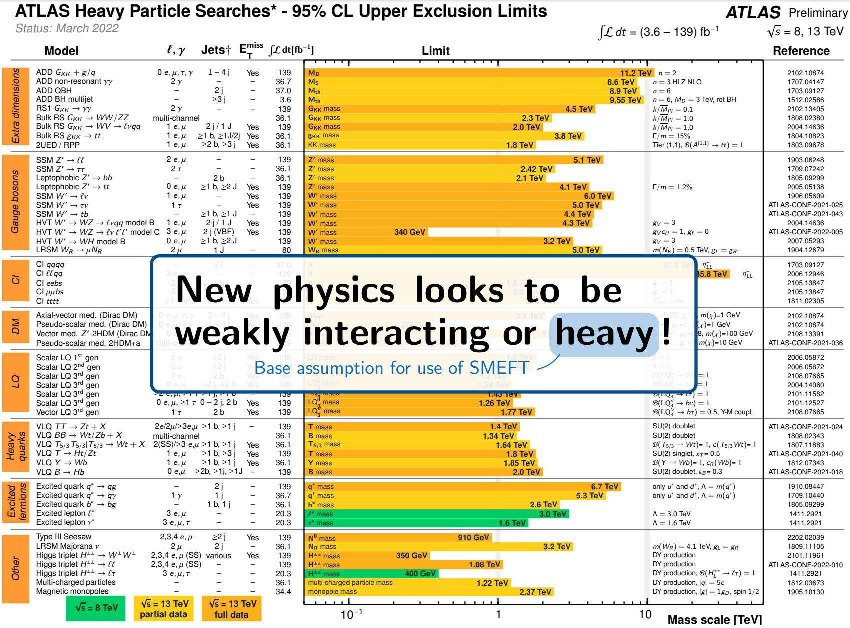
ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	🟧 M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	🟨 M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	🟨 M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH multijet	–	≥3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	139	🟧 G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	🟨 G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	🟧 G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥1 b, ≥1J/2j	Yes	36.1	🟨 g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥2 b, ≥3 j	Yes	36.1	🟨 KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	🟧 Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	🟨 Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	🟨 Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	🟧 Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	🟧 W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	🟧 W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	🟧 W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	🟧 W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\, \ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	🟧 W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	ATLAS-CONF-2022-005
	HVT $W' \to WH$ model B	0 e, μ	≥1 b, ≥2 J		139	🟧 W' mass 3.2 TeV	$g_V = 3$	2007.05293
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	🟨 W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	🟨 Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	🟧 Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	🟧 Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	🟧 Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	🟨 Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	🟧 m_{med} 2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	🟧 m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	🟧 m_{med} 3.1 TeV	tanβ=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	🟧 m_{med} 560 GeV	tanβ=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	🟧 LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	🟧 LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	🟧 LQ_3^u mass 1.2 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	2108.07665
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	🟧 LQ_3^u mass 1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	🟧 LQ_3^d mass 1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	🟧 LQ_3^d mass 1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$	2101.12527
	Vector LQ 3rd gen	1 τ	2 b	Yes	139	🟧 LQ_3^V mass 1.77 TeV	$\mathcal{B}(\mathrm{LQ}_3^V \to b\tau) = 0.5$, Y-M coupl.	2108.07665
Heavy quarks	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	🟧 T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	🟨 B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	🟨 $T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	🟧 T mass 1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	🟨 Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	🟧 B mass 2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	🟧 q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	🟨 q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	🟨 b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	🟧 N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	🟨 N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	🟧 $H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	🟧 $H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	🟨 multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	🟨 monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1 g_D$, spin 1/2	1905.10130

🟩 $\sqrt{s}$ = 8 TeV
🟨 $\sqrt{s}$ = 13 TeV partial data
🟧 $\sqrt{s}$ = 13 TeV full data

Direct searches for new physics

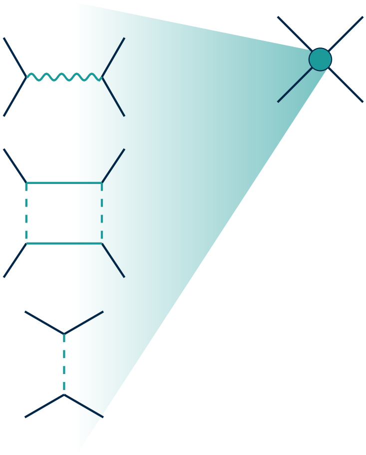


New physics looks to be weakly interacting or heavy!

Base assumption for use of SMEFT

Effective field theory

High-energy BSM physics manifests as contact interactions in the SMEFT

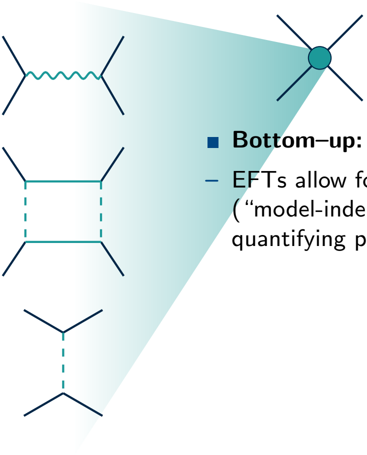


UV Physics

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

Effective field theory

High-energy BSM physics manifests as contact interactions in the SMEFT



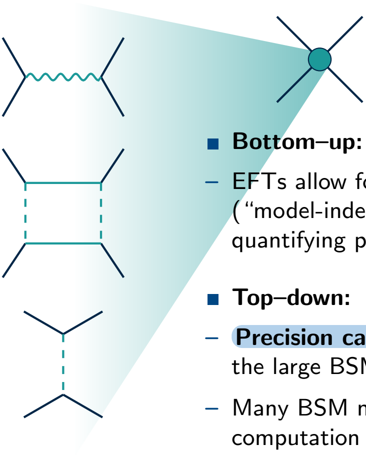
UV Physics

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

- **Bottom–up:**
  - EFTs allow for a **model-comprehensive** ("model-independent") analysis of deviations from the SM, quantifying possible deviations as an expansion in E/Λ

Effective field theory

High-energy BSM physics manifests as contact interactions in the SMEFT

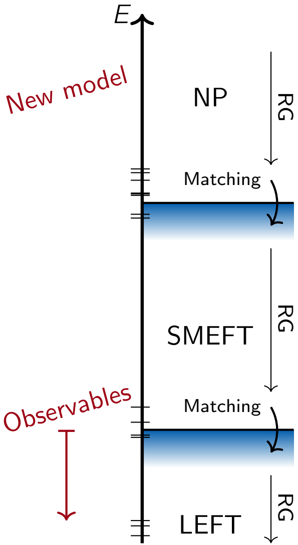


UV Physics

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

- **Bottom–up:**
  - EFTs allow for a **model-comprehensive** ("model-independent") analysis 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 results in the same EFT, ensuring that computation are **reusable**: you only need to compute once in the EFT

Top–down EFT workflow

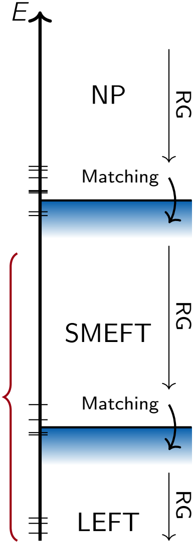


Jenkins, Manohar, Trott [1308.2627]
Jenkins, Manohar, Trott [1310.4838]
Alonso *et al.* [1312.2014]

Jenkins, Manohar, Stoffer [1709.04486]
Dekens, Stoffer [1908.05295]

Jenkins, Manohar, Stoffer [1711.05270]

Top–down EFT workflow



E

NP

RG

Matching

SMEFT

RG

Jenkins, Manohar, Trott [1308.2627]
Jenkins, Manohar, Trott [1310.4838]
Alonso *et al.* [1312.2014]

Included in codes
wilson and **DsixTools**

Aebischer, Kumar, Straub [1804.05033]
Cellis *et al.* [1704.04504]
Fuentes-Martín *et al.* [2010.16341]

Matching

Jenkins, Manohar, Stoffer [1709.04486]
Dekens, Stoffer [1908.05295]

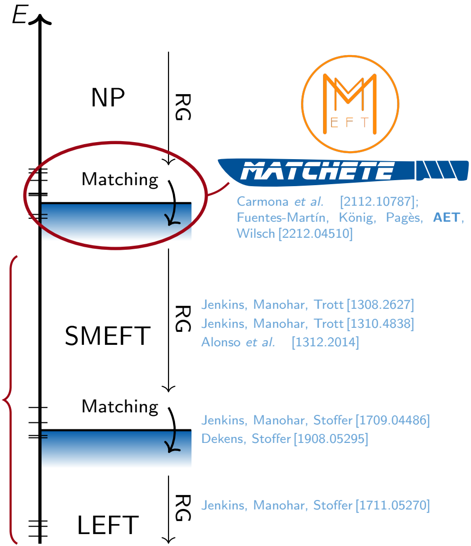
LEFT

RG

Jenkins, Manohar, Stoffer [1711.05270]

The repetitive nature of EFT computations call for **automated tools!**

Top–down EFT workflow



Carmona *et al.* [2112.10787]; Fuentes-Martín, König, Pagès, **AET**, Wilsch [2212.04510]

Jenkins, Manohar, Trott [1308.2627]
Jenkins, Manohar, Trott [1310.4838]
Alonso *et al.* [1312.2014]

Jenkins, Manohar, Stoffer [1709.04486]
Dekens, Stoffer [1908.05295]

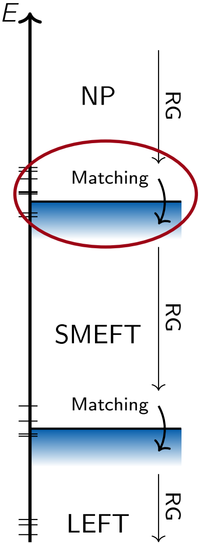
Jenkins, Manohar, Stoffer [1711.05270]

Included in codes **wilson** and **DsixTools**

Aebischer, Kumar, Straub [1804.05033]
Cellis *et al.* [1704.04504]
Fuentes-Martín *et al.* [2010.16341]

The repetitive nature of EFT computations call for **automated tools!**

Matching weakly coupled theories

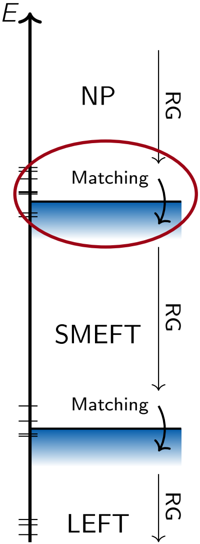


$\mathcal{L}_{\text{EFT}}$ should reproduce the physics of $\mathcal{L}_{\text{UV}}$ at energies $E \ll \Lambda$:

$$\mathcal{L}_{\text{UV}}(\Phi,\, \phi) \xrightarrow{\text{Matching}} \mathcal{L}_{\text{EFT}}(\phi)$$

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

Matching weakly coupled theories



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

$$\begin{tikzcd}
\mathcal{L}_{\text{UV}}(\Phi,\, \phi) \arrow[rr, "\text{Matching}"] \arrow[d] & & \mathcal{L}_{\text{EFT}}(\phi) \arrow[d, "\text{(Tree level only)}"] \\
\Gamma_{\text{UV}}\big[\widehat{\Phi}(\phi),\, \phi\big] & \simeq \arrow[ur, "\text{Diagramatic}"] & \Gamma_{\text{EFT}}[\phi]
\end{tikzcd}$$

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

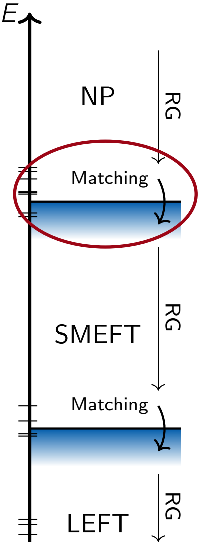
Hard-region matching formula

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

“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



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

$$\begin{tikzcd}
\mathcal{L}_{\text{UV}}(\Phi,\, \phi) \arrow[rr, "\text{Matching}"] \arrow[d] & & \mathcal{L}_{\text{EFT}}(\phi) \arrow[d] \\
\Gamma_{\text{UV}}\big[\widehat{\Phi}(\phi),\, \phi\big] \arrow[urr, "\text{Functional}"] & \simeq \arrow[ur] & \Gamma_{\text{EFT}}[\phi]
\end{tikzcd}$$

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

Hard-region matching formula

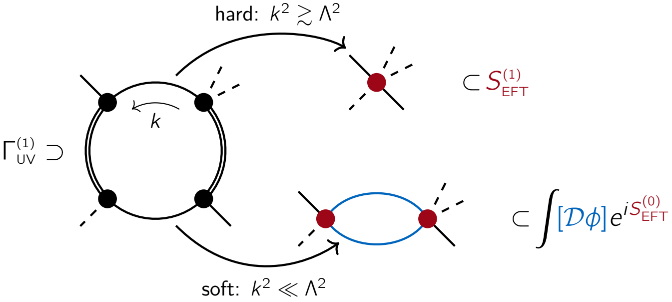
$$S_{\text{EFT}}[\phi] = \Gamma_{\text{UV}}[\widehat{\Phi}, \phi]\big|_{\text{hard}}, \qquad \frac{\delta \Gamma_{\text{UV}}|_{\text{hard}}}{\delta \Phi}[\widehat{\Phi}, \phi] = 0$$

"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]

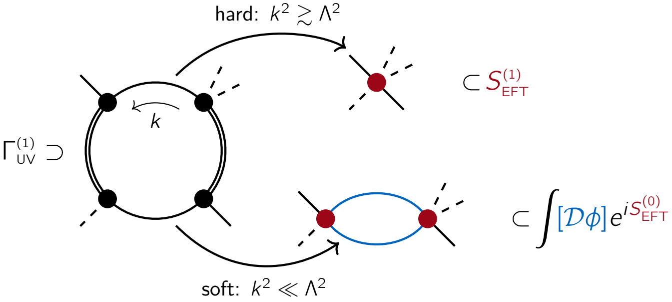
Separation of scales

Mixed (heavy–light) loop example:



Separation of scales

Mixed (heavy–light) loop example:



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

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

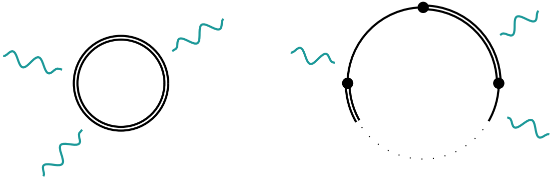
- $\Gamma^{(1)}_{\text{UV}}\big|_{\text{hard}}$: short-distance contributions going into the EFT operators

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

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

One-loop functional matching

The functional trace captures all one-loop matching contributions:



Covariant variations by
Fuentes-Martín *et al.* [1607.02142];
Cohen *et al.* [2011.02484];
Fuentes-Martín, König, Pagès, **AET**,
Wilsch [2012.08506];
Fuentes-Martin, Palavrić, Sánchez,
AET: *WIP*

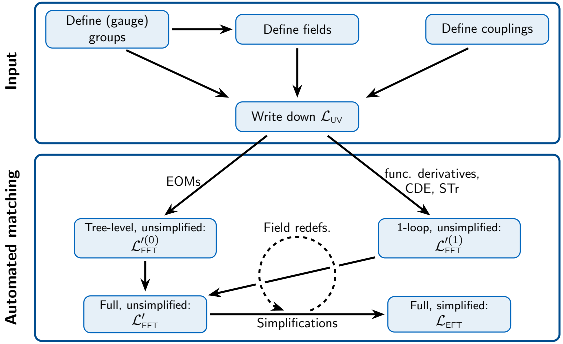
Master formula from path integral manipulation:

$$\frac{\delta^2 S}{\delta\eta(x)\,\delta\eta(y)} = \big[\overset{P_x^2 - m^2}{\Delta}(P_x) - \overset{\text{with bkg. fields}}{X}(x, P_x)\big]\delta(x,y)$$

$$\mathcal{L}_{\text{EFT}}^{(1)} = \bigg[\int_k \log\Delta(k+P_x)\,U(x,y) - \sum_{n=1}^{\infty}\frac{1}{n}\int_k \big[X(x,k+P_x)\,\Delta^{-1}(k+P_x)\big]^n U(x,y)\bigg]_{\substack{y=x\\ \text{hard}}}$$

Evaluation through repeated expansions—no diagrams needed!

Matchete: a general matching tool



Input

Define (gauge) groups

Define fields

Define couplings

Write down $\mathcal{L}_{\text{UV}}$

Automated matching

EOMs

func. derivatives, CDE, STr

Tree-level, unsimplified: $\mathcal{L}'^{(0)}_{\text{EFT}}$

Field redefs.

1-loop, unsimplified: $\mathcal{L}'^{(1)}_{\text{EFT}}$

Full, unsimplified: $\mathcal{L}'_{\text{EFT}}$

Simplifications

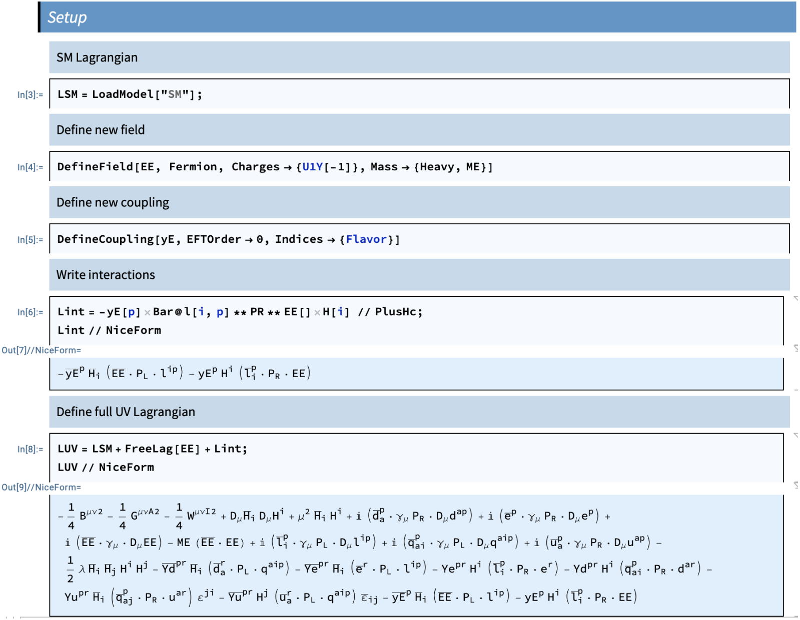
Full, simplified: $\mathcal{L}_{\text{EFT}}$

Fuentes-Martín, König, Pagès, **AET**, Wilsch [2212.04510]

- **Matchete v0.2** is a Mathematica package
- **1-loop matching of any model** with heavy scalars/fermions
- Simple and intuitive input/output
- Fully automated **simplification to EFT basis***
- Handles all group theory

Matchete is general: it is *not* restricted to SMEFT nor to dimension 6

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=

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

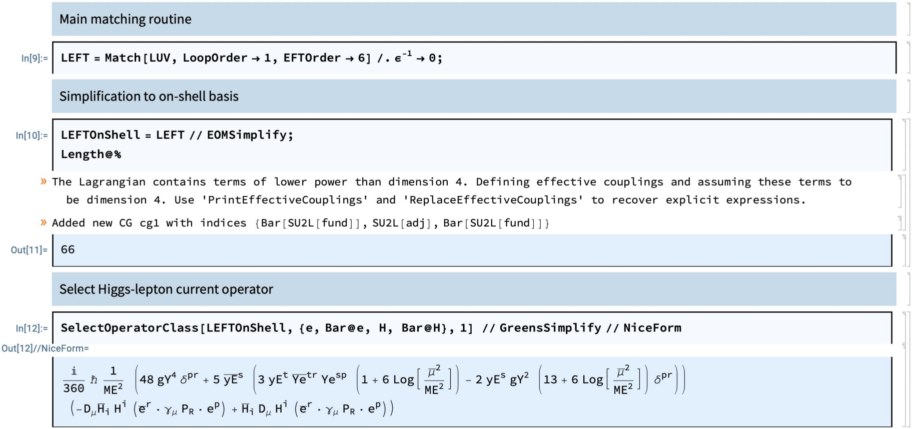
Define full UV Lagrangian

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

Out[9]//NiceForm=

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

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

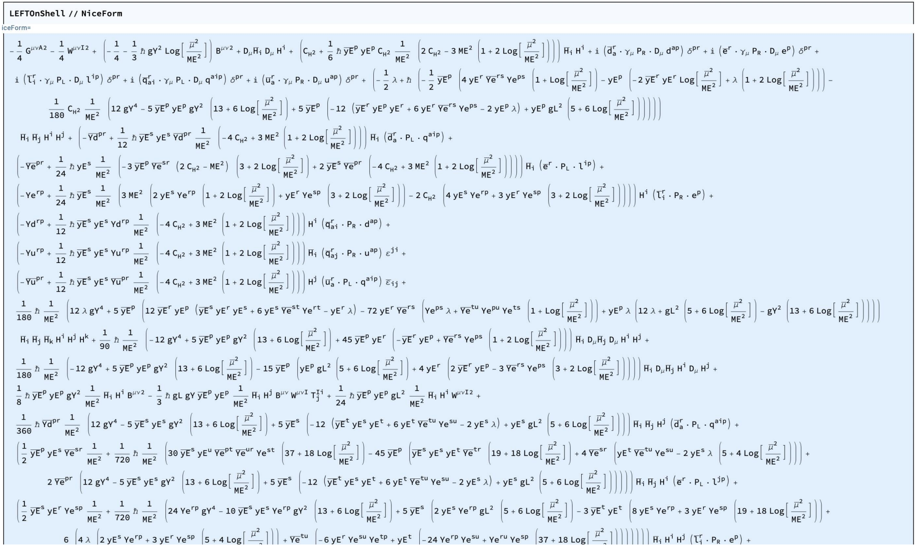
```
In[12]:= SelectOperatorClass[LEFTOnShell, {e, Bar@e, H, Bar@H}, 1] // GreensSimplify // NiceForm
```

Out[12]//NiceForm=

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

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

Example: SM + Vector-like lepton



```
LEFTOnShell // NiceForm
```

iceForm=

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

$$i\, (\overline{l}^{r}_{i} \cdot \gamma_{\mu} P_{L} \cdot D_{\mu}\, l^{ip})\, \delta^{pr} + i\, (\overline{q}^{r}_{ai} \cdot \gamma_{\mu} P_{L} \cdot D_{\mu}\, q^{aip})\, \delta^{pr} + i\, (\overline{u}^{r}_{a} \cdot \gamma_{\mu} P_{R} \cdot D_{\mu}\, u^{ap})\, \delta^{pr} + \left(-\frac{1}{2} \lambda + \hbar \left(-\frac{1}{2} \overline{yE}^{p} \left(4\, yE^{r}\, \overline{Ye}^{rs}\, Ye^{ps} \left(1 + \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right)\right) - yE^{p} \left(-2\, \overline{yE}^{r}\, yE^{r}\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right] + \lambda \left(1 + 2\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]))))\right. -$$

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

$$\overline{H}_{i}\, \overline{H}_{j}\, H^{i}\, H^{j} + \left(-\overline{Yd}^{pr} + \frac{1}{12} \hbar\, \overline{yE}^{s}\, yE^{s}\, \overline{Yd}^{pr} \frac{1}{ME^{2}} \left(-4\, C_{H^2} + 3\, ME^{2} \left(1 + 2\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right)\right)\right) \overline{H}_{i}\, (\overline{d}^{r}_{a} \cdot P_{L} \cdot q^{aip}) +$$

$$\left(-\overline{Ye}^{pr} + \frac{1}{24} \hbar\, yE^{s} \frac{1}{ME^{2}} \left(-3\, \overline{yE}^{p}\, \overline{Ye}^{sr}\, (2\, C_{H^2} - ME^{2}) \left(3 + 2\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right) + 2\, \overline{yE}^{s}\, \overline{Ye}^{pr} \left(-4\, C_{H^2} + 3\, ME^{2} \left(1 + 2\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right)\right)\right)\right) \overline{H}_{i}\, (\overline{e}^{r} \cdot P_{L} \cdot l^{ip}) +$$

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

$$\left(-Yd^{rp} + \frac{1}{12} \hbar\, \overline{yE}^{s}\, yE^{s}\, Yd^{rp} \frac{1}{ME^{2}} \left(-4\, C_{H^2} + 3\, ME^{2} \left(1 + 2\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right)\right)\right) H^{i}\, (\overline{q}^{r}_{ai} \cdot P_{R} \cdot d^{ap}) +$$

$$\left(-Yu^{rp} + \frac{1}{12} \hbar\, \overline{yE}^{s}\, yE^{s}\, Yu^{rp} \frac{1}{ME^{2}} \left(-4\, C_{H^2} + 3\, ME^{2} \left(1 + 2\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right)\right)\right) \overline{H}_{i}\, (\overline{q}^{r}_{aj} \cdot P_{R} \cdot u^{ap})\, \varepsilon^{ji} +$$

$$\left(-\overline{Yu}^{pr} + \frac{1}{12} \hbar\, \overline{yE}^{s}\, yE^{s}\, \overline{Yu}^{pr} \frac{1}{ME^{2}} \left(-4\, C_{H^2} + 3\, ME^{2} \left(1 + 2\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right)\right)\right) H^{j}\, (\overline{u}^{r}_{a} \cdot P_{L} \cdot q^{aip})\, \overline{\varepsilon}_{ij} +$$

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

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

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

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

$$\frac{1}{360} \hbar\, \overline{Yd}^{pr} \frac{1}{ME^{2}} \left(12\, gY^{4} - 5\, \overline{yE}^{s}\, yE^{s}\, gY^{2} \left(13 + 6\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right) + 5\, \overline{yE}^{s} \left(-12\, (\overline{yE}^{t}\, yE^{s}\, yE^{t} + 6\, yE^{t}\, \overline{Ye}^{tu}\, Ye^{su} - 2\, yE^{s} \lambda) + yE^{s}\, gL^{2} \left(5 + 6\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right)\right)\right) \overline{H}_{i}\, \overline{H}_{j}\, H^{j}\, (\overline{d}^{r}_{a} \cdot P_{L} \cdot q^{aip}) +$$

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

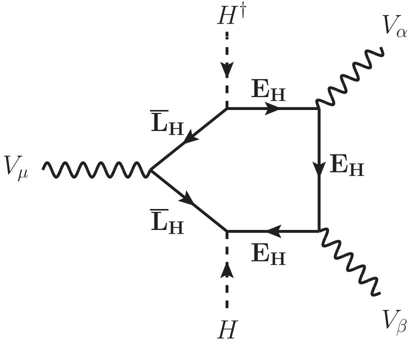
$$2\, \overline{Ye}^{pr} \left(12\, gY^{4} - 5\, \overline{yE}^{s}\, yE^{s}\, gY^{2} \left(13 + 6\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]\right) + 5\, \overline{yE}^{s} \left(-12\, (\overline{yE}^{t}\, yE^{s}\, yE^{t} + 6\, yE^{t}\, \overline{Ye}^{tu}\, Ye^{su} - 2\, yE^{s} \lambda) + yE^{s}\, gL^{2} \left(5 + 6\, \mathrm{Log}\left[\frac{\overline{\mu}^{2}}{ME^{2}}\right]))))))\, \overline{H}_{i}\, \overline{H}_{j}\, H^{i}\, (\overline{e}^{r} \cdot P_{L} \cdot l^{jp}) +\right.\right.$$

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

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

Example: neutral triple gauge interactions

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



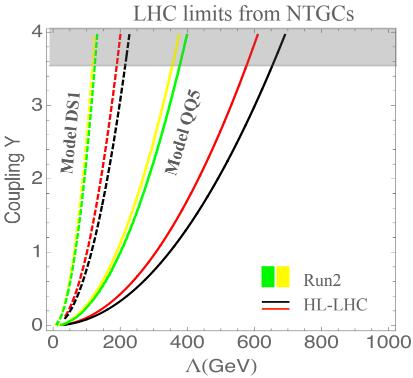
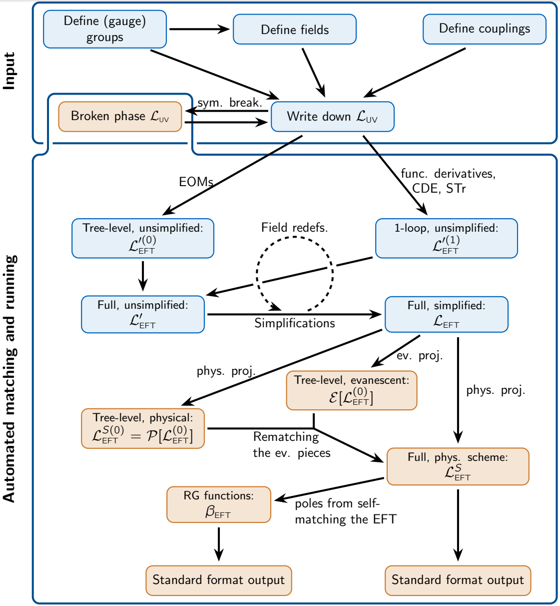


*Diagram and plot from [2402.04306]

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

Matchete: WIP and future plans



Input

Define (gauge) groups

Define fields

Define couplings

Broken phase $\mathcal{L}_{\text{UV}}$

sym. break.

Write down $\mathcal{L}_{\text{UV}}$

Automated matching and running

EOMs

func. derivatives, CDE, STr

Tree-level, unsimplified: $\mathcal{L}'^{(0)}_{\text{EFT}}$

Field redefs.

1-loop, unsimplified: $\mathcal{L}'^{(1)}_{\text{EFT}}$

Full, unsimplified: $\mathcal{L}'_{\text{EFT}}$

Simplifications

Full, simplified: $\mathcal{L}_{\text{EFT}}$

phys. proj.

ev. proj.

Tree-level, evanescent: $\mathcal{E}[\mathcal{L}^{(0)}_{\text{EFT}}]$

phys. proj.

Tree-level, physical: $\mathcal{L}^{S(0)}_{\text{EFT}} = \mathcal{P}[\mathcal{L}^{(0)}_{\text{EFT}}]$

Rematching the ev. pieces

Full, phys. scheme: $\mathcal{L}^{S}_{\text{EFT}}$

RG functions: β_{EFT}

poles from self-matching the EFT

Standard format output

Standard format output

Fuentes-Martín, König, Pagès, **AET**, Wilsch [2212.04510]

- Handling of evanescent contribution
- Interface with EFT toolchain
- 1-loop RG calculations

- SSB and heavy vectors

Outlook

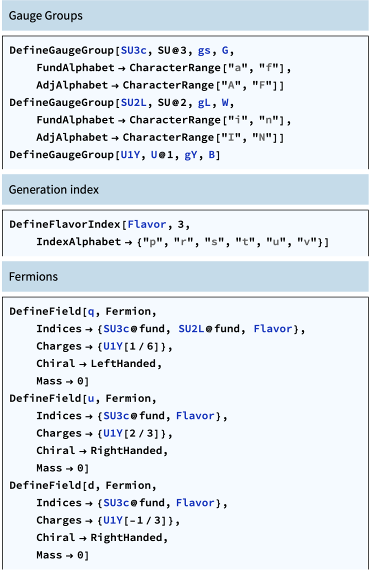
- Matching and RG calculation is crucial EFT technology
- Matchete is easy to use for matching up to 1-loop order
- EFT tools allow for the exploration of interesting new phenomenology
- New and exciting features underway!

https://gitlab.com/matchete/matchete

MATCHETE

Backup

SM implementation



Gauge Groups

```
DefineGaugeGroup[SU3c, SU@3, gs, G,
    FundAlphabet → CharacterRange["a", "f"],
    AdjAlphabet → CharacterRange["A", "F"]]
DefineGaugeGroup[SU2L, SU@2, gL, W,
    FundAlphabet → CharacterRange["i", "n"],
    AdjAlphabet → CharacterRange["I", "N"]]
DefineGaugeGroup[U1Y, U@1, gY, B]
```

Generation index

```
DefineFlavorIndex[Flavor, 3,
    IndexAlphabet → {"p", "r", "s", "t", "u", "v"}]
```

Fermions

```
DefineField[q, Fermion,
    Indices → {SU3c@fund, SU2L@fund, Flavor},
    Charges → {U1Y[1 / 6]},
    Chiral → LeftHanded,
    Mass → 0]
DefineField[u, Fermion,
    Indices → {SU3c@fund, Flavor},
    Charges → {U1Y[2 / 3]},
    Chiral → RightHanded,
    Mass → 0]
DefineField[d, Fermion,
    Indices → {SU3c@fund, Flavor},
    Charges → {U1Y[-1 / 3]},
    Chiral → RightHanded,
    Mass → 0]
```

```
DefineField[l, Fermion,
    Indices → {SU2L@fund, Flavor},
    Charges → {U1Y[-1 / 2]},
    Chiral → LeftHanded,
    Mass → 0]
DefineField[e, Fermion,
    Indices → {Flavor},
    Charges → {U1Y[-1]},
    Chiral → RightHanded,
    Mass → 0]
```

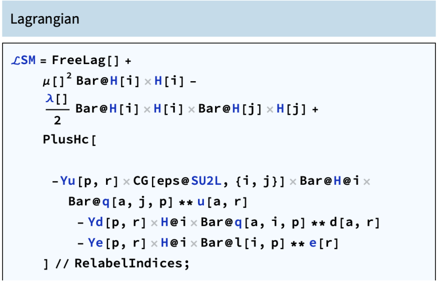
Higgs

```
DefineField[H, Scalar,
    Indices → {SU2L@fund},
    Charges → {U1Y[1 / 2]},
    Mass → 0]
```

Couplings

```
DefineCoupling[μ, SelfConjugate → True, EFTorder → 1]
DefineCoupling[λ, SelfConjugate → True, EFTorder → 0]
DefineCoupling[Ye,
    Indices → {Flavor, Flavor}]
DefineCoupling[Yu,
    Indices → {Flavor, Flavor}]
DefineCoupling[Yd,
    Indices → {Flavor, Flavor}]
```

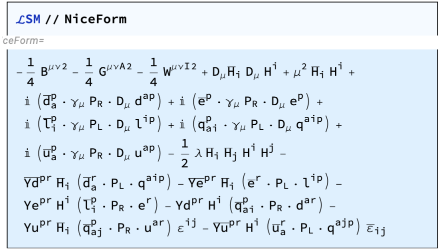
SM implementation



Lagrangian

```
ℒSM = FreeLag[] +
    μ[]^2 Bar@H[i] × H[i] -
    λ[]/2 Bar@H[i] × H[i] × Bar@H[j] × H[j] +
    PlusHc[

     -Yu[p, r] × CG[eps@SU2L, {i, j}] × Bar@H@i ×
       Bar@q[a, j, p] ** u[a, r]
       - Yd[p, r] × H@i × Bar@q[a, i, p] ** d[a, r]
       - Ye[p, r] × H@i × Bar@l[i, p] ** e[r]
    ] // RelabelIndices;
```



```
ℒSM // NiceForm
```

ceForm=

$$
\begin{aligned}
&-\frac{1}{4}\,B^{\mu\nu 2}-\frac{1}{4}\,G^{\mu\nu A 2}-\frac{1}{4}\,W^{\mu\nu I 2}+D_{\mu}\bar{H}_{i}\,D_{\mu}\,H^{i}+\mu^{2}\,\bar{H}_{i}\,H^{i}+\\
&\mathbb{i}\left(\bar{d}^{p}_{a}\cdot\gamma_{\mu}\,P_{R}\cdot D_{\mu}\,d^{ap}\right)+\mathbb{i}\left(\bar{e}^{p}\cdot\gamma_{\mu}\,P_{R}\cdot D_{\mu}\,e^{p}\right)+\\
&\mathbb{i}\left(\bar{l}^{p}_{i}\cdot\gamma_{\mu}\,P_{L}\cdot D_{\mu}\,l^{ip}\right)+\mathbb{i}\left(\bar{q}^{p}_{ai}\cdot\gamma_{\mu}\,P_{L}\cdot D_{\mu}\,q^{aip}\right)+\\
&\mathbb{i}\left(\bar{u}^{p}_{a}\cdot\gamma_{\mu}\,P_{R}\cdot D_{\mu}\,u^{ap}\right)-\frac{1}{2}\,\lambda\,\bar{H}_{i}\,\bar{H}_{j}\,H^{i}\,H^{j}-\\
&\overline{Yd}^{pr}\,\bar{H}_{i}\left(\bar{d}^{r}_{a}\cdot P_{L}\cdot q^{aip}\right)-\overline{Ye}^{pr}\,\bar{H}_{i}\left(\bar{e}^{r}\cdot P_{L}\cdot l^{ip}\right)-\\
&Ye^{pr}\,H^{i}\left(\bar{l}^{p}_{i}\cdot P_{R}\cdot e^{r}\right)-Yd^{pr}\,H^{i}\left(\bar{q}^{p}_{ai}\cdot P_{R}\cdot d^{ar}\right)-\\
&Yu^{pr}\,\bar{H}_{i}\left(\bar{q}^{p}_{aj}\cdot P_{R}\cdot u^{ar}\right)\varepsilon^{ij}-\overline{Yu}^{pr}\,H^{i}\left(\bar{u}^{r}_{a}\cdot P_{L}\cdot q^{ajp}\right)\bar{\varepsilon}_{ij}
\end{aligned}
$$

Practical implementations can simply load in the standard definition of the SM.