Resent Results from ATLAS and CMS on Vector Boson Fusion and Vector Boson Scattering

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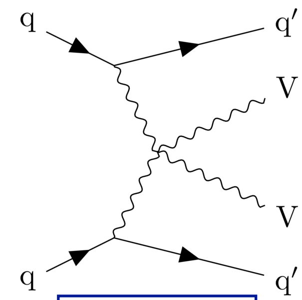
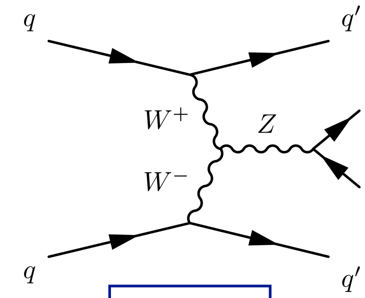
for the ATLAS and CMS Collaborations

Introduction and Motivation

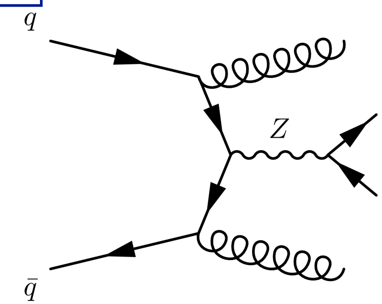
- (Di-)boson production via vector boson scattering/fusion (VBS/VBF)
  - Important component of Vjj/VVjj production proceeding entirely via EW interactions at tree level
  - Given SM Higgs, vector boson self-interactions precisely predicted
    - Deviations from predictions signal new physics in EW sector



VBS VV



VBF Z

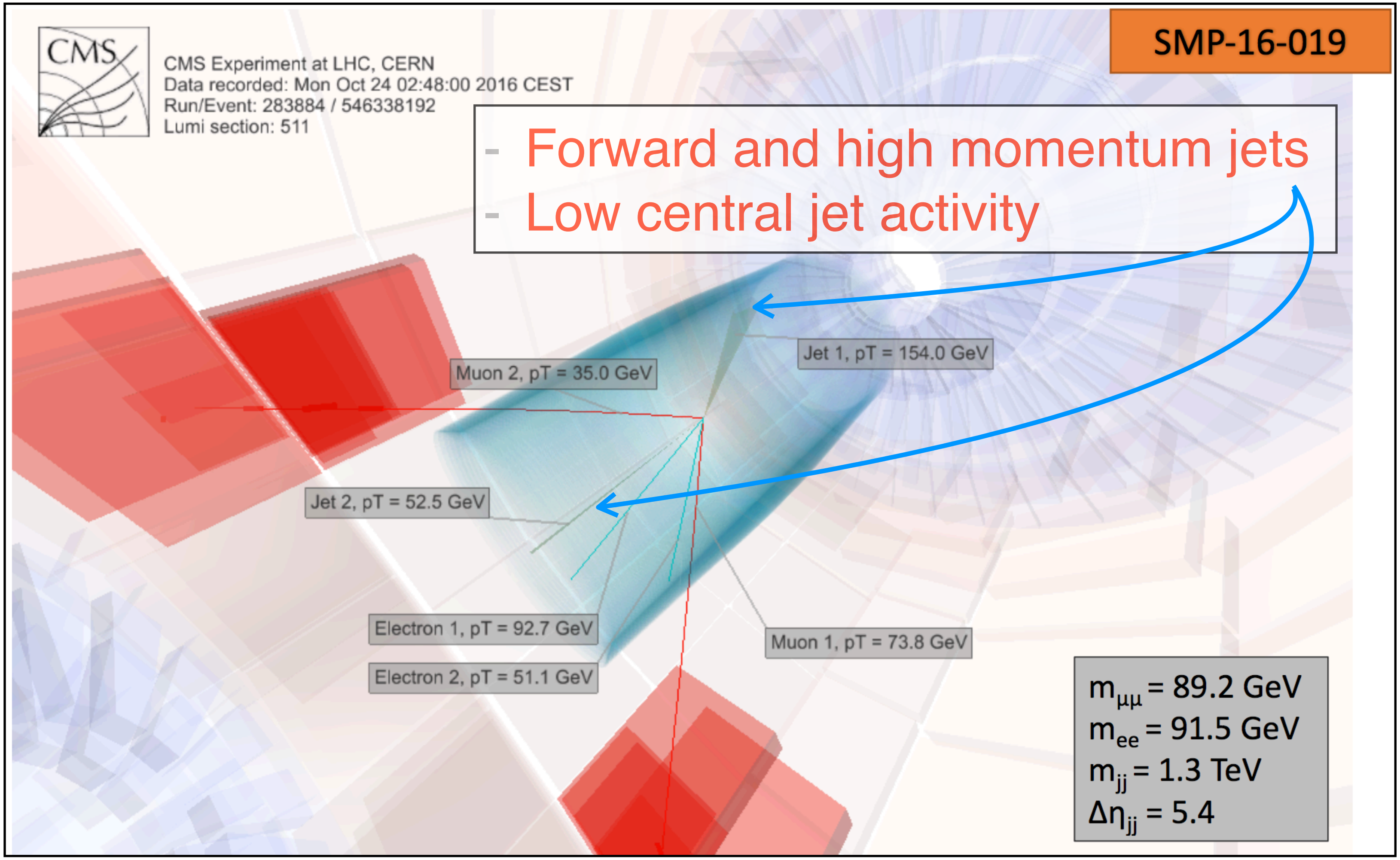


Non-VBF ($\alpha_s^2\alpha$) Zjj production

- High statistics in VBF Z/W allows precise test of SM and tools (e.g. Monte Carlo) and analysis techniques
  - Important implications for Higgs VBF
- Low cross sections for VBS just becoming accessible
  - Quickly moving from observation to measurement

Picture of a VBS-Candidate Event

- VBF/VBS: Radiation of vector bosons, lack of color flow between jets
  - ➡ Distinct kinematic signature for V/VVjj EW component

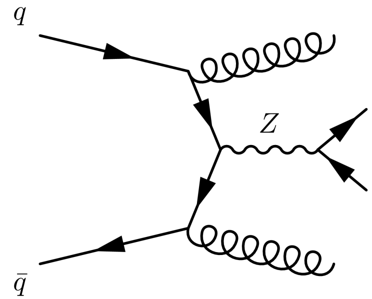


VBS ZZjj Candidate Event from PLB 774 (2017) 682

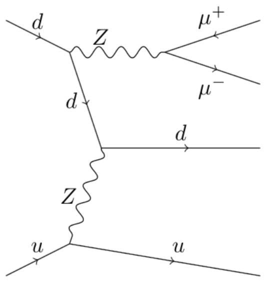
VBF/VBS Measurement Procedure

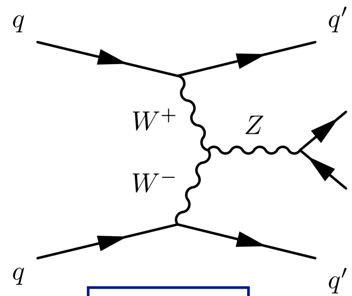
- Backgrounds divided into two classes
  - Nonprompt/fake (reducible)
    - Selected due to mis-ID from data
  - Prompt (irreducible)
    - Selected without mis-ID ⟹ from MC
- All EW-induced O(α^4 or α^3) as signal
- QCD-induced O($\alpha_s^2\alpha$ or $\alpha_s^2\alpha^2$) as background
  - ★ Almost always dominant background
    - Notable exception: same-sign WW production
- Mixed QCD/EW interference terms, O($\alpha_s\alpha^2$ or $\alpha_s\alpha^3$)
  - usually uncertainty on QCD background

Non-VBF ($\alpha_s^2\alpha$)



Non-VBF (α^3)





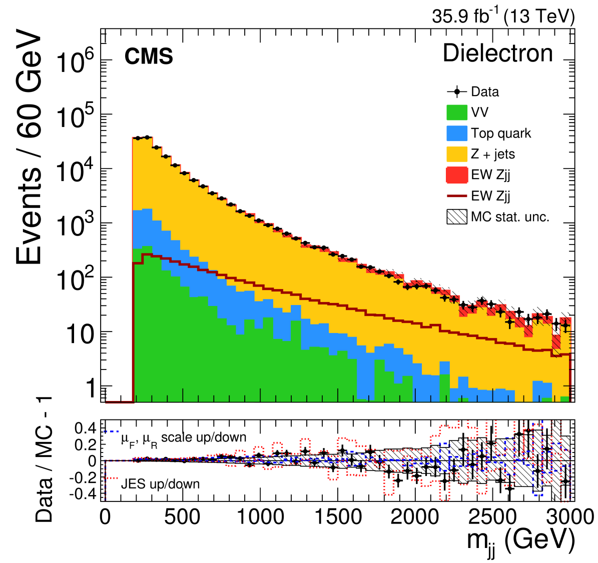
VBF Z

- Procedure: select Vj(VVjj) events, estimate non-Vj(VVjj) backgrounds, distinguish EW and QCD via kinematic selections
  - Low stats, S/B ⟹ MVA or shape-based fit ⟹ theory uncertainty
- Major uncertainties
  - Jet energy scale/resolution, background modeling
  - Modeling uncertainty reduced for combined EW+QCD measurement

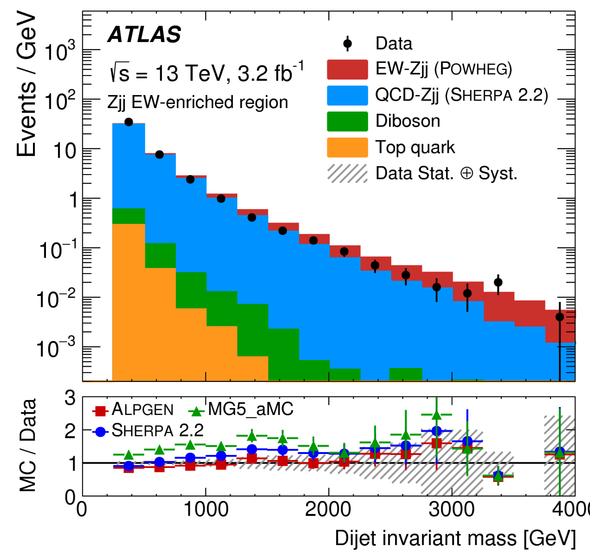
Vector Boson Fusion Measurements

VBF Z at 13 TeV: Overview

- Important "standard candle" for VBF Higgs
- Very high statistics ⟹ precision measurement
- Measurements from CMS and ATLAS with different approaches
  - ➡ Motivated by data/MC agreement



- Selection:
  - Exactly 2 leptons, $|m_{\ell\ell} - m_Z| < 15$ (10) GeV
  - Two jets with $p_T > 30$ (25) GeV, $|\eta| < 4.7$ (4.4)
- Backgrounds:
  - Drell-Yan+jets (QCD Zjj) very dominant
    1. CMS: Modeled with MG5_aMC ≤2j@NLO (FxFx) and MG5_aMC ≤4j@LO (MLM) +Pythia8
    2. ATLAS: Sherpa ≤2j@NLO+4j@LO, Alpgen ≤5j@LO+Py8, MG5_aMC ≤4j@LO+Py8
  - Multi-jet (< 1%)
    - CMS: from MC, ATLAS: from data
  - Others from simulation

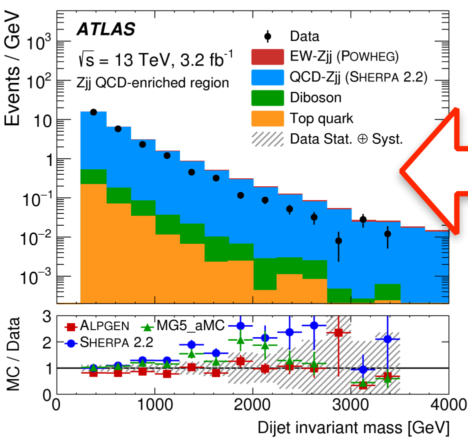


PLB 775 (2017) 206, arXiv:1712.09814

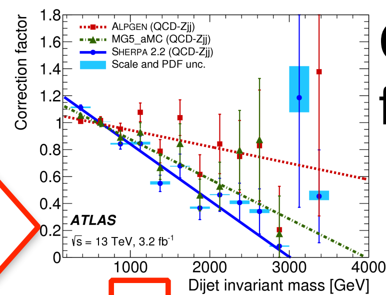
VBF Z at 13 TeV: ATLAS Overview

PLB 775 (2017) 206

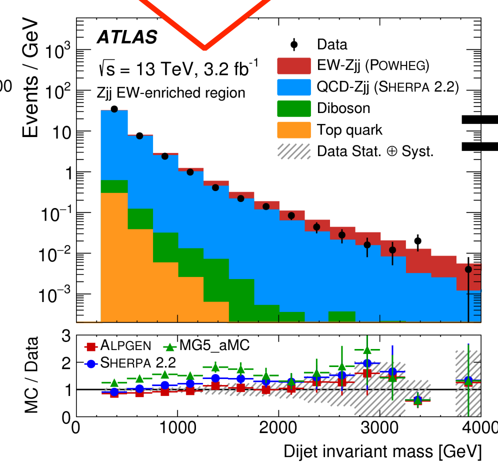
- Extract signal strength from fit to m_{jj}
  - Relies on modeling of DY+jets
- Poor data/MC agreement ⟹ correct MC with data
  - Measure data/MC corrections in m_{jj} in DY-enhanced control region
  - Fit binned ratios in CR (compare several fits) and apply in signal region
- Extract signal strength from fit to corrected distribution



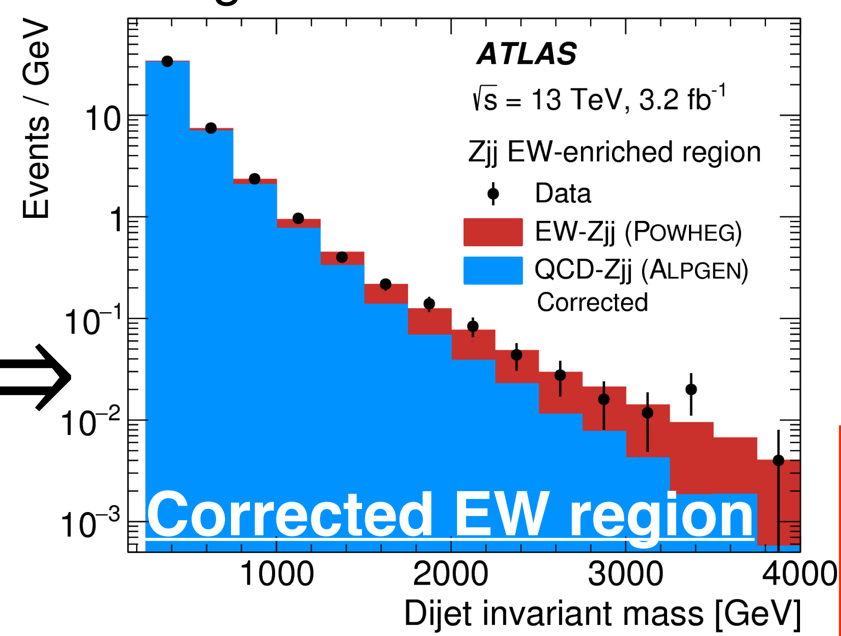
uncorrected QCD region



Correction factors from QCD region



uncor. EW region



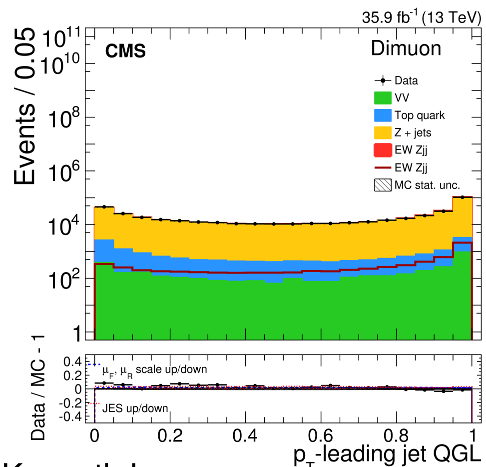
VBF Z at 13 TeV: CMS Overview

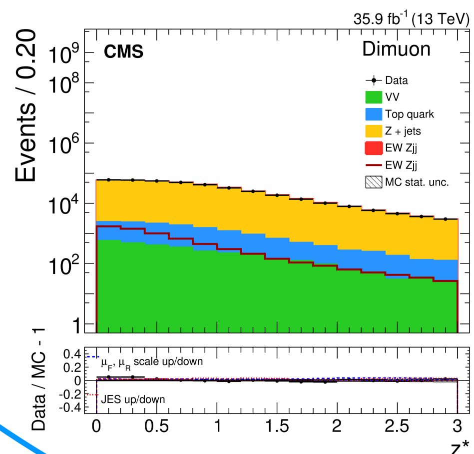
arXiv:1712.09814

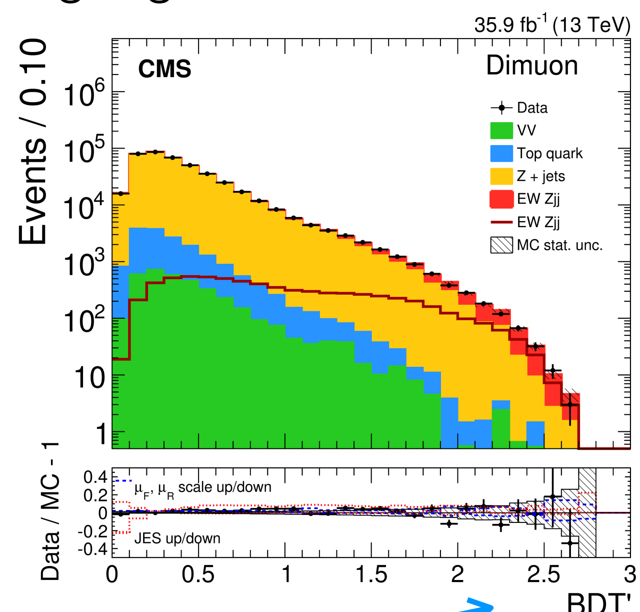
- Train BDT with 7 discriminating variables
  - m_{jj}, $\Delta\eta_{jj}$, $z^*(Z)$, $R(p_T)$, dijet p_T, dijet p_T balance, quark/gluon likelihood
  - BDT trained and fit separately for ee and μμ

$$\eta^*(z) = \eta(z) - 1/2(\eta_{j1}+\eta_{j2})$$
$$z^* = \eta^*(z)/\Delta\eta_{jj}$$

- LO MG5_aMC used for training, NLO used for background in fit
  - Data well-modeled by NLO MC in all distributions considered
  - Shape uncertainty from NLO scale+PDF + EW/QCD inference
    - 10% normalization uncertainty for missing higher orders
- Signal strength via fit to transformed BDT output (BDT')

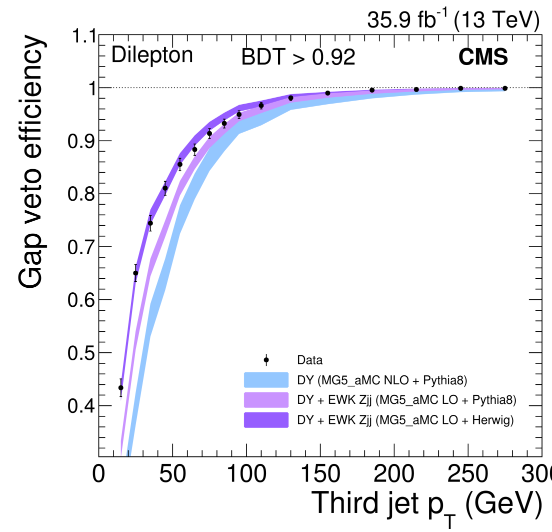


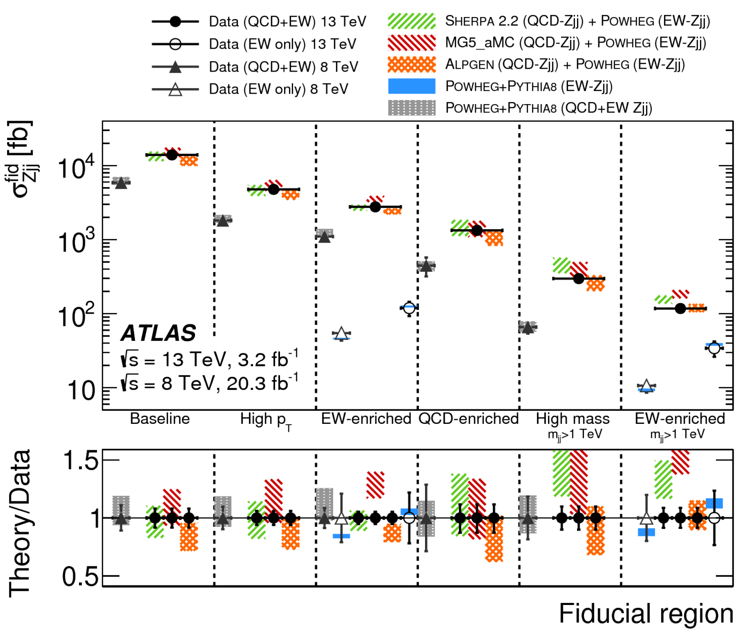




VBF Z at 13 TeV: Results

- CMS: signal strength used to obtain cross section in loose fiducial region (definitions in backup)
- ATLAS: signal strength in EW region via fit to m_{jj}
  - combined EW/QCD in 6 independent fiducial regions of purity
- CMS also presents study of hadronic activity in VBS-enhanced region (compare Herwig++ and Pythia)





ATLAS fiducial cross sections

Fiducial region	EW-Zjj cross-sections [fb]	
	Measured	POWHEG+PYTHIA
EW-enriched, $m_{jj} > 250$ GeV	$119 \pm 16 \pm 20 \pm 2$	125.2 ± 3.4
EW-enriched, $m_{jj} > 1$ TeV	$34.2 \pm 5.8 \pm 5.5 \pm 0.7$	38.5 ± 1.5

stat ± syst ± lumi

CMS fiducial cross section

$$\sigma_{fid} = 552 \pm 19\ (\text{stat}) \pm 55\ (\text{syst})\ \text{fb}$$

Compare to $\sigma_{LO} = 543 \pm 24$ fb, via MG5_aMC

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PLB 775 (2017) 206, arXiv:1712.09814

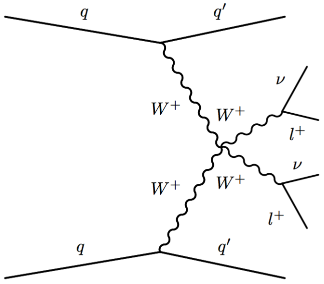
Vector Boson Scattering Measurements

$W^\pm W^\pm$ VBS at 13 TeV from CMS

PRL 120, 081801 (2018)

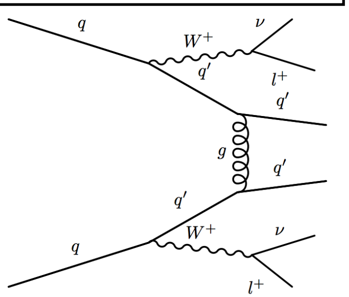
- Why $W^\pm W^\pm jj \to \ell^\pm \ell^\pm jj$?
  - EW production dominant over QCD-induced
  - Distinct same-sign (SS) lepton state, low background

VBS production



- Selection
  - Exactly 2 SS leptons, $|m_{e^\pm e^\pm} - m_Z| > 15$ GeV
  - $p_T^{miss} > 40$ GeV
  - Two jets, $m_{jj} > 500$ GeV; $\Delta\eta_{jj} > 2.5$; $\max(z^*(\ell)) < 0.75$

QCD production



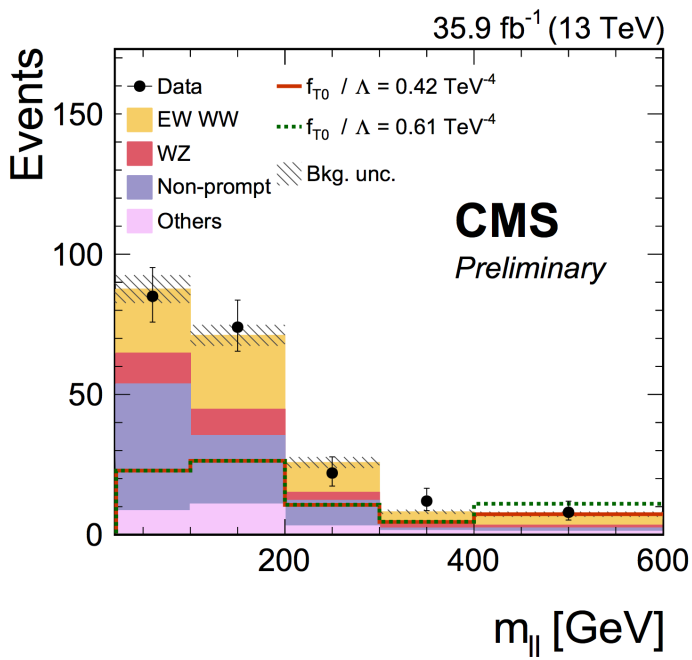
- Backgrounds
- ≥ 2 prompt SS leptons (WZ, QCD WW) $\Longrightarrow$ from Monte Carlo
  - Correct WZ using data in 3ℓ control regions
- Non-prompt backgrounds (dominant) $\Longrightarrow$ data driven
  - Define "loose" ID with ID+isolation relaxed from "tight"
  - Measure ratio of tight/loose in dijet events
  - Apply loose $\longrightarrow$ tight factors to events passing full analysis selection but failing analysis ID (tight)
- Charge mis-ID: simulation corrected with data

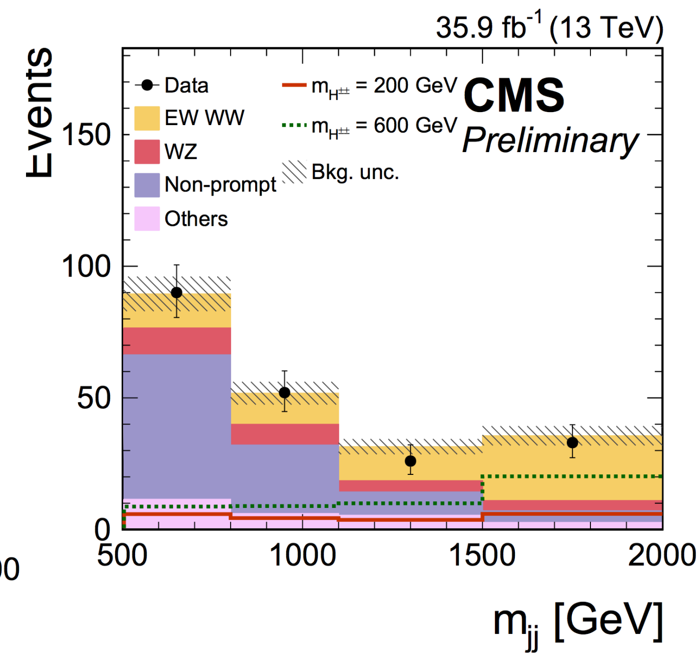
PRL 120, 081801 (2018)

- EW significance and cross section measurement via fit to 2D distribution of m_{jj} and m_{ll}
- Observed (expected) significance of 5.5σ (5.7σ)
  - ★ First > 5σ VBS measurement

$$\sigma_{fid} = 3.83 \pm 0.66\ (\text{stat}) \pm 0.35\ (\text{syst})\ \text{fb}$$

- Agrees with MG5_aMC prediction, $\sigma_{LO} = 4.25 \pm 0.27$





Precisions result expected with full Run II dataset!

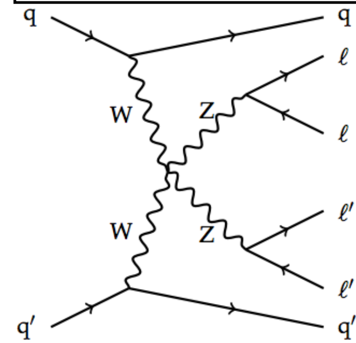
ZZ VBS at 13 TeV from CMS

PLB 774 (2017) 682

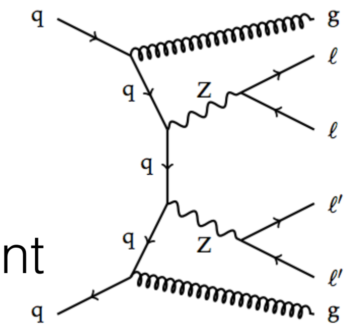
- Why ZZjj ⟶4ℓjj?
  - Extremely clean four lepton signal (ℓ = e,μ)
    - Very low nonprompt (fake) background
  - Fully reconstructed final state
    - Sensitive to resonances (including SM Higgs)
    - Access to boson polarizations via spin correlations

  … But very low production cross section
- Selection
  - 4 leptons, 2 Z candidates with $m_{\ell^+\ell^-} \in [60, 120]$ GeV
  - Two jets with $p_T > 30$ GeV, $|\eta| < 4.7$, $m_{jj} > 100$ GeV
- Backgrounds
  - ≥ 4 prompt leptons (ttV, VVV, QCD ZZ) ⟹ from MC
    - QCD ZZ production via MG5_aMC ≤2j@NLO
      - Low theory uncertainty, good data/MC agreement
      - Validate background modeling in background
      - dominated region with $m_{jj} < 400$ GeV or $\Delta\eta_{jj} < 2.5$
  - Non-prompt backgrounds ⟹ data driven
    - Same technique as for WW, but tight/loose ratios from Z+jets

VBS production



QCD production

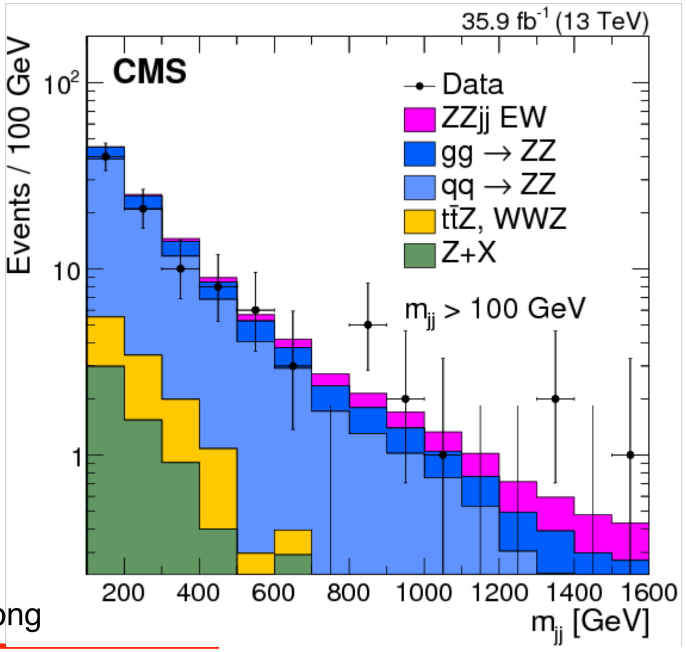


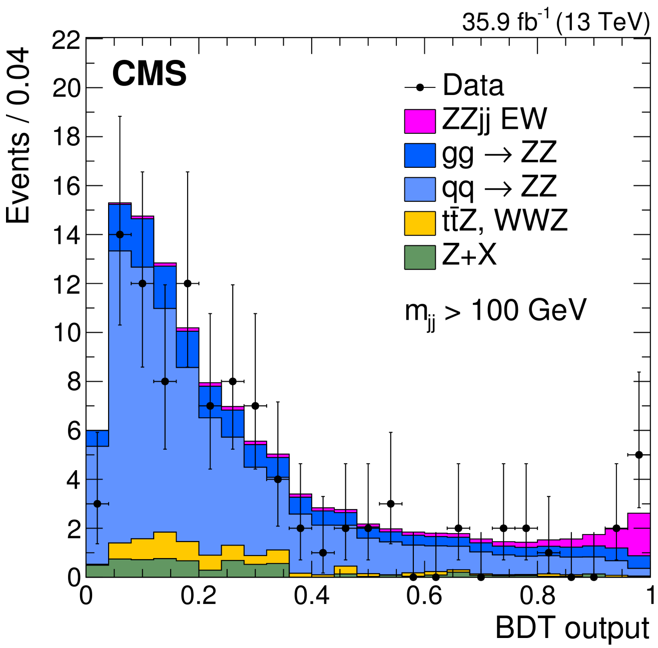
ZZ VBS at 13 TeV: Results

PLB 774 (2017) 682

- Limited statistics ⟹ cut-based analysis insufficient
- ➡ Train BDT with 7 discriminating variables
  - m_{jj}, $\Delta\eta_{jj}$, $z^*(Z_1)$, $z^*(Z_2)$, $R(p_T)$, dijet p_T balance, $m_{4\ell}$
  - Use all events with m_{jj} > 100 GeV
- Significance extracted via fit to BDT output distribution
  - Observed (expected) of 2.7σ (1.6σ)

$$\mu = \sigma_{obs}/\sigma_{th.} = 1.39\ ^{+0.72}_{-0.57}\,(\text{stat})\ ^{+0.46}_{-0.31}\,(\text{syst.})$$



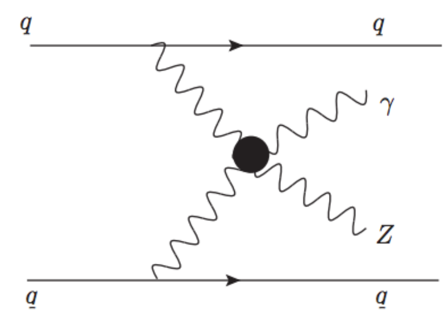


Zγ VBS at 8 TeV: Overview

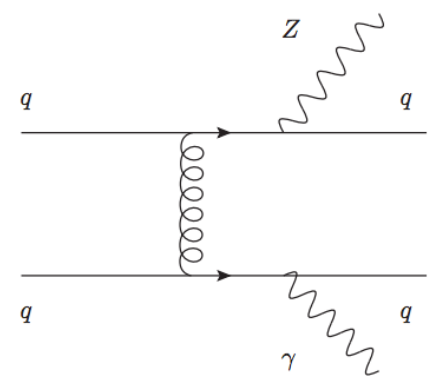
JHEP07(2017)107

- Why Zγjj ⟶ℓℓγjj
  - Probe different quartic couplings than massive V
  - Fully reconstructed final state
- Higher production cross section for Zγjj ⟶ννγjj, but less cleanly reconstructed
  - Most useful for limits on new physics
- Selection (ℓℓγjj)
  - 2 leptons, 1 photon p_T > 15 GeV
  - $|m_{\ell\ell} - m_Z|$ > 40 GeV, $m_{\ell\ell\gamma}$ > 182 GeV
  - m_{jj} > 150 GeV (control region), > 500 GeV (signal)
- Backgrounds
  - WZjj, ttγ, QCD Zγjj from MC
  - ➡ Zγ+≤3j from Sherpa v1.4.5
    - Good data/MC agreement observed
    - Normalization constrained in control region
  - Fake backgrounds (~20%)
    - Z+jets via data-driven estimate with 2D sideband region
    - Shape from region with relaxed m_{jj} for increased stats

VBS production



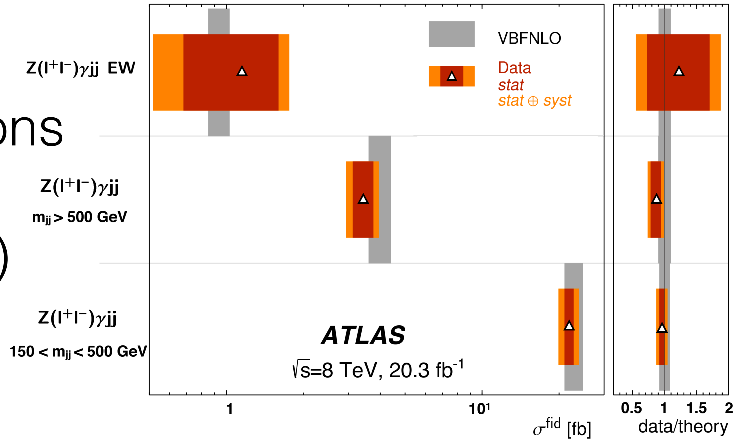
QCD production

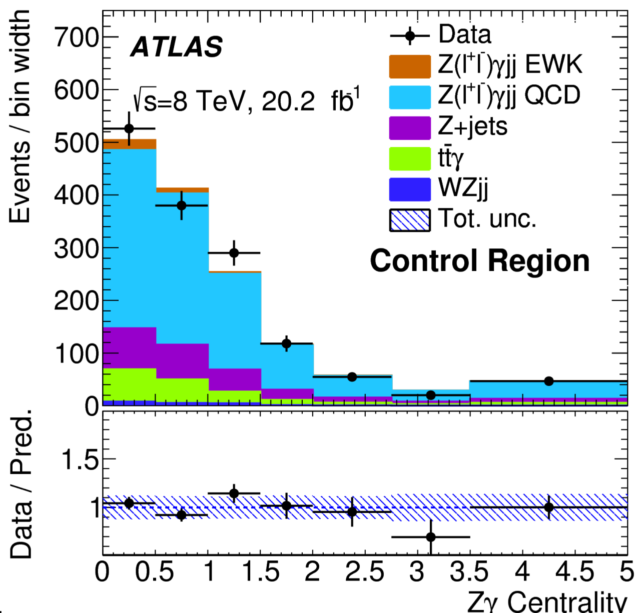


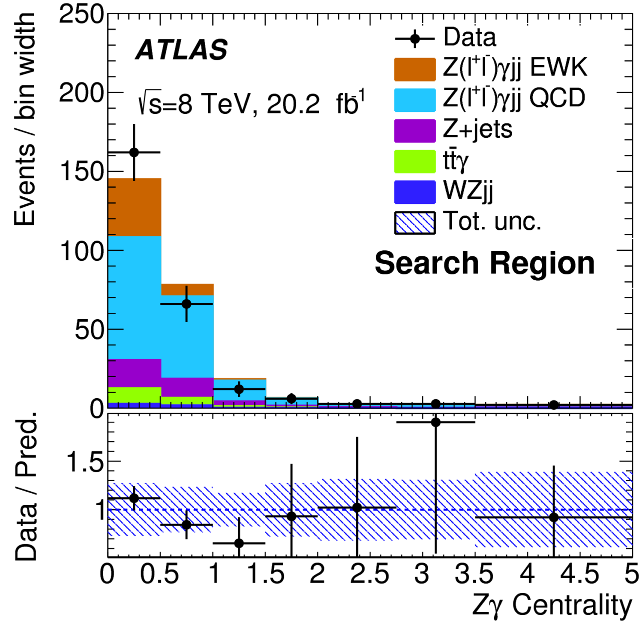
Zγ VBS at 8 TeV: Results

JHEP07(2017)107

- Extraction EW significance via fit to z*(Zγ)
  - Define signal and control regions by m_{jj} (signal > 500 GeV)
  - Simultaneously fit control and signal regions
    - QCD normalization free in fit
- Observed (expected) significance 2.0σ (1.8σ)
- Fit also performed with both EW and QCD treated as signal



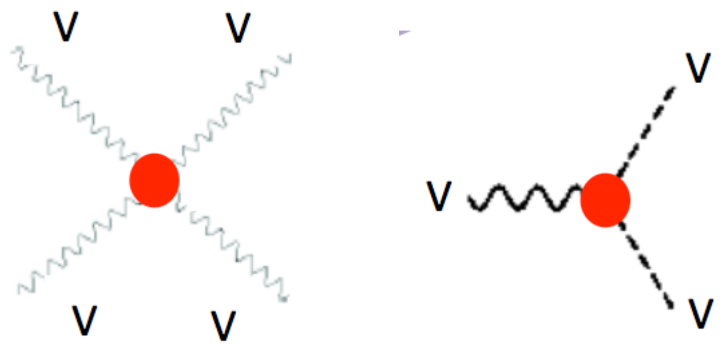




Searches for Anomalous Couplings

Overview of Anomalous Couplings / EFT

- Generalized language for new physics in vector boson interactions
- Anomalous couplings (triple and quartic)
  - Observed as deviations at high mass
  - Defined by modifying SM lagrangian or effective vertices



  - Alternatively… expand in effective field theory (EFT)
    - in terms of Wilson coefficients c_i and New Physics scale Λ

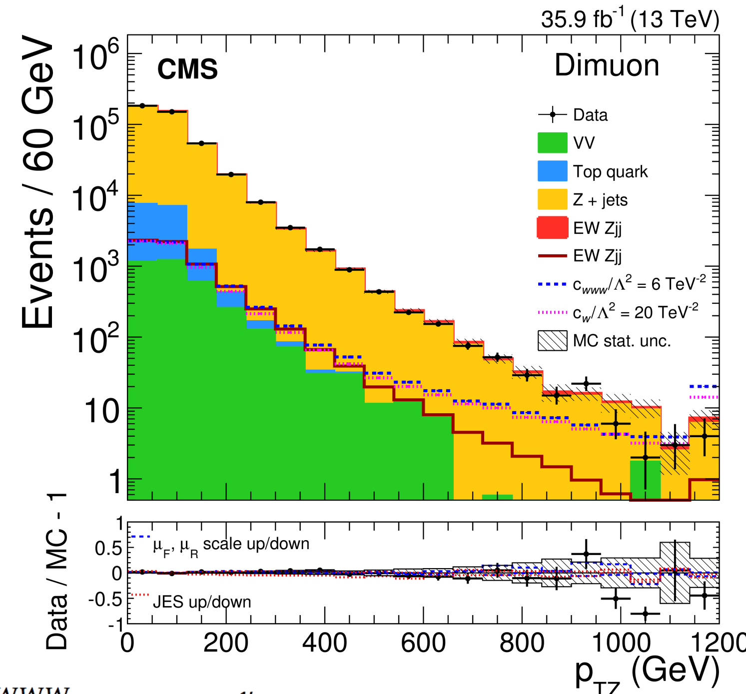
$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_{i}\frac{c_i^{(n)}}{\Lambda^n}\mathcal{O}_i^{(n+4)}$$

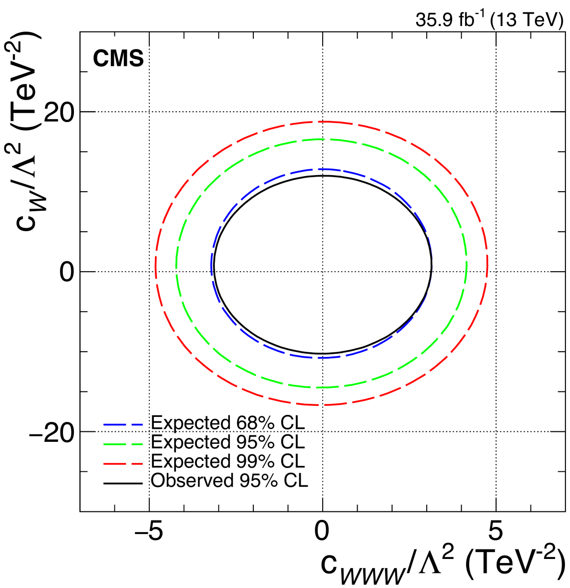
  - Non-unitary as $\sqrt{\hat{s}} \longrightarrow \Lambda$ without form factor
    - Often presented without form factor for simplicity
    - Inclusion of form factor decreases limits

Limits on aTGC from VBF Z

arXiv:1712.09814

- Limits placed on dimension 6 operators and translated into LEP aTGC formulation
  - Simulation via MG5_aMC@NLO @LO
    - Event weights to grid of parameter values
- 1D limits fix all parameters but one to zero, 2D for two non-zero
- Most stringent result so far c_{WWW}





$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_\rho^\mu,$$

$$\mathcal{O}_W = \frac{c_W}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^\nu \Phi),$$

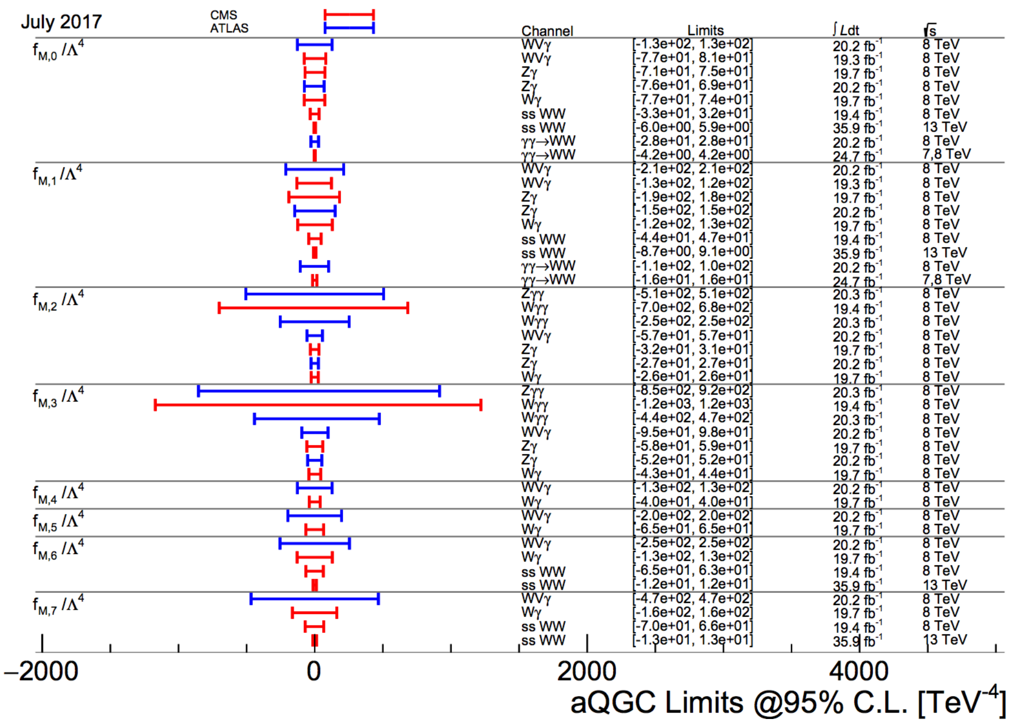
$$\mathcal{O}_B = \frac{c_B}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^\nu \Phi),$$

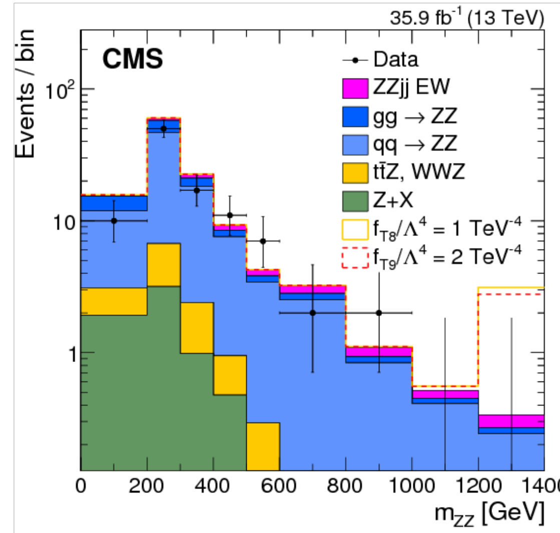
$$\widetilde{\mathcal{O}}_{WWW} = \frac{\widetilde{c}_{WWW}}{\Lambda^2} \widetilde{W}_{\mu\nu} W^{\nu\rho} W_\rho^{\cdot\,\mu},$$

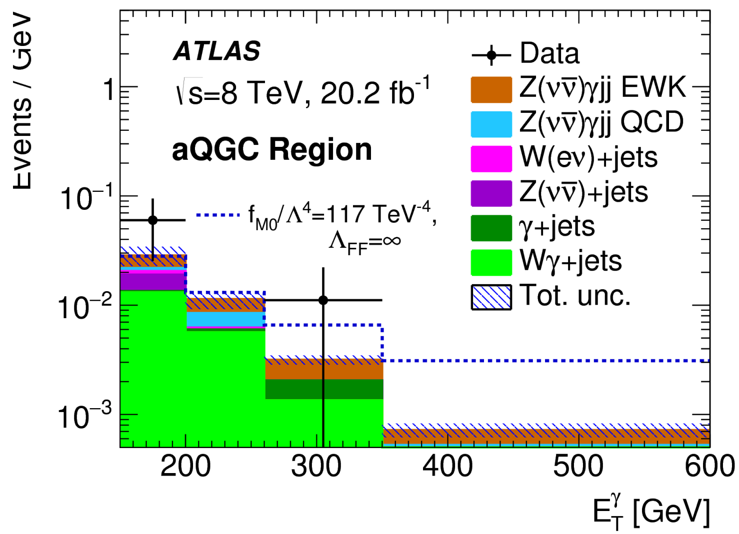
$$\widetilde{\mathcal{O}}_W = \frac{\widetilde{c}_W}{\Lambda^2} (D^\mu \Phi)^\dagger \widetilde{W}_{\mu\nu} (D^\nu \Phi),$$

Limits on aQGC from VBS Results

- Fit to variable sensitive to massive resonance or boost from massive decay
  - ZZ, SS WW: $m_{\ell\ell}$, $m_{4\ell}$
  - Zγ (ℓℓγjj and ννγjj): ET(γ)
- Analyses improve constraints on wide range of operators



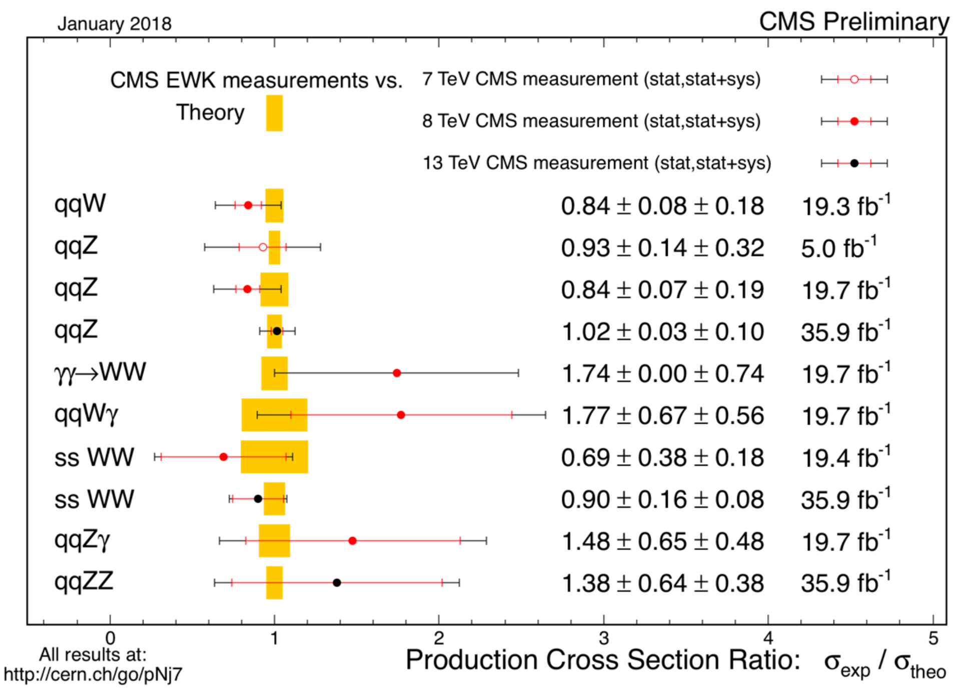


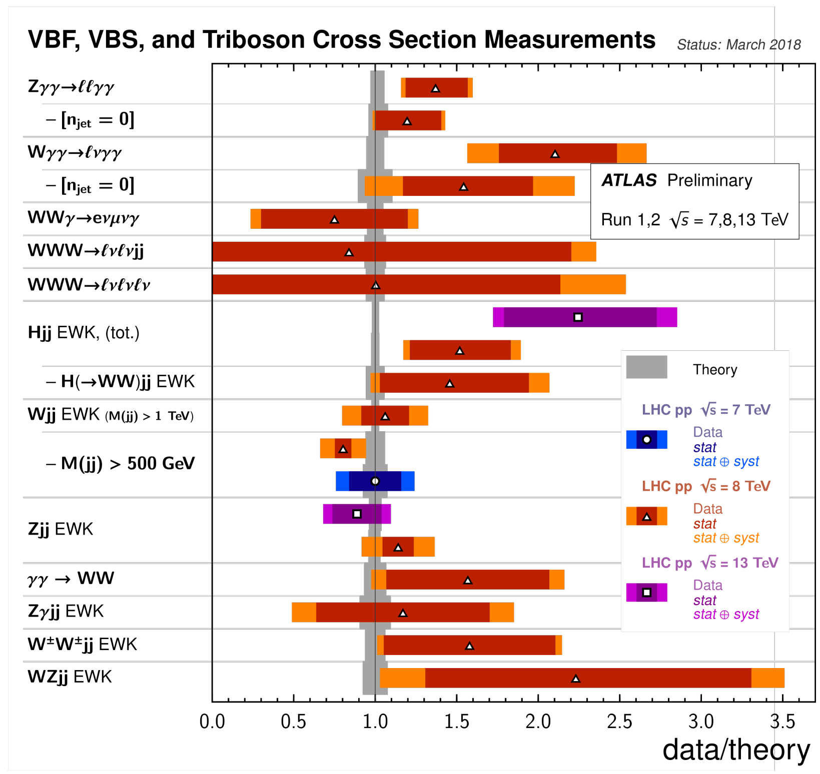


JHEP07(2017)107; PLB 774 (2017) 682; PRL 120, 081801 (2018)

Conclusions

- VBF/VBS measurements provide an important probe of standard model
- So far the standard model is withstanding these new tests
  - Deviations could be subtle
  - More data and improved techniques help look for cracks with increased resolution





Backup

Overview of Experimental Status: 8 TeV

VBS measurements (VV+2jets)		ATLAS	CMS
8 TeV	**EWK W$^{\pm}$W$^{\pm}$ ->lvlv**	PRL 113, 141803 Cross section (EWK, EWK+QCD) and aQGC measurement **Evidence**: EWK signal significance 3.6σ (exp 2.8σ) PRD 96, 012007 Updated aQGC limits	PRL 114 (2015) 051801 Cross section (EWK+QCD) and aQGC measurement EWK signal significance 1.9σ (exp 2.9σ)
	EWK Wγ ->lvγ	-	JHEP 06 (2017) 106 Cross section (EWK, EWK+QCD) and aQGC measurement EWK signal significance 2.7σ (exp 1.5σ)
	EWK Zγ ->llγ	JHEP07(2017)107 Cross section (EWK, EWK+QCD), aQGC measurement EWK signal significance 2.0σ (exp 1.8σ)	PLB 770 (2017) 380 Cross section (EWK, EWK+QCD) and aQGC measurement **Evidence**: EWK signal significance 3.0σ (exp 2.1σ)
	EWK WZ ->lvll	PRD 93, 092004 (2016) Cross section (EWK, EWK+QCD) measurement	PRL 114 (2015) 051801 Cross section (EWK+QCD) measurement
	EWK WV->lvjj	PRD 95 (2017) 032001 aQGC measurement	-

VBF measurements (V+2jets)		ATLAS	CMS
8 TeV	**EWK Z(ll)**	JHEP 04 (2014) 031 Cross section (EWK) and aTGC measurement **Observation**: EWK signal significance ~5σ	EPJC 75 (2015) 66 Cross section (EWK) measurement **Observation**: EWK signal significance ~5σ
	EWK W(lv)	EPJC 77 (2017) 474 Cross section (EWK, EWK+QCD), differential (EWK, EWK+QCD), aTGC measurement **Observation**: EWK signal significance >5σ	JHEP11(2016)147 Cross section (EWK) measurement **Evidence**: EWK signal significance ~4σ

Overview of Experimental Status: 13 TeV

VBS measurements (VV+2jets)		ATLAS	CMS
13 TeV	EWK $W^{\pm}W^{\pm} \to l\nu l\nu$	-	PRL 120, 081801 Cross section (EWK) and aQGC measurement EWK signal significance 5.5σ (exp 5.7σ)
	EWK ZZ ->4l	-	PLB 774 (2017) 682-705 Cross section (EWK) and aQGC measurement EWK signal significance 2.7σ (exp 1.6σ)

VBF measurements (V+2jets)		ATLAS	CMS
13 TeV	EWK Z(ll)	PLB 775 (2017) 206 (3.2 fb^{-1}) Cross section (EWK) measurement	CMS-SMP-16-018 Cross section (EWK) and aTGC measurement **Observation**: EWK signal significance >5σ
	EWK W(lv)	-	-

Many analyses with results at 8 TeV (and some new!) are in progress

ATLAS and CMS VBF Z Fiducial Regions

	Fiducial region					
Object	Baseline	High-mass	High-p_T	EW-enriched	EW-enriched, $m_{jj} > 1$ TeV	QCD-enriched
Leptons	$\lvert\eta\rvert < 2.47$, $p_T > 25$ GeV, $\Delta R_{j,\ell} > 0.4$					
Dilepton pair	$81 < m_{\ell\ell} < 101$ GeV					
	—			$p_T^{\ell\ell} > 20$ GeV		
Jets	$\lvert y\rvert < 4.4$					
	$p_T^{j_1} > 55$ GeV		$p_T^{j_1} > 85$ GeV	$p_T^{j_1} > 55$ GeV		
	$p_T^{j_2} > 45$ GeV		$p_T^{j_2} > 75$ GeV	$p_T^{j_2} > 45$ GeV		
Dijet system	—	$m_{jj} > 1$ TeV	—	$m_{jj} > 250$ GeV	$m_{jj} > 1$ TeV	$m_{jj} > 250$ GeV
Interval jets	—			$N_{\text{jet } (p_T > 25 \text{ GeV})}^{\text{interval}} = 0$		$N_{\text{jet } (p_T > 25 \text{ GeV})}^{\text{interval}} \geq 1$
Zjj system	—			$p_T^{\text{balance}} < 0.15$		$p_T^{\text{balance},3} < 0.15$

CMS fiducial region
- $|m_{\ell\ell} - m_Z| < 15$ GeV
- $p_T(q) > 25$ GeV
- $m_{qq} > 120$ GeV