Study of neutral triple gauge couplings sensitivity to new physics manifestations using augmented vertex function approach with $Z(\nu\bar{\nu})\gamma$ production

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Motivation

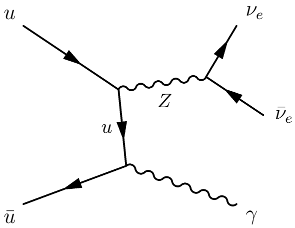
The Standard Model (SM) is a theory of elementary particles and their interactions.

- The SM does not describe some phenomena, so it needs clarification and extension.
- The search for aTGC, which is model-independent approach, since it allows search for new physics without requirements of a specific model.

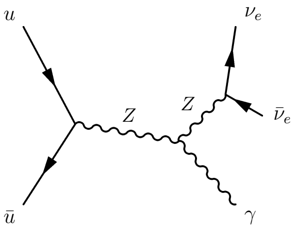
This work examines the process of $Z(\nu\bar{\nu})\gamma$, since it has a high sensitivity to neutral triple gauge couplings (nTGCs) $ZZ\gamma$ and $Z\gamma\gamma$, that are zero in the SM at tree level.

Feynman diagrams of production $Z(\nu\bar{\nu})\gamma$

a) within the SM



b) beyond the SM, including an nTGC vertex



Theoretical introduction

The vertex function [1, 2, 3]

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1, q_2, P) = \frac{i(P^2 - m_V^2)}{m_Z^2}\Big\{ h_1^V (q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{m_Z^2} P^\alpha [(Pq_2) g^{\mu\beta} - q_2^\mu P^\beta] -$$
$$- (h_3^V + h_5^V \frac{P^2}{m_Z^2}) \epsilon^{\mu\alpha\beta\rho} q_{2\rho} - \frac{h_4^V}{m_Z^2} P^\alpha \epsilon^{\mu\beta\rho\sigma} P_\rho q_{1\sigma} + \frac{h_6^V}{m_Z^2} P^2 [q_2^\alpha g^{\mu\beta} - q_2^\mu g^{\alpha\beta}] \Big\}. \quad (1)$$

The anomalous addition to the effective Lagrangian [1, 2, 3]

$$\mathcal{L} = \frac{e}{m_Z^2}\Big\{ -[h_1^\gamma \partial^\sigma A_{\sigma\mu} + h_1^Z \partial^\sigma Z_{\sigma\mu}] Z_\beta A^{\mu\beta} - \Big[\frac{h_2^\gamma}{m_Z^2}\partial_\alpha\partial_\beta\partial^\rho A_{\rho\mu} + \frac{h_2^Z}{m_Z^2}\partial_\alpha\partial_\beta(\partial^2 + m_Z^2) Z_\mu\Big] Z^\alpha A^{\mu\beta} -$$
$$- [h_3^\gamma \partial_\sigma A^{\sigma\rho} + h_3^Z \partial_\sigma Z^{\sigma\rho}] Z^\alpha \widetilde{A}_{\rho\alpha} + \Big[\frac{h_4^\gamma}{2m_Z^2}\partial^2\partial^\sigma A^{\rho\alpha} + \frac{h_4^Z}{2m_Z^2}(\partial^2 + m_Z^2)\partial^\sigma A^{\rho\alpha}\Big] Z_\sigma \widetilde{A}_{\rho\alpha} -$$
$$- \Big[\frac{h_5^\gamma}{m_Z^2}\partial^2\partial_\sigma A^{\rho\sigma} + \frac{h_5^Z}{m_Z^2}\partial^2\partial_\sigma Z^{\rho\sigma}\Big] Z^\alpha \widetilde{A}_{\rho\alpha} - \Big[\frac{h_6^\gamma}{m_Z^2}\partial^2\partial_\sigma A^{\rho\sigma} + \frac{h_6^Z}{m_Z^2}\partial^2\partial_\sigma Z^{\rho\sigma}\Big] Z^\alpha A_{\rho\alpha} \Big\}. \quad (2)$$

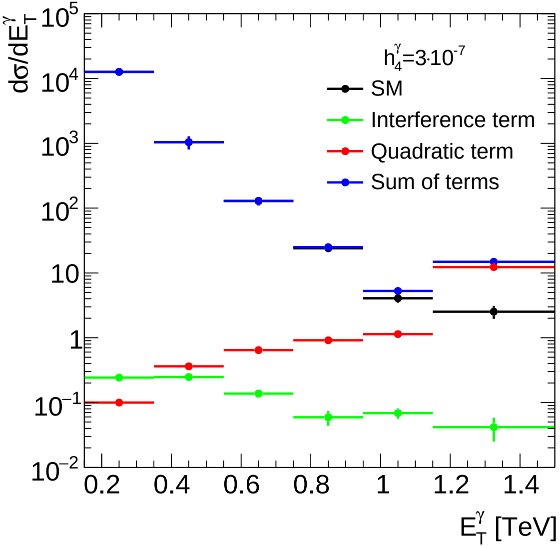
The magnitude of the coupling coefficients h_i^V is unknown, but limits can be set on them. They are equal to zero in the SM.

Methodology

The decomposition method was used during generation. The main idea of the method is that datasets are generated separately for each term from formula

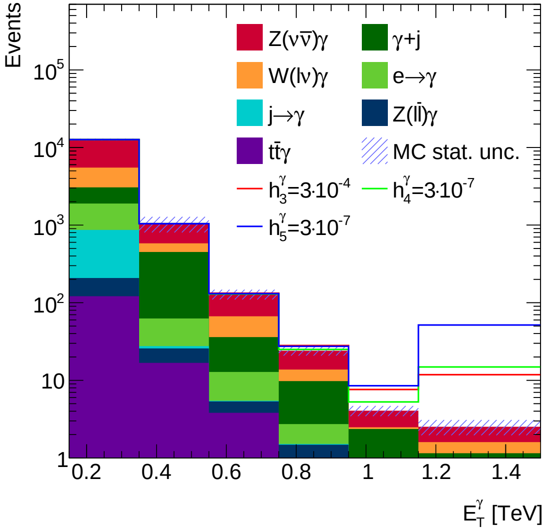
$$|\mathcal{A}|^2 = |\mathcal{A}_{\mathrm{SM}}|^2 + h_i 2\mathrm{Re}\mathcal{A}_{\mathrm{SM}}{}^{\dagger}\mathcal{A}_i + h_i^2|\mathcal{A}_i|^2,$$
$$\text{where } \mathcal{A} = \mathcal{A}_{\mathrm{SM}} + h_i\mathcal{A}_i. \quad (3)$$

MadGraph5 [4] is used to model the full amplitude and all its terms.



Process and selections

- Monte Carlo simulation: MadGraph5 + Pythia8 (hadronization and parton shower) + Delphes3 (detector simulation).
- The systematic uncertainty is assumed to be 10%.
- The model includes background processes in which the final states of the photon and the E_T^{miss} characteristic of the $Z(\nu\bar{\nu})\gamma$ [3, 5].
- The main selections [3]:
  $p_T^j > 50$ GeV, $N_\gamma = 1$, $N_{e,\mu} = 0$,
  $|\Delta\phi(\vec{p}_T^{miss}, \gamma)| > \frac{\pi}{2}$, $E_T^{miss} > 150$ GeV,
  $E_T^\gamma > 150$ GeV,
  $E_T^{miss}/\sqrt{E_T^\gamma + \sum p_T^j} > 10.5$ GeV$^{1/2}$.
  Inclusive case: $N_{jet} \geqslant 0$
  Exclusive case: $N_{jet} = 0$



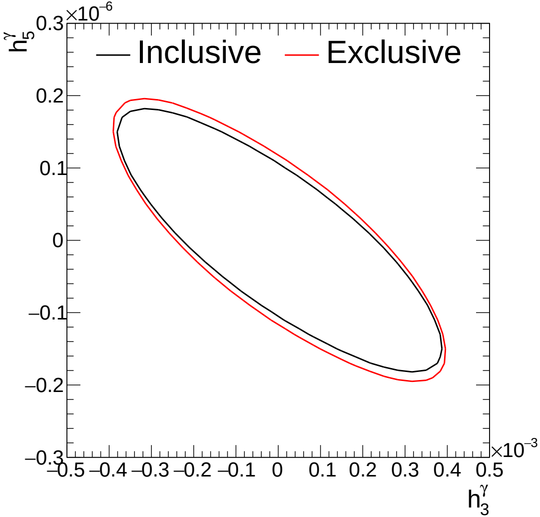
The expected one-dimensional limits

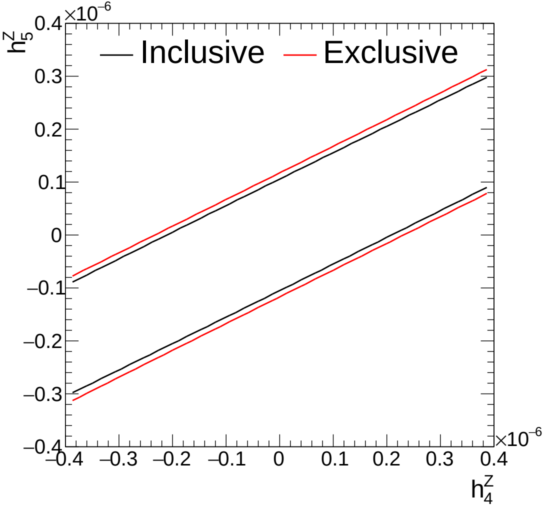
	Expected limits in exclusive case		Expected limits in inclusive case	
Parameter	$L = 140\ \text{pb}^{-1}$	$L = 300\ \text{pb}^{-1}$	$L = 140\ \text{fb}^{-1}$	$L = 300\ \text{fb}^{-1}$
h_3^γ	$[-2.1, 2.1] \times 10^{-4}$	$[-1.6, 1.7] \times 10^{-4}$	$[-2.0, 2.0] \times 10^{-4}$	$[-1.6, 1.6] \times 10^{-4}$
h_3^Z	$[-1.9, 2.0] \times 10^{-4}$	$[-1.5, 1.5] \times 10^{-4}$	$[-1.9, 1.9] \times 10^{-4}$	$[-1.5, 1.5] \times 10^{-4}$
h_4^γ	$[-2.0, 2.0] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$	$[-1.8, 1.8] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$
h_4^Z	$[-2.0, 2.0] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$	$[-1.8, 1.8] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$
h_5^γ	$[-0.9, 1.0] \times 10^{-7}$	$[-7.5, 7.7] \times 10^{-8}$	$[-9.1, 9.2] \times 10^{-8}$	$[-7.3, 7.4] \times 10^{-8}$
h_5^Z	$[-0.9, 1.0] \times 10^{-7}$	$[-7.6, 7.6] \times 10^{-8}$	$[-9.1, 9.2] \times 10^{-8}$	$[-7.3, 7.3] \times 10^{-8}$

- It was found that the coefficients h_3^V, h_4^V, h_5^V behave similarly to the coefficients h_1^V, h_2^V, h_6^V, so the latter ones are shown in the back-up.
- The coefficients h_5^V and h_6^V have never been studied in the LHC experiments before.
- The limits in the inclusive case are more precise than with the jet veto.

Two-dimensional limits

$$|\mathcal{A}|^2 = |\mathcal{A}_{SM}|^2 + h_i^2|\mathcal{A}_i|^2 + h_j^2|\mathcal{A}_j|^2 + h_i 2\mathrm{Re}\mathcal{A}_{SM}{}^{\dagger}\mathcal{A}_i + h_j 2\mathrm{Re}\mathcal{A}_{SM}^{\dagger}\mathcal{A}_j + h_i h_j 2\mathrm{Re}\mathcal{A}_i^{\dagger}\mathcal{A}_j. \quad (4)$$





The unitarity

The partial-wave expansion of the nTGC contributions to the scattering amplitude [2]:

$$a_J = \frac{1}{32\pi} e^{i(\nu' - \nu)\phi} \int_{-1}^{1} d(\cos\theta) d^J_{\nu'\nu}(\cos\theta) \mathcal{T}^{s_f s_{\bar{f}}, \lambda_Z \lambda_\gamma}. \quad (5)$$

The limitations follow from the optical theorem: $|a_J| < \frac{1}{2}$.

The unitarity bounds for two coefficients [3]:

$$|h_3^Z| < \frac{6\sqrt{2}\pi v^2 m_Z}{s_W c_W (T_3 - Q s_W^2) \hat{s}^{3/2}}, \qquad |h_3^\gamma| < \frac{6\sqrt{2}\pi v^2 m_Z}{s_W^2 c_W^2 |Q| \hat{s}^{3/2}}. \quad (6)$$

Unitarity is violated at **17 TeV** for h_3^Z and at **19 TeV** for h_3^γ. The values obtained exceed the energy in the center of mass system $\sqrt{s}$=13 TeV, which is used for the analysis.

The unitarity

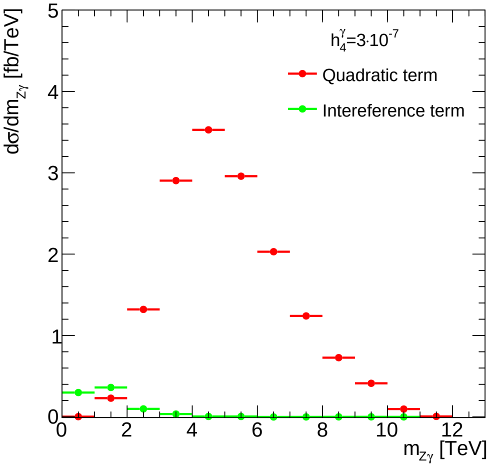
Unitarity boundaries for other coefficients of interest were not considered in the article above, so they were obtained in this work:

$$|h_4^Z| < \frac{12\sqrt{2}\pi v^2 m_Z^3}{s_W c_W (T_3 - Q s_W^2)\hat{s}^{5/2}}, \qquad (7)$$

$$|h_4^\gamma| < \frac{12\sqrt{2}\pi v^2 m_Z^3}{s_W^2 c_W^2 |Q| \hat{s}^{5/2}}, \qquad (8)$$

$$|h_5^Z| < \frac{6\sqrt{2}\pi v^2 m_Z^3}{s_W c_W (T_3 - Q s_W^2)\hat{s}^{5/2}}, \qquad (9)$$

$$|h_5^\gamma| < \frac{6\sqrt{2}\pi v^2 m_Z^3}{s_W^2 c_W^2 |Q| \hat{s}^{5/2}}. \qquad (10)$$



Unitarity is violated at **10 TeV** for h_4^Z, h_5^Z and for **11 TeV** for h_4^γ, h_5^γ.

Conclusion

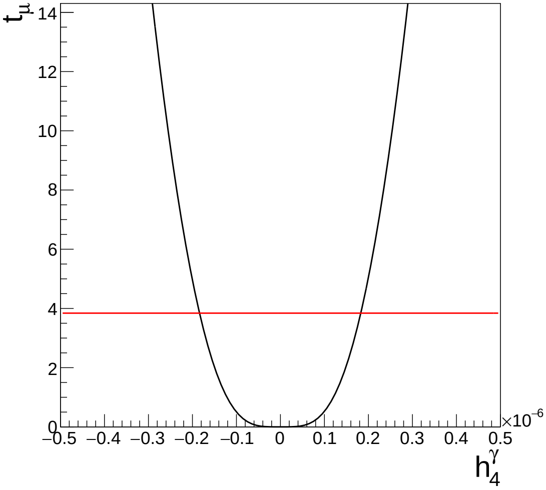
- In this work nTGCs in the production of $Z(\nu\bar{\nu})\gamma$ in collider experiment (e.g. ATLAS) were studied. They are described by 12 parameters, 4 of them are new.
- The work uses a decomposition method, that has not been used before in a similar ATLAS analysis.
- Limits were set in inclusive and exclusive cases, and as a result, the best limits were obtained for the inclusive case.
- It was shown that the coefficients h_3^V, h_4^V, h_5^V behave similarly to the coefficients h_1^V, h_2^V, h_6^V.
- Two-dimensional limits were set. It has been shown that the coefficients h_4^V and h_5^V are completely correlated.
- The problem of violation of unitarity is analyzed. The limits turned out to be unitarized, and further methods of unitarization are not required.

Thank you!

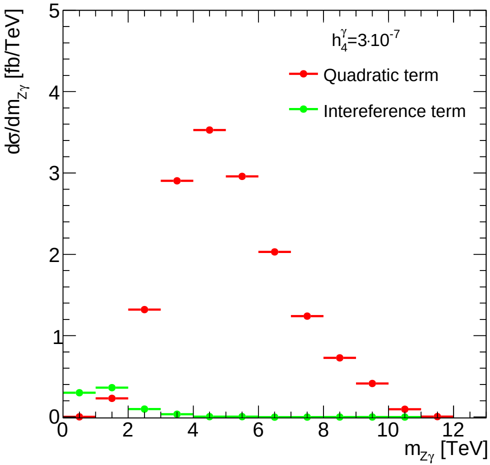
Back-Up

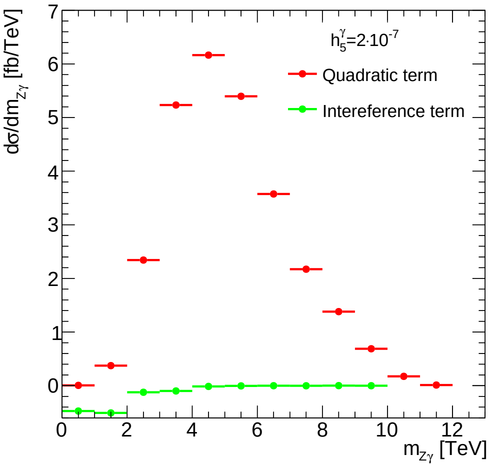
Statistical method

$$t_{\mu} = -2\ln\frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\theta})} \qquad (11)$$



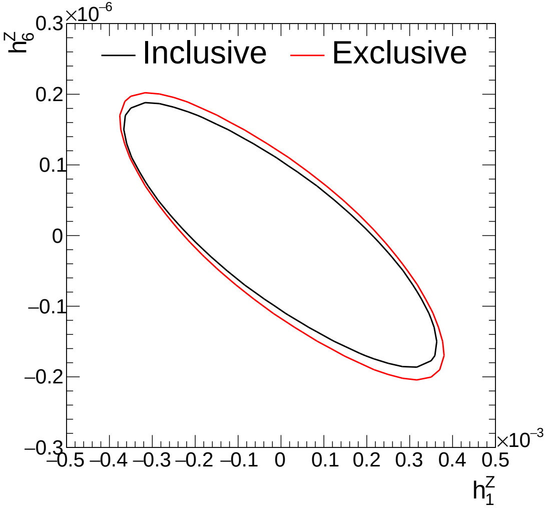
Distributions by $m_{Z\gamma}$

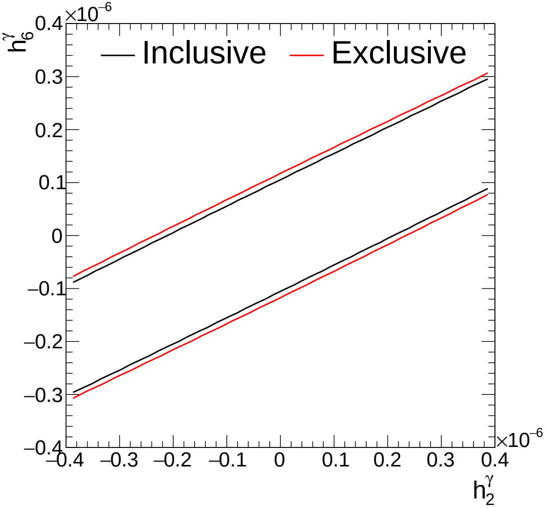




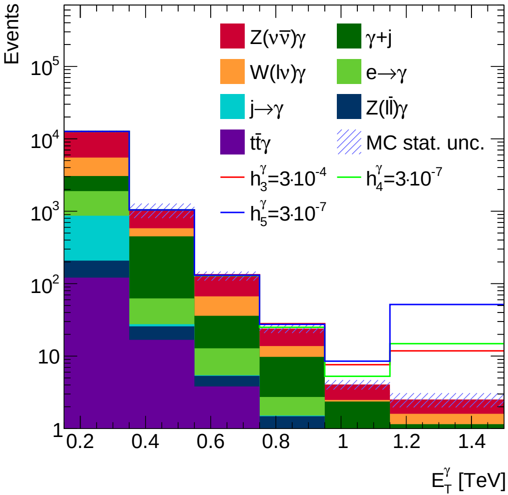
	Previous limits [4]	Expected limits in exclusive case		Expected limits in inclusive case	
Coef.	$L = 36.1$ fb^{-1}	$L = 140$ pb^{-1}	$L = 300$ pb^{-1}	$L = 140$ pb^{-1}	$L = 300$ pb^{-1}
h_1^γ	—	$[-2.1, 2.1] \times 10^{-4}$	$[-1.7, 1.6] \times 10^{-4}$	$[-2.0, 2.0] \times 10^{-4}$	$[-1.6, 1.6] \times 10^{-4}$
h_1^Z	—	$[-1.9, 2.0] \times 10^{-4}$	$[-1.5, 1.5] \times 10^{-4}$	$[-1.9, 1.9] \times 10^{-4}$	$[-1.5, 1.5] \times 10^{-4}$
h_2^γ	—	$[-2.0, 2.0] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$	$[-1.8, 1.8] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$
h_2^Z	—	$[-2.0, 2.0] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$	$[-1.8, 1.8] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$
h_3^γ	$[-3.7, 3.7] \times 10^{-4}$	$[-2.1, 2.1] \times 10^{-4}$	$[-1.6, 1.7] \times 10^{-4}$	$[-2.0, 2.0] \times 10^{-4}$	$[-1.6, 1.6] \times 10^{-4}$
h_3^Z	$[-3.2, 3.3] \times 10^{-4}$	$[-1.9, 2.0] \times 10^{-4}$	$[-1.5, 1.5] \times 10^{-4}$	$[-1.9, 1.9] \times 10^{-4}$	$[-1.5, 1.5] \times 10^{-4}$
h_4^γ	$[-4.4, 4.3] \times 10^{-7}$	$[-2.0, 2.0] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$	$[-1.8, 1.8] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$
h_4^Z	$[-4.5, 4.4] \times 10^{-7}$	$[-2.0, 2.0] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$	$[-1.8, 1.8] \times 10^{-7}$	$[-1.5, 1.5] \times 10^{-7}$
h_5^γ	—	$[-0.9, 1.0] \times 10^{-7}$	$[-7.5, 7.7] \times 10^{-8}$	$[-9.1, 9.2] \times 10^{-8}$	$[-7.3, 7.4] \times 10^{-8}$
h_5^Z	—	$[-0.9, 1.0] \times 10^{-7}$	$[-7.6, 7.6] \times 10^{-8}$	$[-9.1, 9.2] \times 10^{-8}$	$[-7.3, 7.3] \times 10^{-8}$
h_6^γ	—	$[-9.9, 9.9] \times 10^{-8}$	$[-7.6, 7.6] \times 10^{-8}$	$[-9.2, 9.2] \times 10^{-8}$	$[-7.3, 7.3] \times 10^{-8}$
h_6^Z	—	$[-0.9, 1.0] \times 10^{-7}$	$[-7.6, 7.6] \times 10^{-8}$	$[-9.2, 9.2] \times 10^{-8}$	$[-7.3, 7.3] \times 10^{-8}$

Two-dimensional limits

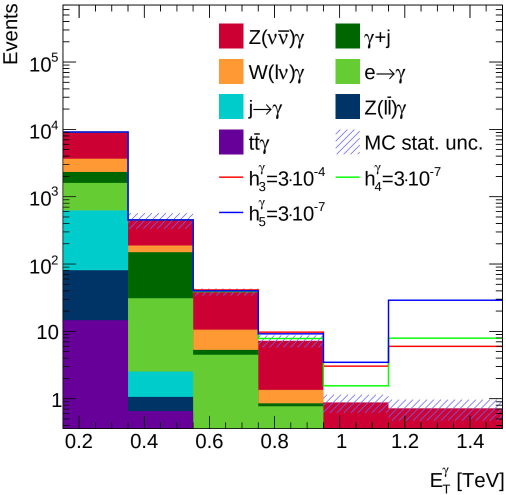




Inclusive case



Exclusive case



Scattering amplitudes

$$h_4^\gamma: \quad \mathcal{T}^{s_f s_{\bar{f}}}(0\pm) = -\frac{\sqrt{2}Qe^2}{8m_Z^5}\sqrt{\hat{s}}(\hat{s}-m_Z^2)^2(\delta_{s_f,\frac{1}{2}} - \delta_{s_f,-\frac{1}{2}} \mp \cos\theta), \qquad (12)$$

$$h_5^\gamma: \quad \mathcal{T}^{s_f s_{\bar{f}}}(0\pm) = \frac{\sqrt{2}Qe^2}{4m_Z^5}\hat{s}^{3/2}(\hat{s}-m_Z^2)(\delta_{s_f,\frac{1}{2}} - \delta_{s_f,-\frac{1}{2}} \mp \cos\theta), \qquad (13)$$

$$h_5^\gamma: \quad \mathcal{T}^{s_f s_{\bar{f}}}\begin{pmatrix} -- & -+ \\ +- & ++ \end{pmatrix} = \frac{Qe^2}{2m_Z^4}\hat{s}(\hat{s}-m_Z^2)\sin\theta\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, \qquad (14)$$

$$h_4^Z: \quad \mathcal{T}^{s_f s_{\bar{f}}}(0\pm) = \frac{\sqrt{2}(T_3 - Qs_W^2)e^2}{8c_W s_W m_Z^2}\hat{s}^{1/2}(\hat{s}-m^2)^2(\delta_{s_f,\frac{1}{2}} - \delta_{s_f,-\frac{1}{2}} \mp \cos\theta), \qquad (15)$$

$$h_5^Z: \quad \mathcal{T}^{s_f s_{\bar{f}}}(0\pm) = \frac{\sqrt{2}(T_3 - Qs_W^2)e^2}{4c_W s_W m_Z^2}\hat{s}^{3/2}(\hat{s}-m^2)(\delta_{s_f,\frac{1}{2}} - \delta_{s_f,-\frac{1}{2}} \mp \cos\theta), \qquad (16)$$

$$h_5^Z: \quad \mathcal{T}^{s_f s_{\bar{f}}}\begin{pmatrix} -- & -+ \\ +- & ++ \end{pmatrix} = \frac{(T_3 - Qs_W^2)e^2}{2m_Z^4 s_W c_W}\hat{s}(\hat{s}-m_Z^2)\sin\theta\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \qquad (17)$$