Results from ATLAS and CMS on the Production of Neutral Diboson States via Vector Boson Scattering

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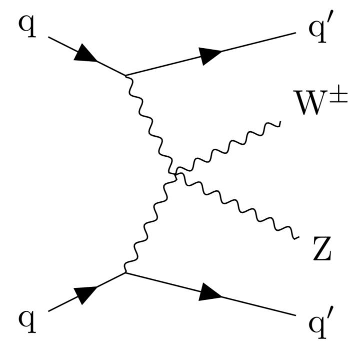
Outline

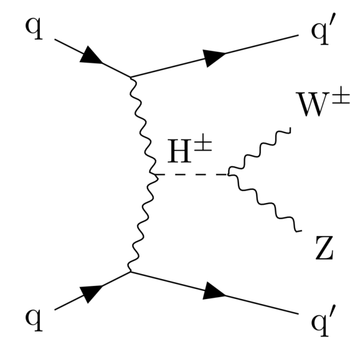
- Introduction and Motivation
  - Overview of VBS Measurement Procedure
- VBS significance and cross section measurements
  - $Z\gamma$ at 8 TeV from ATLAS and CMS
  - ZZ at 13 TeV from CMS
- Limits on aQGC
  - Procedure
  - Results
- Conclusion

Introduction and Motivation

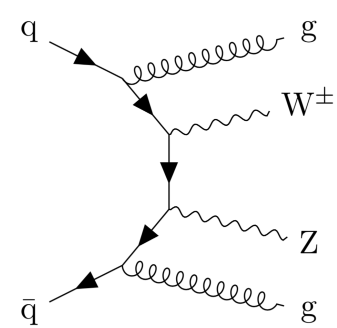
- Diboson production via vector boson scattering
  - Important component of VVjj production proceeding entirely via EW interactions at tree level
  - Given SM Higgs, vector boson self-interactions precisely predicted
    - Deviations from predictions signal new physics in EW sector



VBS WZ



H± Production

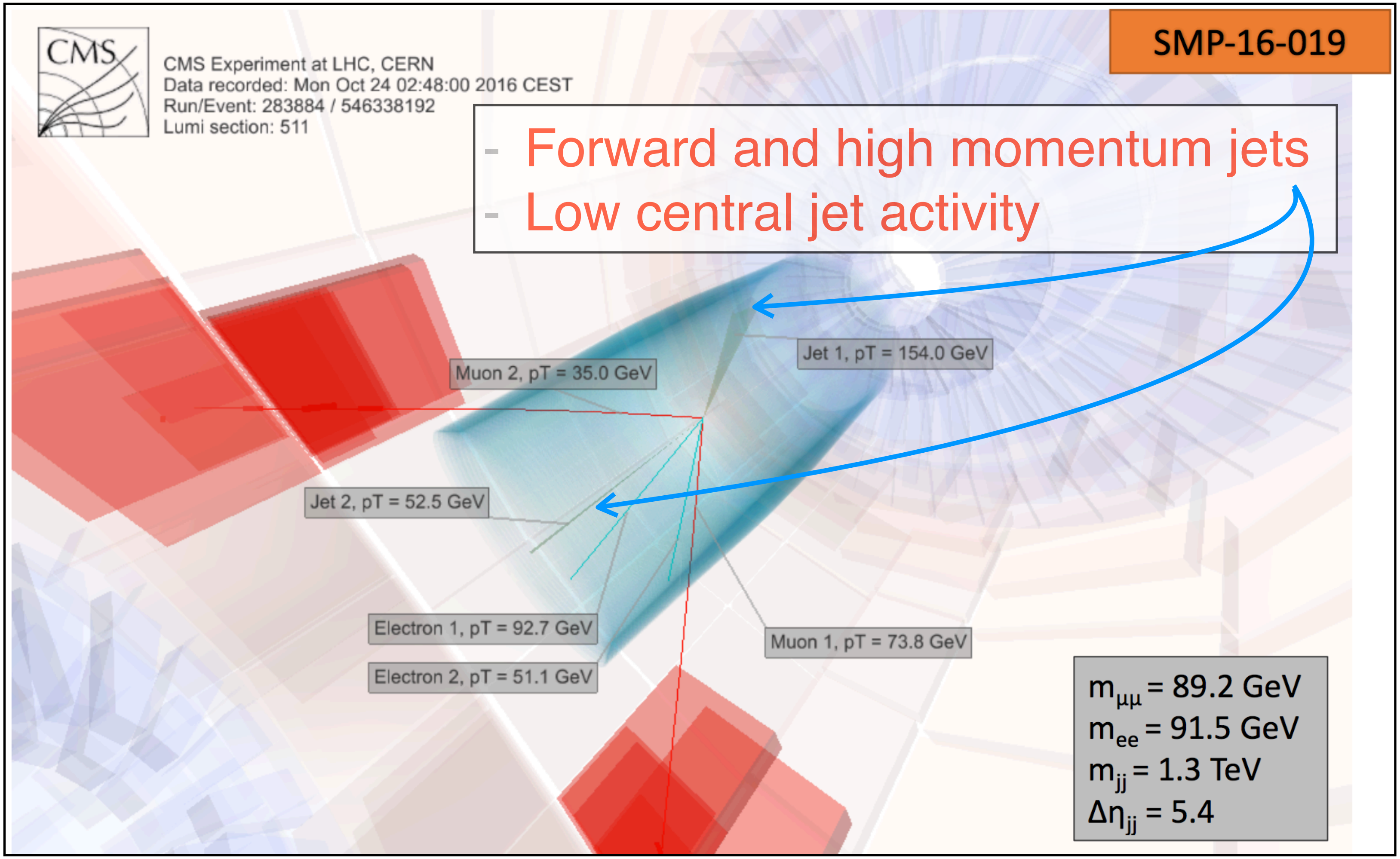


Non-VBF ($\alpha_s^2\alpha^2$) WZjj production

- Low cross sections for VBS just becoming accessible
  - Measurements in new channels at 13 TeV
  - Some channels moving from observation to measurement with the full Run 2 data set

Picture of a VBS Candidate Event

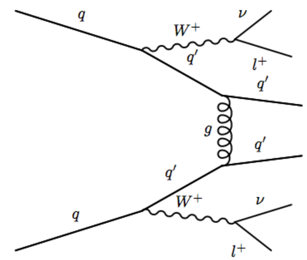
- Radiation of vector bosons, lack of color flow between jets
  - ➡ Distinct kinematic signature for VVjj EW component



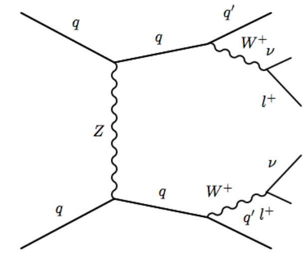
VBS ZZjj Candidate Event from PLB 774 (2017) 682

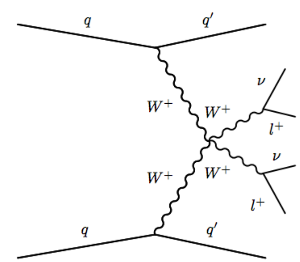
Overview of a VBS Measurement

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



Non-VBS (α^4)





VBS $W^\pm W^\pm$

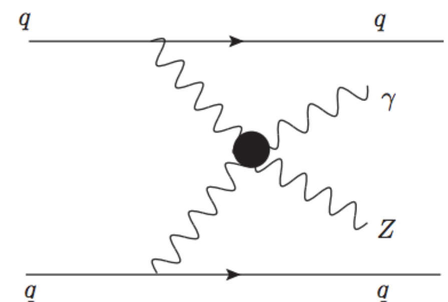
- Backgrounds divided into two classes
  - Nonprompt/fake (reducible)
    - Selected due to mis-ID from data
  - Prompt (irreducible)
    - Selected without mis-ID ⟹ from MC
- All EW-induced $O(\alpha^4)$ as signal
- QCD-induced $O(\alpha_s^2\alpha^2)$ as background
  - ★ Almost always dominant background
    - Notable exception: same-sign WW production
- Mixed QCD/EW interference terms, $O(\alpha_s\alpha^3)$
  - Uncertainty on signal or background
- Procedure: select VVjj events, estimate non-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
  - EW/QCD modeling dependence reduced for combined EW+QCD measurement

Zγ VBS at 8 TeV: Overview

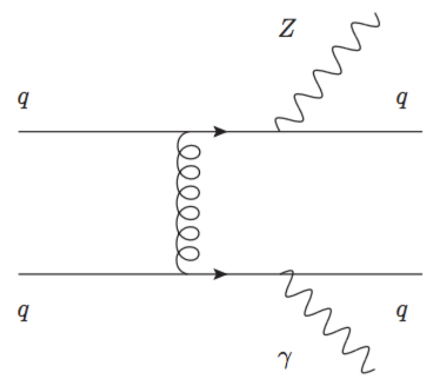
JHEP07(2017)107
PLB 770 (2017) 380

- Why Zγjj ⟶ℓℓγjj
  - Probe neutral quartic couplings
  - Clean signal from leptonic Z decay
  - Fully reconstructed final state
- Higher production cross section for Zγjj ⟶ννγjj, but less cleanly reconstructed
  - Most useful for limits on new physics
- Selection (ℓℓγjj) ATLAS (CMS)
  - 2 leptons, p_T > 20 (25) GeV
  - 1 photon p_T > 15 (25) GeV; |η| < 2.37 (1.44)
  - $m_{\ell\ell}$ > 40 (∈ [70, 110]) GeV,
  - $m_{\ell\ell} + m_{\ell\ell\gamma}$ > 182 GeV
  - p_T(j) > 30 GeV; |η| < 4.7 (4.5)
  - Control region: m_{jj} > 150 GeV
  - Signal region: m_{jj} > 500 (400) GeV

VBS production

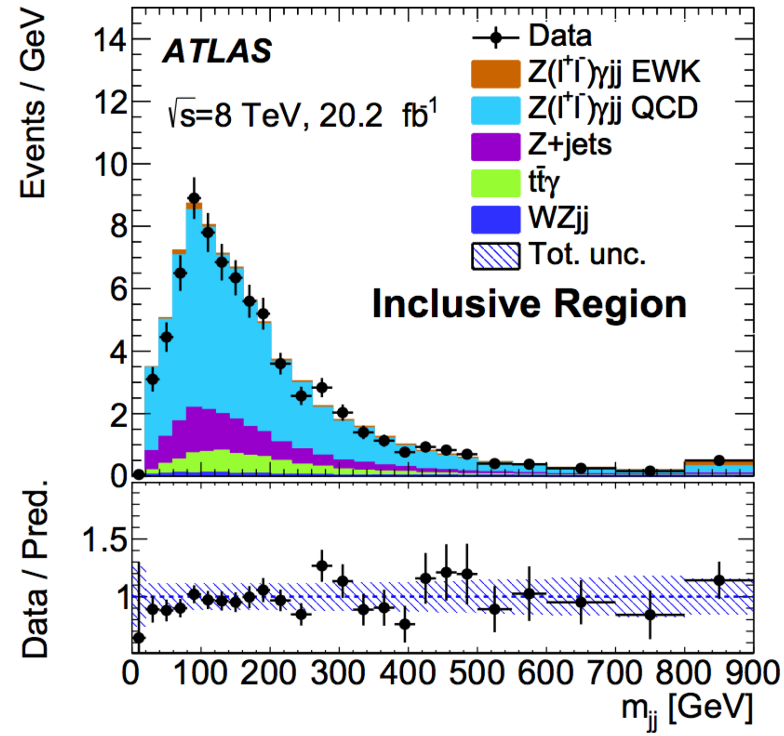


QCD production



Zγ VBS at 8 TeV: Backgrounds

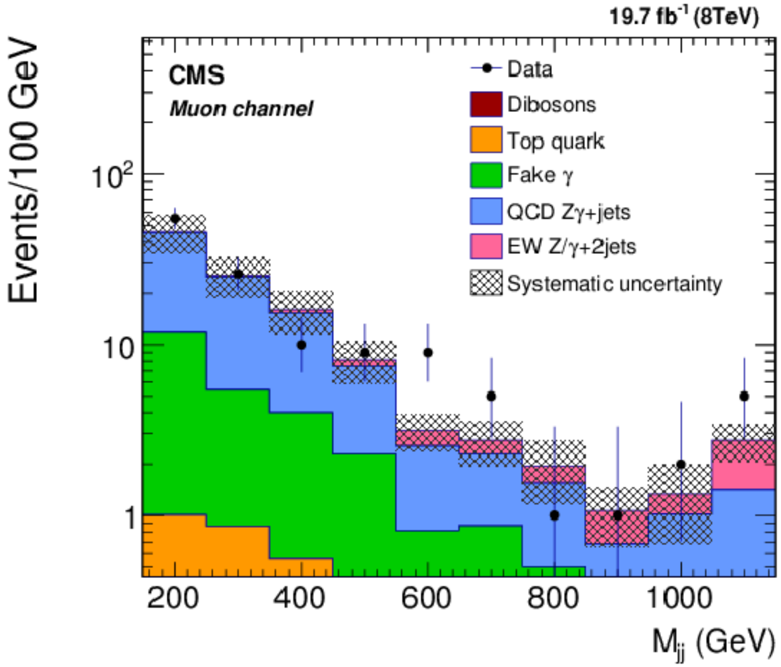
- Backgrounds from Monte Carlo
  - WZjj, ttγ
    - ATLAS: MG5_aMC+Pythia @ LO, normalized to NLO, Sherpa LO
    - CMS: MadGraph++Pythia 6 @LO, Pythia @LO
  - Zγ+≤3j
    - ATLAS: from Sherpa v1.4.5
    - ≤3j@LO, CKKW
    - CMS: MadGraph ≤3j@LO, MLM
    - Good data/MC agreement
    - Normalization constrained in control regions

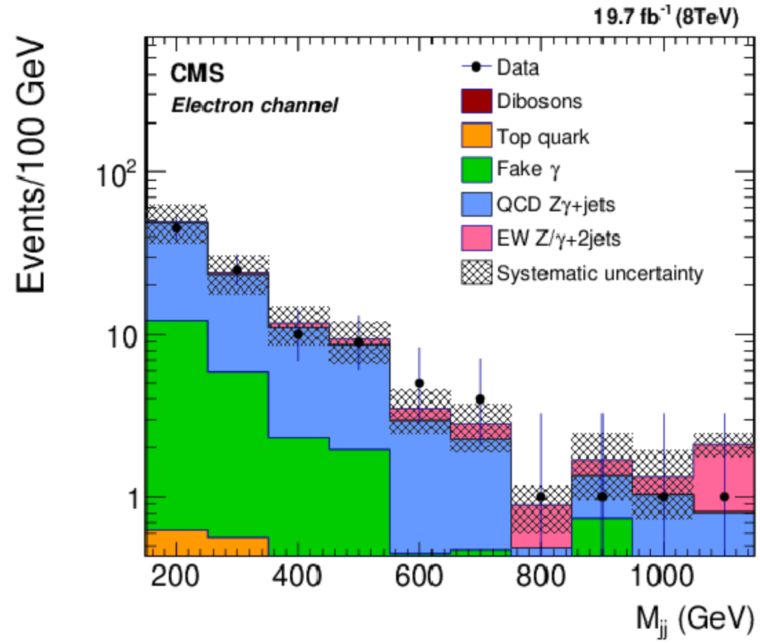


- Fake backgrounds (~20% ATLAS, ~30% CMS)
  - ATLAS:Z+jets via data-driven estimate with 2D sideband region
    - Shape from region with relaxed m_{jj} for increased stats
  - CMS: Extrapolate jets passing loose ID into tight region using tight/loose ratios

Zγ VBS: CMS EW Extraction

- Extraction of EW significance via fit to m_{jj} in bins of (400, 800) and ≥ 800 GeV separately by decay channel
  - Normalize QCD contribution from control region
    - Independent fit, not simultaneous
    - Observed normalization of 1.00 ± 0.22 in good agreement with NLO QCD k-factor of 1.1 from VBFNLO [1]
- Fit also performed with both EW and QCD treated as signal





[1] https://arxiv.org/abs/1407.7857

Zγ VBS: ATLAS EW Extraction

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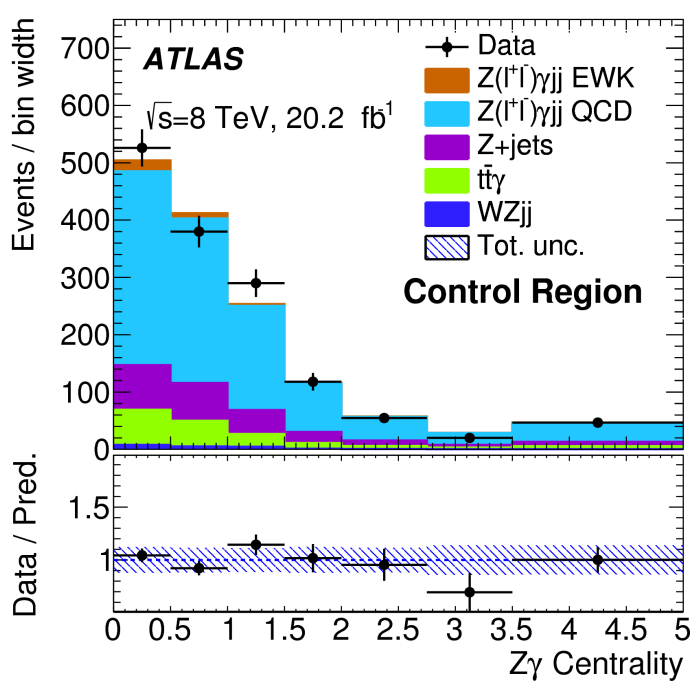
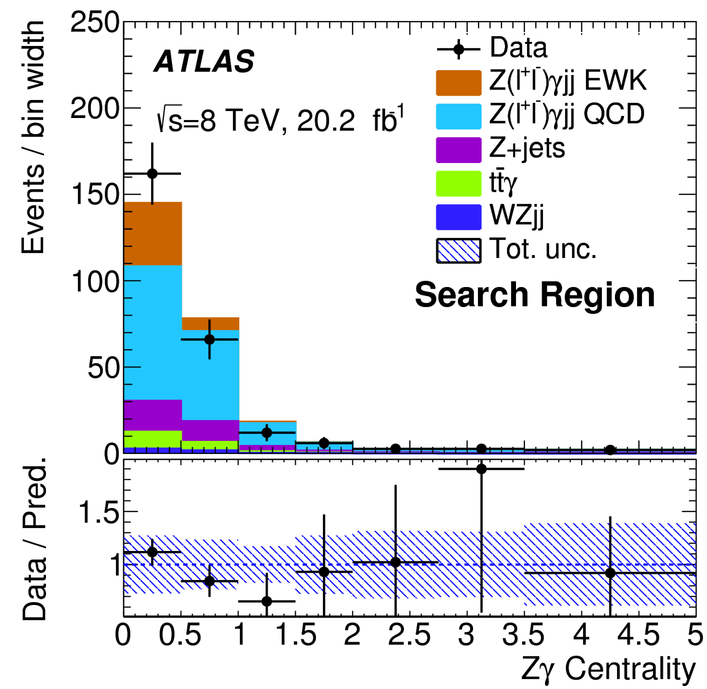
- Extraction of EW significance via fit to $z^*(Z\gamma)$ separated by decay channel
  - Define signal and control regions by m_{jj}
    - Signal > 500 GeV
  - Simultaneously fit control and signal regions
    - QCD normalization free in fit
- Fit also performed with both EW and QCD treated as signal

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



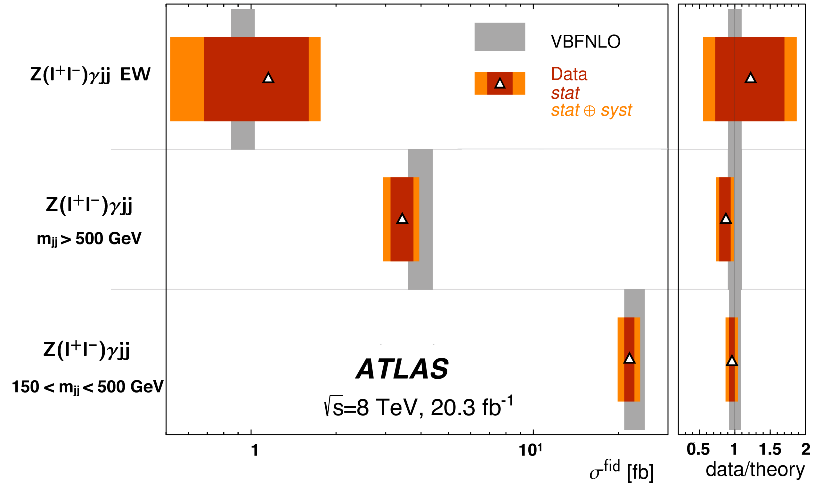


Zγ VBS at 8 TeV: Results

JHEP07(2017)107

- ATLAS
  - ➡ Observed (expected) significance 2.0σ (1.8σ)
  - Upper limit on cross section 2.2 fb (95% C.L.)

EW+QCD cross sections



- CMS
  - ➡ Observed (expected) significance 3.0σ (2.1σ)

LO from MadGraph

Process type	Measured cross-section [fb]	Predicted cross-section [fb]
EWK	$1.86^{+0.90}_{-0.75}(\text{stat})^{+0.34}_{-0.26}(\text{syst}) \pm 0.05(\text{lumi})$	$1.27 \pm 0.11(\text{scale}) \pm 0.05(\text{pdf})$
EWK+QCD	$5.94^{+1.53}_{-1.35}(\text{stat})^{+0.43}_{-0.37}(\text{syst}) \pm 0.13(\text{lumi})$	$5.05 \pm 1.22(\text{scale}) \pm 0.31(\text{pdf})$

Good agreement with SM expectation at LO and NLO

Zγ VBS: Systematic Uncertainties

- Dominated by jet energy calibration and theory unc. on EW and QCD
  - Interference not negligible, but comparable to other theory

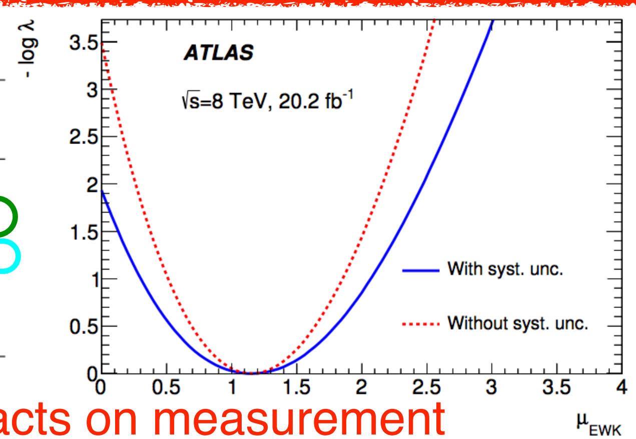
Source of uncertainty	EWK yield [%] $\ell^+\ell^-$ channel	EWK yield [%] $\nu\bar{\nu}$ channel	QCD yield [%] $\ell^+\ell^-$ channel	QCD yield [%] $\nu\bar{\nu}$ channel
Trigger	0.2 (0.4)	2	0.2 (0.4)	2
Pile-up		0.6		
Lepton selection	3.8 (2.3)	-	3.8 (2.3)	-
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	-	0.4	-	0.4
Photon selection	6.5	3.3	6.5	3.3
Jet reconstruction	2.5	3.2	12	3.2
Total experimental	8.0 (7.4)	5.1	13	5.1
Theory	8.7	4.1	3.8	4.1

ATLAS input uncertainties

CMS input uncertainties

Source	Uncertainty
QCD Zγ + jets normalization	22% (400 < M_{jj} < 800 GeV) 24% (M_{jj} > 800 GeV)
Fake photon from jet (p_T^γ dependent)	15% (20–30 GeV) 22% (30–50 GeV) 49% (>50 GeV)
Trigger efficiency	1.2% ($Z \to \mu^+\mu^-$), 1.7% ($Z \to e^+e^-$)
Lepton selection efficiency	1.9% ($Z \to \mu^+\mu^-$), 1.0% ($Z \to e^+e^-$)
Jet energy scale and resolution	14% (M_{jj} > 400 GeV)
$t\bar{t}\gamma$ cross section	20% [3]
Pileup modeling	1.0%
Renormalization/ factorization scale (signal)	9.0% (400 < M_{jj} < 800 GeV), 12% (M_{jj} > 800 GeV) (SM) 14% (aQGC)
PDF (signal)	4.2% (400 < M_{jj} < 800 GeV), 2.4% (M_{jj} > 800 GeV) (SM) 4.3% (aQGC)
Interference (signal)	18% (400 < M_{jj} < 800 GeV), 11% (M_{jj} > 800 GeV) (SM)
Luminosity	2.6%

Source of uncertainty	EWK [%]	Total (EWK+QCD) [%] SR	Total (EWK+QCD) [%] CR
Statistical	40	9	4
Jet energy scale	36	9	4
Theory	10	5	4
All other	8	5	6
Total systematic	38	11	8



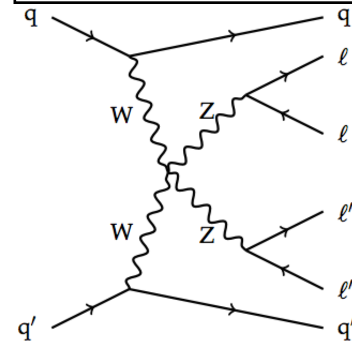
ATLAS uncertainty impacts on measurement

ZZ VBS at 13 TeV: Overview

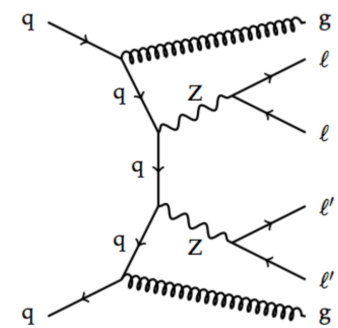
PLB 774 (2017) 682

- 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

VBS production

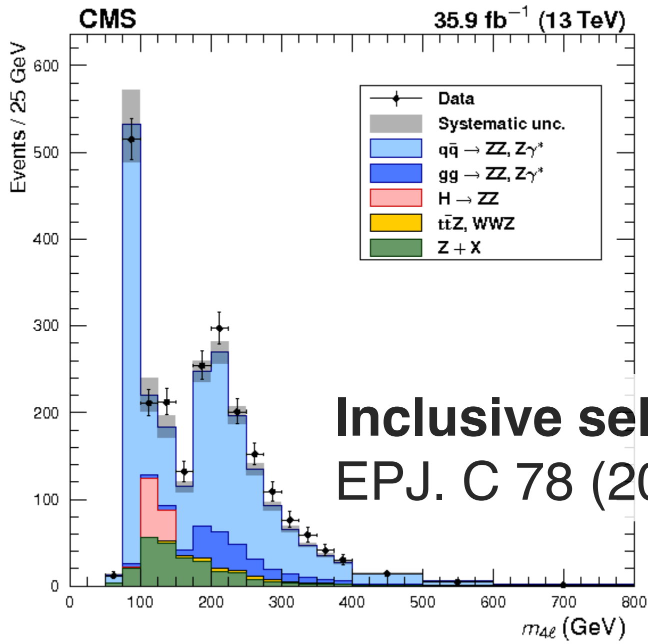


QCD production



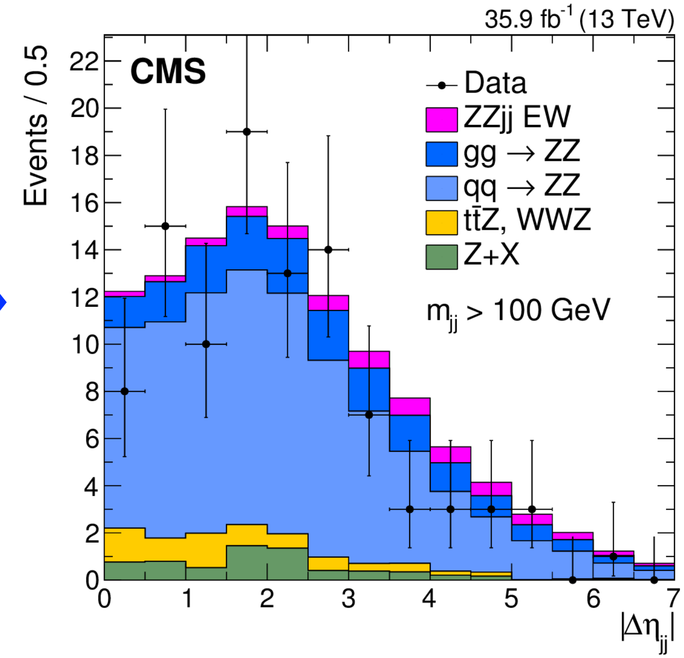
- ZZ Selection
  - Synchronized with H⟶4ℓ (JHEP 11 (2017) 047) and inclusive ZZ (EPJ. C 78 (2018) 165) selections
  - At least 4 leptons
    - $p_T(\mu, e) > 5, 7$ GeV; Leading > 20, 10 GeV
  - 2 Z candidates with $m_{\ell^+\ell^-} \in [60, 120]$ GeV
  - Signal selection (target EW production)
    - Two ak4 jets, $p_T > 30$ GeV, $|\eta| < 4.7$
    - $m_{jj} > 100$ GeV; Expected S/B ~ 1/20

ZZ VBS at 13 TeV: Backgrounds



Inclusive selection
EPJ. C 78 (2018) 165

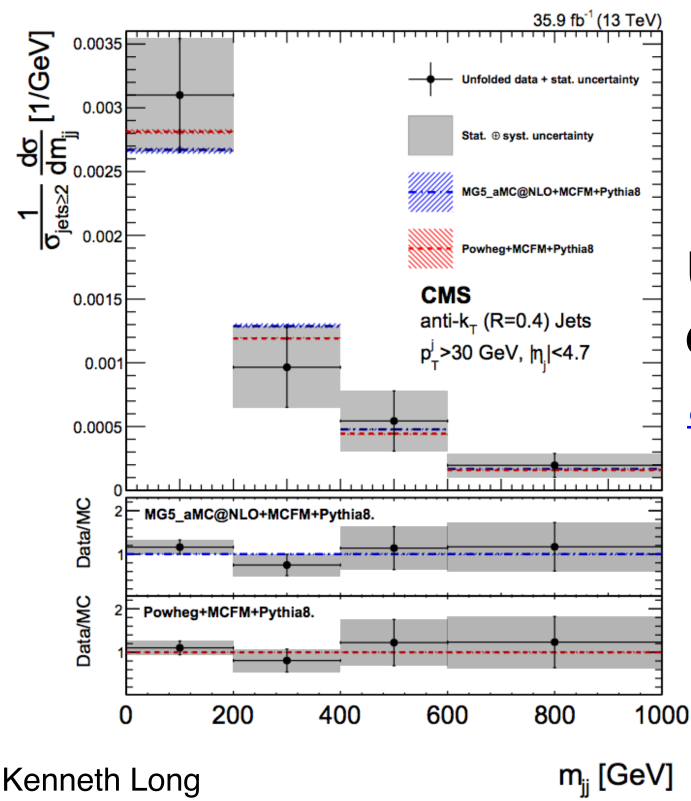
m_{jj} > 100 GeV



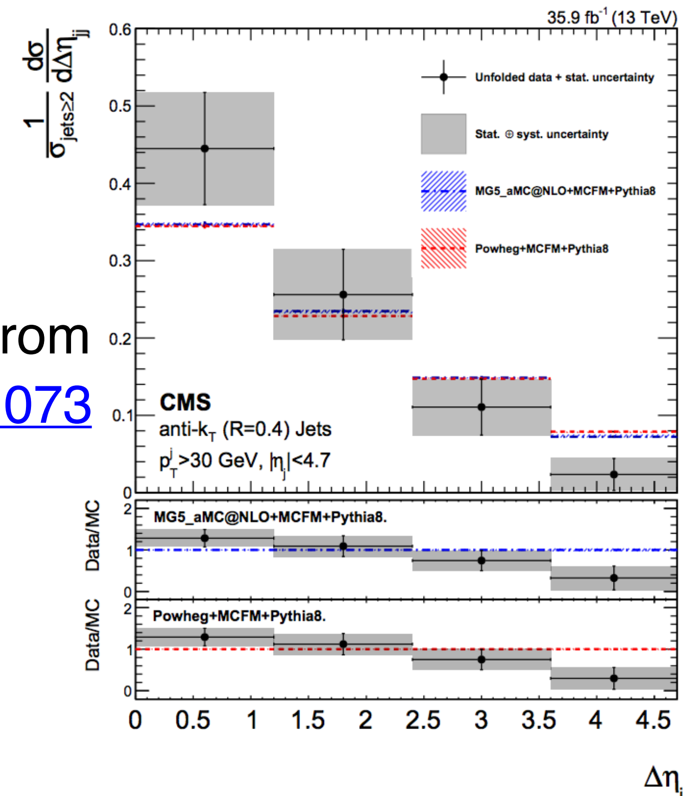
- ≥ 4 prompt leptons (ttV, VVV, QCD ZZ)
  - Simulated at NLO with MadGraph5_aMC@NLO
- Nonprompt background — from data
  1. Define "loose" ID with ID+isolation relaxed from "tight"
  2. Measure tight/loose ratio in Z+jet (dijet) events
  3. Apply loose ⟶ tight factors to events passing full analysis selection but failing analysis ID (tight)

ZZ VBS: Background Modeling

- Overwhelmingly dominant background
  - Taken from MC ⟹ modeling accuracy and uncertainty crucial
    - Model with MG5_aMC@NLO with FxFx merging of ≤2j @NLO
      - Require vector bosons on-shell, decayed with MadSpin
  - Validate MC prediction with data in non-VBS region and with alternative MCs (POWHEG, MG5_aMC@NLO with 2j@LO)



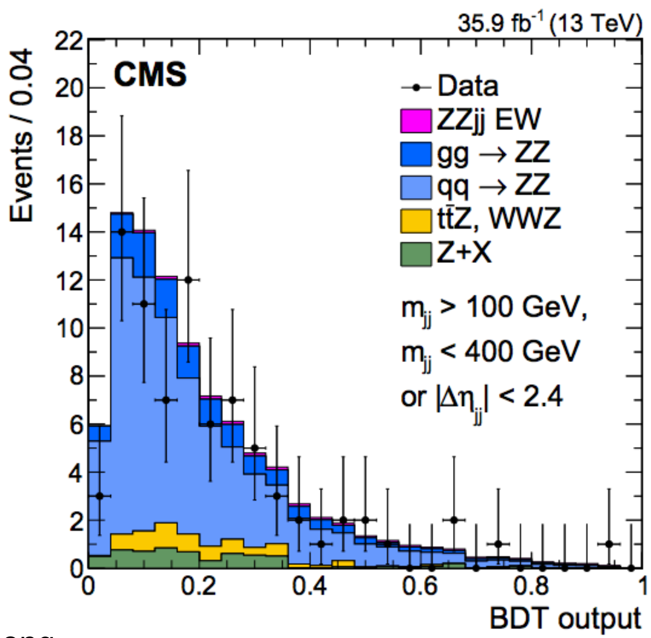
Unfolded distributions from [arxiv:1806.11073](https://arxiv.org/abs/1806.11073)

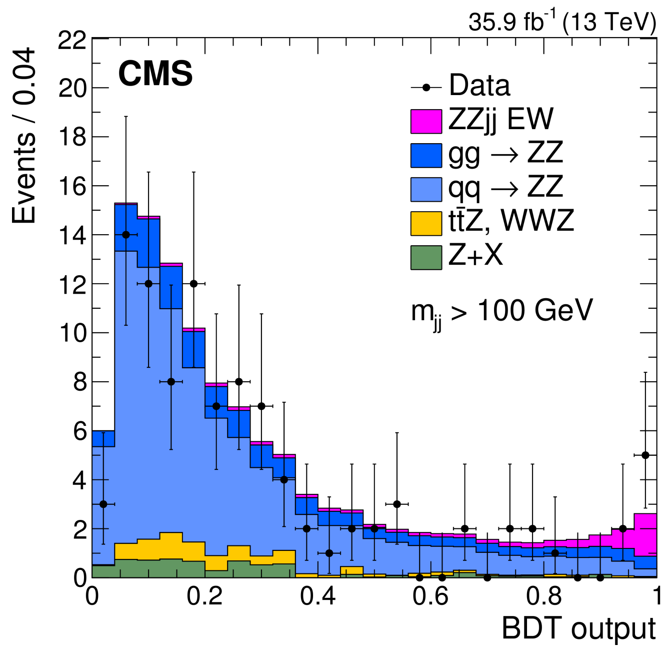


ZZ VBS at 13 TeV: EW Extraction

- Limited statistics, but strong discrimination feasible
- ➡ Train BDT with 7 discriminating variables
  - m_{jj}, $\Delta\eta_{jj}$, $\eta^*(Z_1)$, $\eta^*(Z_2)$, $R(p_T)$, dijet p_T balance, $m_{4\ell}$
  - Use all events with m_{jj} > 100 GeV
- Significance extracted via fit to BDT output distribution
- Check modeling performance in low m_{jj}, $\Delta\eta_{jj}$ region

$$\eta^*_{Z_i} = \eta_{Z_i} - (\eta_{\text{jet}\,1} + \eta_{\text{jet}\,2})/2$$





ZZ VBS at 13 TeV: Results

- Significance extracted via fit to BDT output distribution
  - Observed (expected) of 2.7σ (1.6σ)

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

- Used to derive fiducial xsec

$$0.40^{+0.21}_{-0.16}\,(\text{stat})\ ^{+0.13}_{-0.09}\,(\text{syst})\ \text{fb}$$

$$\sigma_{\text{LO,MG}} = 0.29 \pm 0.03$$

Fiducial Definition

$p_T(\ell) > 20,10,5,5$ GeV

$|\eta(\ell)| < 2.5$

$m_{\ell+\ell-} \in [60,\ 120]$ GeV

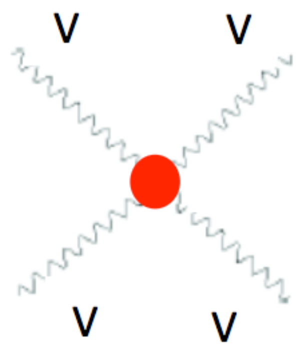
$m_{jj} > 100$ GeV

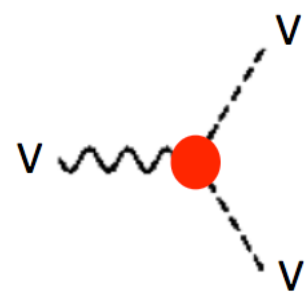
- Dominant systematic uncertainties
  - Jet energy scale and resolution
    - Shape-based, 20-4%, decreasing with BDT score
  - PDF and scale uncertainty on EW signal and QCD background, ~10%
  - Normalization uncertainty on ggZZ production — 40%
    - Taken from scale unc. + comparison of MCFM and MG5_aMC

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





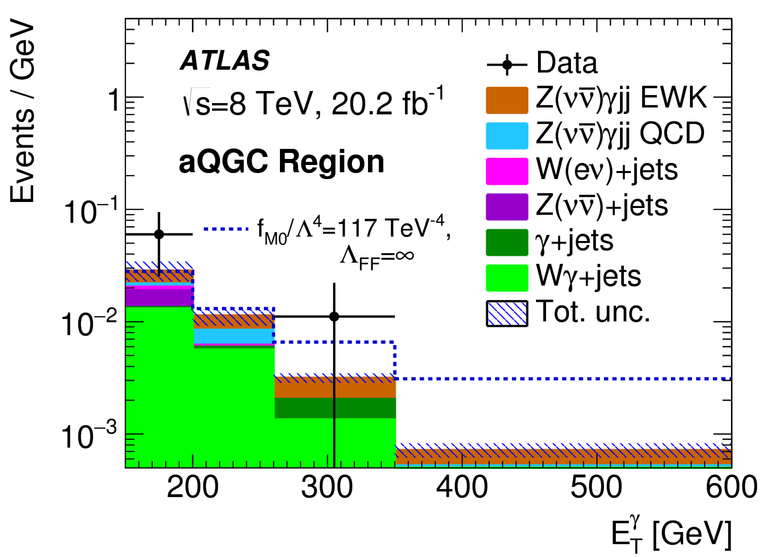
  - Alternatively… expand in effective field theory (EFT)
    - in terms of Wilson coefficients c_i and New Physics scale Λ

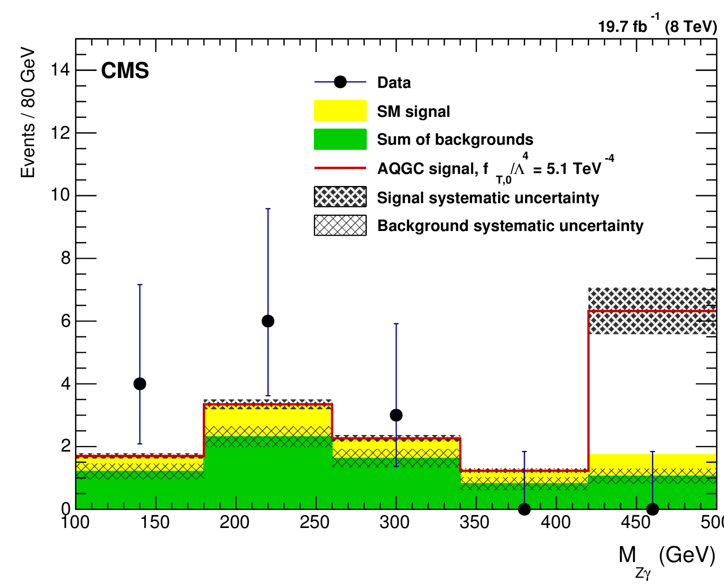
$$\mathcal{L}_{SM} \longrightarrow \mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty}\sum_{i} \frac{c_i^{(n)}}{\Lambda^n}\mathcal{O}_i^{(n+4)}$$

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

Zγ VBS: aQGC Procedure

- Fit to variable sensitive center of mass energy of the scattering system
  - ATLAS and CMS Zγ (ℓℓγjj and ννγjj): $E_T(\gamma)$ and $m_{Z\gamma}$
- Common parameterization from Eboli, Gonzlez-Garcia, Mizukoshi [2]
  - Interpolate between parameter points with quadratic fit to yields
  - Different approaches to unitarization between ATLAS and CMS
    - ATLAS: from factor $f = f_i/(1+ \hat{s}/\Lambda_{FF}^2)^n$ (Λ_{FF} via VBFNLO)
- ATLAS: Include ννγjj channel for increased sensitivity
  - E_T^{miss} > 100 GeV, p_T (γ)> 150 GeV, m_{jj} > 600 GeV
  - Additional cuts on centrality and pT balance





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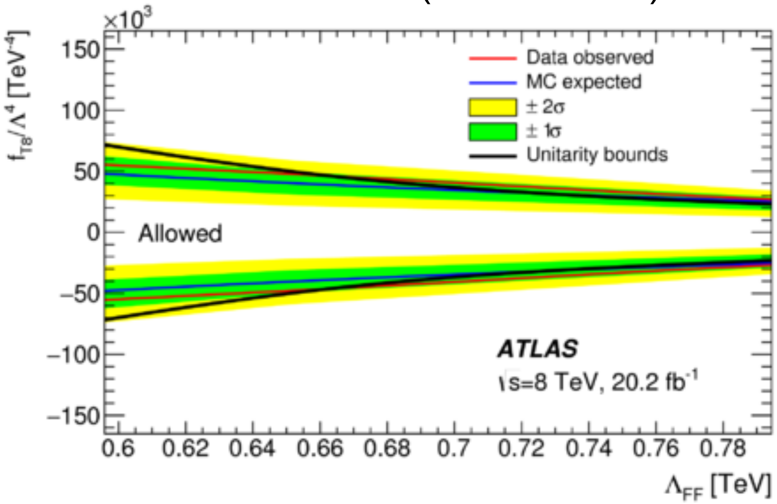
[2] https://arxiv.org/abs/hep-ph/0606118

Zγ VBS: aQGC Results

- ATLAS expected limits (without FF) stronger due to ννγjj channel

	95% CL intervals	Measured [TeV^{-4}]	Expected [TeV^{-4}]	Λ_{FF} [TeV]
$n=0$	f_{T9}/Λ^4	$[-4.1, 4.2] \times 10^3$	$[-2.9, 3.0] \times 10^3$	
	f_{T8}/Λ^4	$[-1.9, 2.1] \times 10^3$	$[-1.2, 1.7] \times 10^3$	
	f_{T0}/Λ^4	$[-1.9, 1.6] \times 10^1$	$[-1.6, 1.3] \times 10^1$	
	f_{M0}/Λ^4	$[-1.6, 1.8] \times 10^2$	$[-1.4, 1.5] \times 10^2$	
	f_{M1}/Λ^4	$[-3.5, 3.4] \times 10^2$	$[-3.0, 2.9] \times 10^2$	
	f_{M2}/Λ^4	$[-8.9, 8.9] \times 10^2$	$[-7.5, 7.5] \times 10^2$	
	f_{M3}/Λ^4	$[-1.7, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	
$n=2$	f_{T9}/Λ^4	$[-6.9, 6.9] \times 10^4$	$[-5.4, 5.3] \times 10^4$	0.7
	f_{T8}/Λ^4	$[-3.4, 3.3] \times 10^4$	$[-2.6, 2.5] \times 10^4$	0.7
	f_{T0}/Λ^4	$[-7.2, 6.1] \times 10^1$	$[-6.1, 5.0] \times 10^1$	1.7
	f_{M0}/Λ^4	$[-1.0, 1.0] \times 10^3$	$[-8.8, 8.8] \times 10^2$	1.0
	f_{M1}/Λ^4	$[-1.6, 1.7] \times 10^3$	$[-1.4, 1.4] \times 10^3$	1.2
	f_{M2}/Λ^4	$[-1.1, 1.1] \times 10^4$	$[-9.2, 9.6] \times 10^3$	0.7
	f_{M3}/Λ^4	$[-1.6, 1.6] \times 10^4$	$[-1.4, 1.3] \times 10^4$	0.8

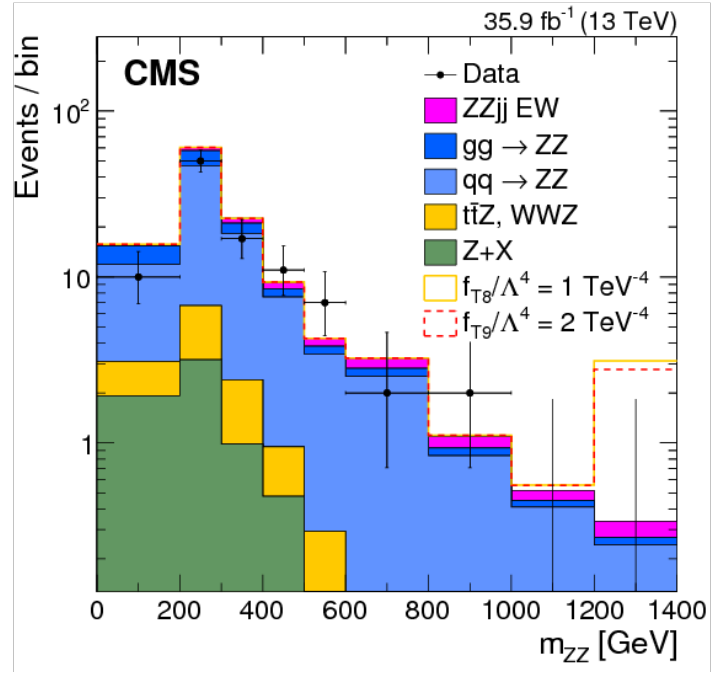
$$f = f_i/(1+\hat{s}/\Lambda_{FF}^2)^n$$



Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-71 < f_{M0}/\Lambda^4 < 75$	$-109 < f_{M0}/\Lambda^4 < 111$
$-190 < f_{M1}/\Lambda^4 < 182$	$-281 < f_{M1}/\Lambda^4 < 280$
$-32 < f_{M2}/\Lambda^4 < 31$	$-47 < f_{M2}/\Lambda^4 < 47$
$-58 < f_{M3}/\Lambda^4 < 59$	$-87 < f_{M3}/\Lambda^4 < 87$
$-3.8 < f_{T0}/\Lambda^4 < 3.4$	$-5.1 < f_{T0}/\Lambda^4 < 5.1$
$-4.4 < f_{T1}/\Lambda^4 < 4.4$	$-6.5 < f_{T1}/\Lambda^4 < 6.5$
$-9.9 < f_{T2}/\Lambda^4 < 9.0$	$-14.0 < f_{T2}/\Lambda^4 < 14.5$
$-1.8 < f_{T8}/\Lambda^4 < 1.8$	$-2.7 < f_{T8}/\Lambda^4 < 2.7$
$-4.0 < f_{T9}/\Lambda^4 < 4.0$	$-6.0 < f_{T9}/\Lambda^4 < 6.0$

ZZ: aQGC Procedure and Results

- Parameterization from Eboli, Gonzlez-Garcia, Mizukoshi [2] from MG5_aMC@NLO
  - Use matrix-element reweighting to obtain events with full detector simulation for grid of parameter values
  - Limits obtained via fit to $m_{4\ell}$
  - Unitarity bound for given operator obtained from VBFNLO also reported

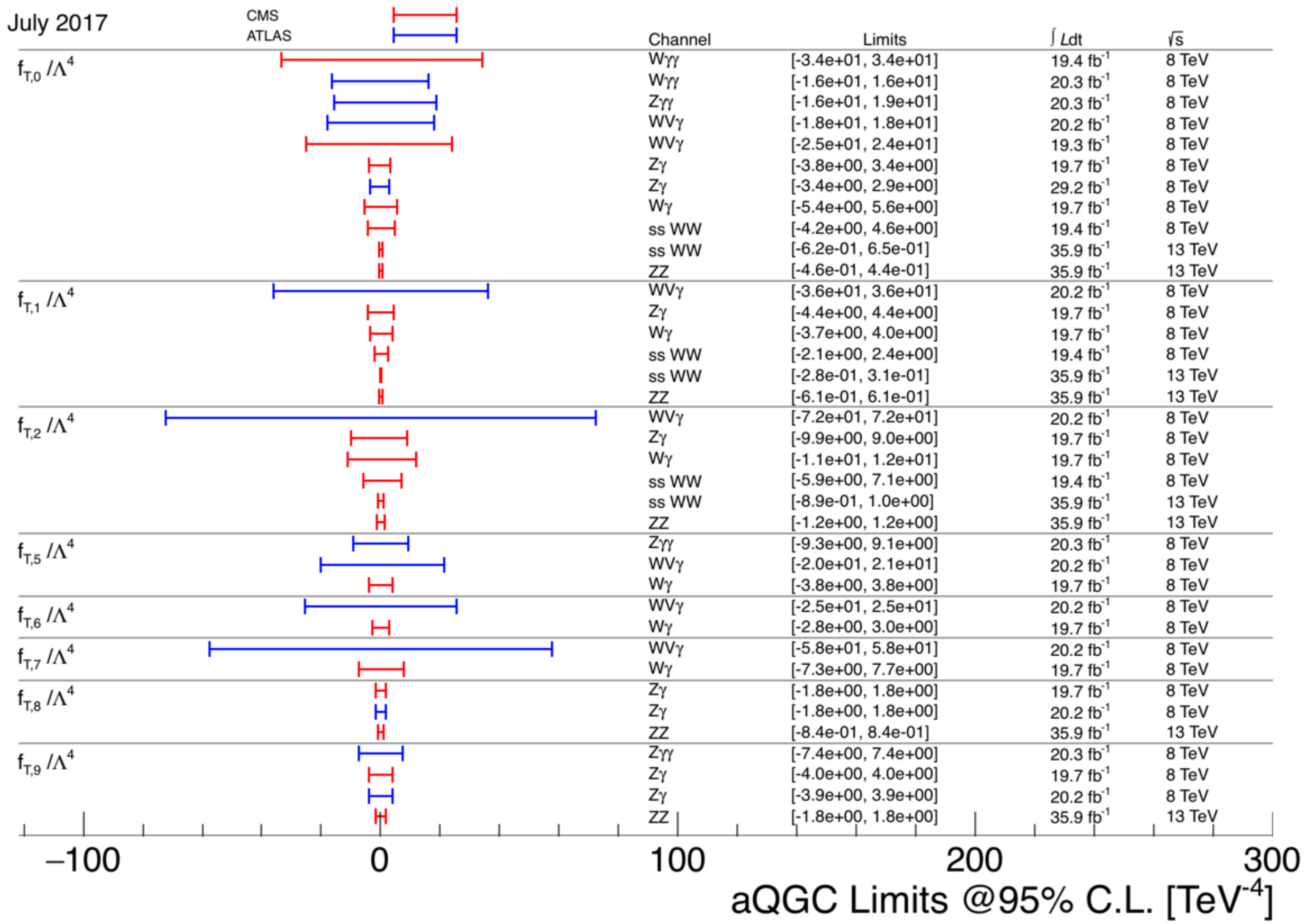


Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.53	0.51	−0.46	0.44	2.5
f_{T1}/Λ^4	−0.72	0.71	−0.61	0.61	2.3
f_{T2}/Λ^4	−1.4	1.4	−1.2	1.2	2.4
f_{T8}/Λ^4	−0.99	0.99	−0.84	0.84	2.8
f_{T9}/Λ^4	−2.1	2.1	−1.8	1.8	2.9

[2] https://arxiv.org/abs/hep-ph/0606118

Limits on aQGCs: Overview

- ZZ and Zγ complement and extend results from other channels
  - Strongest probe for neutral T8 and T9 operators
  - Results shown without unitarization



Conclusions

- VBS measurements provide an important probe of a rich sector of the standard model
- So far the standard model is withstanding these tests
  - Interpreting results in terms of aQGC, fiducial cross sections, or specific models help quantify these tests
- Precision will continue to improve with more data and improved techniques