New opportunities on diboson

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Based on ongoing work with Christophe Grojean and Marc Montull

It seems that there is a mass gap between the SM states and the BSM states, so their effect can be encoded in an EFT

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \dots$$

$D_\mu H^\dagger \sigma^i D_\nu H W^i_{\mu\nu} \quad (D_\mu W_{\mu\nu})^2$

$\bar{f}\gamma_\mu f H^\dagger D_\mu H$

Already nailed by LEP

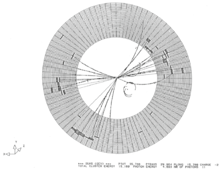
$H^2 G_{\mu\nu} G_{\mu\nu} \quad H^2(\partial_\mu H)^2$

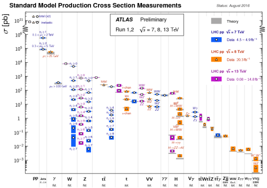
$H^2 H \bar{f} f$

Only job of the LHC

"Lepton colliders are for precision, hadron machines for discovery"

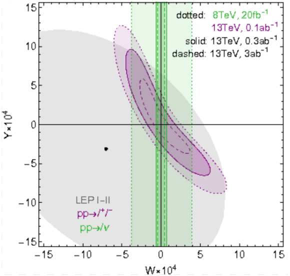
This paradigm has been proven wrong on both sides





One particularly interesting way in which it is wrong is that

"Energy beats accuracy"



Farina et.al.'16

-If a deformation gets enhanced at high energy

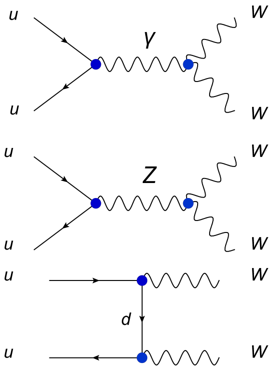
$$\sigma \sim \sigma_{SM} \left(1 + c\, E^2/\Lambda^2 \right)$$

0.1% precision on σ at $E \sim$200GeV $\leftrightarrow$ 10% precision on σ at $E \sim$2TeV

-Previous example, $(D_\mu W_{\mu\nu})$ & $(D_\mu B_{\mu\nu})$ induce E^2 growth in Drell-Yann

-**In this talk, we will focus on diboson.**

Diboson in the SM



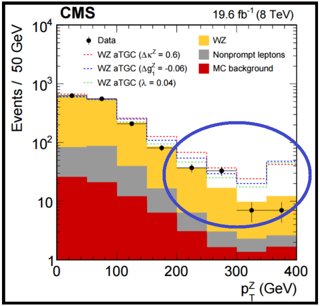
$$\mathcal{M}_\gamma = -i\frac{e^2 \sin\theta}{2m_W^2}\, s\, Q_f$$

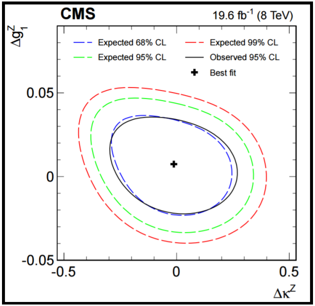
$$\mathcal{M}_Z = -i\frac{e^2 \sin\theta}{2m_W^2}\,\frac{s}{s_W^2}\left(T_f^3 - s_W^2 Q_f\right)$$

$$\mathcal{M}_t = +i\frac{e^2 \sin\theta}{2m_W^2}\,\frac{s}{2s_W^2}$$

Sum does not grow with energy, as expected.
However, it is obvious that a generic deviation from the SM relation will be amplified at large energies.

LHC diboson analyses





likelihood method, Wald gaussian approximation, and Wilks' theorem [59] are used to derive 1D and 2D limits at a 95% confidence level (CL) on each of the three aTGC parameters and every combination of two aTGC parameters, respectively, while all other parameters are set to their SM values. No significant deviation from the SM expectation is observed. Results can be found in Tables 8 and 9, and in Figs. 8, 9, and 10.

$$\text{LEP2} \;:\; \delta g_1^z = 0.051 \pm 0.031, \quad \delta\kappa_\gamma = -0.067 \pm 0.061, \quad \lambda_\gamma = -0.067 \pm 0.036$$
$$\text{LHC} \;:\; \delta g_1^z = 0.010 \pm 0.008, \quad \delta\kappa_\gamma = 0.017 \pm 0.028, \quad \lambda_\gamma = 0.0029 \pm 0.0057$$

This high energy behaviour is whyLHC has surpassed LEP bounds on aTGC, with $\sim$ % on $\delta\kappa_\gamma$, δg_{1z} and λ_γ.

However, this means that LHC is reaching the precision at which Z-pole measurements bounded the $Zf\bar{f}$ vertices. e.g.

$$\mathcal{M}(RR;00) = -i\frac{e^2\sin\theta}{2m_W^2 s_W^2}\, s\left[-\delta g_R^{Zq} + (\delta\kappa_\gamma - \delta\kappa_z)Q_f s_W^2\right] + \mathcal{O}(s^0)$$

We will study diboson including aTGCs

$$\delta g_{1z}\,, \qquad \delta\kappa_\gamma\,, \qquad \lambda_\gamma$$

together with vertex corrections

$$\delta g_L^{Zu}\,, \qquad \delta g_R^{Zu}\,, \qquad \delta g_L^{Zd}\,, \qquad \delta g_R^{Zd}$$

Corrections to W vertices not independent: $\delta g^{Wq} = \delta g_L^{Zu} - \delta g_L^{Zd}$.

LEP anomalous vertices

Model independent bounds on Z coupling to light flavours really bad:

Must reconstruct the charge of the jets to distinguish up- from down-quarks, and quarks from antiquarks for the asymmetries:

$$\delta g_R^{Zu} \sim \delta g_L^{Zu} \sim \delta g_L^{Zd} \sim 5\%\,, \quad \delta g_R^{Zd} \sim 15\%$$

But being agnostic in flavour is not a good attitude in life: if

$$\frac{c_{ij}}{\Lambda^2}\bar{f}_i\gamma_\mu f_j H^\dagger D_\mu H$$

offdiagonal c's must be insanely tuned if $\Lambda \sim$ few TeV.

LEP anomalous vertices

a) MFV: $SU(3)^5$ kills offdiagonal corrections and relates different families, e.g.

$$[\delta g_R^{Zu}]_{ij} = \left(A + B\frac{m_i}{m_3}\right)\delta_{ij}\,, \quad +\mathcal{O}(m_k/m_3 V_{ik} V_{kj}^\star) \text{ for } L$$

$$\begin{array}{lcrcl} \delta g_L^{Zu} & = & -0.002 & \pm & \mathbf{0.003} \\ \delta g_R^{Zu} & = & -0.003 & \pm & \mathbf{0.005} \\ \delta g_L^{Zd} & = & 0.002 & \pm & \mathbf{0.005} \\ \delta g_R^{Zd} & = & 0.016 & \pm & \mathbf{0.027} \end{array}, \quad \rho = \begin{pmatrix} 1 & 0.43 & 0.52 & 0.23 \\ & 1 & 0.19 & 0.36 \\ & & 1 & 0.90 \\ & & & 1 \end{pmatrix}$$

b) Flavour universal:

$$[\delta g_R^{Zu}]_{ij} = A\,\delta_{ij}$$

$$\begin{array}{lcrcl} \delta g_L^{Zu} & = & -0.0017 & \pm & \mathbf{0.002} \\ \delta g_R^{Zu} & = & -0.0023 & \pm & \mathbf{0.005} \\ \delta g_L^{Zd} & = & 0.0028 & \pm & \mathbf{0.0015} \\ \delta g_R^{Zd} & = & 0.019 & \pm & \mathbf{0.008} \end{array}, \quad \rho = \begin{pmatrix} 1 & 0.83 & 0.04 & -0.11 \\ & 1 & -0.13 & -0.05 \\ & & 1 & 0.89 \\ & & & 1 \end{pmatrix}$$

Efrati et al '15

Process	Higgs basis
$\bar{q}_L q_L \to W_T^{\pm} Z_T$	$+\lambda_\gamma$
$\bar{q}_L q_L \to W_L^{\pm} Z_L$	$-\delta g_L^{Zu} + \delta g_L^{Zd} + 0.77\delta g_{1z}$
$\bar{u}_L u_L \to W_T^{+} W_T^{-}$	$+\lambda_\gamma$
$\bar{d}_L d_L \to W_T^{+} W_T^{-}$	$-\lambda_\gamma$
$\bar{u}_L u_L \to W_L^{+} W_L^{-}$	$-\delta g_L^{Zd} + 0.35\delta g_{1z} + 0.05\delta\kappa_\gamma$
$\bar{d}_L d_L \to W_L^{+} W_L^{-}$	$-\delta g_L^{Zu} - 0.43\delta g_{1z} + 0.05\delta\kappa_\gamma$
$\bar{u}_R u_R \to W_L^{+} W_L^{-}$	$-\delta g_R^{Zu} - 0.15\delta g_{1z} + 0.19\delta\kappa_\gamma$
$d_L d_R \to W_L^{+} W_L^{-}$	$-\delta g_R^{Zd} + 0.07\delta g_{1z} - 0.10\delta\kappa_\gamma$

(Notice accidentally small coefficients for TGCs)

We want to perform a global study to answer two questions:

1) Do nonzero Zff affect LHC aTGC constraints?

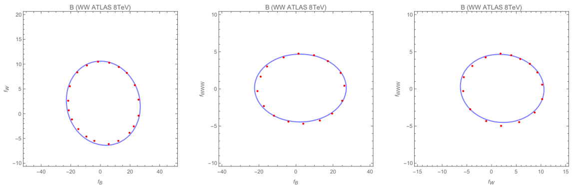
2) Does diboson give us any information on Zff couplings?

LHC diboson analyses

We did an analisis taking into account several dilepton searches at 7, 8 and 13TeV

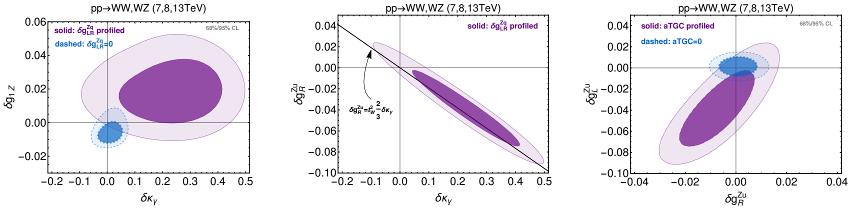
Detector	$\mathcal{L}$[fb^{-1}]	$\sqrt{s}$	Process	Obs.	Ref.
ATLAS	4.6	7TeV	$WW \to \ell\nu\ell\nu$	$p_{T\ell}^{(1)}$	1210.2979
ATLAS	20.3	8TeV	$WW \to \ell\nu\ell\nu$	$p_{T\ell}^{(1)}$	1603.01702
CMS	19.4	8TeV	$WW \to \ell\nu\ell\nu$	$m_{\ell\ell}$	1507.03268
ATLAS	20.3	8TeV	$WZ \to \ell\nu\ell\ell$	p_{TZ}	1603.02151
CMS	19.6	8TeV	$WZ \to \ell\nu\ell\ell$	p_{TZ}	1609.05721
ATLAS	13.3	13TeV	$WZ \to \ell\nu\ell\ell$	m_{WZ}	ATLAS-CONF-2016-043

Cross check with ATLAS/CMS is ok, e.g.



Constraints on aTGCs

Global 7 parameter fit on **diboson data has flat directions**:

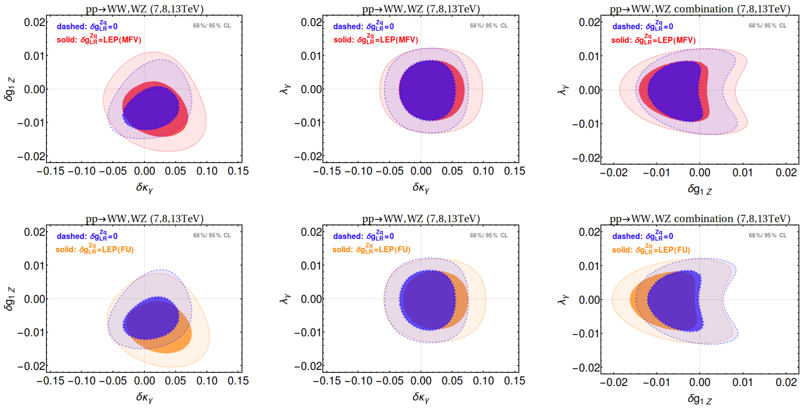


Global fit to diboson / Exclusive fit

When including vertex corrections, LHC data cannot fit the TGCs due to flat directions. Must include LEP constraints on Zff vertices.

$$\chi^2 = \chi^2_{diboson} + \chi^2_{LEP}$$

Constraints on aTGCs



- diboson, anomalous Zff=0
- diboson, anomalous Zff=MFV
- diboson, anomalous Zff=FU

Constraints on aTGCs

Important to remark that there are **no model independent fits**. Even here, hidden assumptions:

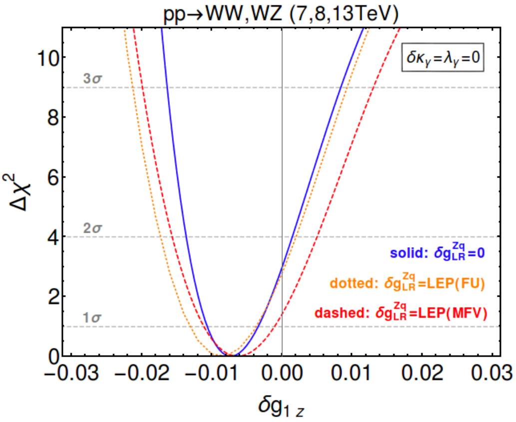
$$\mathcal{L} \supset ie\,\delta\kappa_\gamma W^+_\mu W^-_\nu A_{\mu\nu} + i\frac{e}{m_W^2}\lambda_\gamma W^+_{\mu\nu} W^-_{\nu\rho} A_{\rho\mu}$$

Induces magnetic dipole moment $\sim \delta\kappa_\gamma + \lambda_\gamma$ and electric quadrupole $\sim \delta\kappa_\gamma - \lambda_\gamma$, and both must arise at loop level for minimally coupled theories.

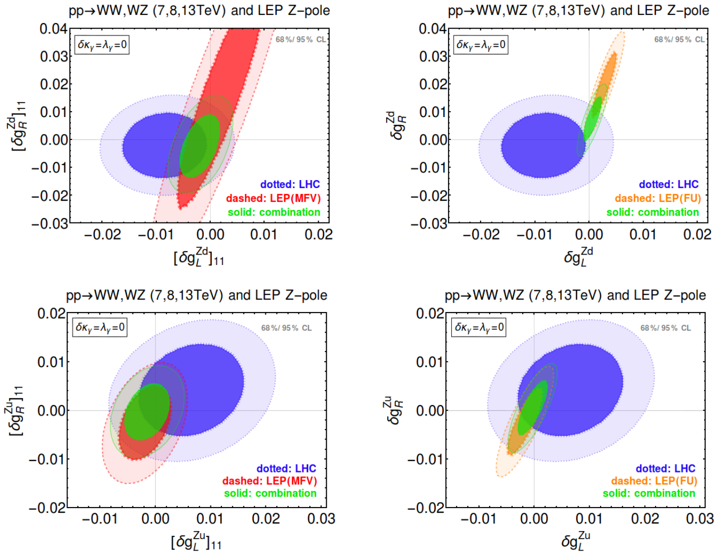
$$\frac{\delta\kappa_\gamma}{\delta g_{1z}} \sim \frac{\lambda_\gamma}{\delta g_{1z}} \sim \frac{1}{16\pi^2}$$

Profiling over $\delta\kappa_\lambda$ and λ_γ assumes to be comparable to δg_{1z}. For a large class of theories, can be set to zero.

Constraints on aTGCs



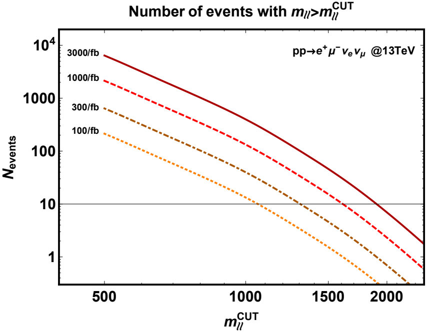
anomalous $Zf\bar{f}$ *@ LHC*



diboson only , LEP MFV , LEP FU , Combination

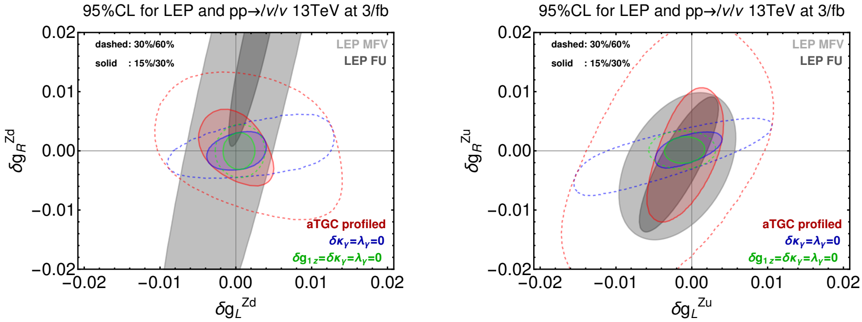
A glimpse to the future

It is interesting to investigate the capabilities of a **HL-LHC phase**

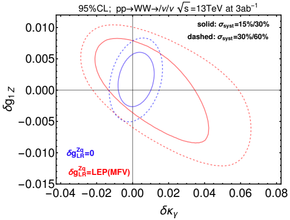


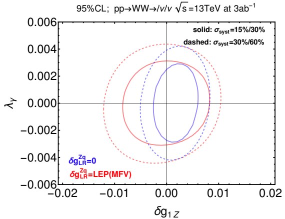
-We used the $m_{\ell\ell}$ observable of $pp \to \ell\nu\ell\nu$ channel.
-Naive rescaling of the 8 and 13TeV systematics: 15% and 30% in the overflow bin. As a dramatic case, we consider 30%/60%.
-The 15%/30% approximately reproduces the ATLAS projections for the TGCs.

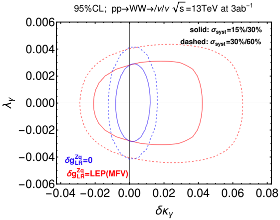
A glimpse to the future

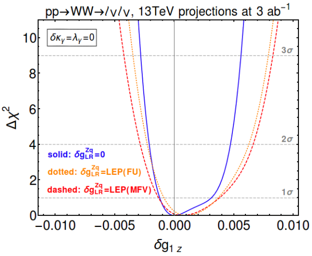


A glimpse to the future









Interpretation

LHC sets bounds $\leq$ %. This means that is probing scales

$$\delta g^{Zu} \sim c\frac{v^2}{\Lambda^2} \quad \rightarrow \quad \Lambda/\sqrt{c} \geq 2\text{TeV}$$

For $c \geq 1$, $\Lambda \geq 2$TeV and $E/\Lambda \ll 1$ thus the EFT expansion makes sense.

At the same time,

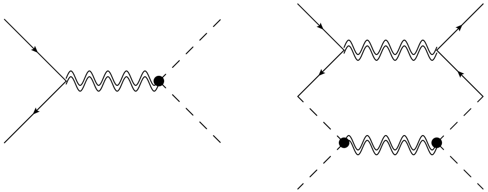
$$\frac{\sigma}{\sigma_{SM}} \sim 1 + \frac{c_6}{g_{SM}}\frac{E^2}{\Lambda^2} + (\frac{c_6^2}{g_{SM}^2} + \frac{c_8}{g_{SM}})\frac{E^4}{\Lambda^4}$$

We are sensitive to c_6^2 terms. To neglect dimension 8 terms, if $c_8 \sim c_6$, we require $c_6 \gg g_{SM}$.

Currently, $E \ll \Lambda$ **guarantees** $c_6^2 \gg g_{SM} c_8$.
This also means that we are only testing strongly coupled theories.

Interpretation

A simple toy model: vector custodial triplets L_μ, R_μ



$$\begin{aligned}\mathcal{L}_{int} &= L^a_\mu \left[\gamma_H g_\star J^{Ha}_\mu + \gamma_V \frac{g}{g_\star} J^a_\mu + \sum_F \gamma_F g_\star J^{Fa}_\mu\right] \\ &+ R^0_\mu \left[\delta_H g_\star J^H_\mu + \delta_V \frac{g'}{g_\star} J_\mu + \sum_F \delta_F g_\star J^F_\mu\right] \\ &+ \frac{1}{\sqrt{2}}(\delta_H g_\star R^+_\mu J^{-H}_\mu + h.c.)\end{aligned}$$

Biektter et al

Interpretation

Assuming $m_\star \gg E$, one can integrate out the heavy vectors and match with the EFT:

$$
\begin{aligned}
\delta g_{1z} &= -\frac{g^2 + g'^2}{g^2}\frac{m_W^2}{m_\star^2}\left[\frac{c_{HW} g_\star^2}{16\pi^2} + \frac{1}{g^2 - g'^2}(g^2\gamma_H\gamma_V + g'^2\delta_H\delta_V) + \dots\right] \\
\delta\kappa_\gamma &= -\frac{g_\star^2}{16\pi^2}\frac{m_W^2}{m_\star^2}(c_{HW} + c_{HB}) \\
\lambda_\gamma &= -\frac{6g^2}{16\pi^2}\frac{m_W^2}{m_\star^2}c_{3W} \\
\delta g_L^{Zu} &= \frac{m_W^2}{m_\star^2}\frac{g_\star^2}{g^2}\left[-\gamma_H\gamma_Q + \frac{g^2}{g_\star^2}\left(+\gamma_Q\gamma_V - \frac{2}{3}\frac{g'^2}{g^2 - g'^2}(\gamma_H\gamma_V + \delta_H\delta_V)\right) + \mathcal{O}(\frac{g^4}{g_\star^4})\right] \\
\delta g_L^{Zd} &= \dots
\end{aligned}
$$

Even the simplest model leads to a hierarchy of couplings:

$$
\delta g_{L,R}^{Zu,d} : \delta g_{1z} : \delta\kappa_\gamma : \lambda_\gamma \quad \sim \quad \frac{g_\star^2}{g^2} : 1 : \frac{g_\star^2}{16\pi^2} : \frac{g^2}{16\pi^2}
$$

for $4\pi \gg g_\star \gg g$, realization of previous assumptions:

$$
\delta g_{L,R}^{Zu,d} \gg \delta g_{1z} \gg \delta\kappa_\gamma \gg \lambda_\gamma
$$

Interpretation

Complementarity among different physics:

$$\text{dijets}\sim \frac{(g_\star \delta_Q)^2}{m_\star^2}\,, \quad \text{higgs}\sim \frac{(g_\star \delta_H)^2}{m_\star^2}\,, \quad \text{diboson}\sim \frac{g_\star^2 \delta_Q \delta_H}{m_\star^2}$$

e.g., composite q_L, $g_\star = 4\pi$,

$$\begin{aligned} dijets: &\quad m_\star \geq \delta_Q\ 40\,TeV \\ higgs: &\quad m_\star \geq \delta_Q\ 8\,TeV \\ dijets + higgs: &\quad m_\star^2 \geq \delta_Q \delta_H\ (18\,TeV)^2 \end{aligned}$$

$$diboson: m_\star^2 \geq \begin{matrix} |\delta_Q \delta_H|\ (14\,TeV)^2\,, & \delta_Q \delta_H < 0 \\ |\delta_Q \delta_H|\ (20\,TeV)^2\,, & \delta_Q \delta_H > 0 \end{matrix}$$

Conclusions

- Diboson offers a window to precision physics at LHC

- Current diboson data can be used to improve some LEP Z-pole constraints.

- In the future, not including the vertex corrections in diboson analyses will not be an option. Huge impact on TGCs and potential improvement with respect LEP.