Tools for EFT matching

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WG1-GLOB Meeting: Global interpretations in (SM)EFT and UV complete models

The EFT approach: motivation

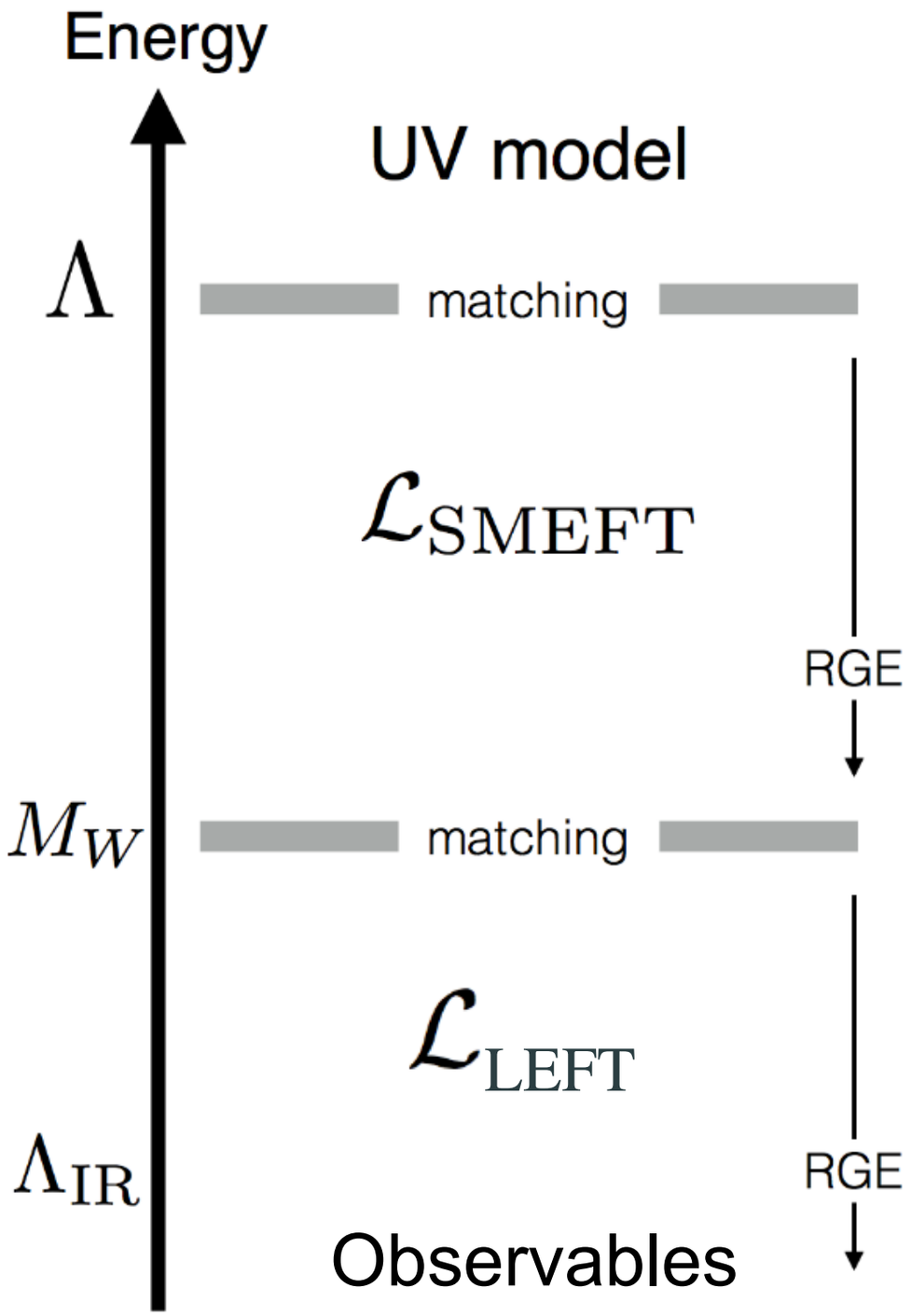
BSM computations of experimental observables are multi-scale problems: Precision requires the EFT approach

Much progress has been made:

- Tree-level matching to the SMEFT is a solved problem

  [de Blas, Criado, Pérez-Victoria, Santiago, 1711.10391]

  MatchingTools: [Criado, 1710.06445]



The EFT approach: motivation

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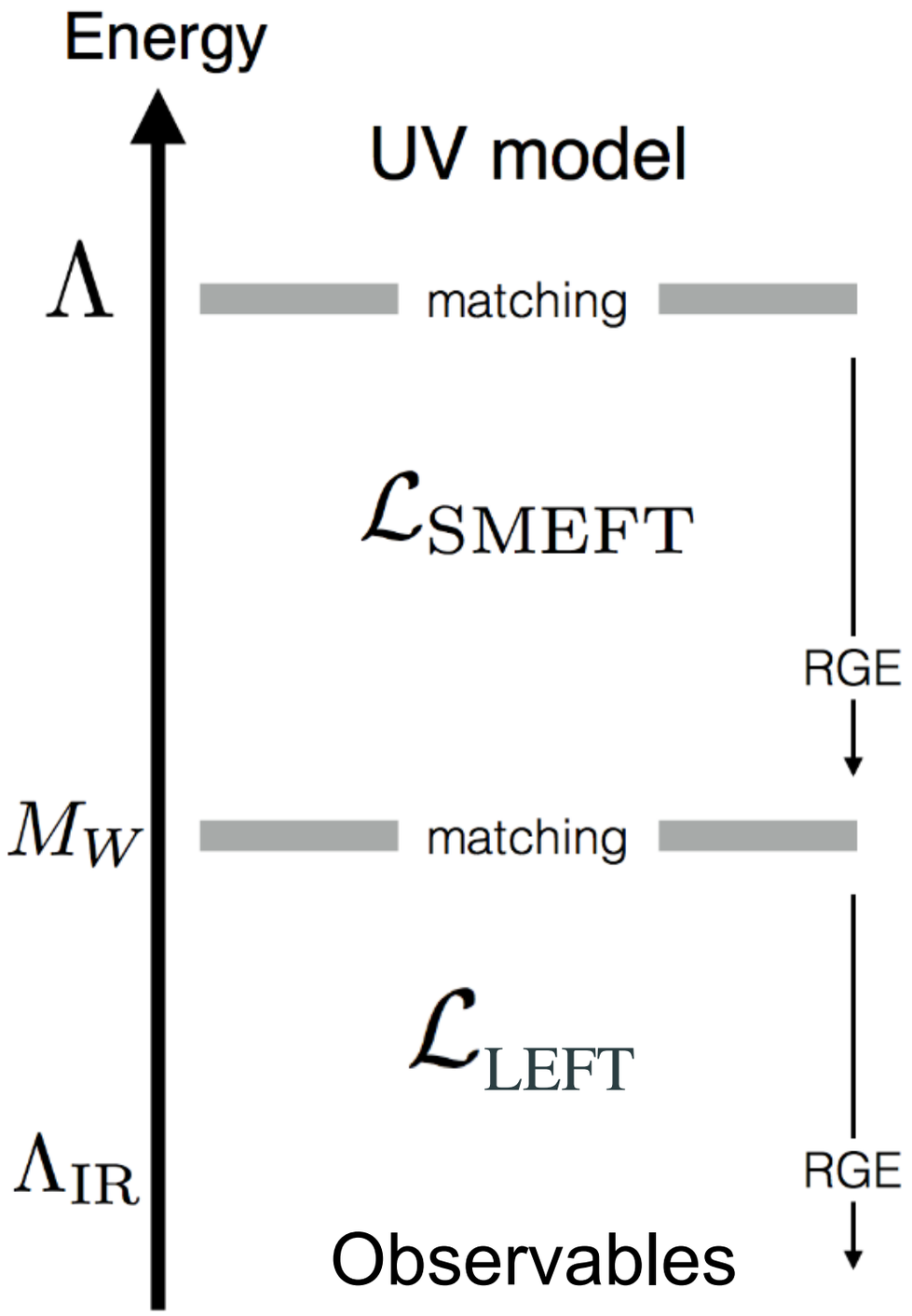
- RGE evolution in the SMEFT and LEFT, and one-loop matching of the SMEFT to the LEFT is also known

  [Jenkins, Manohar, Trott, 1308.2627, 1310.4838, Alonso et al., 1312.2014, Jenkins, Manohar, Stoffer, 1709.04486, 1711.05270; Dekens, Stoffer, 1908.05295]

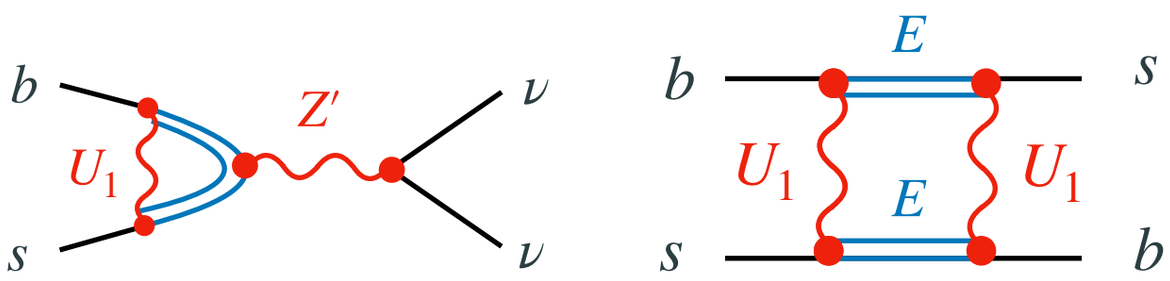
  DsixTools and Wilson:
  [JFM, Ruiz-Femenía, Vicente, Virto, 2010.16341; Aebischer, Kumar, Straub, 1804.05033]



The EFT approach: the need to go beyond

However, it is necessary to go beyond:

- One-loop can be the leading effect in important processes



- Perhaps the relevant EFT below the EW scale is not the SMEFT, e.g.

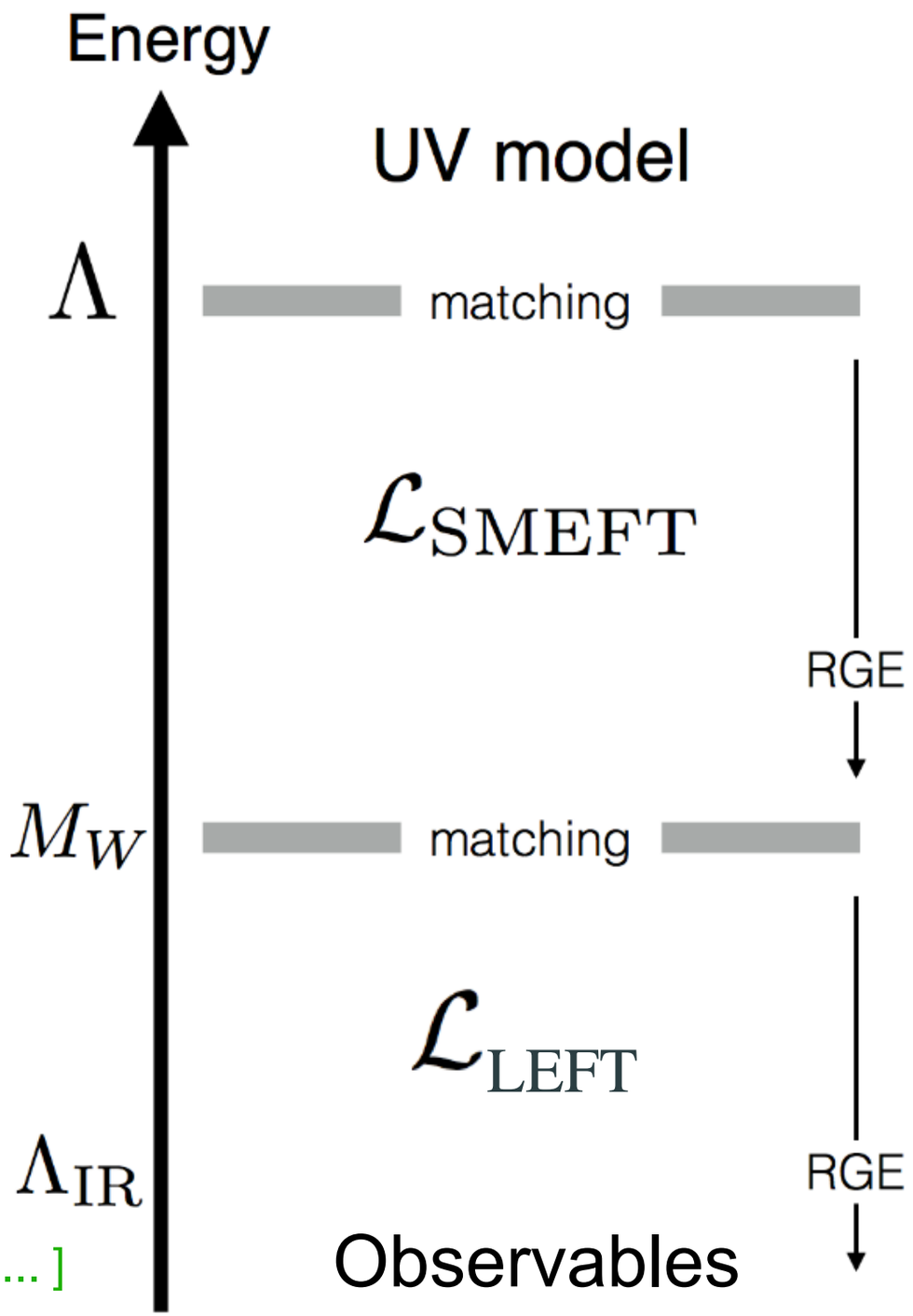
  - SM + ALP EFT

    [Chala, Guedes, Ramos, Santiago, 2012.09017;
    Bauer et al., 2012.12272;
    Galda, Neubert, Renner, 2105.01078;...]

  - SM + DM EFT

    [Criado, Djouadi, Pérez-Victoria, Santiago, 2104.14443,...]

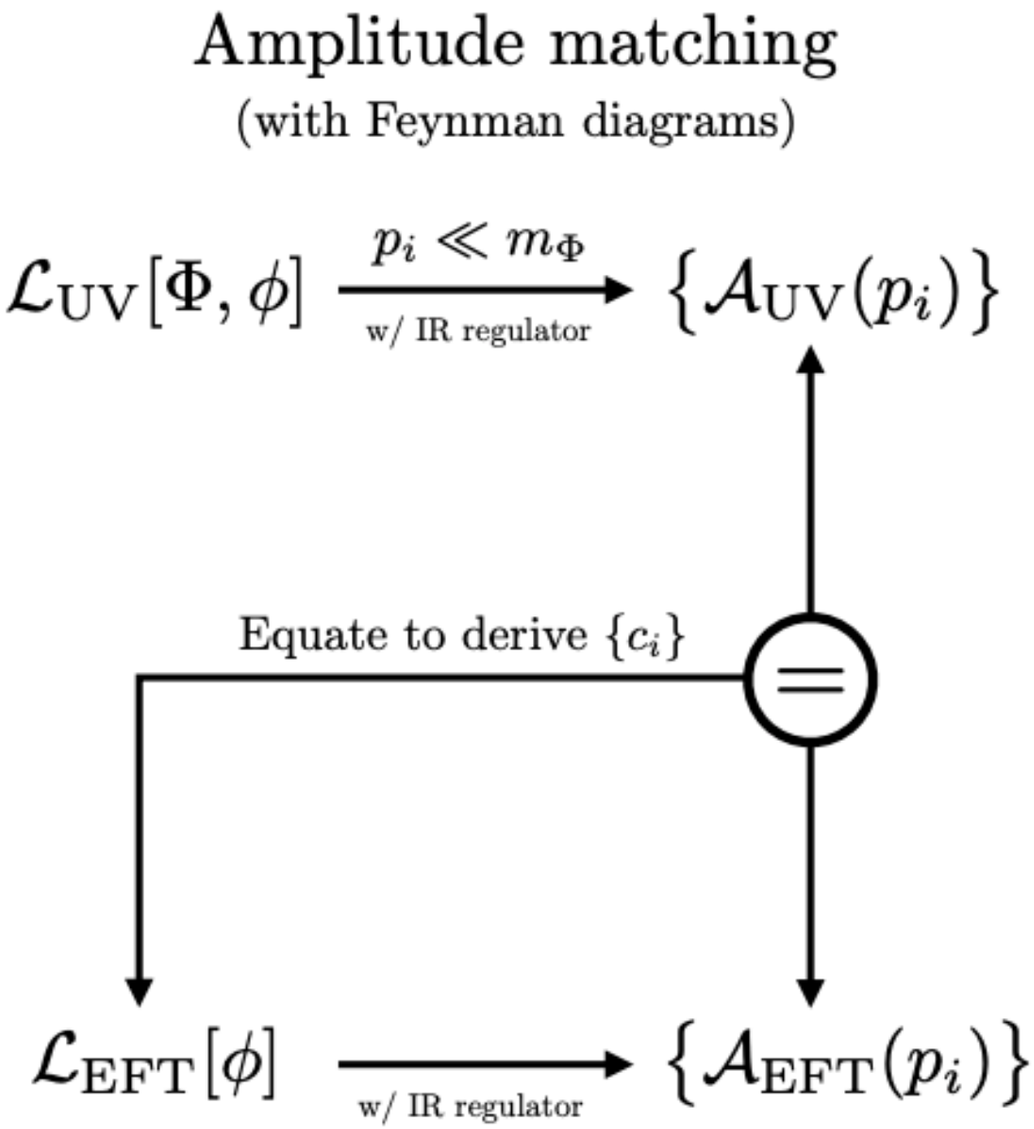
  - …



Current theory status

Matching techniques: strengths and shortcomings

The tools of the trade: diagrammatic matching



[Figure from Cohen, Lu, Zhang, 2011.02484]

- Traditional, well-established matching procedure. Valid to any loop order
- Matching usually done off-shell: Additional redundancies but need to consider 1LPI diagrams only
- Need a priori knowledge of the EFT Lagrangian in Green's basis and with redundancies (e.g. Fierz related ops.)

  [SMEFT basis in Carmona, Lazopoulos, Olgoso, Santiago, 2112.10787; Gherardi, Marzocca, Venturini, 2003.12525]

The tools of the trade: expansion by regions

Expansion by regions provides a method for scale separation in dimensional regularization:

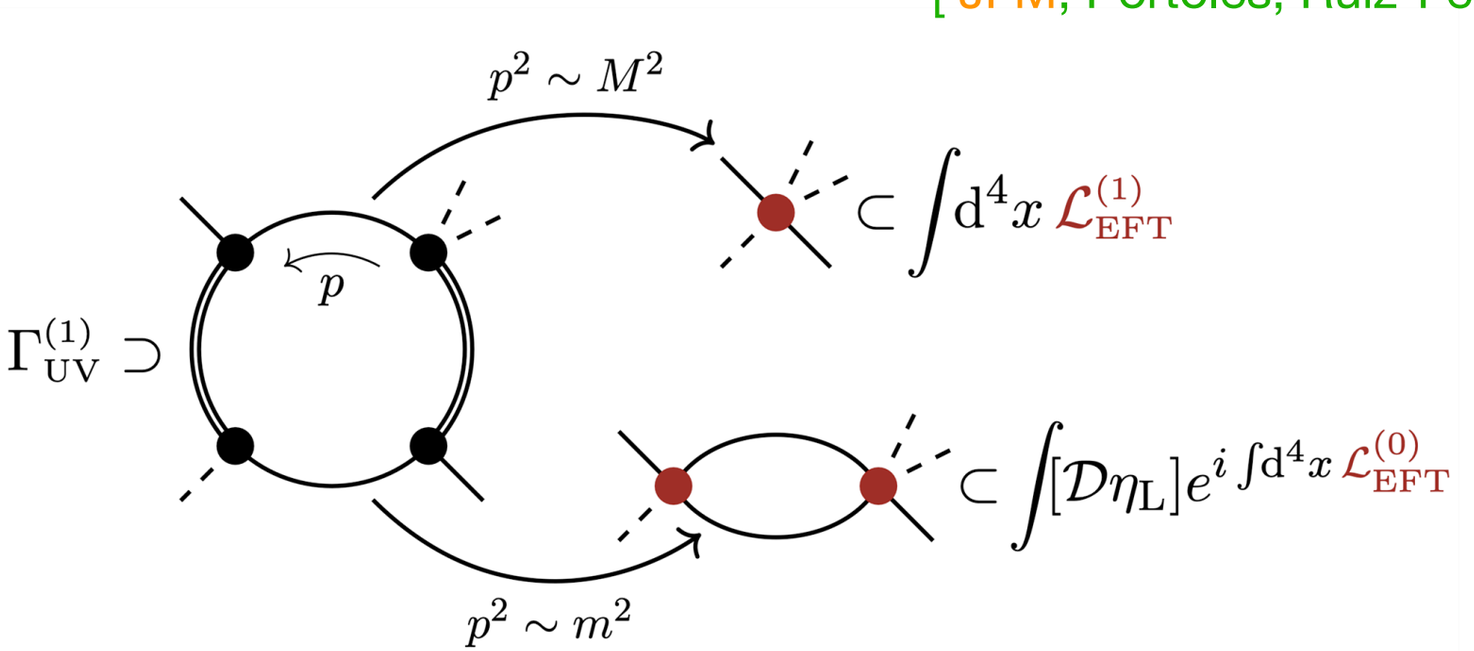
[Beneke, Smirnov, hep-ph/9711391; Jantzen, 1111.2589]

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

Heavy field loops | Mixed field loops | Light field loops

No need to subtract non-local EFT contributions in only the hard part of the loop is considered

[JFM, Portolés, Ruiz-Femenía, 1607.02142]



The tools of the trade: functional matching

Instead, one can use functional methods to *directly* integrate out the heavy dynamics

[modern method based on Henning, Lu, Murayama, 1412.1837; JFM, Portolés, Ruiz-Femenía, 1607.02142]

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

$\hat{\eta}$: Classical configuration (tree lines)

η : Quantum fluctuation (loop lines)

expanding around the classical solution

$$\Gamma^{(1)}_{\rm UV} = \frac{i}{2}\,{\rm STr}\ln\left(\Delta^{-1} - X\right)$$

Contain derivatives

$$\delta_{ij}\,\Delta_i^{-1}(\hat{P}, M_i) - X_{ij}(\hat{P}, \hat{\eta}) = \left.\frac{\delta^2 \mathscr{L}_{\rm UV}}{\delta\eta_j \delta\bar{\eta}_i}\right|_{\eta=\hat{\eta}}$$

master formula for 1-loop matching: (evaluated with CDE) [Cohen, Lu, Zhang, 2011.02484]

$$\int d^d x\ \mathscr{L}^{(1)}_{\rm EFT} = \left.\frac{i}{2}{\rm STr}\left(\ln\,\Delta^{-1}\right)\right|_{\rm hard} - \left.\frac{i}{2}\sum_{n=1}^{\infty}{\rm STr}\left[(\Delta X)^n\right]\right|_{\rm hard}$$

log-type supertrace — power-type supertrace

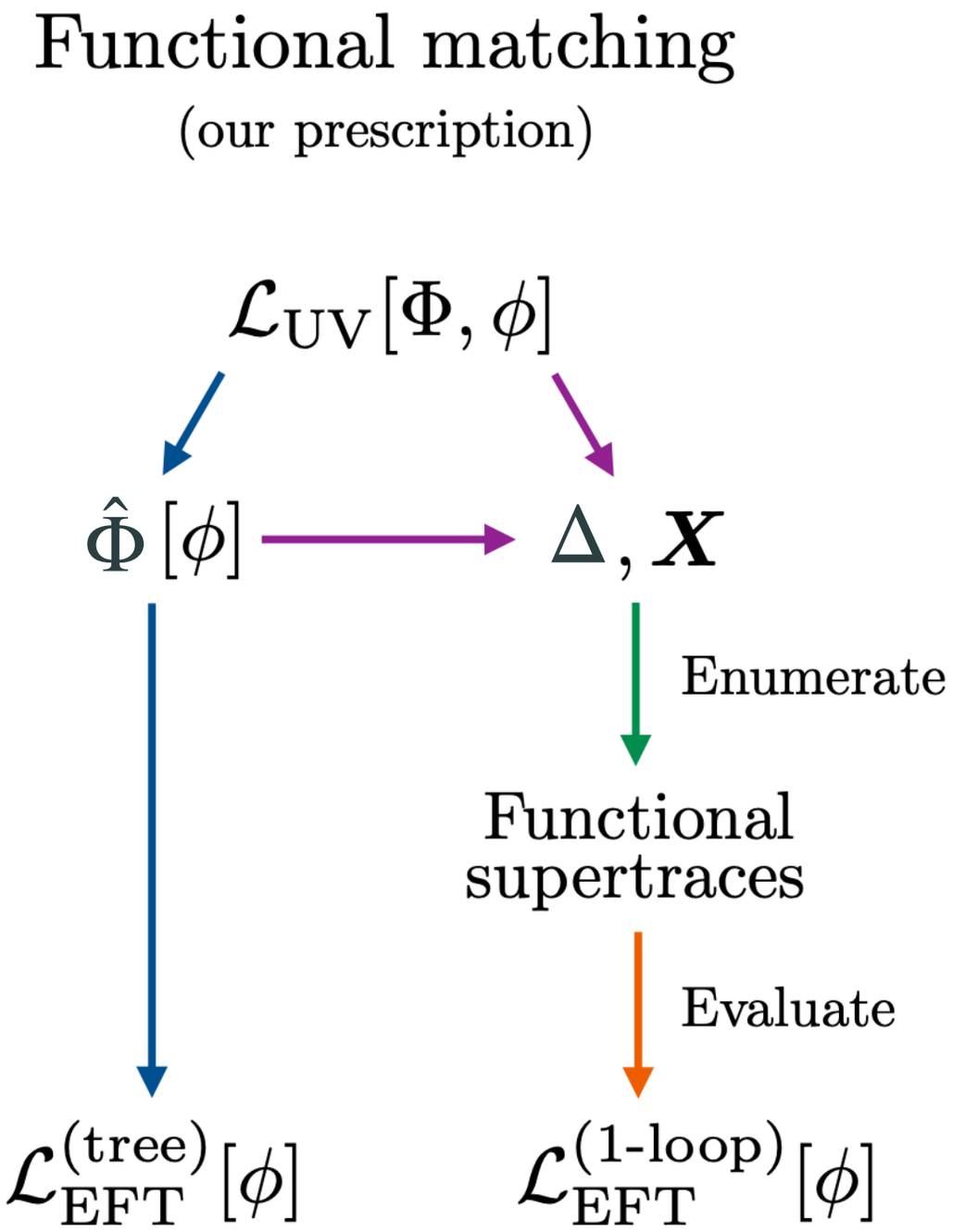
STrEAM

[Cohen, Lu, Zhang, 2012.07851]

SUPER TRACER

[JFM, König, Pagès, Thomsen, Wilsch, 2012.08506]

The tools of the trade: functional matching



[Figure from Cohen, Lu, Zhang, 2011.02484]

- Many aspects developed only recently.
  Currently well-established up to one loop only

  [Henning, Lu, Murayama, 1412.1837; del Aguila, Kunszt, Santiago, 1602.00126; JF, Portolés, Ruiz-Femenía, 1607.02142; Henning, Lu, Murayama, 1604.01019; Zhang, 1610.00710; Cohen, Lu, Zhang, 2011.02484...]

- Some closed-form formulas are known

  [Drozd et al.,1512.03003; Ellis et al., 1604.02445; Ellis et al., 1706.07765; Summ, Voight, 1806.05171; Krämer, Summ, Voight, 1908.04798; Ellis et al., 2006.16260; Angelescu, Huang, 2006.16532]

- Manifestly gauge invariant by construction

  [Gaillard '86, Chan '86, Cheyette '88]

- The EFT Lagrangian comes out automatically.
  No knowledge of the EFT Lagrangian required!

EFT basis reduction

An important limitation in both off-shell diagrammatic matching and functional matching is the reduction of the result to an EFT basis (requiring IBPs, Fierz, group identities,…)

In particular, using 4d Fierz identities and gamma product reduction introduces evanescent contributions

[Buras, Weisz '90; Herrlich, Nierste, hep-ph/9412375;…]

E.g. in $d = 4$ dimensions

$$\left[\mathcal{L}_{\text{EFT}} \supset C_{lqde}^{prst}(\bar{\ell}^p \gamma_\mu q^t)(\bar{d}^s \gamma^\mu e^r)\right] \quad = \quad \left[\tilde{\mathcal{L}}_{\text{EFT}} \supset -2C_{lqde}^{prst}(\bar{\ell}^p e^r)(\bar{d}^s q^t)\right]$$

but at one loop (where $d = 4 - 2\epsilon$)

$$\Gamma^{(1)}_{\text{EFT}} \quad \neq \quad \tilde{\Gamma}^{(1)}_{\text{EFT}}$$

4d Fierz identities require extra contributions coming from evanescent terms

[For dimension-six SMEFT: JFM, König, Pagès, Thomsen, Wilsch, w.i.p]

Code implementations

Towards fully automated one-loop matching

Towards fully automated matching

Wish list for automated (SM)EFT matching codes:*

- Easy to use: Lagrangian in, Lagrangian/Wilson Coefficients out
- Flexible: Valid for any NP models and arbitrary EFTs (not only SMEFT/LEFT or dimension 6)
- Interface with existing SMEFT codes (phenomenology pipeline)
- Easy to test and validate (benchmark models, open source code, etc.)

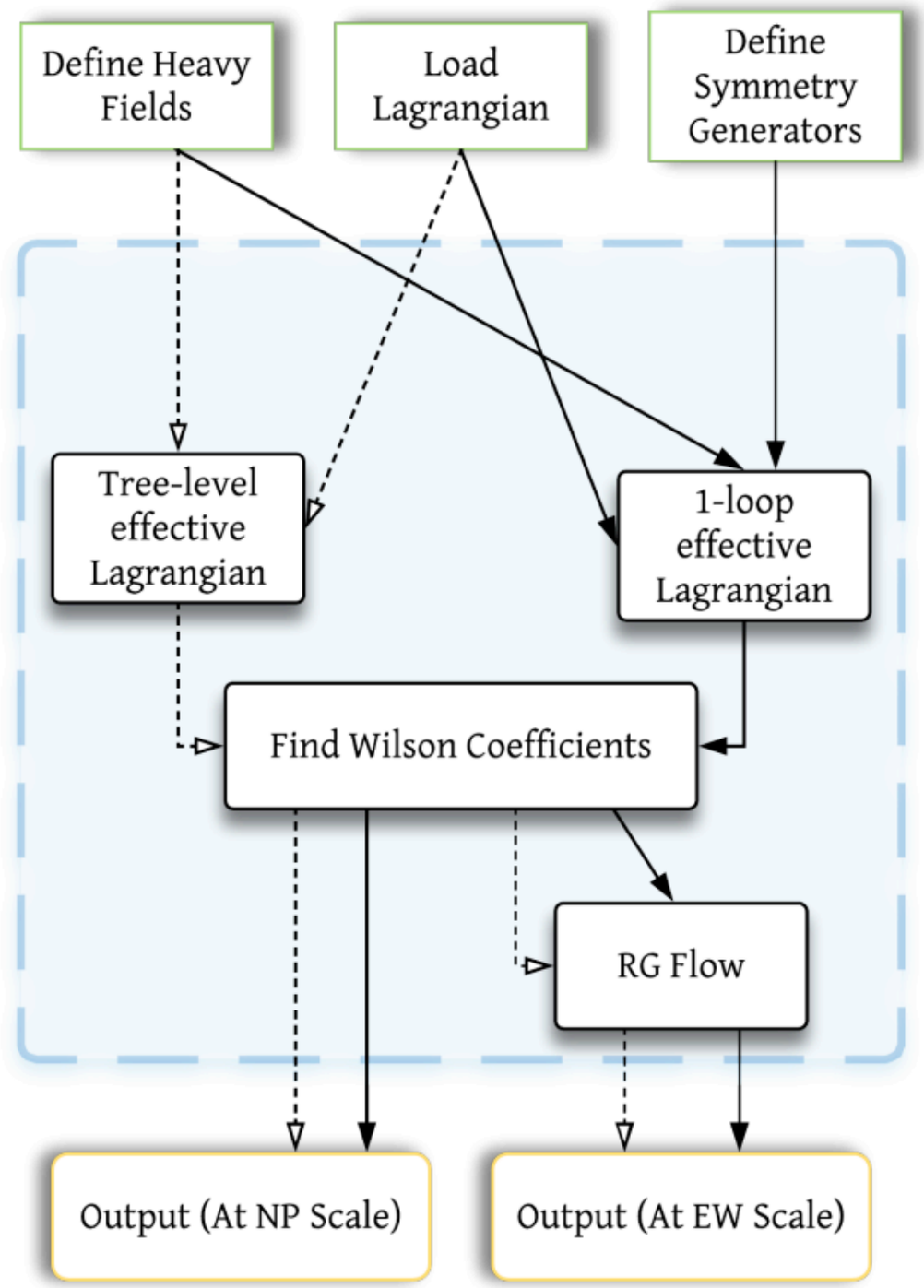
General procedure for code comparison (including theory assumptions, conventions,…) in *LHC EFT WG Area 5 Note: Precision matching of microscopic physics to the SMEFT* (to appear)

https://gitlab.com/modelmatch/ModelMatch

Three collaborations are currently working on implementations

*Comments and wishes from the audience are welcome!

CoDEx



[Das Bakshi, Chakrabortty, Patra, 1808.04403]

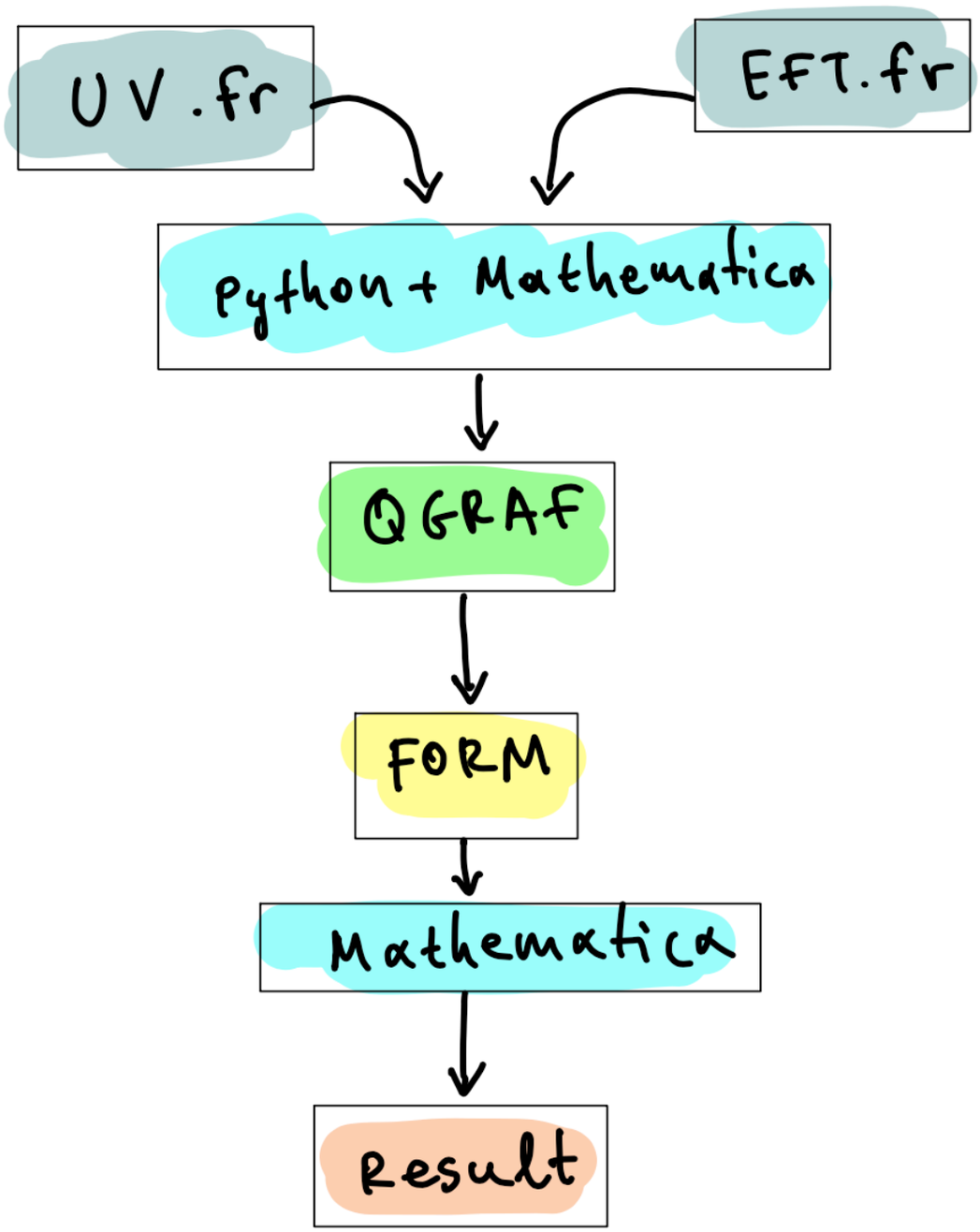
- Mathematica package
- Matching to the dim-6 SMEFT only (Warsaw and SILH bases)
- Based on closed-form functional matching expressions
- Currently only heavy-field loops, and partial mixed heavy-light contributions. Working on including other contributions

[See e.g., Anisha et al., 2111.05876]

MatchmakerEFT

[Carmona, Lazopoulos, Olgoso, Santiago, 2112.10787]

https://ftae.ugr.es/matchmakereft/



[Figure from Lazopoulos at ETH seminar]

Tree-level and one-loop matching of any UV model to its EFT, and RGE computations

- **Input:** UV and EFT models in FeynRules, plus gauge information, reduction to the EFT basis
- **Output:** EFT WCs as a replacement lists
- **Pipeline:**

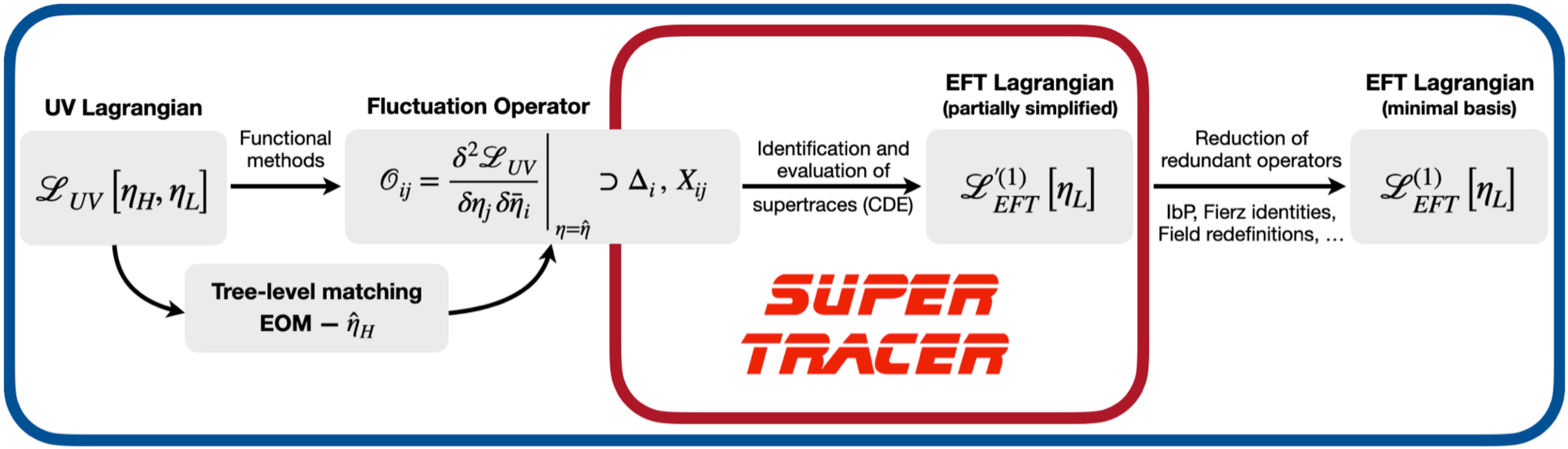
  python+Mathematica prepare internal model files

  QGRAF creates necessary diagrams

  form code does the hard region expansion, tensor reduction and the Dirac algebra

  Mathematica collects results and solves for WCs

Matchete and SuperTracer



MATCHETE

[JFM, König, Pagès, Thomsen, Wilsch, w.i.p]

Mathematica Package(s)

- **User input/output:**

  UV/EFT Lagrangian as one would write on paper (includes group theory module)

  Aim to provide an easy interface with other EFT tools

- **Automation of:**

  ✓ Tree-level matching: derivation and solution of EOMs

  ✓ One-loop matching: construction and evaluation of supertraces (SuperTracer)

  - Output simplifications (w.i.p): removing redundant operators (including evanescent terms)

Let’s see how they work!

An example of Matchmakereft and Matchete in action

A simple matching example

One loop matching of an SM extension with a scalar SM-singlet

$$\mathscr{L}_{\rm UV} = \mathscr{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}M_S^2 S^2 - \frac{1}{24}\lambda_S S^4 - \frac{1}{2}\lambda_{SH}(H^\dagger H) S^2 - \kappa (H^\dagger H) S$$

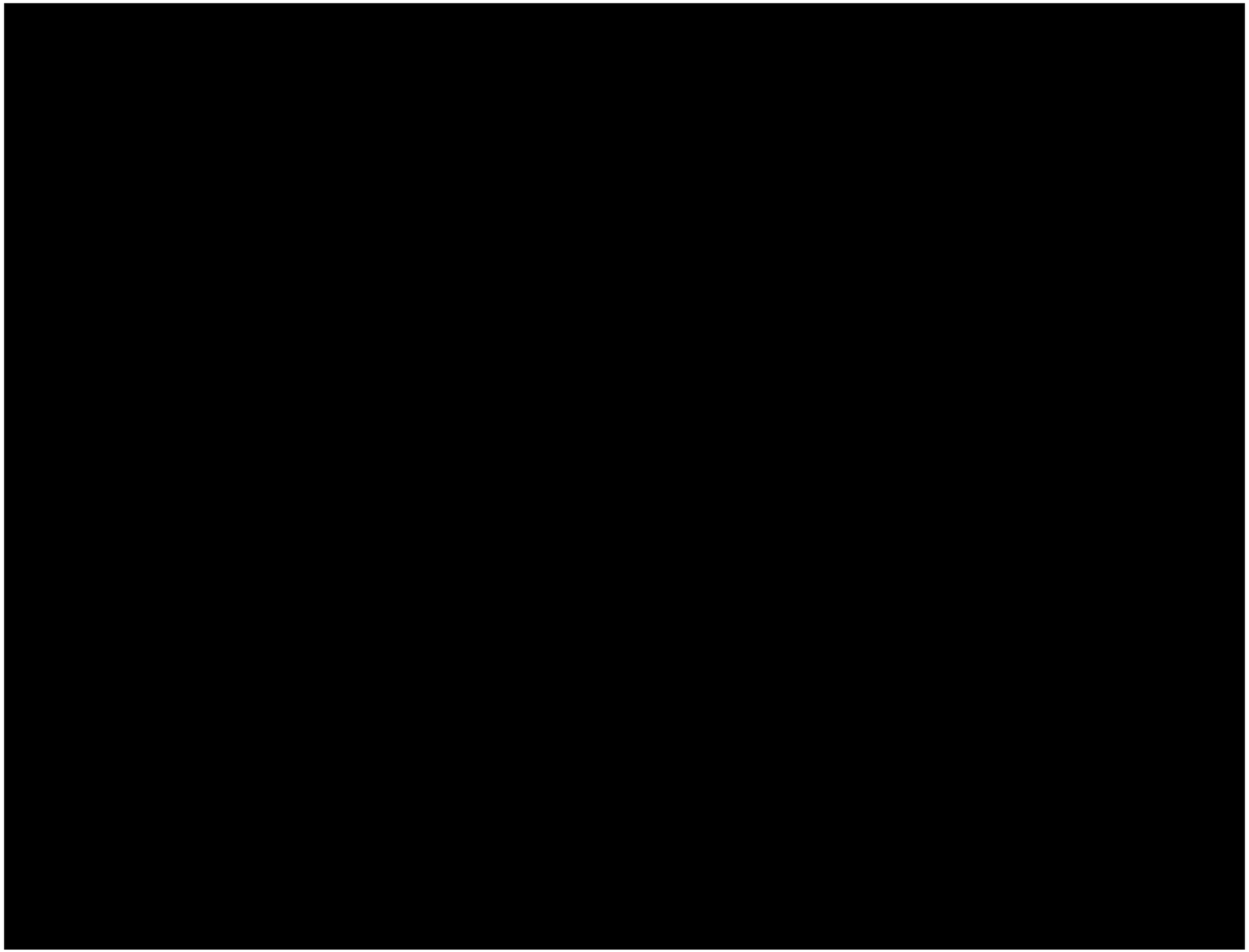
with $M_S\,, \kappa \gg v_{\rm EW}$

About a 1 minute to compute the one-loop matching of the scalar SM-singlet extension (which was correctly computed only after some iterations in the literature)

[Henning, Lu, Murayama 1412.1837;
Ellis, Quevillon, You, Zhang 1706.07765;
Jiang, Craig, Li, Sutherland 1811.08878;
Haisch, Ruhdorfer, Salvioni, Venturini, Weiler 2003.05936]

MatchmakerEFT example

[by Pablo Olgoso at MITP Flavor at the Crossroads]



So, in a nutshell

plus medium- and long-term goals

Outlook

- Automated one-loop matching has already become a reality

Diagrammatic approach:

Matchmakereft completely automates one loop matching from any UV model to any EFT. The RGEs of both UV and EFT models can also be computed

Today, the main bottlenecks are:

- UV and EFT model generation (EFT in Greens's basis and with Fierz redundancies)
- Reduction to the physical basis (including evanescent contributions)

Functional approach:

Functional methods overcome the first bottleneck, but the second remains

A first version of **Matchete** will be publicly available soon. Work is being done on the reduction to EFT basis

Functional methods are being extended to compute RGEs and evanescent contributions

… and future directions

- Automated one-loop matching has already become a reality

- Some medium- and long-term goals include

  - Interplay with **Sym2Int** (R. Fonseca) to automatically generate models

  - On-shell tree-level matching (M. Chala, J. Santiago) to automatically compute the reduction to an EFT basis

  - More adequate treatment of vectors (JFM, P. Olgoso, J. Santiago, A. Thomsen). Automatic breaking of gauge symmetries

  - Two-loop running using functional methods (JFM, König, Pagès, Thomsen, Wilsch)

  - Multi-step matching and running

- Matching models is about to become easy!

Thank you

Matching models is about to become easy!