UC San Diego

Cutting operators with MATCHETE

automatic reduction to a minimal EFT basis and treatment of evanescent operators

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Based on [2012.08506], [2212.04510] and [2211.09144] in collaboration with

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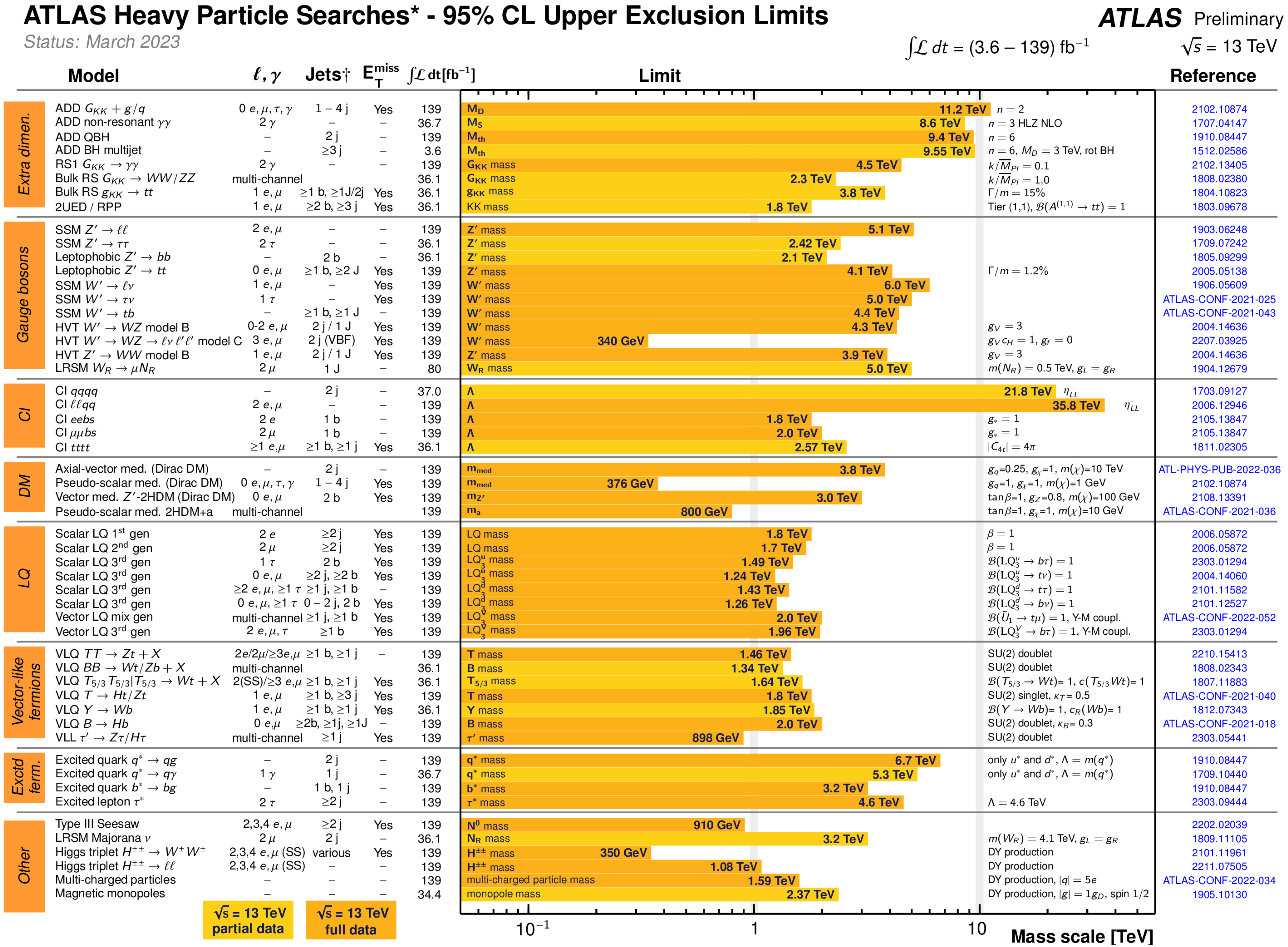
Why SMEFT?



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits
Status: March 2023
ATLAS Preliminary
$\int \mathcal{L}\, dt = (3.6 - 139)$ fb^{-1}
$\sqrt{s}$ = 13 TeV
Model | ℓ, γ | Jets† | E_T^{miss} | $\int \mathcal{L}\, dt$[fb^{-1}] | Limit | Reference
Extra dimen.
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 γγ | 2 γ | – | – | 36.7 | M_S 8.6 TeV | n = 3 HLZ NLO | 1707.04147
ADD QBH | – | 2 j | – | 139 | M_{th} 9.4 TeV | n = 6 | 1910.08447
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 $g_{KK} \to tt$ | 1 e, μ | ≥1 b, ≥1J/2j | Yes | 36.1 | g_{KK} mass 3.8 TeV | Γ/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 | Γ/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 $W' \to WZ$ model B | 0-2 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 | 2207.03925
HVT $Z' \to WW$ model B | 1 e, μ | 2 j / 1 J | Yes | 139 | Z′ mass 3.9 TeV | g_V = 3 | 2004.14636
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 ℓℓqq | 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 μμbs | 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 | $|C_{4t}| = 4\pi$ | 1811.02305
DM
Axial-vector med. (Dirac DM) | – | 2 j | – | 139 | m_{med} 3.8 TeV | g_q=0.25, g_χ=1, $m(\chi)$=10 TeV | ATL-PHYS-PUB-2022-036
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 | $m_{Z'}$ 3.0 TeV | tanβ=1, g_Z=0.8, $m(\chi)$=100 GeV | 2108.13391
Pseudo-scalar med. 2HDM+a | multi-channel | 139 | m_a 800 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 | β = 1 | 2006.05872
Scalar LQ 2nd gen | 2 μ | ≥2 j | Yes | 139 | LQ mass 1.7 TeV | β = 1 | 2006.05872
Scalar LQ 3rd gen | 1 τ | 2 b | Yes | 139 | LQ_3^u mass 1.49 TeV | $\mathcal{B}(LQ_3^u \to b\tau) = 1$ | 2303.01294
Scalar LQ 3rd gen | 0 e, μ | ≥2 j, ≥2 b | Yes | 139 | LQ_3^u mass 1.24 TeV | $\mathcal{B}(LQ_3^u \to t\nu) = 1$ | 2004.14060
Scalar LQ 3rd gen | ≥2 e, μ, ≥1 τ | ≥1 j, ≥1 b | – | 139 | LQ_3^d mass 1.43 TeV | $\mathcal{B}(LQ_3^d \to t\tau) = 1$ | 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 | $\mathcal{B}(LQ_3^d \to b\nu) = 1$ | 2101.12527
Vector LQ mix gen | multi-channel | ≥1 j, ≥1 b | Yes | 139 | LQ_3^V mass 2.0 TeV | $\mathcal{B}(\tilde{U}_1 \to t\mu) = 1$, Y-M coupl. | ATLAS-CONF-2022-052
Vector LQ 3rd gen | 2 e, μ, τ | ≥1 b | Yes | 139 | LQ_3^V mass 1.96 TeV | $\mathcal{B}(LQ_3^V \to b\tau) = 1$, Y-M coupl. | 2303.01294
Vector-like fermions
VLQ $TT \to Zt + X$ | 2e/2μ/≥3e,μ | ≥1 b, ≥1 j | – | 139 | T mass 1.46 TeV | SU(2) doublet | 2210.15413
VLQ $BB \to Wt/Zb + X$ | multi-channel | 36.1 | B mass 1.34 TeV | SU(2) doublet | 1808.02343
VLQ $T_{5/3}T_{5/3}|T_{5/3} \to Wt + X$ | 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
VLL $\tau' \to Z\tau/H\tau$ | multi-channel | ≥1 j | Yes | 139 | τ′ mass 898 GeV | SU(2) doublet | 2303.05441
Exctd ferm.
Excited quark $q^* \to qg$ | – | 2 j | – | 139 | q* mass 6.7 TeV | only u^* and d^*, Λ = 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^*, Λ = m(q*) | 1709.10440
Excited quark $b^* \to bg$ | – | 1 b, 1 j | – | 139 | b* mass 3.2 TeV | 1910.08447
Excited lepton τ^* | 2 τ | ≥2 j | – | 139 | τ* mass 4.6 TeV | Λ = 4.6 TeV | 2303.09444
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 | 2211.07505
Multi-charged particles | – | – | – | 139 | multi-charged particle mass 1.59 TeV | DY production, |q| = 5e | ATLAS-CONF-2022-034
Magnetic monopoles | – | – | – | 34.4 | monopole mass 2.37 TeV | DY production, $|g| = 1g_D$, spin 1/2 | 1905.10130
$\sqrt{s}$ = 13 TeV partial data
$\sqrt{s}$ = 13 TeV full data
10^{-1}
1
10
Mass scale [TeV]

The EFT approach: bottom-up

Extend the SM with an organized tower of new operators:

number of operators at dimension d

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{d=5}^{d_{\max}} \frac{1}{\Lambda^{d-4}} \sum_{i=1}^{n_d} C_i^{[d]} O_i^{[d]}$$

Wilson coefficients

Operator basis

power counting parameter

Advantages:

- RG evolution known (for dim 6 and most of dim 8)
- Generic commonly-used description to parametrize new physics

↪ many fitting tools developed: HEPfit [De Blas et. al., 1910.14012] SMEFiT [Giani et. al., 2302.06660] EOS [van Dyk et. al., 2111.15428] Fitmaker [Ellis et. al., 2012.02779] …

and likelihood generators: flavio [Straub, 1810.08132] smelli [Aebischer et. al., 1810.07698] HighPT [Allwicher et. al., 2207.10756]

A need for the UV

Limitation of the bottom-up EFT approach:

1) Too many parameters!
   2 499 (B conserving) operators at dim 6
   36 971 (B conserving) operators at dim 8
   …
   counting with Hilbert series [Henning, Lu, Melia, Murayama, 1512.03433]

2) no correlation between parameters

→ less predictive

3) only valid up to a cutoff scale → EFT is not a fundamental theory

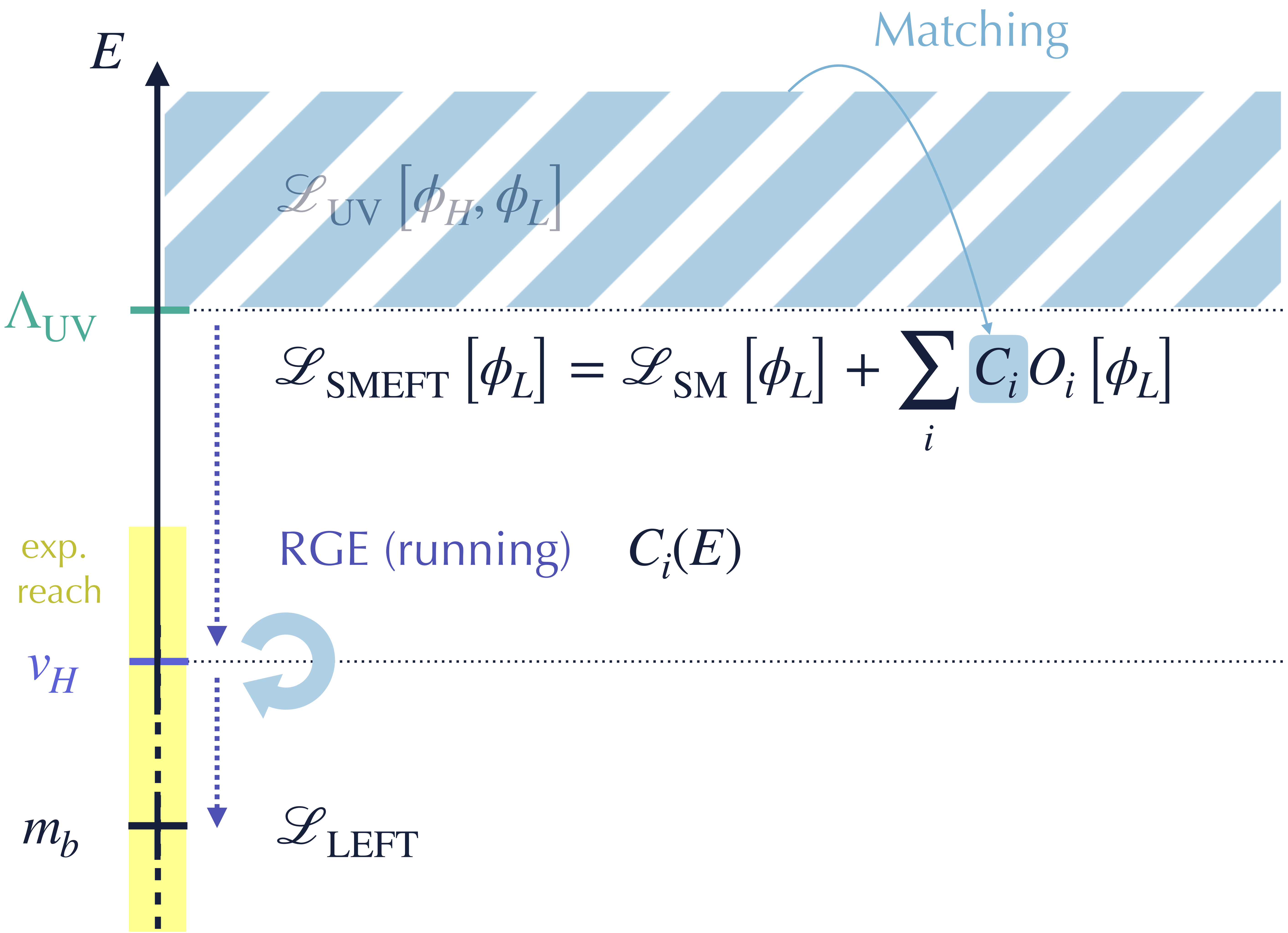
⇒ start from a renormalizable UV theory → 1) ✓ 2) ✓ 3) ✓

But

- new RGE needed for each theory
- new observables calculation for each theory

Take best of both worlds: the top-down EFT approach

~~The EFT approach: top-down~~



The top-down EFT approach:

Combine the reusability of EFTs with the predictivity of UV theories.

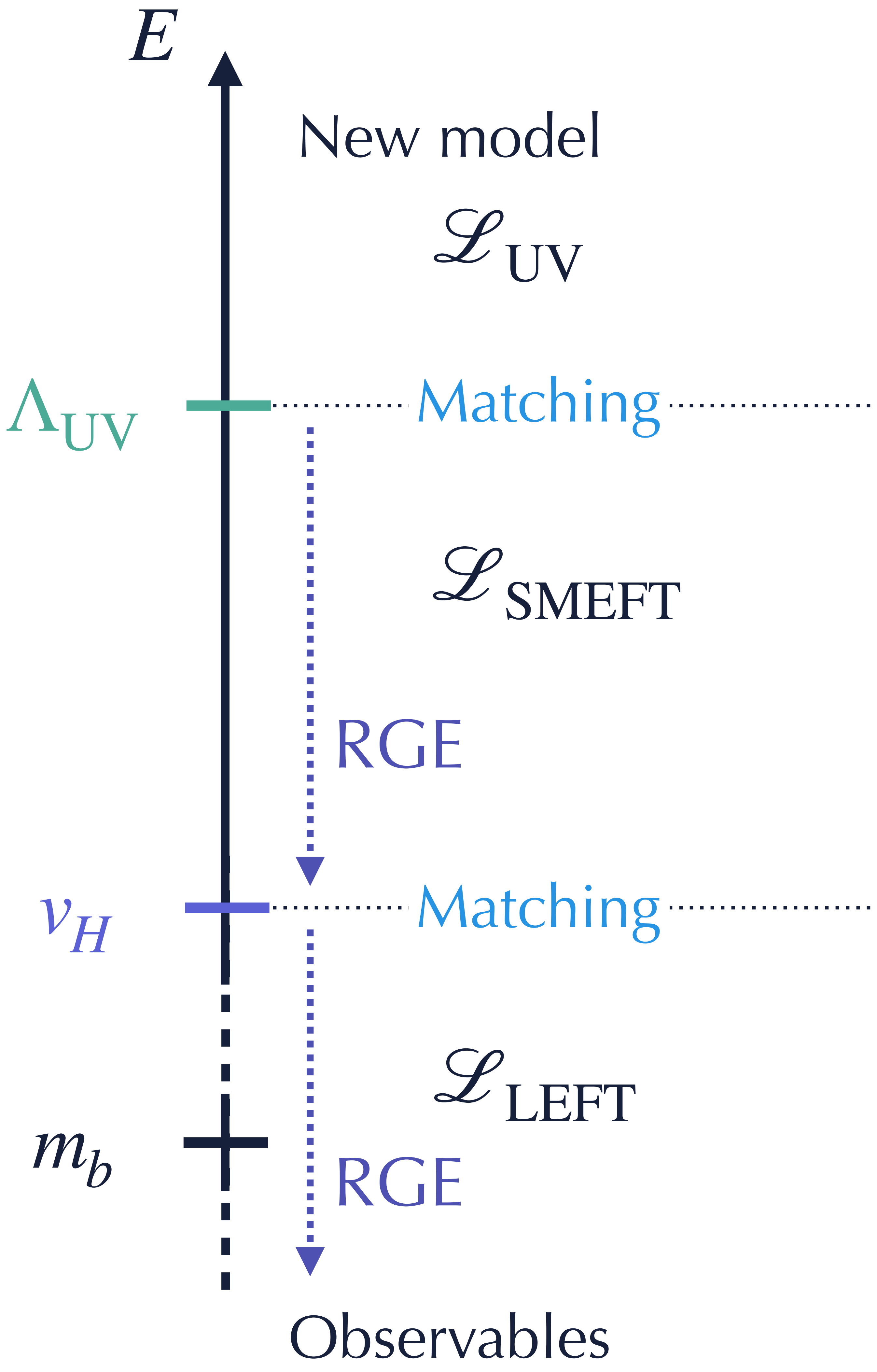
Match at Λ_{UV}

Run from Λ_{UV} to v_H

(Repeat)

Compare at observable scale (e.g. m_b)

The EFT approach: developed tools



For $d_{\text{max}} = 6$

- Tree-level matching to the SMEFT for generic NP mediators
  [de Blas, Criado, Pérez-Victoria, Santiago, 1711.10391]
  MatchingTools [Criado, 1710.06445]

- One-loop RGE in the SMEFT
  [Jenkins, Manohar, Trott, 1308.2627]
  [Jenkins, Manohar, Trott, 1310.4838]
  [Alonso et al., 1312.2014]

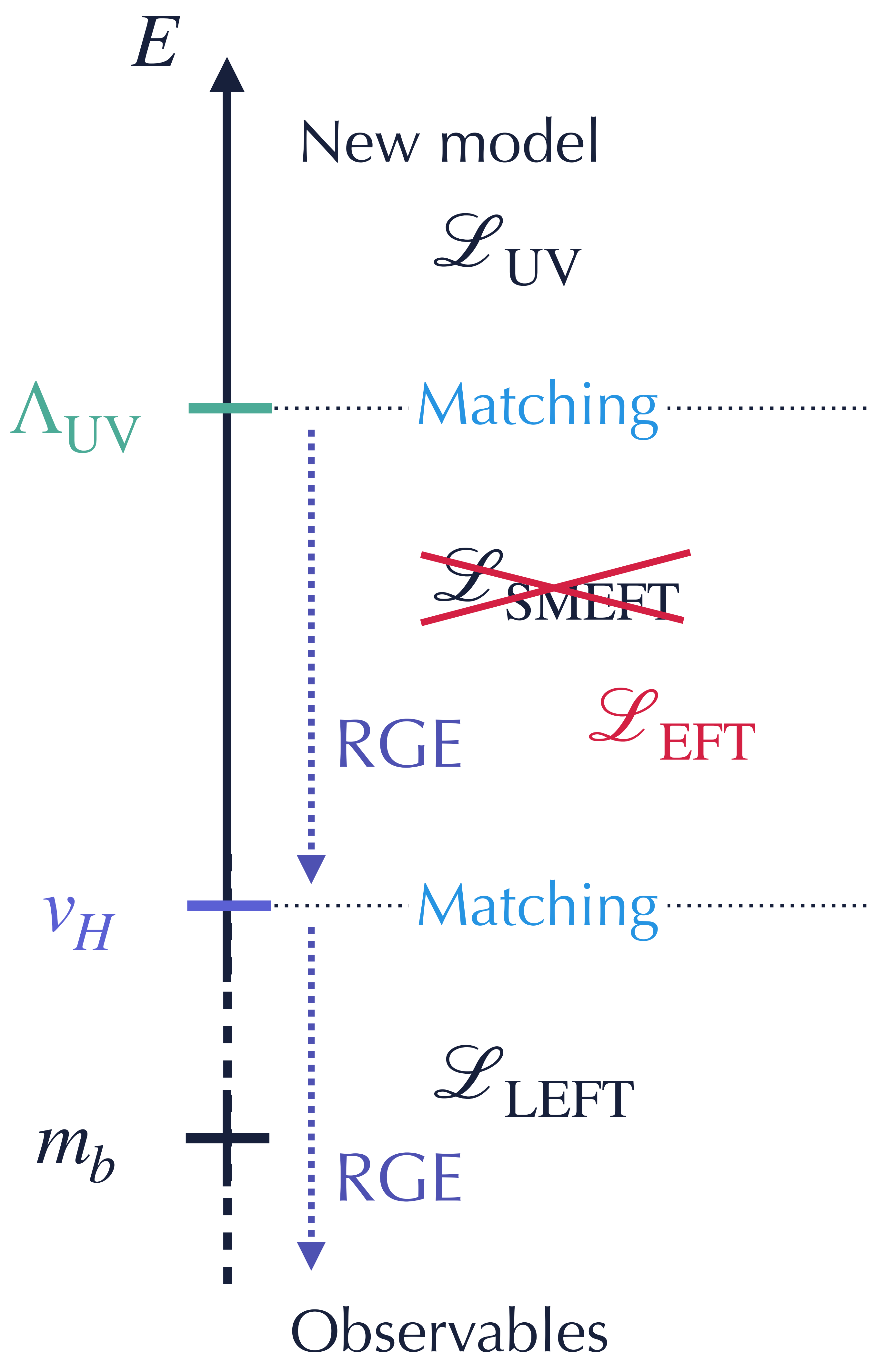
- One-loop matching of SMEFT to LEFT
  [Jenkins, Manohar, Stoffer, 1709.04486]
  [Dekens, Stoffer, 1908.05295]

- One-loop RGE in the LEFT
  [Jenkins, Manohar, Stoffer, 1711.05270]

DsixTools
[Cellis et al., 1704.04504]
[Fuentes-Martín et al., 2010.16341]

wilson
[Aebischer, Kumar, Straub, 1804.05033]

The EFT approach: ongoing effort



- One-loop matching to the SMEFT from any UV theory
- Two-loop
  - matching [Fuentes-Martín, Palavric, Thomsen, 2311.13630]
  - RGE
    → from functional methods?
    → from amplitudes? [Bern, Parra-Martinez, Sawyer, 2005.12917]
    → from field-space geometry? [Jenkins, Manohar, Naterop, JP, 2308.06315 + 2310.19883]
- Higher-dimension operators → growing interest for dimension 8
  - matching e.g. [Hays, Martin, Sanz, Setford, 1808.00442] …
  - RGE → from field-space geometry? [Helset, Jenkins, Manohar, 2212.03253; Assi, Helset, Manohar, JP, Shen, 2307.03187]
- EFT above the electroweak scale is not necessarily the SMEFT
  i.e. contains light states which cannot be integrated out (SM + ALP EFT, SM + DM EFT, …)

Automation of one-loop matching

One-loop matching from an arbitrary UV model to the corresponding EFT must be automatized since:

- there exists a jungle of new physics models
- calculations are very long and repetitive
- algorithmic nature of the computation is more suited for a machine than for a human

Tools to automate:

Functional methods

MATCHETE

[Fuentes-Martín, König, JP, Eller Thomsen, Wilsch, 2212.04510]

Diagrammatic methods

MatchMakerEFT [Carmona, Lazopoulos, Olgoso, Santiago, 2112.10787]

IR/UV dictionary

SOLD [Guedes, Olgoso, Santiago, 2303.16965]

Functional matching

Functional v.s. diagrammatic matching

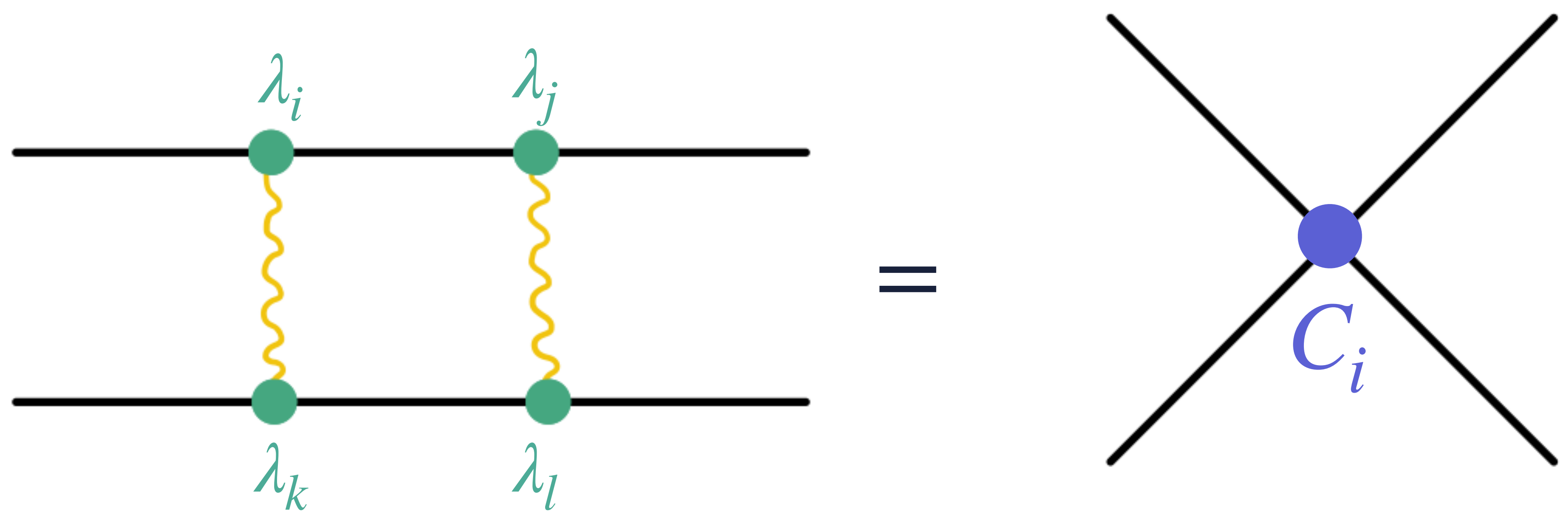
Matching procedure

For $m_H \gg m_L$, compute the Wilson coefficients $\{C_i\}$ as function of $\{\lambda_{\mathrm{UV}}\}$ such that

$$\mathscr{L}_{\mathrm{UV}}[\phi_H, \phi_L] \xrightarrow{E \ll m_H} \mathscr{L}_{\mathrm{EFT}}[\phi_L]$$

Diagrammatic approach

- Equate correlators from diagrams



$$G_{\mathrm{UV}}(\{\lambda_{\mathrm{UV}}\}) = G_{\mathrm{EFT}}(\{C_i\})$$

Functional approach

- Use background field method to compute path integral in UV theory
- Equate the 1LPI effective action

$$\Gamma_{\mathrm{L,UV}}(\{\lambda_{\mathrm{UV}}\}) = \Gamma_{\mathrm{EFT}}(\{C_i\})$$

Functional v.s. diagrammatic matching

Matching procedure

For $m_H \gg m_L$, compute the Wilson coefficients $\{C_i\}$ as function of $\{\lambda_{\rm UV}\}$ such that

$$\mathscr{L}_{\rm UV}[\phi_H, \phi_L] \xrightarrow{E \ll m_H} \mathscr{L}_{\rm EFT}[\phi_L]$$

Diagrammatic approach

- Traditional procedure, valid to any loop order
- Can be performed on-shell
  (more diagrams, no redundancies)
  or off-shell
  (only 1LPI diagrams, additional redundancies)
- EFT basis must be constructed by hand

Functional approach

- Recent developments at two-loop order
- Manifestly gauge invariant
- EFT basis is automatically derived
  (up to redundancies)

Functional matching

Loop expansion

Use background field method $\phi \to \hat{\phi} + \eta$ where

$\hat{\phi}$: background field (tree line)
η : quantum fluctuation (loop line)

on the 1LPI effective action at m_H

$$e^{i\Gamma[\hat{\phi}]} = \int \mathscr{D}\eta \exp\left(i \int d^d x\, \mathscr{L}[\hat{\phi} + \eta]\right)$$

At one-loop:

$$\Gamma[\hat{\phi}] = S[\hat{\phi}] + \frac{i}{2}\mathrm{STr}\log \frac{\delta \mathscr{L}}{\delta \bar{\eta}_i \delta \eta_j}\Bigg|_{\eta=0}$$

where $S[\hat{\phi}] = \int d^4 x\, \mathscr{L}[\hat{\phi}]$

Functional matching

EFT power counting expansion

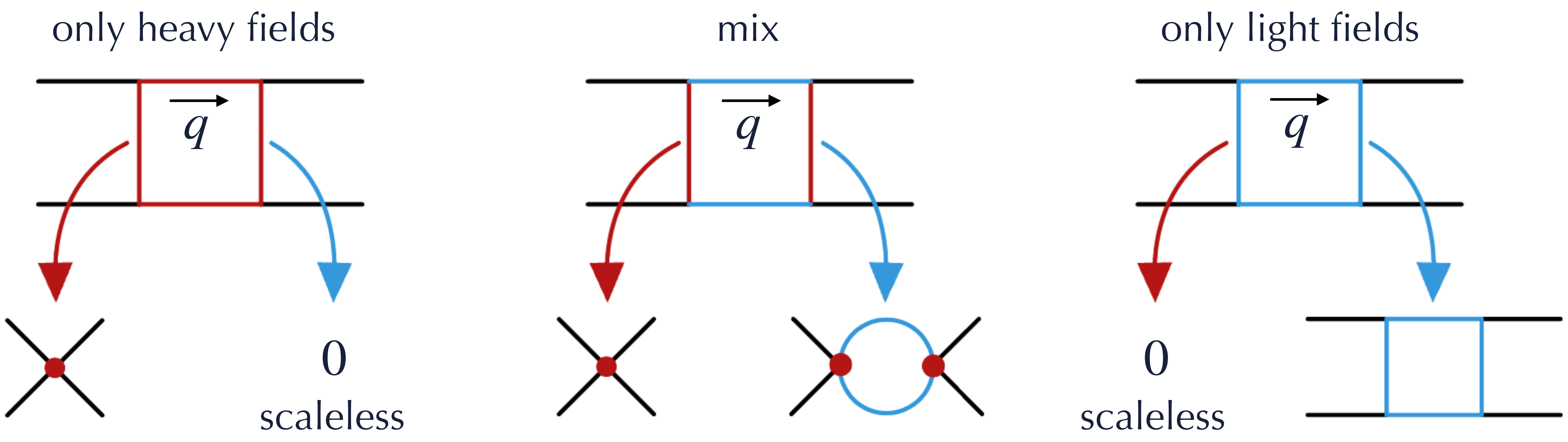
Expand in inverse power of heavy scale m_H^{-1} and replace heavy field by its equation of motion $\phi_H[\phi_L]$

and use method of regions

$$\int I(q)\, d^d q = \underbrace{\int I(q \sim m_H)\, d^d q}_{\text{hard}} + \underbrace{\int I(q \sim m_L \ll m_H)\, d^d q}_{\text{soft}}$$

⇒ The 1LPI effective action can be split:

$$\Gamma = \Gamma\Big|_{\text{hard}} + \Gamma\Big|_{\text{soft}}$$



Matching formula

The matching formula $\Gamma_{\text{EFT}}[\hat{\phi}_L] = \Gamma_{\text{L,UV}}[\hat{\phi}_L] = \Gamma_{\text{UV}}[\hat{\phi}_L, \hat{\phi}_H[\hat{\phi}_L]]$

- At tree level: $\mathscr{L}^{(0)}_{\text{EFT}} = \mathscr{L}_{\text{UV}}[\phi_L, \hat{\phi}_H[\phi_L]]$ with $\left.\frac{\delta \mathscr{L}_{\text{UV}}}{\delta \phi_H}\right|_{\phi_H = \hat{\phi}_H} = 0$ standard EOM technique

- At one-loop level: $\int d^4x\, \mathscr{L}^{(1)}_{\text{EFT}} + \Gamma^{(1)}_{\text{EFT}} = \Gamma^{(1)}_{\text{UV}}[\hat{\phi}_L, \hat{\phi}_H[\hat{\phi}_L]]$

one-loop contribution to $\{C_i\}$ one-loop eff. action from tree-level $\{C_i\}$

$$\int d^4x\, \mathscr{L}^{(1)}_{\text{EFT}} + \left.\Gamma^{(1)}_{\text{EFT}}\right|_{\text{hard}} + \left.\Gamma^{(1)}_{\text{EFT}}\right|_{\text{soft}} = \left.\Gamma^{(1)}_{\text{UV}}\right|_{\text{hard}} + \left.\Gamma^{(1)}_{\text{UV}}\right|_{\text{soft}}$$

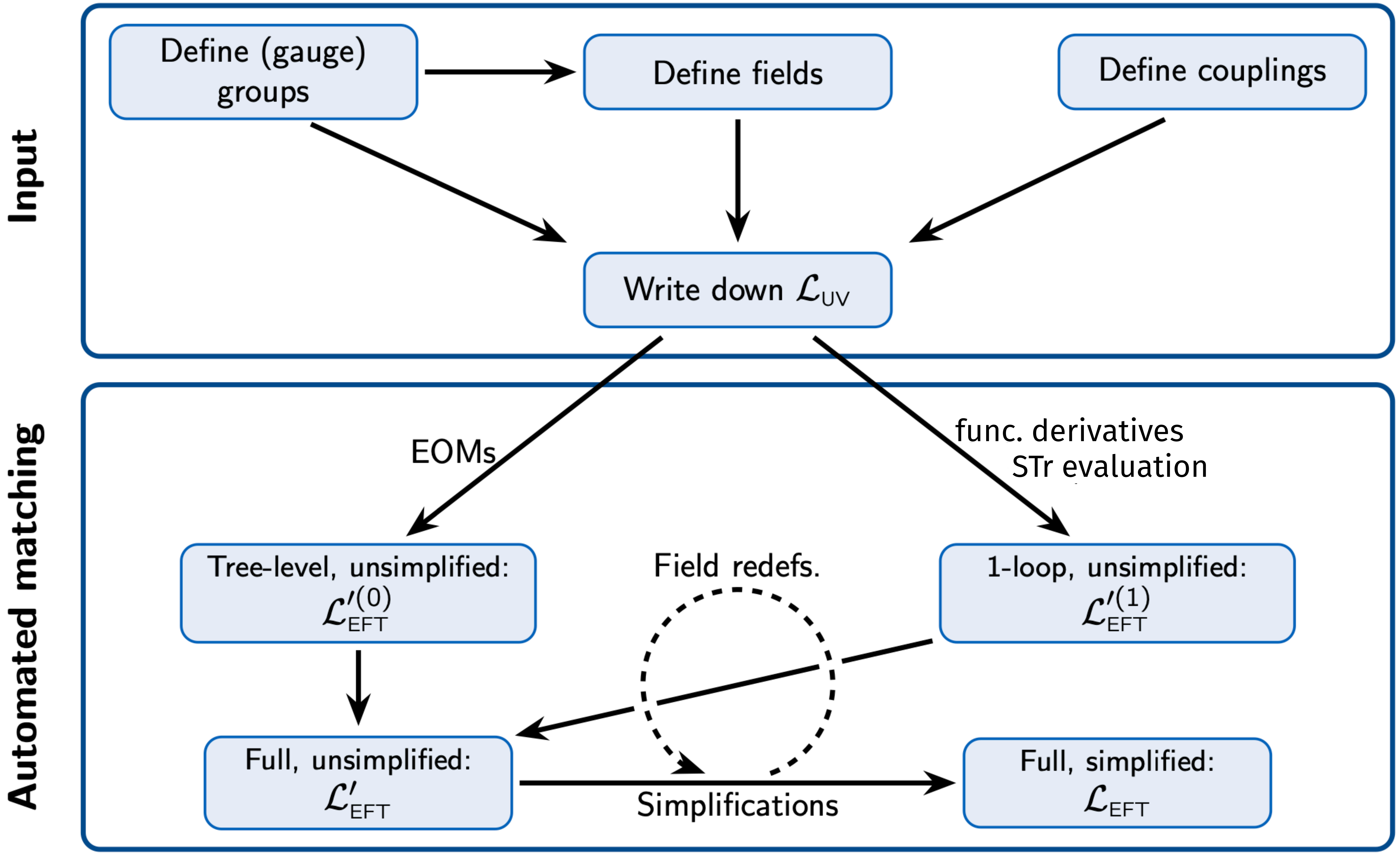
$$\Rightarrow \int d^4x\, \mathscr{L}^{(1)}_{\text{EFT}} = \left.\Gamma^{(1)}_{\text{UV}}\right|_{\text{hard}}$$

hard region matching
[Fuentes-Martín, Portolés, Ruiz-Femenía, 1607.02142]

Automated matching

MATCHETE

MATCHETE: Mathematica package aimed at fully automating one-loop matching of a generic weakly coupled UV theory to the corresponding EFT.



[Fuentes-Martín, König, Pagès, Thomsen, Wilsch, 2212.04510]

Matchete v0.2 publicly available:

- Simple and intuitive usage: input $\mathscr{L}_{UV}$ → output $\mathscr{L}_{EFT}$,
- Can match any UV model with heavy scalar, fermion, vectors*,
  *vectors only at tree-level
- Up to any mass dimension*,
- Handles all representations of any semi-simple Lie group*,
  *only limited by computation time
- Fully simplified output*
  - *fierzing coming soon

Demo with a toy model

Integrating out a heavy vector-like fermion Ψ of mass M, charged under $U(1)_e$

coupling to a neutral light scalar ϕ and a charged light fermion ψ

$$\mathscr{L}_{\mathrm{UV}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial^\mu\phi)(\partial_\mu\phi) + \bar{\psi}\, iD\!\!\!/\, \psi + \bar{\Psi}(iD\!\!\!/ - M)\Psi - \left(y\,\bar{\psi}_L\,\phi\,\Psi_R + \mathrm{h.c.}\right)$$

→ Validated against diagrammatic computation by hand ✔

3 weeks by hand
v.s.
$\sim$ 30 s for Matchete

Demo - model definition

Toy-model with vector-like fermions

Definition of the model

Gauge group, fields and coupling

Define gauge group

```
In[3]:= DefineGaugeGroup[U1e, U1, e, A]
```

Define fields

```
In[4]:= DefineField[Ψ, Fermion, Charges → {U1e[1]}, Mass → {Heavy, M}]
        DefineField[ψ, Fermion, Charges → {U1e[1]}, Mass → 0]
        DefineField[ϕ, Scalar, Mass → 0, SelfConjugate → True]
```

Define coupling

```
In[7]:= DefineCoupling[y]
```

Shortcuts

```
In[8]:= ϕ[]
Out[8]= Field[ϕ, Scalar, {}, {}]

In[9]:= y[]
Out[9]= Coupling[y, {}, 0]
```

Lagrangian

Write interactions

```
In[10]:= Lint = -y[] × Bar@ψ[] ** PR ** Ψ[] × ϕ[] // PlusHc;
```

Define Lagrangian

```
In[11]:= LUV = FreeLag[] + Lint;
         LUV // NiceForm
         CheckLagrangian[LUV]
         CheckLagrangian[LUV, DetailedOutput → True]
```

$$-\frac{1}{4}A^{\mu\nu 2}+\frac{1}{2}\left(D_\mu\phi\right)^2+i\left(\bar{\psi}\cdot\gamma_\mu\cdot D_\mu\psi\right)+i\left(\bar{\Psi}\cdot\gamma_\mu\cdot D_\mu\Psi\right)-M\left(\bar{\Psi}\cdot\Psi\right)-y\,\phi\left(\bar{\psi}\cdot P_R\cdot\Psi\right)-\bar{y}\,\phi\left(\bar{\Psi}\cdot P_L\cdot\psi\right)$$

```
Out[13]= True

Out[14]= <|Open/Complex/InconsistentSpinChains → {}, Hermiticity → True,
          UncontractedIndices → {}, CanonicallyNormalized → True,
          HeavyMassBasis → True, HeavyTadpoles → {}, ChargeNeutral → True,
          FreeOfGaugeFields → True, AllObjectsDefined → True, GaugeAnomalies → {}|>
```

Lagrangian of only light degrees of freedom

```
In[15]:= Llight = FreeLag[ψ, ϕ, A];
         % // NiceForm
```

$$-\frac{1}{4}A^{\mu\nu 2}+\frac{1}{2}\left(D_\mu\phi\right)^2+i\left(\bar{\psi}\cdot\gamma_\mu\cdot D_\mu\psi\right)$$

One-loop matching to the effective Lagrangian

32 operators

```
In[17]:= LEFT = Match[LUV, LoopOrder → 1, EFTOrder → 6] /. ϵ^-1 → 0;
         LEFT - Llight // CollectOperators // NiceForm
```

Out[18]//NiceForm=

$$-\frac{1}{3}\hbar e^2 A^{\mu\nu 2}\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right] + \frac{1}{2}\hbar \bar y y \left(1+2\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D_\mu\phi)^2 - 2\hbar \bar y y M^2\left(1+\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi^2 + \frac{i}{8}\hbar\bar y y\left(3+2\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu\psi) -$$

$$\frac{i}{8}\hbar\bar y y\left(3+2\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D_\mu\bar\psi\cdot\gamma_\mu P_L\cdot\psi) + \frac{7}{270}\hbar e^2\frac{1}{M^2}(D_\rho A^{\mu\nu})^2 + \frac{1}{20}\hbar e^2\frac{1}{M^2}A^{\mu\nu}D^2A^{\mu\nu} + \frac{7}{270}\hbar e^2\frac{1}{M^2}D_\rho A^{\mu\nu}D_\nu A^{\mu\rho} -$$

$$\frac{1}{90}\hbar e^2\frac{1}{M^2}D_\nu A^{\mu\nu}D_\rho A^{\mu\rho} + \frac{1}{20}\hbar e^2\frac{1}{M^2}A^{\mu\nu}D_\nu D_\rho A^{\mu\rho} + \frac{1}{20}\hbar e^2\frac{1}{M^2}A^{\mu\nu}D_\rho D_\nu A^{\mu\rho} - \frac{2}{9}\hbar\bar y y\frac{1}{M^2}\left(1+3\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi D^2D^2\phi -$$

$$\frac{2}{9}\hbar\bar y y\frac{1}{M^2}\left(1+3\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi D_\mu D^2D_\mu\phi + \frac{1}{9}\hbar\bar y y\frac{1}{M^2}\left(7+12\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi D_\mu D_\nu D_\mu D_\nu\phi + \frac{i}{72}\hbar\bar y y\frac{1}{M^2}\left(5+6\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu D^2\psi) -$$

$$\frac{i}{36}\hbar\bar y y\frac{1}{M^2}\left(11+6\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(\bar\psi\cdot\gamma_\mu P_L\cdot D_\nu D_\mu D_\nu\psi) + \frac{i}{72}\hbar\bar y y\frac{1}{M^2}\left(5+6\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(\bar\psi\cdot\gamma_\mu P_L\cdot D^2D_\mu\psi) -$$

$$\frac{i}{72}\hbar\bar y y\frac{1}{M^2}\left(5+6\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D^2D_\nu\bar\psi\cdot\gamma_\nu P_L\cdot\psi) + \frac{i}{36}\hbar\bar y y\frac{1}{M^2}\left(11+6\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D_\mu D_\nu D_\mu\bar\psi\cdot\gamma_\nu P_L\cdot\psi) -$$

$$\frac{i}{72}\hbar\bar y y\frac{1}{M^2}\left(5+6\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D_\mu D^2\bar\psi\cdot\gamma_\mu P_L\cdot\psi) - \hbar\bar y^2y^2\phi^4\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right] + \frac{1}{3}\hbar\bar y^3y^3\frac{1}{M^2}\phi^6 + \frac{13}{12}\hbar\bar y^2y^2\frac{1}{M^2}\phi^2(D_\mu\phi)^2 +$$

$$\frac{13}{12}\hbar\bar y^2y^2\frac{1}{M^2}D^2\phi\,\phi^3 + \frac{1}{3}\hbar\bar y y e^2\frac{1}{M^2}\phi^2A^{\mu\nu 2} + \hbar e\bar y y\frac{1}{M^2}\phi D_\mu D_\nu\phi A^{\rho\sigma}\varepsilon^{\mu\nu\rho\sigma} + \frac{1}{12}\hbar e\bar y y\frac{1}{M^2}\left(9+2\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)D_\nu A^{\mu\nu}(\bar\psi\cdot\gamma_\mu P_L\cdot\psi) -$$

$$\frac{1}{8}\hbar e\bar y y\frac{1}{M^2}A^{\mu\nu}(\bar\psi\cdot\Gamma_{\mu\nu\rho}P_L\cdot D_\rho\psi) - \frac{1}{8}\hbar e\bar y y\frac{1}{M^2}A^{\mu\nu}(D_\rho\bar\psi\cdot\Gamma_{\rho\nu\mu}P_L\cdot\psi) + i\bar y y\frac{1}{M^2}\phi D_\mu\phi(\bar\psi\cdot\gamma_\mu P_L\cdot\psi) +$$

$$\left(i\bar y y\frac{1}{M^2} - \frac{i}{4}\hbar\bar y^2y^2\frac{1}{M^2}\left(5+4\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\right)\phi^2(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu\psi) + \frac{i}{4}\hbar\bar y^2y^2\frac{1}{M^2}\left(5+4\,\text{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi^2(D_\mu\bar\psi\cdot\gamma_\mu P_L\cdot\psi)$$

Operator reduction

Initial output contain many redundancies (off-shell matching).

Allowed operations on the Lagrangian are:

Exact simplifications:

- Integration by parts: add a constant term
- Dirac and group structures identities

GreensSimplify $\rightarrow$ Green's basis

On-shell equivalence:

- Field redefinitions: leave S-matrix invariant

EOMSimplify $\rightarrow$ Minimal basis

Green's Basis

GreensSimplify

Exact simplifications:

- Contraction of generalized Clebsch-Gordon coefficients: GroupMagic
- Linear simplifications
  - Integration by parts identities e.g. $A^{\mu\nu}D^2A_{\mu\nu} = -(D_\rho A_{\mu\nu})^2$
  - Commutation of covariant derivatives $[D_\mu, D_\nu] = F_{\mu\nu}$
  - Jacobi identities $D_\alpha F_{\mu\nu} + D_\mu F_{\nu\alpha} + D_\nu F_{\alpha\mu} = 0$
  - Spinor double derivative $D^2\psi = \not{D}\not{D}\psi - F^{\mu\nu}\sigma_{\mu\nu}\psi$
  - Commutation of gamma matrices $\gamma_\mu\gamma_\nu = -\gamma_\nu\gamma_\mu + 2g_{\mu\nu}$
  - Index symmetries e.g. $\epsilon^{ij}H_iH_j = 0$
  - Product of epsilon $\epsilon_{i_1i_2\ldots}\epsilon_{j_1j_2\ldots} = \sum_\sigma \delta_{\sigma(i_1)\sigma(j_1)}\delta_{\sigma(i_2)\sigma(j_2)}$
  - Projection to a 4D Dirac basis: Levi-Civita relations and Gamma reduction
  - Fierz identities

GreensSimplify

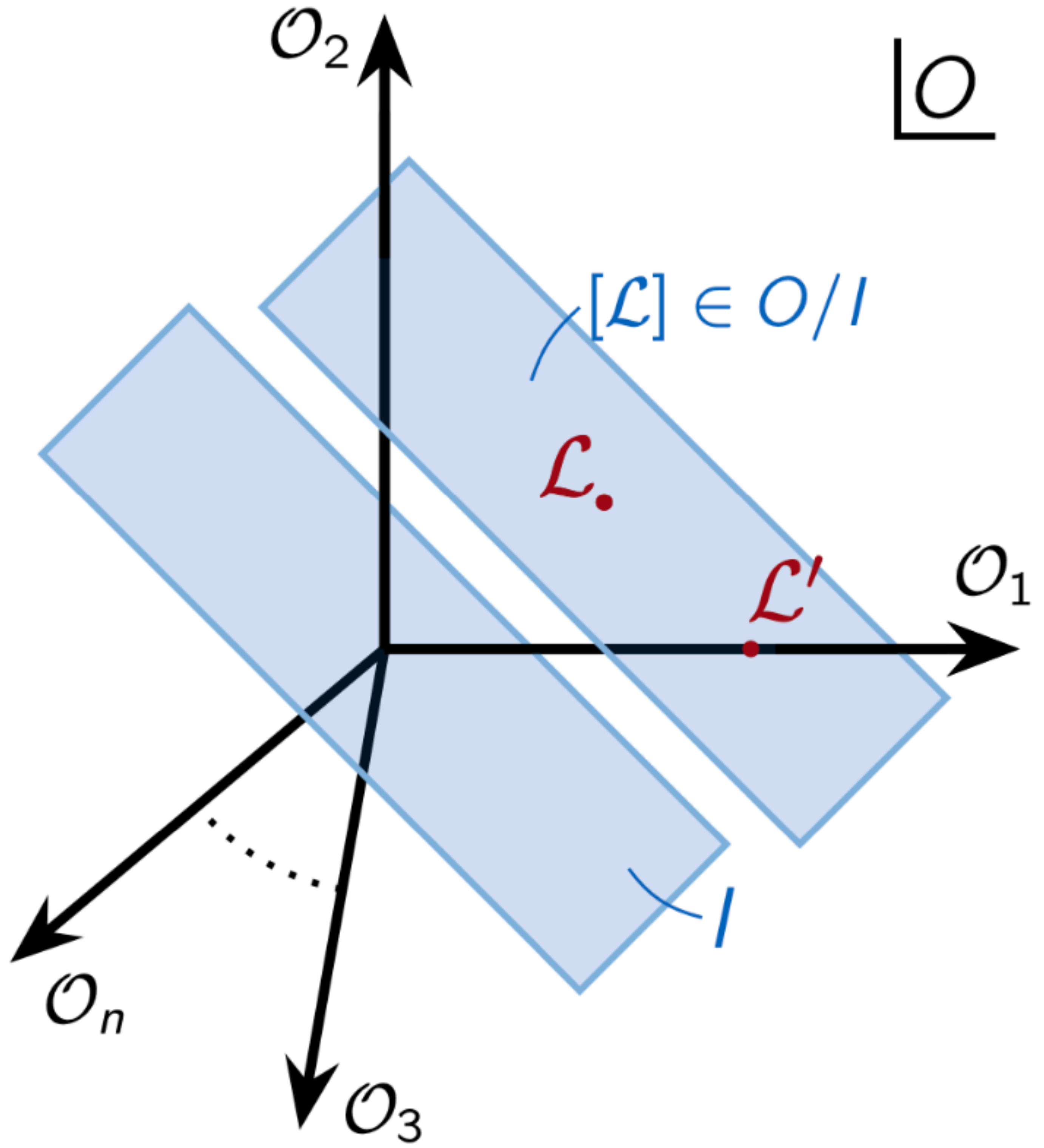
Define $I \subseteq O$ as the space of all operator identities

e.g. $O_1 + 2O_2 = 0$ interpreted as $O_1 + 2O_2 \in I$.

Applying row reduction, we select a representative element for $[\mathscr{L}_{\text{EFT}}] \in O/I$ as our Green's basis.

# of operators

# of identities
$$\begin{pmatrix} 1 & . & . & . & \dots \\ 0 & 1 & . & . & \dots \\ \vdots & \ddots & \ddots & . & \dots \\ 0 & \dots & 0 & 1 & . \end{pmatrix} \begin{pmatrix} O_1 \\ O_2 \\ \vdots \\ O_{n_d} \end{pmatrix} = \vec{0}$$

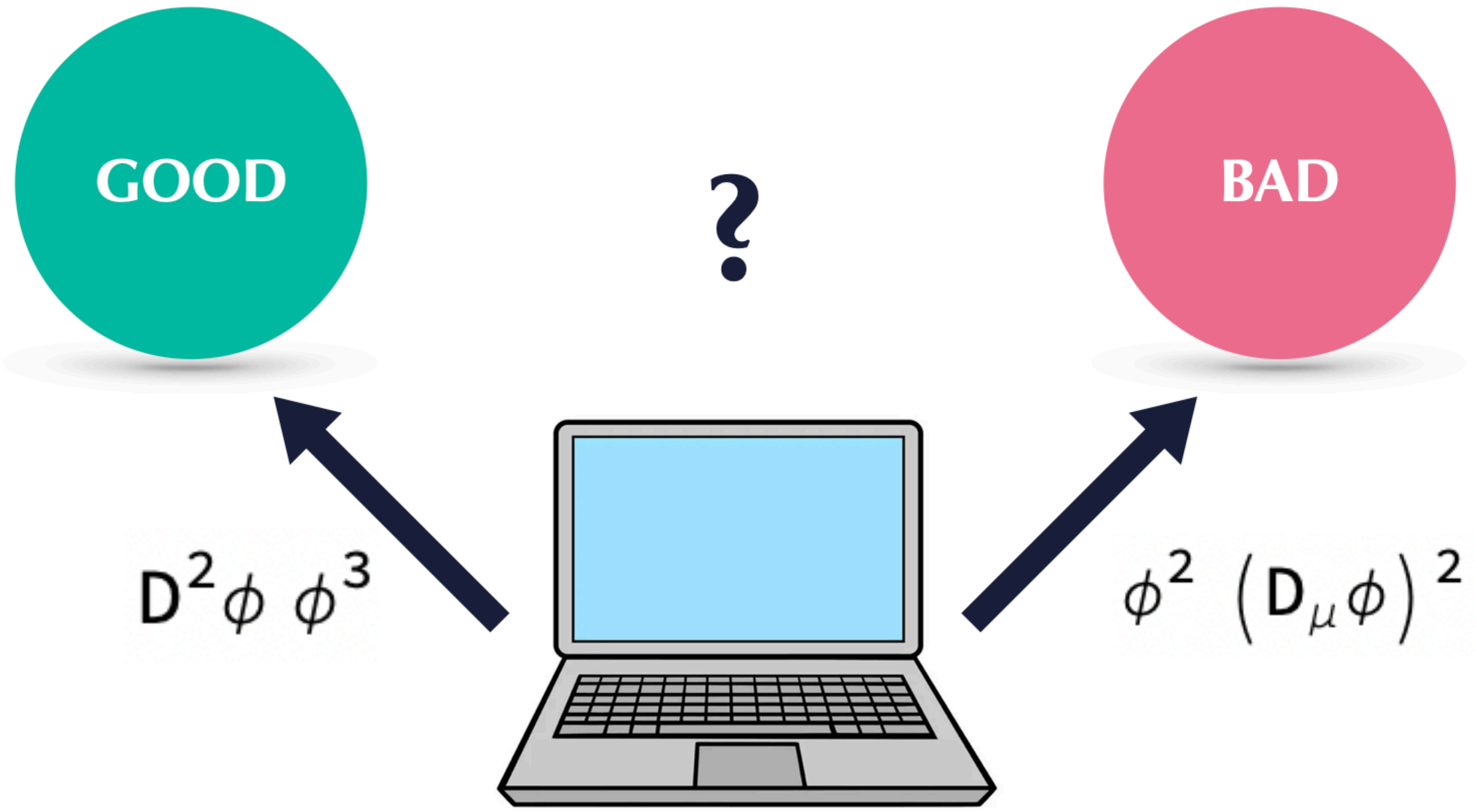


GreensSimplify

Teach computer our taste: assign a score to each operator.

Scoring criteria:

- Includes equation of motion kinetic term +++
- Field strength tensors ++
- Sandwiched indices in covariant derivatives - -
- Self-conjugate operator +
- Group epsilon in operator - -
- Same fermion fields in bilinears ++
- Dirac structure not in Dirac basis - -
- Group indices contracted in bilinears +
- Many transpose in bilinears -
- Double tensor Dirac structure - -



Order them before row reduce $\begin{pmatrix} \mathcal{O}_{--} \\ \mathcal{O}_{-} \\ \mathcal{O}_{+} \\ \mathcal{O}_{++} \end{pmatrix}$

Demo - GreensSimplify

One-loop matching to the effective Lagrangian

```
In[17]:= LEFT = Match[LUV, LoopOrder → 1, EFTOrder → 6] /. ϵ^-1 → 0;
         LEFT - Llight // CollectOperators // NiceForm
```

32 operators

Out[18]//NiceForm=

$$
\begin{aligned}
&-\frac{1}{3}\hbar e^2 A^{\mu\nu\,2}\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right] + \frac{1}{2}\hbar \bar y y \left(1+2\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D_\mu\phi)^2 - 2\hbar \bar y y M^2\left(1+\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi^2 + \frac{i}{8}\hbar \bar y y\left(3+2\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu\psi) - \\
&\frac{i}{8}\hbar \bar y y\left(3+2\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D_\mu\bar\psi\cdot\gamma_\mu P_L\cdot\psi) + \frac{7}{270}\hbar e^2\frac{1}{M^2}(D_\rho A^{\mu\nu})^2 + \frac{1}{20}\hbar e^2\frac{1}{M^2}A^{\mu\nu}D^2A^{\mu\nu} + \frac{7}{270}\hbar e^2\frac{1}{M^2}D_\rho A^{\mu\nu}D_\nu A^{\mu\rho} - \\
&\frac{1}{90}\hbar e^2\frac{1}{M^2}D_\nu A^{\mu\nu}D_\rho A^{\mu\rho} + \frac{1}{20}\hbar e^2\frac{1}{M^2}A^{\mu\nu}D_\nu D_\rho A^{\mu\rho} + \frac{1}{20}\hbar e^2\frac{1}{M^2}A^{\mu\nu}D_\rho D_\nu A^{\mu\rho} - \frac{2}{9}\hbar\bar y y\frac{1}{M^2}\left(1+3\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi D^2D^2\phi - \\
&\frac{2}{9}\hbar\bar y y\frac{1}{M^2}\left(1+3\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi D_\mu D^2 D_\mu\phi + \frac{1}{9}\hbar\bar y y\frac{1}{M^2}\left(7+12\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi D_\mu D_\nu D_\mu D_\nu\phi + \frac{i}{72}\hbar\bar y y\frac{1}{M^2}\left(5+6\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu D^2\psi) - \\
&\frac{i}{36}\hbar\bar y y\frac{1}{M^2}\left(11+6\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(\bar\psi\cdot\gamma_\mu P_L\cdot D_\nu D_\mu D_\nu\psi) + \frac{i}{72}\hbar\bar y y\frac{1}{M^2}\left(5+6\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(\bar\psi\cdot\gamma_\mu P_L\cdot D^2D_\mu\psi) - \\
&\frac{i}{72}\hbar\bar y y\frac{1}{M^2}\left(5+6\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D^2D_\nu\bar\psi\cdot\gamma_\nu P_L\cdot\psi) + \frac{i}{36}\hbar\bar y y\frac{1}{M^2}\left(11+6\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D_\mu D_\nu D_\mu\bar\psi\cdot\gamma_\nu P_L\cdot\psi) - \\
&\frac{i}{72}\hbar\bar y y\frac{1}{M^2}\left(5+6\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)(D_\mu D^2\bar\psi\cdot\gamma_\mu P_L\cdot\psi) - \hbar\bar y^2 y^2\phi^4\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right] + \frac{1}{3}\hbar\bar y^3 y^3\frac{1}{M^2}\phi^6 + \frac{13}{12}\hbar\bar y^2 y^2\frac{1}{M^2}\phi^2(D_\mu\phi)^2 + \\
&\frac{13}{12}\hbar\bar y^2 y^2\frac{1}{M^2}D^2\phi\,\phi^3 + \frac{1}{3}\hbar\bar y y e^2\frac{1}{M^2}\phi^2 A^{\mu\nu\,2} + \hbar e\bar y y\frac{1}{M^2}\phi D_\mu D_\nu\phi A^{\rho\sigma}\varepsilon^{\mu\nu\rho\sigma} + \frac{1}{12}\hbar e\bar y y\frac{1}{M^2}\left(9+2\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)D_\nu A^{\mu\nu}(\bar\psi\cdot\gamma_\mu P_L\cdot\psi) - \\
&\frac{1}{8}\hbar e\bar y y\frac{1}{M^2}A^{\mu\nu}(\bar\psi\cdot\Gamma_{\mu\nu\rho}P_L\cdot D_\rho\psi) - \frac{1}{8}\hbar e\bar y y\frac{1}{M^2}A^{\mu\nu}(D_\rho\bar\psi\cdot\Gamma_{\rho\nu\mu}P_L\cdot\psi) + i\bar y y\frac{1}{M^2}\phi D_\mu\phi(\bar\psi\cdot\gamma_\mu P_L\cdot\psi) + \\
&\left(i\bar y y\frac{1}{M^2} - \frac{i}{4}\hbar\bar y^2 y^2\frac{1}{M^2}\left(5+4\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\right)\phi^2(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu\psi) + \frac{i}{4}\hbar\bar y^2 y^2\frac{1}{M^2}\left(5+4\,\mathrm{Log}\left[\frac{\bar\mu^2}{M^2}\right]\right)\phi^2(D_\mu\bar\psi\cdot\gamma_\mu P_L\cdot\psi)
\end{aligned}
$$

Demo - GreensSimplify

Reduction to Green's basis

14 operators

```
In[19]:= LEFTOffShell = LEFT // GreensSimplify;
         LEFTOffShell - Llight // HcSimplify // NiceForm
```

Out[20]//NiceForm=

$$-\frac{1}{3}\hbar\, e^2 A^{\mu\nu 2}\,\mathrm{Log}\left[\frac{\mu^2}{M^2}\right] + \frac{1}{2}\hbar\, \bar{y}\, y\left(1+2\,\mathrm{Log}\left[\frac{\mu^2}{M^2}\right]\right)(D_\mu\phi)^2 - 2\hbar\,\bar{y}\,y\,M^2\left(1+\mathrm{Log}\left[\frac{\mu^2}{M^2}\right]\right)\phi^2 +$$
$$\frac{i}{4}\hbar\,\bar{y}\,y\left(3+2\,\mathrm{Log}\left[\frac{\mu^2}{M^2}\right]\right)\left(\bar{\psi}\cdot\gamma_\mu P_L\cdot D_\mu\psi\right) + \frac{1}{3}\hbar\,\bar{y}\,y\,\frac{1}{M^2}D^2\phi\, D^2\phi - \frac{2}{15}\hbar\, e^2\frac{1}{M^2}D_\nu A^{\mu\nu} D_\rho A^{\mu\rho} -$$
$$\hbar\,\bar{y}^2 y^2\phi^4\,\mathrm{Log}\left[\frac{\mu^2}{M^2}\right] + \frac{1}{3}\hbar\,\bar{y}^3 y^3\frac{1}{M^2}\phi^6 + \frac{13}{18}\hbar\,\bar{y}^2 y^2\frac{1}{M^2}D^2\phi\,\phi^3 + \frac{1}{3}\hbar\,\bar{y}\,y\,e^2\frac{1}{M^2}\phi^2 A^{\mu\nu 2} +$$
$$\frac{7}{36}\hbar\, e\,\bar{y}\,y\,\frac{1}{M^2}D_\nu A^{\mu\nu}\left(\bar{\psi}\cdot\gamma_\mu P_L\cdot\psi\right) + \frac{1}{8}\hbar\, e\,\bar{y}\,y\,\frac{1}{M^2}\left(A^{\mu\nu}\left(\bar{\psi}\cdot\Gamma_{\nu\mu}\gamma_\rho P_L\cdot D_\rho\psi\right) + A^{\mu\nu}\left(D_\rho\bar{\psi}\cdot\gamma_\rho\Gamma_{\mu\nu}P_L\cdot\psi\right)\right) +$$
$$\left(\frac{i}{2}\bar{y}\,y\,\frac{1}{M^2} - \frac{i}{4}\hbar\,\bar{y}^2 y^2\frac{1}{M^2}\left(5+4\,\mathrm{Log}\left[\frac{\mu^2}{M^2}\right]\right)\right)\left(\phi^2\left(\bar{\psi}\cdot\gamma_\mu P_L\cdot D_\mu\psi\right) - \phi^2\left(D_\mu\bar{\psi}\cdot\gamma_\mu P_L\cdot\psi\right)\right) +$$
$$\frac{i}{6}\hbar\,\bar{y}\,y\,\frac{1}{M^2}\left(\left(D_\mu\bar{\psi}\cdot\gamma_\mu P_L\cdot D^2\psi\right) - \left(D^2\bar{\psi}\cdot\gamma_\nu P_L\cdot D_\nu\psi\right)\right)$$

Evanescent operators

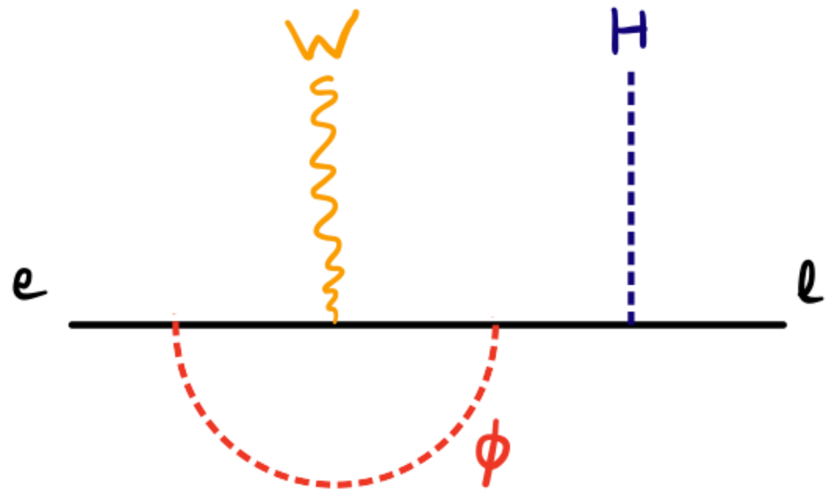
Evanescent operators: 2HDM example

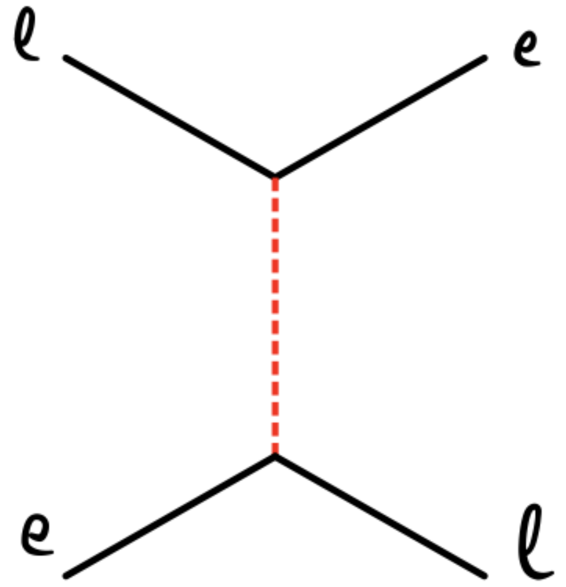
Two-Higgs doublet model:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + D_\mu \phi^\dagger D^\mu \phi - M_\phi^2 \phi^\dagger \phi - \left(y^{pr} \bar{\ell}_p \phi e_r + \text{h.c.} \right)$$

Let us focus on the dipole contribution to $\mathscr{A}_{e_r \to \ell_p W}$.

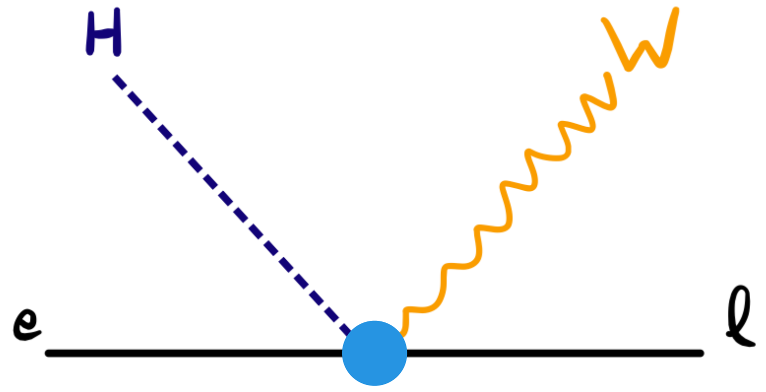
In the full theory

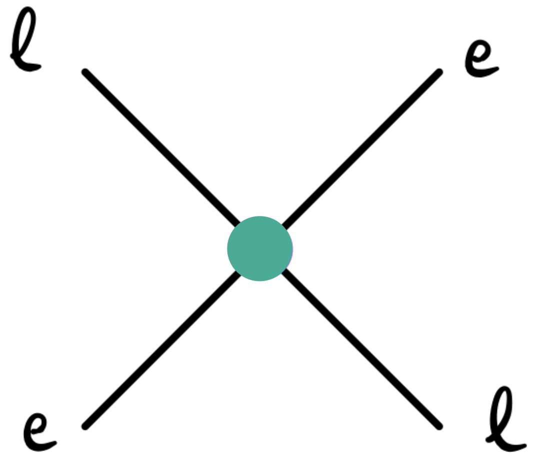




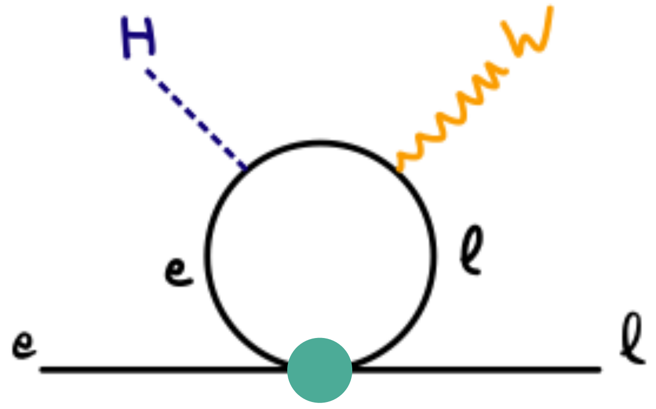
In the EFT, match to

$$\mathscr{L}_{\rm EFT} \supset \quad C_{eW}^{pr} (\bar{\ell}_p \sigma^{\mu\nu} \tau^I e_r) H W^I_{\mu\nu} \quad + \quad C_{\ell e}^{prst} R_{\ell e}^{prst}$$





No contribution from $\Gamma^{(1)}_{\rm EFT}$



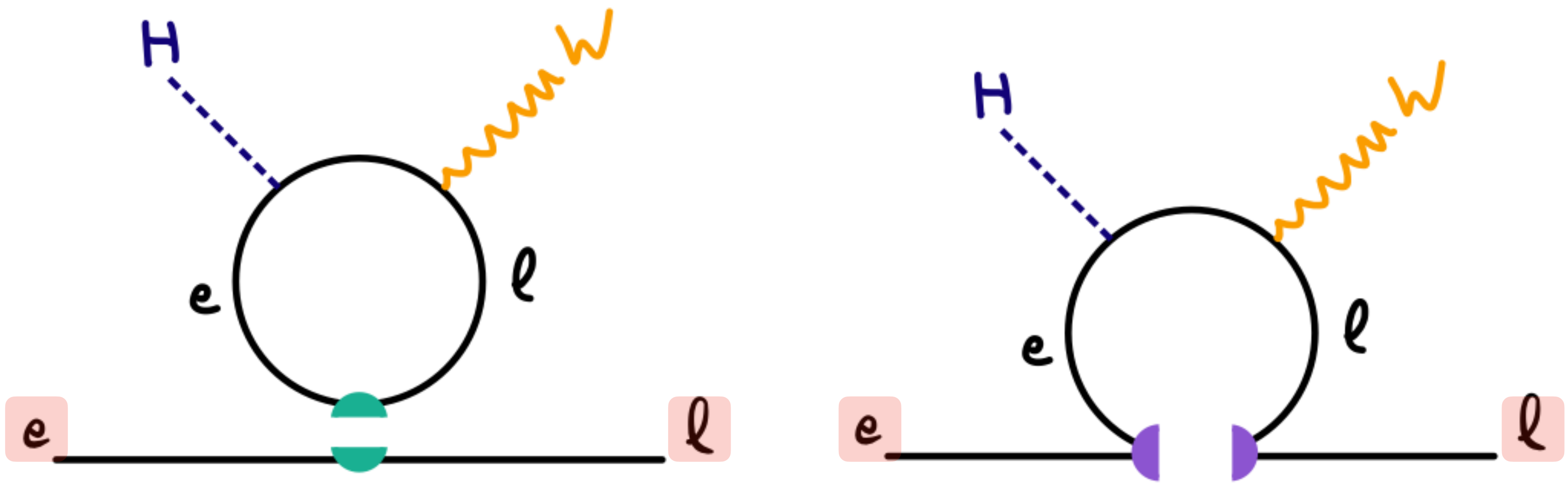
$= 0$

Evanescent operators: 2HDM example

Using Fierz identies we can go from the redundant operator $R_{\ell e}$ to the Warsaw basis operator $Q_{\ell e}$

$$\left.\begin{aligned} R_{\ell e} &= (\bar{\ell} e)(\bar{e} \ell) \\ Q_{\ell e} &= (\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma^\mu e) \end{aligned}\right\} \qquad R_{\ell e}^{prst} \overset{4d}{=} -\frac{1}{2} Q_{\ell e}^{pstr}$$

but their contribution to the dipole amplitude is not the same!

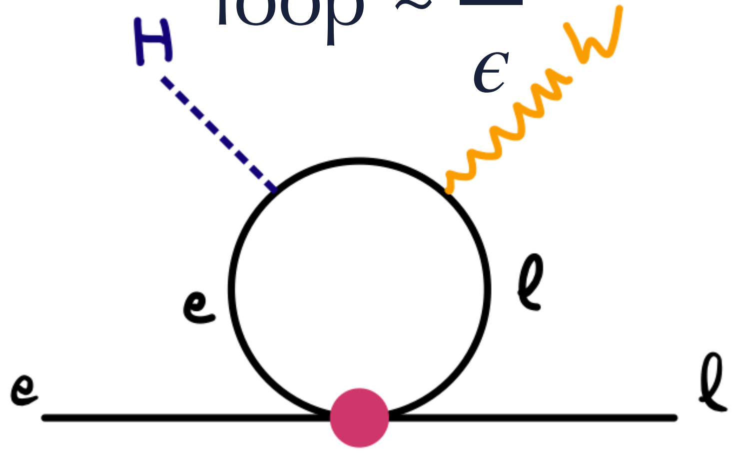


$= 0$ $\qquad\qquad$ $\neq 0$

In dimensional regularization, $d-$dimensional Fierz relations must include evanescent operators (of rank ϵ)

$$R_{\ell e}^{prst} \xrightarrow{d-\text{dim}} -\frac{1}{2} Q_{\ell e}^{pstr} + E_{\ell e}^{prst}$$

loop $\sim \frac{1}{\epsilon}$



$\mathcal{O}(\epsilon)$

gives a finite contribution to the dipole amplitude, cancelling the one from $Q_{\ell e}$.

Evanescent operators: 2HDM example

$$R_{\ell e}^{prst} \xrightarrow{d\text{-dim}} -\frac{1}{2} Q_{\ell e}^{pstr} + E_{\ell e}^{prst}$$

Since, by definition,

$$E \xrightarrow[d \to 4]{} 0$$

the only physical contributions from evanescent operators are finite and local.

In the EFT of the 2HDM, the change of basis is equivalent to

$$\begin{aligned} R_{\ell e}^{prst} &\to -\frac{1}{2} Q_{\ell e}^{pstr} \\ C_{eW} &\to C_{eW} + \Delta C_{eW} \end{aligned}$$

where ΔC_{eW} is generated from $E_{\ell e}^{prst}$ insertion ⇒ trade evanescent operator for a shift in the Wilson coefficient.

Evanescence-free scheme: compute all evanescent contributions to all one-loop diagrams,
then drop completely the evanescent operators in the physical basis.

↪ Evanescence-free SMEFT computed in [Fuentes-Martín, König, JP, Thomsen, Wilsch, 2211.09144]

Evanescent treatment in Matchete

3 sources of evanescent operators from 4D identities: $\Gamma_n = \{P_R, P_L, \gamma^\mu P_R, \gamma^\mu P_L, \sigma_{\mu\nu}\}$

- fierzing

$$(X_1) \otimes [X_2] = \frac{1}{4}\, \mathrm{Tr}_4[\Gamma_n X_1 \tilde{\Gamma}_m X_2]\; (\tilde{\Gamma}_n] \otimes [\Gamma_m) + E_{\mathrm{Fierz}}(X_1, X_2)$$

- gamma reduction

$$X_1 \otimes X_2 = \sum_i b_i(X_1, X_2)\Gamma_i \otimes \tilde{\Gamma}_i + E_{\gamma\mathrm{red}}(X_1, X_2)$$

$$\text{with } \mathrm{Tr}_d[\Gamma_j X_1 \tilde{\Gamma}_j X_2] = \sum_i b_i(X1,X2)\mathrm{Tr}_d[\Gamma_j \Gamma_i \tilde{\Gamma}_j \tilde{\Gamma}_i] + \mathcal{O}(\epsilon^2)$$

- Levi-Civita identities

$$\epsilon_{\mu\nu\rho\sigma}\sigma^{\rho\sigma} = -2i\sigma_{\mu\nu}\gamma_5 + E^{\epsilon}_{\mu\nu}$$
$$\epsilon^{\mu_1\mu_2\mu_3\mu_4}\,\epsilon_{\nu_1\nu_2\nu_3\nu_4} = -24\;\delta^{\mu_1}{}_{[\nu_1}\delta^{\mu_2}{}_{\nu_2}\delta^{\mu_3}{}_{\nu_3}\delta^{\mu_4}{}_{\nu_4]} + (E^{\epsilon})^{\mu_1\mu_2\mu_3\mu_4}_{\nu_1\nu_2\nu_3\nu_4}$$

MATCHETE

All 3 already included in simplification routines.
↪ Compute one-loop EFT diagrams with evanescent insertions to go to the Evanescence-free scheme.

Minimal basis

EOMSimplify

On-shell equivalence:

S-matrix is unchanged by field redefinition [Chisholm, *Nucl.Phys.* 26 (1961) 3]

↪ equivalent to adding an equation of motion (EOM) term to the Lagrangian at leading order

In Matchete: determine shift to perform by identifying "EOM kinetic term"

Field type	Redundant operator	Field redefinition
Real Scalar ϕ	$\chi D^2\phi$	$\phi \to \phi + \chi$
Dirac Fermion ψ	$\chi \not{D}\psi + \psi \overleftarrow{\not{D}}\Delta$	$\psi \to \psi - \frac{i}{2}(\bar{\chi} + \Delta)$
Real vector A	$D_\mu A^{\mu\nu}\chi_\nu$	$A_\mu \to A_\mu - \chi_\mu$

Field redefinition

If working with higher-dimension operators (than 6), field redefinition order by order:

$$\eta \to \eta' = \eta + \frac{\delta\eta^{(1)}}{\Lambda^2} + \frac{\delta\eta^{(2)}}{\Lambda^4} + O(\Lambda^{-6})$$

The shifted EFT Lagrangian is

$$\mathscr{L}[\eta'] = \mathscr{L}[\eta] + \frac{1}{\Lambda^2}\left.\frac{\delta\mathscr{L}[\eta']}{\delta\eta'}\right|_{\eta'=\eta}\delta\eta^{(1)} + \frac{1}{\Lambda^4}\left(\left.\frac{\delta\mathscr{L}[\eta']}{\delta\eta'}\right|_{\eta'=\eta}\delta\eta^{(2)} + \frac{1}{2}\left.\frac{\delta^2\mathscr{L}[\eta']}{\delta\eta'\delta\eta'}\right|_{\eta'=\eta}\left(\delta\eta^{(1)}\right)^2\right) + O(\Lambda^{-6})$$

EOM

Note 1: At leading power, applying equation of motion is equivalent to field redefinition.
At sub-leading power, they are not equivalent anymore.

Note 2: Applying field redefinition after renormalization lead to

- divergent correlation functions
- infinite field anomalous dimension if redundant are ignored [Manohar, JP, Nepveu, 2402.08715]

Demo - EOMSimplify

Reduction to Green's basis

14 operators

```
In[19]:= LEFTOffShell = LEFT // GreensSimplify;
         LEFTOffShell - Llight // HcSimplify // NiceForm
```

Out[20]//NiceForm=

$$-\frac{1}{3}\hbar e^2 A^{\mu\nu 2} \mathrm{Log}\left[\frac{\mu^2}{M^2}\right] + \frac{1}{2}\hbar \bar{y} y \left(1 + 2\,\mathrm{Log}\left[\frac{\mu^2}{M^2}\right]\right)(D_\mu\phi)^2 - 2\hbar \bar{y} y M^2 \left(1 + \mathrm{Log}\left[\frac{\mu^2}{M^2}\right]\right)\phi^2 +$$
$$\frac{i}{4}\hbar \bar{y} y \left(3 + 2\,\mathrm{Log}\left[\frac{\mu^2}{M^2}\right]\right)(\bar{\psi}\cdot\gamma_\mu P_L \cdot D_\mu\psi) + \frac{1}{3}\hbar \bar{y} y \frac{1}{M^2} D^2\phi\, D^2\phi - \frac{2}{15}\hbar e^2 \frac{1}{M^2} D_\nu A^{\mu\nu} D_\rho A^{\mu\rho} -$$
$$\hbar \bar{y}^2 y^2 \phi^4 \mathrm{Log}\left[\frac{\mu^2}{M^2}\right] + \frac{1}{3}\hbar \bar{y}^3 y^3 \frac{1}{M^2}\phi^6 + \frac{13}{18}\hbar \bar{y}^2 y^2 \frac{1}{M^2} D^2\phi\,\phi^3 + \frac{1}{3}\hbar \bar{y} y e^2 \frac{1}{M^2}\phi^2 A^{\mu\nu 2} +$$
$$\frac{7}{36}\hbar e \bar{y} y \frac{1}{M^2} D_\nu A^{\mu\nu}(\bar{\psi}\cdot\gamma_\mu P_L\cdot\psi) + \frac{1}{8}\hbar e \bar{y} y \frac{1}{M^2}\left(A^{\mu\nu}(\bar{\psi}\cdot\Gamma_{\nu\mu}\gamma_\rho P_L\cdot D_\rho\psi) + A^{\mu\nu}(D_\rho\bar{\psi}\cdot\gamma_\rho\Gamma_{\mu\nu}P_L\cdot\psi)\right) +$$
$$\left(\frac{i}{2}\bar{y} y \frac{1}{M^2} - \frac{i}{4}\hbar \bar{y}^2 y^2 \frac{1}{M^2}\left(5 + 4\,\mathrm{Log}\left[\frac{\mu^2}{M^2}\right]\right)\right)\left(\phi^2(\bar{\psi}\cdot\gamma_\mu P_L\cdot D_\mu\psi) - \phi^2(D_\mu\bar{\psi}\cdot\gamma_\mu P_L\cdot\psi)\right) +$$
$$\frac{i}{6}\hbar \bar{y} y \frac{1}{M^2}\left((D_\mu\bar{\psi}\cdot\gamma_\mu P_L\cdot D^2\psi) - (D^2\bar{\psi}\cdot\gamma_\nu P_L\cdot D_\nu\psi)\right)$$

Demo - EOMSimplify

Reduction to minimal basis

7 operators

```
In[19]:= LEFTOnShell = LEFT // EOMSimplify;
         LEFTOnShell - Llight // CollectOperators // NiceForm
```

Out[20]//NiceForm=

$$-\frac{1}{3}\hbar\, e^2 A^{\mu\nu 2}\, \mathrm{Log}\left[\frac{\bar{\mu}^2}{M^2}\right] + \left(C_{\phi^2} + \frac{1}{3}\hbar\, \bar{y}\, y\, C_{\phi^2}\, \frac{1}{M^2}\left(4\, C_{\phi^2} - 3\, M^2\left(1 + 2\, \mathrm{Log}\left[\frac{\bar{\mu}^2}{M^2}\right]\right)\right)\right)\phi^2 + \frac{1}{9}\hbar\, \bar{y}^2 y^2 \frac{1}{M^2}\left(13\, C_{\phi^2} - 9\, M^2\, \mathrm{Log}\left[\frac{\bar{\mu}^2}{M^2}\right]\right)\phi^4 + \frac{1}{3}\hbar\, \bar{y}^3 y^3 \frac{1}{M^2}\phi^6 + \frac{1}{3}\hbar\, \bar{y}\, y\, e^2 \frac{1}{M^2}\phi^2 A^{\mu\nu 2} - \frac{2}{15}\hbar\, e^4 \frac{1}{M^2}\left(\bar{\psi}\cdot\gamma_\mu\cdot\psi\right)^2 + \frac{7}{36}\hbar\, \bar{y}\, y\, e^2 \frac{1}{M^2}\left(\bar{\psi}\cdot\gamma_\mu\cdot\psi\right)\left(\bar{\psi}\cdot\gamma_\mu P_L\cdot\psi\right)$$

Conclusion

Conclusion

❖ Matching is a crucial step in the automation of the EFT approach.

❖ Matchete automates tree-level and one-loop matching by evaluating the supertraces from the path integral formulation.

MATCHETE v0.2.0

❖ Operators reduction also automated to a Green's basis or to a minimal basis allowing

- Output easier to read
- Interface to EFT phenomenology codes
- Comparison between different basis

Ultimate goal: direct evaluation of new physics models with one code performing

- Matching
- RG evolution

} Multiple steps

- Connection to observables

Matchete Roadmap

MATCHETE

v0.2.0 available at:
https://gitlab.com/matchete/matchete

Future versions functionalities will include:

- Full basis reduction in the evanescensce-free scheme — soon
- One-loop matching of heavy vectors and symmetry breaking — theoretical development
- One-loop RGE computations — soon
- Interface with other EFT codes (UFO, WCxf formats) — wip