Observation and Measurements of Vector-Boson Scattering at the ATLAS Detector

ICNFP 2019

Orthodox Academy of Crete
Kolymbari, Greece
21-30 August

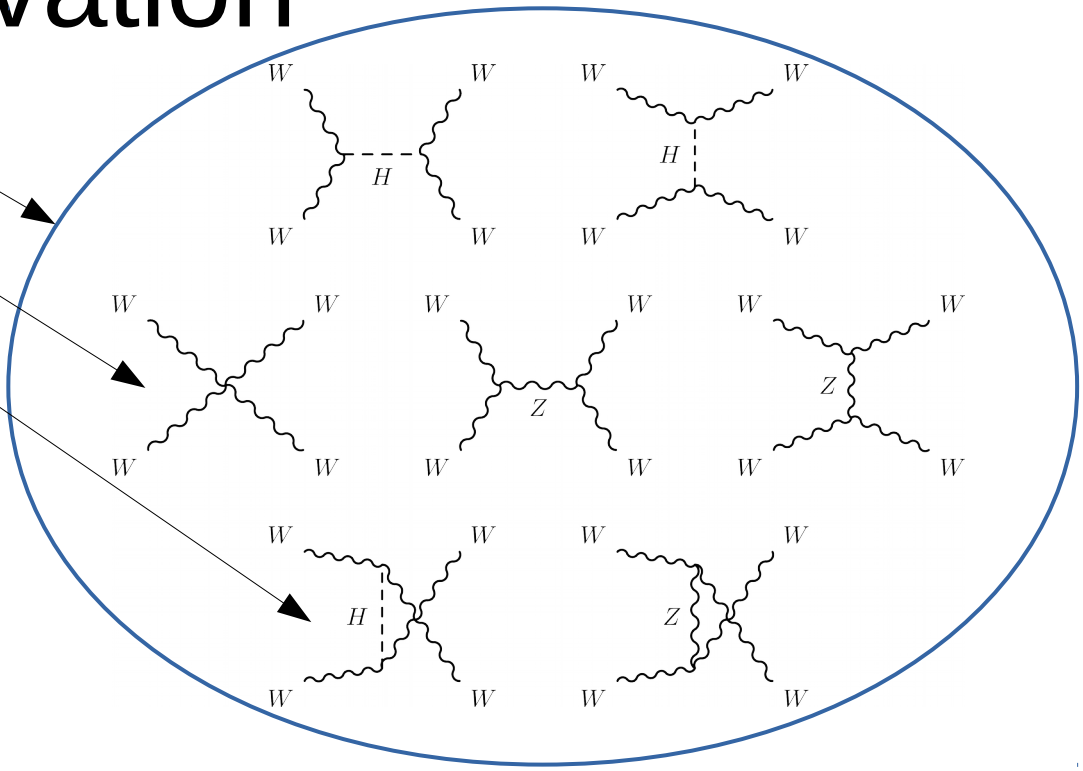
Ondřej Penc
ondrej.penc@cern.ch

on behalf of ATLAS Collaboration

Motivation

Vector boson scattering (massive bosons)

- Test of Standard Model (SM) gauge structure
- QGC becomes accessible (i.e. WWWW)
- Better understanding of the nature of EWSB mechanism since involves Higgs boson
- BSM anomalous QGC limits

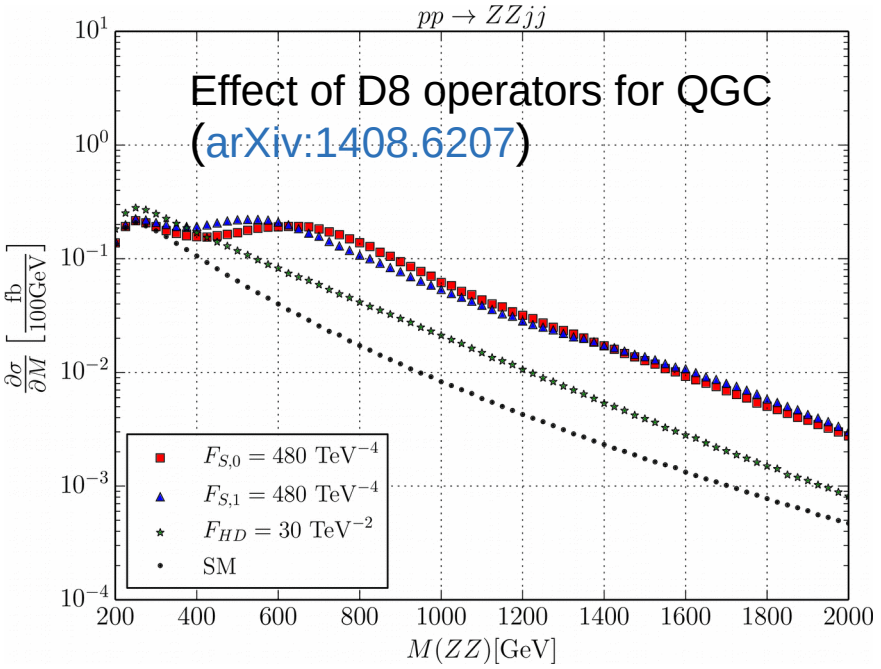


- VBS as Goldstone boson scattering (Goldstone Boson Equivalence Theorem)
  - W± and Z bosons acquire mass spending three Goldstone bosons (angular fields)
  - Parametrisation of weak isodoublet (a = 1,2,3)

$$\Phi(x) = \exp\left(\frac{i}{v}\pi^a(x)\tau^a\right)\begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v + H(x)) \end{pmatrix}$$

- Effective field theory
  - Addition of higher order operators to SM
  - SM as the limit case of the new model
  - Scales beyond the reach of the LHC

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum_{d\geq 4}\sum_{i}\frac{\alpha_i^{(d)}}{\Lambda^{d-4}}O_i^{(d)}$$

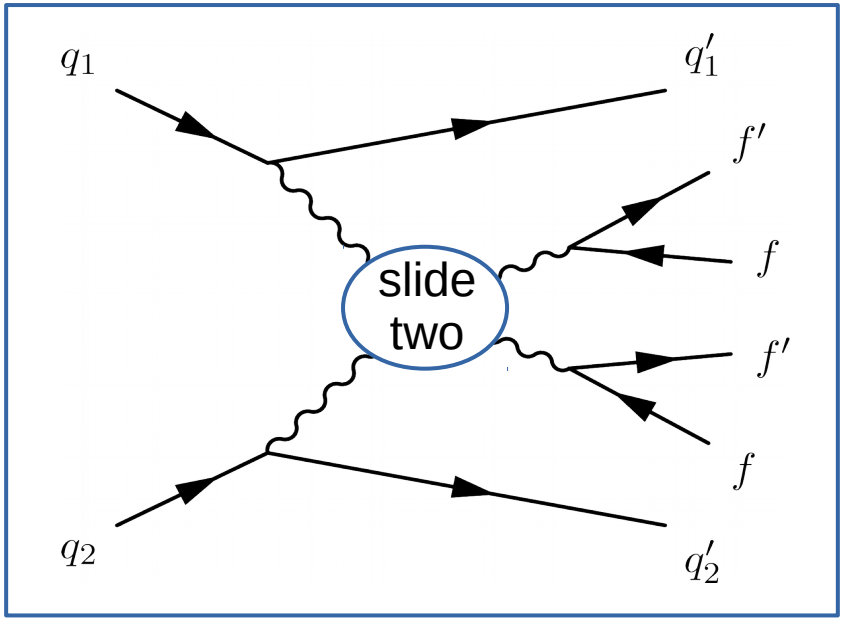


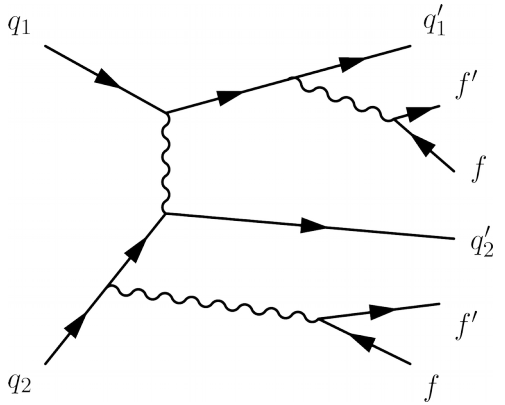
Vector Boson Scattering Diagrams

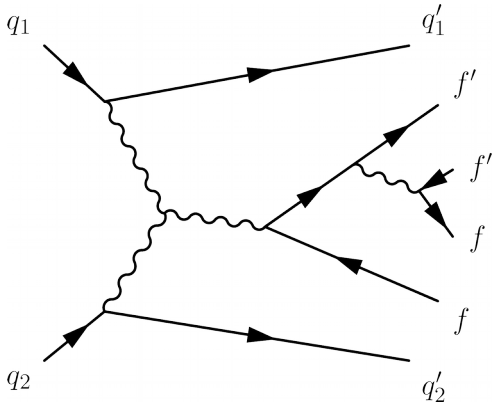
EWK VVjj production

Protons interact electro-weakly

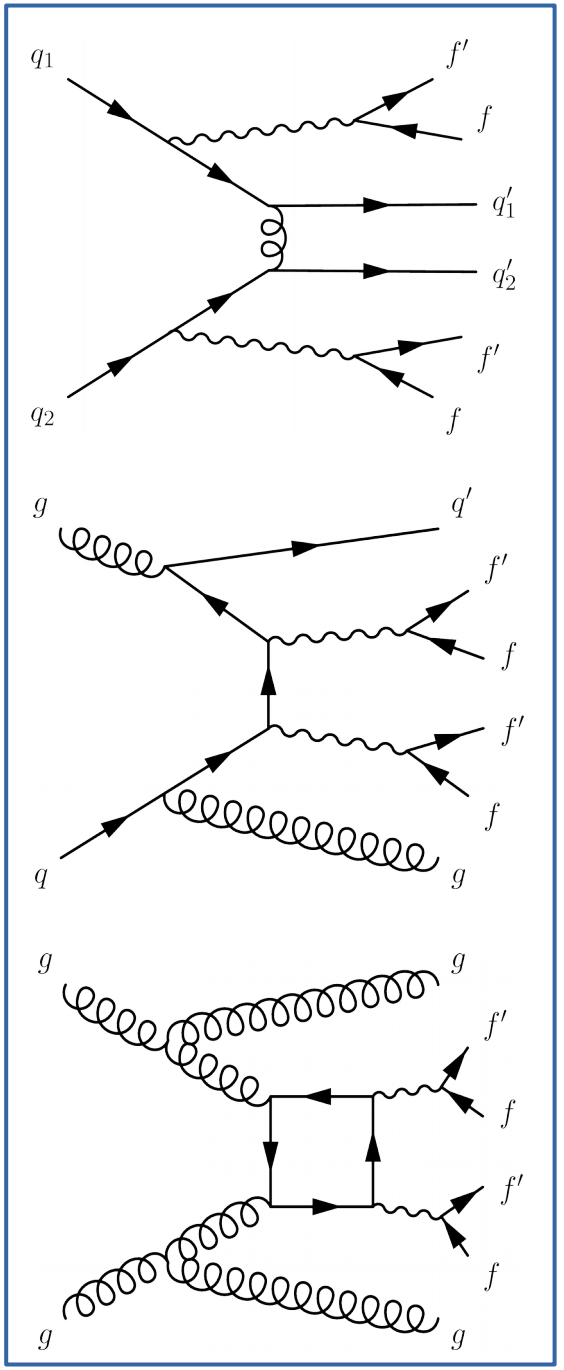
Vector Boson Scattering





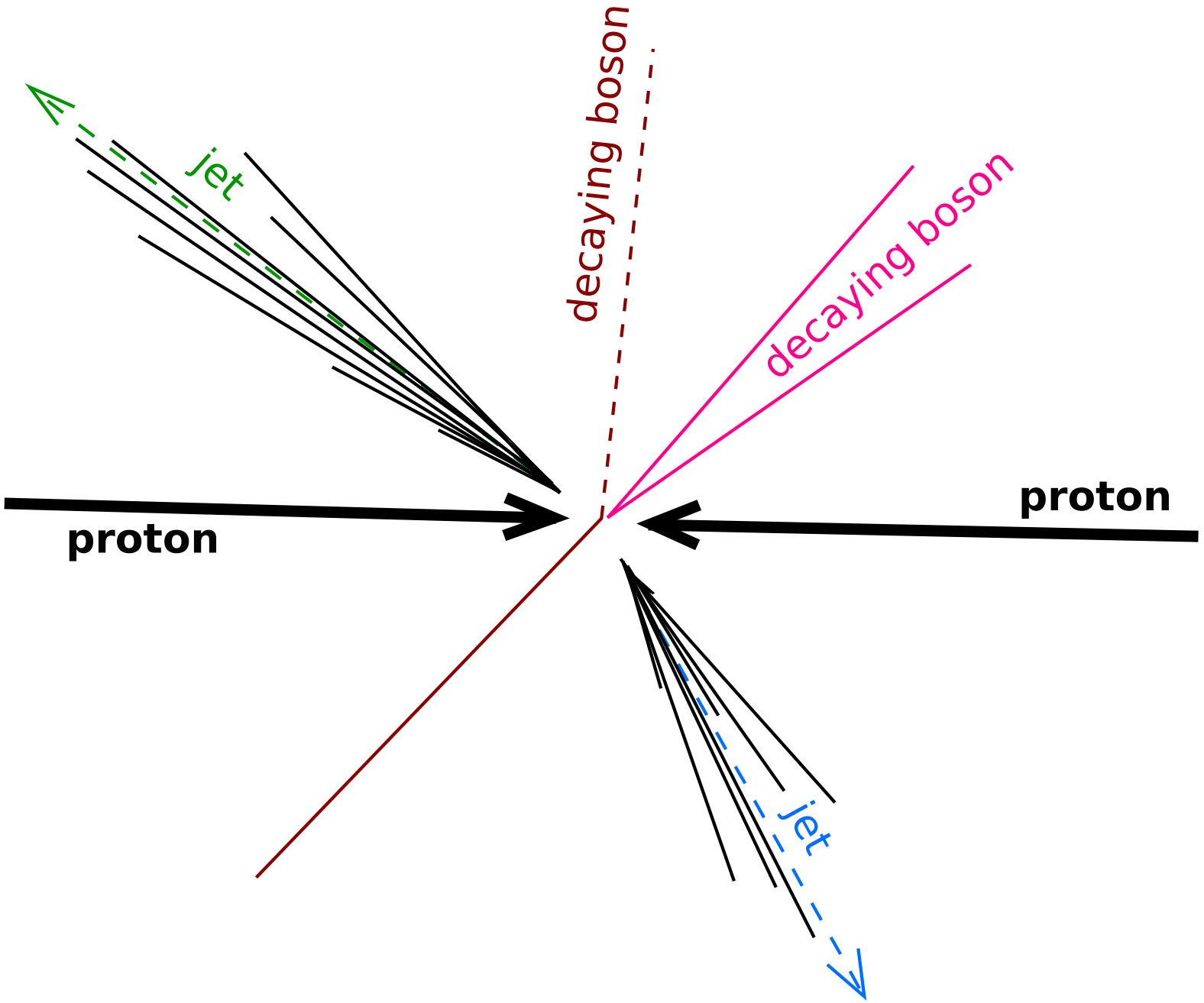


QCD VVjj production



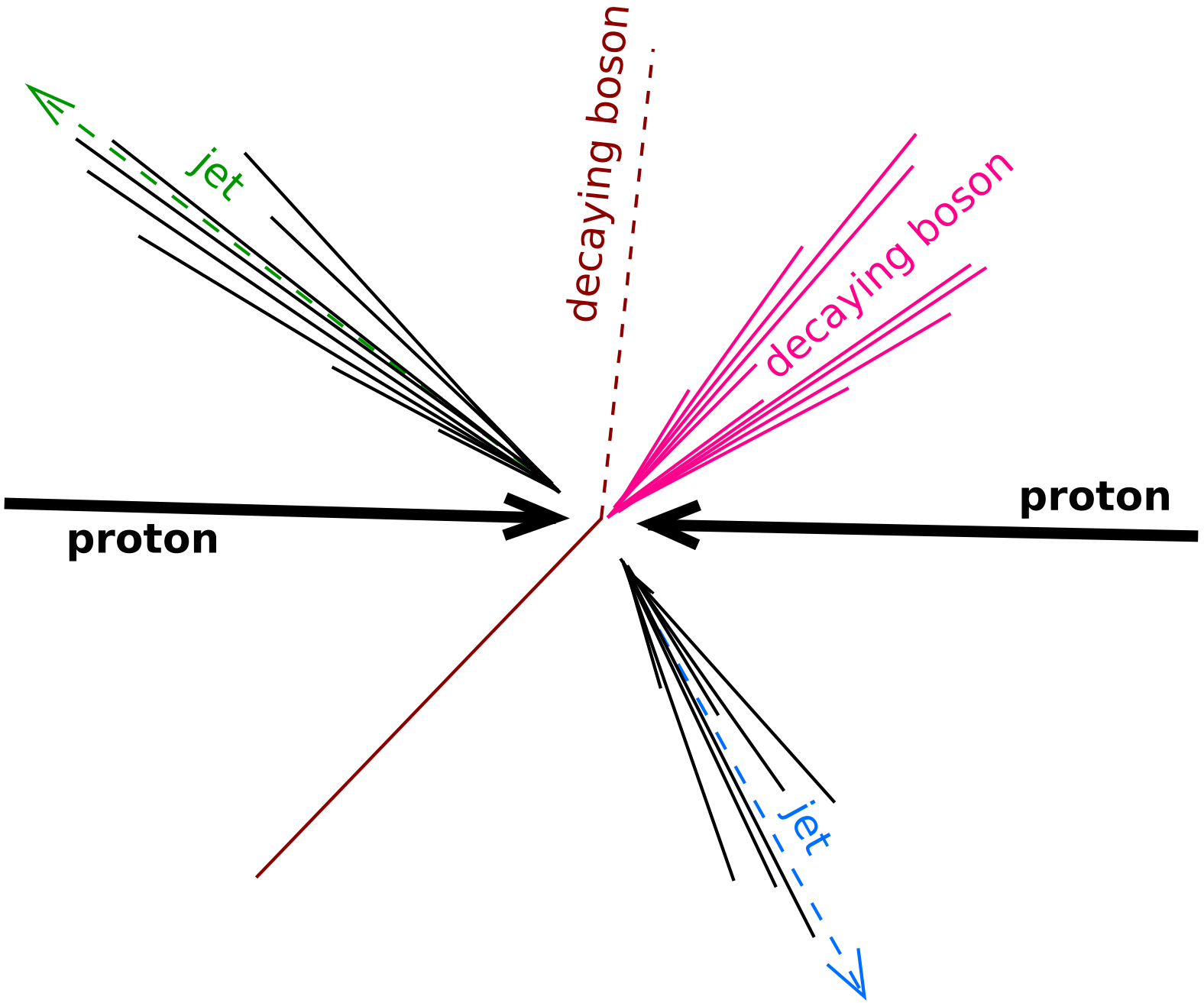
Object Selection

- Leptonic signatures
  - WWjj
    - $\nu\ell + \nu\ell + jj$
  - WZjj
    - $\nu\ell + \ell\ell + jj$
  - ZZjj
    - $\ell\ell + \ell\ell + jj$
    - $\nu\nu + \ell\ell + jj$
- Semi-leptonic signatures
  - VVjj
    - $\ell\ell + jj + jj$
    - $\nu\ell + jj + jj$
    - $\nu\nu + jj + jj$



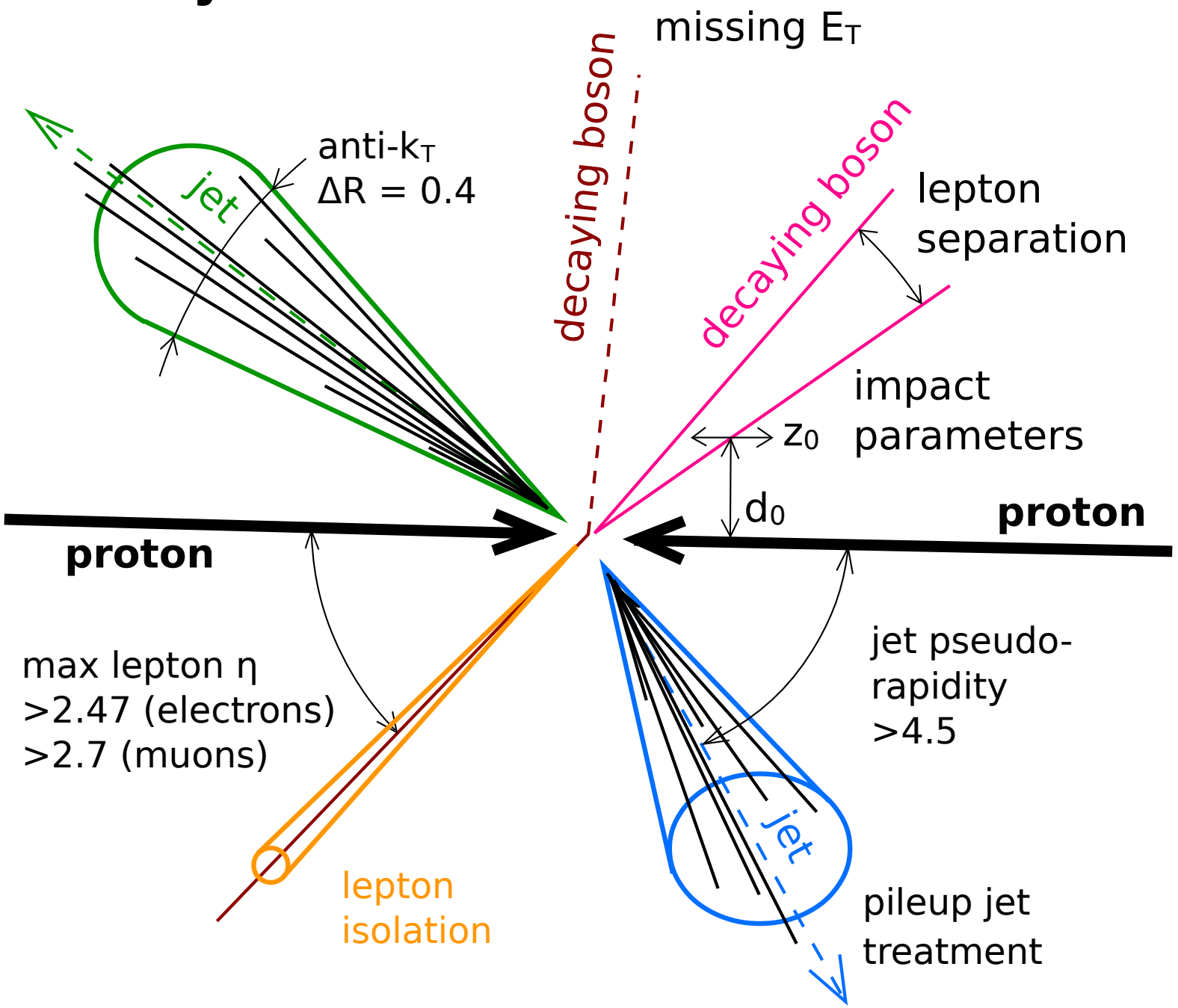
Object Selection

- Leptonic signatures
  - WWjj
    - $\nu\ell + \nu\ell + jj$
  - WZjj
    - $\nu\ell + \ell\ell + jj$
  - ZZjj
    - $\ell\ell + \ell\ell + jj$
    - $\nu\nu + \ell\ell + jj$
- Semi-leptonic signatures
  - VVjj
    - $\ell\ell + jj + jj$
    - $\nu\ell + jj + jj$
    - $\nu\nu + jj + jj$



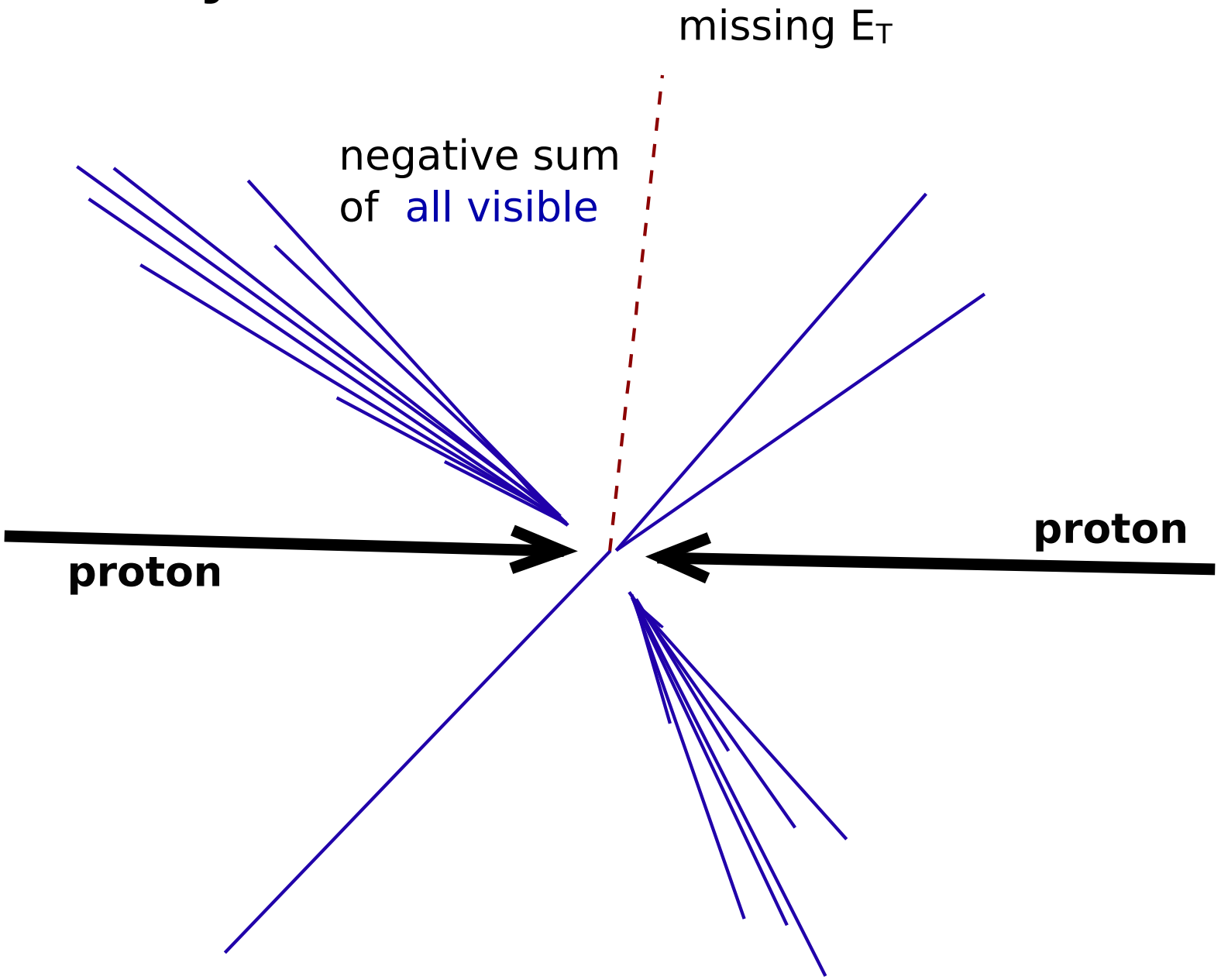
Object Selection

- Transverse momentum
- Detector limit in pseudorapidity (η)
- Impact parameter
  - Cosmic rejection
  - Secondary vertex
- Overlap removal
  - Electrons, Muons, Jets
- Lepton quality and isolation
- Jet reconstruction
  - Anti-kT
  - Standard jet (ΔR = 0.4)
  - Large jet (ΔR = 1.0)
  - Track jet (ΔR = 0.2)
  - Pileup jet tagging
- Missing transverse momentum
  - Negative global vector sum of all identified objects and unclassified tracks and calorimeter clusters



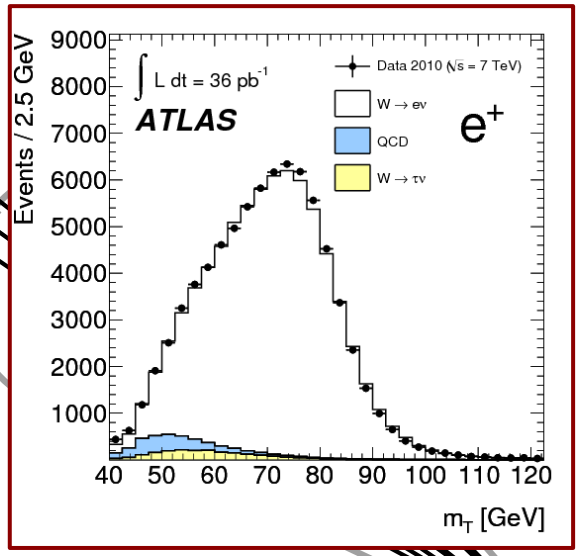
Object Selection

- Transverse momentum
- Detector limit in pseudorapidity (η)
- Impact parameter
  - Cosmic rejection
  - Secondary vertex
- Overlap removal
  - Electrons, Muons, Jets
- Lepton quality and isolation
- Jet reconstruction
  - Anti-kT
  - Standard jet (ΔR = 0.4)
  - Large jet (ΔR = 1.0)
  - Track jet (ΔR = 0.2)
  - Pileup jet tagging
- Missing transverse momentum
  - Negative global vector sum of all identified objects and unclassified tracks and calorimeter clusters



Event Selection

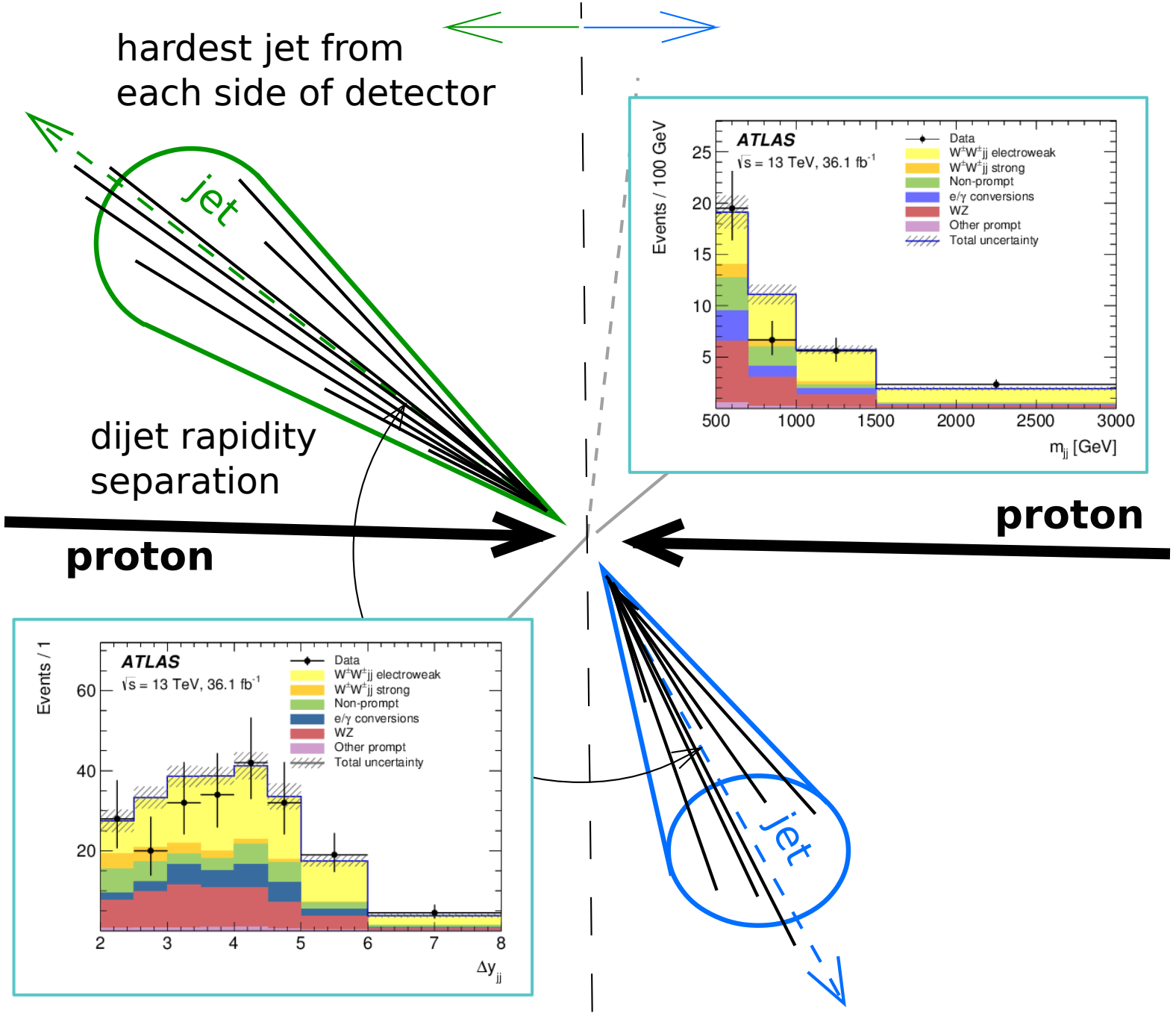
- Leptonic W boson
  - High quality lepton plus missing transverse momentum
  - Additional lepton veto
  - bJet veto
- Leptonic Z boson
  - Same flavour opposite charge di-lepton (SFOC)
  - Di-lepton mass window
- Hadronic boson
  - Two small jets
  - One large jet and jet substructure
  - Di-jet mass window
- Invisible boson
  - Large missing transverse energy
- Tagging di-jet selection
  - Hardest jet from opposite side of detector
  - Di-jet separation in rapidity
  - High di-jet mass requirement
- Jet-lepton centrality



$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$

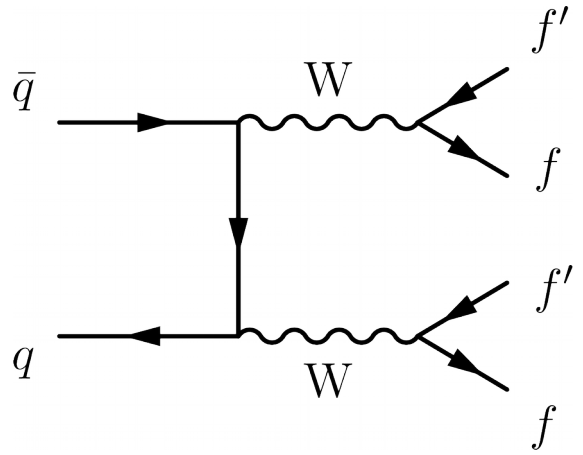
Event Selection

- Leptonic W boson
  - High quality lepton plus missing transverse momentum
  - Additional lepton veto
  - bJet veto
- Leptonic Z boson
  - Same flavour opposite charge di-lepton (SFOC)
  - Di-lepton mass window
- Hadronic boson
  - Two standard jets
  - One large jet and jet substructure
  - Di-jet mass window
- Invisible boson
  - Large missing transverse energy
- Tagging di-jet selection
  - Hardest jet from opposite side of detector
  - Di-jet separation in rapidity
  - High di-jet mass requirement
- Jet-lepton centrality



$W^{\pm}W^{\pm}$ - VBS "Discovery" Channel

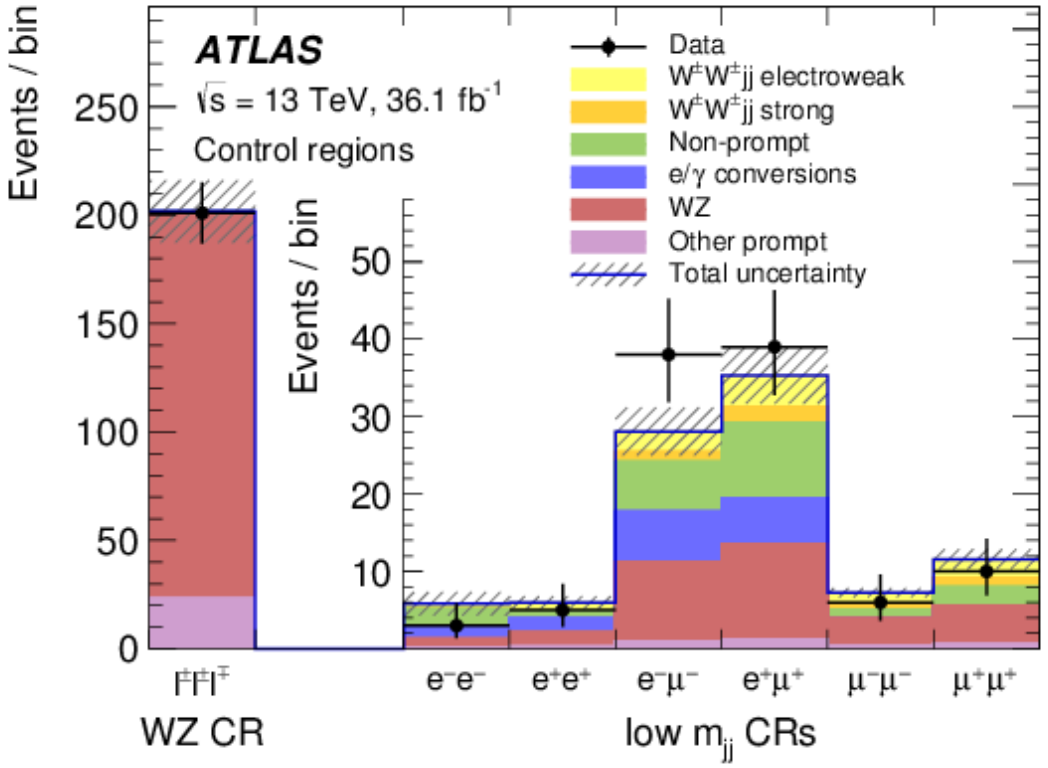
- VBS final state: $\nu\ell^{\pm}\nu\ell^{\pm}$ + jj
- Dataset: 36.1 fb^{-1}, 13 TeV
- Expected significance: 6.5 σ (Powheg-Box) and 4.4 σ (Sherpa)
- Same sign requirement supress $q\bar{q}$ production



- Prompt background (MC modeled)
  - WZ+jets (dominant), WW+jets (QCD), ZZ+jets, and VVV

Non-prompt background (data driven)

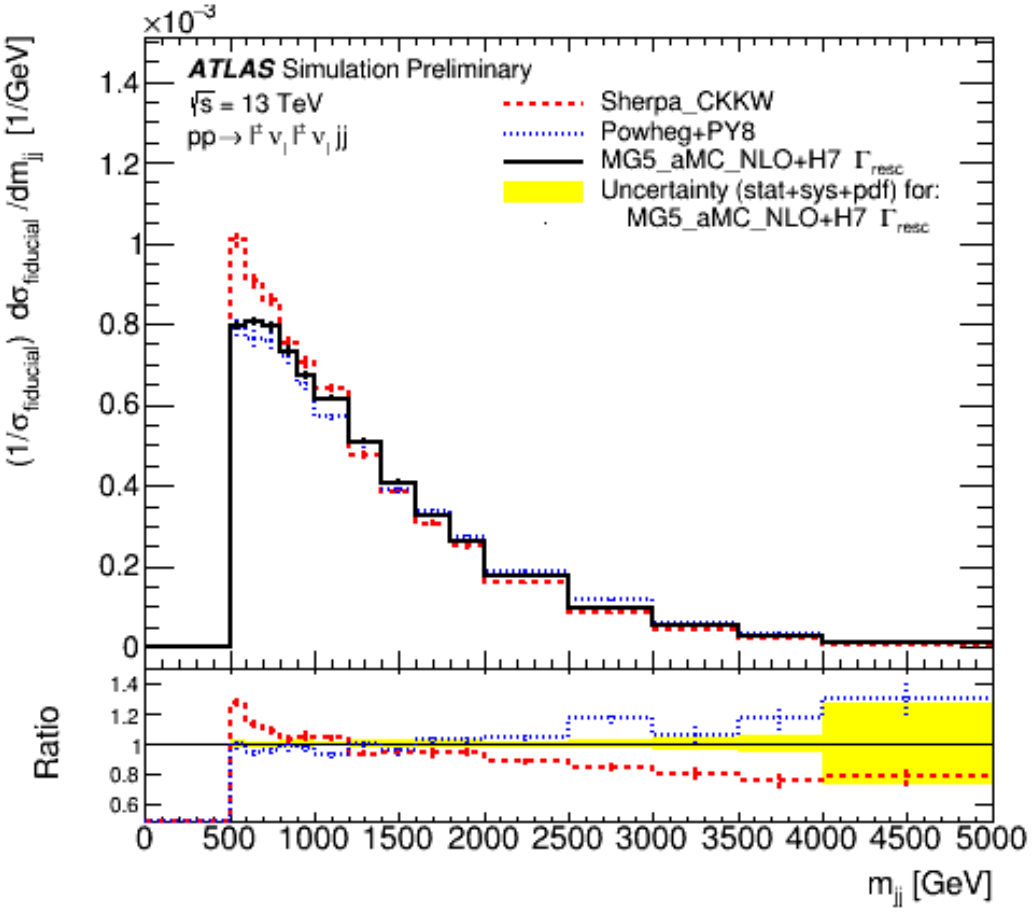
- $t\bar{t}$, WW+jets (QCD), Vγ+jets, W+jets, t+jets
- Lepton misidentification (photon misidentified as electron)
- Charge misidentification (same sign leptons)



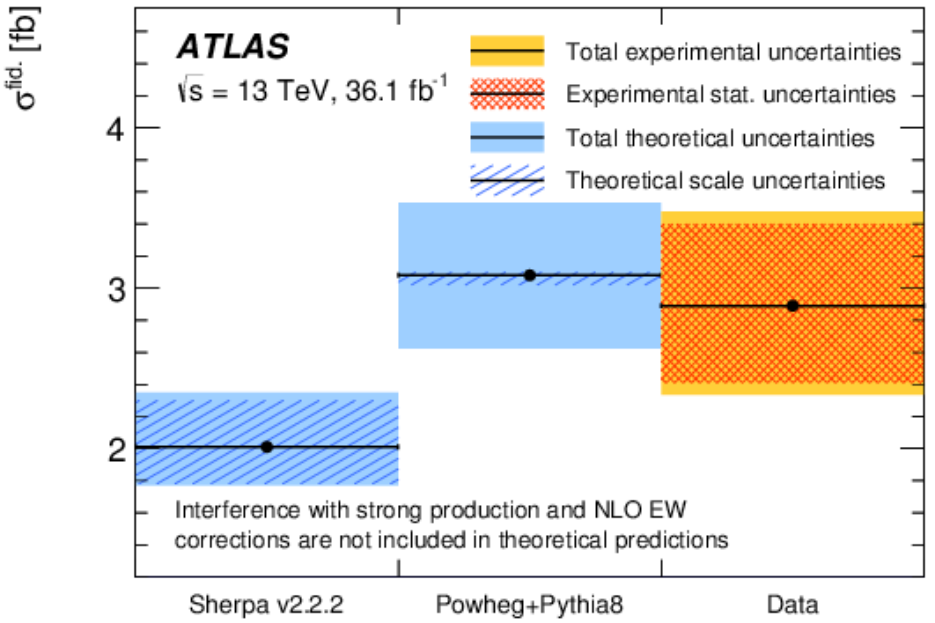
arXiv:1906.03203

MC simulations for $W^{\pm}W^{\pm}$ VBS

- Extensive MC studies for VBS first evidence channel
- Predicted cross-section and kinematic distribution comparison studies
- Low di-jet mass disagreement



- Comparison settings
  - Generators: MadGraph5_aMC@NLO, Powheg-Box 2, Sherpa 2
  - Parton showering: Pythia 8, Herwig 7, Sherpa 2
  - Factorization and renormalization scales effects
    - W mass, di-boson invariant mass, $\sqrt{p_{\mathrm{T}}^{j1}\, p_{\mathrm{T}}^{j2}}$
- Non-optimal setting of the color flow for the Sherpa parton shower



ATL-PHYS-PUB-2019-004

$W^{\pm}W^{\pm}$ - Results

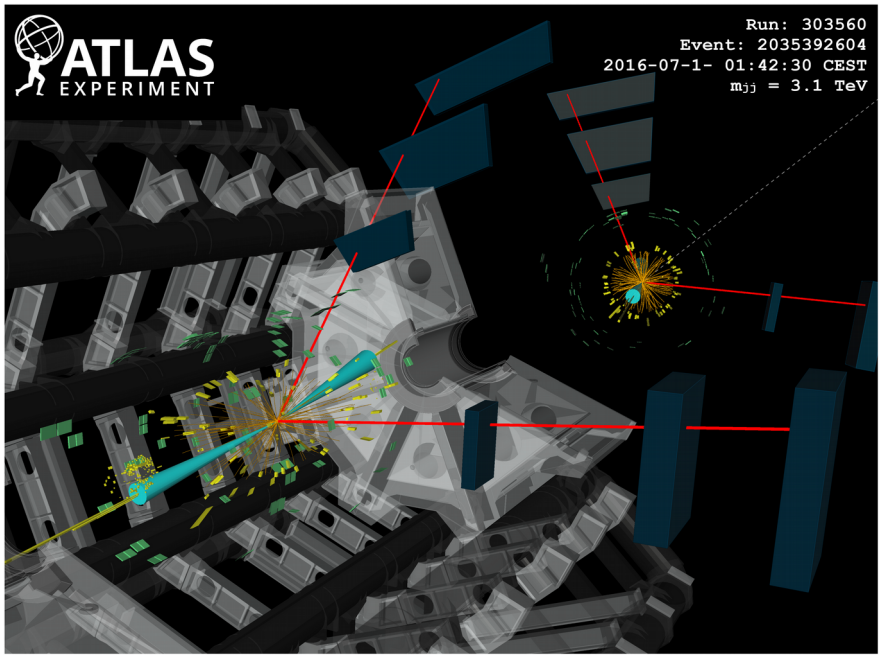
- Signal strength (compared to Sherpa)

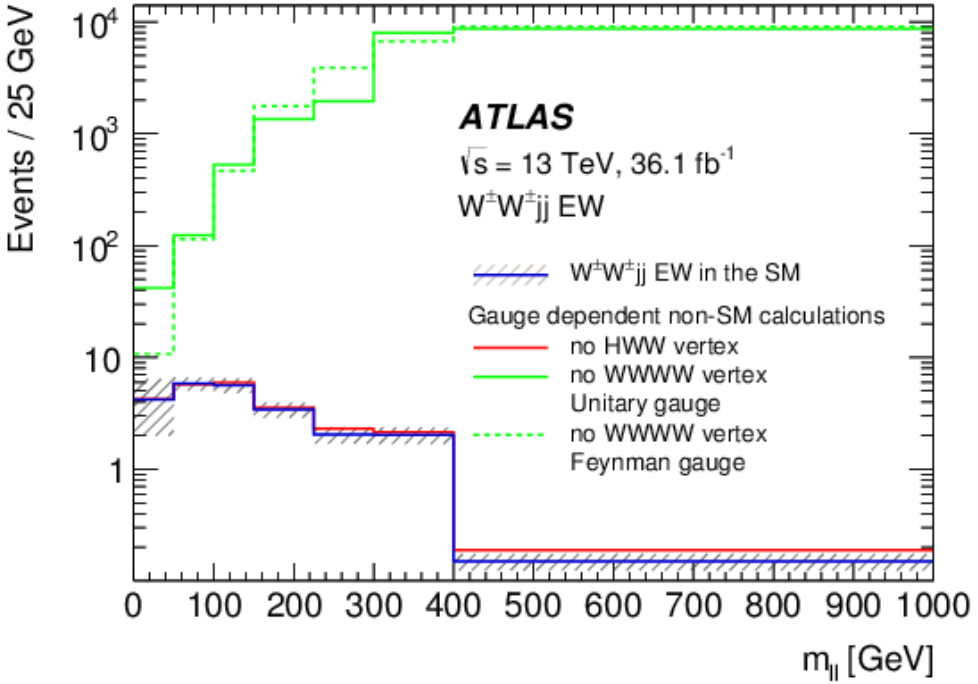
$$1.44^{+0.26}_{-0.24}\,(\mathrm{stat.})^{+0.28}_{-0.22}\,(\mathrm{syst.})$$

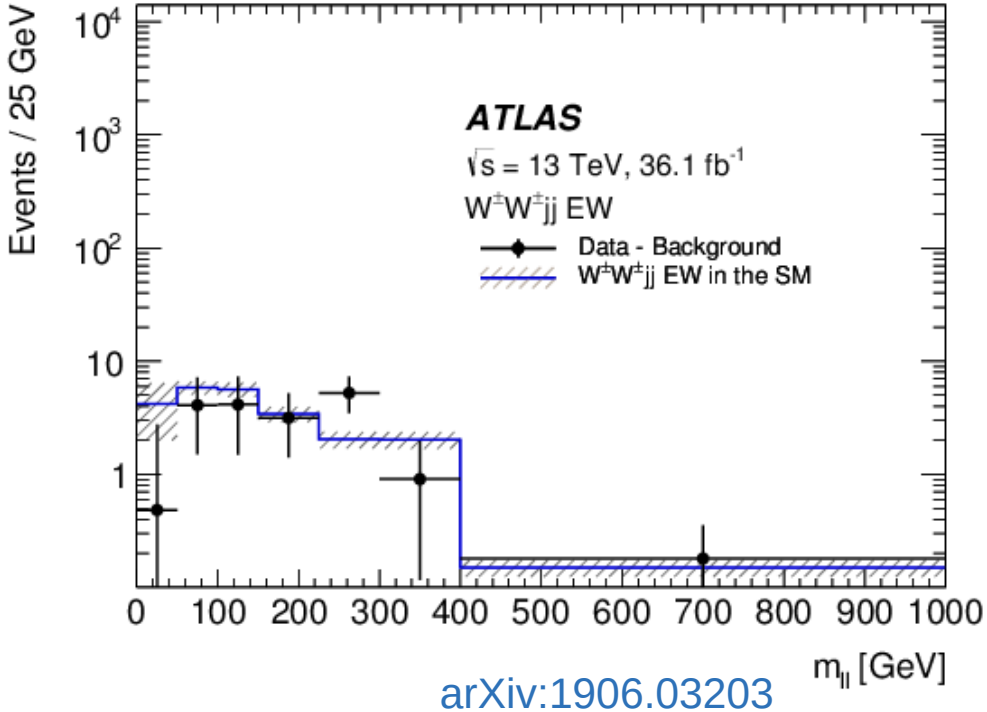
- Background only hypothesis rejected with significance 6.5 σ (expected 4.4/6.5 σ)
- EWK Fiducial cross-section

$$2.89^{+0.51}_{-0.48}\,(\mathrm{stat.})^{+0.29}_{-0.28}\,(\mathrm{syst.})\,\mathrm{fb}$$

- No deviation from SM observed in $W^{\pm}W^{\pm}jj$ EWK







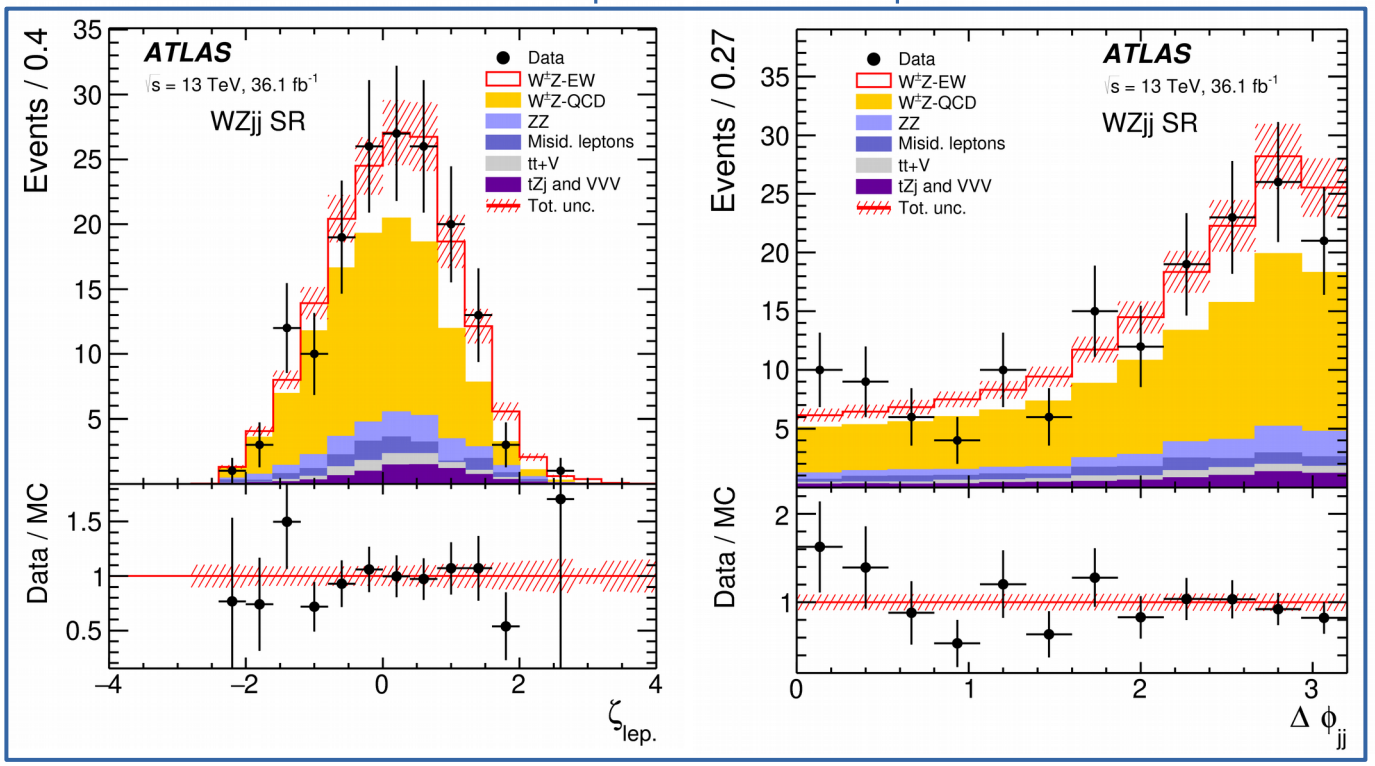
arXiv:1906.03203

$W^{\pm}Z$ – VBS "Mix" Channel

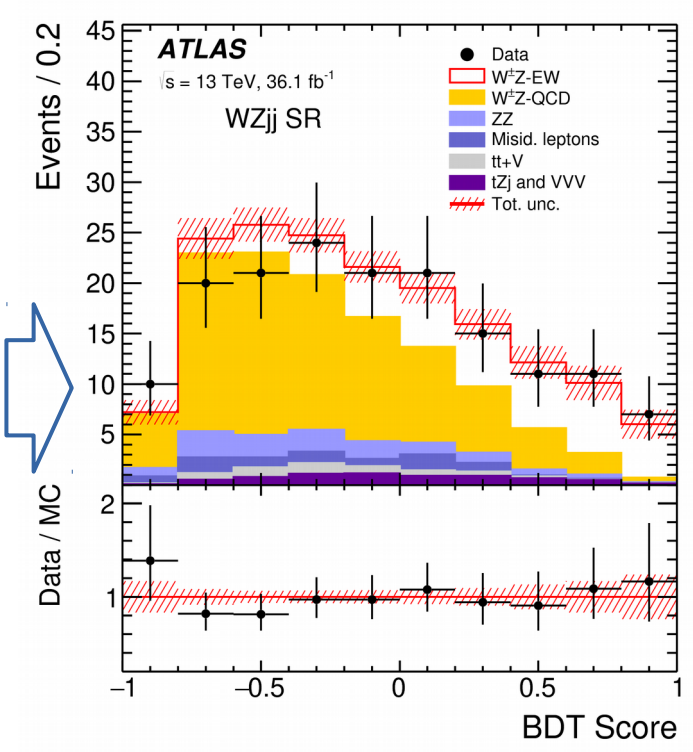
- VBS final state: $\nu\ell\ell\ell$ + jj
- Dataset: 36.1 fb^{-1}, 13 TeV
- Expected significance: 3.2 σ
- MVA: TMVA BDT, 15 variables
- W and Z reconstruction using Resonant Shape algorithm

- Fourth lepton veto
- Prompt background
  - WZ+jets (QCD), ZZ+jets, $t\bar{t}V$, VVV, tZ+jets
- Non-Prompt background
  - Z+jets, Zγ+jets, $t\bar{t}$, Wt+jets, WW+jets
  - Misidentified leptons (data driven)

Example of BDT Input



BDT Score



Phys. Lett. B 793 (2019) 469

$W^{\pm}Z$ – Results

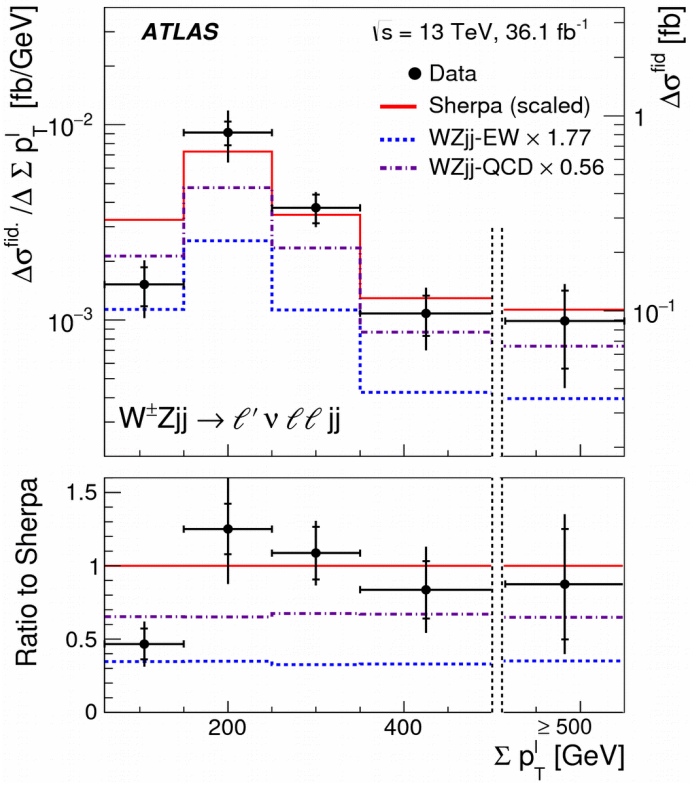
- EWK Signal strength

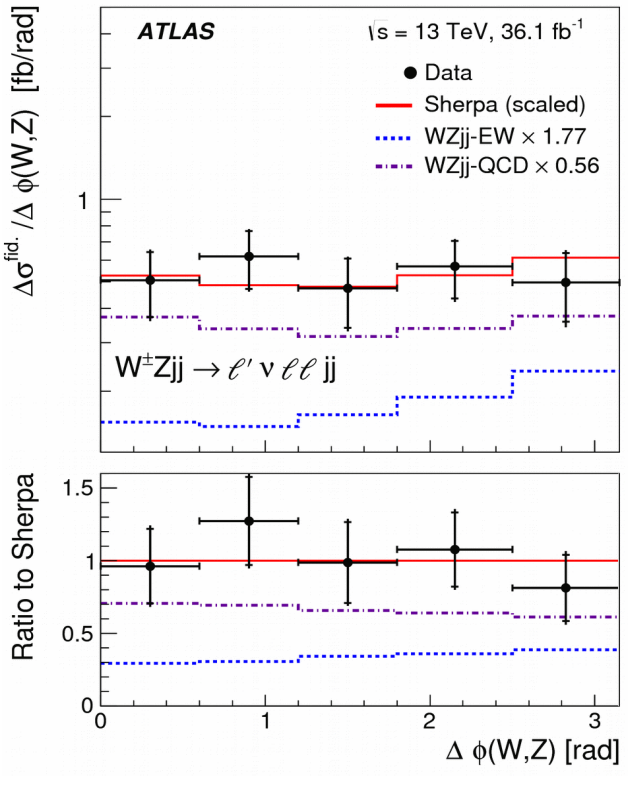
$$1.77^{+0.44}_{-0.40}\,(\text{stat.})^{+0.26}_{-0.21}\,(\text{syst.})$$

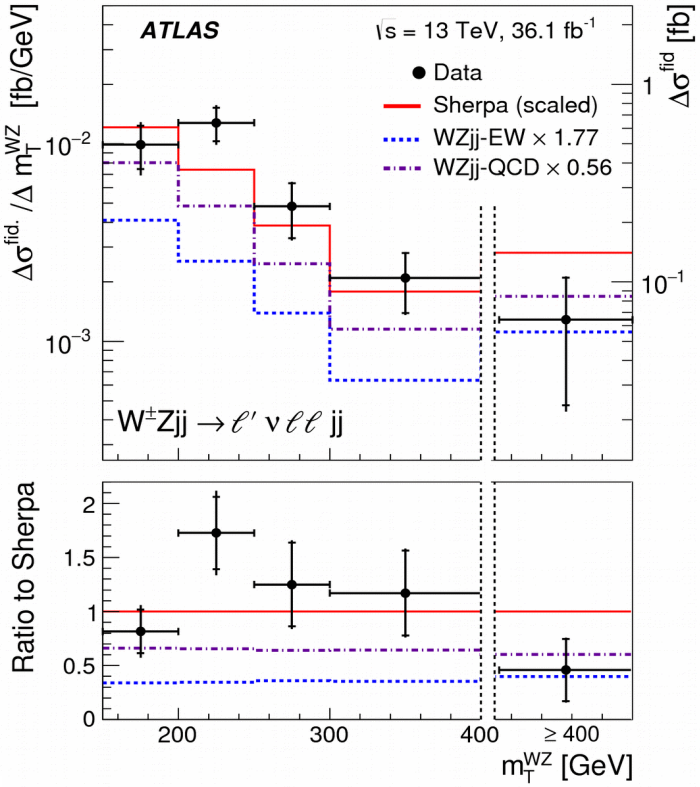
- Background only hypothesis rejected with significance 5.3 σ (expected 3.2 σ)
- EWK fiducial cross-section

$$0.57^{+0.14}_{-0.13}\,(\text{stat.})^{+0.07}_{-0.06}\,(\text{syst.})\,\text{fb}$$

- WZjj EWK production **observed**
- Distributions sensitive to anomalous QGC
  - Inclusive fiducial phase space (EWK + QCD)

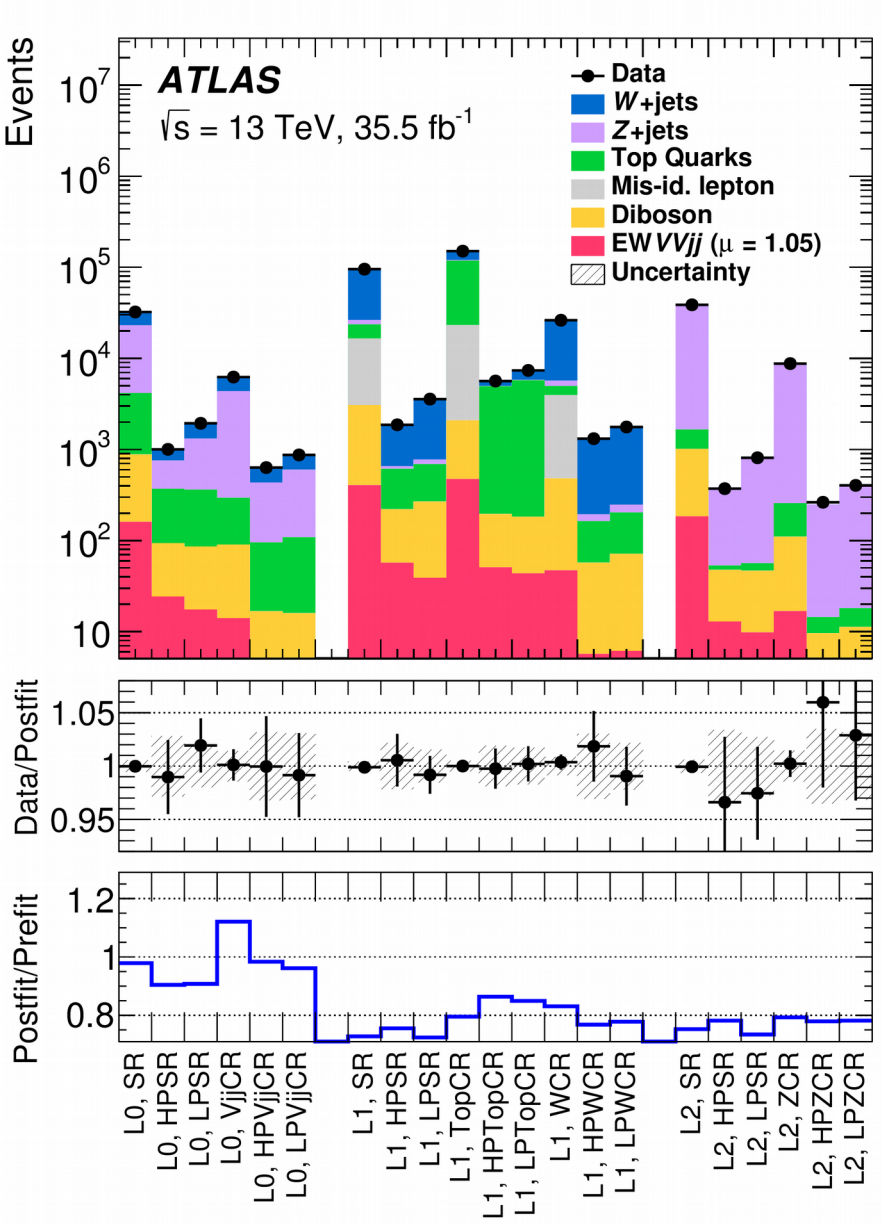






VV Semi-leptonic – VBS "Jet" Channel

- VBS final states: ℓℓjj + jj, ℓνjj + jj, ννjj + jj (2-, 1-, and 0-lepton channel)
- Dataset: 35.5 fb^{-1}, 13 TeV
- Expected significance: 2.5 σ
- MVA: TMVA BDT, 4 – 16 variables
- 9 signal regions, 12 control regions
  - Working points: resolved, high/low purity merged jets
- Dominant background
  - 2-lepton channel
    - Z+jets
  - 1-lepton channel
    - W+jets, $t\bar{t}$
  - 0-lepton channel
    - V+jets, $t\bar{t}$
- Minor background (all channels)
  - VVjj (QCD), t+jets, multijet



VV Semi-leptonic – Results

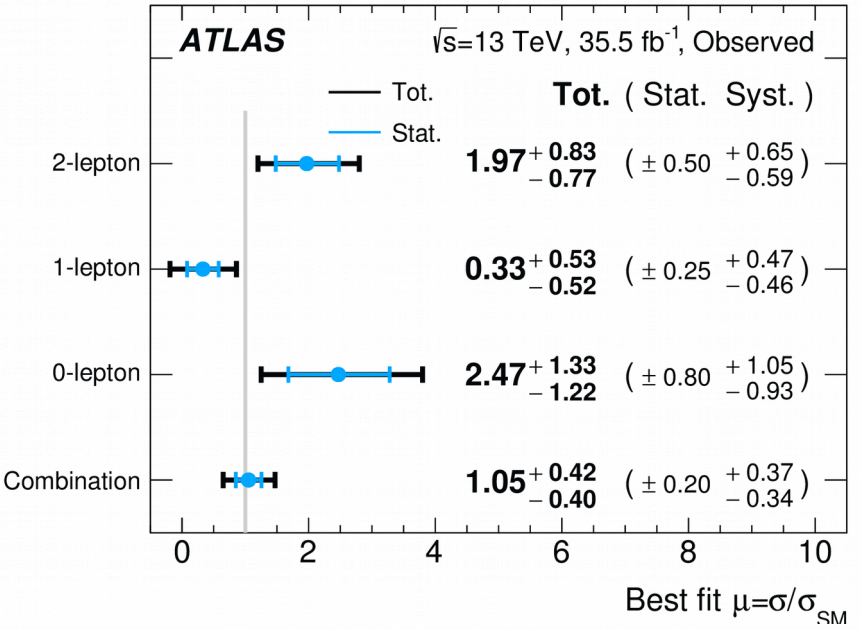
- EWK signal strength

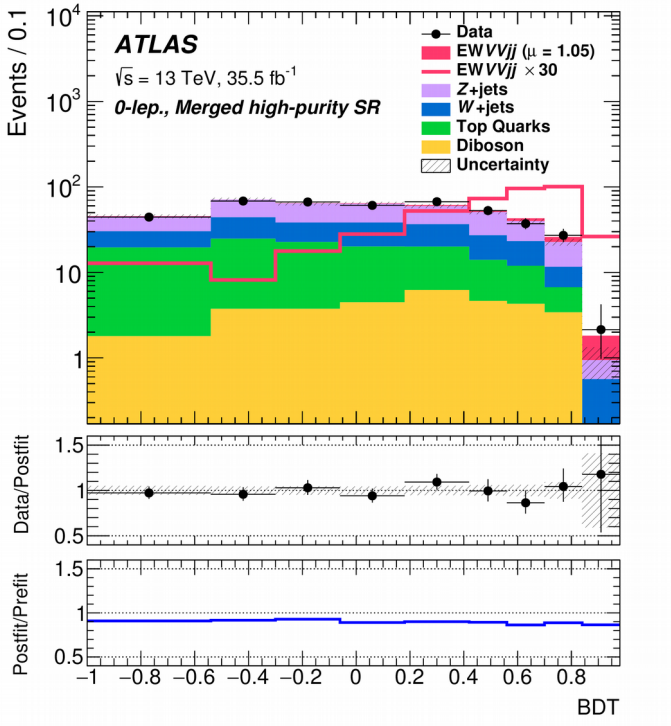
$$1.05^{+0.20}_{-0.20}\,(\text{stat.})^{+0.37}_{-0.34}\,(\text{syst.})$$

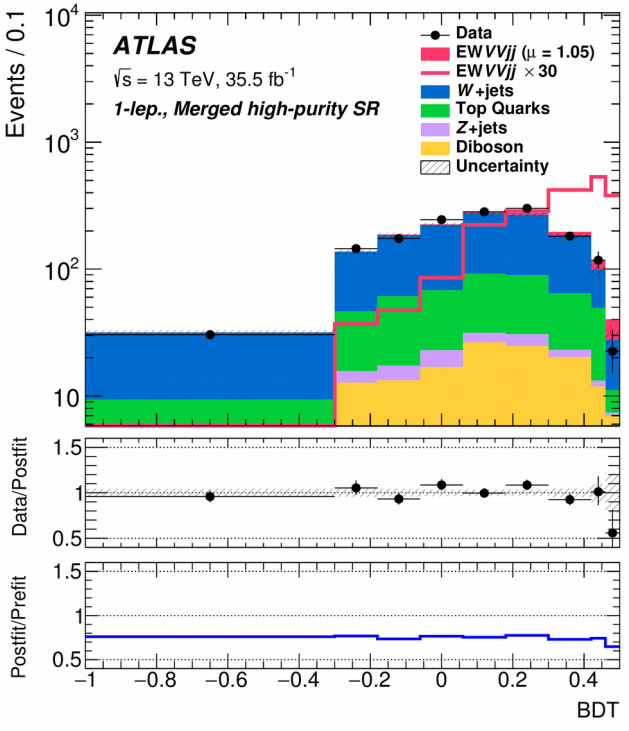
- Background only hypothesis rejected with significance 2.7 σ (expected 2.5 σ)
- EWK fiducial cross-section

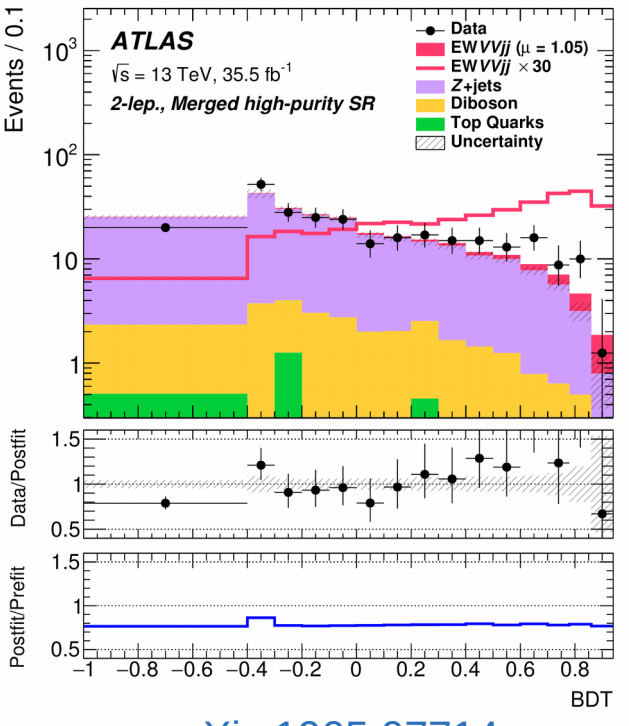
$$45.1^{+8.6}_{-8.6}\,(\text{stat.})^{+15.9}_{-14\,6}\,(\text{syst.})\,\text{fb}$$

- Extensive combined fit (21 signal/control regions)
- Still **waiting for evidence**









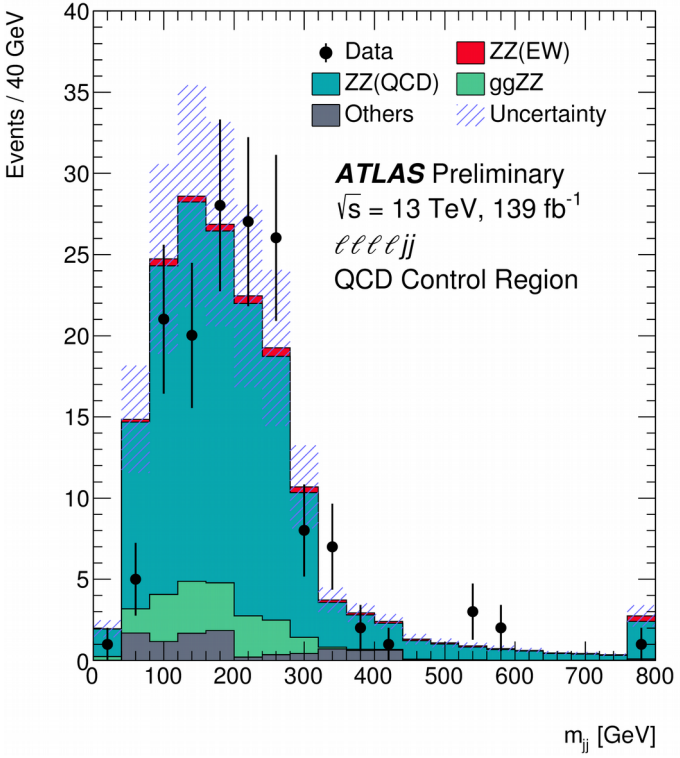
arXiv:1905.07714

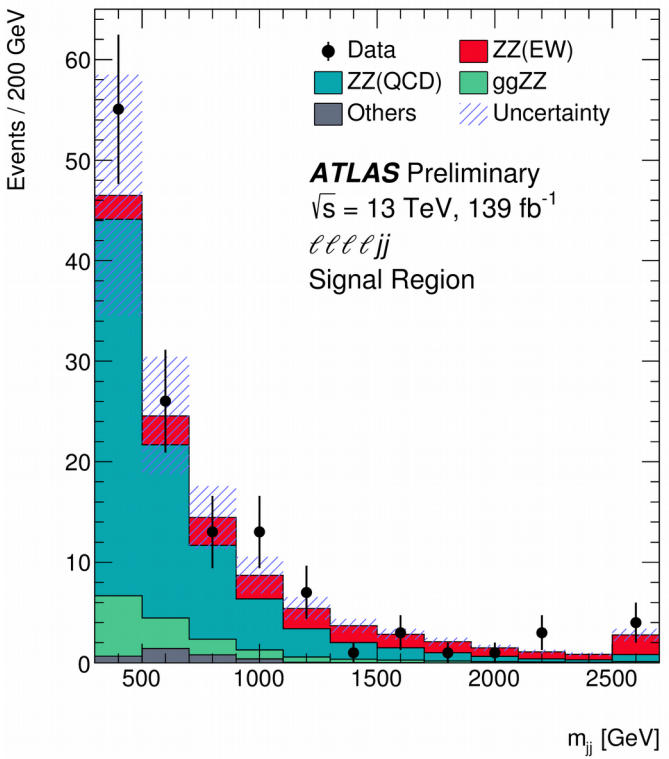
ZZ – VBS “Golden” Channel

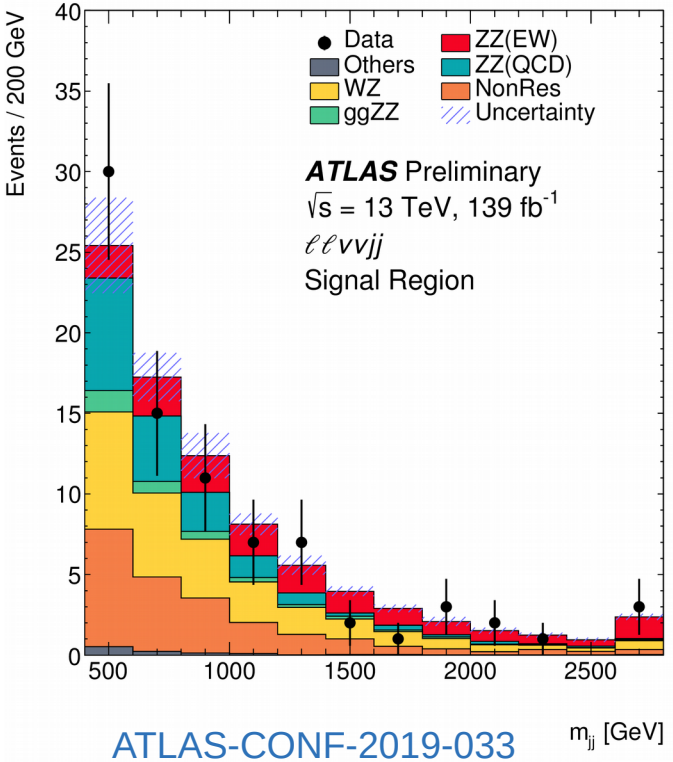
NEW!

- VBS final states: $\ell\ell\ell\ell$ + jj, $\nu\nu\ell\ell$ + jj
- Dataset: 139 fb^{-1}, 13 TeV
  - First VBS analysis of full Run 2 of LHC
- Expected significance: 4.3 σ
- MVA: TMVA Gradient BDT, 14 variables
- 2 signal regions, 1 control region (only $\ell\ell\ell\ell$)

- Background
  - $\ell\ell\ell\ell$
    - Dominant: ZZ+jets (QCD)
    - Otherwise very clean channel (3%): misidentified leptons, Z+jets, $t\bar{t}$, WZ+jets
  - $\nu\nu\ell\ell$
    - Dominant: ZZ+jets (QCD), WZ+jets, WW+jets
    - $t\bar{t}$, Z+jets



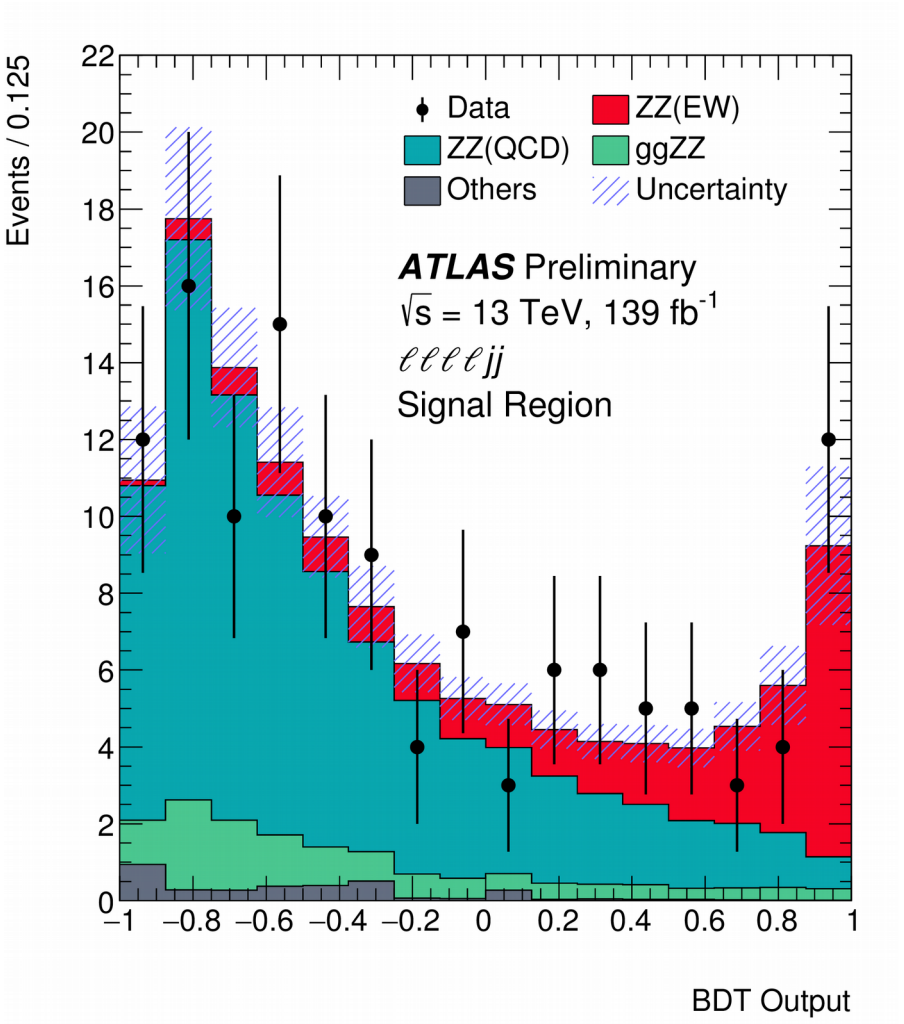


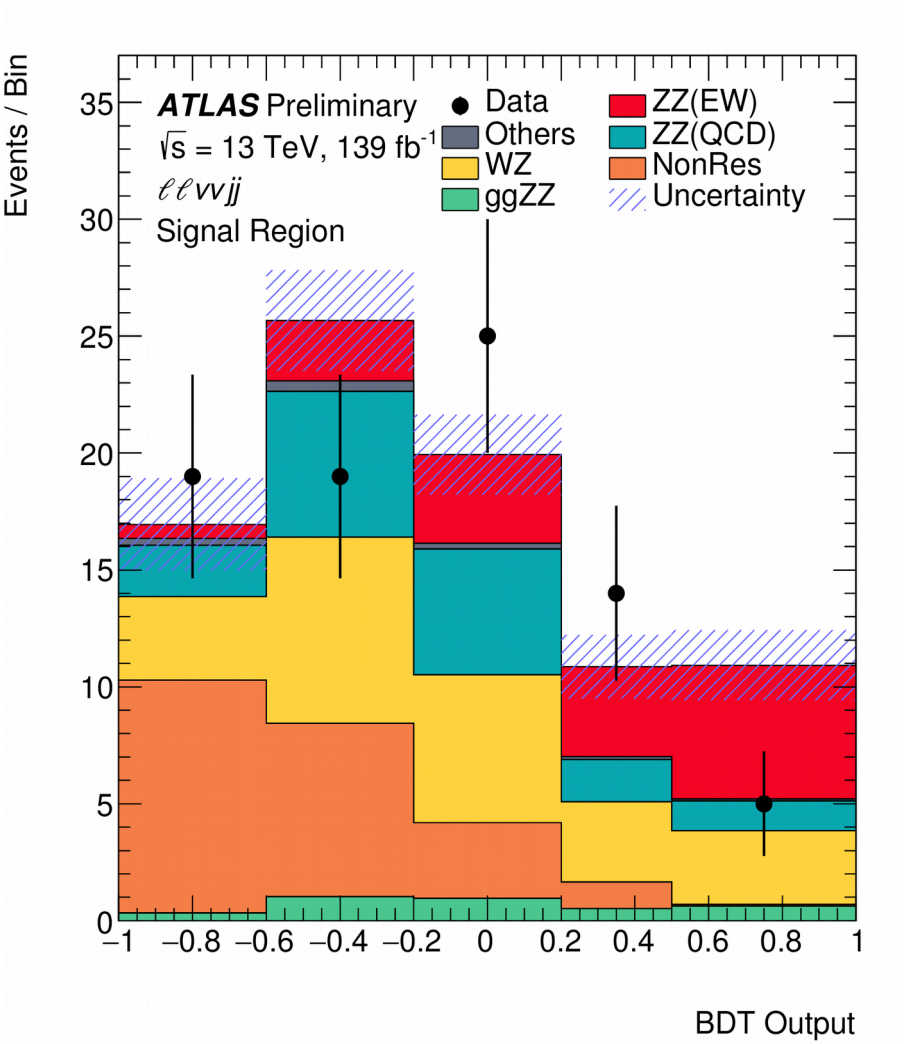


ATLAS-CONF-2019-033

ZZ – Results

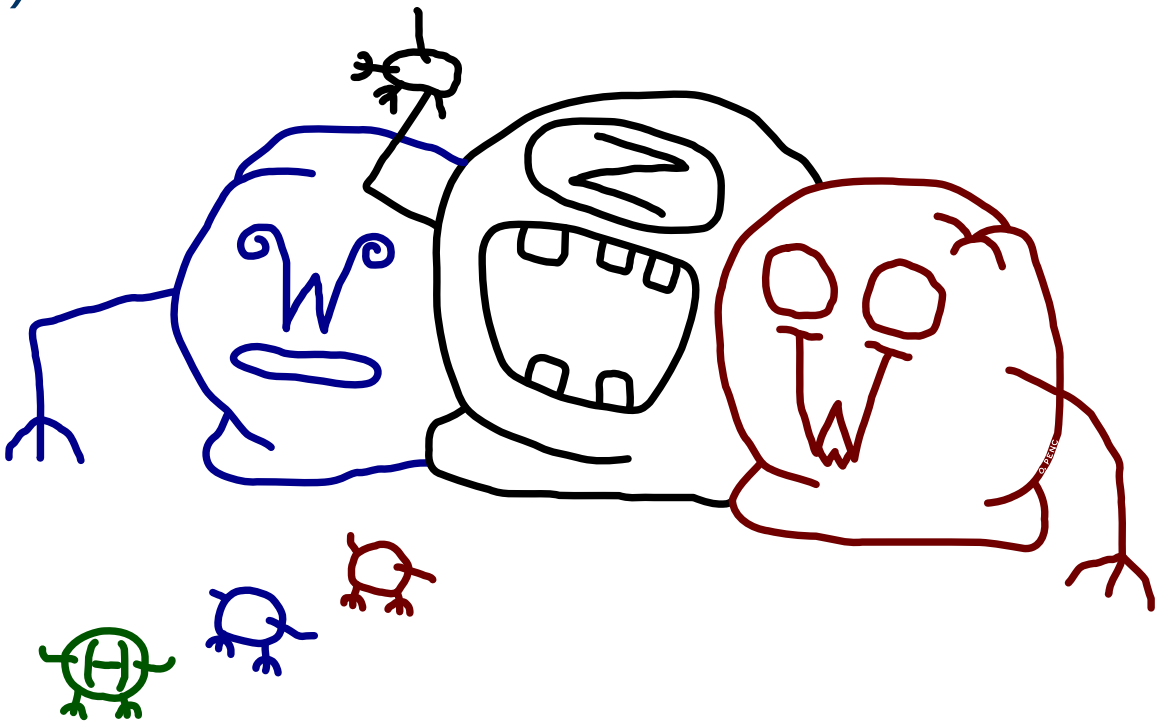
- EWK signal strength 1.35 ± 0.21
- Background only hypothesis rejected with significance 5.5 σ (expected 4.3 σ)
- EWK fiducial cross-section $0.82 \pm 0.34\,\text{fb}$
- ZZjj EWK production **observed**





Summary

- ATLAS Vector Boson Scattering
  - Observation in **all leptonic channels** WW, WZ, ZZ
  - Waiting for evidence in VV semi-leptonic channel
  - Latest observation in the ZZ channel in full Run 2 (139 fb^{-1})
- Beyond the Standard Model
  - No obvious disagreement with standard model observed
  - Limit settings of the anomalous Quartic Gauge Couplings are ongoing
- Outlook
  - Full Run 2 still offers the further studies and measurements of the VBS phenomena
    - Semi-leptonic channel
    - Channels including gamma
    - Polarization studies



BACKUP

Resonant Shape Algorithm

- Used for WZ VBS channel
- arXiv:1603.02151

- Based on value of the following estimator

$$P = \left| \frac{1}{m^2_{(\ell^+,\ell^-)} - \left(m_Z^{\mathrm{PDG}}\right)^2 + i\,\Gamma_Z^{\mathrm{PDG}}\,m_Z^{\mathrm{PDG}}} \right|^2 \times \left| \frac{1}{m^2_{(\ell',\nu_{\ell'})} - \left(m_W^{\mathrm{PDG}}\right)^2 + i\,\Gamma_W^{\mathrm{PDG}}\,m_W^{\mathrm{PDG}}} \right|^2$$

- Input
  - Mass of all possible di-lepton and neutrino-lepton pairs
  - PDG mass and width of W and Z bosons
- The best evaluated triplet is the WZ candidate
  - Highest *P* value
- Monte Carlo independent method