Matching effective theories efficiently

Felix Wilsch

Universität Zürich

In collaboration with:

Javier Fuentes-Martín, Matthias König, Julie Pagès, Anders Eller Thomsen

Les Rencontres de Physique de la Vallée d'Aoste — La Thuile

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EFT matching

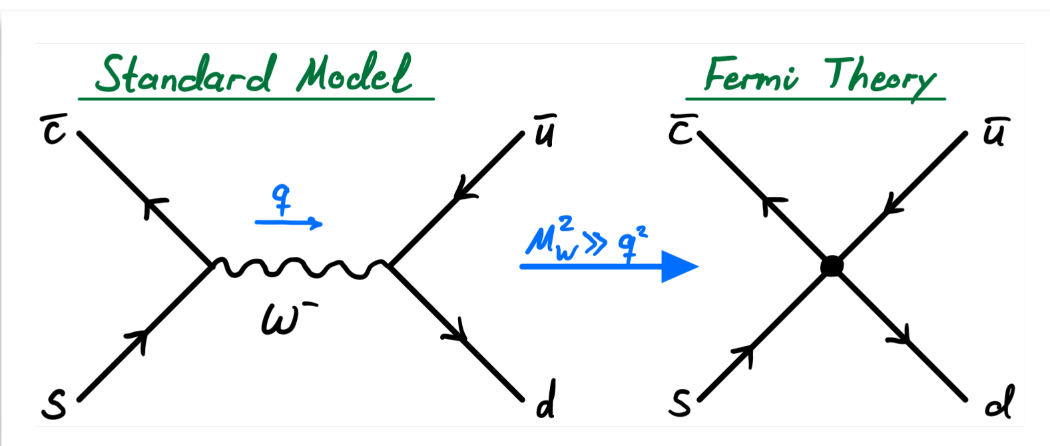
Scenario: theory $\mathscr{L}_{\mathrm{UV}}(\eta_H, \eta_L)$ with large scale separation $m_H \gg m_L$

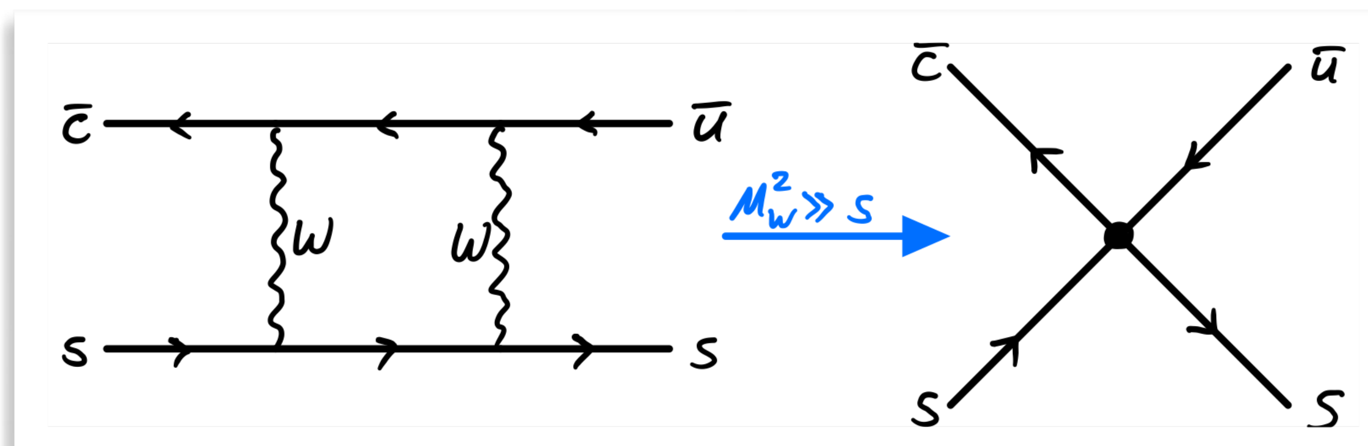
- Analysis of low-energy phenomenology ⇒ construct effective theory (EFT)

$$\mathscr{L}_{\mathrm{EFT}}(\eta_L) = \mathscr{L}_{d=4}(\eta_L) + \sum_{d=5}^{\infty} \frac{1}{m_H^{d-4}} \sum_i C_i^{(d)} Q_i^{(d)}(\eta_L)$$

How to find:
Wilson coefficients $C_i^{(d)}$?
Effective operators $Q_i^{(d)}$?

- Example: Fermi's theory — integrating out the W boson





➡ Diagrammatic matching

- Many interesting phenomena (e.g. FCNC) only at loop-level
- Requires one-loop matching

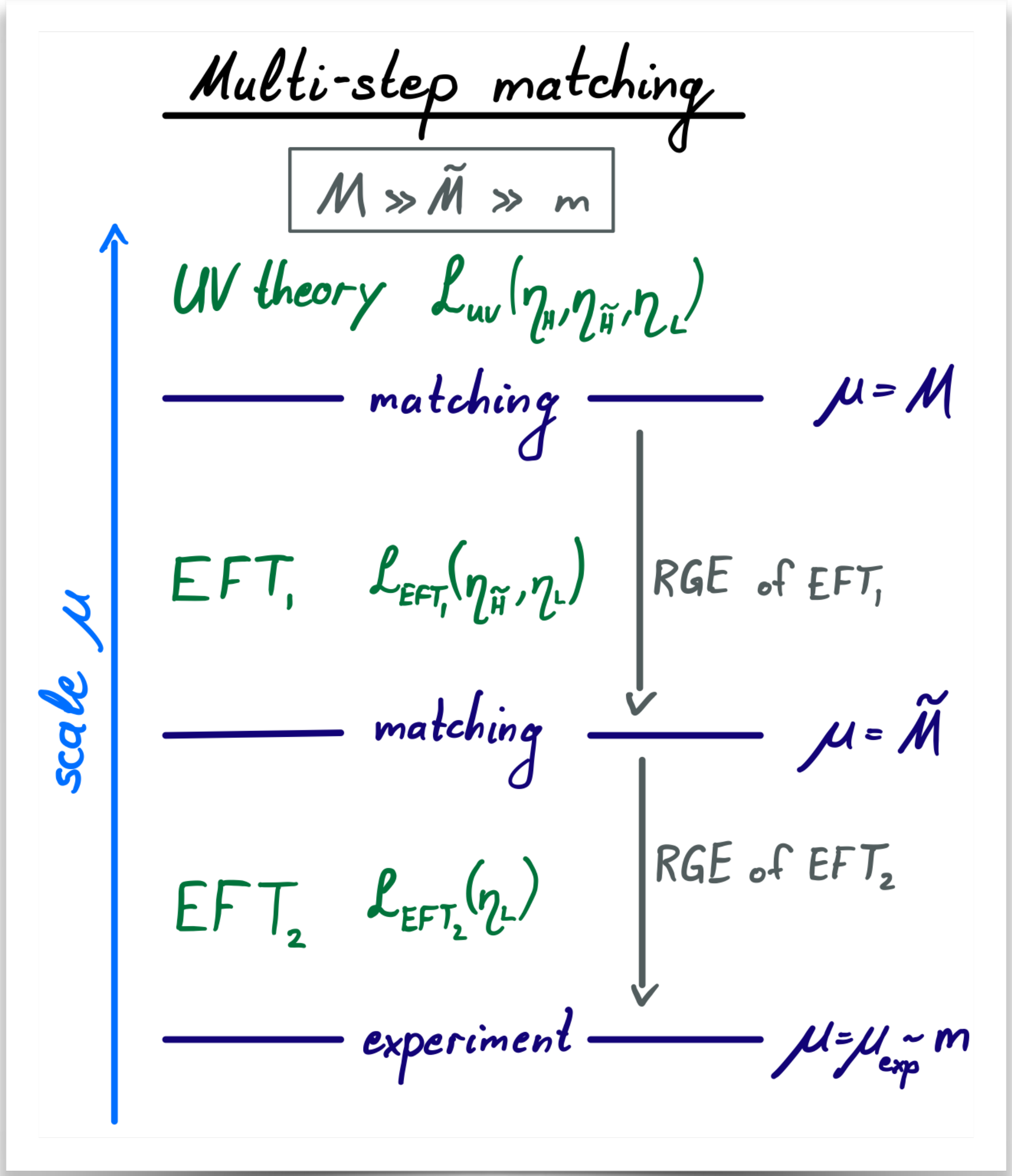
Automation of the matching

Universität Zürich[UZH]

Analysis of great variety of BSM theories:

1. Match UV theory to an EFT
2. Use RGE of the EFT to run to the scale of experiments
   - Possibly multiple matching steps
3. Compare EFT to data

➡ Variety of theories and complexity of computation require automation



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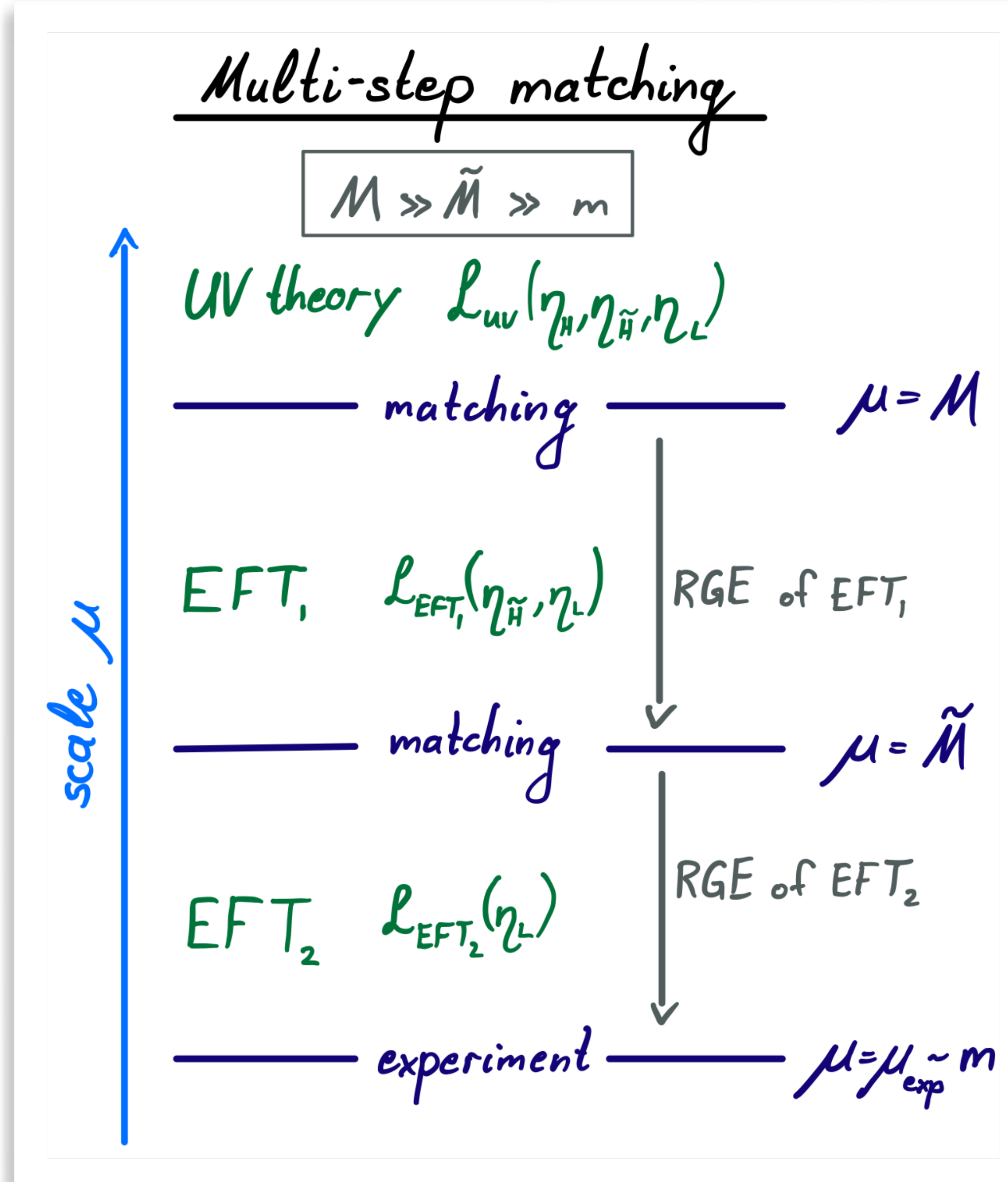

partial automation

STrEAM
Cohen, Lu, Zhang [2012.07851]

MatchingTools
Criado [1710.06445]

CoDEx
Das Bakshi, Chakrabortty, Patra [1808.04403]

SUPER TRACER
Fuentes-Martin, König, Pages, Thomsen, FW [2012.08506]

full automation

Matchmakereft
Carmona, Lazopoulos, Olgoso, Santiago [2112.10787]
[diagrammatic technique]

MATCHETE
Fuentes-Martin, König, Pages, Thomsen, FW [in preparation]
[functional technique]

EFT matching with functional methods

path integral | background field method

Functional matching formalism

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- **Functional formalism:**

Henning, Lu, Murayama [1412.1837]
del Aguila, Kunszt, Santiago [1602.00126]
Fuentes-Martin, Portoles, Ruiz-Femenia [1607.02142]
Henning, Lu, Murayama [1604.01019]
Zhang [1610.00710]
Cohen, Lu, Zhang [2011.02484]

  - Lagrangian $\mathscr{L}_{\rm UV}(\eta)$ with fields $\eta = \left(\eta_H, \eta_L\right)^\intercal$ and hierarchy $m_H \gg m_L$
  - Effective action: $$\exp\left(i\Gamma_{\rm UV}(\eta)\right) = \int \mathscr{D}\eta \, \exp\left(i\int \mathrm{d}^d x \, \mathscr{L}_{\rm UV}(\eta)\right)$$

- **Background field method:** shift all fields $\eta \to \hat{\eta} + \eta$

  $\hat{\eta}$: background configuration satisfying classical equations of motion (EOM)

  η: quantum fluctuation

- **Integrate out η_H:** perform the path integral over the quantum fluctuations η
  - Expand in inverse powers of the heavy masses m_H

➡ Effective action of the EFT describing same low-energy dynamics as $\mathscr{L}_{\rm UV}$

  - Contains all the higher dimensional operators and Wilson coefficients

Tree-level & one-loop matching

- **Expanding the Lagrangian:**

$$\mathscr{L}_{\mathrm{UV}}(\eta) \to \mathscr{L}_{\mathrm{UV}}(\hat{\eta}+\eta) = \mathscr{L}_{\mathrm{UV}}(\hat{\eta}) + \frac{1}{2}\bar{\eta}_i \left.\frac{\delta^2 \mathscr{L}_{\mathrm{UV}}}{\delta\bar{\eta}_i\,\delta\eta_j}\right|_{\eta=\hat{\eta}} \eta_j + \mathcal{O}(\eta^3)$$

Tree-level & one-loop matching

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- **Tree-level matching:** $\mathscr{L}^{(0)}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{UV}}\left(\hat{\eta}_L, \hat{\eta}_H(\hat{\eta}_L)\right)$

  - Substitute $\hat{\eta}_H$ by its EOM and expand in m_H

Tree-level & one-loop matching

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- **Expanding the Lagrangian:**

fluctuation operator $\mathcal{O}_{ij}$

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  - Substitute $\hat{\eta}_H$ by its EOM and expand in m_H
- **One-loop matching:** $\exp\left(i\Gamma_{\text{UV}}^{(1)}\right) = \int \mathcal{D}\eta \exp\left(\int \mathrm{d}^d x \, \frac{1}{2}\bar{\eta}_i\, \mathcal{O}_{ij}\, \eta_j\right)$
  - One-loop effective action is a Gaussian path integral
  - Can be expressed in terms of superdeterminants SDet

generalization of Det to mixed spins

Tree-level & one-loop matching

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higher loop orders

- **Tree-level matching:** $\mathscr{L}^{(0)}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{UV}}\left(\hat{\eta}_L, \hat{\eta}_H(\hat{\eta}_L)\right)$
  - Substitute $\hat{\eta}_H$ by its EOM and expand in m_H
- **One-loop matching:** $\exp\left(i\Gamma^{(1)}_{\mathrm{UV}}\right) = \int \mathscr{D}\eta \exp\left(\int \mathrm{d}^d x\, \frac{1}{2}\bar{\eta}_i\, \mathcal{O}_{ij}\, \eta_j\right)$
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Supertraces

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Cohen, Lu, Zhang [2011.02484]

- **Supertraces:** $\Gamma^{(1)}_{\mathrm{UV}} = \frac{i}{2}\mathrm{STr}\left(\ln\,\mathcal{O}\right) = \pm\frac{i}{2}\int\frac{\mathrm{d}^d p}{(2\pi)^d}\langle p\,|\,\mathrm{tr}(\ln\,\mathcal{O})\,|\,p\rangle$

- **Fluctuation operator:** $\mathcal{O}_{ij} \equiv \left.\frac{\delta^2\mathcal{L}_{\mathrm{UV}}}{\delta\bar{\eta}_i\,\delta\eta_j}\right|_{\eta=\hat{\eta}} = \delta_{ij}\Delta_i^{-1} - X_{ij} = \Delta_i^{-1}(\delta_{ij} - \Delta_i X_{ij})$

  - Separating propagators Δ_i from interaction terms X_{ij}

$$\Delta_i^{-1} = \begin{cases} -(D^2+M_i^2) \\ i\gamma^\mu D_\mu - M_i \\ g^{\mu\nu}(D^2+M_i^2) \end{cases}$$

- Expanding the logarithm in ΔX we find (ΔX is at most $\mathcal{O}(m_H^{-1})$):

$$\Gamma^{(1)}_{\mathrm{UV}} = \boxed{\frac{i}{2}\mathrm{STr}\left(\ln\,\Delta^{-1}\right)} - \boxed{\frac{i}{2}\sum_{n=1}^{\infty}\mathrm{STr}\left[(\Delta X)^n\right]}$$

log-type supertrace | power-type supertrace

  - log-type: model independent, only depend on propagator type Δ
  - power-type: depend on the interaction terms X

STr evaluation see backup

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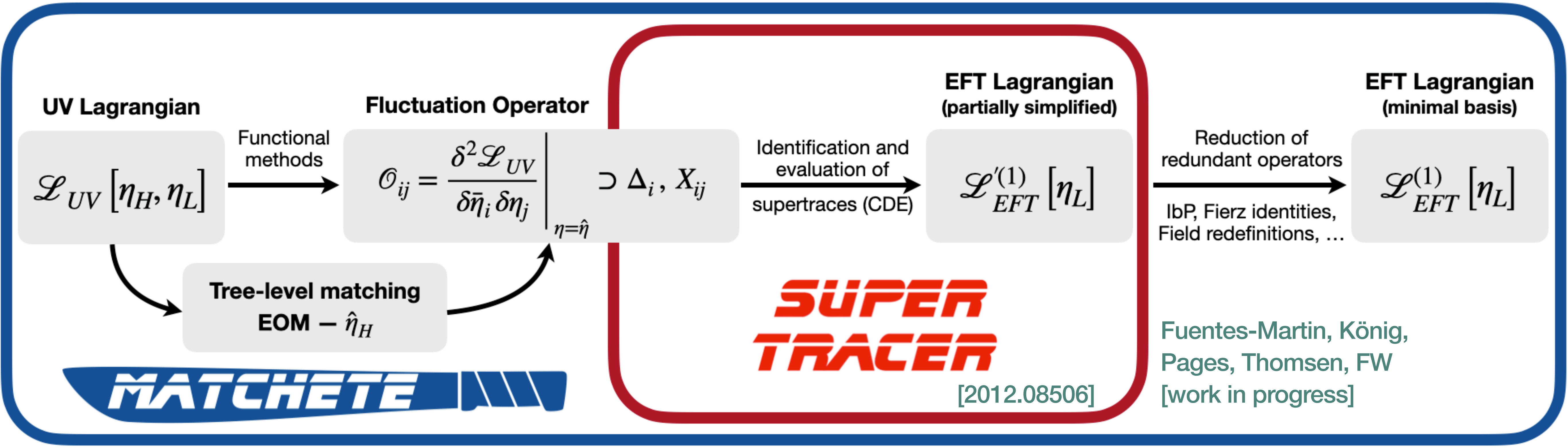
MATCHing Effective Theories Efficiently

A Mathematica package for fully automatic one-loop matching:



Features:

- Compatible with any weakly coupled UV theory with a mass power counting

- Works to arbitrary mass dimension*, only limited by computation time

  *apart from operator simplification

- Automatic reduction of redundant operators in the EFT Lagrangian:

  - Integration by parts,
    Field redefinitions,
    Fierz identities, …

- Output format compatible with other phenomenological codes

Example: vector-like fermions

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Defining models:

In[3]:=
```
<< Matchete`
```

MATCHETE

Preliminary

In[5]:=
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(* define gauge groups *)
DefineGaugeGroup[U1e, U[1], e, A]
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In[6]:=
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(* define field content *)
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(* define couplings *)
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ℒint = -y[] × Bar[ψ[]] ** PR ** Ψ[] ϕ[] // PlusHc;
```

Full Lagrangian

In[11]:=
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(* combine with free Lagrangian *)
ℒ = FreeLag[] + ℒint;
ℒ // NiceForm
```

Out[12]//NiceForm=

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

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y Yukawa coupling order $\mathcal{O}(m_L^0)$

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4) Write Lagrangian

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Universität Zürich UZH

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y Yukawa coupling order $\mathcal{O}(m_L^0)$

4) Write Lagrangian

Predefined models: SM, …

Vector-like model @ one-loop

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Specify loop order: 0 | 1

Specify EFT order: 4 | 5 | 6 | 7 | 8 | ...

Preliminary

One-loop matching

In[15]:=
```
ℒEFT1 = Match[ℒ, LoopOrder → 1, EFTorder → 6];
ℒEFT1 // NiceForm
```

Out[16]//NiceForm=

$$-\frac{1}{4} A^{\mu\nu 2} + \frac{7}{270}\hbar e^2 \frac{1}{M\Psi^2}(D_\rho A^{\mu\nu})^2 + \frac{1}{20}\hbar e^2\frac{1}{M\Psi^2} A^{\mu\nu}D^2A^{\mu\nu} + \frac{1}{240}\hbar e^2 \frac{1}{M\Psi^2} D_\nu D_\rho A^{\mu\nu}A^{\mu\rho} + \frac{1}{240}\hbar e^2\frac{1}{M\Psi^2} D_\rho D_\nu A^{\mu\nu}A^{\mu\rho} + \frac{1}{90}\hbar e^2 \frac{1}{M\Psi^2} D_\rho A^{\mu\nu} D_\nu A^{\mu\rho} + \frac{7}{270}\hbar e^2\frac{1}{M\Psi^2} D_\nu A^{\mu\nu} D_\rho A^{\mu\rho} +$$

$$\frac{7}{240}\hbar e^2\frac{1}{M\Psi^2} A^{\mu\nu}D_\nu D_\rho A^{\mu\rho} + \frac{7}{240}\hbar e^2 \frac{1}{M\Psi^2}A^{\mu\nu}D_\rho D_\nu A^{\mu\rho} + \frac{1}{120}\hbar e^2\frac{1}{M\Psi^2} D_\mu D_\rho A^{\mu\nu}A^{\nu\rho} + \frac{1}{120}\hbar e^2\frac{1}{M\Psi^2} D_\rho D_\mu A^{\mu\nu} A^{\nu\rho} - \frac{2}{135}\hbar e^2\frac{1}{M\Psi^2} D_\rho A^{\mu\nu} D_\mu A^{\nu\rho} + \frac{1}{27}\hbar e^2\frac{1}{M\Psi^2} D_\mu A^{\mu\nu} D_\rho A^{\nu\rho} -$$

$$\frac{1}{40}\hbar e^2\frac{1}{M\Psi^2}A^{\mu\nu}D_\mu D_\rho A^{\nu\rho} - \frac{1}{40}\hbar e^2\frac{1}{M\Psi^2}A^{\mu\nu}D_\rho D_\mu A^{\nu\rho} - \frac{1}{3}\hbar e^2 A^{\mu\nu 2}\,\mathrm{Log}\left[\bar\mu^2 \frac{1}{M\Psi^2}\right] + \frac{1}{2}(D_\mu\phi)^2 - 2\hbar\bar y y M\Psi^2\phi^2 + \frac{1}{3}\hbar \bar y y \frac{1}{M\Psi^2}\phi D^2D^2\phi - 2\hbar\bar y y M\Psi^2 \phi^2\, \mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right] -$$

$$\frac{1}{2}\hbar\bar y y\phi D^2\phi - \hbar\bar y y \phi D^2\phi\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right] + i(\bar\psi\cdot\gamma_\mu\cdot D_\mu\psi) - \frac{i}{6}\hbar\bar y y\frac{1}{M\Psi^2}(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu D^2\psi) + \frac{i}{6}\hbar\bar y y \frac{1}{M\Psi^2}(D_\mu D^2\bar\psi\cdot\gamma_\mu P_L\cdot\psi) + \frac{3i}{8}\hbar\bar y y(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu\psi) +$$

$$\frac{i}{4}\hbar\bar y y(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu\psi)\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right] - \frac{3i}{8}\hbar\bar y y(D_\mu\bar\psi\cdot\gamma_\mu P_L\cdot\psi) - \frac{i}{4}\hbar\bar y y (D_\mu\bar\psi\cdot\gamma_\mu P_L\cdot\psi)\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right] - \hbar\bar y^2 y^2\phi^4\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right] + \frac{1}{3}\hbar\bar y^3 y^3\frac{1}{M\Psi^2}\phi^6 + \frac{13}{12}\hbar\bar y^2y^2\frac{1}{M\Psi^2}\phi^2(D_\mu\phi)^2 +$$

$$\frac{13}{12}\hbar\bar y^2 y^2\frac{1}{M\Psi^2}D^2\phi\,\phi^3 + \frac{1}{3}\hbar\bar y y e^2\frac{1}{M\Psi^2}\phi^2 A^{\mu\nu 2} + \frac{19}{36}\hbar e\bar y y\frac{1}{M\Psi^2}D_\nu A^{\mu\nu}(\bar\psi\cdot\gamma_\mu P_L\cdot\psi) - \frac{1}{12}\hbar e\bar y y\frac{1}{M\Psi^2}D_\mu A^{\mu\nu}(\bar\psi\cdot\gamma_\nu P_L\cdot\psi) + \frac{1}{6}\hbar e\bar y y\frac{1}{M\Psi^2}A^{\mu\nu}(\bar\psi\cdot\gamma_\mu P_L\cdot D_\nu\psi) -$$

$$\frac{1}{8}\hbar e\bar y y\frac{1}{M\Psi^2}A^{\mu\nu}(\bar\psi\cdot\Gamma_{\mu\nu\rho}P_L\cdot D_\rho\psi) + \frac{1}{6}\hbar e\bar y y\frac{1}{M\Psi^2}A^{\mu\nu}(D_\nu\bar\psi\cdot\gamma_\mu P_L\cdot\psi) + \frac{1}{8}\hbar e\bar y y\frac{1}{M\Psi^2}A^{\mu\nu}(D_\rho\bar\psi\cdot\Gamma_{\mu\nu\rho}P_L\cdot\psi) + i\bar y y\frac{1}{M\Psi^2}\phi D_\mu\phi(\bar\psi\cdot\gamma_\mu P_L\cdot\psi) + i\bar y y\frac{1}{M\Psi^2}\phi^2(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu\psi) -$$

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

Simplification

In[17]:=
```
ℒEFT1 // IBPSimplify // RelabelIndices // CollectTerms // HcSimplify // NiceForm
```

Out[17]//NiceForm=

$$\frac{13}{540}\hbar e^2\frac{1}{M\Psi^2}A^{\mu\nu}D^2A^{\mu\nu} + \frac{1}{45}\hbar e^2\frac{1}{M\Psi^2}D_\nu D_\rho A^{\mu\nu}A^{\mu\rho} - \frac{11}{180}\hbar e^2\frac{1}{M\Psi^2}D_\nu A^{\mu\nu}D_\rho A^{\mu\rho} - \frac{1}{540}\hbar e^2\frac{1}{M\Psi^2}D_\mu D_\rho A^{\mu\nu}A^{\nu\rho} + i(\bar\psi\cdot\gamma_\mu\cdot D_\mu\psi) + \frac{1}{3}\hbar\bar y y\frac{1}{M\Psi^2}D^2\phi D^2\phi + \left(-\frac14 - \frac13\hbar e^2\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right]\right)A^{\mu\nu 2} -$$

$$\hbar\bar y^2y^2\phi^4\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right] + \hbar y M\Psi^2\left(-2\bar y - 2\bar y\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right]\right)\phi^2 + \left(\frac12 + \hbar y\left(\frac12\bar y + \bar y\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right]\right)\right)(D_\mu\phi)^2 + \hbar y\left(\frac{3i}{4}\bar y + \frac{i}{2}\bar y\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right]\right)(\bar\psi\cdot\gamma_\mu P_L\cdot D_\mu\psi) +$$

$$\frac13\hbar\bar y^3y^3\frac{1}{M\Psi^2}\phi^6 + \frac{13}{18}\hbar\bar y^2y^2\frac{1}{M\Psi^2}D^2\phi\,\phi^3 + \frac13\hbar\bar y y e^2\frac{1}{M\Psi^2}\phi^2A^{\mu\nu 2} + \frac49\hbar e\bar y y\frac{1}{M\Psi^2}D_\nu A^{\mu\nu}(\bar\psi\cdot\gamma_\mu P_L\cdot\psi) - \frac18\hbar e\bar y y\frac{1}{M\Psi^2}A^{\mu\nu}(\bar\psi\cdot\Gamma_{\mu\nu\rho}P_L\cdot D_\rho\psi) +$$

$$\frac18\hbar e\bar y y\frac{1}{M\Psi^2}A^{\mu\nu}(D_\rho\bar\psi\cdot\Gamma_{\mu\nu\rho}P_L\cdot\psi) + \left(-\frac{i}{6}\hbar\bar y y\frac{1}{M\Psi^2}(D^2\bar\psi\cdot\gamma_\nu P_L\cdot D_\nu\psi) + \left(-\frac{i}{2}\bar y y\frac{1}{M\Psi^2} + \hbar\bar y^2\frac{1}{M\Psi^2}\left(\frac{5i}{4}y^2 + i y^2\,\mathrm{Log}\left[\bar\mu^2\frac{1}{M\Psi^2}\right]\right)\right)\phi^2(D_\mu\bar\psi\cdot\gamma_\mu P_L\cdot\psi) + \mathrm{h.c.}\right)$$

Conclusion

- **Importance of automating one-loop EFT matching due to:**
  - Great variety of BSM models
  - Interesting phenomena at the loop level
  - Complexity of the computation involved

Matchmakereft

Carmona, Lazopoulos, Olgoso, Santiago [2112.10787]

diagrammatic matching

- **Functional method well suited for automation:**
  - Works for any weakly coupled EFT with mass power counting
  - Manifestly covariant formalism
  - EFT basis fully generated by path integral

MATCHETE

Fuentes-Martin, König, Pages, Thomsen, FW [in preparation]

functional matching

- **The eventual goal is a code that combines and automates:**
  - One-loop matching
  - RG evolution
  - Interface to phenomenological codes

(One-loop matching + RG evolution → Multi-step matching)

➡ **Fully automated pipeline from UV to pheno**

Thank you!

Backup

MATCHETE

Matching effective theories efficiently

Diagrammatic matching

Matching off-shell Green's functions

Diagrammatic matching

Universität Zürich[UZH]

- Diagrammatic matching is the most common method in the literature
- **UV theory:** $\mathscr{L}_{\mathrm{UV}}(\eta_H, \eta_L)$ with heavy η_H and light η_L fields
- **EFT construction:** find all effective operators built out of η_L, that are compatible with the symmetries of $\mathscr{L}_{\mathrm{UV}}$ → EFT Lagrangian $\mathscr{L}_{\mathrm{EFT}}(\eta_L)$
- **Matching:** compute all off-shell Green's functions with light external particles in the UV and the EFT
  - Equating the Green's functions ensures that the effective actions (as functions of η_L) of both theories coincide
  - This guarantees that both theories yield the same low-energy dynamics → ***"matching the EFT to the UV"***
  - <u>*Matching conditions:*</u> relate EFT Wilson coefficients $C_i^{(d)}$ to the microscopic UV parameters

A scalar toy model

Universität Zürich[UZH]

Fuentes-Martin, Portoles, Ruiz-Femenia [1607.02142]

- Toy model with heavy Φ and light φ scalar $(M \gg m)$

$$\mathscr{L}_{\rm UV}(\varphi,\Phi) = \frac{1}{2}\left(\partial_\mu\varphi\partial^\mu\varphi - m^2\varphi^2\right) + \frac{1}{2}\left(\partial_\mu\Phi\partial^\mu\Phi - M^2\Phi^2\right) - \frac{\kappa}{4!}\varphi^4 - \frac{\lambda}{3!}\varphi^3\Phi$$

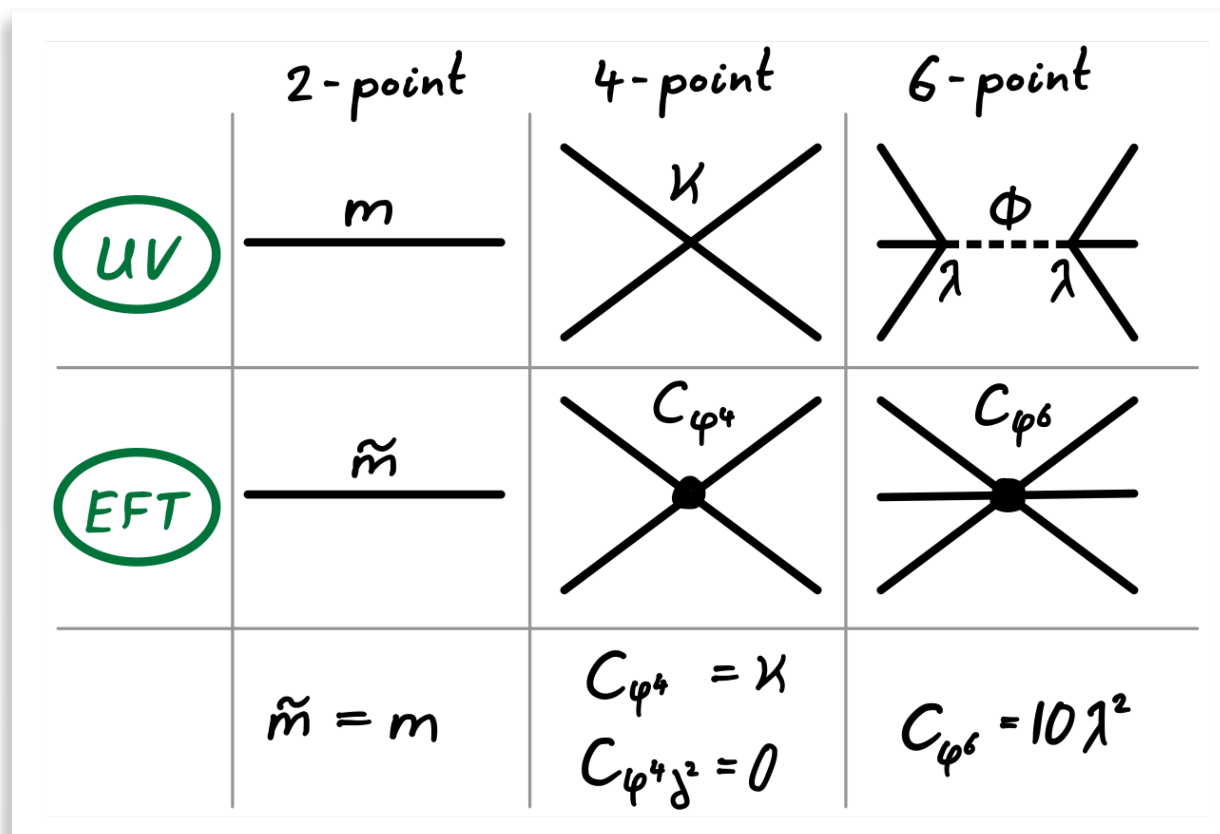
- The corresponding EFT Lagrangian at $d = 6$ is

$$\mathscr{L}_{\rm EFT}(\varphi) = \frac{1}{2}\left(\partial_\mu\varphi\partial^\mu\varphi - \tilde{m}^2\varphi^2\right) + \frac{C_{\varphi^4}}{4!}\varphi^4 + \frac{C_{\varphi^4\partial^2}}{4!M^2}\varphi^2\partial^2\varphi^2 + \frac{C_{\varphi^6}}{6!M^2}\varphi^6 + \mathscr{O}(M^{-4})$$

- At tree-level we find:

equate amplitudes

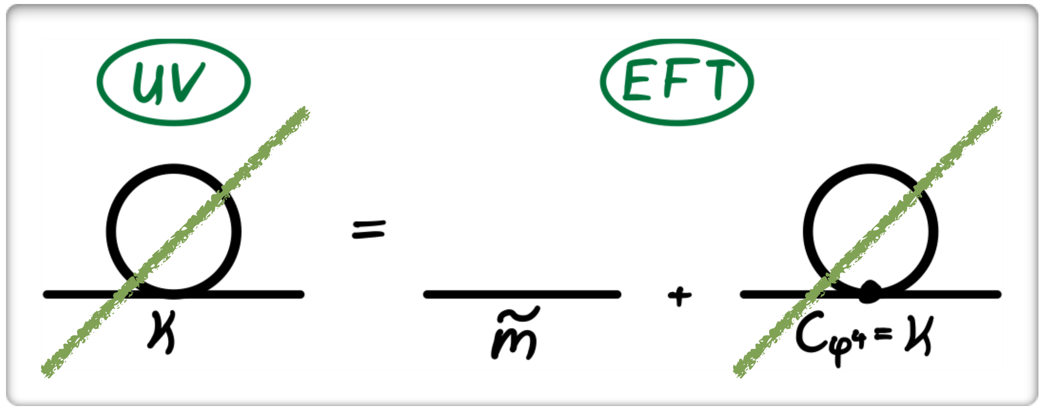
tree-level matching conditions:



Toy model: one-loop matching

Fuentes-Martin, Portoles, Ruiz-Femenia [1607.02142]

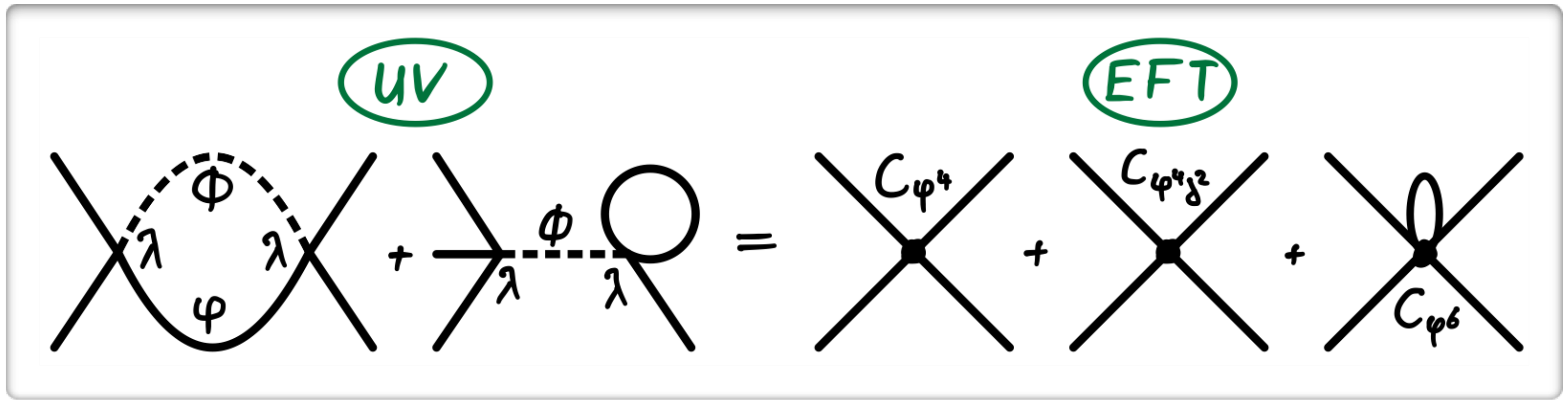
- For the one-loop computation we use dimensional regularization with $\overline{MS}$
- 2-point function:



$\Rightarrow$ matching condition: $\tilde{m} = m$

Diagrams appearing in both UV and EFT always cancel

- 4-point function:



$\Rightarrow$ matching conditions: $C_{\varphi^4} = \kappa + \frac{3}{16\pi^2}\lambda^2\left(1 + \frac{m^2}{M^2}\right), \quad C_{\varphi^4\partial^2} = -\frac{3}{16\pi^2}\frac{\lambda^2}{2}$

- 6-point function: analogous

➡ Difficulty of computation quickly increases with complexity of the UV theory

Functional vs. diagrammatic method

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	Functional integration	Diagrammatic matching
EFT operators	obtained from the path integral (no a priori knowledge required)	complete set of operators has to be derived before the matching
Feynman diagrams	—	all topologies have to be derived
Manifestly covariant formalism	✔	✘

- **Common features:**
  - Method of regions: hard region of the supertraces / Feynman diagrams encodes the full information about the Wilson coefficients
  - Reduction of redundant operators after the matching

➡ Functional method is well suited for automation

EFT matching with functional methods

methods of regions | covariant derivative expansion

Fluctuation operator

- **One-loop effective action:** $\Gamma^{(1)}_{\text{UV}} = \frac{i}{2}\text{STr}\left(\ln\, \mathcal{O}\right)$

- **Supertrace:** STr is the generalization of the trace to matrices with both fermionic and bosonic degrees of freedom carrying opposite signs

- **Fluctuation operator:** $\mathcal{O}_{ij} \equiv \left.\frac{\delta^2 \mathscr{L}_{\text{UV}}}{\delta \eta_j\, \delta \bar{\eta}_i}\right|_{\eta=\hat{\eta}} = \delta_{ij}\Delta_i^{-1} - X_{ij}$

  - Separating the propagators Δ_i from interaction terms X_{ij}
  - Treating light masses (m_L) as interactions
  - Feynman gauge for quantum fluctuations (η), General R_ξ gauge for background fields $(\hat{\eta})$

$$\Delta_i^{-1} = \begin{cases} -(D^2 + M_i^2) \\ i\gamma^\mu D_\mu - M_i \\ g^{\mu\nu}(D^2 + M_i^2) \end{cases}$$

Method of regions

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- $\Gamma^{(1)}_{\text{UV}}$ is the one-loop effective action for the full UV theory
  - EFT Wilson coefficients encode the short distance dynamics only
    $\Rightarrow$ They are determined by the hard momentum region of $\Gamma^{(1)}_{\text{UV}}$ only

- **Method of regions in dimensional regularization:**

Beneke, Smirnov [hep-ph/9711391]
Jantzen [1111.2589]

  - The loop-integrals contain light m_L and heavy m_H masses $(m_H \gg m_L)$
  - Separate the region of *soft-* $\left(p \sim m_L\right)$ and *hard*-momentum $\left(p \sim m_H\right)$ and expand each region in the quantities that are small there
  - Integrate each region over the full *d*-dimensional space
  - Summing both integrals gives the full integral without expansion

$$I = \int \mathrm{d}^d p \, \frac{N}{(p^2 - m_L^2)(p^2 - m_H^2)} = I_{\text{soft}} + I_{\text{hard}}$$

$$I_{\text{soft}} = \int \mathrm{d}^d p \, \frac{N}{(p^2 - m_L^2)(-m_H^2)} \left[1 + \frac{p^2}{m_H^2} + \frac{p^4}{m_H^4} + \cdots\right], \quad I_{\text{hard}} = \int \mathrm{d}^d p \, \frac{N}{p^2(p^2 - m_H^2)} \left[1 + \frac{m_L^2}{p^2} + \frac{m_L^4}{p^4} + \cdots\right]$$

➡ All the short distance effects we are interested in are encoded in hard region

Method of regions: toy model

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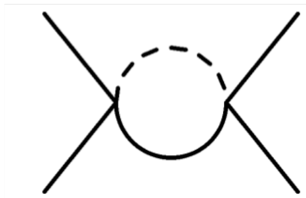
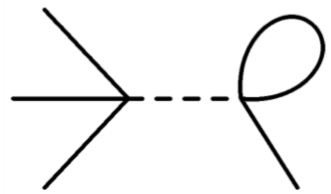
$$\mathscr{L}_{\rm UV}(\varphi,\Phi)=\frac{1}{2}\left(\partial_\mu\varphi\partial^\mu\varphi-m^2\varphi^2\right)+\frac{1}{2}\left(\partial_\mu\Phi\partial^\mu\Phi-M^2\Phi^2\right)-\frac{\kappa}{4!}\varphi^4-\frac{\lambda}{3!}\varphi^3\Phi$$

UV theory



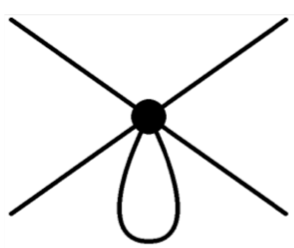
$$=\frac{i}{16\pi^2}\lambda^2\left[3+3\frac{m^2}{M^2}+\frac{s+t+u}{2M^2}\right]\Bigg|_{\rm hard}$$

$$+\frac{i}{16\pi^2}\lambda^2\left[-3\frac{m^2}{M^2}+3\frac{m^2}{M^2}\ln\left(\frac{m^2}{M^2}\right)\right]\Bigg|_{\rm soft}+\mathcal{O}(M^{-4}),$$

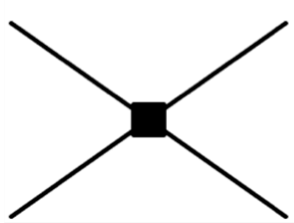


$$=\frac{i}{16\pi^2}\lambda^2\left[-2\frac{m^2}{M^2}+2\frac{m^2}{M^2}\ln\left(\frac{m^2}{M^2}\right)\right]\Bigg|_{\rm soft}+\mathcal{O}(M^{-4}),$$

EFT



$$=\frac{i}{16\pi^2}\lambda^2\left[-5\frac{m^2}{M^2}+5\frac{m^2}{M^2}\log\left(\frac{m^2}{M^2}\right)\right]+\mathcal{O}(M^{-4}),$$



$$=iC_{\varphi^4}-i\frac{C_{\varphi^4\partial^2}}{M^2}(s+t+u)$$

$\Gamma^{(1)}_{\rm UV}\Big|_{\rm hard}$

$\Gamma^{(1)}_{\rm UV}\Big|_{\rm soft}$

cancel exactly

$\mathscr{L}^{(0)}_{\rm EFT}$

$\mathscr{L}^{(1)}_{\rm EFT}$

matching condition

Fuentes-Martin, Portoles, Ruiz-Femenia [1607.02142]

One-loop EFT Lagrangian

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Cohen, Lu, Zhang [2011.02484]

- Split one-loop effective action into *hard*- and *soft*-momentum region

$$\Gamma^{(1)}_{\mathrm{UV}} = \Gamma^{(1)}_{\mathrm{UV}}\Big|_{\mathrm{hard}} + \Gamma^{(1)}_{\mathrm{UV}}\Big|_{\mathrm{soft}}$$

- heavy particle loops → hard
- mixed particle loops → hard and soft
- light particle loops → soft

- $\Gamma^{(1)}_{\mathrm{UV}}\Big|_{\mathrm{soft}}$: long distance contributions from one-loop matrix elements with the tree-level EFT Lagrangian $\mathscr{L}^{(0)}_{\mathrm{EFT}}$

- $\Gamma^{(1)}_{\mathrm{UV}}\Big|_{\mathrm{hard}}$: short distance contributions that can be identified with the EFT Wilson coefficients at one-loop level

- **One-loop EFT Lagrangian:** $$\Gamma^{(1)}_{\mathrm{UV}}\Big|_{\mathrm{hard}} = \int \mathrm{d}^d x\, \mathscr{L}^{(1)}_{\mathrm{EFT}}$$

Covariant derivative expansion

Universität Zürich[UZH]

Henning, Lu, Murayama [1412.1837; 1604.01019]

- Operators $Q(iD_\mu, U_k)$ can depend on covariant derivatives D_μ and a set of momentum-independent functions U_k
- **Supertraces** are not manifestly covariant (open covariant derivatives $D_\mu \mathbb{1}$)

$$\mathrm{STr}\left(Q(iD_\mu, U_k)\right) = \pm \int \frac{\mathrm{d}^d p}{(2\pi)^d} \langle p \,|\, \mathrm{tr}\left(Q(iD_\mu, U_k)\right) |\, p\rangle = \pm \int \mathrm{d}^d x \int \frac{\mathrm{d}^d p}{(2\pi)^d}\, \mathrm{tr}\left(Q(iD_\mu + p_\mu, U_k)\right) \mathbb{1}$$

- **Covariant derivative expansion (CDE)**

  Path integral transformation sandwiching the trace between $e^{-iD\cdot\partial_p}$ and $e^{iD\cdot\partial_p}$

  - These operators vanish when acting to the left / right
  - When passing $e^{-iD\cdot\partial_p}$ through Q to cancel against $e^{iD\cdot\partial_p}$ it has the desired effect of putting all covariant derivatives into commutators

  ➡ This renders the supertraces and the whole functional matching approach manifestly covariant

Example: scalar toy-model

Universität Zürich[UZH]

Fuentes-Martin, Portoles, Ruiz-Femenia [1607.02142]

Two real scalars with $M \gg m$

$$\mathscr{L}_{\mathrm{UV}}(\varphi, \Phi) = \frac{1}{2}\left(\partial_\mu \varphi \partial^\mu \varphi - m^2 \varphi^2\right) + \frac{1}{2}\left(\partial_\mu \Phi \partial^\mu \Phi - M^2 \Phi^2\right) - \frac{\kappa}{4!}\varphi^4 - \frac{\lambda}{3!}\varphi^3 \Phi$$

- Integrate out Φ applying the functional method up to $d = 6$
- **Tree-level matching:**
  - Equation of motion: $M^2 \hat{\Phi} = -D^2 \hat{\Phi} - \frac{\lambda}{3!}\hat{\varphi}^3$
  - Solution: $\hat{\Phi} = -\frac{\lambda}{6M^2}\hat{\varphi}^3 + \mathscr{O}(M^{-4})$
  - Tree-level EFT Lagrangian:

$$\mathscr{L}^{(0)}_{\mathrm{EFT}} = \frac{1}{2}\left(\partial_\mu \hat{\varphi} \partial^\mu \hat{\varphi} - m^2 \hat{\varphi}^2\right) - \frac{\kappa}{4!}\hat{\varphi}^4 + \frac{10\lambda^2}{6!M^2}\hat{\varphi}^6$$

Scalar toy-model @ one-loop

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- The fluctuation operator $\mathcal{O}_{ij}$

$$\Delta_\Phi^{-1} = -\partial^2 - M^2, \qquad X_{\Phi\Phi} = 0, \qquad X_{\varphi\Phi}^{[2]} = (X_{\varphi\Phi})^\dagger = -\frac{\lambda}{2}\hat{\varphi}^2,$$

$$\Delta_\varphi^{-1} = -\partial^2, \qquad X_{\varphi\varphi}^{[2]} = -m^2 - \frac{\kappa}{2}\hat{\varphi}^2 - \lambda\hat{\varphi}\hat{\Phi} = -m^2 - \frac{\kappa}{2}\hat{\varphi}^2 - \frac{\lambda^2}{6M^2}\hat{\varphi}^4$$

- Supertraces to compute using the CDE:
    - Log-type: $\mathrm{STr}\left(\ln \Delta_\Phi^{-1}\right)\Big|_{\mathrm{hard}}$
    - Power-type: $\mathrm{STr}\left(\Delta_\Phi X_{\Phi\varphi}^{[2]}\Delta_\varphi X_{\varphi\Phi}^{[2]}\right)\Big|_{\mathrm{hard}}$, $\mathrm{STr}\left(\Delta_\Phi X_{\Phi\varphi}^{[2]}\Delta_\varphi X_{\varphi\varphi}^{[2]}\Delta_\varphi X_{\varphi\Phi}^{[2]}\right)\Big|_{\mathrm{hard}}$

- One-loop EFT Lagrangian from supertrace evaluation:

$$\mathscr{L}_{\mathrm{EFT}}^{(1)} = \frac{1}{16\pi^2}\frac{\lambda^2}{16}\left[2\left(1+\frac{m^2}{M^2}\right)\hat{\varphi}^4 - \frac{1}{M^2}\hat{\varphi}^2\partial^2\hat{\varphi}^2 + \frac{\kappa}{M^2}\hat{\varphi}^6\right]$$

Scalar toy-model @ one-loop

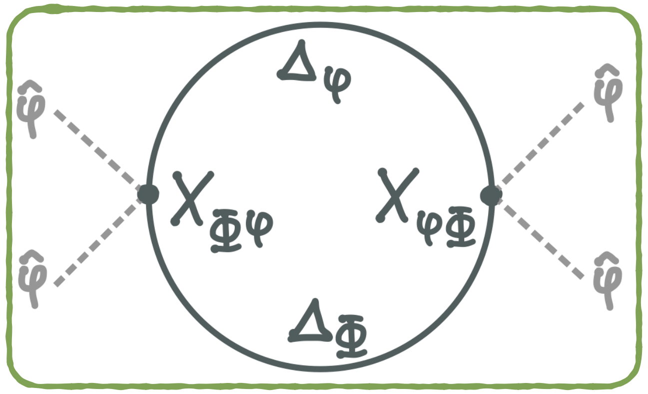
Universität Zürich[UZH]

- The fluctuation operator $\mathcal{O}_{ij}$

$$\Delta_\Phi^{-1} = -\partial^2 - M^2, \qquad X_{\Phi\Phi} = 0, \qquad X_{\varphi\Phi}^{[2]} = (X_{\varphi\Phi})^\dagger = -\frac{\lambda}{2}\hat{\varphi}^2,$$

$$\Delta_\varphi^{-1} = -\partial^2, \qquad X_{\varphi\varphi}^{[2]} = -m^2 - \frac{\kappa}{2}\hat{\varphi}^2 - \lambda\hat{\varphi}\hat{\Phi} = -m^2 - \frac{\kappa}{2}\hat{\varphi}^2 - \frac{\lambda^2}{6M^2}\hat{\varphi}^4$$

- Supertraces to compute using the CDE:
  - Log-type: $\mathrm{STr}\left(\ln \Delta_\Phi^{-1}\right)\Big|_{\mathrm{hard}}$
  - Power-type: $\mathrm{STr}\left(\Delta_\Phi X_{\Phi\varphi}^{[2]}\Delta_\varphi X_{\varphi\Phi}^{[2]}\right)\Big|_{\mathrm{hard}}$, $\mathrm{STr}\left(\Delta_\Phi X_{\Phi\varphi}^{[2]}\Delta_\varphi X_{\varphi\varphi}^{[2]}\Delta_\varphi X_{\varphi\Phi}^{[2]}\right)\Big|_{\mathrm{hard}}$



- One-loop EFT Lagrangian from supertrace evaluation:

$$\mathcal{L}_{\mathrm{EFT}}^{(1)} = \frac{1}{16\pi^2}\frac{\lambda^2}{16}\left[2\left(1+\frac{m^2}{M^2}\right)\hat{\varphi}^4 - \frac{1}{M^2}\hat{\varphi}^2\partial^2\hat{\varphi}^2 + \frac{\kappa}{M^2}\hat{\varphi}^6\right]$$

MATCHETE

MATCHing Effective Theories Efficiently

Challenges for automation

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- Creating a standard for inputing and handling Lagrangians
- User interface:
  - Defining fields, couplings, …
- Creation of a group theory module allowing to use any group / representation
- Implementation of functional derivative to compute EOMs and fluctuation operators
- Treatment of heavy vector bosons (gauge fixing and ghosts)
- Output simplification:
  - Finding a general algorithm to remove redundant operators
  - Targeting specific operator bases

Completed ✓

Work in progress ✎

Redundant operators

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- Path integral / supertrace output: set of redundant effective operators
→ **reduction to a minimal set of operators without redundancies**

- **Simplification methods:**
    - Reduction of Dirac structures to a Dirac basis *(Greek method)*
    - Integration by parts
    - Kinetic- and mass-mixing → requires diagonalization
    - Field redefinitions (equations of motion)
    - Fierz identities in *d*-dimensions → can yield evanescent operators
        - Tree-level evanescent operators inserted in divergent one-loop EFT graphs yield a finite renormalization

- The path integral only yields the set of operators generated by the specific UV theory → a complete basis might not be generated

Field redefinitions

Criado, Perez-Victoria [1811.09413]

- LSZ formula: *S*-matrix is invariant under field redefinitions
- Perturbative field redefinition: $\eta \to \tilde{\eta} = \eta + \frac{1}{\Lambda}\delta\eta$
  - Effect on the EFT Lagrangian:

$$\mathscr{L}[\eta] \to \mathscr{L}[\tilde{\eta}] = \mathscr{L}[\eta] + \frac{1}{\Lambda}\left.\frac{\delta\mathscr{L}[\tilde{\eta}]}{\delta\tilde{\eta}}\right|_{\tilde{\eta}=\eta}\delta\tilde{\eta} + \frac{1}{2\Lambda^2}\left.\frac{\delta^2\mathscr{L}[\tilde{\eta}]}{\delta\tilde{\eta}^2}\right|_{\tilde{\eta}=\eta}\delta\eta^2 + \mathscr{O}\left(\Lambda^{-3}\right)$$

EoM

- The EOMs only capture the leading power contribution of the corresponding field redefinition
- At sub-leading power using EOMs does not give the correct result and field redefinitions have to be used!

Future features

- **Aspired features:**
  - Interface to other codes for phenomenology (e.g. smelli, flavio, …)
    Stangl [2012.12211]; Straub [1810.08132]
  - Wilson coefficient exchange format output: WCxf
    Aebischer et al. [1712.05298]
  - Generation of UFO files for the UV models and EFTs
    Degrande et al. [1108.2040]
- **Long term goals:**
  - Parallelization of the computation
  - Computation of β-functions for the EFT
    - RG evolution (at one-loop)
    - treatment of evanescent operators
  - Automatic breaking of symmetry groups
  - Multi-step matching and running