EDMs & P-Conserving T-Violation

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Outline

I. Intro & Motivation

II. TVPC Interactions: Background

III. EFT Illustration: m_ν & μ_ν

IV. TVPC Interactions & EDMS

V. Summary

Questions for Theory

C and P Symmetries (assuming CPT)

D. Mack, MENU

C	C, P, CP Strong, EM Big SM “background” in any search for new forces	C, ~~P~~, ~~CP~~ Weak (loop-level) Small SM “background” . New sources of ~~P~~, ~~CP~~ constrained by EDM searches
~~C~~	~~C~~, P, ~~CP~~ Weak (loop-level) Small SM “background”. New sources of P, ~~CP~~ less constrained by EDM searches	~~C~~, ~~P~~, CP Weak Big SM “background” in any search for new forces *New sources of PV also constrained by amplitude-sensitive PV asymmetry measurements*

C Violation Basics

D. Mack, MENU

The charge conjugation operator C reverses all generalized charges, effectively replacing a particle by its anti-particle.

C violation is known only in

1. *Weak interactions at tree level which violate P (hence conserving CP)*
2. *Weak interactions at loop level which violate CP*

Both C- and CP-violation are among the Sakharov criteria for baryogensis.

Everybody knows strong and EM forces conserve C …. but direct bounds on C violation in these amplitudes are only ~0.5%. How to improve this?

It is surprisingly hard:

i. *Only a few neutral particles are states of good C and thus suitable for tests (γ, π^0, η, J/ψ, or a self-conjugate system like e^+e^-).*

ii. *Most of the particles of good C appropriate for initial states aren't easy to make in large quantities (and with sufficiently low backgrounds).*

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η Decays Testing C Violation

Why η's?

- *The η full width is only 1.3 keV. It cannot decay by the isospin conserving strong interaction. This means that achievable BR's of 10^{-6} to 10^{-7} probe the weak scale.*
- *η decays are flavor-conserving, a sector less thoroughly studied than $\Delta S = 1$, etc.*
- *Theory calculations predict large mass enhancements, hence relatively crude η decay BR upper limits place tighter constraints than more precise π^0 decay BR upper limits.*
- *The η has a significant s-sbar content, unlike the π^0 or nucleon.*

3γ	$< 1.6 \cdot 10^{-5}$	3
"$\pi^0\gamma$"	$< 9 \cdot 10^{-5}$	
$2\pi^0\gamma$	$< 5 \cdot 10^{-4}$	5
$3\gamma\pi^0$	Nothing published	
$3\pi^0\gamma$	$< 6 \cdot 10^{-5}$	7
$3\gamma 2\pi^0$	Nothing published	

PDG 2012

Considerations of acceptance and phase space have focused us on $\eta \to 3\gamma$ and $\eta \to 2\pi^0\gamma$.

Most C test channels are <u>all-neutral</u> except for $\eta \to \pi^0\gamma^* \to \pi^0 l^+ l^-$.

D. Mack, MENU

Theory Issues for C Violation

Placing the tightest direct limits on C violation sounds interesting to experimentalists, but what about theorists?

- *Little literature on C violation with P conservation.*

  (appropriate models for this would be non-renormalizable - Herczeg)

- *Some literature on T violation with P conservation*

  (under CPT, equivalent to C violation with P conservation).

- *By contrast, tremendous literature on CP violation and EDM's.*

- *C violation without P violation is apparently not on the radar of those working with SUSY, leptoquarks.*

- *C violation does arise in discussions of violation of Lorentz invariance, but the predicted C violating η decay BR's are effectively zero for any experiment, ever.*

We'd like theorists studying T violation with P conservation to know that η decays can place tight limits in an isospin-violating sector.

TVPC Interactions: Background

TVPC Interactions

• *Herczeg: No renormalizable TVPC boson-exchange interactions involving only SM fields [Hyperfine Int, **75** (1992) 127]*

• *Low-energy (k << Λ_{EW}) four fermion interactions first arise at d=7 :*

$$\mathcal{O}_7^{ff'} = C_7^{ff'}\,\bar{\psi}_f \overleftrightarrow{D}_\mu \gamma_5 \psi_f \bar{\psi}_{f'} \gamma^\mu \gamma_5 \psi_{f'}$$

Khriplovich '91
Conti & Khriplovich '92
Engel, Frampton, Springer '96

TVPC Interactions, cont'd

• *Additional low-energy (k << Λ_{EW}) d=7 interactions:*

$$\mathcal{O}_7^{\gamma g} = C_7^{\gamma g}\bar{\psi}\sigma_{\mu\nu}\lambda^a\psi F^{\mu\lambda}G_\lambda^{a\nu}$$

$$\mathcal{O}_7^{\gamma Z} = C_7^{\gamma Z}\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\lambda}Z_\lambda^{\nu}$$

+ …

MR-M '99
Kurylov, McLaughlin, MR-M '01

TPVC Observables

- *"D Coefficient" in β-decay:*

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle\frac{\vec{J}}{J}\rangle \cdot \left[A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + D\,\frac{\vec{p}_e \times \vec{p}_\nu}{E_e\, E_\nu} \right] + \ldots \right\}$$

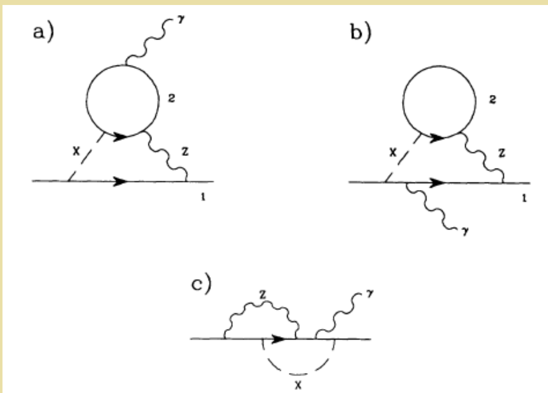
- *Correlations in $\vec{n}$+A scattering:*

$$\vec{\sigma}_n \cdot \vec{k}_n \times \vec{J} \ \left(\vec{k}_n \cdot \vec{J} \right)$$

- $\eta \to 3\,\gamma\,,\ \eta \to 2\pi^0\,\gamma\,, \ldots$:

TPVC Interactions & EDMs

- *Conti & Khriplovich: TVPC interactions + SM radiative corrections (PV) induce non-vanishing EDMs*



$$\mathcal{O}_5 = -\frac{i}{2} C_5^f \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}$$

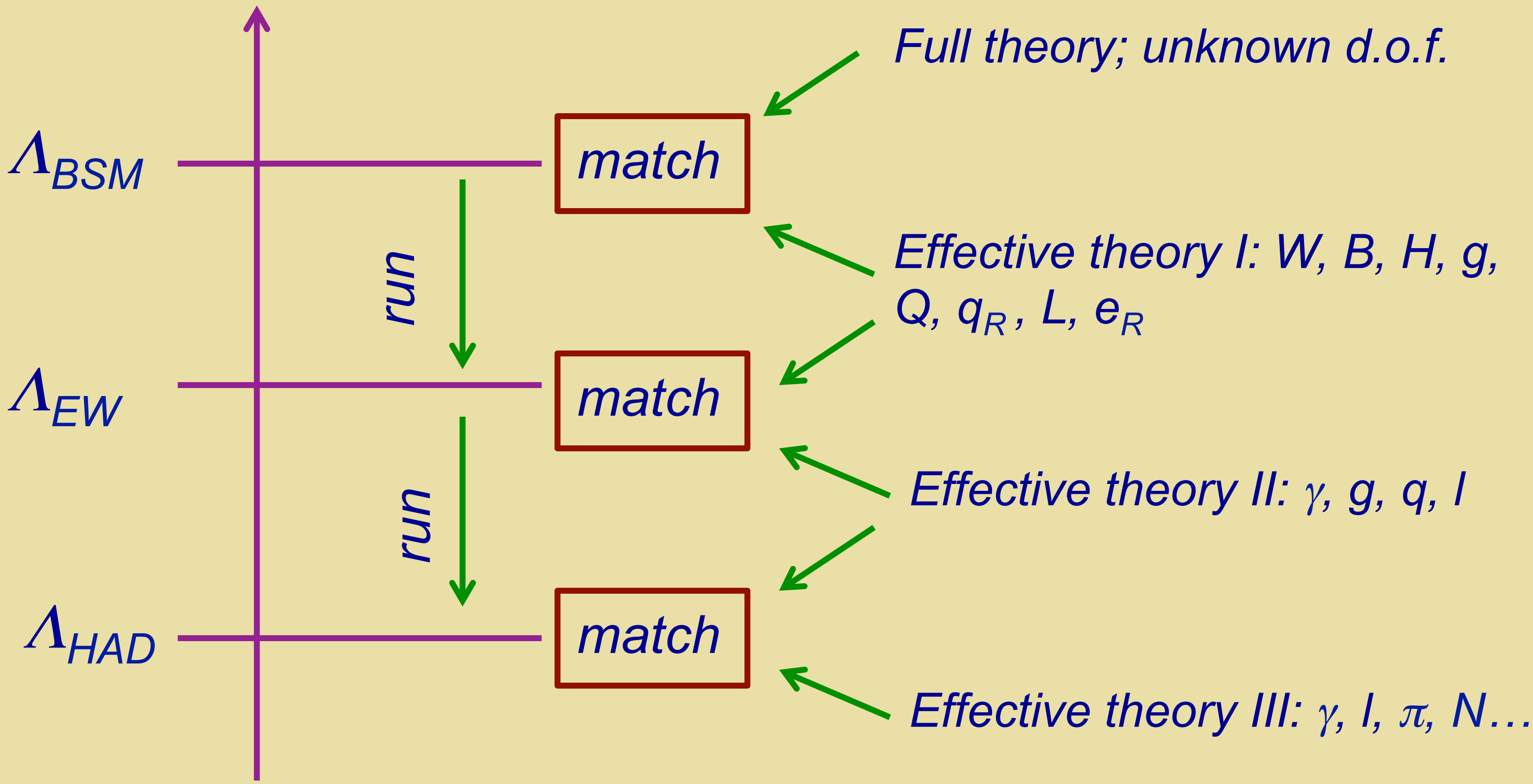
- *EDM limits imply vanishingly small effects from TVPC interactions*

$$C_7^{ff'} \lesssim \left(\frac{\Lambda_{TVPC}}{1\ \mathrm{TeV}} \right) \times 10^{-3}$$

How Robust Is Bound?

- *Non-renormalizable interactions: EFT, running, matching & "naturalness"*
- *Illustration with neutrino magnetic moments*
- *Application to TVPC interactions*

Non-Renormalizable Interactions & EFT



Effective Theory I

$$\mathcal{L}_{\rm CPV} = \mathcal{L}_{\rm CKM} + \mathcal{L}_{\bar\theta} + \mathcal{L}_{\rm BSM}^{\rm eff}$$

$$\mathcal{L}_{\rm BSM}^{\rm eff} = \frac{1}{\Lambda^2} \sum_i \alpha_i^{(n)} O_i^{(6)} \qquad + \ldots$$

Effective theory I: W, B, H, g, Q, q_R, L, e_R

Effective Theory II

$$\mathcal{L}_{\text{new}} = \mathcal{L}_4 + \frac{1}{\Lambda_{\text{TVPC}}}\mathcal{L}_5 + \frac{1}{\Lambda_{\text{TVPC}}^2}\mathcal{L}_6 + \frac{1}{\Lambda_{\text{TVPC}}^3}\mathcal{L}_7 + \ldots,$$

+…

Effective theory II: γ, g, q, l

Effective Theory II

$$\mathcal{L}_{\text{new}} = \mathcal{L}_4 + \frac{1}{\Lambda_{\text{TVPC}}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\text{TVPC}}}\mathcal{L}_6 + \frac{1}{\Lambda^3_{\text{TVPC}}}\mathcal{L}_7 + \ldots,$$

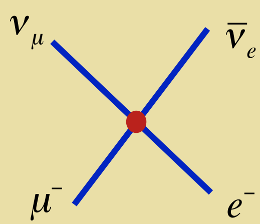
+…

Effective theory II: γ, g, q, l

Matching I & II: compute in II with massive W,Z

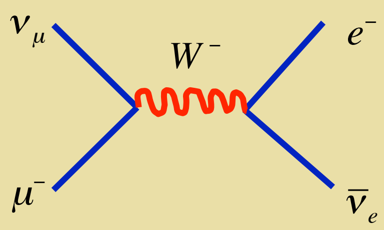
Matching

Fermi Effective Theory



$\sim \mathcal{O}(G_F)$

Standard Model



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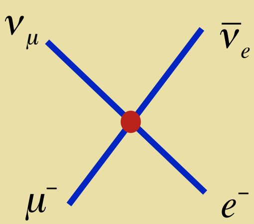
Matching

Fermi Effective Theory



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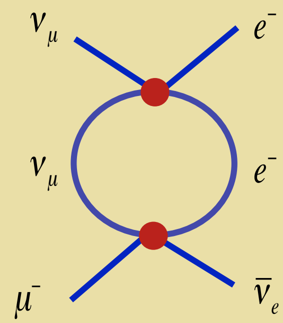
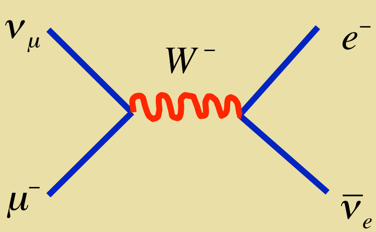


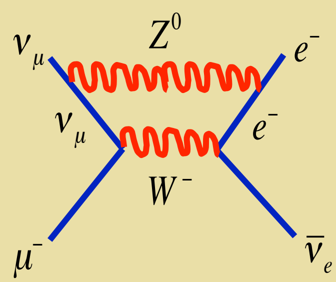
$\sim \mathcal{O}(G_F^2\ m_e^2)$

Loop momenta
$p << M_W^2$

Standard Model



$\sim \mathcal{O}(G_F)$



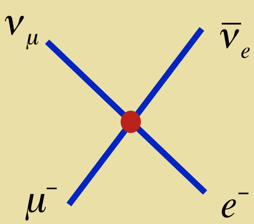
$\sim \mathcal{O}(G_F\ \alpha\ /\ \pi)$

Loop momenta
$p \sim M_W^2$

Matching

Match EFT onto full theory by considering $p \sim \Lambda$ (NDA)

Fermi Effective Theory



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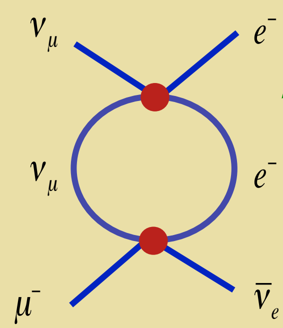

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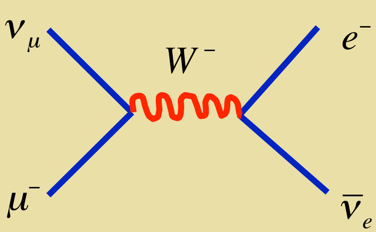
Standard Model



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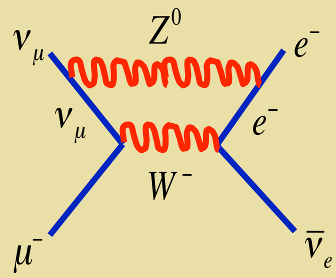

$\sim \mathcal{O}(G_F\, \alpha / \pi)$

Loop momenta
$p \sim M_W^2$

EFT Ilustration: m_{ν} & μ_{ν}

Bell, Cirigliano, R-M, Vogel, Wise ’05
Also
Bell, Gorchtein, R-M, Vogel, Wang ‘06
Erwin, Kile, R-M, Wang ‘07
Kile, R-M ‘07

Neutrino Magnetic Moments

Can neutrinos have magnetic moments?

Dirac neutrinos

$$\nu_L \longrightarrow e^{i\alpha_L}\,\nu_L \quad \nu_R \longrightarrow e^{i\alpha_R}\,\nu_R$$

$$m_\nu\,\bar{\nu}\nu = m_\nu\{\bar{\nu}_L\nu_R + \bar{\nu}_R\nu_L\}$$

$\mathcal{L}$ *not invariant if* $m_\nu \neq 0$ *and* $\alpha_L \neq \alpha_R$

Magnetic moment operator forbidden

$$\mu_\nu\,\bar{\nu}\sigma_{\alpha\beta}\nu\,F^{\alpha\beta} = \mu_\nu\{\bar{\nu}_L\sigma_{\alpha\beta}\nu_R + \bar{\nu}_R\sigma_{\alpha\beta}\nu_L\}F^{\alpha\beta}$$

The Scale of m_ν and μ_ν

Minimal extension of the Standard Model with ν_R and non-vanishing m_ν gives

$$\mu_\nu \approx 3 \times 10^{-19} \mu_B \, [m_\nu / 1\,\mathrm{eV}]$$

Too small to be observed

What about new physics at scale $\Lambda > \upsilon$? NDA

$$\mu_\nu \sim eG/\Lambda \quad , \quad m_\nu \sim G\Lambda$$

$$m_\nu \sim \frac{\Lambda^2}{2m_e} \frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B} \left(\frac{\Lambda}{1\,\mathrm{TeV}} \right)^2 \mathrm{eV}$$

Evading the NDA Estimates

NDA

$$m_\nu \sim \frac{\Lambda^2}{2m_e}\frac{\mu_\nu}{\mu_B} \sim \frac{\mu_\nu}{10^{-18}\mu_B}\left(\frac{\Lambda}{1\,\mathrm{TeV}}\right)^2 \mathrm{eV}$$

The "Voloshin" mechanism: a loophole

$SU(2)_\nu$ symmetry:

(ν, ν^c) transf as doublet

m_ν term transforms as triplet	*forbidden*
μ_ν transforms as singlet	*allowed*

Evading the NDA Estimates

NDA

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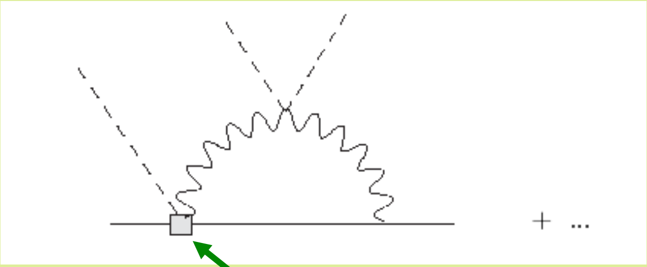

electroweak μ_ν operators

Radiatively-induced neutrino mass

Voloshin sym & generalizations broken by SM gauge & Yukawa interactions: m_ν bounds on μ_ν

Dirac Neutrinos

$$\delta m_\nu = -C_3^6(v)\frac{v^3}{2\sqrt{2}\Lambda^2} \qquad \frac{\mu_\nu}{\mu_B} = -4\sqrt{2}\left(\frac{m_e v}{\Lambda^2}\right)C_+(v) \qquad C_+ = C_1^6 + C_2^6$$

Operator Basis:

$$O_M^{(4)} = \bar{L}\tilde{\phi}\nu_R \qquad \tilde{\phi} = i\tau_2\phi^*$$

$$O_1^{(6)} = g_1(\bar{L}\sigma^{\mu\nu}\tilde{\phi})\ell_R B_{\mu\nu}$$

$$O_2^{(6)} = g_2(\bar{L}\sigma^{\mu\nu}\tau^a\widetilde{\phi})\nu_R W_{\mu\nu}^a$$

$$O_3^{(6)} = (\bar{L}\widetilde{\phi}\nu_R)\ (\phi^+\phi)$$

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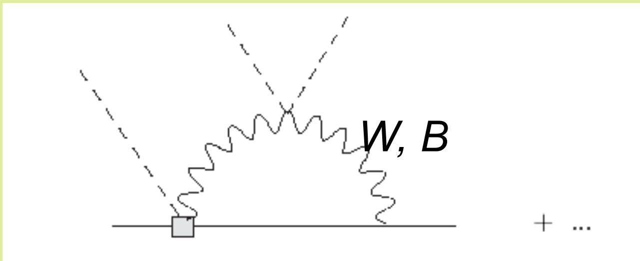
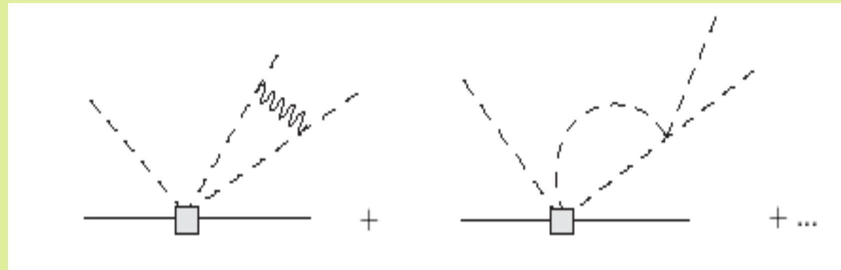
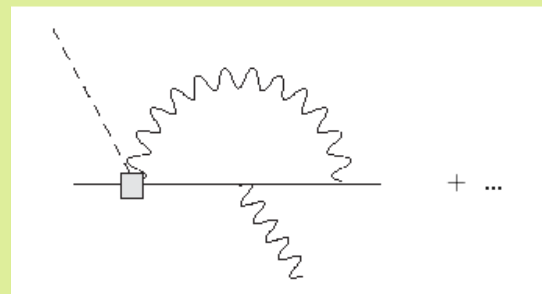
Close under renormalization

Dirac Neutrinos: Mixing







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$$O_3^{(6)} = (\bar{L}\tilde{\phi}\nu_R)\,(\phi^+\phi)$$

Close under renormalization

Dirac Neutrinos: Mixing & "Naturalness"

Renormalization Group: Leading Log

Solution with $C_3^6(\Lambda) = 0$: δm_ν generated entirely from radiative corrections

$$\frac{|\mu_\nu|}{\mu_B} = \frac{G_F m_e}{\sqrt{2}\pi\alpha}\left[\frac{\delta m_\nu}{\alpha \ln(\Lambda/v)}\right]\frac{32\pi \sin^4\theta_W}{9|f|}$$

$$f = (1-r) - \frac{2}{3} r \tan^2\theta_W - \frac{1}{3}(1+r)\tan^4\theta_W \qquad r = C_-/C_+$$

$$\frac{|\mu_\nu|}{\mu_B} \lesssim 8 \times 10^{-15} \times \left(\frac{\delta m_\nu}{1\,\mathrm{eV}}\right)\frac{1}{|f|}$$

Dirac Neutrinos

$$\delta m_\nu = -C_3^6(v)\frac{v^3}{2\sqrt{2}\Lambda^2} \qquad \frac{\mu_\nu}{\mu_B} = -4\sqrt{2}\left(\frac{m_e v}{\Lambda^2}\right)C_+(v) \qquad C_+ = C_1^6 + C_2^6$$

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$$O_3^{(6)} = (\bar{L}\widetilde{\phi}\nu_R)\ (\phi^+\phi)$$

Matching at scale Λ

Close under renormalization

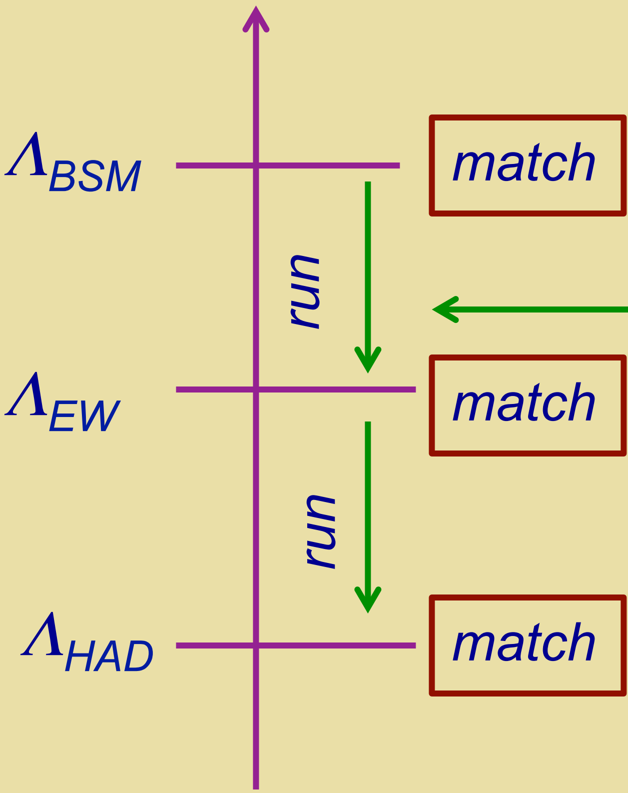
Dirac Neutrinos: Matching & "Naturalness"

Solution with $C_3^6(\Lambda) = 0$: δm_ν generated entirely from radiative corrections via $k_{loop} \sim \Lambda$, thereby inducing nonzero $C_M^4(\Lambda)$

$$\delta m_\nu \sim \frac{\alpha}{32\pi} \frac{\Lambda^2}{m_e} \frac{\mu_\nu}{\mu_B},$$

$$\frac{\mu_\nu}{\mu_B} \lesssim 10^{-14} \left(\frac{1 \text{ TeV}}{\Lambda}\right)^2 \left(\frac{\delta m_\nu}{1 \text{ eV}}\right)$$

Interpretation



Matching: uncertain

$$\frac{|\mu_\nu|}{\mu_B} \lesssim 10^{-14} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \left(\frac{\delta m_\nu}{1\ \mathrm{eV}}\right)$$

Running & mixing: calculable

$$\frac{|\mu_\nu|}{\mu_B} \lesssim 8 \times 10^{-15} \left(\frac{\delta m_\nu}{1\ \mathrm{eV}}\right) \frac{1}{|f|}$$

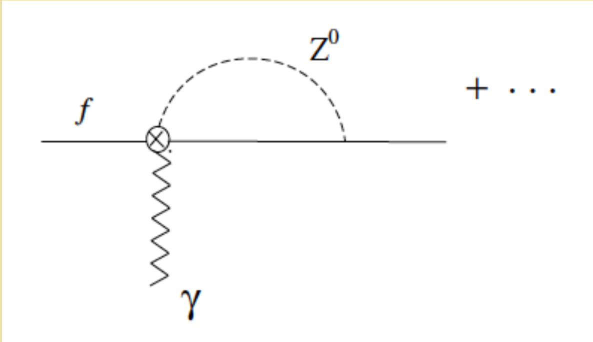
Applying to TVPC Interactions & EDMs

- *Khripolovich approach: compute in EFT II w/ cut-off regulator*
- *Khriplovich approach a la MR-M: compute in EFT II w/ dim reg*
- *Recast in EFT I framework*

Applying to TVPC Interactions & EDMs

$$\mathcal{O}_7^{\gamma g} = C_7^{\gamma g}\bar{\psi}\sigma_{\mu\nu}\lambda^a\psi F^{\mu\lambda}G_\lambda^{a\nu}$$

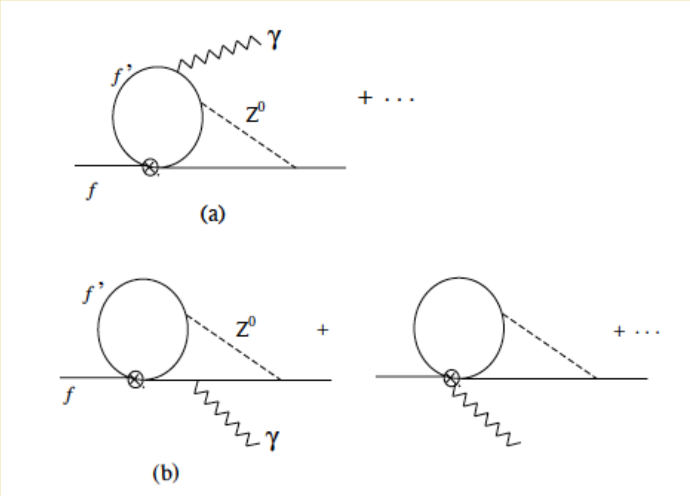
$$\mathcal{O}_7^{\gamma Z} = C_7^{\gamma Z}\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\lambda}Z_\lambda^{\nu}$$



$$C_5^f \sim eC_7^{\gamma Z}\left(\frac{M_Z}{\Lambda_{\rm TVPC}}\right)^2\left(\frac{1}{s_W c_W}\right)g_A^f\left(\frac{1}{96\pi^2}\right)\ln\frac{M_Z^2}{\mu^2}$$

Applying to TVPC Interactions & EDMs

$$\mathcal{O}_7^{ff'} = C_7^{ff'}\,\bar{\psi}_f \overleftrightarrow{D}_\mu \gamma_5 \psi_f \bar{\psi}_{f'} \gamma^\mu \gamma_5 \psi_{f'}$$



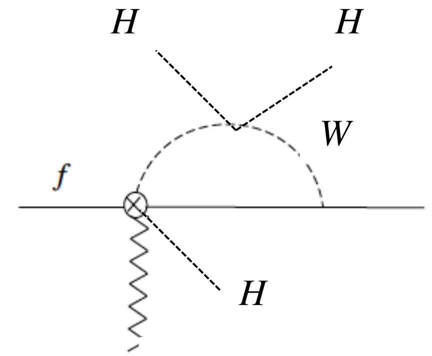
$$C_5^f \sim -eC_7^{ff'}\left(\frac{5}{12}\right)\left(\frac{M_Z}{\Lambda_{\mathrm{TVPC}}}\right)^2 Q_f g_V^f g_A^{f'}\left(\frac{G_F M_Z^2}{\sqrt{2}}\right) \times \left(\frac{1}{8\pi^2}\right)^2\left(\ln\frac{M_Z^2}{\mu^2}\right)^2,$$

The EFT I Computation

$$\mathcal{O}^{(8)}_{\rm fWB} = \bar{F}\sigma^{\mu\nu}\frac{\tau^a}{2}H f_R \widetilde{W}^a_{\mu\alpha}B^\alpha_\nu$$

$$\mathcal{O}^{(8)}_{\rm fW} = \bar{F}\sigma^{\mu\nu}\frac{\tau^a}{2}H f_R \widetilde{W}^a_{\mu\alpha}\, H^\dagger H$$

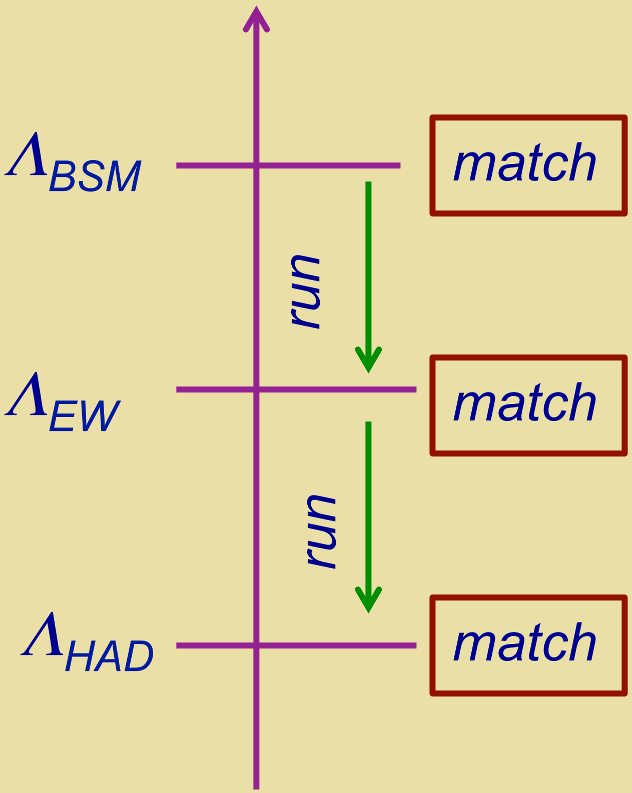
$$\mathcal{O}^{(8)}_{\rm fB} = \bar{F}\sigma^{\mu\nu} H f_R \widetilde{B}^a_{\mu\alpha}\, H^\dagger H$$



$$+ \cdots$$

$$C^{(8)}_{\rm fV} \sim \left(\frac{\alpha}{4\pi}\right) C^{(8)}_{\rm TVPC}$$

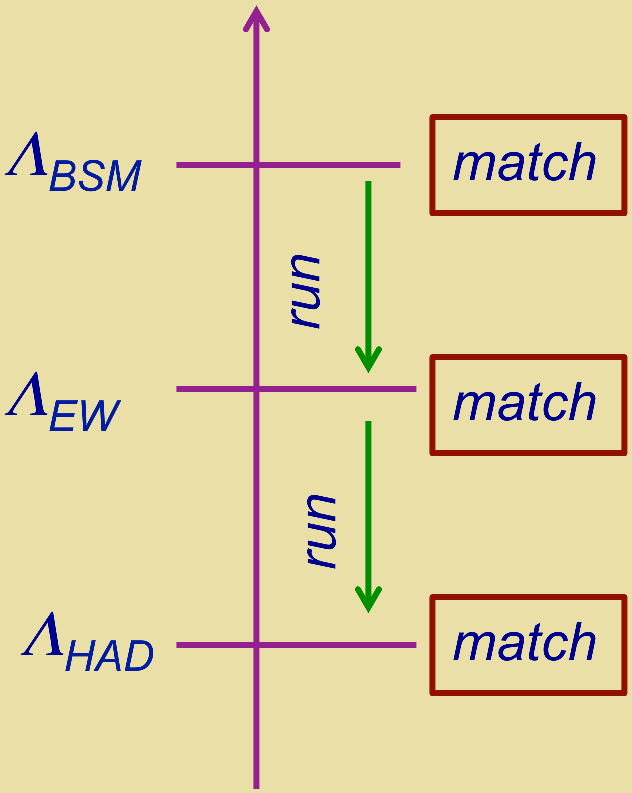
Interpretation



$$d_f \sim \frac{1}{v}\left[C_{\rm fV}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\rm fV}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

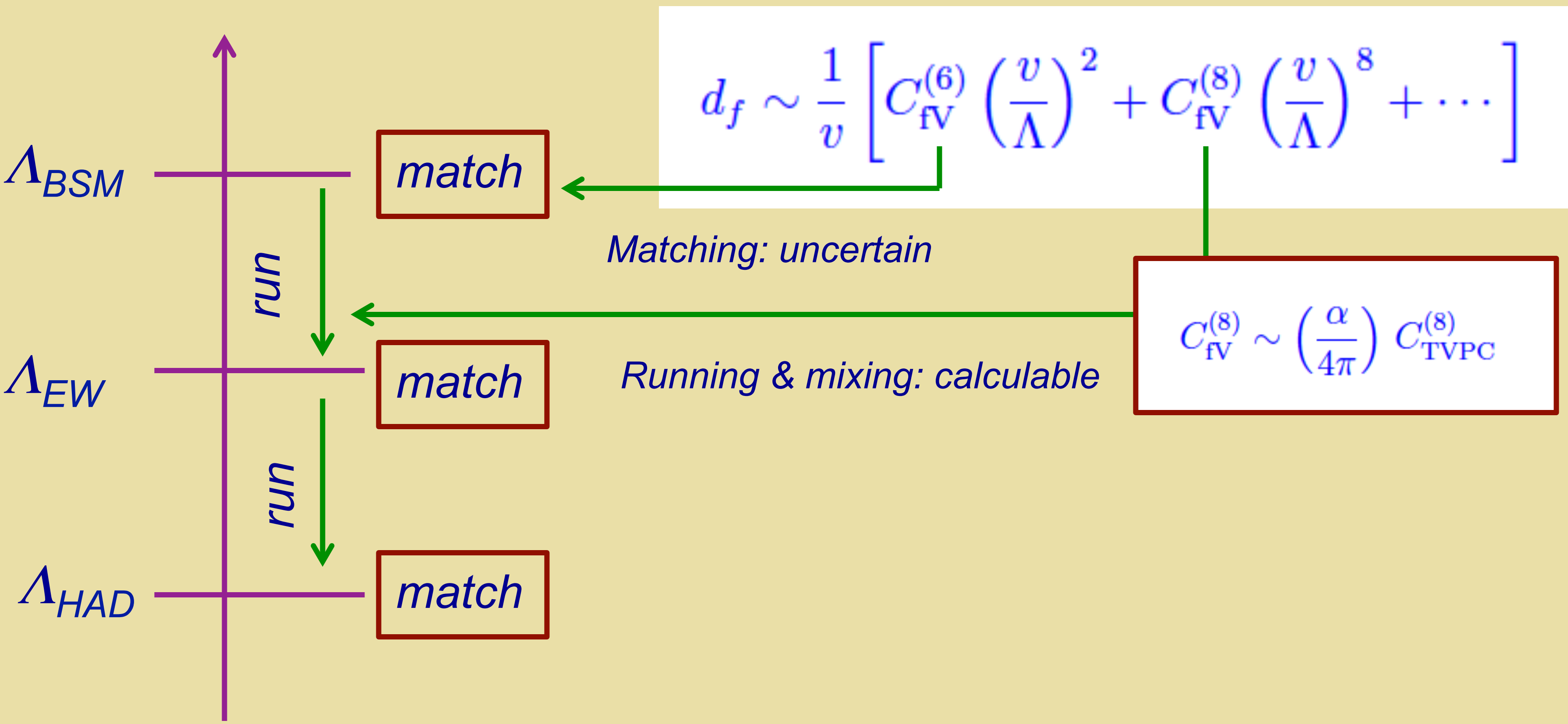
Interpretation

$$d_f \sim \frac{1}{v}\left[C^{(6)}_{\mathrm{fV}}\left(\frac{v}{\Lambda}\right)^2 + C^{(8)}_{\mathrm{fV}}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

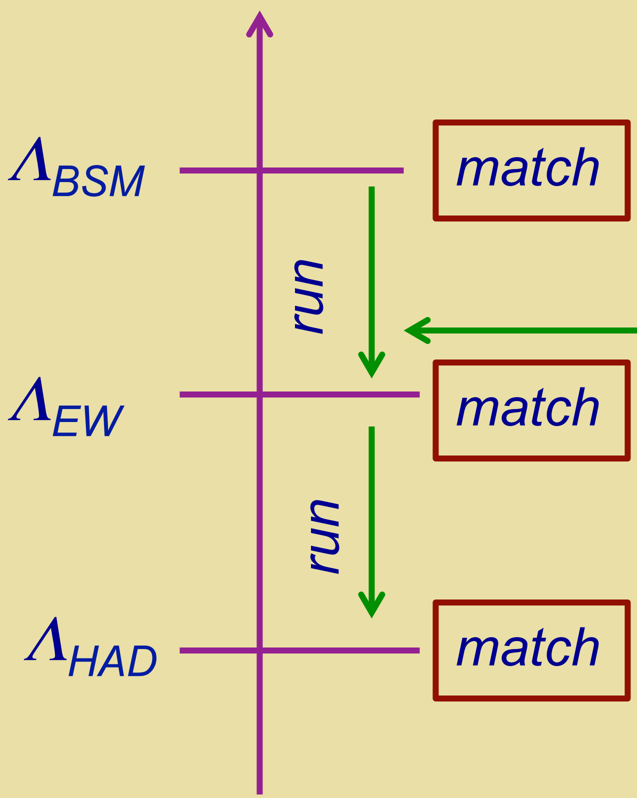


Matching: uncertain

Interpretation



Limits: Short Distance Parity Cons



$$d_f \sim \frac{1}{v}\left[C_{\mathrm{fV}}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\mathrm{fV}}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

Matching: uncertain

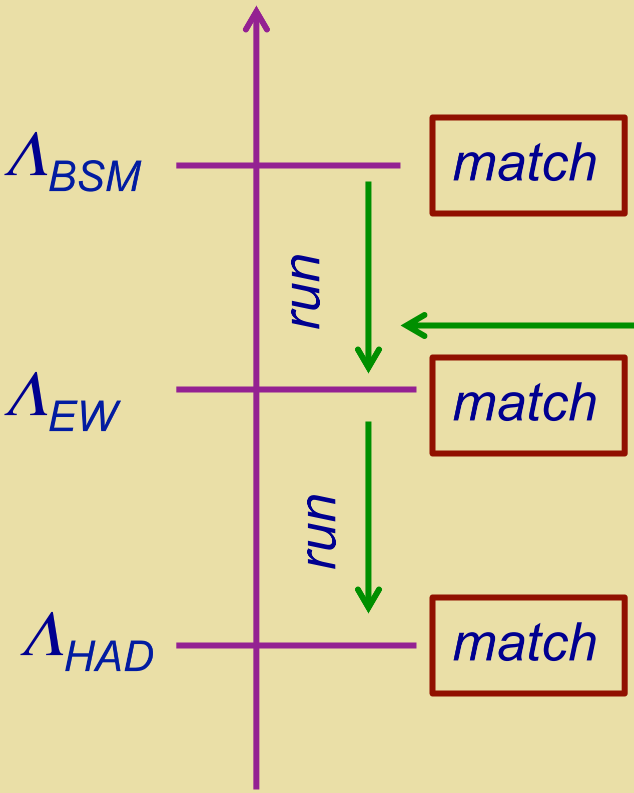
Running & mixing: calculable

$$C_{\mathrm{fV}}^{(8)} \sim \left(\frac{\alpha}{4\pi}\right) C_{\mathrm{TVPC}}^{(8)}$$

A. $\Lambda_{PV} < \Lambda_{TVPC}$: $C_{fV}^{(6)} = 0$

$$C_{\mathrm{TVPC}}^{(8)}\left(\frac{v}{\Lambda_{TVPC}}\right)^4 \lesssim 10^{-7}$$

Limits: Naturaleness



$$d_f \sim \frac{1}{v}\left[C_{\mathrm{fV}}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\mathrm{fV}}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

Matching: uncertain

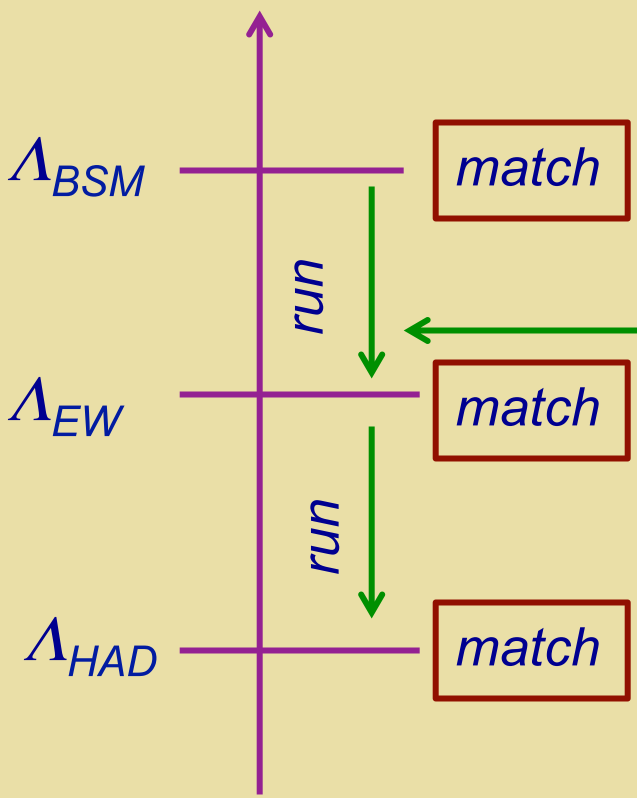
Running & mixing: calculable

$$C_{\mathrm{fV}}^{(8)} \sim \left(\frac{\alpha}{4\pi}\right) C_{\mathrm{TVPC}}^{(8)}$$

B. "Naturalness":

$$C_{\mathrm{TVPC}}^{(8)}\left(\frac{v}{\Lambda_{TVPC}}\right)^4 \lesssim 10^{-7}$$

Limits: Symmetry or Conspiracy



$$d_f \sim \frac{1}{v}\left[C_{\mathrm{fV}}^{(6)}\left(\frac{v}{\Lambda}\right)^2 + C_{\mathrm{fV}}^{(8)}\left(\frac{v}{\Lambda}\right)^8 + \cdots\right]$$

Matching: uncertain

Running & mixing: calculable

$$C_{\mathrm{fV}}^{(8)} \sim \left(\frac{\alpha}{4\pi}\right) C_{\mathrm{TVPC}}^{(8)}$$

C. Symmetry or conspiracy:

d_f suppressed $\rightarrow$
C_{TVPC} unconstrained

Implications

A. $\Lambda_{PV} < \Lambda_{TVPC}$: $C_{fV}^{(6)} = 0$

B. "Naturalness"

$$\alpha_T = \frac{\langle f|\, \mathcal{O}^{(8)}_{TVPC}\, |i\rangle}{\langle f|\, \mathcal{O}_{QCD}\, |i\rangle} \sim C^{(8)}_{\mathrm{TVPC}} \left(\frac{v}{\Lambda_{TVPC}}\right) \left(\frac{p}{\Lambda_{TVPC}}\right)^3 \lesssim 10^{-15}$$

for $\Lambda_{TVPC} \sim v$, $p \sim 1$ *GeV*

C. Symmetry or conspiracy

$$\alpha_T = \frac{\langle f|\, \mathcal{O}^{(8)}_{TVPC}\, |i\rangle}{\langle f|\, \mathcal{O}_{QCD}\, |i\rangle} \sim C^{(8)}_{\mathrm{TVPC}} \left(\frac{v}{\Lambda_{TVPC}}\right) \left(\frac{p}{\Lambda_{TVPC}}\right)^3 \lesssim 10^{-7}$$

for $\Lambda_{TVPC} \sim v$, $p \sim 1$ *GeV* , *and* $C_{TVPC} \sim 1$

Implications: Further Thoughts

C. Symmetry or conspiracy

$$\mathcal{O}^{(8)}_{\rm fWB} = \bar{F}\sigma^{\mu\nu}\frac{\tau^a}{2}H f_R \widetilde{W}^a_{\mu\alpha}B^\alpha_\nu$$

$$\mathcal{O}^{(8)}_{\rm fWW} = \bar{F}\sigma^{\mu\nu}H f_R \widetilde{W}^a_{\mu\alpha}W^{a\,\alpha}_\mu$$

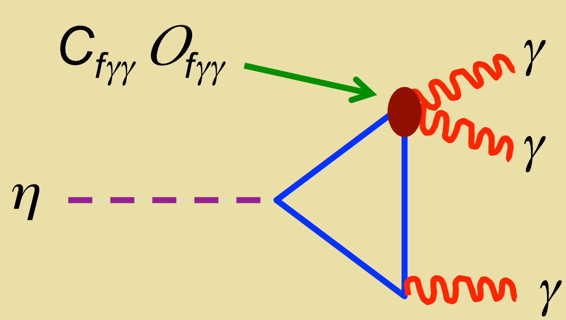
$$\mathcal{O}^{(8)}_{\rm fBB} = \bar{F}\sigma^{\mu\nu}\; H f_R \widetilde{B}_{\mu\alpha}B^\alpha_\nu$$

→

$$\mathcal{O}^{(8)}_{\rm f\gamma\gamma} = \bar{F}\sigma^{\mu\nu}f_R \widetilde{F}_{\mu\alpha}F^\alpha_\nu$$ $\eta \rightarrow 3\,\gamma$

$$\mathcal{O}^{(8)}_{\rm f\gamma Z} = \bar{F}\sigma^{\mu\nu}f_R \widetilde{F}_{\mu\alpha}Z^\alpha_\nu$$ EDM

C_{fWB} , C_{fWW} , C_{fBB} ⟶ $C_{f\gamma Z} = 0$, $C_{f\gamma\gamma} \neq 0$



⟶

$$\frac{v}{\Lambda}\frac{1}{\Lambda^3}\,\eta\,F^3$$

Summary & Outlook

- *C-Violating $\leftrightarrow$ TVPC interactions are a largely unexplored direction for fundamental symmetry tests*

- *Analyzing their effects for light quark systems requires an EFT approach, as the do not arise at tree-level via renormalizable gauge interactions*

- *In general, EDMs place stringent constraints on such interactions via EW radiative corrections from the standpoint of short distance parity restoration and/or naturalness*

- *Exceptions may exist in the presence of a conspiracy or new symmetry at the TVPC matching scale*

- *Magnitude of low-energy amplitude ~ $(p/\Lambda)^3 < 10^{-7}$ for $\Lambda > v$*

- *C-Violating $\leftrightarrow$ TVPC interactions are an interesting direction worthy of further exploration*

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