HEFT2015 Chicago

New Physics in Vector Boson Scattering

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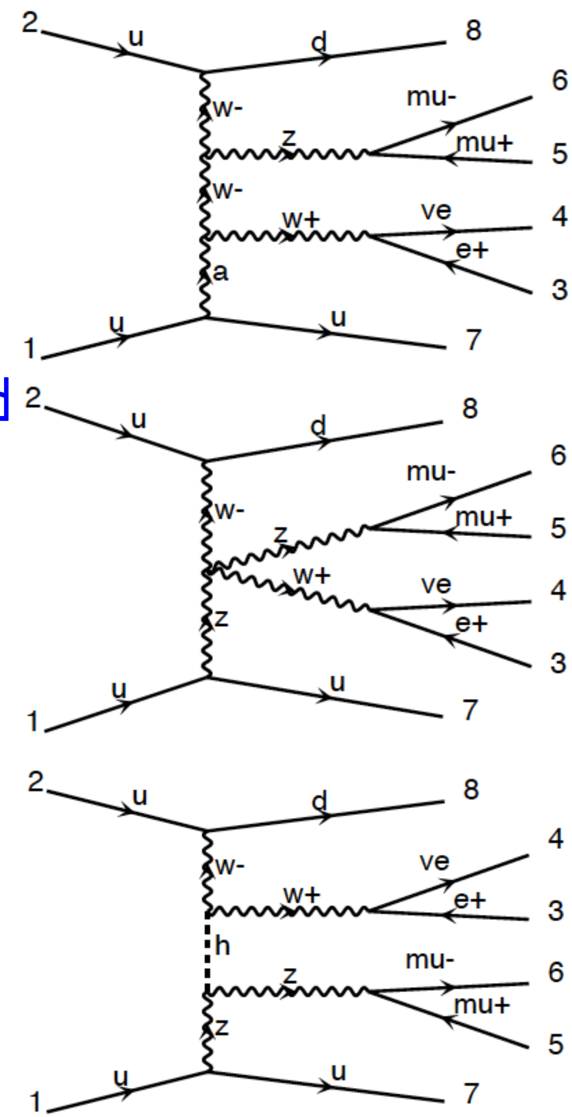
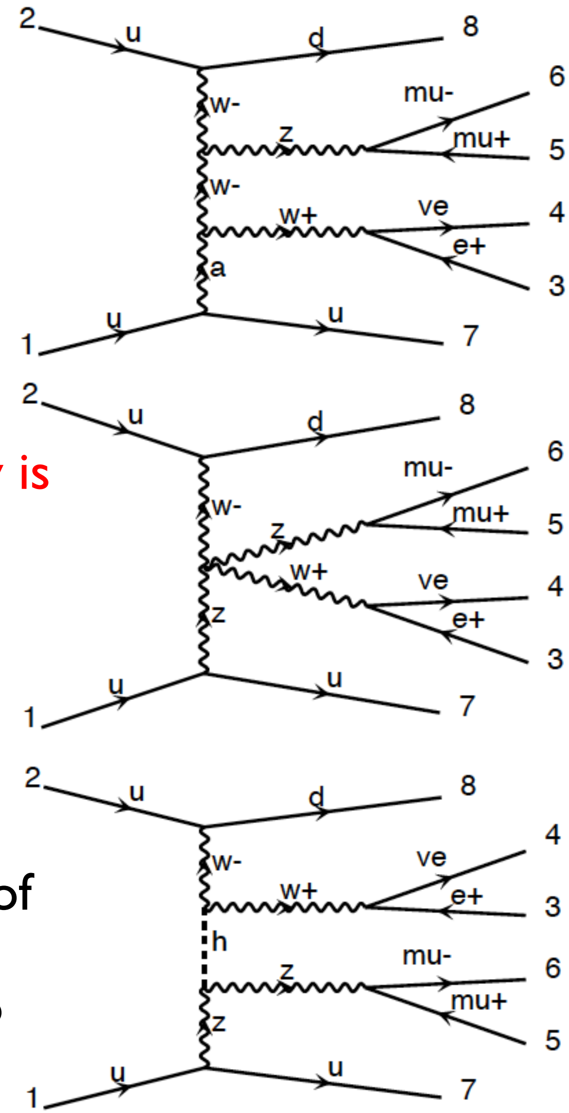
Vector Boson Scattering

- SM Vector boson scattering (VBS) interactions
  - Double triple gauge couplings, t and s channel
  - Quartic gauge coupling (QGC)
  - t channel scattering via a Higgs
  - s channel Higgs production via vector boson fusion
- Standard model expectation precisely predicted
  - All scattering contributions individually rise quickly with CM energy and violate unitarity
  - Unitarity conserved by interference effects
  - Unitarization with the inclusion of the Higgs contribution is a fundamental prediction of the SM
  - QGC and scattering of massive longitudinal vector bosons are unique rare SM processes that we would like to observe
- VBS is key to the further exploration of Electroweak symmetry breaking(EWSB)



New Physics in VBS

- New physics in VBS
- EWSB sector is the least explored part of the SM.
  - Has the most room for non SM physics
  - A direct window on non-SM electroweak symmetry breaking contributions
  - Example: Exchange of new heavy particles such as extra scalars (additional Higgs) 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
  - Large m(VV) or the high tail of pT(V) distribution
- Effective field theory in VBS
  - New physics often described in generalized context of anomalous quartic gauge couplings (aQGC)
  - Can use an effective field theory aQGC formalism to study new physics



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 $SU(3)_C x SU(2)_L x U(1)$ symmetry
    - Operators constructed as products of the fields
  - For 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
      - If Λ is large enough then the exact form of a possible propagator not so relevant
      - Due to constraints and direct searches we know that Λ is probably 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 be extended to do NLO calculation

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

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

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

  - 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

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 independent aQGC interactions are D8
  - Example: $\left[(D_\mu \Phi)^\dagger D_\nu \Phi\right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi\right]$
  - You insert D and Higgs VEV to get the quartic gauge terms

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

    - 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 approach

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 the most interesting

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

$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi\right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi\right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times B_{\mu\beta}B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times B_{\beta\nu}B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

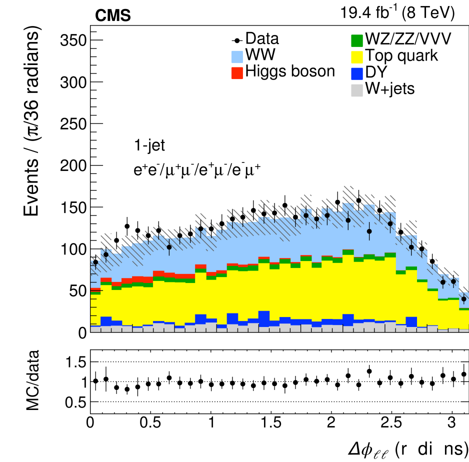
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$,$\mathcal{L}_{M,6}$,$\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O
$\mathcal{L}_{M,2}$,$\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$,$\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O
$\mathcal{L}_{T,0}$,$\mathcal{L}_{T,1}$,$\mathcal{L}_{T,2}$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

aQGC and VBS

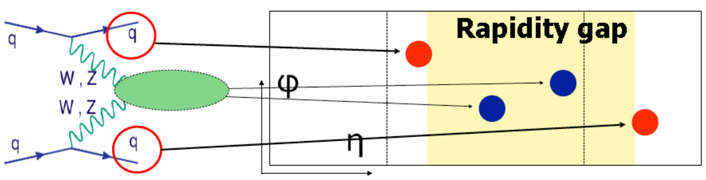
- Example Searching for VV→WW
  - Complex process with many contributions
  - Standard model WW+2jets
    - Central jets, WW mass falls quickly from threshold, includes large top contribution
  - Gluon fusion Higgs
    - Central jets, resonant WW mass, scalar angular distribution
  - Vector boson fusion Higgs
    - Forward tagging jets, resonant WW mass, scalar angular distribution
  - WW,ZZ scattering through t channel Z,γ,W double WWZ,γ TGC to WW
    - Forward tagging jets, less central distribution, WW mass falls from threshold mass
  - WW,ZZ scattering through QGC or t channel Higgs exchange to WW
    - Forward tagging jets, central distribution, flatter WW mass distribution
  - aQGC
    - Sign of massive resonant particles or scattering. Gauge particles, 2^{nd} Higgs, other scalar
    - Forward tagging jets, central distribution, larger contribution at high m(ll) or high pTl
  - Angular distributions of W decays and scattering jets also have discrimination

aQGC and VBS

- WW→WW Strategy
- LHC Run 1
  - Measurement of WW cross section
  - With differential distributions including associated 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



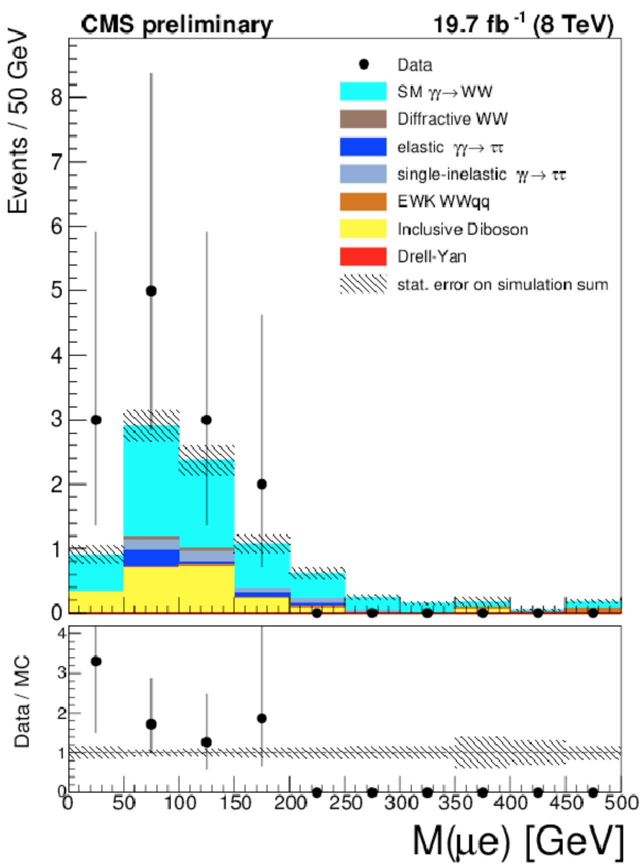
- LHC HL-LHC
  - Extract SM QGC coupling.
    - Proportional to fs0-fs1 operators combination
  - Isolate longitudinal component of vector boson scattering
    - W decay and jet angular distributions help.
    - Increased detector acceptance enhances sensitivity.
  - Search for aQGC
    - Use angular distributions and other scattering interactions to study and disentangle any non SM contributions

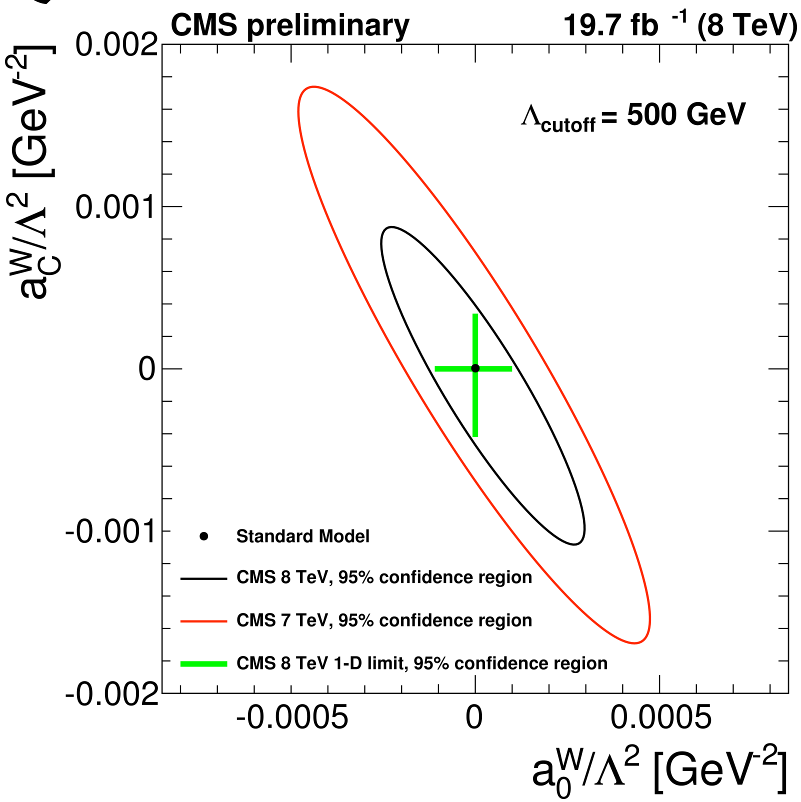
aQGC and VBS Possibilities

- LHC Run 1:
  - VBS evidence in Wγ, Zγ, γγ→WW, ssWW
  - aQGC limits in all VBS modes. Strongest in above modes
- LHC Run 2
  - VBS observation in Wγ, Zγ, ssWW: ~20-50fb^{-1}
  - VBS observation in WW, WZ ~100-200fb^{-1}
  - VBS observation in ZZ ~200-300fb^{-1}
  - Stronger aQGC limits 10x - substantial energy enhancement
- LHC HL-LHC
  - Accurate SM QQC measurements
  - Stronger aQGC limits 2x
  - Evidence for longitudinal VBS, combines across modes or experiments

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

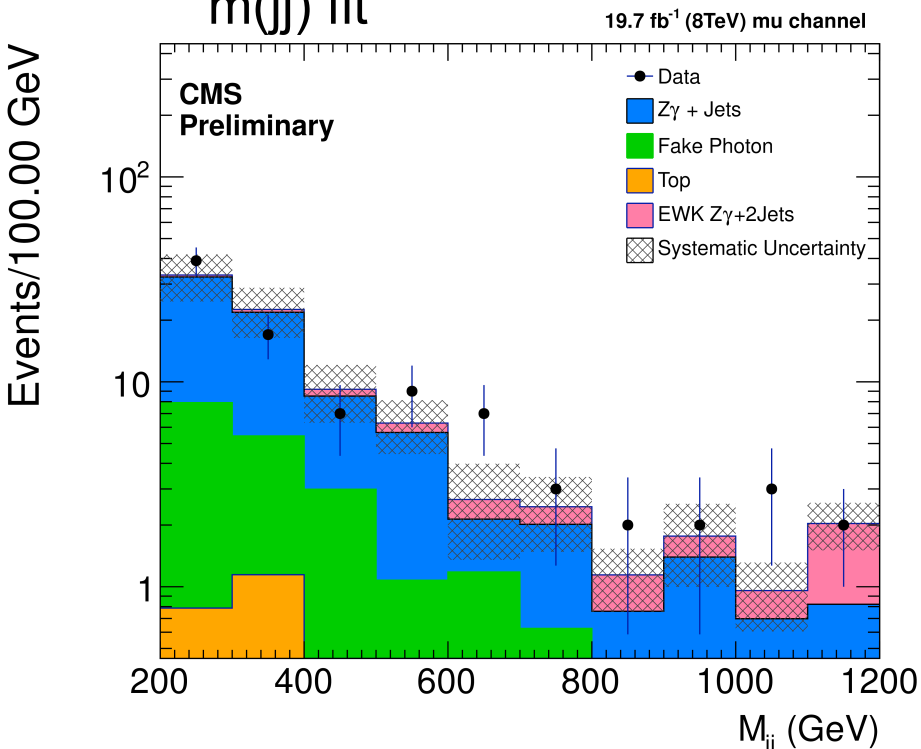
Conversion to D8 EFT parameters via linear transformation

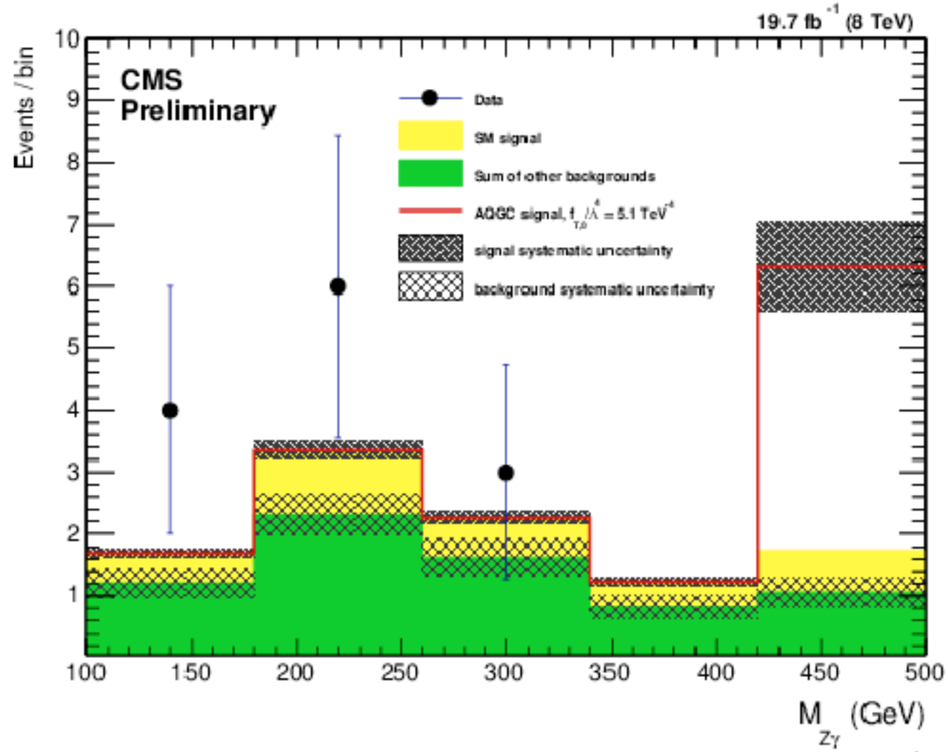
- 3.6σ evidence
- σ(γγ → WW) = 12.3+5.5-4.4 fb, SM: 6.9 ± 0.6

Evidence for EWK Zγ

- Zγ → llγ + 2 jets
  - EWK cross section measured in VBS phase space: Δη(jj) and m(jj) using m(jj) fit

CMS PAS SMP-14-018



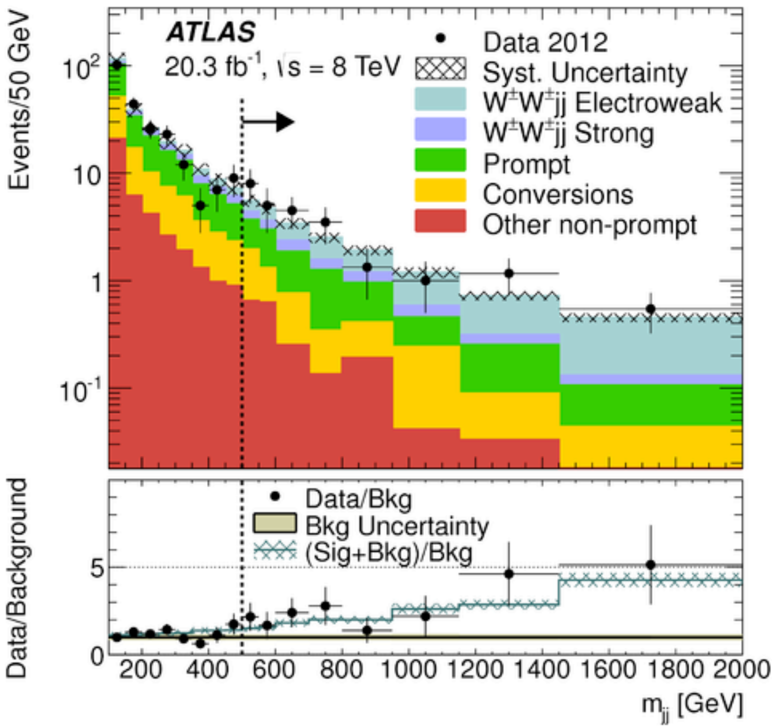


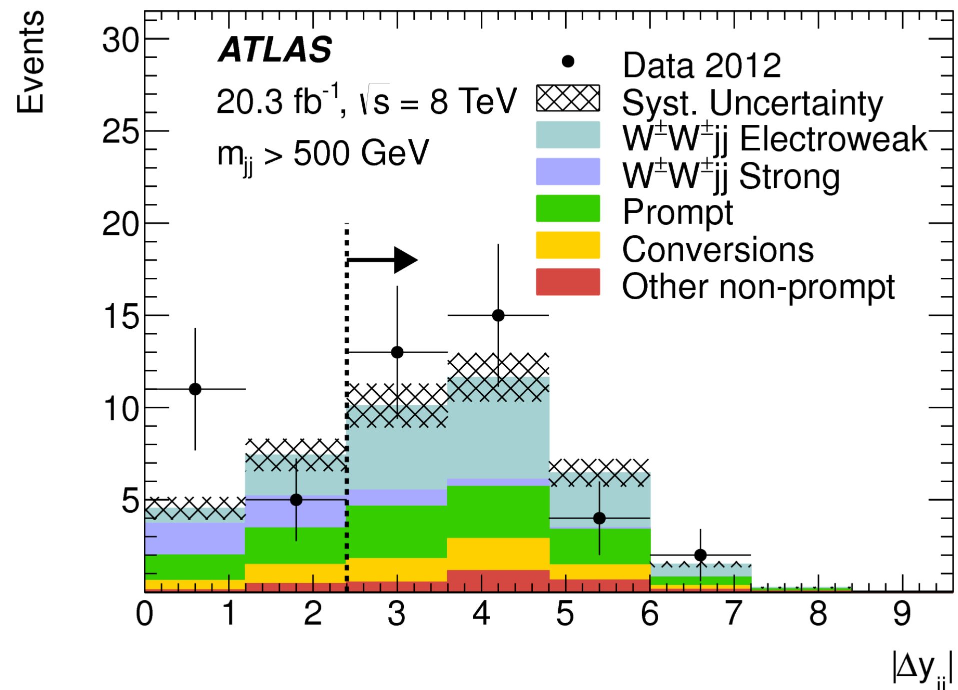
- 3.0σ evidence
- $\sigma(\text{EWK } Z\gamma) = 1.86^{+0.89}_{-0.75}(stat.)^{+0.41}_{-0.27}(sys.) \pm 0.05(lumi.)$ fb
- SM: $1.26 \pm 0.11(scale) \pm 0.05(PDF)$

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

Evidence for EWK ss WW

- EWK WW →lνlν + 2 jets   ATLAS Phys. Rev. Lett. 113, 141803 (2014)
- EWK cross section measured in VBS phase space: Δη(jj) and m(jj)

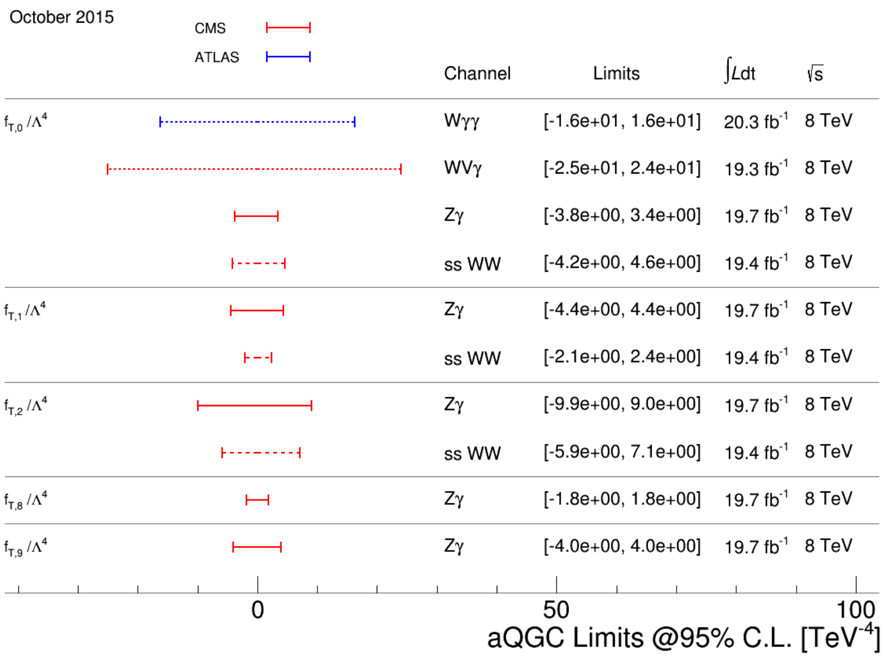


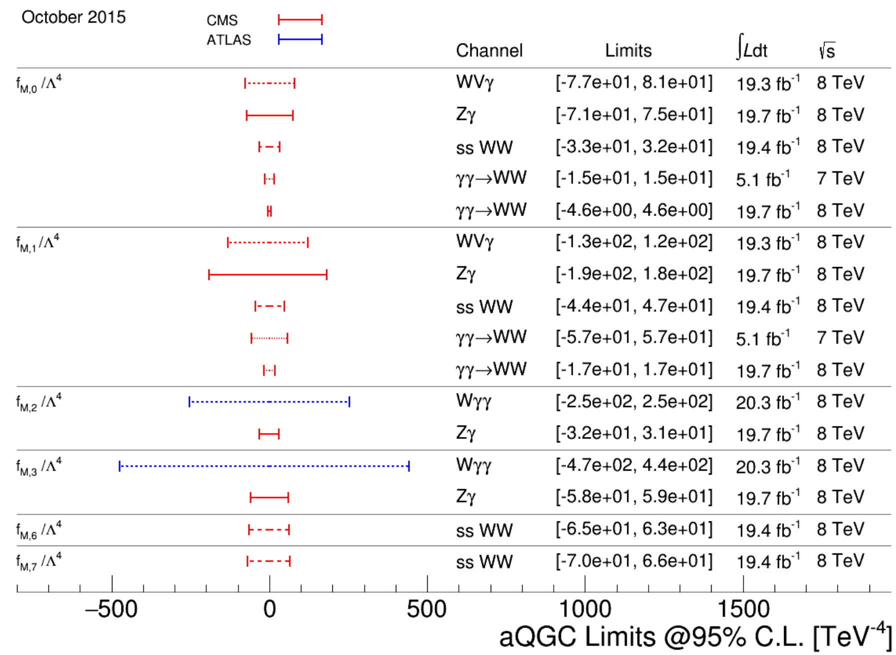


- 3.6σ evidence
- σ(EWK ssWW: $\sigma^{\mathrm{fid}} = 1.3 \pm 0.4(\mathrm{stat}) \pm 0.2(\mathrm{syst})$ fb
- SM: 0.95 ± 0.06 fb

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

LHC Run 1 aQGC Limits





- 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?

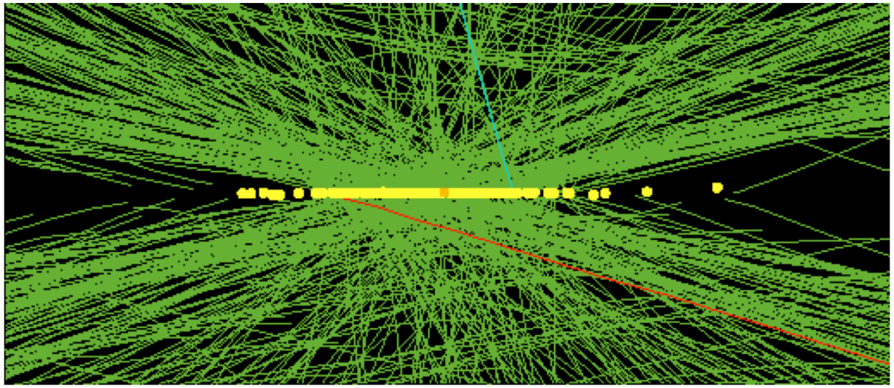
Naive interesting scale would be: $f/\Lambda^4 = 1$

NP: $\Lambda = 1$ TeV

$f = 1$

Run 2 and HL-LHC

- LHC Run 2
  - Energy: 13 TeV
  - Integrated Luminosity: $300 fb^{-1}$
  - Substantial improvement in sensitivity due to increased energy
- HL-LHC upgrade
  - Design energy: 14 TeV
  - High Luminosity: Order 140 pileup
  - Integrated Luminosity: $3 ab^{-1}$
- CMS Upgrade (representative of either detector)
  - New silicon tracker $|\eta| < 4$
  - New forward calorimeter, increased granularity
  - Extended muon coverage

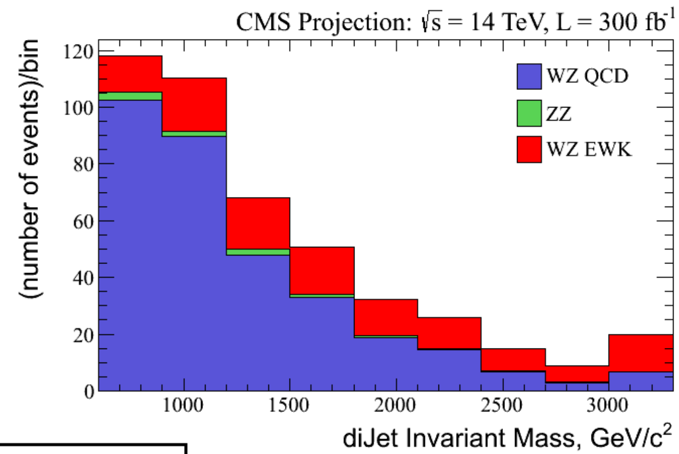


Effective rejection of jets from pileup, improve background to VBS topology.

Extended angular coverage for leptons and jets, Improves ability to distinguish longitudinal polarization in VBS

Run 2 VBS

- Run 2 and HL-LHC physics studies
  - Based on Delphes fast detector simulation
  - Performance parameterized from full simulation of upgraded detectors
  - Done by both CMS and ATLAS
- CMS Run 2 VBS results
- Accessed luminosity for
  3σ and 5σ sigma observation



WZ m(jj)

Significance	3σ	5σ
SM Rate discovery	110 fb^{-1}	260 fb^{-1}

CMS PAS FTR-13-006

ssWW M(ll),R

Significance	3σ	5σ
SM Rate discovery	20 fb^{-1}	50 fb^{-1}

CMS PAS SMP-14-008

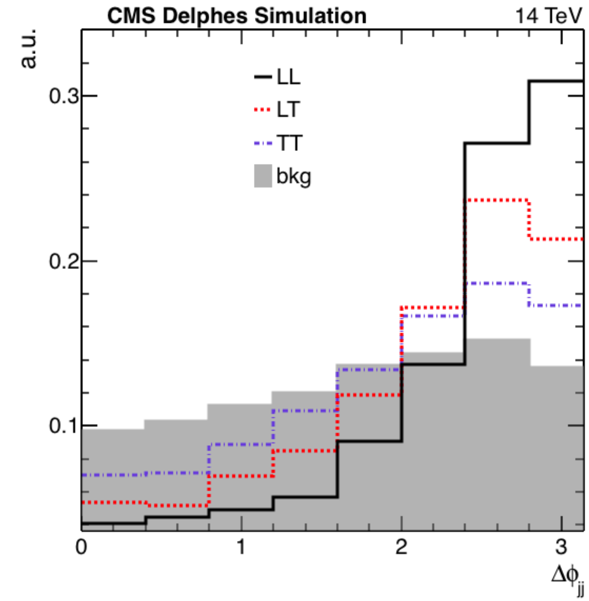
In Physics TP

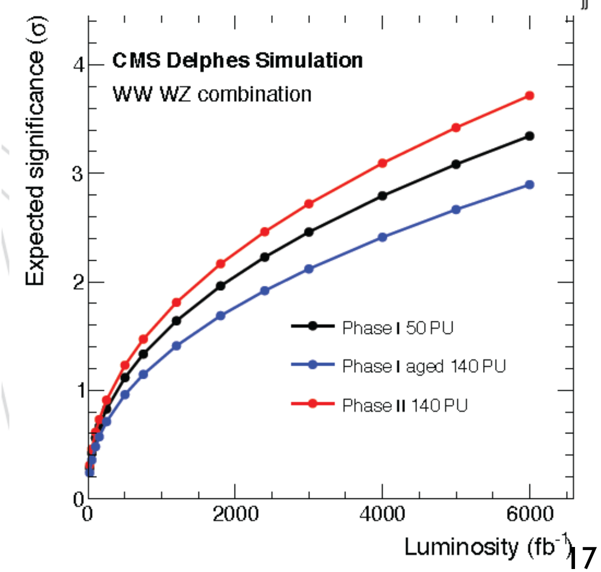
HL-LHC longitudinal VBS

- CMS HL-LHC physics studies
  – Compares various detector scenarios
  – Combined ss WW and WZ modes
- Accessed sensitivity as a function of luminosity for:
  – Detecting partial unitarization scenario
  – Significance for longitudinal vector boson scattering
  – aQGC for all relevant D8 EFT parameters

- 2.5σ significance expected
- 2D fit to $\Delta\phi(jj)$, pTl
- Combining more modes or between experiments would enhance sensitivity

CMS PAS SMP-14-008





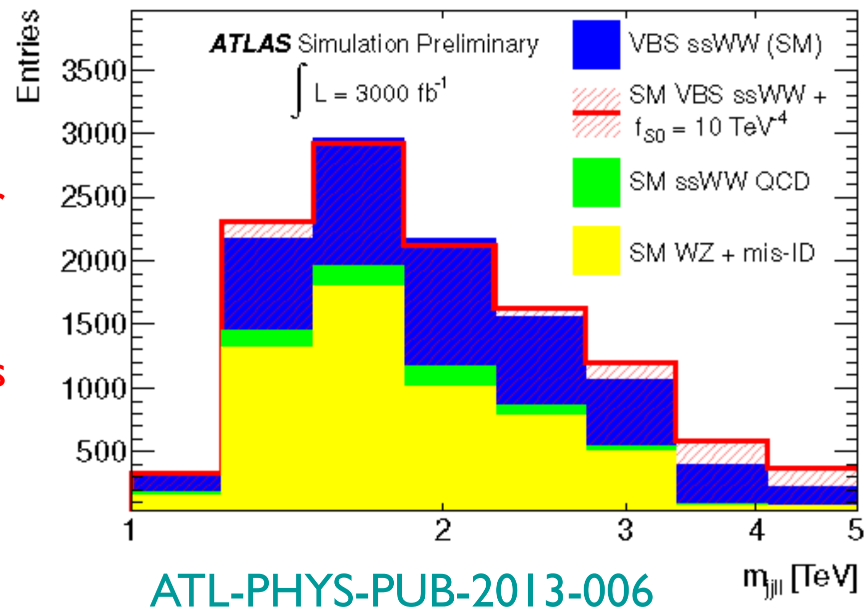
Run 2 & HL-LHC aQGC

- aQGC studies (CMS and ATLAS)

CMS PAS SMP-14-008

	phase I	phase II	phase I aged
S_0	1.06	1.07	1.17
S_1	3.51	3.55	3.87
M_0	0.78	0.75	0.82
M_1	1.10	1.06	1.14
M_6	1.56	1.49	1.63
M_7	1.37	1.32	1.45
T_0	0.067	0.077	0.083
T_1	0.036	0.033	0.036
T_2	0.119	0.111	0.119

m(nl) or m(nljj) Used to set lmits



ATL-PHYS-PUB-2013-006

Parameter	dimension	channel	Λ_{UV} [TeV]	300 fb^{-1}		3000 fb^{-1}	
				5σ	95% CL	5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	34 TeV^{-2}	20 TeV^{-2}	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^\pm W^\pm$	2.0	10 TeV^{-4}	6.8 TeV^{-4}	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	1.3 TeV^{-4}	0.7 TeV^{-4}	0.6 TeV^{-4}	0.3 TeV^{-4}
f_{T8}/Λ^4	8	$Z\gamma\gamma$	12	0.9 TeV^{-4}	0.5 TeV^{-4}	0.4 TeV^{-4}	0.2 TeV^{-4}
f_{T9}/Λ^4	8	$Z\gamma\gamma$	13	2.0 TeV^{-4}	0.9 TeV^{-4}	0.7 TeV^{-4}	0.3 TeV^{-4}

Achieve sensitivity to interesting aQGC effects for many operators

Summary

- Vector boson scattering
  - Primary component of massive vector boson scattering is scattering via a Higgs boson
  - A central topic to understanding the role of the Higgs boson within the context of the SM
- New physics
  - NP physics such as additional scalar particles, for instance more Higgs bosons, would substantial effect the scattering at high energy
  - EWSB sector is the newest and least explored area of the SM
- Effective field theory
  - Allows generalized investigation of the possible effects of high energy scale NP on VBS
- LHC Run 2 and HL-LHC will start the exploration of these NP possibilities.

Backup