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SMEFT at higher orders: matching and RG evolution

Presented by Jason Aebischer

MARIE SKŁODOWSKA-CURIE ACTIONS

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CERN

Outline

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SM Effective Theory (SMEFT)

Symmetry

$SU(3)_C \times SU(2)_L \times U(1)_Y$

Fields

$u, d, c, s, b, t, \ell, \nu_\ell, g, W, Z, H$

Poincaré invariance

Dim 6 operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}^{(4)} + \frac{1}{\Lambda} C^{(5)} \mathcal{O}^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + \ldots$$

Weak Effective Theory (WET)

Symmetry

$SU(3)_C \times U(1)_{em}$

Fields

$u, d, c, s, b, \ell, \nu_\ell, g, \gamma$

Poincaré invariance

Dim 6 operators

$$\mathcal{L}_{\text{WET}} = \mathcal{L}^{(4)} + \frac{1}{\Lambda} \sum_i L_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2} \sum_i L_i^{(6)} O_i^{(6)} + \ldots$$

Outline

The Beginnings

Dimension 5 Weinberg: Phys. Rev. Lett. 43, 1566-1570 (1979)

Weinberg operator: $(\tilde{H}^\dagger \ell)^T C (\tilde{H}^\dagger \ell)$

Dimension 6 Buchmuller/Wyler: Nucl. Phys. B 268, 621-653 (1986)

first full basis

Dimension 6 Grzadkowski/Iskrzynski/Misiak/Rosiek: 1008.4884

non-redundant basis: Warsaw basis

Dimension 7

Operator basis

Lehman: 1410.4193

20 operators

$\not{L}$ (& $\not{\mathcal{B}}$)

Helset/Kobach: 1604.05726, 1909.05853

$\frac{\Delta\mathcal{B}-\Delta L}{2} = d \mod 2$

Non-redundant Basis

Liao/Ma: 1607.07309

EOM, Fierz $\rightarrow$ 18 operators

Dimension ≥ 8

Dimension 8

Li/Ren/Shu/Xiao/Yu/Zheng: 2005.00008
Murphy: 2005.00059

13 classes: f^4H^2, f^4X, f^4HD, f^4D^2, f^2X^2H, f^2XH^3, $f^2H^2D^3$, f^2H^5, f^2H^4D, f^2X^2D, f^2XH^2D, f^2XHD^2, $f^2H^3D^2$

Dimension 9

Li/Ren/Xiao/Yu/Zhen: 2007.07899
Liao/Ma: 2007.08125

amplitude-operator correspondence and Hilbert series

Dimension 10,11,12

Harlander/Kempkens/Schaaf: 2305.06832

`AutoEFT`

Green’s bases

Dimension 6 — Gherardi/Marzocca/Venturini: 2003.12525

one-loop LQ matching

Dimension 7 — Zhang: 2306.03008

together with novel physical basis + reduction

Dimension 8 — Ren/Yu: 2211.01420

amplitude methods

Evanescent bases

Evanescent SMEFT basis

Fuentes-Martín/König/Pagès/Thomsen/Wilsch: 2211.09144

one-loop matching

Evanescent WET basis

Naterop/Stoffer: 2310.13051

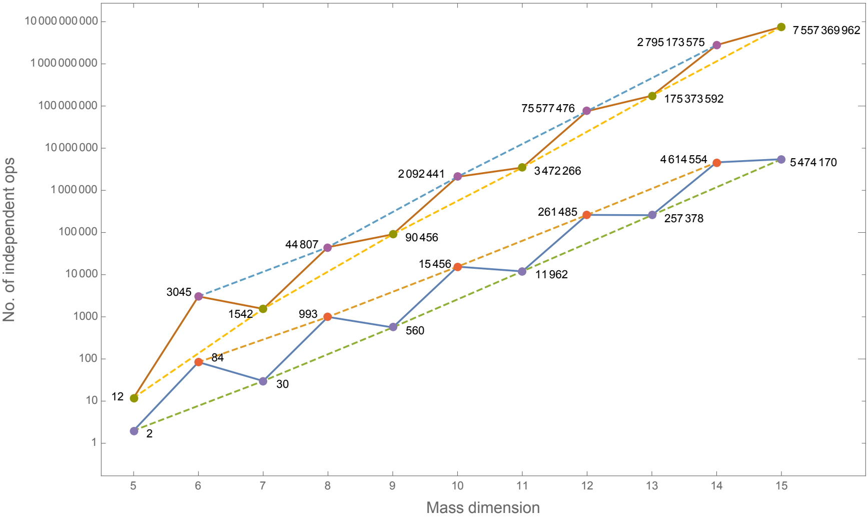
’t Hooft-Veltman

SMEFT operator bases

Dimension	Number of operators	Basis	Green's Basis
5	2	✓	–
6	84	✓	✓
7	30	✓	✓
8	993	✓	✓
9	560	✓	–
10	15 456	✓	–
11	11 962	✓	–
12	261 485	✓	–

Number of Operators

Henning/Lu/Melia/Murayama: 1512.03433



Outline

Automation: `WCxf`

JA et al.: 1712.05298

Exchange format

Set of predefined bases

Tree-level basis transformation between bases

Public codes

`WCxf` interface

input/output via: `YAML`, `JSON`

Codes

`DsixTools`, `flavio`, `EOS`, `FlavorKit`, `SPheno`, `FormFlavor`, `SuperIso`, `HEPfit`, `wilson`, `MatchingTools`, `SMEFTsim`, `SMEFT Feynman Rules` ...

Bases in `WCxf`

$\mu = \Lambda$

SMEFT:
- Warsaw
- Warsaw-up
- Warsaw-mass

$\mu = \mu_W$

WET:
- JMS
- `flavio`
- formflavor
- FlavorKit
- EOS
- Bern

Energy scale

One-loop example: LQ matching

JA/Crivellin/Greub: 1811.08907

Scalar leptoquark

$$\mathcal{L}_{q\ell}^{LQ} = \bar{q}\left(\Gamma_L^S P_L + \Gamma_R^S P_R\right)\ell\,\Phi^* + \mathrm{h.c.}$$

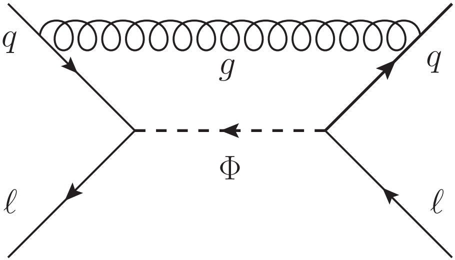
Matching

SL operators

QCD corrections

$\sim 10\ \%$ corrections

Matching: Example



Issue

Matching: LQ basis

$$\widetilde{O}_S^{AB} = (\bar{q} P_A \ell)(\bar{\ell} P_B q)$$
$$\widetilde{O}_T^{A} = (\bar{q} \sigma_{\mu\nu} P_A \ell)(\bar{\ell} \sigma^{\mu\nu} P_A q)$$

Running: SM basis

$$O_S^{AB} = (\bar{q} P_A q)(\bar{\ell} P_B \ell)$$
$$O_T^{A} = (\bar{q} \sigma_{\mu\nu} P_A q)(\bar{\ell} \sigma^{\mu\nu} P_A \ell)$$

Combine results

One-loop Fierz

Basis change

Tree-level Fierz

$$R_0 = \begin{pmatrix} -\frac{1}{2} & -\frac{1}{8} \\ -6 & \frac{1}{2} \end{pmatrix}$$

One-loop Fierz

$$R_1 = \begin{pmatrix} 0 & \frac{N_c^2-1}{16N_c} \\ \frac{7-7N_c^2}{N_c} & 0 \end{pmatrix}$$

$$\begin{pmatrix} O_S^{AA} \\ O_T^{A} \end{pmatrix} = R_0 \begin{pmatrix} \widetilde{O}_S^{AA} \\ \widetilde{O}_T^{A} \end{pmatrix} + \frac{\alpha_s}{4\pi} R_1 \begin{pmatrix} \widetilde{O}_S^{AA} \\ \widetilde{O}_T^{A} \end{pmatrix}$$

Generalization: One-loop Fierz identities

Four-Fermi operators

JA/Pesut: 2208.10513

$$\vec{\mathcal{O}} = R_0 \,\vec{\mathcal{O}}' + \frac{\alpha_s}{4\pi} R_1^s \vec{\mathcal{O}}' + \frac{\alpha_e}{4\pi} R_1^e \vec{\mathcal{O}}'$$

Dipole operators

JA/Pesut/Polonsky: 2211.01379

$\mathcal{O}_i' =$ dipole operators

Scheme factorization

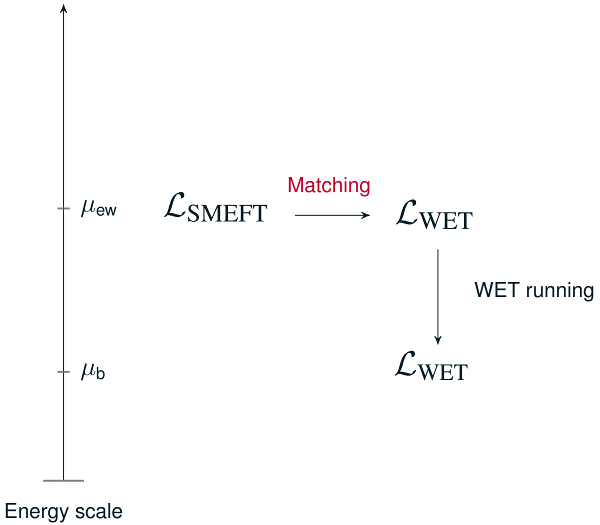
JA/Pesut/Polonsky: 2306.16449

simultaneous scheme- & basis change

Outline

SMEFT/WET

JA/Crivellin/Fael/Greub: 1512.02830



Matching for $b \to s$ and $b \to c$

JA/Crivellin/Fael/Greub: 1512.02830

Tree-level

complete dim-6

One-loop level

for ops that did not enter at tree-level

Pheno: $\overline{B} \to X_s\gamma$

$$-3.3 \times 10^{-3} \leq C_{Hud}^{33}[\mu_W = 160\,\text{GeV}]\frac{v^2}{\Lambda^2} \leq 2.7 \times 10^{-3}$$

One-loop matching

Dipole operator

Grzadkowski/Misiak: 0802.1413

Wtb coupling

$\Delta S = \Delta B = 2$

Bobeth/Buras/Celis/Jung: 1703.04753

modified Z-couplings

$\Delta F = 2$

Endo/Kitahara/Ueda: 1811.04961

all ops

One- and two-loop matching

FCNC ψ^4 Hurth/Renner/Shepherd: 1903.00500

$U(3)^5$

One-loop matching Dekens/Stoffer: 1908.05295

complete

Two-loop matching Haisch/Schnell: 2410.13304

3rd gen ψ^4

Matching tools

`Codex` Das Bakshi/Chakrabortty/Patra: 1808.04403

ϕ, f onto SMEFT

`MatchmakerEFT` Carmona/Lazopoulos/Olgoso/Santiago: 2112.10787

one-loop matching onto SMEFT

`Matchete` Fuentes-Martín/König/Pagès/Thomsen: 2212.04510

ϕ, f onto arbitrary theory

Outline

One-loop SMEFT RGEs

λ dependence — Jenkins/Manohar/Trott: 1308.2627

λ, λ^2, λy^2 terms

Yukawa dependence — Jenkins/Manohar/Trott: 1310.4838

y^2, y^4 terms

Gauge dependence — Alonso/Jenkins/Manohar/Trott: 1312.2014

g^2, g^4

$\not{B}$ — Alonso/Chang/Jenkins/Manohar/Shotwell: 1405.0486

Q_{duql}, Q_{qque}, Q_{qqql}, Q_{duue}

Sakurai prize

Aneesh V. Manohar

2025 recipient

For outstanding contributions to the physics of baryons, including deriving many physical properties of nucleons and hyperons in the large number of colors limit of quantum chromodynamics and deriving the renormalization group evolution of the standard model effective field theory at one loop.

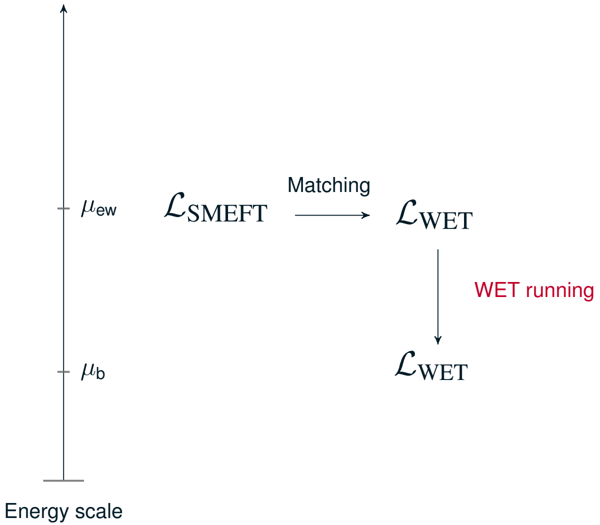
Elizabeth E. Jenkins

2025 recipient

For outstanding contributions to the physics of baryons, including deriving many physical properties of nucleons and hyperons in the large number of colors limit of quantum chromodynamics and deriving the renormalization group evolution of the standard model effective field theory at one loop.

SMEFT/WET

JA/Fael/Greub/Virto: 1704.06639



BSM *B* physics at One Loop

JA/Fael/Greub/Virto: 1704.06639

Operator basis

Classes I-VII

RGE equations

QCD and QED

Evolution matrices

Mathematica notebook

Class	Flavour structure	Number of Ops.	Other flavours	ADM	Example process
Class I	$\bar{s}b\,\bar{s}b$	5+3	$\bar{d}b\,\bar{d}b$	$\hat{\gamma}_{\rm I}$	$B_q - \bar{B}_q$ mixing
Class II	$\bar{u}b\,\bar{\ell}\nu_{\ell'}$	$(2+3)\times 9$	$\bar{c}b\,\bar{\ell}\nu_{\ell'}$	$\hat{\gamma}_{\rm II}$	$\bar{B}_d \to \pi^+\mu^-\bar{\nu}$
Class III	$\bar{s}b\,\bar{u}c$	10+10	$\bar{s}b\,\bar{c}u$ $\bar{d}b\,\bar{u}c$ $\bar{d}b\,\bar{c}u$	$\hat{\gamma}_{\rm III}$	$B^- \to \bar{D}^0 K^-$
Class IV	$\bar{s}b\,\bar{s}d$	5+5	$\bar{d}b\,\bar{d}s$ $\bar{b}s\,\bar{b}d$	$\hat{\gamma}_{\rm IV}$	$B^- \to \bar{K}^0 K^-$
Class V	$\bar{s}b\,\bar{q}q$ $\bar{s}b\,F$, $\bar{s}b\,G$ $\bar{s}b\,\bar{\ell}\ell$	57+57	$\bar{d}b\,\bar{q}q$ $\bar{d}b\,F$, $\bar{d}b\,G$ $\bar{d}b\,\bar{\ell}\ell$	$\hat{\gamma}_{\rm V}$	$\bar{B}_d \to D^+ D_s^-$ $\bar{B}_d \to X_s\gamma$ $B^- \to K^-\mu^+\mu^-$
Class Vb	$\bar{s}b\,\bar{\ell}\ell'$, $\ell \neq \ell'$	$(5+5)\times 6$	$\bar{d}b\,\bar{\ell}\ell'$	$\hat{\gamma}_{\rm Vb}$	$\bar{B}_s \to \mu^-\tau^+$
Class Vν	$\bar{s}b\,\bar{\nu}_\ell\nu_{\ell'}$	$(1+1)\times 9$	$\bar{d}b\,\bar{\nu}_\ell\nu_{\ell'}$	zero	$B^- \to K^-\bar{\nu}\nu$
Class VI	$\bar{u}b\,\bar{\ell}\nu^c$	$(3+2)\times 9$	$\bar{c}b\,\bar{\ell}\nu^c$	$\hat{\gamma}_{\rm VIIa}$	$\bar{B}_d \to \pi^+\mu^-\nu$
	$\bar{s}b\,\bar{\nu}\nu^c$	$(2+1)\times 6$	$\bar{d}b\,\bar{\nu}\nu^c$	$\hat{\gamma}_{\rm VIb}$	$B^- \to K^-\bar{\nu}\bar{\nu}$
	$\bar{s}b\,\bar{\nu}^c\nu$	$(1+2)\times 6$	$\bar{d}b\,\bar{\nu}^c\nu$	$\hat{\gamma}_{\rm VIc}$	$B^- \to K^-\nu\nu$
Class VII	$\bar{\ell}^c b\,\bar{c}^c u$	$(5+5)\times 3$	None	$\hat{\gamma}_{\rm VIIa}$	$\bar{B}_d \to \Lambda_c^- e^+$
	$\bar{\ell}^c b\,\bar{u}^c u$	$(2+2)\times 3$	$\bar{\ell}^c b\,\bar{c}^c c$	$\hat{\gamma}_{\rm VIIb}$	$B_d \to p\,e^-$
	$\bar{\nu}^c b\,\bar{u}^c s$	5×3	$\bar{\nu}^c b\,\bar{u}^c d$ $\bar{\nu}^c b\,\bar{c}^c s$ $\bar{\nu}^c b\,\bar{c}^c d$	$\hat{\gamma}_{\rm VIIc}$	$B^+ \to p\,\nu$
	$\bar{\nu}^c b\,\bar{u}^c b$	2×3	$\bar{\nu}^c b\,\bar{c}^c b$	$\hat{\gamma}_{\rm VIId}$	$\Lambda_b^0 \to B_d\,\bar{\nu}$

Generalization

WET basis Jenkins/Manohar/Stoffer: 1709.04486

complete

1-loop RGEs Jenkins/Manohar/Stoffer: 1711.05270

complete

wilson

JA/Kumar/Straub: 1804.05033

A Phyton package, which includes

SMEFT running

Complete 1-loop RGEs — Alonso/Jenkins/Manohar/Trott: 1312.2014, 1308.2627, 1310.4838

Matching

Complete tree-level matching — JA/Crivellin/Fael/Greub: 1512.02830; Jenkins/Manohar/Stoffer: 1709.04486

Complete one-loop matching — Dekens/Stoffer: 1908.05295

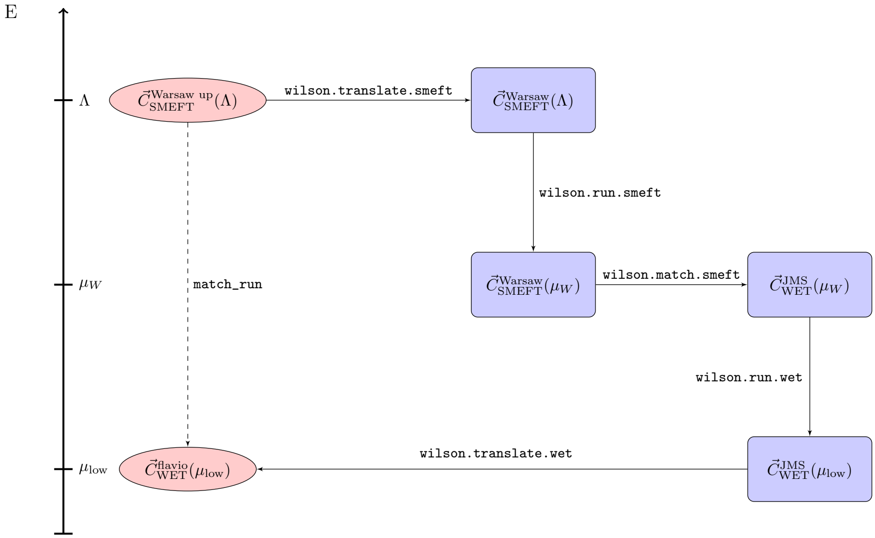
WET running

Complete 1-loop running — JA/Fael/Greub/Virto: 1704.06639; Jenkins/Manohar/Stoffer: 1711.05270

GitHub: https://github.com/wilson-eft/wilson

wilson

JA/Kumar/Straub: 1804.05033



Dsixtools

Celis/Fuentes-Martin/Ruiz-Femenia/Vicente/Virto: 1704.04504, 2010.16341

A Mathematica package, which includes

SMEFT running

Complete 1-loop RGEs

Alonso/Jenkins/Manohar/Trott: 1312.2014, 1308.2627, 1310.4838

Matching

Complete tree-level matching

JA/Crivellin/Fael/Greub: 1512.02830
Jenkins/Manohar/Stoffer: 1709.04486

Complete one-loop matching

Dekens/Stoffer: 1908.05295

WET running

Complete 1-loop running

JA/Fael/Greub/Virto: 1704.06639
Jenkins/Manohar/Stoffer: 1711.05270

Two-loop renormalization

$\Delta F = 2$

QCD, top

JA/Buras/Kumar: 2203.11224

Dipole operators

$\psi^4, \psi^2 H^3 \to \psi^2 XH$

Panico/Pomarol/Riembau: 1810.09413

Different contributions

$X^2 H^2, \psi^2 XH \to X^3, \quad \psi^2 H^3 \to \psi^4$,...

Miro/Ingoldby/Riembau: 2005.06983

Bosonic two-loop renormalization

Scalar

general formula

Jenkins/Manohar/Naterop/Pagès: 2308.06315

Scalar

H^6, $H^4 D^2$

Jenkins/Manohar/Naterop/Pagès: 2310.19883

Complete bosonic sector

Functional methods

Born/Fuentes-Martín/Kvedaraitė/Thomsen: 2410.07320

Outline

Summary

SMEFT Operator basis

regular: up to 12, Green's: up to 8

SMEFT-WET Matching

full one-loop, partial two-loop

SMEFT Renormalization

Full one-loop, two-loop bosonic