Time to go beyond Triple-Gauge-Coupling interpretation of *W* pair production

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Based on:

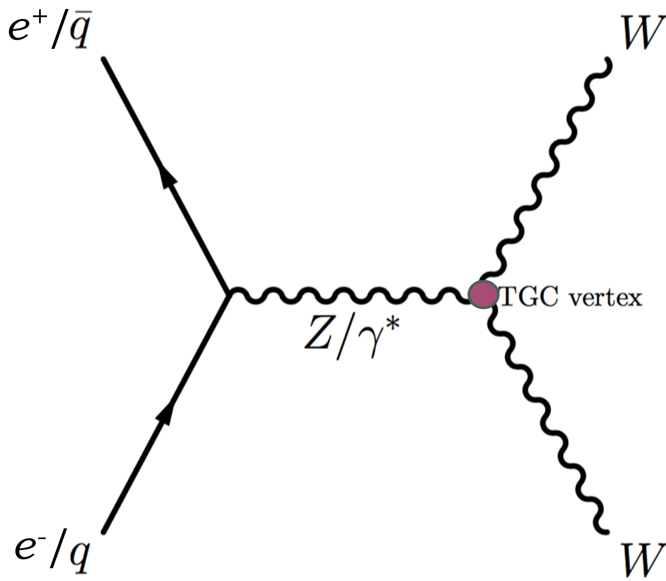
- **ZZ, Phys.Rev.Lett.118,011803, arXiv: 1610.01618**

See also: Grojean, Montull, Riembau, ZZ, to appear

Introduction

- It is often said…

"W pair production measures triple gauge couplings (TGCs)…"



$$\begin{aligned}\mathcal{L}_{\mathrm{TGC}} \;=\; ig\Big\{ & (W^+_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^{+\mu})\big[(1+\delta g_{1z})\, c_\theta Z^\nu + s_\theta A^\nu\big] \\ & + \frac{1}{2} W^+_{[\mu,} W^-_{\nu]} \big[(1+\delta\kappa_z)\, c_\theta Z^{\mu\nu} + (1+\delta\kappa_\gamma)\, s_\theta A^{\mu\nu}\big] \\ & + \frac{1}{m_W^2} W_\mu^{+\nu} W_\nu^{-\rho} \big(\lambda_z c_\theta Z_\rho{}^\mu + \lambda_\gamma s_\theta A_\rho{}^\mu\big)\Big\}\end{aligned}$$

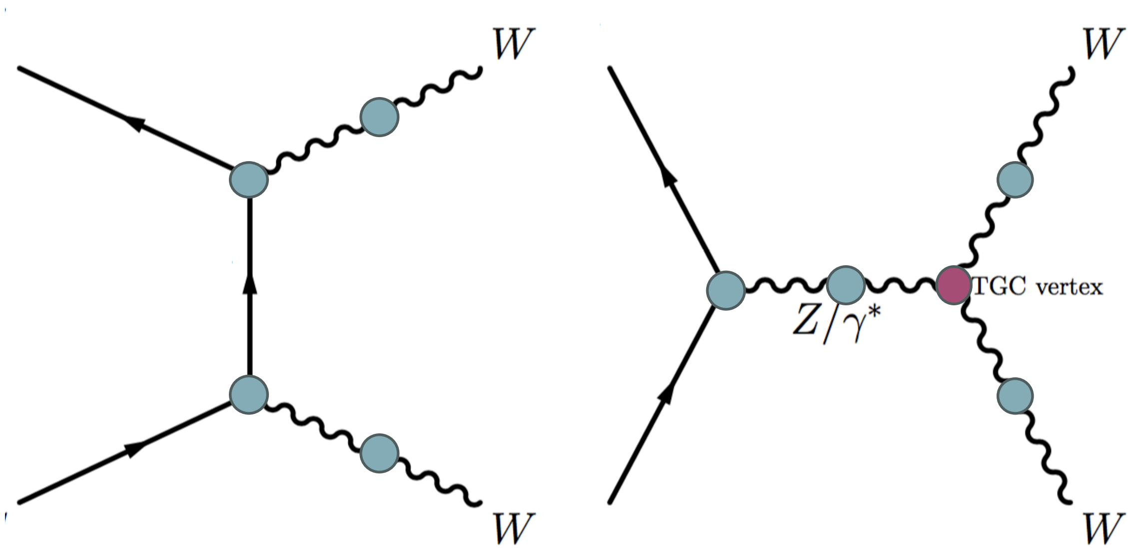
Anomalous TGCs

- =0 in the Standard Model,
- may be nonzero due to new physics

-- *Hagiwara, Hikasa, Peccei, Zeppenfeld (1987)*

Introduction

- But there can be **other new physics effects**!



- How do we know we are measuring the **TGC vertex**?

Introduction

- Common lore:

"We are measuring TGCs because other new physics effects are constrained to be very small by electroweak precision data (EWPD). So if there is any new physics showing up in W pair production, it should be dominated by anomalous TGCs."

- We shall call this the **TGC dominance assumption**.
- This underlies TGC interpretation of *W* pair production.
  - *Is it valid?*
  - *Will it be valid forever?*
  - *If not, what should we do?*

This talk

- **Effective field theory (EFT)** as a tool to critically assess the validity of the TGC dominance assumption.

- From LEP to LHC: TGC interpretation of W pair production used to be justified, but is **not any more**!

- **Going beyond TGC framework** to learn more about new physics from current and future data.

Effective field theory (EFT):
organization of new physics effects

- New physics could be anything.
- But at energies much lower than new particle masses Λ,

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i c_i \frac{\mathcal{O}_i}{v^2} + \ldots \quad \text{where} \quad c_i \sim \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$$

  - Dimension-6 effective operators (dominant new physics effects).
  - Higher-order terms (usually less important).
- Theory prediction for observables

$$\hat{\mathcal{O}}_{\rm theory} = \hat{\mathcal{O}}_{\rm SM}\left(1 + \delta(c_i)\right)$$

- Data → EFT operator coefficients (c_i) → infer new physics.

W pair production in EFT

- At tree level, the following dimension-6 operators contribute to $f\bar{f} \to W^+W^-$:

$$\mathcal{O}_{HWB} = H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_{HD} = |H^\dagger (D_\mu H)|^2,$$
$$\mathcal{O}_{3W} = \epsilon^{abc} W^{a\nu}_{\mu} W^{b\rho}_{\nu} W^{c\mu}_{\rho}, \quad [\mathcal{O}_{ll}]_{ijkn} = (\bar{l}_i \gamma_\mu l_j)(\bar{l}_k \gamma^\mu l_n),$$
$$[\mathcal{O}^{(3)}_{HF}]_{ij} = i\big(H^\dagger \sigma^a (D_\mu H) - (D_\mu H^\dagger)\sigma^a H\big)(\bar{F}_i \gamma^\mu \sigma^a F_j),$$
$$[\mathcal{O}^{(1)}_{HF}]_{ij} = i\big(H^\dagger (D_\mu H) - (D_\mu H^\dagger) H\big)(\bar{F}_i \gamma^\mu F_j),$$
$$[\mathcal{O}_{Hf}]_{ij} = i\big(H^\dagger (D_\mu H) - (D_\mu H^\dagger) H\big)(\bar{f}_i \gamma^\mu f_j),$$

  - Notation: F = q, l; f = u, d, e.

- I have adopted the Warsaw basis.
  - Physics is basis-independent.

New physics effects from dimension-6 operators

- **Anomalous TGCs**

$$\mathcal{L}_{\rm TGC} = ig\Big\{(W^+_{\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu})\big[(1+\delta g_{1z})\,c_\theta Z^\nu + s_\theta A^\nu\big] + \frac{1}{2}W^+_{[\mu,}W^-_{\nu]}\big[(1+\delta\kappa_z)\,c_\theta Z^{\mu\nu} + (1+\delta\kappa_\gamma)\,s_\theta A^{\mu\nu}\big] + \frac{1}{m_W^2}W_\mu^{+\nu}W_\nu^{-\rho}(\lambda_z c_\theta Z_\rho{}^\mu + \lambda_\gamma s_\theta A_\rho{}^\mu)\Big\}$$

- ***W* boson mass shift**

$$\mathcal{L}_{m_W} = (1+\delta_m)^2\frac{g^2v^2}{4}W^+_\mu W^{-\mu}$$

- ***Zff*, *Wff'* vertex corrections** [*f'* = *SU(2)$_L$* partner of *f*]

$$\mathcal{L}_{\rm vertex} = \sum_f \frac{g}{c_\theta}\big((T^3_f - Q_f s_\theta^2)\delta_{ij} + [\delta g^{Zf}_{L/R}]_{ij}\big)Z_\mu \bar f_i\gamma^\mu f_j + \frac{g}{\sqrt{2}}\Big[(\delta_{ij} + [\delta g^{Wq}_L]_{ij})W^+_\mu \bar u_{Li}\gamma^\mu(V_{\rm CKM}d_L)_j + (\delta_{ij} + [\delta g^{Wl}_L]_{ij})W^+_\mu \bar\nu_i\gamma^\mu e_{Lj} + \text{h.c.}\Big]$$

Each **anomalous coupling** is a function of operator coefficients.

New physics effects from dimension-6 operators

Number of independent parameters:

- 3 anomalous TGCs

$$\delta g_{1z} = \frac{1}{c_\theta^2 - s_\theta^2}\left(-\frac{s_\theta}{c_\theta} C_{HWB} - \frac{1}{4} C_{HD} - \delta v\right),$$

$$\delta\kappa_\gamma = \frac{c_\theta}{s_\theta} C_{HWB}, \quad \lambda_\gamma = -\frac{3}{2} g\, C_{3W}$$

- 1 W boson mass shift

$$\delta_m = -\frac{1}{c_\theta^2 - s_\theta^2}\left(c_\theta s_\theta C_{HWB} + \frac{1}{4} c_\theta^2 C_{HD} + s_\theta^2 \delta v\right)$$

- 3+4 (leptonic+hadronic) *Zff, Wff'* vertex corrections

$$\left[\delta g_L^{Zf}\right]_{ij} = T_f^3 \left[C_{HF}^{(3)}\right]_{ij} - \frac{1}{2}\left[C_{HF}^{(1)}\right]_{ij} - \left[Q_f \frac{c_\theta s_\theta}{c_\theta^2 - s_\theta^2} C_{HWB} + \left(T_f^3 + Q_f \frac{s_\theta^2}{c_\theta^2 - s_\theta^2}\right)\left(\frac{1}{4} C_{HD} + \delta v\right)\right]\delta_{ij},$$

$$\left[\delta g_R^{Zf}\right]_{ij} = -\frac{1}{2}\left[C_{Hf}\right]_{ij} - Q_f \left[\frac{c_\theta s_\theta}{c_\theta^2 - s_\theta^2} C_{HWB} + \frac{s_\theta^2}{c_\theta^2 - s_\theta^2}\left(\frac{1}{4} C_{HD} + \delta v\right)\right]\delta_{ij}$$

where $\delta v \equiv \frac{1}{2}\left([C_{Hl}^{(3)}]_{11} + [C_{Hl}^{(3)}]_{22}\right) - \frac{1}{4}\left([C_{ll}]_{1221} + [C_{ll}]_{2112}\right)$

TGCs vs. other anomalous couplings

TGC dominance assumption =

- The **additional 1 + (3+4) parameters** are very constrained by EWPD, and **can be neglected** in W pair production.
- Therefore, W pair production can be **interpreted** as probing the **3 anomalous TGCs**.

"How good is this assumption?"

- We focus on the following observables:
  - $\frac{d\sigma}{d\cos\theta}(e^+e^- \to W^+W^- \to qq\ell\nu)$ at LEP2 [LEP2 report, 1302.3415]
  - $pp \to W^+W^- \to e^\pm\mu^\mp\nu\nu$ leading lepton p_T at 8TeV LHC [ATLAS, 1603.01702]

TGCs vs. other anomalous couplings

We compare:

- anomalous TGC effects considered in conventional TGC fits

vs.

- possible effects from other 8 anomalous couplings which are neglected in conventional TGC fits.

In particular, we set each parameter to its 2σ upper bound.

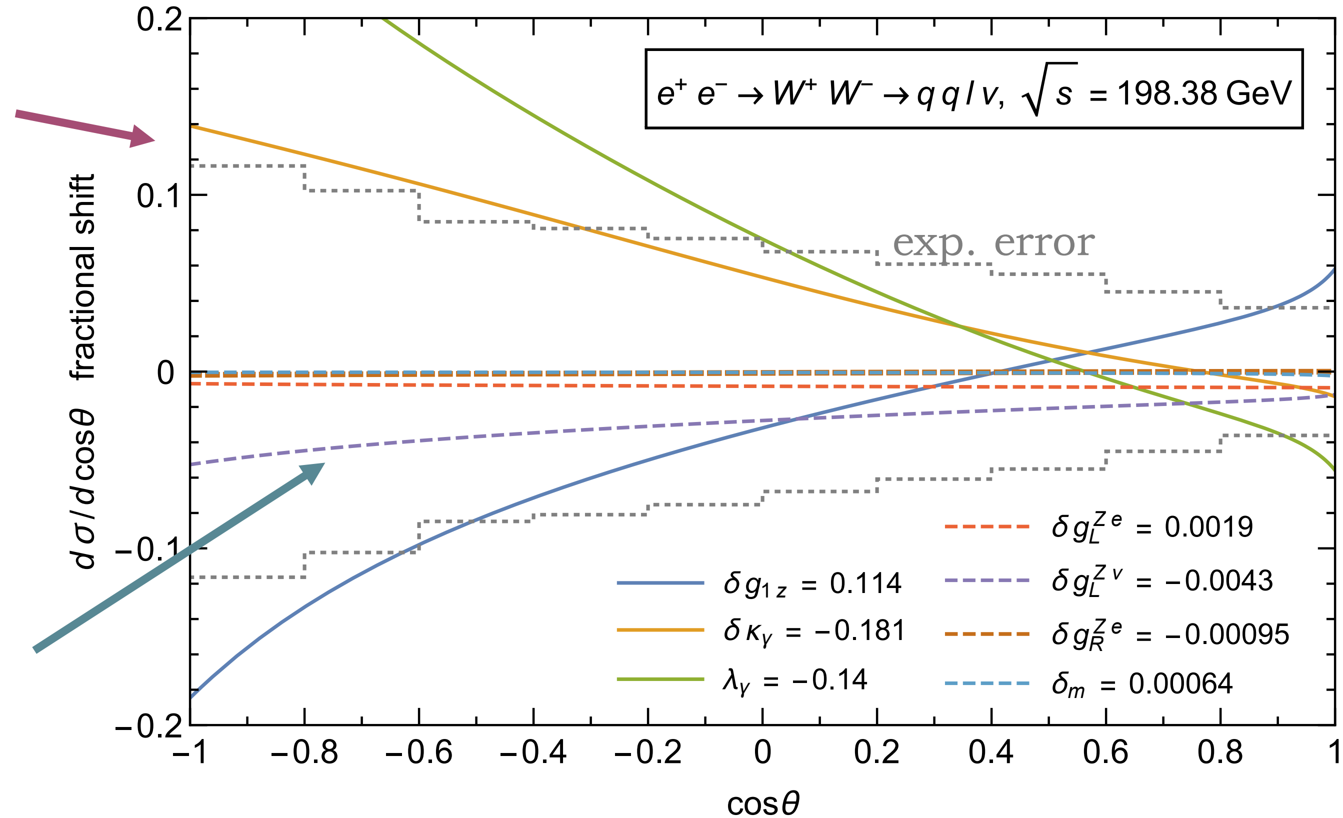
- TGCs from: [LEPEWWG/TGC/2002-02] [Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, Plehn, Rauch, 1604.03105].
- EWPD constraints from: [Falkowski, Riva, 1411.0669].

See also: Pomarol, Riva, 1308.2803; Ellis, Sanz, You, 1410.7703; Ellis, You, 1510.04561; Berthier, Bjørn, Trott, 1606.06693; Falkowski, Gonzalez-Alonso, Greljo, Marzocca, Son, 1609.06312; Ellis, Roloff, Sanz, You, 1701.04804.

TGCs vs. other anomalous couplings: the case of LEP2

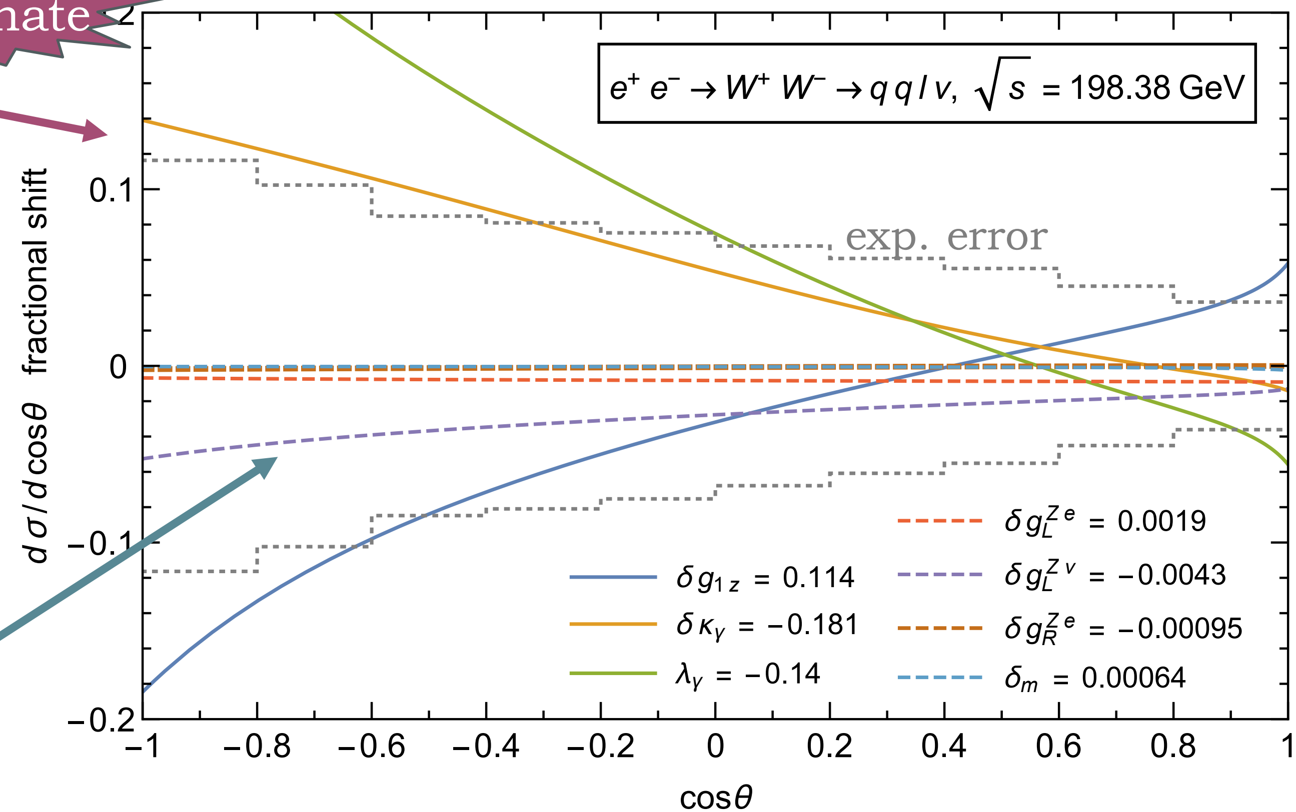
Solid: anomalous TGCs

Dashed: other anomalous couplings



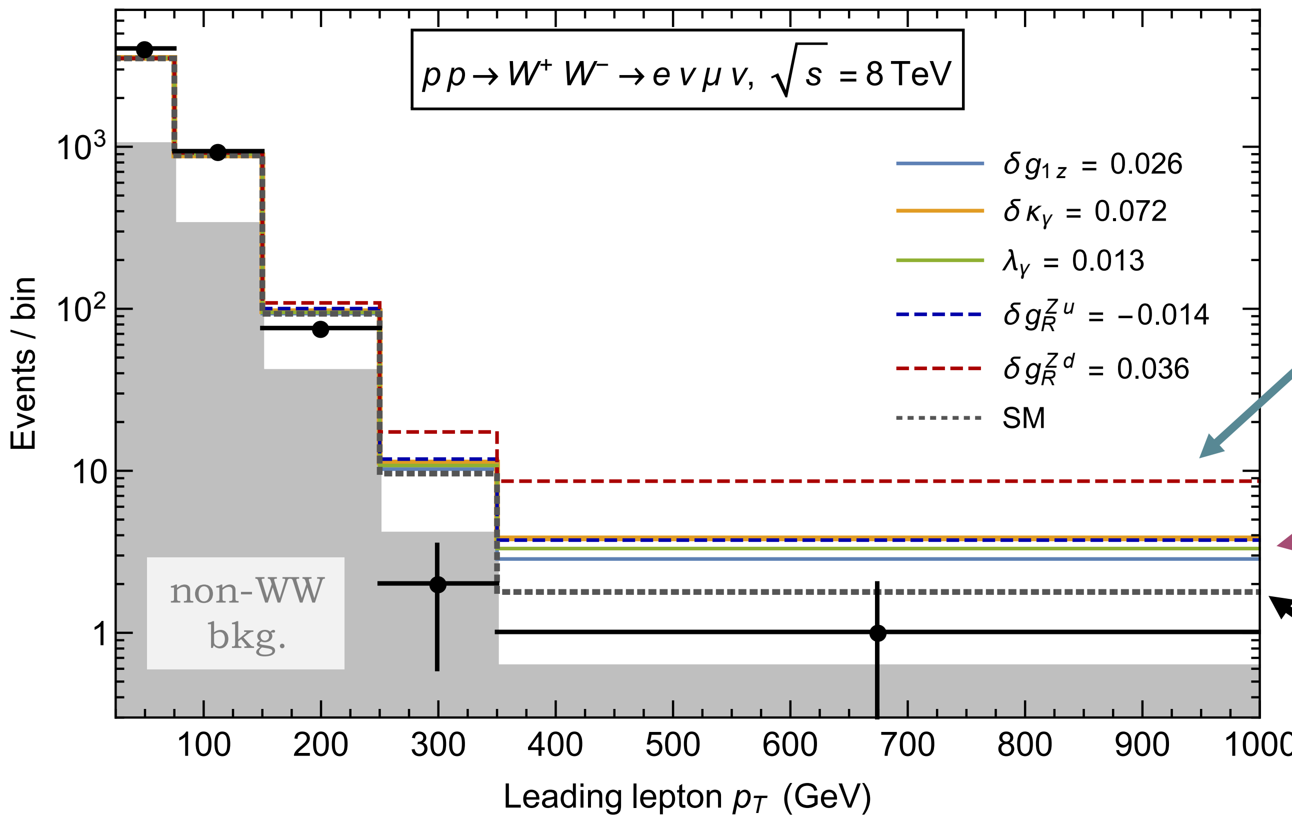
TGCs vs. other anomalous couplings: the case of LEP2

Solid: dominate **anomalous TGCs**



Dashed: other anomalous couplings

TGCs vs. other anomalous couplings: the case of 8TeV LHC

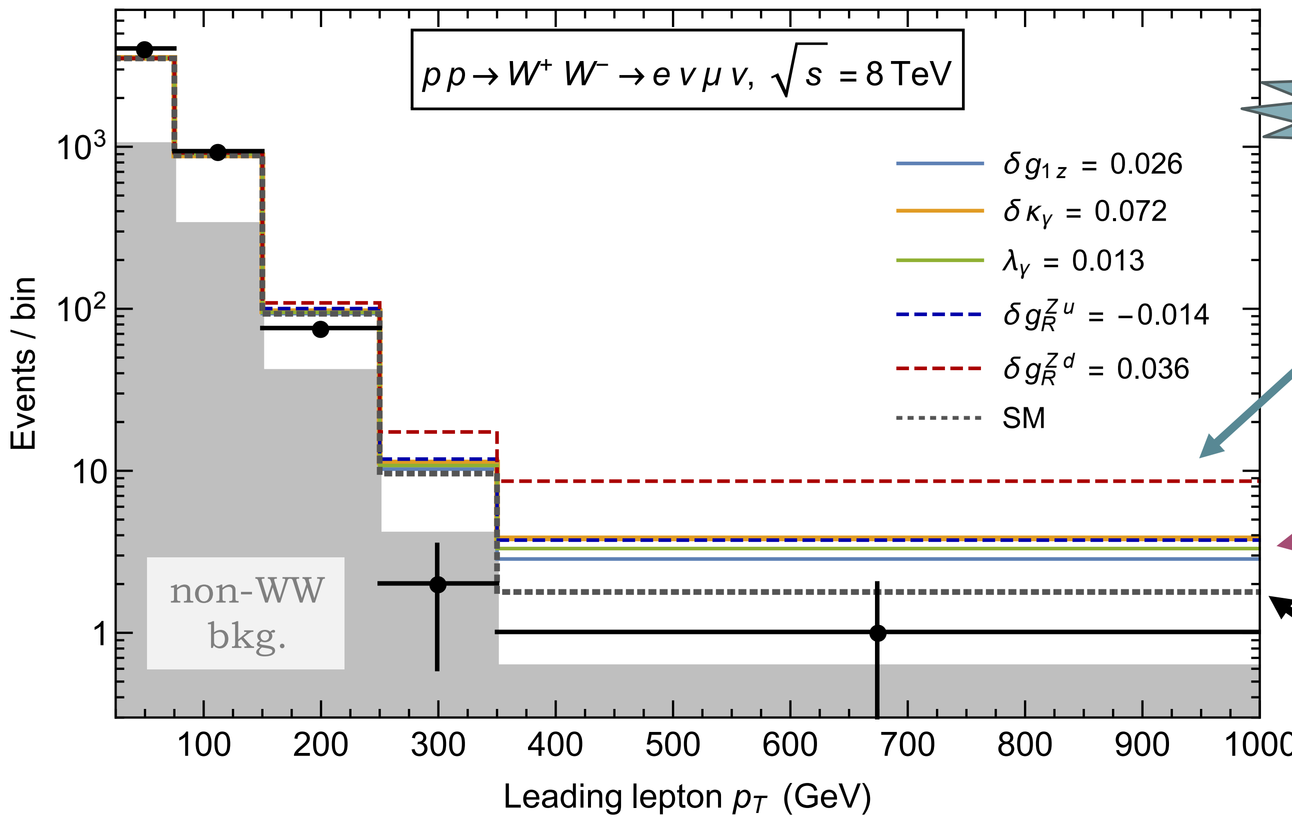


Dashed: other anomalous couplings

Solid: anomalous TGCs

Dotted: SM prediction

TGCs vs. other anomalous couplings: the case of 8TeV LHC



dominate

Dashed: other anomalous couplings

Solid: anomalous TGCs

Dotted: SM prediction

What do we learn?

- Interpreting W pair production as TGC measurements **was** justified by EWPD at LEP2, but **is not** at the LHC.

"Will the situation hold in the future?"
"How about a future lepton collider such as CLIC?"
"If TGC interpretation fails, what should we do?"
…

To address these questions, let's first understand:

- What makes the difference between LEP2 and LHC?

What do we learn?

What makes the difference between LEP2 and LHC?

- Z couplings to (RH) quarks are less constrained + $Z \rightarrow bb$ anomaly.
- Effects constrained by EWPD are enhanced at higher energy, e.g.

$$\mathcal{A}(f_R \bar{f}_L \to W_L^+ W_L^-) = \frac{\hat{s}}{2m_W^2} g^2 \sin\theta \left[-\delta g_R^{Zf} + Q_f \left(s_\theta^2 \delta g_{1z} - \frac{s_\theta^2}{c_\theta^2} \delta\kappa_\gamma \right) \right] + \mathcal{O}(\hat{s}^0)$$

constrained by EWPD but not negligible here!

How to understand this high-energy behavior?

- Goldstone equivalence theorem + dimensional analysis.

What do we learn?

- Important operators here are of the form

$$\mathcal{O}_{Hf} = i\big(H^\dagger(D_\mu H) - (D_\mu H^\dagger)H\big)(\bar{f}\gamma^\mu f) \supset i(\phi^-\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^-)(\bar{f}\gamma^\mu f)$$

  - Higgs fields take their Goldstone components rather than vev.

$$\begin{aligned}
\mathcal{A}(f_R\bar{f}_L \to W_L^+W_L^-) &= \mathcal{A}(f_R\bar{f}_L \to \phi^+\phi^-)\left[1 + \mathcal{O}\Big(\frac{m_W^2}{\hat{s}}\Big)\right] \\
&= \frac{\hat{s}}{4m_W^2} g^2 \sin\theta \left(C_{Hf}\right) + \mathcal{O}(\hat{s}^0) \\
&= \frac{\hat{s}}{2m_W^2} g^2 \sin\theta \left[-\delta g_R^{Zf} + Q_f\Big(s_\theta^2\delta g_{1z} - \frac{s_\theta^2}{c_\theta^2}\delta\kappa_\gamma\Big)\right] + \mathcal{O}(\hat{s}^0)
\end{aligned}$$

  - Note: This type of operators also contributes to $f\bar{f} \to Z^{(*)} \to f'\bar{f}'$, but their effects are not enhanced at high energy because $|H|^2 \to v^2/2$ (so Drell-Yan does not help!)

What do we learn?

"So the situation will hold in the future, as we continue to explore the high-energy frontier."

See also Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer, 1609.08157 for similar discussion.

- It is time to update the way we perform EFT analyses.

- To take better advantage of high-energy data to learn about new physics, we need a more complete picture of EFT.

[Grojean, Montull, Riembau, ZZ, to appear]

An updated picture of EFT analyses?

AC	EWPD	$e^+e^- \to W^+W^-$	$pp \to W^+W^-$
δ_m	$\surd$		
δg_L^{Ze}	$\surd$		
$\delta g_L^{Z\nu}$	$\surd$		
δg_R^{Ze}	$\surd$		
δg_L^{Zu}	$\surd$		
δg_L^{Zd}	$\surd$		
δg_R^{Zu}	$\surd$		
δg_R^{Zd}	$\surd$		
δg_{1z}		$\surd^\star$	$\surd^\star$
$\delta \kappa_\gamma$		$\surd^\star$	$\surd^\star$
λ_γ		$\surd^\star$	$\surd^\star$

anomalous couplings (ACs) constrained by EWPD (δ_m through δg_R^{Zd})

anomalous TGCs (δg_{1z}, $\delta \kappa_\gamma$, λ_γ)

*** = enhanced at high energy**

An updated picture of EFT analyses?

LHC

AC	EWPD	$e^+e^- \to W^+W^-$	$pp \to W^+W^-$
δ_m	$\surd$		$\surd$
δg_L^{Ze}	$\surd$		
$\delta g_L^{Z\nu}$	$\surd$		
δg_R^{Ze}	$\surd$		
δg_L^{Zu}	$\surd$		$\surd^\star$
δg_L^{Zd}	$\surd$		$\surd^\star$
δg_R^{Zu}	$\surd$		$\surd^\star$
δg_R^{Zd}	$\surd$		$\surd^\star$
δg_{1z}		$\surd^\star$	$\surd^\star$
$\delta \kappa_\gamma$		$\surd^\star$	$\surd^\star$
λ_γ		$\surd^\star$	$\surd^\star$

anomalous couplings (ACs) constrained by EWPD (δ_m through δg_R^{Zd})

anomalous TGCs (δg_{1z}, $\delta \kappa_\gamma$, λ_γ)

*** = enhanced at high energy**

An updated picture of EFT analyses?

		CLIC/ILC/CEPC/FCC-ee	**LHC**
AC	EWPD	$e^+e^- \to W^+W^-$	$pp \to W^+W^-$
δ_m	$\surd$	$\surd$	$\surd$
δg_L^{Ze}	$\surd$	$\surd$	
$\delta g_L^{Z\nu}$	$\surd$	$\surd^\star$	
δg_R^{Ze}	$\surd$	$\surd^\star$	
δg_L^{Zu}	$\surd$		$\surd^\star$
δg_L^{Zd}	$\surd$		$\surd^\star$
δg_R^{Zu}	$\surd$		$\surd^\star$
δg_R^{Zd}	$\surd$		$\surd^\star$
δg_{1z}		$\surd^\star$	$\surd^\star$
$\delta \kappa_\gamma$		$\surd^\star$	$\surd^\star$
λ_γ		$\surd^\star$	$\surd^\star$

anomalous couplings (ACs) constrained by EWPD: δ_m through δg_R^{Zd}

anomalous TGCs: δg_{1z}, $\delta \kappa_\gamma$, λ_γ

*** = enhanced at high energy**

Conclusions

- Interpretation of W pair production as TGC measurements is based on the TGC dominance assumption.
- This assumption was justified by EWPD for LEP2, but is already challenged by recent LHC data.
- Going to higher energy changes the way we should think about EFT and new physics.
- It is time to go beyond TGC interpretation. High-energy data at present (LHC) and in the future (CLIC etc.) require a more complete treatment of all EFT parameters.