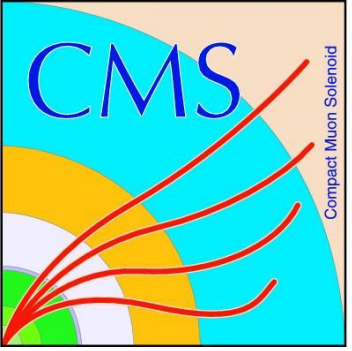

EWK Diboson Production and aQGCs of Massive Vector Bosons

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Multi-Boson Interactions 2019

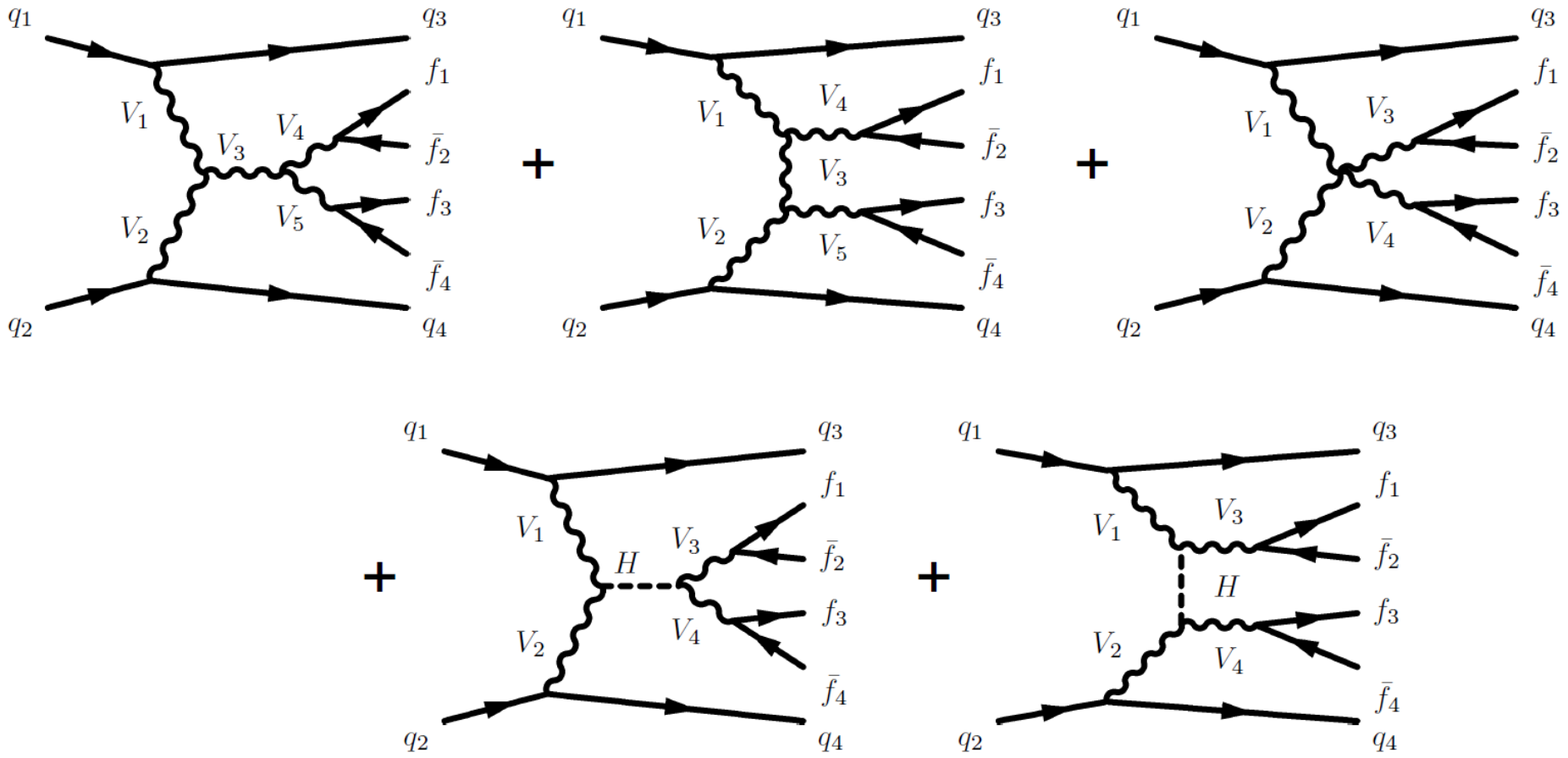
Introduction

- Electroweak-induced (EWK) WWjj, WZjj, and ZZjj, production is predicted by the SM with 0.1-50 fb cross sections at 13 TeV
- Mechanisms include quartic couplings and double triple gauge couplings, including t-channel and s-channel Higgs boson exchange
- Anomalous quartic couplings predicted in new physics models and effective field theories would enhance cross sections
- All 3 channels with t-channel Higgs diagrams ($W^{\pm}W^{\pm}jj$, WZjj, and ZZjj) have been observed now by at least one experiment, and variety of other results have been recently released

Outline

- Theoretical background information
- Summary of significances in different channels and summary of aQGC measurements in different channels
- Details about 5 recent results from ATLAS and CMS
  - ATLAS, submitted to PRL: Observation of EWK $W^{\pm}W^{\pm}jj$ production
  - ATLAS, published in PLB: Observation of EWK WZjj production
  - ATLAS, preliminary result: Observation of EWK ZZjj production
  - CMS, submitted to PLB: Measurement of EWK VVjj production, semileptonic
  - ATLAS, submitted to PRD: Measurement of EWK VVjj production, semileptonic

Relevant Feynmann Diagrams



Source: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-06/

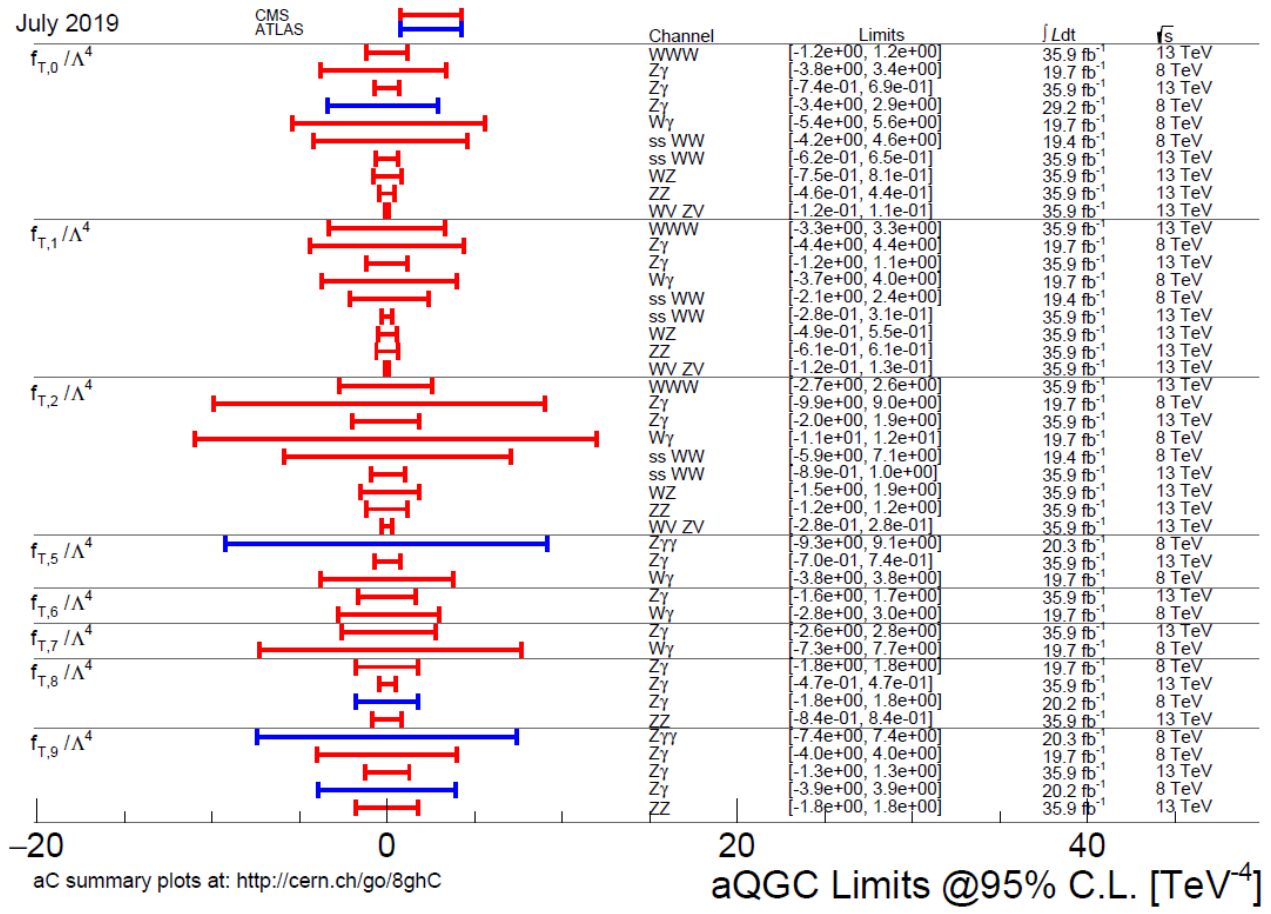
Anomalous Couplings Frameworks

- Quantify deviations from the Standard Model in a general or model-independent way
- Allows us to compare measurements in different channels and different experiments
- Dimension 8 Effective Field Theory
  - $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{F_i}{\Lambda^4} \mathcal{O}_i$
  - Operators involving $D_\mu\phi$: $L_{S0\text{-}1}$
  - Operators involving $B_{\mu\nu}$ or $W^i{}_{\mu\nu}$: $L_{T0\text{-}9}$
  - Operators involving $D_\mu\phi$ and either $B_{\mu\nu}$ or $W^i{}_{\mu\nu}$: $L_{M0\text{-}7}$
  - For example: $L_{T8} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$

Electroweak-induced VVjj production significances, fully leptonic results

Experiment	CoM Energy	$W^{\pm}W^{\mp}jj$	$W^{\pm}W^{\pm}jj$	$W^{\pm}Zjj$	$ZZjj$
CMS	8 TeV		2.0 σ		
ATLAS	8 TeV		4.5 σ		
CMS	13 TeV		5.5 σ	2.2 σ	2.7 σ
ATLAS	13 TeV		6.5 σ	5.3 σ	5.5 σ

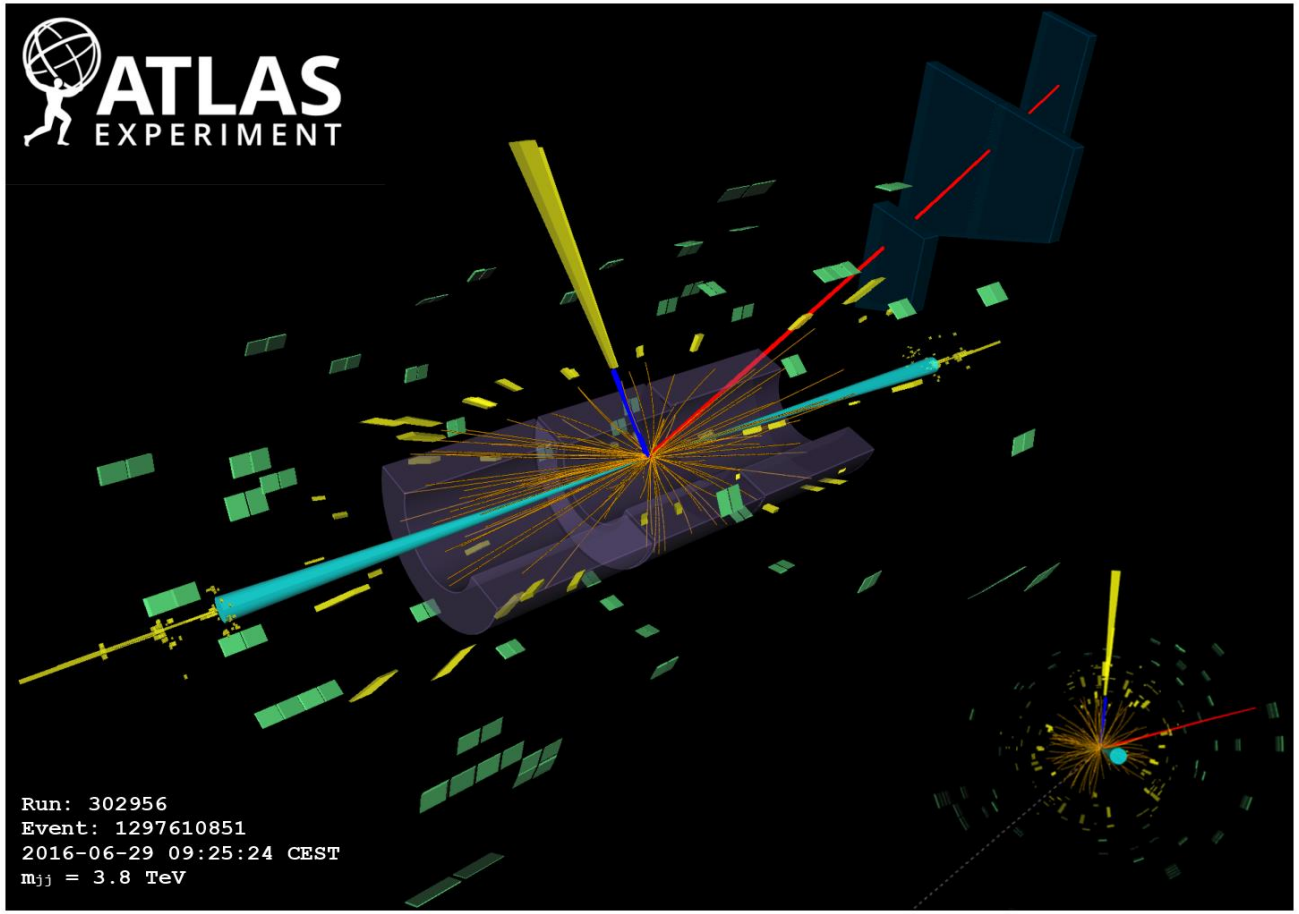
Limits on dimension 8 EFT operators



Credit: Matthew Herndon

ATLAS: Observation of EWK $W^{\pm}W^{\pm}$ production (I)

- Based on 36.1 fb^{-1} collected at 13 TeV
- Fully leptonic final state (lepton = electron or muon)
- Observed signal significance: 6.5 σ
- Expected signal significance based on Sherpa (LO-QCD, 0 and 1 jets): 4.4 σ
- Expected signal significance based on POWHEG (NLO-QCD): 6.5 σ
- Significance is extracted by performing a simultaneous fit in the signal region and two control regions



ATLAS: Observation of EWK $W^{\pm}W^{\pm}$ production (II)

Signal region selection

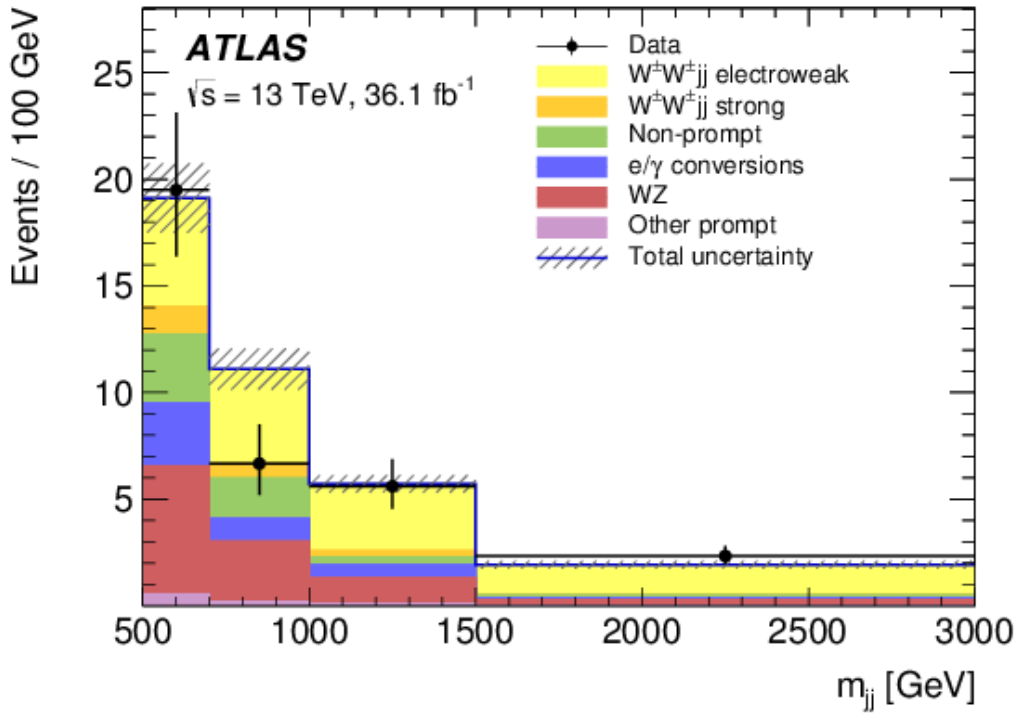
- Single lepton triggers
- $m_{ll} > 20$ GeV
- MET > 30 GeV
- Leading jet $p_T > 65$ GeV, $|\eta| < 4.5$
- Sub-leading jet $p_T > 35$ GeV, $|\eta| < 4.5$
- Lepton $p_T > 27$ GeV, $|\eta| < 2.5$
- $m_{jj} > 500$ GeV
- $|\Delta y_{jj}| > 2$
- B-tagged jet veto
- Split into 6 categories for $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, and $\mu^{\pm}\mu^{\pm}$ and 4 m_{jj} bins

Control region selections

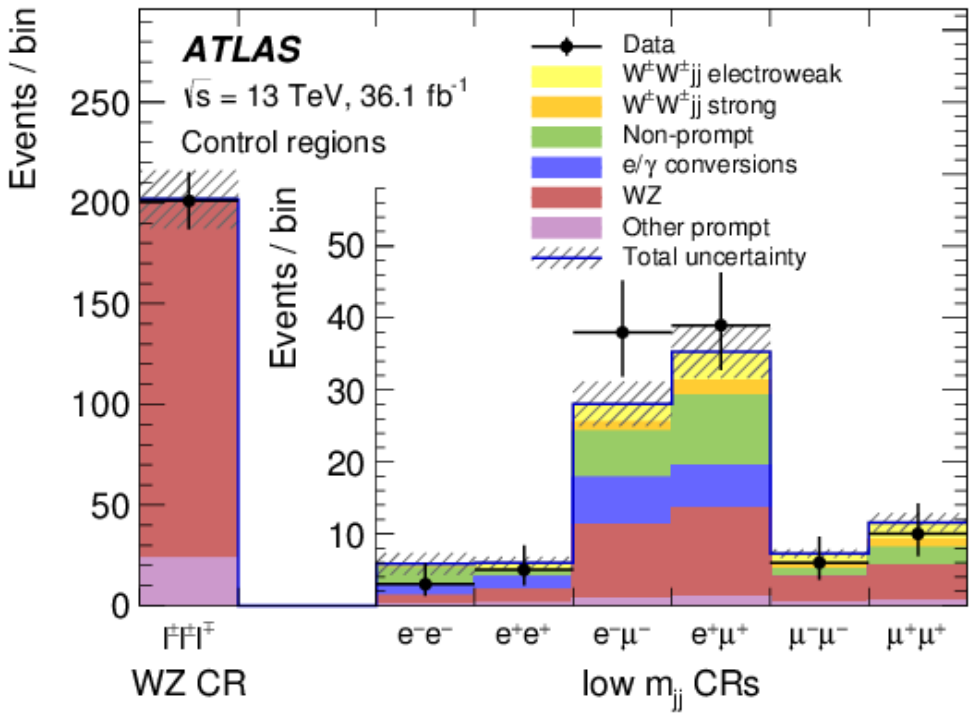
- Low m_{jj} control region
  - Replace $m_{jj} > 500$ GeV with $200 < m_{jj} < 500$ GeV
- WZ control region
  - Apply signal region selection to first two leptons, looser selection to third lepton
  - Contains a single bin
  - Normalization of WZ is a floating parameter

ATLAS: Observation of EWK $W^{\pm}W^{\pm}$ production (III)

Signal region



Control region

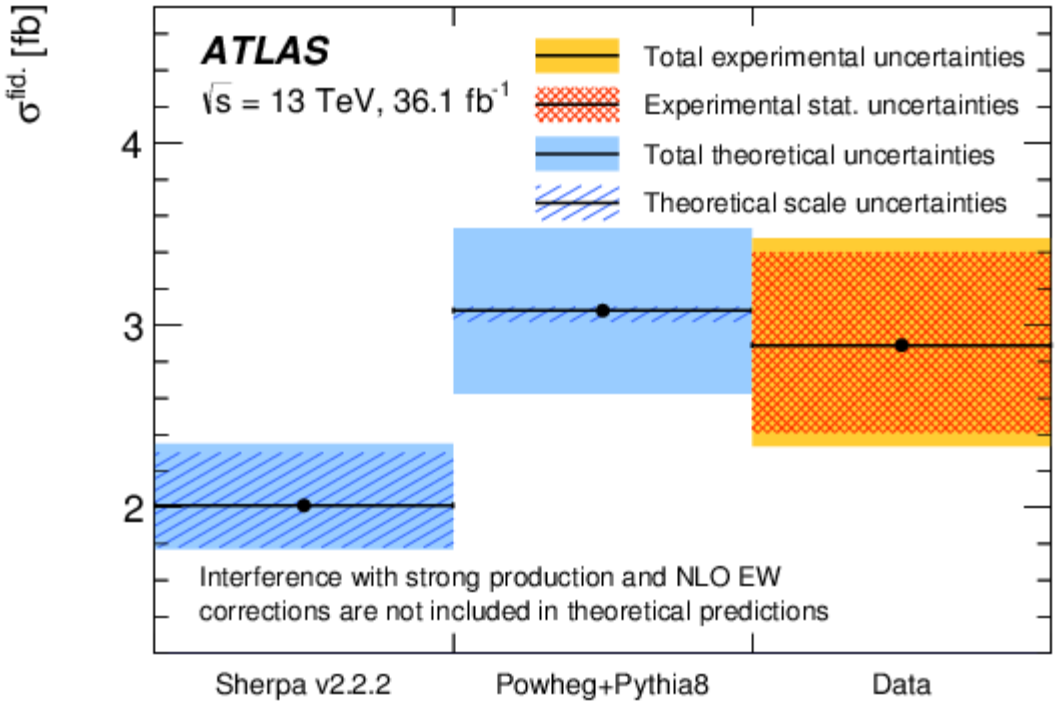


ATLAS: Observation of EWK $W^{\pm}W^{\pm}$ production (IV)

- WZ background normalization determined from WZ control region
- Method to estimate fake (non-prompt) lepton background
  1. Define a scale factor between fake leptons passing a control lepton selection and the signal lepton selection
  2. Measure scale factor in data events with one b jet and one control lepton as a function of scalar sum of lepton pt and tracks within $\Delta R = 0.3$ of the control lepton
  3. Subtract contamination from real leptons in numerator and denominator of scale factor
  4. Apply scale factors to data events that pass signal selection with signal lepton replaced with control lepton
- Method to estimate electron charge flip background
  1. Measure charge flip rates in data using Z → ee events
  2. Apply charge flip rates to opposite sign events in simulation

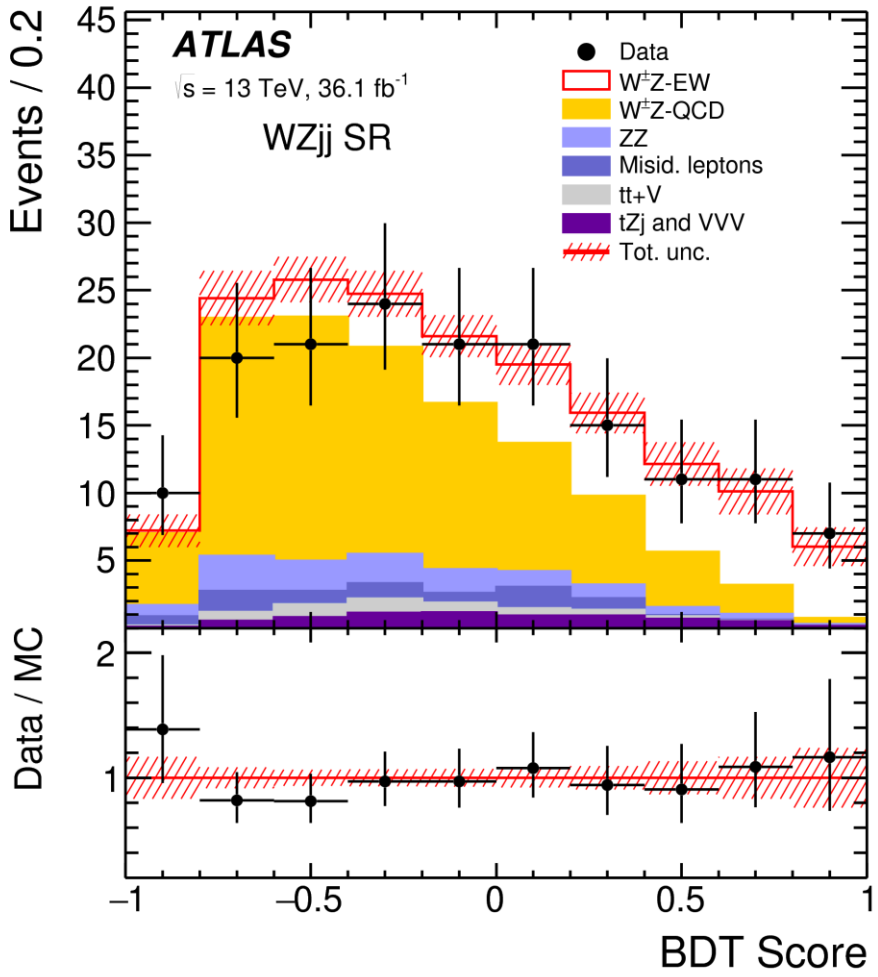
ATLAS: Observation of EWK $W^{\pm}W^{\pm}$ production (V)

- Fiducial region definition:
  - Leading (sub-leading) jet $p_T > 65$ GeV (> 35 GeV) and $|\eta_j| < 4.5$
  - Lepton $p_T > 27$ GeV and $|\eta| < 2.5$
  - ΔR_{lj}, $\Delta R_{ll} > 0.5$
  - $m_{jj} > 500$ GeV and $|y_{jj}| > 2$
  - $m_{ll} > 20$ GeV
  - MET > 30 GeV
  - Leptons are dressed with photons within $\Delta R = 0.1$
- Fiducial cross section measurement:
  $\sigma = 2.89^{+0.51}_{-0.48}(\text{stat.})^{+0.24}_{-0.22}(\text{exp. syst.})^{+0.14}_{-0.16}(\text{mod. syst.})^{+0.08}_{-0.06}\ (\text{lumi.})$ fb
- Sherpa prediction: $2.01^{+0.33}_{-0.23}$ fb
- POWHEG prediction: $3.08^{+0.45}_{-0.46}$ fb
- Measurement is based on signal strength fit with Sherpa as signal, with the fit only considering shape theoretical uncertainties



ATLAS: Observation of EWK WZ production (I)

- Fully leptonic final state (lepton = electron or muon)
- Using 2015 and 2016 data
- Observed EWK signal significance: 5.3 σ
- Expected EWK signal significance: 3.2 σ
- BDT trained to distinguish EWK WZjj from QCD WZjj
- Significance extracted from simultaneous fit of 4 regions
  1. BDT score in the EW WZjj SR
  2. m_{jj} distribution in QCD WZjj CR
  3. multiplicity of b-tagged jets in b-tagged CR
  4. m_{jj} distribution in ZZ CR



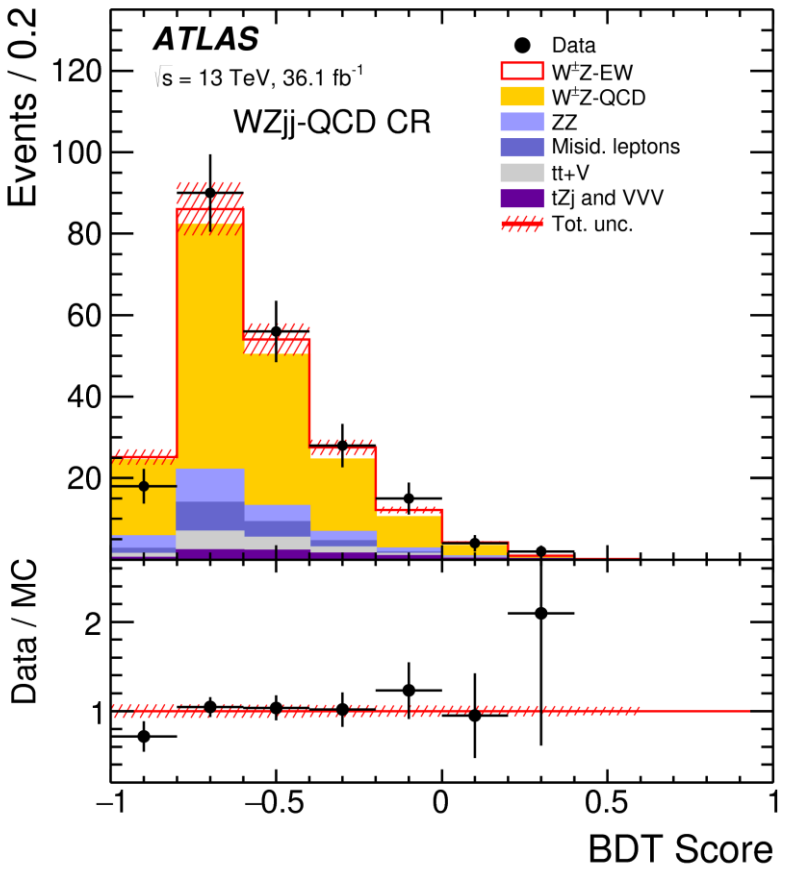
ATLAS: Observation of EWK WZ production (ll)

- BDT input variables
  - m_{jj}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, $p_T^{j_1}$, $p_T^{j_2}$
  - Leading jet y
  - Jet multiplicity
  - p_T^W, p_T^Z, p_T^{WZjj}, η^W (defined with kinematic fit)
  - m_T^{WZ}, $|y_Z - y_{l,W}|$
  - ΔR(leading jet,Z)
  - $\min(\Delta\eta_-, \Delta\eta_+)$ where
    - $\Delta\eta_- = \min(\eta_l^W, \eta_{l_1}^Z, \eta_{l_2}^Z) - \min(\eta_{j_1}, \eta_{j_2})$
    - $\Delta\eta_+ = \max(\eta_{j_1}, \eta_{j_2}) - \max(\eta_l^W, \eta_{l_1}^Z, \eta_{l_2}^Z)$

- Signal region
  - Single lepton triggers
  - Leading lepton p_T > 25 GeV (27 GeV) for 2015 (2016) data
  - Leading jet p_T > 40 GeV
  - 4th lepton veto with veto lepton p_T > 5 GeV
  - m_{jj} > 500 GeV
  - m_T^W > 30 GeV
  - Veto of b-tagged jets

ATLAS: Observation of EWK WZ production (III)

- Reducible background estimation
  - Measure efficiency and misidentification probabilities for loose and tight lepton selections
  - Construct matrix which converts between lepton selection triplets (e.g. pass fail pass) and lepton source triplets (e.g. prompt prompt nonprompt)
  - Invert matrix



ATLAS: Observation of EWK WZ production (IV)

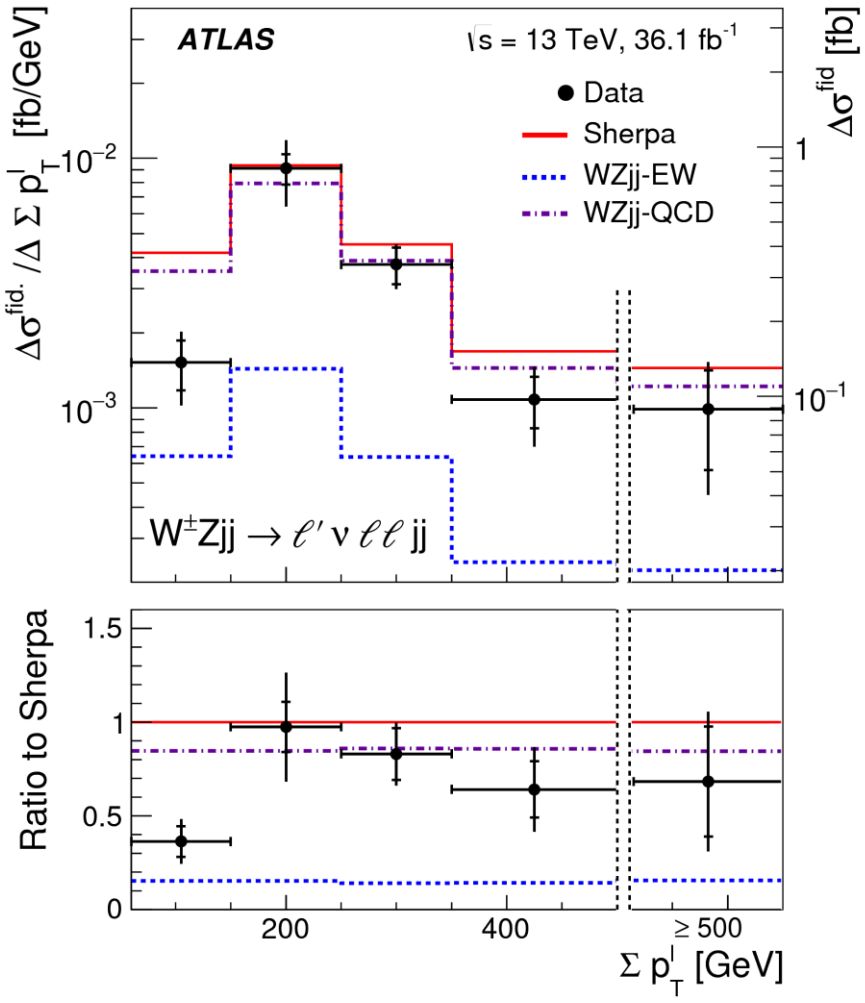
- Measured electroweak fiducial cross section:
  $\sigma = 0.57^{+0.14}_{-0.13}(\text{stat.})^{+0.05}_{-0.04}(\text{exp. syst.})^{+0.05}_{-0.04}(\text{mod. syst.})^{+0.01}_{-0.01}\ (\text{lumi.})\ \text{fb}$
- Sherpa LO prediction:

  $\sigma = 0.321 \pm 0.002\ (\text{stat}) \pm 0.005(\text{PDF})^{+0.027}_{-0.023}(\text{scale})\ \text{fb}$
- Measured inclusive fiducial cross section:
  $\sigma = 1.68 \pm 0.16\ (\text{stat}) \pm 0.12\ (\text{exp. syst.}) \pm 0.13\ (\text{mod. syst.}) \pm 0.044\ (\text{lumi.})\ \text{fb}$
- Sherpa LO prediction:
  $\sigma = 2.15 \pm 0.01\ (\text{stat}) \pm 0.05\ (\text{PDF})^{+0.65}_{-0.44}(\text{scale})\ \text{fb}$
- Electroweak cross section measured using signal strength fit and inclusive cross section measured using the formula

$$\sigma = \frac{N_{data} - N_{bkg}}{L \cdot C_{WZjj}} \times \left(1 - \frac{N_{\tau}}{N_{all}}\right)$$

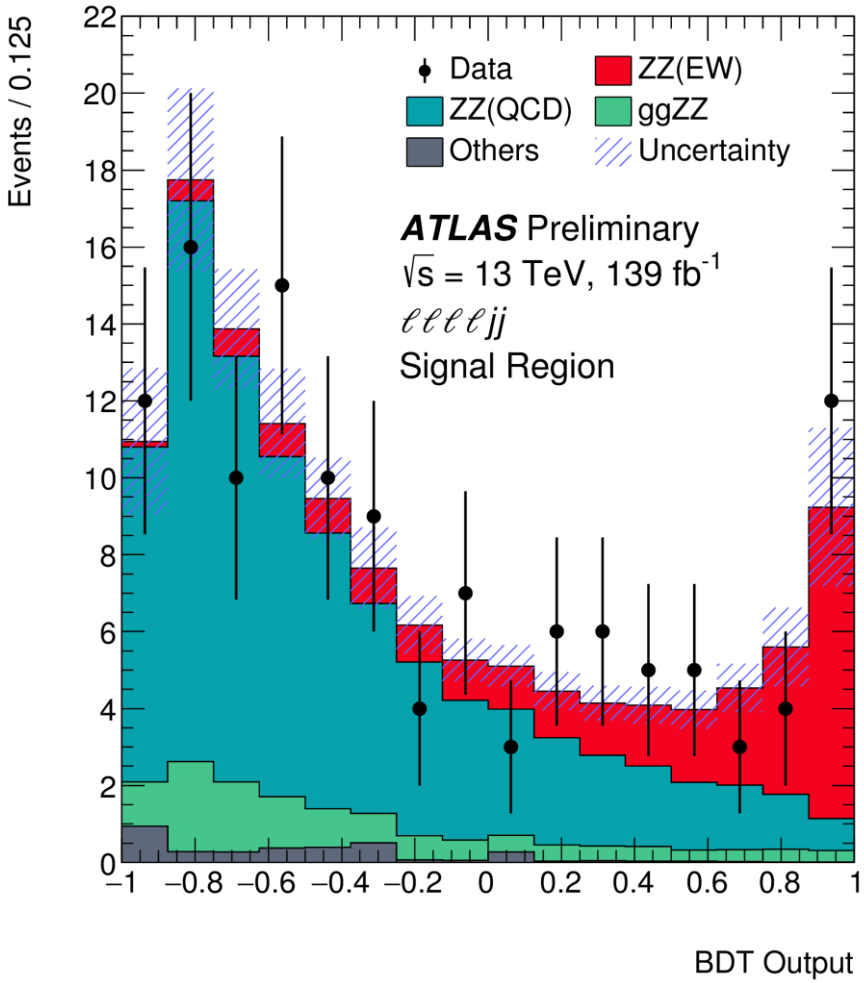
ATLAS: Observation of EWK WZ production (V)

- Differential cross sections for 8 variables: number of jets, number of jets between the two tagged jets, $\Delta\phi_{jj}$, Δy_{jj} m_T^{WZ}, $\Delta\phi$(W,Z), m_{jj}, $\sum p_T^l$
- Iterative Bayesian unfolding with three iterations
- m_{jj}, $\sum p_T^l$, and m_T^{WZ} are sensitive to anomalous couplings



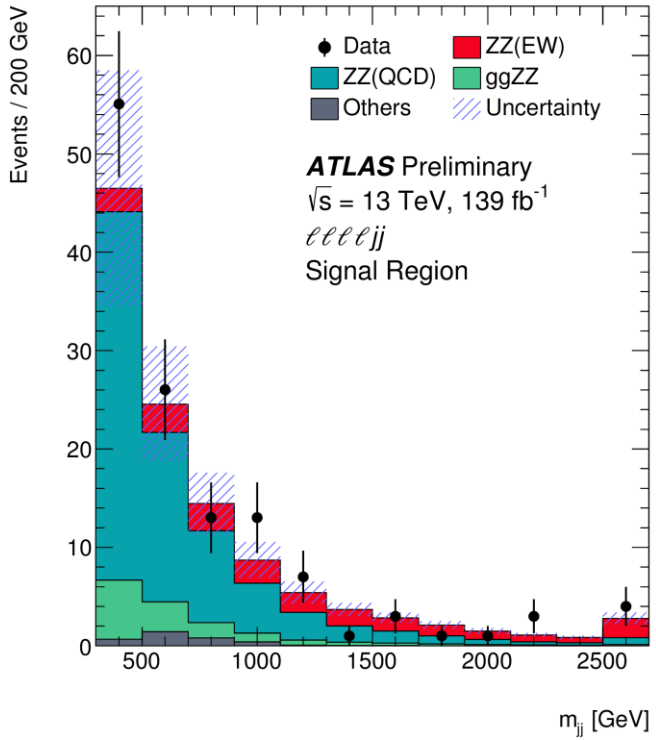
ATLAS: Observation of EWK ZZ production (I)

- Based on the full run 2 dataset 2015 - 2018
- Observed signal significance: 5.5 σ
- Expected signal significance: 4.3 σ
- Includes 4l channel and 2l2v channel
- BDT trained to distinguish the EWK signal from simulated backgrounds
- Significance is extracted based on fit to BDT in 4l and 2l2v signal regions and a low $m_{jj}/\Delta\eta_{jj}$ 4l control region

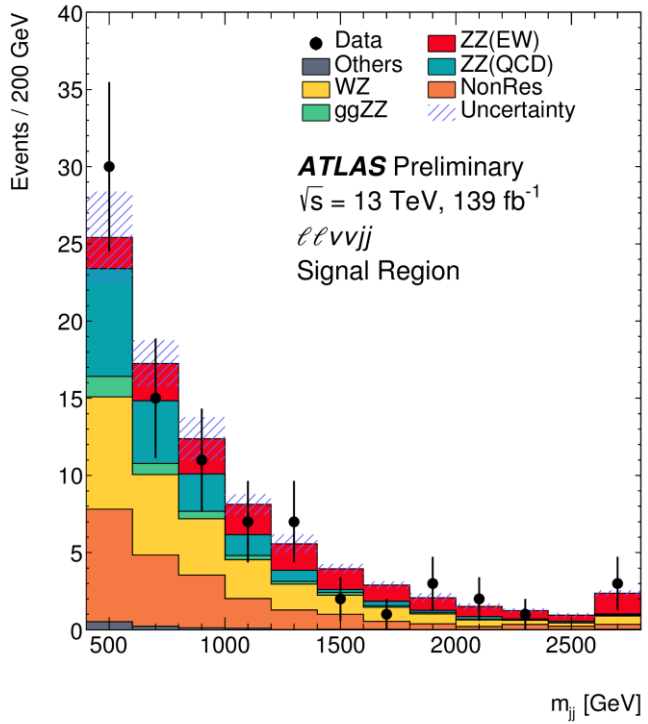


ATLAS: Observation of EWK ZZ production (ll)

m_{jj} distribution in the 4l signal region



m_{jj} distribution in the 2l2v signal region



ATLAS: Observation of EWK ZZ production (III)

	$\ell\ell\ell\ell jj$	$\ell\ell\nu\nu jj$
Electrons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$ $\lvert d_0/\sigma_{d_0}\rvert < 5$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	
Muons	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.7$ $\lvert d_0/\sigma_{d_0}\rvert < 3$ and $\lvert z_0 \times \sin\theta\rvert < 0.5$ mm	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$
Jets	$p_{\mathrm{T}} > 30$ (40) GeV for $\lvert\eta\rvert < 2.4$ ($2.4 < \lvert\eta\rvert < 4.5$)	$p_{\mathrm{T}} > 60$ (40) GeV for the leading (sub-leading) jet
ZZ selection	$p_{\mathrm{T}} > 20$, 20, 10 GeV for the leading, sub-leading and third leptons Two OSSF lepton pairs with smallest $\lvert m_{\ell^+\ell^-} - m_Z\rvert + \lvert m_{\ell'^+\ell'^-} - m_Z\rvert$ $m_{\ell^+\ell^-} > 10$ GeV for lepton pairs $\Delta R(\ell, \ell') > 0.2$ $66 < m_{\ell^+\ell^-} < 116$ GeV	$p_{\mathrm{T}} > 30$ (20) GeV for the leading (sub-leading) lepton One OSSF lepton pair and no third leptons $80 < m_{\ell^+\ell^-} < 100$ GeV No b-tagged jets $E_{\mathrm{T}}^{\mathrm{miss}}$ significance > 12
Dijet selection	Two most energetic jets with $y_{j_1} \times y_{j_2} < 0$ $m_{jj} > 300$ GeV and $\Delta y(jj) > 2$	$m_{jj} > 400$ GeV and $\Delta y(jj) > 2$

ATLAS: Observation of EWK ZZ production (IV)

- BDT input variables, 4l BDT
  - m_{jj},Δy(j,j)
  - $p_T^{j_1}$, $p_T^{j_2}$
  - y_{Z1}, y_{Z2}
  - $y_{j1} \times y_{Z2}$
  - $m_{4l,}$ p_T^{4l}
  - p_T of the third lepton
  - p_T of the Z boson with mass closer to the nominal Z boson mass
  - $p_T^{ZZjj}/(p_T^{j_1} + p_T^{j_2} + p_T^{Z1} + p_T^{Z2})$
- BDT input variables, 2l2v BDT
  - m_{jj},Δy(j,j)
  - $p_T^{j_2}$
  - $y_{j1} \times y_{Z2}$
  - $p_T^{ZZjj}/(p_T^{j_1} + p_T^{j_2} + p_T^{Z1} + p_T^{Z2})$
  - MET, MET significance
  - Δη(l,l), Δϕ(l,l), ΔR(l,l), m_{ll}
  - $p_T^{l_1}$, $p_T^{l_2}$

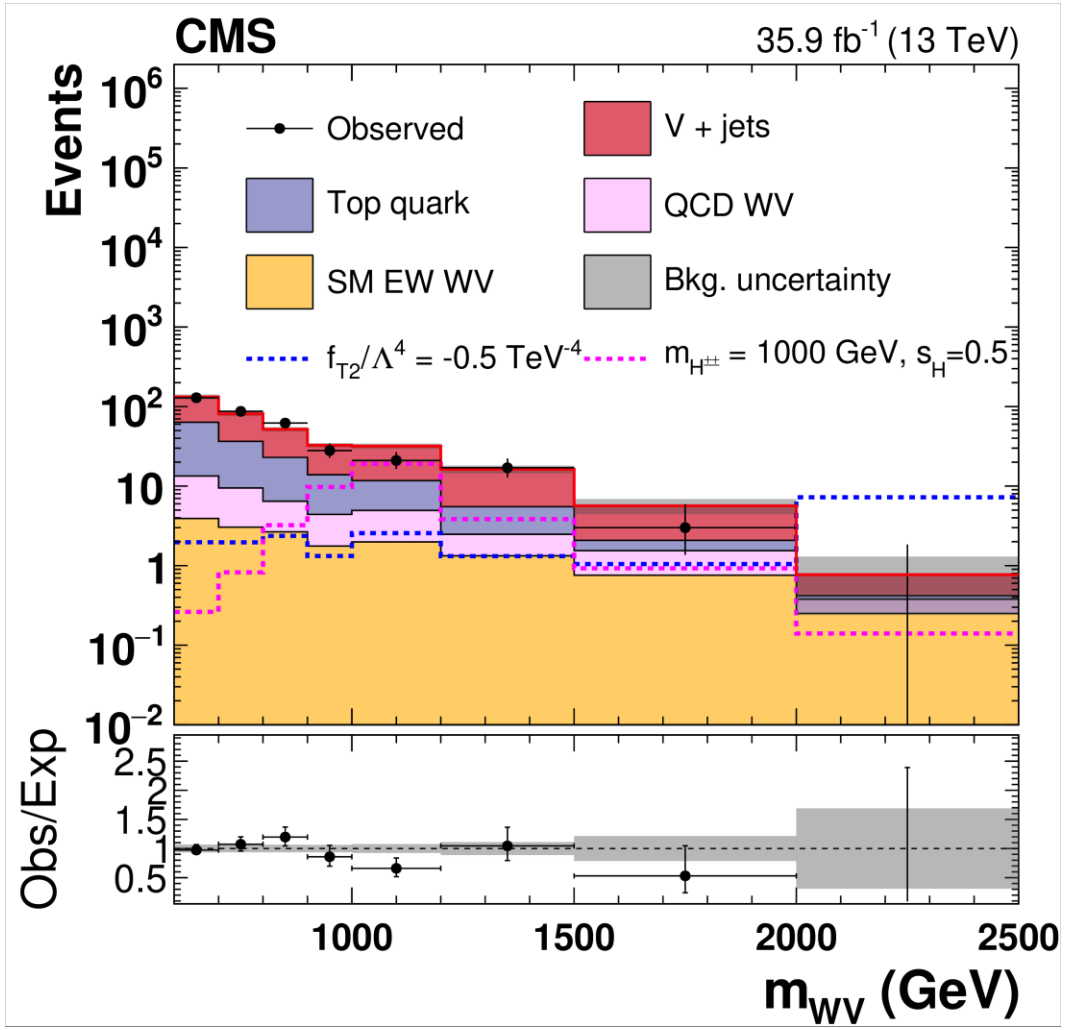
ATLAS: Observation of EWK ZZ production (V)

- Fiducial region definition:
  - Defined at particle level with the same cuts as the detector-level selections, with the following exceptions
  - Leptons are dressed with photons within $\Delta R = 0.1$
  - Relaxed dilepton mass requirement of $60 < m_{ll} < 120$ GeV
  - In 2l2v channel, MET significance > 12 replaced by MET > 130 GeV
  - Electron and muon $|\eta|$ cuts replaced by $|\eta| < 2.5$

- Fiducial cross section, measured, 4l: $\sigma = 1.27 \pm 0.12$ (stat) ± 0.02 (theo) ± 0.07 (exp) ± 0.01 (bkg) ± 0.03 (lumi)
- Fiducial cross section, predicted, 4l: $\sigma = 1.14 \pm 0.04$ (stat) ± 0.20 (theo)
- Fiducial cross section measured, 2l2v: $\sigma = 1.22 \pm 0.30$ (stat) ± 0.04 (theo) ± 0.06 (exp) ± 0.16 (bkg) ± 0.03 (lumi)
- Fiducial cross section, predicted, 2l2v: $\sigma = 1.07 \pm 0.01$ (stat) ± 0.12 (theo)

CMS: Measurement of EWK VV production, semileptonic (I)

- Based on 35.9 fb^{-1} collected at 13 TeV
- Reconstruct jets using anti-k_T algorithm with $\Delta R = 0.8$
- N-subjettiness, τ_N, quantifies (with small values meaning well and large values meaning not well) how well a jet can be described as N subjets
- Use $\tau_2/\tau_1 < 0.55$ to select jets likely to be merged
- Use a WV and ZV channel, with V indicating the merged jet



CMS: Measurement of EWK VV production, semileptonic (II)

- Selection
  - One lepton with $p_T > 50$ GeV
  - MET > 50 (80) GeV in electron (muon) channel
  - At least one V jet with $p_T > 200$ GeV, $|\eta| < 2.4$, and 65 < soft-drop tagger mass < 105 GeV
  - Veto of events with b-tagged jets
  - Veto of second leptons for WV and third leptons for ZV
  - $\left|\eta^W - \frac{\eta^{j1}+\eta^{j2}}{2}\right| / \left|\Delta\eta_{jj}\right| < 0.3$ and $\left|\eta^V - \frac{\eta^{j1}+\eta^{j2}}{2}\right| / \left|\Delta\eta_{jj}\right| < 0.3$
  - $\min(\min(\eta_W, \eta_V) - \min(\eta_{j1}, \eta_{j2}), \max(\eta_{j1}, \eta_{j2}) - \max(\eta_W, \eta_V)) > 1$

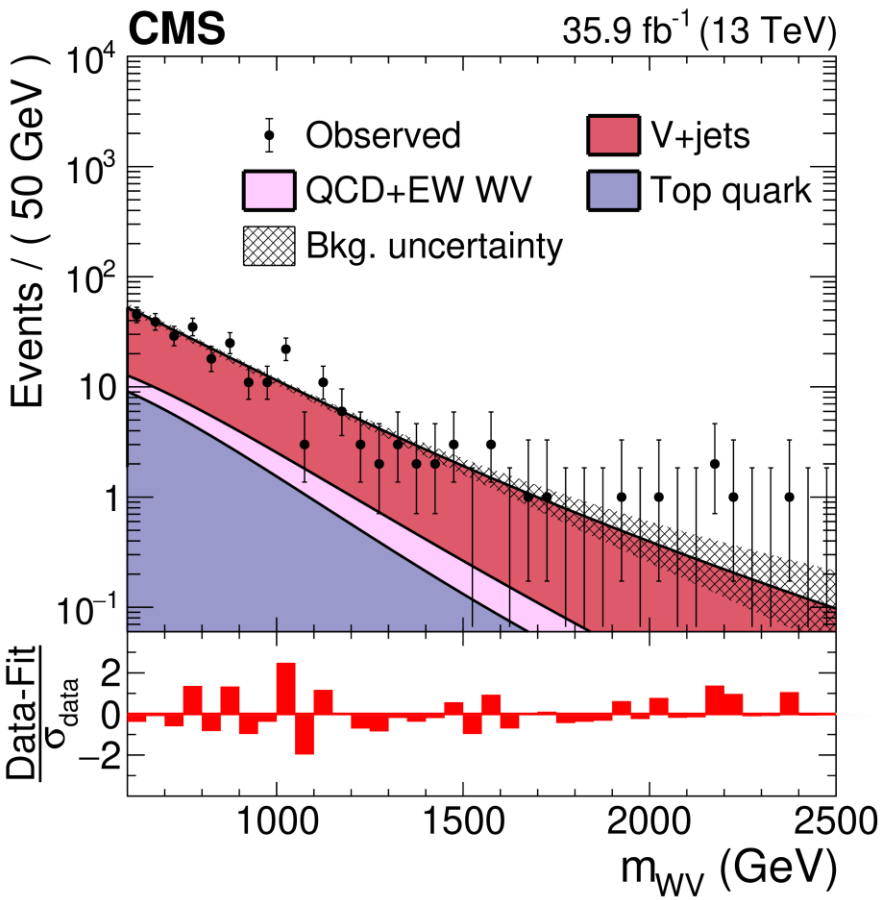
CMS: Measurement of EWK VV production, semileptonic (III)

- Limits set based on the m_{VZ} and m_{VW} distributions
- Limits are set on operator coefficient/(unknown mass scale)^4 and are quoted in units of TeV^{-4}
- No form-factor is used
- These are the world's best limits for all 9 operators

	Obs Low	Obs High	Exp Low	Exp High
$F_{S,0}$	−2.7	2.7	-4.2	4.2
$F_{S,1}$	-3.4	3.4	-5.2	5.2
$F_{M,0}$	−0.69	0.70	-1.0	1.0
$F_{M,1}$	-2.0	-2.1	-3.0	3.0
$F_{M,6}$	-1.3	1.3	-1.4	1.4
$F_{M,7}$	-3.4	3.4	-5.1	5.1
$F_{T,0}$	-0.12	0.11	-0.17	0.16
$F_{T,1}$	-0.12	0.13	-0.18	0.18
$F_{T,2}$	-0.28	0.28	-0.41	0.41

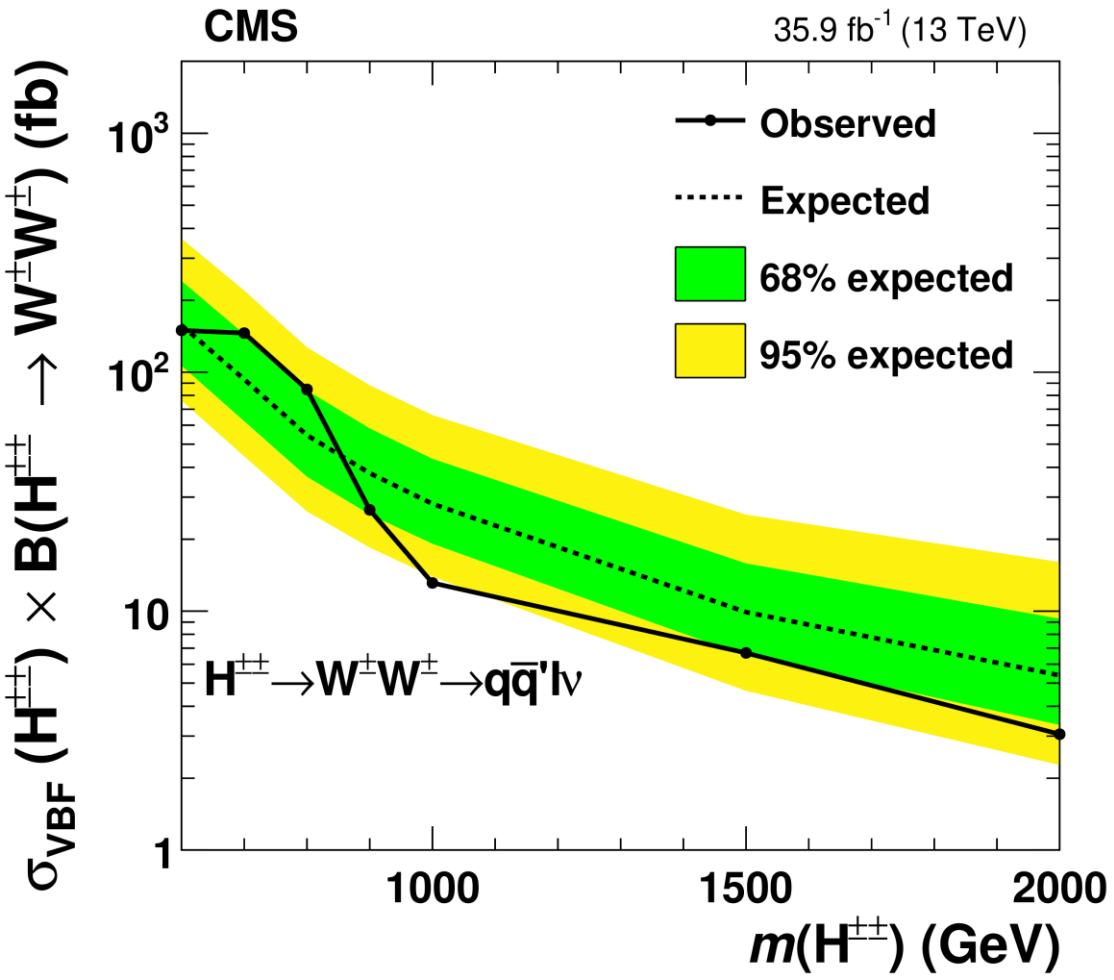
CMS: Measurement of EWK VV production, semileptonic (IV)

- Estimate the background due to W+jets and Z+jets using the m_V sidebands 40 < mass < 65 GeV and 105 < mass < 150 GeV
- Exponential-like function exp $[-m/(c_0 + c_1 m)]$ used to model W+jets and Z+jets
- Extrapolate to 65 < mass < 105 GeV using W+jets and Z+jets simulation



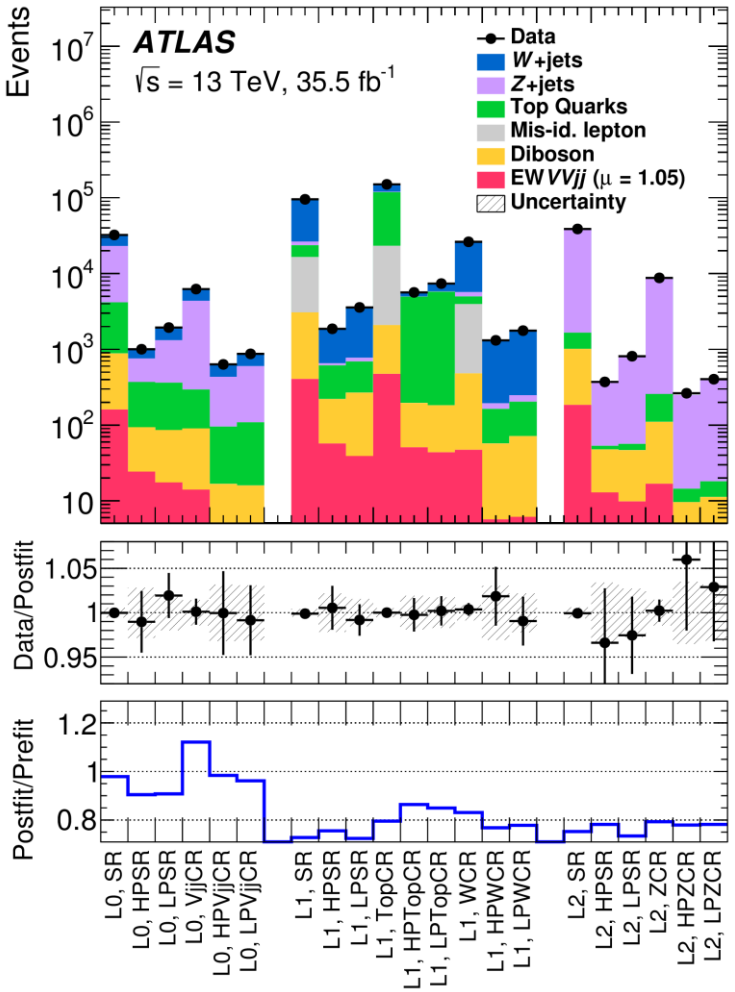
CMS: Measurement of EWK VV production, semileptonic (V)

- The Georgi–Machacek model is an extension of the SM that includes singly-charged and doubly-charged Higgs bosons
- The VBF production mechanism and decay to VV pairs results in the same final state as this analysis
- Cross section times branching ratio limits were set as a function of mass for both $H^{\pm}$ and $H^{\pm\pm}$



ATLAS: Measurement of EWK VV production, semileptonic (I)

- Based on 35.5 fb^{-1} collected at 13 TeV
- Observed signal significance: 2.7 σ
- Expected signal significance: 2.5 σ
- Select one hadronically decaying V boson and a second V boson that decays to νν, lν, or ll
- One signal region for resolved V bosons and two signal regions for merged V bosons
- For the merged case, high purity and low purity signal regions defined by different cuts of the jet substructure discriminant $D_2^{(\beta=1)}$
- 9 signal regions plus 12 control regions are fit simultaneously to extract the signal strength



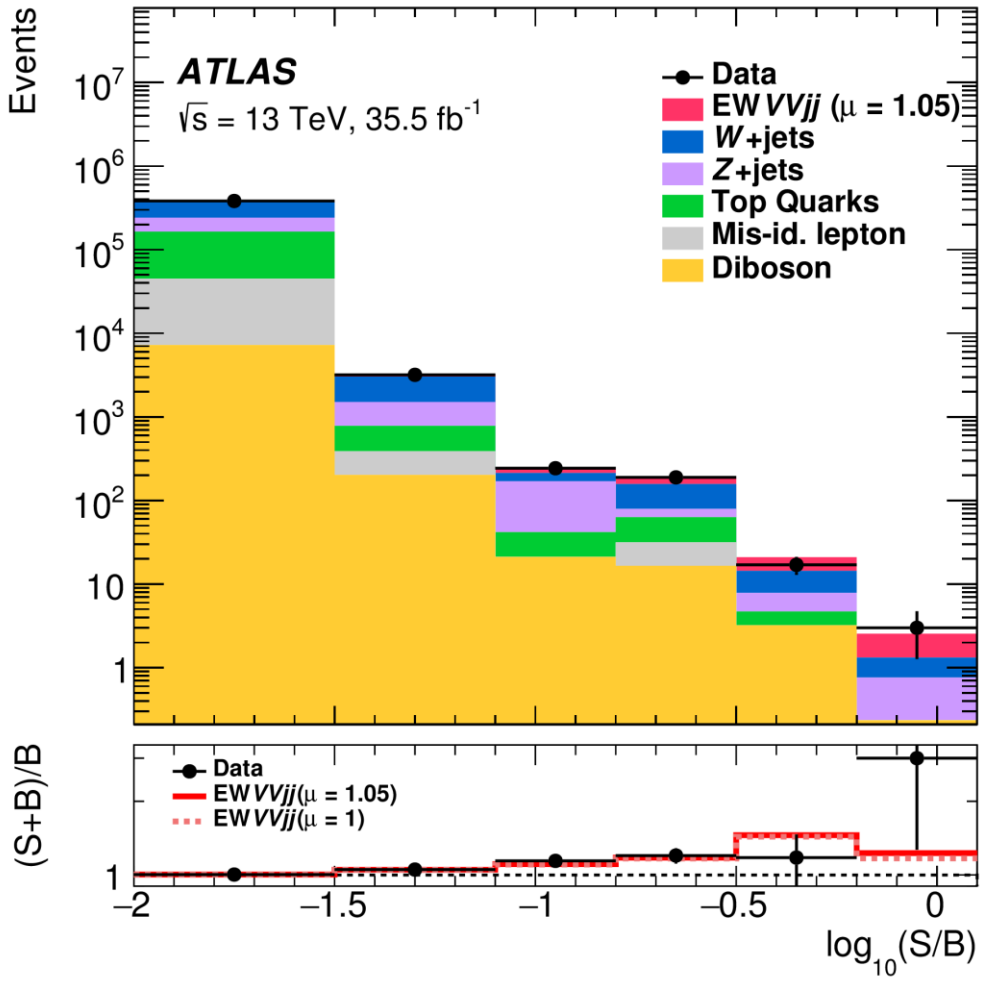
ATLAS: Measurement of EWK VV production, semileptonic (II)

- Signal region selection on the right
- Control regions are defined by:
  - Inverting the m_J cut in merged case and the m_{jj} cut in the resolved case (ZCRs, WCRs, and VjjCRs)
  - Inverting the b-tagging requirement for the 1-lepton signal region (TopCR)
- The m_{jj}^{tag} distribution of the W+jets and Z+jets simulated samples is reweighted based on the data in the WCRs and the ZCRs

Selection	0-lepton	1-lepton	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$ triggers	Single-electron triggers Single-muon or $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers	Single-lepton triggers
Leptons	0 'loose' leptons with $p_{\mathrm{T}} > 7$ GeV	1 'tight' lepton with $p_{\mathrm{T}} > 27$ GeV 0 'loose' leptons with $p_{\mathrm{T}} > 7$ GeV	2 'loose' leptons with $p_{\mathrm{T}} > 20$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 28$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 200 GeV	> 80 GeV	–
$m_{\ell\ell}$	–	–	$83 < m_{ee} < 99$ GeV $-0.0117 \times p_{\mathrm{T}}^{\mu\mu} + 85.63 < m_{\mu\mu} < 0.0185 \times p_{\mathrm{T}}^{\mu\mu} + 94$ GeV
Small-R jets	$p_{\mathrm{T}} > 20$ GeV if $\lvert\eta\rvert < 2.5$, and $p_{\mathrm{T}} > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$		
Large-R jets	$p_{\mathrm{T}} > 200$ GeV, $\lvert\eta\rvert < 2$		
$V_{\mathrm{had}} \to J$ $V_{\mathrm{had}} \to jj$	V boson tagging, $\min(\lvert m_J - m_W\rvert, \lvert m_J - m_Z\rvert)$ $64 < m_{jj} < 106$ GeV, jj pair with $\min(\lvert m_{jj} - m_W\rvert, \lvert m_{jj} - m_Z\rvert)$, leading jet with $p_{\mathrm{T}} > 40$ GeV		
Tagging-jets	$j \notin V_{\mathrm{had}}$, not b-tagged, $\Delta R(J, j) > 1.4$ $\eta_{\mathrm{tag},j_1} \cdot \eta_{\mathrm{tag},j_2} < 0$, $m_{jj}^{\mathrm{tag}} > 400$ GeV, $p_{\mathrm{T}} > 30$ GeV		
Num. of b-jets	–	0	–
Multijet removal	$p_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$ $\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{small-}R \text{ jet})] > \pi/6$ $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, V_{\mathrm{had}}) > \pi/9$	–	–

ATLAS: Measurement of EWK VV production, semileptonic (III)

- BDT is trained with simulated samples to distinguish signal versus sum of all backgrounds
- 6 BDTs are trained due to choice of merged vs. resolved and choice of 0, 1, or 2 leptons
- The BDT distributions are fit in the 9 signal regions and the m_{jj}^{tag} distributions are fit in the control regions, except the TopCR which has just 1 bin



ATLAS: Measurement of EWK VV production, semileptonic (IV)

Input variables used in the resolved BDTs

Variable	0-lepton	1-lepton	2-lepton
m_{jj}^{tag}	✓	–	✓
$\Delta\eta_{jj}^{\text{tag}}$	–	–	✓
$p_{\text{T}}^{\text{tag},j_1}$	✓	✓	–
$p_{\text{T}}^{\text{tag},j_2}$	✓	✓	✓
$\Delta\eta_{jj}$	✓	✓	✓
$p_{\text{T}}^{j_1}$	✓	–	–
$p_{\text{T}}^{j_2}$	✓	✓	✓
w^{j_1}	✓	✓	✓
w^{j_2}	✓	✓	✓
$n_{\text{tracks}}^{j_1}$	–	✓	✓
$n_{\text{tracks}}^{j_2}$	–	✓	✓
w^{tag,j_1}	✓	✓	✓
w^{tag,j_2}	✓	✓	✓
$n_{\text{tracks}}^{\text{tag},j_1}$	–	✓	✓
$n_{\text{tracks}}^{\text{tag},j_2}$	–	✓	✓
$n_{j,\text{track}}$	✓	–	✓
$n_{j,\text{extr}}$	✓	–	–
$E_{\text{T}}^{\text{miss}}$	✓	–	–
η_ℓ	–	✓	–
$\Delta R(\ell,\nu)$	–	✓	–
ζ_V	–	✓	✓
m_{VV}	–	–	✓
m_{VVjj}	–	✓	–

Input variables used in the merged BDTs

Variable	0-lepton	1-lepton	2-lepton
m_{jj}^{tag}	✓	–	✓
$\Delta\eta_{jj}^{\text{tag}}$	–	–	✓
$p_{\text{T}}^{\text{tag},j_2}$	✓	✓	✓
m_J	✓	–	–
$D_2^{(\beta=1)}$	✓	–	✓
$E_{\text{T}}^{\text{miss}}$	✓	–	–
$\Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, J)$	✓	–	–
η_ℓ	–	✓	–
$n_{j,\text{track}}$	✓	–	–
ζ_V	–	✓	✓
m_{VV}	–	–	✓
p_{T}^{VV}	–	–	✓
m_{VVjj}	–	✓	–
p_{T}^{VVjj}	–	–	✓
w^{tag,j_1}	✓	–	–
w^{tag,j_2}	✓	–	–

ATLAS: Measurement of EWK VV production, semileptonic (V)

- Fiducial cross section measurement:
  $\sigma = 45.1 \pm 8.6(\text{stat.})^{+15.9}_{-14.6}(\text{syst.})$ fb
- Theoretically predicted fiducial cross section based on MadGraph5_aMC@NLO LO-QCD sample:
  σ = 43.0 ± 2.4 fb
- Fiducial cross section reported in each of the 6 channels
- Performed simultaneous fit in all 6 channels with one signal strength per lepton multiplicity

Fiducial phase space		Predicted $\sigma^{\text{fid,SM}}_{\text{EW}\,VVjj}$ [fb]	Measured $\sigma^{\text{fid,obs}}_{\text{EW}\,VVjj}$ [fb]
Merged	0-lepton	$4.1 \pm 0.3\,(\text{theo.})$	$10.1 \pm 3.3\,(\text{stat.})\ ^{+4.2}_{-3.8}\,(\text{syst.})$
	1-lepton	$6.1 \pm 0.5\,(\text{theo.})$	$2.0 \pm 1.5\,(\text{stat.})\ ^{+2.9}_{-2.8}\,(\text{syst.})$
	2-lepton	$1.2 \pm 0.1\,(\text{theo.})$	$2.4 \pm 0.6\,(\text{stat.})\ ^{+0.8}_{-0.7}\,(\text{syst.})$
Resolved	0-lepton	$9.2 \pm 0.6\,(\text{theo.})$	$22.8 \pm 7.4\,(\text{stat.})\ ^{+9.4}_{-8.5}\,(\text{syst.})$
	1-lepton	$16.4 \pm 1.0\,(\text{theo.})$	$5.5 \pm 4.1\,(\text{stat.})\ ^{+7.7}_{-7.5}\,(\text{syst.})$
	2-lepton	$6.0 \pm 0.4\,(\text{theo.})$	$11.8 \pm 3.0\,(\text{stat.})\ ^{+3.8}_{-3.5}\,(\text{syst.})$
Inclusive	0-lepton	$13.3 \pm 0.8\,(\text{theo.})$	$32.9 \pm 10.7\,(\text{stat.})\ ^{+13.5}_{-12.3}\,(\text{syst.})$
	1-lepton	$22.5 \pm 1.5\,(\text{theo.})$	$7.5 \pm 5.6\,(\text{stat.})\ ^{+10.5}_{-10.2}\,(\text{syst.})$
	2-lepton	$7.2 \pm 0.4\,(\text{theo.})$	$14.2 \pm 3.6\,(\text{stat.})\ ^{+4.6}_{-4.2}\,(\text{syst.})$

Summary

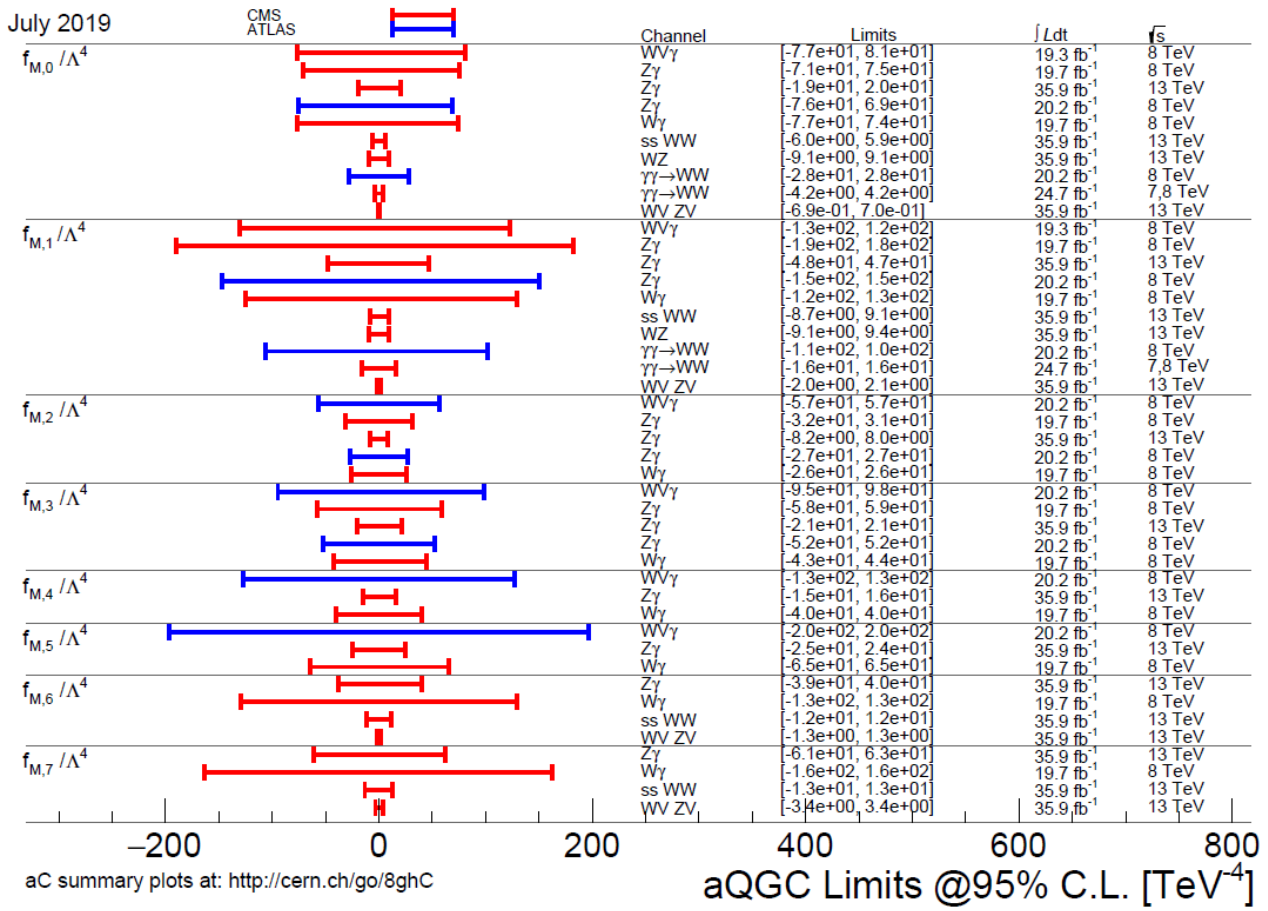
- A variety of AQGC and EWK VVjj results have been released by ATLAS and CMS
- EWK signal significances, 1D dimension 8 EFT limits, fiducial cross sections, differential cross sections, and Georgi–Machacek model limits are the most common
- Many analyses used simultaneous fits in the signal region and one or more control regions to boost the significance
- Jet substructure techniques applied successfully in semileptonic channels
- ATLAS and CMS analyses methods are very similar, other than use of BDTs and reporting of AQGC limits
- Run 2 data still being analyzed

Backup

Electroweak-induced VVjj production significances, fully leptonic results, including Vγ channels

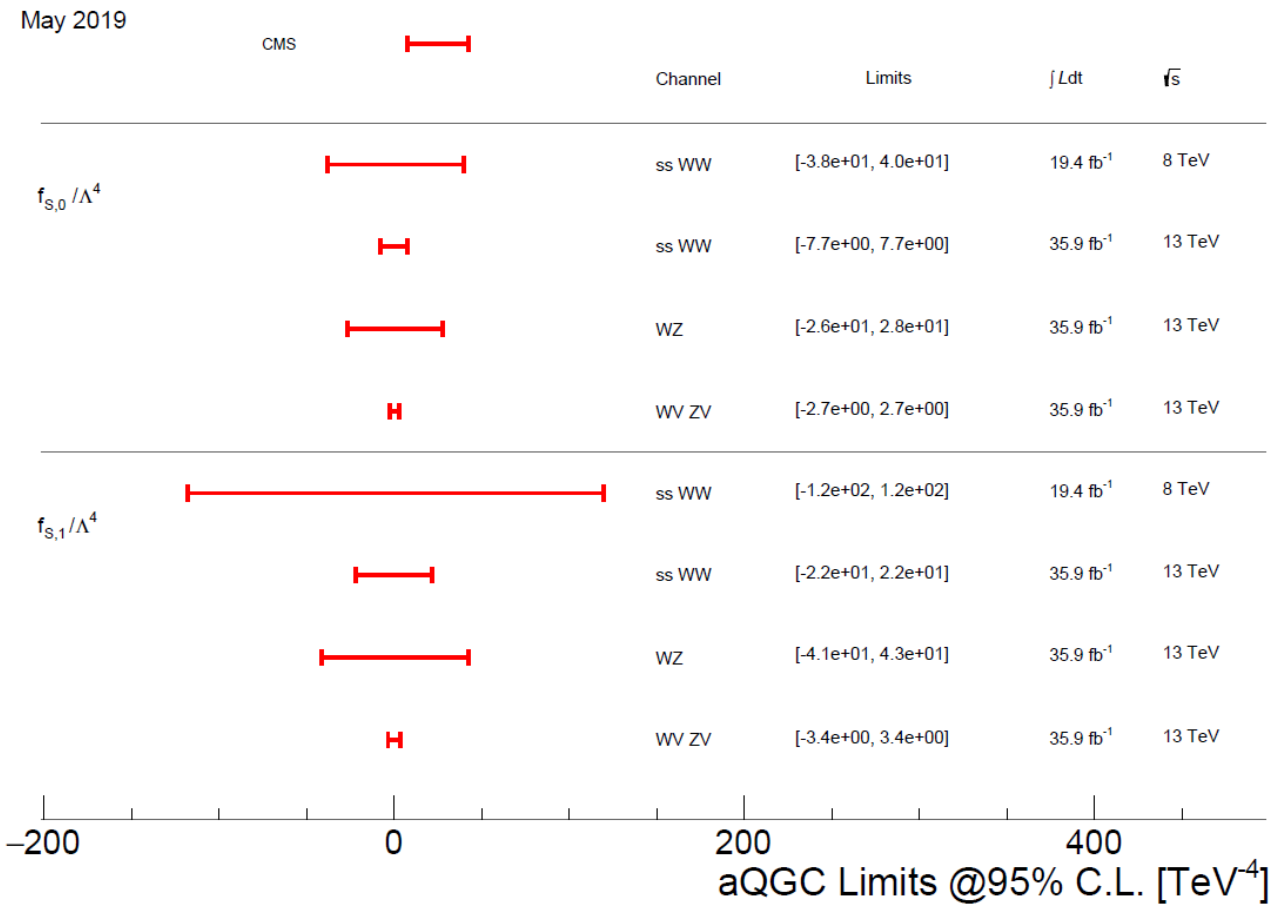
Experiment	CoM Energy	$W^{\pm}W^{\mp}jj$	$W^{\pm}W^{\pm}jj$	$W^{\pm}Zjj$	$ZZjj$	$W\gamma jj$	$Z\gamma jj$
CMS	8 TeV		2.0 σ			2.7 σ	
ATLAS	8 TeV		4.5 σ				
CMS	13 TeV		5.5 σ	2.2 σ	2.7 σ		2.7 σ
ATLAS	13 TeV		6.5 σ	5.3 σ	5.5 σ		5.5 σ

Limits on dimension 8 EFT operators (FM)



Credit: Matthew Herndon

Limits on dimension 8 EFT operators (FS)



Credit: Matthew Herndon