Overview of experimental multiboson results

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LHC EW General meeting

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Introduction

Multiboson measurements at the LHC: **Came a long way** since the early days
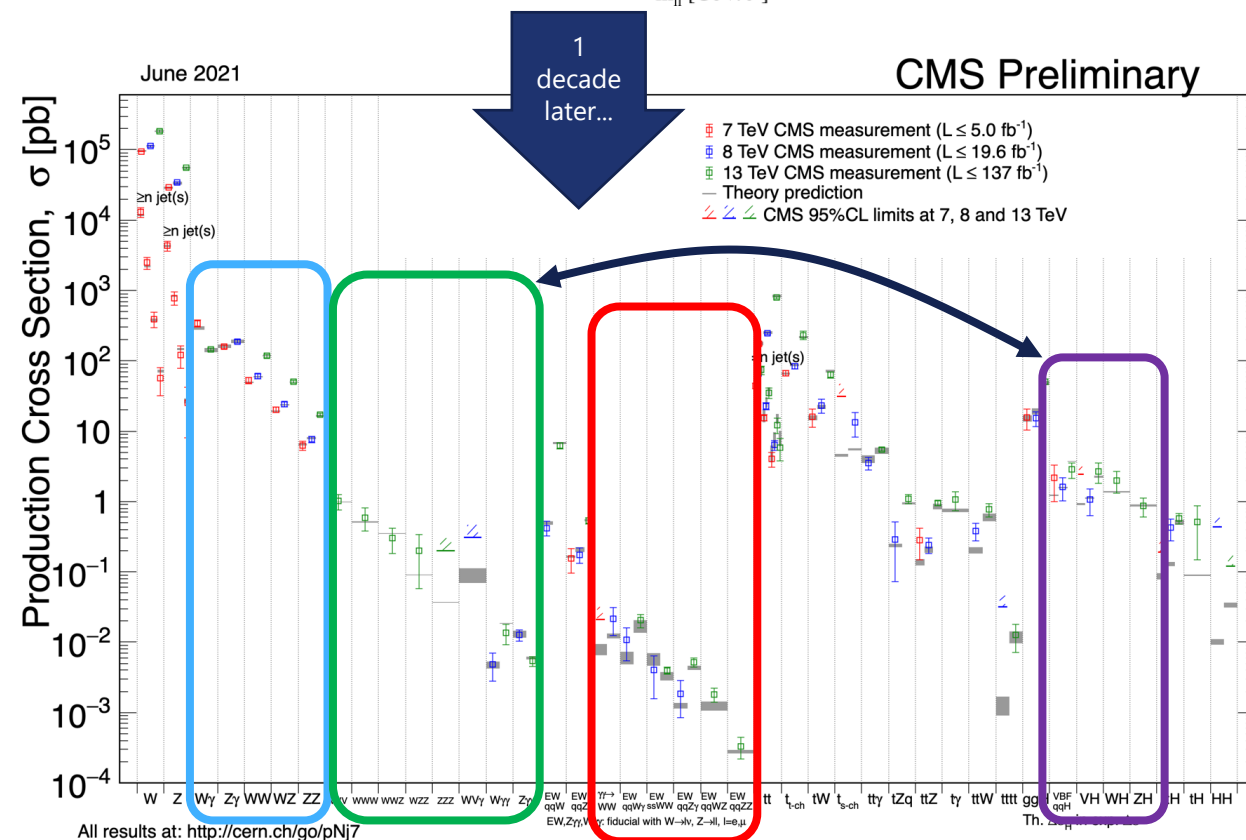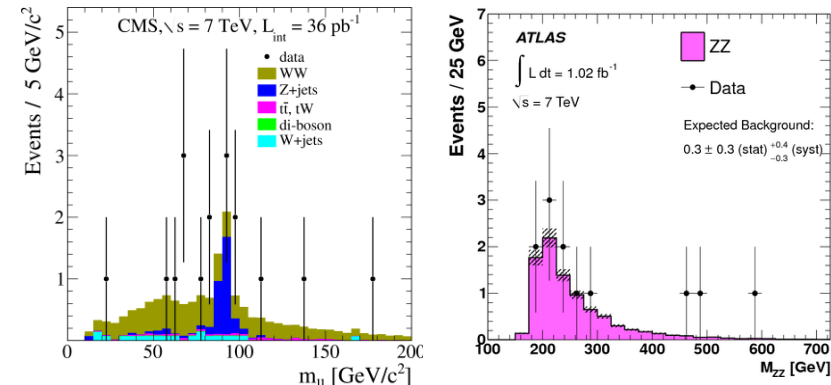
Today: Comprehensive suite of multiboson results

A few **key directions** for current efforts:

- Inclusive diboson production (agnostic of production mode)
  - Well established, **differential measurements** achieved
  - Background to other measurements
- Triboson production
  - Recently experimentally established
  - Strong interplay with **Higgs sector**
- Electroweak VVjj production
  - Interest in Vector-boson scattering, triple/quartic gauge couplings
  - Probe of EW sector
  - Competition / interference with **strong production**
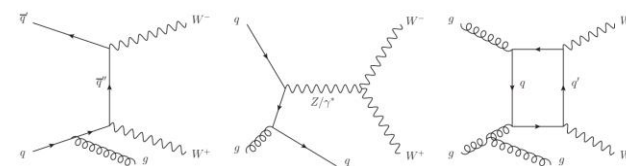 - Some overlap with **triboson** ("s-channel VVjj")

This talk:
Summary of recent results with **focus on theoretical limitations / hindrances / problems**
Not going to cover interpretations (EFT, aTGC/QGC, etc) – time!
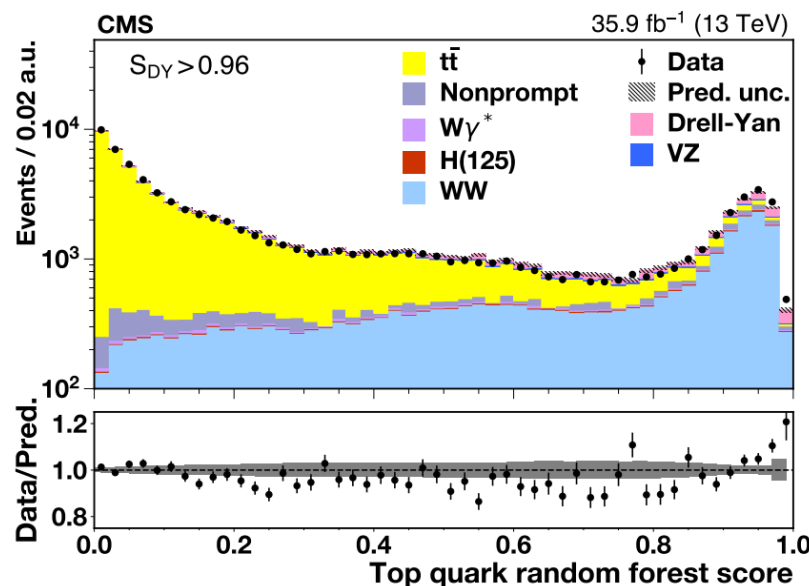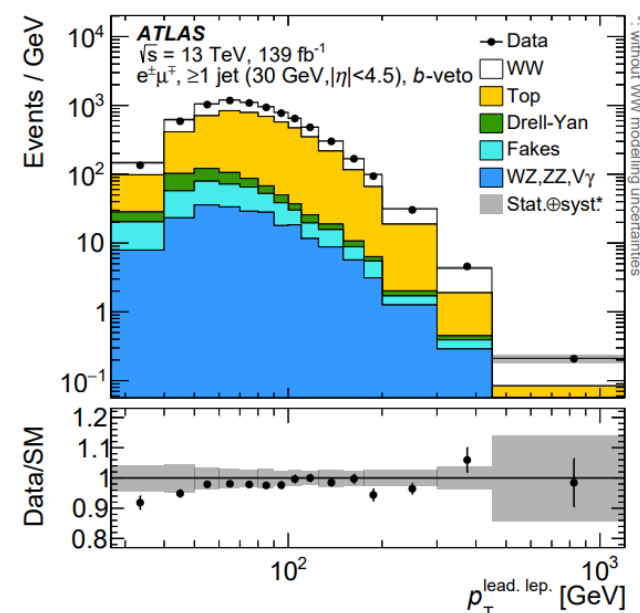
Differential WW

WW measured **differentially** by ATLAS and CMS using partial and full (ATLAS) run-2 data

- Exploit **leptonic** WW decay modes – dominant backgrounds: **top**, **DY**
  - Suppression strategy includes **b-veto**, **DF lepton pairs**, Z-veto (for SF)

Measurements becoming **more inclusive** over time:

Jet veto (ATLAS, 36/fb) → 0,1j cut-based + MVA jet multiplicity (CMS, 36/fb) → inclusive 1+jets (ATLAS full R2)

CMS: Use of a **MVA** (random forest) discriminant to improve purity for jet multiplicity measurement
→ Price: Increased sensitivity to **WW p_T modelling** uncertainties.
→ "Classical" cut based approach used for remaining fiducial XS measurements (0/1j)

ATLAS: Lower purity than CMS

- precise data-driven *differential* estimate of top background using in-situ b-efficiency measurement
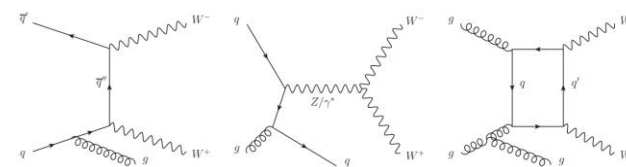
Differential WW
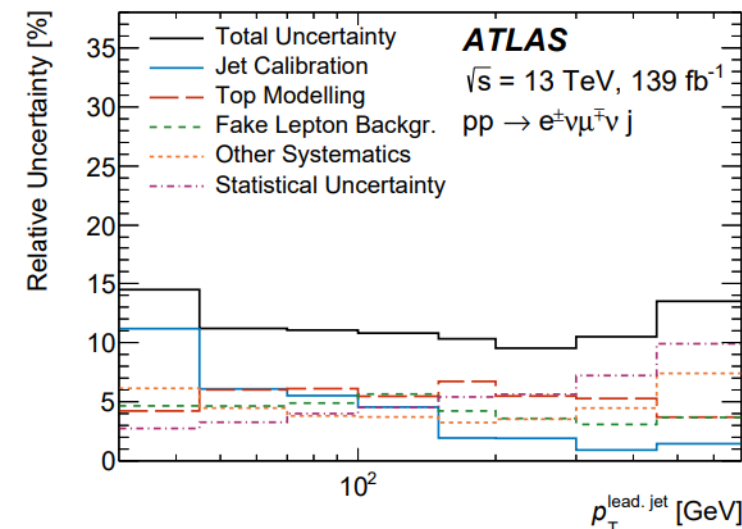
Inclusive and differential **cross-sections** extracted
- Unfolding methods vary across experiments
- ATLAS: Bayesian iterative
- CMS: Likelihood unfolding and matrix inversion for N_{jets}

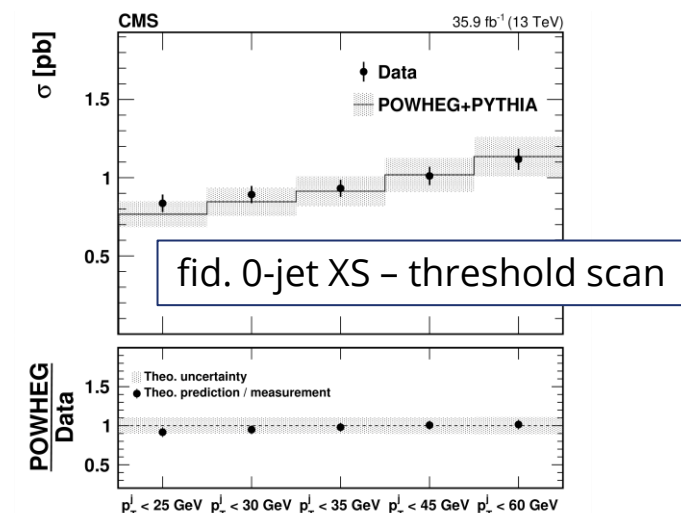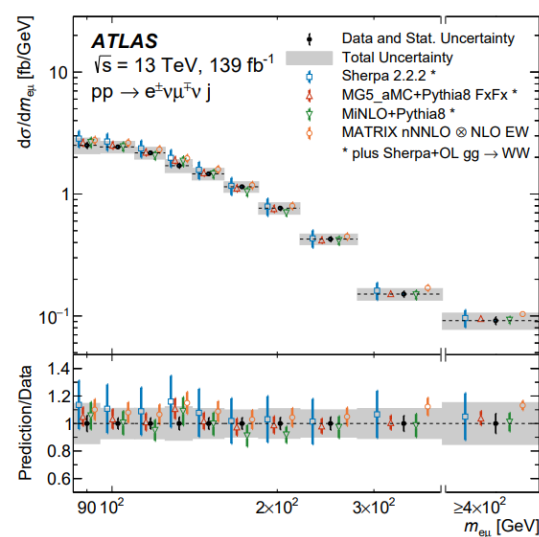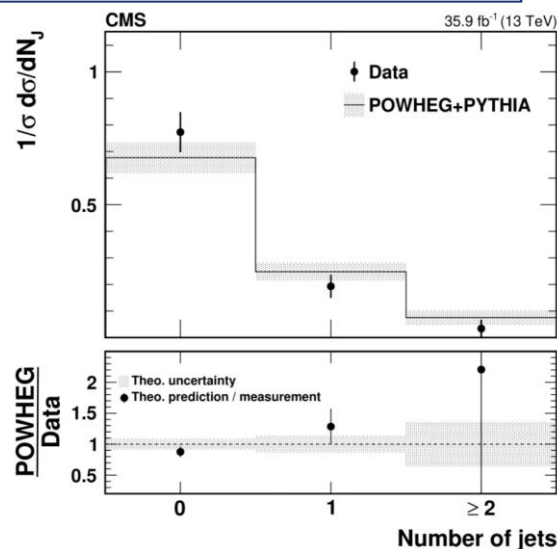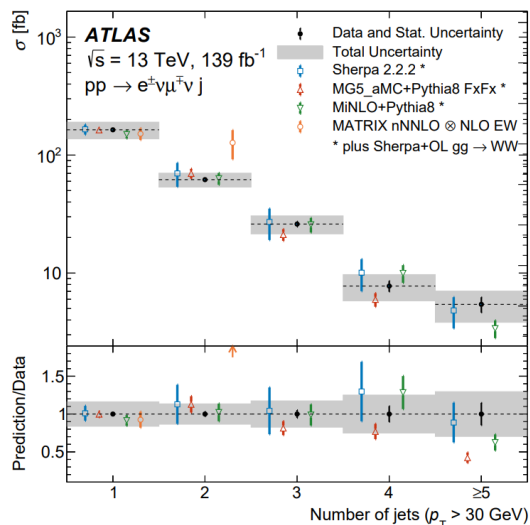High available statistics: Measurements becoming **systematically** limited
- Main uncertainties currently **experimental** – in particular **jet calibration**
- Could profit from advances in **top modelling** – dominant background
  - Partially mitigated by use of data-driven techniques
- Impact of signal modelling: Comparable to statistics for total XS (CMS), but below experimental sources
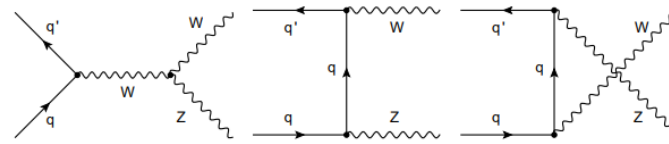

ATLAS Sherpa errors: Scale uncertainties (2+3j @ LO ME)

fid. 0-jet XS – threshold scan

Differential WZ

Measurements exploit **3l** final state

- High purity – main backgrounds: ZZ (missed lepton), ttZ,tZq + non-prompt leptons
  - Data-driven non-prompt leptons, other backgrounds normalized to data in control regions
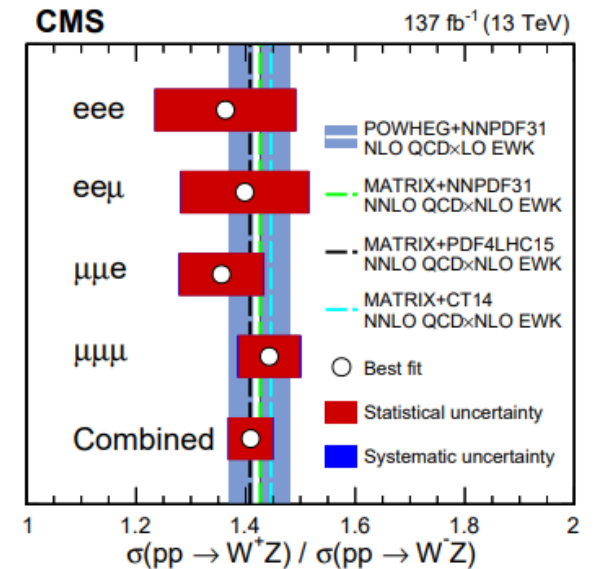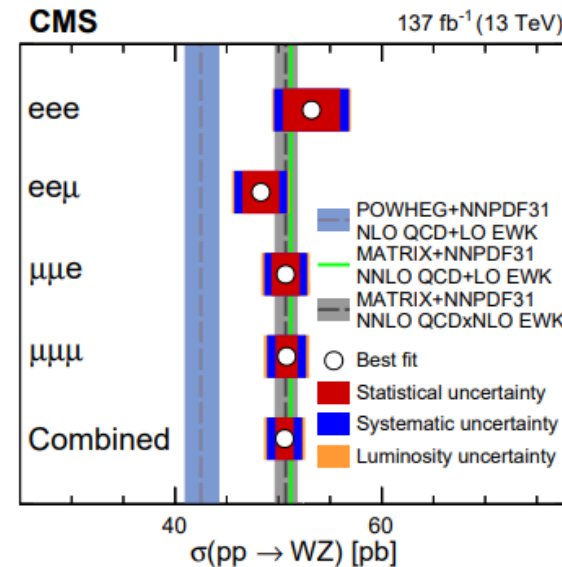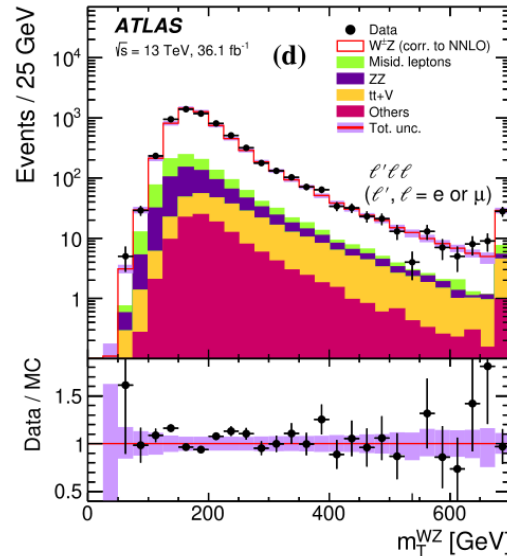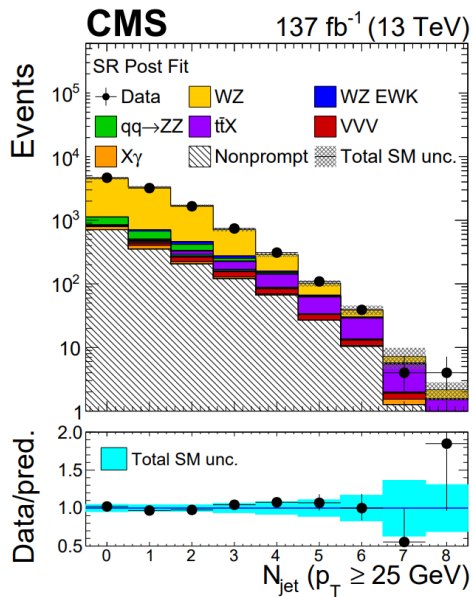
Measured **fid and total XS** well predicted by NNLO QCD+NLO EW calculations

- Consistent across experiments
- Uncertainties limited by (experimental) systematics - negligible impact of theory on fid. XS extraction
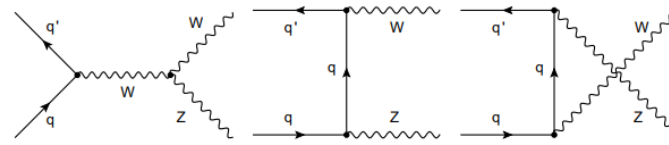
Extraction of **charge asymmetry** – major cancellation of uncertainties.

- Allows to probe PDFs

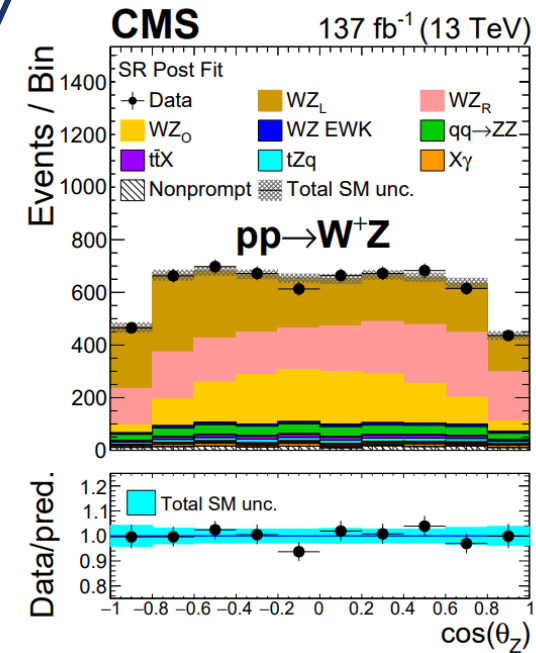ATLAS results comparable – showing CMS (larger sample)

Differential WZ

Extraction of **polarization** fractions using MC templates
- Templates generated by reweighting in full phase-space (analytical description)
- Presence of longitudinally polarized W/Z observed at > 5σ at CMS
  - 4.2σ evidence at ATLAS with partial data
  - Use W mass constraint to resolve escaping neutrino

Extraction of **differential XS** by both collaborations

ZZ (and inclusive 4-leptons)

ZZ (4l): High-purity final state

• Main backgrounds: non-prompt leptons, ttV, triboson

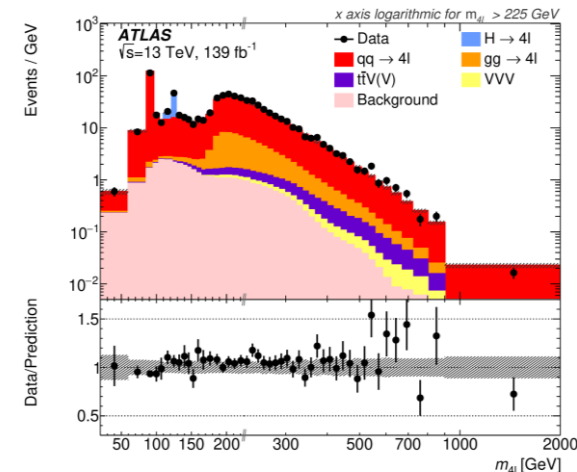Interesting: **Complementary** approaches in most recent publications:

• CMS: Focus on ZZ production, ATLAS: Inclusive 4l production

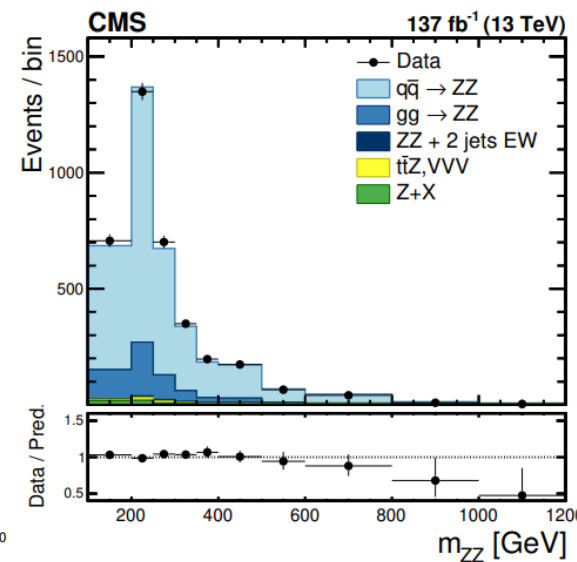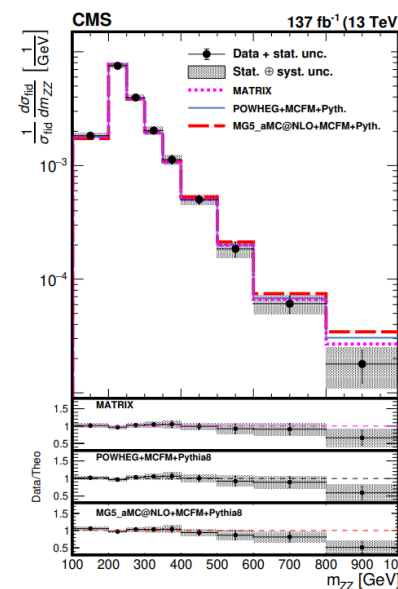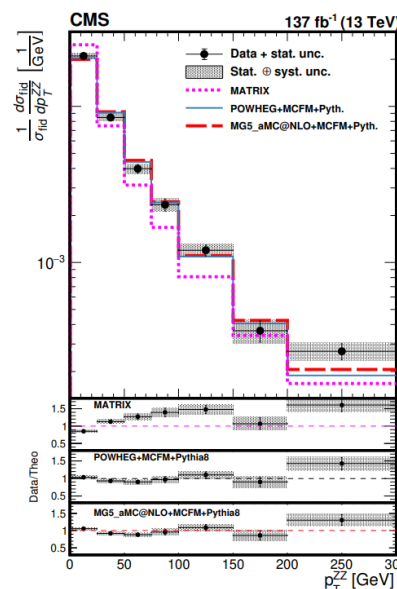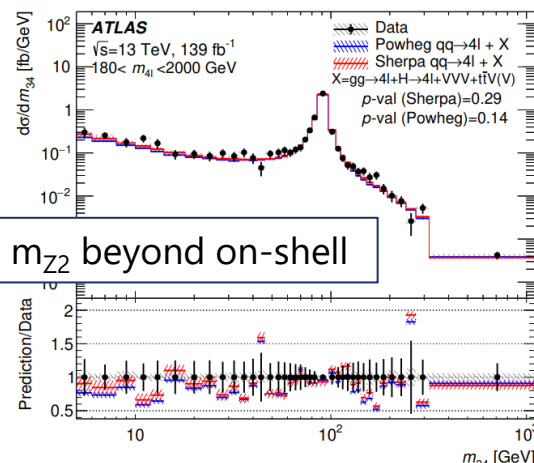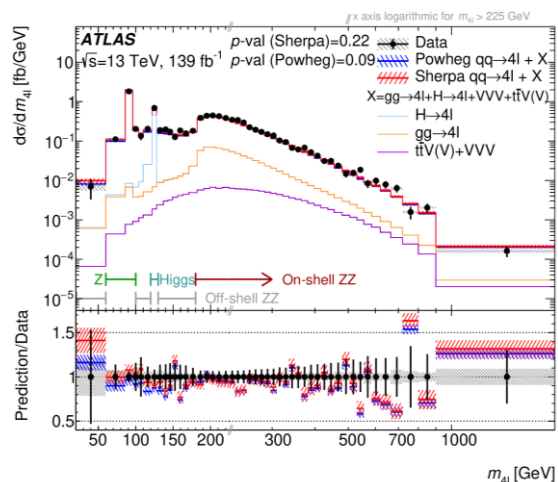**Fiducial** (and for CMS, total ZZ) XS extracted – compatible with SM

Differential cross-sections extracted using matrix inversion (CMS) or iterative Bayesian (ATLAS)

• Role of **NLO EW** corrections at high m_{4l}!

Complementary strategies!

m_{Z2} beyond on-shell

Detour: Off-shell Higgs production

Interesting feature in ZZ **continuum**: Effect of **s-channel Higgs** diagram

- **Destructive** interference with gg→ZZ – affects ZZ lineshape at high mass
  - Most pronounced above $2m_{top}$
- Sensitive to **off-shell Higgs** signal strength
  - Under certain assumptions: Use to constrain **Higgs width**

Recent CMS result: **First evidence** for off-shell Higgs contribution

- Combination of 4l and 2l2v
- Sensitivity enhanced using matrix element discriminants

Theory uncertainties on **ZZ production**: Among the **leading systematics**

- Both qq→ZZ and (higher-order) **gg→ZZ** – hard to constrain using data
- Use of jet information (VBF Higgs): Jet modelling in ZZ production
- → Advances will benefit future measurements

absence of s-chan would **enhance** rates

Triboson observations

First **massive triboson observation**: CMS, combining WWW/WWZ (+WZZ/ZZZ)

- Using SS2L / 3L for WWW; 4L for WWZ, 5/6L for WZZ/777
- Discovery driven by WWW/WWZ (3.3/3.4σ)

Recently: **Standalone WWW observation** in ATLAS

- Again, combination of SS2L and 3L channels
- 8.0 (5.4) σ observed (expected)
- Measured signal strength ~2.6σ above NLO QCD – still within CMS errors

A few **common features / challenges**

- **WZ diboson** now a **background** – non-negligible modelling uncertainty
  - Though (still) statistically limited
  - Partially mitigated by normalization to data (CRs)
  - Second leading systematic – behind non-prompt background
- Important role of s-channel **WH➔WWW*** production in interpretation
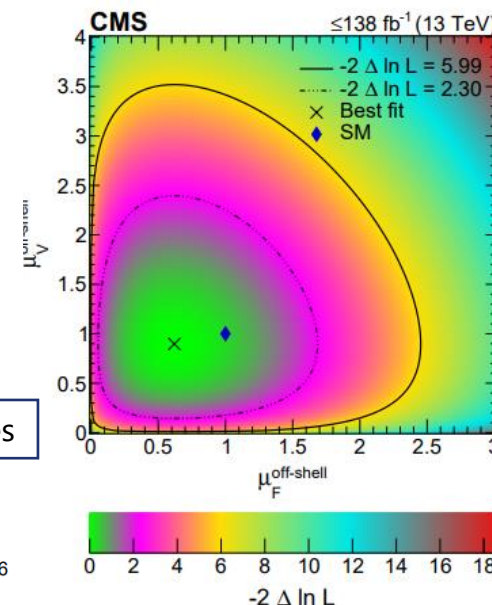 - Depending on analysis, 30-40% of total triboson yield
- Discovery sensitivity enhanced by **multivariate discriminants** (BDT) in both analyses

Role of **WZ /ZZ** as a **background** process!

Electroweak production – VBF / VBS

Of particular interest: **Vector boson scattering**
- Important role of triple / quartic gauge couplings
- Sensitive to EWSB, close relation to Higgs sector

Even at LHC luminosities, **rare process**
- Typically, $O(\alpha_{EW}^4)$ x decay BR

'Classic' signature: **VBS jet topology**

- Two forward jets in opposite hemispheres, high m_{jj}, little jet activity in rapidity gap

- Challenge for modelling – in particular when fitting m_{jj} or vetoing gap jets

Strong VV+jj production is now a **key background**

- ➤ Jets either from **hard scatter**, or (rarely) from **pileup** activity

- Gives rise to **modelling uncertainties** for EW signal extraction

- **Interference** with the EW signal

Suppressing QCD diboson – same-sign WW

Same-sign WW: Strong production suppressed to $\mathcal{O}(\alpha_S^2)$

➤ EW process more enriched than in other channels

- **Observation** already achieved in both experiments - using partial Run-2 data

Key backgrounds: **WZ** (missed l.), non-prompt leptons, Vγ (conversions)
- Constrained using data-driven methods and MC normalization in control regions

Recent **CMS** result: Measurement of W **polarization fractions**

- Use of BDT to enhance longitudinal against transverse components
- Limits on $W_L W_L$, absence of longitudinal W disfavoured at 2.3σ

Even if strong WW suppressed: **Non-negligible theory uncertainties**

- Strong WW normalization and interference with EW component
- WZ modelling
- Acceptance and shape predictions for EW ssWW signal
- **NLO EW** corrections to signal – sizeable effects
  - Fairly recent – adoption still in progress

JHEP 10(2017) 124

Opposite-sign EW WW

Recent CMS measurement: WW VBS in *opposite-sign* final states

Very large ttbar background, strong WW more prominent as well

- Separation of flavor channels and use of MVA (NN) in eμ region maximises sensitivity
- DD estimate of non-prompt leptons and control-region normalisation of ttbar / DY

Significant **theory** contribution to uncertainties

- Scale uncertainties in ttbar background (NLO)
- Signal modelling for VBF

Observation established at 5.6σ – cross-section consistent with the SM

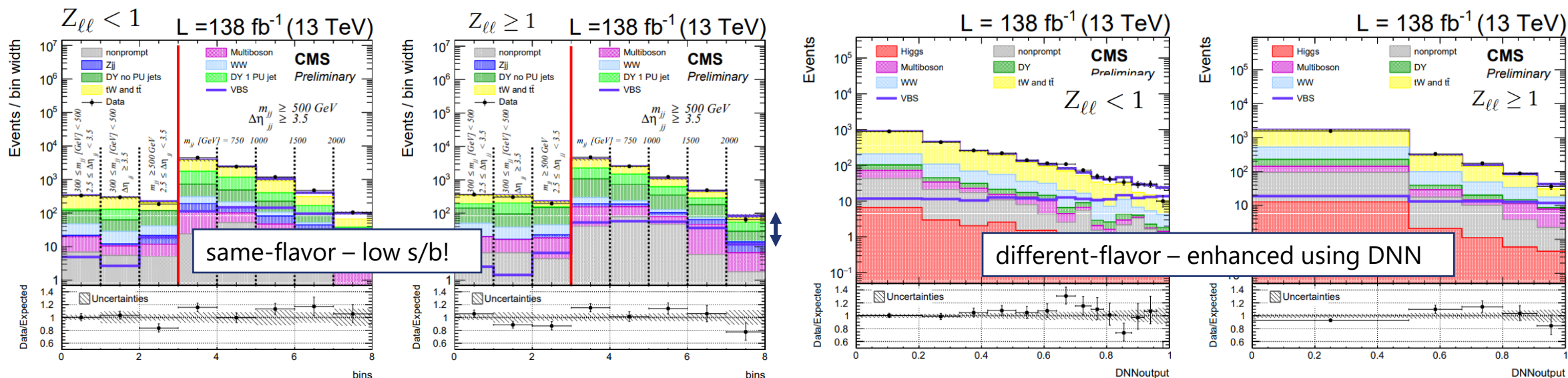| Uncertainty source	Impact
QCD-induced W^+W^- normalization	5.3%
$t\bar{t}$ QCD scale	5.1%
QCD factorisation scale for VBS signal	5.0%
$t\bar{t}$ normalization	4.9%
b tagging	3.5%
Prefiring corrections	3.3%
DY normalization	2.9%
Jet energy scale + resolution	2.6%
p_T^{miss} energy scale	2.4%
QCD-induced W^+W^- QCD scale	2.1%
Luminosity	2.1%
Muon efficiency	2.0%
Pileup	1.8%
Electron efficiency	1.5%
Underlying event	1.3%
Parton shower	1.0%
Other	< 1%
Total systematic uncertainty	13.1%
Total statistical uncertainty	14.9%
Total uncertainty	19.8%

same-flavor – low s/b!

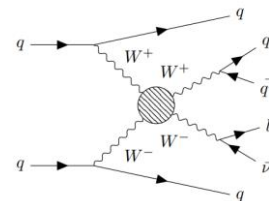different-flavor – enhanced using DNN
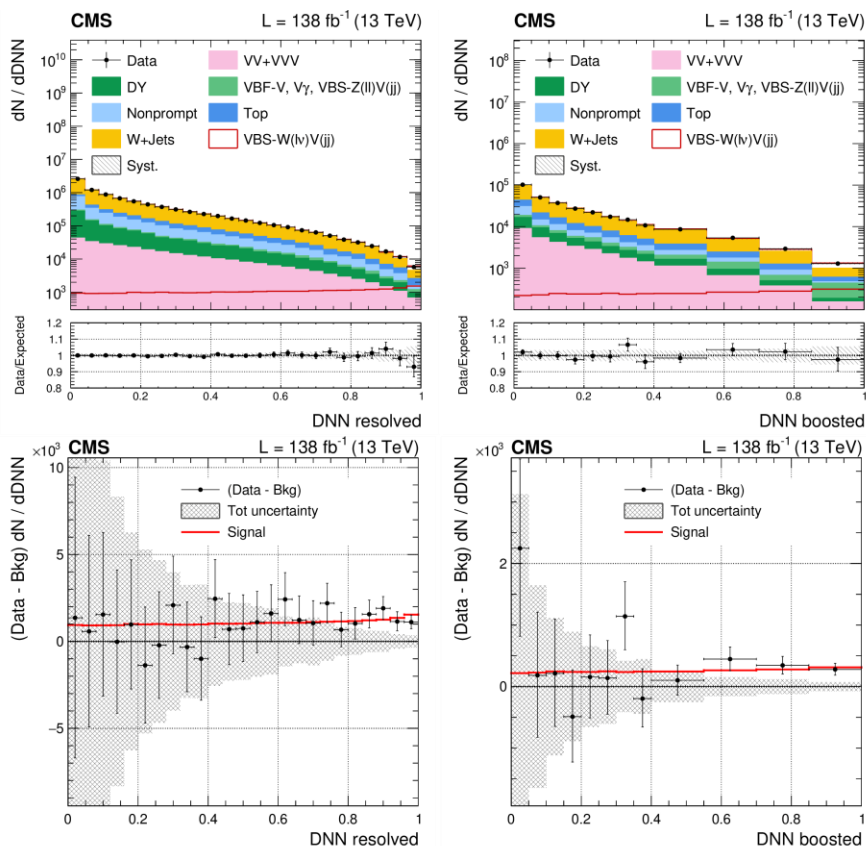
Electroweak WZ+jj

Electroweak WZ+jj **established** in **3l** final state by both experiments

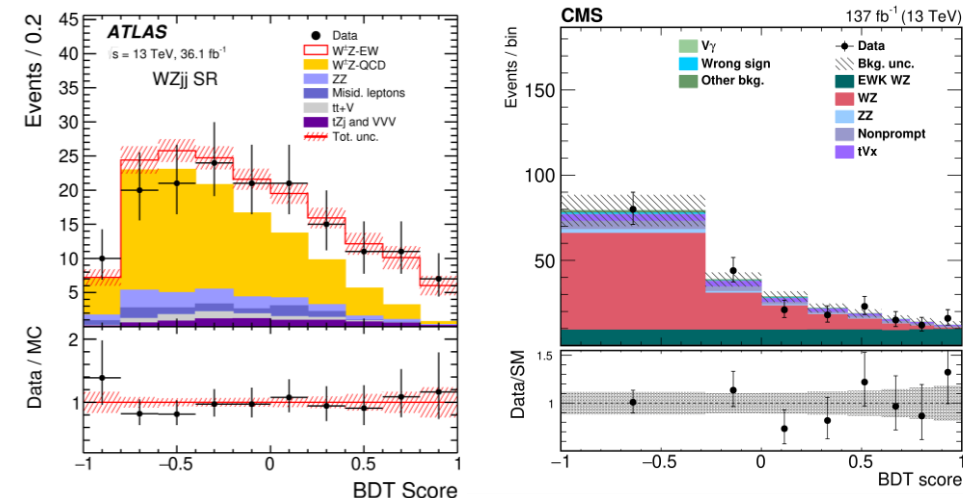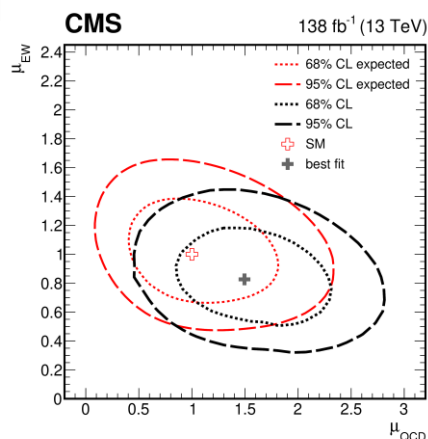- Use of MVA techniques (BDT) to enrich against strong production

Recent addition: First evidence of EW WZ in **semihadronic** final state

Uncertainty source	$\Delta\mu_{EW}$
Statistical	0.12
Limited sample size	0.10
Normalization of backgrounds	0.08
Experimental	
b-tagging	0.05
Jet energy scale and resolution	0.04
Integrated luminosity	0.01
Lepton identification	0.01
Boosted V boson identification	0.01
Total	0.06
Theory	
Signal modeling	0.09
Background modeling	0.08
Total	0.12
Total	0.22

Semihadronic search: Combine **resolved 4-jet** with "boosted" **dijet + large-R jet** topologies

- Large W+jets and top backgrounds
- Signal enhancement using **DNN** classifiers

Result: 4.4 σ evidence of EW process.

- Also perform simultaneous measurement with strong process

Again: **Large theory uncertainties** – above experimental and statistical sources

Electroweak ZZ+jj

Textbook example of strong vs EW separation problem: **EW ZZ**

- 4l final state dominated by **strong** + EW ZZ
  - EW enhanced against strong using **multivariate** discriminants (ME for CMS, BDT for ATLAS)
  - ATLAS: Addition of **semileptonic** (llvv) decays to the search
    - WZ, top, WW background from MC, normalized to data
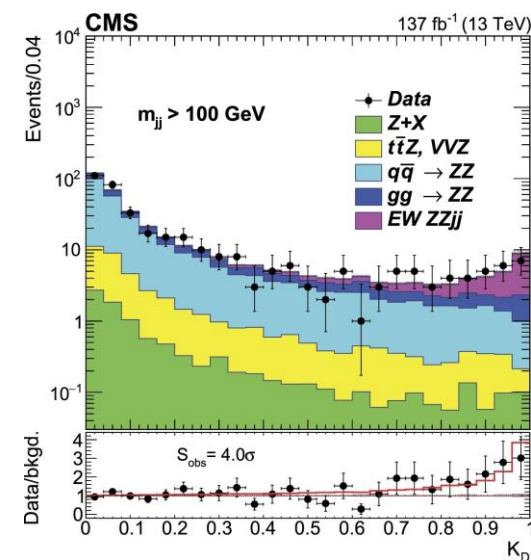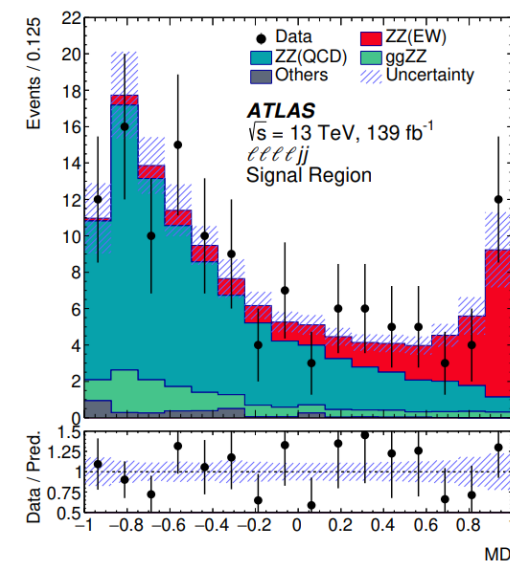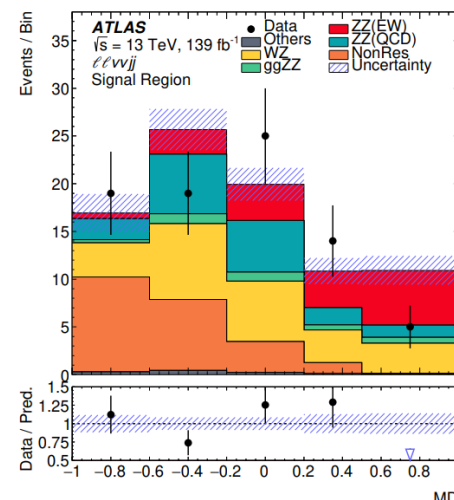
EW signal successfully extracted:

- **Evidence** (4.0σ) at CMS
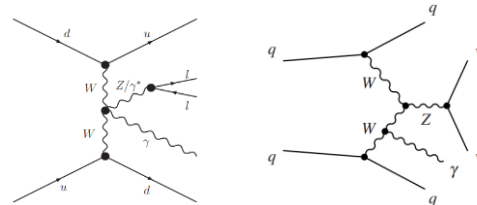- **Observation** (5.5σ) at ATLAS

with fiducial cross-sections **consistent with SM**

Currently, **statistically** limited

- However: ZZ modelling among top systematics
  - Both for EW signal and for QCD process
- Again, sizeable NLO EW effects predicted
- Stand to profit from modelling advances as Run-3/4 dataset is collected

Electroweak Zγ

Recent results in **EW Zγ**:

- **2-lepton** decay mode **observed** by both experiments

- **invisible** Z decay **observed** by ATLAS

Key non-diboson background: **Z+jets** with non-prompt photon

- Estimated using **data-driven** techniques in both experiments

- For invisible decay: Additional background from W decays
  - Lost leptons – constrained by control region data

Enrichment against **QCD** production using **m_{jj}** spectrum

- All measurements observe signal strength **consistent with SM**

CMS: **Differential measurements** using likelihood-based unfolding

Common feature: **Large theory uncertainties**

➢ Dominant source besides statistics and jets (CMS)

➢ Split ~equally between strong and EW modelling

A different approach to VBS – **photon-induced** WW

Photon-Photon scattering: Can leave **initial protons intact**

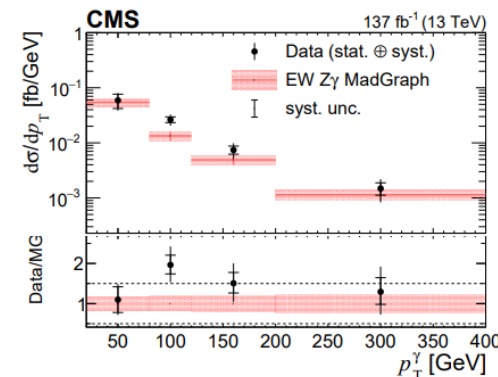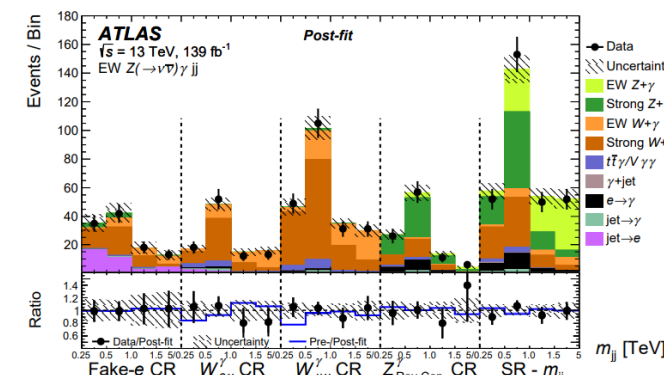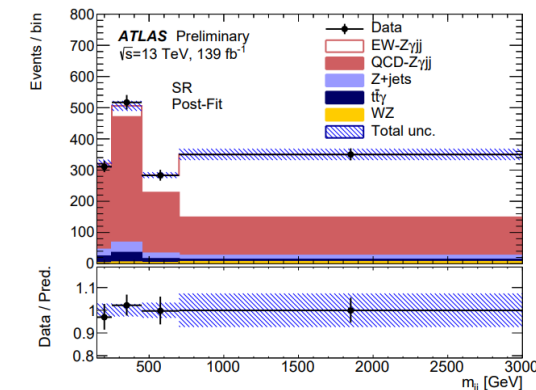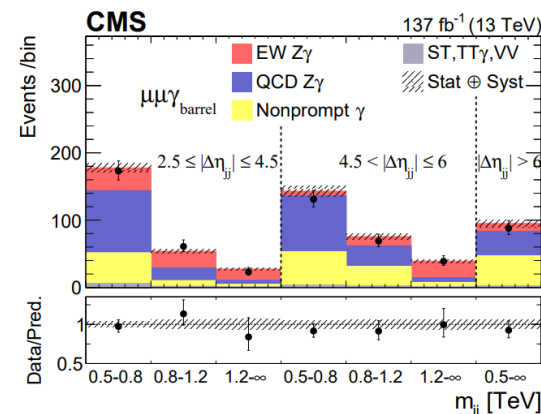**Unique topology**: Initial protons either escape intact or fragment outside tracking detector acceptance

➤ Signature of W decay products in **isolation of other charged-particle activity**

Strategy based on **track counting**:

Count **additional charged tracks n_{trk}** within **1mm** of the lepton pair vertex

➤ Select **signal** by **vetoing** additional tracks (n_{trk} =0)

Requires **excellent understanding** of pileup and underlying event properties!
- Pileup tracks: Reduce signal efficiency
- Underlying event: Determines background rates

Data-driven corrections to simulation to describe collision data

➤ Dedicated auxiliary measurement of **charged particle production** in Z->ll as function of boson p_T

ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
70 GeV < m_{ll} < 105 GeV

Data (Total uncertainty)
DY Sherpa
DY Powheg+Pythia8
DY Powheg+Herwig7

$\frac{1}{N_{ev}} \frac{dN_{ev}}{dn_{ch}}$

MC / Data

Number of charged particles, n_{ch}

A different approach to VBS – **photon-induced** WW

[Phys. Lett. B 816 (2021) 136190](#)

Main surviving background after selection: Strong **WW** production

- Further sources: Non-prompt leptons and DY (tautau)
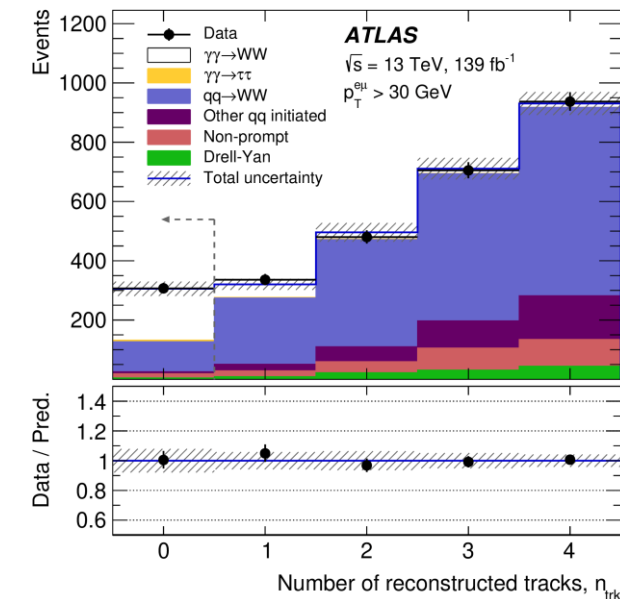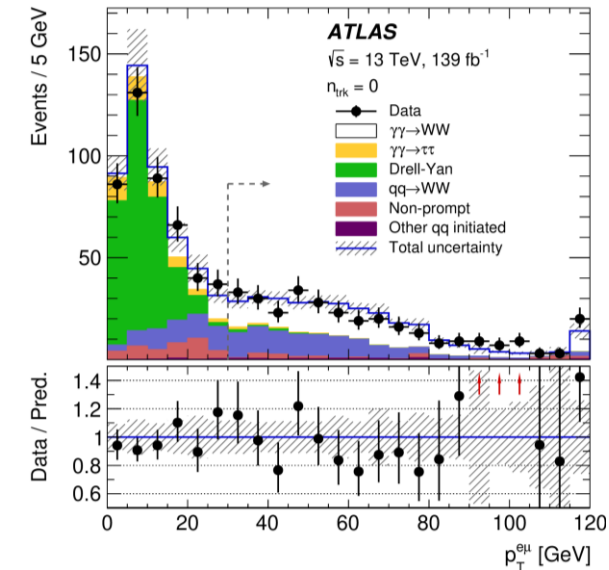 - Data-driven estimate of non-prompt, constraint of DY to data in low-p_T CR

Observe photon-induced process at **8.4σ**, signal strength (1.33) **compatible** with **SM** prediction

Resulting **fiducial cross-section** of 3.13 ± 0.31 (stat.) ± 0.28 (syst.) fb agrees with predictions after accounting for dissociative contributions and survival factor

Uncertainties include non-negligible **theory** component

- Signal and **strong WW** modelling
- This time: From underlying event rather than jet observables

Further potential for this type of measurement – e.g. proton tagging

Summary

Rich diboson programme established at the LHC – barely able to scratch the surface in this talk!

From a modelling perspective: **Inclusive diboson** measurements fairly "safe"
- Experimental uncertainties tend to dominate over modelling for direct measurement
- Improved modelling still beneficial: Role as **background** in other measurements
  - Both within the diboson area and outside (BSM searches, Higgs)

Triboson searches see inclusive dibosons as a **background**
- Depending on choice of sensitive observables, modelling can become a limitation with high statistics

Largest potential from modelling improvements: **Electroweak** and **VBS** measurements
- Strong diboson production often dominant background
- Reliance on precise modelling of jet observables – both in EW signal and strong background
- Will profit as availability and adoption of higher-order signal corrections increases