BRIDGING THE UV AND THE IR AT THE LOOP LEVEL

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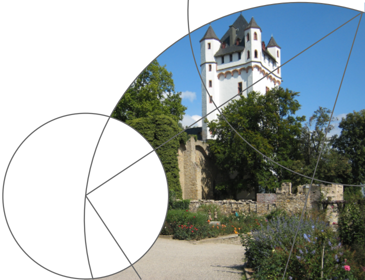
ERC WORKSHOP ON EFFECTIVE FIELD THEORIES FOR COLLIDER PHYSICS FLAVOR PHENOMENA AND EWSB



September 13, 2016

The 750 stages of grief

The LHC has proven another model to be right, the Kübler-Ross one

1. Denial — *They did not publish yet the spin-2 analysis!*
2. Anger — *Damned experimentalists! Enough of ambulance-chasing!*
3. Bargaining — *A simple 2σ anomaly would be enough!*
4. Depression — *The field is dying!*
5. Acceptance

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KEEP CALM AND SEARCH FOR NP

EFT AS A DISCOVERY TOOL

the bottom-up approach

- In its search for NP, the LHC indicates the existence of a non-negligible mass gap $v \ll \Lambda$

- We can therefore write the most general non-renormalizable $\mathcal{L}$ compatible with the observed symmetries and dof

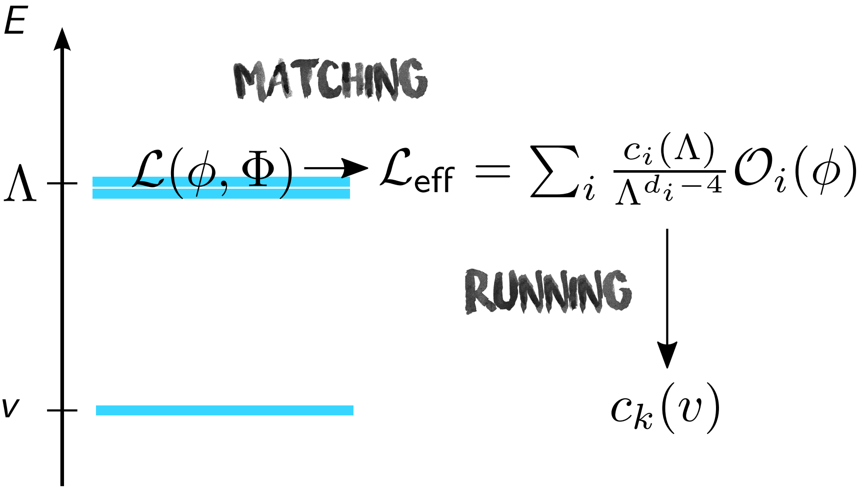
$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(4)} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \frac{1}{\Lambda^3}\mathcal{L}^{(7)} + \dots$$

- Mapping experimental observables to the Wilson coefficients in $\mathcal{L}_{\text{eff}}$ allows us to search for NP in a model independent way!

- We dispose nowadays of an impressive fit of the SM EFT to data (EWPD, LHC data, ...) Ciuchini, Franco, Mishima, Silvestrini, '13; de Blas, Chala, Santiago, '13,'15; Pomarol, Riva, '14, Pruna, Signer, '14; Falkowski, Riva, '15; Buckley, Englert, Ferrando, Miller, Moore, Russel, White, '15; Berthier, Trott, '15; Aebischer, Crivellin, Fael, Greub, '15; Ghezzi, Gomez-Ambrosio, Passarino, Uccirati, '15; Hartman, Trott, '15; David, Passarino, '15; Boggia, Gomez-Ambrosio, Passarino, '16; de Blas, Ciuchini, Franco, Mishima, Pierini, Reina, Silvestrini, '16;.

EFT AS A DISCOVERY TOOL

the top-down approach



OUTLINE

- UV/IR tree-level dictionary
- UV/IR one-loop dictionary
  - Effective Lagrangian at one loop: functional methods and matching
  - MATCHMAKER Anastasiou, AC, Lazopoulos, Santiago, to appear soon
    automated one-loop matching in effective field theories
- Conclusions

TREE LEVEL MATCHING

We can perform the tree-level matching for the following Lagrangian

$$\mathcal{L}_{\mathsf{UV}}(\phi,\Phi) = \mathcal{L}_{\mathsf{SM}}(\phi) + [\Phi^\dagger F(\phi) + \text{h.c.}] + \Phi^\dagger \left[-D^2 - m_\phi^2 - U(\phi)\right]\Phi + \mathcal{O}(\Phi^3)$$

by using equations of motion

$$\left[D^2 + m_\Phi^2 + U(\phi)\right]\Phi_c = F(\phi) + \mathcal{O}(\Phi_c^2)$$

which leads to

$$\begin{aligned}\Phi_c &= \frac{1}{D^2 + m_\Phi^2 + U}F = \frac{1}{m_\Phi^2\left[1 + m_\Phi^{-1}(D^2+U)\right]}F \\ &= \frac{1}{m_\Phi^2} - \frac{1}{m_\Phi^2}(D^2+U)\frac{1}{m_\Phi^2}F + \frac{1}{m_\Phi^2}(D^2+U)\frac{1}{m_\Phi^2}(D^2+U)\frac{1}{m_\Phi^2}F + \ldots\end{aligned}$$

and

$$\mathcal{L}_{\mathsf{eff}}^{\mathsf{tree}} = \mathcal{L}_{\mathsf{UV}}(\phi, \Phi_c(\Phi))$$

TREE LEVEL MATCHING

We already have a tree-level dictionary for non-mixed contributions!

$Q^{(m)}$	U	D	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(3,3)_{-\frac{1}{3}}$

New Quarks: del Aguila, Perez-Victoria, Santiago, '00

Leptons	N	E	$\begin{pmatrix} N \\ E^- \end{pmatrix}$	$\begin{pmatrix} E^- \\ E^{--} \end{pmatrix}$	$\begin{pmatrix} E^+ \\ N \\ E^- \end{pmatrix}$	$\begin{pmatrix} N \\ E^- \\ E^{--} \end{pmatrix}$
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$
Spinor	Dirac/Majorana	Dirac	Dirac	Dirac	Dirac/Majorana	Dirac

New Leptons: del Aguila, de Blas, Perez-Victoria, '08

TREE LEVEL MATCHING

We already have a tree-level dictionary for non-mixed contributions!

Vector	$\mathcal{B}_\mu$	$\mathcal{B}^1_\mu$	$\mathcal{W}_\mu$	$\mathcal{W}^1_\mu$	$\mathcal{G}_\mu$	$\mathcal{G}^1_\mu$	$\mathcal{H}_\mu$	$\mathcal{L}_\mu$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,\mathrm{Adj})_0$	$(1,\mathrm{Adj})_1$	$(\mathrm{Adj},1)_0$	$(\mathrm{Adj},1)_1$	$(\mathrm{Adj},\mathrm{Adj})_0$	$(1,2)_{-\frac{3}{2}}$

Vector	$\mathcal{U}^2_\mu$	$\mathcal{U}^5_\mu$	$\mathcal{Q}^1_\mu$	$\mathcal{Q}^5_\mu$	$\mathcal{X}_\mu$	$\mathcal{Y}^1_\mu$	$\mathcal{Y}^5_\mu$
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,\mathrm{Adj})_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

New Vectors: del Aguila, de Blas, Perez-Victoria, '10

Colorless Scalars	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ_0	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$

Colored Scalars	ω_1	ω_2	ω_4	Π_1	Π_7	ζ
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$

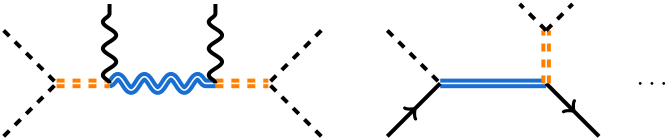
Colored Scalars	Ω_1	Ω_2	Ω_4	Υ	Φ
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$

New Scalars: de Blas, Chala, Perez-Victoria, Santiago, '15

TREE LEVEL MATCHING

- Dimensionful couplings imply that particles with different spin can simultaneously contribute to $\mathcal{L}_{\rm eff}^{d=6}$ at tree level contributions

$$\kappa\phi_1\phi_2\phi_3 + \kappa' V^\mu D_\mu\phi + \kappa'' V^\mu V'_\mu + \ldots$$



- Only a subset of the irreps in the previous lists contributes

- Work in progress: de Blas, Chala, Criado, Perez-Victoria, Santiago, to appear soon

- Then, the tree-level UV/IR dictionary will be complete!

ONE LOOP MATCHING

- Many contributions to the effective Lagrangian can be only generated at the quantum level
- Even contributions that can potentially arise at tree-level only appear at loop level in specific models
- The dictionary should be extended to one loop if we want to account for these cases
- The number of possibilities increases dramatically!! Automation seems compulsory.
- The matching can be performed
  - Diagrammatically Anastasiou, AC, Lazapoulos, Santiago
  - By functional methods Henning, Lu + Murayama, '14; Drozd, Ellis, Quevillon, You, '15; Henning, Lu, Murayama, '16; Ellis, Quevillon, You, Zhang, '16; Fuentes-Martin, Portoles, Ruiz-Femenia, '16

ONE LOOP MATCHING BY FUNCTIONAL METHODS

The effective action

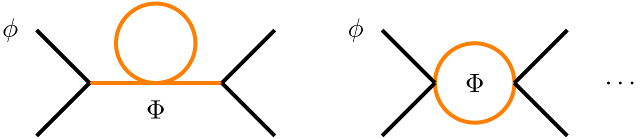
$$e^{iS_{\text{eff}}(\phi)} = \int \mathcal{D}\Phi\, e^{iS_{\text{UV}}(\phi,\Phi)}$$

leads at one-loop order in the saddle-point approximation to

$$S_{\text{eff}}(\phi) = S_{\text{UV}}(\phi, \Phi_c(\phi)) + \frac{i}{2}\log\det\left(-\left.\frac{\delta^2 S_{\text{UV}}(\phi,\Phi)}{\delta\Phi^2}\right|_{\Phi_c}\right)$$

where

$$\left.\frac{\delta S(\phi,\Phi)}{\delta\Phi}\right|_{\Phi_c} = 0 \Rightarrow \Phi_c(\phi)$$



ONE LOOP MATCHING BY FUNCTIONAL METHODS

Henning, Lu + Murayama, '14 resuscitated the Covariant Derivative Expansion (CDE) Gaillard, '86; Cheyette, 86 for the calculation of

$$\Delta S_{\text{eff}}(\phi) = ic_s \mathrm{Tr}\log\left(-\left.\frac{\delta^2 S_{\text{UV}}(\phi,\Phi)}{\delta\Phi^2}\right|_{\Phi_c}\right) = ic_s \mathrm{Tr}\log\left[D^2 + m_\Phi^2 - U(\phi)\right]$$

obtaining

$$\Delta S_{\text{eff}}(\phi) = ic_s \int \mathrm{d}^4x \int \frac{\mathrm{d}^4 q}{(2\pi)^4} \,\mathrm{tr}\log\left[-\left(q_\mu + \tilde{G}_{\mu\nu}\frac{\partial}{\partial q_\nu}\right)^2 + m_\Phi^2 + \tilde{U}\right]$$

where

$$\tilde{G}_{\mu\nu} = \sum_{n=0}^{\infty} \frac{n+1}{(n+2)!}\left[P_{\alpha_1},\left[\ldots\left[P_{\alpha_n},\left[D_\mu, D_\nu\right]\right]\right]\right] \frac{\partial^n}{\partial q_{\alpha_1}\partial q_{\alpha_2}\cdots\partial q_{\alpha_n}}$$

$$\tilde{U}_{\mu\nu} = \sum_{n=0}^{\infty} \frac{1}{n!}\left[P_{\alpha_1},\left[\ldots\left[P_{\alpha_n}, U\right]\right]\right] \frac{\partial^n}{\partial q_{\alpha_1}\partial q_{\alpha_2}\cdots\partial q_{\alpha_n}}$$

ONE LOOP MATCHING BY FUNCTIONAL METHODS

Henning, Lu + Murayama, '14

After expanding in $\Delta = (q^2 - m_\Phi^2)^{-1}$ one obtains (for $\mathrm{d}q = \mathrm{d}^4 q/(2\pi)^4$)

$$\Delta\mathcal{L}_{\text{eff}} = -ic_s \int \mathrm{d}q \int \mathrm{d}m_\Phi^2 \mathrm{tr} \frac{1}{\Delta^{-1}\left[1 + \Delta\left(\left\{q_\mu, \tilde{G}_{\mu\nu}\partial^\mu\right\} + \tilde{G}_{\sigma\mu}\tilde{G}^\sigma_\nu \partial^\mu\partial^\nu - \tilde{U}\right)\right]}$$

or

$$\Delta\mathcal{L}_{\text{eff}} = -ic_s \int \mathrm{d}q \int \mathrm{d}m_\Phi^2 \mathrm{tr}\left[\Delta - \Delta\left(\{q, \tilde{G}\} + \tilde{G}^2 - \tilde{U}\right)\Delta \right.$$
$$\left. + \Delta\left(\{q, \tilde{G}\} + \tilde{G}^2 - \tilde{U}\right)\Delta\left(\{q, \tilde{G}\} + \tilde{G}^2 - \tilde{U}\right)\Delta + \ldots\right]$$

In the case $m_\Phi \propto \mathbf{1}$,

$$[\Delta, [P_{\alpha_1}, [\ldots, [P_{\alpha_n}, [D_\mu, D_\nu]]]]] = [\Delta, [P_{\alpha_1}, [\ldots, [P_{\alpha_n}, U]]]] = 0$$

so the $\mathrm{d}q$ integrals factor out of the trace and can be computed once and for all!

ONE LOOP MATCHING BY FUNCTIONAL METHODS

Henning, Lu + Murayama, '14

$$\mathcal{L}_{\text{eff},1-\text{loop}} = \frac{c_s}{(4\pi)^2}\,\text{tr}\Bigg\{$$

$$+ m^4\left[-\frac{1}{2}\left(\log\frac{m^2}{\mu^2}-\frac{3}{2}\right)\right]$$

$$+ m^2\left[-\left(\log\frac{m^2}{\mu^2}-1\right)U\right]$$

$$+ m^0\left[-\frac{1}{12}\left(\log\frac{m^2}{\mu^2}-1\right)G'^2_{\mu\nu}-\frac{1}{2}\log\frac{m^2}{\mu^2}\,U^2\right]$$

$$+ \frac{1}{m^2}\left[-\frac{1}{60}\,(P_\mu G'_{\mu\nu})^2-\frac{1}{90}\,G'_{\mu\nu}G'_{\nu\sigma}G'_{\sigma\mu}-\frac{1}{12}\,(P_\mu U)^2-\frac{1}{6}\,U^3-\frac{1}{12}\,UG'_{\mu\nu}G'_{\mu\nu}\right]$$

$$+ \frac{1}{m^4}\Bigg[\frac{1}{24}\,U^4+\frac{1}{12}\,U(P_\mu U)^2+\frac{1}{120}\,(P^2U)^2+\frac{1}{24}\left(U^2G'_{\mu\nu}G'_{\mu\nu}\right)$$

$$-\frac{1}{120}\,[(P_\mu U),(P_\nu U)]\,G'_{\mu\nu}-\frac{1}{120}\,[U[U,G'_{\mu\nu}]]\,G'_{\mu\nu}\Bigg]$$

$$+ \frac{1}{m^6}\left[-\frac{1}{60}\,U^5-\frac{1}{20}\,U^2(P_\mu U)^2-\frac{1}{30}\,(UP_\mu U)^2\right]$$

$$+ \frac{1}{m^8}\left[\frac{1}{120}\,U^6\right]\Bigg\}$$

where $P_\mu A = [P_\mu, A]\,,\;\; G'_{\mu\nu} = [D_\mu, D_\nu]$

ONE LOOP MATCHING BY FUNCTIONAL METHODS

This was generalized to the non-degenerate case by Drozd, Ellis, Quevillon, You, '15

$$
\begin{aligned}
-ic_s \Big\{ & f_1^i + f_2^i U_{ii} + f_3^i G'^2_{\mu\nu,ij} + f_4^{ij} U_{ij}^2 \\
& + f_5^{ij}(P_\mu G'_{\mu\nu,ij})^2 + f_6^{ij}(G'_{\mu\nu,ij})(G'_{\nu\sigma,jk})(G'_{\sigma\mu,ki}) + f_7^{ij}[P_\mu, U_{ij}]^2 + f_8^{ijk}(U_{ij}U_{jk}U_{ki}) \\
& + f_9^{ij}(U_{ij}G'_{\mu\nu,jk}G'_{\mu\nu,ki}) \\
& + f_{10}^{ijkl}(U_{ij}U_{jk}U_{kl}U_{li}) + f_{11}^{ijk} U_{ij}[P_\mu, U_{jk}][P_\mu, U_{ki}] \\
& + f_{12,a}^{ij}\,[P_\mu,[P_\nu,U_{ij}]]\,[P_\mu,[P_\nu,U_{ji}]] + f_{12,b}^{ij}\,[P_\mu,[P_\nu,U_{ij}]]\,[P_\nu,[P_\mu,U_{ji}]] \\
& + f_{12,c}^{ij}\,[P_\mu,[P_\mu,U_{ij}]]\,[P_\nu,[P_\nu,U_{ji}]] \\
& + f_{13}^{ijk} U_{ij}U_{jk}G'_{\mu\nu,kl}G'_{\mu\nu,li} + f_{14}^{ijk}\,[P_\mu,U_{ij}]\,[P_\nu,U_{jk}]\,G'_{\nu\mu,ki} \\
& + \left(f_{15a}^{ijk} U_{i,j}[P_\mu, U_{j,k}] - f_{15b}^{ijk}[P_\mu, U_{i,j}]U_{j,k}\right)[P_\nu, G'_{\nu\mu,ki}] \\
& + f_{16}^{ijklm}(U_{ij}U_{jk}U_{kl}U_{lm}U_{mi}) + f_{17}^{ijkl} U_{ij}U_{jk}[P_\mu,U_{kl}][P_\mu,U_{li}] + f_{18}^{ijkl} U_{ij}[P_\mu,U_{jk}]U_{kl}[P_\mu,U_{li}] \\
& + f_{19}^{ijklmn}(U_{ij}U_{jk}U_{kl}U_{lm}U_{mn}U_{ni}) \Big\}
\end{aligned}
$$

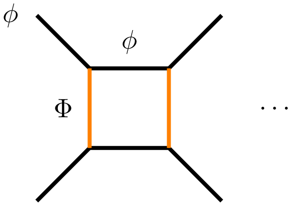
Light heavy mixing

However, such formulas are only valid in the absence of linear terms in Φ

Bilenky, Santamaria, 95; del Aguila, Kunszt, Santiago, 16

$$\mathcal{L}(\phi, \Phi) \supset \Phi^\dagger F(\phi) + \text{h.c.}$$

since they do not consider diagrams with ϕ running in the loop



LIGHT HEAVY MIXING

We will always get the same physical amplitudes providing we perform a local transformation $\Phi \to \Phi_c + \Phi'$

$$\Phi_c = \left[D^2 + m_\Phi^2 + U\right]^{-1} F \approx \frac{1}{m_\Phi^2} \sum_{n=0}^{N-1} \left(- \left[D^2 + U(\phi)\right] \frac{1}{m_\Phi^2} \right)^n F(\phi)$$

Therefore, even though we can suppress the linear coupling to order $\mathcal{O}(m_\Phi^{-2N})$ for arbitrary N

$$\mathcal{L}_{\mathrm{UV}}(\phi, \Phi') \supset \Phi'^\dagger \left(\left[D^2 + U(\phi)\right] \frac{1}{m_\Phi^2} \right)^N F(\phi) + \text{h.c.}$$

it will still contribute to certain amplitudes at $\mathcal{O}(m_\Phi^{-2})$

LIGHT HEAVY MIXED CONTRIBUTIONS PART I

Henning, Lu, Murayama, '16

We need to match non-local objects to their local truncated expansions

$$\Gamma^{(1)}_{\mathsf{L,UV}}(\phi) = \frac{i}{2}\log\det\left(-\left.\frac{\delta^2 S_{\mathsf{UV}}(\phi,\Phi)}{\delta(\phi,\Phi)^2}\right|_{\Phi_c}\right)$$

$$\Gamma^{(1)}_{\mathsf{L,EFT}}(\phi) = S^{(1)}_{\mathsf{EFT}}(\phi) + \frac{i}{2}\log\det\left(-\frac{\delta^2 S^{(0)}_{\mathsf{EFT}}(\phi)}{\delta^2\phi}\right)$$

Since

$$\log\det\left(-\left.\frac{\delta^2 S(\phi,\Phi)}{\delta(\phi,\Phi)^2}\right|_{\Phi_c}\right) = \log\det\left(-\left.\frac{\delta^2 S(\phi,\Phi)}{\delta\Phi^2}\right|_{\Phi_c}\right) + \log\det\left(-\frac{\delta^2 S(\phi,\Phi_c(\phi))}{\delta\phi^2}\right)$$

we get

$$\int dx \sum_i c^{(1)}_{i,\mathsf{mixed}}\mathcal{O}_i(\phi) = \frac{i}{2}\log\det\left(-\frac{\delta^2 S_{\mathsf{UV}}(\phi,\Phi_c(\phi))}{\delta\phi^2}\right) - \frac{i}{2}\log\det\left(-\frac{\delta^2 S^{(0)}_{\mathsf{EFT}}(\phi)}{\delta^2\phi}\right)$$

Light heavy mixed contributions part I

Henning, Lu, Murayama, '16

One only needs to keep the rest after dropping the truncated or local counterpart

$$\int \mathrm{d}x \sum_i c^{(1)}_{i,\text{mixed}} \mathcal{O}_i(\phi) = \frac{i}{2} \log\det \left(-\frac{\delta^2 S_{\text{UV}}(\phi, \Phi_c(\phi))}{\delta\phi^2} \right)_d$$

where if, for instance,

$$\frac{1}{-D^2 - m_\Phi^2} = -\frac{1}{m_\Phi^2} + \frac{1}{m_\Phi^2} \frac{-D^2}{-D^2 - m_\Phi^2} = \left(\frac{1}{-D^2 - m_\Phi^2} \right)_{\text{tr}} + \left(\frac{1}{-D^2 - m_\Phi^2} \right)_{\text{rest}}$$

d means to drop in

$$\log\det \left(-\frac{\delta^2 S_{\text{UV}}(\phi, \Phi_c(\phi))}{\delta\phi^2} \right) = \text{Tr}\log \Bigg[1 - \frac{1}{-D^2 - m_\Phi^2} A_{11}(x) \\ - \frac{1}{-D^2 - m_\Phi^2} A_{21}(x) \frac{1}{-D^2 - m_\Phi^2} A_{22}(x) + \ldots \Bigg]$$

the terms where all heavy propagators are replaced by $-1/m_\Phi^2$

Light heavy mixed contributions part II

Ellis, Quevillon, You, Zhang, '16

One can integrate about both classical solutions, ϕ_c and Φ_c,

$$\phi = \phi_c + \phi', \quad \Phi \to \Phi_c + \Phi'$$

and do exactly the same with

$$\mathbf{U} = \begin{pmatrix} U_{\phi\phi} & U_{\phi\Phi} \\ U_{\phi\Phi} & U_{\Phi\Phi} \end{pmatrix}$$

After subtracting from $f_n^{ikj\ldots}$ the contributions arising from loop diagrams with tree-level generated operators $\Delta f_n^{ikj\ldots}$, one can compute the mixed terms by plugging $(f_n^{ijk\ldots})_{\text{sub}} = f_n^{ikj\ldots} - \Delta f_n^{ikj\ldots}$ into their universal expressions

However,

- it can not be applied when $U_{\phi\Phi}$ contains derivatives!
- it has to be generalized to cases with mixed statistics!

LIGHT HEAVY MIXED CONTRIBUTIONS PART III

Fuentes-Martin, Portoles, Ruiz-Femenia, '16

It is possible to diagonalize

$$\mathcal{L} = \frac{1}{2}(\Phi^\dagger, \phi^\dagger) \begin{pmatrix} \Delta_H & X_{LH}^\dagger \\ X_{LH} & \Delta_L \end{pmatrix} \begin{pmatrix} \Phi \\ \phi \end{pmatrix} = \frac{1}{2}\eta^\dagger \mathcal{O} \eta$$

by

$$P^\dagger \mathcal{O} P = \begin{pmatrix} \tilde{\Delta}_H & 0 \\ 0 & \Delta_L \end{pmatrix}, \text{ where } P = \begin{pmatrix} \mathbf{1} & 0 \\ -\Delta_L^{-1} X_{LH} & \mathbf{1} \end{pmatrix}$$

and

$$\tilde{\Delta}_H = \Delta_H - X_{LH}^\dagger \Delta_L^{-1} X_{LH} = -D^2 - m_\Phi^2 - U$$

getting

$$S_H = \mp \frac{i}{2} \int d^d x \sum_{n=1}^{\infty} \frac{1}{n} \int \frac{d^d p}{(2\pi)^d} \mathrm{tr} \left(\frac{2ipD + D^2 + U(x, \partial_x + ip)}{p^2 - m_\Phi^2} \right)^n$$

and

$$\int \mathrm{d}^d x \, \mathcal{L}_{\mathrm{EFT}}^{1-\mathrm{loop}} = S_H^{\mathrm{hard}}$$

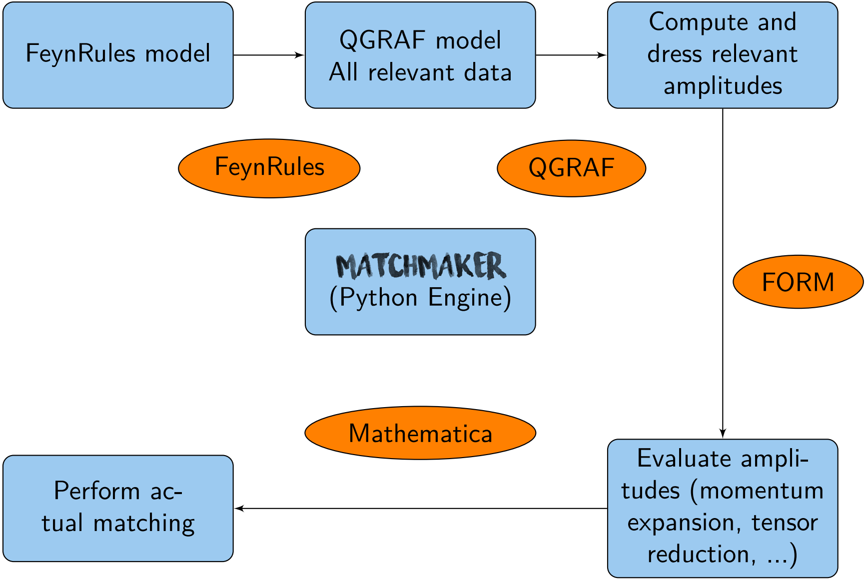
MATCHMAKER

Anastasiou, AC, Lazopoulos, Santiago; work in progress

- We are developing an automated tool to perform tree-level and one-loop matching of arbitrary theories into arbitrary effective Lagrangians
- Based on standard, well-tested tools (FeynRules, QGRAF, FORM, Mathematica, Python)
- Flexible (from full matching to specific operators), fully automated and general
- Unified treatment (effective theory just another model)
- Off-shell matching with (initially) massless particles in the effective theory (e.g. unbroken phase of the SM)

MATCHMAKER

Anastasiou, AC, Lazopoulos, Santiago; work in progress



MATCHMAKER

Anastasiou, AC, Lazopoulos, Santiago; work in progress

Current status

- bosonic operators ✓
- two-fermion operators ✓
- four-fermion operators *Well advanced!*

SUMMARY

- Having a complete UV/IR dictionary that maps arbitrary UV completions to experimental observables would be fantastic
- The tree-level, dimension-6 dictionary is (almost) finished
- The required automation for the one-loop dictionary is well advanced
- MatchMaker: General, fully automated and flexible code to compute tree-level and one-loop matching conditions

Thanks!

ONE LOOP MATCHING BY FUNCTIONAL METHODS

$$\Delta S_{\mathrm{eff}}(\phi) = i c_s \int \mathrm{d}^4 x \int \frac{\mathrm{d}^4 q}{(2\pi)^4} \operatorname{tr}\log\left[-\left(q_\mu + \tilde{G}_{\mu\nu}\frac{\partial}{\partial q_\nu}\right)^2 + m_\Phi^2 + \tilde{U}\right]$$

where

- for real (complex) scalars $c_s = 1/2\,(1)$ and $U(x) = M^2(x)$ and
- for fermions $c_s = -1/2$ and

$$U(x) = -\frac{i}{2}\sigma^{\mu\nu} G'_{\mu\nu} + 2 m_\Phi M(x) + M^2(x) + \left[\not{P}, M(x)\right]$$

- for massless gauge fields
  - the ghost piece $c_s = -1,\ m_\Phi^2 = U(x) = 0$
  - the gauge piece $c_s = 1/2,\ m_\Phi^2 = 0,\ U(x) = -i\mathcal{J}^{\mu\nu} G'_{\mu\nu}$
- for massive gauge fields
  - the ghost piece $c_s = -1,\ U(x) = 0$
  - the gauge piece $c_s = 1/2,\ m_\Phi^2 = 0,\ U(x) = -i\mathcal{J}^{\mu\nu}(G'_{\mu\nu} + \frac{1}{2}M_{\mu\nu})$
  - the Goldstone piece $c_s = 1/2,\ U(x) = 0$