Functional EFT Methods:
New Developments and the Matchete Tool

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UNIVERSITÄT BERN
AEC
ALBERT EINSTEIN CENTER
FOR FUNDAMENTAL PHYSICS

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EFTs in BSM physics

What they are and how to use them

Direct searches for new physics

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

Status: March 2022

ATLAS Preliminary

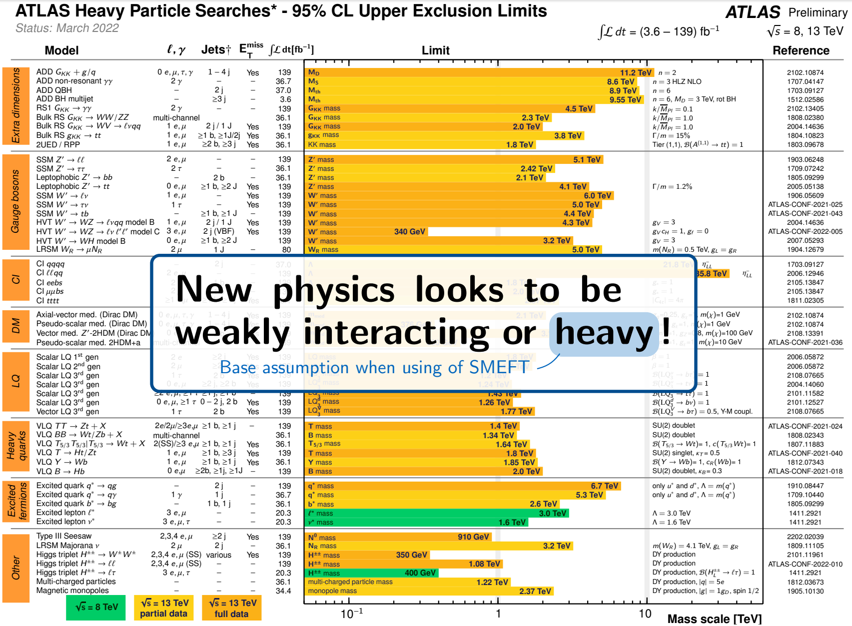
$\int \mathcal{L}\, dt = (3.6 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\, \ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	ATLAS-CONF-2022-005
	HVT $W' \to WH$ model B	0 e, μ	≥1 b, ≥2 J		139	W' mass 3.2 TeV	$g_V = 3$	2007.05293
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	m_{med} 3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med} 560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.2 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2108.07665
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^V mass 1.77 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 0.5$, Y-M coupl.	2108.07665
Heavy quarks	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass 1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3} T_{5/3} \| T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3} Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1 g_D$, spin 1/2	1905.10130

$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

10^{-1} 1 10 **Mass scale [TeV]**

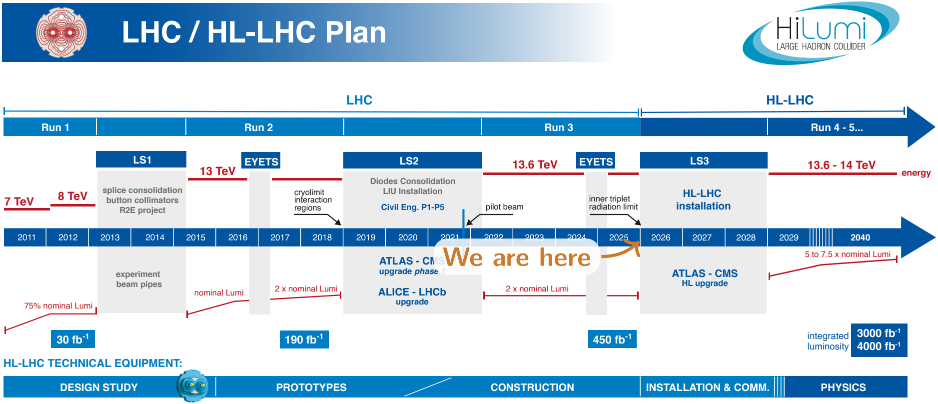
Direct searches for new physics



New physics looks to be weakly interacting or heavy!

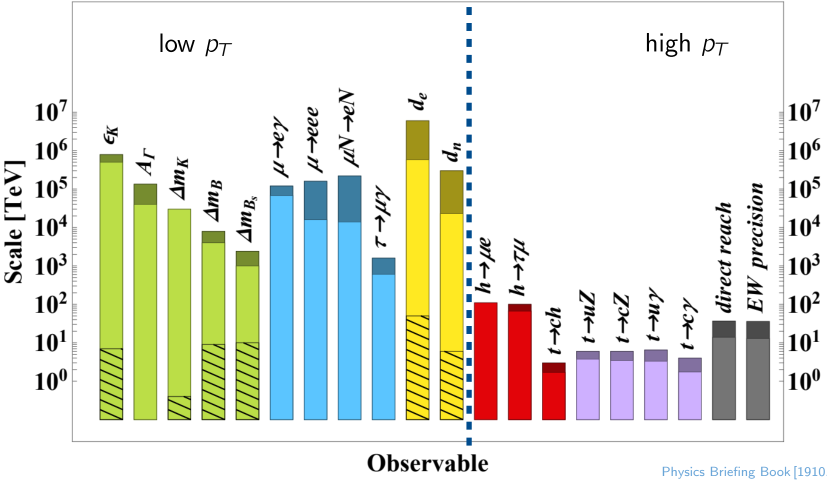
Base assumption when using of SMEFT

Lots of luminosity



- Marginal increase in energy, but **$\sim 20\times$ more int. luminosity!**
- Rather than looking for resonances, we can look for **traces of new physics**

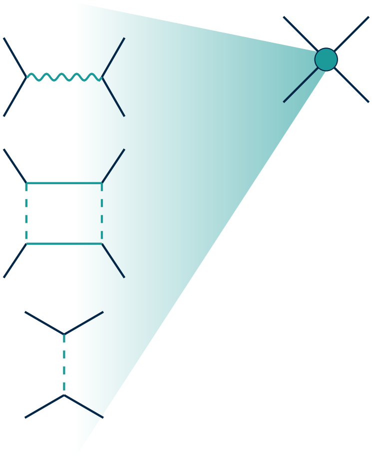
Probing high-scales through precision



Physics Briefing Book [1910.11775]

Effective field theory

High-energy BSM physics manifests as contact interactions in the SMEFT

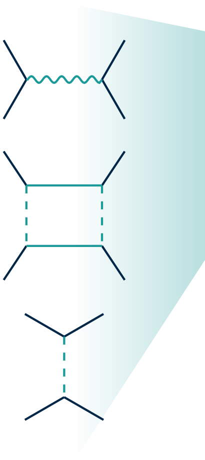


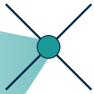
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d=5} \sum_{k} \frac{C_{d,k}}{\Lambda^{d-4}} \mathcal{O}_{d,k}$$

UV Physics

Effective field theory

High-energy BSM physics manifests as contact interactions in the SMEFT





UV Physics

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- **Bottom–up:**
  - EFTs allow for a **model-comprehensive** ("model-independent") analysis of deviations from the SM, quantifying possible deviations as an expansion in E/Λ

Effective field theory

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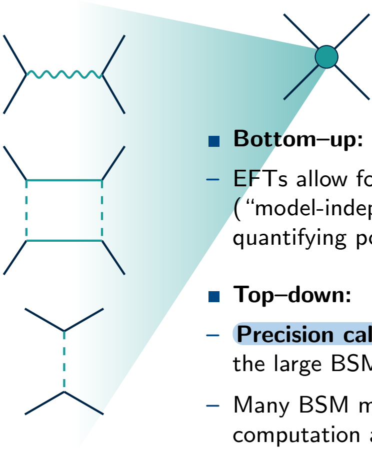

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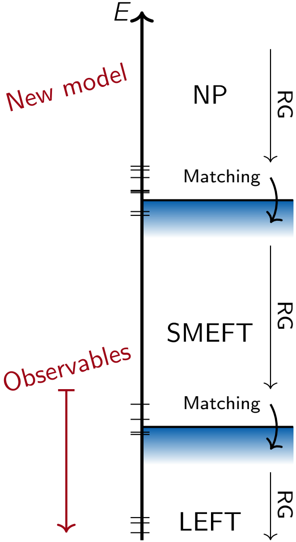
- **Bottom–up:**
  - EFTs allow for a **model-comprehensive** ("model-independent") analysis of deviations from the SM, quantifying possible deviations as an expansion in E/Λ
- **Top–down:**
  - **Precision calculations** necessitates the use of EFTs to separate the large BSM energy scales
  - Many BSM models results in the same EFT, ensuring that computation are **reusable**: you only need to compute once in the EFT

Top–down EFT workflow



Jenkins, Manohar, Trott [1308.2627]
Jenkins, Manohar, Trott [1310.4838]
Alonso *et al.* [1312.2014]

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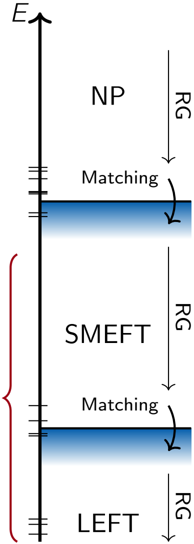

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wilson
Dsix Tools

Aebischer, Kumar, Straub [1804.05033]
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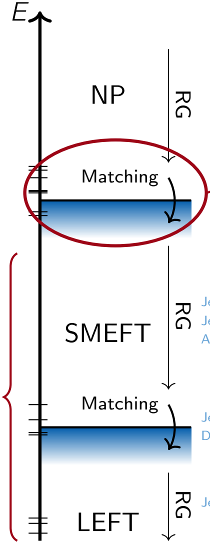
Fuentes-Martín *et al.* [2010.16341]

The repetitive nature of EFT computations calls for **automated tools!**

Top–down EFT workflow



MATCHETE

Carmona *et al.* [2112.10787]; Fuentes-Martín, König, Pagès, **AET**, Wilsch [2212.04510]

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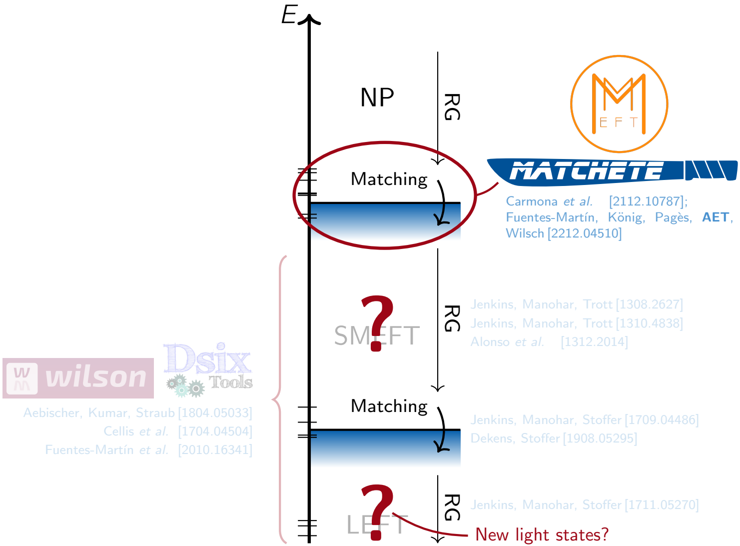
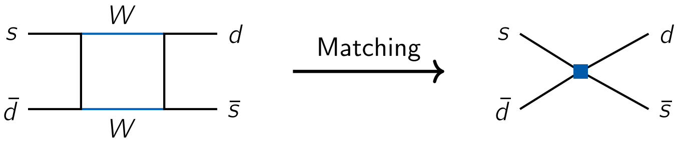


The repetitive nature of EFT computations calls for **automated tools!**

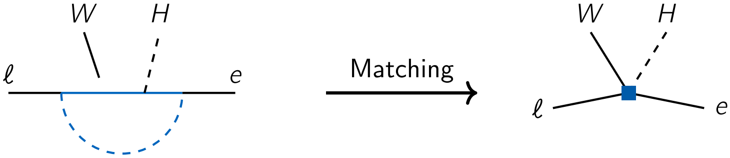
Matching beyond tree level

1-loop matching is often the **leading contribution** from high-scale physics

- FCNCs in the SM

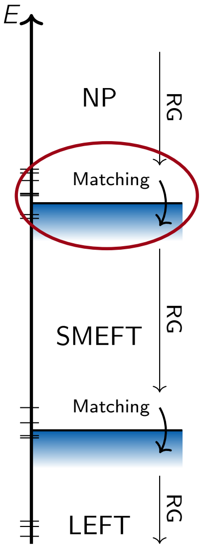


- In BSM models: dipoles, FCNCs, EW precision, ...



Matching weakly coupled theories

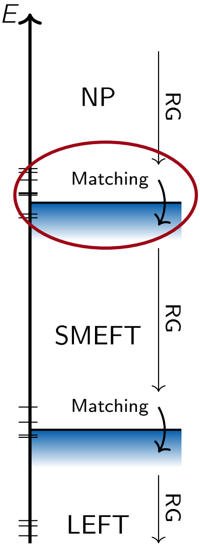
$\mathcal{L}_{\text{EFT}}$ should reproduce the physics of $\mathcal{L}_{\text{UV}}$ at energies $E \ll \Lambda$:



$$\mathcal{L}_{\text{UV}}(\Phi,\, \phi) \xrightarrow{\text{Off-shell matching}} \mathcal{L}_{\text{EFT}}(\phi)$$

$$\mathcal{L}_{\text{EFT}}(\phi) = \mathcal{L}_{d=4}(\phi) + \sum_{d=5}^{\infty} \sum_{\ell=0}^{\infty} \sum_{k} \frac{\overset{\text{the goal!}}{\boxed{C_{d,k}^{(\ell)}}}}{\underbrace{(16\pi^2)^{\ell}\, \Lambda^{d-4}}_{\text{double expansion}}} \mathcal{O}_{d,k}$$

Matching weakly coupled theories



$\mathcal{L}_{\text{EFT}}$ should reproduce the physics of $\mathcal{L}_{\text{UV}}$ at energies $E \ll \Lambda$:

Off-shell matching

$$\begin{tikzcd} \mathcal{L}_{\text{UV}}(\Phi,\, \phi) \arrow[rr, "\text{Off-shell matching}"] \arrow[d] & & \mathcal{L}_{\text{EFT}}(\phi) \arrow[d, "\text{(Tree level only)}"] \\ \Gamma_{\text{UV}}\big[\widehat{\Phi}(\phi),\, \phi\big] & \simeq \arrow[ur, "\text{Diagramatic}"] & \Gamma_{\text{EFT}}[\phi] \end{tikzcd}$$

$$\mathcal{L}_{\text{EFT}}(\phi) = \mathcal{L}_{d=4}(\phi) + \sum_{d=5}^{\infty} \sum_{\ell=0}^{\infty} \sum_{k} \underbrace{\frac{C^{(\ell)}_{d,k}}{(16\pi^2)^{\ell}\, \Lambda^{d-4}}}_{\text{double expansion}} \mathcal{O}_{d,k}$$

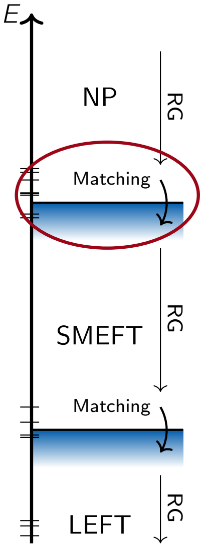
Hard-region matching formula

$$S_{\text{EFT}}[\phi] = \Gamma_{\text{UV}}[\widehat{\Phi}, \phi]\Big|_{\text{hard}}, \qquad \frac{\delta \Gamma_{\text{UV}}|_{\text{hard}}}{\delta \Phi}[\widehat{\Phi}, \phi] = 0$$

"hard" denotes the part without *any* soft loop momenta (it includes all tree-level contributions)

Fuentes-Martin *et al.* [1607.02142]; Zhang [1610.00710]; Fuentes-Martin, Palavrić, **AET** [2311.13630]; Fuentes-Martín, Moreno, Palavrić, **AET** [2412.12270]

Matching weakly coupled theories



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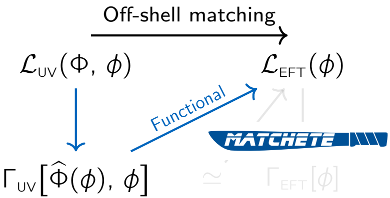

$$\mathcal{L}_{\text{EFT}}(\phi) = \mathcal{L}_{d=4}(\phi) + \sum_{d=5}^{\infty} \sum_{\ell=0}^{\infty} \sum_{k} \underbrace{\frac{C^{(\ell)}_{d,k}}{(16\pi^2)^{\ell}\,\Lambda^{d-4}}}_{\text{double expansion}} \mathcal{O}_{d,k}$$

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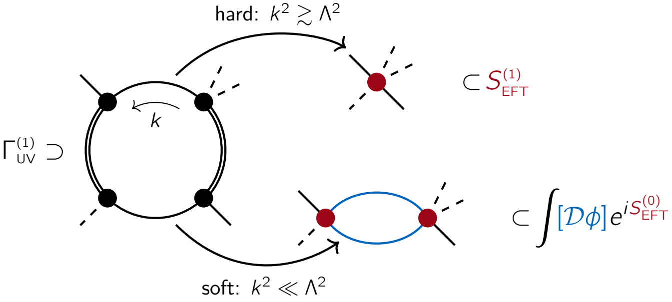
Separation of scales: hard-region matching

Mixed (heavy–light) loop example:



Separation of scales: hard-region matching

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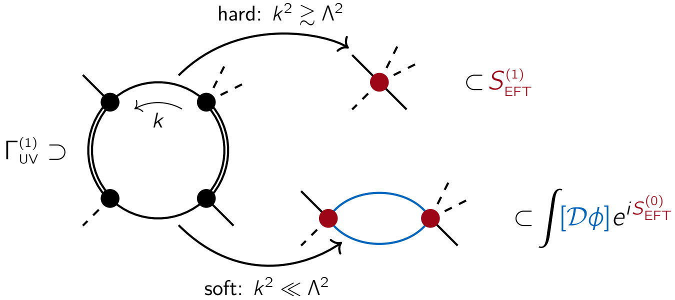


- $\Gamma^{(1)}_{\text{UV}}\big|_{\text{soft}}$: long-distance contributions included in 1-loop matrix elements of tree-level EFT operators

$$\Gamma^{(1)}_{\text{UV}}\big|_{\text{soft}} = \Gamma^{(1)}_{\text{EFT}}$$

- $\Gamma^{(1)}_{\text{UV}}\big|_{\text{hard}}$: short-distance contributions going into the EFT operators

$$\Gamma^{(1)}_{\text{UV}}\big|_{\text{hard}} = S^{(1)}_{\text{EFT}}$$

Functional Methods

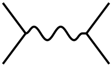
For matching and RG calculations

What are functional methods anyway?

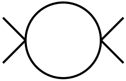
$$\mathcal{L}(\eta, D\eta)$$

Amplitudes

Functionals



$$\mathcal{W}[\mathcal{J}]$$

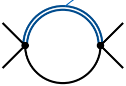


$$\Gamma[\hat{\eta}]$$

Quantum information

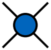
Functional methods for counterterm calculations

- EFT matching—extraction of EFT couplings



Changed high-k int

$$\sim \int_k \frac{1}{(k^2 - M^2)} \frac{1}{(k+p)^2 - m^2} \sim \frac{-1}{M^2} \int_k \frac{1}{(k+p)^2 - m^2} +$$



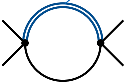
Functional methods @ one-loop order:
Aitchison, Fraser '84; Cheyette '85, Gaillard '86; Dittmaier, Gorsse-Knetter [hep-ph/9501285]; Henning, Lu, Murayamma [1412.1837], Drozd, Ellis, Quevillon, You [1512.03003]; Aguila, Kunzst, Santiago [1602.00126]; Cohen, Lu, Zhang [2011.02484]. . . (and many more)

Functional methods for counterterm calculations

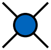
- EFT matching—extraction of EFT couplings

UV theory

Changed high-k int



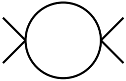
$$\sim \int_k \frac{1}{(k^2 - M^2)} \frac{1}{(k+p)^2 - m^2} \sim \frac{-1}{M^2} \int_k \frac{1}{(k+p)^2 - m^2} +$$



EFT vertex

- Renormalization/RG functions—extraction of counterterms

Gives RG functions



$$\sim \int \frac{\mathrm{d}^4 k}{(2\pi)^4} \frac{1}{(k^2 - M^2)^2} \longrightarrow \int \frac{\mathrm{d}^d k}{(2\pi)^d} \frac{1}{(k^2 - M^2)^2} + \boldsymbol{\delta\lambda}$$

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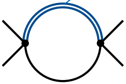
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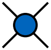

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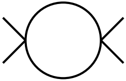
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- Computation of the effective potential: derivative expansion

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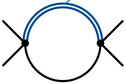
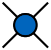
 $$\sim \int_k \boxed{\frac{1}{(k^2 - M^2)}} \frac{1}{(k+p)^2 - m^2} \sim \frac{-1}{M^2} \int_k \frac{1}{(k+p)^2 - m^2} +$$ 

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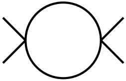 $$\sim \int \frac{d^4 k}{(2\pi)^4} \frac{1}{(k^2 - M^2)^2} \longrightarrow \boxed{\int \frac{d^d k}{(2\pi)^d}} \frac{1}{(k^2 - M^2)^2} + \boldsymbol{\delta\lambda}$$

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- Amplitudes? Why not?!
  But there might be little point... and some *trouble* $\leftsquigarrow$ non-local

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Semi-classical approximation

The **quantum effective action** is the generating functional of 1PI functions

$$e^{i\Gamma_{\mathrm{UV}}[\hat{\eta}]} = \int \mathcal{D}\eta \, \exp\Big(i S_{\mathrm{UV}}[\eta + \hat{\eta}] + i \underbrace{J_I \eta^I}_{\int_x J_a(x)\eta^a(x)} \Big) \,, \qquad \frac{\delta \Gamma[\hat{\eta}]}{\delta \hat{\eta}^I} = -J_I$$

The action is expanded by legs and loop order (including counterterms)

$$S[\eta + \hat{\eta}] = \widehat{S} + \sum_{\ell=0}^{\infty} \hbar^{\ell} \Big(\eta_I \widehat{\mathcal{V}}^{(\ell)}_I + \tfrac{1}{2} \eta_I \widehat{\mathcal{V}}^{(\ell)}_{IJ} \eta_J + \tfrac{1}{6} \eta_I \eta_J \eta_K \widehat{\mathcal{V}}^{(\ell)}_{IJK} + \tfrac{1}{24} \eta_I \eta_J \eta_K \eta_L \widehat{\mathcal{V}}^{(\ell)}_{IJKL} + \ldots \Big)$$

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With a **saddlepoint approximation**

$$e^{i\Gamma_{\mathrm{UV}}[\hat{\eta}]} = e^{i\widehat{S}} \int \mathcal{D}\eta \, \exp\!\Big(\frac{i}{2} \eta^I \underbrace{\widehat{\mathcal{Q}}_{IJ}}_{\mathcal{V}^{(0)}_{IJ}} \eta^J \Big) \Big[1 + \frac{i}{24} \eta_I \eta_J \eta_K \eta_L \widehat{\mathcal{V}}^{(0)}_{IJKL} - \frac{1}{72} \big(\eta_I \eta_J \eta_K \widehat{\mathcal{V}}^{(0)}_{IJK} \big)^2 + \ldots \Big]$$

Semi-classical approximation

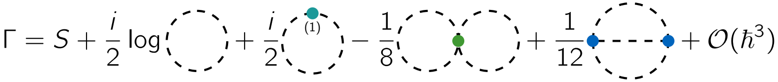
The loop-expansion is a polynomium of tensor contractions

$$\Gamma[\hat{\eta}] = \widehat{S} + \frac{i\hbar}{2}\overbrace{\zeta_{II}\Big(\log\widehat{\mathcal{Q}}\Big)_{II}}^{\mathrm{STr}\log\mathcal{Q}} + \frac{i\hbar^2}{2}\zeta_{II}\,\widehat{\mathcal{Q}}^{-1}_{IJ}\,\widehat{\mathcal{V}}^{(1)}_{JI} - \frac{\hbar^2}{8}\widehat{\mathcal{Q}}^{-1}_{IJ}\,\widehat{\mathcal{Q}}^{-1}_{KL}\,\widehat{\mathcal{V}}^{(0)}_{IJKL}$$

$$+\frac{\hbar^2}{12}\zeta_{IM}\zeta_{JN}\zeta_{IN}\,\widehat{\mathcal{Q}}^{-1}_{LI}\,\widehat{\mathcal{Q}}^{-1}_{MJ}\,\widehat{\mathcal{Q}}^{-1}_{NK}\,\widehat{\mathcal{V}}^{(0)}_{IJK}\,\widehat{\mathcal{V}}^{(0)}_{LMN} + \mathcal{O}(\hbar^3)$$

Spin statistics: ± 1

or as supergraphs



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$$+ \frac{\hbar^2}{12}\,\underbrace{\zeta_{IM}\zeta_{JN}\zeta_{IN}}_{\text{Spin statistics: } \pm 1}\,\widehat{\mathcal{Q}}^{-1}_{LI}\,\widehat{\mathcal{Q}}^{-1}_{MJ}\,\widehat{\mathcal{Q}}^{-1}_{NK}\,\widehat{\mathcal{V}}^{(0)}_{IJK}\,\widehat{\mathcal{V}}^{(0)}_{LMN} + \mathcal{O}(\hbar^3)$$

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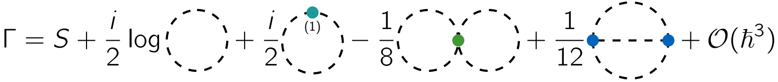
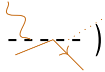
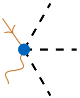


All **vertices and propagators are fully dressed** with background fields

$$\mathcal{Q}_{IJ}[\hat\eta] = \frac{\delta^2 S}{\delta\eta^I\delta\eta^J}[\hat\eta] = \Big(\quad\Big)^{-1}$$



$$\mathcal{V}^{(0)}_{IJK}[\hat\eta] =$$



What does this look like at one-loop order

Locality of the action ensures the form of the 2-point function

$$\mathcal{Q}_{IJ} = \underbrace{Q_{ac}(x,\, \overset{iD_\mu}{P_x})\delta^c{}_b(x,y)}_{\text{manifestly covariant}}$$

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$$\mathcal{Q} = \boldsymbol{\Delta} - \mathcal{X}, \qquad \Delta(P_x) = \begin{cases} \pm(P_x^2 - m^2) & \text{for scalars (ghosts)} \\ \not{P}_x - m & \text{for fermions} \\ -g_{\mu\nu}(P_x^2 - m^2) & \text{for gauge fields} \end{cases}$$

The **tricky one-loop** effective action

$$\Gamma^{(1)} \supset \frac{i\hbar}{2}\,\mathrm{Tr}\log\mathcal{Q}$$

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$$\Gamma^{(1)} \supset \frac{i\hbar}{2}\operatorname{Tr}\log\mathcal{Q} = \frac{i\hbar}{2}\underbrace{\operatorname{Tr}\log\boldsymbol{\Delta}}_{p(F_{\mu\nu})} - \frac{i\hbar}{2}\sum_{n=1}^{\infty}\frac{1}{n}\operatorname{Tr}\left(\boldsymbol{\Delta}^{-1}\mathcal{X}\right)^n \equiv \Gamma^{(1)}_{\text{log}} + \Gamma^{(1)}_{\text{power}}$$

A master formula for the one-loop effective action

$$\Gamma^{(1)}_{\text{power}} = -\frac{i\hbar}{2}\sum_{n=1}^{\infty}\frac{1}{n}\underbrace{\int_{x,y}\delta^{b}{}_{a}(y,x)}_{\text{func. Tr}}\underbrace{\big(\Delta^{-1}(x,P_x)X(x,P_x)\big)^{n}_{ac}\delta^{c}{}_{b}(x,y)}_{(\boldsymbol{\Delta}^{-1}\mathcal{X})^{n}}$$

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And in momentum space

$$\Gamma^{(1)}_{\text{power}} = -\frac{i\hbar}{2}\sum_{n=1}^{\infty}\frac{1}{n}\int_{x,y}\int_{k}e^{-ik\cdot(x-y)}\delta^{b}{}_{a}(y,x)\big(\Delta^{-1}(x,P_x+k)X(x,P_x+k)\big)^{n}_{ac}\,\overbrace{U^{c}{}_{b}(x,y)}^{\text{Wilson line}}$$

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$$\begin{aligned}\Gamma^{(1)}_{\text{power}} &= -\frac{i\hbar}{2}\sum_{n=1}^{\infty}\frac{1}{n}\int_{x,y}\int_k e^{-ik\cdot(x-y)}\,\delta^b{}_a(y,x)\big(\Delta^{-1}(x,P_x+k)X(x,P_x+k)\big)^n_{ac}\,U^c{}_b(x,y)\\ &= -\frac{i\hbar}{2}\sum_{n=1}^{\infty}\frac{1}{n}\int_x\int_k\big(\Delta^{-1}(x,k+P_x)\,X(x,k+P_x)\big)^n_{ab}\,U^b{}_a(x,y)\Big|_{y=x}\end{aligned}$$

The master formula for the one-loop quantum effective action

- is **manifestly gauge invariant**, simplifying calculations
- is unwieldy and non-local in the general case
- matching (and RG) calculations care only about a local piece: $\boldsymbol{S_{\text{EFT}} = R_{\text{hard}}\Gamma_{\text{UV}}}$ (and $\delta S = \bar{\boldsymbol{R}}^*\Gamma$)

Evaluating the one-loop effective action

$$\Gamma^{(1)}_{\text{power}} = -\frac{i\hbar}{2}\sum_{n=1}^{\infty}\frac{1}{n}\int_{x,y}\delta^{b}{}_{a}(y,x)\big(\Delta^{-1}(x,P_x)X(x,P_x)\big)^{n}_{ac}\delta^{c}{}_{b}(x,y)$$

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RG calculations (with $\boldsymbol{R}_{\text{hard}}$ or $\bar{\boldsymbol{R}}^{*}$) call for expansion of the propagators:

- Typical propagator: $\dfrac{1}{(k+P_x)^2-m^2} = \dfrac{1}{k^2} - \dfrac{2k\cdot P_x}{(k^2-m^2)^2} + \dots$
- Typical X-term: $X_{\phi A_\mu} \supset 2g\phi(P_x^{\mu}+k^{\mu})$
- Closed(-ish) formula $P_x^{\mu_1}\cdots P_x^{\mu_m}U(x,y)\Big|_{y=x} = p_m\big(P_x,\,G_{\mu\nu}\big)$ polynomial

Evaluating the one-loop effective action

$$\Gamma^{(1)}_{\text{power}} = -\frac{i\hbar}{2}\sum_{n=1}^{\infty}\frac{1}{n}\int_{x,y}\delta^{b}{}_{a}(y,x)\big(\Delta^{-1}(x,P_x)X(x,P_x)\big)^{n}_{ac}\delta^{c}{}_{b}(x,y)$$

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Summary: to evaluate simply **tensor-contract, expand, loop-integrate**

Two-loop formulas

2-loop contributions introduce 3- and 4-point functional tensors, e.g.,

$$\mathcal{V}^{(0)}_{IJK} \equiv V_{ade}(x,\ P_y,\ P_z)\delta^{d}{}_{b}(x,y)\delta^{e}{}_{c}(x,z)$$

Locality of the action

$$V_{abc}(x,\ P_y,\ P_z) = \sum_{m,n=0} V^{(\underline{m},\underline{n})}_{abc}(x) P_y^{\underline{m}} P_z^{\underline{n}} \equiv \sum_{m,n=0} V^{(\mu_1\ldots\mu_m,\nu_1\ldots\nu_n)}_{abc}(x) P_y^{\mu_1}\cdots P_y^{\mu_m} P_z^{\nu_1}\cdots P_z^{\nu_n}$$

Looks more scary than it is

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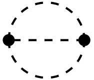
The remaining **basic ingredients repeat** beyond 1-loop order



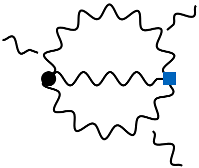
2-loop integral

$$= \sum_{m,n,m',n'} (-1)^{m+n} \int_x \int_{k\ell} V^{(\underline{m},\underline{n})}_{abc}(x) Q^{-1}_{aa'}(y,\, P_y - k - \ell) V^{(\underline{m}',\underline{n}')}_{a'b'c'}(y)$$
$$\times \left[(P_x + k)^{\overleftarrow{\underline{m}}} Q^{-1}_{be}(x,\, P_x + k)(P_x + k)^{\underline{m}'} U^{e}{}_{b'}(x,y)\right]$$
$$\times \left[(P_x + \ell)^{\overleftarrow{\underline{n}}} Q^{-1}_{cf}(x,\, P_x + \ell)(P_x + \ell)^{\underline{n}'} U^{f}{}_{c'}(x,y)\right]\Bigg|_{y=x}$$

$$Q^{-1} = \Delta^{-1} + \Delta^{-1}X\Delta^{-1} + \Delta^{-1}X\Delta^{-1}X\Delta^{-1} + \ldots$$

The figure-8 and the counterterm topologies are (even) simpler

And generalization to higher loop order: Fuentes-Martín, Moreno, Palavrić, **AET** [2412.12270]



```
L = FreeLag[] + cGt[] Gtilde;
L // NiceForm
```

iceForm=

$$-\frac{1}{4} G^{\mu\nu x2} + \left(D_\mu \bar{c}_G{}^x \cdot D_\mu c_G{}^x\right) + g\, G^{\mu y} \left(\bar{c}_G{}^x \cdot D_\mu c_G{}^z\right) f^{xyz} + \frac{1}{6}\, \text{cGt}\, G^{\mu\rho y} G^{\nu\rho z} G^{\sigma\kappa x} f^{xyz} \varepsilon^{\mu\nu\sigma\kappa}$$

```
ctlag = CountertermLagrangian[L, EFTOrder → 6] // EchoTiming;
ctlag // NiceForm
```

» Added new CG cg1 with indices {SU3c[adj], SU3c[adj], SU3c[adj], SU3c[adj]}

» Added new CG cg2 with indices {SU3c[adj], SU3c[adj], SU3c[adj], SU3c[adj], SU3c[adj]}

13 695.1 — Mathematica, single core

'/NiceForm=

$$-\frac{11}{4}\hbar \frac{1}{\epsilon} g^2 G^{\mu\nu x2} - \frac{51}{4}\hbar^2 \frac{1}{\epsilon} g^4 G^{\mu\nu x2} - 3\hbar \frac{1}{\epsilon}\, \text{cGt}\, g^2 G^{\mu\nu x} G^{\rho\sigma y} G^{\sigma\kappa z} f^{xyz} \varepsilon^{\mu\nu\rho\kappa} - \frac{21}{2}\hbar^2 \frac{1}{\epsilon^2}\, \text{cGt}\, g^4 G^{\mu\nu x} G^{\rho\sigma y} G^{\sigma\kappa z} f^{xyz} \varepsilon^{\mu\nu\rho\kappa} - \frac{425}{24}\hbar^2 \frac{1}{\epsilon}\, \text{cGt}\, g^4 G^{\mu\nu x} G^{\rho\sigma y} G^{\sigma\kappa z} f^{xyz} \varepsilon^{\mu\nu\rho\kappa}$$

Born, Fuentes-Martín, Kvedaraitė, **AET** [2410.07320]

Result agrees with de Vries *et al.* [1907.04923]

Two-loop SMEFT RG

New challenges in full SMEFT

Born, Fuentes-Martín, **AET** [2601.xxxxx]

- Evanescent operators (leveraging `Matchete features`)
- Non-trivial interplay with evanescent operators and $\boldsymbol{R}^*$-method
- Treatment of γ_5: non-cyclicity of the anti-commuting γ_5

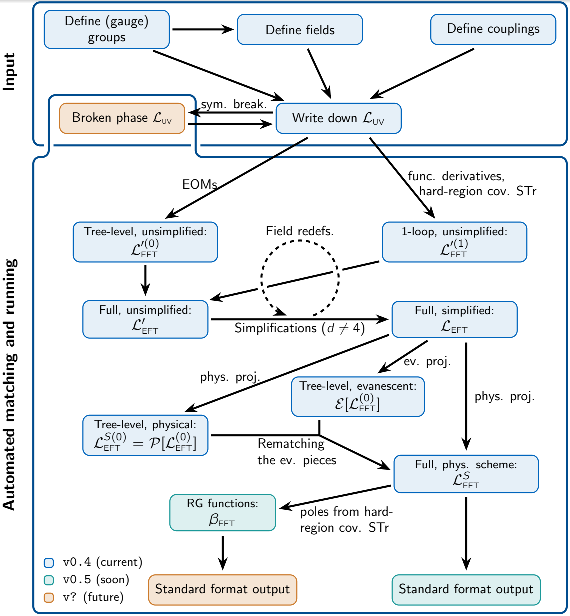
$$
\begin{aligned}
\beta^{(2)}_{C^{pr}_{eH}} = {} & \frac{1}{12} g_L^2 \Big(22 Y_e^{pr} \mathrm{T}_{\ell H} - 243 (C^\dagger_{\ell\ell HH} C_{\ell\ell HH} Y_e)^{pr} \Big) + \frac{1}{12} g_Y^2 \Big(38 Y_e^{pr} \mathrm{T}_{\ell H} + 51 (C^\dagger_{\ell\ell HH} C_{\ell\ell HH} Y_e)^{pr} \Big) + \frac{1}{2} \Big(7 (C^\dagger_{\ell\ell HH} C_{\ell\ell HH} Y_e Y_e^\dagger Y_e)^{pr} \\
& + 7 (Y_e Y_e^\dagger C^\dagger_{\ell\ell HH} C_{\ell\ell HH} Y_e)^{pr} + 30 (Y_e Y_e^\dagger Y_e)^{pr} \mathrm{T}_{\ell H} - 7 (C^\dagger_{\ell\ell HH} Y_e^\dagger Y_e C_{\ell\ell HH} Y_e)^{pr} - 10 \mathrm{T}_2 (C^\dagger_{\ell\ell HH} C_{\ell\ell HH} Y_e)^{pr} \Big) \\
& - \lambda \Big(5 (C^\dagger_{\ell\ell HH} C_{\ell\ell HH} Y_e)^{pr} + 24 Y_e^{pr} \mathrm{T}_{\ell H} \Big) - 6 Y_e^{pr} \, \mathrm{Tr}\Big[C^\dagger_{\ell\ell HH} C_{\ell\ell HH} Y_e Y_e^\dagger \Big] + \bigg\{ 24 \lambda Y_e^{pr} - 48 (Y_e Y_e^\dagger Y_e)^{pr} \bigg\} C_H + \bigg\{ \frac{1}{2} \lambda^2 Y_e^{pr} + \frac{47}{54} g_Y^2 g_L^2 Y_e^{pr} \\
& + \lambda \Big(\frac{9}{4} g_L^2 Y_e^{pr} + \frac{163}{36} g_Y^2 Y_e^{pr} + 5 \mathrm{T}_2 Y_e^{pr} - \frac{53}{2} (Y_e Y_e^\dagger Y_e)^{pr} \Big) + g_Y^2 \Big(\frac{1}{12} \mathrm{T}_2 Y_e^{pr} + \frac{71}{16} (Y_e Y_e^\dagger Y_e)^{pr} \Big) + \frac{25}{8} (Y_e Y_e^\dagger Y_e Y_e^\dagger Y_e)^{pr} + \frac{45}{2} Y_e^{pr} \, \mathrm{Tr}\Big[Y_d^\dagger Y_d Y_u^\dagger Y_u \Big] \\
& - g_L^2 \Big(\frac{17}{12} \mathrm{T}_2 Y_e^{pr} + \frac{23}{16} (Y_e Y_e^\dagger Y_e)^{pr} \Big) - \frac{74}{27} g_Y^4 Y_e^{pr} - \frac{71}{24} g_L^4 Y_e^{pr} - \frac{13}{4} \mathrm{T}_4 Y_e^{pr} - \frac{9}{2} \mathrm{T}_2 (Y_e Y_e^\dagger Y_e)^{pr} \bigg\} C^{(\|)}_{HD} + \bigg\{ \lambda^2 Y_e^{pr} + \lambda \Big(\frac{287}{36} g_Y^2 Y_e^{pr} \\
& + \frac{51}{4} g_L^2 Y_e^{pr} - 31 (Y_e Y_e^\dagger Y_e)^{pr} \Big) + g_Y^2 \Big(\frac{1}{6} \mathrm{T}_2 Y_e^{pr} + \frac{17}{4} (Y_e Y_e^\dagger Y_e)^{pr} \Big) + g_L^2 \Big(\frac{3}{2} \mathrm{T}_2 Y_e^{pr} + \frac{43}{8} (Y_e Y_e^\dagger Y_e)^{pr} \Big) + \frac{133}{96} g_L^4 Y_e^{pr} + 2 (Y_e Y_e^\dagger Y_e Y_e^\dagger Y_e)^{pr} \\
& - \frac{7}{4} \mathrm{T}_4 Y_e^{pr} - \frac{1955}{864} g_Y^4 Y_e^{pr} - 3 \mathrm{T}_2 (Y_e Y_e^\dagger Y_e)^{pr} - \frac{2143}{432} g_Y^2 g_L^2 Y_e^{pr} - \frac{27}{2} Y_e^{pr} \, \mathrm{Tr}\Big[Y_d^\dagger Y_d Y_u^\dagger Y_u \Big] \bigg\} C^{(\times)}_{HD} + \bigg\{ g_Y^4 \Big(\frac{53}{6} Y_e^{pr} \, \mathrm{Tr}\Big[Y_d^\dagger Y_d \Big] - \frac{79}{6} Y_e^{pr} \, \mathrm{Tr}\Big[Y_u^\dagger Y_u \Big] \\
& - \frac{43}{2} Y_e^{pr} \, \mathrm{Tr}\Big[Y_e^\dagger Y_e \Big] - \frac{375}{4} (Y_e Y_e^\dagger Y_e)^{pr} \Big) + \frac{49}{2} \lambda g_Y^4 Y_e^{pr} - \frac{49}{3} g_Y^4 g_L^2 Y_e^{pr} - 242 g_Y^6 Y_e^{pr} \bigg\} C_{HB} + \bigg\{ g_Y^4 \Big(\frac{39i}{2} Y_e^{pr} \, \mathrm{Tr}\Big[Y_e^\dagger Y_e \Big] + \frac{477i}{4} (Y_e Y_e^\dagger Y_e)^{pr} \\
& - \frac{3i}{2} Y_e^{pr} \, \mathrm{Tr}\Big[Y_d^\dagger Y_d \Big] - \frac{33i}{2} Y_e^{pr} \, \mathrm{Tr}\Big[Y_u^\dagger Y_u \Big] \Big) + \frac{153i}{2} \lambda g_Y^4 Y_e^{pr} + \frac{1469i}{12} g_Y^6 Y_e^{pr} - \frac{21i}{4} g_Y^4 g_L^2 Y_e^{pr} \bigg\} C_{H\widetilde{B}} + \bigg\{ g_L^4 \Big(\frac{3}{2} \mathrm{T}_2 Y_e^{pr} - \frac{243}{4} (Y_e Y_e^\dagger Y_e)^{pr} \Big) \\
& + \frac{77}{3} g_L^6 Y_e^{pr} + \frac{147}{2} \lambda g_L^4 Y_e^{pr} - 19 g_Y^2 g_L^4 Y_e^{pr} \bigg\} C_{HW} + \bigg\{ g_L^4 \Big(\frac{9i}{2} Y_e^{pr} \, \mathrm{Tr}\Big[Y_e^\dagger Y_e \Big] + \frac{27i}{2} Y_e^{pr} \, \mathrm{Tr}\Big[Y_d^\dagger Y_d \Big] + \frac{213i}{4} (Y_e Y_e^\dagger Y_e)^{pr} - \frac{27i}{2} Y_e^{pr} \, \mathrm{Tr}\Big[Y_u^\dagger Y_u \Big] \Big) \\
& + \frac{51i}{2} \lambda g_L^4 Y_e^{pr} - \frac{21i}{4} g_Y^2 g_L^4 Y_e^{pr} - \frac{341i}{4} g_L^6 Y_e^{pr} \bigg\} C_{H\widetilde{W}} - g_s^4 \bigg\{ 176 Y_e^{pr} \, \mathrm{Tr}\Big[Y_d^\dagger Y_d \Big] + 176 Y_e^{pr} \, \mathrm{Tr}\Big[Y_u^\dagger Y_u \Big] \bigg\} C_{HG} + g_s^4 \bigg\{ 144i Y_e^{pr} \, \mathrm{Tr}\Big[Y_d^\dagger Y_d \Big] \\
& - 144i Y_e^{pr} \, \mathrm{Tr}\Big[Y_u^\dagger Y_u \Big] \bigg\} C_{H\widetilde{G}} + \bigg\{ g_Y^2 g_L^2 \Big(\frac{23}{4} Y_e^{pr} \, \mathrm{Tr}\Big[Y_e^\dagger Y_e \Big] + \frac{25}{4} Y_e^{pr} \, \mathrm{Tr}\Big[Y_d^\dagger Y_d \Big] + \frac{33}{4} (Y_e Y_e^\dagger Y_e)^{pr} + \frac{47}{4} Y_e^{pr} \, \mathrm{Tr}\Big[Y_u^\dagger Y_u \Big] \Big) + \frac{23}{6} g_Y^2 g_L^4 Y_e^{pr} \\
& + \frac{63}{4} \lambda g_Y^2 g_L^2 Y_e^{pr} - \frac{181}{12} g_Y^4 g_L^2 Y_e^{pr} \bigg\} C_{HWB} + \bigg\{ g_Y^2 g_L^2 \Big(\frac{27i}{4} Y_e^{pr} \, \mathrm{Tr}\Big[Y_u^\dagger Y_u \Big] - \frac{9i}{4} Y_e^{pr} \, \mathrm{Tr}\Big[Y_d^\dagger Y_d \Big] - \frac{15i}{4} Y_e^{pr} \, \mathrm{Tr}\Big[Y_e^\dagger Y_e \Big] - 12i (Y_e Y_e^\dagger Y_e)^{pr} \Big) \\
& + \frac{11i}{3} g_Y^4 g_L^2 Y_e^{pr} - \frac{13i}{12} g_Y^2 g_L^4 Y_e^{pr} - \frac{81i}{4} \lambda g_Y^2 g_L^2 Y_e^{pr} \bigg\} C_{H\widetilde{W}B} + \bigg\{ g_L^6 \Big(3 \mathrm{T}_2 Y_e^{pr} - \frac{9}{4} (Y_e Y_e^\dagger Y_e)^{pr} \Big) + \frac{103}{12} g_L^8 Y_e^{pr} - 6 \lambda g_L^6 Y_e^{pr}
\end{aligned}
$$

Preliminary

MATCHETE

To make your way through the BSM jungle

Automated EFT matching with MATCHETE



Fuentes-Martín, König, Pagès, **AET**, Wilsch [2212.04510]

- **Matchete v0.4** is a Mathematica package
- Matching of **any model** with heavy scalars/fermions
- Simple and intuitive input/output
- Handles arbitrary* group theory
- Simplifies to EFT basis
- Handles of evanescent contributions

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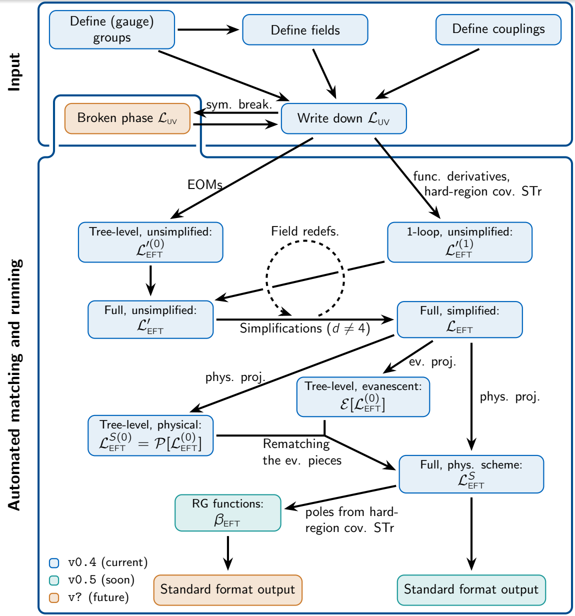

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Future plans:

- Interface with EFT tool chain
- 1-loop RG computations
- SSB and heavy vectors
- Many more...

Example: SM + Vector-like lepton

Setup

SM Lagrangian

In[3]:=
```
LSM = LoadModel["SM"];
```

Define new field

In[4]:=
```
DefineField[EE, Fermion, Charges → {U1Y[-1]}, Mass → {Heavy, ME}]
```

Define new coupling

In[5]:=
```
DefineCoupling[yE, EFTOrder → 0, Indices → {Flavor}]
```

Write interactions

In[6]:=
```
Lint = -yE[p] × Bar@l[i, p] ** PR ** EE[] × H[i] // PlusHc;
Lint // NiceForm
```

Out[7]//NiceForm=

$$-\overline{yE}^{p}\,\bar{H}_{i}\,\left(\overline{EE}\cdot P_{L}\cdot l^{ip}\right)-yE^{p}\,H^{i}\,\left(\bar{l}^{p}_{i}\cdot P_{R}\cdot EE\right)$$

Define full UV Lagrangian

In[8]:=
```
LUV = LSM + FreeLag[EE] + Lint;
LUV // NiceForm
```

Out[9]//NiceForm=

$$-\frac{1}{4}B^{\mu\nu 2}-\frac{1}{4}G^{\mu\nu A2}-\frac{1}{4}W^{\mu\nu I2}+D_{\mu}\bar{H}_{i}\,D_{\mu}H^{i}+\mu^{2}\,\bar{H}_{i}\,H^{i}+i\left(\bar{d}^{p}_{a}\cdot\gamma_{\mu}P_{R}\cdot D_{\mu}d^{ap}\right)+i\left(\bar{e}^{p}\cdot\gamma_{\mu}P_{R}\cdot D_{\mu}e^{p}\right)+$$
$$i\left(\overline{EE}\cdot\gamma_{\mu}\cdot D_{\mu}EE\right)-ME\left(\overline{EE}\cdot EE\right)+i\left(\bar{l}^{p}_{i}\cdot\gamma_{\mu}P_{L}\cdot D_{\mu}l^{ip}\right)+i\left(\bar{q}^{p}_{ai}\cdot\gamma_{\mu}P_{L}\cdot D_{\mu}q^{aip}\right)+i\left(\bar{u}^{p}_{a}\cdot\gamma_{\mu}P_{R}\cdot D_{\mu}u^{ap}\right)-$$
$$\frac{1}{2}\lambda\,\bar{H}_{i}\,\bar{H}_{j}\,H^{i}\,H^{j}-\overline{Yd}^{pr}\,\bar{H}_{i}\left(\bar{d}^{r}_{a}\cdot P_{L}\cdot q^{aip}\right)-\overline{Ye}^{pr}\,\bar{H}_{i}\left(\bar{e}^{r}\cdot P_{L}\cdot l^{ip}\right)-Ye^{pr}\,H^{i}\left(\bar{l}^{p}_{i}\cdot P_{R}\cdot e^{r}\right)-Yd^{pr}\,H^{i}\left(\bar{q}^{p}_{ai}\cdot P_{R}\cdot d^{ar}\right)-$$
$$Yu^{pr}\,\bar{H}_{i}\left(\bar{q}^{p}_{aj}\cdot P_{R}\cdot u^{ar}\right)\varepsilon^{ji}-\overline{Yu}^{pr}\,H^{j}\left(\bar{u}^{r}_{a}\cdot P_{L}\cdot q^{aip}\right)\bar{\varepsilon}_{ij}-\overline{yE}^{p}\,\bar{H}_{i}\left(\overline{EE}\cdot P_{L}\cdot l^{ip}\right)-yE^{p}\,H^{i}\left(\bar{l}^{p}_{i}\cdot P_{R}\cdot EE\right)$$

Example: SM + Vector-like lepton

Main matching routine

In[9]:=
```
LEFT = Match[LUV, LoopOrder → 1, EFTOrder → 6] /. ϵ^-1 → 0;
```

Simplification to on-shell basis

In[10]:=
```
LEFTOnShell = LEFT // EOMSimplify;
Length@%
```

```
» The Lagrangian contains terms of lower power than dimension 4. Defining effective couplings and assuming these terms to
  be dimension 4. Use 'PrintEffectiveCouplings' and 'ReplaceEffectiveCouplings' to recover explicit expressions.
» Added new CG cg1 with indices {Bar[SU2L[fund]], SU2L[adj], Bar[SU2L[fund]]}
```

Out[11]= 66

Select Higgs-lepton current operator

In[12]:=
```
SelectOperatorClass[LEFTOnShell, {e, Bar@e, H, Bar@H}, 1] // GreensSimplify // NiceForm
```

Out[12]//NiceForm=

$$\frac{i}{360}\hbar\frac{1}{\mathrm{ME}^2}\left(48\,\mathrm{gY}^4\,\delta^{pr}+5\,\overline{\mathrm{yE}}^{s}\left(3\,\mathrm{yE}^{t}\,\overline{\mathrm{Ye}}^{tr}\,\mathrm{Ye}^{sp}\left(1+6\,\mathrm{Log}\left[\frac{\bar{\mu}^2}{\mathrm{ME}^2}\right]\right)-2\,\mathrm{yE}^{s}\,\mathrm{gY}^2\left(13+6\,\mathrm{Log}\left[\frac{\bar{\mu}^2}{\mathrm{ME}^2}\right]\right)\delta^{pr}\right)\right)$$
$$\left(-D_\mu\bar{H}_i\,H^i\left(\bar{e}^r\cdot\gamma_\mu P_R\cdot e^p\right)+\bar{H}_i\,D_\mu H^i\left(\bar{e}^r\cdot\gamma_\mu P_R\cdot e^p\right)\right)$$

$$Q_{He}^{pr}=(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$$

Example: SM + Vector-like lepton

```
LEFTOnShell // NiceForm
```

iceForm=

$$-\frac{1}{4} G^{\mu\nu A2} - \frac{1}{4} W^{\mu\nu I2} + \left(-\frac{1}{4} - \frac{1}{3}\hbar\, gY^2\, \mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) B^{\mu\nu 2} + D_\mu \bar H_i\, D_\mu H^i + \left(C_{H2} + \frac{1}{6}\hbar\, \overline{yE}^p\, yE^p\, C_{H2}\, \frac{1}{ME^2} \left(2 C_{H2} - 3 ME^2 \left(1 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\right)\right) \bar H_i H^i + i\,(\bar d^r_a \cdot \gamma_\mu P_R \cdot D_\mu d^{ap})\,\delta^{pr} + i\,(\bar e^r \cdot \gamma_\mu P_R \cdot D_\mu e^p)\,\delta^{pr} +$$

$$i\,(\bar l^r_i \cdot \gamma_\mu P_L \cdot D_\mu l^{ip})\,\delta^{pr} + i\,(\bar q^r_{ai} \cdot \gamma_\mu P_L \cdot D_\mu q^{aip})\,\delta^{pr} + i\,(\bar u^r_a \cdot \gamma_\mu P_R \cdot D_\mu u^{ap})\,\delta^{pr} + \Big(-\frac{1}{2}\lambda + \hbar\,\Big(-\frac{1}{2}\overline{yE}^p \Big(4\, yE^r\, \overline{Ye}^{rs}\, Ye^{ps} \left(1 + \mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) - yE^p \Big(-2\,\overline{yE}^r\, yE^r\, \mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right] + \lambda\left(1 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big)\Big) -$$

$$\frac{1}{180} C_{H2}\, \frac{1}{ME^2} \Big(12\, gY^4 - 5\,\overline{yE}^p\, yE^p\, gY^2 \left(13 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) + 5\,\overline{yE}^p \Big(-12\,(\overline{yE}^r\, yE^p\, yE^r + 6\, yE^r\, \overline{Ye}^{rs}\, Ye^{ps} - 2\, yE^p\lambda) + yE^p\, gL^2 \left(5 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big)\Big)\Big)$$

$$\bar H_i \bar H_j H^i H^j + \left(-\overline{Yd}^{pr} + \frac{1}{12}\hbar\,\overline{yE}^s\, yE^s\, \overline{Yd}^{pr}\, \frac{1}{ME^2}\left(-4 C_{H2} + 3 ME^2 \left(1 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\right)\right) \bar H_i\, (\bar d^r_a \cdot P_L \cdot q^{aip}) +$$

$$\Big(-\overline{Ye}^{pr} + \frac{1}{24}\hbar\, yE^s\, \frac{1}{ME^2} \Big(-3\,\overline{yE}^p\, \overline{Ye}^{sr}\, (2 C_{H2} - ME^2)\left(3 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) + 2\,\overline{yE}^s\, \overline{Ye}^{pr} \left(-4 C_{H2} + 3 ME^2\left(1 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\right)\Big)\Big) \bar H_i\, (\bar e^r \cdot P_L \cdot l^{ip}) +$$

$$\Big(-Ye^{rp} + \frac{1}{24}\hbar\,\overline{yE}^s\, \frac{1}{ME^2}\Big(3 ME^2 \Big(2\, yE^s\, Ye^{rp}\left(1 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) + yE^r\, Ye^{sp}\left(3 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big) - 2 C_{H2}\Big(4\, yE^s\, Ye^{rp} + 3\, yE^r\, Ye^{sp}\left(3 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big)\Big) H^i\, (\bar l^r_i \cdot P_R \cdot e^p) +$$

$$\left(-Yd^{rp} + \frac{1}{12}\hbar\,\overline{yE}^s\, yE^s\, Yd^{rp}\, \frac{1}{ME^2}\left(-4 C_{H2} + 3 ME^2\left(1 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\right)\right) H^i\, (\bar q^r_{ai} \cdot P_R \cdot d^{ap}) +$$

$$\left(-Yu^{rp} + \frac{1}{12}\hbar\,\overline{yE}^s\, yE^s\, Yu^{rp}\, \frac{1}{ME^2}\left(-4 C_{H2} + 3 ME^2\left(1 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\right)\right) \bar H_i\, (\bar q^r_{aj} \cdot P_R \cdot u^{ap})\, \varepsilon^{ji} +$$

$$\left(-\overline{Yu}^{pr} + \frac{1}{12}\hbar\,\overline{yE}^s\, yE^s\, \overline{Yu}^{pr}\, \frac{1}{ME^2}\left(-4 C_{H2} + 3 ME^2\left(1 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\right)\right) H^j\, (\bar u^r_a \cdot P_L \cdot q^{aip})\, \bar\varepsilon_{ij} +$$

$$\frac{1}{180}\hbar\, \frac{1}{ME^2}\Big(12\lambda\, gY^4 + 5\,\overline{yE}^p \Big(12\,\overline{yE}^r\, yE^p\,(\overline{yE}^s\, yE^r\, yE^s + 6\, yE^s\, \overline{Ye}^{st}\, Ye^{rt} - yE^r\lambda) - 72\, yE^r\, \overline{Ye}^{rs}\Big(Ye^{ps}\lambda + \overline{Ye}^{tu}\, Ye^{pu}\, Ye^{ts}\left(1 + \mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big) + yE^p\lambda\Big(12\lambda + gL^2\left(5 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) - gY^2\left(13 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big)\Big)\Big)$$

$$\bar H_i \bar H_j \bar H_k H^i H^j H^k + \frac{1}{90}\hbar\, \frac{1}{ME^2}\Big(-12\, gY^4 + 5\,\overline{yE}^p\, yE^p\, gY^2\left(13 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) + 45\,\overline{yE}^p\, yE^r\Big(-\overline{yE}^r\, yE^p + \overline{Ye}^{rs}\, Ye^{ps}\left(1 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big) \bar H_i\, D_\mu \bar H_j\, D_\mu H^i H^j +$$

$$\frac{1}{180}\hbar\, \frac{1}{ME^2}\Big(-12\, gY^4 + 5\,\overline{yE}^p\, yE^p\, gY^2\left(13 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) - 15\,\overline{yE}^p\Big(yE^p\, gL^2\left(5 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) + 4\, yE^r\Big(2\,\overline{yE}^r\, yE^p - 3\,\overline{Ye}^{rs}\, Ye^{ps}\left(3 + 2\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big)\Big) \bar H_i\, D_\mu \bar H_j\, H^i D_\mu H^j +$$

$$\frac{1}{8}\hbar\,\overline{yE}^p\, yE^p\, gY^2\, \frac{1}{ME^2}\, \bar H_i H^i B^{\mu\nu 2} - \frac{1}{3}\hbar\, gL\, gY\, \overline{yE}^p\, yE^p\, \frac{1}{ME^2}\, \bar H_i H^j B^{\mu\nu} W^{\mu\nu I}\, T^{Ii}_j + \frac{1}{24}\hbar\,\overline{yE}^p\, yE^p\, gL^2\, \frac{1}{ME^2}\, \bar H_i H^i W^{\mu\nu I2} +$$

$$\frac{1}{360}\hbar\,\overline{Yd}^{pr}\, \frac{1}{ME^2}\Big(12\, gY^4 - 5\,\overline{yE}^s\, yE^s\, gY^2\left(13 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) + 5\,\overline{yE}^s\Big(-12\,(\overline{yE}^t\, yE^s\, yE^t + 6\, yE^t\, \overline{Ye}^{tu}\, Ye^{su} - 2\, yE^s\lambda) + yE^s\, gL^2\left(5 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big) \bar H_i \bar H_j H^j\, (\bar d^r_a \cdot P_L \cdot q^{aip}) +$$

$$\Big(\frac{1}{2}\overline{yE}^p\, yE^s\, \overline{Ye}^{sr}\, \frac{1}{ME^2} + \frac{1}{720}\hbar\, \frac{1}{ME^2}\Big(30\,\overline{yE}^s\, yE^u\, \overline{Ye}^{pt}\, \overline{Ye}^{ur}\, Ye^{st}\left(37 + 18\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) - 45\,\overline{yE}^p\Big(\overline{yE}^s\, yE^s\, yE^t\, \overline{Ye}^{tr}\left(19 + 18\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) + 4\,\overline{Ye}^{sr}\Big(yE^t\, \overline{Ye}^{tu}\, Ye^{su} - 2\, yE^s\lambda\left(5 + 4\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big) +$$

$$2\,\overline{Ye}^{pr}\Big(12\, gY^4 - 5\,\overline{yE}^s\, yE^s\, gY^2\left(13 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) + 5\,\overline{yE}^s\Big(-12\,(\overline{yE}^t\, yE^s\, yE^t + 6\, yE^t\, \overline{Ye}^{tu}\, Ye^{su} - 2\, yE^s\lambda) + yE^s\, gL^2\left(5 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big)\Big)\Big) \bar H_i \bar H_j H^i\, (\bar e^r \cdot P_L \cdot l^{jp}) +$$

$$\Big(\frac{1}{2}\overline{yE}^s\, yE^r\, Ye^{sp}\, \frac{1}{ME^2} + \frac{1}{720}\hbar\, \frac{1}{ME^2}\Big(24\, Ye^{rp}\, gY^4 - 10\,\overline{yE}^s\, yE^s\, Ye^{rp}\, gY^2\left(13 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) + 5\,\overline{yE}^s\Big(2\, yE^s\, Ye^{rp}\, gL^2\left(5 + 6\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right) - 3\,\overline{yE}^t\, yE^t\Big(8\, yE^s\, Ye^{rp} + 3\, yE^r\, Ye^{sp}\left(19 + 18\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big) +$$

$$6\Big(4\lambda\Big(2\, yE^s\, Ye^{rp} + 3\, yE^r\, Ye^{sp}\left(5 + 4\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big) + \overline{Ye}^{tu}\Big(-6\, yE^r\, Ye^{su}\, Ye^{tp} + yE^t\Big(-24\, Ye^{rp}\, Ye^{su} + Ye^{ru}\, Ye^{sp}\left(37 + 18\,\mathrm{Log}\left[\frac{\bar\mu^2}{ME^2}\right]\right)\Big)\Big)\Big)\Big)\Big)\Big) \bar H_i H^i H^j\, (\bar l^r_i \cdot P_R \cdot e^p) +$$

Matching to a particular EFT basis

In[2]:=
```
LEFT = Match@LoadModel@"E_VLL";
LTarget = LoadModel@"SMEFT";
MapEffectiveCouplings[LEFT, LTarget] // TableForm // NiceForm
```

» Added new CG cg1 with indices {SU2L[fund], SU2L[adj], SU2L[fund]}

» The Lagrangian contains terms of lower power than dimension 4. Defining effective couplings and assuming these terms to be dimension 4. Use 'PrintEffectiveCouplings' and 'ReplaceEffectiveCouplings' to recover explicit expressions.

Out[4]//NiceForm=

$g_L \to g_L$

$g_s \to g_s$

$g_Y \to g_Y - \frac{2}{3}\hbar\frac{1}{\epsilon} g_Y{}^3 - \frac{2}{3}\hbar\, g_Y{}^3 \,\mathrm{Log}\left[\frac{\bar{\mu}^2}{M_{\mathcal{E}}{}^2}\right]$

$Y_d{}^{i1\_i2\_} \to Y_d{}^{i1i2} - \frac{1}{4}\hbar\,\overline{yE}^p\, yE^p\, Y_d{}^{i1i2} - \frac{1}{2}\hbar\frac{1}{\epsilon}\overline{yE}^p\, yE^p\, Y_d{}^{i1i2} + \frac{1}{3}\hbar\, C_{H^2}\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\, yE^p\, Y_d{}^{i1i2} - \frac{1}{2}\hbar\,\overline{yE}^p$

$Y_e{}^{i1\_i2\_} \to -\frac{3}{8}\hbar\,\overline{yE}^p\, yE^{i1}\, Y_e{}^{pi2} - \frac{1}{4}\hbar\frac{1}{\epsilon}\overline{yE}^p\, yE^{i1}\, Y_e{}^{pi2} + \frac{3}{4}\hbar\, C_{H^2}\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\, yE^{i1}\, Y_e{}^{pi2} + \frac{1}{2}\hbar\frac{1}{\epsilon}C_{H^2}\frac{1}{M_{\mathcal{E}}{}^2}\,\overline{y}$

$Y_u{}^{i1\_i2\_} \to Y_u{}^{i1i2} - \frac{1}{4}\hbar\,\overline{yE}^p\, yE^p\, Y_u{}^{i1i2} - \frac{1}{2}\hbar\frac{1}{\epsilon}\overline{yE}^p\, yE^p\, Y_u{}^{i1i2} + \frac{1}{3}\hbar\, C_{H^2}\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\, yE^p\, Y_u{}^{i1i2} - \frac{1}{2}\hbar\,\overline{yE}^p$

$\lambda \to -\frac{5}{9}\hbar\, C_{H^2}\, g_L{}^2\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\, yE^p - \frac{2}{3}\hbar\frac{1}{\epsilon}C_{H^2}\, g_L{}^2\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\, yE^p + 2\hbar\frac{1}{\epsilon}\overline{yE}^p\,\overline{yE}^r\, yE^p\, yE^r - 2\hbar\, C_{H^2}\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\,\overline{y}$

$\mu 2 \to C_{H^2} - \frac{1}{2}\hbar\, C_{H^2}\overline{yE}^p\, yE^p - \hbar\frac{1}{\epsilon}C_{H^2}\overline{yE}^p\, yE^p + \frac{1}{3}\hbar\, C_{H^2}{}^2\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\, yE^p - \hbar\, C_{H^2}\overline{yE}^p\, yE^p\,\mathrm{Log}\left[\frac{\bar{\mu}^2}{M_{\mathcal{E}}{}^2}\right]$

$\mathcal{C}_{llHH}{}^{i1\_i2\_} \to 0$

$\mathcal{C}_{dB}{}^{i1\_i2\_} \to 0$

$\mathcal{C}_{dd}{}^{i1\_i2\_i3\_i4\_} \to -\frac{2}{135}\hbar\, g_Y{}^4\frac{1}{M_{\mathcal{E}}{}^2}\delta_{i1i2}\,\delta_{i3i4}$

$\mathcal{C}_{dG}{}^{i1\_i2\_} \to 0$

$\mathcal{C}_{dH}{}^{i1\_i2\_} \to -\frac{5}{36}\hbar\, g_L{}^2\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\, yE^p\, Y_d{}^{i1i2} - \frac{1}{6}\hbar\frac{1}{\epsilon}g_L{}^2\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\, yE^p\, Y_d{}^{i1i2} - \frac{1}{2}\hbar\frac{1}{M_{\mathcal{E}}{}^2}\overline{yE}^p\,\overline{yE}^r\, yE^p\, yE^r\, Y$

$\mathcal{C}_{duq}{}^{i1\_i2\_i3\_i4\_} \to 0$

$\mathcal{C}_{duu}{}^{i1\_i2\_i3\_i4\_} \to 0$

Simplification and basis reduction

Number of SMEFT generators (1 gen., dim. 6):

$$\underset{\text{Buchmüller, Wyler '86}}{80} \qquad (1986) \qquad \longrightarrow \qquad \underset{\text{Grzadkowski \textit{et al.} [1008.4884]}}{59} \qquad (2017)$$

Simplification and basis reduction

$$\mathcal{L} = -\tfrac{1}{2}\phi\partial^2\phi - \tfrac{1}{2}m^2\phi^2 - \frac{\lambda}{24}\phi^4 + \frac{C_1}{\Lambda^2}\phi^6 + \frac{C_2}{\Lambda^2}\phi^3\partial^2\phi + \frac{C_3}{\Lambda^2}\phi^2(\partial_\mu\phi)^2$$

Simplification and basis reduction

$$\mathcal{L} = -\tfrac{1}{2}\phi\partial^2\phi - \tfrac{1}{2}m^2\phi^2 - \frac{\lambda}{24}\phi^4 + \frac{C_1}{\Lambda^2}\phi^6 + \frac{C_2}{\Lambda^2}\phi^3\partial^2\phi + \cancel{\frac{C_3}{\Lambda^2}\phi^2(\partial_\mu\phi)^2}$$

Exact simplification (linear):
IBP, Dirac algebra, group identities, commutation relations,...

$$\mathcal{L} = -\tfrac{1}{2}\phi\partial^2\phi - \tfrac{1}{2}m^2\phi^2 - \frac{\lambda}{24}\phi^4 + \frac{C_1}{\Lambda^2}\phi^6 + \cancel{\frac{3C_2 - C_3}{3\Lambda^2}\phi^3\partial^2\phi}$$

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On-shell equivalence (non-linear):

Field redefinition: $\qquad \phi \longrightarrow \phi + \frac{3C_2 - C_3}{3\Lambda^2}\phi^3$

$$\mathcal{L} \longrightarrow -\tfrac{1}{2}\phi\partial^2\phi - \tfrac{1}{2}m^2\phi^2 - \left(\frac{\lambda}{24} + \frac{(3C_2 - C_3)\,m^2}{3\Lambda^2}\right)\phi^4 + \frac{18C_1 - \lambda(3C_2 - C_3)}{18\Lambda^2}\phi^6$$

Simplification and basis reduction

$$\mathcal{L} = -\tfrac{1}{2}\phi\partial^2\phi - \tfrac{1}{2}m^2\phi^2 - \frac{\lambda}{24}\phi^4 + \frac{C_1}{\Lambda^2}\phi^6 + \frac{C_2}{\Lambda^2}\phi^3\partial^2\phi + \cancel{\frac{C_3}{\Lambda^2}\phi^2(\partial_\mu\phi)^2}$$

Exact simplification (linear):
IBP, Dirac algebra, group identities, commutation relations,...

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Removal of evanescent operators: complicated but **fully automated**

Buras, Weisz '90; Dugan, Grinstein '91; Herrlich, Nierste [hep-ph/9412375]; Aebischer *et al.* [2211.01379]; **AET** *et al.* [2211.09144];...

Linear simplifications the Matchete way

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

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

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

Linear simplifications the Matchete way

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

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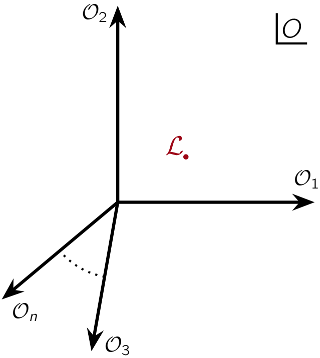
```
Out[12]//NiceForm=

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

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



Linear simplifications the Matchete way

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

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Out[12]//NiceForm=

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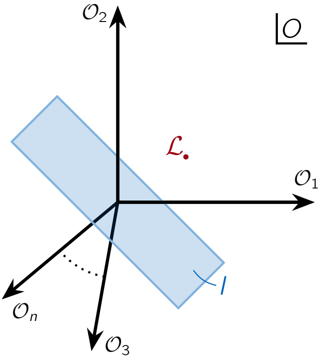


$I \subseteq O$ is the space of all operator identities, e.g., IBP relations such as

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

is interpreted as

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

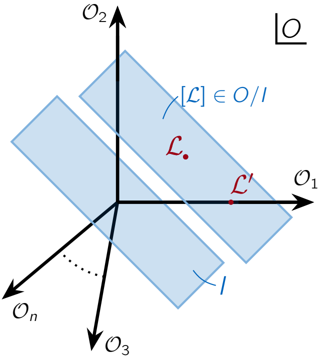
Linear simplifications the Matchete way

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

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

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

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



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Linear simplifications the Matchete way

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

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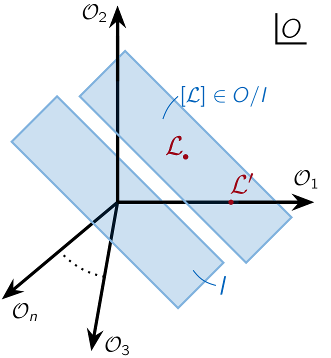
$$\mathcal{L}_{\text{EFT}} = \sum_i C_i \mathcal{O}_i \in O$$

With **linear algebra** on the basis of I we find a simple representative element for $[\mathcal{L}_{\text{EFT}}] \in O/I$:

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

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

Green's basis



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

is interpreted as

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

Summary and outlook

- (Automatic) EFT matching and running is crucial to BSM phenomenology
- Functional methods provides a direct approach to automated matching and RG calculations
- **Matchete** is a public code for EFT matching. It greatly simplifies the matching task and many more features are planned for the near-future
- Keep an eye out for the 2-loop SMEFT RG-functions! Born, Fuentes-Martín [2601.——]

https://gitlab.com/matchete/matchete

Backup

Matchete SM implementation

Gauge Groups

```
DefineGaugeGroup[SU3c, SU@3, gs, G,
    FundAlphabet → CharacterRange["a", "f"],
    AdjAlphabet → CharacterRange["A", "F"]]
DefineGaugeGroup[SU2L, SU@2, gL, W,
    FundAlphabet → CharacterRange["i", "n"],
    AdjAlphabet → CharacterRange["I", "N"]]
DefineGaugeGroup[U1Y, U@1, gY, B]
```

Generation index

```
DefineFlavorIndex[Flavor, 3,
    IndexAlphabet → {"p", "r", "s", "t", "u", "v"}]
```

Fermions

```
DefineField[q, Fermion,
    Indices → {SU3c@fund, SU2L@fund, Flavor},
    Charges → {U1Y[1/6]},
    Chiral → LeftHanded,
    Mass → 0]
DefineField[u, Fermion,
    Indices → {SU3c@fund, Flavor},
    Charges → {U1Y[2/3]},
    Chiral → RightHanded,
    Mass → 0]
DefineField[d, Fermion,
    Indices → {SU3c@fund, Flavor},
    Charges → {U1Y[-1/3]},
    Chiral → RightHanded,
    Mass → 0]
```

```
DefineField[l, Fermion,
    Indices → {SU2L@fund, Flavor},
    Charges → {U1Y[-1/2]},
    Chiral → LeftHanded,
    Mass → 0]
DefineField[e, Fermion,
    Indices → {Flavor},
    Charges → {U1Y[-1]},
    Chiral → RightHanded,
    Mass → 0]
```

Higgs

```
DefineField[H, Scalar,
    Indices → {SU2L@fund},
    Charges → {U1Y[1/2]},
    Mass → 0]
```

Couplings

```
DefineCoupling[λ, SelfConjugate → True]
DefineCoupling[μ, SelfConjugate → True,
  EFTorder → 1];
DefineCoupling[Ye,
    Indices → {Flavor, Flavor}]
DefineCoupling[Yu,
    Indices → {Flavor, Flavor}]
DefineCoupling[Yd,
    Indices → {Flavor, Flavor}]
```

Matchete SM implementation

Lagrangian

```
ℒSM = FreeLag[] +
    -μ[]^2 Bar@H[i] × H[i] -
    λ[]/2 Bar@H[i] × H[i] × Bar@H[j] × H[j] +
    PlusHc[
        -Yu[p, r] × CG[eps@SU2L, {i, j}] ×
       Bar@H@i × Bar@q[a, j, p] ** u[a, r]
        - Yd[p, r] × H@i × Bar@q[a, i, p] ** d[a, r]
        - Ye[p, r] × H@i × Bar@l[i, p] ** e[r]
    ] // RelabelIndices;
```

```
ℒSM // NiceForm
```

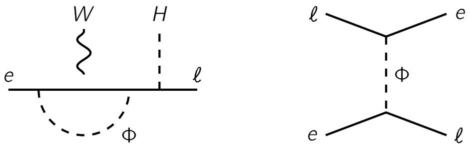
Form=

$$
\begin{aligned}
&-\frac{1}{4} B^{\mu\nu 2} - \frac{1}{4} G^{\mu\nu A 2} - \frac{1}{4} W^{\mu\nu I 2} + D_\mu \bar{H}_i\, D_\mu H^i - \\
&\mu^2 \bar{H}_i H^i + i\left(\bar{d}^p_a \cdot \gamma_\mu P_R \cdot D_\mu d^{ap}\right) + i\left(\bar{e}^p \cdot \gamma_\mu P_R \cdot D_\mu e^p\right) + \\
&i\left(\bar{l}^p_i \cdot \gamma_\mu P_L \cdot D_\mu l^{ip}\right) + i\left(\bar{q}^p_{ai} \cdot \gamma_\mu P_L \cdot D_\mu q^{aip}\right) + \\
&i\left(\bar{u}^p_a \cdot \gamma_\mu P_R \cdot D_\mu u^{ap}\right) - \frac{1}{2} \lambda \bar{H}_i \bar{H}_j H^i H^j - \\
&\overline{Yd}^{pr} \bar{H}_i \left(\bar{d}^r_a \cdot P_L \cdot q^{aip}\right) - \overline{Ye}^{pr} \bar{H}_i \left(\bar{e}^r \cdot P_L \cdot l^{ip}\right) - \\
&Ye^{pr} H^i \left(\bar{l}^p_i \cdot P_R \cdot e^r\right) - Yd^{pr} H^i \left(\bar{q}^p_{ai} \cdot P_R \cdot d^{ar}\right) - \\
&Yu^{pr} \bar{H}_i \left(\bar{q}^p_{aj} \cdot P_R \cdot u^{ar}\right) \varepsilon^{ij} - \overline{Yu}^{pr} H^i \left(\bar{u}^r_a \cdot P_L \cdot q^{ajp}\right) \bar{\varepsilon}_{ij}
\end{aligned}
$$

EFT from a 2HDM

Example: SM + leptophilic Higgs, $\Phi \sim (\mathbf{1}, \mathbf{2})_{1/2}$:

$$\mathcal{L} \supset \mathcal{L}_{\text{SM}} + D_\mu \Phi^\dagger D^\mu \Phi - M_\Phi^2 \, \Phi^\dagger \Phi - \left(y_{\Phi e}^{pr} \, \bar{\ell}_p \Phi e_r + \text{h.c.} \right) + \ldots$$



Below the scale $M_\Phi \gg v_{\text{EW}}$

$$\mathcal{L}_{\text{EFT}} \supset C_{eW}^{pr} Q_{eW}^{pr} + C_{\ell e}^{prst} R_{\ell e}^{prst}$$

But the tree-level operator **$R_{\ell e}$ is not part of the Warsaw basis**

Changing basis in an EFT

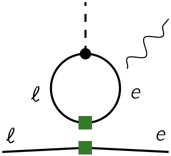
In $d=4$ dimensions, $\mathcal{L}_{\text{EFT}} = \widetilde{\mathcal{L}}_{\text{EFT}}$, where

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

$$\widetilde{\mathcal{L}}_{\text{EFT}} \supset C_{eW}^{pr} Q_{eW}^{pr} - \tfrac{1}{2} C_{\ell e}^{ptsr} Q_{\ell e}^{prst} \qquad Q_{\ell e}^{ptsr} = (\bar{\ell}_p \gamma_\mu \ell_t)(\bar{e}_s \gamma^\mu e_r)$$

But the 1-loop EFT **amplitudes disagree!**

$$i\big(\mathcal{A}_{eH\to\ell W} - \widetilde{\mathcal{A}}_{eH\to\ell W}\big) = \frac{g_2}{64\pi^2} [C_{\ell e}]^{prst} y_e^{ts} \big(\bar{u}\tau^I \sigma_{\mu\nu} P_R u\big) q^\mu \varepsilon^{*\nu}$$



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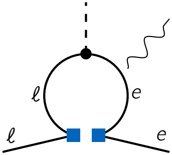

For $d \neq 4$, there is an **evanescent operator:**

$$R_{\ell e}^{prst} = -\tfrac{1}{2} Q_{\ell e}^{ptsr} + E_{\ell e}^{prst}, \qquad E_{\ell e}^{prst} \xrightarrow{d\to 4} 0$$