FTAE High Energy Theory

Junta de Andalucía

Universidad de Granada

Recent Developments on Effective Field Theories

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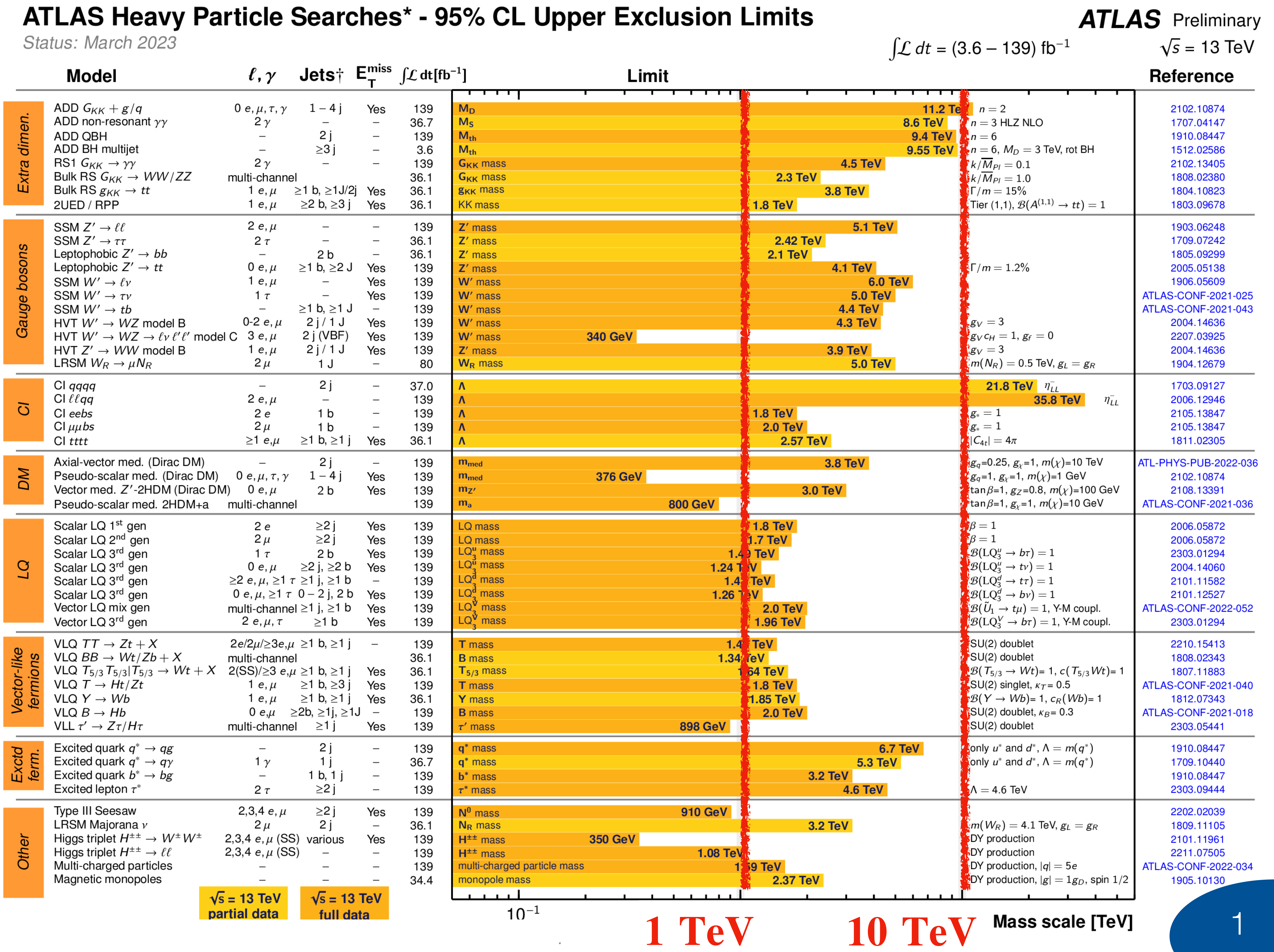
XVII CPAN Days, Valencia | 19-21 November 2025

What is experiment telling us?

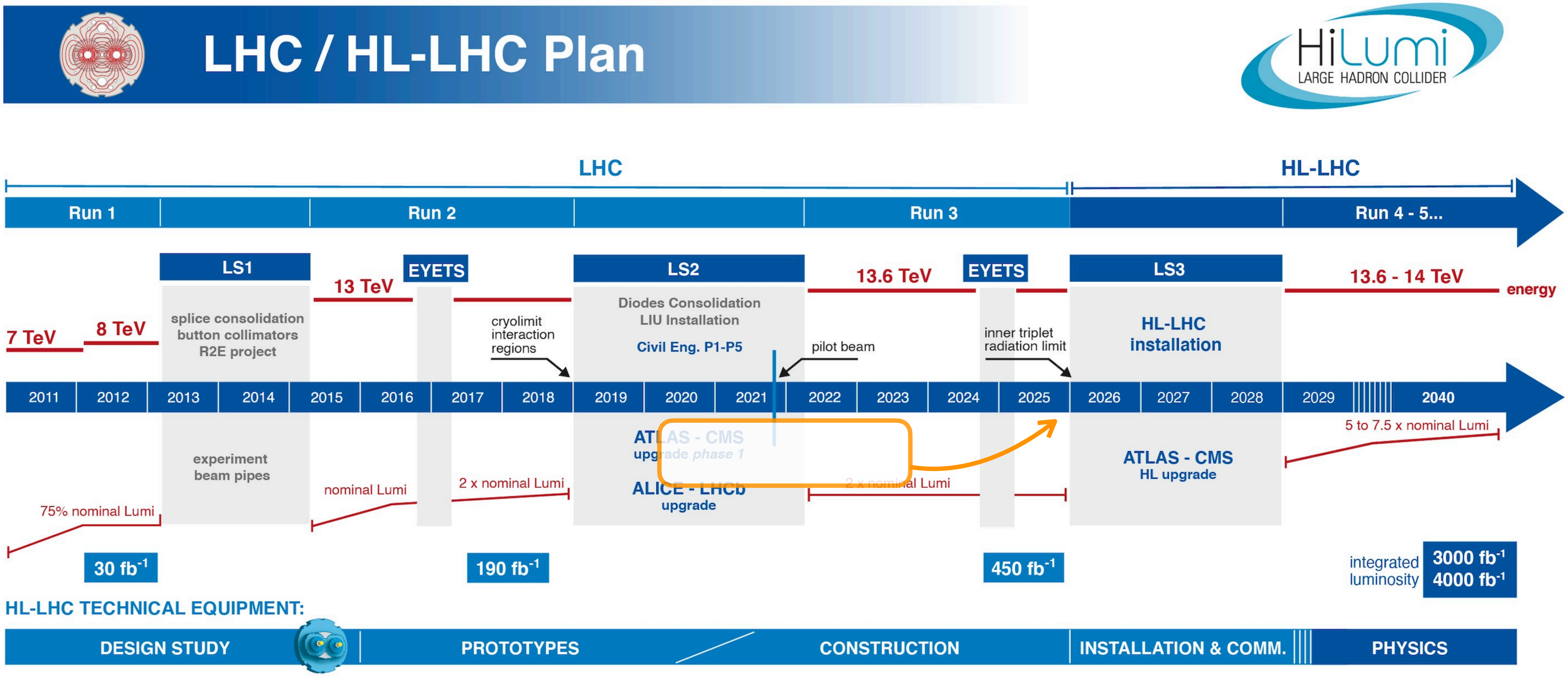
No **direct evidence for NP** despite the many reasons for it

[**presence of a mass gap?**]

Indirect NP searches?

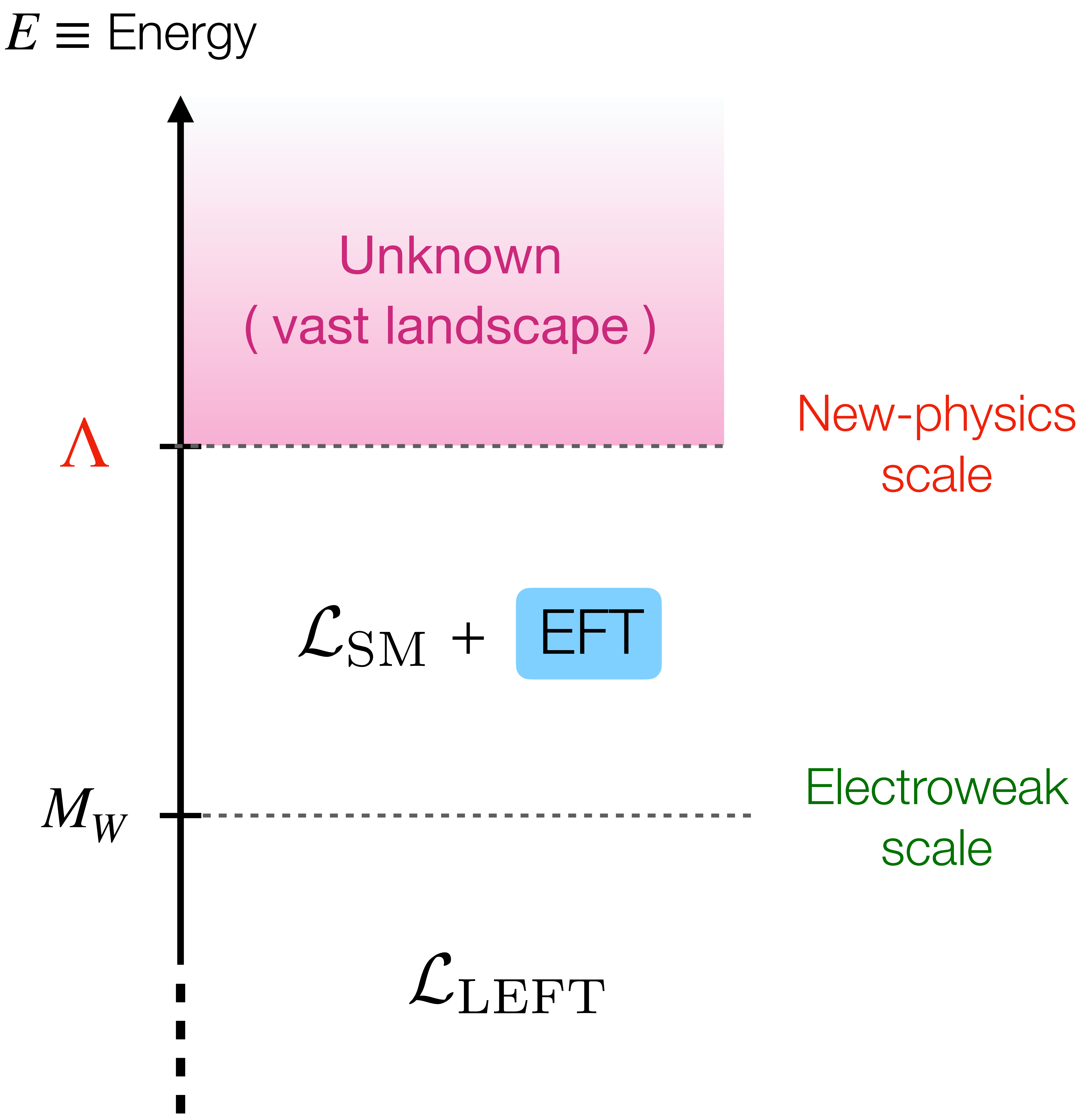


A new precision era



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

Effective Field Theories (EFT): bottom-up

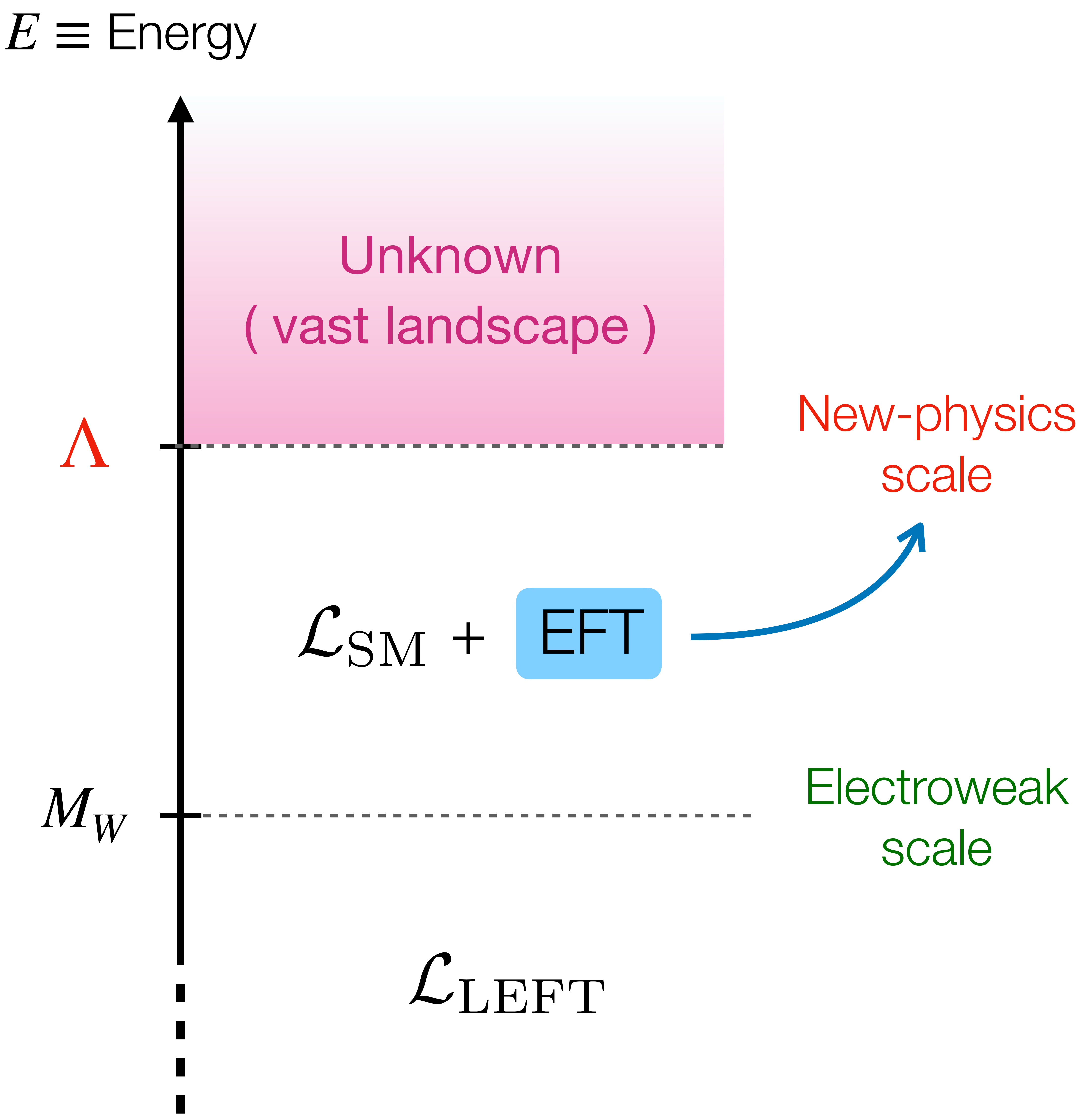


EFTs are great for parametrizing the unknown:

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

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

Effective Field Theories (EFT): bottom-up



EFTs are great for parametrizing the unknown:

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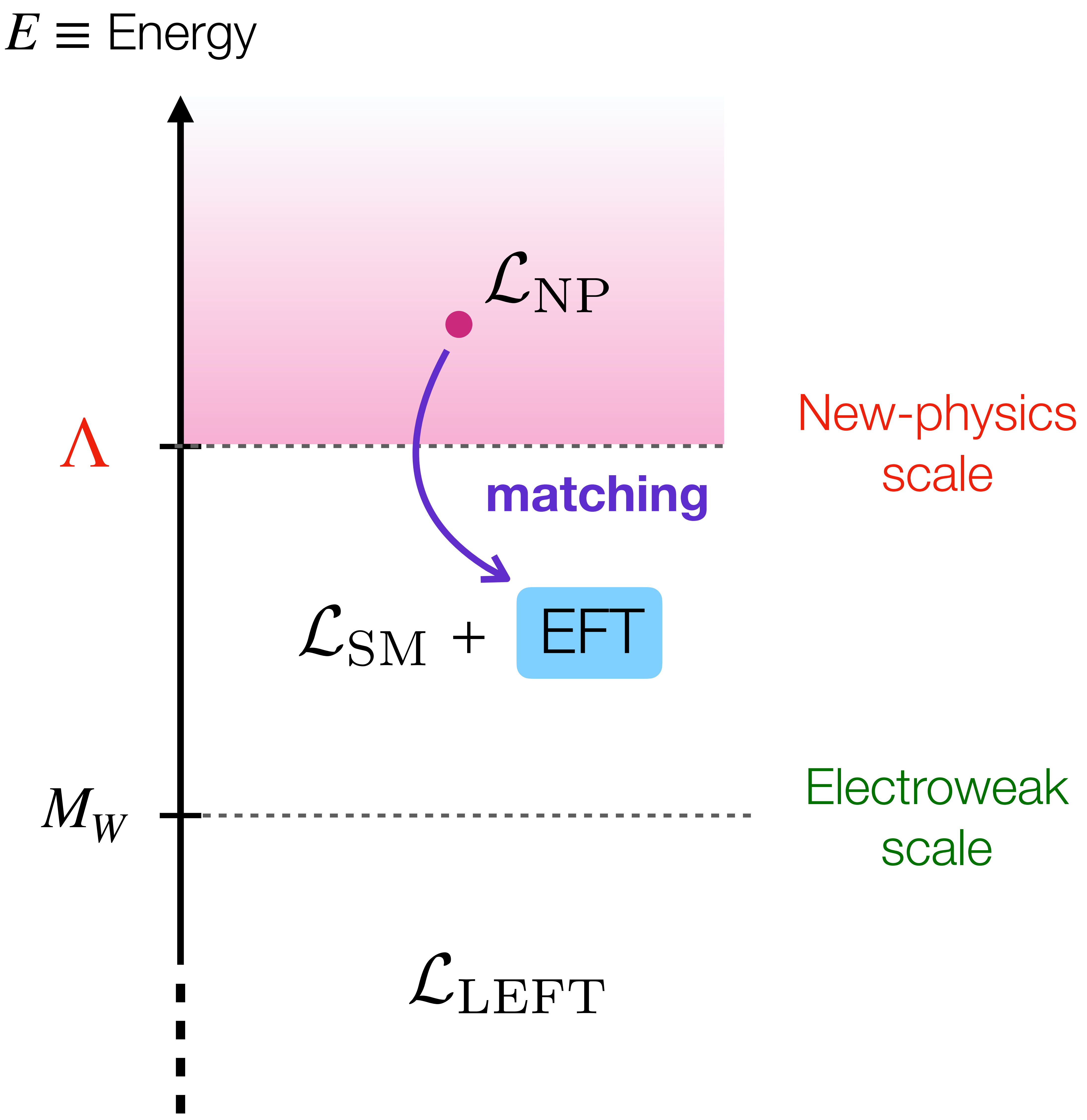
- Systematically improvable by adding extra terms in a double expansion in quantum corrections and E/Λ

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

For example,

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

Effective Field Theories (EFT): top-down



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/Λ arising from quantum corrections

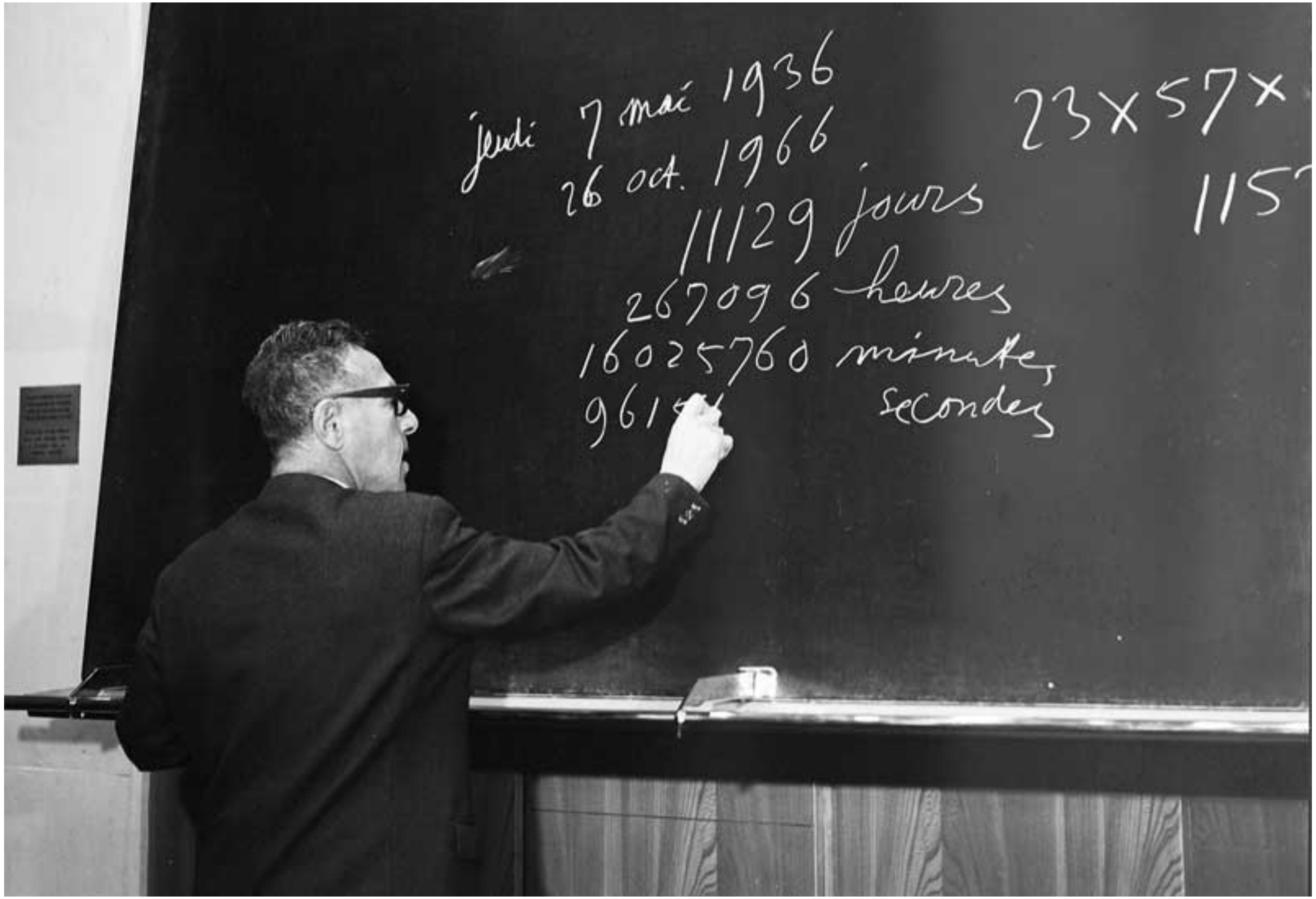
The step to build an EFT from a model is called **matching**

→ 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”



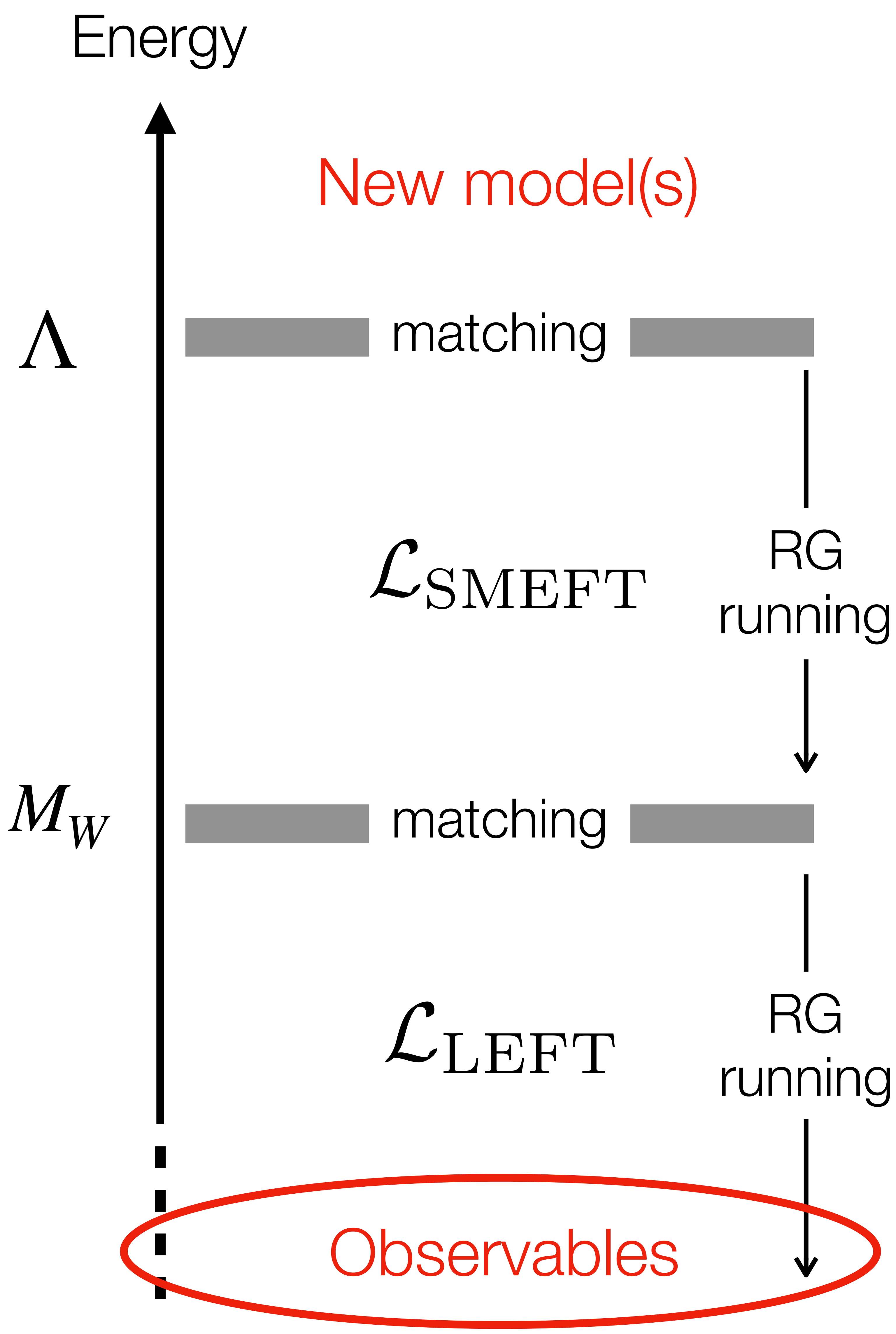
The EFT approach: The rise of automation

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

HighPT

Allwicher et al. '22

HEPfit

De Blas et al. '19

Fitmaker

Ellis et al '20

SMEFiT

Giani et al. '23

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

The EFT approach: The rise of automation

Energy

New model(s)

Λ — matching

$\mathcal{L}_{\mathrm{SMEFT}}$ — RG running

M_W — matching

$\mathcal{L}_{\mathrm{LEFT}}$ — RG running

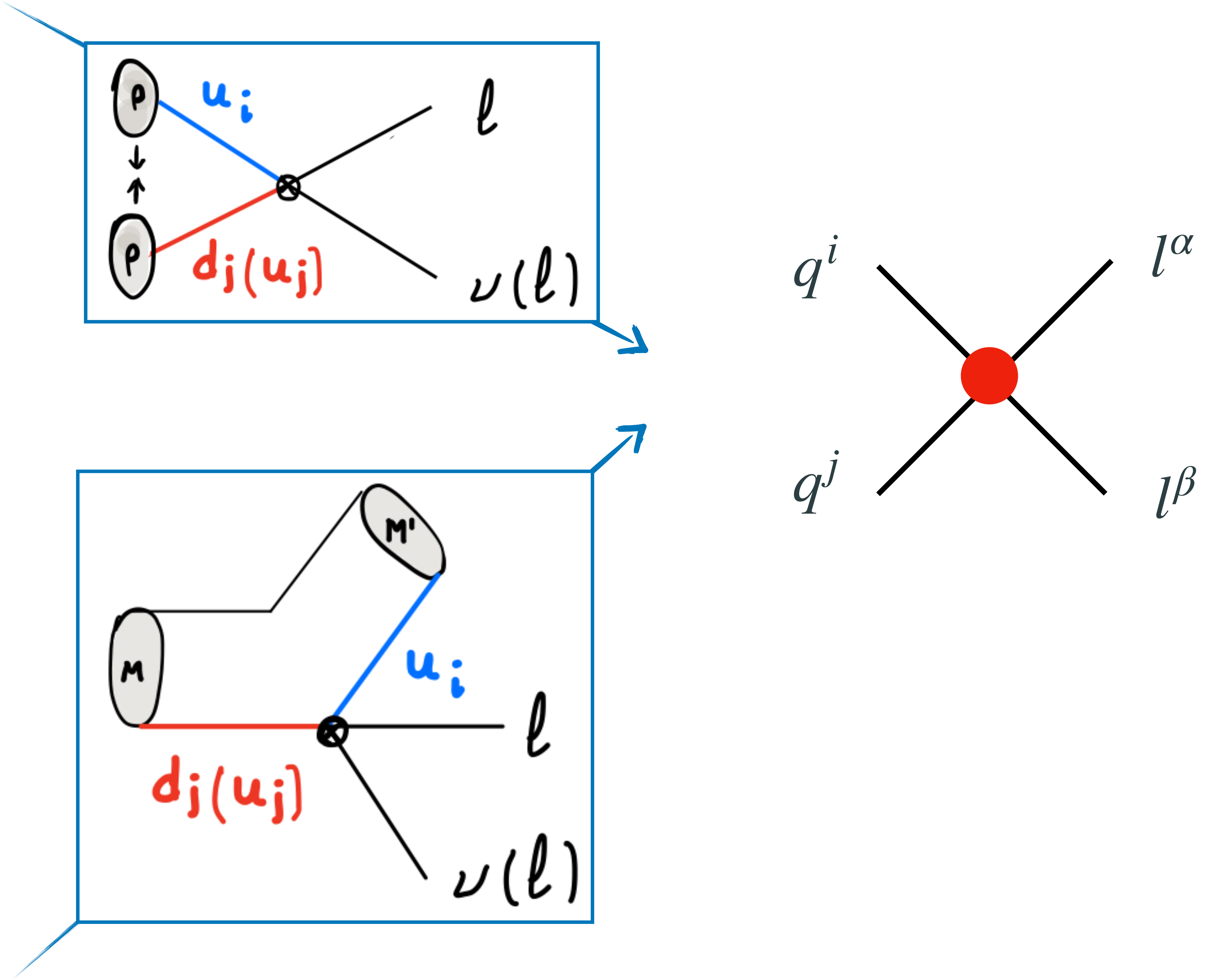
Observables

Exploit <u>complementary information</u> in high- and low-energy probes:

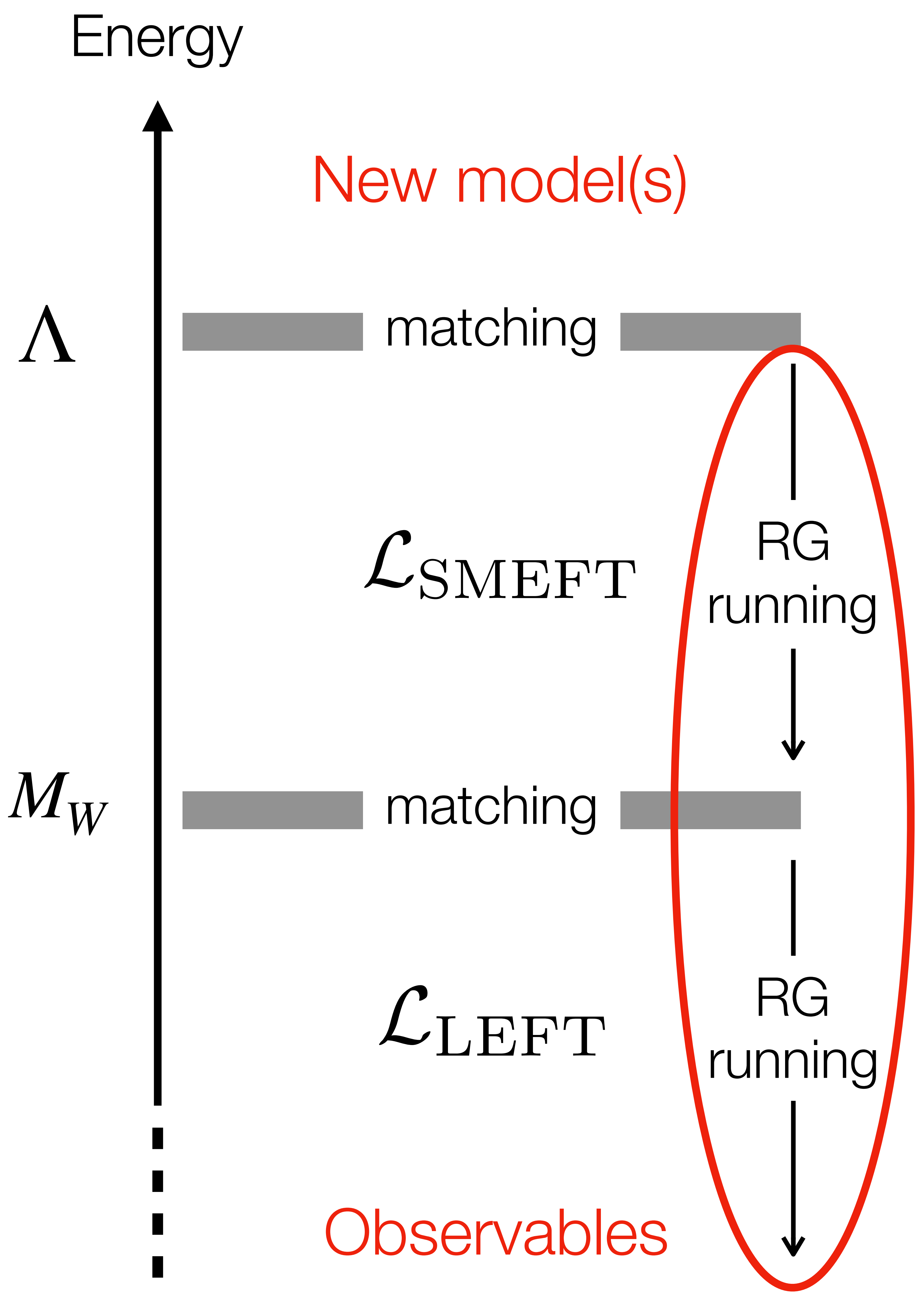
→ For this, RG running and SMEFT-LEFT matching are crucial !!

ATLAS EXPERIMENT, CMS

Belle II, LHCb, BESIII ...



The EFT approach: The rise of automation



DsixTools

JFM et al. '17 & '21

wilson

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

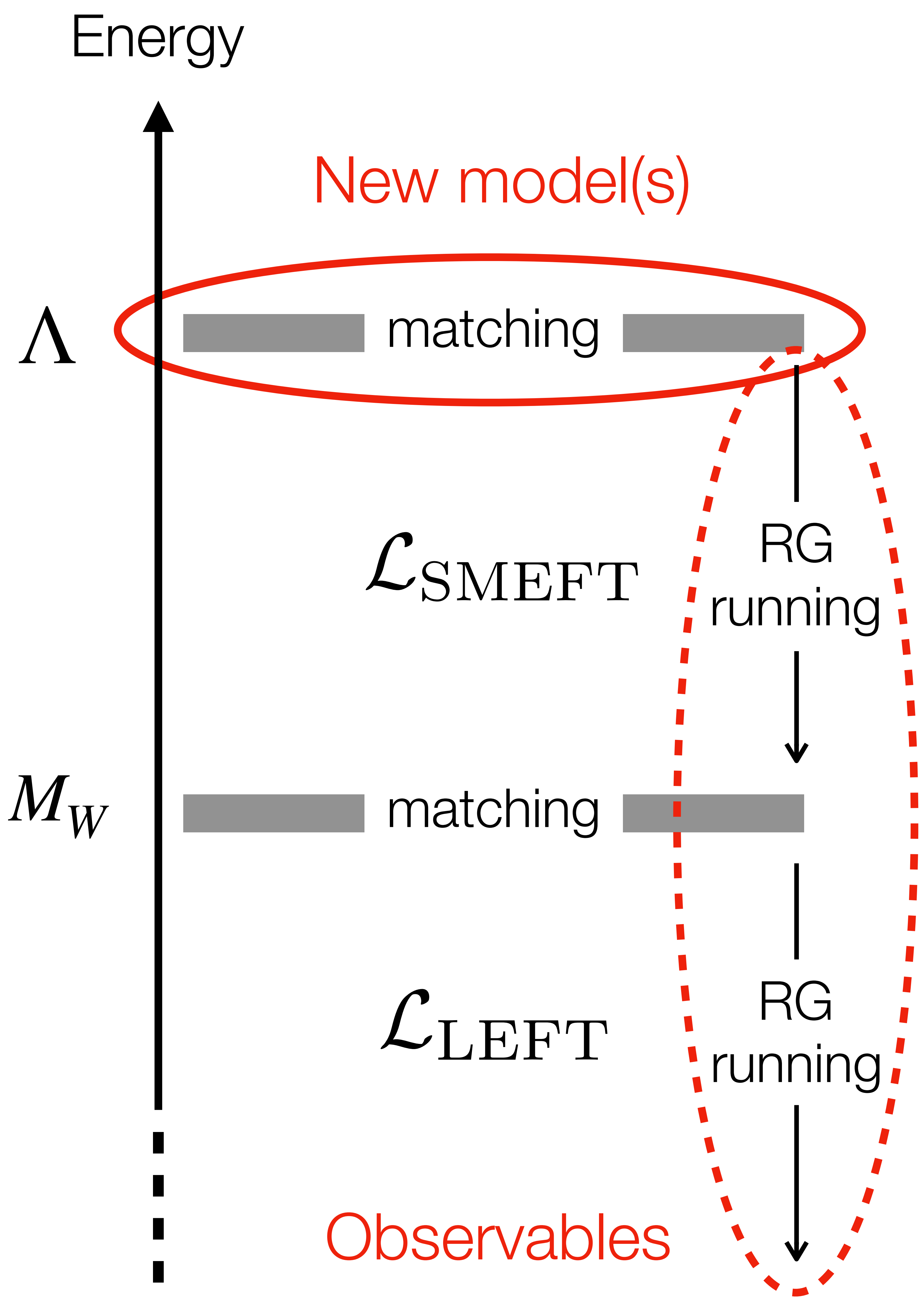
Very recent developments in the LEFT:

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

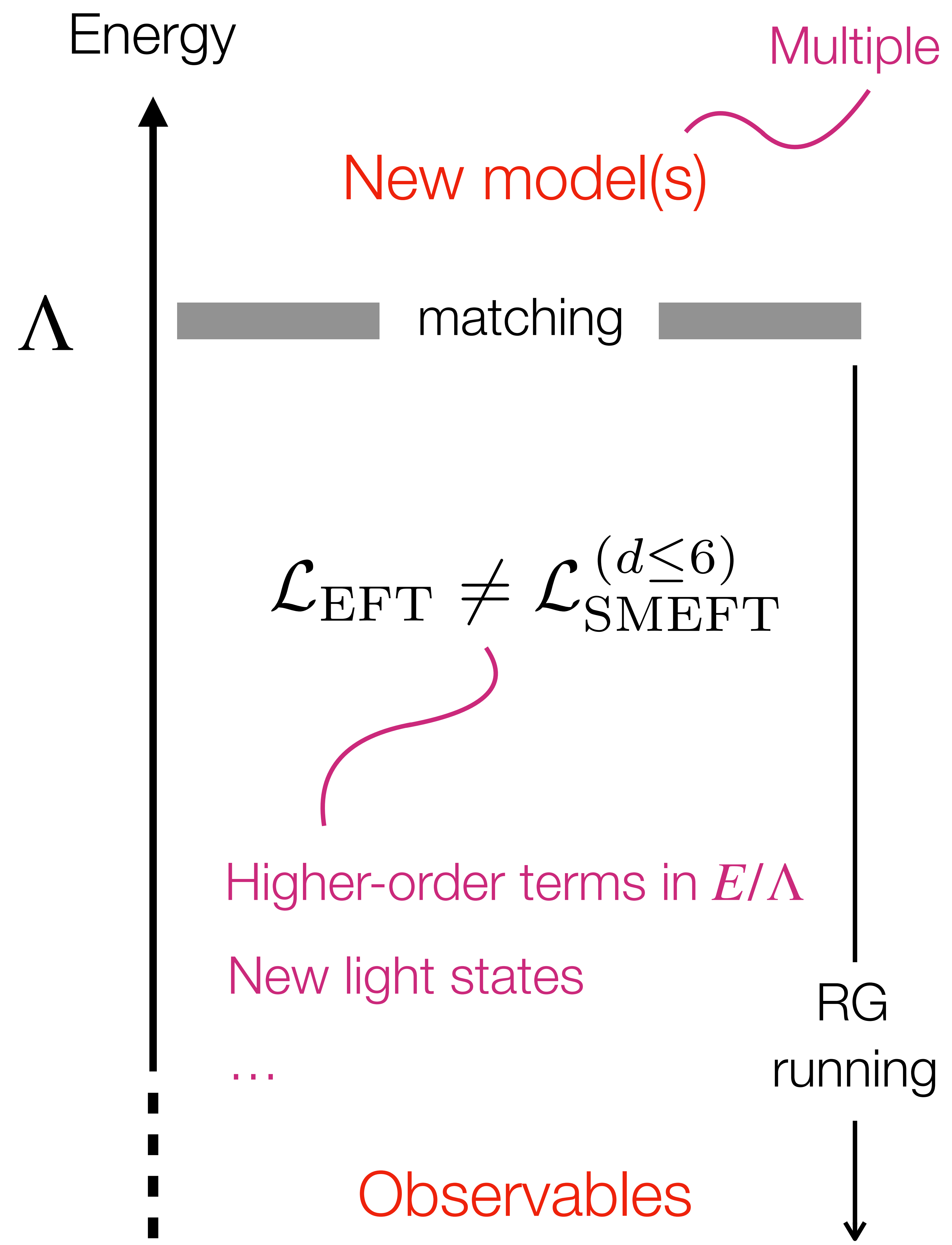
JFM et al. '23

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

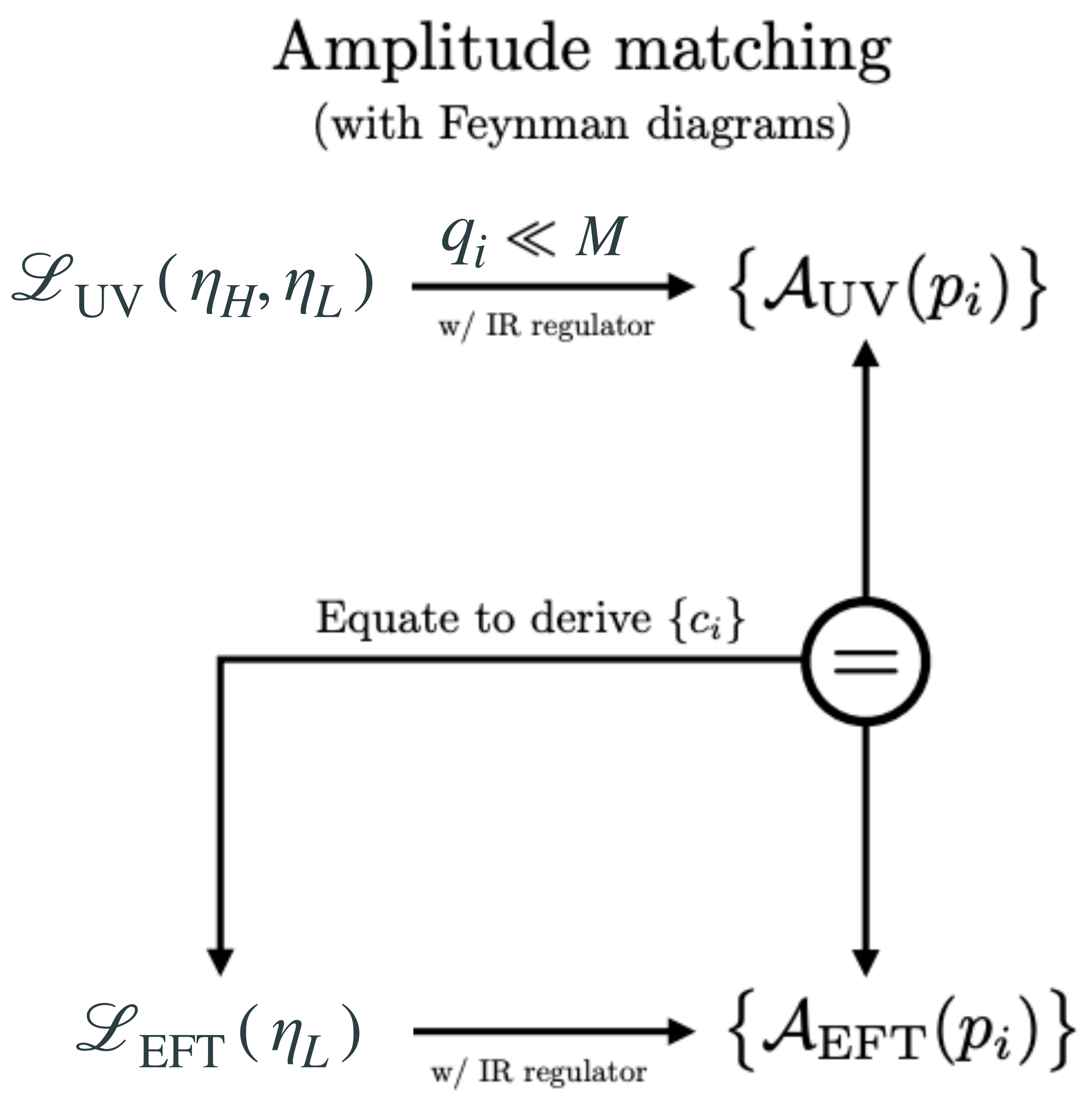


Figure from Cohen, Lu, Zhang, 2011.02484

✓ 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

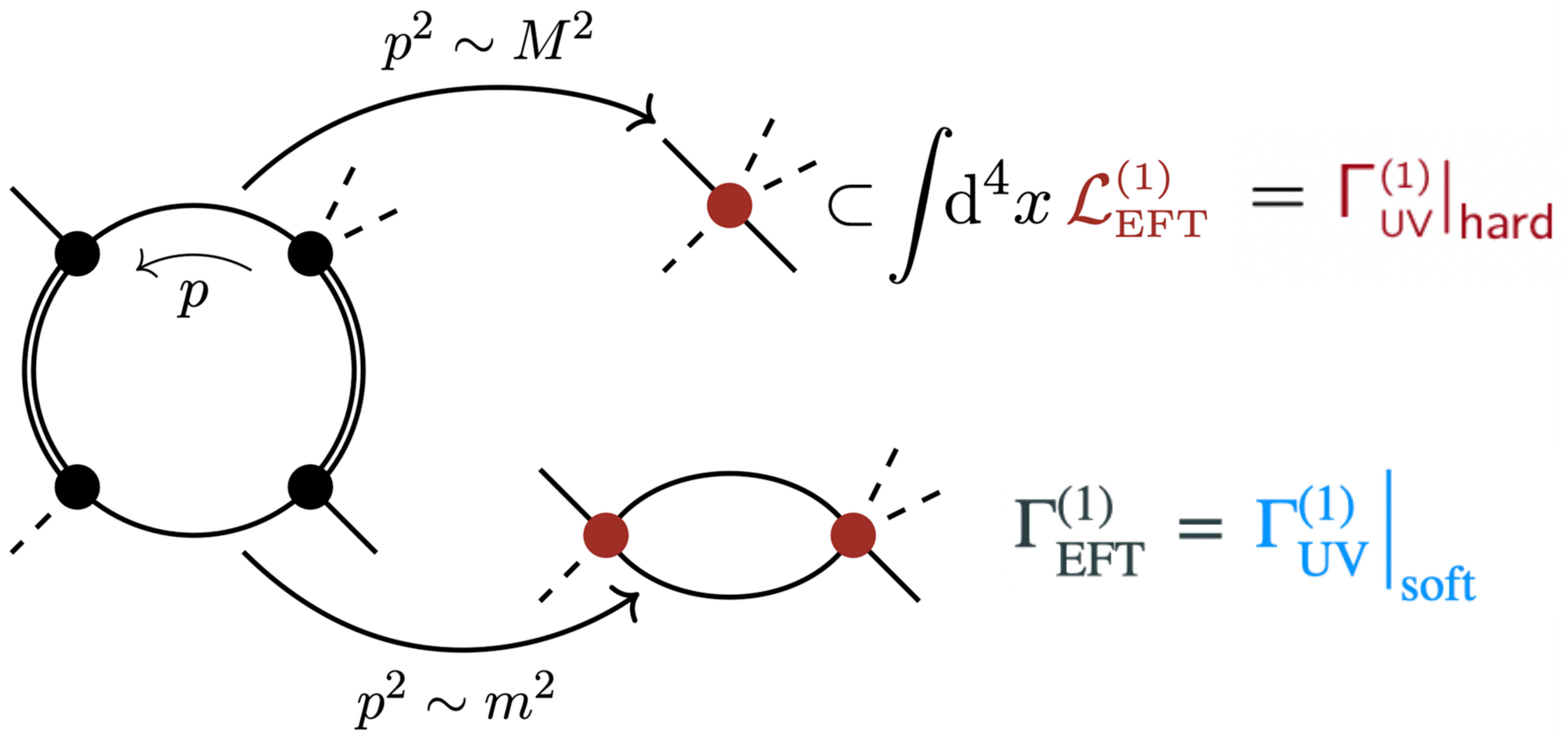
We can separate loop integrals in two regions (for $q^2, m^2 \ll M^2$): hard ($p^2 \sim M^2$) & soft ($p^2 \sim m^2$)

Method of regions: Beneke, Smirnov ’97, Jantzen ‘11

If only the <u>hard part of the loop</u> 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)

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

Using Equations of Motion (EOMs)

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

Method of regions

$$\mathscr{L}_{\mathrm{EFT}}(\eta_L)$$

Not in a basis

Based on the Wilsonian approach : split vibrating fields into fast (η_H) and slow (η_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:** $\mathscr{L}_{\mathrm{UV}}$ with fields $\eta = (\eta_H \; \eta_L)$ and hierarchy $m_H \gg m_L$

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

  $\hat{\eta}$: background fields (satisfy the quantum EOM) — Tree lines in Feynman graphs

  $\hat{\eta}$: quantum fluctuations — Loop lines in Feynman graphs

- **Quantum effective action:**

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

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

A taste on functional matching

- **Expanding the Lagrangian in η:**

$$\mathscr{L}_{\text{UV}}(\hat{\eta}+\eta) = \mathscr{L}_{\text{UV}}(\hat{\eta}) + \frac{\delta \mathscr{L}_{\text{UV}}}{\delta \eta_a}\bigg|_{\eta=\hat{\eta}} \eta_a + \frac{1}{2}\eta_a(x)\frac{\delta^2 \mathscr{L}_{\text{UV}}}{\delta \eta_b(x')\,\delta \eta_a(x)}\bigg|_{\eta=\hat{\eta}} \eta_b(x') + \mathcal{O}(\eta^3)$$

A taste on functional matching

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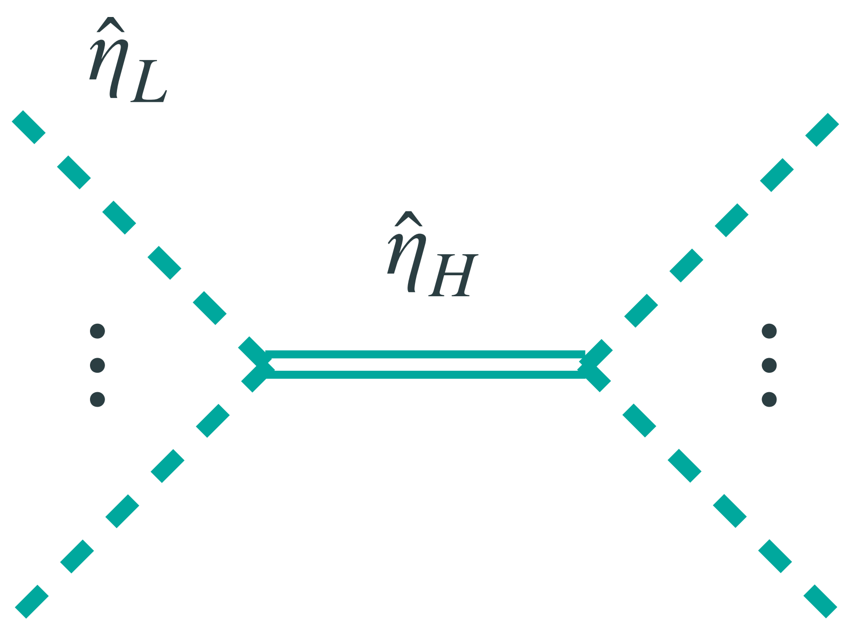
- **Tree-level:** $\mathscr{L}^{(0)}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{UV}}\big(\hat\eta_L, \hat\eta_H(\hat\eta_L)\big)$

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

[Simpler than computing Feynman graphs]

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



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A taste on functional matching

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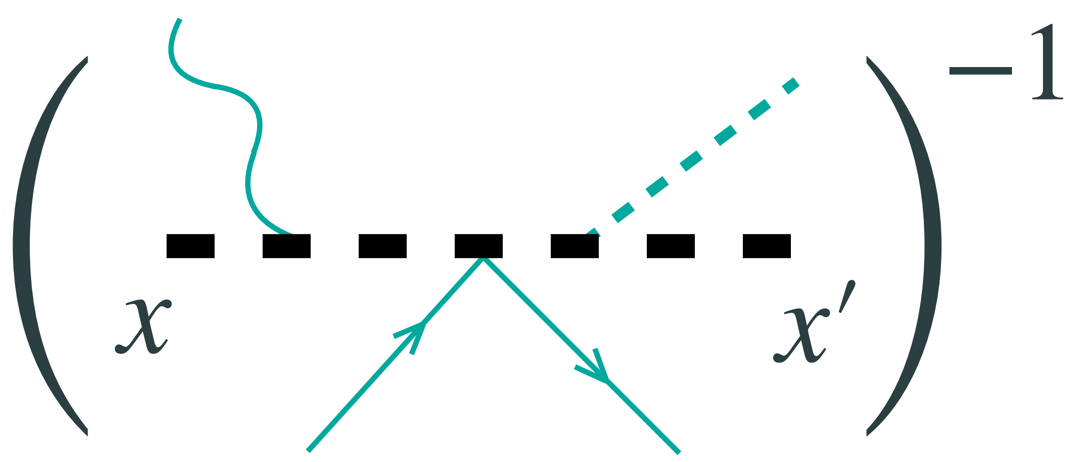
- **Inverse quantum-field propagator:**

Wilson line

[parallel transport $x \leftrightarrow x'$]

$$\mathcal{Q}_{ab}(x,x') = Q_{ac}\left(\hat\eta(x), \hat D_x^{\mu_1}\cdots\hat D_x^{\mu_n}\hat\eta(x), \hat D_x^{\mu}\right) \boldsymbol{U_{cb}(x,x')}\,\delta(x-x')$$

$$\hat D_x^{\mu_1}\cdots\hat D_x^{\mu_n}\,U(x,x')\Big|_{x=x'} = p_n\left(G^{\mu\nu}, D^\mu G^{\nu\rho}, \ldots\right)$$



Kuzenko, McArthur, '03

JFM, Moreno, Palavrić, Thomsen, 2412.12270

A taste on functional matching

- **Expanding the Lagrangian in η:**

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Higher-loop orders

- **Inverse quantum-field propagator:**

Wilson line

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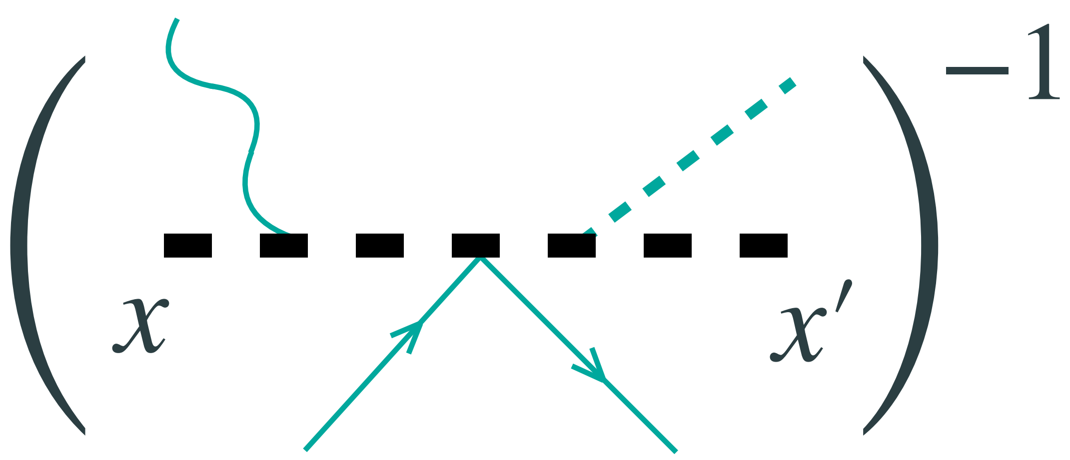

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Kuzenko, McArthur, '03

JFM, Moreno, Palavrić, Thomsen, 2412.12270

A taste on functional matching

- **Expanding the Lagrangian in η:**

$$\int_{x'} \mathcal{Q}_{ab}(x,x')$$

$$\parallel$$

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

Higher-loop orders
(see 2412.12270)

- **1-loop effective action:**

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

Gaussian integration

How to evaluate supertraces

$$\Gamma^{(1)}_{\mathrm{UV}}[\hat{\eta}] = \frac{i}{2}\,\mathrm{STr}\ln\mathcal{Q} = \pm\frac{i}{2}\int_{x,x'} \delta(x-x')\,\overbrace{[\,\ln Q(x, iD^\mu_x)\,]_{ab}\,U_{ba}(x,x')\,\delta(x-x')}^{[\ln \mathcal{Q}(x,x')]_{aa}}$$

How to evaluate supertraces

$$\int_k e^{ik(x-x')}$$

$$\Gamma^{(1)}_{\rm UV}[\hat{\eta}] = \frac{i}{2}\,\mathrm{STr}\ln\mathcal{Q} = \pm\frac{i}{2}\int_{x,x'} \delta(x-x')\,\overbrace{[\,\ln Q(x, iD^{\mu}_x)\,]_{ab}\, U_{ba}(x,x')\,\delta(x-x')}^{[\ln\mathcal{Q}(x,x')]_{aa}}$$

$$= \pm\frac{i}{2}\int_{x,k} [\ln Q\big(x, i\hat{D}^{\mu}_x - k\big)]_{ab}\, U_{ba}(x,x')\Big|_{x=x'}$$

How to evaluate supertraces

$$\Gamma^{(1)}_{\mathrm{UV}}[\hat{\eta}] = \frac{i}{2}\,\mathrm{STr}\ln\mathcal{Q} = \pm\frac{i}{2}\int_{x,x'} \delta(x-x')\,\overbrace{[\,\ln Q(x, iD^{\mu}_{x})\,]_{ab}\,U_{ba}(x,x')\,\underbrace{\delta(x-x')}_{\int_k e^{ik(x-x')}}}^{[\ln\mathcal{Q}(x,x')]_{aa}}$$

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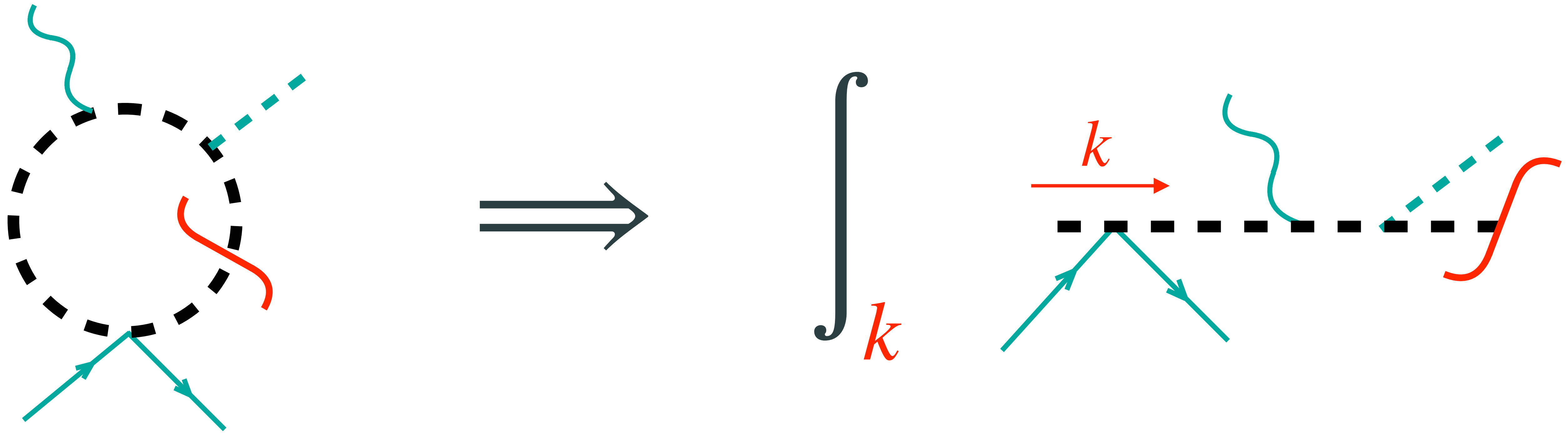

How to evaluate supertraces

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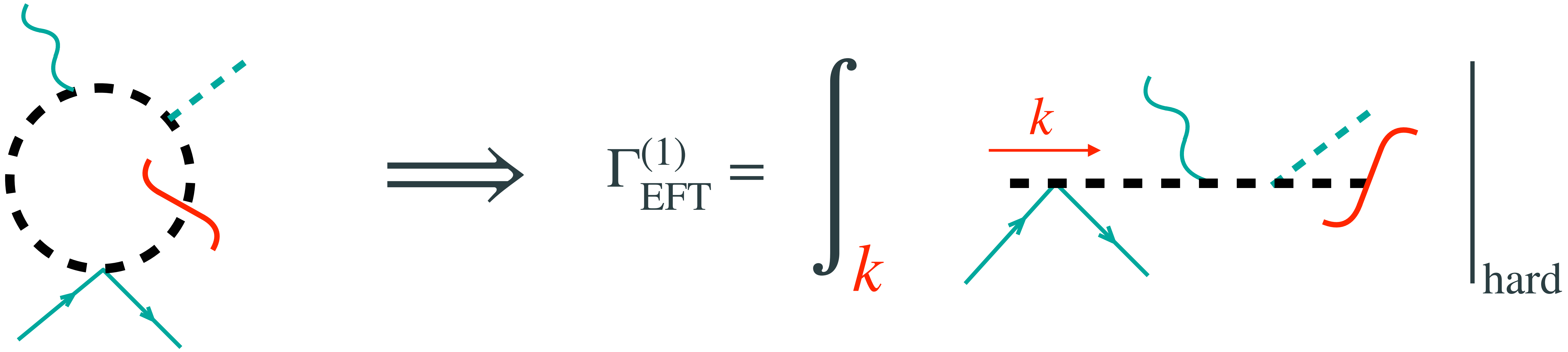


The EFT action (to arbitrary EFT order) is obtained *directly* from the hard-momentum expansion: $k \gtrsim m_H$

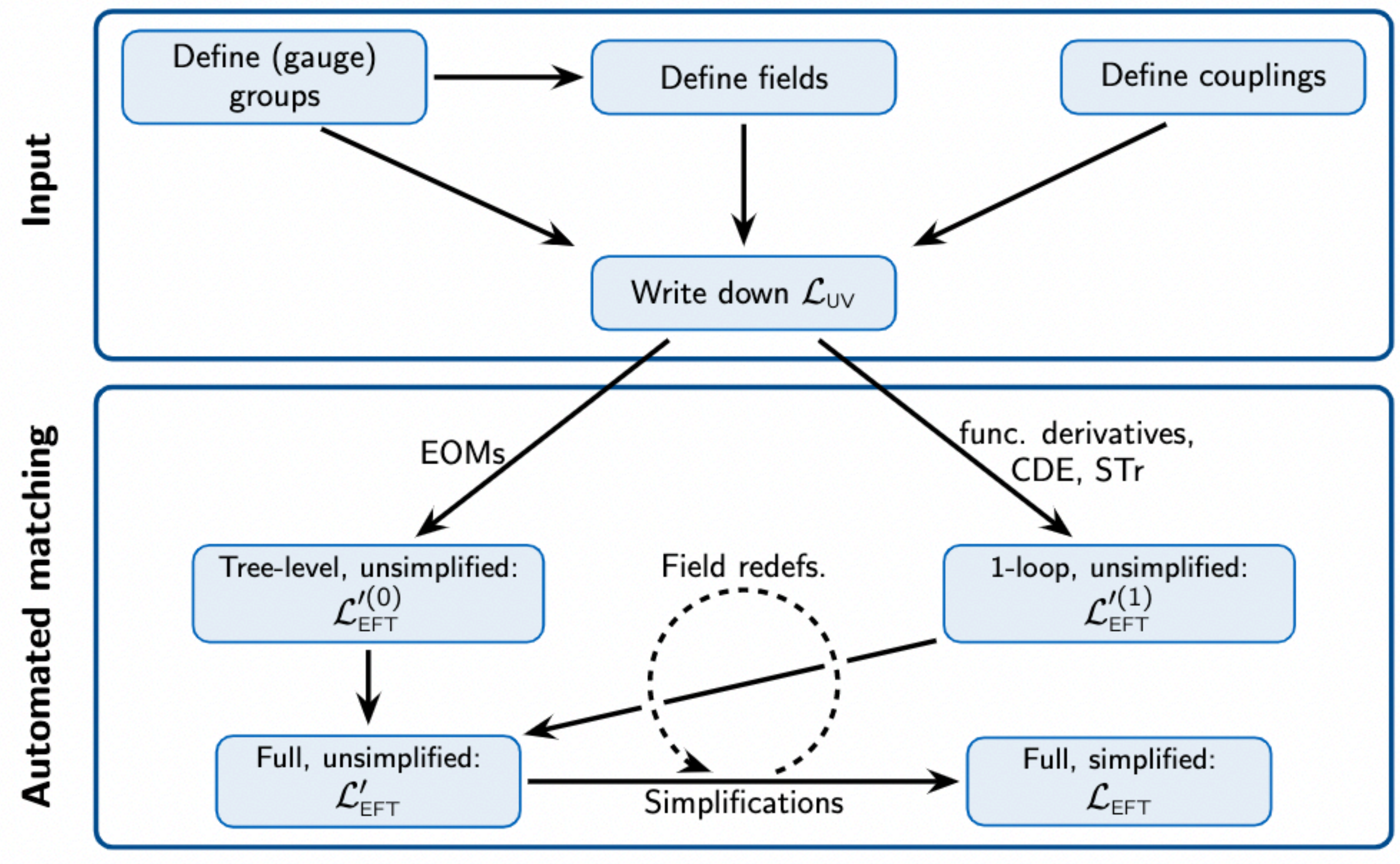
JFM, Portolés, Ruiz-Femenía, 1607.02142; Zhang 1610.00710

MATCHETE

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



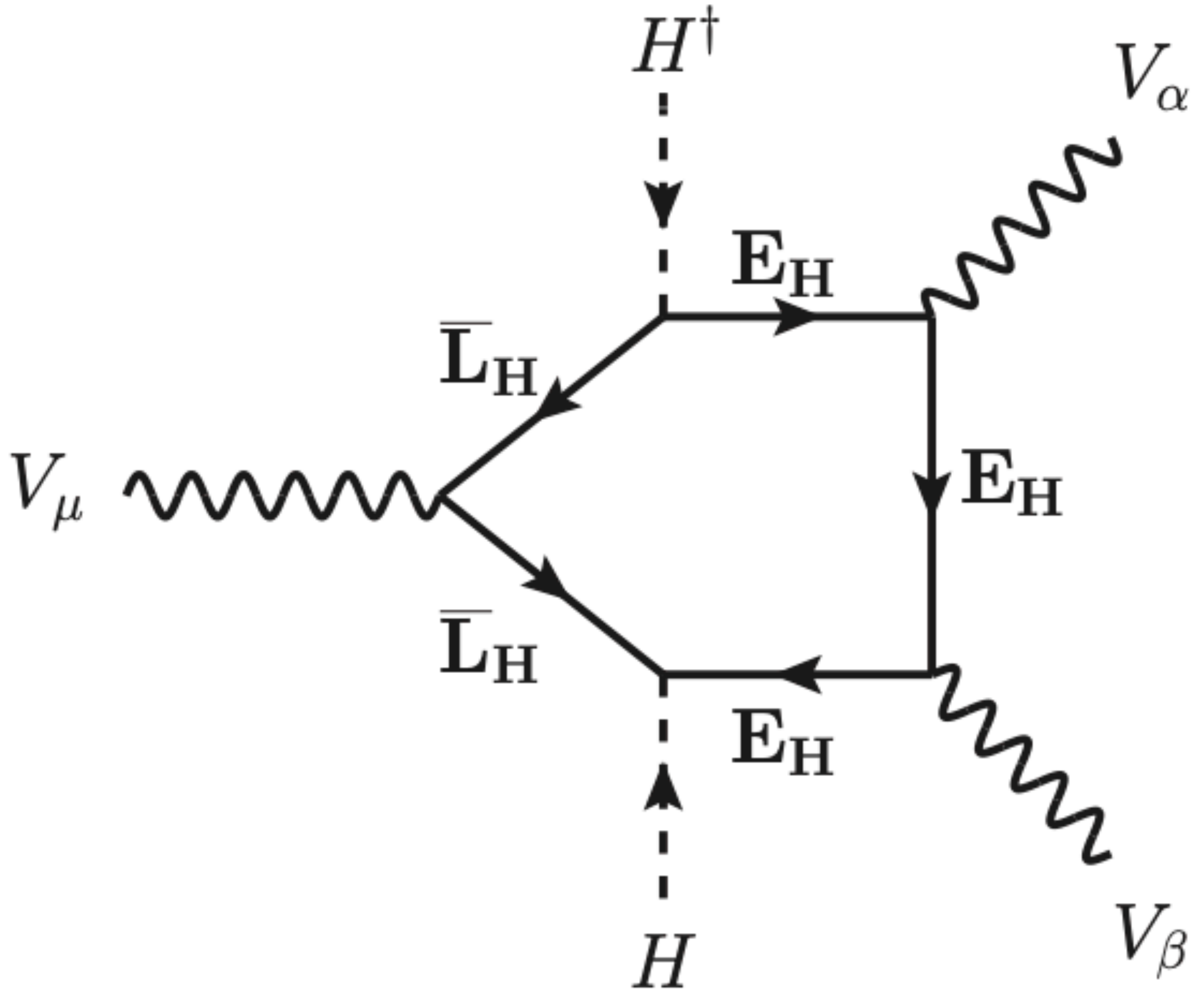
JFM, König, Pagès, Thomsen, Wilsch, 2212.04510

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

Example: neutral triple-gauge interactions

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



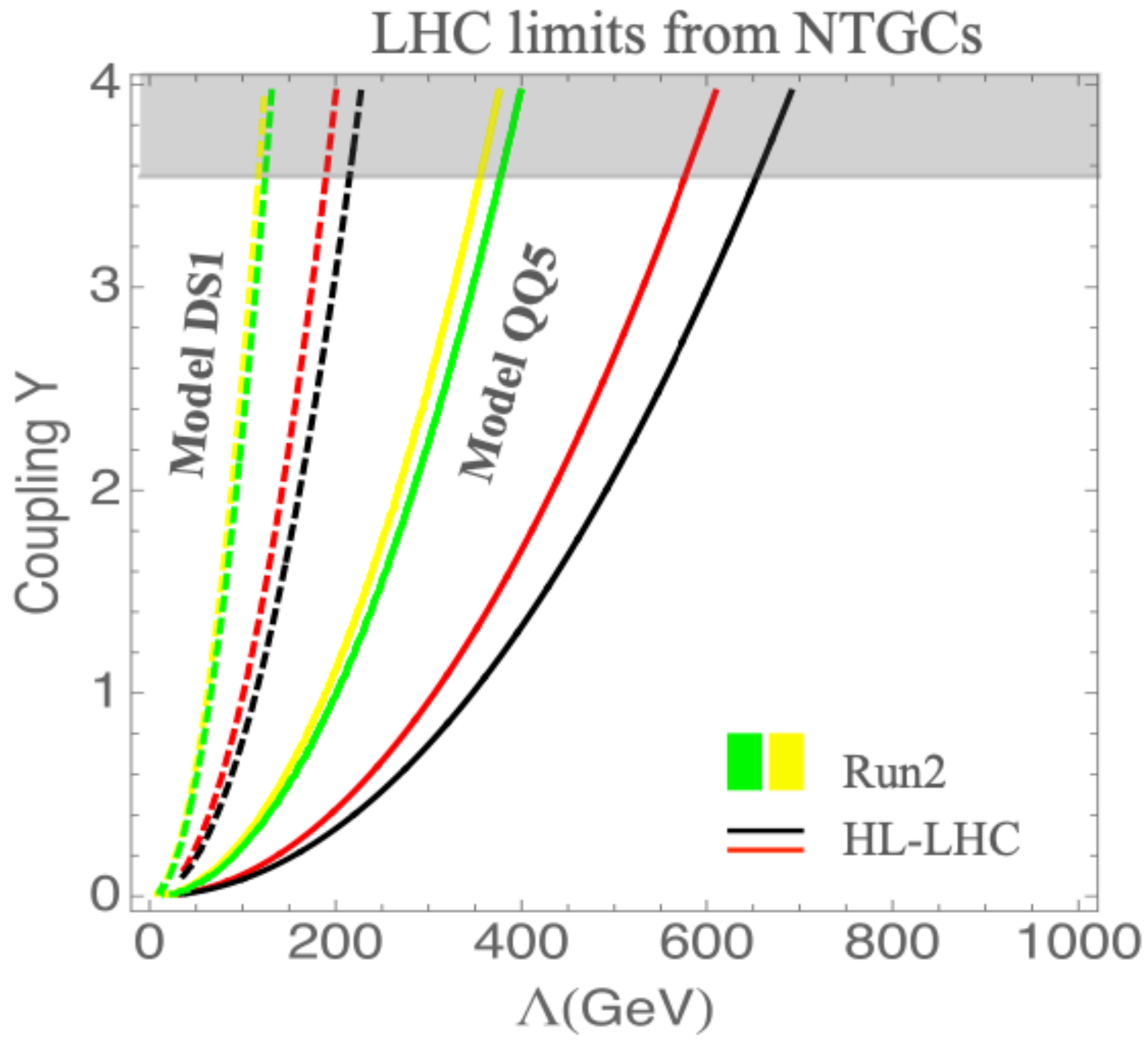
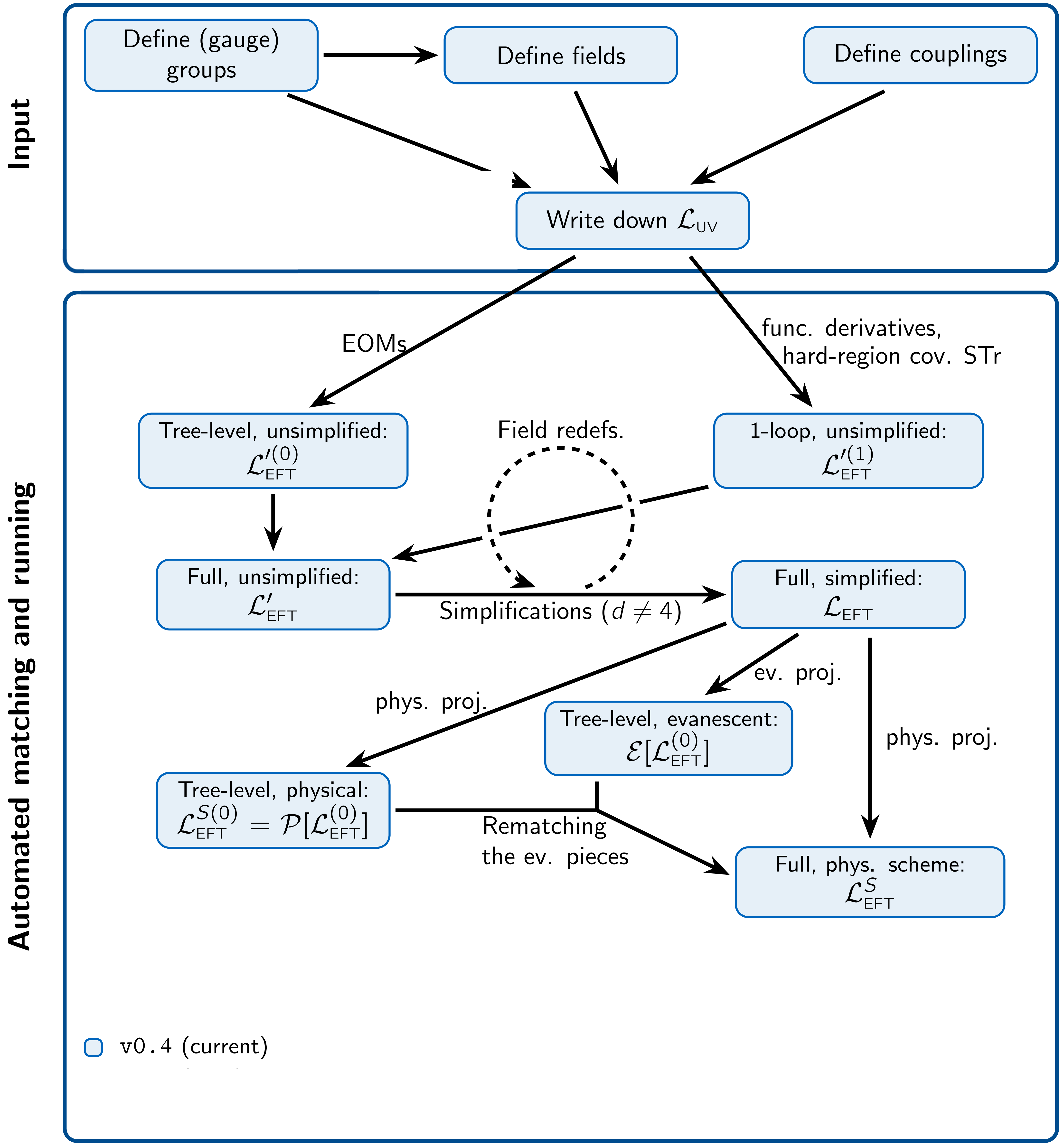


*Diagram and plot from [2402.04306]

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 $\longrightarrow$ 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!

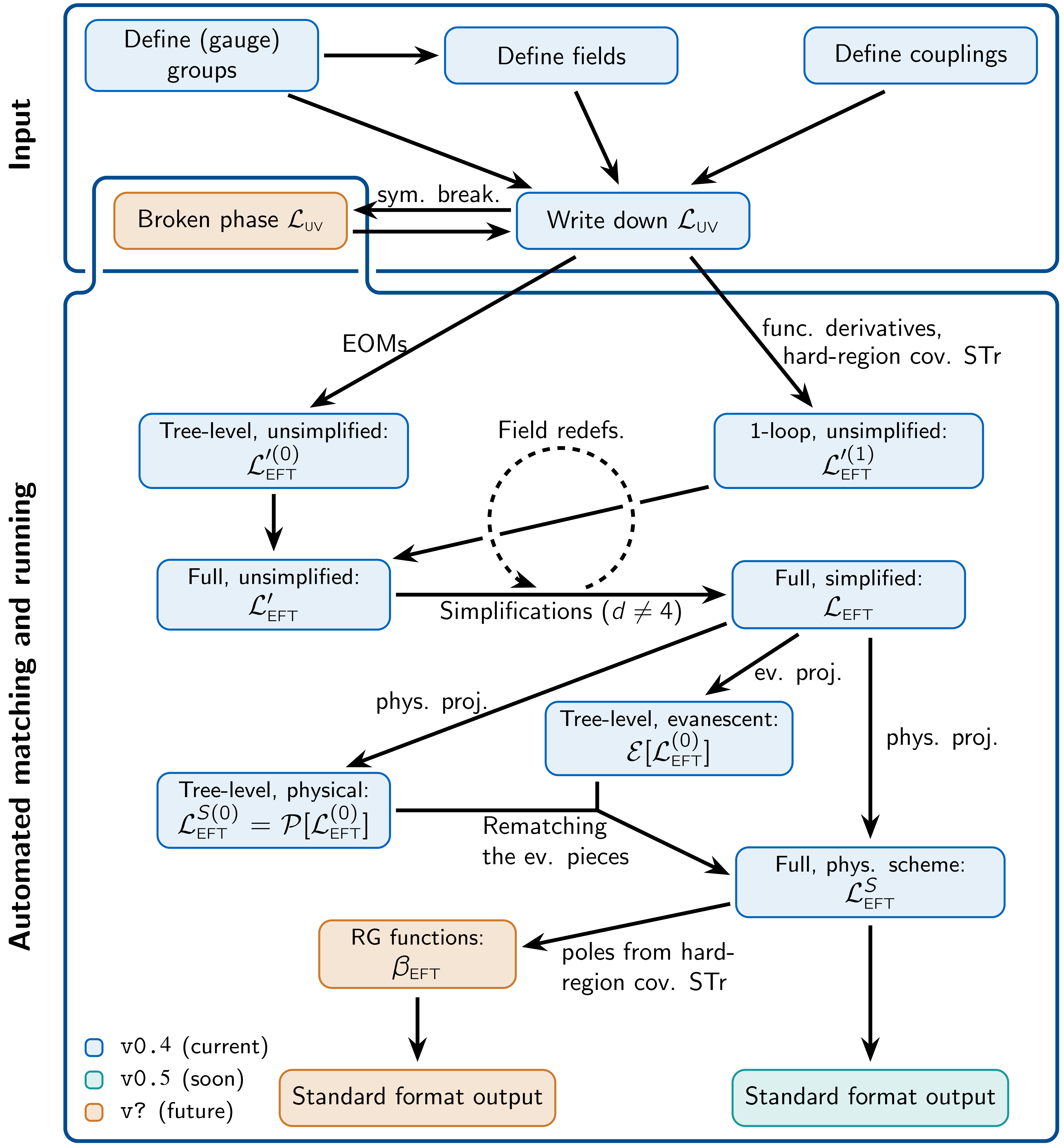
- **Other new features:**

  - 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 β functions
- Symmetry breaking and heavy vectors

- 't Hooft-Veltman scheme for γ_5

  JFM, Moreno-Sanchez, Thomsen 2507.19589 + w.i.p

- Thermal Field Theory

  JFM, Lopez-Miras, Moreno-Sanchez, w.i.p

Longer term

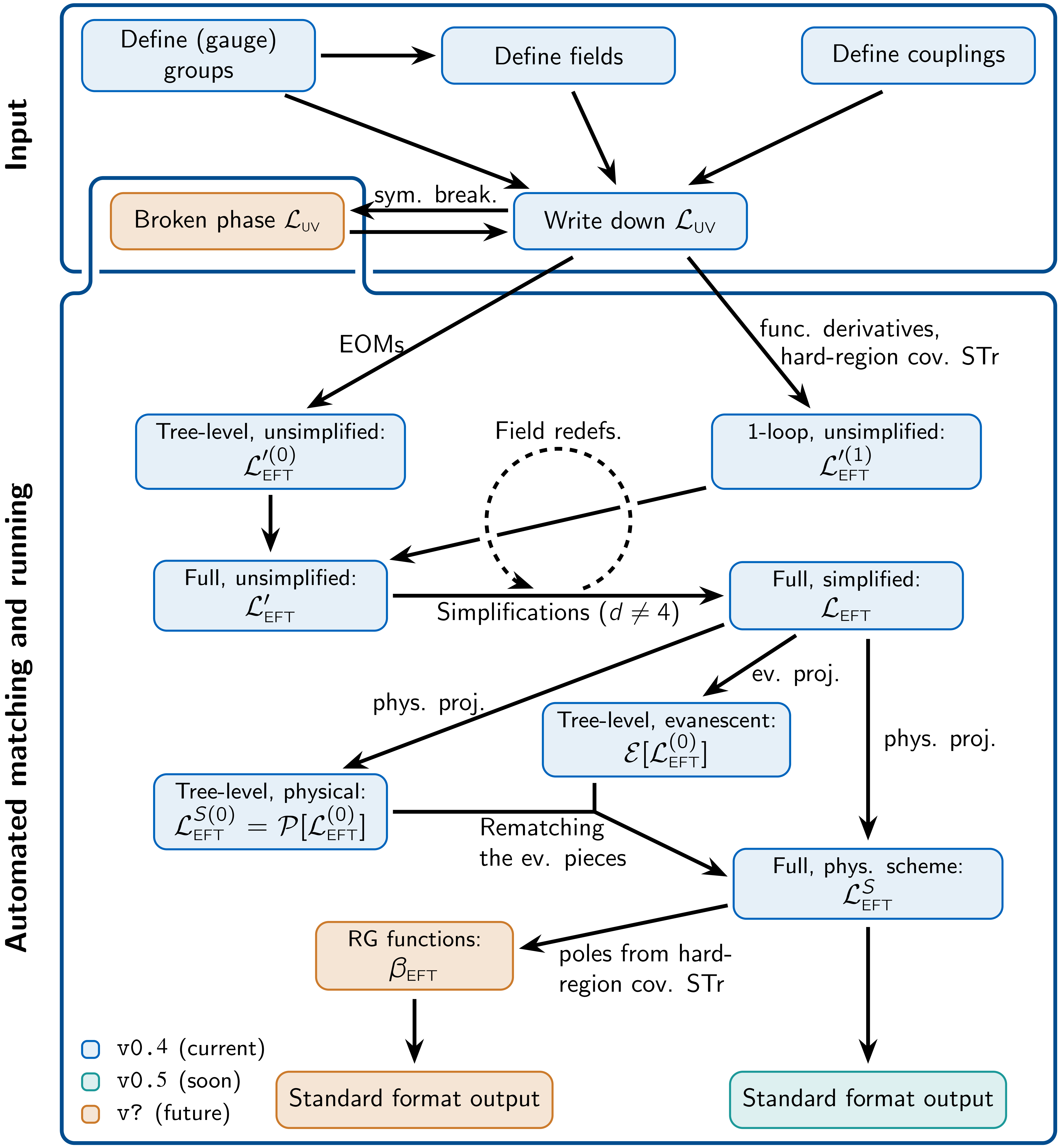
- RG and matching beyond one loop

  — 2-loop RG in the SMEFT

  Born, JFM, Kvedaraitė, Thomsen, 2410.07320

  Born, JFM, Thomsen, w.i.p

Work in progress and future plans



Coming next

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

See talk by Ferrando

- 't Hooft-Veltman scheme for γ_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

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  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 MATCHETE

Born, JFM, Kvedaraitė, Thomsen, 2410.07320

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

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

	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 bosonic SMEFT at NLL

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

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

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

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

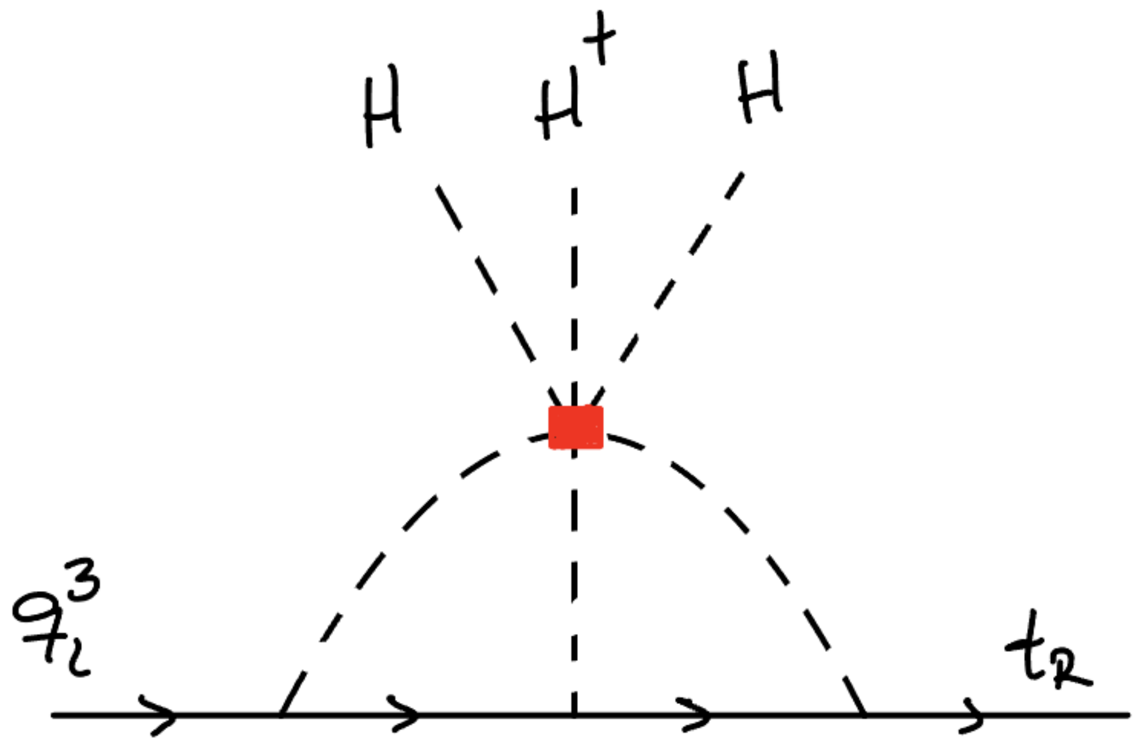
Enlarged mixing: Most operators mix at NLL

Some results in the 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.



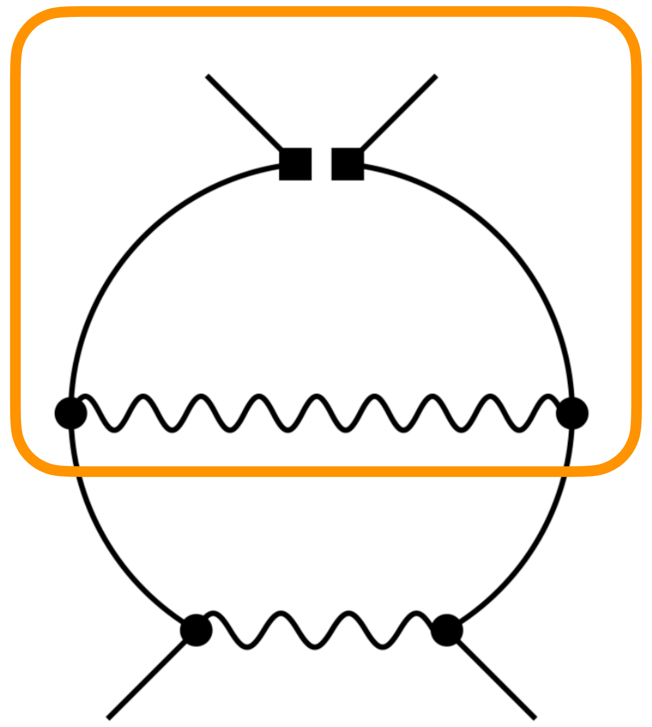
$$\beta^{(2)}_{C_{uH}^{33}} \supset -48\, y_t^3\, C_H$$

Two-loop SMEFT RGEs: new challenges with fermions

Born, JFM, Thomsen, *coming soon*

- Impact of evanescence-free scheme into 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)

- Naive treatment of γ_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 know; 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!

MATCHETE

http://matchete.gitlab.io/

Going beyond one loop

JFM, Palavrić, Thomsen, 2311.13630

JFM, Moreno, Palavrić, Thomsen, 2412.12270

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

$$\mathscr{V}_{IJK} \equiv \left. \frac{\delta^3 \mathscr{L}_{\mathrm{UV}}}{\delta\eta_I\, \delta\eta_J\, \delta\eta_K} \right|_{\eta=\hat{\eta}} \qquad \mathscr{V}_{IJKL} \equiv \left. \frac{\delta^4 \mathscr{L}_{\mathrm{UV}}}{\delta\eta_I\, \delta\eta_J\, \delta\eta_K\, \delta\eta_L} \right|_{\eta=\hat{\eta}}$$

N.B.: $\mathscr{V}_{IJK} = \sum_{m,n} V^{(m,n)}_{ade}(x)\, P^m_y P^n_z\, U(x,y)_{db} U(x,z)_{ec}\, \delta(x-y)\delta(x-z)$

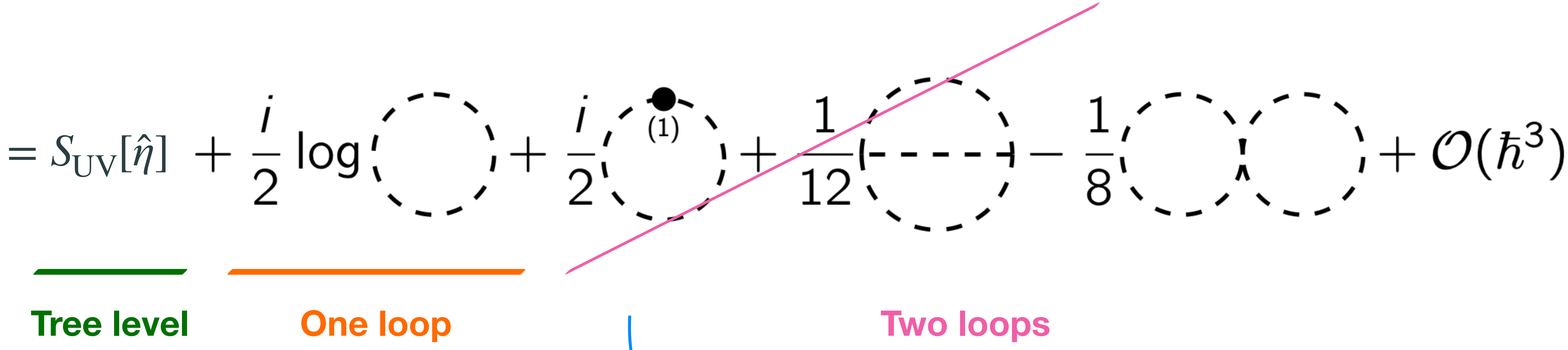
Going beyond one loop

JFM, Palavrić, Thomsen, 2311.13630

JFM, Moreno, Palavrić, Thomsen, 2412.12270

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

$$= S_{\mathrm{UV}}[\hat{\eta}] + \frac{i\hbar}{2}\mathrm{STr}\ln\mathcal{Q} + \frac{i\hbar^2}{2}\mathcal{Q}^{-1}_{IJ}\mathcal{V}^{(1)}_{JI} + \frac{\hbar^2}{12}\mathcal{V}_{IJK}\,\mathcal{Q}^{-1}_{IL}\mathcal{Q}^{-1}_{JM}\mathcal{Q}^{-1}_{KN}\,\mathcal{V}_{LMN} - \frac{\hbar^2}{8}\mathcal{Q}^{-1}_{IJ}\,\mathcal{V}_{IJKL}\,\mathcal{Q}^{-1}_{KL} + \mathcal{O}(\hbar^3)$$

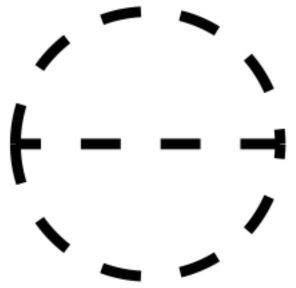


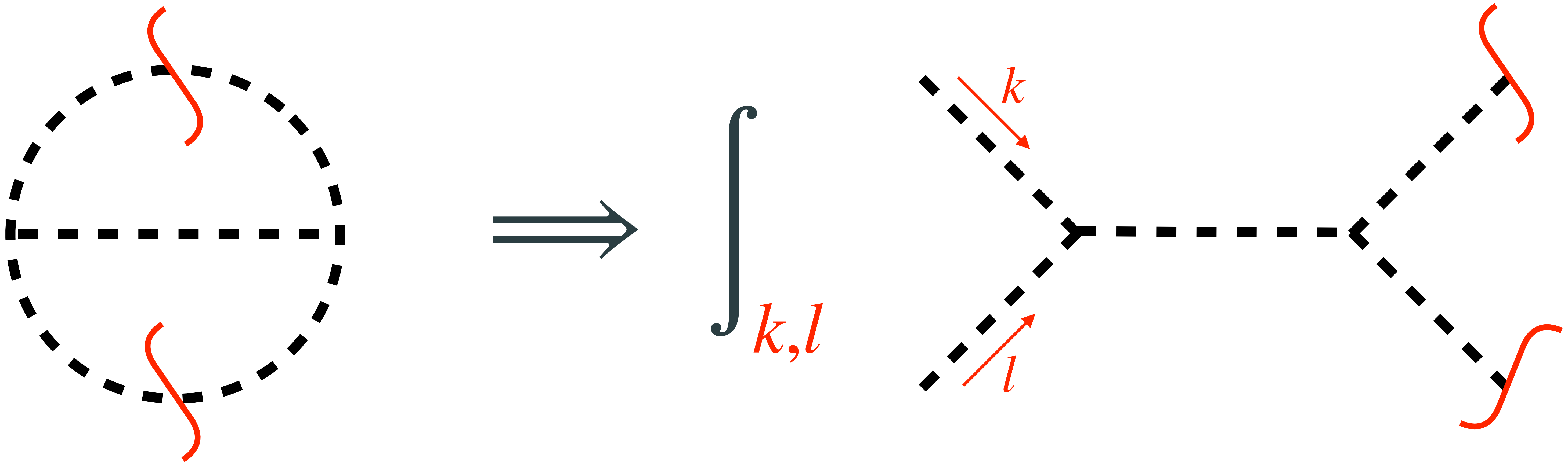
Every two-loop contribution is included here!

Two-loop functional evaluation

JFM, Palavrić, Thomsen, 2311.13630

JFM, Moreno, Palavrić, Thomsen, 2412.12270

How to evaluate  ?



Two-loop functional evaluation

JFM, Palavrić, Thomsen, 2311.13630

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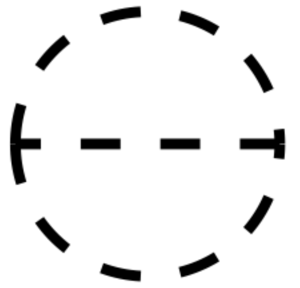
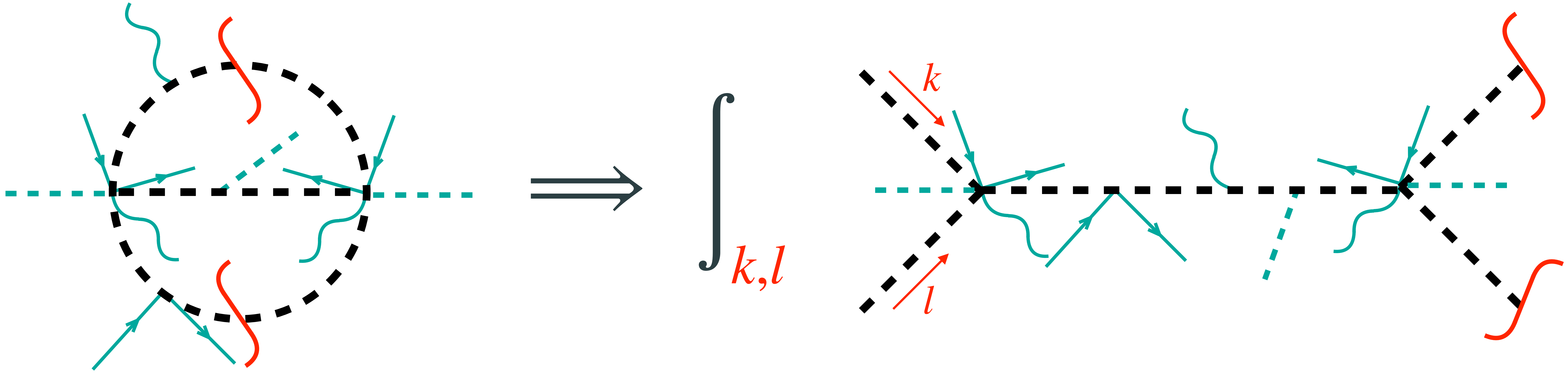
How to evaluate  ?

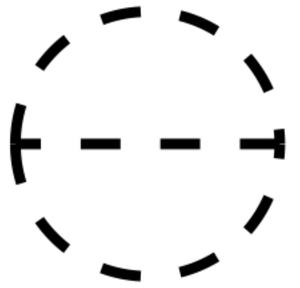


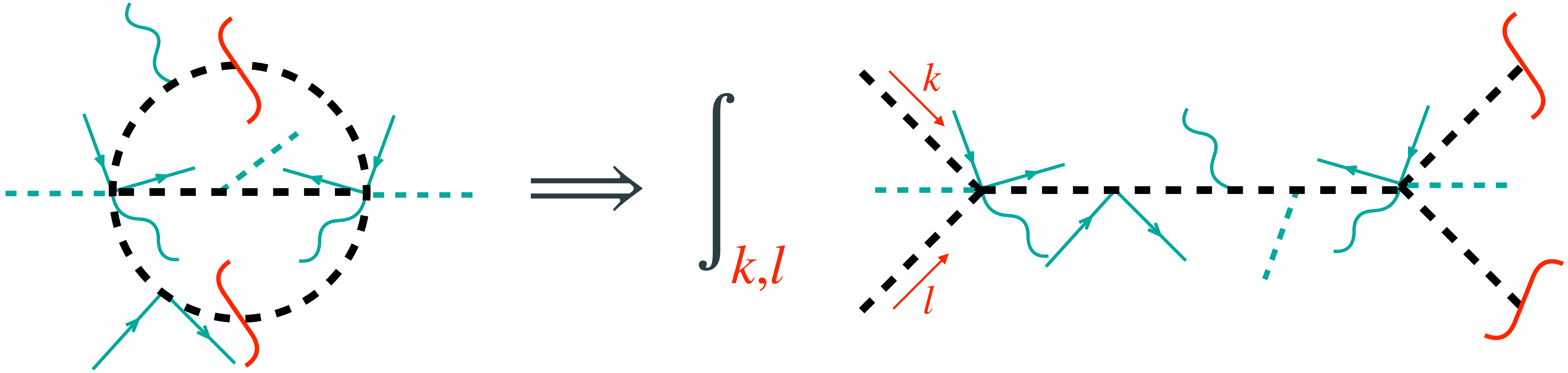
Every (non-factorizable) two-loop contribution is included here!

Two-loop functional evaluation

JFM, Palavrić, Thomsen, 2311.13630

JFM, Moreno, Palavrić, Thomsen, 2412.12270

How to evaluate  ?



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

Valid to *all orders* in the EFT expansion!

γ_5 schemes in dimensional regularization

- Naive Dimensional Regularization (NDR) scheme:

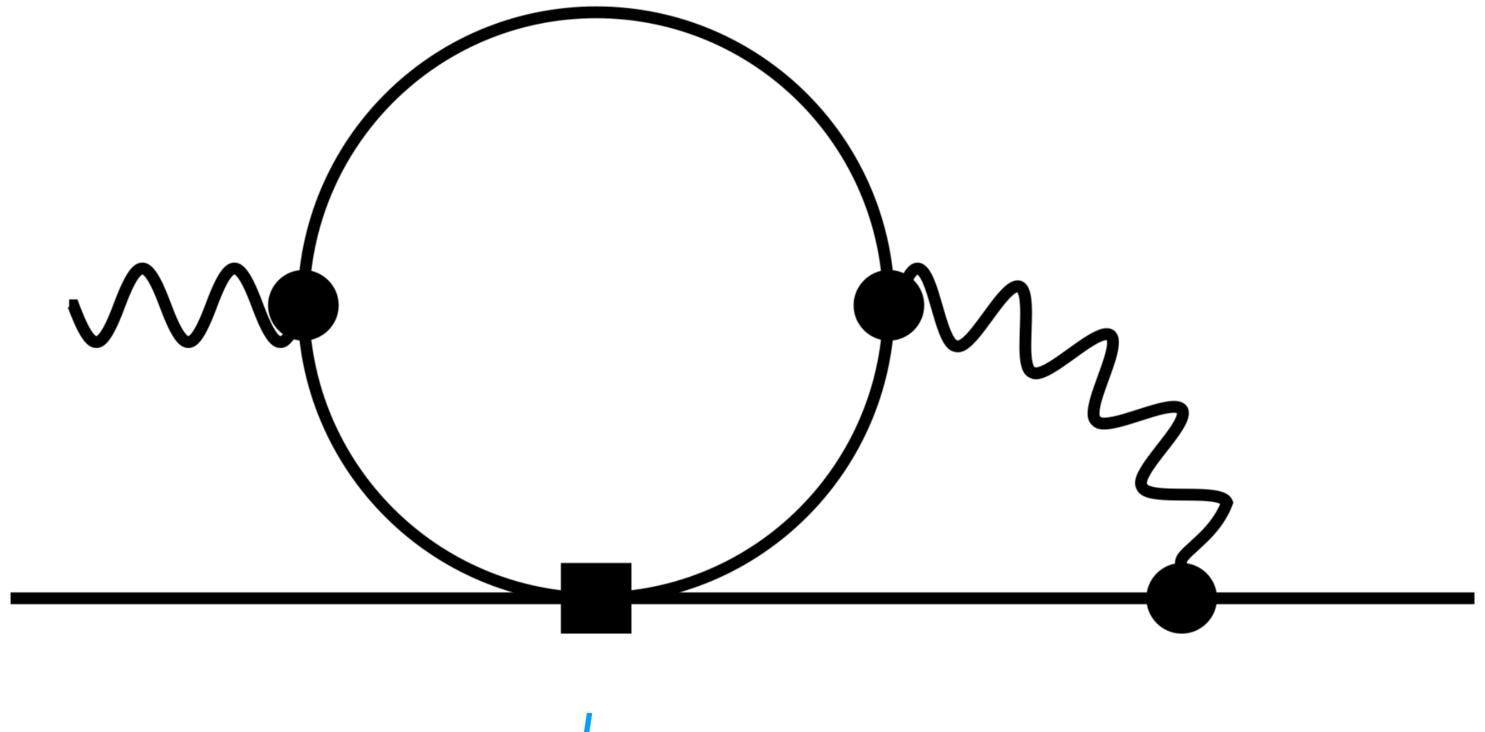
$$\left.\begin{array}{l} \{\gamma_\mu,\gamma_\nu\} = 2g_{\mu\nu}, \qquad \{\gamma_\mu,\gamma_5\} = 0, \qquad \gamma_5^2 = I \\ \mathrm{tr}\left[\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_5\right] \xrightarrow[d\to 4]{} -4i\varepsilon_{\mu\nu\rho\sigma} \end{array}\right\} \Longrightarrow \begin{array}{l}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

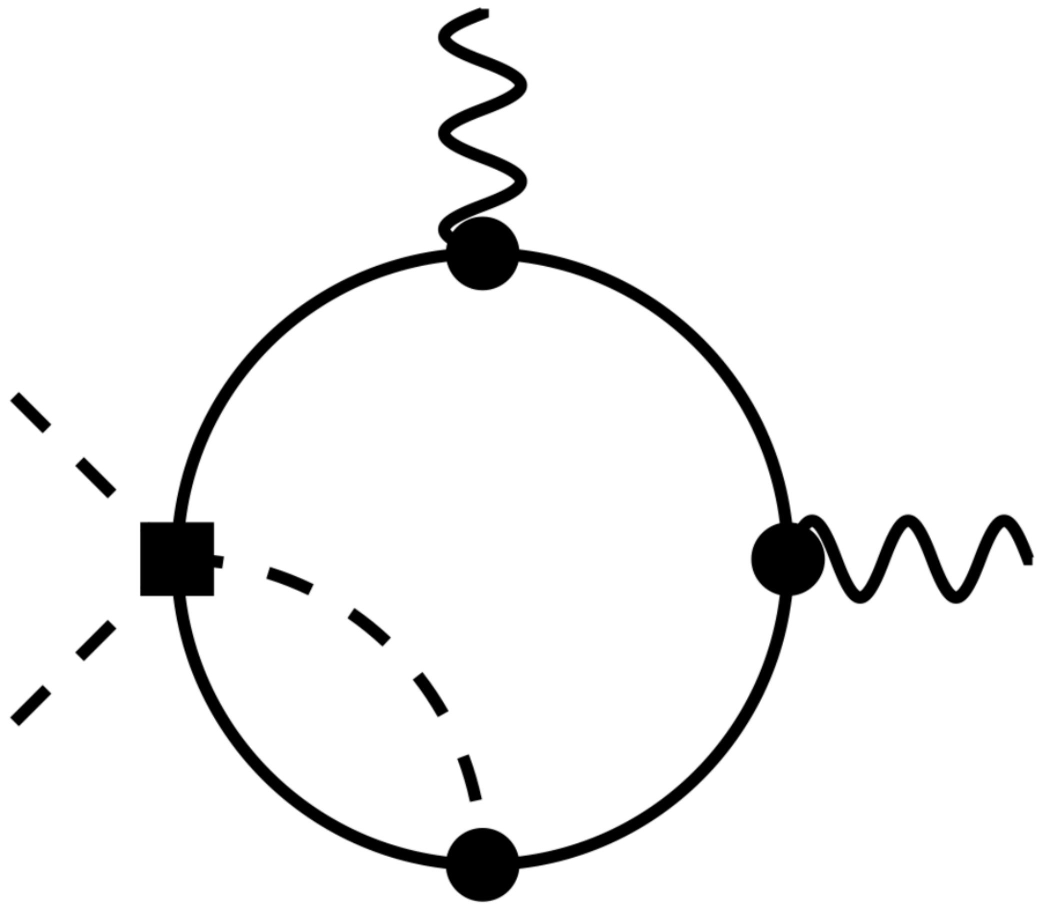
- Breitenlohner-Maison-'t Hooft-Veltman (BMHV) scheme:

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

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

Start at dimension-six operator





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

“Unclear” prescription