CP violation in the Standard Model EFT

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Based on 2112.03889 - 23XX.YYYYY, with Q. Bonnefoy, C. Grojean, J. Ruderman

BSM physics: how to

Fundamental Physics

SUSY, Leptoquarks, Composite Higgs, …

This talk

Effective Field Theory

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \dots$$

Low(er) energy

Meson physics, EDMs, nuclear and atomic physics, …

We study CP violation in the extension of the SM to an Effective Field Theory (SMEFT)

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \sum_{n\geq 5} \frac{c_n}{\Lambda^{n-4}} \mathcal{O}^{(n)}$$

The EFT has enough structure to give us nontrivial information

Non-interference theorem: a lot of possible sources of CPV are more suppresses than expected (secondary coefficients)

Some of the remaining ones (primary coefficients) could be larger than the SM CPV (with caveat)

Why CPV?

In the Standard Model, only one source of CPV (assuming $\theta_{QCD} = 0$), from the weak sector

Delicate structure, could be broken by New Physics

Low energy observables can be used to probe high energy NP scales

CPV in the SM

In the electroweak sector, CP violation is encoded in the CKM matrix

$$\mathcal{L}_{\text{mix}} = \frac{e}{\sqrt{2}\sin\theta_w}\left[\bar{u}_L V \not{W}^{+} d_L \; + \; \bar{d}_L V^{\dagger} \not{W}^{-} u_L\right]$$

$$= \frac{e}{\sqrt{2}\sin\theta_w}\left[W_\mu^{+} \bar{u} V \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) d \; + W_\mu^{-} \bar{d} V^{\dagger} \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) u\right]$$

Under CP

$$\mathcal{L}_{\text{mix}} \to \frac{e}{\sqrt{2}\sin\theta_w}\left[W_\mu^{+} \bar{u} \left(V^{\dagger}\right)^{T} \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) d + W_\mu^{-} \bar{d} V^{T} \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) u\right]$$

So $V^* \neq V$ implies CPV (?)

CPV in the SM

V_{CKM} can be parametrized in various ways

We stick to the Wolfenstein parametrization (1983)

CP violating coefficients

$$Y_u = \mathrm{diag}(a_u\lambda^8,\ a_c\lambda^4, a_t\lambda^0)$$

$$Y_d = V_{\mathrm{CKM}}\mathrm{diag}(a_d\lambda^7,\ a_c\lambda^4, a_b\lambda^3)$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = \sin\theta_C \sim 0.22$$

Flavor invariant CPV

Parametrizations are done after picking a basis, but we know physics is basis invariant

$$\begin{array}{ccc} Q & \to & U_Q \cdot Q \\ u & \to & U_u \cdot u \\ d & \to & U_d \cdot d \end{array} \Rightarrow \begin{array}{ccc} Y_u & \to & U_Q \cdot Y_u \cdot U_u^\dagger \\ Y_d & \to & U_Q \cdot Y_u \cdot U_d^\dagger \end{array}$$

For the most unambiguous parametrization, use an invariant

Jarlskog (1985)

$$J_4 \equiv \mathrm{Im}\,\mathrm{Tr}\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]^3$$

CP conserved iff $J_4 = 0$

$$J_4 \sim A^2 a_b^4 a_c^2 a_s^2 a_t^4 \eta \lambda^{36}$$

Collective breaking!

Do we need flavor invariants for SMEFT?

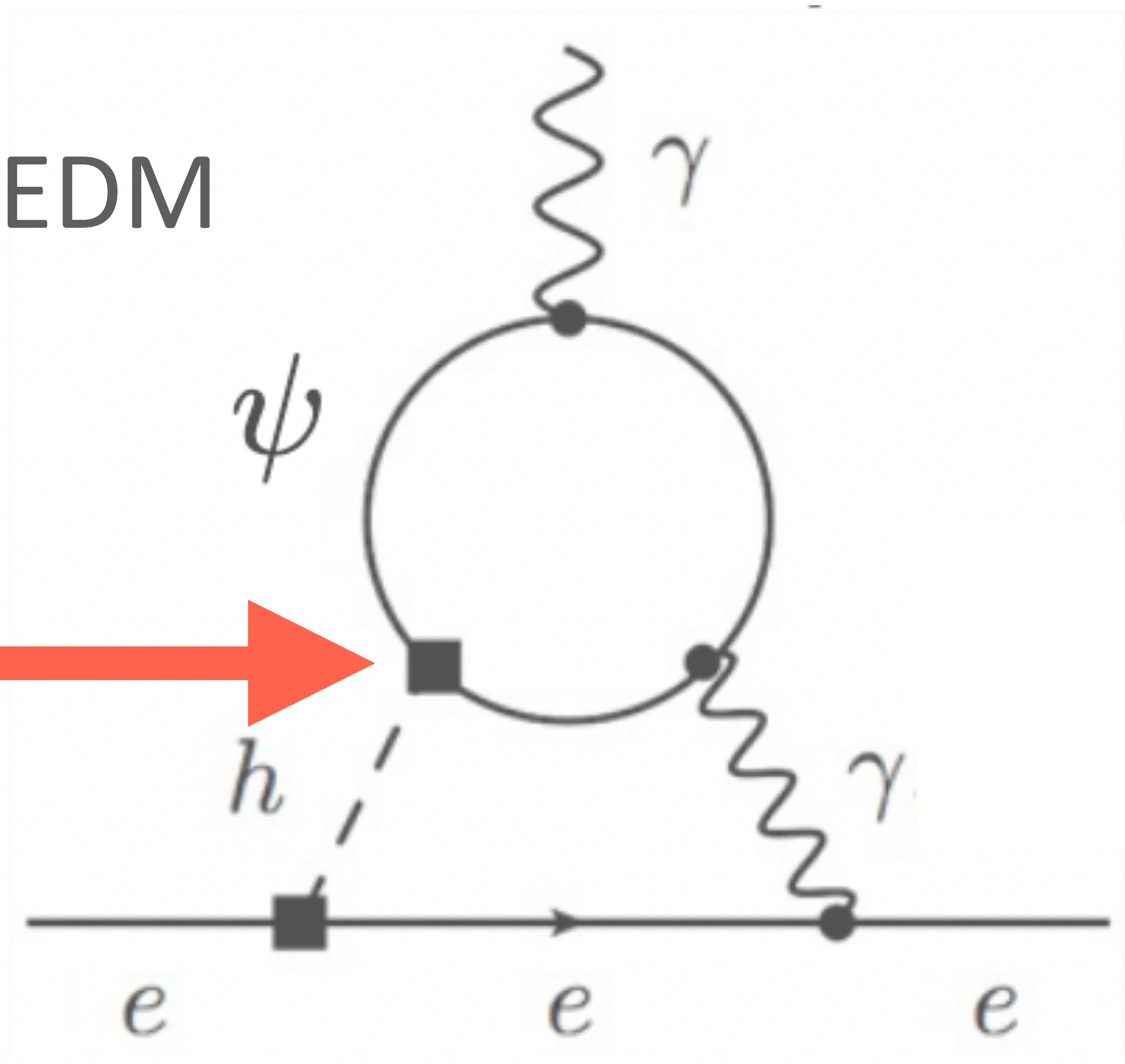
Yes!

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{C_{uH}}{\Lambda^2}|H|^2\bar{Q}_L u_R \tilde{H}$$

$$u_R \to e^{-i\arg(C_{uH})} u_R$$

Electron EDM

C_{uH}



$$\frac{d_e}{e} \propto m_u \frac{\mathrm{Im}(C_{uH})}{\Lambda^2}$$

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Yes!

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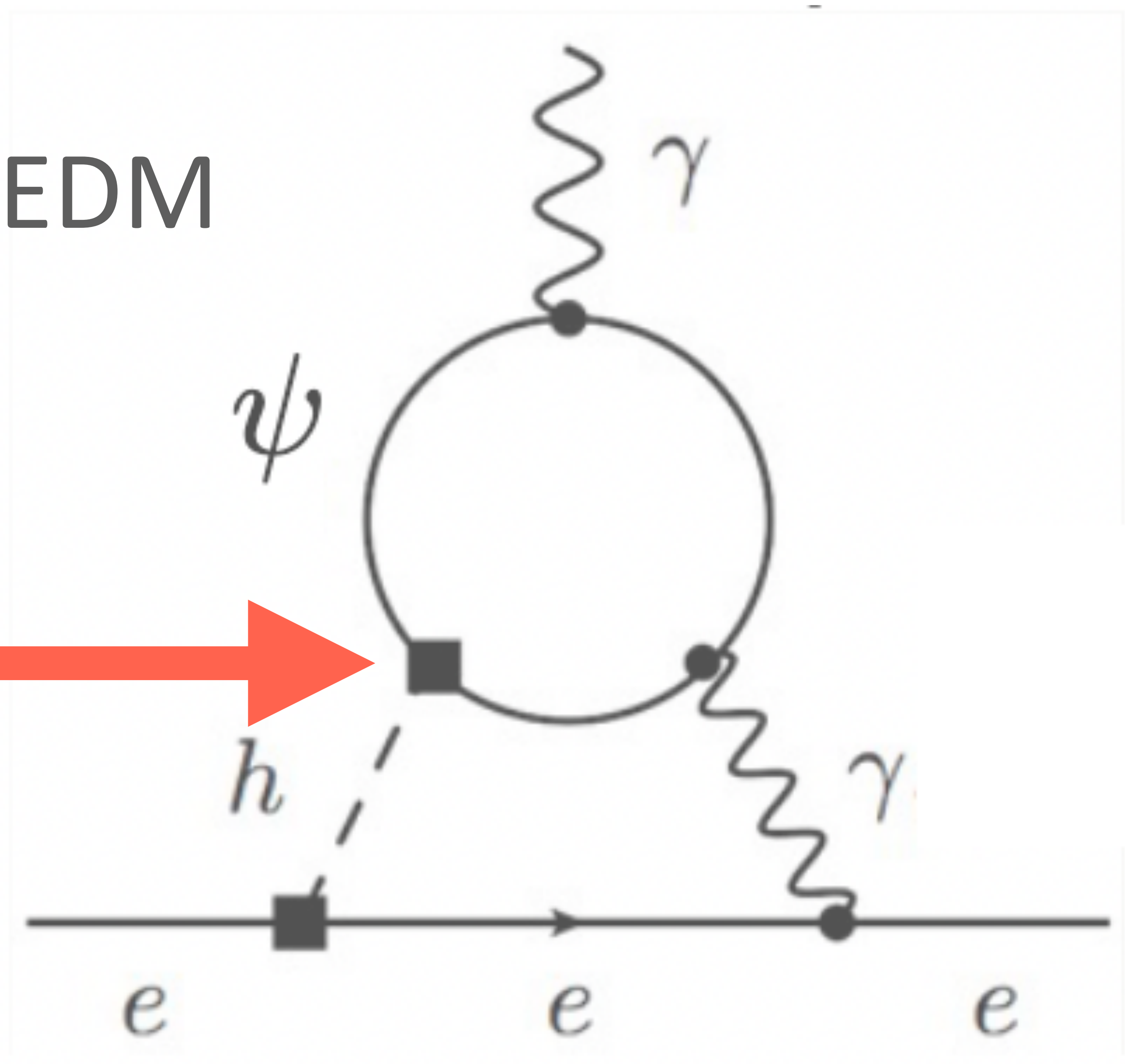
Rephasing invariant!

Electron EDM

C_{uH}



$$\frac{d_e}{e} \propto \frac{\mathrm{Im}(m_u^* C_{uH})}{\Lambda^2}$$

What about three flavors?

$$\mathcal{O}_{HQ}^{(1)} = C_{HQ,mn}^{(1)} \left(H^\dagger i \overleftrightarrow{D}_\mu H\right) \bar{Q}_m \gamma^\mu Q_n$$

Hermitian 3x3 matrix: 3 imaginary coefficients

$$L_1^{HQ(1)} = \mathrm{ImTr}(Y_u Y_u^\dagger Y_d Y_d^\dagger C_{HQ}^{(1)})$$
$$L_2^{HQ(1)} = \mathrm{ImTr}((Y_u Y_u^\dagger)^2 (Y_d Y_d^\dagger)^2 C_{HQ}^{(1)})$$
$$L_3^{HQ(1)} = \mathrm{ImTr}(Y_u Y_u^\dagger Y_d Y_d^\dagger (Y_u Y_u^\dagger)^2 (Y_d Y_d^\dagger)^2 C_{HQ}^{(1)})$$

CP is conserved **iff**

$$J_4 = L_1^{HQ(1)} = L_2^{HQ(1)} = L_3^{HQ(1)} = 0$$

What can you do with them?

Non interference theorem (in lepton sector)

$$Y_e = \mathrm{diag}(y_e, y_\mu, y_\tau)$$ → $U(1)^3$ symmetry of observables

$$(m_\nu = 0)$$

Charged under $U(1)^3$

$$\mathcal{O}_{He} = \frac{1}{\Lambda^2} C_{He,mn} \, (H^\dagger i \overleftrightarrow{D}_\mu H) \, \bar{e}_m \gamma^\mu e_n$$

$$C_{He} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{12}^* & c_{22} & c_{23} \\ c_{13}^* & c_{23}^* & c_{33} \end{pmatrix}$$

If we stop at $1/\Lambda^2$, # of imaginary coefficients: $1143 \to 699$

Primary coefficients

How large are the invariants (compared to J_4)?

In the SM, CPV is accidentally small

$$J_4 \equiv \mathrm{Im}\,\mathrm{Tr}\left[Y_u Y_u^\dagger, Y_d Y_d^\dagger\right]^3 \sim \lambda^{36}$$

Less flavor suppression!

$$\mathcal{O}_{HQ}^{(1)} = C_{HQ,mn}^{(1)} \left(H^\dagger i \overleftrightarrow{D}_\mu H\right) \bar{Q}_m \gamma^\mu Q_n$$

$$\begin{pmatrix} L_1 \\ L_2 \\ L_3 \end{pmatrix} = \begin{pmatrix} A a_b^2 a_t^2 \mathrm{Im} C_{HQ,23}^{(1)} \lambda^8 \\ 0 \\ 0 \end{pmatrix} + \mathcal{O}(\lambda^9)$$

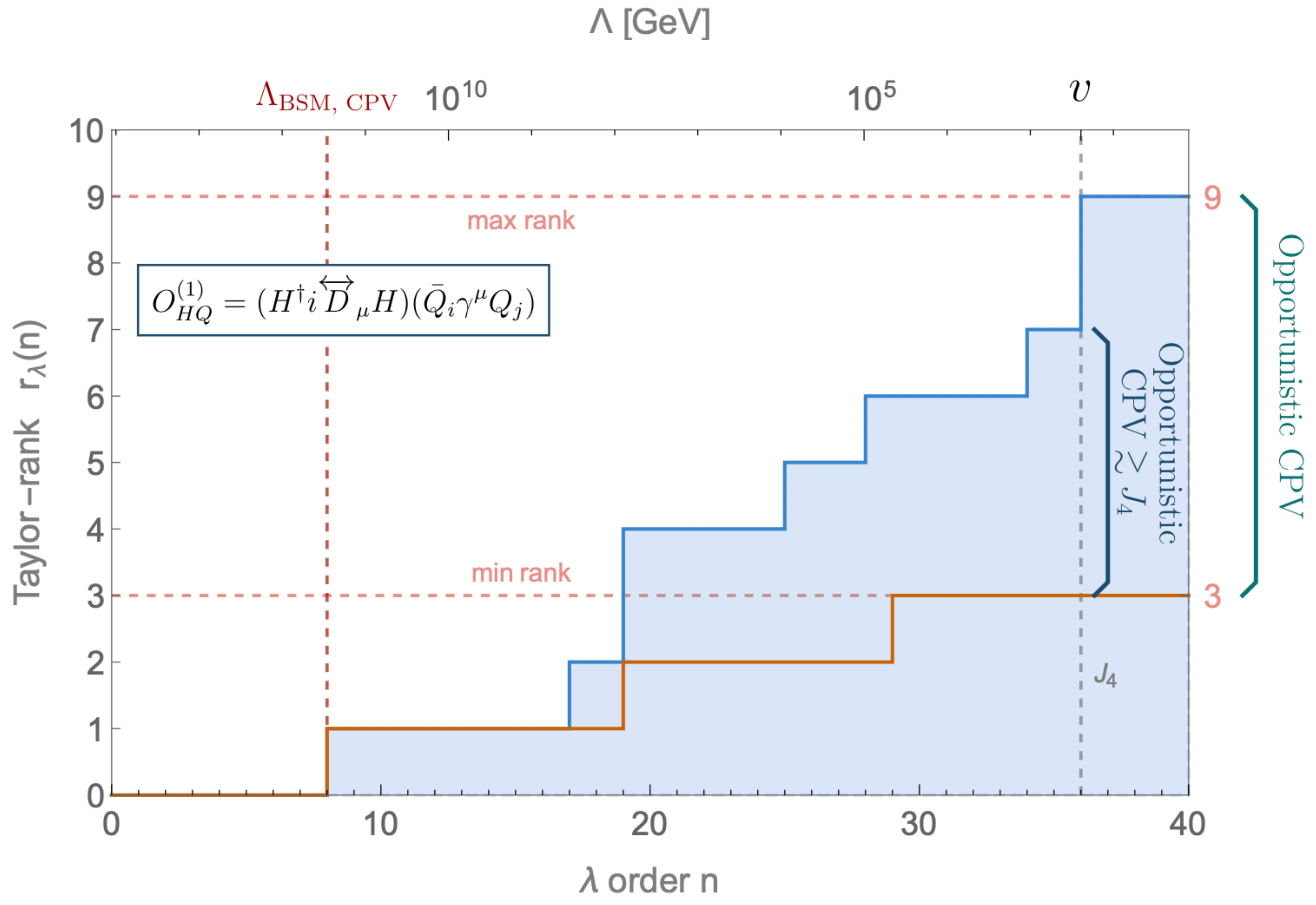
Assuming $\dfrac{\delta\mathcal{O}_{\mathrm{CPV}}}{\mathcal{O}_{\mathrm{CPV}}} \sim \dfrac{v^2}{\Lambda^2}\dfrac{L}{J_4}$

$L_1 \sim J_4 \longrightarrow \Lambda \sim 10^5\ \mathrm{TeV}$

Opportunistic CPV

Since $J_4 \neq 0$, CPV from imaginary coefficients (minimal basis) and from interference of real ones and J_4 (maximal basis) at $1/\Lambda^2$. We call the latter Opportunistic CPV.

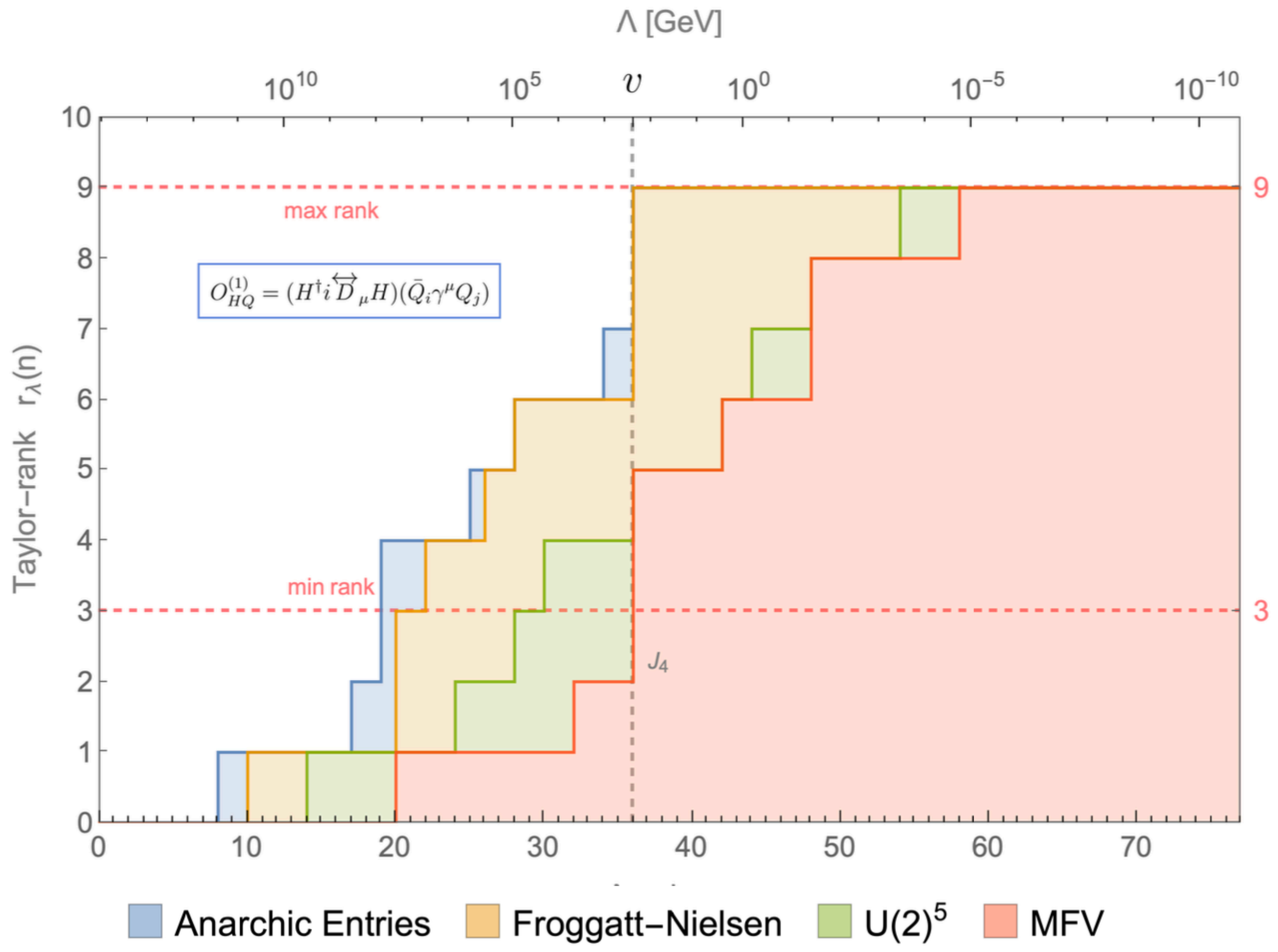
# of independent invariants



Flavor scenarios

Making *some* assumption on the flavor structure can help understand the relation between difference scenarios

# of independent invariants



Conclusions and open questions

The study of SMEFTs properties can bring additional information on CPV

We developed theoretical tools to unambiguously map the parameter space

Connection to observables is crucial to link theoretical tools to experiments: the invariants are the correct objects to constrain

Connections to UV models to be explored

Thank you!