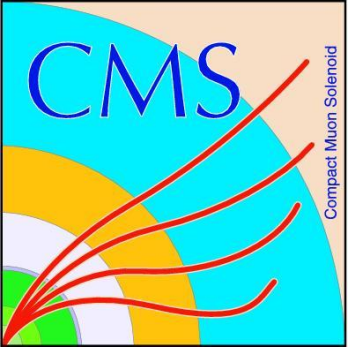


Overview of SMEW at the LHC

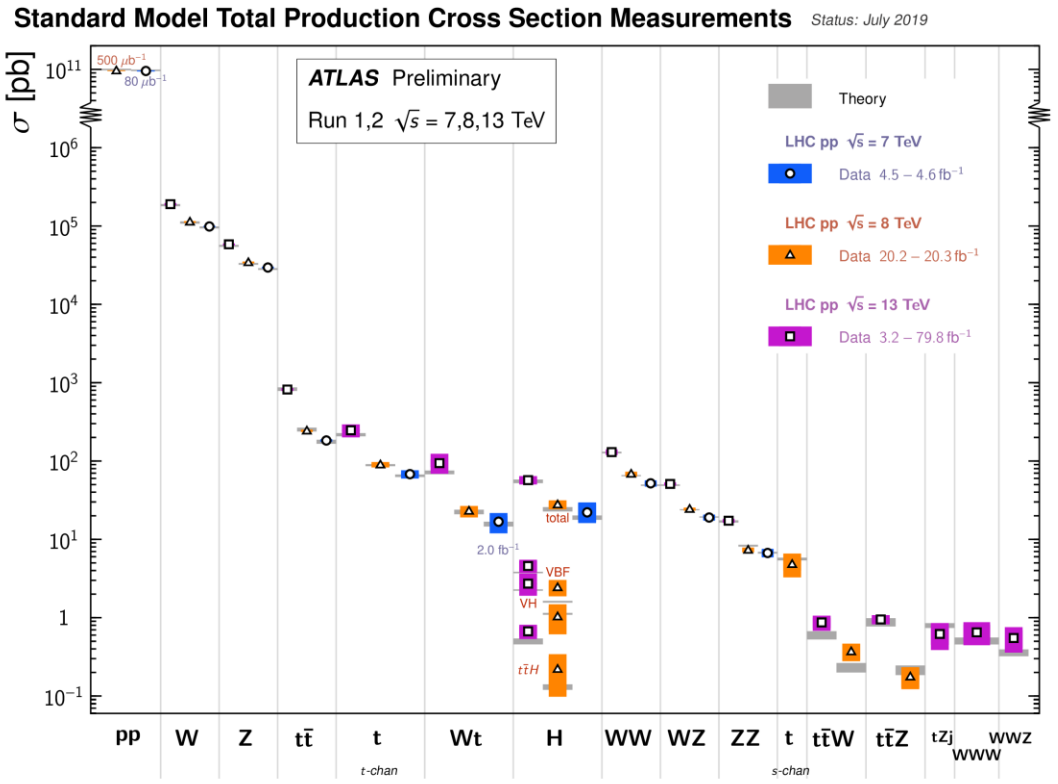
Andrew Levin (Peking University)

26 October 2019

CLHCP 2019

Introduction

- Main categories of SMEW measurements
  - Boson+jets
  - Diboson+jets
  - Triboson+jets
  - Jets
- Boson = γ, W, Z
- Important tests of EW theory, perturbative QCD, and non-perturbative QCD
- This talk contains
  - Long list of recent CMS and ATLAS results
  - Details about some selected analyses
  - Introduction to anomalous coupling frameworks and anomalous coupling limit summary



Recent CMS and ATLAS single boson results

- CMS, published in PRL: Search for W → πππ
- ATLAS, submitted to JHEP: Inclusive isolated-photon cross section
- ATLAS, submitted to PLB: High p_T Z(→ bb) + photon production
- ATLAS, accepted by EPJC: W and Z cross sections at 2.76 TeV
- ATLAS, published in JHEP: ZZ production, semileptonic
- ATLAS, accepted by EPJC: W cross section and W^+/W^+ asymmetry at 8 TeV
- ATLAS, published in JHEP: Photon 8/13 TeV cross section ratio
- ATLAS, accepted by EPJC: Z+jets cross section
- CMS, preliminary result: Z + c/b cross section ratios
- CMS, preliminary result: W + c

Recent CMS and ATLAS diboson results

- ATLAS, preliminary result: Zγ cross section
- CMS, preliminary result: WW production from double-parton interactions
- 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: EWK VVjj production, semileptonic
- ATLAS, submitted to PRD: EWK VVjj production, semileptonic
- CMS, preliminary result: EWK Zγjj production
- ATLAS, submitted to PLB: EWK Zγjj production
- CMS, preliminary result: ZZ cross section
- CMS, published in JHEP: WZ cross section
- ATLAS, published in EPJC: WZ cross section and gauge boson polarization

Recent CMS and ATLAS triple boson results

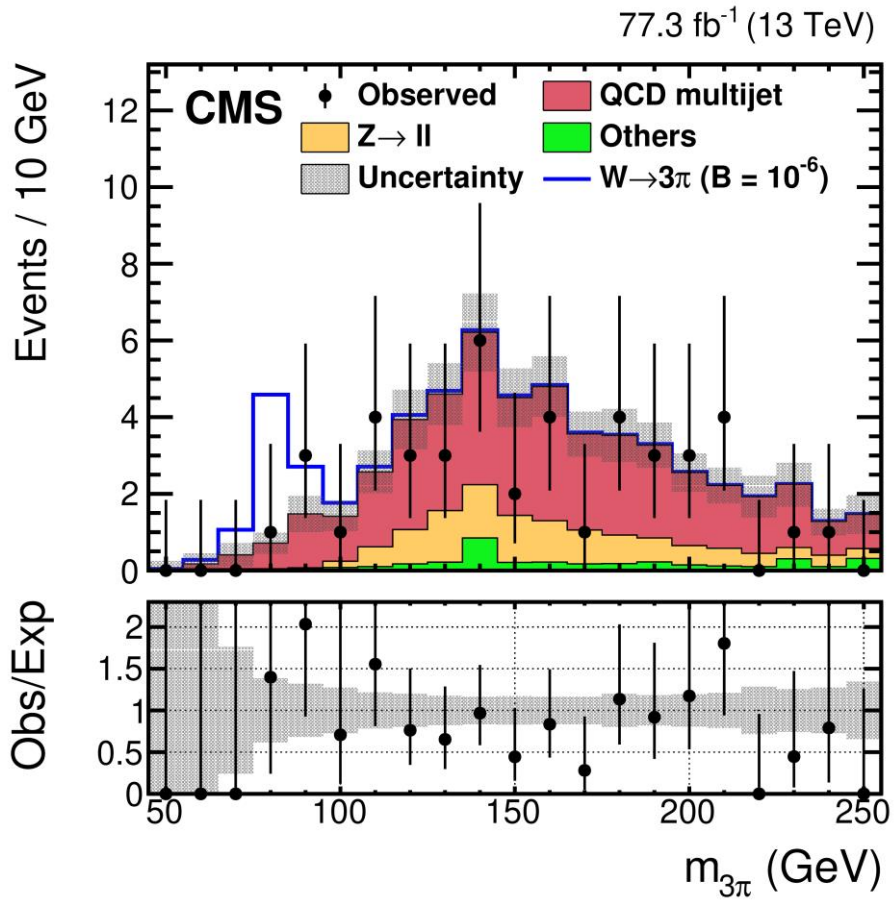
- ATLAS, accepted by PLB: Evidence for the production of three massive vector bosons
- CMS, published in PRD: Search for WWW

Recent CMS and ATLAS jet results

- CMS, preliminary result: Measurement of the dependence of inclusive jet production cross sections on the anti-k_T parameter
- ATLAS, published in PRD: Properties of jet fragmentation using charged particles
- ATLAS, published in JHEP: Measurement of jet shapes at 13 TeV

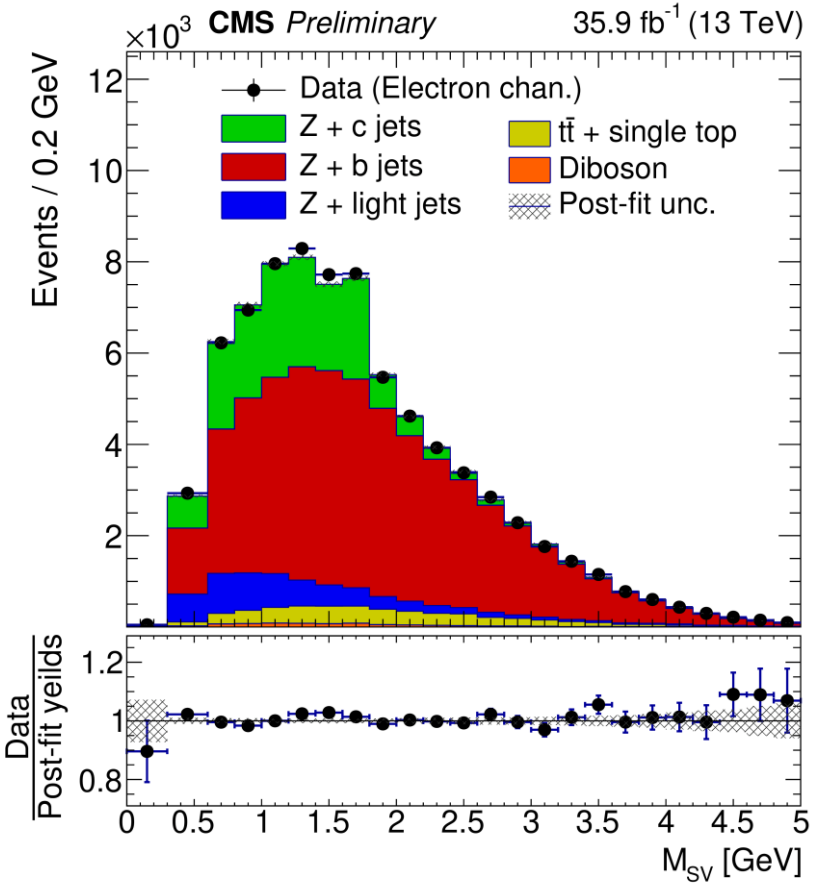
CMS: Search for W → πππ

- Based on 77.3 fb^{-1} collected at 13 TeV
- A fully reconstructed final state would be useful to measure the W boson mass
- Can occur in the SM through: $W^+ \to u\bar{d}, u \to ug, \bar{d} \to \bar{d}g\ , g \to d\bar{d}, g \to u\bar{u}$
- Upper limit on branching ratio set at 1.01×10^{-6}
- Reuses the τ HLT reconstruction of πs
  - Two π candidates with $p_T > 35$ GeV selected in the HLT
  - Third π candidate selected offline with $p_T > 18$ GeV



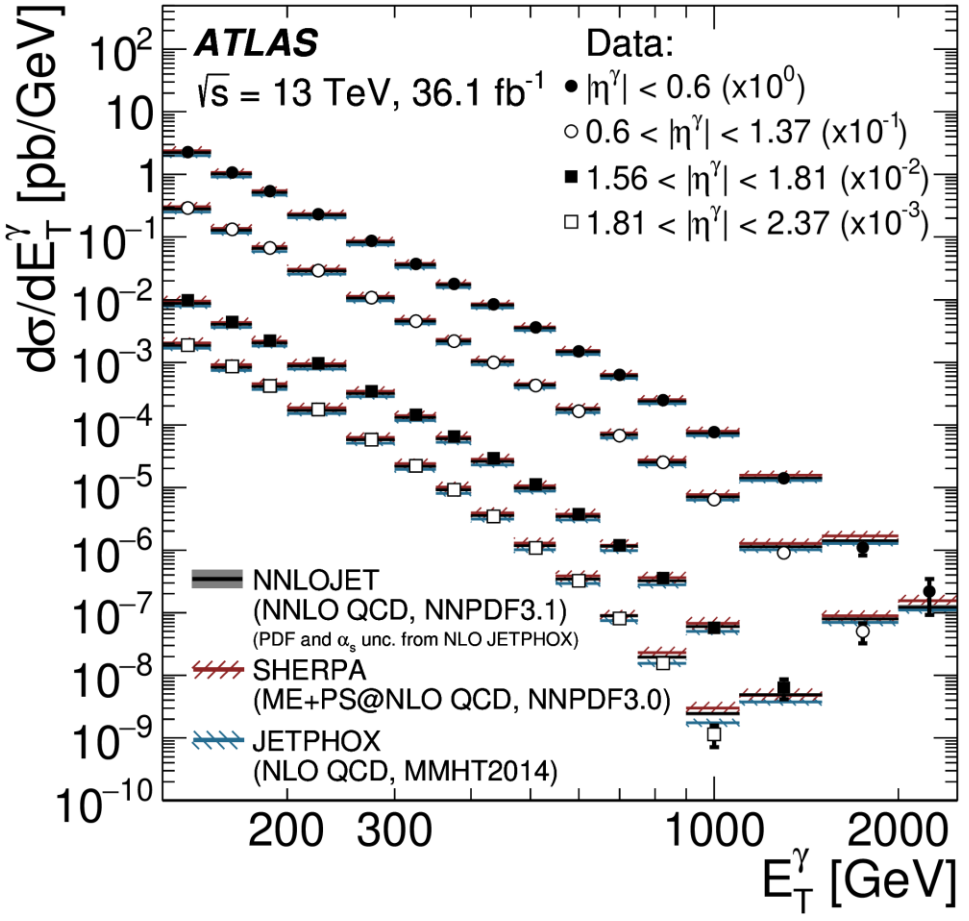
CMS: Z+b/c cross section ratios

- Based on 36 fb^{-1} collected at 13 TeV
- First select the Z boson, then select HF-tag jets
- Perform fits to M_{SV}, the mass associated with the secondary vertex, to extract cross section ratios
- Main results are:
  - $\sigma(Z + c\ jets)/\sigma(Z + jets) = 0.102 \pm 0.002 \pm 0.009$
  - $\sigma(Z + b\ jets)/\sigma(Z + jets) = 0.0633 \pm 0.0004 \pm 0.0015$
  - $\sigma(Z + c\ jets)/\sigma(Z + b\ jets) = 1.62 \pm 0.03 \pm 0.15$
- Consistent with predictions obtained with both the 4-flavor scheme and 5-flavor scheme



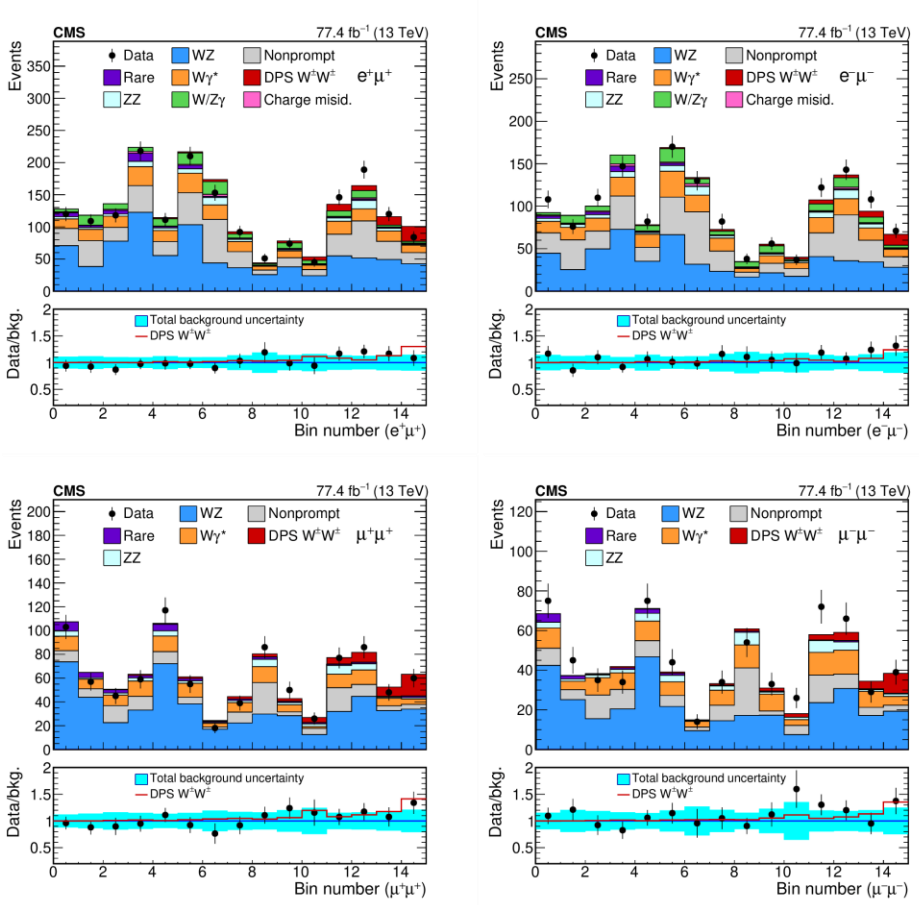
ATLAS: Isolated-photon cross section

- Based on 36.1 fb^{-1} collected at 13 TeV
- Photon isolation based on the amount of energy within $\Delta R = 0.4$ of the photon, excluding a region with $\Delta\eta = 0.125$ and $\Delta\phi = 0.125$ centered on the barycenter of the photon cluster
- Two sources of prompt photons: direct and fragmentation
- JETPHOX generates both direct and fragmentation photons, while SHERPA and NNLOJET generate direct photons and rely on the parton shower to generate fragmentation photons
- Double differential cross section in photon η and photon E_T shown on the right
- NNLOJET prediction agrees well with the data, NLO prediction agreement depends on PDF set → can be used to constrain PDF



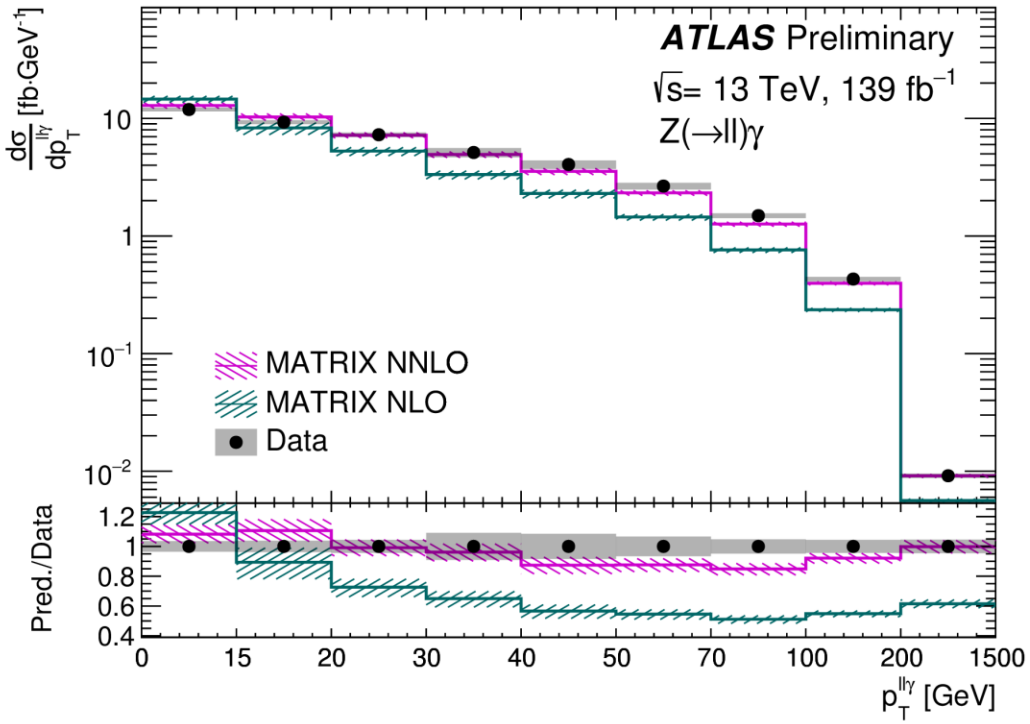
CMS: WW production from double-parton interaction

- Based on 77.4 fb^{-1} collected at 13 TeV
- Observed significance: 3.9 σ
- $\sigma_{AB}^{DPS} = \frac{n}{2}\frac{\sigma_A \sigma_B}{\sigma_{eff}}$
  - n = 2 if A = B and 1 otherwise
  - σ_{eff} is an effective cross section common to DPS processes, measured to be between 15 to 26 mb
- Pythia used to model the signal shape
- Train one BDT to discriminate between signal and WZ background, and second BDT to discriminate between signal and nonprompt background
- Combine contiguous regions in the BDT1-BDT2 plane to create 15 bins, where the signal extraction is done
- Assuming the NNLO-QCD and NLO-EWK W+jets cross section, can also measure the effective DPS cross: $\sigma_{eff} = 12.7^{+5.0}_{-2.9}$mb



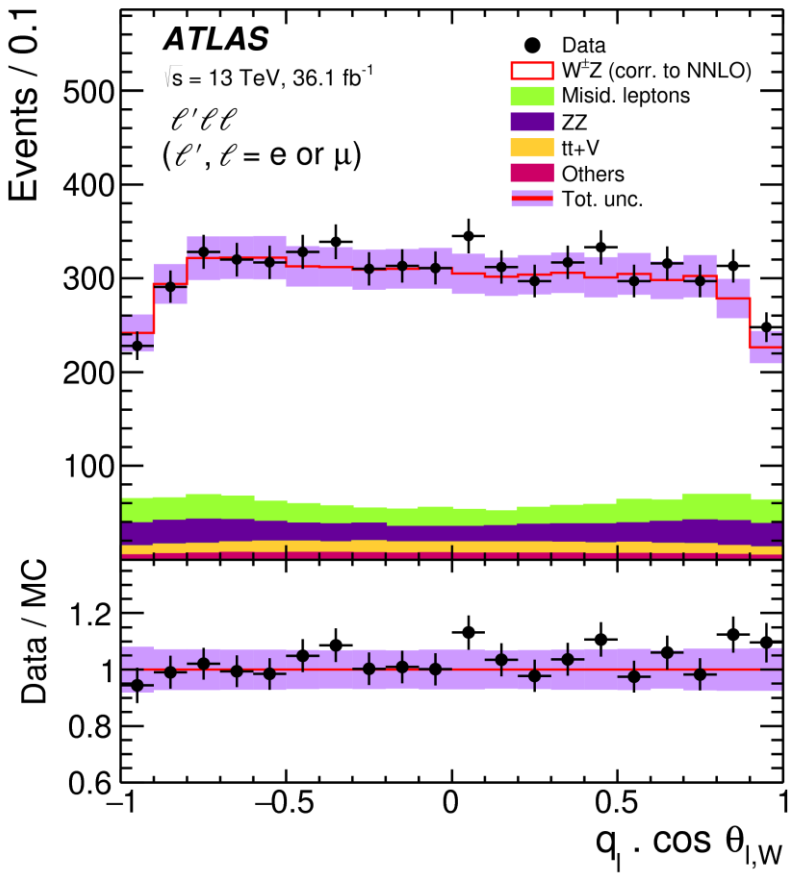
ATLAS: Zγ cross-section

- Based on 139 fb^{-1} collected at 13 TeV
- Use single lepton (electron and muon) triggers
- Background due to pileup photons estimated using a data-driven method by extrapolating the photon direction back to the beam axis, such that the shape of the Δz for pileup events can be determined and compared with the shape of Δz for non-pileup photons
- Prediction from Sherpa at LO underestimates the overall rate by 20-30% and also mis-models the shape of $p_T^{ll\gamma}$
- Prediction from MadGraph5_aMC@NLO with 1 jet at NLO and 2-3 jets at LO models the $p_T^{ll\gamma}$ shape well and slightly underestimates the normalization
- MATRIX generator models both the $p_T^{ll\gamma}$ shape and normalization well when run at NNLO



ATLAS: $W^{\pm}Z$ production cross section and gauge boson polarization

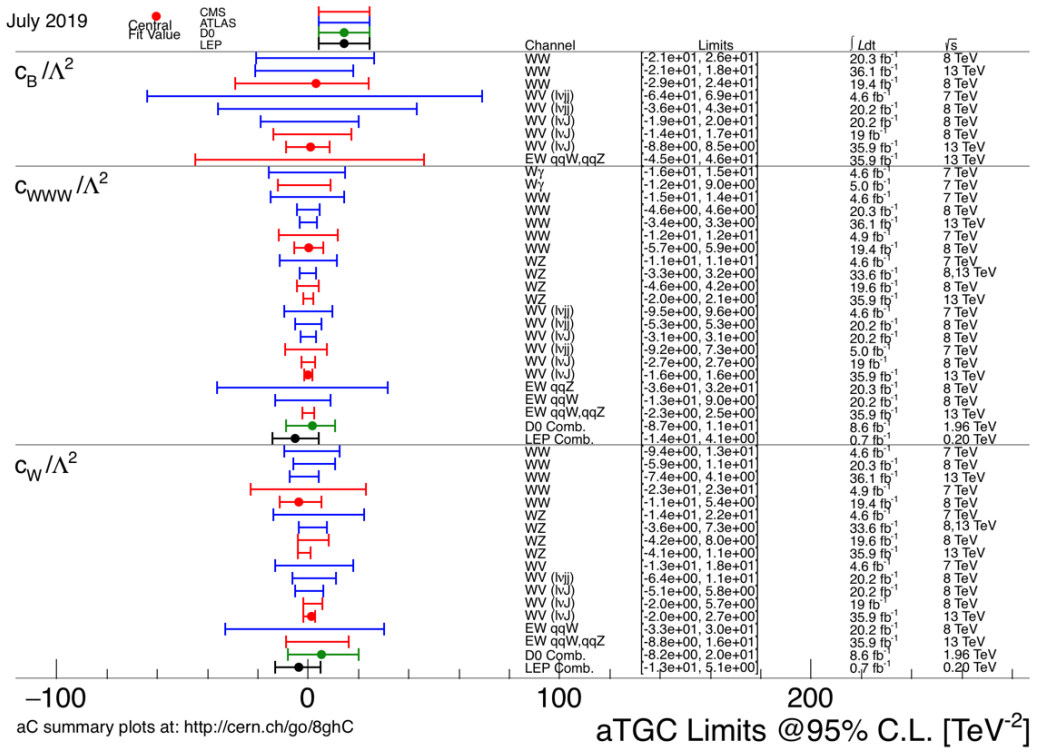
- Based on 36.1 fb^{-1} collected at 13 TeV
- First time the helicity of the W or the Z boson is measured in pair-produced events
- f_0, f_R, and f_L are longitudinal, transverse right-handed and transverse left-handed diagonal elements in the spin density matrix
- Analytic formula for differential cross section in $\cos\theta_{l,W}$, decay angle of the charged lepton in the W rest frame relative to the WZ frame: $\frac{3}{8}f_L\left[\left(1\mp\cos\theta_{l,W}\right)^2\right]+\frac{3}{8}f_R\left[\left(1\pm\cos\theta_{l,W}\right)^2\right]+\frac{3}{8}f_0\sin^2\theta_{l,W}$
- Perform independent fits to $q_l\cos\theta_{l,W}$ and $\sin\theta_{l,W}$
- Measured longitudinal polarization fractions: W $f_0 = 0.26 \pm 0.06$, Z $f_0 = 0.24 \pm 0.04$

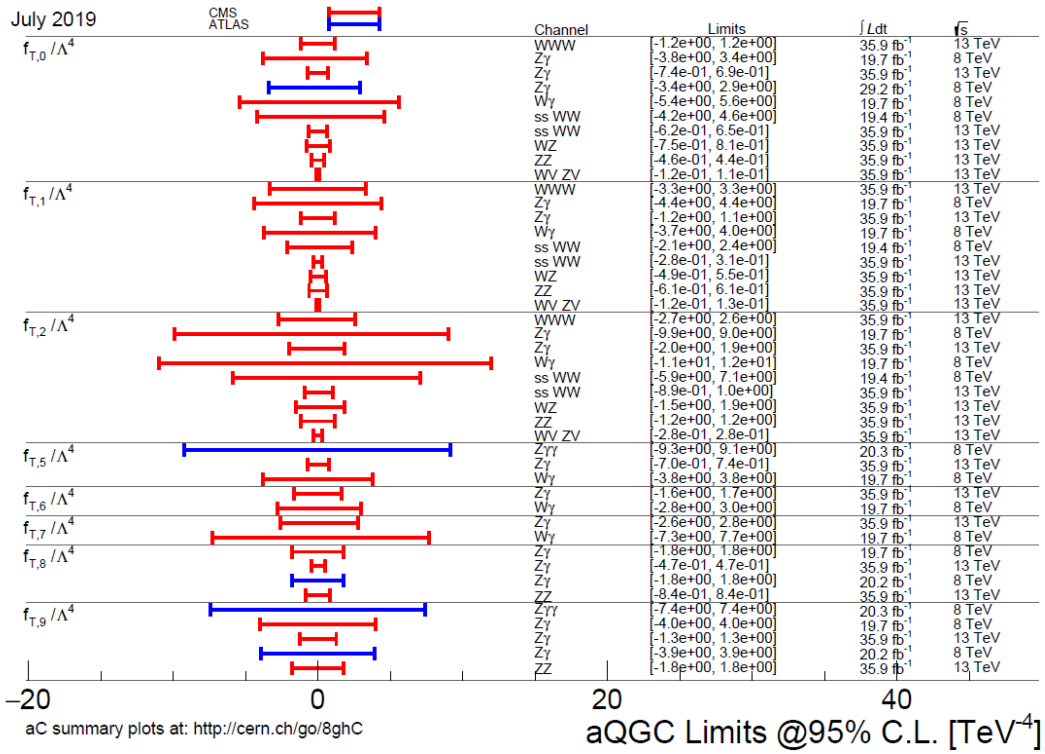


Anomalous coupling and effective field theory

- $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{F_i}{\Lambda^4}\mathcal{O}_i$ or $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{F_i}{\Lambda^2}\mathcal{O}_i$ where Λ is the unknown mass scale of new physics
- EWDim6 is a dimension 6 framework that contains the 5 operators that modify triple gauge couplings (also available at NLO)
- SMEFT is a more complete dimension 6 framework that includes 59 operators that is likely to be used much more in Run 3 by Higgs, SM, and top analyses
- Dimension 8 EFT
  - 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: $L_{T8} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$

Anomalous coupling limits



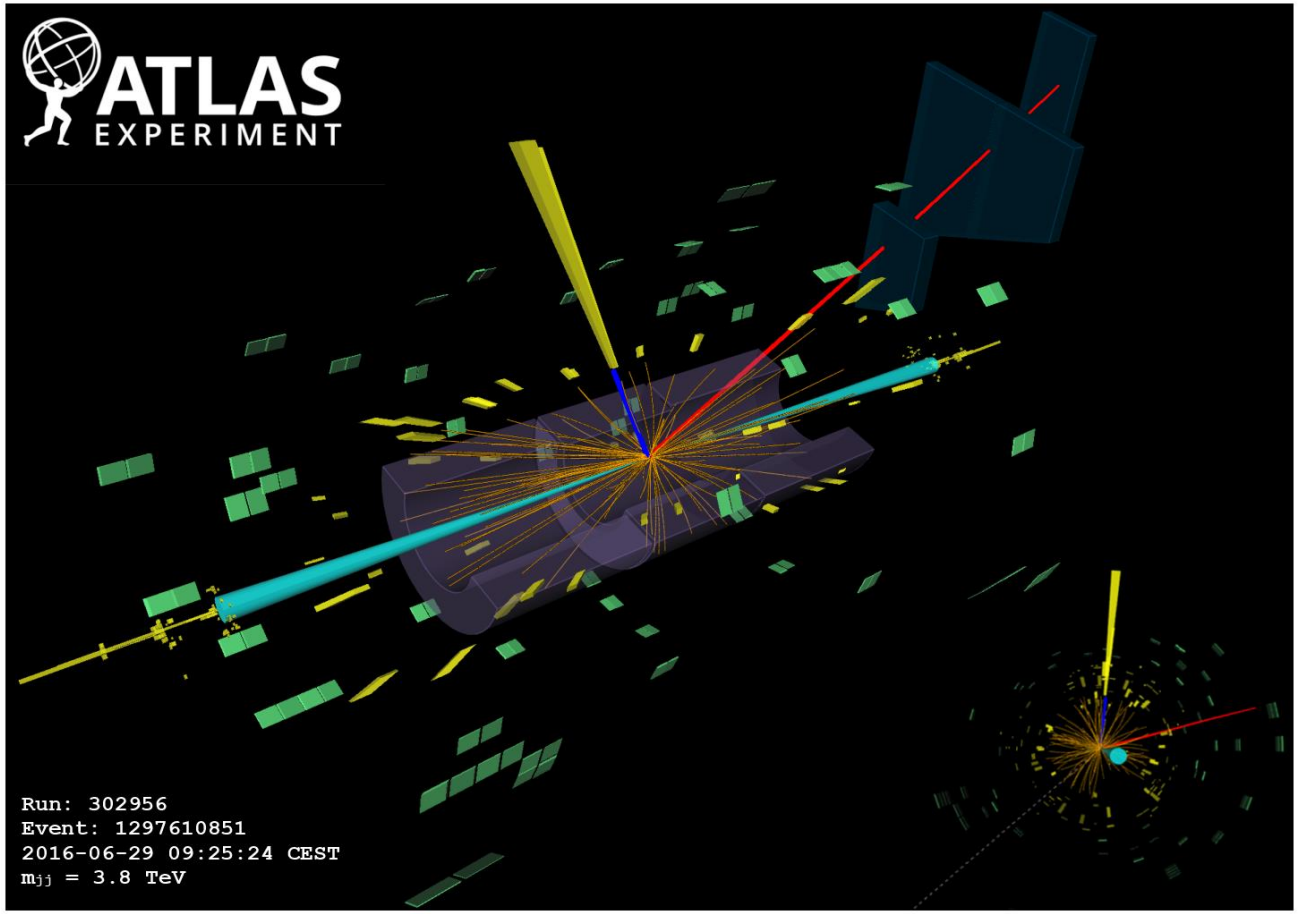


Electroweak-induced VVjj production significances, fully leptonic results

Experiment	CoM Energy	$W^{\pm}W^{\mp}jj$	$W^{\pm}W^{\pm}jj$	$W^{\pm}Zjj$	$ZZjj$	$W^{\pm}\gamma jj$	$Z\gamma jj$
CMS	8 TeV		2.0 σ			2.7 σ	3.0 σ
ATLAS	8 TeV		4.5 σ				
CMS	13 TeV		5.5 σ	2.2 σ	2.7 σ		3.9 σ
ATLAS	13 TeV		6.5 σ	5.3 σ	5.5 σ		4.1 σ

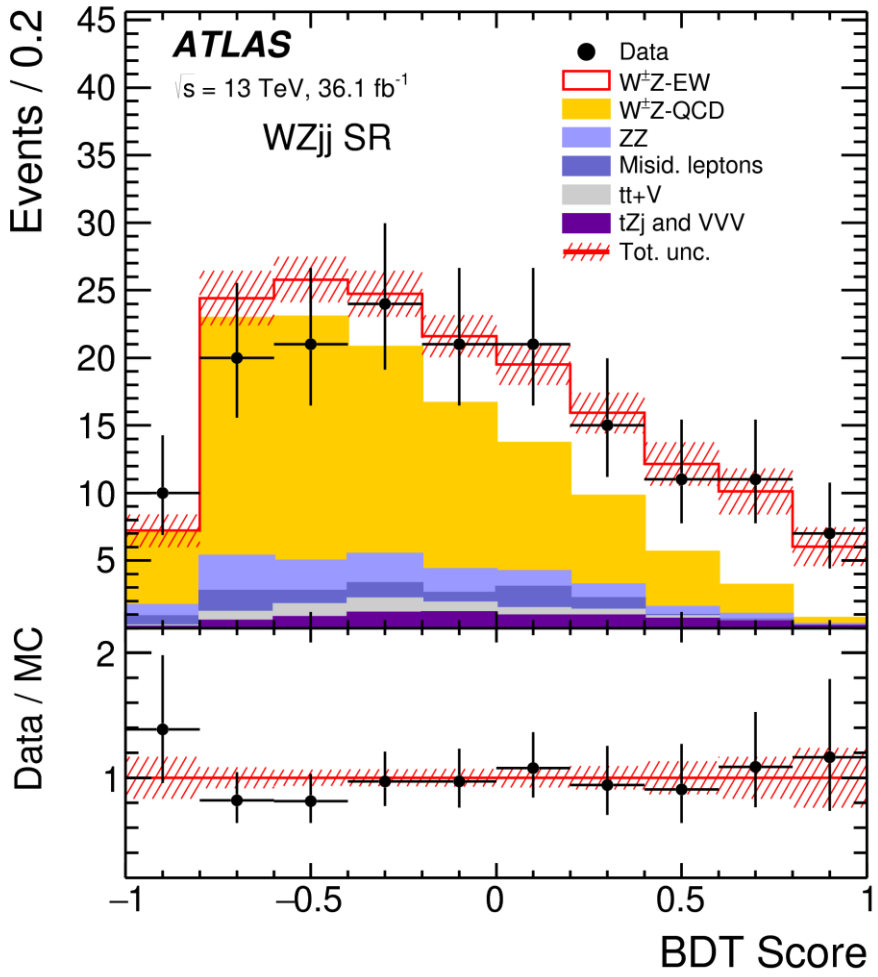
ATLAS: Observation of EWK $W^{\pm}W^{\pm}$ production

- 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
- Non-prompt lepton background estimated using data-driven lepton selection ratio method
- Significance is extracted by performing a simultaneous fit in the signal region and two control regions
  - Signal region: $m_{jj} > 500$ GeV, $|\Delta y_{jj}| > 2$, 4 mjj bins
  - Low m_{jj} control region
  - WZ control region



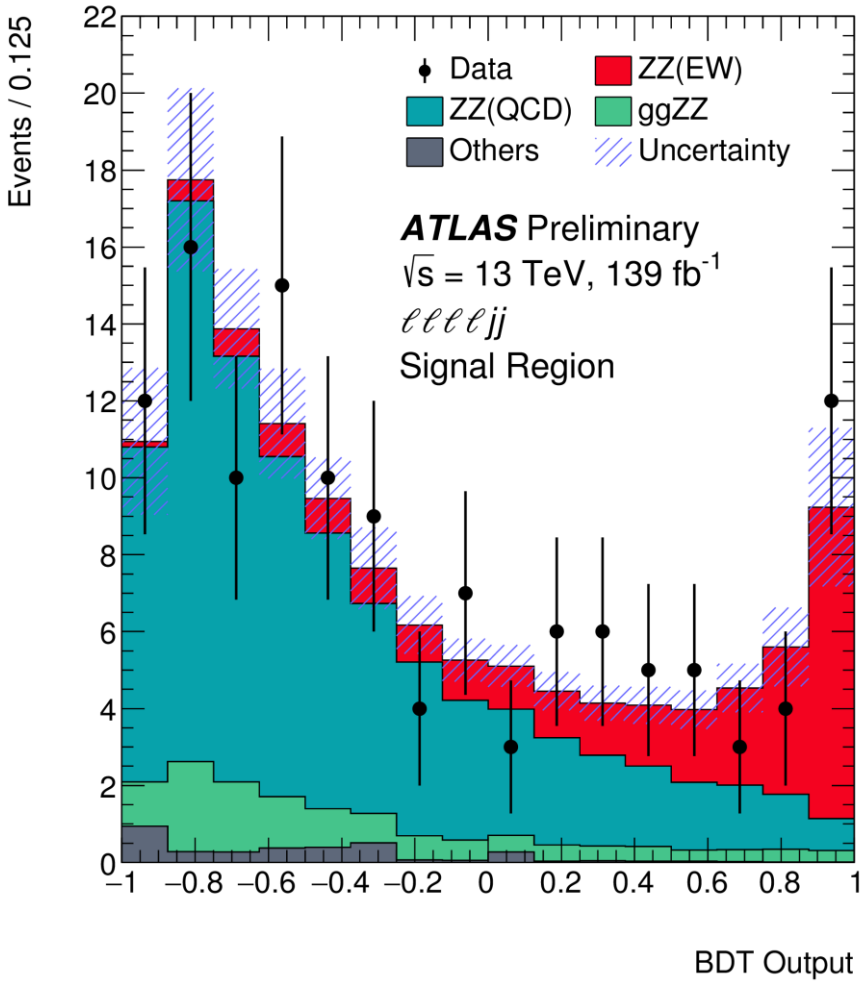
ATLAS: Observation of EWK WZ production

- Based on 36.1 fb^{-1} at 13 TeV
- Fully leptonic final state (lepton = electron or muon)
- 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



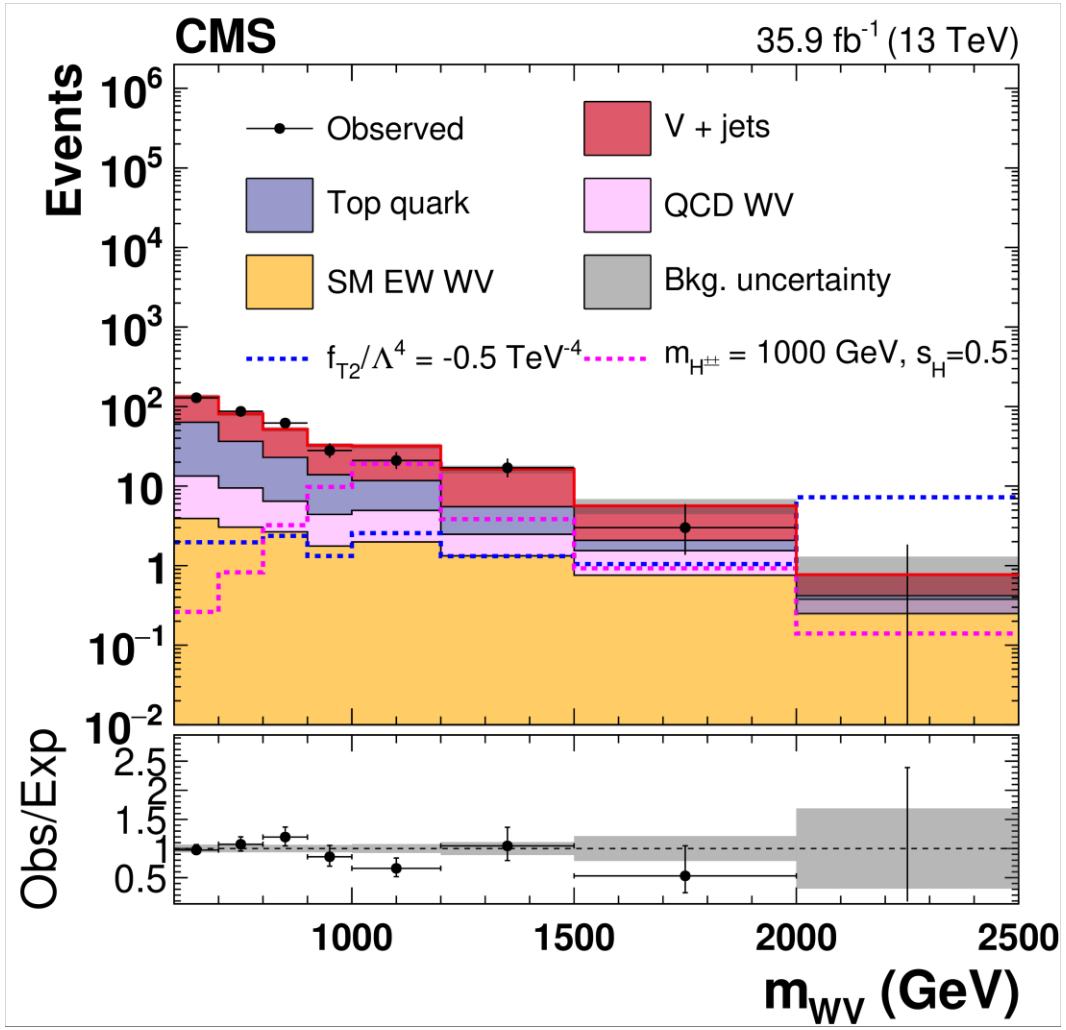
ATLAS: Observation of EWK ZZ production

- Based on 139 fb^{-1} at 13 TeV
- Observed signal significance: 5.5 σ
- Expected signal significance: 4.3 σ
- Includes 4l channel and 2l2ν channel
- BDT trained to distinguish the EWK signal from simulated backgrounds
- Significance is extracted based on fit to BDT in 4l and 2l2ν signal regions and a low $m_{jj}/\Delta\eta_{jj}$ 4l control region
- Fiducial cross section, measured, 4l: σ = 1.27 ± 0.12 (stat) ± 0.02 (theo) ± 0.07 (exp) ± 0.01 (bkg) ± 0.03 (lumi)
- Experimental uncertainty dominated by jet energy scale and resolution and background estimation
- Talk by Jing Chen on Thursday



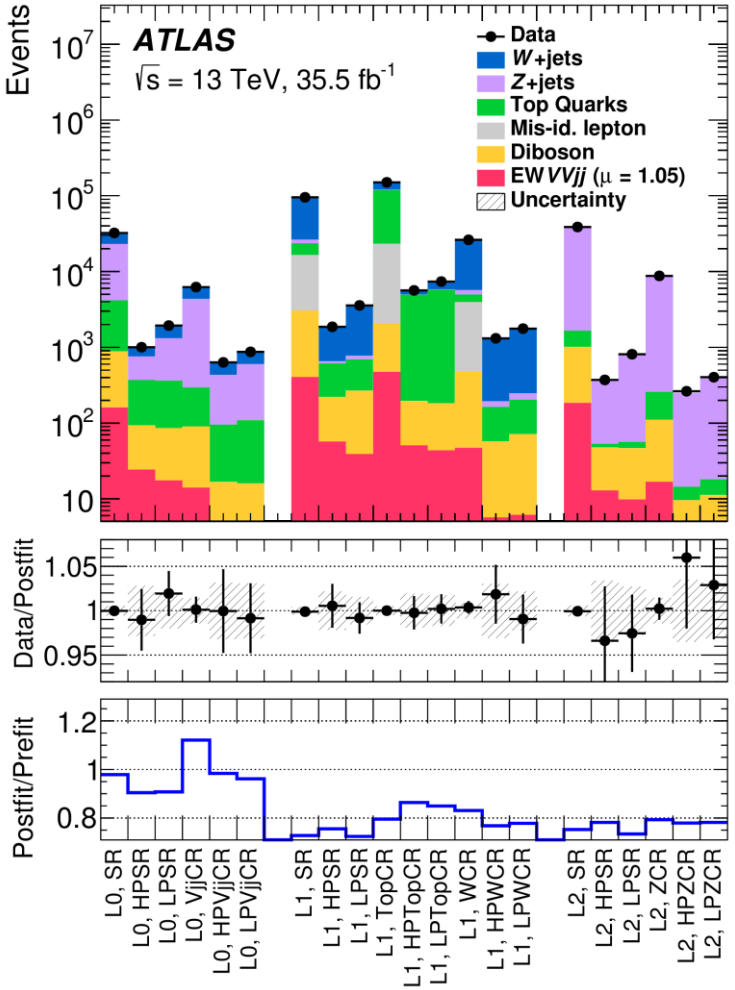
CMS: EWK VV production, semileptonic

- 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
- Very sensitive to anomalous couplings → set world's best limits on 9 dimension 8 operator coefficients



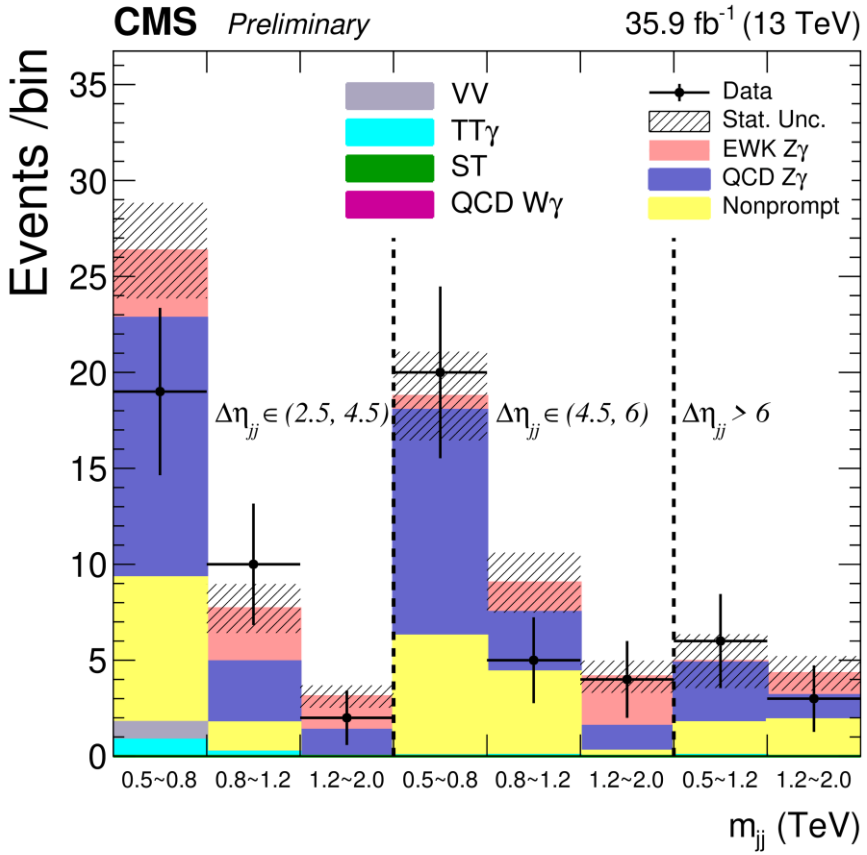
ATLAS: EWK VV production, semileptonic

- 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



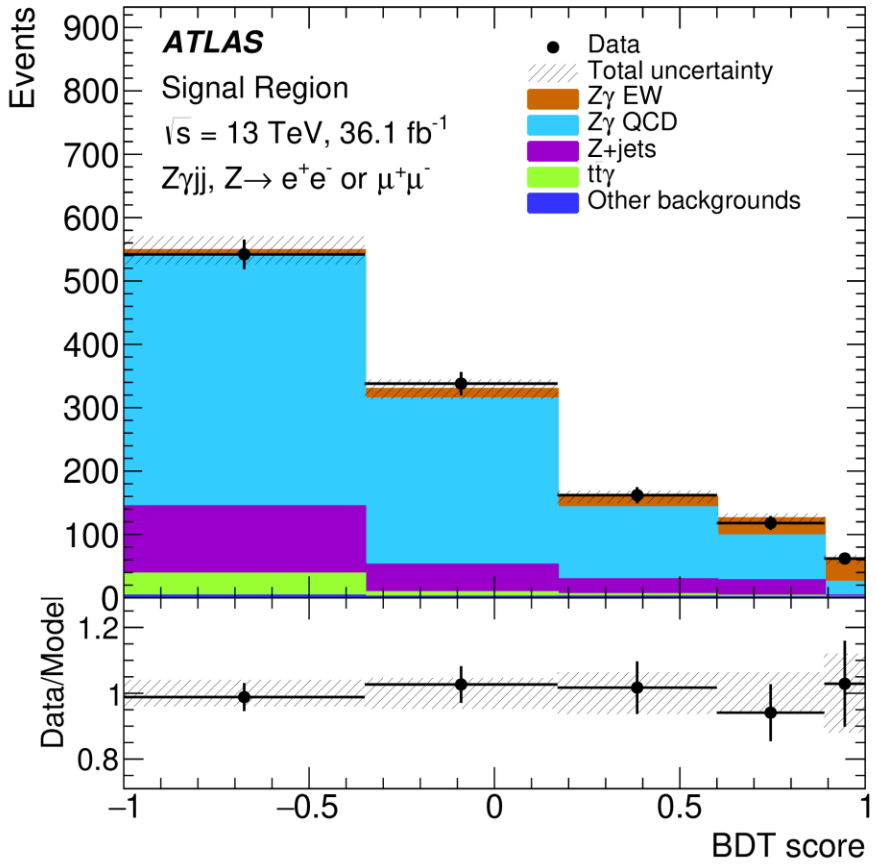
CMS: EWK Zγ production

- Based on 35.9 fb -1 collected at 13 TeV
- Observed signal significance: 5.5 σ
- Expected signal significance: 4.7 σ
- Simultaneous fit of signal region and control region
- Signal region: 2D m_{jj} vs. $\Delta\eta_{jj}$ binning on the right
- Signal region selection:
  - $\Delta\phi(\phi_{Z\gamma},\phi_{jj}) > 1.9$
  - $|\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2| < 2.4$
  - $m_{jj} > 500$ GeV
  - $\Delta\eta_{jj} > 2.5$
- Control region: $150 < m_{jj} < 400$ GeV
- Talk by Meng Lu on Thursday



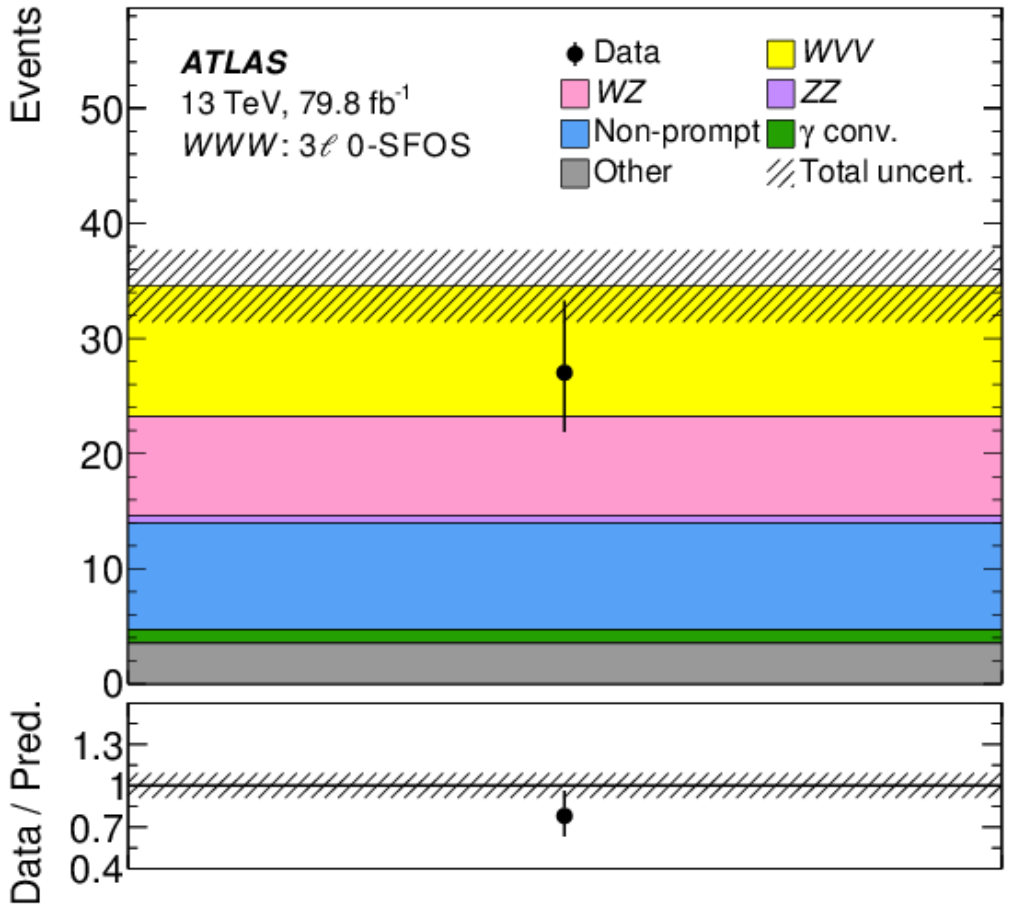
ATLAS: EWK Zγ production

- Based on 36.1 fb^{-1} collected at 13 TeV
- Observed signal significance: 4.1 σ
- Expected signal significance: 3.8 σ
- Signal region defined by $|\Delta\eta_{jj}|>1$, no b-tagged jets, and $\left|\frac{y_{ll\gamma}-(y_{j_1}+y_{j_2})/2}{(y_{j_1}-y_{j_2})}\right| < 5$
- BDT trained to separate signal from all backgrounds excluding Z+jets
- With a cut -based cross check of in which the BDT variable is replaced with the centrality, the observed (expected) significances are 2.9 (2.7) σ



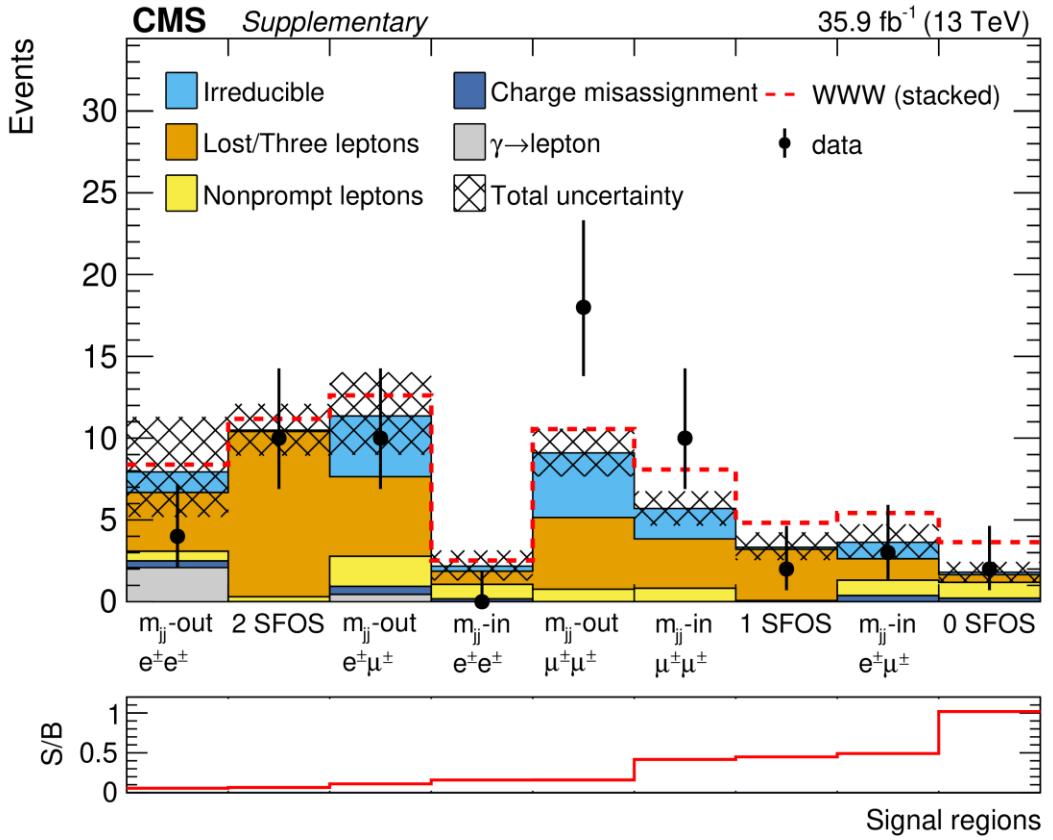
ATLAS: Production of three massive vector bosons

- Based on 80 fb^{-1} collected at 13 TeV
- Expected significance: 3.1 σ
- Observed significance: 4.1 σ
- Captures 5 final states:
  - WWW → lvlvqq
  - WWW → lvlvlv
  - WWZ →lvqqll
  - WWZ → lvlvll
  - WZZ → qqllll
- Further divided based on lepton flavor, jet multiplicity, and jet multiplicity, in order to obtain 11 signal regions
- Separate BDT trained to distinguish signal from background in each channel



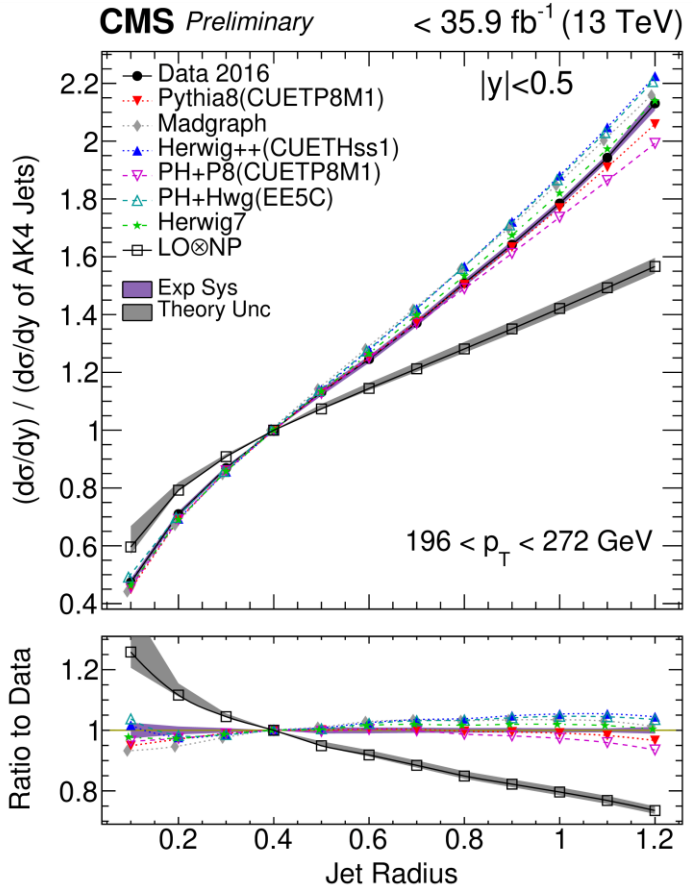
CMS: Search for WWW

- Based on 35.9 fb^{-1} at 13 TeV
- Observed significance: 0.6 σ
- Expected significance: 1.8 σ
- Use WWW → lvlvlv and WWW → lvlvqq same-sign
- Divide WWW → lvlvqq same-sign into lepton flavor categories and m_{jj} in/out of the W mass window categories
- Divide WWW → lvlvlv into 0,1, and 2 same-flavor opposite sign pair categories
- Main background is from 3 lepton events where one of the leptons is "lost"



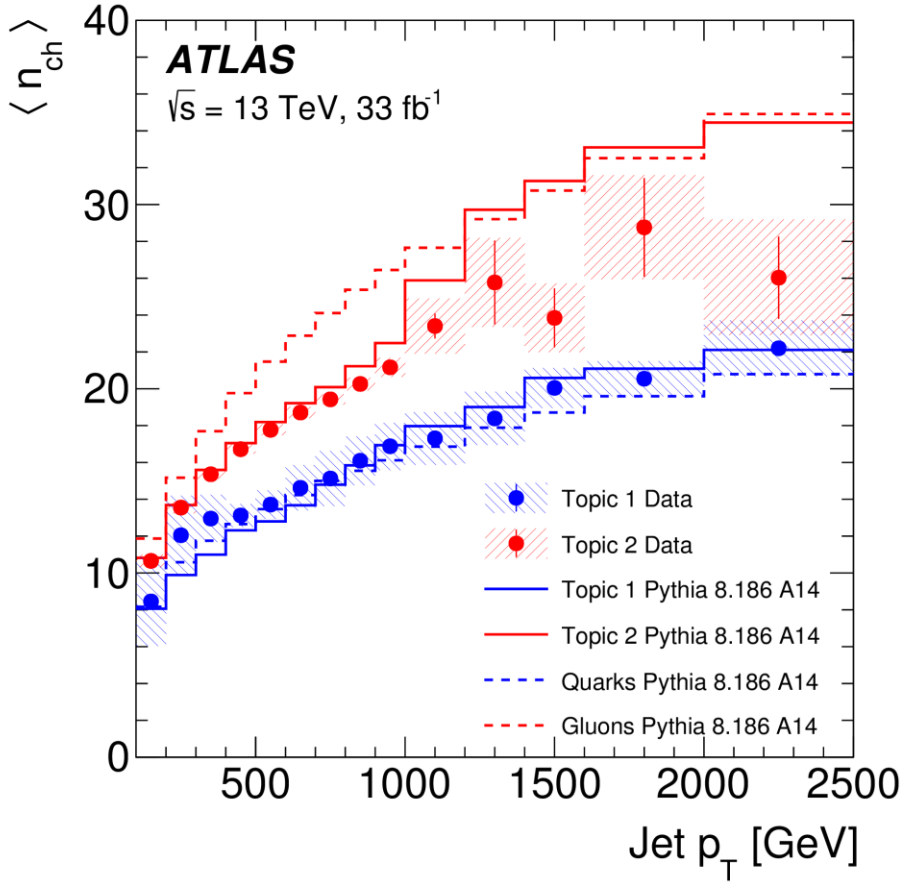
CMS: Dependence of inclusive jet production cross sections on the anti-kT distance parameter

- Based on 35.9 fb^{-1} at 13 TeV
- Tests both perturbative and non-perturbative aspects of QCD
- Based on the CMS so-called particle-flow algorithm which aims to reconstruct in a consistent way all particles in the event
- Measured the unfolded ratio of the cross section to the AK4 cross section
- Data compared with the standard generator tools, and also NLOJET++, a fixed order generator, and a correction for non-perturbative effects, labeled as LO⊗NP because while NLOJET++ is LO, the ratio is leading order



ATLAS: Properties of jet fragmentation using charged particles

- Based on 33 fb^{-1} at 13 TeV
- Use track-based jet reconstruction
- Observables sensitive to jet fragmentation:
  - Charged-particle multiplicity
  - Summed fragmentation function
  - Transverse momentum
  - Radial profile
- Topic analysis is a way of automatically clustering data, and can be used to perform quark-gluon discrimination with no input from simulation
- Disagreement between data and Sherpa, Herwig, and Pythia found in several observables → very useful for tuning the hadronization model



Conclusions

- Many measurements are becoming systematic limited with the full run 2 data
- Other than measuring inclusive cross sections ad masses we are doing:
  - Searches for rare processes
  - Differential, double differential, or event triple differential unfolding
  - Anomalous coupling frameworks limits
  - Polarization studies
  - VBS analyses with connections to electroweak symmetry breaking
- Many important, interesting, creative results
- Not just background to Higgs searches!