

# Recent Developments on Effective Field Theories

**Javier Fuentes-Martín**  
University of Granada

What is experiment telling us?

No direct evidence for NP despite the many reasons for it [ presence of a mass gap? ]



Indirect NP searches?

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

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

$\sqrt{s} = 13 \text{ TeV}$

| Model                |                                                                 | $\ell, \gamma$               | Jets†                       | $E_T^{\text{miss}}$ | $\int \mathcal{L} dt [\text{fb}^{-1}]$ | Limit                       |          | Reference                                                                                                                                                                                       |
|----------------------|-----------------------------------------------------------------|------------------------------|-----------------------------|---------------------|----------------------------------------|-----------------------------|----------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Extra dimen.         | ADD $G_{KK} + g/q$                                              | $0 e, \mu, \tau, \gamma$     | $1 - 4 j$                   | Yes                 | 139                                    | $M_D$                       | 11.2 TeV | $n = 2$<br>2102.10874                                                                                                                                                                           |
|                      | ADD non-resonant $\gamma\gamma$                                 | $2 \gamma$                   | –                           | –                   | 36.7                                   | $M_S$                       | 8.6 TeV  | $n = 3$ HLZ NLO<br>1707.04147                                                                                                                                                                   |
|                      | ADD QBH                                                         | –                            | $2 j$                       | –                   | 139                                    | $M_{\text{th}}$             | 9.4 TeV  | $n = 6$<br>1910.08447                                                                                                                                                                           |
|                      | ADD BH multijet                                                 | –                            | $\geq 3 j$                  | –                   | 3.6                                    | $M_{\text{th}}$             | 9.55 TeV | $n = 6, M_D = 3 \text{ TeV}$ , rot BH<br>1512.02586                                                                                                                                             |
|                      | RS1 $G_{KK} \rightarrow \gamma\gamma$                           | $2 \gamma$                   | –                           | –                   | 139                                    | $G_{KK}$ mass               | 4.5 TeV  | $k/\overline{M}_{Pl} = 0.1$<br>2102.13405                                                                                                                                                       |
|                      | Bulk RS $G_{KK} \rightarrow WW/ZZ$                              | multi-channel                | –                           | –                   | 36.1                                   | $G_{KK}$ mass               | 2.3 TeV  | $k/\overline{M}_{Pl} = 1.0$<br>1808.02380                                                                                                                                                       |
|                      | Bulk RS $g_{KK} \rightarrow tt$                                 | $1 e, \mu$                   | $\geq 1 b, \geq 1 J/2 j$    | Yes                 | 36.1                                   | $g_{KK}$ mass               | 3.8 TeV  | $\Gamma/m = 15\%$<br>1804.10823                                                                                                                                                                 |
|                      | 2UED / RPP                                                      | $1 e, \mu$                   | $\geq 2 b, \geq 3 j$        | Yes                 | 36.1                                   | KK mass                     | 1.8 TeV  | Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow tt) = 1$<br>1803.09678                                                                                                                           |
| Gauge bosons         | SSM $Z' \rightarrow \ell\ell$                                   | $2 e, \mu$                   | –                           | –                   | 139                                    | $Z'$ mass                   | 5.1 TeV  | $\Gamma/m = 1.2\%$<br>1903.06248                                                                                                                                                                |
|                      | SSM $Z' \rightarrow \tau\tau$                                   | $2 \tau$                     | –                           | –                   | 36.1                                   | $Z'$ mass                   | 2.42 TeV |                                                                                                                                                                                                 |
|                      | Leptophobic $Z' \rightarrow bb$                                 | –                            | $2 b$                       | –                   | 36.1                                   | $Z'$ mass                   | 2.1 TeV  |                                                                                                                                                                                                 |
|                      | Leptophobic $Z' \rightarrow tt$                                 | $0 e, \mu$                   | $\geq 1 b, \geq 2 J$        | Yes                 | 139                                    | $Z'$ mass                   | 4.1 TeV  |                                                                                                                                                                                                 |
|                      | SSM $W' \rightarrow \ell\nu$                                    | $1 e, \mu$                   | –                           | Yes                 | 139                                    | $W'$ mass                   | 6.0 TeV  |                                                                                                                                                                                                 |
|                      | SSM $W' \rightarrow \tau\nu$                                    | $1 \tau$                     | –                           | Yes                 | 139                                    | $W'$ mass                   | 5.0 TeV  | ATLAS-CONF-2021-025<br>ATLAS-CONF-2021-043<br>$g_V = 3$<br>$g_V c_H = 1, g_f = 0$<br>$g_V = 3$<br>$m(N_R) = 0.5 \text{ TeV}, g_L = g_R$<br>2004.14636<br>2207.03925<br>2004.14636<br>1904.12679 |
|                      | SSM $W' \rightarrow tb$                                         | –                            | $\geq 1 b, \geq 1 J$        | –                   | 139                                    | $W'$ mass                   | 4.4 TeV  |                                                                                                                                                                                                 |
|                      | HVT $W' \rightarrow WZ$ model B                                 | $0-2 e, \mu$                 | $2 j / 1 J$                 | Yes                 | 139                                    | $W'$ mass                   | 4.3 TeV  |                                                                                                                                                                                                 |
|                      | HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \ell'$ model C | $3 e, \mu$                   | $2 j$ (VBF)                 | Yes                 | 139                                    | $W'$ mass                   | 340 GeV  |                                                                                                                                                                                                 |
|                      | HVT $Z' \rightarrow WW$ model B                                 | $1 e, \mu$                   | $2 j / 1 J$                 | Yes                 | 139                                    | $Z'$ mass                   | 3.9 TeV  |                                                                                                                                                                                                 |
| CI                   | CI $qqqq$                                                       | –                            | $2 j$                       | –                   | 37.0                                   | $\Lambda$                   | 21.8 TeV | $\eta_{LL}^-$<br>1703.09127                                                                                                                                                                     |
|                      | CI $\ell\ell qq$                                                | $2 e, \mu$                   | –                           | –                   | 139                                    | $\Lambda$                   | 35.8 TeV | $\eta_{LL}^-$<br>2006.12946                                                                                                                                                                     |
|                      | CI $eebs$                                                       | $2 e$                        | $1 b$                       | –                   | 139                                    | $\Lambda$                   | 1.8 TeV  | $g_* = 1$<br>2105.13847                                                                                                                                                                         |
|                      | CI $\mu\mu bs$                                                  | $2 \mu$                      | $1 b$                       | –                   | 139                                    | $\Lambda$                   | 2.0 TeV  | $g_* = 1$<br>2105.13847                                                                                                                                                                         |
|                      | CI $tttt$                                                       | $\geq 1 e, \mu$              | $\geq 1 b, \geq 1 j$        | Yes                 | 36.1                                   | $\Lambda$                   | 2.57 TeV | $ C_{4t}  = 4\pi$<br>1811.02305                                                                                                                                                                 |
|                      |                                                                 |                              |                             |                     |                                        |                             |          |                                                                                                                                                                                                 |
| DM                   | Axial-vector med. (Dirac DM)                                    | –                            | $2 j$                       | –                   | 139                                    | $m_{\text{med}}$            | 3.8 TeV  | $g_q = 0.25, g_\chi = 1, m(\chi) = 10 \text{ TeV}$<br>ATL-PHYS-PUB-2022-036                                                                                                                     |
|                      | Pseudo-scalar med. (Dirac DM)                                   | $0 e, \mu, \tau, \gamma$     | $1 - 4 j$                   | Yes                 | 139                                    | $m_{\text{med}}$            | 376 GeV  | $g_q = 1, g_\chi = 1, m(\chi) = 1 \text{ GeV}$<br>2102.10874                                                                                                                                    |
|                      | Vector med. $Z'$ -2HDM (Dirac DM)                               | $0 e, \mu$                   | $2 b$                       | Yes                 | 139                                    | $m_{Z'}$                    | 3.0 TeV  | $\tan\beta = 1, g_Z = 0.8, m(\chi) = 100 \text{ GeV}$<br>2108.13391                                                                                                                             |
|                      | Pseudo-scalar med. 2HDM+a                                       | multi-channel                | –                           | –                   | 139                                    | $m_a$                       | 800 GeV  | $\tan\beta = 1, g_\chi = 1, m(\chi) = 10 \text{ GeV}$<br>ATLAS-CONF-2021-036                                                                                                                    |
| LQ                   | Scalar LQ 1 <sup>st</sup> gen                                   | $2 e$                        | $\geq 2 j$                  | Yes                 | 139                                    | LQ mass                     | 1.8 TeV  | $\beta = 1$<br>2006.05872                                                                                                                                                                       |
|                      | Scalar LQ 2 <sup>nd</sup> gen                                   | $2 \mu$                      | $\geq 2 j$                  | Yes                 | 139                                    | LQ mass                     | 1.7 TeV  | $\beta = 1$<br>2006.05872                                                                                                                                                                       |
|                      | Scalar LQ 3 <sup>rd</sup> gen                                   | $1 \tau$                     | $2 b$                       | Yes                 | 139                                    | $LQ_3^u$ mass               | 1.4 TeV  | $\mathcal{B}(LQ_3^u \rightarrow b\tau) = 1$<br>2303.01294                                                                                                                                       |
|                      | Scalar LQ 3 <sup>rd</sup> gen                                   | $0 e, \mu$                   | $\geq 2 j, \geq 2 b$        | Yes                 | 139                                    | $LQ_3^d$ mass               | 1.24 TeV | $\mathcal{B}(LQ_3^d \rightarrow t\nu) = 1$<br>2004.14060                                                                                                                                        |
|                      | Scalar LQ 3 <sup>rd</sup> gen                                   | $\geq 2 e, \mu, \geq 1 \tau$ | $\geq 1 j, \geq 1 b$        | –                   | 139                                    | $LQ_3^d$ mass               | 1.4 TeV  | $\mathcal{B}(LQ_3^d \rightarrow t\tau) = 1$<br>2101.11582                                                                                                                                       |
|                      | Scalar LQ 3 <sup>rd</sup> gen                                   | $0 e, \mu, \geq 1 \tau$      | $0 - 2 j, 2 b$              | Yes                 | 139                                    | $LQ_3^d$ mass               | 1.26 TeV | $\mathcal{B}(LQ_3^d \rightarrow b\nu) = 1$<br>2101.12527                                                                                                                                        |
|                      | Vector LQ mix gen                                               | multi-channel                | $\geq 1 j, \geq 1 b$        | Yes                 | 139                                    | $LQ_3^V$ mass               | 2.0 TeV  | $\mathcal{B}(\tilde{U}_1 \rightarrow t\mu) = 1$ , Y-M coupl.<br>ATLAS-CONF-2022-052                                                                                                             |
|                      | Vector LQ 3 <sup>rd</sup> gen                                   | $2 e, \mu, \tau$             | $\geq 1 b$                  | Yes                 | 139                                    | $LQ_3^V$ mass               | 1.96 TeV | $\mathcal{B}(LQ_3^V \rightarrow b\tau) = 1$ , Y-M coupl.<br>2303.01294                                                                                                                          |
| Vector-like fermions | VLQ $TT \rightarrow Zt + X$                                     | $2e/2\mu \geq 3e, \mu$       | $\geq 1 b, \geq 1 j$        | –                   | 139                                    | T mass                      | 1.4 TeV  | SU(2) doublet<br>2210.15413                                                                                                                                                                     |
|                      | VLQ $BB \rightarrow Wt/Zb + X$                                  | multi-channel                | –                           | –                   | 36.1                                   | B mass                      | 1.34 TeV | SU(2) doublet<br>1808.02343                                                                                                                                                                     |
|                      | VLQ $T_{5/3} T_{5/3}  T_{5/3} \rightarrow Wt + X$               | $2(SS)/\geq 3 e, \mu$        | $\geq 1 b, \geq 1 j$        | Yes                 | 36.1                                   | $T_{5/3}$ mass              | 1.64 TeV | $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3} Wt) = 1$<br>1807.11883                                                                                                                      |
|                      | VLQ $T \rightarrow Ht/Zt$                                       | $1 e, \mu$                   | $\geq 1 b, \geq 3 j$        | Yes                 | 139                                    | T mass                      | 1.8 TeV  | SU(2) singlet, $\kappa_T = 0.5$<br>ATLAS-CONF-2021-040                                                                                                                                          |
|                      | VLQ $Y \rightarrow Wb$                                          | $1 e, \mu$                   | $\geq 1 b, \geq 1 j$        | Yes                 | 36.1                                   | Y mass                      | 1.85 TeV | $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$<br>1812.07343                                                                                                                                  |
|                      | VLQ $B \rightarrow Hb$                                          | $0 e, \mu$                   | $\geq 2b, \geq 1j, \geq 1J$ | –                   | 139                                    | B mass                      | 2.0 TeV  | SU(2) doublet, $\kappa_B = 0.3$<br>ATLAS-CONF-2021-018                                                                                                                                          |
|                      | VLL $\tau' \rightarrow Z\tau/H\tau$                             | multi-channel                | $\geq 1 j$                  | Yes                 | 139                                    | $\tau'$ mass                | 898 GeV  | SU(2) doublet<br>2303.05441                                                                                                                                                                     |
| Excited ferm.        | Excited quark $q^* \rightarrow qg$                              | –                            | $2 j$                       | –                   | 139                                    | $q^*$ mass                  | 6.7 TeV  | only $u^*$ and $d^*$ , $\Lambda = m(q^*)$<br>1910.08447                                                                                                                                         |
|                      | Excited quark $q^* \rightarrow q\gamma$                         | $1 \gamma$                   | $1 j$                       | –                   | 36.7                                   | $q^*$ mass                  | 5.3 TeV  | only $u^*$ and $d^*$ , $\Lambda = m(q^*)$<br>1709.10440                                                                                                                                         |
|                      | Excited quark $b^* \rightarrow bg$                              | –                            | $1 b, 1 j$                  | –                   | 139                                    | $b^*$ mass                  | 3.2 TeV  | 1910.08447                                                                                                                                                                                      |
|                      | Excited lepton $\tau^*$                                         | $2 \tau$                     | $\geq 2 j$                  | –                   | 139                                    | $\tau^*$ mass               | 4.6 TeV  | $\Lambda = 4.6 \text{ TeV}$<br>2303.09444                                                                                                                                                       |
| Other                | Type III Seesaw                                                 | $2,3,4 e, \mu$               | $\geq 2 j$                  | Yes                 | 139                                    | $N^0$ mass                  | 910 GeV  | $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$<br>DY production<br>2202.02039                                                                                                                            |
|                      | LRSM Majorana $\nu$                                             | $2 \mu$                      | $2 j$                       | –                   | 36.1                                   | $N_R$ mass                  | 3.2 TeV  |                                                                                                                                                                                                 |
|                      | Higgs triplet $H^{\pm\pm} \rightarrow W^\pm W^\pm$              | $2,3,4 e, \mu$ (SS)          | various                     | Yes                 | 139                                    | $H^{\pm\pm}$ mass           | 350 GeV  |                                                                                                                                                                                                 |
|                      | Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$                 | $2,3,4 e, \mu$ (SS)          | –                           | –                   | 139                                    | $H^{\pm\pm}$ mass           | 1.08 TeV |                                                                                                                                                                                                 |
|                      | Multi-charged particles                                         | –                            | –                           | –                   | 139                                    | multi-charged particle mass | 1.39 TeV | DY production, $ q  = 5e$<br>ATLAS-CONF-2022-034                                                                                                                                                |
|                      | Magnetic monopoles                                              | –                            | –                           | –                   | 34.4                                   | monopole mass               | 2.37 TeV | DY production, $ g  = 1g_D$ , spin 1/2<br>1905.10130                                                                                                                                            |
|                      |                                                                 |                              |                             |                     |                                        |                             |          |                                                                                                                                                                                                 |

$\sqrt{s} = 13 \text{ TeV}$   
partial data

$\sqrt{s} = 13 \text{ TeV}$   
full data

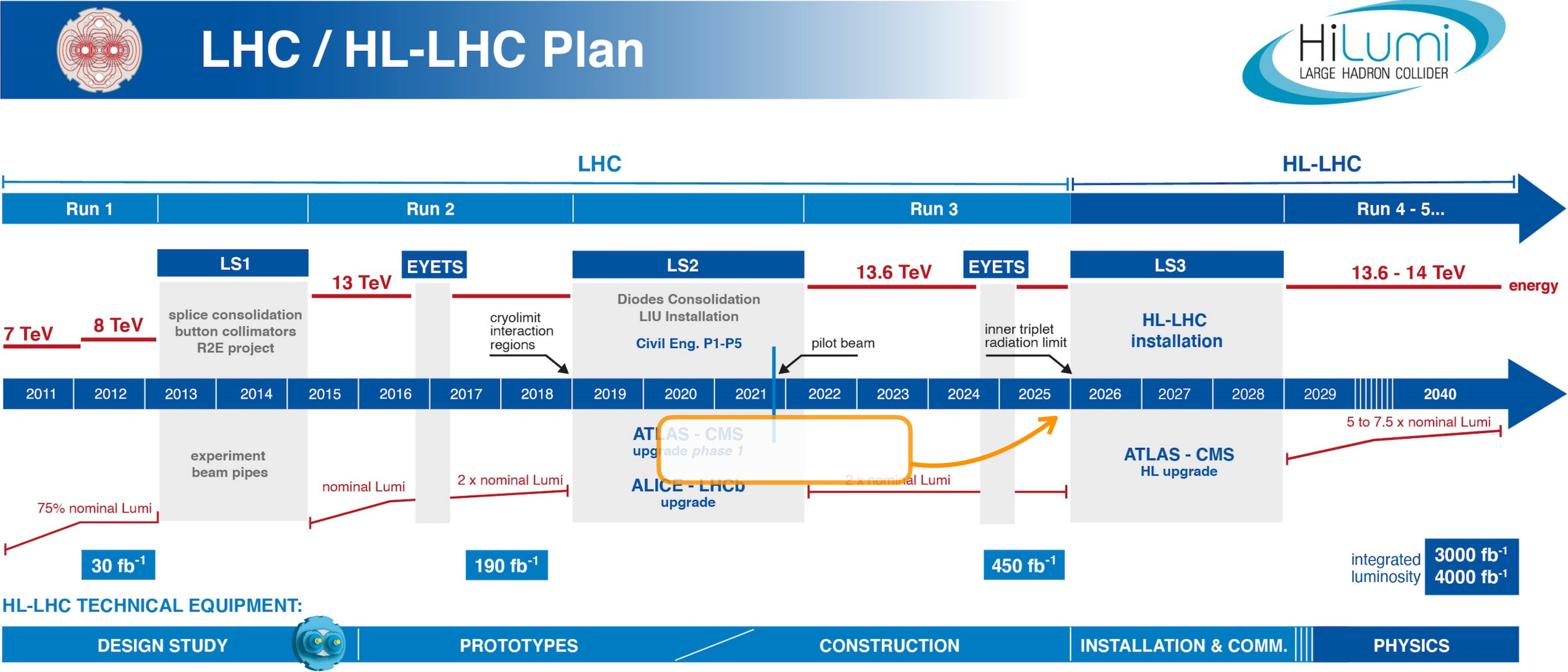
$10^{-1}$

1 TeV

10 TeV

Mass scale [TeV]

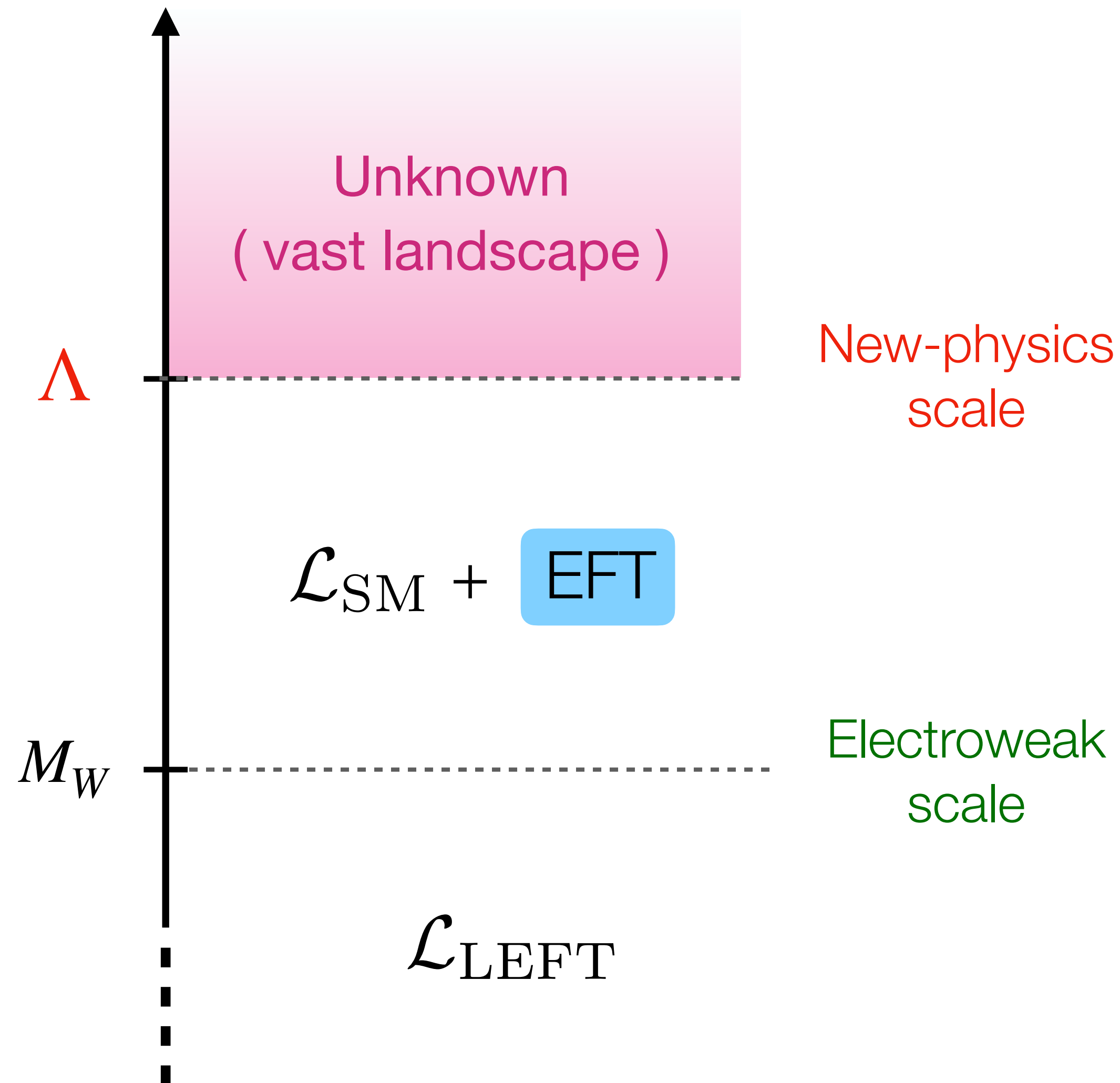
# A new precision era



Marginal increase in energy, but  $\sim 20 \times$  more luminosity!

# Effective Field Theories (EFT): bottom-up

$E \equiv$  Energy



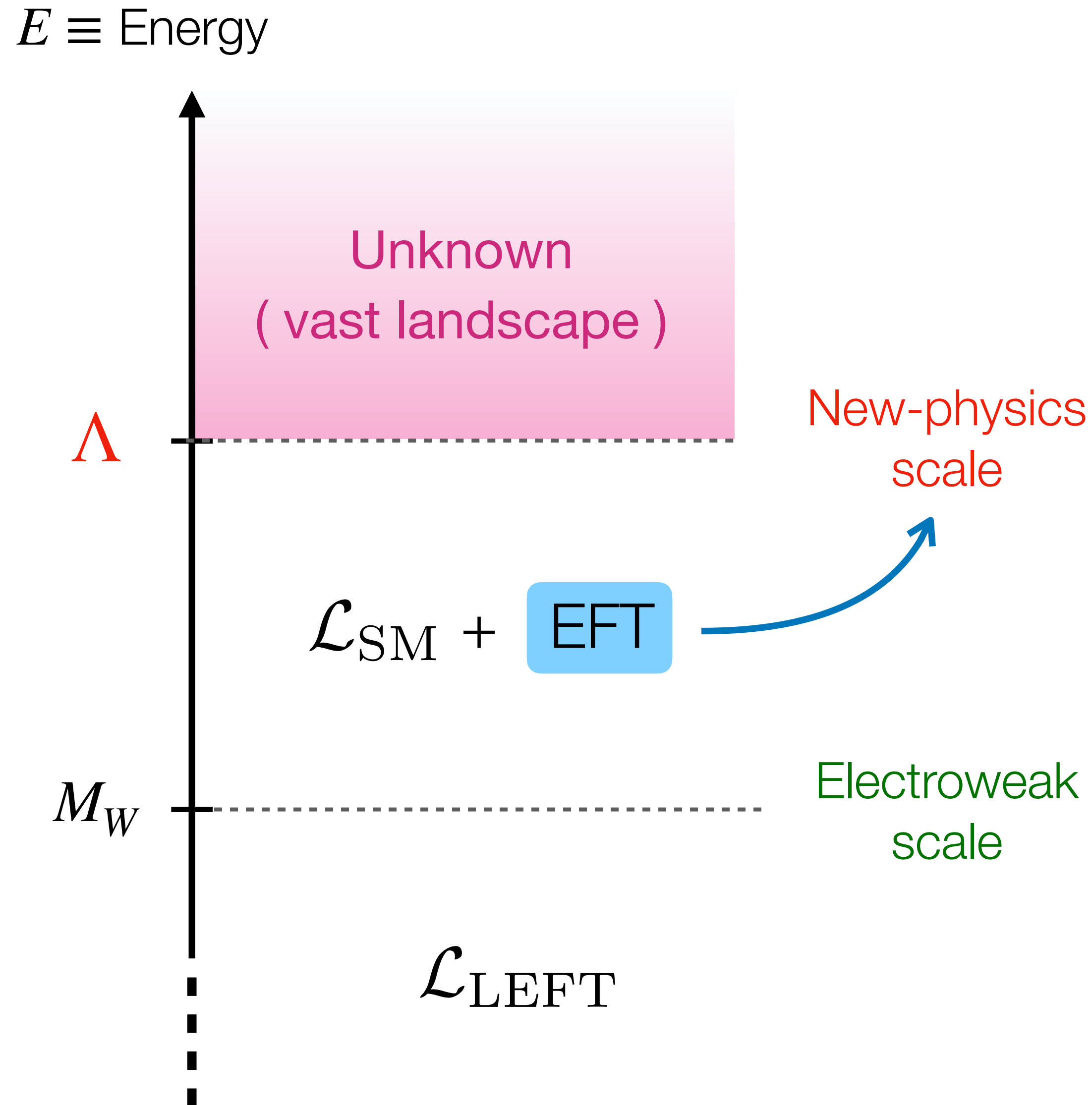
EFTs are great for parametrizing the **unknown**:

- Can be formulated without knowing the full theory
- Systematically improvable by adding extra terms in a double expansion in quantum corrections and  $E/\Lambda$

$$\mathcal{L}_{\text{EFT}}(\eta_L) = \mathcal{L}_{d=4}(\eta_L) + \sum_{\ell=0}^{\infty} \sum_{n=5}^{\infty} \sum_k \frac{C_{n,k}^{(\ell)}}{(16\pi^2)^\ell \Lambda^{n-4}} O_{n,k}(\eta_L)$$

UV physics

# Effective Field Theories (EFT): bottom-up



EFTs are great for parametrizing the **unknown**:

- Can be formulated **without knowing the full theory**
- **Systematically improvable** by adding extra terms in a double expansion in quantum corrections and  $E/\Lambda$

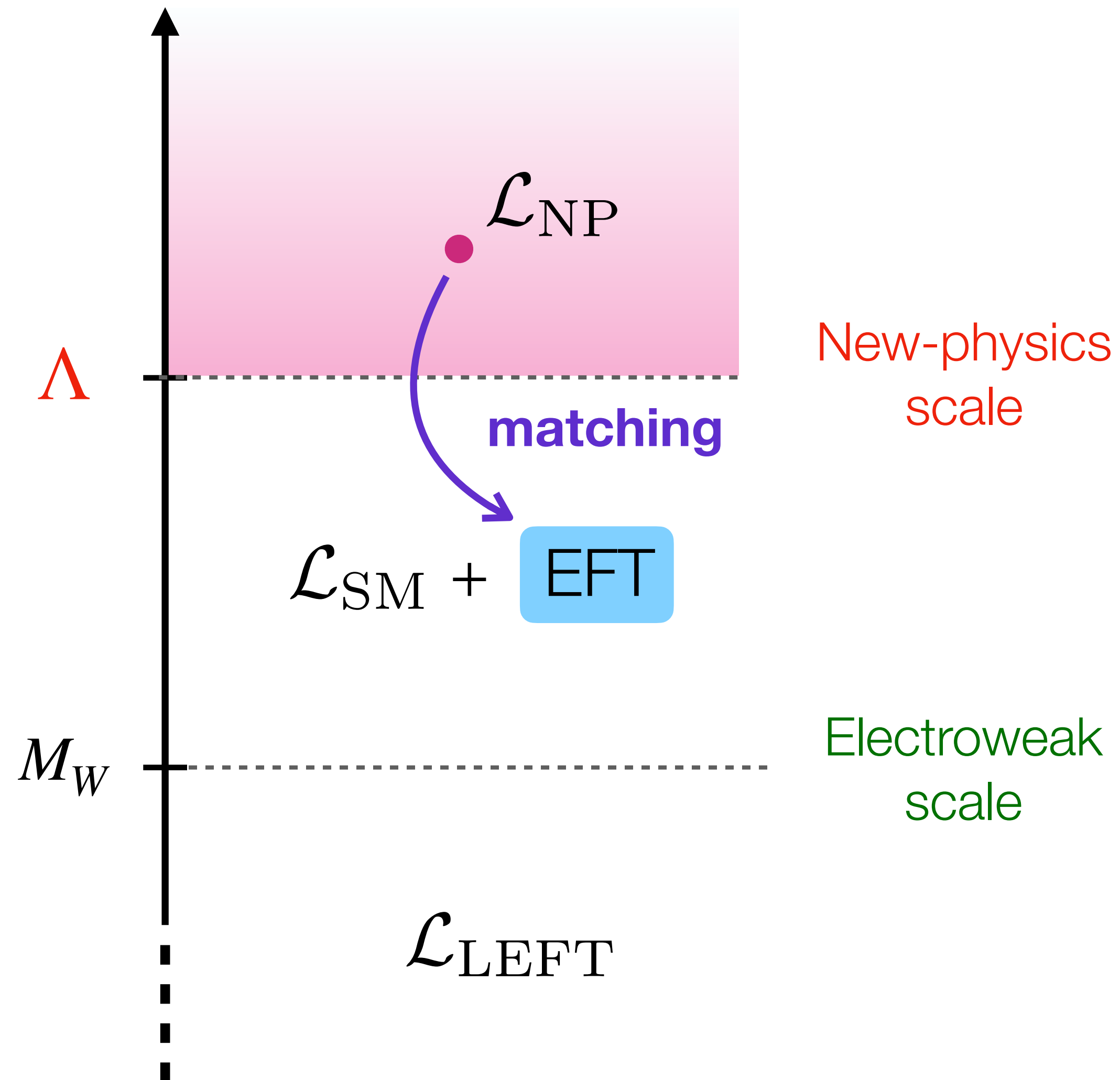
They give an indication on **new-physics scales** where a **new fundamental theory** has to be formulated

For example,

LEFT  $\rightarrow$  Electroweak scale  $\rightarrow$  Standard Model (SM)  
[ Fermi Theory ]

# Effective Field Theories (EFT): top-down

$E \equiv$  Energy



Given a **specific new-physics** idea:

- Many models share the same EFT, providing a **universal framework** to connect models with data
- **Precision necessitates EFTs**: summation of ( large ) logarithms of  $E/\Lambda$  arising from quantum corrections

The step to build an EFT from a model is called **matching**

→ **extremely repetitive and time-consuming** task

Entire journal publications for the (one-loop) matching of *simple* NP models

# The EFT approach: The rise of automation

Wim Klein, CERN “human computer”



# The EFT approach: The rise of automation

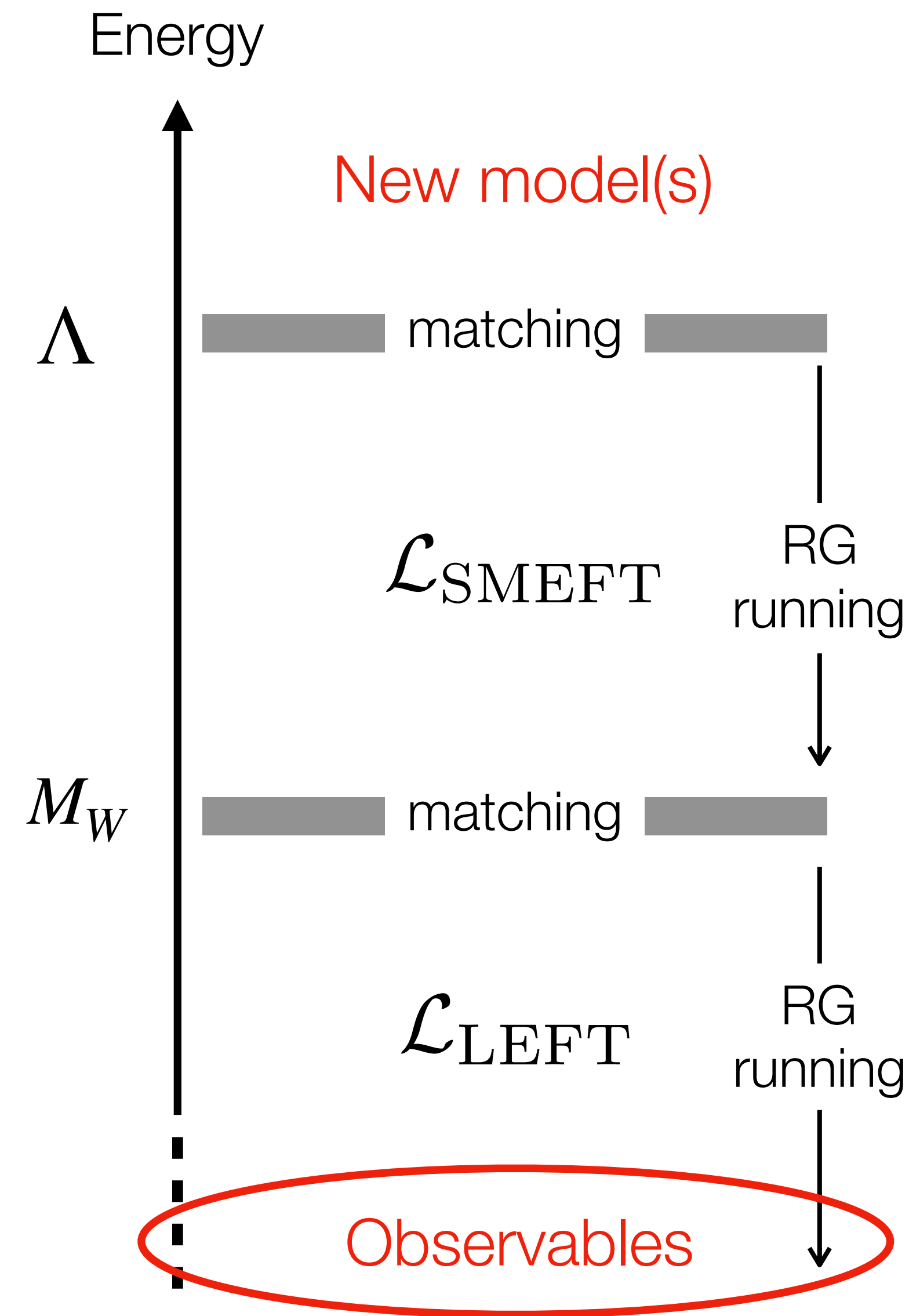
CERN first electronic computer



## The (SM)EFT software project:

Upgrading from “human computers” to computers

# The EFT approach: The rise of automation



SMEFT likelihood ( smelli )  
Aebischer et al. '18



flavio  
Straub '16



Allwicher et al. '22



De Blas et al. '19



Giani et al. '23

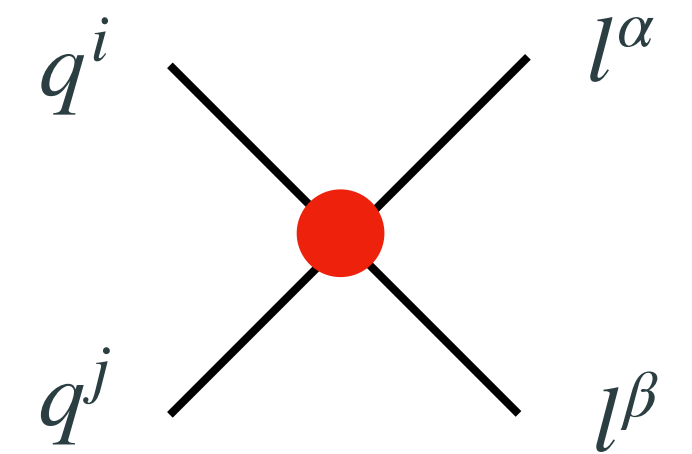
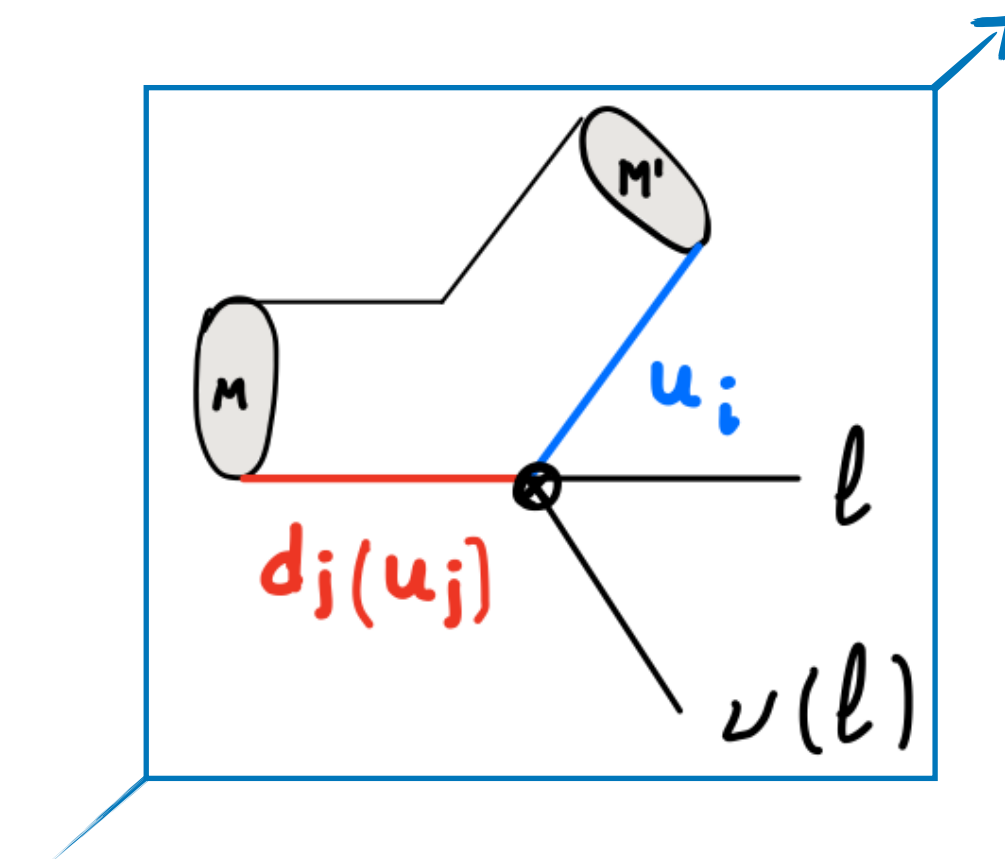
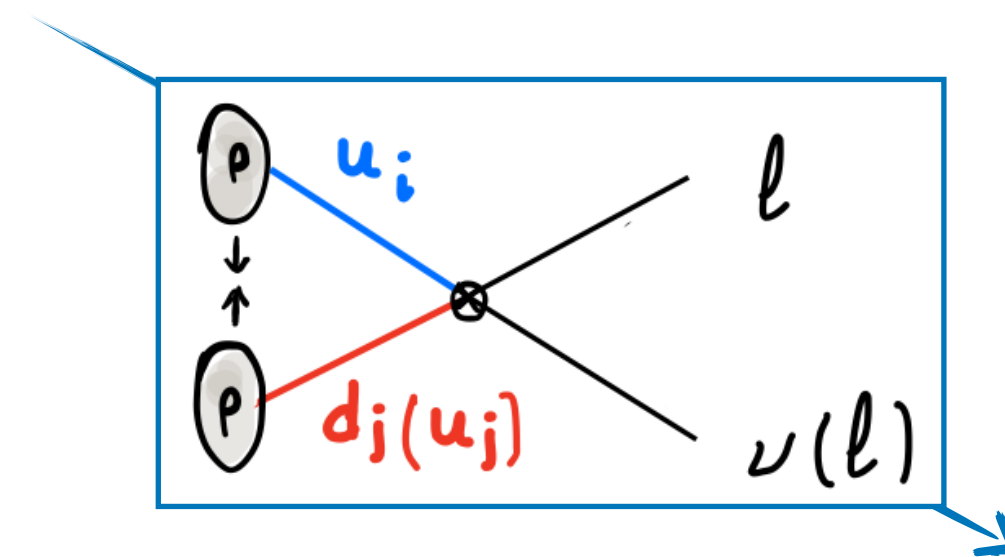
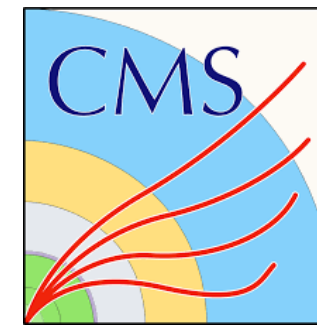
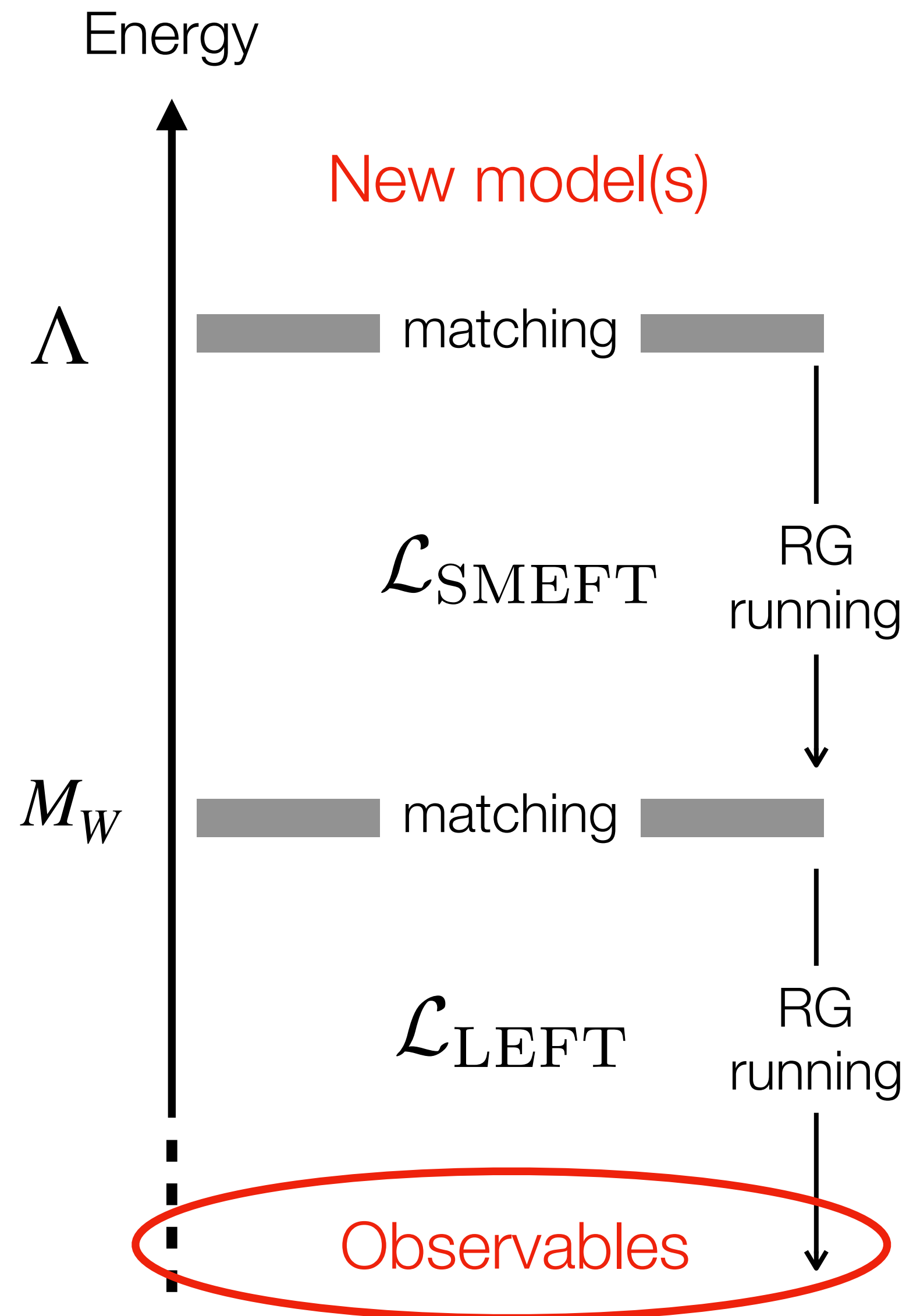
Fitmaker  
Ellis et al '20

+ others ( see, e.g., Gonzalez-Alonso et al. )

# The EFT approach: The rise of automation

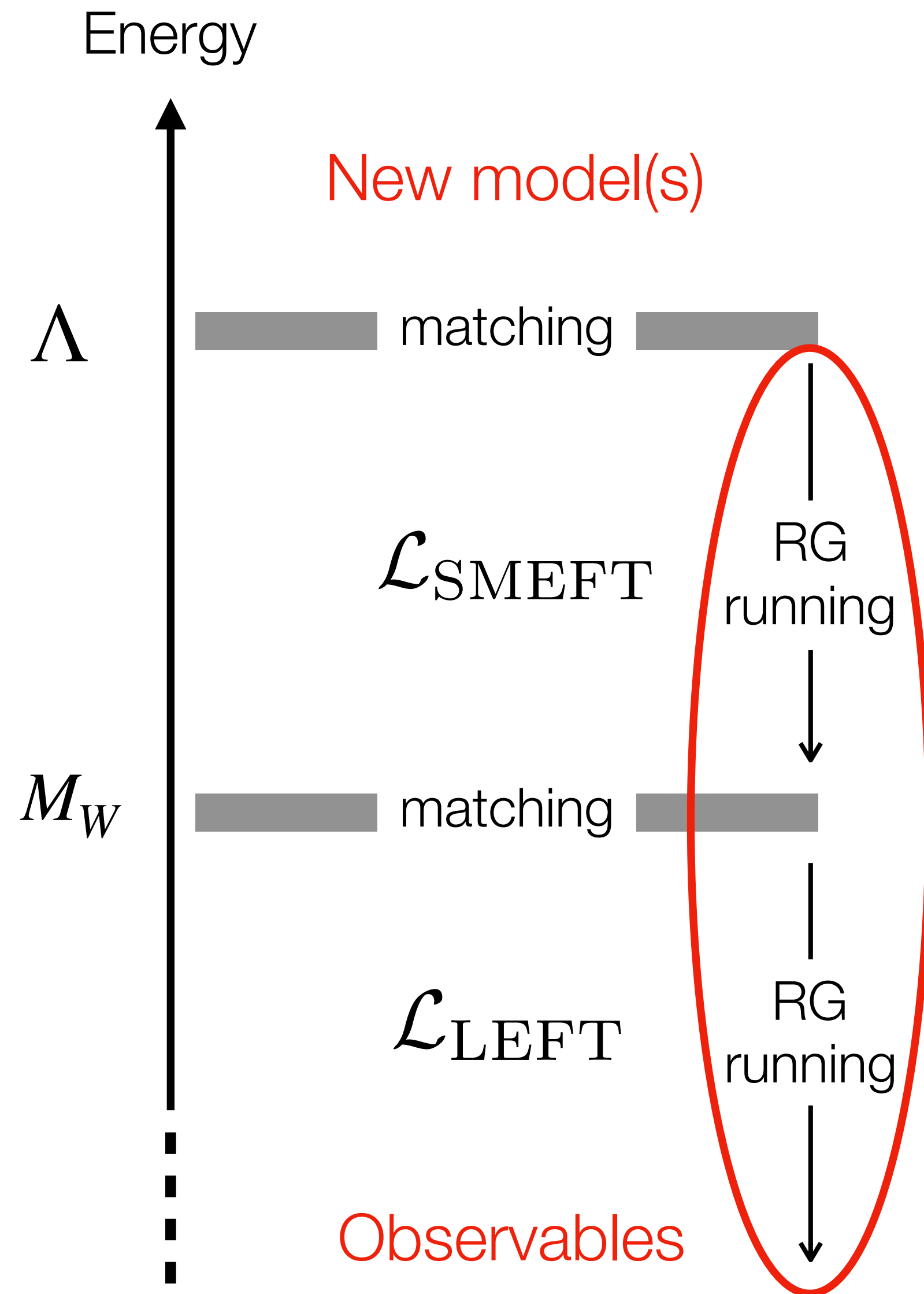
Exploit complementary information in high- and low-energy probes:

→ For this, RG running and SMEFT-LEFT matching are crucial !!



...

# The EFT approach: The rise of automation



JFM et al. '17 & '21



Aebischer et al. '18

Building from “human computed” one-loop results:

[SMEFT running](#): Jenkins et al. '13, '14; Alonso et al. '14

[LEFT basis](#): Jenkins et al. '18

[SMEFT-LEFT matching](#): Dekens, Stoffer '19

[LEFT running](#): Jenkins et al. '18

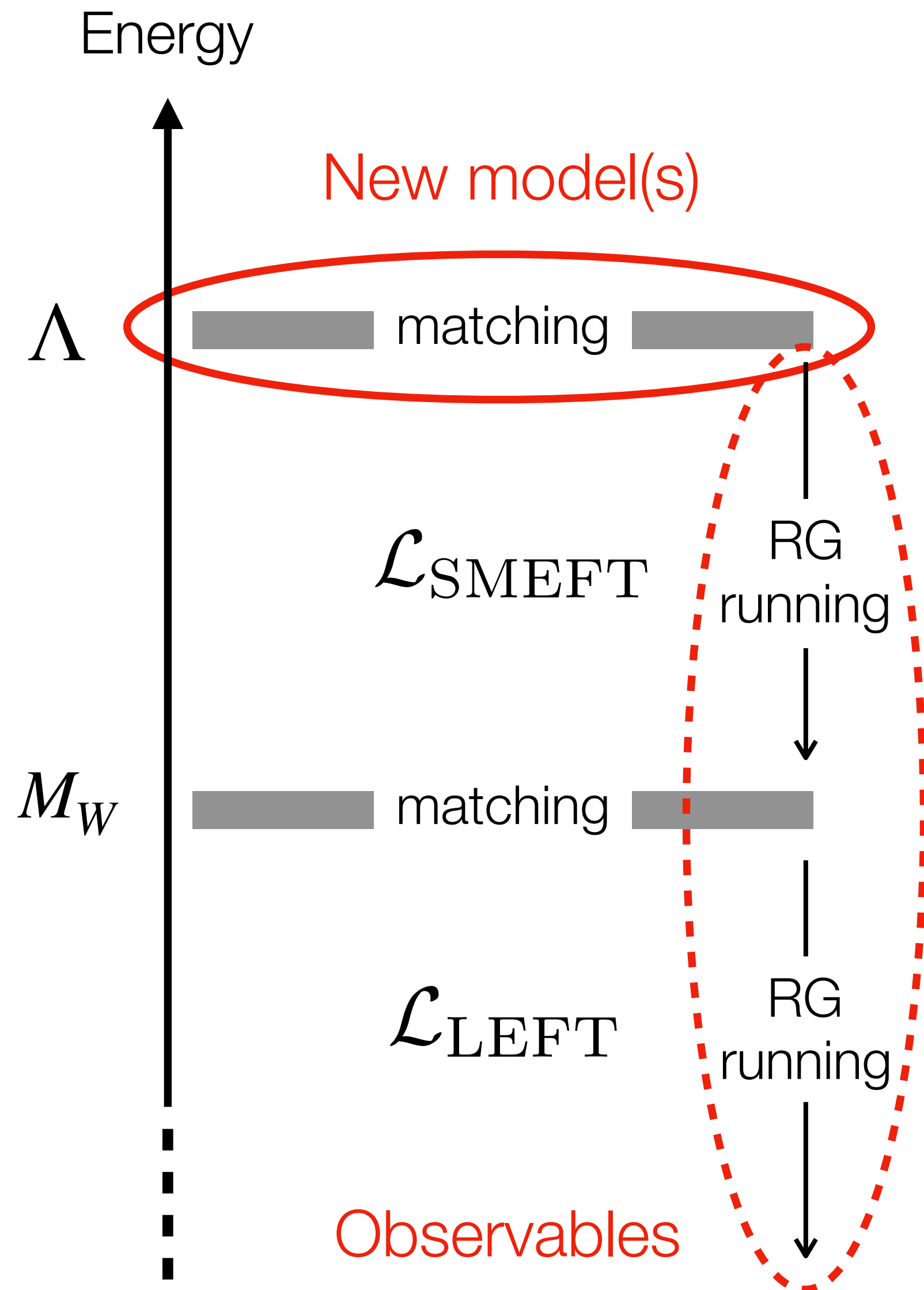
Very **recent developments** in the LEFT:

**LEFT 2-loop RGEs:**

Aebischer, Morell, Pesut, Virto, [2501.08384](#)

Naterop, Stoffer, [2412.13251](#), [2507.08926](#)

# The EFT approach: The rise of automation



matchmakereft  
Carmona et al. '22



JFM et al. '23

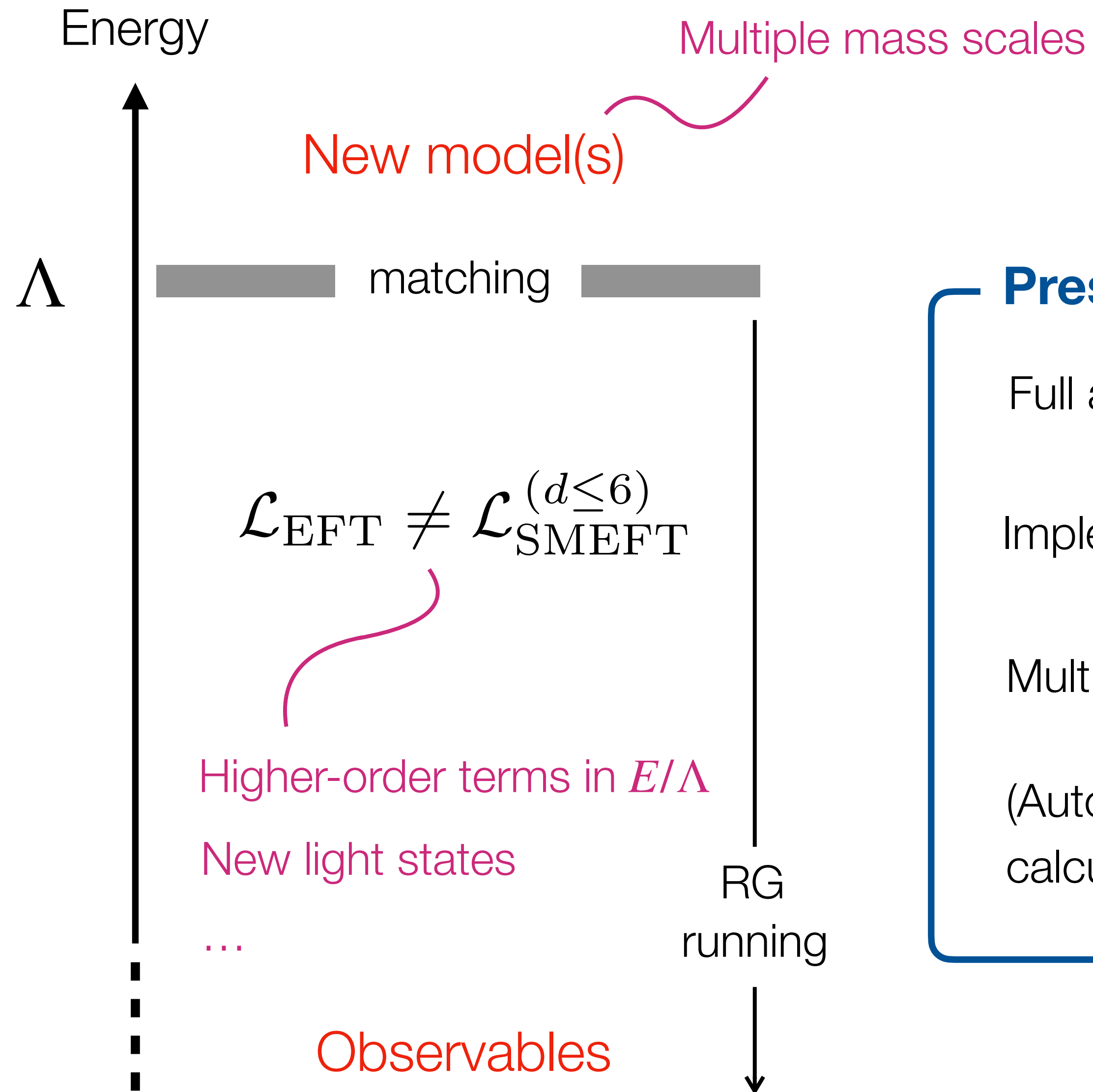
Automated one-loop RG  
and matching calculations  
for *many* models



Guedes et al. '23

UV-SMEFT  
dictionaries

# Going beyond the state-of-the-art



## Present limitations & ongoing efforts

Full automation only for simpler scenarios (no heavy vectors yet!)

Implementation of many observables at one loop is still needed

Multiple efforts to extend this program beyond dimension 6

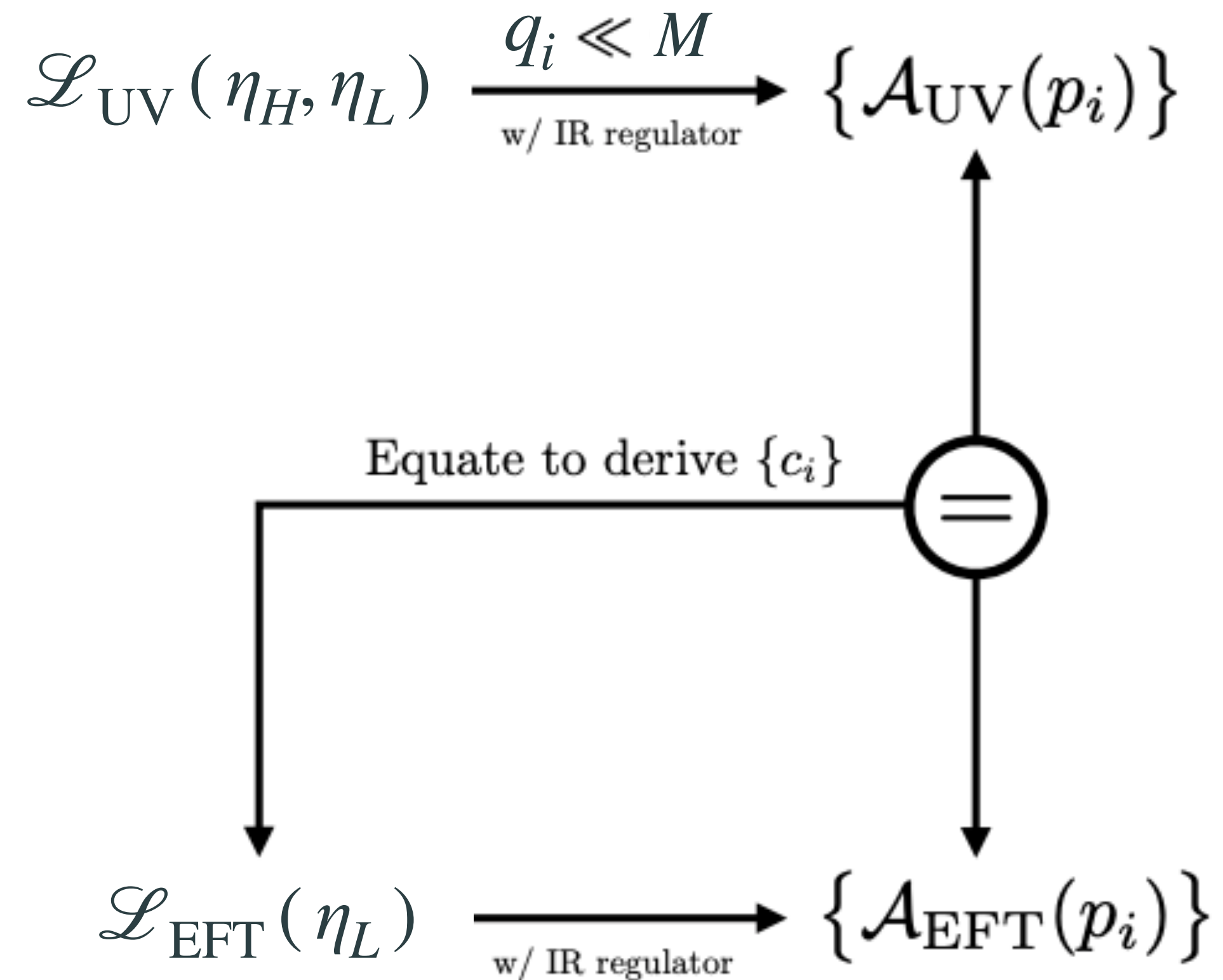
(Automated) inclusion of higher-loop orders in RG and matching calculations has recently started

# EFT matching (and running)

The path-integral approach in a nutshell

# Diagrammatic matching: off-shell and on-shell

## Amplitude matching (with Feynman diagrams)



Traditional, well-established procedure



Requires a priori knowledge of the EFT Lagrangian

- **Off-shell amplitudes**: only 1PI diagrams but EFT Lagrangian contains many operators ( off-shell d-dimensional Lagrangian )
- **On-shell matching**: only need to know on-shell EFT Lagrangian but, a priori, more complicated calculations. See [Chala et al., 2411.12798](#) for a numerical approach using rational kinematics



Breaks gauge invariance in intermediate steps

# Simplified diagrammatic matching: method of regions

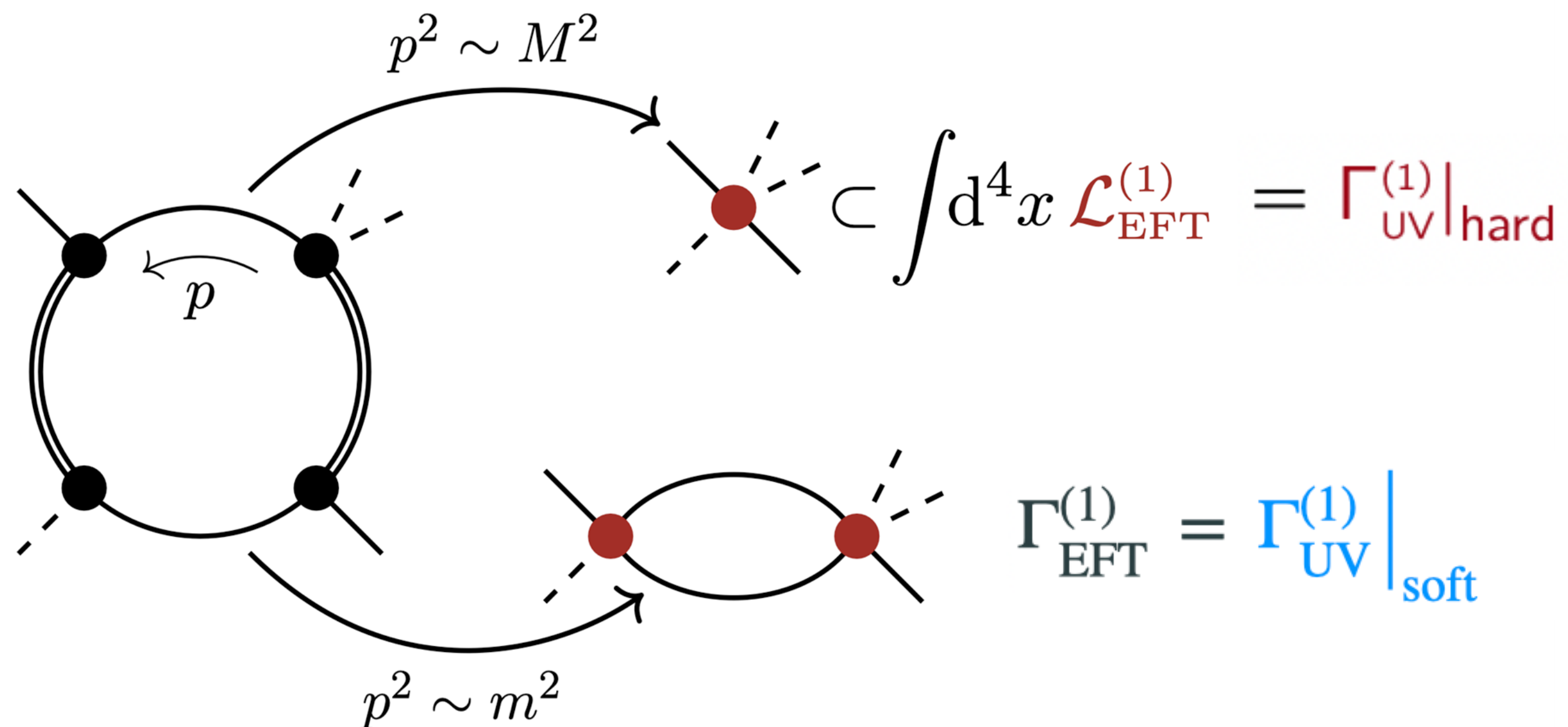
We can separate loop integrals in two regions ( for  $q^2, m^2 \ll M^2$  ): **hard** ( $p^2 \sim M^2$ ) & **soft** ( $p^2 \sim m^2$ )

**Method of regions:** Beneke, Smirnov '97, Jantzen '11

If only the hard part of the loop is considered, we get the EFT Lagrangian *directly*

JFM, Portolés, Ruiz-Femenía, '16

Zhang, '16



# The functional approach to EFT matching

Functional matching  
(path-integral methods)

$$\mathcal{L}_{UV}(\eta_H, \eta_L)$$

Using Equations  
of Motion (EOMs)

$$\Gamma_{UV}[\hat{\eta}_H(\eta_L), \eta_L]$$

Method of regions

$$\mathcal{L}_{EFT}(\eta_L)$$

Not in a basis

Based on the **Wilsonian approach** : split vibrating fields into fast ( $\eta_H$ ) and slow ( $\eta_L$ ) vibrations and “integrate out” the fast ones

Wilson, 1965

- ✓ More systematic and efficient approach
- ✓ The EFT Lagrangian comes out directly
- ✓ Manifestly gauge invariant at every step
- ✗ Final results need to be reduced to a basis ( off-shell matching )

# A taste on functional matching

- **Lagrangian:**  $\mathcal{L}_{UV}$  with fields  $\eta = (\eta_H \ \eta_L)$  and hierarchy  $m_H \gg m_L$

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

$\hat{\eta}$  : background fields ( satisfy the quantum EOM )

$\eta$  : quantum fluctuations

Tree lines in Feynman graphs

Loop lines in Feynman graphs

- **Quantum effective action:**

$$e^{i\Gamma_{UV}[\hat{\eta}]} = \int \mathcal{D}\eta \exp\left(i \int d^d x \ \mathcal{L}_{UV}(\eta + \hat{\eta})\right)$$

**Goal:** Evaluate the path integral  
( “integrate out” the quantum fluctuations )  
and isolate the EFT contribution

# A taste on functional matching

- Expanding the Lagrangian in  $\eta$ :

$$\mathcal{L}_{\text{UV}}(\hat{\eta} + \eta) = \mathcal{L}_{\text{UV}}(\hat{\eta}) + \left. \frac{\delta \mathcal{L}_{\text{UV}}}{\delta \eta_a} \right|_{\eta=\hat{\eta}} \eta_a + \frac{1}{2} \eta_a(\textcolor{red}{x}) \left. \frac{\delta^2 \mathcal{L}_{\text{UV}}}{\delta \eta_b(\textcolor{red}{x}') \delta \eta_a(\textcolor{red}{x})} \right|_{\eta=\hat{\eta}} \eta_b(\textcolor{red}{x}') + \mathcal{O}(\eta^3)$$

# A taste on functional matching

- Expanding the Lagrangian in  $\eta$ :

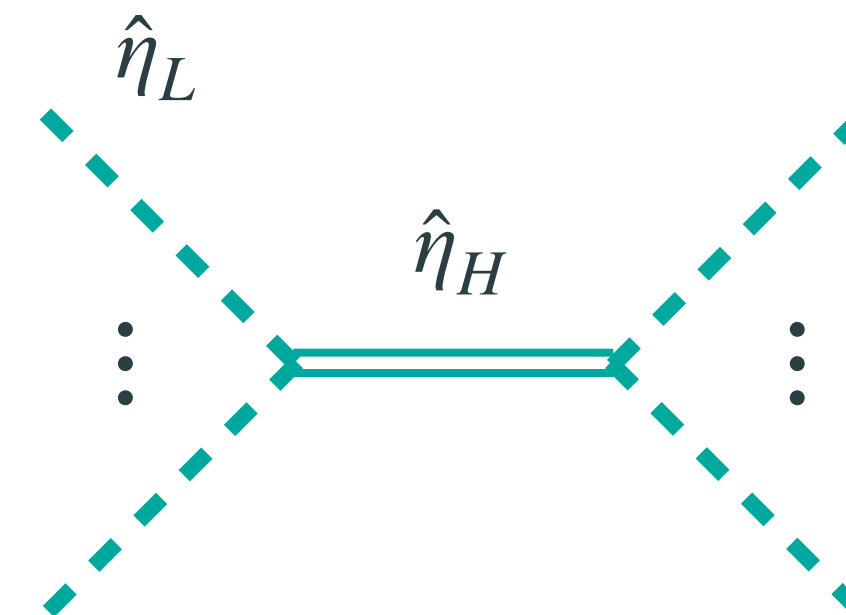
$$\mathcal{L}_{\text{UV}}(\hat{\eta} + \eta) = \boxed{\mathcal{L}_{\text{UV}}(\hat{\eta})} + \left. \frac{\delta \mathcal{L}_{\text{UV}}}{\delta \eta_a} \right|_{\eta=\hat{\eta}} \eta_a + \frac{1}{2} \eta_a(x) \left. \frac{\delta^2 \mathcal{L}_{\text{UV}}}{\delta \eta_b(x') \delta \eta_a(x)} \right|_{\eta=\hat{\eta}} \eta_b(x') + \mathcal{O}(\eta^3)$$

- **Tree-level:**  $\mathcal{L}_{\text{EFT}}^{(0)} = \mathcal{L}_{\text{UV}}(\hat{\eta}_L, \hat{\eta}_H(\hat{\eta}_L))$

— Substitute  $\hat{\eta}_H$  by its EOM expanded in  $m_H^{-1}$

[ Simpler than computing Feynman graphs ]

$$\left. \frac{\delta \mathcal{L}_{\text{UV}}}{\delta \eta_H} \right|_{\eta=\hat{\eta}} = 0$$



# A taste on functional matching

- Expanding the Lagrangian in  $\eta$ :

$$\mathcal{L}_{UV}(\hat{\eta} + \eta) = \boxed{\mathcal{L}_{UV}(\hat{\eta})} + \cancel{\frac{\delta \mathcal{L}_{UV}}{\delta \eta_a} \bigg|_{\eta=\hat{\eta}}} \overset{0}{\eta_a} + \frac{1}{2} \eta_a(x) \frac{\delta^2 \mathcal{L}_{UV}}{\delta \eta_b(x') \delta \eta_a(x)} \bigg|_{\eta=\hat{\eta}} \eta_b(x') + \mathcal{O}(\eta^3)$$

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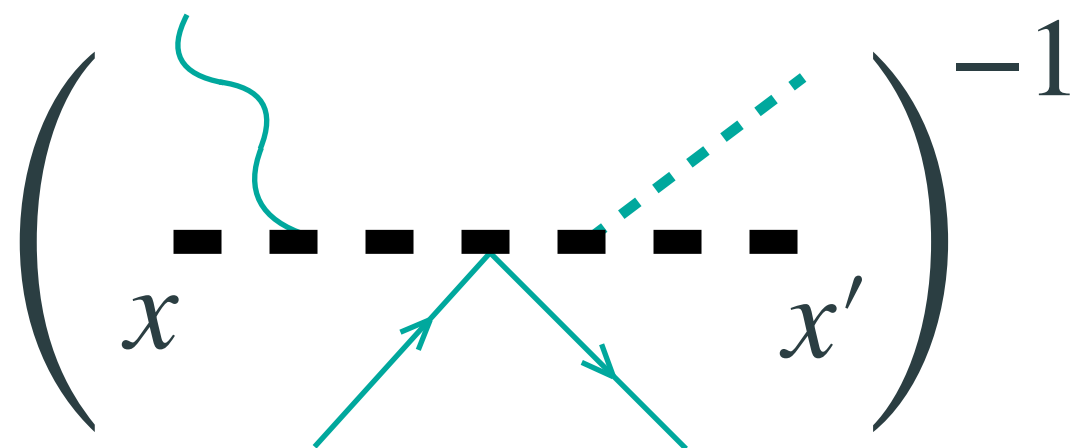
- Inverse quantum-field propagator:

**Wilson line**

[ parallel transport  $x \leftrightarrow x'$  ]

$$\mathcal{Q}_{ab}(x, x') = Q_{ac}(\hat{\eta}(x), \hat{D}_x^{\mu_1} \dots \hat{D}_x^{\mu_n} \hat{\eta}(x), \hat{D}_x^\mu) U_{cb}(x, x') \delta(x - x')$$

$$\hat{D}_x^{\mu_1} \dots \hat{D}_x^{\mu_n} U(x, x') \bigg|_{x=x'} = p_n(G^{\mu\nu}, D^\mu G^{\nu\rho}, \dots)$$



Kuzenko, McArthur, '03

JFM, Moreno, Palavrić, Thomsen, [2412.12270](#)

# A taste on functional matching

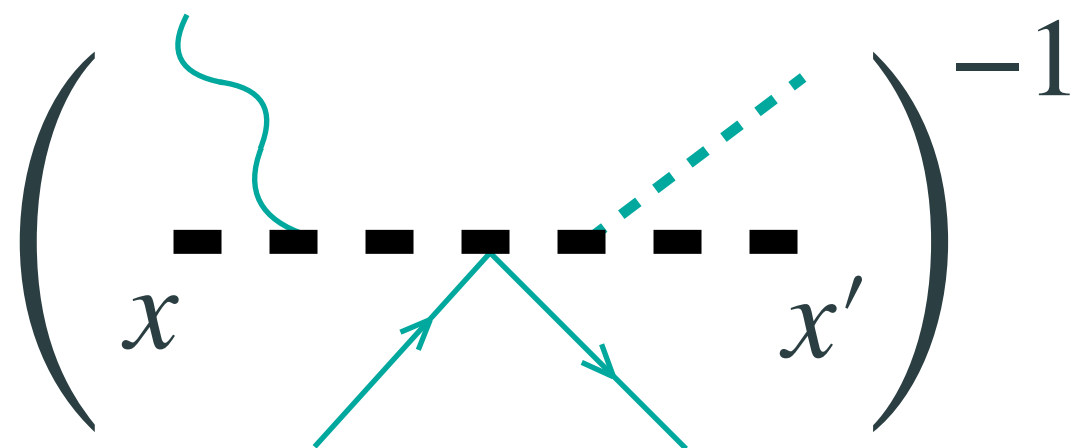
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Higher-loop orders

- Inverse quantum-field propagator:

$$\hat{\mathcal{Q}}_{ab}(x, x') = Q_{ac}(\hat{\eta}(x), \hat{D}_x^{\mu_1} \dots \hat{D}_x^{\mu_n} \hat{\eta}(x), \hat{D}_x^\mu) U_{cb}(x, x') \delta(x - x')$$



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# A taste on functional matching

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Higher-loop orders  
( see [2412.12270](#) )

- 1-loop effective action:

$$e^{i\Gamma_{\text{UV}}^{(1)}[\hat{\eta}]} = \int \mathcal{D}\eta \exp\left( i \int_{x,x'} \eta_a(x) \mathcal{Q}_{ab}(x, x') \eta_b(x') \right) \implies \Gamma_{\text{UV}}^{(1)}[\hat{\eta}] = -i \ln \text{SDet } \mathcal{Q}^{-1/2} = \frac{i}{2} \text{STr} \ln \mathcal{Q}$$

Gaussian integration

## How to evaluate supertraces

$$[\ln \mathcal{Q}(x, x')]_{aa}$$

$$\Gamma_{\text{UV}}^{(1)}[\hat{\eta}] = \frac{i}{2} \text{STr} \ln \mathcal{Q} = \pm \frac{i}{2} \int_{x, x'} \delta(x - x') [\ln \mathcal{Q}(x, iD_x^\mu)]_{ab} U_{ba}(x, x') \delta(x - x')$$

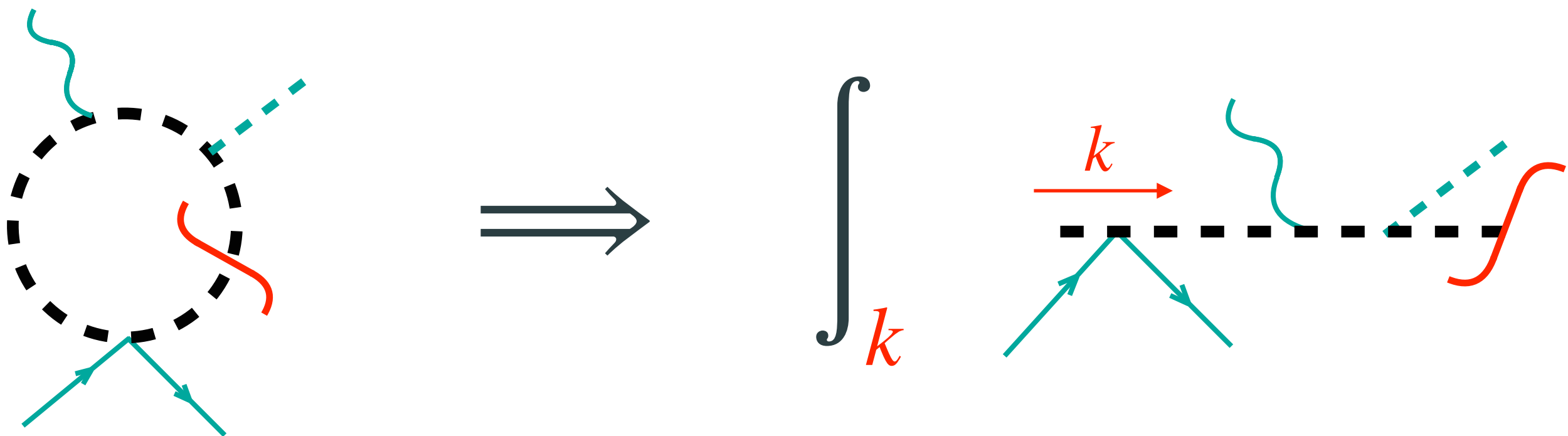
## How to evaluate supertraces

$$\begin{aligned}
 \Gamma_{\text{UV}}^{(1)}[\hat{\eta}] &= \frac{i}{2} \text{STr} \ln \mathcal{Q} = \pm \frac{i}{2} \int_{x,x'} \delta(x-x') [\ln \mathcal{Q}(x, iD_x^\mu)]_{ab} U_{ba}(x, x') \delta(x-x') \\
 &= \pm \frac{i}{2} \int_{x,k} [\ln \mathcal{Q}(x, i\hat{D}_x^\mu - \mathbf{k})]_{ab} U_{ba}(x, x') \Big|_{x=x'} \int_k e^{ik(x-x')}
 \end{aligned}$$

Diagrammatic annotations: An orange arc connects the term  $[\ln \mathcal{Q}(x, iD_x^\mu)]_{ab}$  in the first line to the term  $[\ln \mathcal{Q}(x, i\hat{D}_x^\mu - \mathbf{k})]_{ab}$  in the second line. A red arc connects the  $\delta(x-x')$  term in the first line to the  $\int_k e^{ik(x-x')}$  term in the second line.

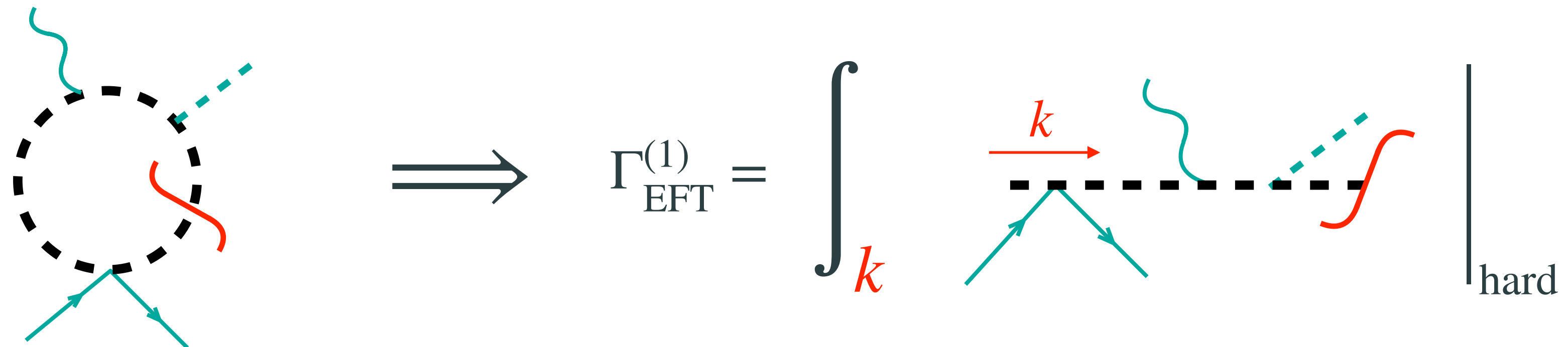
# How to evaluate supertraces

$$\begin{aligned}
 \Gamma_{\text{UV}}^{(1)}[\hat{\eta}] &= \frac{i}{2} \text{STr} \ln \mathcal{Q} = \pm \frac{i}{2} \int_{x,x'} \delta(x-x') \overbrace{[\ln \mathcal{Q}(x, iD_x^\mu)]_{ab}}^{[\ln \mathcal{Q}(x, x')]_{aa}} U_{ba}(x, x') \underbrace{\delta(x-x')}_{\int_k e^{ik(x-x')}} \\
 &= \pm \frac{i}{2} \int_{x,k} [\ln \mathcal{Q}(x, i\hat{D}_x^\mu - \textcolor{red}{k})]_{ab} U_{ba}(x, x') \Big|_{x=x'}
 \end{aligned}$$



# How to evaluate supertraces

$$\begin{aligned}
 \Gamma_{\text{UV}}^{(1)}[\hat{\eta}] &= \frac{i}{2} \text{STr} \ln \mathcal{Q} = \pm \frac{i}{2} \int_{x,x'} \delta(x-x') [\ln \mathcal{Q}(x, iD_x^\mu)]_{ab} U_{ba}(x, x') \delta(x-x') \int_k e^{ik(x-x')} \\
 &= \pm \frac{i}{2} \int_{x,k} [\ln \mathcal{Q}(x, i\hat{D}_x^\mu - \mathbf{k})]_{ab} U_{ba}(x, x') \Big|_{x=x'}
 \end{aligned}$$



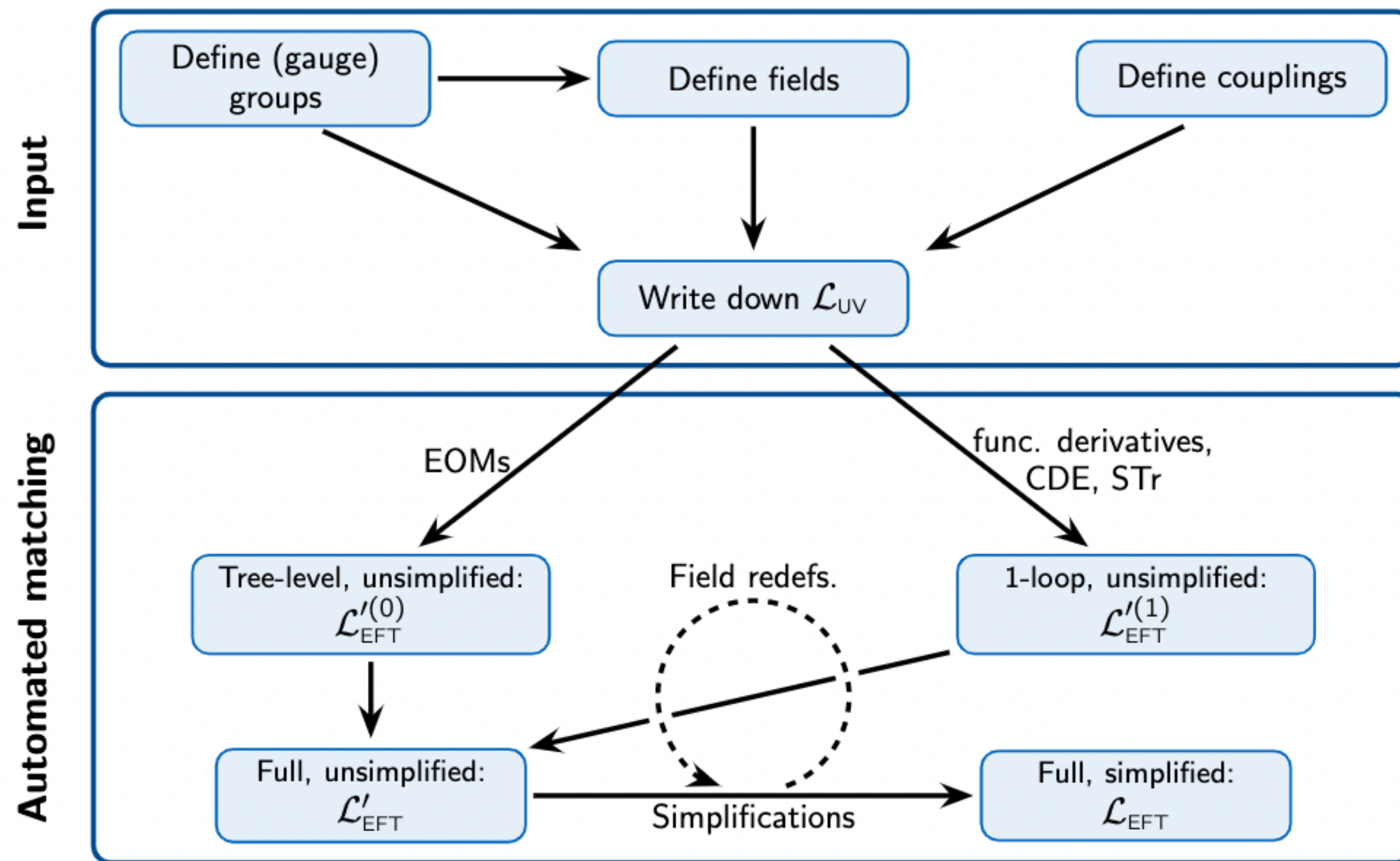
The EFT action (to arbitrary EFT order) is obtained *directly* from the hard-momentum expansion:  $k \gtrsim m_H$



To make your way through the BSM jungle

# The Matchete package

**MATCHETE** is a Mathematica package aimed at fully automating EFT matching and running of arbitrary *weakly-coupled* UV theories using functional methods

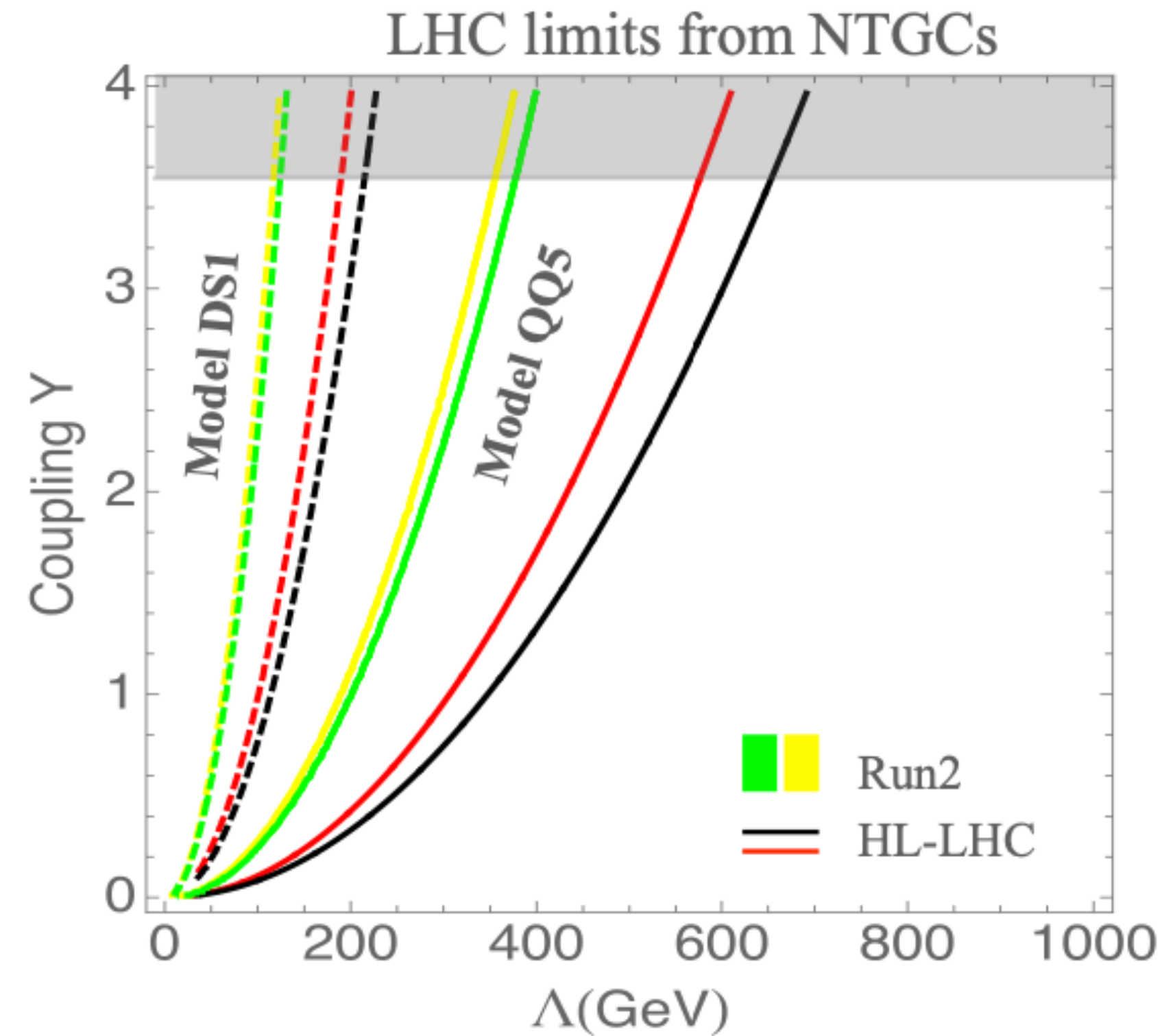
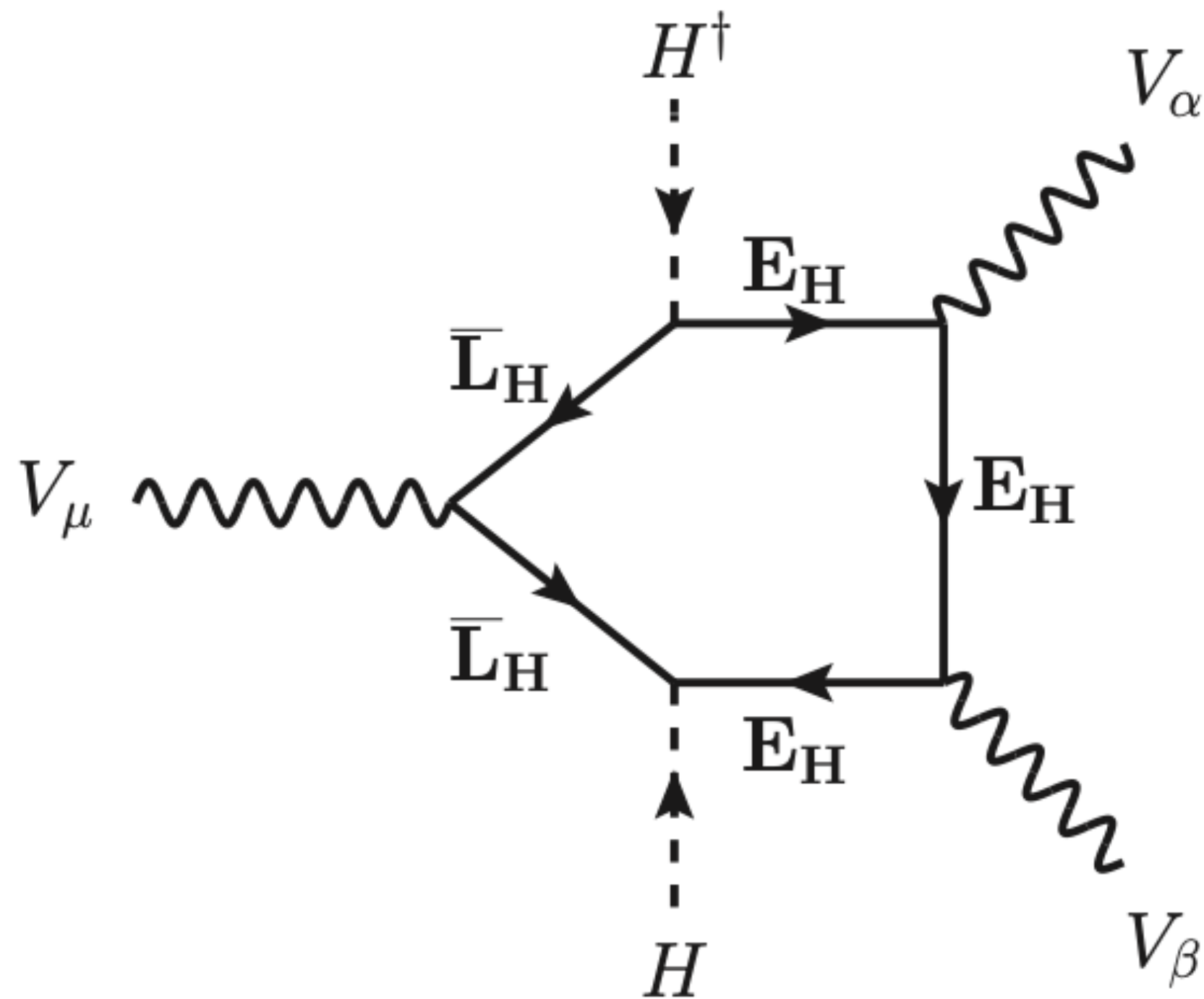


First public version of **Matchete**

- One-loop matching of *any* model with heavy scalars and/or fermions
- Simple and intuitive input/output
- Automated handling of group theory
- Automated simplifications to EFT basis
  - Linear simplifications ( IBP, group theory,... )  
**Not** including Fierz ( evanescent contributions )
  - Field redefinitions/EOMs

# Example: neutral triple-gauge interactions

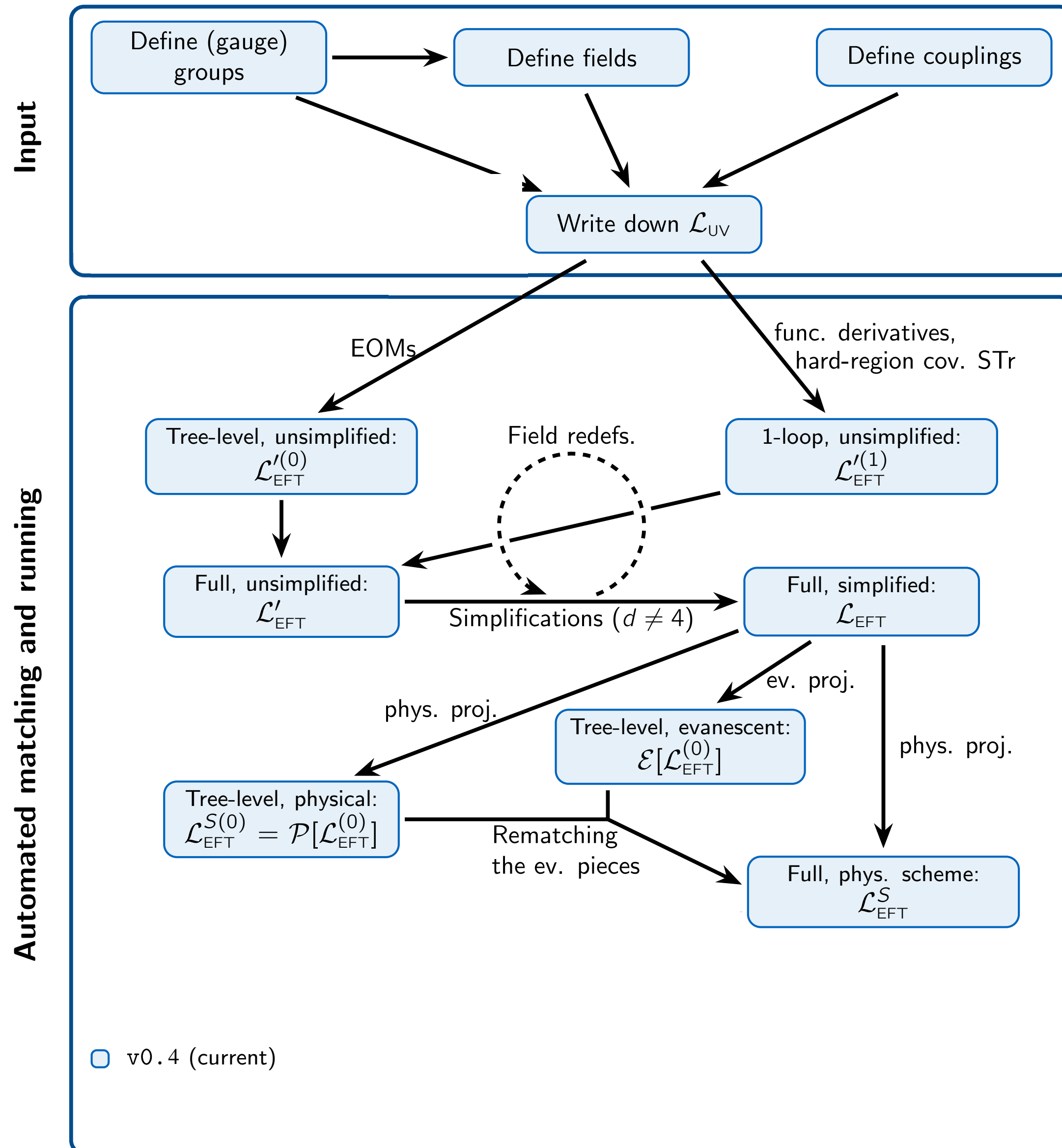
New physics in  $Z(\gamma, Z)(\gamma^*, Z^*)$ ?



\* 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]

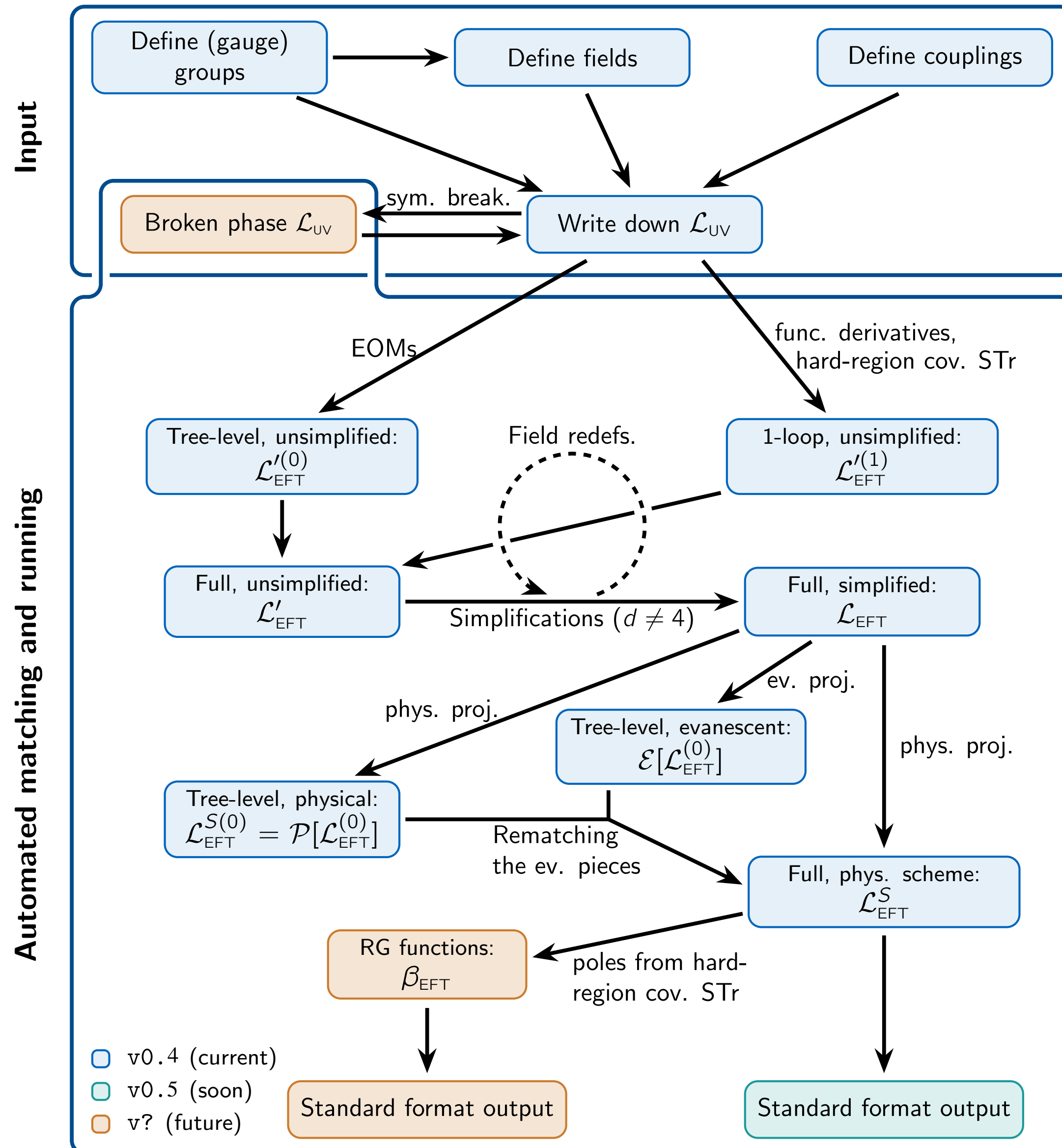
# New Matchete workflow



## v0.1 → v0.4 changes:

- Automated handling of evanescent operators  
JFM, König, Pagès, Thomsen, Wilsch, [2212.04510](#)
- Theoretically-cleaner evaluation procedure  
Covariant Derivative Expansion → Wilson lines
- More robust and considerably faster  
The community has been of **great help** bringing issues to our attention!
- **Other new features:**
  - Heavy-particle flavor indices,
  - Mapping to predefined EFT bases
  - Partial documentation...

# Work in progress and future plans



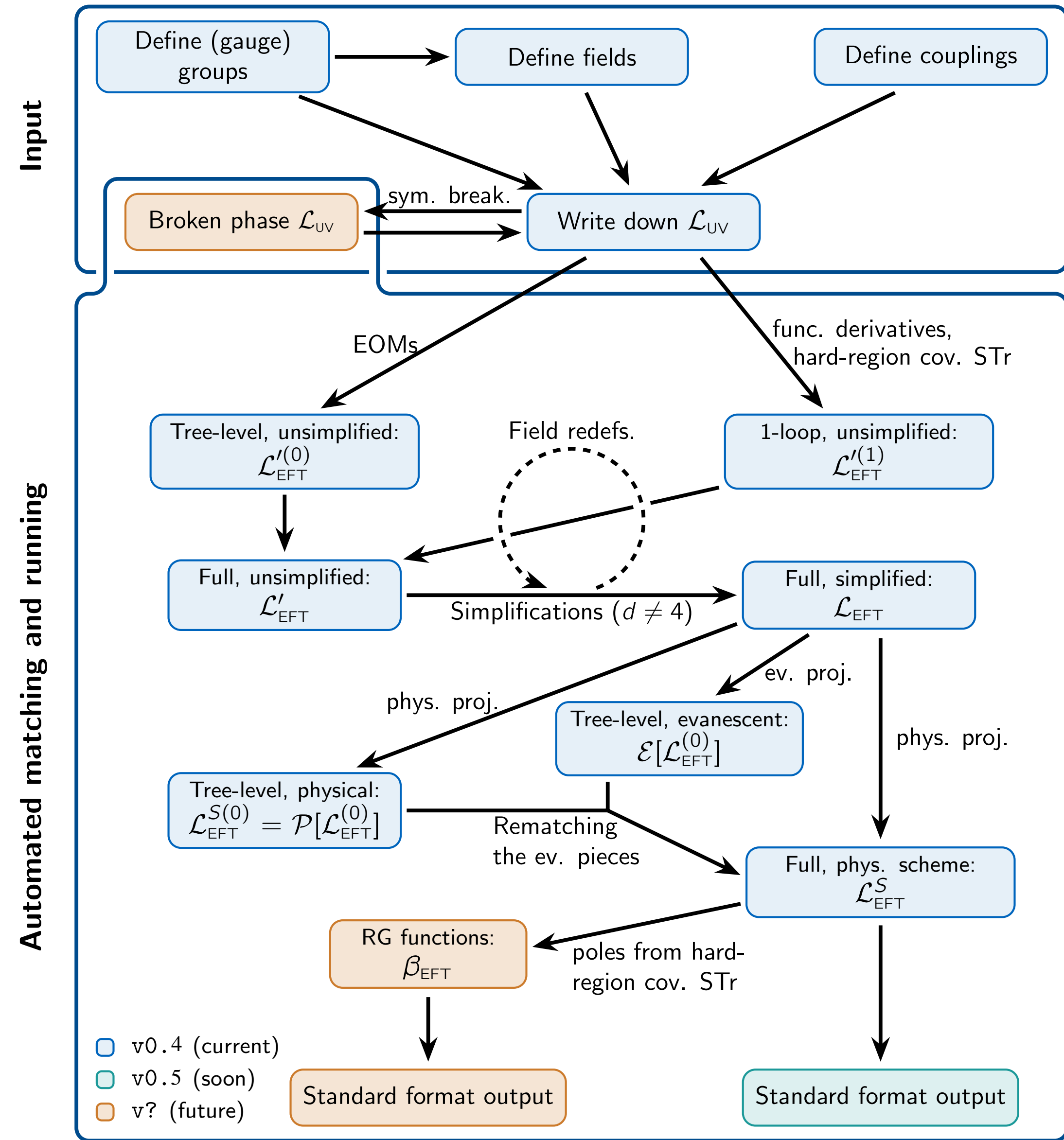
## Coming next

- Interface with other EFT tools
- Automated one-loop  $\beta$  functions
- Symmetry breaking and heavy vectors
- 't Hooft-Veltman scheme for  $\gamma_5$   
JFM, Moreno-Sanchez, Thomsen [2507.19589](#) + w.i.p
- Thermal Field Theory  
JFM, Lopez-Miras, Moreno-Sanchez, w.i.p

## Longer term

- RG and matching beyond one loop
  - 2-loop RG in the SMEFT  
Born, JFM, Kvedaraitė, Thomsen, [2410.07320](#)
  - Born, JFM, Thomsen, w.i.p

# Work in progress and future plans



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- Interface with other EFT tools
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See talk by Ferrando

- 't Hooft-Veltman scheme for  $\gamma_5$   
JFM, Moreno-Sanchez, Thomsen [2507.19589](#) + ...

See talks by Fiore, Dashko, Gil, and Hill

- Thermal Field Theory  
JFM, Lopez-Miras, Moreno-Sanchez, w.i.p

## Longer term

- RG and matching beyond one loop
  - 2-loop RG in the SMEFT  
Born, JFM, Kvedaraitė, Thomsen, [2410.07320](#)  
Born, JFM, Thomsen, w.i.p

See talk by López-Miras

# Two-loop RGEs in the bosonic SMEFT

We have implemented functional methods at 2-loops into a custom version ( still private ) of 

Born, JFM, Kvedaraitė, Thomsen, [2410.07320](#)

First application: 2-loop RGEs in the bosonic SMEFT:

$$\begin{aligned} \mathcal{L}_{bSMEFT} = & -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}W^{I\mu\nu}W^I_{\mu\nu} - \frac{1}{4}G^{A\mu\nu}G^A_{\mu\nu} \\ & + D_\mu H^\dagger D^\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2 \\ & + \mathcal{L}_{\text{gf.}} + \mathcal{L}_{\text{gh.}} + \mathcal{L}_\theta \end{aligned} \quad +$$

|                       | $X^2 H^2$                                                    |                     | $X^3$                                                          |
|-----------------------|--------------------------------------------------------------|---------------------|----------------------------------------------------------------|
| $C_{HB}$              | $H^\dagger H B^{\mu\nu} B_{\mu\nu}$                          | $C_W$               | $f^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$             |
| $C_{HW}$              | $H^\dagger H W^{I\mu\nu} W^I_{\mu\nu}$                       | $C_G$               | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$             |
| $C_{HG}$              | $H^\dagger H G^{A\mu\nu} G^A_{\mu\nu}$                       | $C_{\widetilde{W}}$ | $f^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ |
| $C_{H\widetilde{B}}$  | $H^\dagger H B^{\mu\nu} \widetilde{B}_{\mu\nu}$              | $C_{\widetilde{G}}$ | $f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ |
| $C_{H\widetilde{W}}$  | $H^\dagger H W^{I\mu\nu} \widetilde{W}^I_{\mu\nu}$           |                     | $H^4 D^2$ and $H^6$                                            |
| $C_{H\widetilde{G}}$  | $H^\dagger H G^{A\mu\nu} \widetilde{G}^A_{\mu\nu}$           | $C_H$               | $(H^\dagger H)^3$                                              |
| $C_{HWB}$             | $(H^\dagger \sigma^I H) B^{\mu\nu} W^I_{\mu\nu}$             | $C_{H\Box}$         | $(H^\dagger H) \Box (H^\dagger H)$                             |
| $C_{H\widetilde{W}B}$ | $(H^\dagger \sigma^I H) B^{\mu\nu} \widetilde{W}^I_{\mu\nu}$ | $C_{HD}$            | $(H^\dagger D_\mu H)^* (H^\dagger D^\mu H)$                    |

## Some results in the bosonic SMEFT at NLL

$$\frac{dC_i}{d \ln \mu} = \frac{\beta_i^{(1)}}{(16\pi^2)} + \frac{\beta_i^{(2)}}{(16\pi^2)^2} + \dots$$

$$\beta_{C_{HD}}^{(1)} = \left( \frac{9}{2}g_L^2 + 6\lambda - \frac{5}{6}g_Y^2 \right) C_{HD} + \frac{20}{3}g_Y^2 C_{H\Box}$$

$$\beta_{C_{H\Box}}^{(1)} = \left( 12\lambda - \frac{4}{3}g_Y^2 - 4g_L^2 \right) C_{H\Box} + \frac{5}{3}g_Y^2 C_{HD}$$

$$\begin{aligned} \beta_{C_{HD}}^{(2)} = & \left[ \lambda \left( \frac{5}{2}g_Y^2 - \frac{45}{2}g_L^2 \right) + \frac{299}{216}g_Y^4 + \frac{41}{2}g_Y^2g_L^2 - \frac{1}{8}g_L^4 - 36\lambda^2 \right] C_{HD} \\ & + \left( \frac{70}{27}g_Y^4 - \frac{227}{9}g_Y^2g_L^2 - \frac{136}{3}\lambda g_Y^2 \right) C_{H\Box} \\ & + \left( 32g_Y^3g_L - 68g_Yg_L^3 - 96\lambda g_Yg_L \right) C_{HWB} \\ & + \left( \frac{32}{3}g_Y^4 + 12g_Y^2g_L^2 - 48\lambda g_Y^2 \right) C_{HB} \\ & + 28g_Y^2g_L^2 C_{HW} + 26g_Y^2g_L^3 C_W \end{aligned}$$

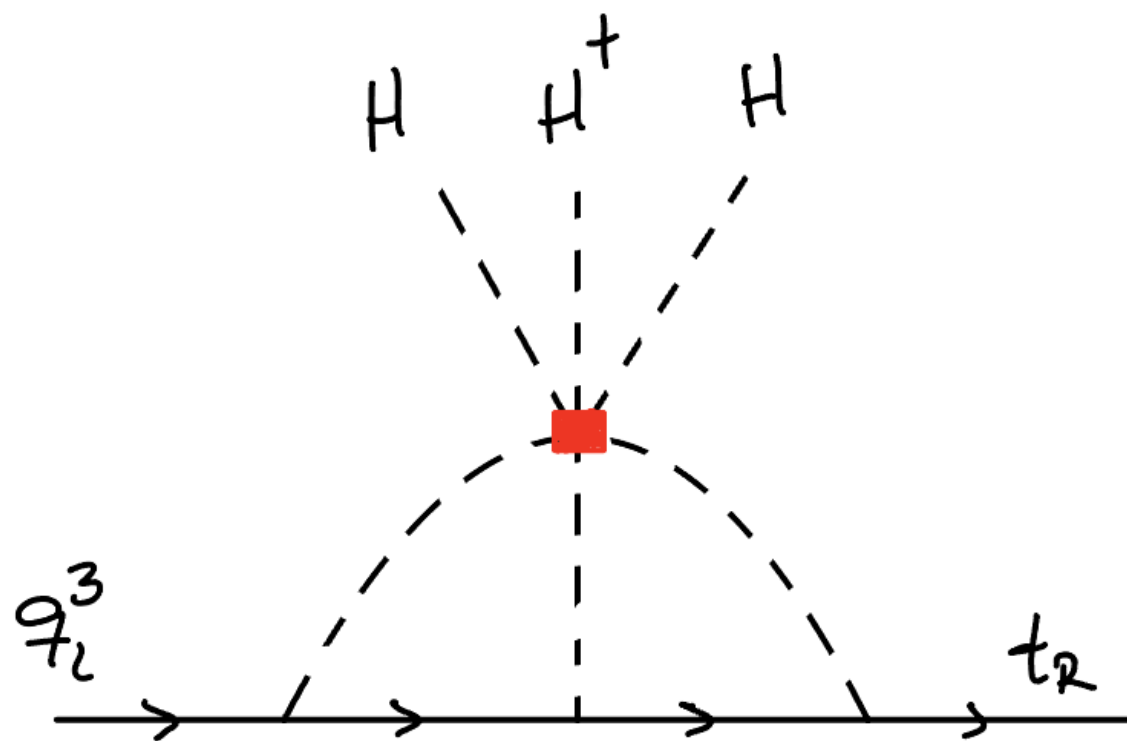
**Enlarged mixing:** Most operators mix at NLL

## Some results in the bosonic SMEFT at NLL

$$\frac{dC_i}{d \ln \mu} = \frac{\beta_i^{(1)}}{(16\pi^2)} + \frac{\beta_i^{(2)}}{(16\pi^2)^2} + \dots$$

$C_H$  does not mix into any other bosonic SMEFT operator, even at two loops

- Already anticipated using amplitude methods [Bern, Parra-Martinez, Sawyer, 2005.12917](#)
- This is no longer the case in the complete SMEFT, e.g.

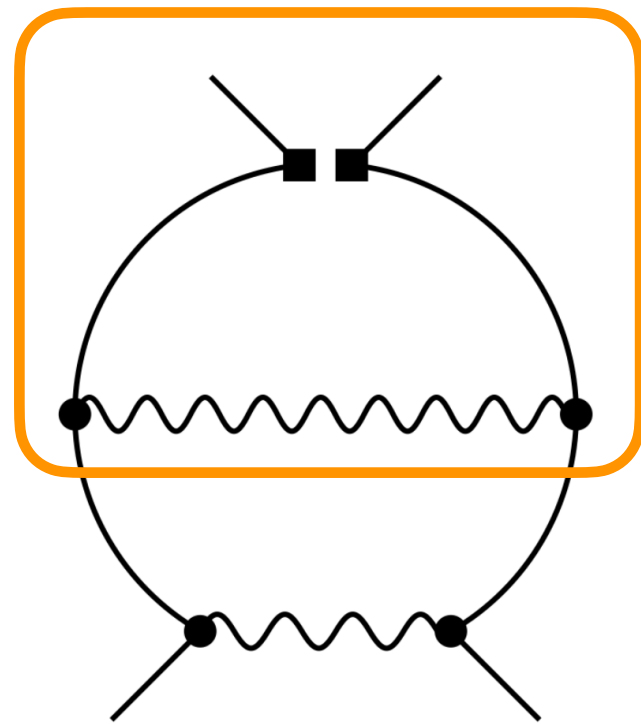


$$\beta_{C_{uH}^{33}}^{(2)} \supset -48 y_t^3 C_H$$

# Two-loop SMEFT RGEs: new challenges with fermions

Born, JFM, Thomsen, *coming soon*

- Impact of **evanescence-free scheme** into  $\beta$  functions
- Treatment of subdivergences:  **$R^*$  operation** in presence of fermions and evanescent operators



**Global renormalization:** Subtract subdivergence adding all one-loop counterterms ( cumbersome )

**Local renormalization:** Subtract subdivergence directly at the graph level (  $R^*$  operation )

- Naive treatment of  $\gamma_5$  is challenging ( ambiguous diagrams / reading points )

# Summary and outlook

- The **EFT program** has entered an **era of automation**, considerably simplifying phenomenology



The *dream* of fully automating (heavy) BSM studies is becoming a reality

- **Huge progress** in the recent years ( better precision and more breadth )
  - UV-to-EFT matching is reaching NLO precision ( key differences with LO results )
  - 2-loop LEFT RGEs are known; 2-loop SMEFT RGEs are coming soon!
  - More and more observables in global fits; including direct efforts from experimental collaborations!
- **Functional methods** play a crucial role in EFT matching and running calculations, especially when combined with computer tools

# Thank you

BSM phenomenology is about to become easy!



<http://matchete.gitlab.io/>

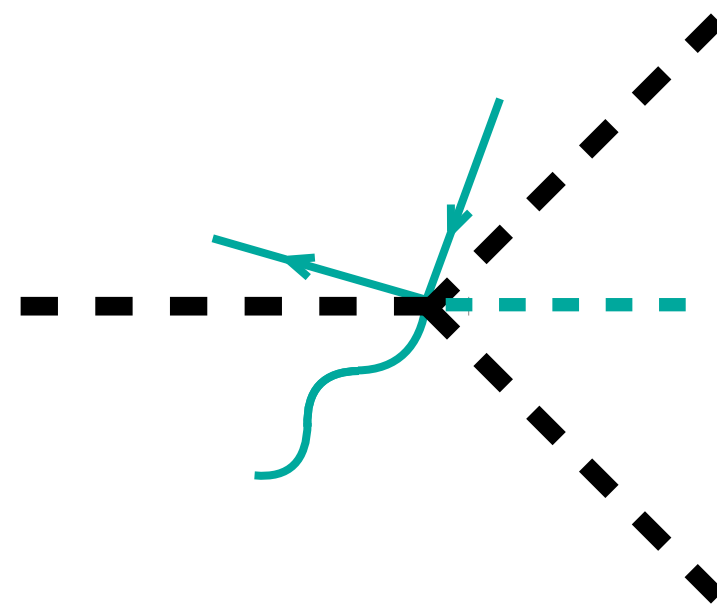
# Going beyond one loop

JFM, Palavrić, Thomsen, [2311.13630](#)

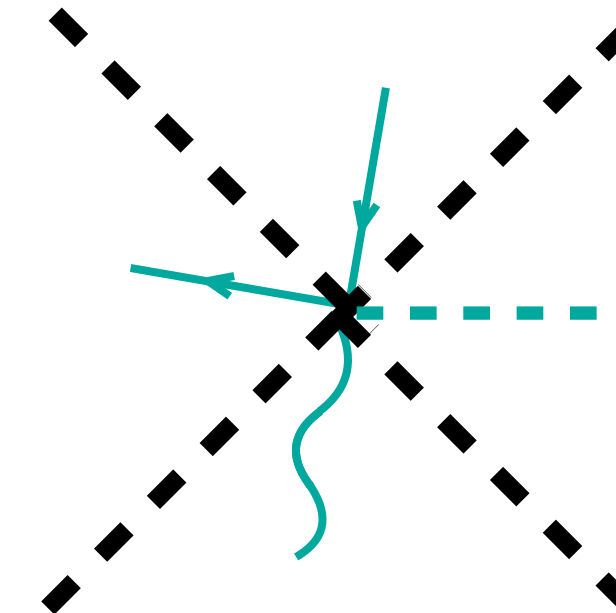
JFM, Moreno, Palavrić, Thomsen, [2412.12270](#)

$$\Gamma_{\text{UV}}[\hat{\eta}] = S_{\text{UV}}[\hat{\eta}] - i \ln \int \mathcal{D}\eta \exp \left[ i \left( \frac{1}{2} \eta_I \mathcal{Q}_{IJ} \eta_J + \frac{1}{3!} \eta_K \eta_J \eta_I \mathcal{V}_{KJI} + \frac{1}{4!} \eta_L \eta_K \eta_J \eta_I \mathcal{V}_{IJKL} + \dots \right) \right]$$

$$\mathcal{V}_{IJK} \equiv \left. \frac{\delta^3 \mathcal{L}_{\text{UV}}}{\delta \eta_I \delta \eta_J \delta \eta_K} \right|_{\eta=\hat{\eta}}$$



$$\mathcal{V}_{IJKL} \equiv \left. \frac{\delta^4 \mathcal{L}_{\text{UV}}}{\delta \eta_I \delta \eta_J \delta \eta_K \delta \eta_L} \right|_{\eta=\hat{\eta}}$$



N.B.:  $\mathcal{V}_{IJK} = \sum_{m,n} V_{ade}^{(m,n)}(x) P_y^m P_z^n U(x,y)_{db} U(x,z)_{ec} \delta(x-y) \delta(x-z)$

# Going beyond one loop

$$\Gamma_{\text{UV}}[\hat{\eta}] = S_{\text{UV}}[\hat{\eta}] - i \ln \int \mathcal{D}\eta \exp \left[ i \left( \frac{1}{2} \eta_I \mathcal{Q}_{IJ} \eta_J + \frac{1}{3!} \eta_I \eta_J \eta_K \mathcal{V}_{IJK} + \frac{1}{4!} \eta_I \eta_J \eta_K \eta_L \mathcal{V}_{IJKL} + \dots \right) \right]$$
$$= S_{\text{UV}}[\hat{\eta}] + \frac{i\hbar}{2} \text{STr} \ln \mathcal{Q} + \frac{i\hbar^2}{2} \mathcal{Q}_{IJ}^{-1} \mathcal{V}_{JI}^{(1)} + \frac{\hbar^2}{12} \mathcal{V}_{IJK} \mathcal{Q}_{IL}^{-1} \mathcal{Q}_{JM}^{-1} \mathcal{Q}_{KN}^{-1} \mathcal{V}_{LMN} - \frac{\hbar^2}{8} \mathcal{Q}_{IJ}^{-1} \mathcal{V}_{IJKL} \mathcal{Q}_{KL}^{-1} + \mathcal{O}(\hbar^3)$$

$$= S_{\text{UV}}[\hat{\eta}] + \frac{i}{2} \log \left( \text{circle} \right) + \frac{i}{2} \left( \text{circle with dot} \right) + \frac{1}{12} \left( \text{triangle} \right) - \frac{1}{8} \left( \text{two circles} \right) + \mathcal{O}(\hbar^3)$$

Tree level

One loop

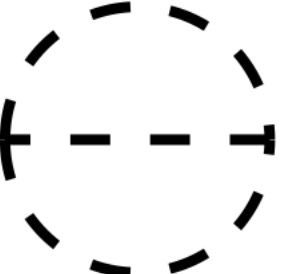
Two loops

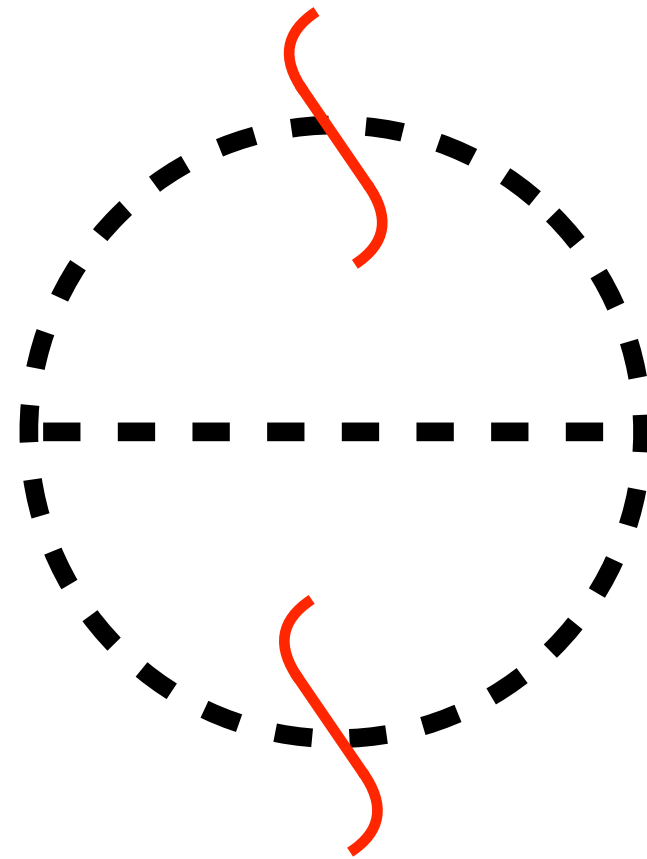
Every two-loop contribution is included here!

# Two-loop functional evaluation

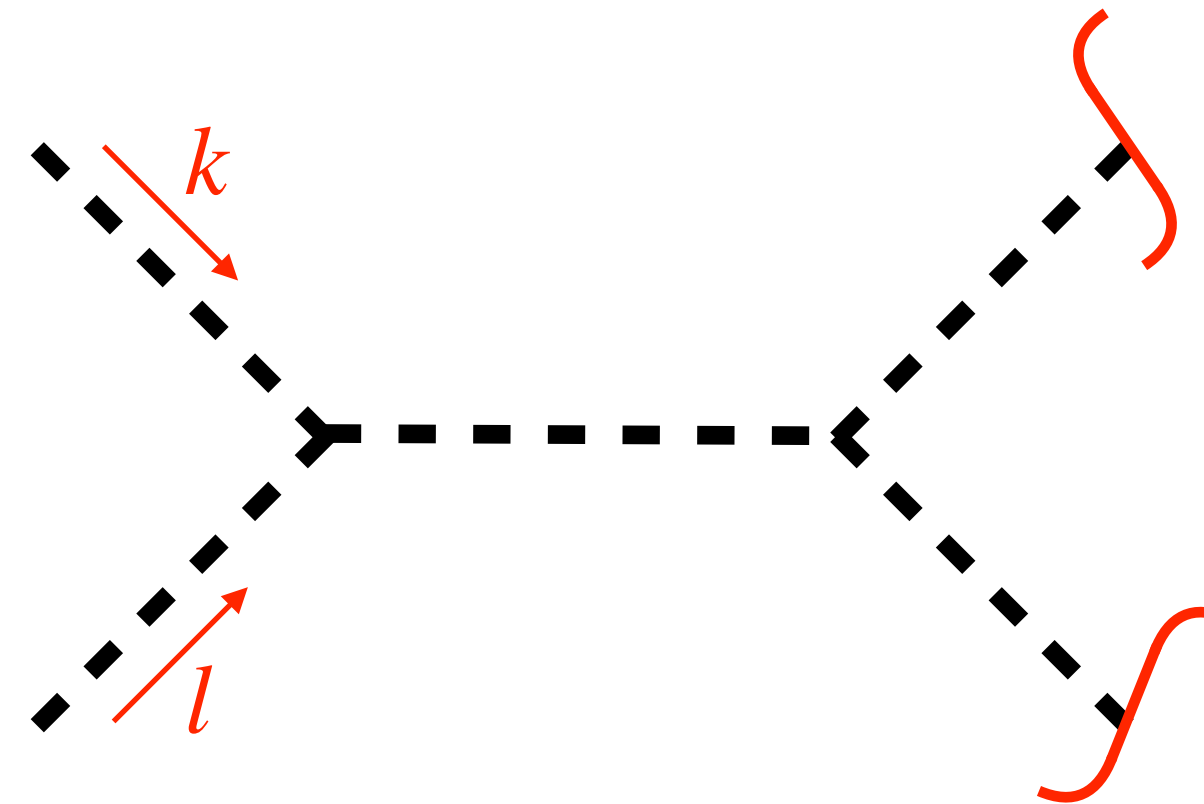
JFM, Palavrić, Thomsen, [2311.13630](#)

JFM, Moreno, Palavrić, Thomsen, [2412.12270](#)

How to evaluate  ?



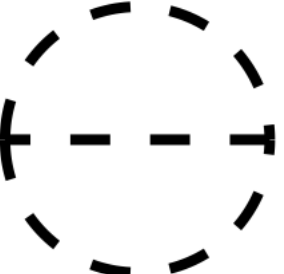
$\int_{k,l}$

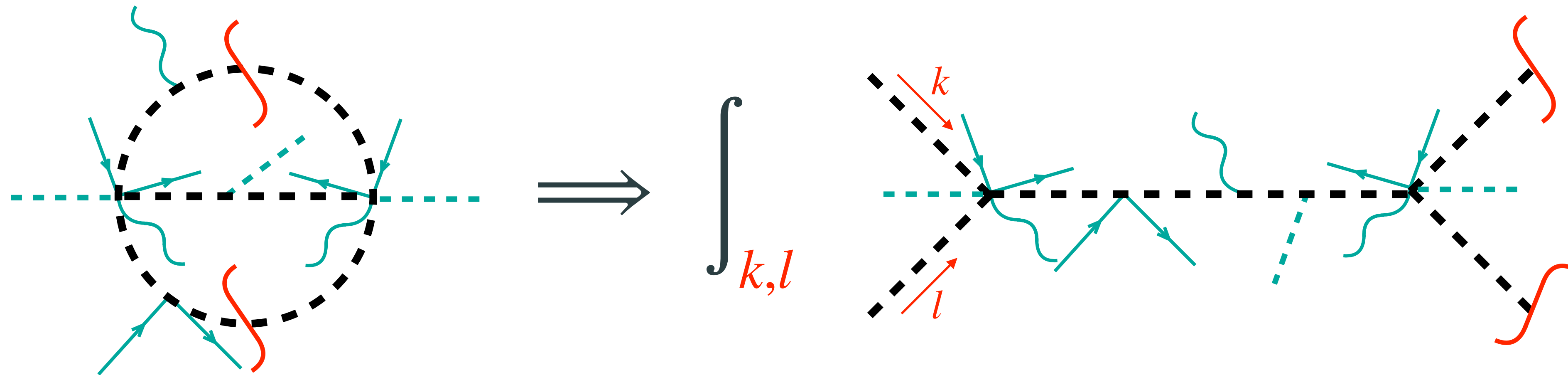


# Two-loop functional evaluation

JFM, Palavrić, Thomsen, [2311.13630](#)

JFM, Moreno, Palavrić, Thomsen, [2412.12270](#)

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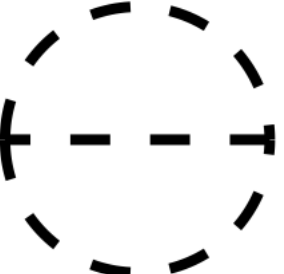


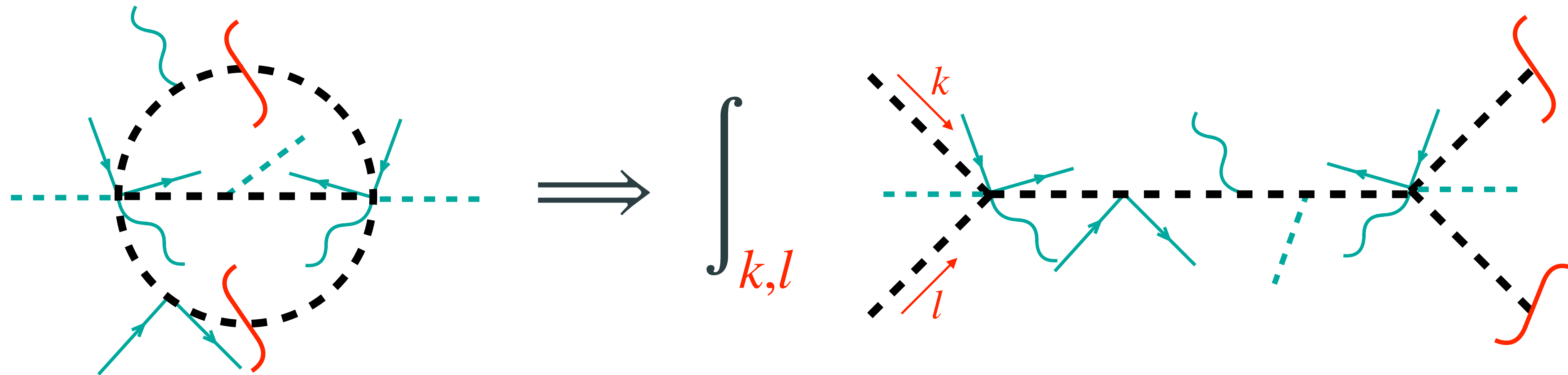
*Every* (non-factorizable) two-loop contribution is included here!

# Two-loop functional evaluation

JFM, Palavrić, Thomsen, [2311.13630](#)

JFM, Moreno, Palavrić, Thomsen, [2412.12270](#)

How to evaluate  ?



$$G_{\ominus} = \int_x \int_{k,l} V_{abc}(x) Q_{aa'}^{-1}(x', iD_{x'} + \mathbf{k} + \mathbf{l}) V_{a'b'c'}(x') [Q_{bd}^{-1}(x, iD_x - \mathbf{k}) U_{db'}(x, x')] [Q_{ce}^{-1}(x, iD_x - \mathbf{l}) U_{ec'}(x, x')]$$

Valid to *all orders* in the EFT expansion!

# $\gamma_5$ schemes in dimensional regularization

- Naive Dimensional Regularization (NDR) scheme:

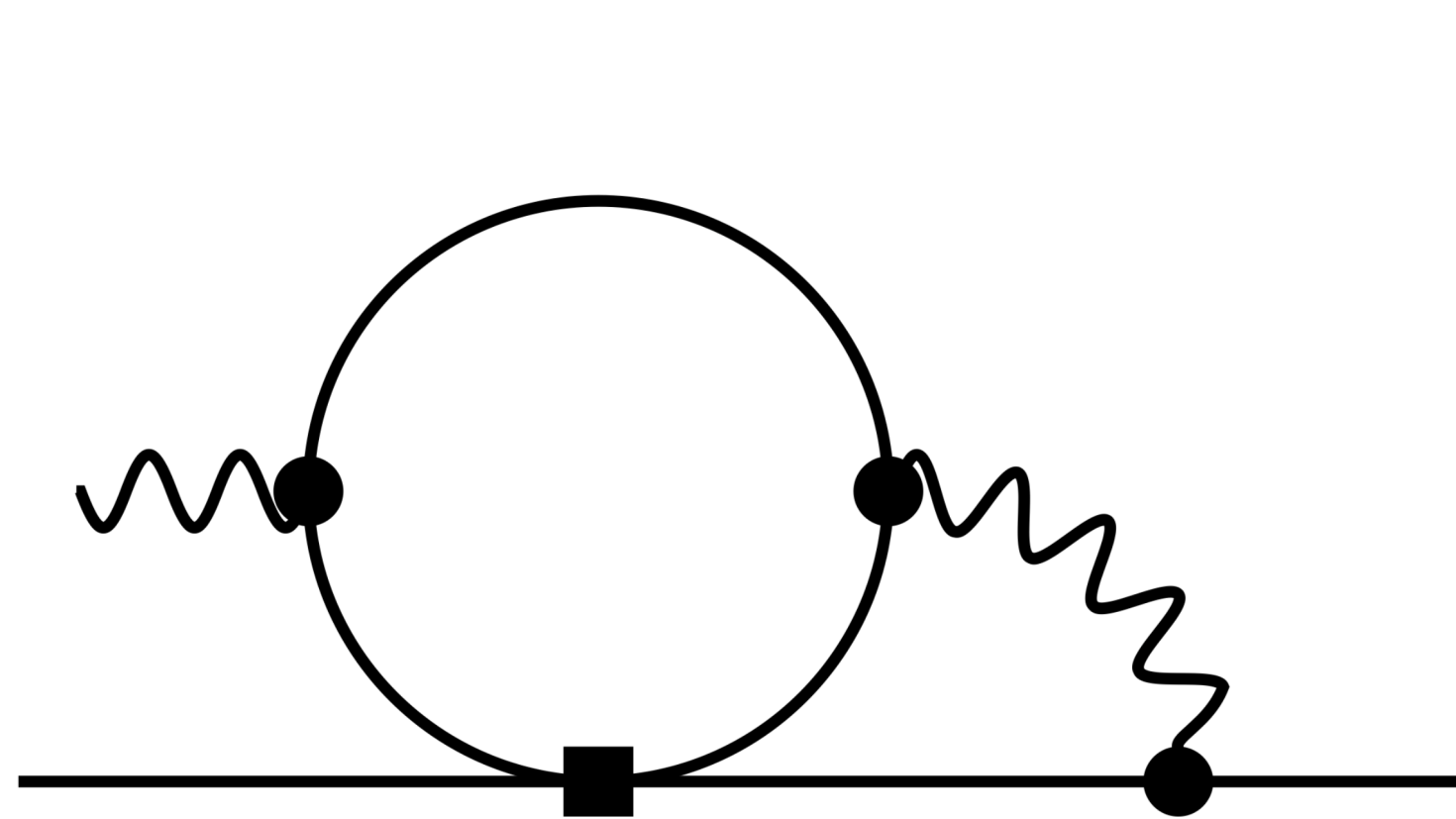
$$\left. \begin{aligned} \{\gamma_\mu, \gamma_\nu\} &= 2g_{\mu\nu}, & \{\gamma_\mu, \gamma_5\} &= 0, & \gamma_5^2 &= I \\ \text{tr}[\gamma_\mu \gamma_\nu \gamma_\rho \gamma_\sigma \gamma_5] &\xrightarrow{d \rightarrow 4} -4i\epsilon_{\mu\nu\rho\sigma} \end{aligned} \right\} \Rightarrow \begin{aligned} \text{tr}[\gamma^\alpha \gamma^\rho \gamma^\sigma \gamma_\alpha \gamma^\mu \gamma^\nu \gamma_5] &= 4i(4-d)\epsilon^{\mu\nu\rho\sigma} \\ \text{tr}[\gamma^\rho \gamma^\sigma \gamma_\alpha \gamma^\mu \gamma^\nu \gamma_5 \gamma^\alpha] &= -4i(4-d)\epsilon^{\mu\nu\rho\sigma} \end{aligned}$$

- Breitenlohner-Maison-'t Hooft-Veltman (BMHV) scheme:

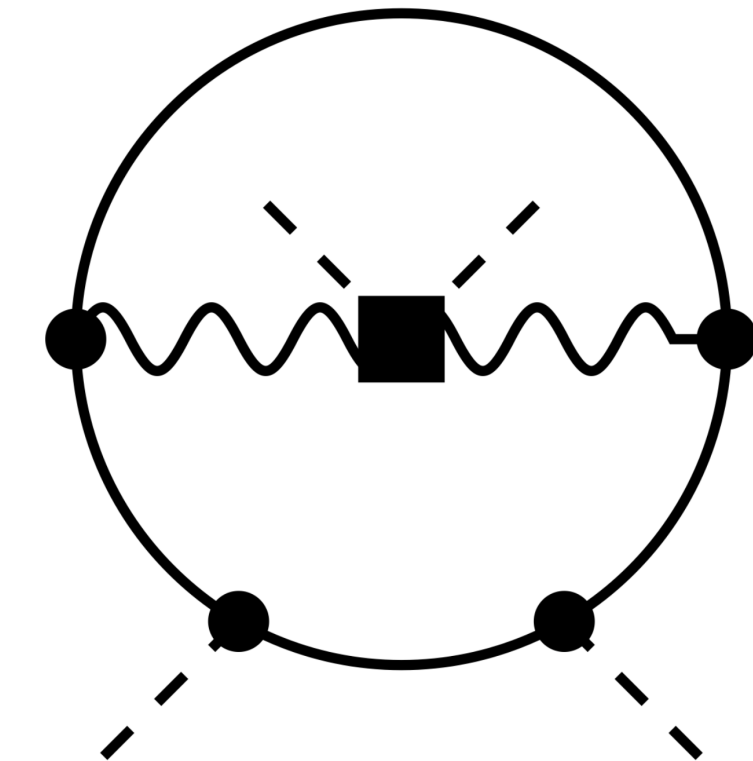
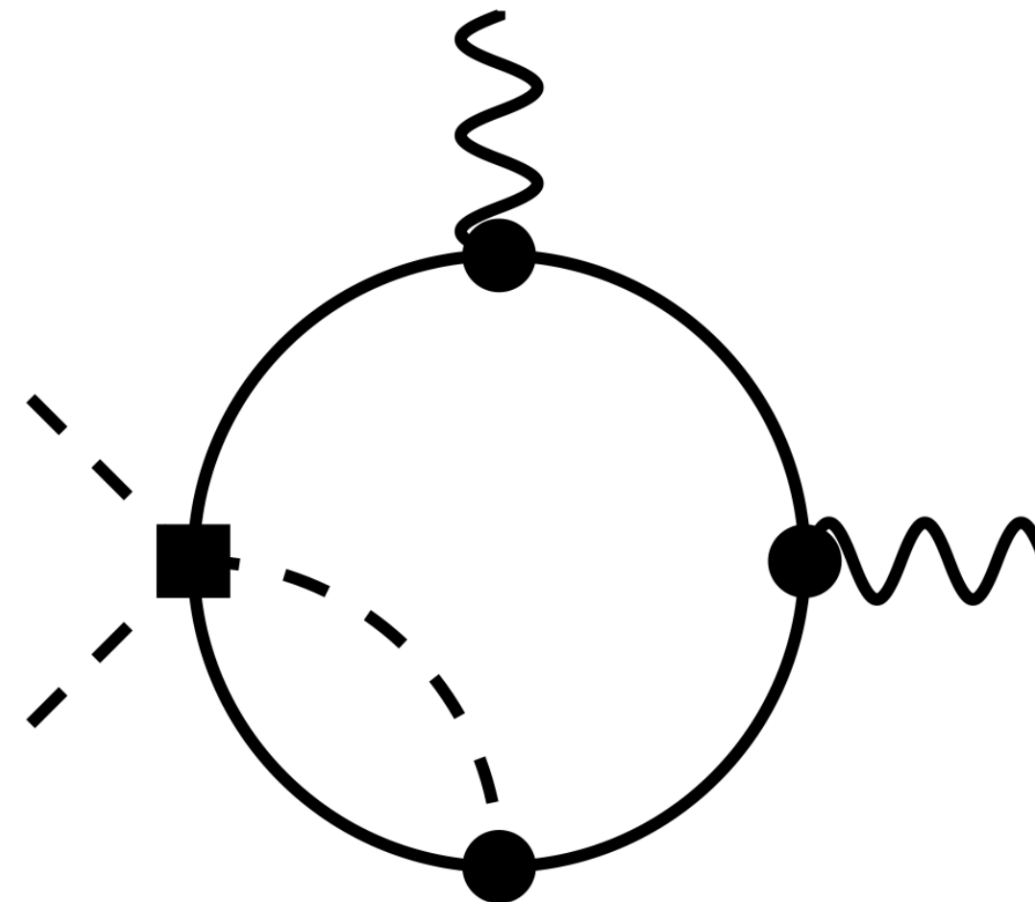
$$\left. \begin{aligned} \overset{4 \text{ dim}}{\gamma_\mu} &= \overset{4 \text{ dim}}{\gamma_{\bar{\mu}}} + \overset{d-4 \text{ dim}}{\gamma_{\hat{\mu}}} & \gamma_{\bar{\mu}} \gamma^{\hat{\mu}} &= 0 \\ \gamma_5 &= -\frac{i}{4!} \epsilon_{\bar{\mu}\bar{\nu}\bar{\rho}\bar{\sigma}} \gamma^{\bar{\mu}} \gamma^{\bar{\nu}} \gamma^{\bar{\rho}} \gamma^{\bar{\sigma}} & \gamma_5^2 &= I \end{aligned} \right\} \Rightarrow \begin{aligned} \{\gamma_5, \gamma^{\bar{\mu}}\} &= 0 \\ [\gamma_5, \gamma^{\hat{\mu}}] &= 0 \end{aligned}$$

# Two-loop SMEFT RGEs: reading-point ambiguities in NDR

Start at dimension-six operator



“Unclear” prescription



Unambiguous in the “open basis” ( Fierz + evanescent )