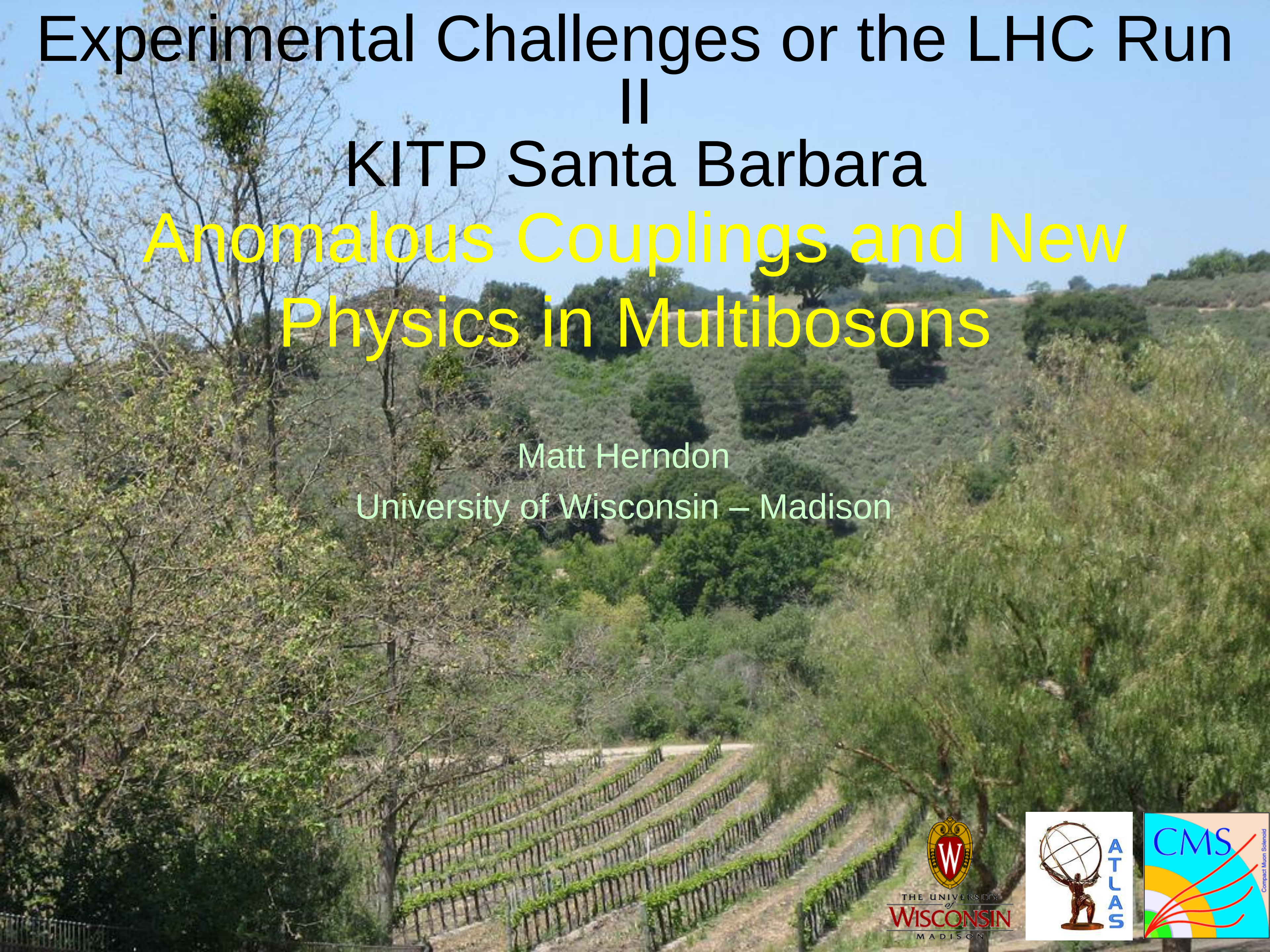


Experimental Challenges or the LHC Run II

KITP Santa Barbara

Anomalous Couplings and New Physics in Multibosons

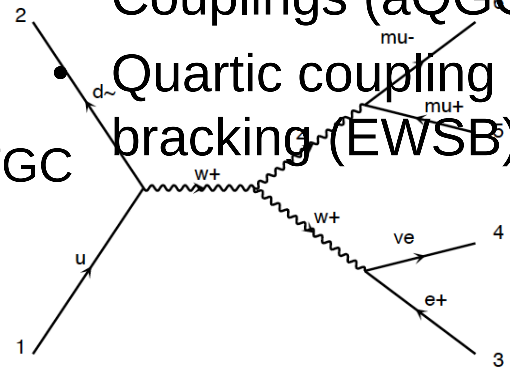
Matt Herndon

University of Wisconsin – Madison

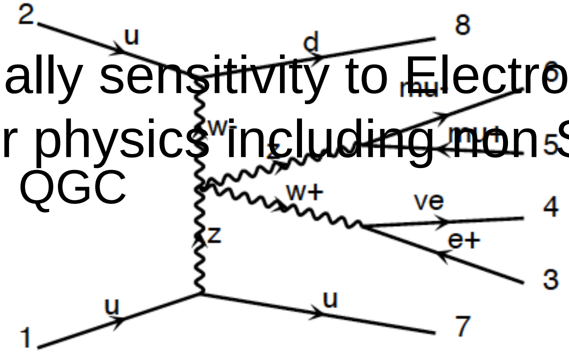
Multiboson Production and AC

- Fundamental test of Standard Model
  - Multiple vector boson interactions possible due to the non-Abelian gauge structure of the Standard Model
  - Results in tree level triple and quartic gauge couplings, TGCs and QGCs
  - Electroweak (EWK) component of interactions precisely predicted by SM
- Probe for new physics though anomalous couplings
  - Indirect search for tree or loop effects of massive new particles in Anomalous Triple Gauge Couplings (aTGC) and Quartic Gauge Couplings (aQGC)
  - Quartic coupling especially sensitivity to Electrow bracking (EWSB) sector physics including non S

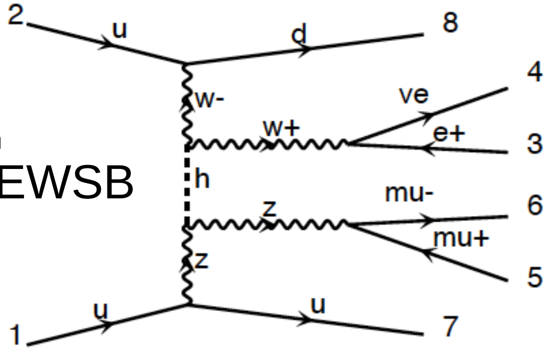
TGC



QGC

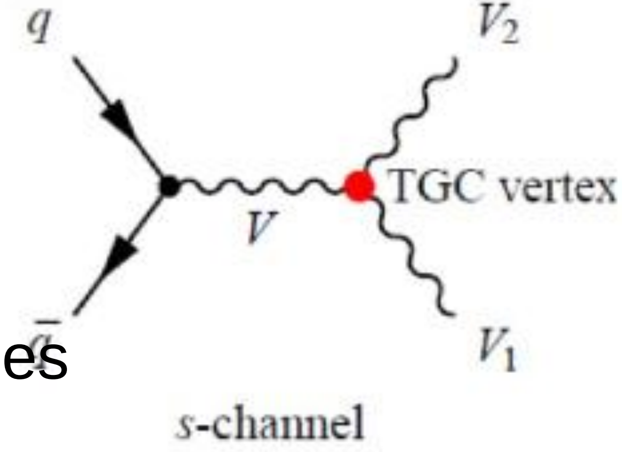


EWSB



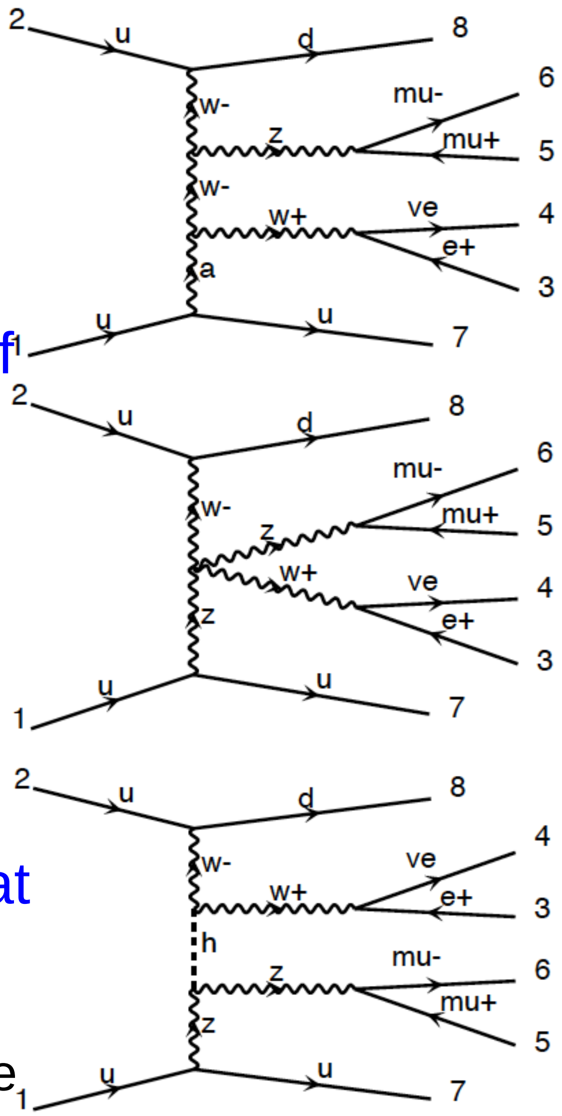
aTGC Searches

- General search for new physics in the gauge sector
  - Search new physics at high energy scales in single- or di-boson final states
  - Energy scales can be higher the LHC kinematic reach
  - Tree level or loop level NP contributions
  - NP can add anomalous contributions to TGC vertices
- EWK interactions precisely predicted by the SM
  - Diboson cross sections predicted at NLO, NNLO (QCD) and NLO (EWK)
  - Significant deviation would indicate new physics
  - New physics typically leads to high pT vector bosons and large diboson masses



aQGC Searches

- General search for new physics in the Gauge and Electroweak symmetry breaking sector (EWSB)
  - New physics in Vector boson scattering VBS and triple gauge boson production
- EWSB sector is one of the least explored part of the SM.
  - Current measurements leave room for non SM physics
- Examples: Exchange of new heavy particles such as extra scalars (additional Higgs) or new gauge bosons (from extended gauge groups of unification models)
- In VBS NP changes how unitarity is preserved at high CM scattering energy
  - New physics would be evident at high energies in distributions dependent on the center of mass of the scattering system



aTGC Results and Discussion

- aGC vs EFT
- Charged aTGC
  - Wγ, WW, WZ, WV (V = W or Z)
  - Charged TGC couplings present in SM – searching for deviations
  - WZ as an illustrative example
- Neutral aTGC
  - Zγ, ZZ
  - Neutral TGC effects forbidden in SM – new physics generally caused by higher order operators
  - Zγ as example
- Issues in aTGC
- Summary plots
- aTGC in Run II

Anomalous Couplings or Effective Field Theory

- Anomalous gauge coupling (aGC) approach
  - – Consider all possible combinations and types of gauge boson interactions
    - Generally based on naively possible Feynman diagrams
    - Specify coupling constants for each one
    - Allows very arbitrary couplings
    - Doesn’t consider effect of these new couplings would have in loops
  - – Can develop a reduced parameterization to obey expected symmetries, typically
    - SU(2)xU(1) with
    - $SU(2)_C$ custodial symmetry which fixes: $r = \frac{M_W^2}{M_Z^2 \cos^2(q_W)} = 1(SM)$
    - Constraints on C/P violation
  - – Dependence on q^2 can be introduced via a form factor
  - – HEP approach to aTGC has previously been through anomalous couplings

Anomalous Couplings or Effective Field Theory

- Effective field theory
  - – Generally based on considering possible Lagrangian terms
  - – SM can be represented by an effective field theory
    - All D4 (mass dimension) operators allowed by $SU(3)_C xSU(2)_L xU(1)$ symmetry
    - Operators constructed as products of the fields
      - – Important if you have a light Higgs (linear realization of SU(2)) or no Higgs or heavy Higgs (non linear realization of SU(2)).
  - – To add new physics add higher order operators that respect symmetries
    - Higher order operators suppressed by a new physics scale $1/\Lambda^{n-4}$
      - – If due to a new particle Λ is order the mass of that particle
      - – Λ large enough that the exact form of a possible propagator is irrelevant
      - – Generally due to previous constraints and direct searches we know that Λ is large
    - lowest order operators will have the largest impact
    - D6 is the lowest interesting order for gauge boson interactions
    - Automatically respects symmetries we expect
    - Can represent a tree level new particle or a loop effect
    - Understood how to calculate loop effects

Example: Fermi Theory

- Effective field theory approach
  - Introduce a new operator for 4 fermion interaction.
  - Simplest operator at higher order, must be suppressed by a mass factor: c/Λ^2
  - Essentially representing a particle exchange
- Consider the propagator and couplings of the weak force

$$\frac{g^2}{8}\frac{1}{q^2 - M_W^2} \rightarrow \frac{-g^2}{8}\frac{1}{M_W^2}\left(1+\frac{q^2}{M_W^2}\right) \xrightarrow{q^2<<M_W^2} -\frac{g^2}{8}\frac{1}{M_W^2}$$

$$\frac{c}{\Lambda^2} = \frac{G_F}{\sqrt{2}} = \frac{g^2}{8}\frac{1}{M_W^2}$$

Where g is a constant of order 1

  - At low energies the weak interactions presents as a simple contact interaction with strength given by a coupling constant suppressed by a mass to the appropriate power
  - Weak force fully explored by considering various operators with conserve or violate C and P analyzing their effects on distributions such as angular distributions

Example: Charged aTGC

- SM Lagrangian in the Charged Sector

$$\mathcal{L}_{WWV}^{\mathrm{eff}} = i g_{WWV}[g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}$$

$$V = \gamma, Z \qquad + \frac{\lambda_V}{M_W^2} W^{+\nu}_\mu W^{-\rho}_\nu V^\mu_\rho], \qquad g_{WW\gamma} = -e, g_{WWZ} = -e \cot\theta_W$$

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

- Anomalous coupling approach
  - General TGC Lagrangian has 15 couplings
  - Enforcing SU(2)xU(1), C and P symmetries reduces this to 3
    - Closely related to SM terms that respected the gauge symmetries

$$\Delta g_1^Z, \Delta\kappa_z = \Delta\kappa_\gamma - \Delta g_1^Z \tan^2\theta_W, \Delta\lambda_Z = \Delta\lambda_\gamma$$

  - Aggressive reduction since C and P may be violated
    - Angular analysis needed to distinguish C and/or P conserving and violating cases: not currently done at LHC

Example: Charged aTGC

- Effective field theory approach
  - SM Lagrangian + operators allowed by symmetries
  - and add D6 operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \cdots$$

    - Linear realization (light Higgs included)

$$\begin{aligned}
\mathcal{O}_{WWW} &= \mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W_{\rho}^{\mu}] \\
\mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)
\end{aligned}$$

$$D_\mu = \partial_\mu + \frac{i}{2}g\tau^I W_\mu^I + \frac{i}{2}g' B_\mu$$

$$W_{\mu\nu} = \frac{i}{2}g\tau^I(\partial_\mu W_\nu^I - \partial_\nu W_\mu^I + g\epsilon_{IJK}W_\mu^J W_\nu^K)$$

$$B_{\mu\nu} = \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu)$$

  - Multiplied by terms to get the correct dimensions

$$\frac{c_{WWW}}{L^2}, \frac{c_W}{L^2}, \frac{c_B}{L^2} \qquad Dg_1^Z = \frac{c_W m_Z^2}{2L^2}, Dk_Z = \left(c_W - c_B \tan^2 q_W\right)\frac{m_W^2}{2L^2}, /_Z = \frac{3c_{WWW}g^2 m_W^2}{2L^2}$$

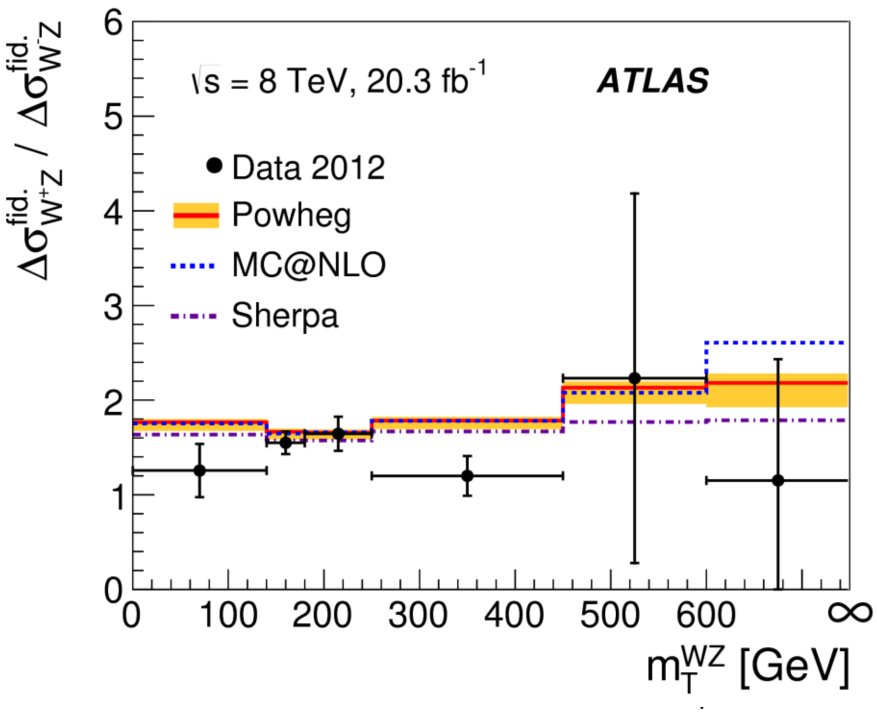
  - Note: without a light Higgs (nonlinear realization)
    - Includes a generic goldstone boson and D_μ is chosen to enforce SU(2)$_C$
    - different lowest order terms will respect the symmetries
    - ☐ λ occurs as λ/M^2 correspond to a D8 term, suppressed by Λ^4
    - Dimension counting partially assesses strength of anomalous contributions

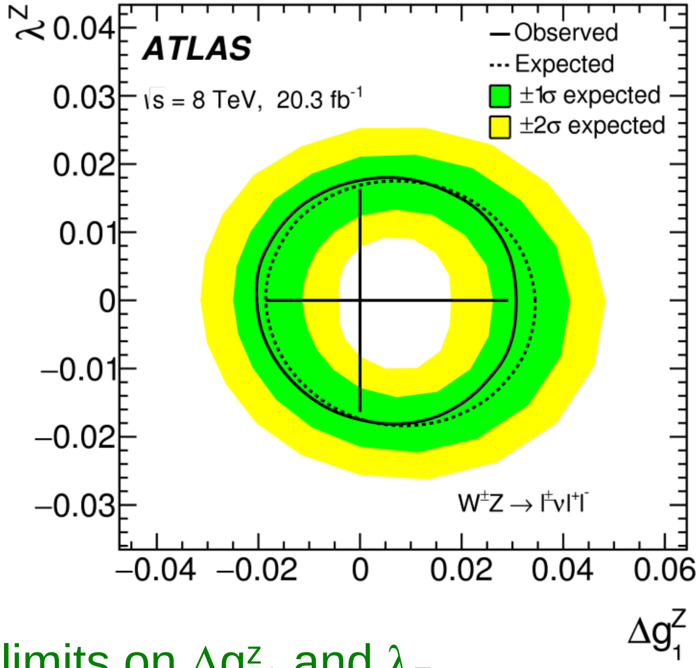
WZ aTGC

- WZ aTGC search

ATLAS STDM-2014-02

- Integrated into an analysis including total and differential cross section measurements
- Demonstrates excellent understanding at NLO accuracy of basic distributions used for NP aTGC (aQGC) searches

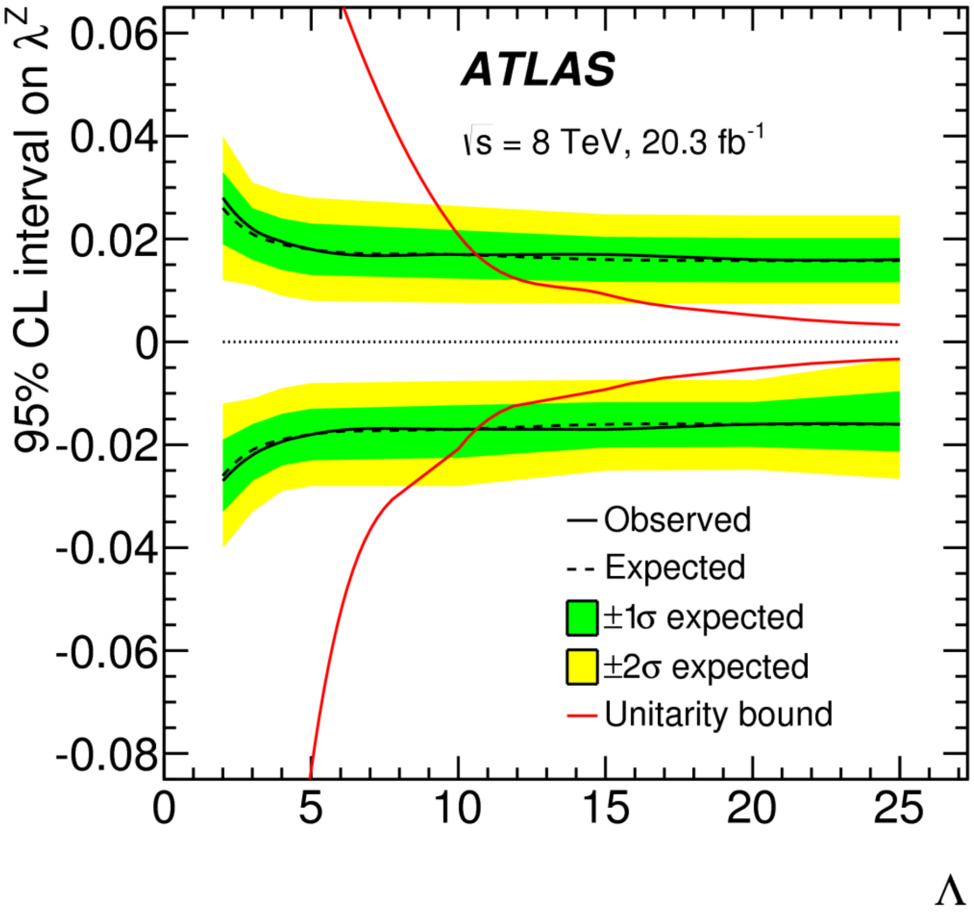




Best limits on Δg^z_1 and λ_Z

Issue: Unitarity

- Unitarity
  - Higher dimensional operators are typically not renormalizable
  - Will violate unitarity at higher energy
- Minimal approach
  - Check if unitarity is violated at the energy scales probed by your interaction
  - Answer, No: aC or EFT approach is okay



For Δg^z_1 and λ_Z WZ shows unitarity violation is above 10 TeV. aQ/EFT approach is fine for reasonably high energy NP. Worse for $\Delta\kappa_Z$

Issues: Unitarity

- Strategies for Unitarity violation
  - Form factors, actual new physics will introduce term like a form factor
  - Disadvantages
    - Real factor might not be the dimension you choose
    - Doesn't account for issues like widths
    - You don't know the actual NP scale
  - Model: Probes specific (well motivated) new physics
  - Disadvantage
    - Many models with no indications of the correct one

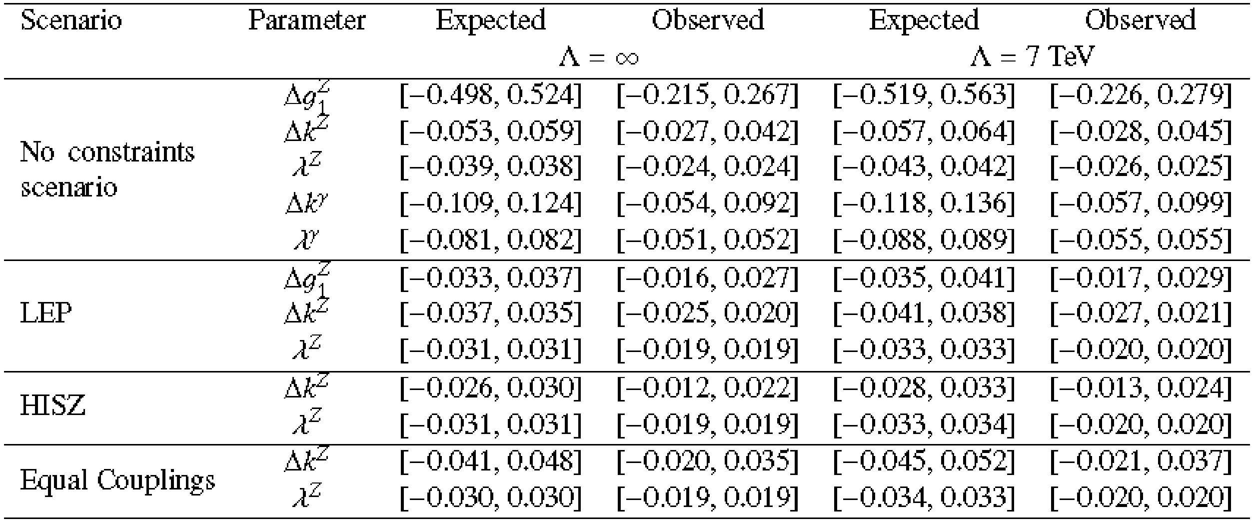
$\Lambda_{\rm co}$	Coupling	Expected	Observed
2 TeV	Δg_1^Z	$[-0.023\ ;\ 0.055]$	$[\ -0.029\ ;\ 0.050]$
	$\Delta\kappa^Z$	$[-0.22\ ;\ 0.36]$	$[\ -0.23\ ;\ 0.46]$
	λ^Z	$[-0.026\ ;\ 0.026]$	$[\ -0.028\ ;\ 0.028]$
15 TeV	Δg_1^Z	$[-0.016\ ;\ 0.033]$	$[\ -0.019\ ;\ 0.029]$
	$\Delta\kappa^Z$	$[-0.17\ ;\ 0.25]$	$[\ -0.19\ ;\ 0.30]$
	λ^Z	$[-0.016\ ;\ 0.016]$	$[\ -0.017\ ;\ 0.017]$
∞	Δg_1^Z	$[-0.016\ ;\ 0.032]$	$[-0.019\ ;\ 0.029]$
	$\Delta\kappa^Z$	$[-0.17\ ;\ 0.25]$	$[-0.19\ ;\ 0.30]$
	λ^Z	$[-0.016\ ;\ 0.016]$	$[-0.016\ ;\ 0.016]$

WZ Δg^Z_1 and λ_Z results show no form factor dependence above 5 TeV energy.

If we saw lower scale new physics we could compare against form factor energy dependences to estimate the scale

Issues: Constraints

- Constraints in anomalous coupling approach
  - General TGC Lagrangian has 15 couplings
  - Enforcing SU(2)xU(1), C and P symmetries reduced this to 3
  - Aggressive reduction since C and P may be violated
- Can reintroduce C and P violation
  - LHC not often that sensitive
- Can remove SU(2)xU(1) constraints or apply different ones



Scenario	Parameter	Expected	Observed	Expected	Observed
		$\Lambda = \infty$		$\Lambda = 7$ TeV	
No constraints scenario	Δg_1^Z	[−0.498, 0.524]	[−0.215, 0.267]	[−0.519, 0.563]	[−0.226, 0.279]
	Δk^Z	[−0.053, 0.059]	[−0.027, 0.042]	[−0.057, 0.064]	[−0.028, 0.045]
	λ^Z	[−0.039, 0.038]	[−0.024, 0.024]	[−0.043, 0.042]	[−0.026, 0.025]
	Δk^γ	[−0.109, 0.124]	[−0.054, 0.092]	[−0.118, 0.136]	[−0.057, 0.099]
	λ^γ	[−0.081, 0.082]	[−0.051, 0.052]	[−0.088, 0.089]	[−0.055, 0.055]
LEP	Δg_1^Z	[−0.033, 0.037]	[−0.016, 0.027]	[−0.035, 0.041]	[−0.017, 0.029]
	Δk^Z	[−0.037, 0.035]	[−0.025, 0.020]	[−0.041, 0.038]	[−0.027, 0.021]
	λ^Z	[−0.031, 0.031]	[−0.019, 0.019]	[−0.033, 0.033]	[−0.020, 0.020]
HISZ	Δk^Z	[−0.026, 0.030]	[−0.012, 0.022]	[−0.028, 0.033]	[−0.013, 0.024]
	λ^Z	[−0.031, 0.031]	[−0.019, 0.019]	[−0.033, 0.034]	[−0.020, 0.020]
Equal Couplings	Δk^Z	[−0.041, 0.048]	[−0.020, 0.035]	[−0.045, 0.052]	[−0.021, 0.037]
	λ^Z	[−0.030, 0.030]	[−0.019, 0.019]	[−0.034, 0.033]	[−0.020, 0.020]

ATLAS STDM-2013-07

ATLAS WW: Releasing constraints weakens limits.

However, order of magnitude doesn't change

Zγ aTGC

- Zγ → ννγ aTGC search
- Integrated into total cross section analysis
  - Compared to NNLO (QCD) cross section prediction
- Uses $p_{T\gamma}$ distribution for aTGC search

CMS PAS-SMP-2014-19

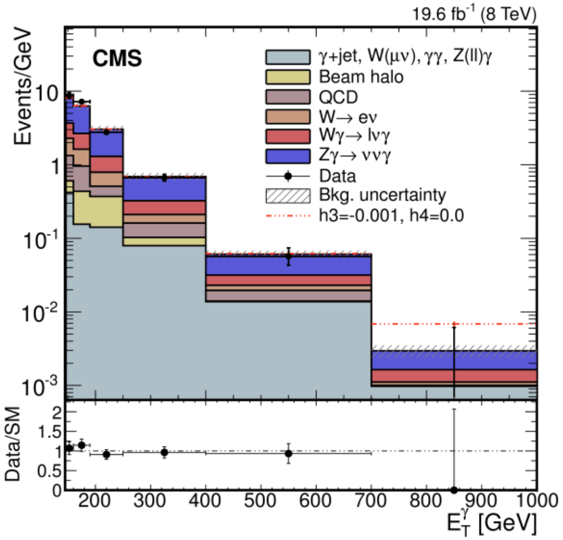
Submitted to PLB

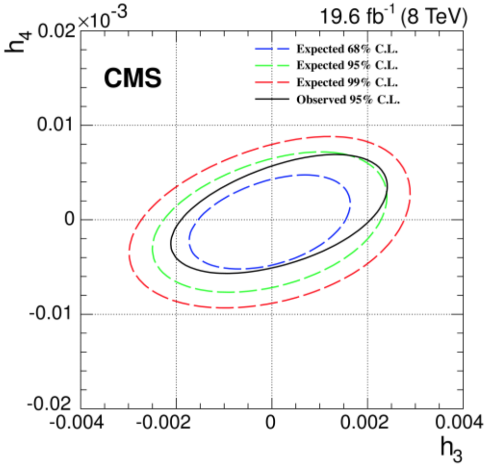
Best limits on ZZγ Zγγ couplings.

h3 operator c/Λ^2

h4 operator c/Λ^4

Analogous to WZ case these limits don't have unitarity issues for reasonably high energy new physics





Coupling	h_3 lower limit	h_3 upper limit	h_4 lower limit	h_4 upper limit
ZZγ	-1.5×10^{-3}	1.6×10^{-3}	-3.9×10^{-6}	4.5×10^{-6}
Zγγ	-1.1×10^{-3}	0.9×10^{-3}	-3.8×10^{-6}	4.3×10^{-6}

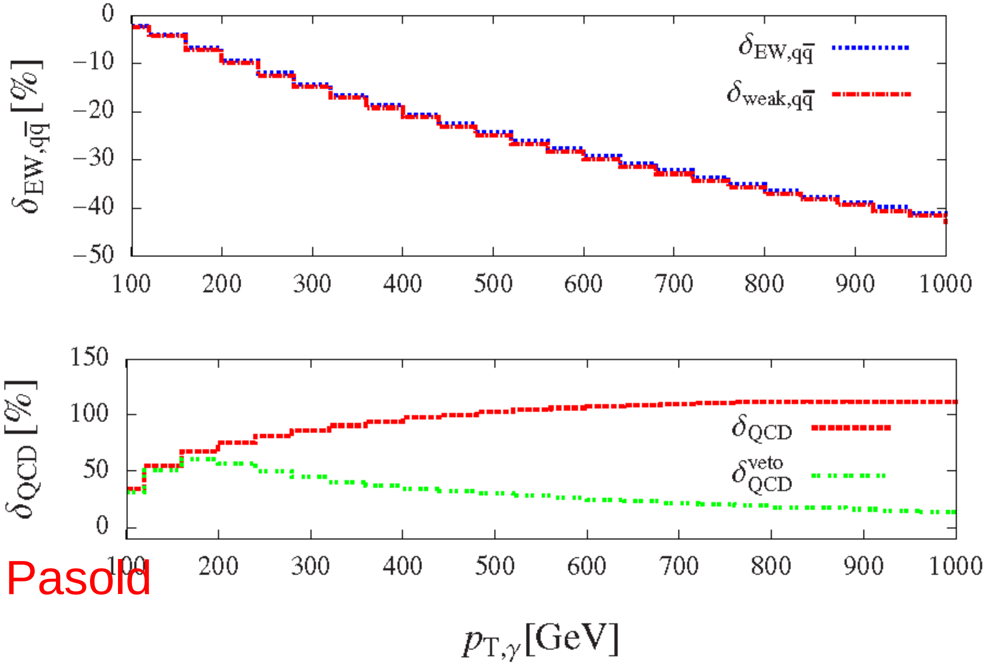
NNLO QCD and NLO EWK

- NLO, NNLO QCD and EWK corrections affect the total cross section and shapes of distributions as a function of energy
  - SM corrections known and substantial at high energy
- NLO QCD MCs with aGC new physics becoming available
- New physics effects could be substantial
  - QCD/EWK-NP correction factorize to first order (Higgs experience)
  - EWK effects could be large

QCD and EWK effects on SM are large and often opposite directions.

Corrections available in SM cases

In principle NLO QCD or EWK effects can be treated in a MC in the EFT framework.



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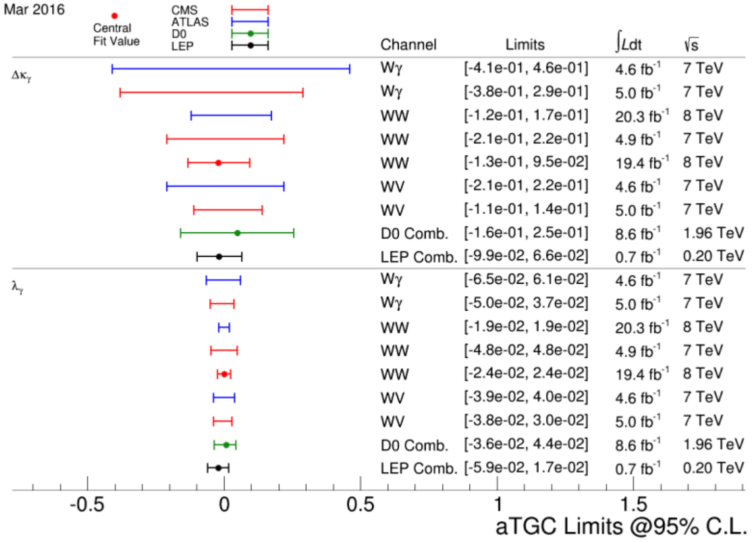
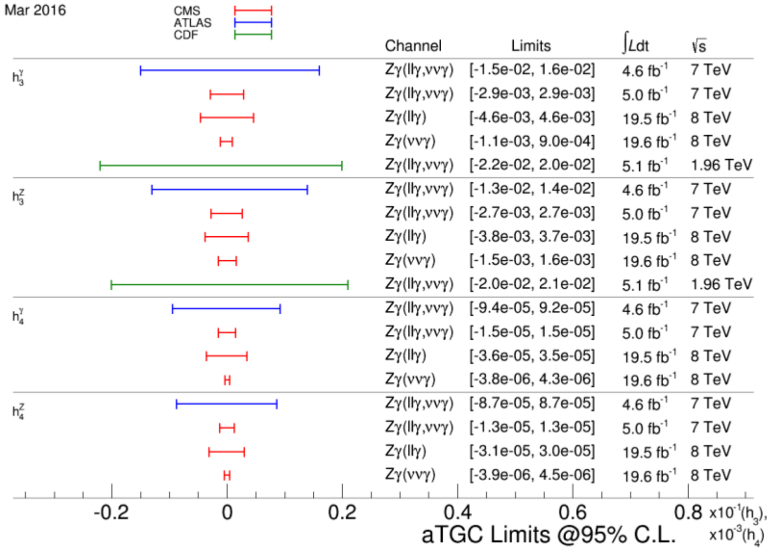
Denner, Dittmaier, Hecht, Pasold

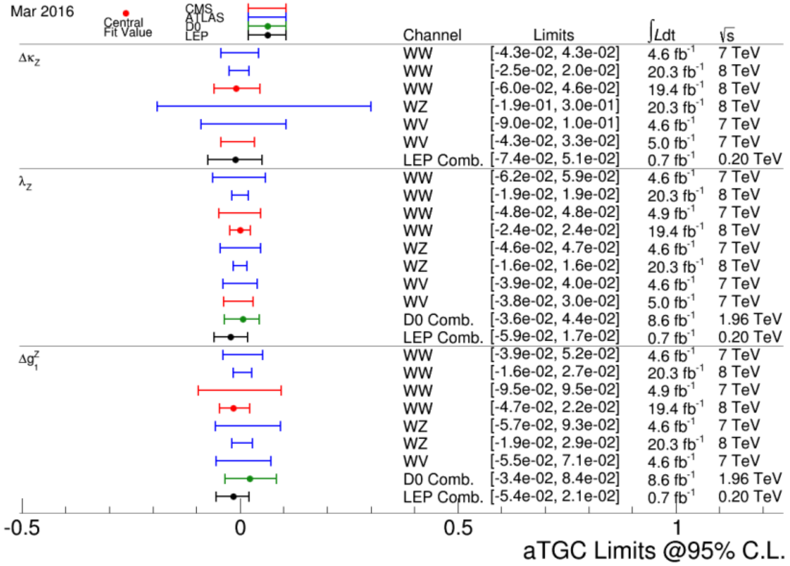
aTGC Summary



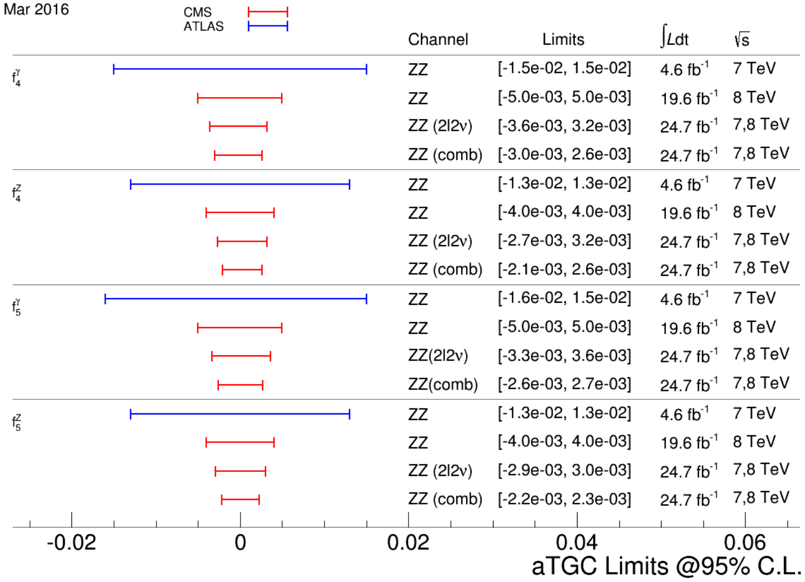
	Channel	Limits	$\int L dt$	$\sqrt{s}$
$\Delta\kappa_\gamma$	Wγ	[-4.1e-01, 4.6e-01]	4.6 fb^{-1}	7 TeV
	Wγ	[-3.8e-01, 2.9e-01]	5.0 fb^{-1}	7 TeV
	WW	[-1.2e-01, 1.7e-01]	20.3 fb^{-1}	8 TeV
	WW	[-2.1e-01, 2.2e-01]	4.9 fb^{-1}	7 TeV
	WW	[-1.3e-01, 9.5e-02]	19.4 fb^{-1}	8 TeV
	WV	[-2.1e-01, 2.2e-01]	4.6 fb^{-1}	7 TeV
	WV	[-1.1e-01, 1.4e-01]	5.0 fb^{-1}	7 TeV
	D0 Comb.	[-1.6e-01, 2.5e-01]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-9.9e-02, 6.6e-02]	0.7 fb^{-1}	0.20 TeV
λ_γ	Wγ	[-6.5e-02, 6.1e-02]	4.6 fb^{-1}	7 TeV
	Wγ	[-5.0e-02, 3.7e-02]	5.0 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV



	Channel	Limits	$\int L dt$	$\sqrt{s}$
h_3^γ	Zγ(llγ,ννγ)	[-1.5e-02, 1.6e-02]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-2.9e-03, 2.9e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-4.6e-03, 4.6e-03]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-1.1e-03, 9.0e-04]	19.6 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-2.2e-02, 2.0e-02]	5.1 fb^{-1}	1.96 TeV
h_3^Z	Zγ(llγ,ννγ)	[-1.3e-02, 1.4e-02]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-2.7e-03, 2.7e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.8e-03, 3.7e-03]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-1.5e-03, 1.6e-03]	19.6 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-2.0e-02, 2.1e-02]	5.1 fb^{-1}	1.96 TeV
h_4^γ	Zγ(llγ,ννγ)	[-9.4e-05, 9.2e-05]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-1.5e-05, 1.5e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.6e-05, 3.5e-05]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.8e-06, 4.3e-06]	19.6 fb^{-1}	8 TeV
h_4^Z	Zγ(llγ,ννγ)	[-8.7e-05, 8.7e-05]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-1.3e-05, 1.3e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.1e-05, 3.0e-05]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.9e-06, 4.5e-06]	19.6 fb^{-1}	8 TeV

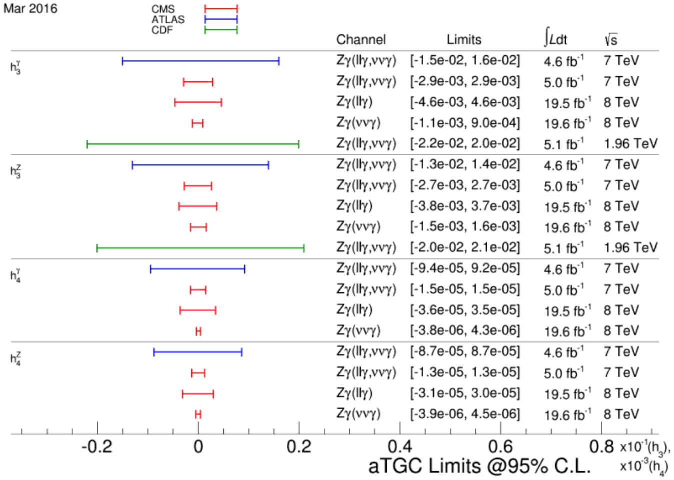


	Channel	Limits	$\int L dt$	$\sqrt{s}$
$\Delta\kappa_Z$	WW	[-4.3e-02, 4.3e-02]	4.6 fb^{-1}	7 TeV
	WW	[-2.5e-02, 2.0e-02]	20.3 fb^{-1}	8 TeV
	WW	[-6.0e-02, 4.6e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-1.9e-01, 3.0e-01]	20.3 fb^{-1}	8 TeV
	WV	[-9.0e-02, 1.0e-01]	4.6 fb^{-1}	7 TeV
	WV	[-4.3e-02, 3.3e-02]	5.0 fb^{-1}	7 TeV
	LEP Comb.	[-7.4e-02, 5.1e-02]	0.7 fb^{-1}	0.20 TeV
λ_Z	WW	[-6.2e-02, 5.9e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.9e-02, 1.9e-02]	20.3 fb^{-1}	8 TeV
	WW	[-4.8e-02, 4.8e-02]	4.9 fb^{-1}	7 TeV
	WW	[-2.4e-02, 2.4e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-4.6e-02, 4.7e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.6e-02, 1.6e-02]	20.3 fb^{-1}	8 TeV
	WV	[-3.9e-02, 4.0e-02]	4.6 fb^{-1}	7 TeV
	WV	[-3.8e-02, 3.0e-02]	5.0 fb^{-1}	7 TeV
	D0 Comb.	[-3.6e-02, 4.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.9e-02, 1.7e-02]	0.7 fb^{-1}	0.20 TeV
Δg_1^Z	WW	[-3.9e-02, 5.2e-02]	4.6 fb^{-1}	7 TeV
	WW	[-1.6e-02, 2.7e-02]	20.3 fb^{-1}	8 TeV
	WW	[-9.5e-02, 9.5e-02]	4.9 fb^{-1}	7 TeV
	WW	[-4.7e-02, 2.2e-02]	19.4 fb^{-1}	8 TeV
	WZ	[-5.7e-02, 9.3e-02]	4.6 fb^{-1}	7 TeV
	WZ	[-1.9e-02, 2.9e-02]	20.3 fb^{-1}	8 TeV
	WV	[-5.5e-02, 7.1e-02]	4.6 fb^{-1}	7 TeV
	D0 Comb.	[-3.4e-02, 8.4e-02]	8.6 fb^{-1}	1.96 TeV
	LEP Comb.	[-5.4e-02, 2.1e-02]	0.7 fb^{-1}	0.20 TeV



	Channel	Limits	$\int L dt$	$\sqrt{s}$
f_4^γ	ZZ	[-1.5e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-3.6e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (comb)	[-3.0e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
f_4^Z	ZZ	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
	ZZ	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.7e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (comb)	[-2.1e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
f_5^γ	ZZ	[-1.6e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ(2l2ν)	[-3.3e-03, 3.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ(comb)	[-2.6e-03, 2.7e-03]	24.7 fb^{-1}	7,8 TeV
f_5^Z	ZZ	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
	ZZ	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.9e-03, 3.0e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (comb)	[-2.2e-03, 2.3e-03]	24.7 fb^{-1}	7,8 TeV

aTGC – interesting yet?

- Are these aTGC limits interesting yet?
  - Useful to consider aTGC in effective field theory
  - Essentially the same as looking for weak force effect well below the mass scale of the W and Z
  - $h \approx c m_V^2/\Lambda^2$
  - Natural assumption for coupling constant c: order 1
  - Assumption new physics scale. 1 to 3 TeV
- 

Mar 2016

	Channel	Limits	$\int L dt$	$\sqrt{s}$
h_3^γ	Zγ(llγ,ννγ)	[-1.5e-02, 1.6e-02]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-2.9e-03, 2.9e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-4.6e-03, 4.6e-03]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-1.1e-03, 9.0e-04]	19.6 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-2.2e-02, 2.0e-02]	5.1 fb^{-1}	1.96 TeV
h_3^Z	Zγ(llγ,ννγ)	[-1.3e-02, 1.4e-02]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-2.7e-03, 2.7e-03]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.8e-03, 3.7e-03]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-1.5e-03, 1.6e-03]	19.6 fb^{-1}	8 TeV
	Zγ(llγ,ννγ)	[-2.0e-02, 2.1e-02]	5.1 fb^{-1}	1.96 TeV
h_4^γ	Zγ(llγ,ννγ)	[-9.4e-05, 9.2e-05]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-1.5e-05, 1.5e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.6e-05, 3.5e-05]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.8e-06, 4.3e-06]	19.6 fb^{-1}	8 TeV
h_4^Z	Zγ(llγ,ννγ)	[-8.7e-05, 8.7e-05]	4.6 fb^{-1}	7 TeV
	Zγ(llγ,ννγ)	[-1.3e-05, 1.3e-05]	5.0 fb^{-1}	7 TeV
	Zγ(llγ)	[-3.1e-05, 3.0e-05]	19.5 fb^{-1}	8 TeV
	Zγ(ννγ)	[-3.9e-06, 4.5e-06]	19.6 fb^{-1}	8 TeV

1×10^{-3} interesting

- h4 described by higher dimension operator but limits 100x more stringent
- At level of interesting sensitivity.

aTGC in Run II

- NLO, NNLO QCD issues
  - Theory calculations exist - apply as differential k factors
  - Factorize for NP so consider applying there also
- NLO QCD MCs
  - MCs available with some new physics models – incorporate in analysis
- NLO EWK MCs
  - On the way – use when available. In principle NP model could incorporate as well
- Unitarity
  - All analysis should check unitarity
  - Consider applying form factors in cases with unitarity violation is at low energy scales
- Parameterizations
  - Should agree on standard parameterization
  - Moving in direction of EFT approach. Interesting parameterizations available including Higgs couplings
  - Keep aGC approach when easily translated for comparison to previous results
- Models
  - Encourage groups to test well motivated models when of interest
- Combination
  - Many analysis with similar sensitivity. Especially in charged aTGC
  - Combination effort in progress, test combination have been done
  - Also combination with Higgs measurements in development
- New physics discovery
  - Many strategies to tackle this when we find it. Angular analysis, energy dependence, multiple

aQGC Results and Discussion

- aQGC Parameterizations
- VBS and triboson production with photons
  - Wγ, Zγ, WVγ, Wγγ, Zγγ
  - Zγ and Wγγ, Zγγ as examples
- VBS with Ws and Zs
  - Same sign WW, WZ
  - Same sign WW as an example
- Issues in aQGC
- Summary plots
- aQGC in Run II

aQQCs

- Anomalous quartic gauge couplings in effective field theory
- aQGCs for SM allowed processes introduced at D6.
  - However they are the same operators that modify the (a)TGCs or Higgs gauge boson couplings which will be better measured

$$\mathcal{O}_{\phi d} = \partial_\mu \left(\phi^\dagger \phi\right) \partial^\mu \left(\phi^\dagger \phi\right)$$

$$\mathcal{O}_{\phi W} = \left(\phi^\dagger \phi\right) \mathrm{Tr}[W^{\mu\nu} W_{\mu\nu}]$$

$$\mathcal{O}_{\phi B} = \left(\phi^\dagger \phi\right) B^{\mu\nu} B_{\mu\nu}$$

- Lowest in s are
  - Example

$$\left[(D_\mu \Phi)^\dagger D_\nu \Phi\right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi\right]$$

  - You inse uge terms

$$D_\mu \Phi = (\partial_\mu - igW^j_\mu \frac{\sigma^j}{2} - ig' B_\mu \frac{1}{2})\Phi$$

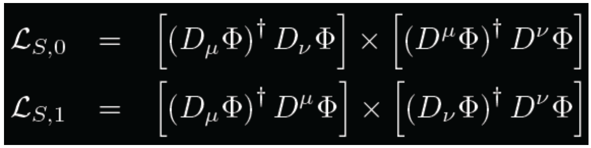
    - All aQGCs that conserve charge are possible
  - Note: Previous work in “nonlinear” realization of SU(2) $_L$xU(1) symmetry
    - Symmetries enforced without light Higgs
    - Lower dimension D4, D6 aQGCs
    - Have to connect with that work , LEP, LHC limits already set in that

WWWW, WWZZ, ZZZZ,WWγγ, WWZγ, Zγγγ, ZZγγ, ZZZγ

aQQCs

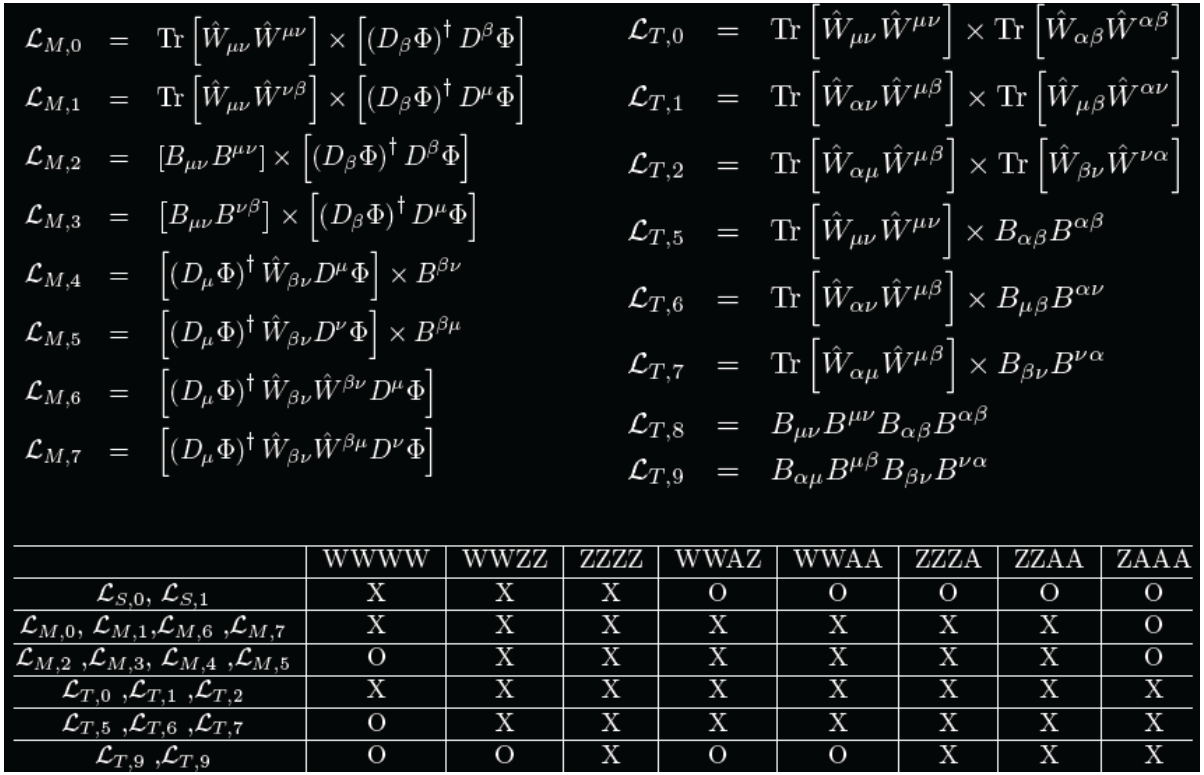
- For the record: All D8 aQGCs operators
  - Eboli's notation
- Operators
  - Names based on vector boson polarizations
  - T: transverse
  - S: scalar, longitudinal
  - M: mixed
- S operators only occur for massive vector boson scattering interactions
  - These will be some of the most interesting

hep-ph/0606118 QGC at D8 O. Eboli et. Al.



$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$



$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$

$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$

$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$

$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$

$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

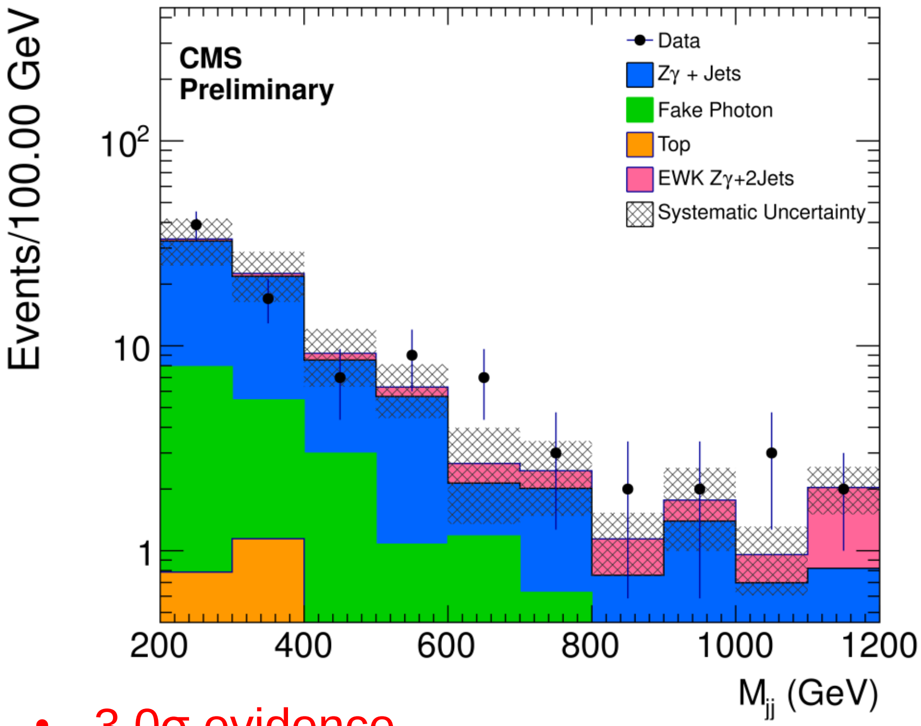
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O
$\mathcal{L}_{T,0}$,$\mathcal{L}_{T,1}$,$\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$,$\mathcal{L}_{T,6}$,$\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$,$\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X

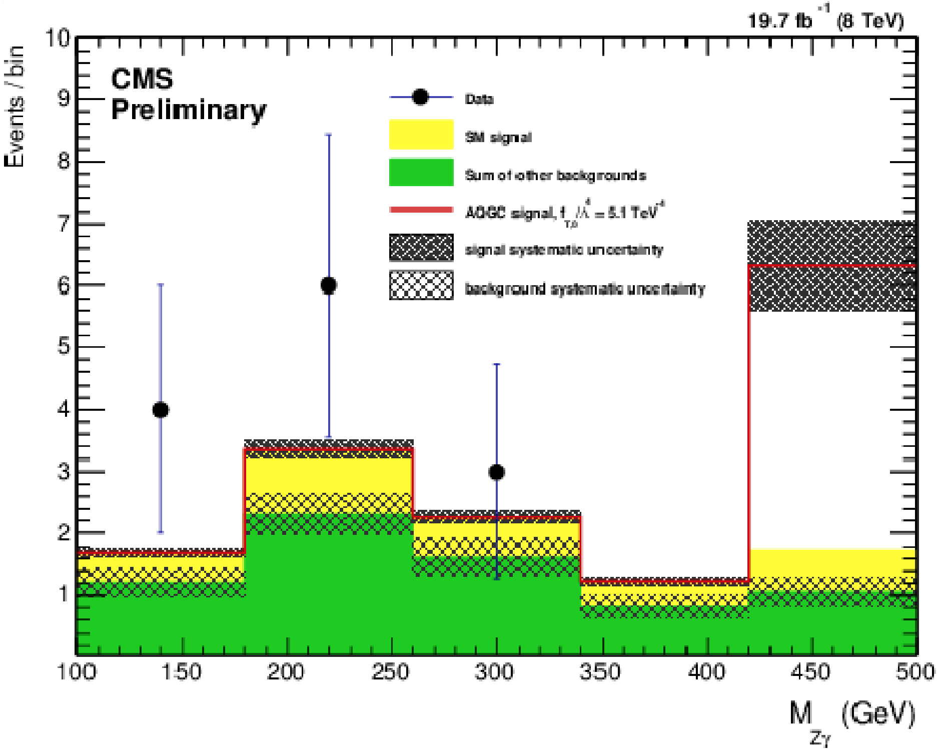
Evidence for EWK Zγ and aQGC

- $Z\gamma \rightarrow ll\gamma$ + 2 jets

CMS PAS SMP-14-018

  - EWK cross section measured in VBS phase space: $\Delta\eta$(jj) and m(jj) using m(jj) fit

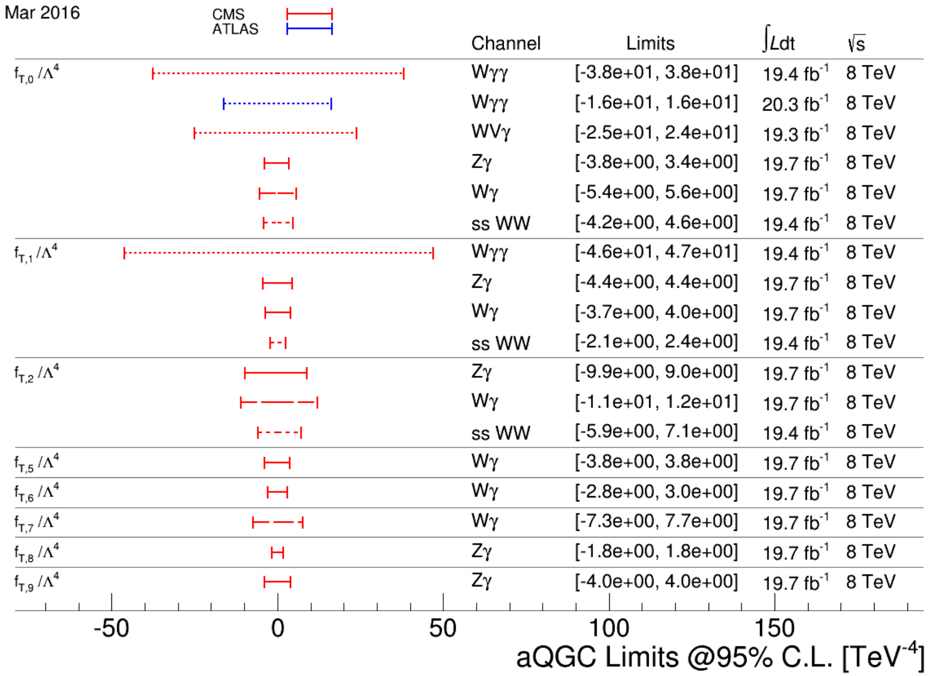




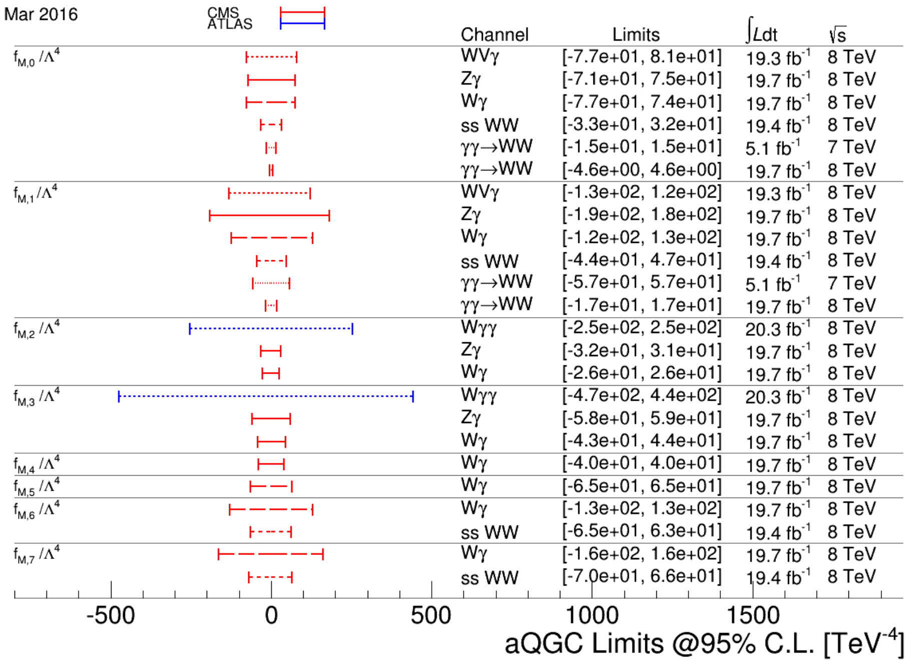
- 3.0σ evidence
- We can see it. Should be a strong for aQGC
- Additional selection for aQGC search, Higher γ E_T

D8 EFT limits put on fT and fM parameters using m($Z\gamma$)

aQGC fM, fT, Summary



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{T,0}/\Lambda^4$	Wγγ	[-3.8e+01, 3.8e+01]	19.4 fb^{-1}	8 TeV
	Wγγ	[-1.6e+01, 1.6e+01]	20.3 fb^{-1}	8 TeV
	WVγ	[-2.5e+01, 2.4e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-3.8e+00, 3.4e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-5.4e+00, 5.6e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.2e+00, 4.6e+00]	19.4 fb^{-1}	8 TeV
$f_{T,1}/\Lambda^4$	Wγγ	[-4.6e+01, 4.7e+01]	19.4 fb^{-1}	8 TeV
	Zγ	[-4.4e+00, 4.4e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-3.7e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV
	ss WW	[-2.1e+00, 2.4e+00]	19.4 fb^{-1}	8 TeV
$f_{T,2}/\Lambda^4$	Zγ	[-9.9e+00, 9.0e+00]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.1e+01, 1.2e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-5.9e+00, 7.1e+00]	19.4 fb^{-1}	8 TeV
$f_{T,5}/\Lambda^4$	Wγ	[-3.8e+00, 3.8e+00]	19.7 fb^{-1}	8 TeV
$f_{T,6}/\Lambda^4$	Wγ	[-2.8e+00, 3.0e+00]	19.7 fb^{-1}	8 TeV
$f_{T,7}/\Lambda^4$	Wγ	[-7.3e+00, 7.7e+00]	19.7 fb^{-1}	8 TeV
$f_{T,8}/\Lambda^4$	Zγ	[-1.8e+00, 1.8e+00]	19.7 fb^{-1}	8 TeV
$f_{T,9}/\Lambda^4$	Zγ	[-4.0e+00, 4.0e+00]	19.7 fb^{-1}	8 TeV



	Channel	Limits	$\int L dt$	$\sqrt{s}$
$f_{M,0}/\Lambda^4$	WVγ	[-7.7e+01, 8.1e+01]	19.3 fb^{-1}	8 TeV
	Zγ	[-7.1e+01, 7.5e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-7.7e+01, 7.4e+01]	19.7 fb^{-1}	8 TeV
	ss WW	[-3.3e+01, 3.2e+01]	19.4 fb^{-1}	8 TeV
	γγ→WW	[-1.5e+01, 1.5e+01]	5.1 fb^{-1}	7 TeV
	γγ→WW	[-4.6e+00, 4.6e+00]	19.7 fb^{-1}	8 TeV
$f_{M,1}/\Lambda^4$	WVγ	[-1.3e+02, 1.2e+02]	19.3 fb^{-1}	8 TeV
	Zγ	[-1.9e+02, 1.8e+02]	19.7 fb^{-1}	8 TeV
	Wγ	[-1.2e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-4.4e+01, 4.7e+01]	19.4 fb^{-1}	8 TeV
	γγ→WW	[-5.7e+01, 5.7e+01]	5.1 fb^{-1}	7 TeV
	γγ→WW	[-1.7e+01, 1.7e+01]	19.7 fb^{-1}	8 TeV
$f_{M,2}/\Lambda^4$	Wγγ	[-2.5e+02, 2.5e+02]	20.3 fb^{-1}	8 TeV
	Zγ	[-3.2e+01, 3.1e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-2.6e+01, 2.6e+01]	19.7 fb^{-1}	8 TeV
$f_{M,3}/\Lambda^4$	Wγγ	[-4.7e+02, 4.4e+02]	20.3 fb^{-1}	8 TeV
	Zγ	[-5.8e+01, 5.9e+01]	19.7 fb^{-1}	8 TeV
	Wγ	[-4.3e+01, 4.4e+01]	19.7 fb^{-1}	8 TeV
$f_{M,4}/\Lambda^4$	Wγ	[-4.0e+01, 4.0e+01]	19.7 fb^{-1}	8 TeV
$f_{M,5}/\Lambda^4$	Wγ	[-6.5e+01, 6.5e+01]	19.7 fb^{-1}	8 TeV
$f_{M,6}/\Lambda^4$	Wγ	[-1.3e+02, 1.3e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-6.5e+01, 6.3e+01]	19.4 fb^{-1}	8 TeV
$f_{M,7}/\Lambda^4$	Wγ	[-1.6e+02, 1.6e+02]	19.7 fb^{-1}	8 TeV
	ss WW	[-7.0e+01, 6.6e+01]	19.4 fb^{-1}	8 TeV

- D8 limits placed on EFT aQGC parameters
  - Conversion performed from D6 parameters
- Issue: Unitarity violated at LHC energies for aQGC parameters this large
- Strategies: Form factors, k-Matrix unitarization, or ignore violation understanding that later analysis will have better sensitivity.

Are these limits interesting?

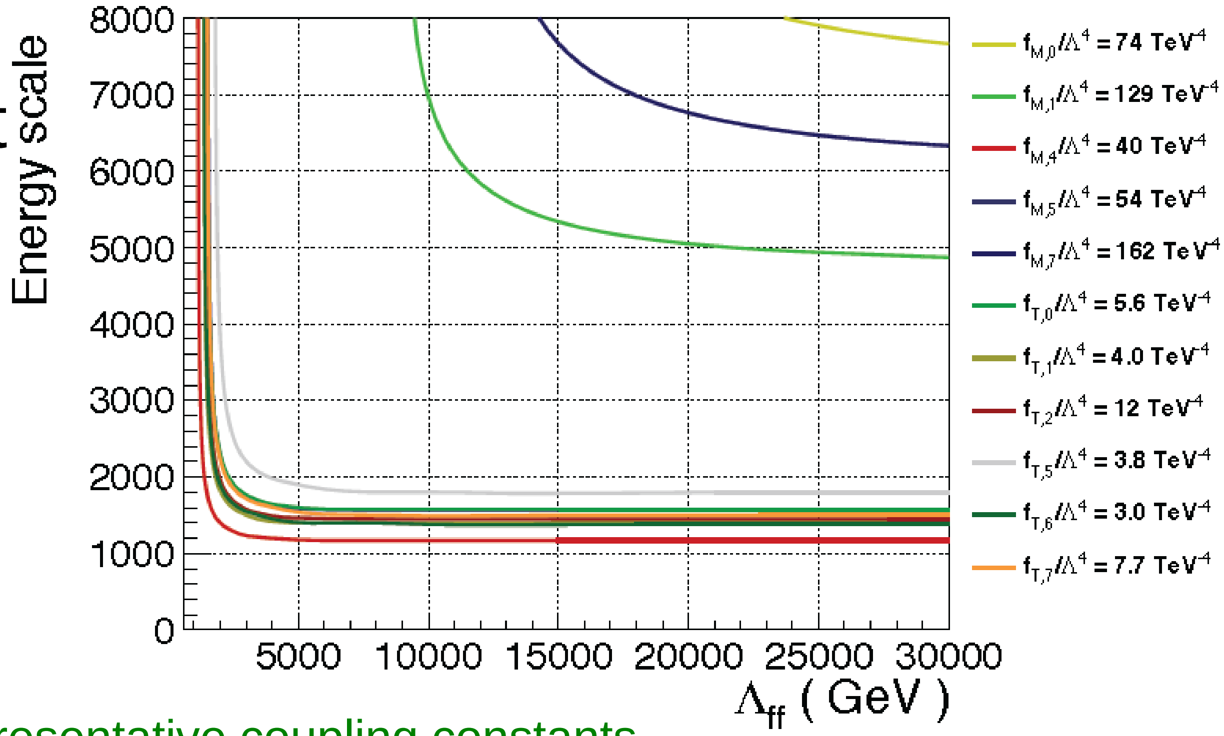
Naive interesting scale would be: $f/\Lambda^4 = 1$

NP: $\Lambda = 1$ TeV

$f = 1$

Unitarity

- Expect unitarily violated at modest energies in VBS
  - NP perturbs cancelation between TGC, QGC, Higgs diagrams



Unitarily curves with representative coupling constants
Unitarily violated at energies above the curves.
Effect of form factor considered

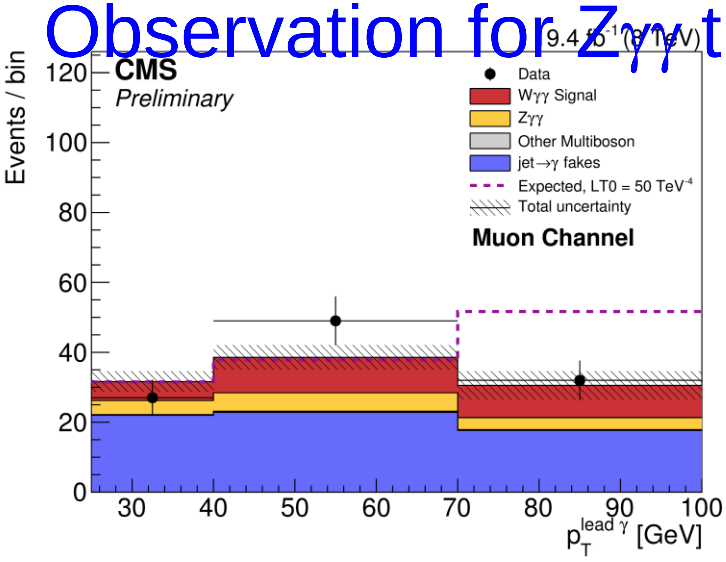
Generally unitarily violated at modest energies for most parameters!

Zγγ,Wγγ aQGC

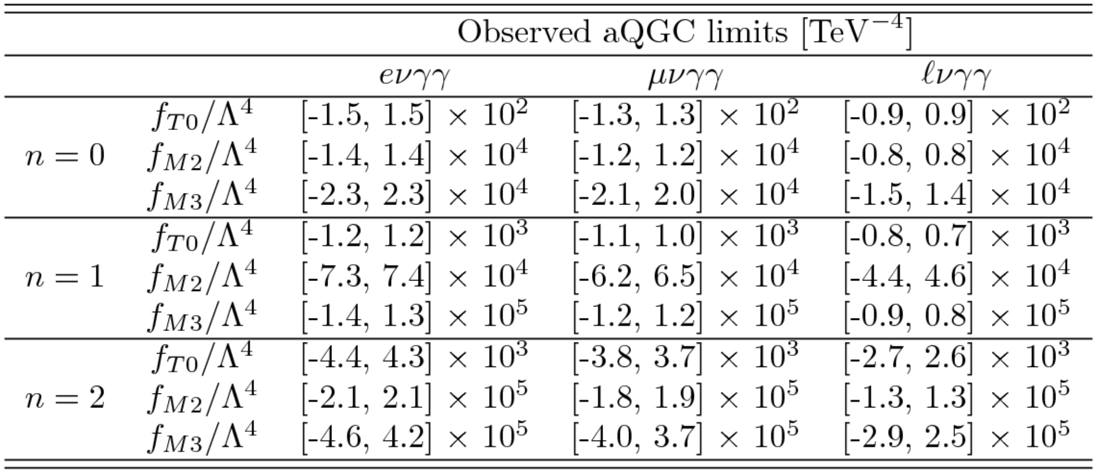
- Search for triboson production and aQGC in Zγγ and Wγγ
- Evidence found for Wγγ triboson production, ATLAS
- Observation for Zγγ triboson production, CMS

ATLAS PRL 115, 031802 (2015)

CMS PAS SMP-15-008



ATLAS checked various choices of form factor exponent. Form factors at 500-600 GeV



		Observed aQGC limits [TeV^{-4}]		
		$e\nu\gamma\gamma$	$\mu\nu\gamma\gamma$	$\ell\nu\gamma\gamma$
$n=0$	f_{T0}/Λ^4	$[-1.5,\ 1.5] \times 10^2$	$[-1.3,\ 1.3] \times 10^2$	$[-0.9,\ 0.9] \times 10^2$
	f_{M2}/Λ^4	$[-1.4,\ 1.4] \times 10^4$	$[-1.2,\ 1.2] \times 10^4$	$[-0.8,\ 0.8] \times 10^4$
	f_{M3}/Λ^4	$[-2.3,\ 2.3] \times 10^4$	$[-2.1,\ 2.0] \times 10^4$	$[-1.5,\ 1.4] \times 10^4$
$n=1$	f_{T0}/Λ^4	$[-1.2,\ 1.2] \times 10^3$	$[-1.1,\ 1.0] \times 10^3$	$[-0.8,\ 0.7] \times 10^3$
	f_{M2}/Λ^4	$[-7.3,\ 7.4] \times 10^4$	$[-6.2,\ 6.5] \times 10^4$	$[-4.4,\ 4.6] \times 10^4$
	f_{M3}/Λ^4	$[-1.4,\ 1.3] \times 10^5$	$[-1.2,\ 1.2] \times 10^5$	$[-0.9,\ 0.8] \times 10^5$
$n=2$	f_{T0}/Λ^4	$[-4.4,\ 4.3] \times 10^3$	$[-3.8,\ 3.7] \times 10^3$	$[-2.7,\ 2.6] \times 10^3$
	f_{M2}/Λ^4	$[-2.1,\ 2.1] \times 10^5$	$[-1.8,\ 1.9] \times 10^5$	$[-1.3,\ 1.3] \times 10^5$
	f_{M3}/Λ^4	$[-4.6,\ 4.2] \times 10^5$	$[-4.0,\ 3.7] \times 10^5$	$[-2.9,\ 2.5] \times 10^5$

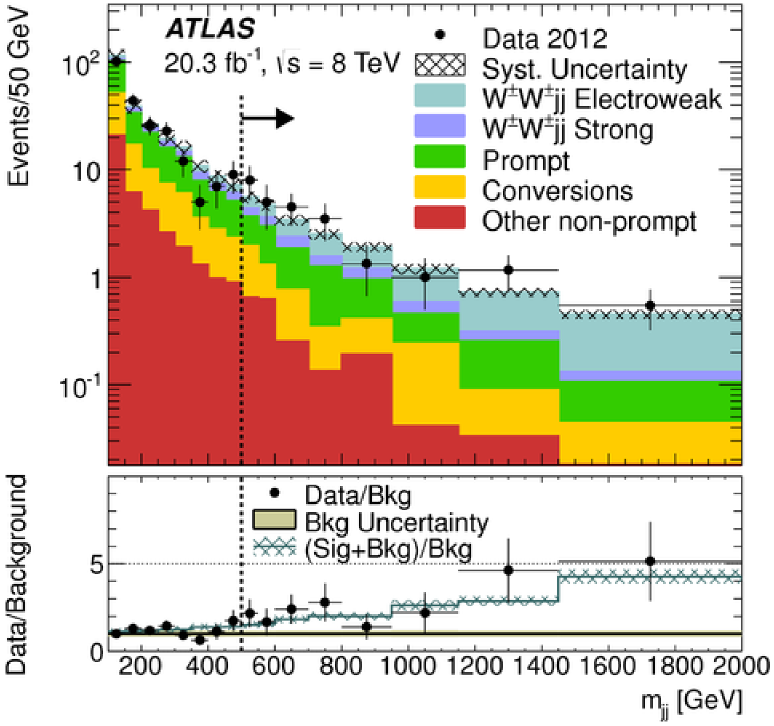
Can be translated to fM operators

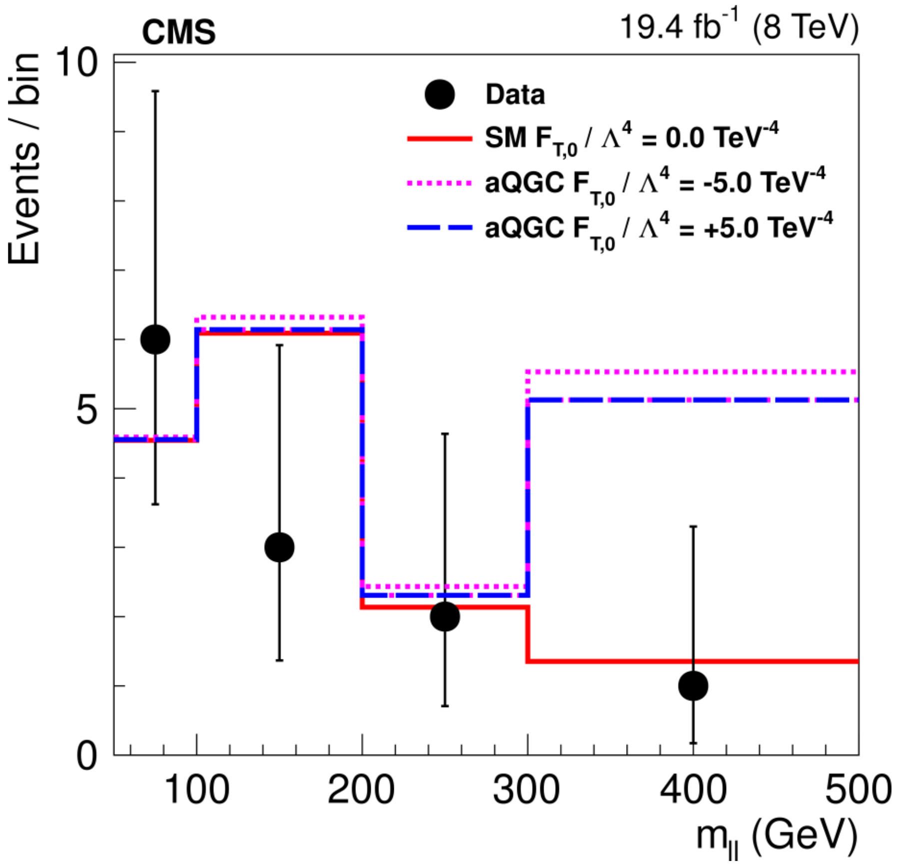
Evidence for EWK ssWW and aQGC

- EWK WW →lνlν + 2 jets

ATLAS Phys. Rev. Lett. 113, 141803 (2014)

CMS Phys. Rev. Lett. 114 (2015) 051801





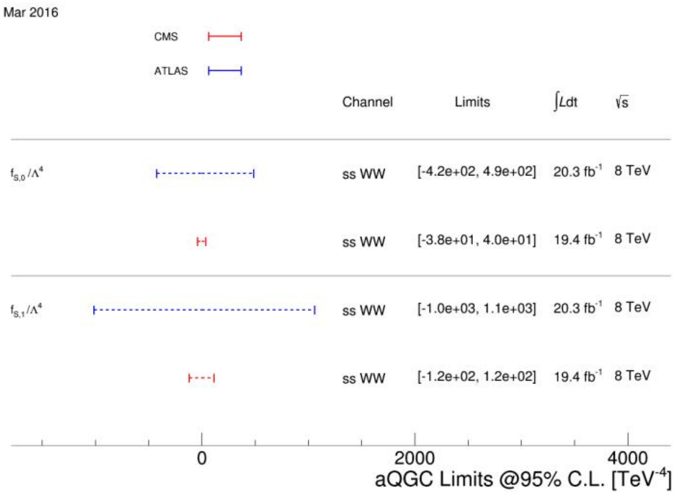
- 3.6σ evidence in ATLAS analysis
- Should be good sensitivity

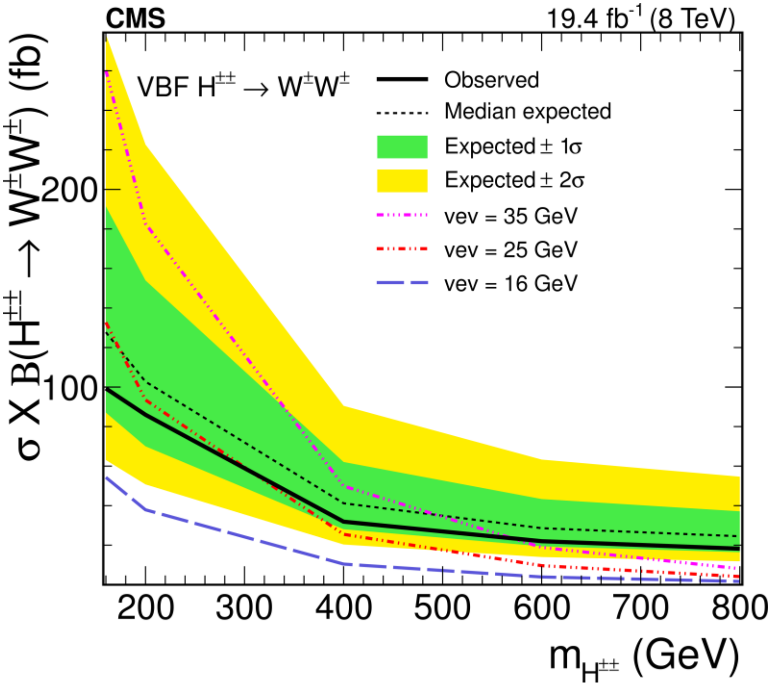
D6, D8 limits placed on aQGC EFT parameters by ATLAS and CMS

Unitarity Options

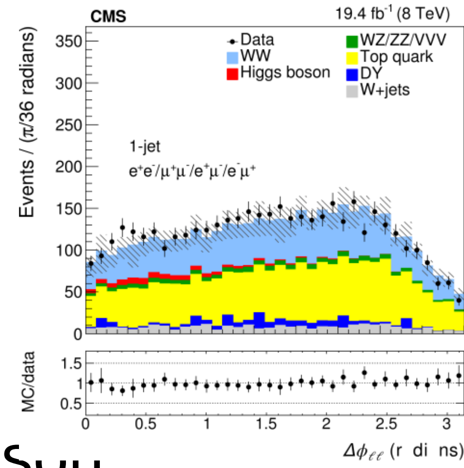
- Ignore
  - Probably okay for now.
  - We are likely only sensitive to new physics when we are measuring couplings of f=1 for order TeV Physics
- Form factors
  - Now also have the disadvantage that they don't control unitarily unless at low or high energies.
- Cutoff or kmatrix schemes
  - Cutoff absolutely, at a given energy, or minimally at various energies limit the cross section.
  - Not realistic. However, estimates your loss of sensitivity when applying a model that enforces unitarity.
- Model. Assume model. H++→W+W+ in this case

Unitary scheme leads to factor 10 loss in sensitivity.

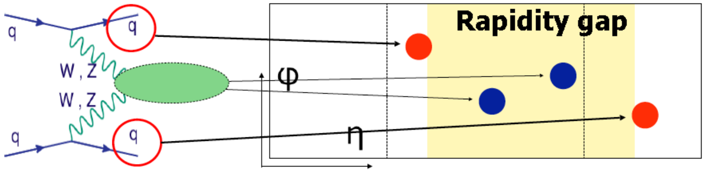




aQGC in VBS Strategy



- WW→WW Strategy
- LHC Run 1
  - Measurement of WW cross section
  - With differential distributions including jets
  - VBF mode helped with discovery of Higgs boson
- LHC Run 2
  - Measure pure EWK WW production
    - Isolate VBS topology. WW and forward scattering jets large Δη(jj) and m(jj)
  - Search for aQGCs in the high mll distribution
    - Use angular distributions, energy dependence and other scattering interactions to study and disentangle any non SM contributions



Conclusions

- aTGC and aQGC an interesting place to search for new physics
- Sensitivity to new Gauge and EWSB physics
- Many measurements entering the true range of sensitivity in Run II
- Range of challenges to address
  - Calculation of signal and background rates given higher order QCD and EWK contributions
  - Interpretation of results in a realistic way
  - Analysis of a possible new physics effect if one is observed

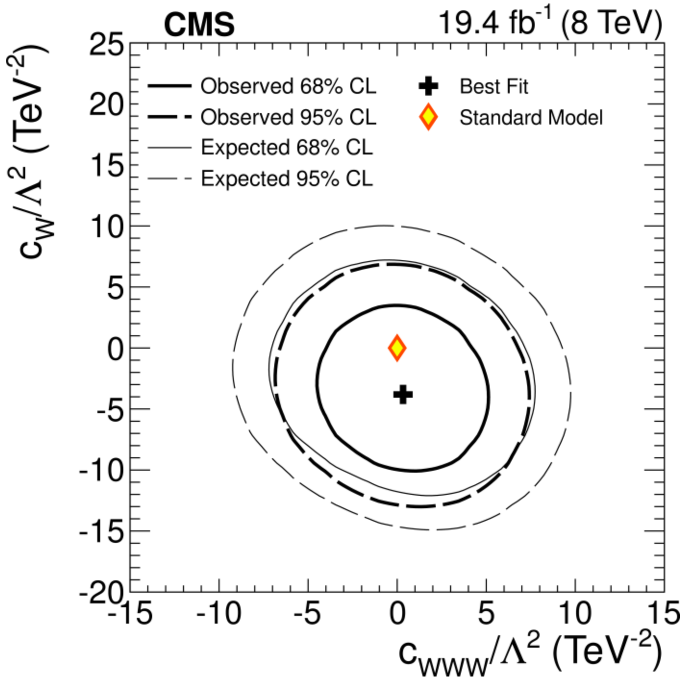
Backup

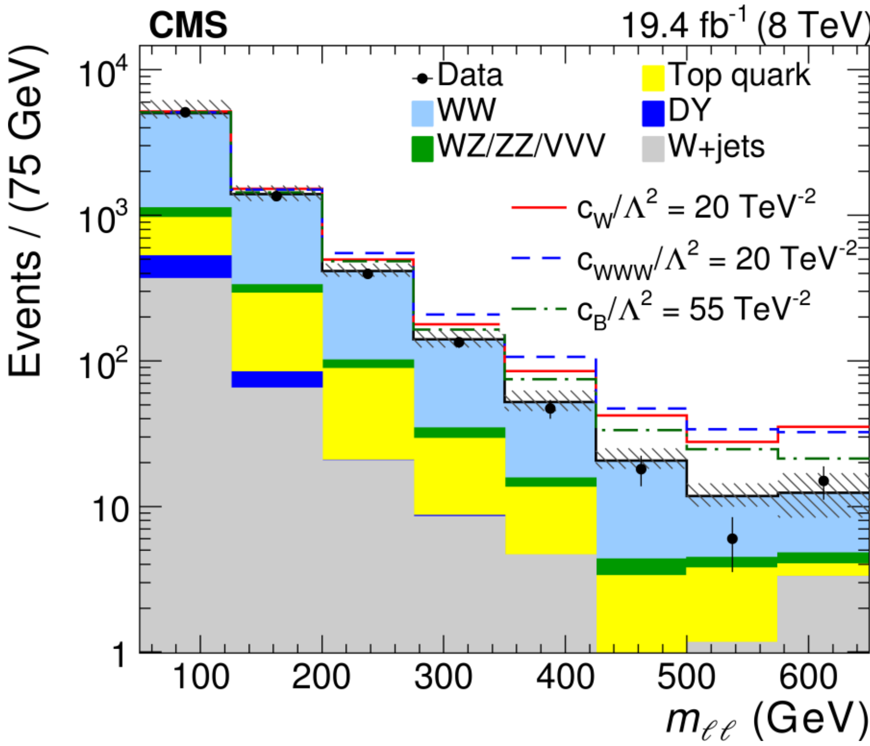
WW aTGC update

CMS PAS SMP-14-016

Submitted to Eur. Phys. J. C

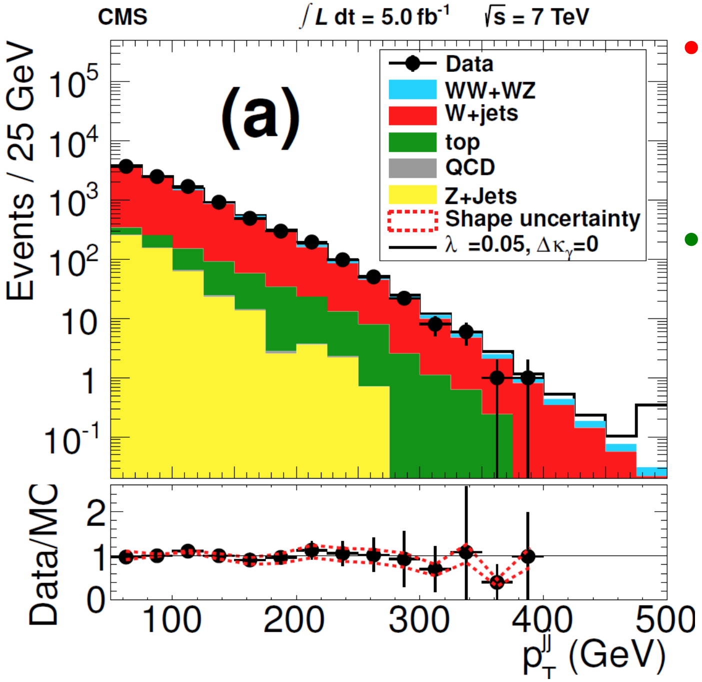
- aTGC search
  - Exploit expected high transvers momentum of vector boson using leading lepton p_T distribution
- Limits Limits on WWγ and WWZ couplings



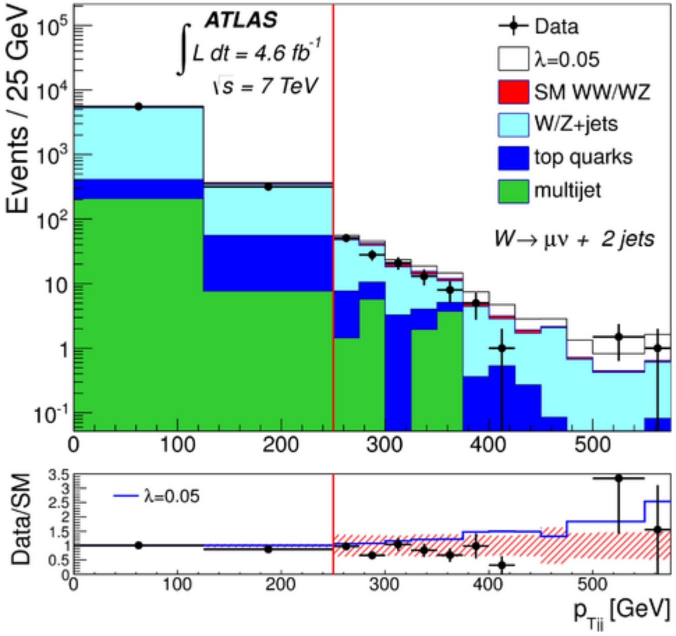


WW+WZ aTGC

- aTGC search Eur. Phys. J. C 73 (2013) 2283 JHEP 01 (2015) 049
  - Exploit expected high transverse momentum of vector boson using hadronically decaying vector boson p_T distribution
  - Weak sensitivity to gZ1. Set to SM



- Limits Limits on WWγ and WWZ
- Continuing this analysis requires using jet substructure

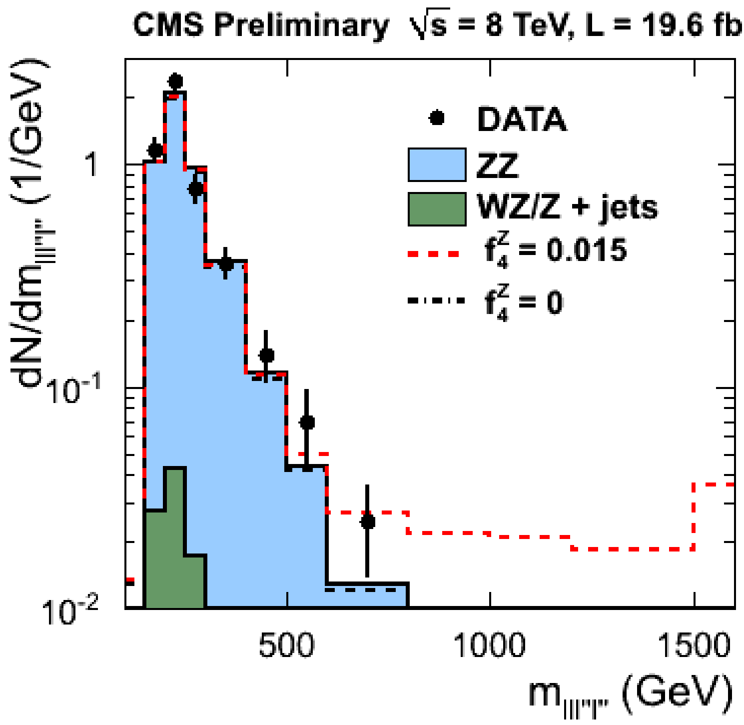


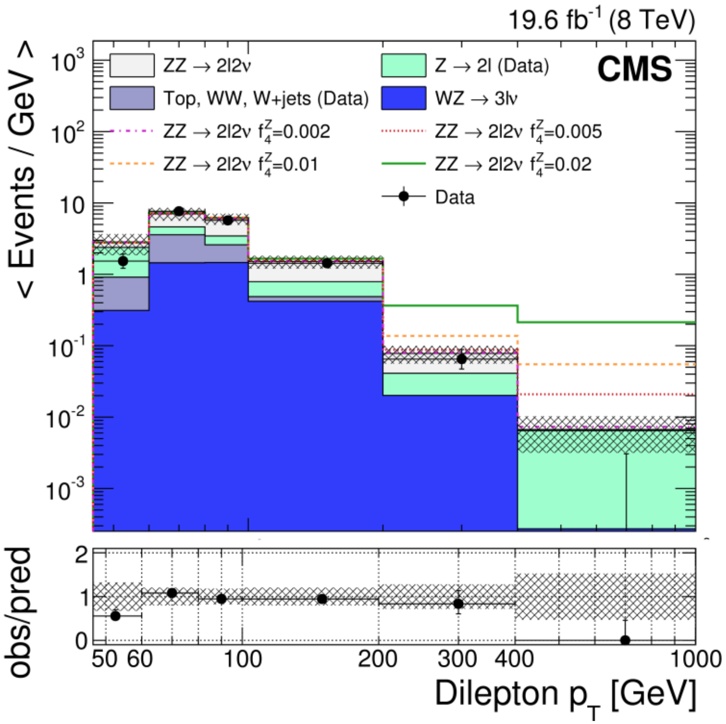
ZZ aTGC

- aTGC search in 4l and 2l2ν
  - Exploit expected high transvers momentum of vector bosons using the 4l mass or Z pT.
- World leading sensitivity to ZZγ and

EPJC 75 (2015) 511

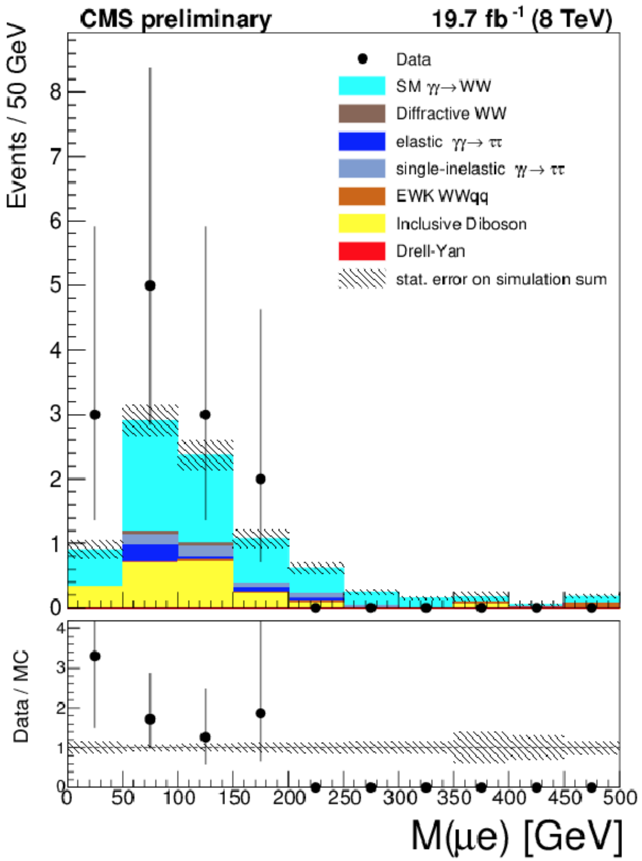
PLB 740 (2015) 250

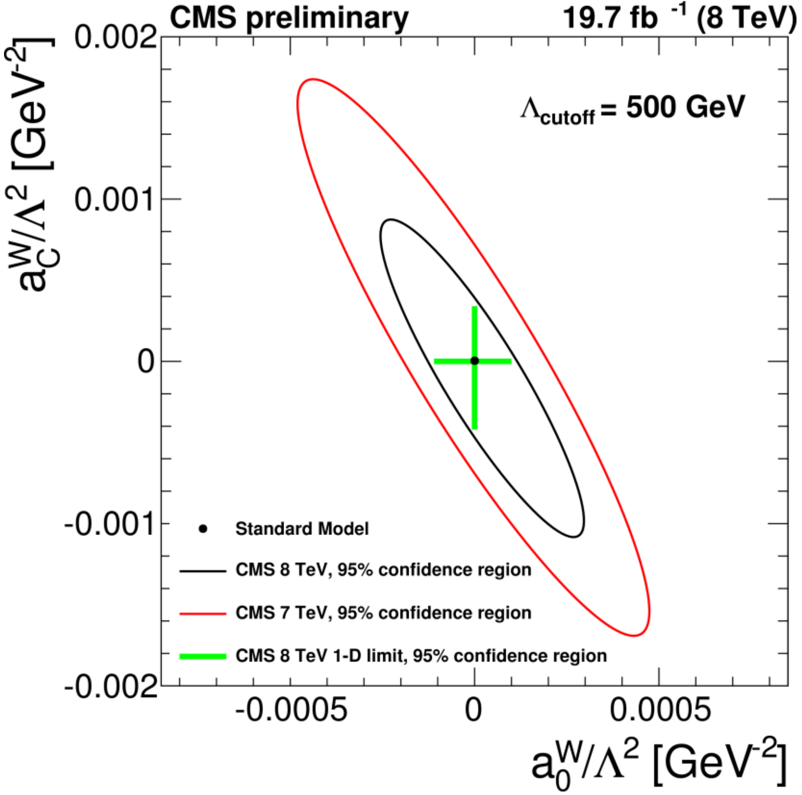




Evidence for γγ → WW & aQGC

- γγ → WW in Central exclusive production CMS PAS FSQ-13-008
  - Signal: dileptons (eμ) and missing E_T with central track veto
  - Use pTeμ to search for aQGC.





D6 EFT parameter limits

Conversion to D8 EFT parameters via linear transformation

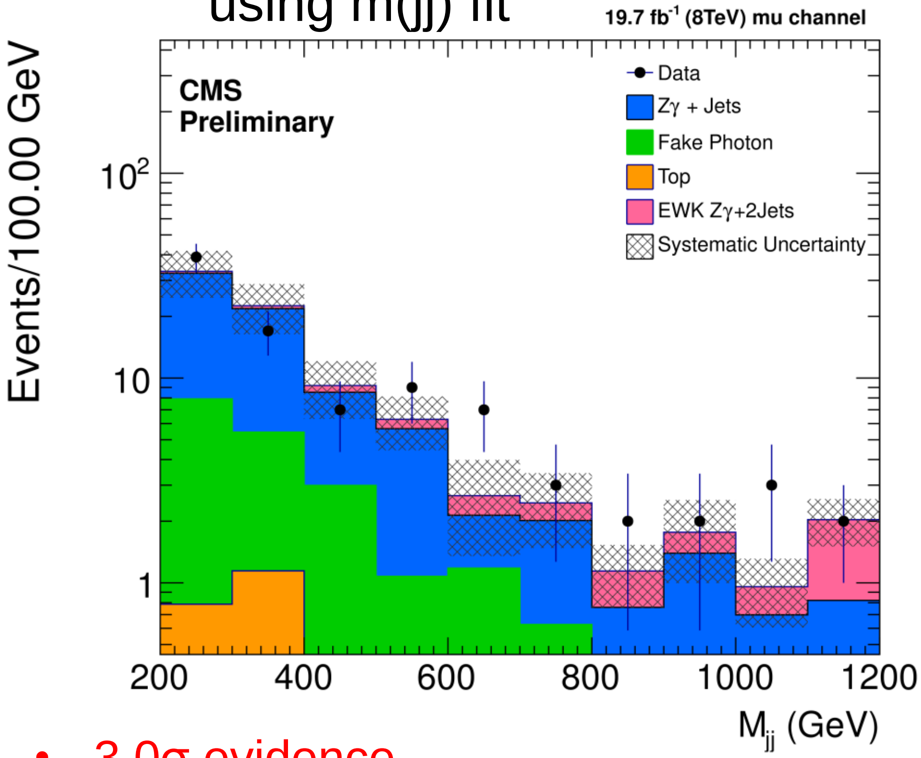
- 3.6σ evidence
- σ(γγ → WW) = 12.3+5.5-4.4 fb, SM: 6.9 ± 0.6

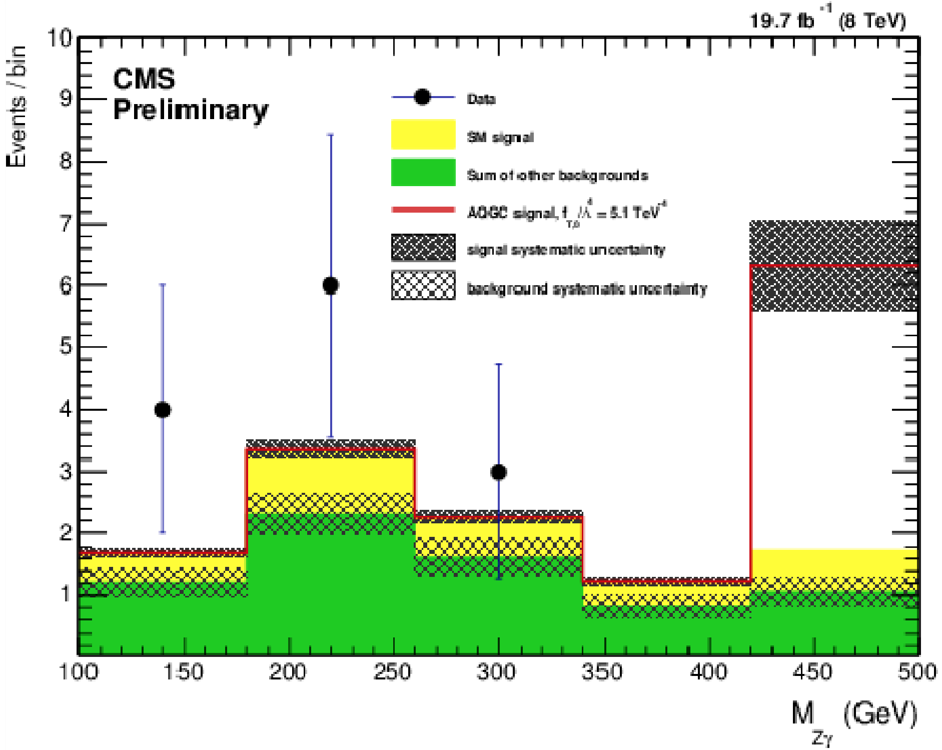
Evidence for EWK Zγ and aQGC

- Zγ → llγ + 2 jets

  CMS PAS SMP-14-018

  - EWK cross section measured in VBS phase space: Δη(jj) and m(jj) using m(jj) fit





- 3.0σ evidence
- σ(EWK Zγ) = $1.86^{+0.89}_{-0.75}(stat.)^{+0.41}_{-0.27}(sys.) \pm 0.05(lumi.)$ fb
- SM: $1.26 \pm 0.11(scale) \pm 0.05(PDF)$

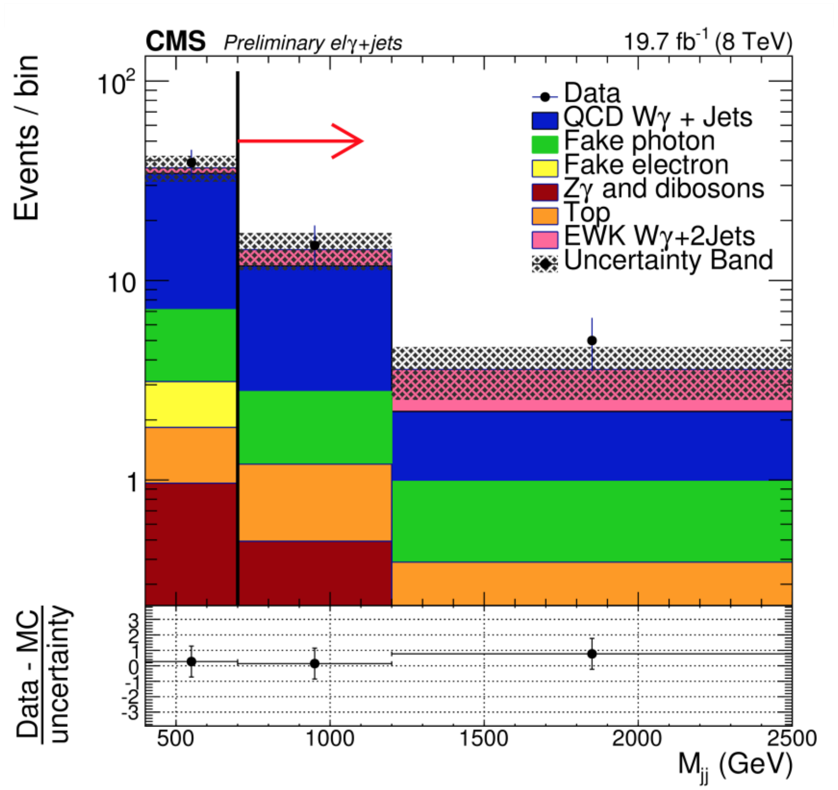
D8 EFT limits put on fT and fM parameters using m(Zγ)

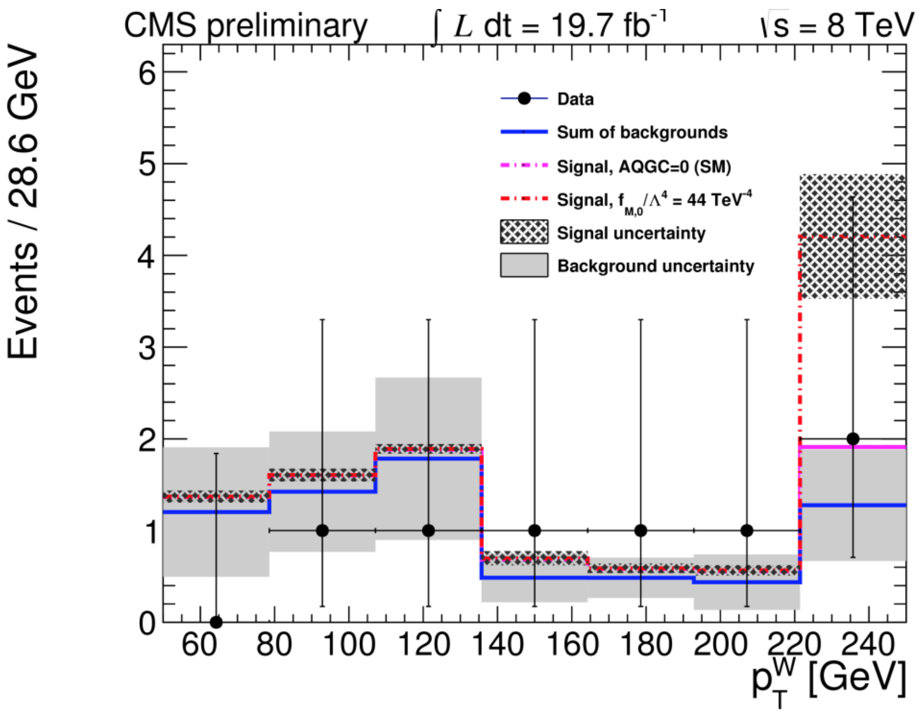
Search for EWK Wγ and aQGC

- Wγ → lνγ + 2 jets

CMS PAS SMP-14-011

  - EWK cross section measured in VBS phase space: Δη(jj) and m(jj) using m(jj) fit





D8 EFT limits put on fT and fM parameters using m(Zγ)