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SMEFT-WET matching

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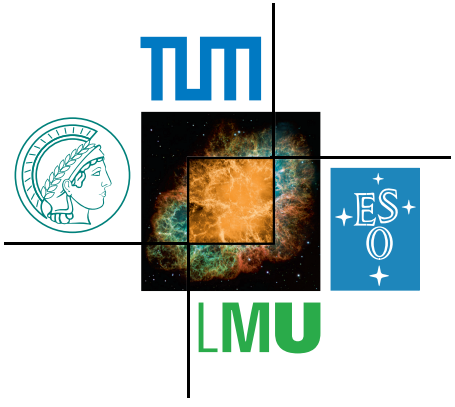


Outline

Outline

Motivation

No direct NP

NP indirectly through loops

Number of parameters

SMEFT: 2499
WET: 5963

Logs

Resummed: $\sum_N \alpha_s^N \log^N \left(\frac{\mu}{M_W} \right)$

Weak effective theory

(also LEFT, WEFT, weak Hamiltonians...)

Symmetry

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

Fields

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

Poincaré invariance

Dim 6 operators

WET: Operators $d \leq 5$

d=3

fermion mass terms, $\mathcal{O}_\nu = (\nu_L^T C \nu_L)$

d=4

Kinetic terms, $\theta_{\text{QCD}} G^A_{\mu\nu} \widetilde{G}^{A\,\mu\nu}$, $\theta_{\text{QED}} F_{\mu\nu} \widetilde{F}^{\mu\nu}$

d=5

Dipoles: $(\bar{f}\,\sigma^{\mu\nu} f)\, F_{\mu\nu}$, $(\bar{q}\,\sigma^{\mu\nu} T^A q)\, G^A_{\mu\nu}$

WET: Operators $d = 6$

Gluonic

$\mathcal{O}_G = f^{ABC} G^{A\,\nu}_{\mu} G^{B\,\rho}_{\nu} G^{C\,\mu}_{\rho}$

$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}^{A\,\nu}_{\mu} G^{B\,\rho}_{\nu} G^{C\,\mu}_{\rho}$

4 Fermi

$(\overline{\psi}\Gamma_1\psi)(\overline{\psi}\Gamma_2\psi)$

Vectors: $(\overline{L}L)(\overline{L}L), (\overline{R}R)(\overline{R}R), (\overline{L}L)(\overline{R}R)$

Scalars, Tensors: $(\overline{L}R)(\overline{L}R), (\overline{L}R)(\overline{R}L)$ + h.c.

~~B~~, ~~L~~

4 leptons: $(\overline{\ell}^c\Gamma_1\ell)(\overline{\ell}\Gamma_2\ell), (\overline{\ell}^c\Gamma_1\ell)(\overline{\ell}^c\Gamma_2\ell)$

2 leptons, 2 quarks: $(\overline{\ell}^c\Gamma_1\ell)(\overline{q}\Gamma_2 q)$

1 lepton, 3 quarks: $(\overline{q}^c\Gamma_1 q)(\overline{\ell}\Gamma_2 q), (\overline{q}^c\Gamma_1 q)(\overline{q}^c\Gamma_2\ell)$

Dim $\leq$ 5 operators

$\nu\nu + \text{h.c.}$	
$\mathcal{O}_\nu$	$(\nu_{Lp}^T C \nu_{Lr})$

$(\nu\nu)X + \text{h.c.}$	
$\mathcal{O}_{\nu\gamma}$	$(\nu_{Lp}^T C \sigma^{\mu\nu} \nu_{Lr}) F_{\mu\nu}$

$(\overline{L}R)X + \text{h.c.}$	
$\mathcal{O}_{e\gamma}$	$\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr} \, F_{\mu\nu}$
$\mathcal{O}_{u\gamma}$	$\bar{u}_{Lp} \sigma^{\mu\nu} u_{Rr} \, F_{\mu\nu}$
$\mathcal{O}_{d\gamma}$	$\bar{d}_{Lp} \sigma^{\mu\nu} d_{Rr} \, F_{\mu\nu}$
$\mathcal{O}_{uG}$	$\bar{u}_{Lp} \sigma^{\mu\nu} T^A u_{Rr} \, G^A_{\mu\nu}$
$\mathcal{O}_{dG}$	$\bar{d}_{Lp} \sigma^{\mu\nu} T^A d_{Rr} \, G^A_{\mu\nu}$

X^3	
$\mathcal{O}_G$	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC} \widetilde{G}^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

$(\overline{L}L)(\overline{L}L)$

$\mathcal{O}_{\nu\nu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{\nu}_{Ls}\gamma_\mu\nu_{Lt})$
$\mathcal{O}_{ee}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$
$\mathcal{O}_{\nu e}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{e}_{Ls}\gamma_\mu e_{Lt})$
$\mathcal{O}_{\nu u}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{\nu d}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{eu}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{ed}^{V,LL}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{\nu edu}^{V,LL}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Ls}\gamma_\mu u_{Lt})+\text{h.c.}$
$\mathcal{O}_{uu}^{V,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Ls}\gamma_\mu u_{Lt})$
$\mathcal{O}_{dd}^{V,LL}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{ud}^{V1,LL}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{d}_{Ls}\gamma_\mu d_{Lt})$
$\mathcal{O}_{ud}^{V8,LL}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{d}_{Ls}\gamma_\mu T^A d_{Lt})$

$(\overline{R}R)(\overline{R}R)$

$\mathcal{O}_{ee}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{eu}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{ed}^{V,RR}$	$(\bar{e}_{Rp}\gamma^\mu e_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{uu}^{V,RR}$	$(\bar{u}_{Rp}\gamma^\mu u_{Rr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{dd}^{V,RR}$	$(\bar{d}_{Rp}\gamma^\mu d_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V1,RR}$	$(\bar{u}_{Rp}\gamma^\mu u_{Rr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V8,RR}$	$(\bar{u}_{Rp}\gamma^\mu T^A u_{Rr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$

$(\overline{L}L)(\overline{R}R)$

$\mathcal{O}_{\nu e}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{ee}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{\nu u}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{\nu d}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu\nu_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{eu}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{ed}^{V,LR}$	$(\bar{e}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ue}^{V,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{de}^{V,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{e}_{Rs}\gamma_\mu e_{Rt})$
$\mathcal{O}_{\nu edu}^{V,LR}$	$(\bar{\nu}_{Lp}\gamma^\mu e_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt})+\text{h.c.}$
$\mathcal{O}_{uu}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{uu}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{u}_{Rs}\gamma_\mu T^A u_{Rt})$
$\mathcal{O}_{ud}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu u_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{ud}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A u_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$
$\mathcal{O}_{du}^{V1,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{u}_{Rs}\gamma_\mu u_{Rt})$
$\mathcal{O}_{du}^{V8,LR}$	$(\bar{d}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{u}_{Rs}\gamma_\mu T^A u_{Rt})$
$\mathcal{O}_{dd}^{V1,LR}$	$(\bar{d}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Rs}\gamma_\mu d_{Rt})$
$\mathcal{O}_{dd}^{V8,LR}$	$(\bar{d}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A d_{Rt})$
$\mathcal{O}_{uddu}^{V1,LR}$	$(\bar{u}_{Lp}\gamma^\mu d_{Lr})(\bar{d}_{Rs}\gamma_\mu u_{Rt})+\text{h.c.}$
$\mathcal{O}_{uddu}^{V8,LR}$	$(\bar{u}_{Lp}\gamma^\mu T^A d_{Lr})(\bar{d}_{Rs}\gamma_\mu T^A u_{Rt})+\text{h.c.}$

$(\overline{L}R)(\overline{L}R)+\text{h.c.}$

$\mathcal{O}_{ee}^{S,RR}$	$(\bar{e}_{Lp}e_{Rr})(\bar{e}_{Ls}e_{Rt})$
$\mathcal{O}_{eu}^{S,RR}$	$(\bar{e}_{Lp}e_{Rr})(\bar{u}_{Ls}u_{Rt})$
$\mathcal{O}_{eu}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{u}_{Ls}\sigma_{\mu\nu}u_{Rt})$
$\mathcal{O}_{ed}^{S,RR}$	$(\bar{e}_{Lp}e_{Rr})(\bar{d}_{Ls}d_{Rt})$
$\mathcal{O}_{ed}^{T,RR}$	$(\bar{e}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu}d_{Rt})$
$\mathcal{O}_{\nu edu}^{S,RR}$	$(\bar{\nu}_{Lp}e_{Rr})(\bar{d}_{Ls}u_{Rt})$
$\mathcal{O}_{\nu edu}^{T,RR}$	$(\bar{\nu}_{Lp}\sigma^{\mu\nu}e_{Rr})(\bar{d}_{Ls}\sigma_{\mu\nu}u_{Rt})$
$\mathcal{O}_{uu}^{S1,RR}$	$(\bar{u}_{Lp}u_{Rr})(\bar{u}_{Ls}u_{Rt})$
$\mathcal{O}_{uu}^{S8,RR}$	$(\bar{u}_{Lp}T^A u_{Rr})(\bar{u}_{Ls}T^A u_{Rt})$
$\mathcal{O}_{ud}^{S1,RR}$	$(\bar{u}_{Lp}u_{Rr})(\bar{d}_{Ls}d_{Rt})$
$\mathcal{O}_{ud}^{S8,RR}$	$(\bar{u}_{Lp}T^A u_{Rr})(\bar{d}_{Ls}T^A d_{Rt})$
$\mathcal{O}_{dd}^{S1,RR}$	$(\bar{d}_{Lp}d_{Rr})(\bar{d}_{Ls}d_{Rt})$
$\mathcal{O}_{dd}^{S8,RR}$	$(\bar{d}_{Lp}T^A d_{Rr})(\bar{d}_{Ls}T^A d_{Rt})$
$\mathcal{O}_{uddu}^{S1,RR}$	$(\bar{u}_{Lp}d_{Rr})(\bar{d}_{Ls}u_{Rt})$
$\mathcal{O}_{uddu}^{S8,RR}$	$(\bar{u}_{Lp}T^A d_{Rr})(\bar{d}_{Ls}T^A u_{Rt})$

$(\overline{L}R)(\overline{R}L)+\text{h.c.}$

$\mathcal{O}_{eu}^{S,RL}$	$(\bar{e}_{Lp}e_{Rr})(\bar{u}_{Rs}u_{Lt})$
$\mathcal{O}_{ed}^{S,RL}$	$(\bar{e}_{Lp}e_{Rr})(\bar{d}_{Rs}d_{Lt})$
$\mathcal{O}_{\nu edu}^{S,RL}$	$(\bar{\nu}_{Lp}e_{Rr})(\bar{d}_{Rs}u_{Lt})$

$\Delta L = 4 + \text{h.c.}$

$\mathcal{O}_{\nu\nu}^{S,LL}$	$(\nu_{Lp}^T C \nu_{Lr})(\nu_{Ls}^T C \nu_{Lt})$

$\Delta L = 2 + \text{h.c.}$

$\mathcal{O}_{\nu e}^{S,LL}$	$(\nu_{Lp}^T C \nu_{Lr})(\bar{e}_{Rs} e_{Lt})$
$\mathcal{O}_{\nu e}^{T,LL}$	$(\nu_{Lp}^T C \sigma^{\mu\nu} \nu_{Lr})(\bar{e}_{Rs} \sigma_{\mu\nu} e_{Lt})$
$\mathcal{O}_{\nu e}^{S,LR}$	$(\nu_{Lp}^T C \nu_{Lr})(\bar{e}_{Ls} e_{Rt})$
$\mathcal{O}_{\nu u}^{S,LL}$	$(\nu_{Lp}^T C \nu_{Lr})(\bar{u}_{Rs} u_{Lt})$
$\mathcal{O}_{\nu u}^{T,LL}$	$(\nu_{Lp}^T C \sigma^{\mu\nu} \nu_{Lr})(\bar{u}_{Rs} \sigma_{\mu\nu} u_{Lt})$
$\mathcal{O}_{\nu u}^{S,LR}$	$(\nu_{Lp}^T C \nu_{Lr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{\nu d}^{S,LL}$	$(\nu_{Lp}^T C \nu_{Lr})(\bar{d}_{Rs} d_{Lt})$
$\mathcal{O}_{\nu d}^{T,LL}$	$(\nu_{Lp}^T C \sigma^{\mu\nu} \nu_{Lr})(\bar{d}_{Rs} \sigma_{\mu\nu} d_{Lt})$
$\mathcal{O}_{\nu d}^{S,LR}$	$(\nu_{Lp}^T C \nu_{Lr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{\nu edu}^{S,LL}$	$(\nu_{Lp}^T C e_{Lr})(\bar{d}_{Rs} u_{Lt})$
$\mathcal{O}_{\nu edu}^{T,LL}$	$(\nu_{Lp}^T C \sigma^{\mu\nu} e_{Lr})(\bar{d}_{Rs} \sigma_{\mu\nu} u_{Lt})$
$\mathcal{O}_{\nu edu}^{S,LR}$	$(\nu_{Lp}^T C e_{Lr})(\bar{d}_{Ls} u_{Rt})$
$\mathcal{O}_{\nu edu}^{V,RL}$	$(\nu_{Lp}^T C \gamma^{\mu} e_{Rr})(\bar{d}_{Ls} \gamma_{\mu} u_{Lt})$
$\mathcal{O}_{\nu edu}^{V,RR}$	$(\nu_{Lp}^T C \gamma^{\mu} e_{Rr})(\bar{d}_{Rs} \gamma_{\mu} u_{Rt})$

$\Delta B = \Delta L = 1 + \text{h.c.}$

$\mathcal{O}_{udd}^{S,LL}$	$\epsilon_{\alpha\beta\gamma}(u_{Lp}^{\alpha T} C d_{Lr}^{\beta})(d_{Ls}^{\gamma T} C \nu_{Lt})$
$\mathcal{O}_{duu}^{S,LL}$	$\epsilon_{\alpha\beta\gamma}(d_{Lp}^{\alpha T} C u_{Lr}^{\beta})(u_{Ls}^{\gamma T} C e_{Lt})$
$\mathcal{O}_{uud}^{S,LR}$	$\epsilon_{\alpha\beta\gamma}(u_{Lp}^{\alpha T} C u_{Lr}^{\beta})(d_{Rs}^{\gamma T} C e_{Rt})$
$\mathcal{O}_{duu}^{S,LR}$	$\epsilon_{\alpha\beta\gamma}(d_{Lp}^{\alpha T} C u_{Lr}^{\beta})(u_{Rs}^{\gamma T} C e_{Rt})$
$\mathcal{O}_{uud}^{S,RL}$	$\epsilon_{\alpha\beta\gamma}(u_{Rp}^{\alpha T} C u_{Rr}^{\beta})(d_{Ls}^{\gamma T} C e_{Lt})$
$\mathcal{O}_{duu}^{S,RL}$	$\epsilon_{\alpha\beta\gamma}(d_{Rp}^{\alpha T} C u_{Rr}^{\beta})(u_{Ls}^{\gamma T} C e_{Lt})$
$\mathcal{O}_{dud}^{S,RL}$	$\epsilon_{\alpha\beta\gamma}(d_{Rp}^{\alpha T} C u_{Rr}^{\beta})(d_{Ls}^{\gamma T} C \nu_{Lt})$
$\mathcal{O}_{ddu}^{S,RL}$	$\epsilon_{\alpha\beta\gamma}(d_{Rp}^{\alpha T} C d_{Rr}^{\beta})(u_{Ls}^{\gamma T} C \nu_{Lt})$
$\mathcal{O}_{duu}^{S,RR}$	$\epsilon_{\alpha\beta\gamma}(d_{Rp}^{\alpha T} C u_{Rr}^{\beta})(u_{Rs}^{\gamma T} C e_{Rt})$

$\Delta B = -\Delta L = 1 + \text{h.c.}$

$\mathcal{O}_{ddd}^{S,LL}$	$\epsilon_{\alpha\beta\gamma}(d_{Lp}^{\alpha T} C d_{Lr}^{\beta})(\bar{e}_{Rs} d_{Lt}^{\gamma})$
$\mathcal{O}_{udd}^{S,LR}$	$\epsilon_{\alpha\beta\gamma}(u_{Lp}^{\alpha T} C d_{Lr}^{\beta})(\bar{\nu}_{Ls} d_{Rt}^{\gamma})$
$\mathcal{O}_{ddu}^{S,LR}$	$\epsilon_{\alpha\beta\gamma}(d_{Lp}^{\alpha T} C d_{Lr}^{\beta})(\bar{\nu}_{Ls} u_{Rt}^{\gamma})$
$\mathcal{O}_{ddd}^{S,LR}$	$\epsilon_{\alpha\beta\gamma}(d_{Lp}^{\alpha T} C d_{Lr}^{\beta})(\bar{e}_{Ls} d_{Rt}^{\gamma})$
$\mathcal{O}_{ddd}^{S,RL}$	$\epsilon_{\alpha\beta\gamma}(d_{Rp}^{\alpha T} C d_{Rr}^{\beta})(\bar{e}_{Rs} d_{Lt}^{\gamma})$
$\mathcal{O}_{udd}^{S,RR}$	$\epsilon_{\alpha\beta\gamma}(u_{Rp}^{\alpha T} C d_{Rr}^{\beta})(\bar{\nu}_{Ls} d_{Rt}^{\gamma})$
$\mathcal{O}_{ddd}^{S,RR}$	$\epsilon_{\alpha\beta\gamma}(d_{Rp}^{\alpha T} C d_{Rr}^{\beta})(\bar{e}_{Ls} d_{Rt}^{\gamma})$

Matching

Degrees of freedom reduced

$\mathcal{L}_{\text{SMEFT}}(\ell, \nu_\ell, u, d, c, s, v, t, g, \gamma, W, Z, h)$
$\hookrightarrow \mathcal{L}_{\text{WET}}(\ell, \nu_\ell, u, d, c, s, v, \cancel{t}, g, \gamma, \cancel{W}, \cancel{Z}, \cancel{h})$

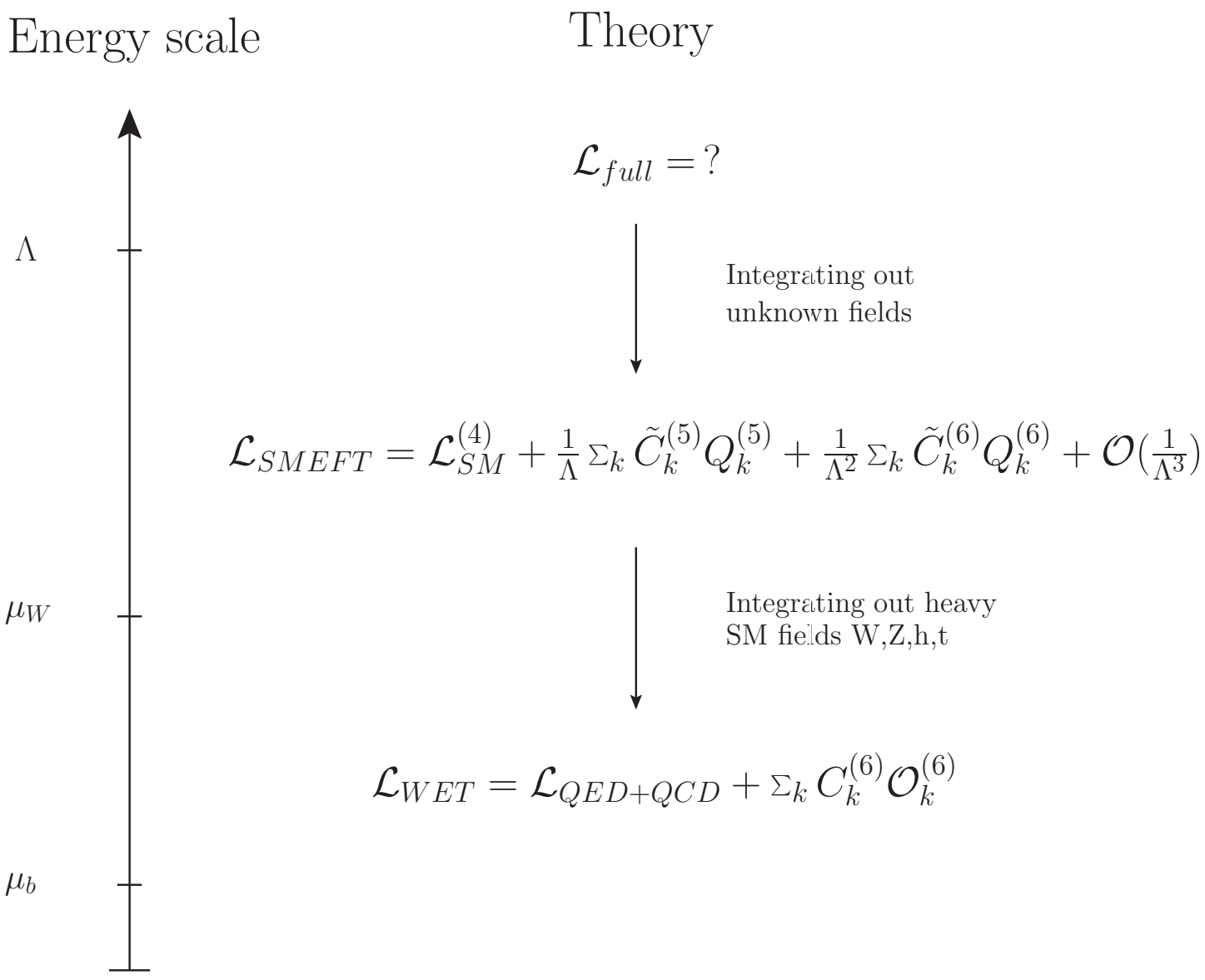
Matching scale μ_W

$A_{\text{WET}} \overset{!}{=} A_{\text{SMEFT}}$

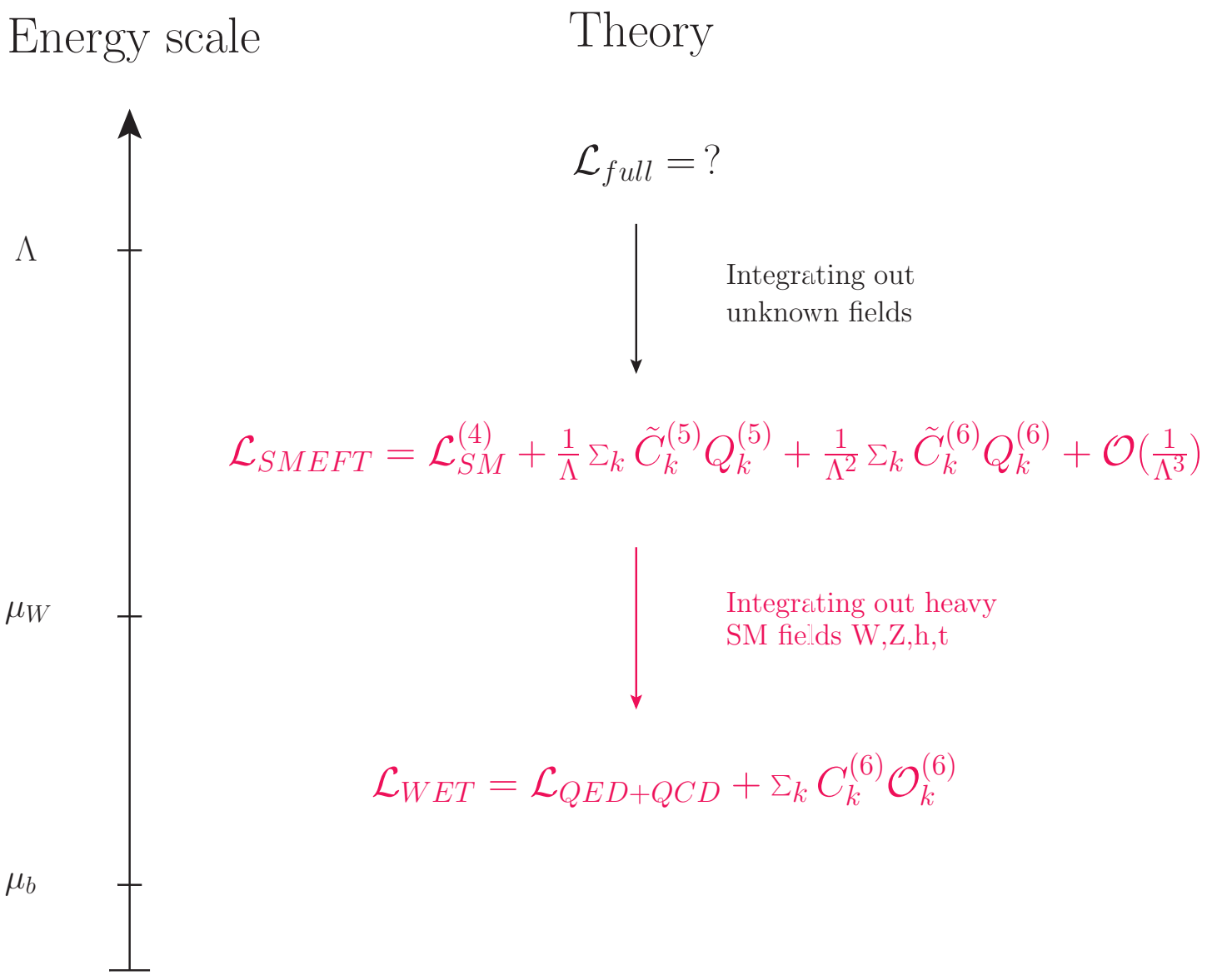
Basis

Up-mass basis

Big picture


Energy scale
Theory
$\mathcal{L}_{full} = ?$
Λ
Integrating out
unknown fields
$\mathcal{L}_{SMEFT} = \mathcal{L}^{(4)}_{SM} + \frac{1}{\Lambda}\Sigma_k \tilde{C}^{(5)}_k Q^{(5)}_k + \frac{1}{\Lambda^2}\Sigma_k \tilde{C}^{(6)}_k Q^{(6)}_k + \mathcal{O}(\frac{1}{\Lambda^3})$
μ_W
Integrating out heavy
SM fields W,Z,h,t
$\mathcal{L}_{WET} = \mathcal{L}_{QED+QCD} + \Sigma_k C^{(6)}_k \mathcal{O}^{(6)}_k$
μ_b

Big picture


Energy scale
Theory
$\mathcal{L}_{full} = ?$
Λ
Integrating out
unknown fields
$\mathcal{L}_{SMEFT} = \mathcal{L}^{(4)}_{SM} + \frac{1}{\Lambda}\Sigma_k \tilde{C}^{(5)}_k Q^{(5)}_k + \frac{1}{\Lambda^2}\Sigma_k \tilde{C}^{(6)}_k Q^{(6)}_k + \mathcal{O}(\frac{1}{\Lambda^3})$
μ_W
Integrating out heavy
SM fields W,Z,h,t
$\mathcal{L}_{WET} = \mathcal{L}_{QED+QCD} + \Sigma_k C^{(6)}_k \mathcal{O}^{(6)}_k$
μ_b

Outline

Tree-level

Expansion

External momenta, masses

Power counting

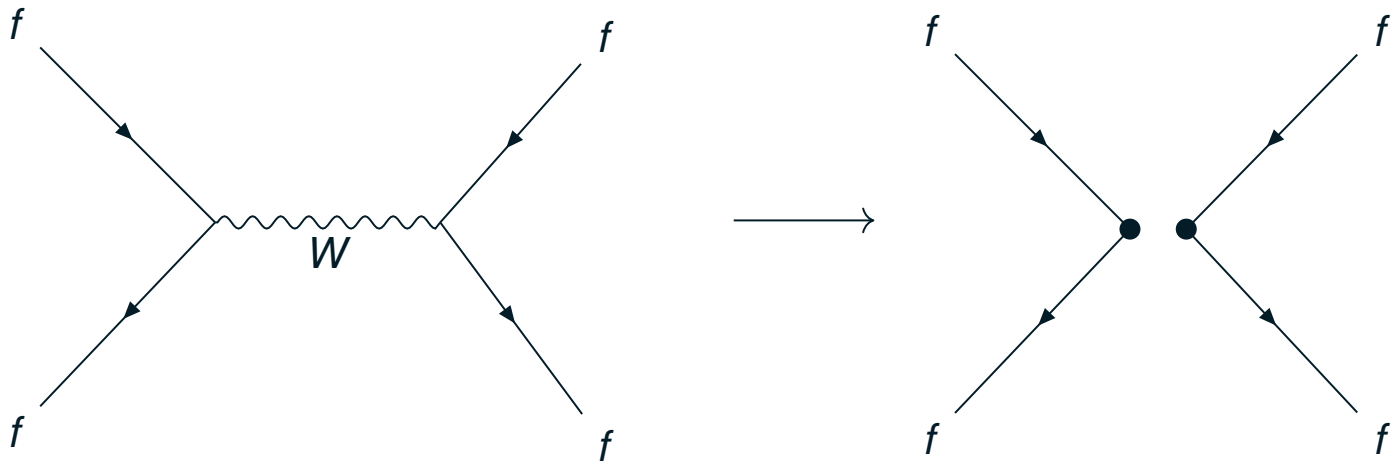
$$\cdots \frac{1}{\Lambda^n} = \cdots \underbrace{\frac{1}{v^n}}_{WETcounting} \times \underbrace{\frac{v^n}{\Lambda^n}}_{SMEFTcounting}$$

Tree-level Matching

Jenkins/Manohar/Stoffer: 1709.04486

Completely known

Tree-level: Example



$$\frac{1}{p^2 - M_W^2} = \frac{-1}{M_W^2} \frac{1}{1 - \frac{p^2}{M_W^2}} = \frac{-1}{M_W^2} \left(1 + \mathcal{O}(p^2/M_W^2)\right)$$

Tree-level matching

Couplings

Shifted after EWSB

Contact terms

one-to-one

Modified Z, W, H exchange

Tree-diagrams

Couplings

Masses

$$M_f = \frac{\bar{v}}{\sqrt{2}}\left[Y_f - \frac{1}{2}v^2 C^*_{\psi\varphi}\right], \qquad \mathcal{O}_{\psi\varphi} = (\varphi^\dagger\varphi)(\overline{\psi}_L\psi_R\varphi)$$

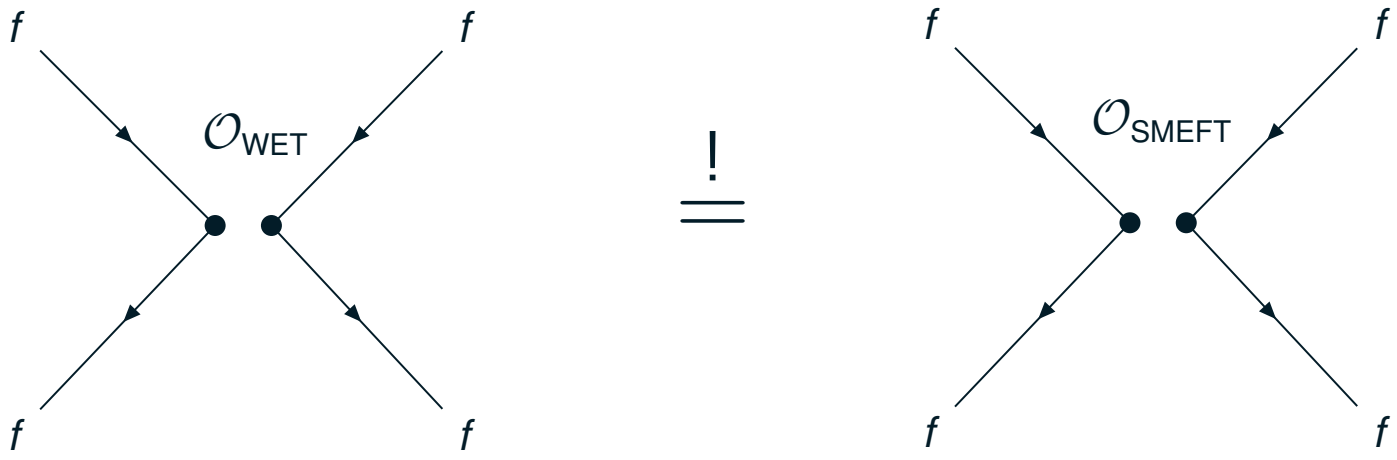
$$\bar{v} = v\left(1 + \frac{3C_\varphi v^2}{8\lambda}\right), \qquad \mathcal{O}_\varphi = (\varphi^\dagger\varphi)^3$$

Gauge couplings

$$g_s = \bar{g}_3 = g_3(1 + C_{\varphi G}\bar{v}^2), \qquad \mathcal{O}_{\varphi G} = (\varphi^\dagger\varphi)\, G^A_{\mu\nu} G^{A,\,\mu\nu}$$

$$e = \bar{g}_2 \sin\bar{\theta} - \frac{1}{2}\cos\bar{\theta}\bar{g}_2\bar{v}^2 C_{\varphi WB}, \qquad \mathcal{O}_{\varphi WB} = (\varphi^\dagger\tau^I\varphi)\, W^I_{\mu\nu} B^{\mu\nu}$$

Contact terms



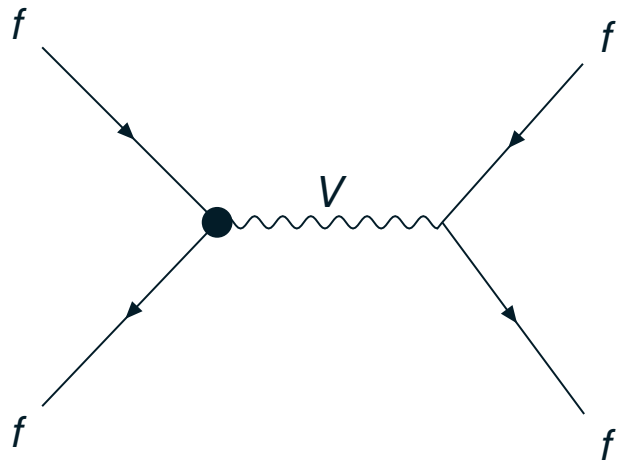
4-Fermi

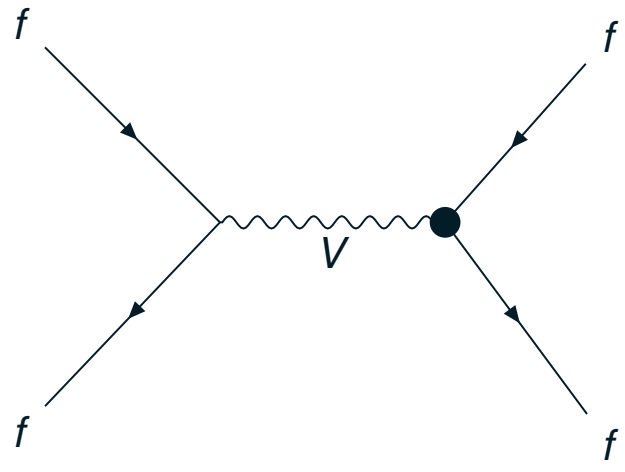
All sectors: V,S,T

Others

dipoles: $C_{f\gamma}$, C_{fG}, gluonic: C_G, $C_{\widetilde{G}}$

Tree-level: Vectors





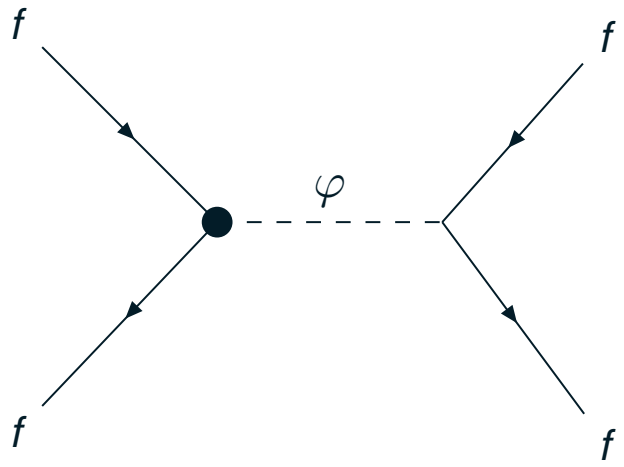
Modified W

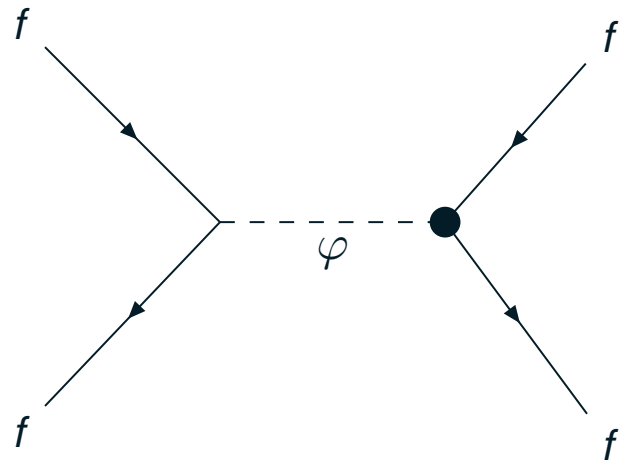
$\mathcal{O}_{\varphi q}^{(3)}$, $\mathcal{O}_{\varphi \ell}^{(3)}$, $\mathcal{O}_{\varphi ud}$: Example: $\mathcal{O}_{\varphi ud} = (\widetilde{\varphi}^{\dagger} D_{\mu} \varphi)(\bar{u} \gamma^{\mu} d) \rightarrow \frac{1}{2} v^2 C_{\varphi ud} (\bar{u} \gamma^{\mu} d)$

Modified Z

$\mathcal{O}_{\varphi q}^{(1),(3)}$, $\mathcal{O}_{\varphi \ell}^{(1),(3)}$, $\mathcal{O}_{\varphi u}$, $\mathcal{O}_{\varphi d}$, $\mathcal{O}_{\varphi e}$

Tree-level: Higgs





Higgs

vertex$^2 \sim (m/v)^2, mv/\Lambda^2, v^4/\Lambda^4 \rightarrow$ dim 7 or 8 contribution

No tree-level contribution

Vector 4-fermi

$O_{uddu}^{V8,LR}$

Scalars, Tensors

$O_{eu}^{S,RL}$, $O_{ee}^{S,RL}$, $O_{ed}^{S,RR}$, $O_{ed}^{T,RR}$, $O_{dd,uu}^{S1,RR}$, $O_{dd,uu}^{S8,RR}$

$\Delta L = 4, 3, \pm 1$ and $\Delta B = 1$

e.g. $\mathcal{O}_{\nu\gamma}$

Outline

1-Loop Matching

Motivation

larger parameter space explored

Many partial results

Weinberg operator
LFV
TGC
$\Delta F = 2$, B physics
...

Full 1-Loop Matching

still missing

Checks

Gauge invariance

Unitary, R_ξ

Renormalization

Alonso/Jenkins/Manohar/Trott: 1308.2627, 1310.4838, 1312.2014
Stoffer/Jenkins/Manohar: 1711.05270

Anomalous dimension matrix

IR behaviour

Divergences

Dipole to Weinberg operator

Kamenik/Papucci/Weiler: 1107.3143

Top dipole

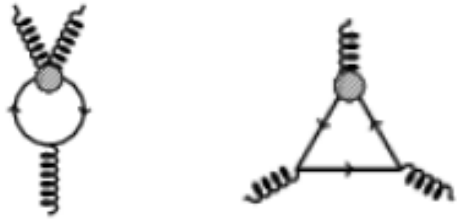
Neutron EDM

Operator

$\mathcal{O}_{uG}$

Matched

$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}^{A,\nu}_{\mu} G^{B,\rho}_{\nu} G^{C,\mu}_{\rho}$



Lepton flavour violation

Crivellin/Najjari/Rosiek: 1312.0634

LFV

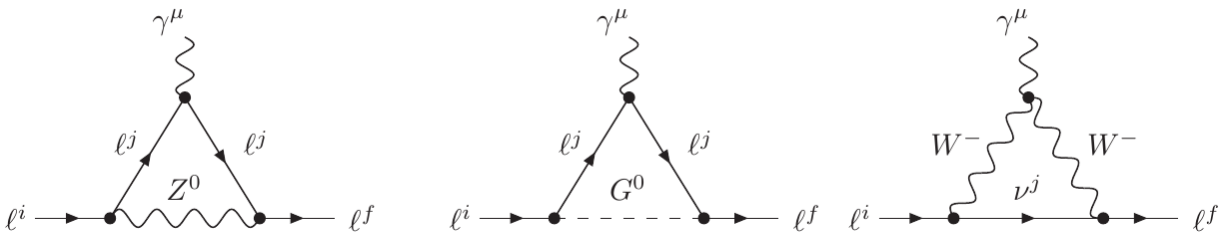
$\ell \to \ell'\gamma,\ Z \to \ell\ell',$ 3-body decays

Operators

4-lepton, semileptonic, Modified Z- W couplings, $\mathcal{O}_{eB}, \mathcal{O}_{eW}$

Matched

$\mathcal{O}_{e\gamma}, \mathcal{O}_{ee}^{V,LL}, \mathcal{O}_{ee}^{V,RR}, \mathcal{O}_{ee}^{V,LR}, \mathcal{O}_{ee}^{S,RR}$



Triple gauge couplings

Bobeth/Haisch: 1503.04829

Dipole and semileptonic operators

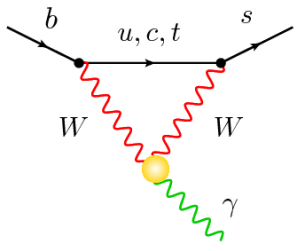
$b \to s\gamma,\ K \to \pi\nu\bar{\nu},\ \epsilon'/\epsilon$

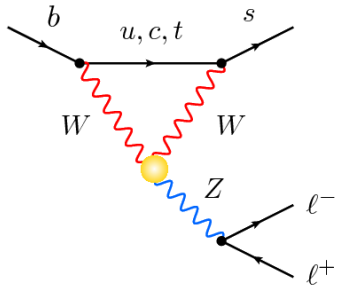
Operators

$\mathcal{O}_{\varphi B}, \mathcal{O}_{\varphi W}, \mathcal{O}_{W}$

Matched

$\mathcal{O}_{e\gamma}, \mathcal{O}_{ed}^{V,LL}, \mathcal{O}_{ed}^{V,RR}$





$b \to s, b \to c$

JA/Crivellin/Fael/Greub: 1512.02830

Full tree-level

$\Delta B = \Delta S = 2, 1$, $\Delta B = \Delta C = 1$

'NLO' 1loop

Only t_R in loop

Matched

$O_{d\gamma}$, O_{dG}, 4-quark, semileptonic

Tree-level

$\psi^2 X\varphi$		$\psi^2\varphi^2 D$		$(\bar{L}R)(\bar{R}L)$ or $(\bar{L}R)(\bar{L}R)$	
Q_{dW}	$(\bar{q}_i\sigma^{\mu\nu}d_j)\tau^I\varphi W^I_{\mu\nu}$	$Q^{(1)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_i\gamma^\mu q_j)$	$Q_{\ell edq}$	$(\bar{\ell}^a_i e_j)(\bar{d}_k q^a_l)$
Q_{dB}	$(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi q}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_i\tau^I\gamma^\mu q_j)$	$Q^{(1)}_{quqd}$	$(\bar{q}^a_i u_j)\varepsilon_{ab}(\bar{q}^b_k d_l)$
Q_{dG}	$(\bar{q}_i\sigma^{\mu\nu}T^A d_j)\varphi G^A_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_i\gamma^\mu d_j)$	$Q^{(3)}_{quqd}$	$(\bar{q}^a_i T^A u_j)\varepsilon_{ab}(\bar{q}^b_k T^A d_l)$
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$Q^{(1)}_{qq}$	$(\bar{q}_i\gamma_\mu q_j)(\bar{q}_k\gamma^\mu q_l)$	Q_{dd}	$(\bar{d}_i\gamma_\mu d_j)(\bar{d}_k\gamma^\mu d_l)$	$Q_{\ell d}$	$(\bar{\ell}_i\gamma_\mu \ell_j)(\bar{d}_k\gamma^\mu d_l)$
$Q^{(3)}_{qq}$	$(\bar{q}_i\gamma_\mu\tau^I q_j)(\bar{q}_k\gamma^\mu\tau^I q_l)$	Q_{ed}	$(\bar{e}_i\gamma_\mu e_j)(\bar{d}_k\gamma^\mu d_l)$	Q_{qe}	$(\bar{q}_i\gamma_\mu q_j)(\bar{e}_k\gamma^\mu e_l)$
$Q^{(1)}_{\ell q}$	$(\bar{\ell}_i\gamma_\mu \ell_j)(\bar{q}_k\gamma^\mu q_l)$	$Q^{(1)}_{ud}$	$(\bar{u}_i\gamma_\mu u_j)(\bar{d}_k\gamma^\mu d_l)$	$Q^{(1)}_{qu}$	$(\bar{q}_i\gamma_\mu q_j)(\bar{u}_k\gamma^\mu u_l)$
$Q^{(3)}_{\ell q}$	$(\bar{\ell}_i\gamma_\mu\tau^I \ell_j)(\bar{q}_k\gamma^\mu\tau^I q_l)$	$Q^{(8)}_{ud}$	$(\bar{u}_i\gamma_\mu T^A u_j)(\bar{d}_k\gamma^\mu T^A d_l)$	$Q^{(8)}_{qu}$	$(\bar{q}_i\gamma_\mu T^A q_j)(\bar{u}_k\gamma^\mu T^A u_l)$
				$Q^{(1)}_{qd}$	$(\bar{q}_i\gamma_\mu q_j)(\bar{d}_k\gamma^\mu d_l)$
				$Q^{(8)}_{qd}$	$(\bar{q}_i\gamma_\mu T^A q_j)(\bar{d}_k\gamma^\mu T^A d_l)$

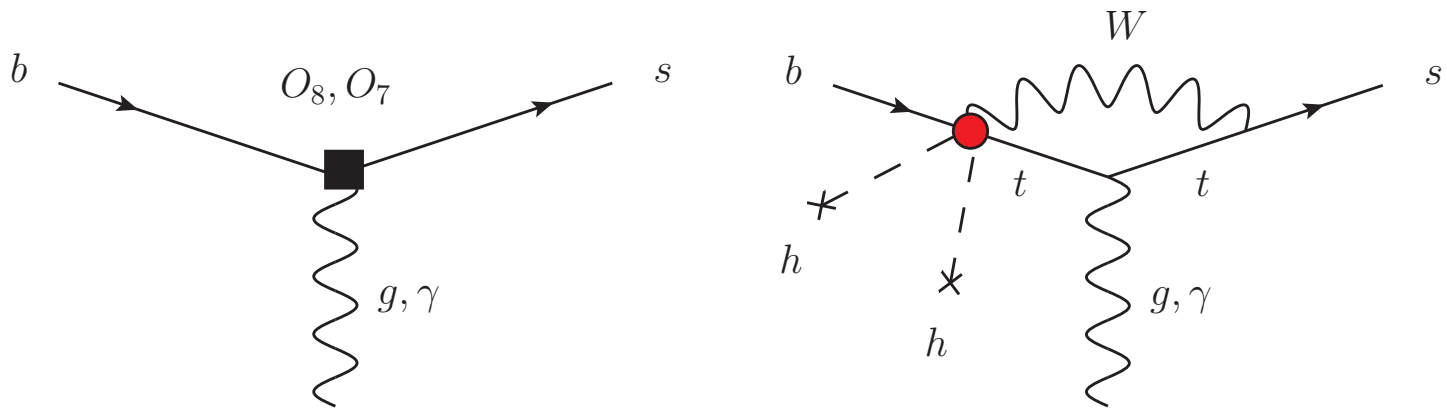
One-loop

Q_{uW}	$(\bar{q}_i \sigma^{\mu\nu} u_j)\, \tau^I\, \widetilde{\varphi}\, W^I_{\mu\nu}$	$Q^{(1)}_{ud}$	$(\bar{u}_i \gamma_\mu u_j)(\bar{d}_k \gamma^\mu d_l)$	Q_{uu}	$(\bar{u}_i \gamma_\mu u_j)(\bar{u}_k \gamma^\mu u_l)$
Q_{uB}	$(\bar{q}_i \sigma^{\mu\nu} u_j)\, \widetilde{\varphi}\, B_{\mu\nu}$	$Q^{(8)}_{ud}$	$(\bar{u}_i \gamma_\mu T^A u_j)(\bar{d}_k \gamma^\mu T^A d_l)$	$Q_{\ell u}$	$(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{u}_k \gamma^\mu u_l)$
Q_{uG}	$(\bar{q}_i \sigma^{\mu\nu} T^A u_j)\widetilde{\varphi} G^A_{\mu\nu}$	$Q^{(1)}_{qu}$	$(\bar{q}_i \gamma_\mu q_j)(\bar{u}_k \gamma^\mu u_l)$	Q_{eu}	$(\bar{e}_i \gamma_\mu e_j)(\bar{u}_k \gamma^\mu u_l)$
$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger i D_\mu \varphi)(\bar{u}_i \gamma^\mu d_j)$	$Q^{(8)}_{qu}$	$(\bar{q}_i \gamma_\mu T^A q_j)(\bar{u}_k \gamma^\mu T^A u_l)$	$Q_{\varphi u}$	$(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi)(\bar{u}_i \gamma^\mu u_j)$

Example: O_7, O_8

also Grzadkowski/Misiak: 0802.1413
Drobnak/Fajfer/Kamenik: 1109.2357

$$Q^{33}_{\varphi ud} = (\widetilde{\varphi}^\dagger\, iD_\mu \varphi)(\bar{t}\gamma^\mu b)$$



$$C_7 = \frac{m_t}{m_b}\frac{v^2}{\Lambda^2} E^7_{\varphi ud}(x_t)\, \widetilde{C}^{33}_{\varphi ud}\, V^*_{ts}$$

$$C_8 = \frac{m_t}{m_b}\frac{v^2}{\Lambda^2} E^8_{\varphi ud}(x_t)\, \widetilde{C}^{33}_{\varphi ud}\, V^*_{ts}$$

$\Delta S = \Delta B = 2$

Bobeth/Buras/Celis/Jung: 1703.04753

FCNC

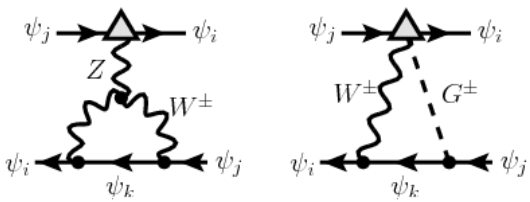
$\Delta S = \Delta B = 2$

Operators

4-lepton, semileptonic, Modified Z- W couplings, $\mathcal{O}_{\varphi q}^{(1)}, \mathcal{O}_{\varphi q}^{(3)}, \mathcal{O}_{\varphi d}$

Matched

$\mathcal{O}_{dd}^{V,LL}, \mathcal{O}_{dd}^{V,RR}, \mathcal{O}_{dd}^{V1,LR}, \mathcal{O}_{dd}^{V8,LR}, \mathcal{O}_{dd}^{S1,RR}, \mathcal{O}_{dd}^{S8,RR}$



$\Delta F = 2$

Endo/Kitahara/Ueda: 1811.04961

Top quark effects in $\Delta F = 2$

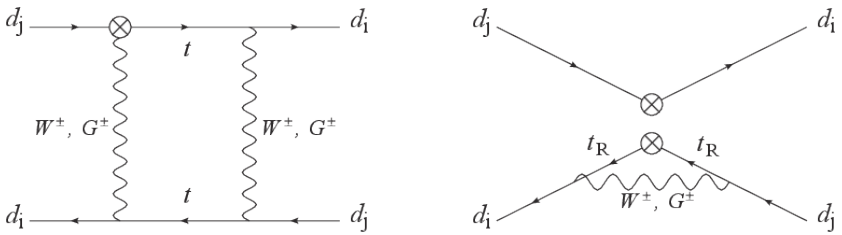
Complete 1-loop matching

Operators

4-quark, Modified Z and W couplings

Matched

$\mathcal{O}_{dd}^{V,LL}, \mathcal{O}_{dd}^{V,RR}, \mathcal{O}_{dd}^{V1,LR}, \mathcal{O}_{dd}^{V8,LR}, \mathcal{O}_{dd}^{S1,RR}, \mathcal{O}_{dd}^{S8,RR}$



Flavour-symmetric SMEFT

Hurth/Renner/Shepherd: 1903.00500

FCNC

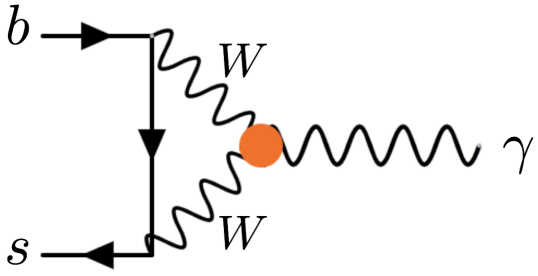
$\Delta B = \Delta S = 1, 2$

Flavour symmetry

$U(3)^5$

Additional 1-loop operators

4-fermi with t_L, $\mathcal{O}_{\varphi WB} = (\varphi^\dagger \tau^I \varphi) W^I_{\mu\nu} B^{\mu\nu}$, $\mathcal{O}_{\varphi D} = (\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$,



Outline

JA/Kumar/Straub: 1804.05033

Python module

Numerical in- and output

Running

Full SMEFT running
Full WET running

Matching

Complete tree-level matching

DsixTools: 

Celis/Fuentes-Martin/Vincente/Virto: 1704.04504

Mathematica package

Symbolic expressions for matching, running

Running

Full SMEFT running
Full WET running

Matching

Complete tree-level matching

MatchingTools

Criado: 1710.06445

Python Module

Symbolic matching

General

Every full onto every effective theory

Path integral formalism

Provide $\mathcal{L}$

WCxf

Python Module

Numerical matching

Bases

SMEFT and WET

Interfacing with codes

EOS, SMEFTSim, flavio, wilson, DsixTools, FlavorKit....

Outline

Summary

Tree-level Matching

completely known

1-Loop Matching

partially known

Codes

wilson, DsixTools,...