Beyond the Standard Model CP Violation: The gradient flow formalism

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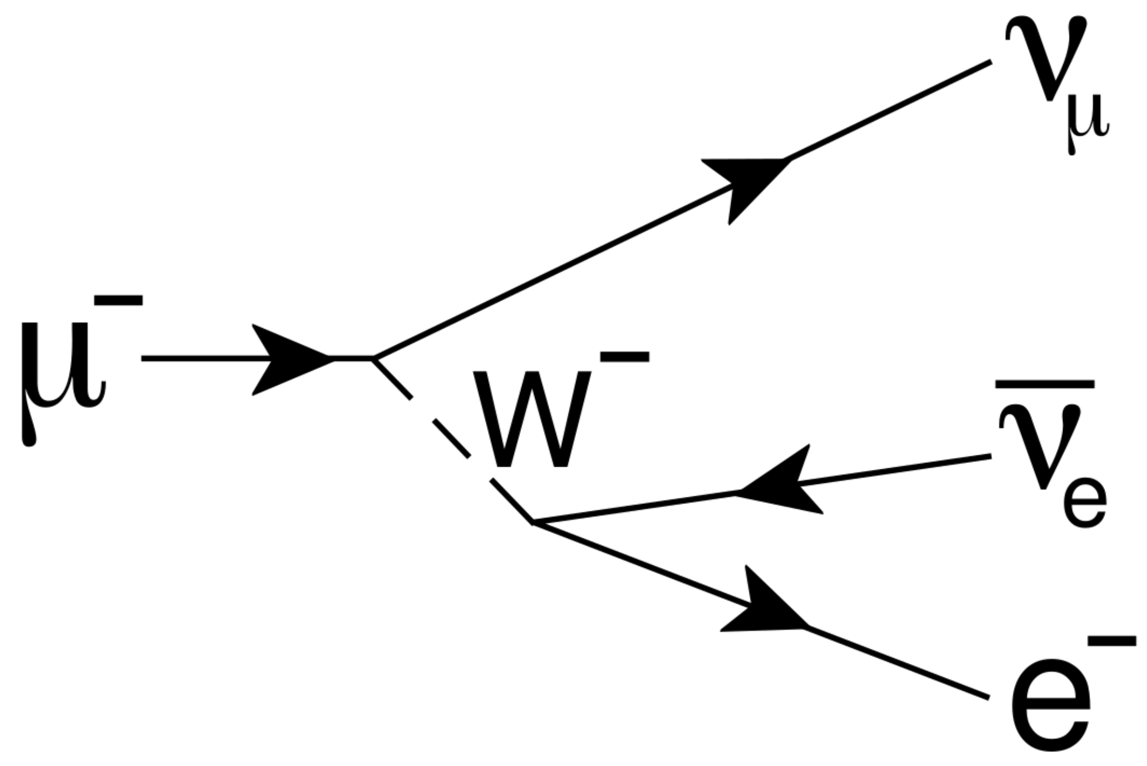
“Effective Field Theories” in one slide

- Assume a heavy boson interacting with two fermions as in muon decay:

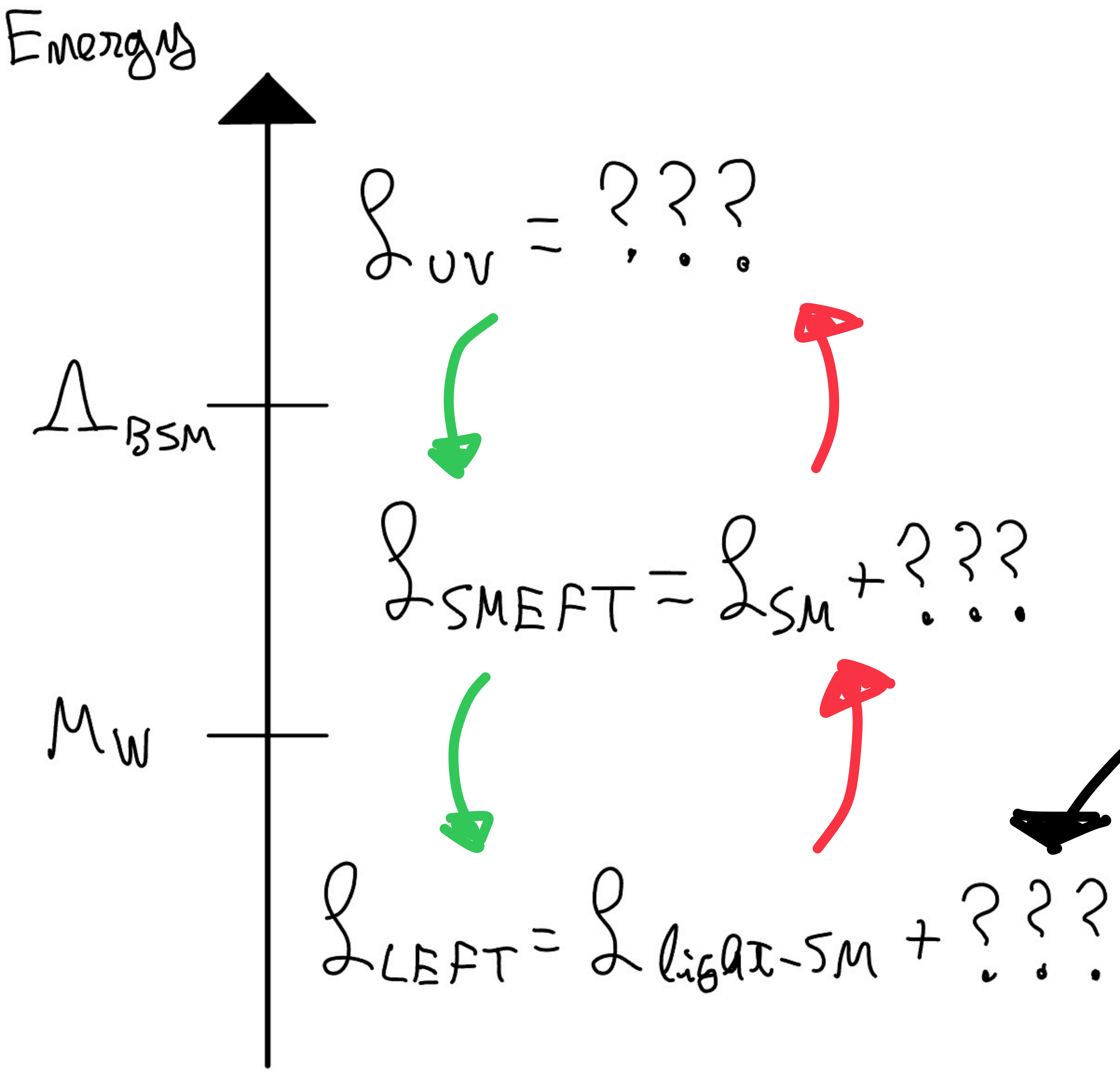


$$\sim \frac{1}{p^2 - M_W^2} \sim -\frac{1}{M_W^2}\left(1 + \frac{p^2}{M_W^2} + \ldots\right)$$

- This process can be effectively described by adding terms in your Lagrangian. At first order:

$$\mathscr{L} \sim C_1(\overline{\psi}\psi)(\overline{\psi}\psi)$$

Our Goal



- Baryon asymmetry tells us that we need more CP Violation than the one we have in the SM (CKM phase + possible theta term)
- Hadronic Electric Dipole Moments (EDMs) are sources of CP violation!
- Hadronic EDMs are non-perturbative quantities, we need lattice calculations.

$$D = 4 - 2\epsilon$$

$$d_N \sim \sum L_i < N | \mathcal{O}_i^{MS} | N\gamma >$$

Lattice Scheme $D \in \mathbb{N}$

Ok… but how?

The Gradient Flow Formalism

- The gradient flow is a $D+1$ gauge theory that extends the D dimensional Euclidean Yang-Mills Theory. The extra dimension is parametrized by a flow time t:

$$
\begin{array}{c} B_\mu(x, t=0) = G_\mu(x) \\ \chi(x, t=0) = \psi(x) \end{array}
\quad\Longrightarrow\quad
\begin{array}{l} \partial_t B_\mu = D_\nu \left(\partial_\mu B_\nu - \partial_\nu B_\mu + [B_\mu, B_\nu] \right) + \alpha_0 D_\mu \partial_\nu B_\nu \\ \partial_t \chi = D_\mu D_\mu \partial \chi - \alpha_0 (\partial_\mu B_\mu) \chi \end{array}
$$

- At small t we can perform an Operator Product Expansion (in an EFT sense) to relate flowed operators $\mathcal{O}_i(t)$ to MS operators (“normal”) $\mathcal{O}_j^{MS}(\mu)$

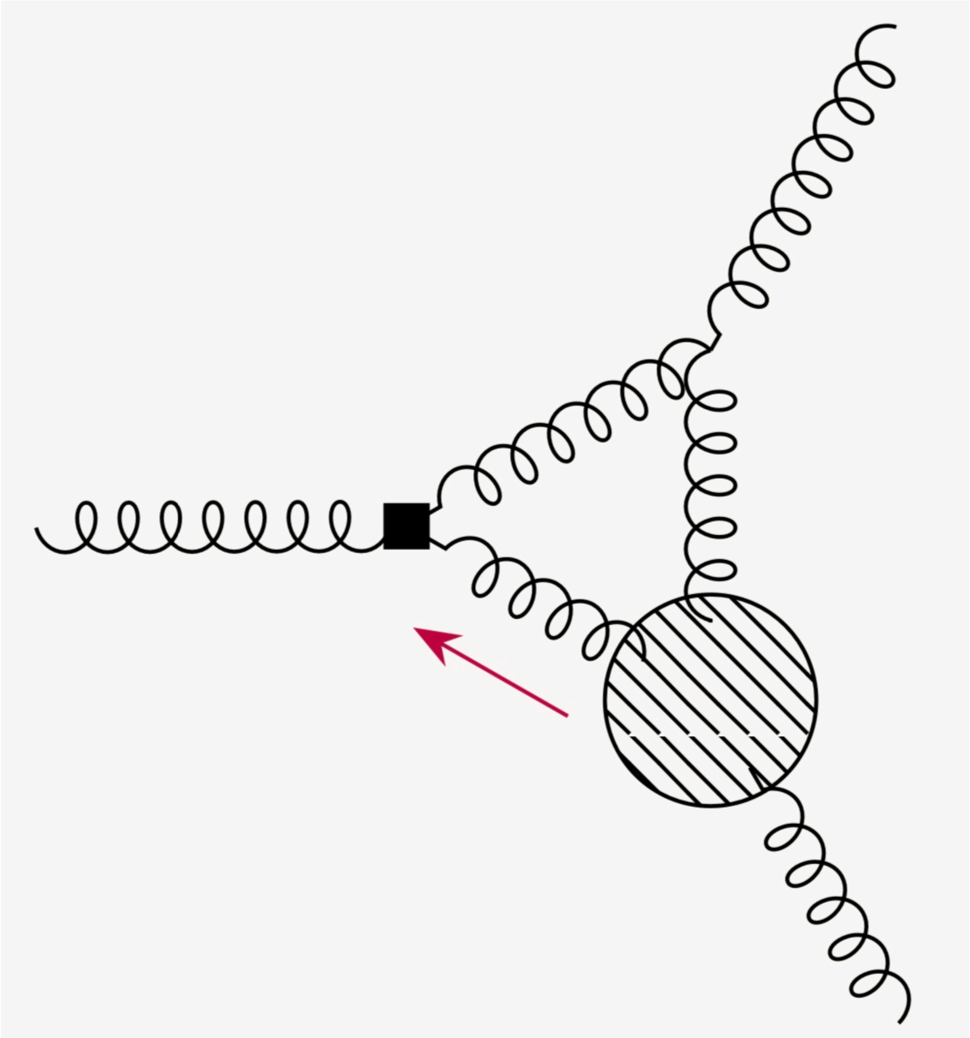
$$
\mathcal{O}_i(t) = \sum_j C_j(\mu, t) \mathcal{O}_j^{MS}(\mu)
$$

The procedure

$$\mathcal{O}_i(t) = \sum_j C_j(\mu, t)\mathcal{O}_j^{MS}(\mu)$$

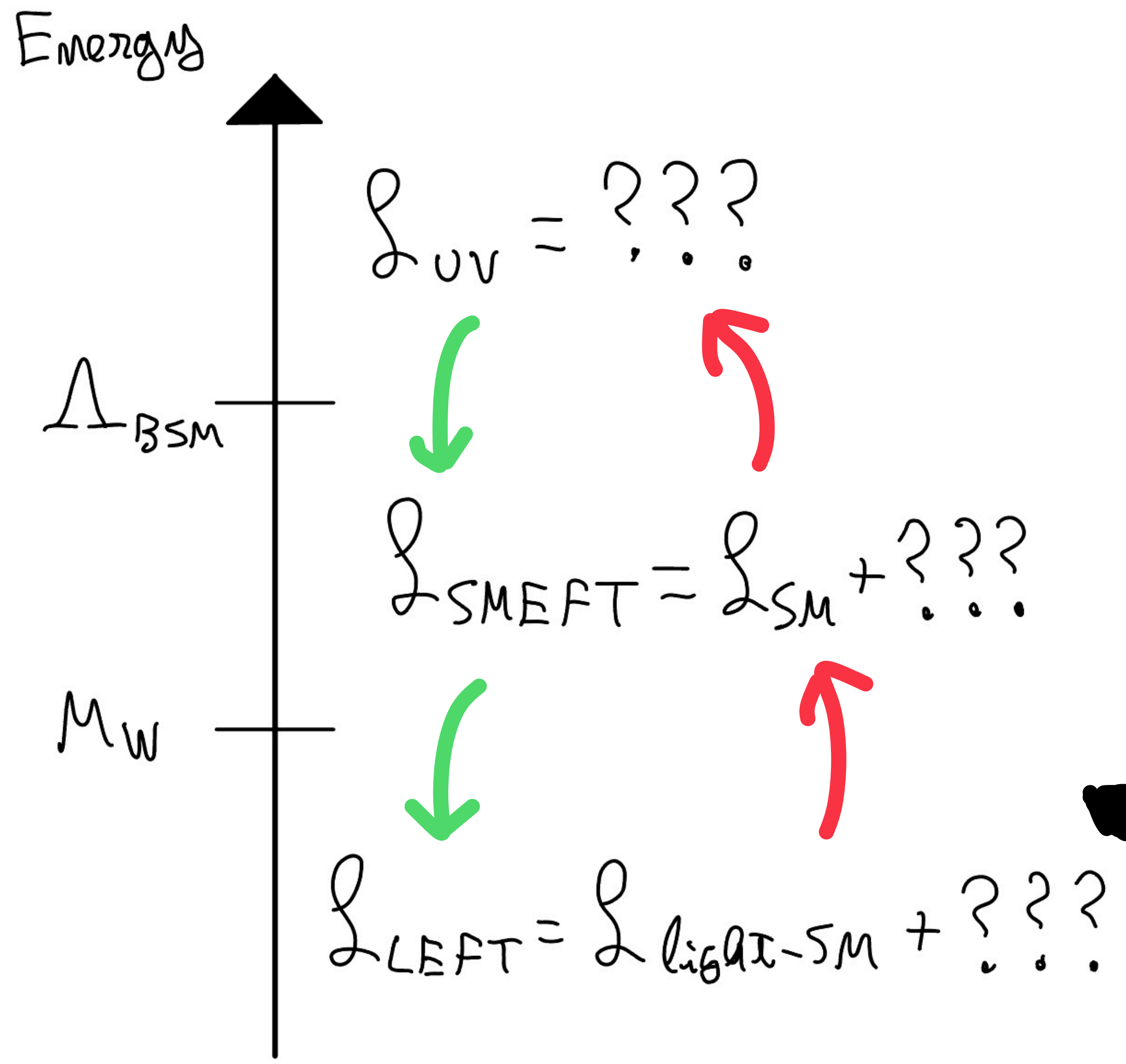
- To make the translation between lattice and MS, we "just" need to obtain C_j
- We obtain C_j by performing an off-shell matching at one loop.
- This is where the fun begins

$$\mathcal{O}_W = f^{abc}\epsilon^{\alpha\beta\gamma\delta}G^a_{\mu\alpha}G^b_{\beta\gamma}G^{\mu,c}_{\delta}$$



Conclusion

- We need more CP Violation to accommodate observations.
- EDMs give us more CP Violation, but they are non-perturbative quantities.
- We need lattice input, but also a “translation” between the lattice scheme and MS(bar).



$$D = 4 - 2\epsilon$$

$$d_N \sim \sum L_i < N | \mathcal{O}_i^{MS} | N\gamma > \quad \longleftarrow \quad \text{Lattice Scheme } D \in \mathbb{N}$$