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Fermionic UV models for NTGCs

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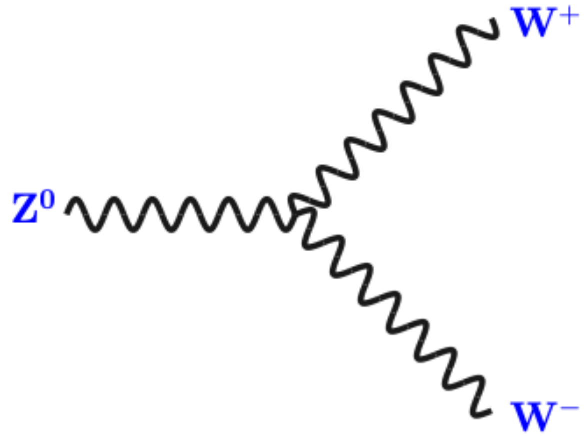
EFT AND BEYOND, 05.12.2024

1. Neutral Triple Gauge Couplings

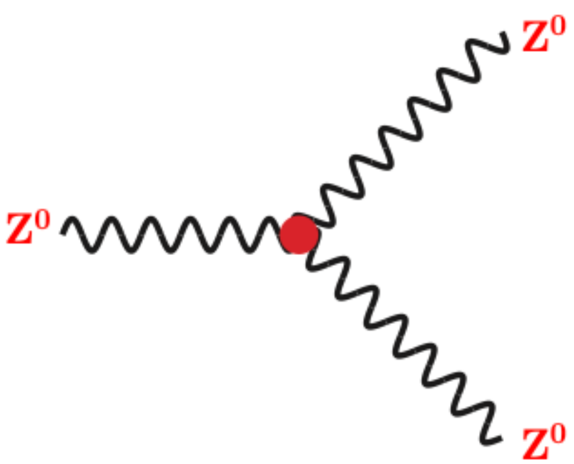
Triple gauge boson vertices



In the SM:

Triple gauge boson vertices from self-coupling in field strength tensor

$$W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu - g\epsilon^{IJK} W^J_\mu W^K_\nu$$



But:

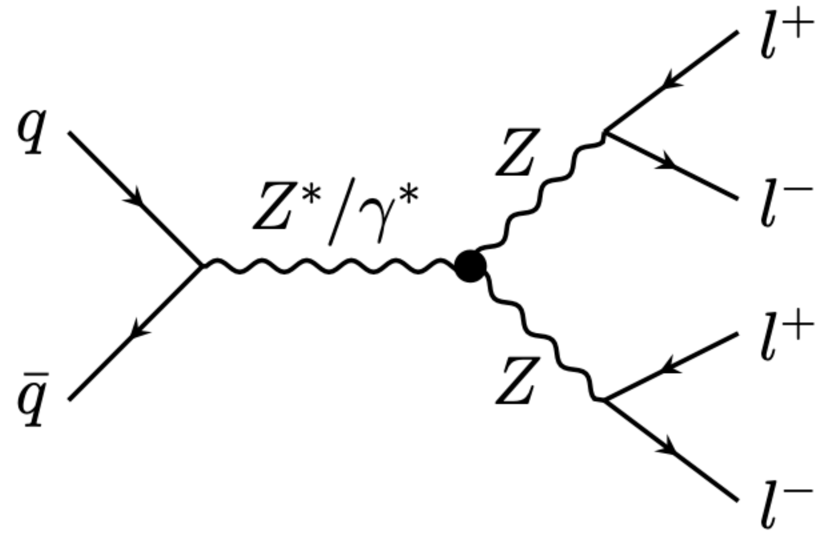
no Neutral Triple Gauge Couplings (NTGCs) due to ϵ^{IJK}

→ Anomalous NTGC (aNTGC)

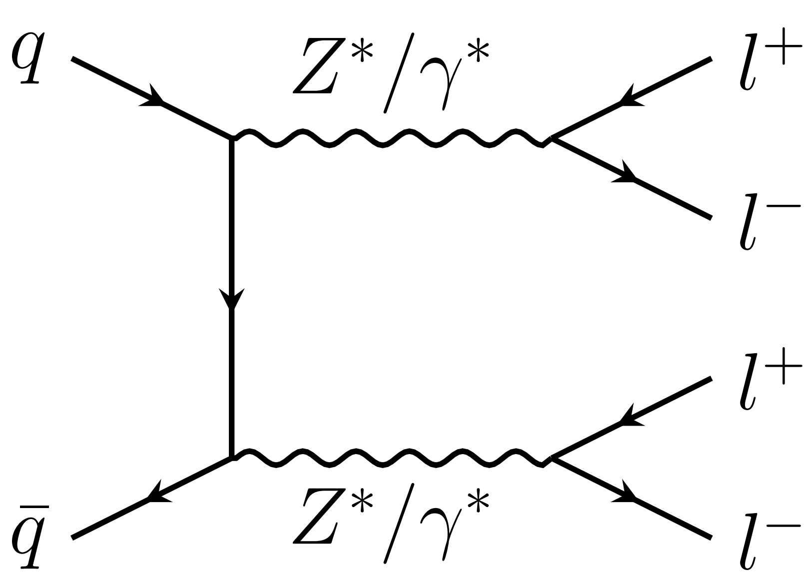
aNTGC provide important tests for the gauge structure of the SM

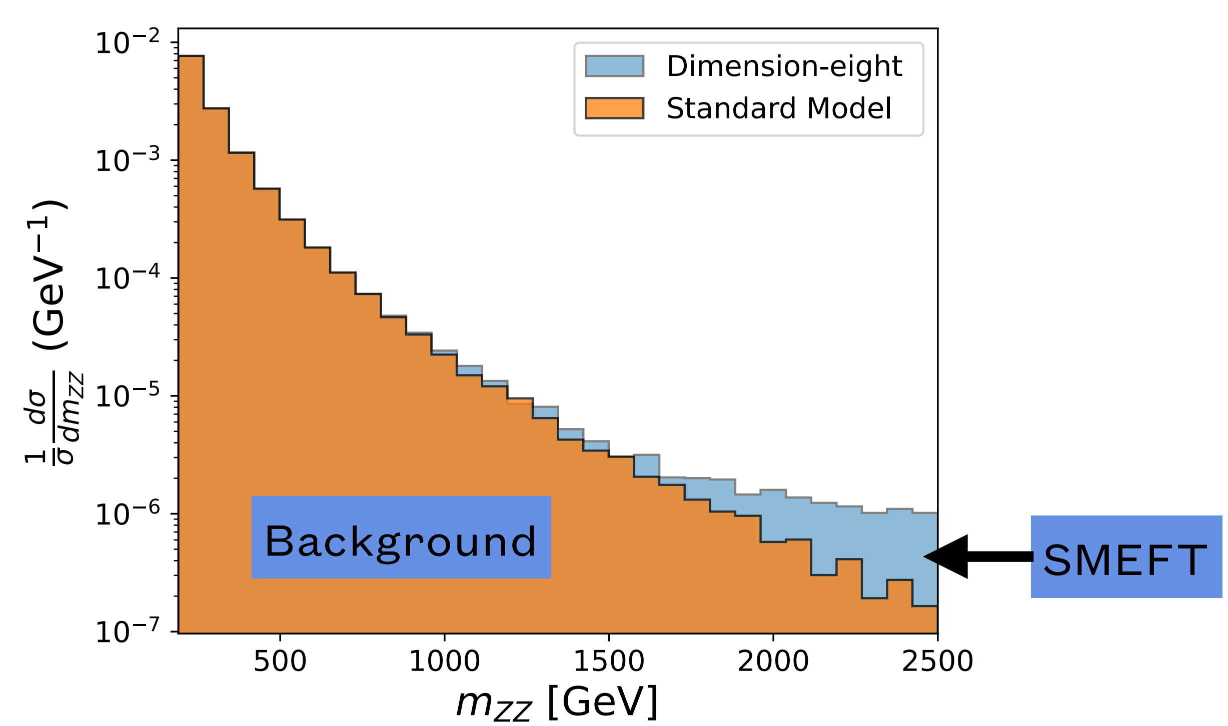
→ Searches for aNTGC at ATLAS and CMS

Searches for NTGCs



- Cleanest final state: $ZZ \to 4l$
- Rare channel, will increase its power with more data
- Not background limited
  $\Rightarrow$ Increase sensitivity with luminosity





Form factors for NTGCs

CP conserving (CPC) vertices after EWSB, taking into account Bose symmetry and gauge invariance

→ NTGC with 3 on-shell bosons vanish

→ $V = \gamma^*, Z^*$ has to be off-shell

[Gounaris et al. 1999]
[Gounaris et al. 2000]

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

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

- Form factors f_5^V, h_3^V and h_4^V are independent parameters, but h_4^V is not generated at 1-loop and dim-8
- CP-violating vertices or vertices with more than one boson off-shell are not discussed here
  → experimentally irrelevant

Lagrangians for NTGCs

Effective Lagrangian for all NTGC CPC vertices

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

[Gounaris et al. 1999]

Why is there a dual field strength in the CPC vertices? $\tilde{X}_{\mu\nu} = 1/2\, \epsilon_{\mu\nu\alpha\beta} X^{\alpha\beta}$

CP-transformations:

$C(Z_\mu) \to -Z_\mu$ and $P(Z_0) \to +Z_0, P(Z_i) \to -Z_i$

$P(\partial_0) \to +\partial_0, P(\partial_i) \to -\partial_i$ and $P(\epsilon^{\mu\alpha\beta\rho}) \to -\epsilon^{\mu\alpha\beta\rho}$

What type of SMEFT operators can produce this Lagrangian?

2. SMEFT operators for NTGCs

Gauge couplings in SMEFT

In Greens basis for SMEFT list all operators at $d = 6$ containing only bosons

MatchMakerEFT (1908.05295):

X^3	
$\mathcal{O}_{3G}$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{3\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{3W}$	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$\mathcal{O}_{3\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$X^2 D^2$	
$\mathcal{R}_{2G}$	$-\frac{1}{2}(D_\mu G^{A\mu\nu})(D^\rho G^A_{\rho\nu})$
$\mathcal{R}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W^I_{\rho\nu})$
$\mathcal{R}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$

$X^2 H^2$	
$\mathcal{O}_{HG}$	$G^A_{\mu\nu} G^{A\mu\nu}(H^\dagger H)$
$\mathcal{O}_{H\widetilde{G}}$	$\widetilde{G}^A_{\mu\nu} G^{A\mu\nu}(H^\dagger H)$
$\mathcal{O}_{HW}$	$W^I_{\mu\nu} W^{I\mu\nu}(H^\dagger H)$
$\mathcal{O}_{H\widetilde{W}}$	$\widetilde{W}^I_{\mu\nu} W^{I\mu\nu}(H^\dagger H)$
$\mathcal{O}_{HB}$	$B_{\mu\nu} B^{\mu\nu}(H^\dagger H)$
$\mathcal{O}_{H\widetilde{B}}$	$\widetilde{B}_{\mu\nu} B^{\mu\nu}(H^\dagger H)$
$\mathcal{O}_{HWB}$	$W^I_{\mu\nu} B^{\mu\nu}(H^\dagger \sigma^I H)$
$\mathcal{O}_{H\widetilde{W}B}$	$\widetilde{W}^I_{\mu\nu} B^{\mu\nu}(H^\dagger \sigma^I H)$

$H^2 X D^2$	
$\mathcal{R}_{WDH}$	$D_\nu W^{I\mu\nu}(H^\dagger \mathrm{i} \overleftrightarrow{D}^I_\mu H)$
$\mathcal{R}_{BDH}$	$\partial_\nu B^{\mu\nu}(H^\dagger \mathrm{i} \overleftrightarrow{D}_\mu H)$

$H^2 D^4$	
$\mathcal{R}_{DH}$	$(D_\mu D^\mu H)^\dagger (D_\nu D^\nu H)$

$H^4 D^2$	
$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\dagger (H^\dagger D_\mu H)$
$\mathcal{R}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger (D^\mu H)$
$\mathcal{R}''_{HD}$	$(H^\dagger H) D_\mu (H^\dagger \mathrm{i} \overleftrightarrow{D}^\mu H)$

H^6	
$\mathcal{O}_H$	$(H^\dagger H)^3$

$\mathcal{O}_{HB}, \mathcal{O}_{HWB}, \mathcal{O}_{HW}, \mathcal{O}_{3W}$ contain TGC, but no NTGC

$\Rightarrow$ need to go to dimension-8

d=8 operators for NTGCs

Four d=8 operators that generate the effective Lagrangian, all in the class $X^2H^2D^2$

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

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

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

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

4 independent form factors f_5^Z, f_5^γ, h_3^Z, h_3^γ

$\Rightarrow$ these 4 operators are the maximal set

d=8 operators for NTGC

Relations to the form factors:

$$
\begin{aligned}
f_5^Z &= \frac{v^2 m_Z^2}{\Lambda^4}\frac{1}{c_W s_W}\left[s_W^2 c_{DB\tilde{B}} + c_W^2 c_{DW\tilde{W}} + \frac{1}{2}c_W s_W (c_{DW\tilde{B}} + c_{DB\tilde{W}})\right],\\
f_5^\gamma &= \frac{v^2 m_Z^2}{\Lambda^4}\frac{1}{c_W s_W}\left[c_W s_W (-c_{DB\tilde{B}} + c_{DW\tilde{W}}) - \frac{1}{2}(s_W^2 c_{DW\tilde{B}} - c_W^2 c_{DB\tilde{W}})\right],\\
h_3^Z &= \frac{v^2 m_Z^2}{\Lambda^4}\frac{1}{c_W s_W}\left[c_W s_W (-c_{DB\tilde{B}} + c_{DW\tilde{W}}) + \frac{1}{2}(c_W^2 c_{DW\tilde{B}} - s_W^2 c_{DB\tilde{W}})\right],\\
h_3^\gamma &= \frac{v^2 m_Z^2}{\Lambda^4}\frac{1}{c_W s_W}\left[c_W^2 c_{DB\tilde{B}} + s_W^2 c_{DW\tilde{W}} - \frac{1}{2}c_W s_W (c_{DW\tilde{B}} + c_{DB\tilde{W}})\right],
\end{aligned}
$$

For our models, we always find $c_{DW\tilde{B}} = c_{DB\tilde{W}}$

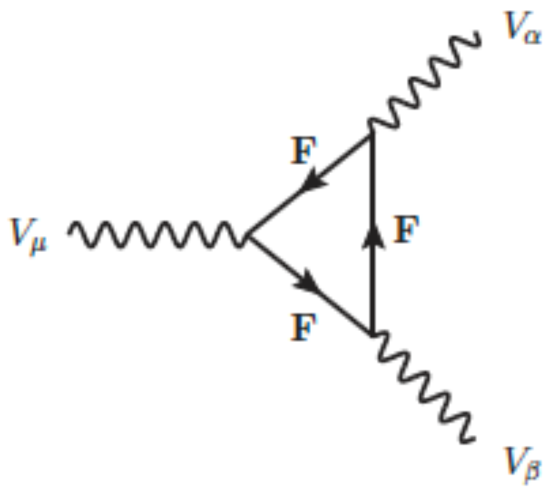
$\Rightarrow f_5^\gamma = h_3^Z$, only 3 independent form factors

3. Models for NTGCs

What UV models generate NTGCs at dim-8?

Models that DO NOT generate NTGCs at dim-8:

- Models with scalar states (e.g. 2HDM) can produce CPC and CPV NTGCs, but they appear only at d=12 [Moyotl et al. 2015] [Belusca-Maito et al 2018]



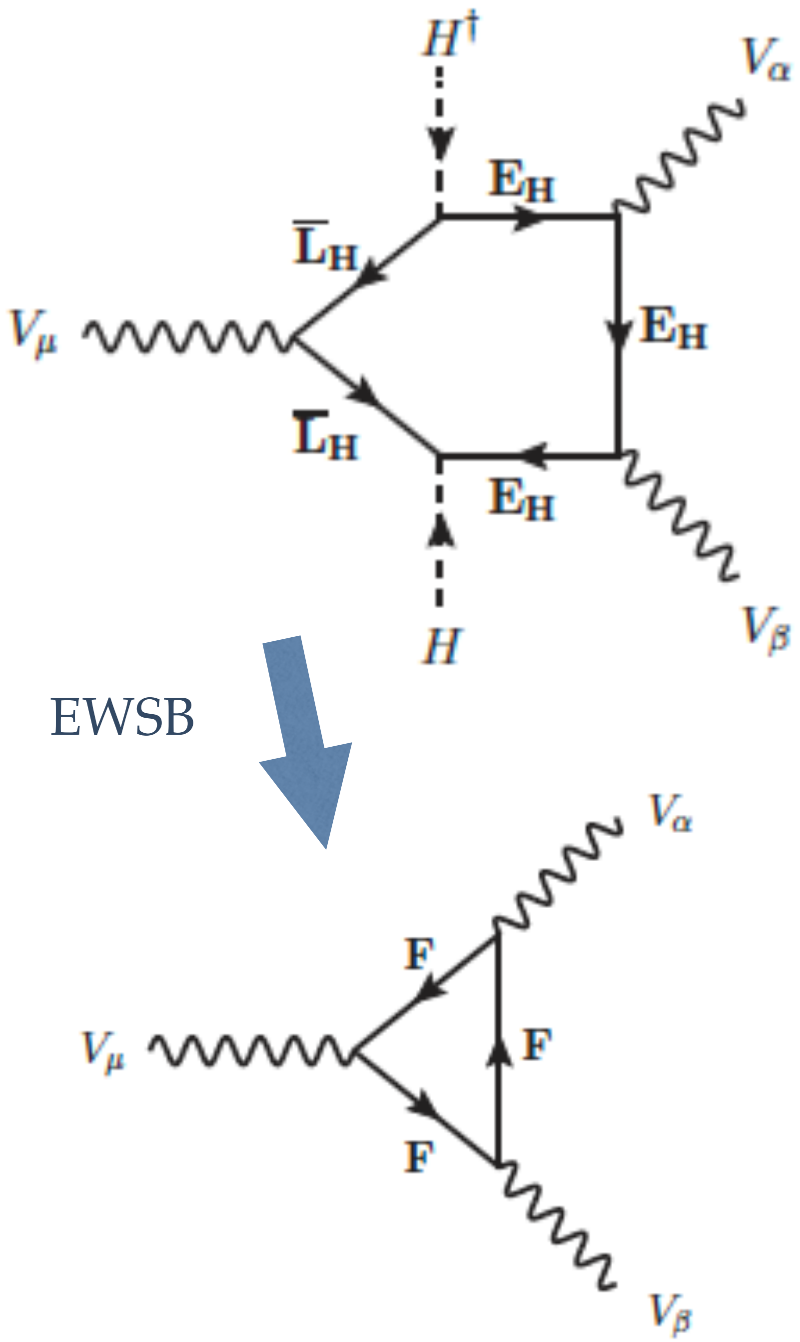
- Triangles with SM or BSM fermions in the mass eigenstate basis (needs EWSB):

  → could generate NTGCs [Gounaris et al. 2000]

  → but the contributions quickly vanish with $\sqrt{s}$, they do not correspond to the correct EFT limit

⇒ We need two fermions and Higgs insertions in the loop!

Models for NTGCs



- We searched for models at d=8 using a diagrammatic approach
- Contributions from *pentagon diagrams* with two heavy *vector-like leptons* and two *Higgs insertions*
- **prototype model:** $L_H = F_{1,2,-1/2}$ and $E_H = F_{1,1,-1}$
- left-and right-handed couplings must differ for CPC vertices

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

- heavy-light Yukawa couplings are strongly constrained by dimension-6 operators at tree-level, $Y_{HL} \ll 1$
  $\Rightarrow$ Numerically important contributions only from models with two heavy fermions
- pentagon diagrams reduces to triangle diagrams after EWSB breaking ($\sim$ v^2) and mass mixing

We matched 22 models for NTGCs

- 2 VLFs coupling to a Higgs boson: SU(2) products needs to contain a doublet & $\Delta Y = 1/2$
- scan different options for QNs: table up to **hypercharge 4** and **SU(2) quintuplets**

Singlets & Doublets

Model	Particles	$\tilde{c}_{DB\tilde{B}}$	$\tilde{c}_{DW\tilde{B}} = \tilde{c}_{DB\tilde{W}}$	$\tilde{c}_{DW\tilde{W}}$
MDS1	(L_H, E_H)	$\frac{23}{960}$	$-\frac{7}{480}$	$\frac{1}{320}$
MDS2	$(F_{1,2,-\frac{3}{2}}, F_{1,1,-1})$	$-\frac{21}{320}$	$-\frac{13}{480}$	$-\frac{1}{320}$
MDS3	$(F_{1,2,-\frac{3}{2}}, F_{1,1,-2})$	$\frac{41}{\ldots}$	$-\frac{17}{\ldots}$	$\frac{1}{320}$
MDS4	$(F_{1,2,-\frac{5}{2}}, F_{1,1,-2})$	$-\ldots$	[illegible]	$-\frac{1}{320}$
MDS5	$(F_{1,2,-\frac{5}{2}}, F_{1,1,-3})$	[illegible]	[illegible]	$\frac{1}{320}$
MDS6	$(F_{1,2,-\frac{7}{2}}, F_{1,1,-3})$	$-\frac{141}{320}$	$-\frac{11}{160}$	$-\frac{1}{320}$
MDS7	$(F_{1,2,-\frac{7}{2}}, F_{1,1,-4})$	$\frac{563}{960}$	$-\frac{37}{480}$	$\frac{1}{320}$

Doublets & Triplets

Model	Particles	$\tilde{c}_{DB\tilde{B}}$	$\tilde{c}_{DW\tilde{B}} = \tilde{c}_{DB\tilde{W}}$	$\tilde{c}_{DW\tilde{W}}$
MTD1	$(F_{1,3,0}, F_{1,2,-\frac{1}{2}})$	$-\frac{\sqrt{3}}{\ldots}$	$\frac{11}{\ldots}$	$-\frac{49}{960\sqrt{3}}$
MTD2	$(F_{1,3,-1}, F_{1,2,-\frac{1}{2}})$	$\frac{2\ldots}{320\ldots}$	[illegible]	$\frac{49}{960\sqrt{3}}$
MTD3	$(F_{1,3,-1}, F_{1,2,-\frac{3}{2}})$	$-\frac{2\ldots}{\ldots}$	[illegible]	$-\frac{49}{960\sqrt{3}}$
MTD4	$(F_{1,3,-2}, F_{1,2,-\frac{3}{2}})$	$\frac{41\sqrt{3}}{320}$	$\frac{89}{480\sqrt{3}}$	$\frac{49}{960\sqrt{3}}$
MTD5	$(F_{1,3,-2}, F_{1,2,-\frac{5}{2}})$	$-\frac{203}{320\sqrt{3}}$	$\frac{37}{160\sqrt{3}}$	$-\frac{49}{960\sqrt{3}}$

Triplets & Quartuplets

Model	Particles	$\tilde{c}_{DB\tilde{B}}$	$\tilde{c}_{DW\tilde{B}} = \tilde{c}_{DB\tilde{W}}$	$\tilde{c}_{DW\tilde{W}}$
MQT1	$(F_{1,4,-\frac{1}{2}}, F_{1,3,0})$	$-\frac{\sqrt{\frac{3}{2}}}{160}$	$-\frac{19}{240\sqrt{6}}$	$-\frac{109}{480\sqrt{6}}$
MQT2	$(F_{1,4,-\frac{1}{2}}, F_{1,3,-1})$	$\frac{23}{160\sqrt{\ldots}}$	$\frac{17}{\ldots}$	$\frac{109}{480\sqrt{6}}$
MQT3	$(F_{1,4,-\frac{3}{2}}, F_{1,3,-1})$	$-\frac{21\sqrt{\ldots}}{16\ldots}$	[illegible]	$-\frac{109}{480\sqrt{6}}$
MQT4	$(F_{1,4,-\frac{3}{2}}, F_{1,3,-2})$	$\frac{41\sqrt{\ldots}}{160}$	$-\frac{\ldots}{240\sqrt{6}}$	$\frac{109}{480\sqrt{6}}$
MQT5	$(F_{1,4,-\frac{5}{2}}, F_{1,3,-2})$	$-\frac{203}{160\sqrt{6}}$	$-\frac{53}{80\sqrt{6}}$	$-\frac{109}{480\sqrt{6}}$

Quartuplets & Quintuplets

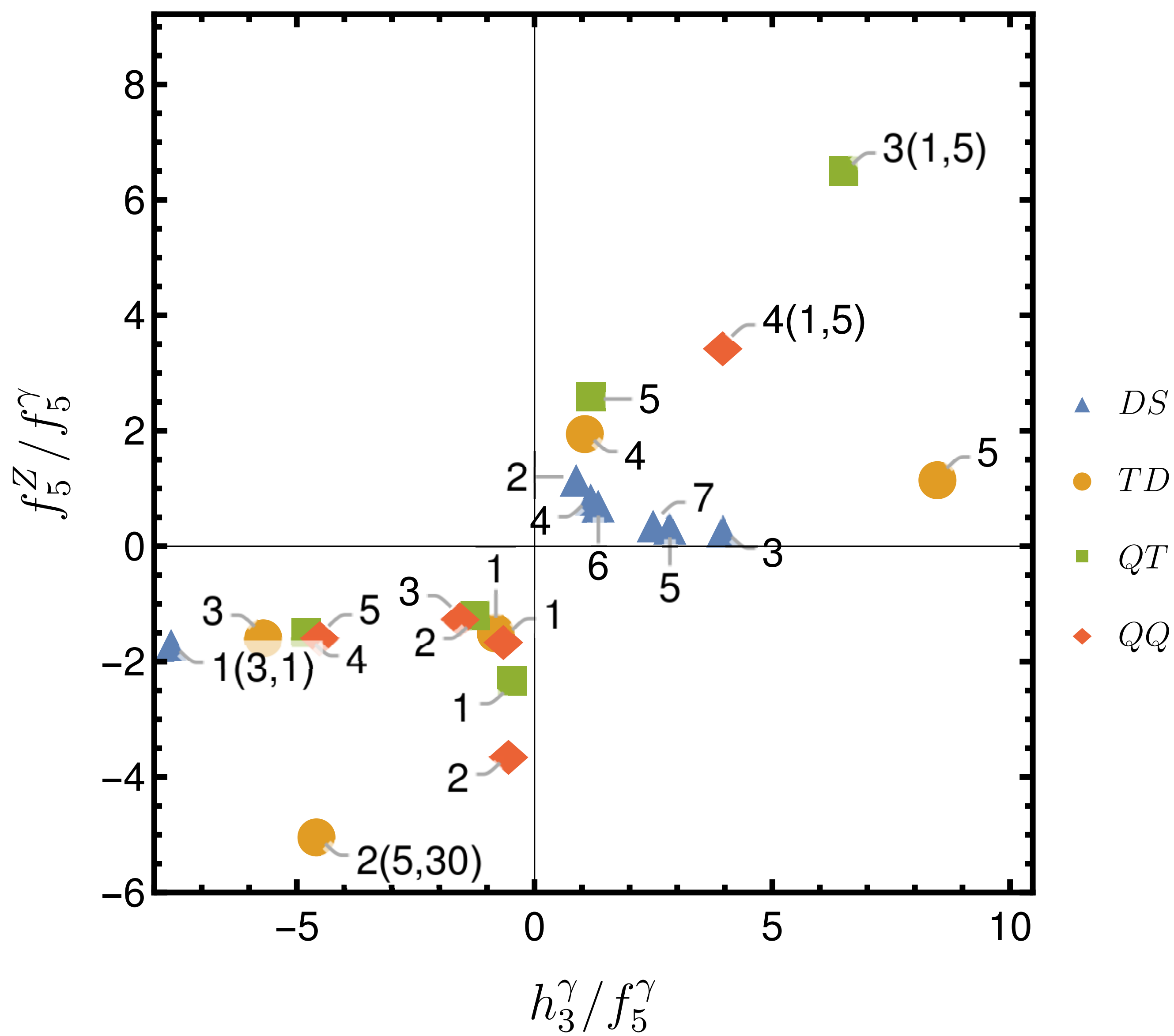
Model	Particles	$\tilde{c}_{DB\tilde{B}}$	$\tilde{c}_{DW\tilde{B}} = \tilde{c}_{DB\tilde{W}}$	$\tilde{c}_{DW\tilde{W}}$
MQQ1	$(F_{1,5,0}, F_{1,4,-\frac{1}{2}})$	$-\frac{1}{32\sqrt{10}}$	$\frac{7}{48\sqrt{10}}$	$-\frac{21}{32\sqrt{10}}$
MQQ2	$(F_{1,5,-1}, F_{1,4,-\frac{1}{2}})$	$\frac{23}{96\sqrt{10}}$	[illegible]	$\frac{21}{32\sqrt{10}}$
MQQ3	$(F_{1,5,-1}, F_{1,4,-\frac{3}{2}})$	$-\frac{21}{32\sqrt{1\ldots}}$	[illegible]	$-\frac{21}{32\sqrt{10}}$
MQQ4	$(F_{1,5,-2}, F_{1,4,-\frac{3}{2}})$	$\frac{41}{32\sqrt{10}}$	$\frac{53}{48\sqrt{10}}$	$\frac{21}{32\sqrt{10}}$
MQQ5	$(F_{1,5,-2}, F_{1,4,-\frac{5}{2}})$	$-\frac{203}{96\sqrt{10}}$	$\frac{67}{48\sqrt{10}}$	$-\frac{21}{32\sqrt{10}}$

Matching done with ***Matchete***

$$c_{DAB} = \frac{1}{16\pi^2} g_A g_B |Y|^2 \tilde{c}_{DAB},$$

Form factors

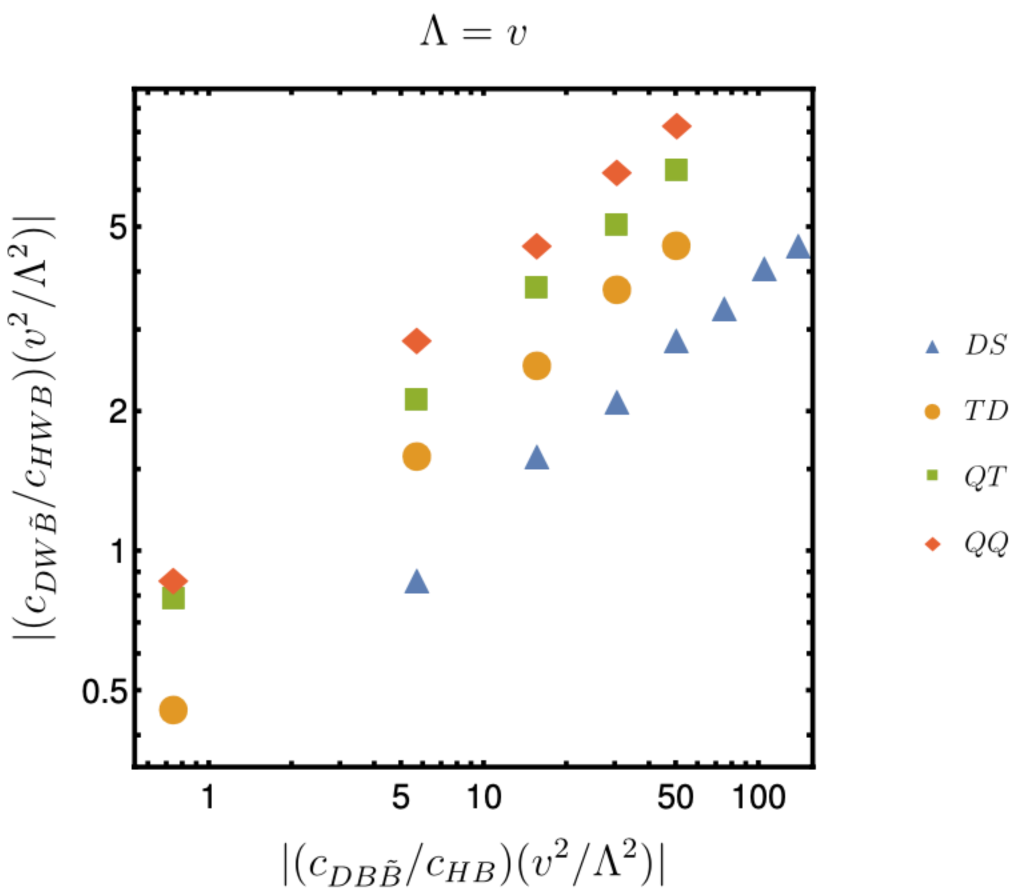
- calculate form factors from Wilson coefficients for all models
- we can form two independent ratios of form factors, independent of Λ
- all models have either both ratios positive or negative, but different predictions for all models
- experimentally accessible: ZZ (f_5^γ) and Zγ (h_3^γ) final state
  → ratio of these channels could discriminate the true UV model

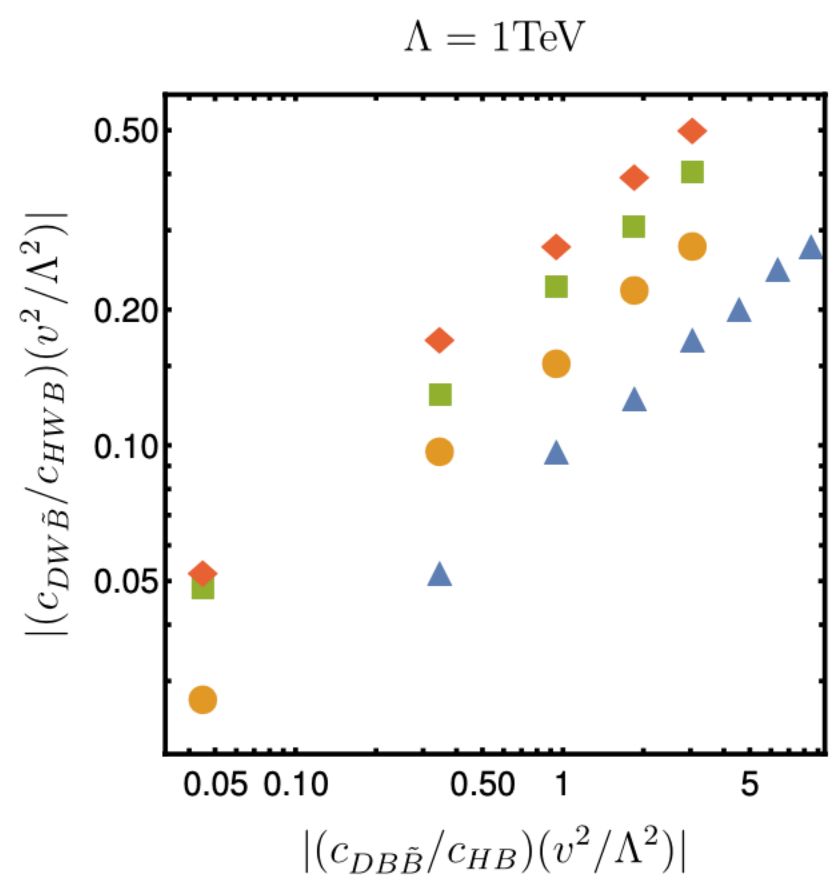


dim-6 vs. dim-8

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

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



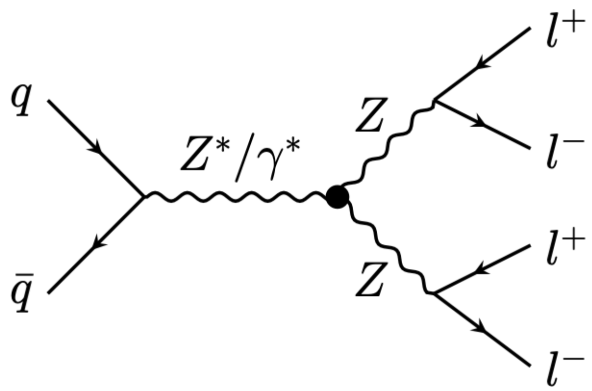


d=8 grows fast with energy and will compete with d=6

→ strong gain for ZZ and Zγ searches vs WW and Zjj at large invariant mass

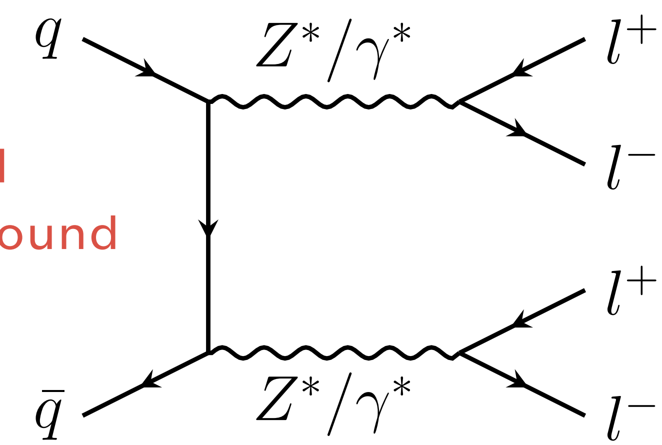
4. Experimental limits

Measuring $ZZ \to 4l$

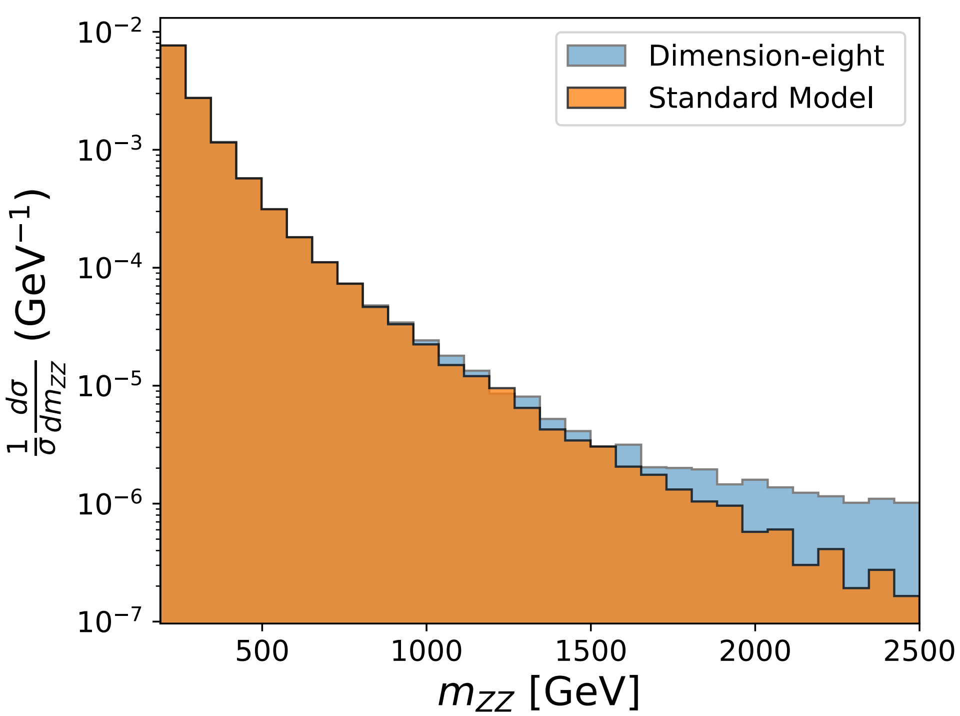


signal
at
dim-8

SM
background

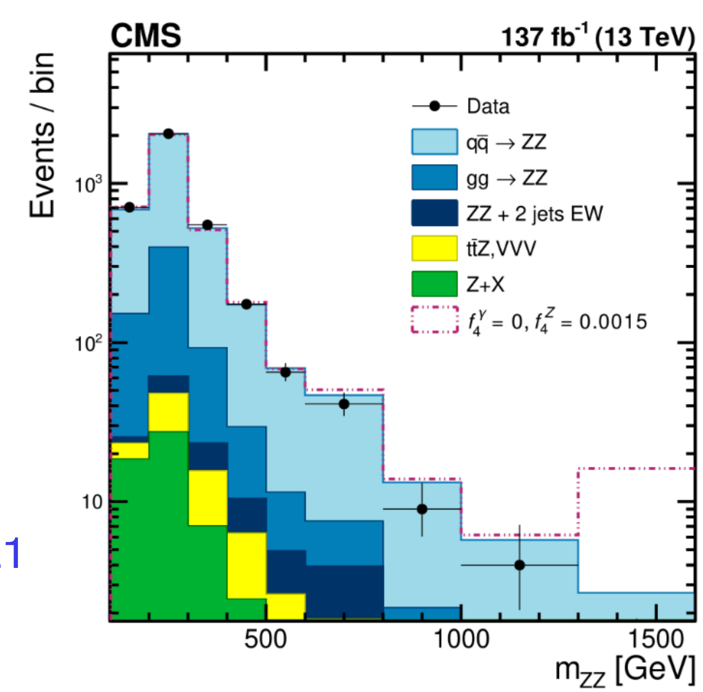


- Both ATLAS and CMS search for ZZ and $Z\gamma$ final states
- Dimension-8 contribution increases with energy relative to the background
- CMS analysis contains a bin without events but SM prediction and uncertainty

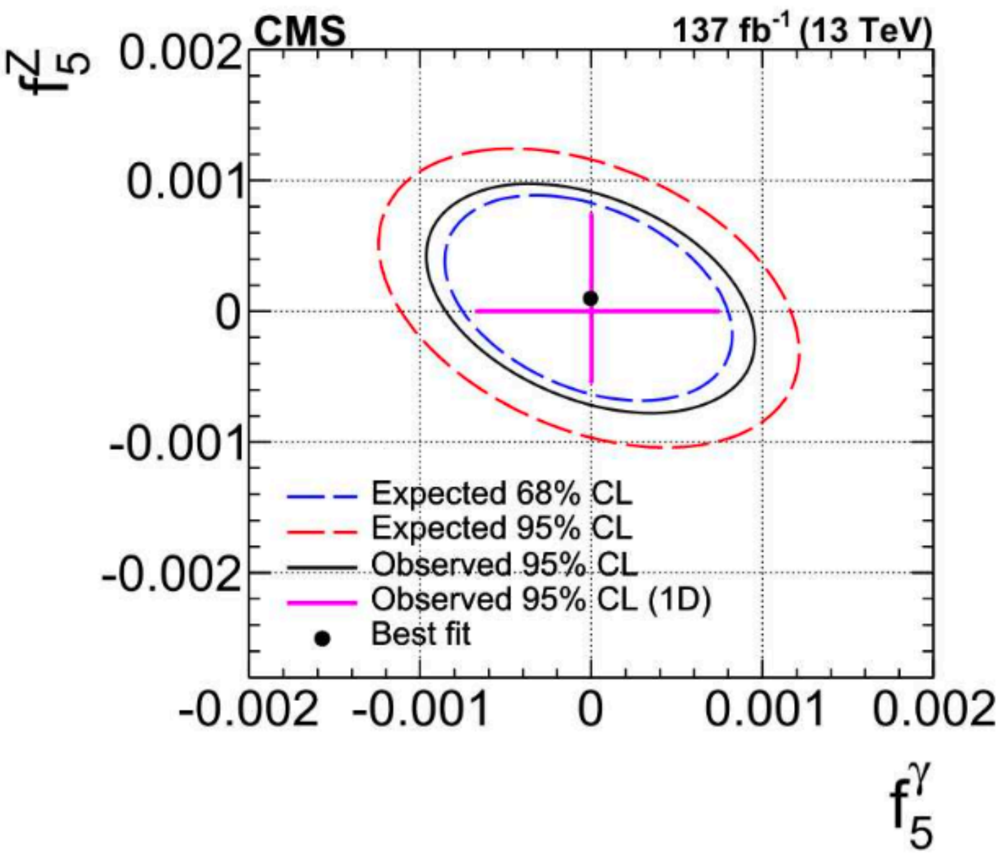


cross section
vs. invariant
mass

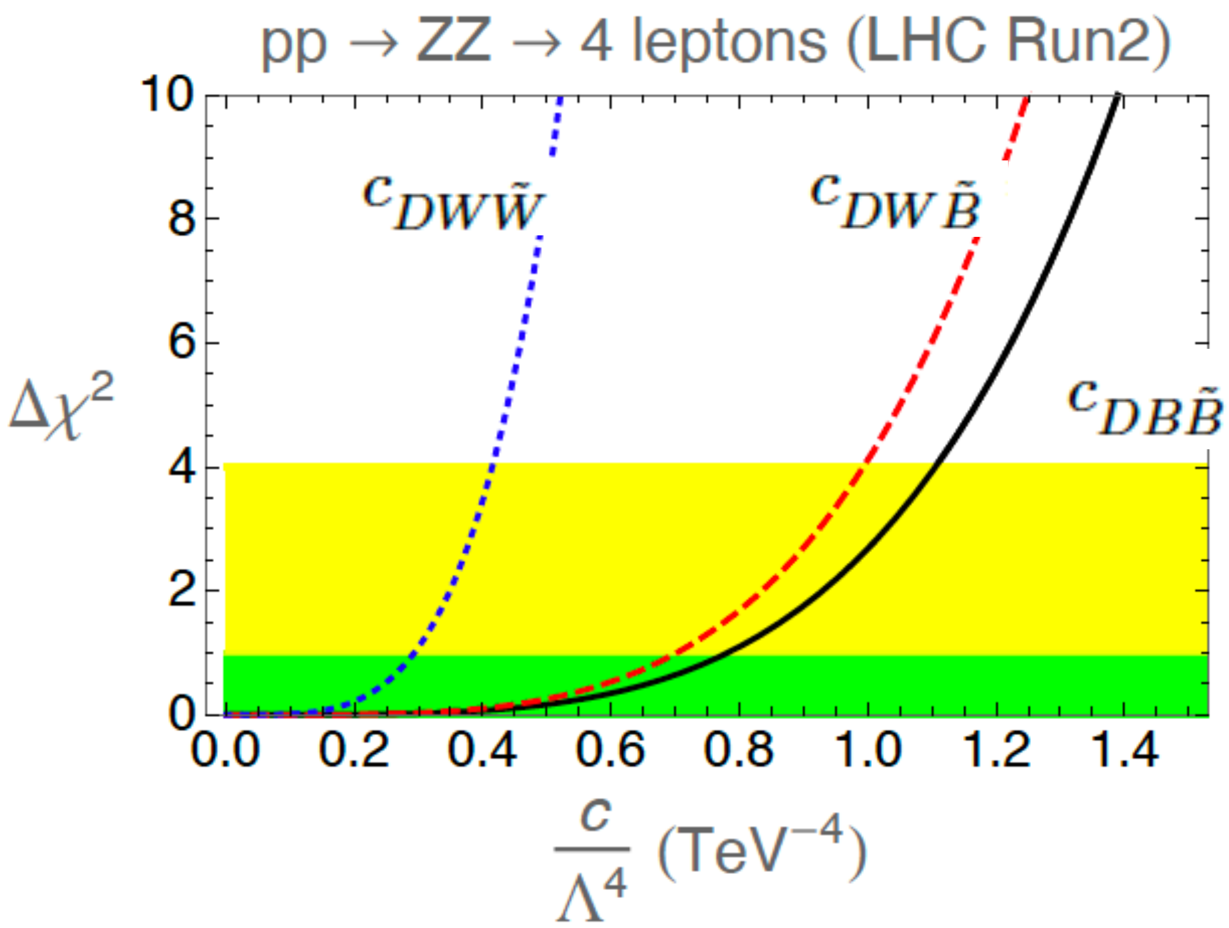
CMS 2021



Limits on NTGCs

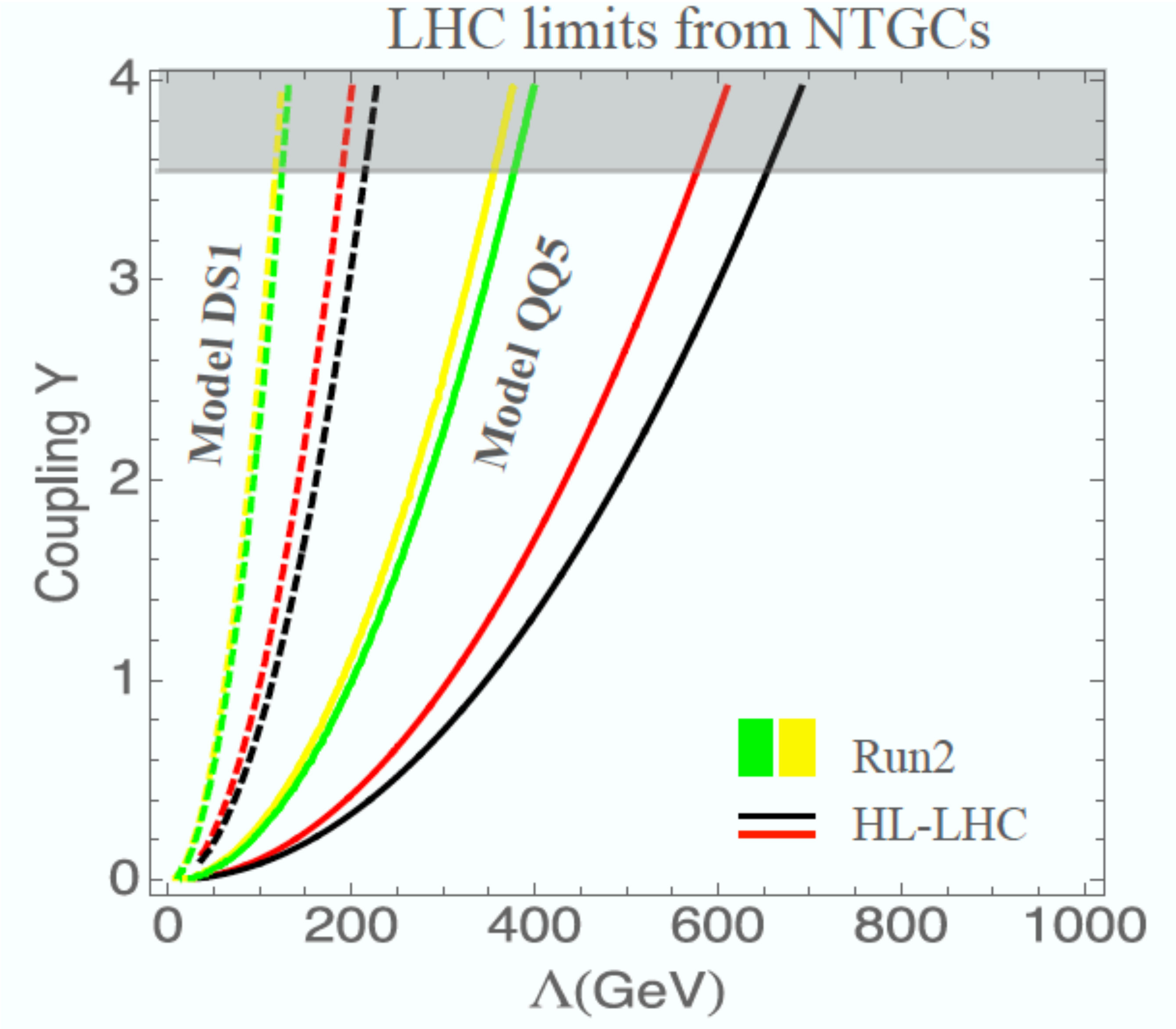


Limits on f_5^Z and f_5^γ from CMS



Combined ATLAS and CMS
1 and 2 sigma limits on
dim-8 Wilson coefficients

Limits on the models



Translate the limits on the WCs into limits on the mass and coupling of the benchmark models

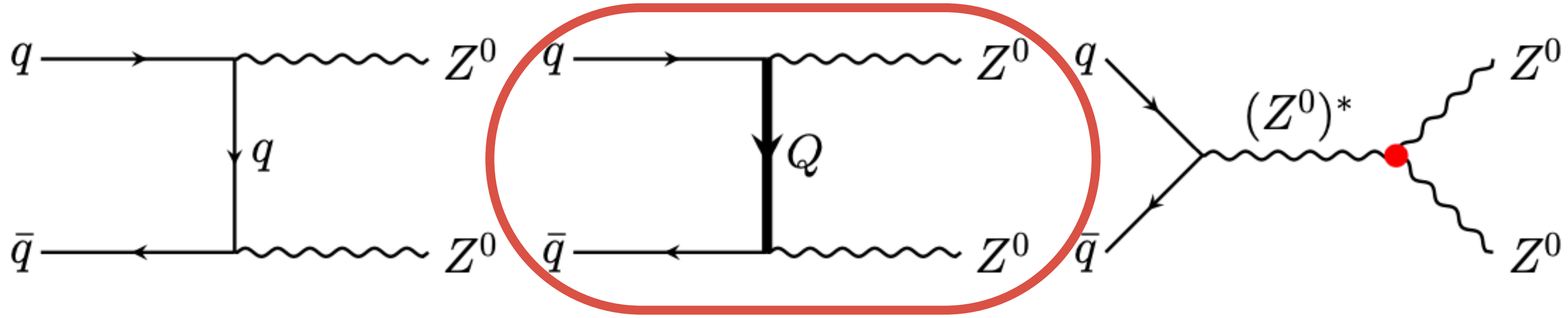
Current limits on models very weak: $\Lambda > 100$ GeV

Prediction for HL-LHC, sensitivity based on projecting the luminosity and using the last bin only

Based on [Cepedello, FE, Hirsch, Sanz ’24]: 2409.06776

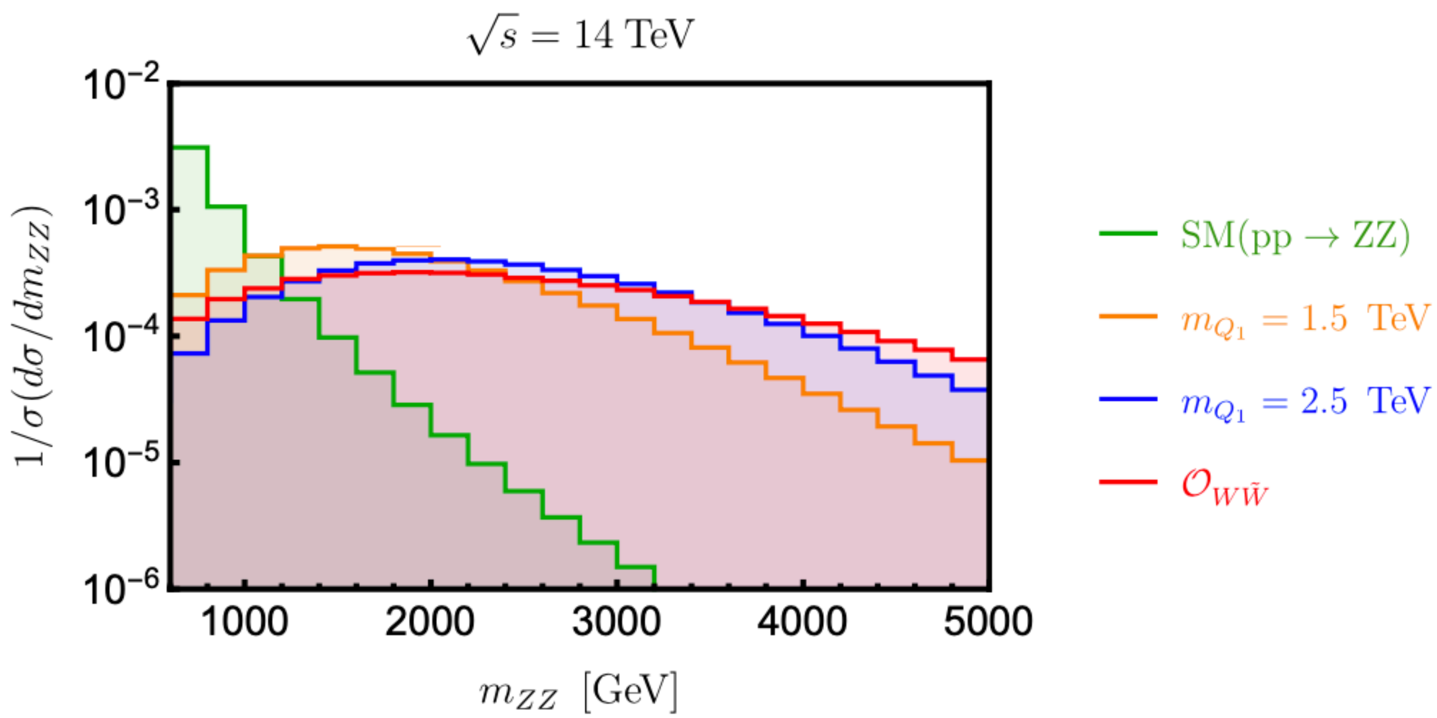
Bonus: Faking ZZZ?!

Faking ZZZ with VLQs



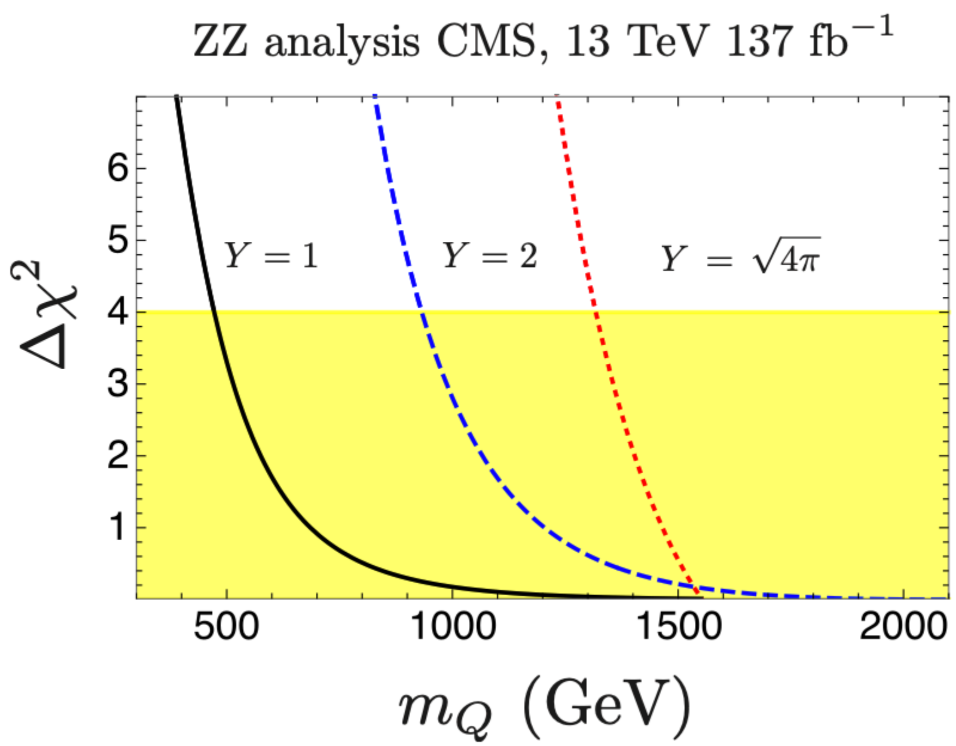
NTGC searches via $pp \to ZZ \to 4l$, ZZ can also be produced at tree-level via a VLQ

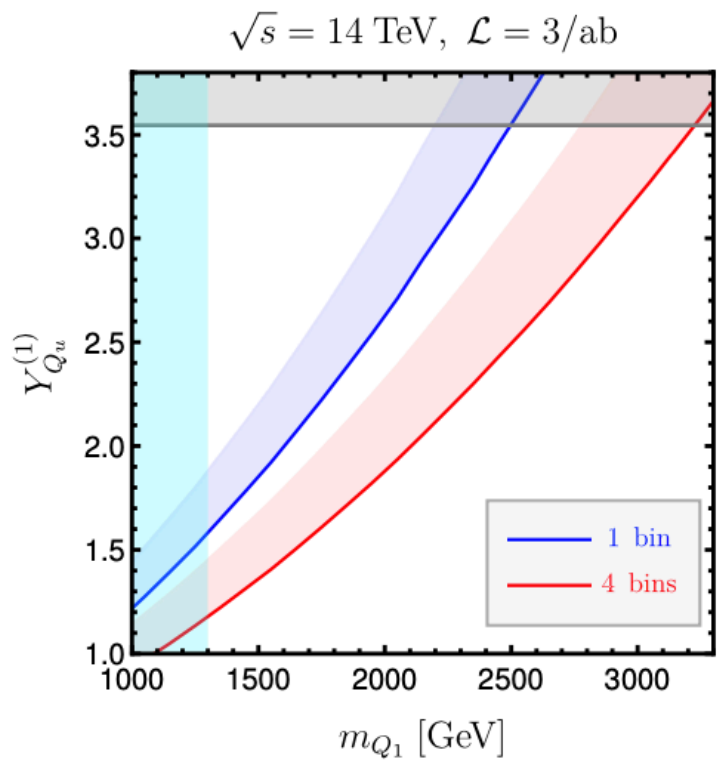
q-Q mixing $\sim \frac{y_Q v}{m_Q}$ suppressed with $m_Q \Rightarrow$ diagram scales as m_Q^{-4}, same as dim-8 operators!



Vector-like quarks

- we can have 7 different VLQs that couple to a SM quark + Higgs boson
- take into account constraints from low-energy and LHC data (e.g. Δm_W, CKM unitarity, β-, K-, D-, B- decays, Z pole cross section)
- focus on one VLQ Q_1 with $\mathscr{L}_Y \supset Y_{Q_u} \bar{Q}_1 u_R H^\dagger$ and only $Y^{(1)}_{Q_u} \neq 0$ for $m_{Q_1} \sim$ TeV and $Y^{(1)}_{Q_u} \lesssim 1$





direct limit $m_{Q_1} \gtrsim 1.3$ TeV from pair production VLQ searches

NTGC searches additionally constrain only a small region close to $Y \sim \sqrt{4\pi}$

Conclusions

- NTGC searches provide important tests for the gauge structure of the SM, clean channel that improves with higher luminosity
- no dim-6 contributions, we presented a basis of dimension-8 operators that generate all 4 form factors
- We classified specific UV completions: Models with two heavy vector-like leptons that contribute via pentagon diagrams
- Limits on the models derived from $ZZ \to 4l$ at ATLAS and CMS very weak, in some cases below $\Lambda = 100$ GeV (EFT assumption not valid)
- Design tailored (direct) searches for these models
- On-shell ZZ could be explained by VLQs instead of NTGC, might be interesting for HL LHC

EFTs and Beyond

3–5 December 2024

Online workshop

Topics covered:

Standard Model Effective Field Theory (SMEFT)

Computational Tools and Methods in EFTs

EFTs in the Standard Model and Beyond

Thank you!

Backup slides

Analytic matching formula

We can derive an analytic formula for the matching of fermionic UV models to the NTGCs

(r: SU(2) representation, y: hypercharge)

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

Mixing of VLQs

Yukawa interactions

$$\mathcal{L}_{\mathrm{Y}} = Y_{U_R}\overline{Q}U_RH^\dagger + Y_{D_R}\overline{Q}D_RH + Y_{Q_u}\overline{Q_1}u_RH^\dagger + Y_{Q_d}\overline{Q_1}d_RH + Y_{Q_7}\overline{Q_7}u_RH + Y_{Q_5}\overline{Q_5}d_RH^\dagger + Y_{T_2}\overline{Q}T_2H^\dagger + Y_{T_1}\overline{Q}T_1H + \mathrm{h.c.}$$

Mass terms

$$\mathcal{L}_{\mathrm{M}} = m_{U_R}\overline{U_L}U_R + m_{D_R}\overline{D_L}D_R + m_{Q_1}\overline{Q_{1,L}}Q_{1,R} + m_{Q_5}\overline{Q_{5,L}}Q_{5,R} + m_{Q_7}\overline{Q_{7,L}}Q_{7,R} + m_{T_1}\overline{T_{1,L}}T_{1,R} + m_{T_2}\overline{T_{2,L}}T_{2,R} + \mathrm{h.c.}$$

Up and down type mass matrix

$$\mathcal{M}_d = \begin{pmatrix} \frac{1}{\sqrt{2}}y_dv & 0 \\ \frac{1}{\sqrt{2}}Y_{Q_d}v & m_{Q_1} \end{pmatrix}, \qquad \mathcal{M}_u = \begin{pmatrix} \frac{1}{\sqrt{2}}y_uv & 0 & 0 \\ \frac{1}{\sqrt{2}}Y_{Q_u}v & m_{Q_1} & 0 \\ -\frac{1}{\sqrt{2}}Y_{Q_7}v & 0 & m_{Q_7} \end{pmatrix}.$$

Left and right mixing matrix

$$s^V_{i4,d} \simeq \frac{Y^{(i)}_{Q_d}v}{\sqrt{2}m_{Q_1}}\left(\frac{m_{d_i}}{m_{Q_1}}\right), \qquad s^V_{i4,u} \simeq \frac{Y^{(i)}_{Q_{u/7}}v}{\sqrt{2}m_{Q_{1/7}}}\left(\frac{m_{u_i}}{m_{Q_{1/7}}}\right),$$

$$s^U_{i4,d} \simeq \frac{Y^{(i)}_{Q_d}v}{\sqrt{2}m_{Q_1}}, \qquad s^U_{i4,u} \simeq \frac{Y^{(i)}_{Q_{u/7}}v}{\sqrt{2}m_{Q_{1/7}}},$$

Modified CC and NC vertices

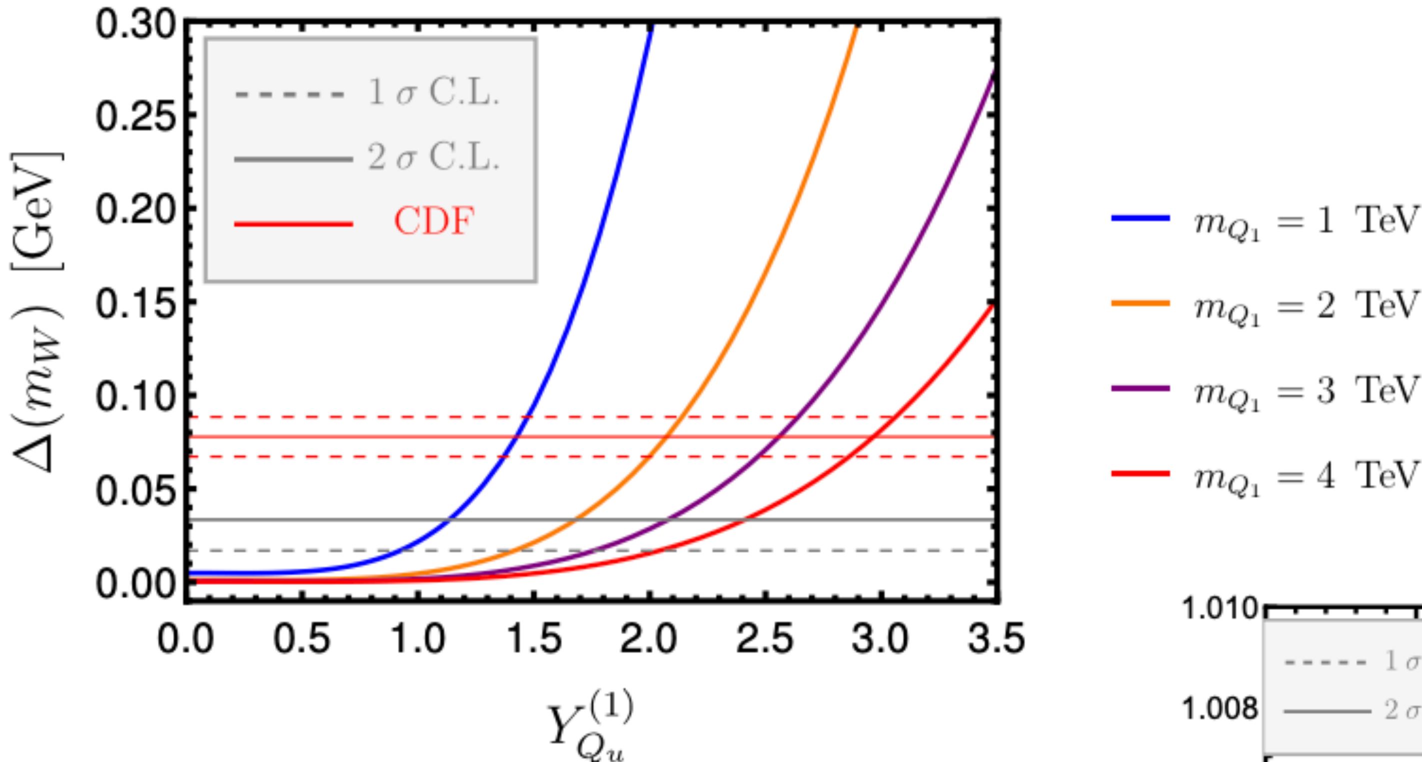
Modified q-q-W and q-q-Z couplings from integrating out the VLQs

$$\begin{aligned}
\mathcal{L}_{W,Z} = &-\frac{g_2}{\sqrt{2}} W_\mu^+ \bar{u}_i \gamma^\mu \quad \Big([V_{CKM}(\mathbb{1} + v^2 C_{Hq}^3)]_{ij} P_L + \frac{v^2}{2}[C_{Hud}]_{ij} P_R \Big) d_j + \text{h.c.} \\
&-\frac{g_2}{6c_W} Z_\mu \bar{u}_i \gamma^\mu \quad \Big([(3 - 4s_W^2)\mathbb{1} + 3v^2 V_{CKM}\{C_{Hq}^{(3)} - C_{Hq}^{(1)}\} V_{CKM}^\dagger]_{ij} P_L \\
&\qquad\qquad\qquad\quad - [4s_W^2 \mathbb{1} + 3v^2 C_{Hu}]_{ij} P_R \Big) u_j \\
&-\frac{g_2}{6c_W} Z_\mu \bar{d}_i \gamma^\mu \quad \Big([(2s_W^2 - 3)\mathbb{1} + 3v^2\{C_{Hq}^{(3)} + C_{Hq}^{(1)}\}]_{ij} P_L \\
&\qquad\qquad\qquad\quad + [2s_W^2 \mathbb{1} + 3v^2 C_{Hd}]_{ij} P_R \Big) d_j .
\end{aligned}$$

matching for the dim-6 SMEFT WCs

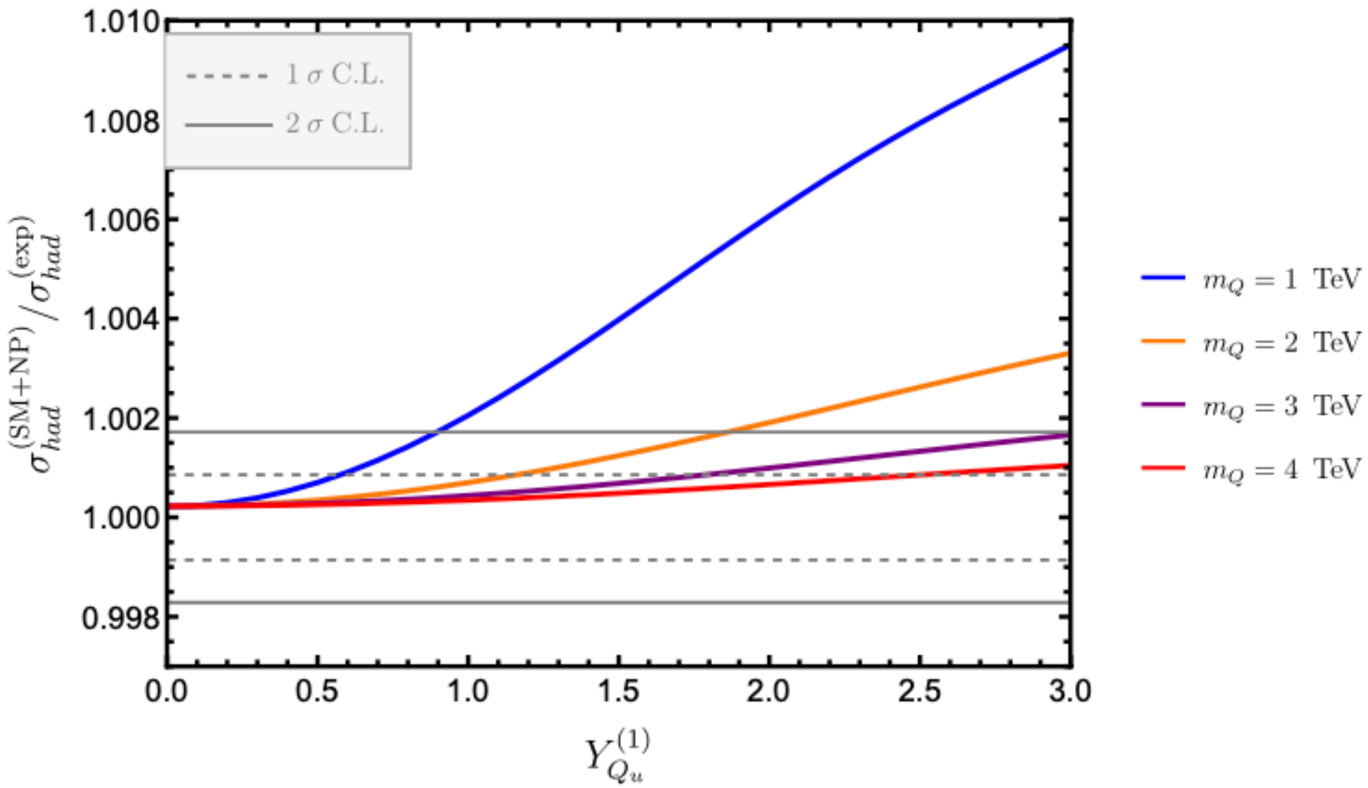
$$\begin{aligned}
[C_{Hu}]_{ij} &= -\frac{(Y_{Q_u}^{(i)})^* Y_{Q_u}^{(j)}}{2m_{Q_1}^2} + \frac{(Y_{Q_7}^{(i)})^* Y_{Q_7}^{(j)}}{2m_{Q_7}^2}, \\
[C_{Hd}]_{ij} &= \frac{(Y_{Q_d}^{(i)})^* Y_{Q_d}^{(j)}}{2m_{Q_1}^2}, \\
[C_{Hud}]_{ij} &= \frac{(Y_{Q_u}^{(i)})^* Y_{Q_d}^{(j)}}{2m_{Q_1}^2}, \\
[C_{Hq}^{(3)}]_{ij} &= [C_{Hq}^{(1)}]_{ij} = 0.
\end{aligned}$$

Constraints on VLQ

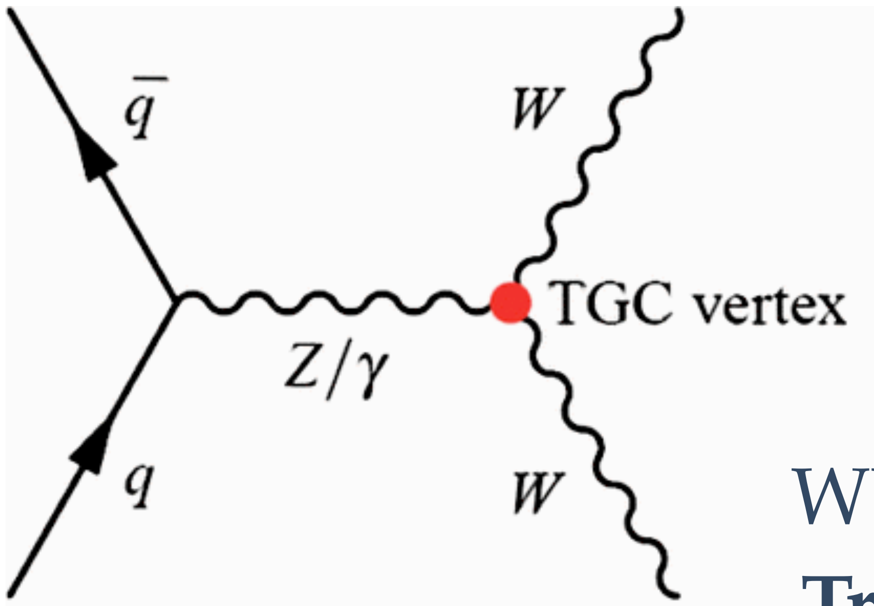


Constraints on m_{Q_1} and $Y^{(1)}_{Q_u}$ from $\Delta(m_W)$: CDF measurement compatible with sizeable Yukawa couplings $Y^{(1)}_{Q_u} \gtrsim 1$

Constraints on m_{Q_1} and $Y^{(1)}_{Q_u}$ from σ_{had}: $Y^{(1)}_{Q_u} \lesssim 1$ for $m_{Q_1} = 1$ TeV and weaker for larger masses



Diboson Production



Anomalous gauge couplings provide a strong test of the mechanism of EWSB

WW(Z/A) coupling, clean channel, high stats
Traditional: dilepton+MET (since LEP times) and now we also got Z+jj from VBF

Within SMEFT, several operators contribute at **dimension-six**

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

and

$$\mathcal{O}_{3W} = \frac{c_{3W}}{\Lambda^2} W_\mu^\nu W_\nu^\rho W_\rho^\mu$$