High Energy Theory

Junta de Andalucía

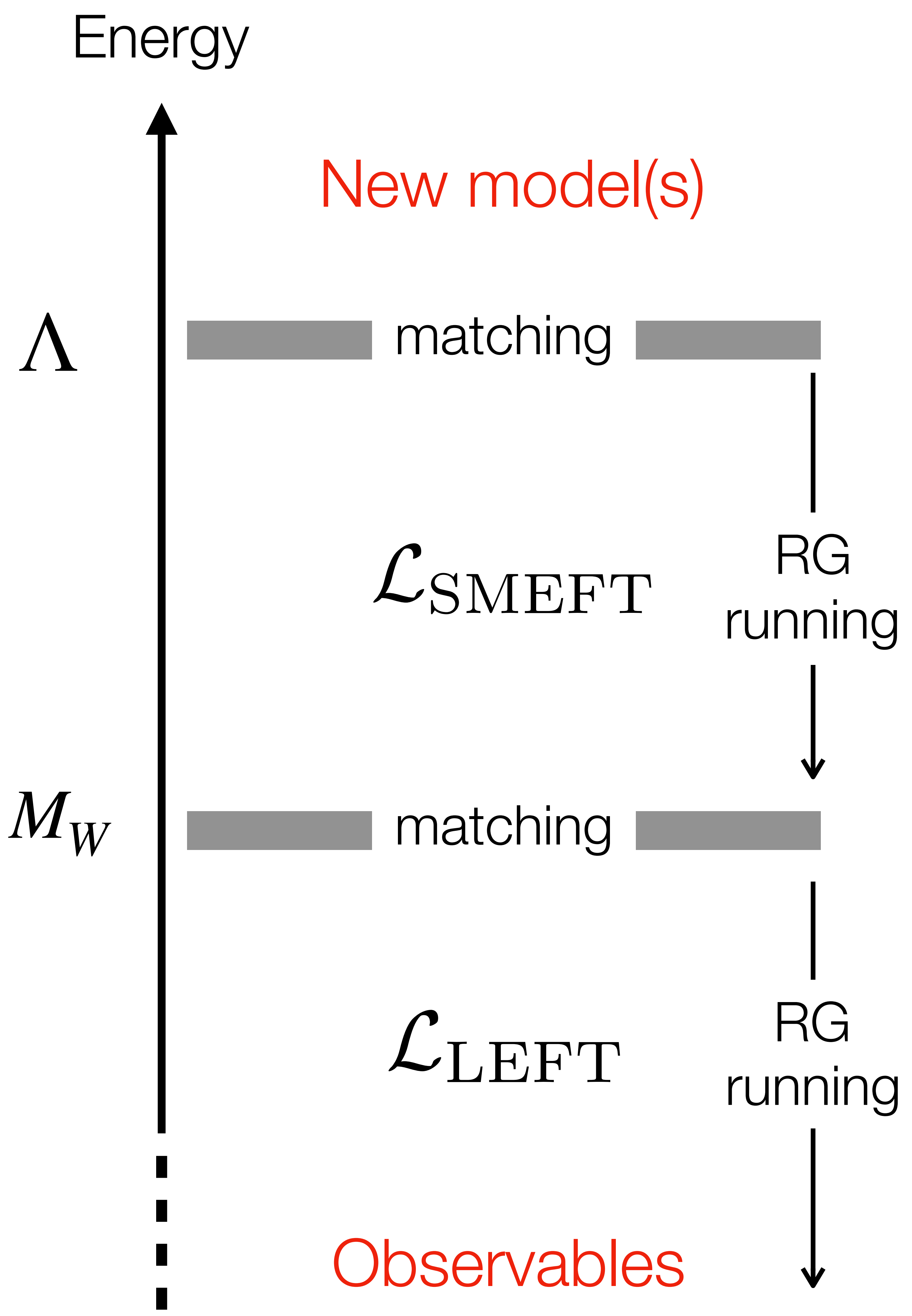
Universidad de Granada

Automated EFT Matching and Running: Recent Developments and Applications

Javier Fuentes-Martín
University of Granada

SMEFT meets χEFT, TRIUMF | 29 September-3 October 2025

The EFT approach

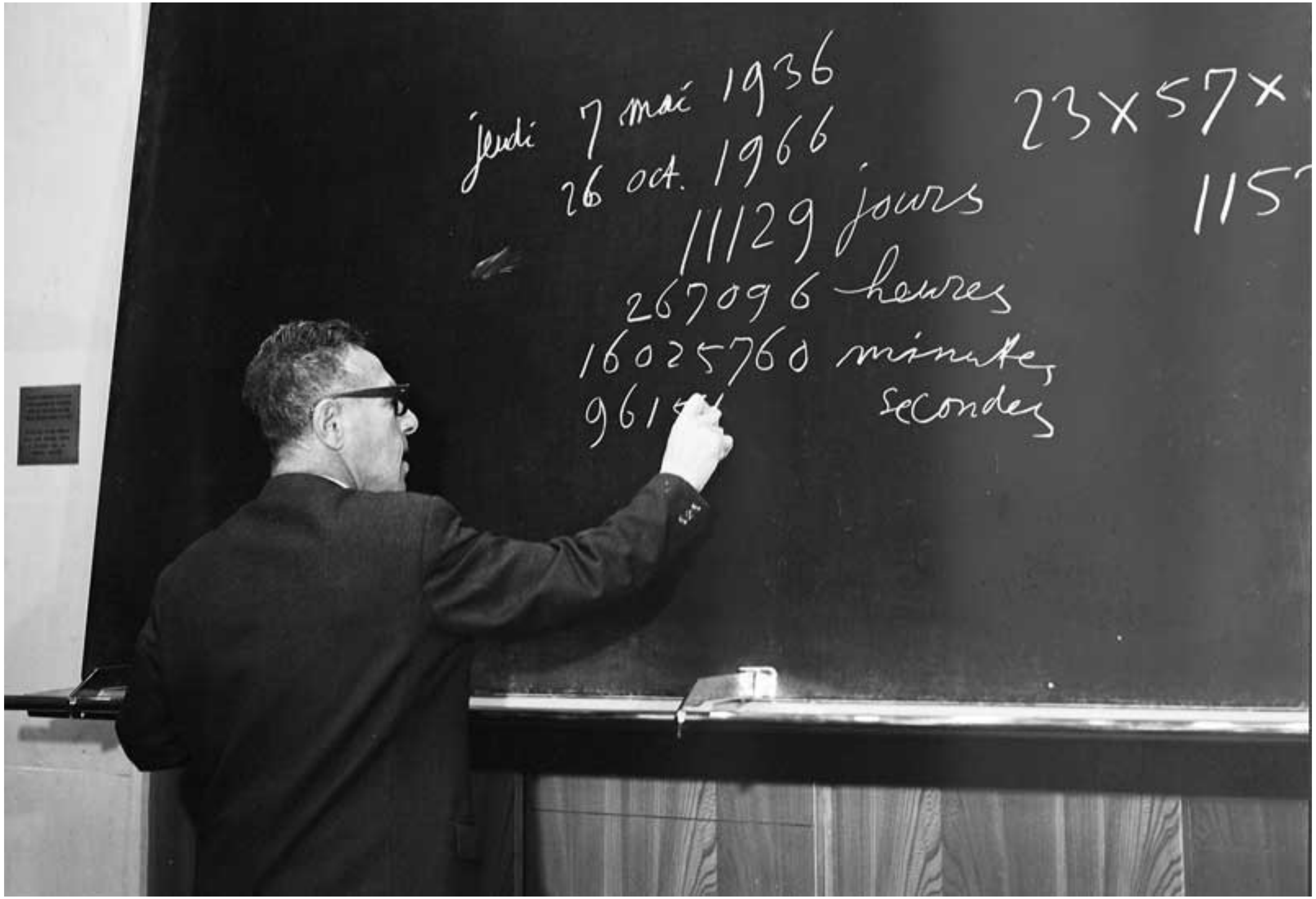


Main motivation

The vast landscape of BSM models and the repetitive nature of EFT computations call for automated solutions

The EFT approach: The rise of automation

Wim Klein, CERN “human computer”



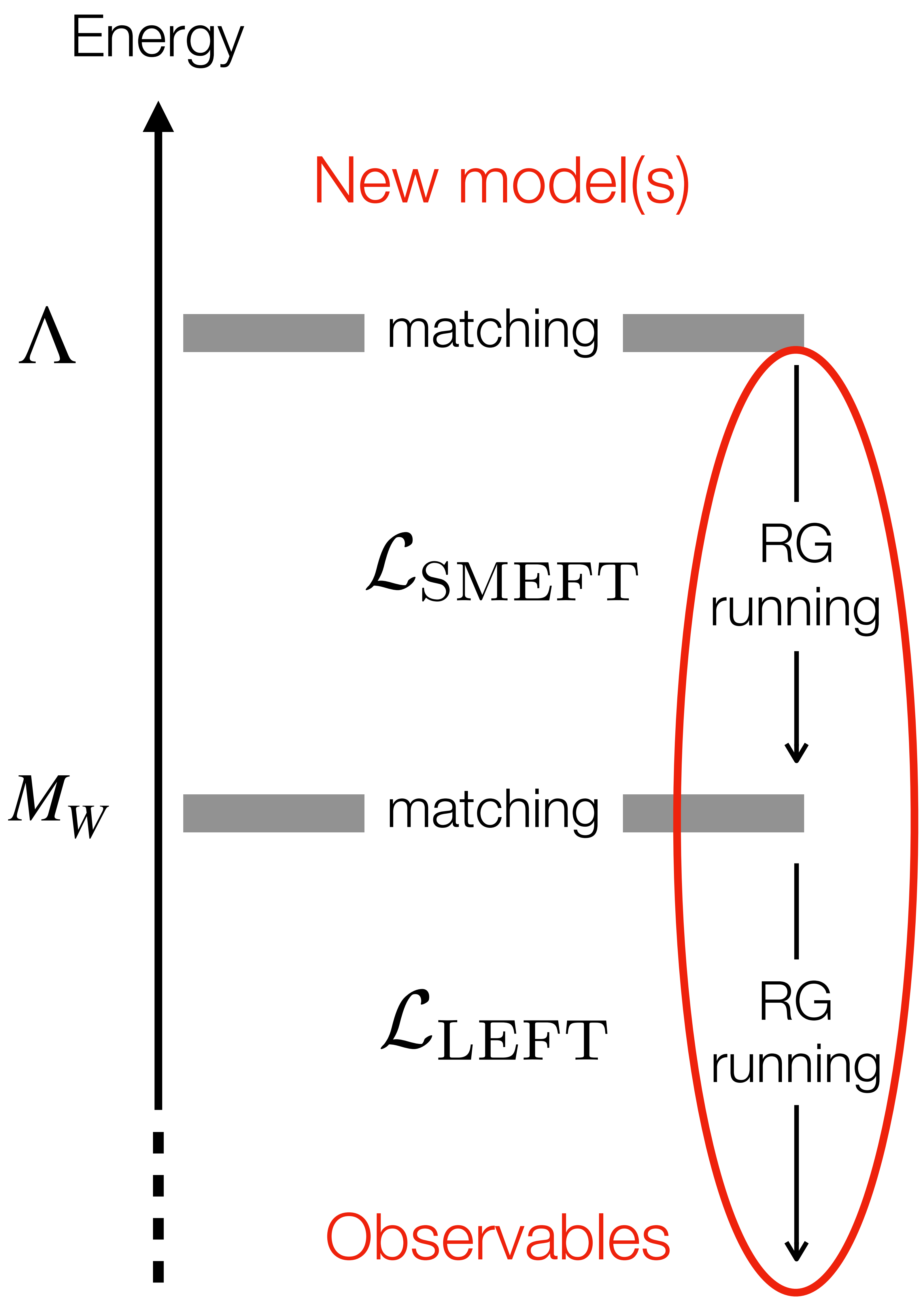
The EFT approach: The rise of automation

CERN first electronic computer

The (SM)EFT software project:

Upgrading from “human computers” to computers

The EFT approach: The rise of automation



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

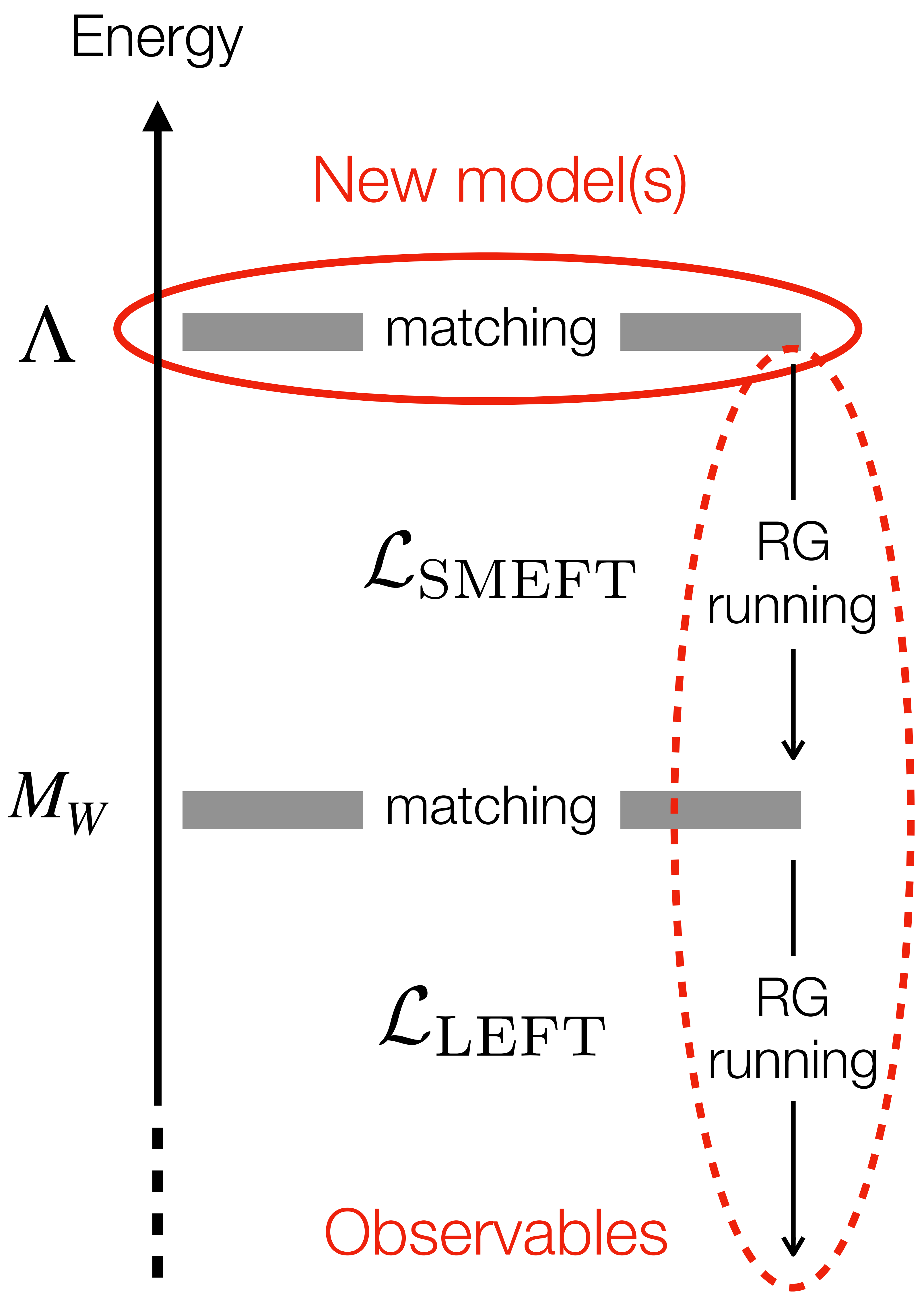
Very recent developments in the LEFT:

LEFT 2-loop RGEs:

Aebischer, Morell, Pesut, Virto, 2501.08384

Naterop, Stoffer, 2412.13251, 2507.08926

The EFT approach: The rise of automation



matchmakereft

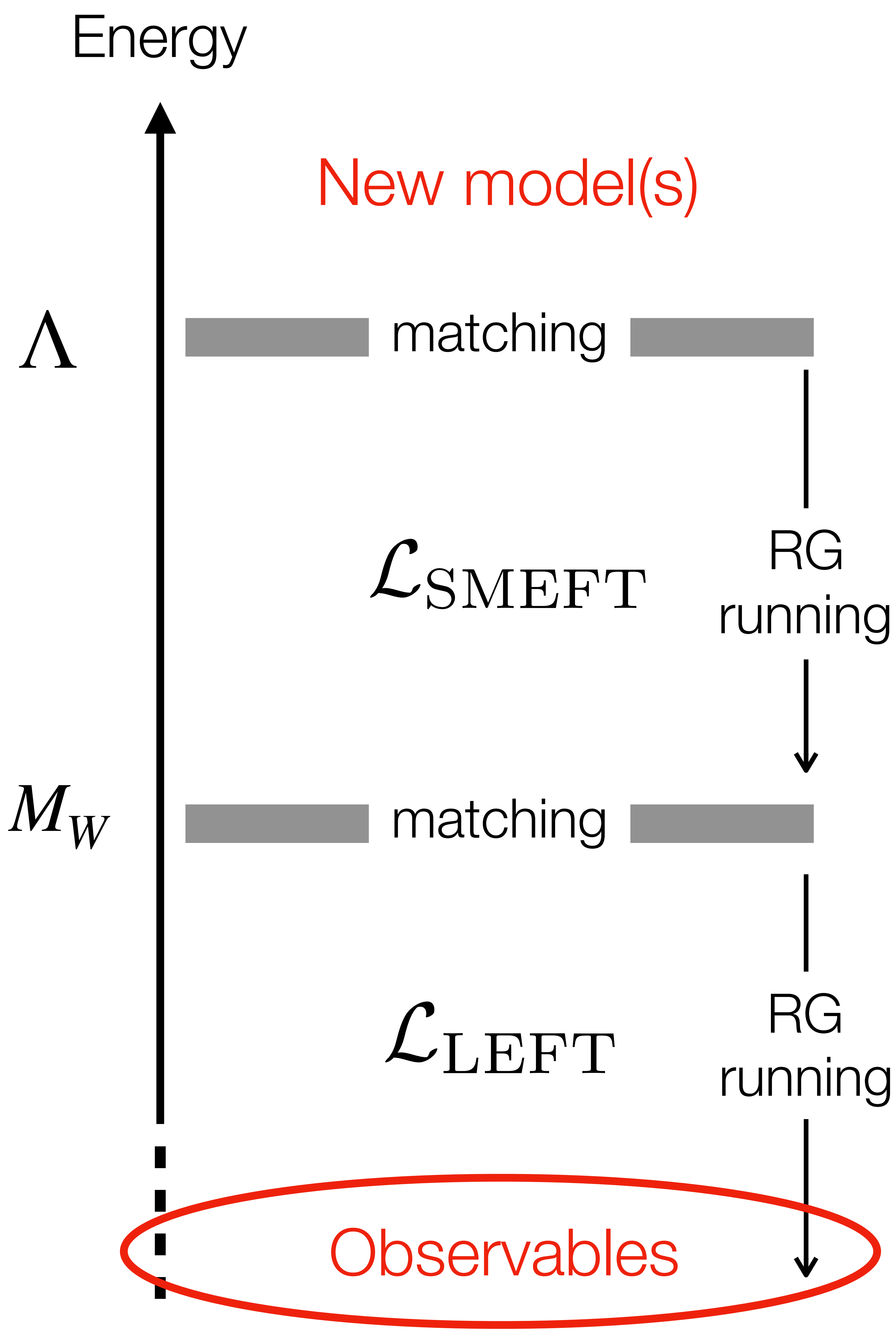
Carmona et al. '22

MATCHETE

JFM et al. '23

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

The EFT approach: The rise of automation



SMEFT likelihood (smelli)

Aebischer et al. '18

flavio

Straub '16

HighPT

Allwicher et al. '22

HEPfit

De Blas et al. '19

Fitmaker

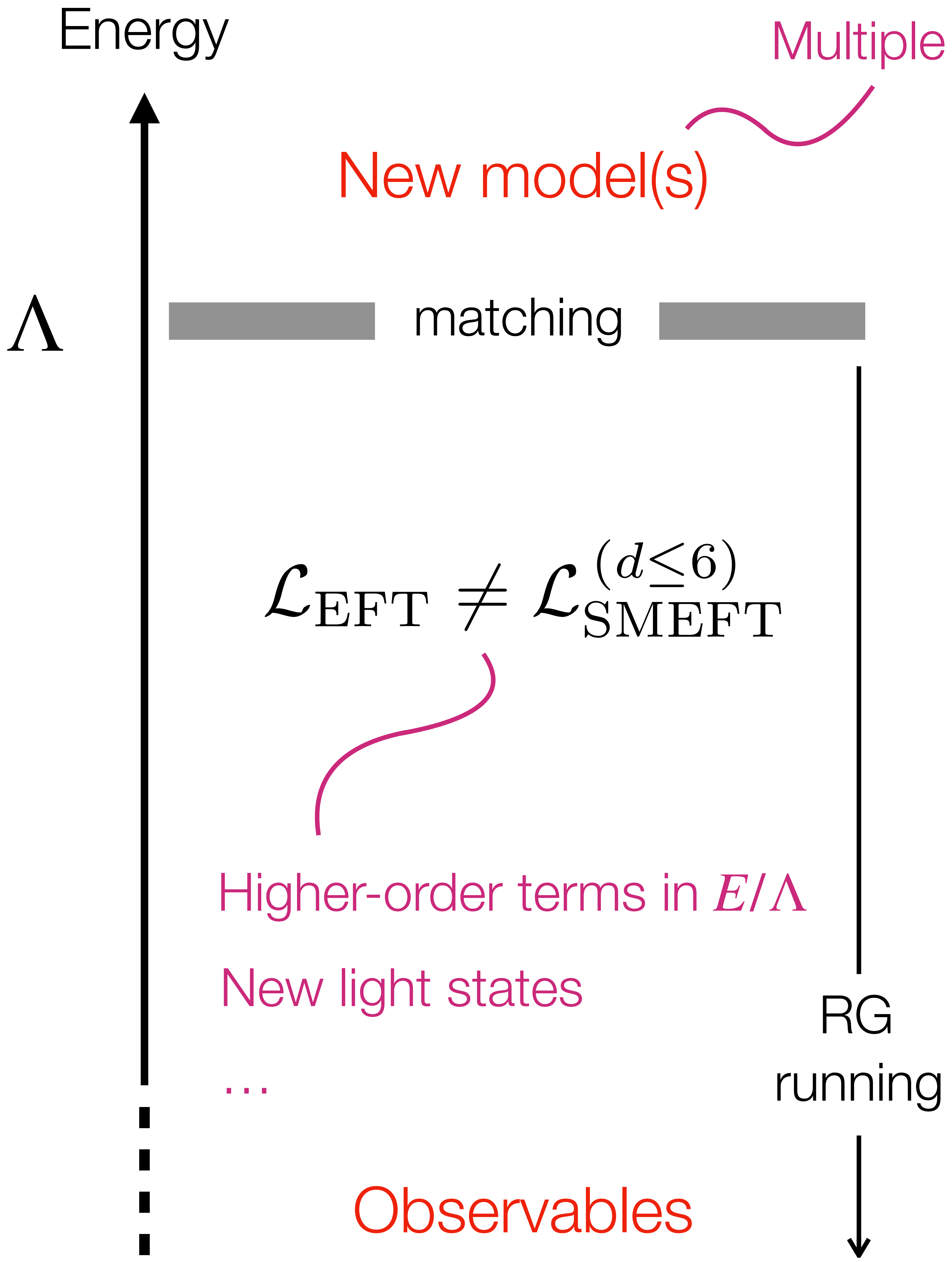
Ellis et al '20

SMEFiT

Giani et al. '23

+ others

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

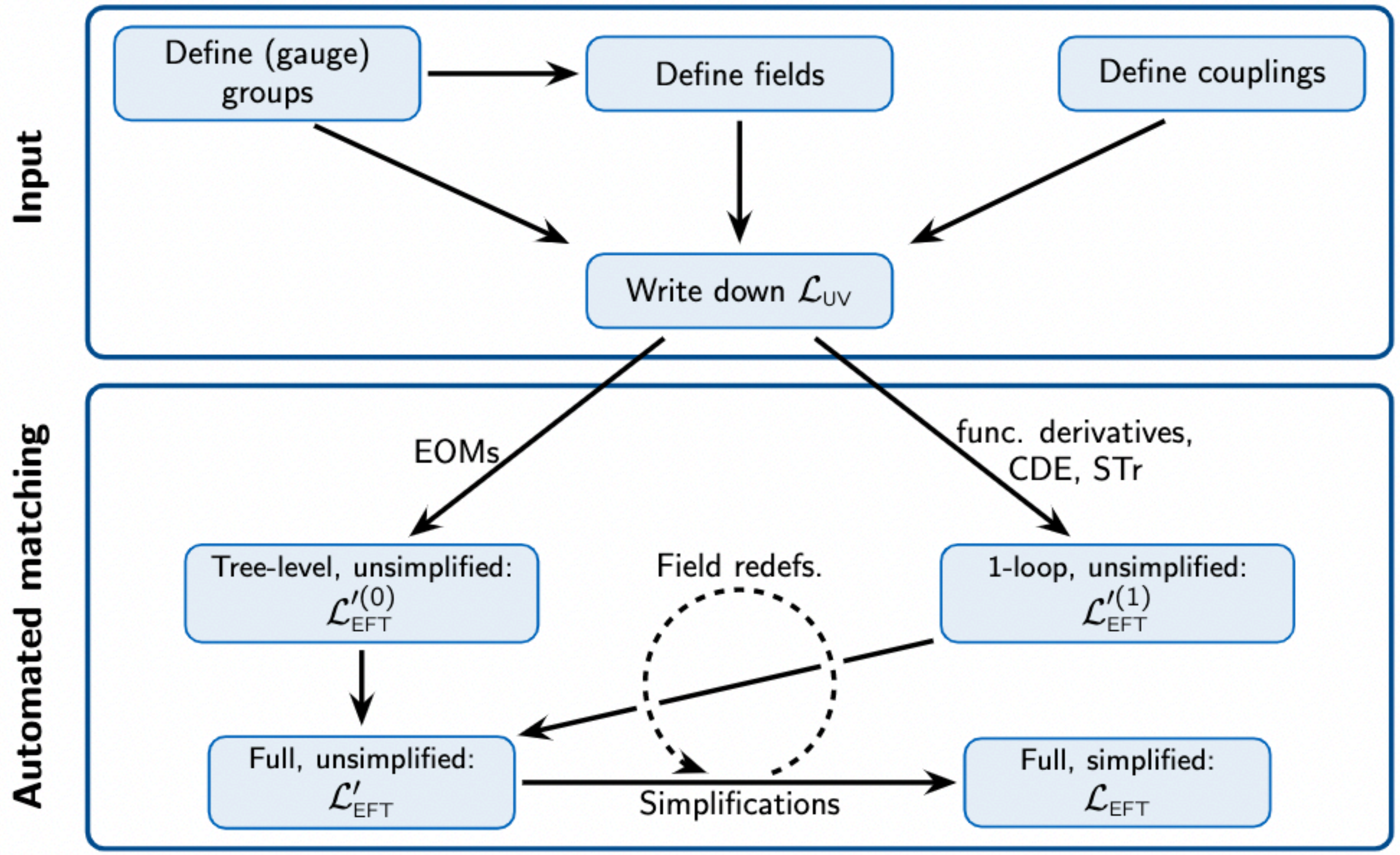
Multiple efforts to extend this program beyond dimension 6

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

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

See Anders talk



[JFM, König, Pagès, Thomsen, Wilsch, 2212.04510]

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

Linear simplifications

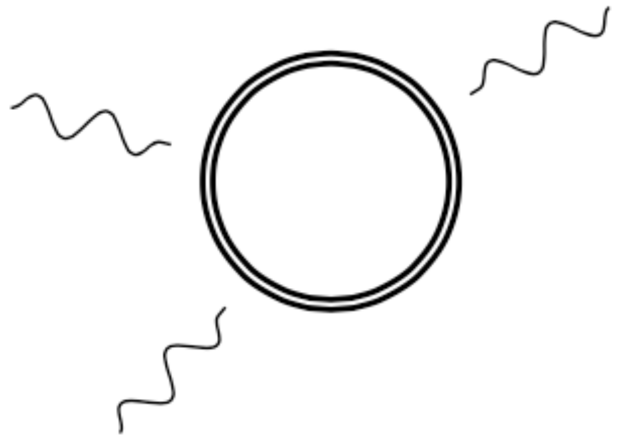
Example: Integrating out a heavy fermion in the fundamental representation of SU(3)

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

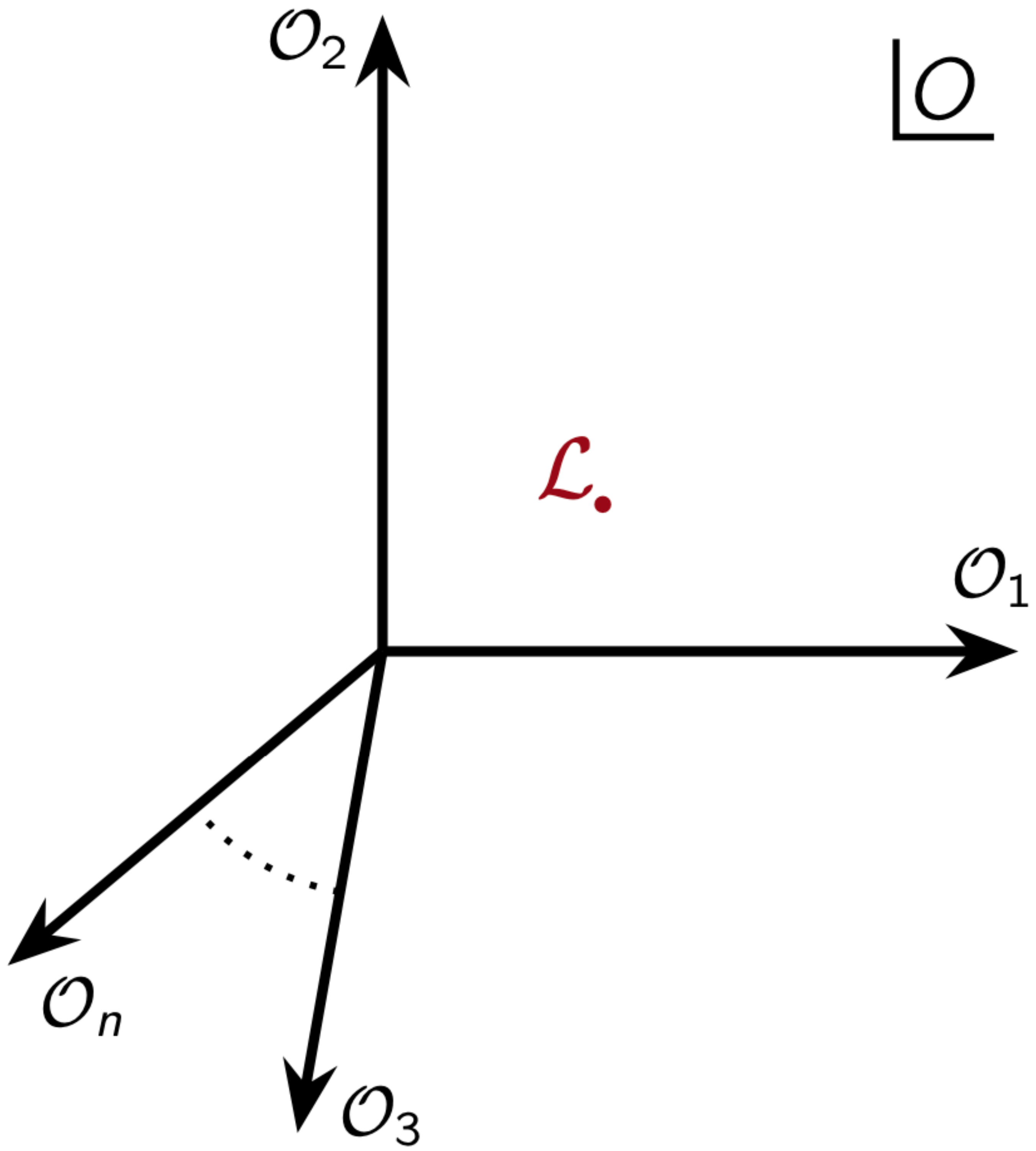
Out[12]//NiceForm=

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

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



(log supertrace)



Linear simplifications

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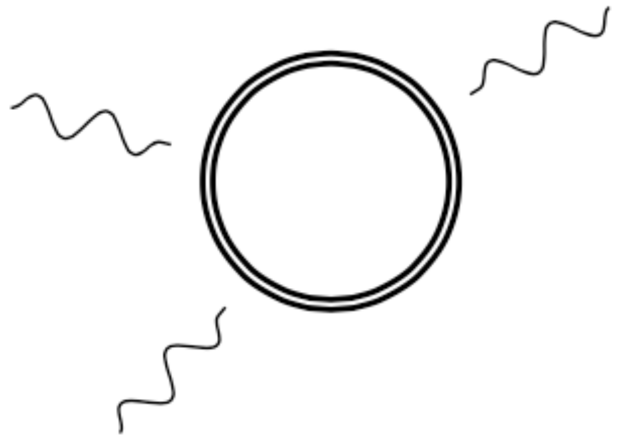

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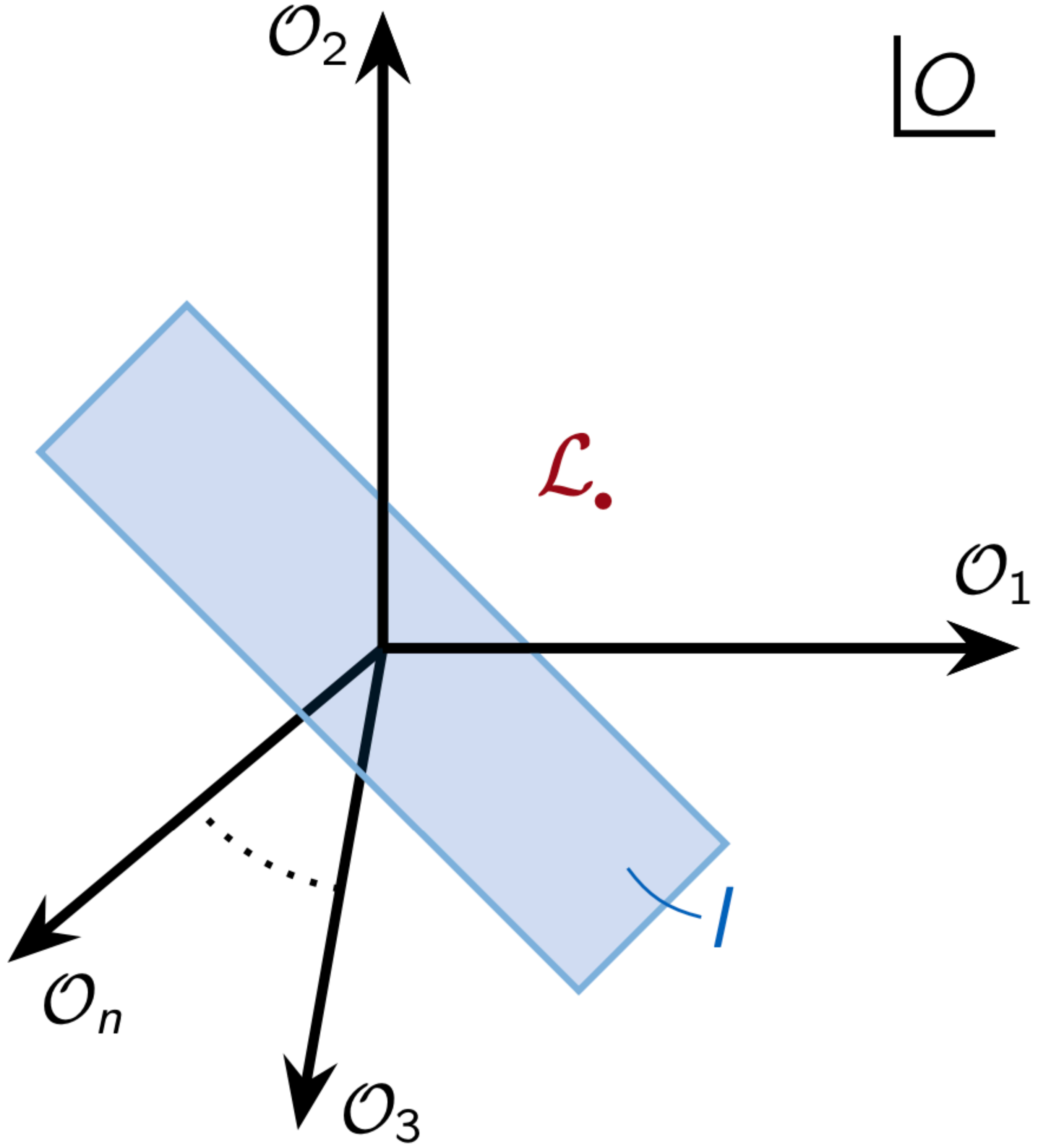

$I \subseteq O$ is the space of all operators identities, such as IBP relations, yielding e.g.

$$\mathscr{O}_1 + 2\,\mathscr{O}_3 = 0$$

interpreted as

$$\mathscr{O}_1 + 2\,\mathscr{O}_3 \in I$$

Linear simplifications

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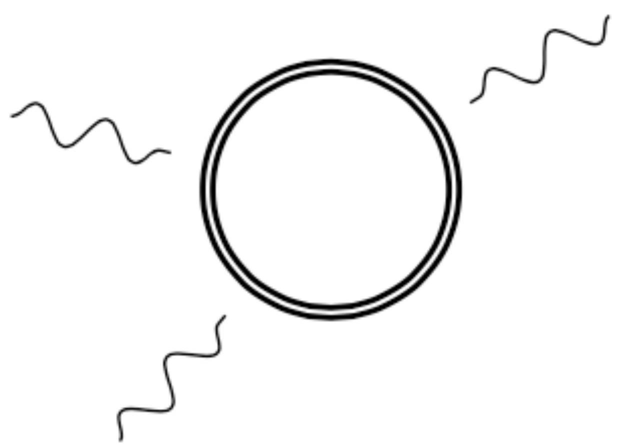

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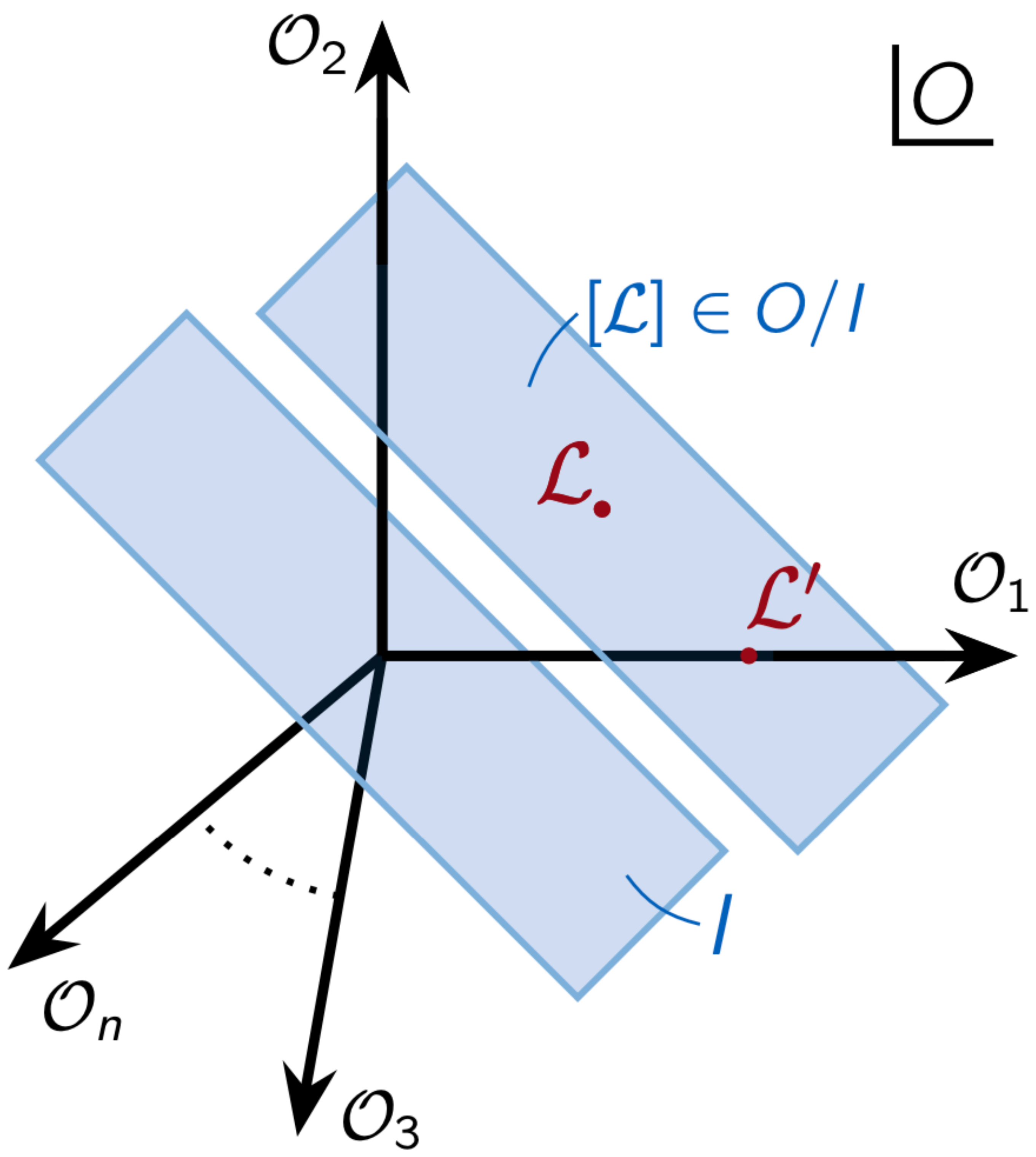

$$\mathscr{L}_{\text{EFT}} = \sum_i C_i \mathcal{O}_i \in O$$

By gaussian elimination, we can *choose* a representative element for $[\mathscr{L}_{\text{EFT}}] \in O/I$ to get an EFT basis

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

Out[13]//NiceForm=

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

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

interpreted as

$$\mathcal{O}_1 + 2\,\mathcal{O}_3 \in I$$

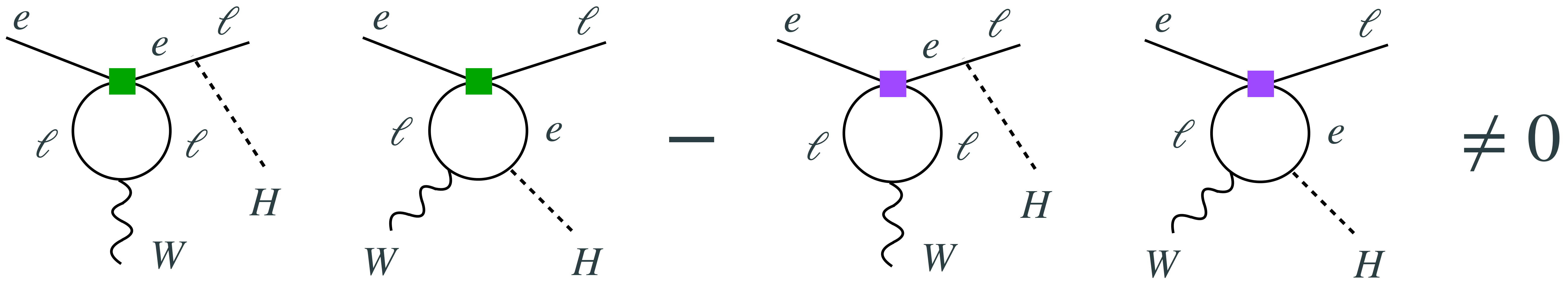
Evanescent operators

In $d = 4$, we can use the Fierz identity $R_{\ell e} = -\frac{1}{2} Q_{\ell e}$

$$\mathscr{L}_{\text{EFT}} \supset C_{\ell e}^{prst} R_{\ell e}^{prst} \qquad\qquad R_{\ell e}^{prst} = (\bar{\ell}_p e_r)(\bar{e}_s \ell_t)$$

$$\mathscr{L}'_{\text{EFT}} \supset -\frac{1}{2} C_{\ell e}^{prst} Q_{\ell e}^{prst} \qquad\qquad Q_{\ell e}^{prst} = (\bar{\ell}_p \gamma_\mu \ell_t)(\bar{e}_s \gamma^\mu e_r)$$

so that $\mathscr{L}_{\text{EFT}} = \mathscr{L}'_{\text{EFT}}$ at <u>tree level</u>. However,



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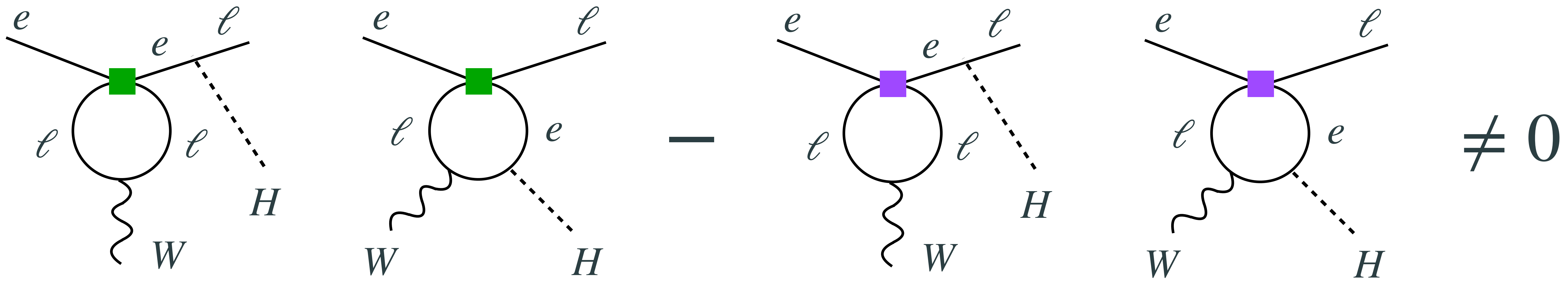


In $d = 4 - 2\epsilon$, there is an evanescent operator that also contributes to the amplitude

$$R_{\ell e}^{prst} = -\frac{1}{2} Q_{\ell e}^{prst} + E_{\ell e}^{prst} \qquad E_{\ell e}^{prst} \xrightarrow{\epsilon \to 0} 0 \qquad E_{\ell e}^{prst} \to -\frac{g_L\, y_e^{ts}}{128\pi^2} Q_{eW}^{pr} + \text{[many other contributions]}$$

Linear simplifications with evanescent operators

Evanescent operators appear from a special type of linear simplification (valid only for $d = 4$)

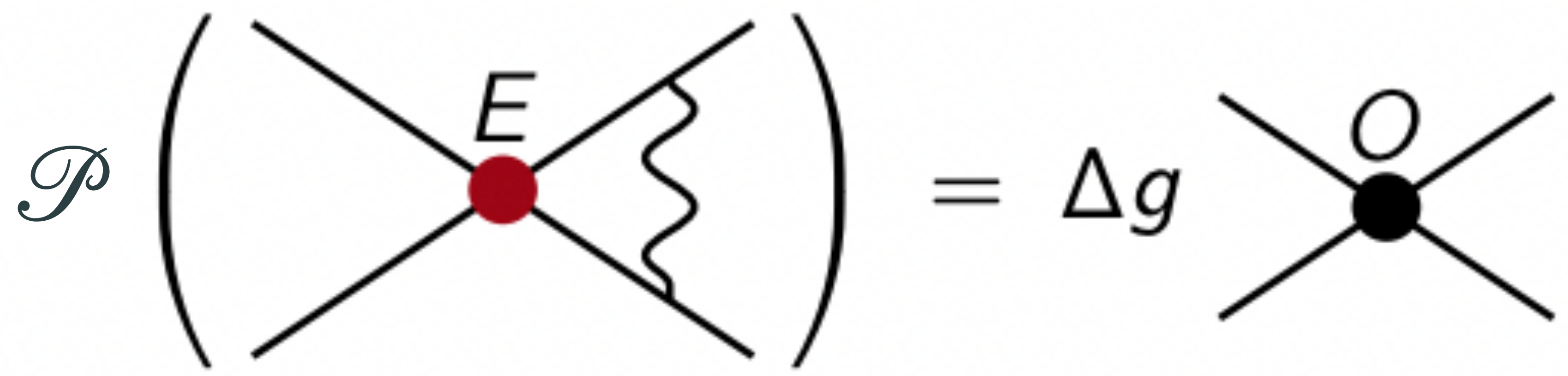
$$O_d = \underbrace{\mathscr{P}\,O_d}_{\text{Physical part}} + \underbrace{\overset{Id-\mathscr{P}}{\mathscr{E}}\,O_d}_{\text{Evanescent part}}$$

$\mathscr{P} \equiv$ Projection to the physical ($d = 4$) basis

E.g. Fierz identities

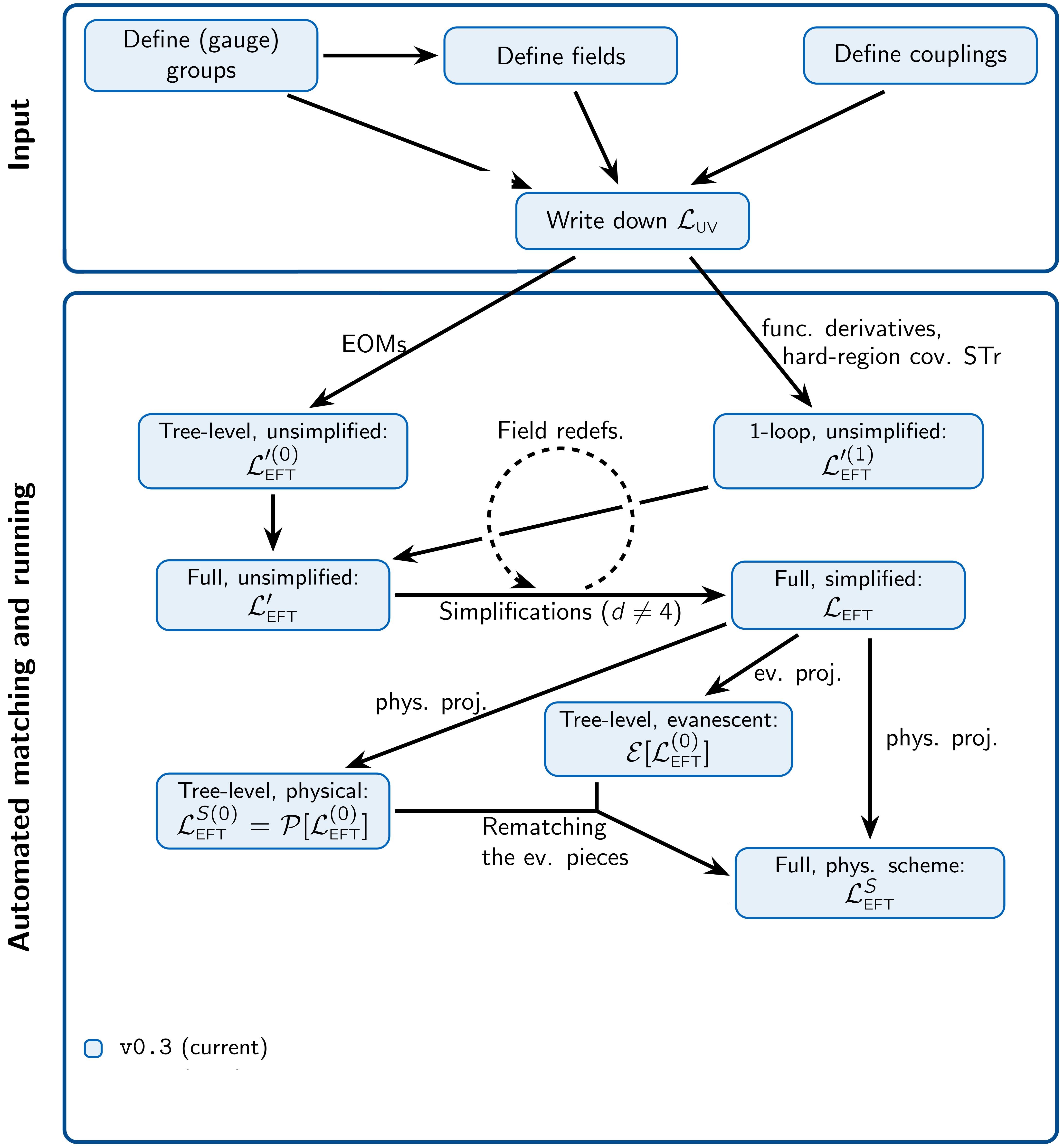
$$(\bar{\ell}_p e_r)(\bar{e}_s \ell_t) = -\frac{1}{2}(\bar{\ell}_p \gamma_\mu \ell_t)(\bar{e}_s \gamma^\mu e_r) + \overset{\text{rank}\,(d-4)}{E^{prst}_{\ell e}} \longrightarrow (\bar{\ell}_p e_r)(\bar{e}_s \ell_t) + \frac{1}{2}(\bar{\ell}_p \gamma_\mu \ell_t)(\bar{e}_s \gamma^\mu e_r) - E^{prst}_{\ell e} \in I$$

Representative elements are chosen so evanescent operators are retained. Afterwards, these are removed by shifting the coefficients of physical operators (*evanescence-free scheme*)



e.g. $E^{prst}_{\ell e} \to -\dfrac{g_L\, y_e^{ts}}{128\pi^2}\, Q^{pr}_{eW} +$ [other contributions]

New Matchete workflow



v0.2 ⟶ v0.3 changes

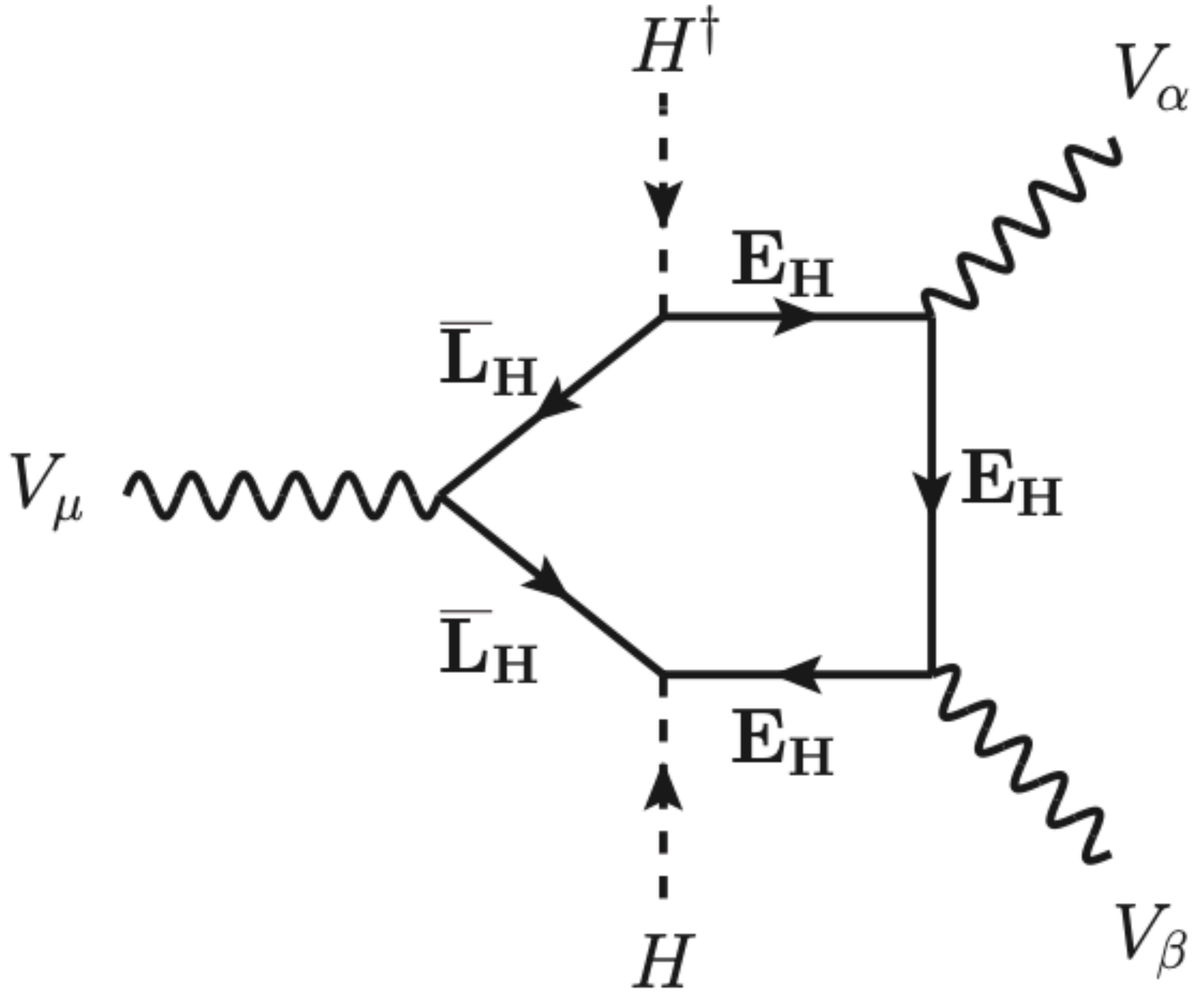
- Handling of evanescent contributions
- More stable & faster
- Partial documentation

Let’s see how it works!

An example of Matchete in action

Example: neutral triple-gauge interactions

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



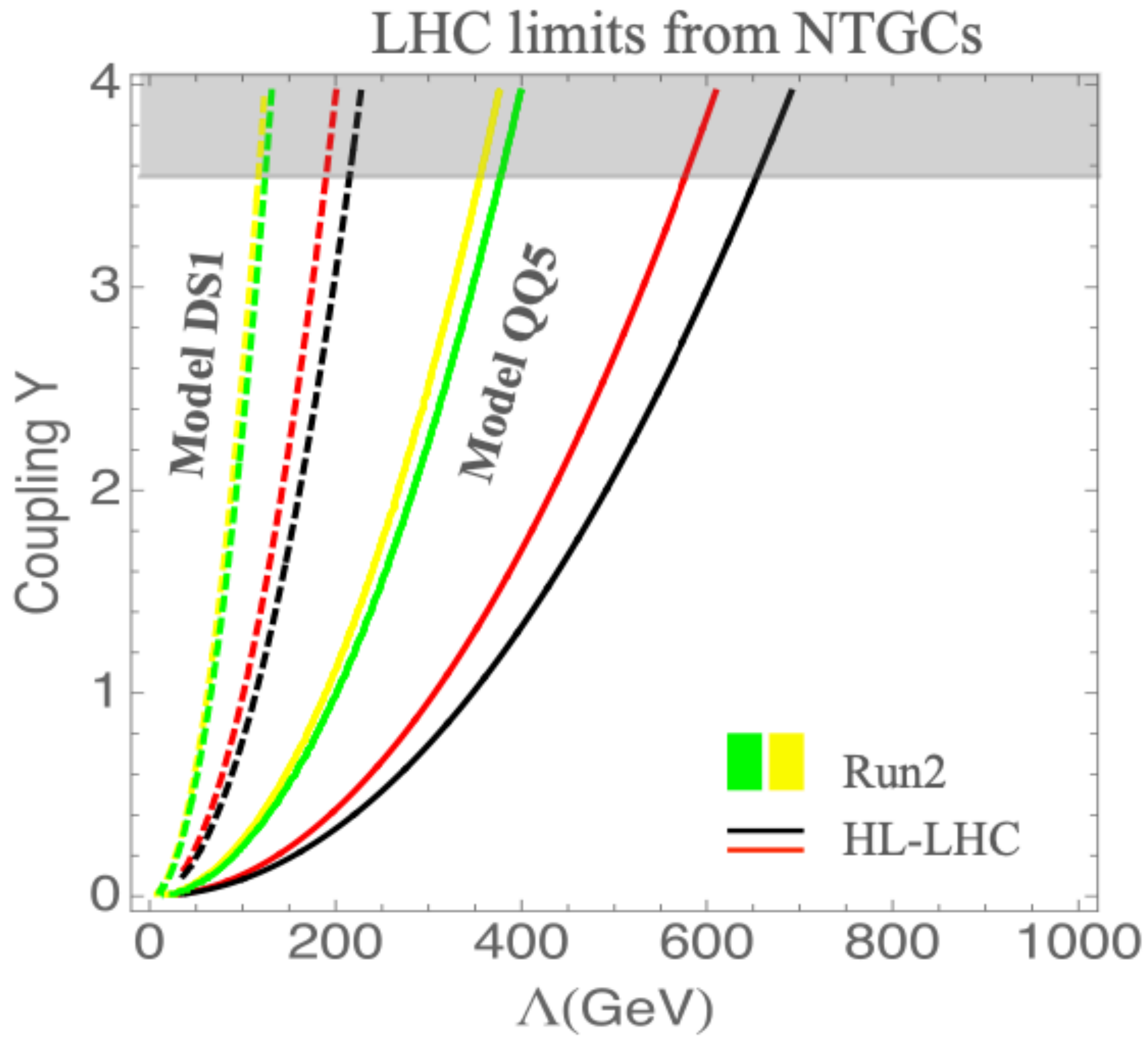
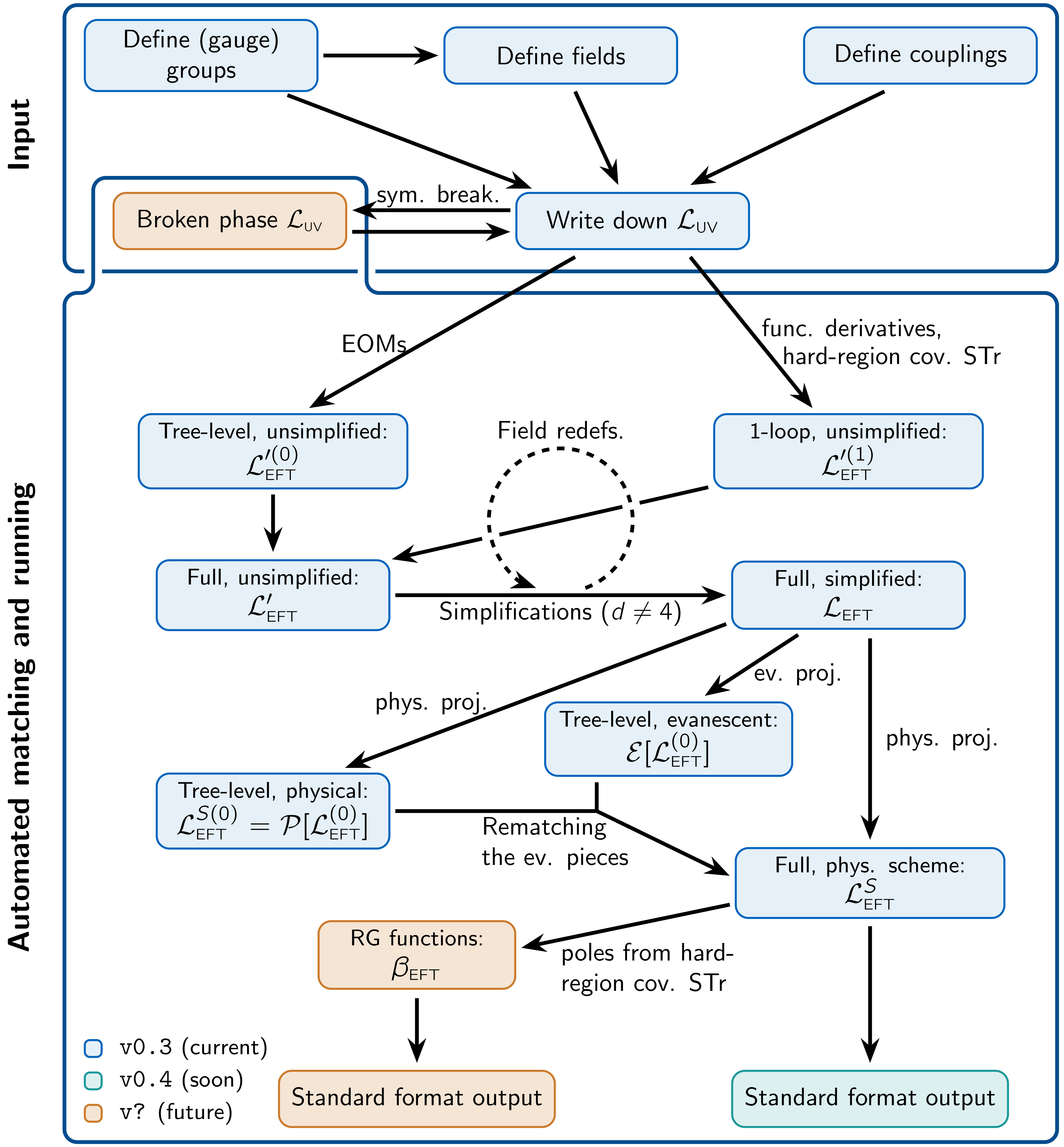


*Diagram and plot from [2402.04306]

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

Work in progress and future plans



v0.2 $\longrightarrow$ v0.3 changes

- Handling of evanescent contributions
- More stable & faster
- Partial documentation

Coming next

- Interface with other EFT tools
- Automated one-loop β functions
- Symmetry breaking and heavy vectors

Longer term

- RG and matching beyond one loop
  - — 2-loop RG in the bosonic SMEFT
    [Born, JFM, Kvedaraitė, Thomsen, 2410.07320]
  - — 2-loop RG in the *complete* SMEFT
    [Born, JFM, Thomsen, w.i.p]

Two-loop RGEs in the bosonic SMEFT (bSMEFT)

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

See Anders talk

[Born, JFM, Kvedaraitė, Thomsen, 2410.07320]

First application: 2-loop RGEs in the bosonic SMEFT (bSMEFT) :

$$\mathscr{L}_{bSMEFT} = -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}W^{I\,\mu\nu}W^{I}_{\mu\nu} - \frac{1}{4}G^{A\,\mu\nu}G^{A}_{\mu\nu}$$
$$+D_\mu H^\dagger D^\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$
$$+\mathscr{L}_{\text{gf.}} + \mathscr{L}_{\text{gh.}} + \mathscr{L}_\theta$$

$+$

	X^2H^2
C_{HB}	$H^\dagger H\, B^{\mu\nu}\, B_{\mu\nu}$
C_{HW}	$H^\dagger H\, W^{I\,\mu\nu}\, W^I_{\mu\nu}$
C_{HG}	$H^\dagger H\, G^{A\,\mu\nu}\, G^A_{\mu\nu}$
$C_{H\widetilde{B}}$	$H^\dagger H\, B^{\mu\nu}\, \widetilde{B}_{\mu\nu}$
$C_{H\widetilde{W}}$	$H^\dagger H\, W^{I\,\mu\nu}\, \widetilde{W}^I_{\mu\nu}$
$C_{H\widetilde{G}}$	$H^\dagger H\, G^{A\,\mu\nu}\, \widetilde{G}^A_{\mu\nu}$
C_{HWB}	$(H^\dagger\sigma^I H) B^{\mu\nu}\, W^I_{\mu\nu}$
$C_{H\widetilde{W}B}$	$(H^\dagger\sigma^I H) B^{\mu\nu}\, \widetilde{W}^I_{\mu\nu}$

	X^3
C_W	$f^{IJK}\, W^{I\,\nu}_{\mu}\, W^{J\,\rho}_{\nu}\, W^{K\,\mu}_{\rho}$
C_G	$f^{ABC}\, G^{A\,\nu}_{\mu}\, G^{B\,\rho}_{\nu}\, G^{C\,\mu}_{\rho}$
$C_{\widetilde{W}}$	$f^{IJK}\, \widetilde{W}^{I\,\nu}_{\mu}\, W^{J\,\rho}_{\nu}\, W^{K\,\mu}_{\rho}$
$C_{\widetilde{G}}$	$f^{ABC}\, \widetilde{G}^{A\,\nu}_{\mu}\, G^{B\,\rho}_{\nu}\, G^{C\,\mu}_{\rho}$
	H^4D^2 and H^6
C_H	$(H^\dagger H)^3$
$C_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
C_{HD}	$(H^\dagger D_\mu H)^*\,(H^\dagger D^\mu H)$

Some results in the bSMEFT at NLL

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

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

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

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

Enlarged mixing: Most operators mix at NLL

Some results in the bSMEFT at NLL

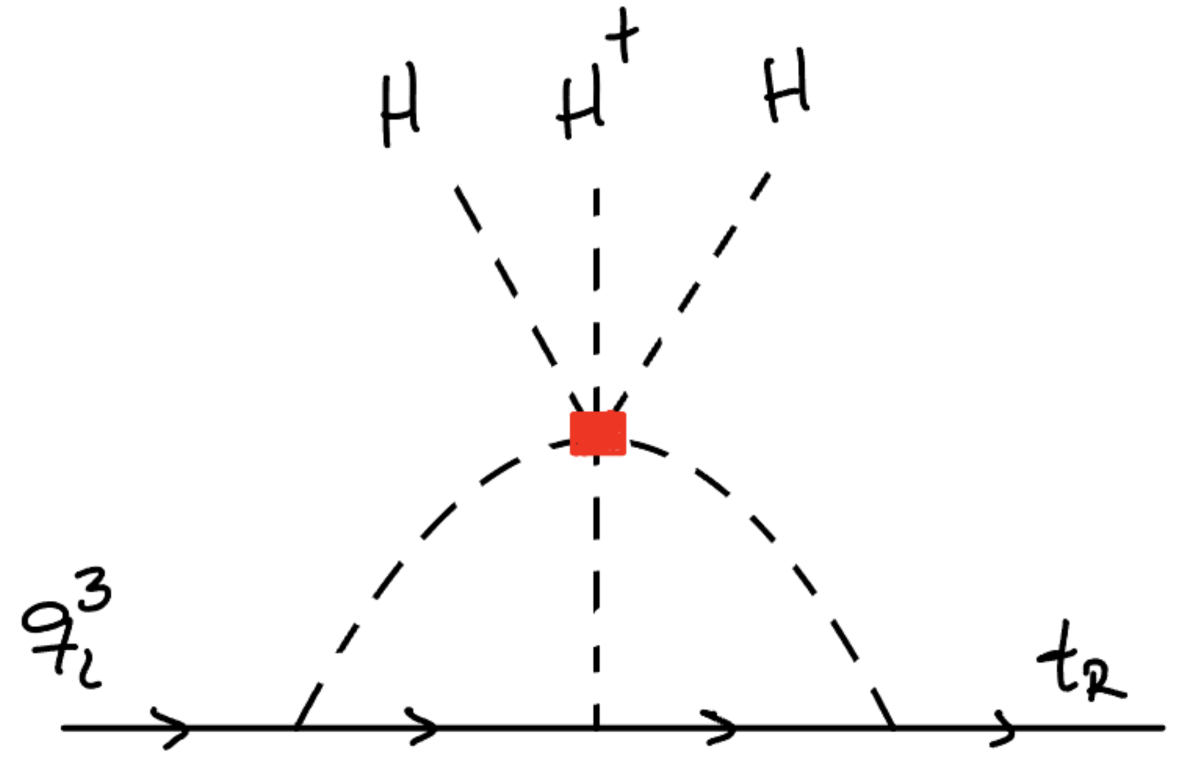
$$\frac{dC_i}{d\ln\mu} = \frac{\beta_i^{(1)}}{(16\pi^2)} + \frac{\beta_i^{(2)}}{(16\pi^2)^2} + \dots$$

C_H does not mix into any other bSMEFT operator, even at two loops

→ This is no longer the case in the complete SMEFT

This result was already anticipated using amplitude methods

[Bern, Parra-Martinez, Sawyer, 2005.12917]

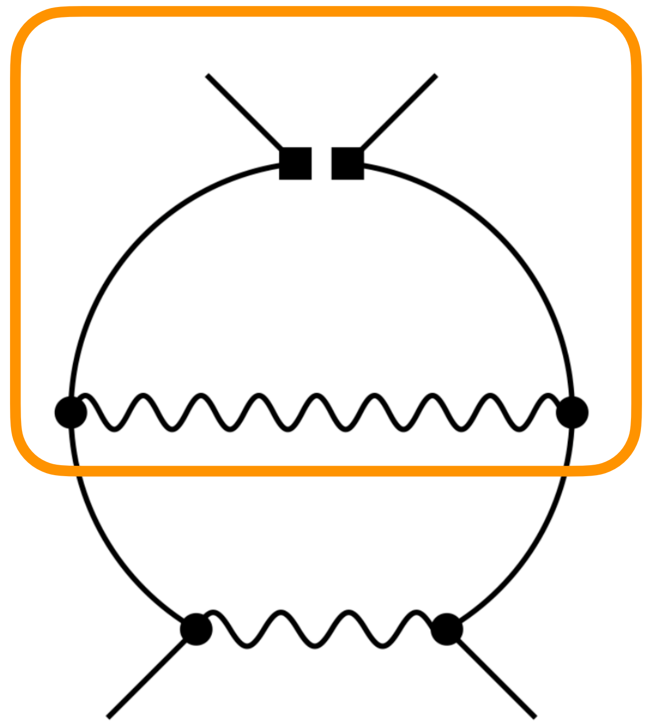


[Top-Yukawa correction]

Two-loop SMEFT RGEs: new challenges with fermions

[Born, JFM, Thomsen, *coming soon*]

- Extension of the functional evaluation to fermions (e.g. Grassmanian signs)
- Impact of evanescence-free scheme into β functions
- Treatment of subdivergences: R^* operation in presence of fermions and evanescent operators



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

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

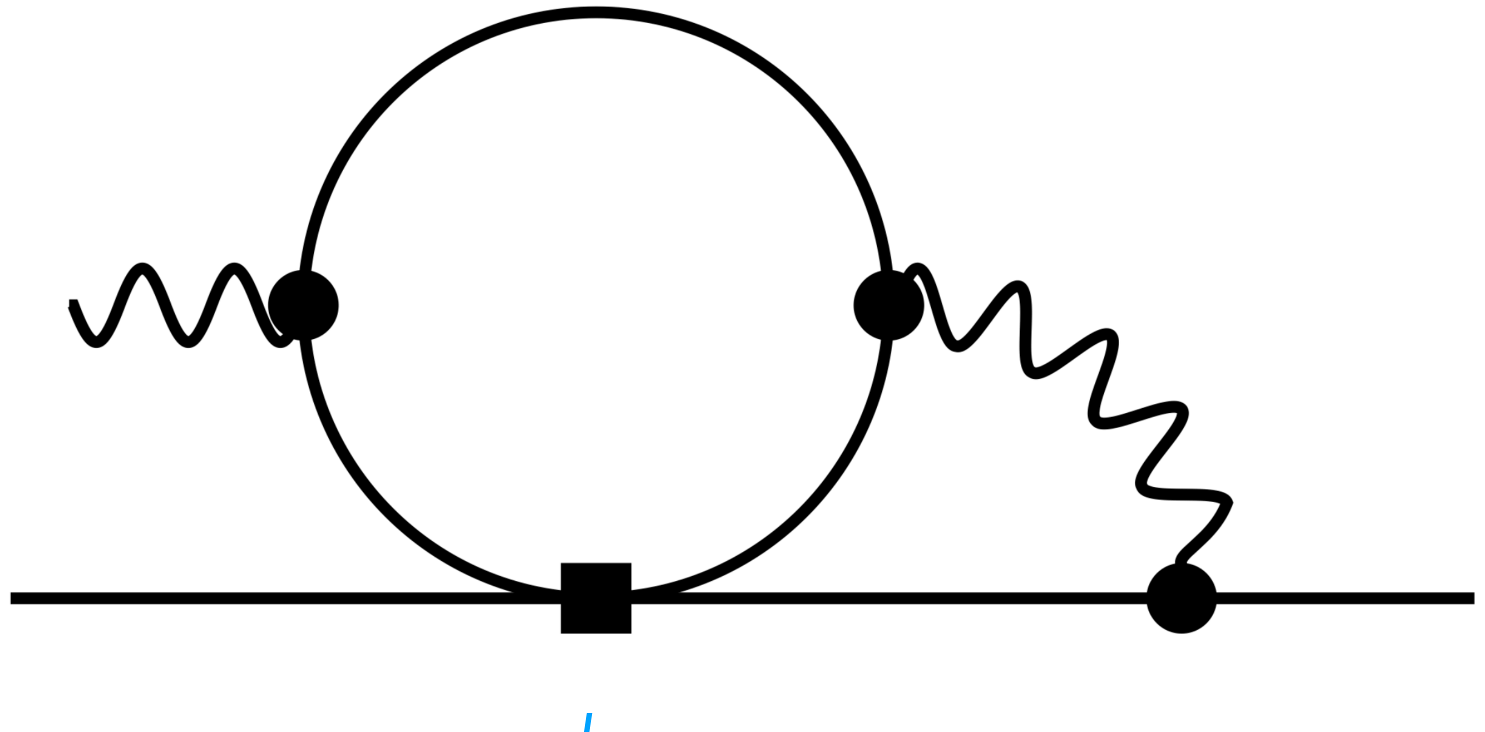
γ_5 schemes in dimensional regularization

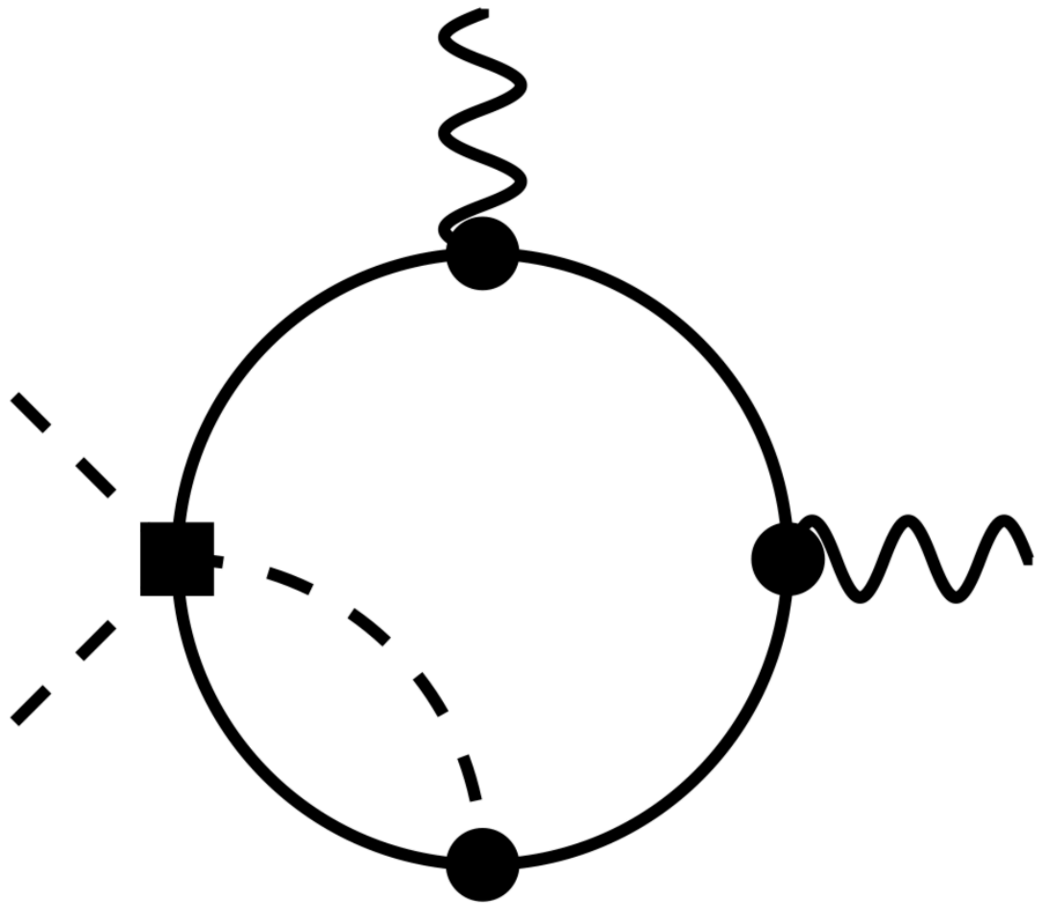
- Naive Dimensional Regularization (NDR) scheme:

$$\left.\begin{array}{l} \{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu}, \qquad \{\gamma_\mu, \gamma_5\} = 0, \qquad \gamma_5^2 = I \\[2ex] \qquad \mathrm{tr}\left[\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_5\right] \xrightarrow[d\to 4]{} -4i\varepsilon_{\mu\nu\rho\sigma} \end{array}\right\} \Longrightarrow \begin{array}{l} \mathrm{tr}\left[\gamma^\alpha\gamma^\rho\gamma^\sigma\gamma_\alpha\gamma^\mu\gamma^\nu\gamma_5\right] = 4i(4-d)\,\epsilon^{\mu\nu\rho\sigma} \\[2ex] \mathrm{tr}\left[\gamma^\rho\gamma^\sigma\gamma_\alpha\gamma^\mu\gamma^\nu\gamma_5\gamma^\alpha\right] = -4i(4-d)\,\varepsilon^{\mu\nu\rho\sigma} \end{array}$$

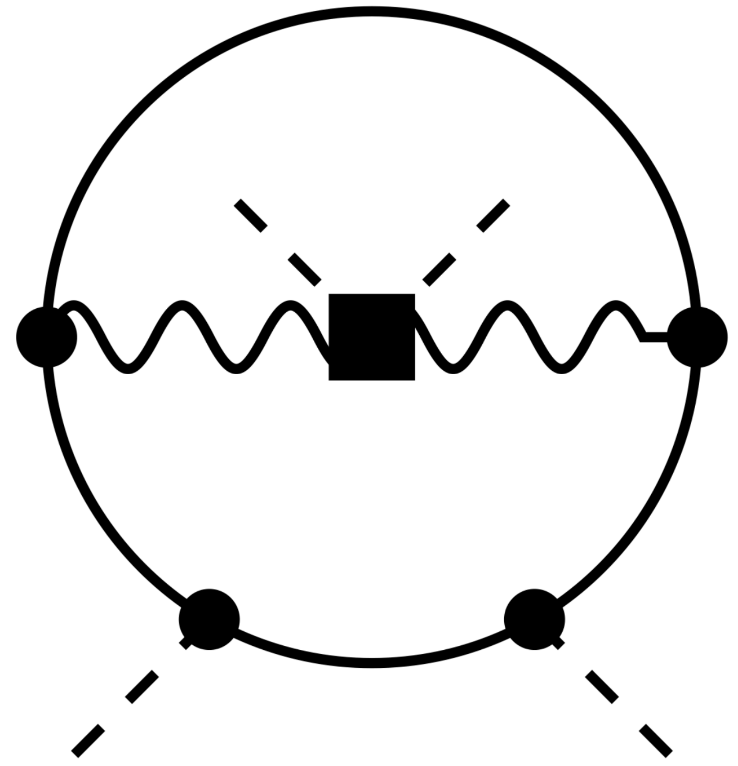
Two-loop SMEFT RGEs: reading-point ambiguities in NDR

Start at dimension-six operator





“Unclear” prescription



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

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- Naive Dimensional Regularization (NDR) scheme:

$$\left.\begin{array}{c} \{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu}, \qquad \{\gamma_\mu, \gamma_5\} = 0, \qquad \gamma_5^2 = I \\[2ex] \mathrm{tr}\left[\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_5\right] \xrightarrow[d\to 4]{} -4i\varepsilon_{\mu\nu\rho\sigma} \end{array}\right\} \Longrightarrow \begin{array}{l} \mathrm{tr}\left[\gamma^\alpha\gamma^\rho\gamma^\sigma\gamma_\alpha\gamma^\mu\gamma^\nu\gamma_5\right] = 4i(4-d)\,\epsilon^{\mu\nu\rho\sigma} \\[2ex] \mathrm{tr}\left[\gamma^\rho\gamma^\sigma\gamma_\alpha\gamma^\mu\gamma^\nu\gamma_5\gamma^\alpha\right] = -4i(4-d)\,\varepsilon^{\mu\nu\rho\sigma} \end{array}$$

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

$$\left.\begin{array}{ll} \gamma_\mu = \underbrace{\gamma_{\bar\mu}}_{4\ \mathrm{dim}} + \underbrace{\gamma_{\hat\mu}}_{d-4\ \mathrm{dim}} & \gamma_{\bar\mu}\gamma^{\hat\mu} = 0 \\[2ex] \gamma_5 = -\dfrac{i}{4!}\,\varepsilon_{\bar\mu\bar\nu\bar\rho\bar\sigma}\gamma^{\bar\mu}\gamma^{\bar\nu}\gamma^{\bar\rho}\gamma^{\bar\sigma} & \gamma_5^2 = I \end{array}\right\} \Longrightarrow \begin{array}{l} \{\gamma_5, \gamma^{\bar\mu}\} = 0 \\[2ex] [\gamma_5, \gamma^{\hat\mu}] = 0 \end{array}$$

Fermion Lagrangian in the BMHV scheme

Kinetic term must be promoted to d dimensions: $^{(*)}$

Evanescent (singlet) fermion

$$\mathscr{L}^{\mathrm{Fer}}_{(d)} = i\,\overline{\psi}\gamma^{\bar{\mu}}P_{\mathrm{L}}D_{\bar{\mu}}\psi + i\,\overline{\psi}_{\mathrm{ev}}\gamma^{\bar{\mu}}P_{\mathrm{R}}\partial_{\bar{\mu}}\psi_{\mathrm{ev}} + \left(i\,\overline{\psi}\gamma^{\hat{\mu}}P_{\mathrm{R}}\partial_{\hat{\mu}}\psi_{\mathrm{ev}} + \mathrm{h.c.}\right)$$

- Explicit breaking of gauge (and BRST) invariance (*local*, as the *offending term* is evanescent)
- Gauge symmetry can and must be restored via counterterms
- Determining the counterterms requires (inverse) gauge variations of the effective action

$^{(*)}$ N.B.: This extension is not unique, see e.g. [Ebert, Kühler Stöckinger Weißwange, 2411.02543]

Spurious gauge invariance in the BMHV scheme

[Olgoso, Vecchi, 2406.17013]

Formally restore gauge invariance introducing a spurion field Ω:

$$\mathscr{L}^{\text{Fer}}_{(d)} = i\,\overline{\psi}\gamma^{\bar{\mu}}P_{\text{L}}D_{\bar{\mu}}\psi + i\,\overline{\psi}_{\text{ev}}\gamma^{\bar{\mu}}P_{\text{R}}\partial_{\bar{\mu}}\psi_{\text{ev}} + \left(i\,\overline{\psi}\,\Omega\,\gamma^{\bar{\mu}}P_{\text{R}}\partial_{\bar{\mu}}\psi_{\text{ev}} + \text{h.c.}\right)$$

which transforms as ψ and is taken unitary (analogously to chiral fields)

$$\psi \to U\psi \qquad\qquad \Omega \to U\Omega \qquad\qquad \Omega^\dagger\Omega = I$$

Gauge-symmetry restoring counterterms obtained directly from the spurious-dependent effective action

$$\Delta S^{(\ell)}_{\text{ct}} = -\lim_{\Omega\to I}\Gamma^{(\ell)}_{\Omega}$$

The **spurion-dependent effective action** $\Gamma^{(\ell)}_{\Omega}$ can be easily determined using **functional methods**

[JFM, Moreno-Sánchez, Thomsen, 2507.19589]

Summary and outlook

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

- **Functional methods** play a crucial role in EFT matching and running calculations, especially when combined with computer tools
  - — Compact, systematic, and manifestly gauge invariant at all steps

- First results towards the **2-loop SMEFT RGE** already available, the complete result is coming soon!

- The ultimate goal is a code (or chain of codes) that fully automates
  - Matching
  - RG evolution

  } **Multi-step matching**

  MATCHETE

  - Connection to observables / fit to data

  streamlining future BSM analyses

Thank you

BSM phenomenology is about to become easy!

MATCHETE

https://gitlab.com/matchete/matchete

Reducing the EFT Lagrangian to its basis

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

Exact simplifications (linear): IBP, Dirac and group identities, commutation relations…

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

On-shell equivalence (non-linear): Field redefinitions (sometimes equivalent to using of EOMs)

$$\phi \to \phi + \frac{3\,C_2 - C_3}{3\,\Lambda^2}\phi^3 \qquad \left[\partial^2\phi = -\,m^2\phi - \frac{\lambda}{3!}\phi^3 + \mathscr{O}(\Lambda^{-2})\right]$$

$$\mathscr{L} \to \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m^2\phi^2 - \left(\frac{\lambda}{4!} + \frac{m^2(3C_2 - C_3)}{3\,\Lambda^2}\right)\phi^4 + \frac{18\,C_1 - \lambda\,(3C_2 - C_3)}{18\,\Lambda^2}\phi^6$$

Removal of evanescent operators: Solved for SMEFT [JFM, König, Pagès, Thomsen, Wilsch, 2211.09144]