Anomaly Cancellation in SMEFT and Neutral Gauge Boson Vertices

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This presentation is based on the paper:
"Anomaly Cancellation in SMEFT and Neutral Gauge Boson Vertices"
A. Dedes et al., arXiv:2404.02047 [hep-ph]

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Contents

Introduction

Chiral anomalies reveal a deep connection between quantum mechanics and symmetries in particle physics:

- An anomaly in quantum field theory refers to a situation where a classical symmetry that holds at the level of the equations of motion does not survive quantization.
- The SMEFT Lagranian is expressed as:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \frac{C_d}{\Lambda^{d-4}} O_d.$$

Set of operators that contribute to chiral anomalies on SMEFT :

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

Ward Identity from gauge-fixing-parameter independence

- Feynman Diagrams for the Process
  $e^+(p_1) + e^-(p_2) \to V_i^*(q) \to V_j^\nu(k_1) + V_k^\rho(k_2)$

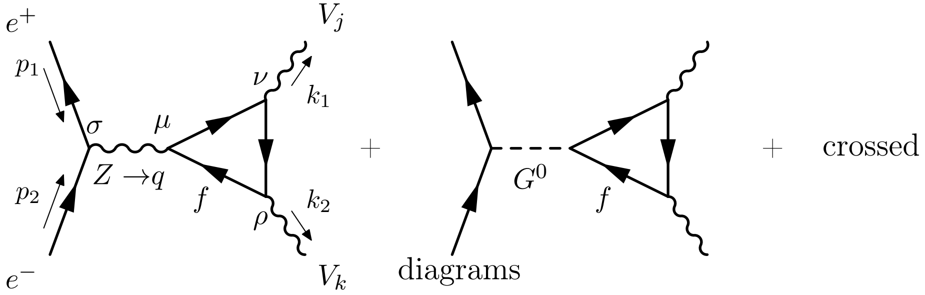


Figure 1: *Feynman diagrams for s-channel contributions to $e^+e^- \to V_jV_k$ amplitude.*

Ward Identity from gauge-fixing-parameter independence

- ξ-dependent part of the process:

$$+\frac{2\,b_Z^{(e)}\,m_e}{q^2-\xi_Z M_Z^2}\cdot\frac{1}{M_Z^2}\,\bar{v}(p_1)\gamma^5 u(p_2)\sum_f\Big[q_\mu\Delta^{\mu\nu\rho(f)}_{ZV_jV_k}(k_1,k_2)+iM_Z\Delta^{\nu\rho(f)}_{G^0V_jV_k}(k_1,k_2)\Big]\epsilon^*_\nu(k_1)\,\epsilon^*_\rho(k_2).$$

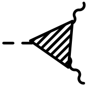
- Generalized Ward Identities (WI) for each incoming gauge boson V_i:

$$q_\mu\,\Delta^{\mu\nu\rho}_{V_iV_jV_k}(k_1,k_2)+\beta(V_i)\,M_{V_i}\,\Delta^{\nu\rho}_{G_iV_jV_k}(k_1,k_2)=0\,,$$
$$\{\beta(Z)=i\,,\;\beta(W^+)=-1\,,\;\beta(W^-)=+1\}\,.$$

- The WI may be anomalous due to γ^5 ambiguity and divergent triangles.

Cancellations of the triangle anomalies in the SM EFT

Diagrammatic Structure of the Ward Identity in SMEFT:

$q_\mu \cdot \Big(V_i^\mu$  $\Big) + M_{V_i} \cdot \Big(G_i$  $\Big) = 0$

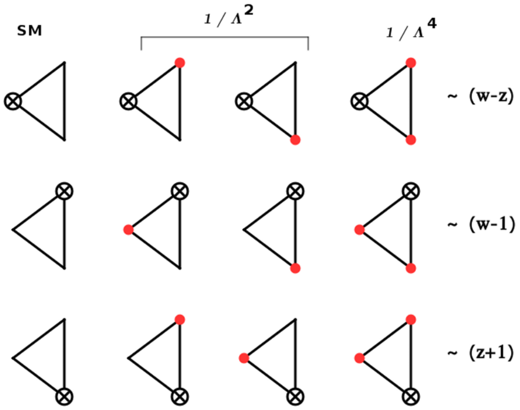
- With an appropriate choice of momentum routing, we arrive at the algebraic form of the Ward Identity:

$$q_\mu \Delta^{\mu\nu\rho}_{V_i V_j V_k}(k_1, k_2; a) + iM_{V_i}\, \Delta^{\nu\rho}_{G_i V_j V_k}(k_1, k_2; a) = \sum_f \Big[\Pi^{\nu\rho(f)}_{V_i V_j V_k}(k_1, k_2; a) - \widetilde{\Pi}^{\nu\rho(f)}_{V_i V_j V_k}(k_1, k_2; a) \Big]$$

See also:
A. Dedes and K. Suxho,
Phys. Rev. D 85 (2012) 095024, arXiv:1202.4940 [hep-ph]

- The **chiral anomaly terms** cancel algebraically by choosing appropriate momentum routing parameters (w, z).

Cancellations of the triangle anomalies in the SM EFT



- Momentum routing plan for the pair (w, z) in the loop vector $a^\mu = zk_1^\mu + wk_2^\mu$, ensuring anomaly cancellation in SMEFT. Red blob denotes a pure dimension-6 EFT insertion; $\otimes$ marks momentum contraction.

Neutral triple gauge boson triangle vertices

- Form Factors of Neutral Triple Gauge Vertices in the Low- and High-energy Limits for the Vertex $V_i^* V_j V_k$:

Form factor	High-energy limit $s >> m_t^2$
$h_\gamma^3(s)$	$\frac{e g_Z}{8\pi^2}\left(\frac{M_Z^2}{s}\right)\left(\frac{v^2}{\Lambda^2}\right)\left[C_{\varphi\ell}^{(1)} + C_{\varphi\ell}^{(3)} - C_{\varphi e} + \frac{1}{3}(5C_{\varphi q}^{(1)} - 3C_{\varphi q}^{(3)} - 4C_{\varphi u} - C_{\varphi d})\right]$
$h_Z^3(s)$	$\frac{M_Z^2}{2\pi^2 s}\sum_f a_Z^{(f)} a_\gamma^{(f)} b_Z^{(f)}$
$f_Z^5(s)$	$\frac{M_Z^2}{6\pi^2 s}\sum_f \left[\left(b_Z^{(f)}\right)^3 + 3\left(a_Z^{(f)}\right)^2 b_Z^{(f)}\right]$

Form factor	Low energy limit $s << m_t^2$
$h_3^\gamma(s)$	$\frac{e g_Z}{8\pi^2}\frac{M_Z^2}{s}\left[\frac{4}{3} + \frac{v^2}{\Lambda^2}\left(C_{\varphi\ell}^{(1)} + C_{\varphi\ell}^{(3)} - C_{\varphi e} + \frac{1}{3}(C_{\varphi q}^{(1)} + C_{\varphi q}^{(3)} - C_{\varphi d})\right)\right]$
$h_3^Z(s)$	$\frac{M_Z^2}{2\pi^2 s}\sum_{f\neq t} a_Z^{(f)} a_\gamma^{(f)} b_Z^{(f)} - \frac{1}{8\pi^2}\frac{M_Z^2}{m_t^2} a_Z^{(t)} a_\gamma^{(t)} b_Z^{(t)}$
$f_5^Z(s)$	$-\frac{1}{8\pi^2}\frac{M_Z^2}{m_t^2} a_Z^{(t)} a_Z^{(t)} b_Z^{(t)} + \mathcal{O}\left(\frac{M_Z^4}{s^2}, \frac{M_Z^2 s}{m_t^4}\right)$

UV Completion via a Heavy Vector-like Electron

- We consider a heavy vector-like electron $E(1,1,-1)$, singlet under $SU(3)_c \times SU(2)_L$, with hypercharge $Y = -1$ (as e_R).

$$\mathcal{L}_{\text{BSM}} = \bar{E}_L i\not{D} E_L + \bar{E}_R i\not{D} E_R - M(\bar{E}_L E_R + \bar{E}_R E_L) \\ - y_E \, \bar{\ell}_L \cdot \varphi \, E_R - y_E^* \, \bar{E}_R \, \varphi^\dagger \cdot \ell_L$$

- It has a Dirac mass $M \gg v$ and couples to SM fields via:

$$\mathcal{L}_{\text{int}} = -y_E \bar{\ell}_L \cdot \phi \, E_R - y_E^* \bar{E}_R \phi^\dagger \cdot \ell_L$$

.

- Integrating out E generates dimension-6 SMEFT operators:

$$C_{\varphi\ell}^{(1)} = C_{\varphi\ell}^{(3)} = \frac{|y_E|^2}{4M^2}, \quad C^{\phi e} = 0.$$

UV Completion via a Heavy Vector-like Electron

- Gauge anomalies cancel trivially in the UV model due to its vector-like fermion structure.

- Contribution to $h_3^\gamma(s)$ from the UV model with vector-like electron E, for $Z\gamma\gamma(\Lambda^2 >> s >> 4m_t^2)$:

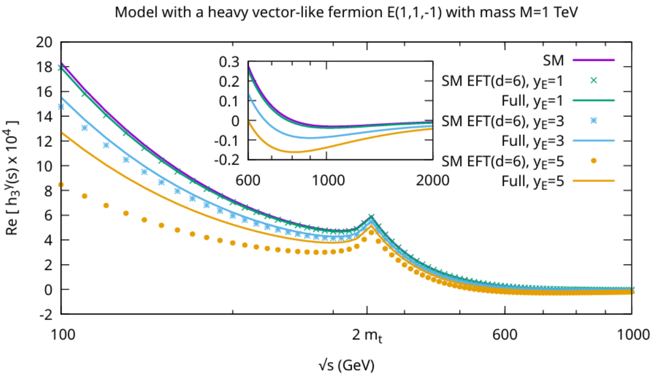
$$\Re[h_3^\gamma(s)] \simeq -\frac{g_Z e}{8\pi^2}\left(\frac{|y_E|^2 v^2}{M^2}\right)\left[\frac{M_Z^2}{2s} + \frac{1}{24}\frac{M_Z^2}{M^2}\right].$$

R. Cepedello, F. Esser, M. Hirsch and V. Sanz, JHEP 07 (2024) 275,

arXiv:2402.04306 [hep-ph]

- The SMEFT contribution reproduces the UV result up to $\mathcal{O}(1/\Lambda^2)$, confirming consistent decoupling behavior for E.

Phenomenology



Model	$\sqrt{s} = 200$ **GeV**	$\sqrt{s} = 900$ **GeV**
SM	7.2×10^{-4}	$-2.4 \times 10^{-6} - 3.0 \times 10^{-5} i$
SMEFT ($y_E = 1$)	7.1×10^{-4}	$-3.3 \times 10^{-6} - 3.0 \times 10^{-5} i$
SMEFT ($y_E = 3$)	6.2×10^{-4}	$-8.9 \times 10^{-6} - 3.0 \times 10^{-5} i$

Conclusions

- SMEFT is anomaly-free at one-loop, even with multiple dimension-6 insertions, using consistent momentum routing.
- Ward identities are preserved in triangle diagrams, validating SMEFT consistency.
- Neutral triple gauge vertices (e.g., $Z^*\gamma\gamma$) exhibit enhanced sensitivity to SMEFT at high energies.
- Dimension-6 operators yield leading deviations; SMEFT offers a robust framework for probing new physics at colliders.

Thank you for your attention!