Neutral triple gauge boson vertices and fermionic UV models

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Based on: R. Cepedello, F. Esser, M. Hirsch and V. Sanz
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Contents

$\mathcal{I}.$

Introduction

Anomalous NTGCs

Considering Bose symmetry and gauge invariance, the following CP-conserving vertices can be written down (after EWSB):

Gounaris et al. 1999 & 2000

$$ie\Gamma^{\alpha\beta\mu}_{ZZV}(q_1, q_2, q_3) = e\frac{(q_3^2 - m_V^2)}{m_Z^2}\Big[f_5^V\,\epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho\Big],$$

$$ie\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1, q_2, q_3) = e\frac{(q_3^2 - m_V^2)}{m_Z^2}\Big[h_3^V\,\epsilon^{\mu\alpha\beta\rho}q_{2,\rho} + \frac{h_4^V}{m_Z^2}q_3^\alpha\,\epsilon^{\mu\beta\rho\sigma}q_{3,\rho}q_{2,\sigma}\Big].$$

Anomalous NTGCs

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A few comments:

$\Rightarrow$ aNTGC vanish for all 3 bosons on-shell

$\Rightarrow$ "form factors" f_5^V, h_3^V and h_4^V in principle independent parameters
($\rightarrow h_4^V$ can not be generated at 1-loop and $d=8$)

$\Rightarrow$ There are also CP-violating vertices (ignored in this talk!)

$\Rightarrow$ More vertices posible for more than one boson off-shell
$\rightarrow$ experimentally irrelevant (therefore ignored here)

$\Rightarrow$ experimentally at LHC cleanest final state is $ZZ\rightarrow 4l$

$\mathcal{II}.$

NTGCs and EFT

SMEFT and NTGCs

In Greens basis for SMEFT list all operators at $d=6$ containing only bosons
`MatchMakerEFT` (1908.05295):

X^3		X^2H^2		H^2D^4	
$\mathcal{O}_{3G}$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{HG}$	$G^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$	$\mathcal{R}_{DH}$	$(D_\mu D^\mu H)^\dagger(D_\nu D^\nu H)$
$\mathcal{O}_{3\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\widetilde{G}}$	$\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}(H^\dagger H)$	**H^4D^2**	
$\mathcal{O}_{3W}$	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HW}$	$W^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{3\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{H\widetilde{W}}$	$\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}(H^\dagger H)$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\dagger(H^\dagger D_\mu H)$
X^2D^2		$\mathcal{O}_{HB}$	$B_{\mu\nu}B^{\mu\nu}(H^\dagger H)$	$\mathcal{R}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger(D^\mu H)$
$\mathcal{R}_{2G}$	$-\frac{1}{2}(D_\mu G^{A\mu\nu})(D^\rho G^A_{\rho\nu})$	$\mathcal{O}_{H\widetilde{B}}$	$\widetilde{B}_{\mu\nu}B^{\mu\nu}(H^\dagger H)$	$\mathcal{R}''_{HD}$	$(H^\dagger H)D_\mu(H^\dagger i\overleftrightarrow{D}^\mu H)$
$\mathcal{R}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W^I_{\rho\nu})$	$\mathcal{O}_{HWB}$	$W^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$	**H^6**	
$\mathcal{R}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$	$\mathcal{O}_{H\widetilde{W}B}$	$\widetilde{W}^I_{\mu\nu}B^{\mu\nu}(H^\dagger\sigma^I H)$	$\mathcal{O}_H$	$(H^\dagger H)^3$
		H^2XD^2			
		$\mathcal{R}_{WDH}$	$D_\nu W^{I\mu\nu}(H^\dagger i\overleftrightarrow{D}^I_\mu H)$		
		$\mathcal{R}_{BDH}$	$\partial_\nu B^{\mu\nu}(H^\dagger i\overleftrightarrow{D}_\mu H)$		

$\Rightarrow$ Only X^3, X^2D^2 and H^2X^2 contains three (or more) gauge bosons

$\Rightarrow$ No NTGC in any of these operators

$\Rightarrow$ Need to go to $d=8$ operators!

$d = 8$ basis for NTGCs

The following four $d = 8$ operators generate the NTGCs shown previously:

$$\mathcal{O}_{DB\tilde{B}} = i\frac{c_{DB\tilde{B}}}{\Lambda^4} H^\dagger \tilde{B}_{\mu\nu}(D^\rho B_{\nu\rho}) D_\mu H + \text{h.c.}\,,$$

$$\mathcal{O}_{DW\tilde{W}} = i\frac{c_{DW\tilde{W}}}{\Lambda^4} H^\dagger \tilde{W}_{\mu\nu}(D^\rho W_{\nu\rho}) D_\mu H + \text{h.c.}\,,$$

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All are type:

$X\tilde{Y}H^2D^2$

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\end{aligned}$$

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$\Rightarrow$ All 4 operators are necessary to describe f_5^Z, f_5^γ, h_3^Z and h_3^γ as independent parameters

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\end{aligned}$$

All are type:

$X\tilde{Y}H^2D^2$

⇒ All 4 operators are necessary to describe f_5^Z, f_5^γ, h_3^Z and h_3^γ as independent parameters

⇒ We disagree with previous literature (Degrande, 2013) that defines:

$$\mathcal{O}_{\tilde{B}W} = i\frac{c_{\tilde{B}W}}{\Lambda^4} H^\dagger \tilde{B}_{\mu\nu}(W_{\mu\rho})\{D^\rho, D_\mu\}H + \text{h.c.}\,,$$

⇒ This operator can not describe all of f_5^Z, f_5^γ, h_3^Z and h_3^γ

Form factors

The relation to the form factors are:

$$f_5^Z = \frac{v^2 m_Z^2}{\Lambda^4} \frac{1}{c_W s_W} \left[s_W^2 c_{DB\tilde{B}} + c_W^2 c_{DW\tilde{W}} + \frac{1}{2} c_W s_W (c_{DW\tilde{B}} + c_{DB\tilde{W}}) \right],$$

$$f_5^\gamma = \frac{v^2 m_Z^2}{\Lambda^4} \frac{1}{c_W s_W} \left[c_W s_W (-c_{DB\tilde{B}} + c_{DW\tilde{W}}) - \frac{1}{2} (s_W^2 c_{DW\tilde{B}} - c_W^2 c_{DB\tilde{W}}) \right],$$

$$h_3^Z = \frac{v^2 m_Z^2}{\Lambda^4} \frac{1}{c_W s_W} \left[c_W s_W (-c_{DB\tilde{B}} + c_{DW\tilde{W}}) + \frac{1}{2} (c_W^2 c_{DW\tilde{B}} - s_W^2 c_{DB\tilde{W}}) \right],$$

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Note that in the special case of $c_{DW\tilde{B}} = c_{DB\tilde{W}}$ (true in many models):

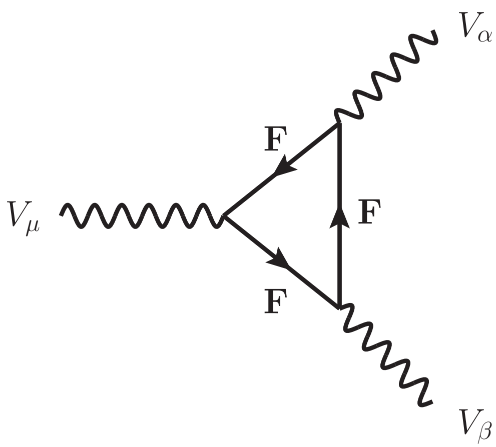
$$f_5^\gamma = \frac{v^2 m_Z^2}{\Lambda^4} \frac{1}{c_W s_W} \left[c_W s_W (-c_{DB\tilde{B}} + c_{DW\tilde{W}}) + \frac{1}{2} c_{DW\tilde{B}} (c_W^2 - s_W^2) \right],$$

$$h_3^Z = \frac{v^2 m_Z^2}{\Lambda^4} \frac{1}{c_W s_W} \left[c_W s_W (-c_{DB\tilde{B}} + c_{DW\tilde{W}}) + \frac{1}{2} c_{DW\tilde{B}} (c_W^2 - s_W^2) \right],$$

$\mathcal{III}.$

NTGCs in (fermionic) models

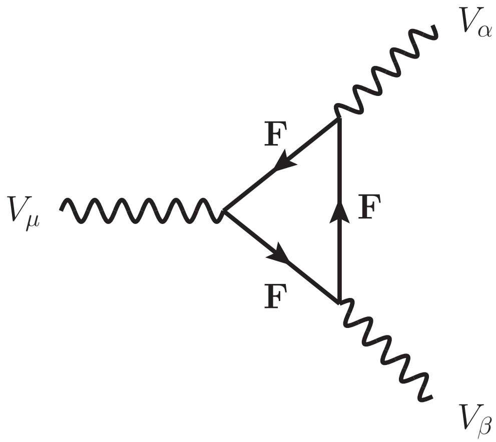
Fermionic loops



Fermionic triangle diagram
in the mass eigenstate basis

Adequate for calculation
in broken phase

Fermionic loops



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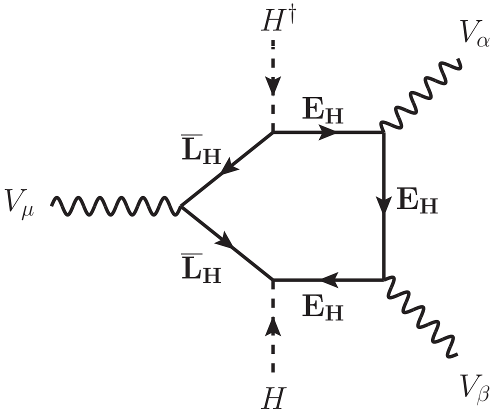
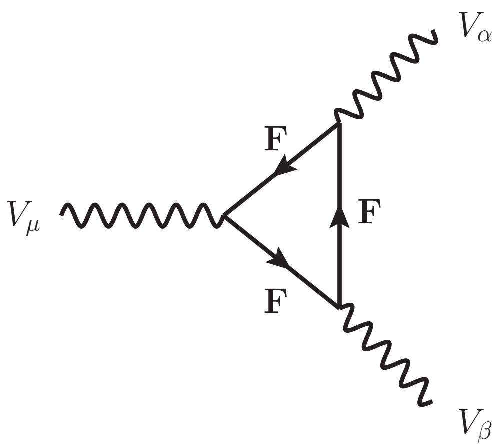


Fermionic pentagram diagram
in the weak eigenstate basis

Adequate for calculation
in SMEFT

Fermionic loops



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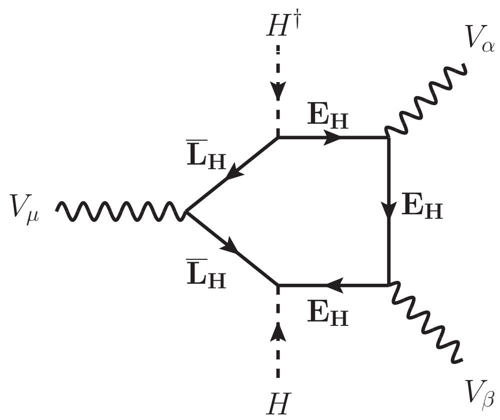


Fermionic pentagram diagram
in the weak eigenstate basis

Adequate for calculation
in SMEFT

$L_H = F_{1,2,-1/2}$ and $E_H = F_{1,1,-1}$
"vector-like" leptons

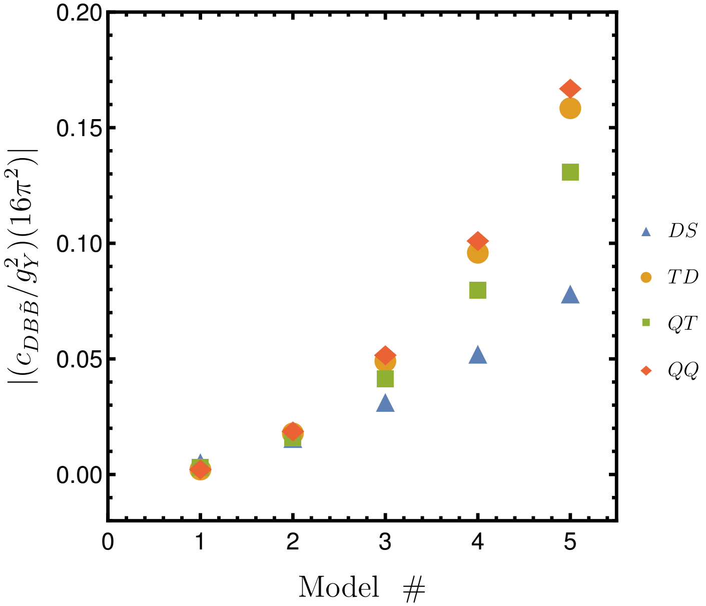
Diracology:

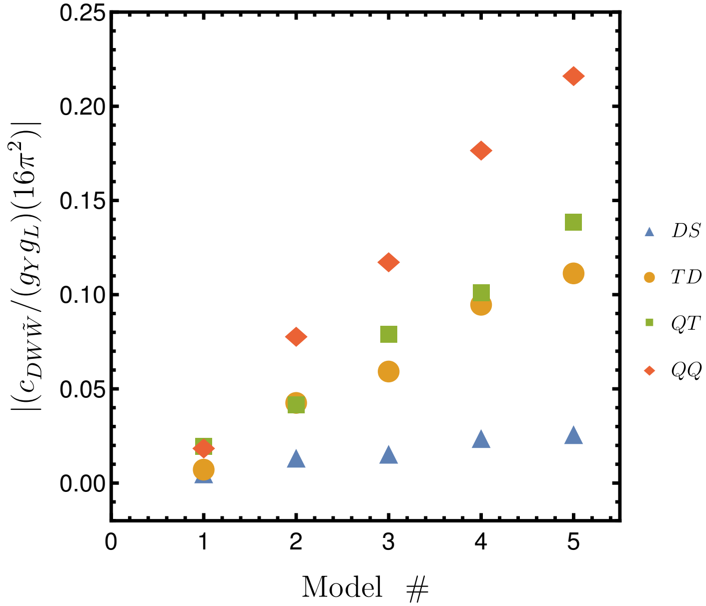
$$\mathrm{tr}[\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma P_{L/R}] = 2(g_{\mu\nu}g_{\rho\sigma} - g_{\mu\rho}g_{\nu\sigma} + g_{\mu\sigma}g_{\nu\rho} \pm i\epsilon^{\mu\nu\rho\sigma}).$$

$\Rightarrow$ left-handed and right-handed couplings must differ!

Models and matching

Matching for: $c_{DB\tilde{B}}$ $c_{DB\tilde{W}}$





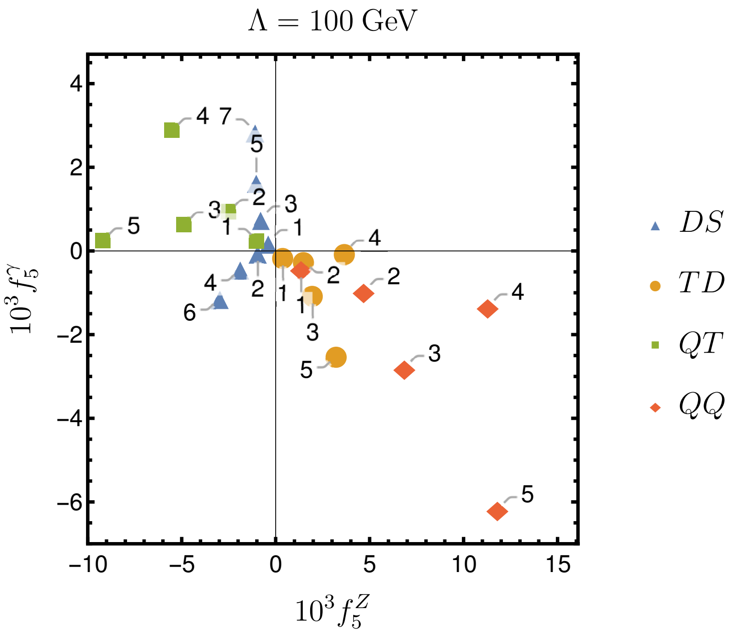
$\Rightarrow$ All models need two fermions with $\Delta(Y) = (1/2)$

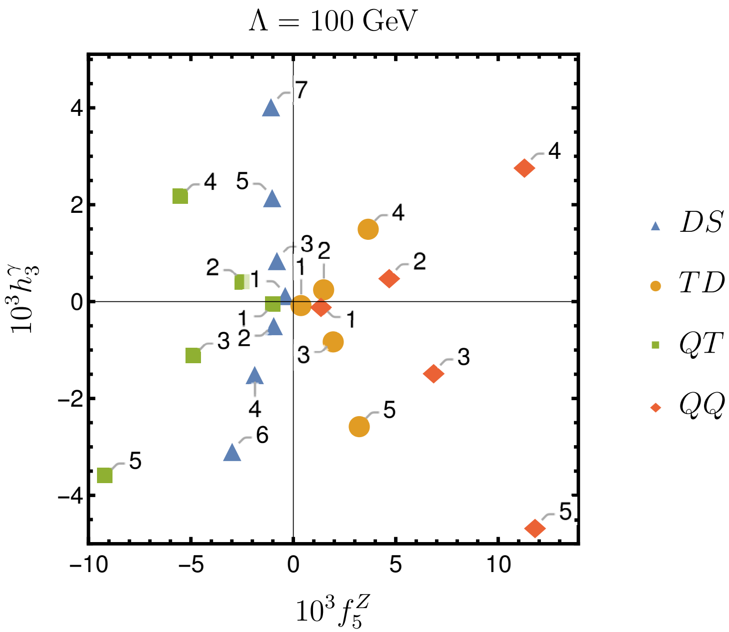
$\Rightarrow$ Product of $SU_L(2)$ needs to contain doublet:

$\rightarrow$ $\mathbf{2} \times \mathbf{1}$ (DS), $\mathbf{3} \times \mathbf{2}$ (TD), $\mathbf{4} \times \mathbf{3}$ (QT), $\mathbf{5} \times \mathbf{4}$ (QQ), $\cdots$

$\rightarrow$ Model # increasing hypercharge from $1 = (0, -1/2)$ to $5 = (-2, -5/2)$
(except DS, which starts at $1 = (-1/2, -1)$)

Form factors

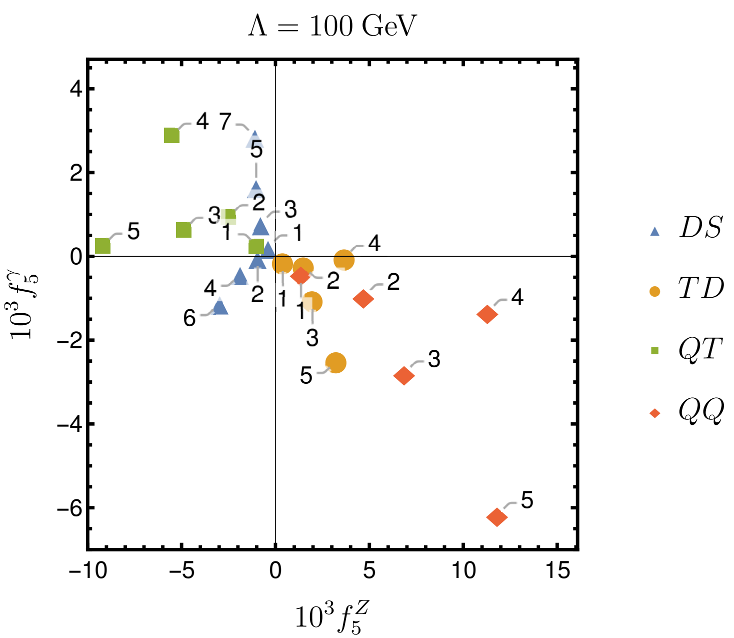


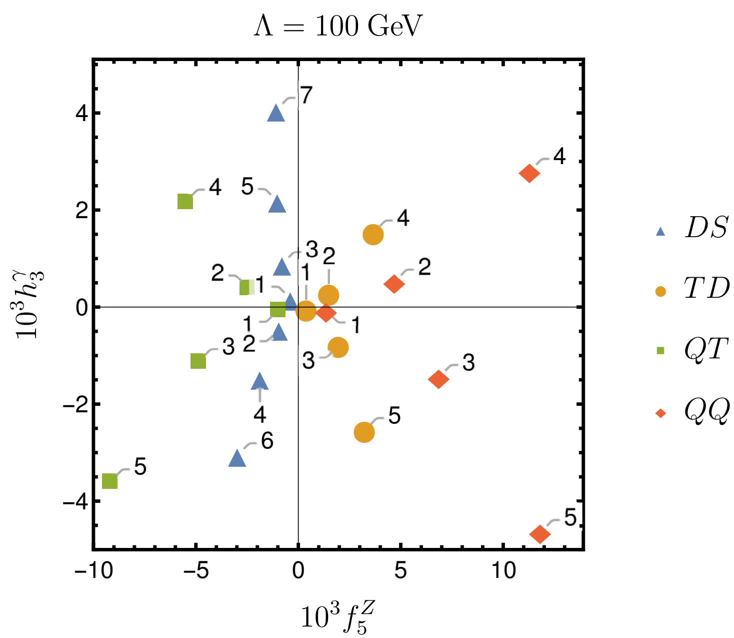


$\Rightarrow$ For $\Lambda = 0.1$ TeV typically (few) 10^{-3}

$\Rightarrow$ All models make different predictions!

Form factors





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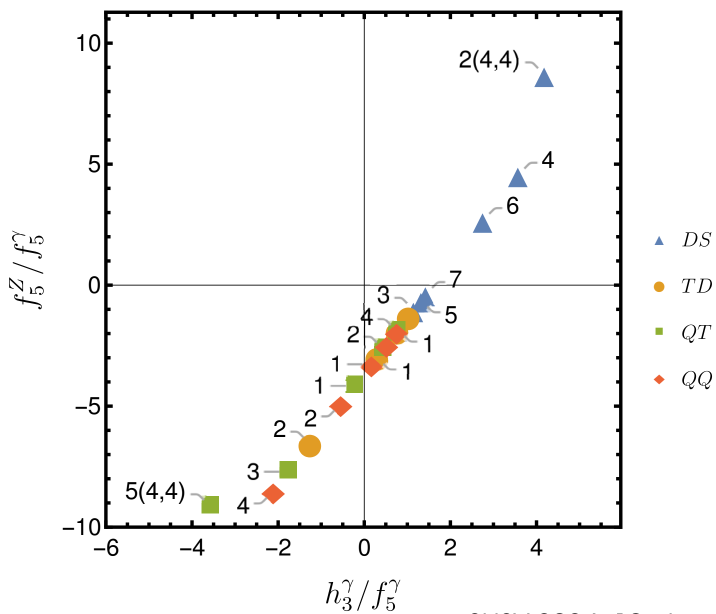

Plot double-ratio:
Independent of Λ
ALL models lie along a line!

$d = 6$ *versus* $d = 8$

All models that generate NTGCs also will generate the following $d = 6$ operators:

$$
\begin{aligned}
\mathcal{O}_{HB} &= \frac{c_{HB}}{\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}, \\
\mathcal{O}_{HWB} &= \frac{c_{HWB}}{\Lambda^2} H^\dagger H W_{\mu\nu} B^{\mu\nu}, \\
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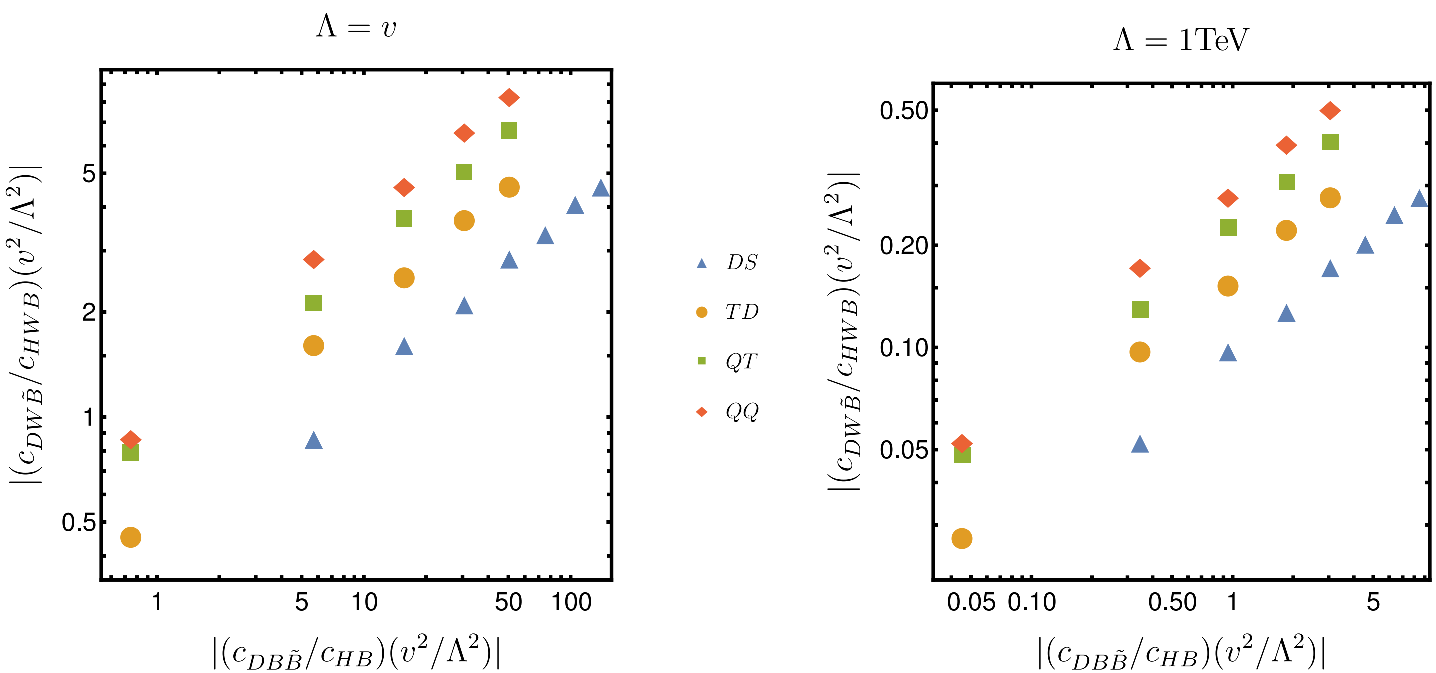


Plot:

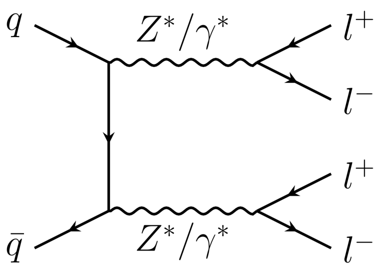
double-ratio

$(d = 6)/(d = 8)$

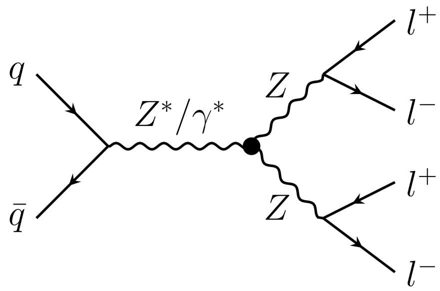
$\mathcal{IV}.$

Experimental limits on NTGCs

Measuring $ZZ \to 4l$

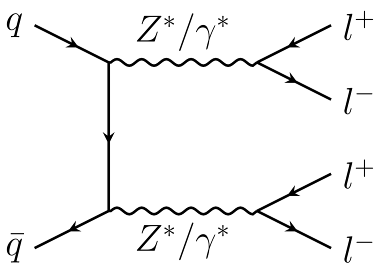


SM background



NTGC signal

Measuring $ZZ \to 4l$



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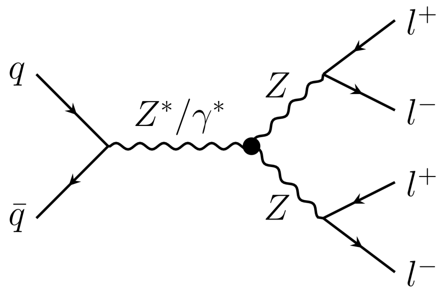

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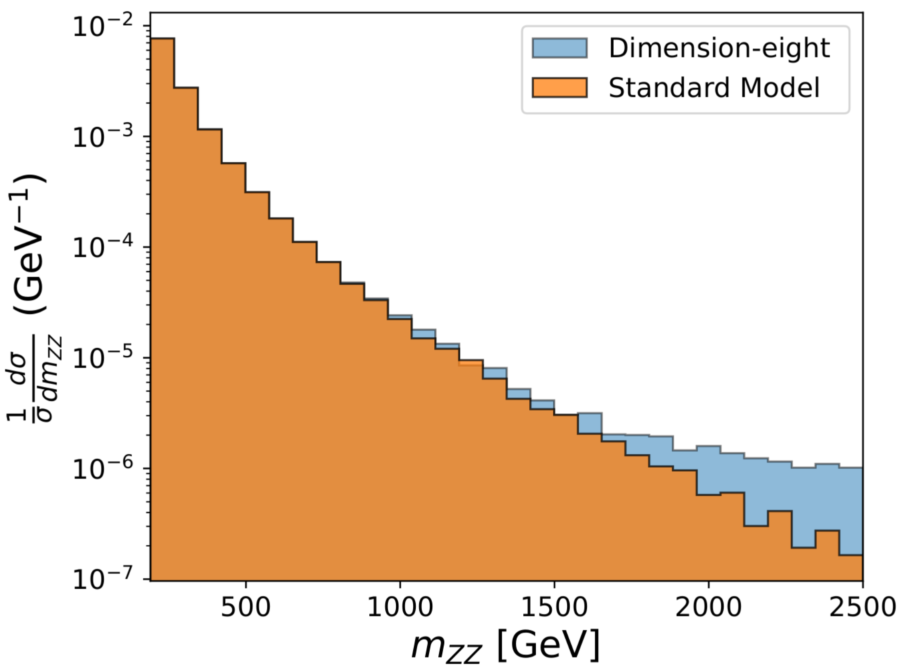
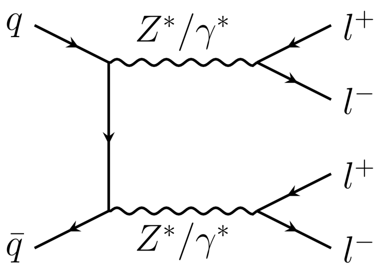


X-section versus invariant mass of 4 lepton system

Measuring $ZZ \to 4l$



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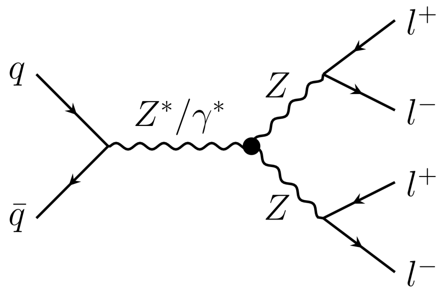

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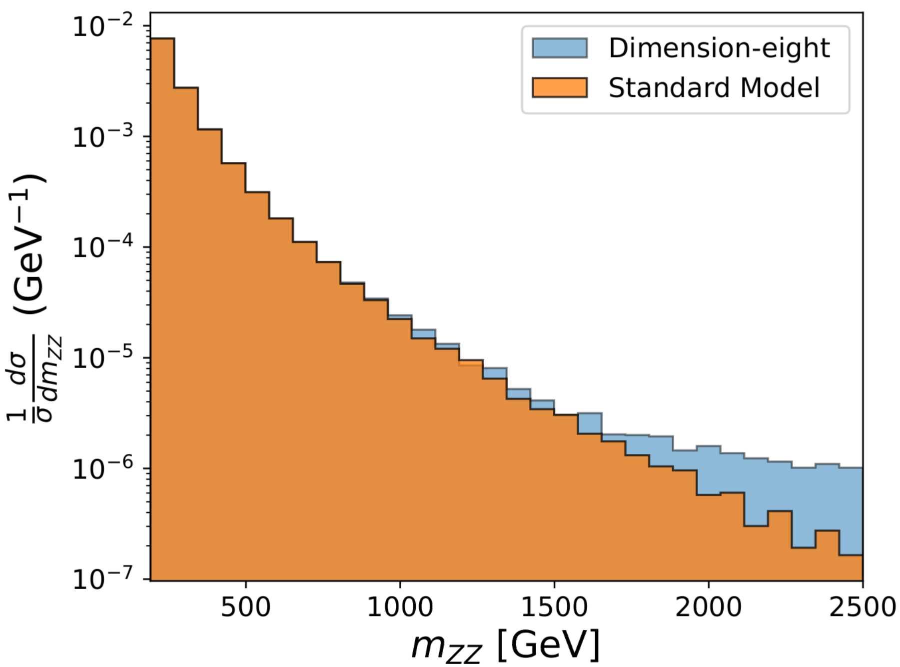
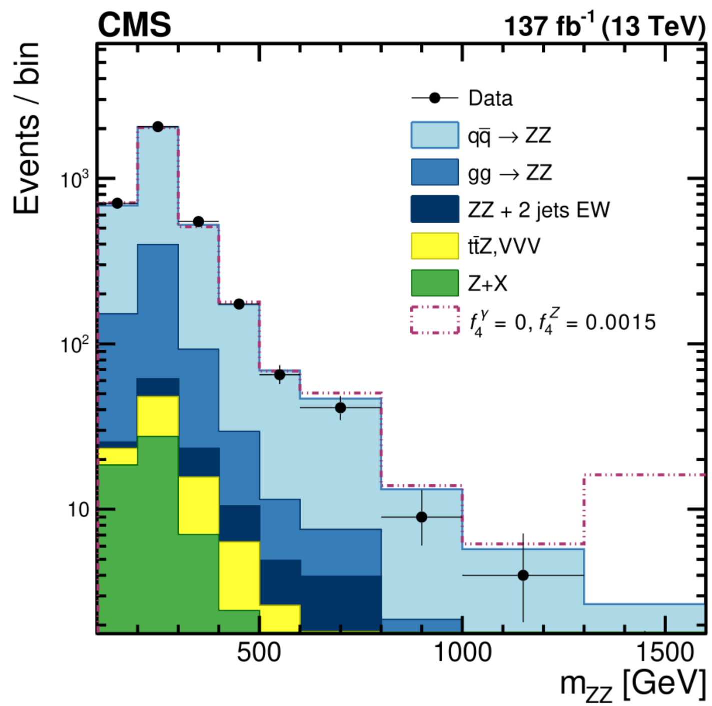
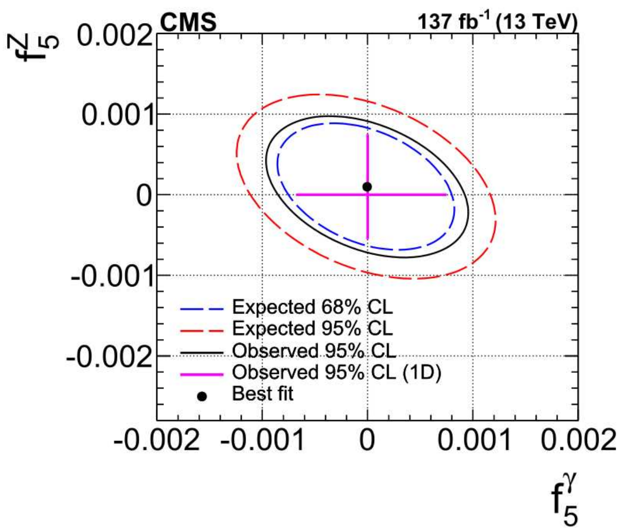




X-section versus invariant mass of 4 lepton system

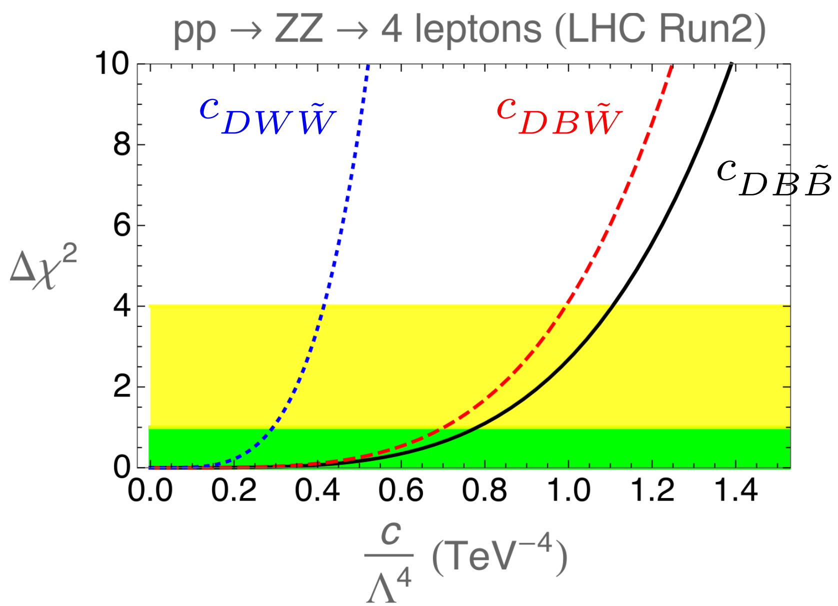
CMS, 2021

Limits

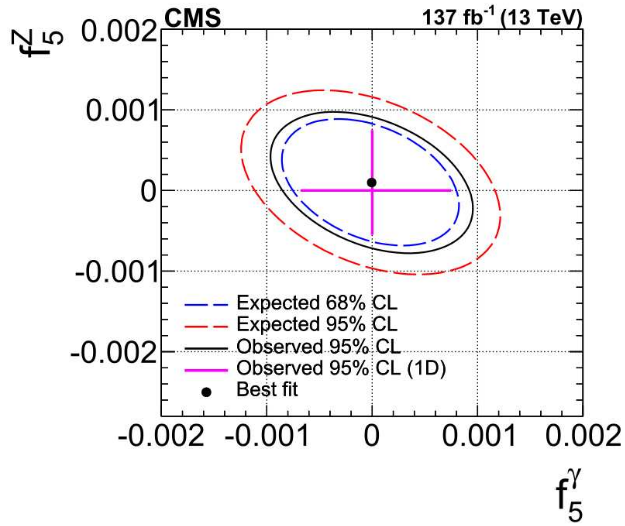


Limits on f_5^Z and f_5^γ from CMS

Limits



Limits on $d = 8$ operators



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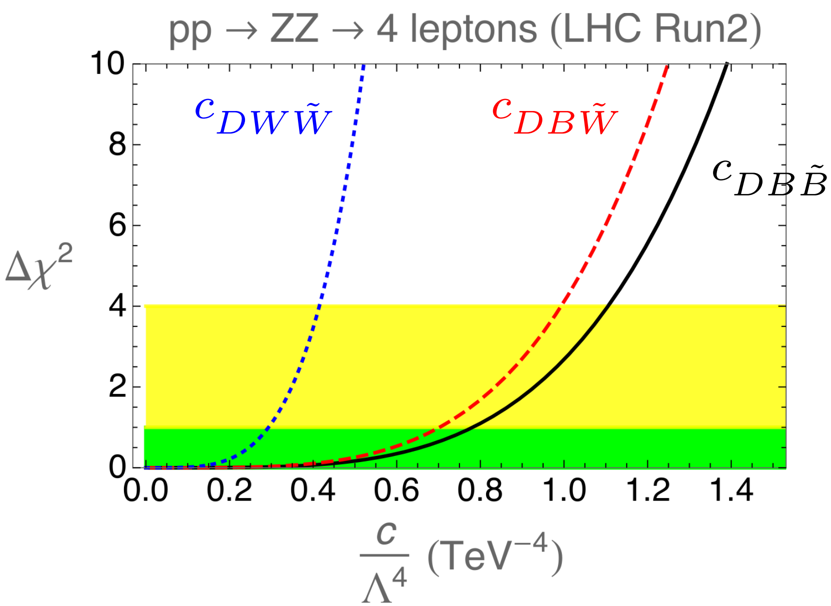

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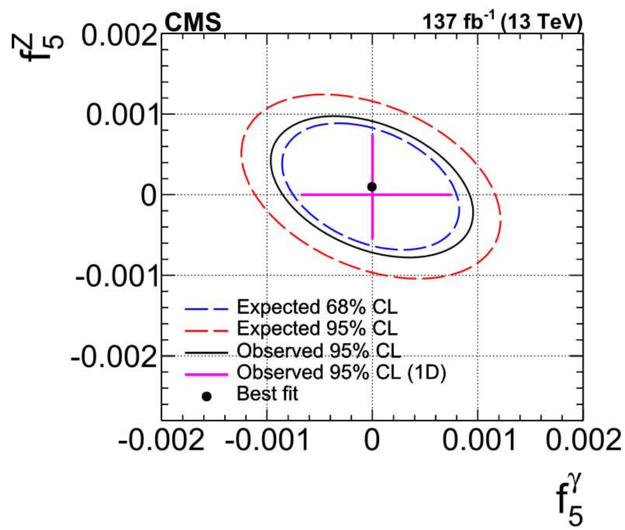
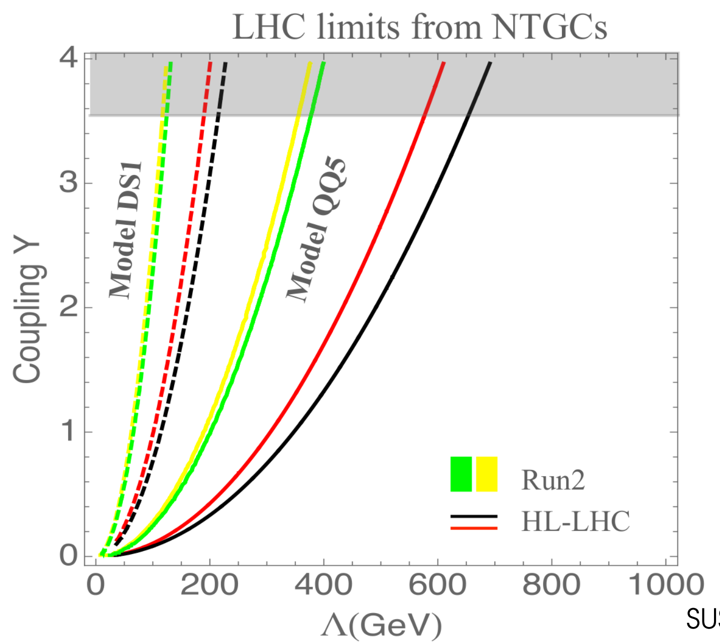


Limits on f_5^Z and f_5^γ from CMS

Limits on models
very weak!

$\Lambda \gtrsim 100$ GeV (now)
$\gtrsim$ (few) 100 GeV for $3/$ab



Conclusions

$\Rightarrow$ Complete and correct $d = 8$ operator basis for NTGCs found

$\Rightarrow$ Correcting existing literature!

$\Rightarrow$ Limits derived on operators from experimental searches by ATLAS and CMS: $\Lambda \sim \mathcal{O}(1)$ TeV, depending on operator

$\Rightarrow$ Set of fermionic UV models for NTGCs constructed

$\Rightarrow$ Limits derived on models, but ...

Limits on models very weak! Not even $\Lambda = 100$ GeV in some cases
(EFT assumption not valid!)

Backup

General matching formulas

It is actually possible to derive an analytic formula for $\tilde{c}_{DAB}$ for all models:

$$\begin{aligned}
\tilde{c}_{DB\tilde{B}} &= \frac{1}{160}(-1)^{(\mathbf{r_1} \bmod 2)}\mathrm{sgn}\big(y_2^2 - y_1^2\big)\sqrt{2\mathbf{r_1}\mathbf{r_2}}\left(y_1^2 + y_2^2 + \frac{4}{3}y_2 y_1\right), \\
\tilde{c}_{DW\tilde{W}} &= \frac{1}{160}(-1)^{(\mathbf{r_1} \bmod 2)}\mathrm{sgn}\big(y_2^2 - y_1^2\big)\sqrt{2\mathbf{r_1}\mathbf{r_2}}\,\frac{1}{12}\left[(\mathbf{r_1}^2 - 1) + (\mathbf{r_2}^2 - 1) + \frac{4}{3}(\mathbf{r_1}\mathbf{r_2} - 2)\right] \\
\tilde{c}_{DW\tilde{B}} &= \frac{1}{48}(-1)^{(\mathbf{r_1} \bmod 2)}\sqrt{2\mathbf{r_1}\mathbf{r_2}}\,\frac{1}{12}(y_1 + y_2)\left[(\mathbf{r_1} + \mathbf{r_2}) + \frac{3}{5}(y_1 - y_2)\right], \\
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\end{aligned}$$

NTGCs - Lagrangian

The following effective Lagrangian generates all NTGC CPC vertices:

Gounaris et al., 1999

$$\mathcal{L}_{\rm NP}^{CPC} = \frac{e}{2m_Z^2} \Big[f_5^\gamma (\partial^\sigma F_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta + f_5^Z (\partial^\sigma Z_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta - h_3^\gamma (\partial^\sigma F_{\sigma\mu}) \tilde{F}^{\mu\beta} Z_\beta - h_3^Z (\partial^\sigma Z_{\sigma\mu}) \tilde{F}^{\mu\beta} Z_\beta + \frac{h_4^\gamma}{2m_Z^2} [\Box (\partial^\sigma F^{\rho\alpha})] \tilde{F}_{\rho\alpha} Z_\sigma + \frac{h_4^Z}{2m_Z^2} [(\Box + m_Z^2)(\partial^\sigma Z^{\rho\alpha})] \tilde{F}_{\rho\alpha} Z_\sigma \Big],$$

with $\tilde{X}_{\mu\nu} = 1/2\, \epsilon_{\mu\nu\alpha\beta} X^{\alpha\beta}$. Note: This Lagrangian requires EWSB!

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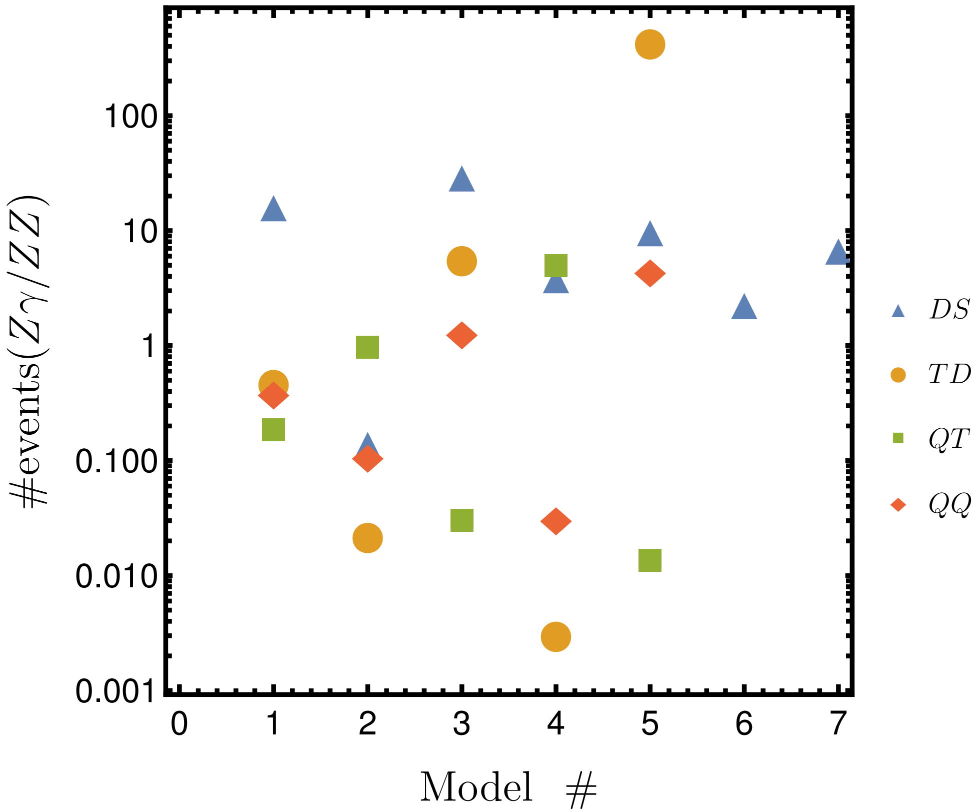
$\Rightarrow$ What type of SMEFT operator can produce this Lagrangian?

γZ versus ZZ

Ratio of number of events in γZ and ZZ final states versus model:



Large variation ...

but $>$ 1/2 of models have $(\gamma Z)/(ZZ) > 1$