SMEFT Atlas of $\Delta F = 2$ transitions

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Reference

Based on work done with Andrzej Buras, Christoph Bobeth and Jason Aebischer

SMEFT ATLAS of $\Delta F = 2$ transitions

Jason Aebischer (UC, San Diego), Christoph Bobeth (Munich U.), Andrzej J. Buras (TUM-IAS, Munich), Jacky Kumar (Montreal U.) (Sep 15, 2020)

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Standard Model Effective Field Theory

- Field content same as that of Standard Model.
- Electroweak symmetry is broken by one Higgs-doublet.
- Full SM gauge symmetry is respected.

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{eff}$$

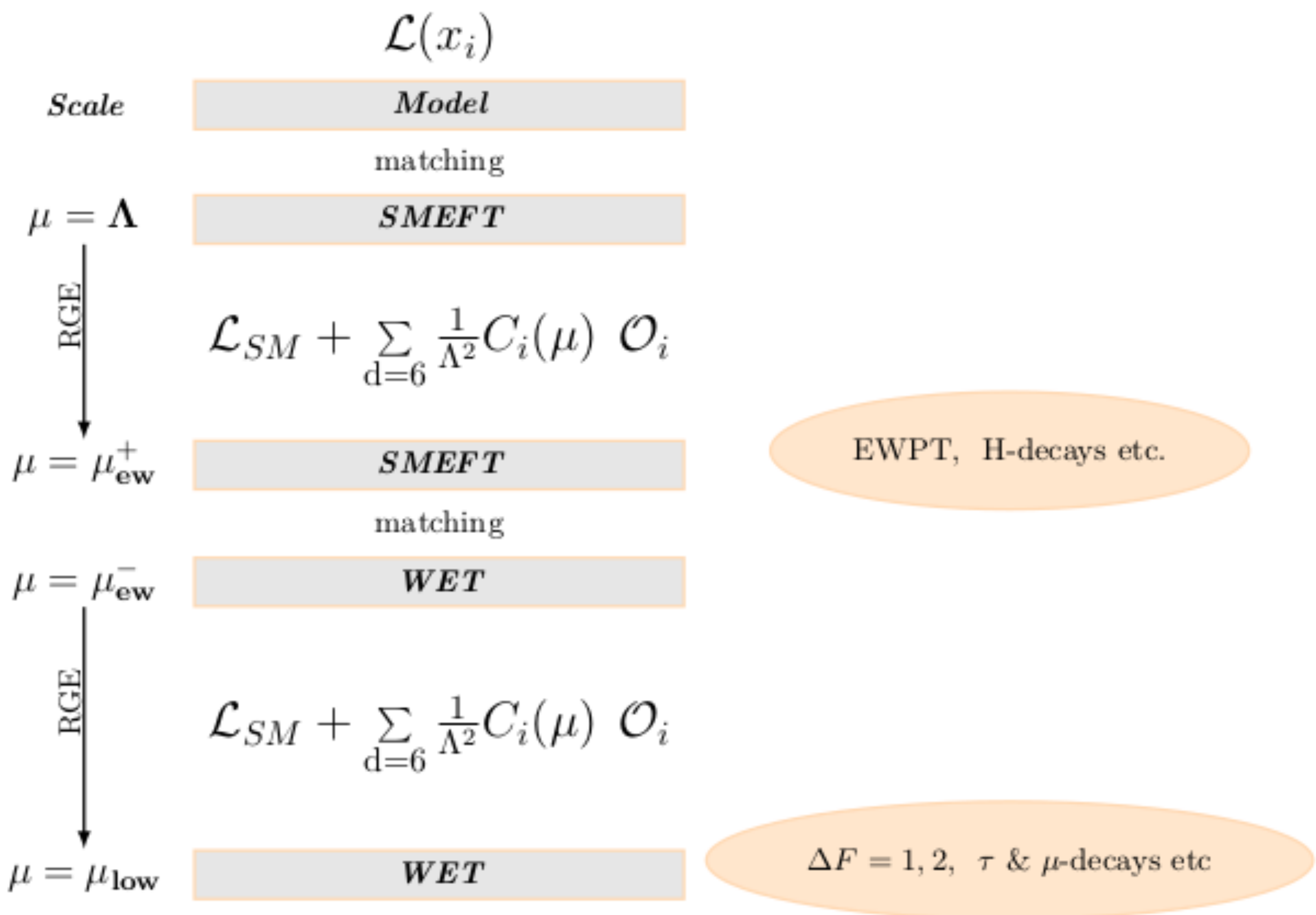
$$\mathscr{L}_{\text{eff}} = \sum_{d=5,6,..} C_j O_j$$

Buchmuller and Wyler 1986

15 (bosonic) +
19 (single-fermion current) +
25 (four-fermion) = 59 Operators

Warsaw Basis

General Strategy



SM Effective Field Theory : SMEFT

Weak Effective Theory : WET

Goal of present work

Master Formula for $\Delta F = 2$ processes in terms of SMEFT Wilson-coefficients at **new physics (NP) scale** (Λ) .

Facilitate the model independent studies of $\Delta F = 2$ observables.

Ingredients:

2-Loop RG running from low to EW scale — Buras, Jager and Urban 2001; Buras, Misiak and Urban 2000

1-Loop Matching SMEFT to WET at the EW scale — Dekens and Stoffer 2019

1-Loop RG running from EW to NP scale — Jenkins, Manohar, Trott 2013 & 14; Alonso, Jenkins, Manohar, Trott 2013

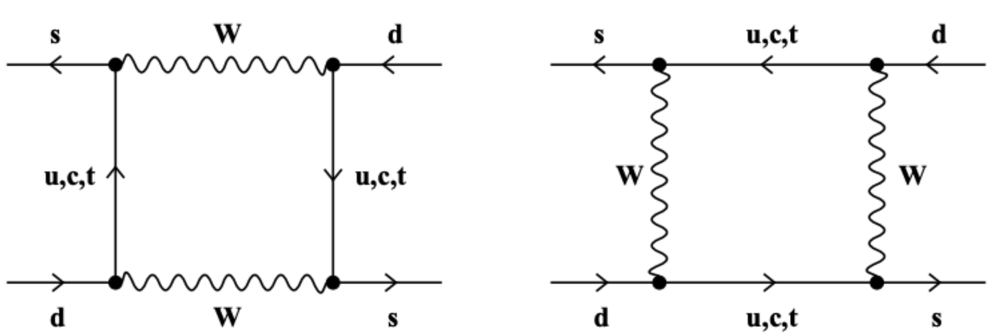
$\Delta F = 2$ Observables

$$ij = ds: \qquad \Delta M_K = 2\,\mathrm{Re}\big(M_{12}^{ds}\big), \qquad \varepsilon_K \propto \mathrm{Im}\big(M_{12}^{ds}\big),$$

$$ij = ib: \qquad \Delta M_{B_i} = 2\big|M_{12}^{ib}\big|, \qquad \phi_i = \mathrm{Arg}\big(M_{12}^{ib}\big).$$

$$[M_{12}^{ij}] = [M_{12}^{ij}]_{\rm SM} + [M_{12}^{ij}]_{\rm BSM} = \langle M^0 \,|\, \mathscr{H}^{ij}_{\Delta F=2} \,|\, \bar{M}^0 \rangle$$

$$ij \;=\; ds,\;\; sb,\;\; db:\;\; K^0,\;\; B_s,\;\; B_d$$



$$[M_{12}^{ij}] = \frac{1}{2M_{M^0}} \sum C_a^{ij}(\mu)\langle Q_a^{ij}(\mu)\rangle$$

$$\mathscr{H}^{ij}_{\Delta F=2} = [\mathscr{H}^{ij}_{\Delta F=2}]_{\rm SM} + \sum_a C_a^{ij} Q_a^{ij} + h.c$$

Q_a^{ij} **: WET operators in a suitable basis.**

WET Operator Basis

BMU Basis:

Good for WET RG running

$$Q^{ij}_{\rm VLL} = [\bar{d}_i\gamma_\mu P_L d_j][\bar{d}_i\gamma^\mu P_L d_j],$$

$$Q^{ij}_{\rm LR,1} = [\bar{d}_i\gamma_\mu P_L d_j][\bar{d}_i\gamma^\mu P_R d_j], \qquad Q^{ij}_{\rm LR,2} = [\bar{d}_i P_L d_j][\bar{d}_i P_R d_j],$$

$$Q^{ij}_{\rm SLL,1} = [\bar{d}_i P_L d_j][\bar{d}_i P_L d_j], \qquad Q^{ij}_{\rm SLL,2} = -[\bar{d}_i\sigma_{\mu\nu} P_L d_j][\bar{d}_i\sigma^{\mu\nu} P_L d_j],$$

Buras, Misiak, and Urban 2000

JMS Basis:

Good for 1-loop matching onto SMEFT

$$[Q^{VLL}_{dd}]_{ijij} = Q^{ij}_{\rm VLL}\,,$$

$$[Q^{VRR}_{dd}]_{ijij} = Q^{ij}_{\rm VRR}\,,$$

$$[Q^{V1,LR}_{dd}]_{ijij} = Q^{ij}_{\rm LR,1}\,,$$

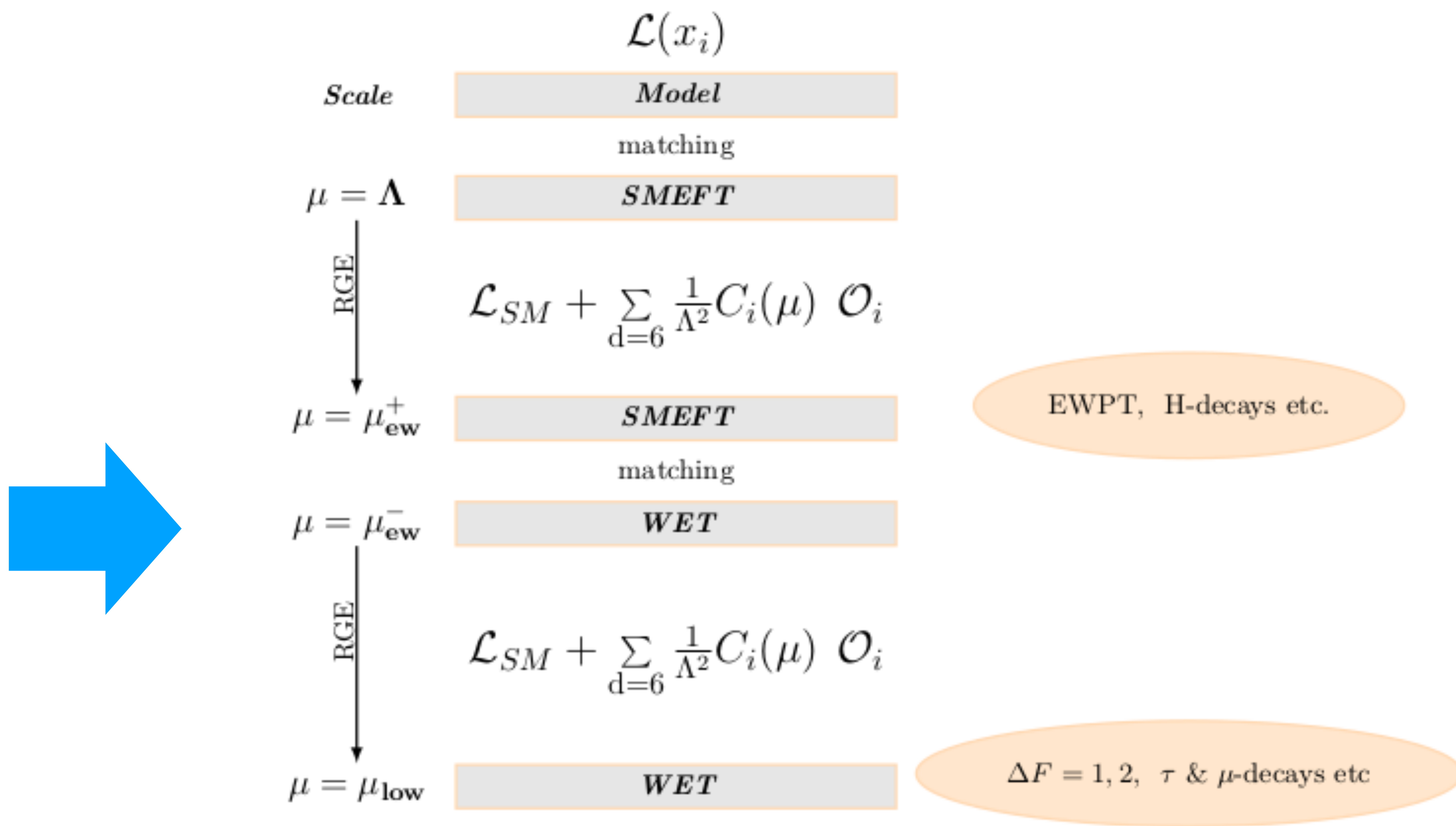
$$[Q^{V8,LR}_{dd}]_{ijij} = [\bar{d}_i\gamma_\mu P_L T^A d_j][\bar{d}_i\gamma^\mu P_R T^A d_j] = -\frac{1}{6}Q^{ij}_{\rm LR,1} - Q^{ij}_{\rm LR,2}\,,$$

$$[Q^{S1,RR}_{dd}]_{ijij} = Q^{ij}_{\rm SRR,1}\,,$$

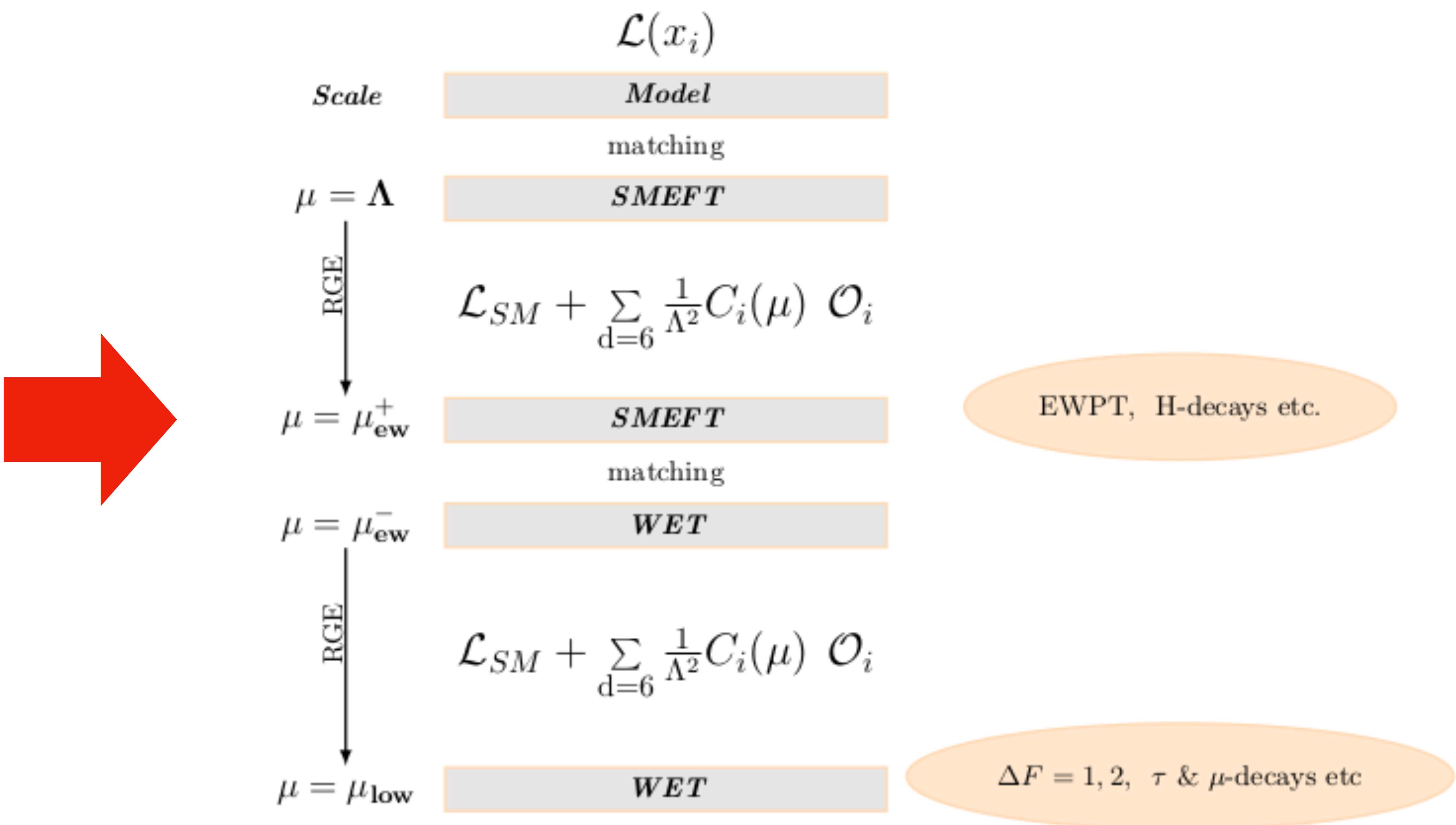
$$[Q^{S8,RR}_{dd}]_{ijij} = [\bar{d}_i P_R T^A d_j][\bar{d}_i P_R T^A d_j] = -\frac{5}{12}Q^{ij}_{\rm SRR,1} + \frac{1}{16}Q^{ij}_{\rm SRR,2}\,,$$

Jenkins, Manohar, Stoffer 2018

+ Chirality flipped operators = 8 operators



$\mathcal{L}(x_i)$
Scale
Model
matching
$\mu = \Lambda$
SMEFT
RGE
$\mathcal{L}_{SM} + \sum_{d=6} \frac{1}{\Lambda^2} C_i(\mu)\ \mathcal{O}_i$
$\mu = \mu_{ew}^{+}$
SMEFT
EWPT, H-decays etc.
matching
$\mu = \mu_{ew}^{-}$
WET
RGE
$\mathcal{L}_{SM} + \sum_{d=6} \frac{1}{\Lambda^2} C_i(\mu)\ \mathcal{O}_i$
$\mu = \mu_{low}$
WET
$\Delta F = 1, 2,\ \ \tau$ & μ-decays etc



$\mathcal{L}(x_i)$
Scale
Model
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$\mu = \boldsymbol{\Lambda}$
SMEFT
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Matching of WET onto SMEFT

SMEFT operators: $B = \left\{\mathcal{C}_{qq}^{(1)}, \quad \mathcal{C}_{qq}^{(3)}, \quad \mathcal{C}_{qa}^{(1)}, \quad \mathcal{C}_{qa}^{(8)}, \quad \mathcal{C}_{aa}\right\},$

$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$		

Tree-level Matching to WET in JMS basis:

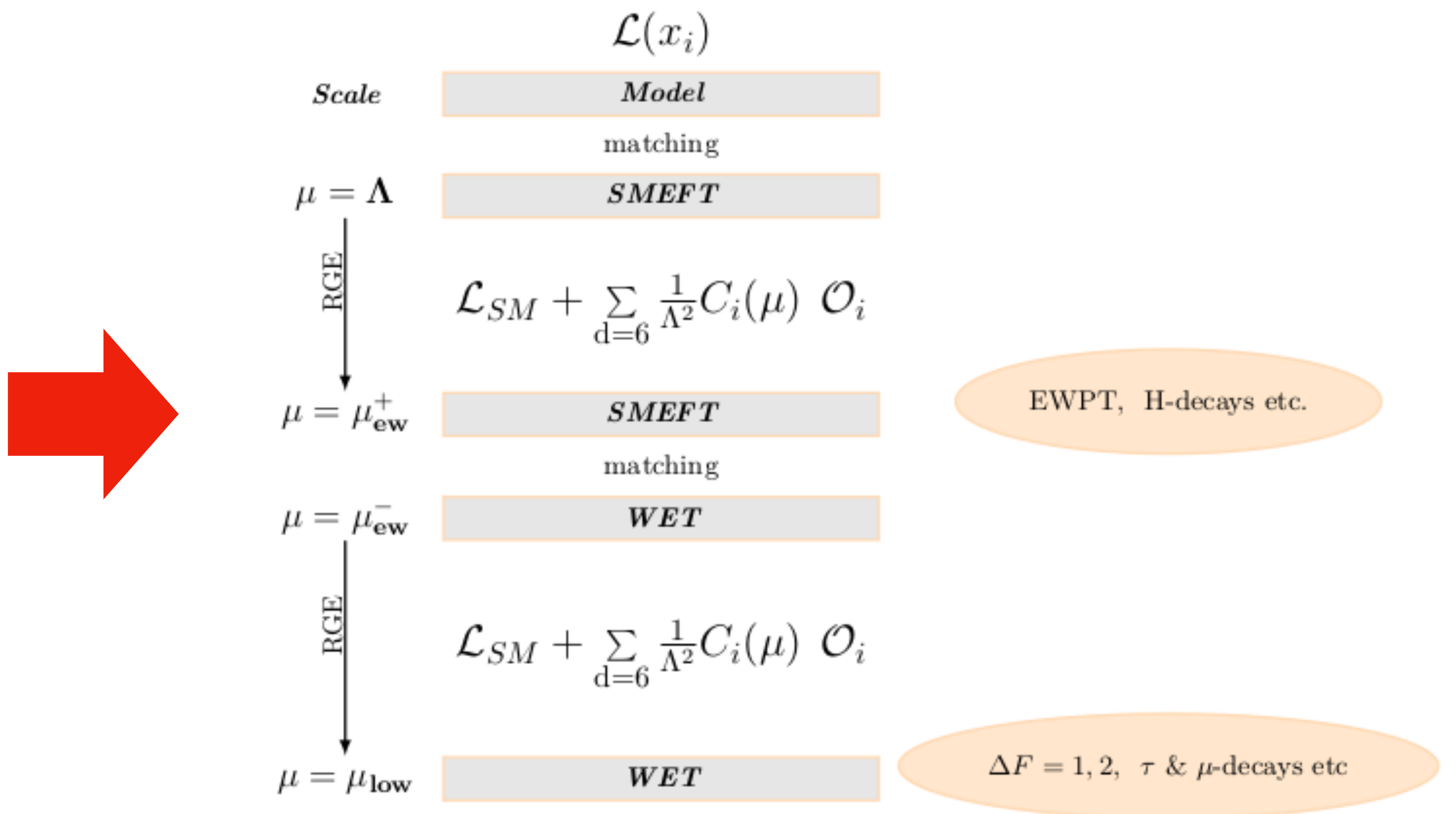
$$[C_{dd}^{V,LL}]_{ijij} = -\left[\mathcal{C}_{qq}^{(1)}\right]_{ijij} - \left[\mathcal{C}_{qq}^{(3)}\right]_{ijij}, \qquad [C_{dd}^{V1,LR}]_{ijij} = -\left[\mathcal{C}_{qd}^{(1)}\right]_{ijij}$$

$$[C_{dd}^{V,RR}]_{ijij} = -\left[\mathcal{C}_{dd}\right]_{ijij}, \qquad [C_{dd}^{V8,RR}]_{ijij} = -\left[\mathcal{C}_{qd}^{(8)}\right]_{ijij}$$

$C_{dd}^{S1,RR}, C_{dd}^{S8,RR}$ **: No tree-level SMEFT matching to WET scalar operators!**

$$C_d(\mu_{\rm ew}) = \sum_{b\in B} M_{db}^{(0)}(\mu_{\rm ew})\,\mathcal{C}_b(\mu_{\rm ew}) + \sum_{c\in C} M_{dc}^{(1)}(\mu_{\rm ew})\,\mathcal{C}_c(\mu_{\rm ew}) + \ldots,$$

Tree-level **1-loop**



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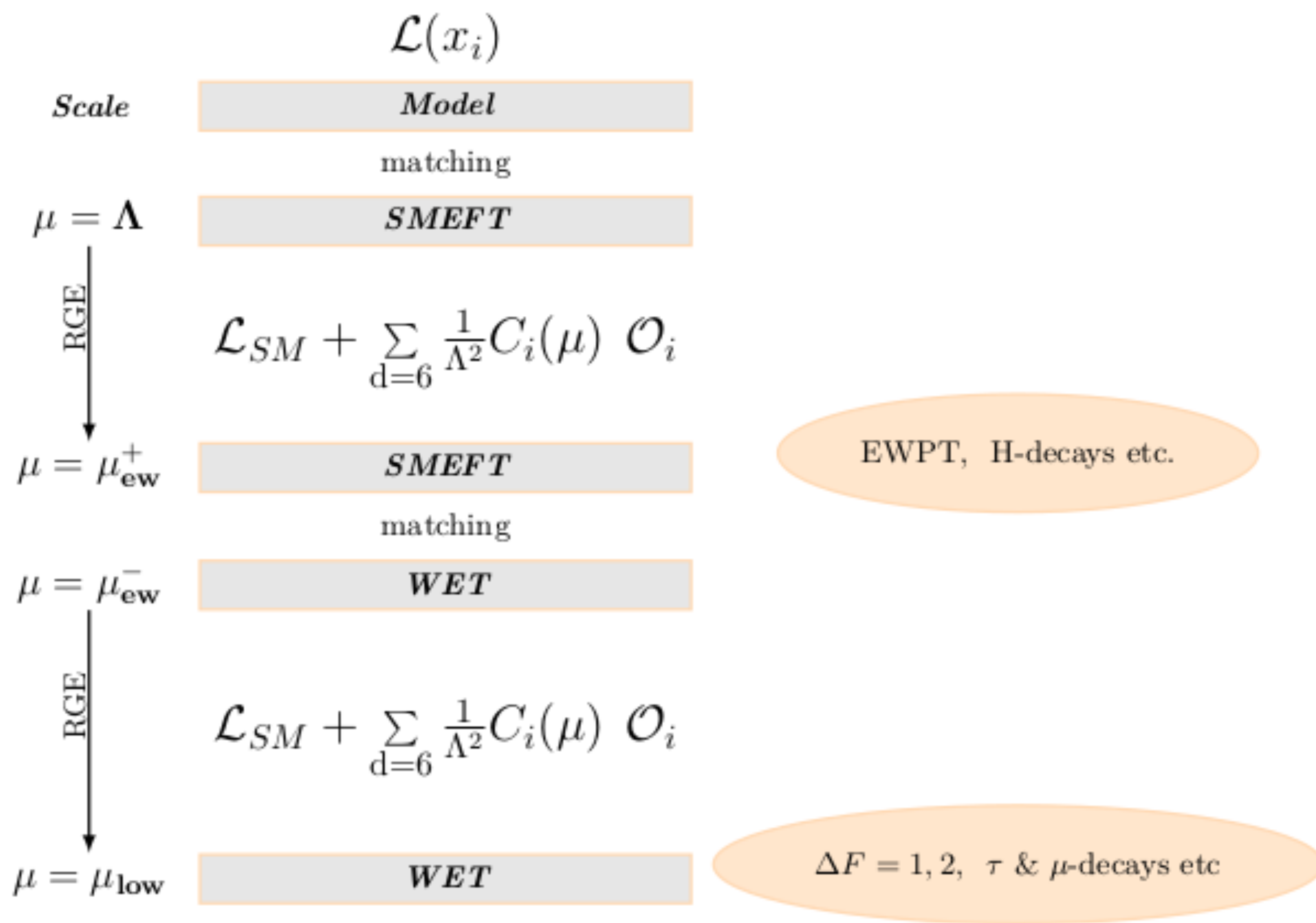
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$\mu = \mu_{\mathbf{low}}$
WET
$\Delta F = 1, 2,\ \tau$ & μ-decays etc

SMEFT RG running effects

Yukawa dependence:

Flavour dependent!

$$[\mathcal{C}_{qq}^{(1)}]_{ijij}(\mu_{\rm ew}) = [\mathcal{C}_{qq}^{(1)}]_{ijij} + y_t^2\Big[\lambda_t^{ik}[\mathcal{C}_{qq}^{(1)}]_{kjij} + \lambda_t^{kj}[\mathcal{C}_{qq}^{(1)}]_{ikij} - \lambda_t^{ij}\Big([\mathcal{C}_{qu}^{(1)}]_{ij33} + \frac{1}{12}[\mathcal{C}_{qu}^{(8)}]_{ij33} - [\mathcal{C}_{\phi q}^{(1)}]_{ij}\Big)\Big]L\,,$$

Gauge coupling dependence:

Flavour independent!

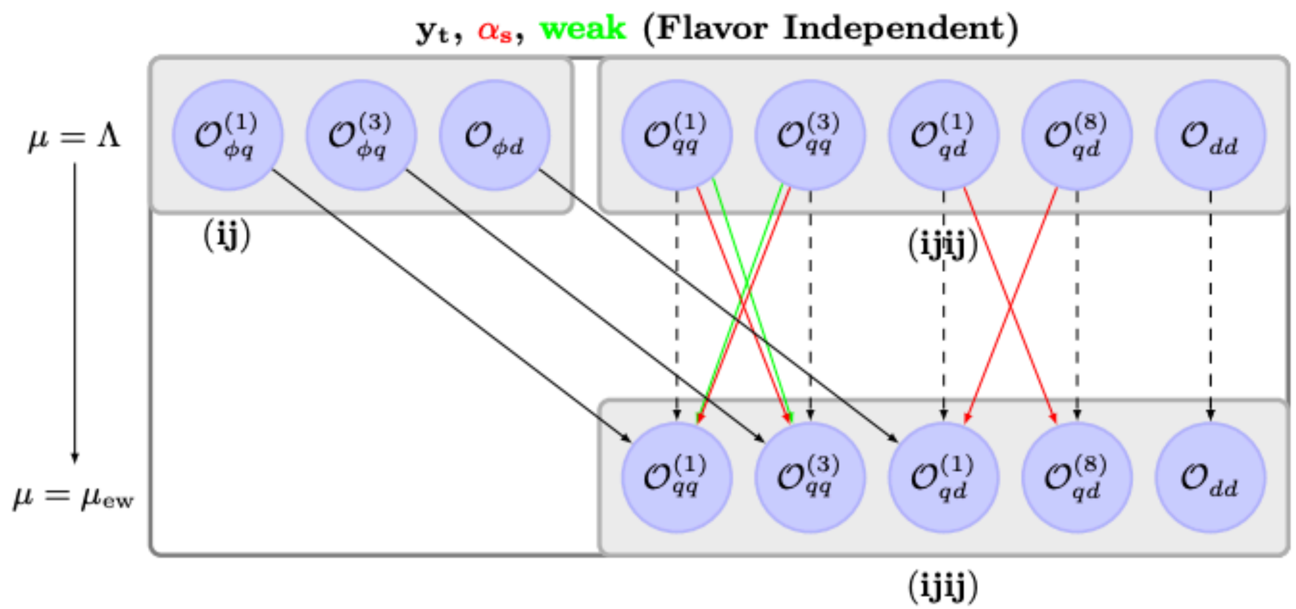
$$[\mathcal{C}_{qq}^{(1)}]_{ijij}(\mu_{\rm ew}) = [\mathcal{C}_{qq}^{(1)}]_{ijij} + \left[\left(\frac{g'^2}{3} + g_s^2\right)[\mathcal{C}_{qq}^{(1)}]_{ijij} + 9\left(g^2 + g_s^2\right)[\mathcal{C}_{qq}^{(3)}]_{ijij}\right]L$$

Similar RG eqs for $C_{qq}^{(3)}, C_{qd}^{(1)}, C_{qd}^{(8)}, C_{dd}$

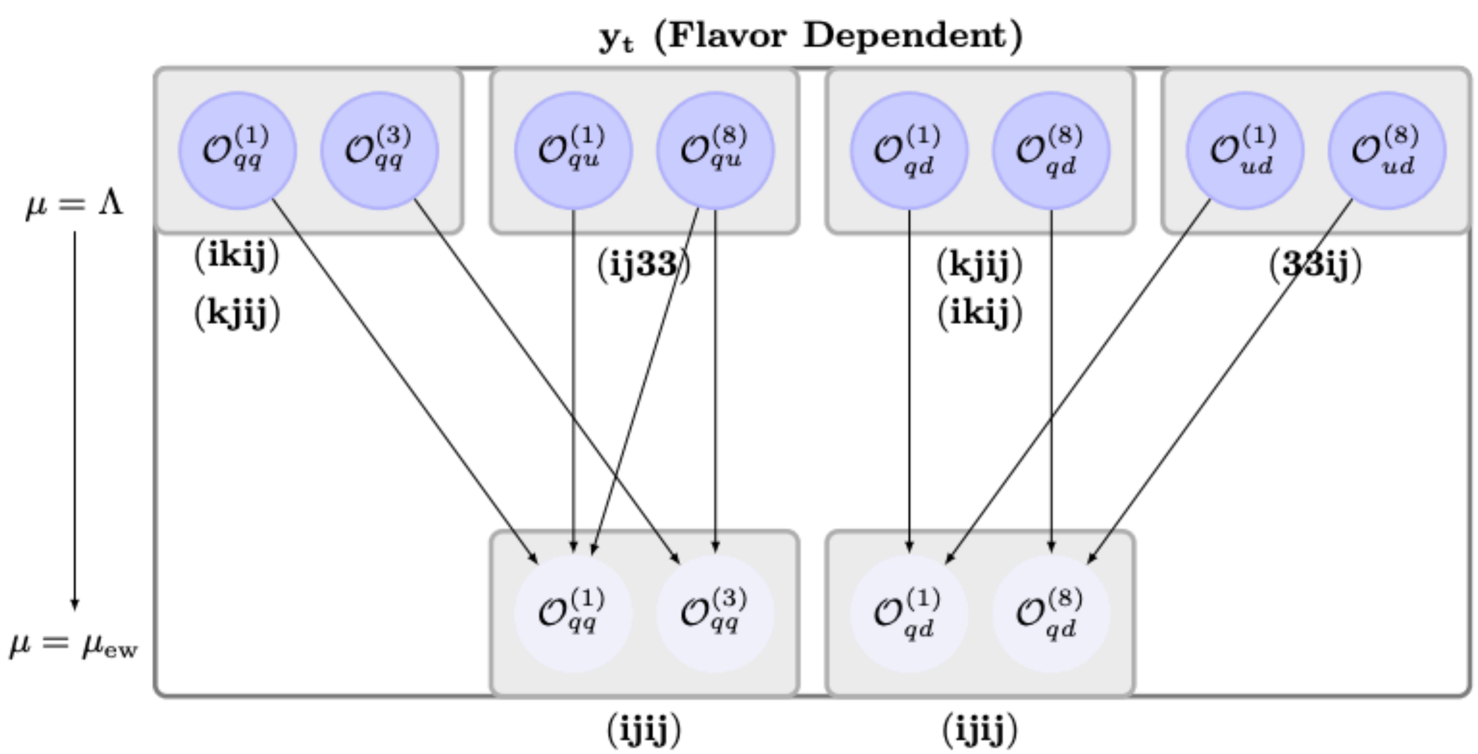
$$L = \frac{1}{(4\pi)^2}\ln\left(\frac{\mu_{\rm ew}}{\Lambda}\right)$$

SMEFT RG running effects

Yukawa
Strong
Weak



ij -> ij



ik, kj, 33 -> ij

SMEFT RG running effects

$$B = \left\{\mathcal{C}_{qq}^{(1)}\,, \quad \mathcal{C}_{qq}^{(3)}\,, \quad \mathcal{C}_{qa}^{(1)}\,, \quad \mathcal{C}_{qa}^{(8)}\,, \quad \mathcal{C}_{aa}\right\},$$

Tree-level Matching

flavour-structure = ijij

+ $$\left\{\mathcal{C}_{qu}^{(1)}\,, \quad \mathcal{C}_{qu}^{(8)}\,, \quad \mathcal{C}_{ud}^{(1)}\,, \quad \mathcal{C}_{ud}^{(8)}\,, \quad \mathcal{C}_{\phi q}^{(1)}\,, \quad \mathcal{C}_{\phi q}^{(3)}\,, \quad \mathcal{C}_{\phi d}\right\}.$$

1-loop RGE

$$\text{four-quark}: \quad [\mathcal{C}_{quqd}^{(1)}],\ [\mathcal{C}_{quqd}^{(8)}];$$

$$\text{semileptonic}: \quad [\mathcal{C}_{lq}^{(1)}],\ [\mathcal{C}_{lq}^{(3)}],\ [\mathcal{C}_{ld}],\ [\mathcal{C}_{qe}],\ [\mathcal{C}_{ledq}],\ [\mathcal{C}_{lequ}^{(1)}],\ [\mathcal{C}_{lequ}^{(3)}].$$

With complicated flavour-structure!!

+ $$C = B' + \{\mathcal{C}_{uW}\}.$$

1-loop Matching

At NP scale a large number of SMEFT operators contribute!

Master Formulae

$$2\left[M_{12}^{ij}\right]_{\text{BSM}} = (\Delta M_{ij})_{\text{exp}} \sum_a P_a^{ij}(\Lambda)\ \left[\mathcal{C}_a\right]_{ij}(\Lambda) = (\Delta M_{ij})_{\text{exp}} \sum_a P_a^{ij}(\Lambda) \frac{\left[c_a\right]_{ij}(\Lambda)}{\Lambda^2}$$

Sum over all operators.

Wilson Coefficients at the NP scale.

We calculate P_a^{ij} **at the NP scale.**

$$[\Sigma_{12}^{ij}]_{\text{BSM}} = \frac{2[M_{12}^{ij}]_{[\text{BSM}]}}{\Delta M_{ij}^{\text{exp}}}$$

Master Formulae

$\Lambda = 5TeV$

$$\Sigma_{qq1}^{B_s} = -3.9\cdot 10^2 \left[c_{qq}^{(1)}\right]_{2323} - 5.4\cdot 10^{-1}\left[c_{qq}^{(1)}\right]_{2333} + 3.1\cdot 10^{-1}\left[c_{qq}^{(1)}\right]_{2223} - 6.8\cdot 10^{-2} e^{i22^\circ}\left[c_{qq}^{(1)}\right]_{1232},$$

$$\Sigma_{qq1}^{B_d} = -9.1\cdot 10^3 \left[c_{qq}^{(1)}\right]_{1313} + 7.2\left[c_{qq}^{(1)}\right]_{1213} + 2.7 e^{i22^\circ}\left[c_{qq}^{(1)}\right]_{1333} - 1.6 e^{i22^\circ}\left[c_{qq}^{(1)}\right]_{1113} - 1.2\cdot 10^{-1} e^{i23^\circ}\left[c_{qq}^{(1)}\right]_{1323} + 2.3\cdot 10^{-2} e^{i21^\circ}\left[c_{qq}^{(1)}\right]_{1332} + 5.8\cdot 10^{-3} e^{i22^\circ}\left[c_{qq}^{(1)}\right]_{1223} - 5.7\cdot 10^{-3}\left[c_{qq}^{(1)}\right]_{1212} - 5.1\cdot 10^{-3} e^{i44^\circ}\left[c_{qq}^{(1)}\right]_{1331},$$

$$\Sigma_{qq1}^{K} = -3.6\cdot 10^4 \left[c_{qq}^{(1)}\right]_{1212} - 6.0\cdot 10^{1}\left[c_{qq}^{(1)}\right]_{1213} + 1.3\cdot 10^{1} e^{i22^\circ}\left[c_{qq}^{(1)}\right]_{1232} - 5.7\cdot 10^{-1} e^{i23^\circ}\left[c_{qq}^{(1)}\right]_{1222} + 2.5\cdot 10^{-1} e^{i23^\circ}\left[c_{qq}^{(1)}\right]_{1112} + 1.2\cdot 10^{-1} e^{i23^\circ}\left[c_{qq}^{(1)}\right]_{1233} - 1.0\cdot 10^{-1}\left[c_{qq}^{(1)}\right]_{1313} + 2.6\cdot 10^{-2} e^{i23^\circ}\left[c_{qq}^{(1)}\right]_{1332} - 5.2\cdot 10^{-3} e^{i24^\circ}\left[c_{qq}^{(1)}\right]_{1223}.$$

Fraction of NP contribution compared to its central experimental value.
For example: $\Sigma_{qq1}^{B_s} = 0.1$ means 10% NP contribution.

For NP contribution under 10%, $[c_{qq}^{(1)}]_{2323} \lesssim 2.6.10^{-4}$.

Similarly, $|[c_{qq}^{(1)}]_{2333}| \lesssim 1.9.10^{-1}$. Correlations!

Summary

Given the non-observation of the new states at the LHC, SMEFT provides a convenient framework to parameterise the NP effects.

Master formulae for $\Delta F = 2$ observables are presented at the NP scale taking into account the RG running effects above and below the EW scale.

SMEFT RG running effects due to Yukawas can lead to complicated operator mixing pattern which can result into correlations, e.g. with $\Delta F = 1$ sector.

Thanks for your attention !!