Triple **G**auge **C**ouplings and **Q**uartic **G**auge **C**ouplings

Particle Physics at the LHC

Gernot Knippen

Faculty of Mathematics and Physics
University of Freiburg

June 17, 2014

Table of content

QED Lagrangian

Quantum electrodynamics described by

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi - Q\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}.$$

free fermion propagation ($\mathcal{L}_0$)

fermion photon interaction

photon kinetic energy

Theory invariant under local phase transformation ($U(1)$)

$$\psi \rightarrow \psi' = e^{iQ\alpha(x)}\psi.$$

$$(A_\mu \rightarrow A'_\mu = A_\mu + \partial_\mu\chi)$$

Electroweak Lagrangian

Theory invariant under $SU(2)_L \otimes U(1)$

$$\psi \rightarrow \psi' = e^{\frac{i}{2}\vec{\tau}\vec{\alpha}(x)} e^{i\frac{Y}{2}\beta(x)}\psi.$$

$$\mathcal{L} = \bar{\chi}_L \gamma^\mu \left(i\partial_\mu - g\frac{\vec{\tau}}{2}\vec{W}_\mu - g'\frac{Y}{2}B_\mu \right) \chi_L + \bar{\psi}_R \left(i\partial_\mu - g'\frac{Y}{2}B_\mu \right) \psi_R + \mathcal{L}_{kin}$$

with gauge invariant term describing gauge field kinetics:

$$\mathcal{L}_{kin} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\vec{W}_{\mu\nu}\vec{W}^{\mu\nu}$$

resulting from non-abelian gauge structure

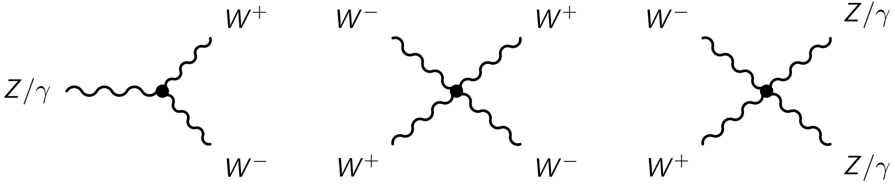
$$B_{\mu\nu} := \partial_\mu B_\nu - \partial_\nu B_\mu \qquad \vec{W}_{\mu\nu} := \partial_\mu \vec{W}_\nu - \partial_\nu \vec{W}_\mu + g\vec{W}_\mu \times \vec{W}_\nu$$

Gauge boson self-coupling in the electroweak theory

Cubic and quartic interaction terms resulting from $\mathcal{L}_{kin}$:

$$\begin{aligned}\mathcal{L}_3 = &- ie\cot\theta_W \Big[\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right) W^\dagger_\mu Z_\nu - \left(\partial^\mu W^{\nu\,\dagger} - \partial^\nu W^{\mu\,\dagger}\right) W_\mu Z_\nu + W_\mu W^\dagger_\nu \left(\partial^\mu Z^\nu - \partial^\nu Z^\mu\right) \Big] \\ &- ie\Big[\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right) W^\dagger_\mu A_\nu - \left(\partial^\mu W^{\nu\,\dagger} - \partial^\nu W^{\mu\,\dagger}\right) W_\mu A_\nu + W_\mu W^\dagger_\nu \left(\partial^\mu A^\nu - \partial^\nu A^\mu\right) \Big]\end{aligned}$$

$$\begin{aligned}\mathcal{L}_4 = &- \frac{e^2}{2\sin^2\theta_W}\Big[(W^\dagger_\mu W^\mu)^2 - W_\mu{}^\dagger W^{\mu\,\dagger} W_\nu W^\nu\Big] - e^2\cot^2\theta_W\Big[W^\dagger_\mu W^\mu Z_\nu Z^\nu - W^\dagger_\mu Z^\mu W_\nu Z^\nu\Big] \\ &- e\cot\theta_W\Big[2W^\dagger_\mu W^\mu Z_\nu A^\nu - W^\dagger_\mu Z^\mu W_\nu A^\nu - W^\dagger_\mu A^\mu W_n u Z^\nu\Big] \\ &- e^2\Big[W^\dagger_\mu W^\mu A_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu A^\nu\Big]\end{aligned}$$



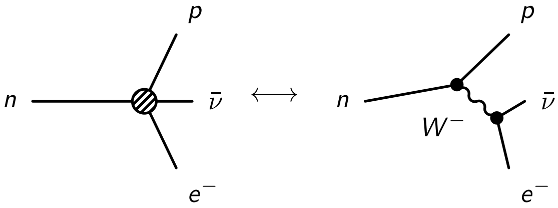
Effective field theory (EFT)

Assumption: New physics separated by different (energy) scale Λ from accessible region. ($s \ll \Lambda^2$)

$\rightarrow$ Describe observations by parametrized, most general Lagrangian which recovers the Standard Model in the limit $\Lambda \rightarrow \infty$.
(Unitary should be preserved.)

$\rightarrow$ Model independent approach for physics BSM.

Example: Fermi theory of β decay (quartic coupling with coupling strength G_F, describing two weak interaction vertices at low energies $s \ll M_W$.)



Limits on anomalous neutral triple gauge couplings

Neutral triple gauge couplings (nTGC)

Forbidden in Standard Model but possibly realized as "anomalous" coupling (in EFT approach).

Construct Lagrangian from general process properties:

- 9 total helicity states but only 7 valid (angular momentum conservation)
- bose statistics have to be respected

→ Effective ZZV Lagrangian:

violating CP invariance

$$\mathcal{L}_{ZZV} = \frac{e^2}{M_Z^2}\Big(-\left[\mathbf{f}_4^\gamma\left(\partial_\mu F^{\mu\nu}\right) + \mathbf{f}_4^Z\left(\partial_\mu Z^{\mu\nu}\right)\right] Z_\sigma\left(\partial^\sigma Z_\nu\right)$$

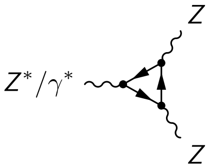
$$-\left[\mathbf{f}_5^\gamma\left(\partial^\rho F_{\rho\lambda}\right) + \mathbf{f}_5^Z\left(\partial^\rho Z_{\rho\lambda}\right)\right] \tilde{Z}^{\lambda\xi} Z_\xi \Big)$$

conserving CP invariance

SM and some new physics contributions to nTGC

SM

NLO and higher order contributions
(only CP conserving f_5^V)



MSSM

1-loop (and higher order) contributions from charginos and neutralinos

New bosons

CP violating coupling f_4^V sensitive to two-Higgs-doublet model in 1-loop corrections.

Limits on anomalous nTGC from ZZ production in pp collisions

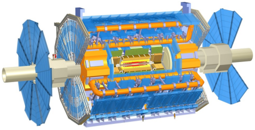
CERN-PH-EP-2012-318

Strategy:
Obtain limits on anomalous ZZZ and $ZZ\gamma$ couplings from differential cross section $\frac{\mathrm{d}\sigma_{ZZ}}{\mathrm{d}p_T^Z}$.
Analyse ZZ signal channels: $ZZ^{(*)} \to l^+l^-l^+l^-$ and $ZZ \to l^+l^-\nu\bar{\nu}$

Extended-lepton selection

UNI FREIBURG

Aim: Increase selection acceptance in the $ZZ^{(*)} \to l^+l^-l^+l^-$ channel by using leptons which are normally not used due to detector geometry.



Forward spectrometer muons

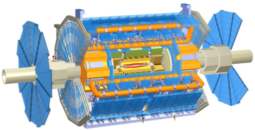
Muons outside the nominal ID range with $2.5 < |\eta| < 2.7$.
Are required to have *a*) full track in muon spectrometer, *b*) $p_T > 10\,\text{GeV}$ and *c*) $\sum E_T$ of calorimeter deposites inside $\Delta R = 0.2$ smaller that 15 % of muon p_T.

Calorimeter-tagged muons

Muons in the muon spectrometer limited coverage range $|\eta| < 0.1$.
Are required to *a*) have calorimeter deposit consistent with muon which is matched to ID track *b*) have $p_T > 20\,\text{GeV}$ and *c*) fulfill same impact parameter and isolation criteria as "standard muons".

Extended-lepton selection

Aim: Increase selection acceptance in the $ZZ^{(*)} \to l^+l^-l^+l^-$ channel by using leptons which are normally not used due to detector geometry.



Calorimeter-only electrons

Electrons outside the ID range with $2.5 < |\eta| < 3.16$.
Are required to *a*) have $p_T > 20\,\text{GeV}$ and *b*) pass the tight identification requirement.
p_T is calculated from calorimeter energy and electron direction.
Charge is assigned depending on the charge of the other electron(s).

At most one lepton from each extended category!

Signal region definitions

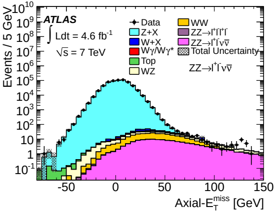
$ZZ^{(*)} \to l^+l^-l^+l^-$:

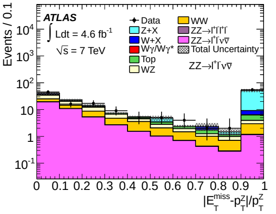
- exactly 4 isolated leptons, two same-flavour opposite charge pairs ($e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$ or $\mu^+\mu^-\mu^+\mu^-$)
- $\Delta R(l_1, l_2) > 0.2$
- ambiguity in lepton combinations removed by choosing combination with lowest $|m_{l^+l^-} - M_Z|$
- at least one lepton pair fulfills $66 < m_{l^+l^-} < 116\,\text{GeV}$ (the other $m_{l^+l^-} > 20\,\text{GeV}$)

Signal region definitions

$ZZ \to l^+l^-\nu\bar{\nu}$:

- exactly 2 leptons of same flavour with $p_T > 20$ GeV
- $\Delta R(l_1, l_2) > 0.3$
- $76 < m_{l^+l^-} < 106$ GeV
- axial-$E_T^{miss} = -\vec{E}_T^{miss} \cdot \vec{p}^Z / p_T^Z > 75$ GeV and $|E_T^{miss} - p_T^Z|/p_T^Z < 0.4$
- jet veto
- no additional lepton with $10 < p_T \leq 20$ GeV





Background estimation for the $ZZ^{(*)} \to l^+l^-l^+l^-$ channel

Background estimated via data-driven (dd.) method

$$N(BG) = [N(lllj) - N(ZZ)] \times f - N(lljj) \times f^2,$$

where

- $N(lllj)$ = number of events with 3 leptons and 1 lepton-like jet satisfying all selection criteria
- $N(lljj)$ = number of events with 2 leptons and 2 lepton-like jet satisfying all selection criteria
- $N(ZZ)$ = MC estimate for real leptons classified as lepton-like jet
- f = ratio of the probability for a non-lepton to satisfy the full lepton selection criteria to the probability for a non-lepton to satisfy the lepton-like jet criteria.

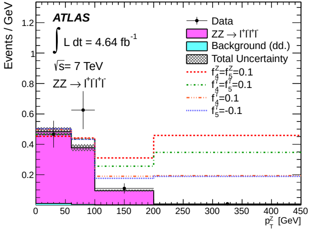
Determining limits on anomalous nTGC

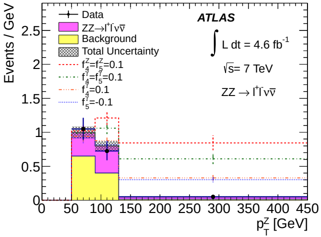
- Couplings are parametrized in form-factor approach

$$f_i^V = \frac{1}{(1 + \hat{s}/\Lambda^2)^n} f_{i,0}^V \xrightarrow[s\to\infty]{} 0$$

with $n = 3$ and $\Lambda = 3\,\text{TeV}$ to ensure unitarity is not violated at LHC energies.

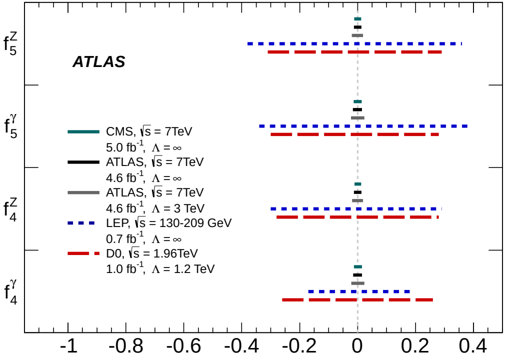
- To obtain simulated p_T^Z distributions for different f_i^V a reweighting method $(|\mathcal{M}|^2/|\mathcal{M}_{SM}|^2)$ is used.
- Dependency of couplings on the expected number of events in each p_T^Z bin is parametrized.
- Limits on couplings are obtained by using a maximum likelihood fit.

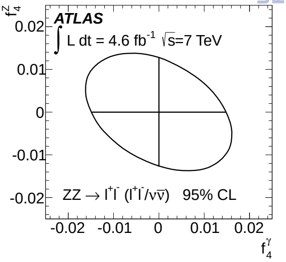


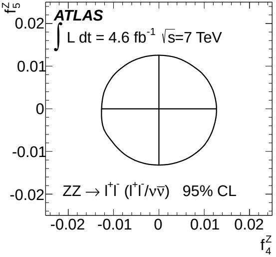


Limits on anomalous nTGC

The limit(s) on the coupling(s) is/are obtained assuming all other couplings are zero (as in SM).







Limits on charged triple gauge couplings

Charged triple gauge couplings (cTGC)

Already realized as ZWW and γWW in Standard Model but further coupling contributions from new physics possible in EFT approach.

Construct Lagrangian from general process properties:

- 9 total helicity states but only 7 valid (angular momentum conservation)
- demand C and P conservation

$\rightarrow$ Effective WWV Lagrangian ($V = Z$ and γ):

$$\mathcal{L}_{WWV} = ig_{WWV}\Big(g_1^V \left(W^+_{\mu\nu}W^{-\mu} - W^{+\mu}W^-_{\mu\nu}\right) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu}\Big)$$

with $g_1^\gamma = 1$.

The values of cTGC

In the SM the general cTGC couplings are given by

$$g_1^Z = \kappa_Z = \kappa_\gamma = 1$$
$$\lambda_Z = \lambda_\gamma = 0.$$

Often the differences from the SM

$$\Delta g_1^Z = g_1^Z - 1$$
$$\Delta \kappa_Z = \kappa_Z - 1$$
$$\Delta \kappa_\gamma = \kappa_\gamma - 1$$

and not the absolute values are denoted.

Limits on anomalous charged TGC from W^+W^- production in pp collisions

UNI FREIBURG

CERN-PH-EP-2012-242

Analysis strategy:

- Select W^+W^- events by "$ll' + E_T^{miss}$".
- Measure differential cross section $\frac{\mathrm{d}\sigma_{WW}}{\mathrm{d}p_T}$ in selection phase space region.
- Extract limits on couplings from differential cross section.

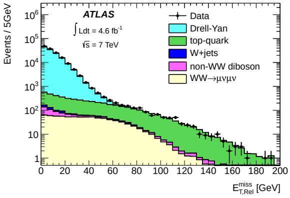
Selection criteria

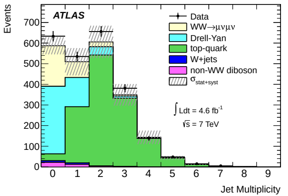
- two opposite charged leptons (at least one matched to trigger reconstructed lepton) ($\to$ 3 channels: ee, $e\mu$, $\mu\mu$)
- cut on invariant lepton mass $m_{ll'}$ and $E_{T,Rel}^{miss}$, where

$$E_{T,Rel}^{miss} = \begin{cases} E_T^{miss} \times \sin(\Delta\phi) & \text{if } \Delta\phi^a < \pi/2 \\ E_T^{miss} & \text{if } \Delta\phi \geq \pi/2 \end{cases}$$

(to remove Drell-Yan background)

- jet veto
- $p_T(ll') > 30\,\text{GeV}$





[a] $\Delta\phi$ = azimutal angle difference between E_T^{miss} and nearest lepton or jet

"Coupling-scenarios" investigated

equal coupling scenario

$$\Delta\kappa_Z = \Delta\kappa_\gamma,\ \lambda_Z = \lambda_\gamma \text{ and } g_1^Z = 1$$

LEP scenario

$$\Delta\kappa_\gamma = \frac{\cos^2\theta_W}{\sin^2\theta_W}\left(\Delta g_1^Z - \Delta\kappa_Z\right) \text{ and } \lambda_Z = \lambda_\gamma$$

HISZ scenario

$$\Delta g_1^Z = \frac{1}{\cos^2\theta_W - \sin^2\theta_W}\Delta\kappa_Z,$$

$$\Delta\kappa_\gamma = 2\Delta\kappa_Z\frac{\cos^2\theta_W}{\cos^2\theta_W - \sin^2\theta_W} \text{ and } \lambda_Z = \lambda_\gamma$$

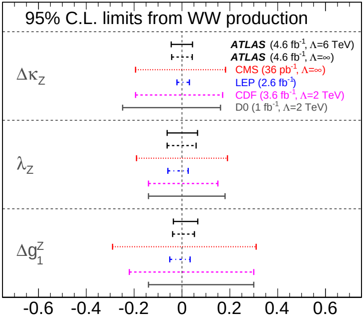
Obtaining limits on cTGC

Similar to the $pp \rightarrow ZZ$ analysis (form factor approach, reweighting method, dependency of $p_T(l_1)$ on couplings).

Limits are obtained by the maximum likelihood principle.
(Point in parameter space is discarded if the negative log-likelihood function increases by more that 1.92 units above the minimum.)

Limits on cTGC

Scenario	Parameter	Expected ($\Lambda = 6$ TeV)	Observed ($\Lambda = 6$ TeV)	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)
LEP	$\Delta\kappa_Z$	$[-0.043, 0.040]$	$[-0.045, 0.044]$	$[-0.039, 0.039]$	$[-0.043, 0.043]$
	$\lambda_Z = \lambda_\gamma$	$[-0.060, 0.062]$	$[-0.062, 0.065]$	$[-0.060, 0.056]$	$[-0.062, 0.059]$
	Δg_1^Z	$[-0.034, 0.062]$	$[-0.036, 0.066]$	$[-0.038, 0.047]$	$[-0.039, 0.052]$
HISZ	$\Delta\kappa_Z$	$[-0.040, 0.054]$	$[-0.039, 0.057]$	$[-0.037, 0.054]$	$[-0.036, 0.057]$
	$\lambda_Z = \lambda_\gamma$	$[-0.064, 0.062]$	$[-0.066, 0.065]$	$[-0.061, 0.060]$	$[-0.063, 0.063]$
Equal Couplings	$\Delta\kappa_Z$	$[-0.058, 0.089]$	$[-0.061, 0.093]$	$[-0.057, 0.080]$	$[-0.061, 0.083]$
	$\lambda_Z = \lambda_\gamma$	$[-0.060, 0.062]$	$[-0.062, 0.065]$	$[-0.060, 0.056]$	$[-0.062, 0.059]$



Parameter	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)
$\Delta\kappa_Z$	$[-0.077, 0.086]$	$[-0.078, 0.092]$
λ_Z	$[-0.071, 0.069]$	$[-0.074, 0.073]$
λ_γ	$[-0.144, 0.135]$	$[-0.152, 0.146]$
Δg_1^Z	$[-0.449, 0.546]$	$[-0.373, 0.562]$
$\Delta\kappa_\gamma$	$[-0.128, 0.176]$	$[-0.135, 0.190]$

Limits on anomalous quartic gauge couplings

Quartic gauge couplings (QGC)

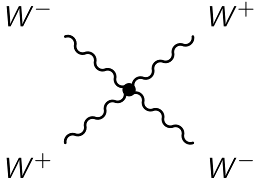
In SM realized as $WWWW$, $WWZZ$, $WW\gamma Z$ and $WW\gamma\gamma$. Further contributions from physics BSM in EFT approach possible.

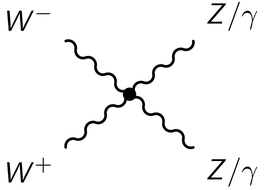
Construct Lagrangian from following constraints:

- Consider couplings to logitudinal polarization degree of gauge bosons only.
- Custodial symmetry

$$\rho = \left(\frac{M_W}{M_Z \cos\theta_W}\right)^2 = 1$$

should be respected.





Quartic gauge couplings (QGC)

→ Two effective anomalous vector boson scattering (VBS) Lagrangian terms:

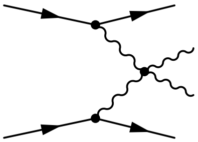
$$\mathcal{L}_4 = \frac{\alpha_4}{16\pi^2}\,\mathrm{Tr}(V_\mu V_\nu)\,\mathrm{Tr}(V^\mu V^\nu)$$
$$\mathcal{L}_5 = \frac{\alpha_5}{16\pi^2}\,\mathrm{Tr}(V_\mu V^\mu)\,\mathrm{Tr}(V_\nu V^\nu)$$

with $V_\mu = -igW_\nu + ig' B_\mu$ (in unitary gauge)

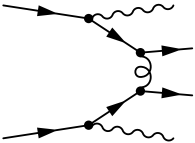
Limits on aQGC from $W^{\pm}W^{\pm}jj$ production in pp collisions

"Evidence of the electroweak production of $W^{\pm}W^{\pm}jj$ in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ with the ATLAS detector" *(ATLAS-CONF-2014-013)*

- Published in March 2014.
- *First analysis* being able to give direct constraints on QGC from VBS.
- Limits on aQGC determined from measured cross section in signal region phase space.



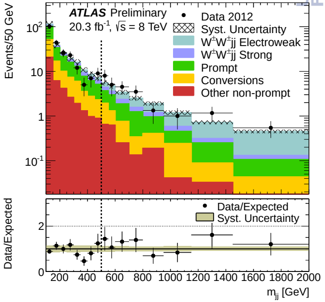
$W^{\pm}W^{\pm}jj$ electroweak

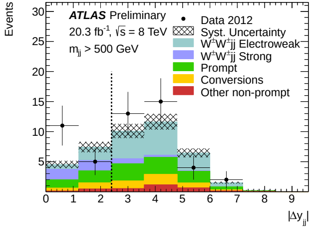


$W^{\pm}W^{\pm}jj$ strong

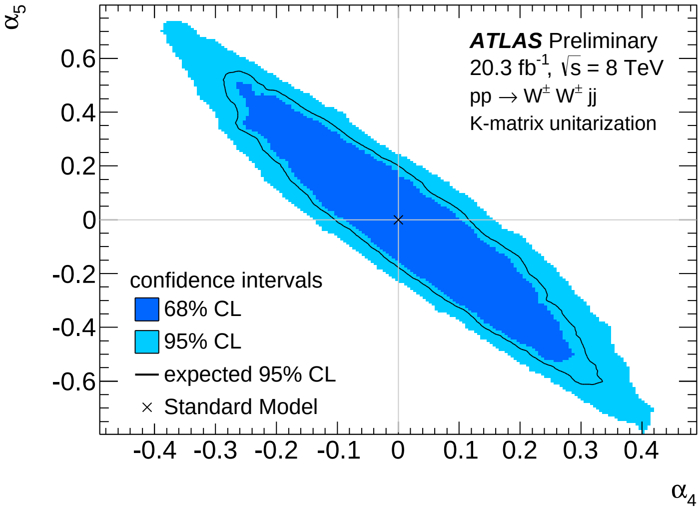
Signal region definition

- 2 same electric charge leptons
- 2 jets with $p_T > 30$ GeV & $|\eta| < 4.5$
- additional loose lepton veto
- $m_{ll} > 20$ GeV
- $|m_{ee} - M_Z| > 10$ GeV
- $E_T^{miss} > 40$ GeV
- b-jet veto
- $m_{jj} > 500$ GeV
- $|\Delta y_{jj}| > 2.4$





Limits on aQGC



Summary & Outlook

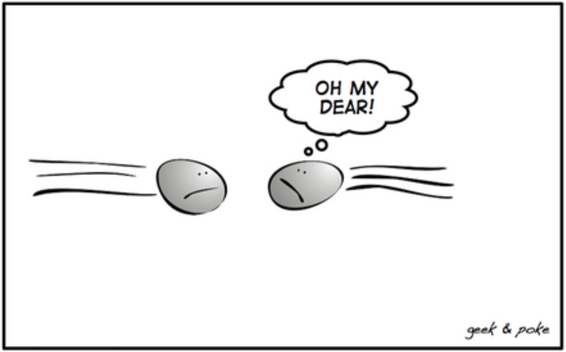
Summary

- Effective field theory approach yields possibility to probe physics BSM in model independent way.
- LHC experiments could improve the limits on anomalous nTGC from LEP and reach a similar precision on limits on cTGC.
- New analysis (03/2014) gives first direct constraints on aQGC from $pp \to W^{\pm}W^{\pm}jj$.
- No physics BSM observed! (But higher precision may show contributions!)

Outlook

- Run 2 of LHC will probably increase sensitivity.
- Triboson production analysis (yielding limits on aQGC) may be realizable for new phase.

The END



LATELY INSIDE THE LHC:
2 PROTONS 0.0000000000000000001 SEC BEFORE THE COLLISION