Multiboson Production at the LHC

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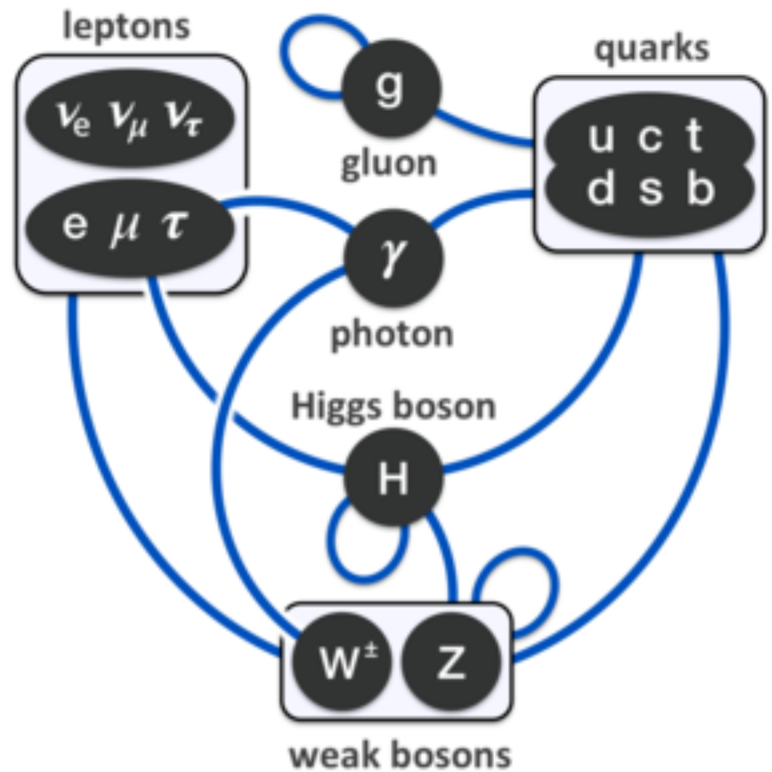
Physics Workshop At The LPC: Multibosons At The Energy Frontier

Multiboson Interactions

- Electroweak vector boson interactions
  - Interact with all the fermions
    - Except: photon – neutrino
  - Interactions between the vector bosons
    - Non-abelian structure
    - Interactions with the Higgs boson
    - Explains the observed behavior of the weak force
  - Many connections to new physics
- This talk: “QCD” production via radiation from quarks and/or TGC production



Multiboson Interactions are so complex that every diagram you find like this is wrong!
In this case the ZγWW vertex not represented

Multiboson Production Theory

- State of the art in cross section predictions:
- NNLO QCD
  - Total, fiducial and differential (example: MATRIX) with 3% uncertainty,
  - 10-20% corrections on the high energy tails (often positive) with 5-10% uncertainty
- Resumation: adds logarithmic accuracy
- NLO EW
  - 10-20% corrections on the high energy tails (often negative)
- MC generators
  - NLO QCD with PS and matching (examples: POWHEG or Magraph aMC@NLO with Pythia)
  - NLO EW with EW PS
  - NLO QCD+EW (in POWHEG BOW with Pythia)
- PDFs
  - NNLO accuracy
  - Improved treatment of initial state particles such as photons (important for NLO EW)
- In development
  - NNLO QCD + NLO EW
  - General framework with NLO QCD+EW with PS
  - N3LO?

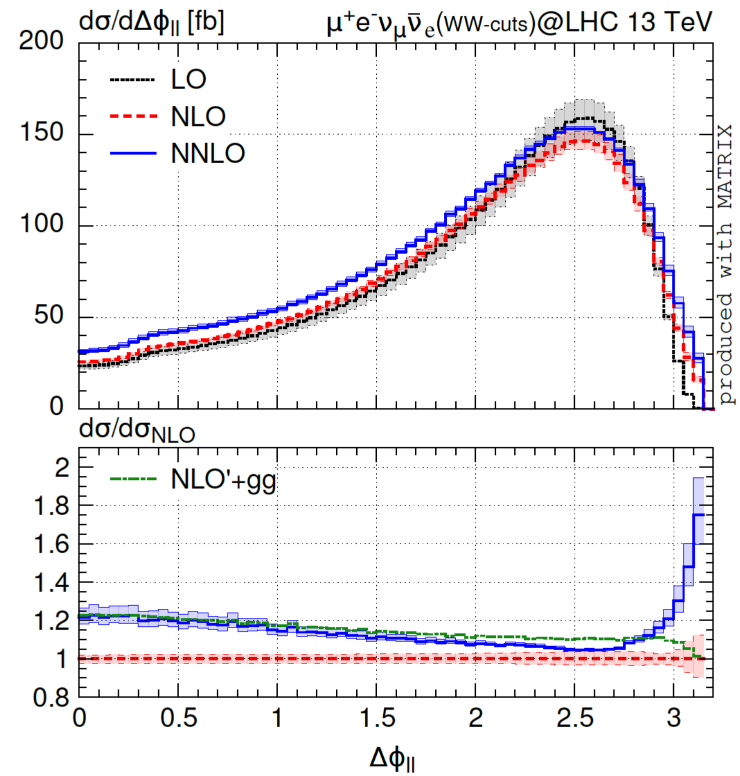
MATRIX: hep-ph 1711.06631
Grazzini et. Al.

NLO EW with PS in VV:
hep-ph 1906.01863 Denner et. Al.

NLO QCD+EW with PS In VH:
hep-ph 1706.03522 Gramata et. Al.

What We Should Measure Now

- Total and Fiducial cross sections
  - With 2-3% uncertainty
    - Fiducial - lower uncertainty without extrapolation to total cross section
    - Theory frameworks allow comparison is specific phase spaces
- Unfolded differential cross sections
  - With 5-10% uncertainty
  - Concentration on interesting distributions!
  - pT V or VV mass tails
    - new physics sensitivity
    - NNLO QCD and/or NLO EW sensitivity
  - Distributions with NNLO contribution sensitivity
    - Angular variables between vector bosons or leptons
  - Number of jets and jet kinematics
    - Comparisons between LO fixed order with PS, NLO fixed order with PS, and NNLO predictions
    - Cross sections with Jet vetoes
    - dijet system kinematic variables
  - Variables with intrinsic physics content
    - Vector boson polarization
- I present a selection of these type of results



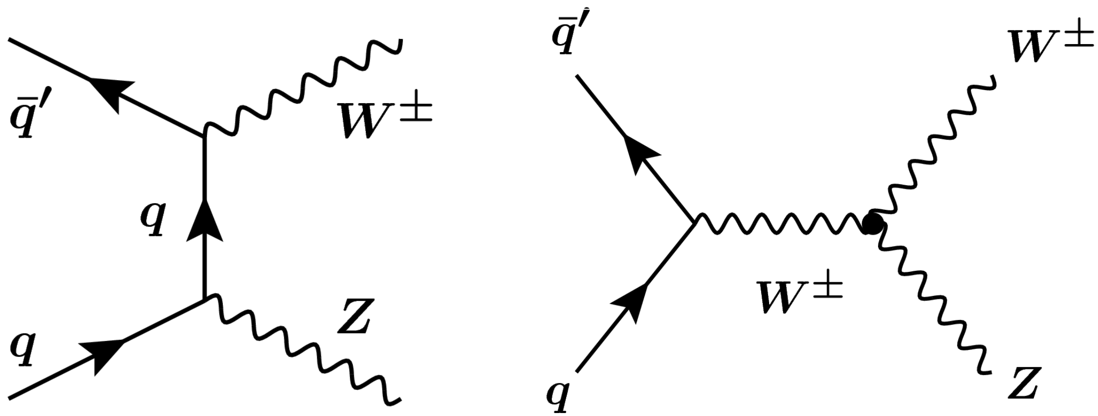
W+W- production: hep-ph/1605.02716
JHEP08(2016)140 Grazzini et. Al.

Total Cross Sections: WZ

- Example: ATLAS 8 TeV WZ analysis

ATLAS WZ: hep-ex 1603.02151
Phys. Rev. D 93, 092004 (2016)

  - Probes quark-boson and multi-gauge boson interactions
  - Production via combination of radiation and TGC diagrams



  - Precision cross section measurement feasible!
    - Reasonably low background
    - High statistics given background

Total Cross Section: WZ

- ATLAS 8 TeV WZ

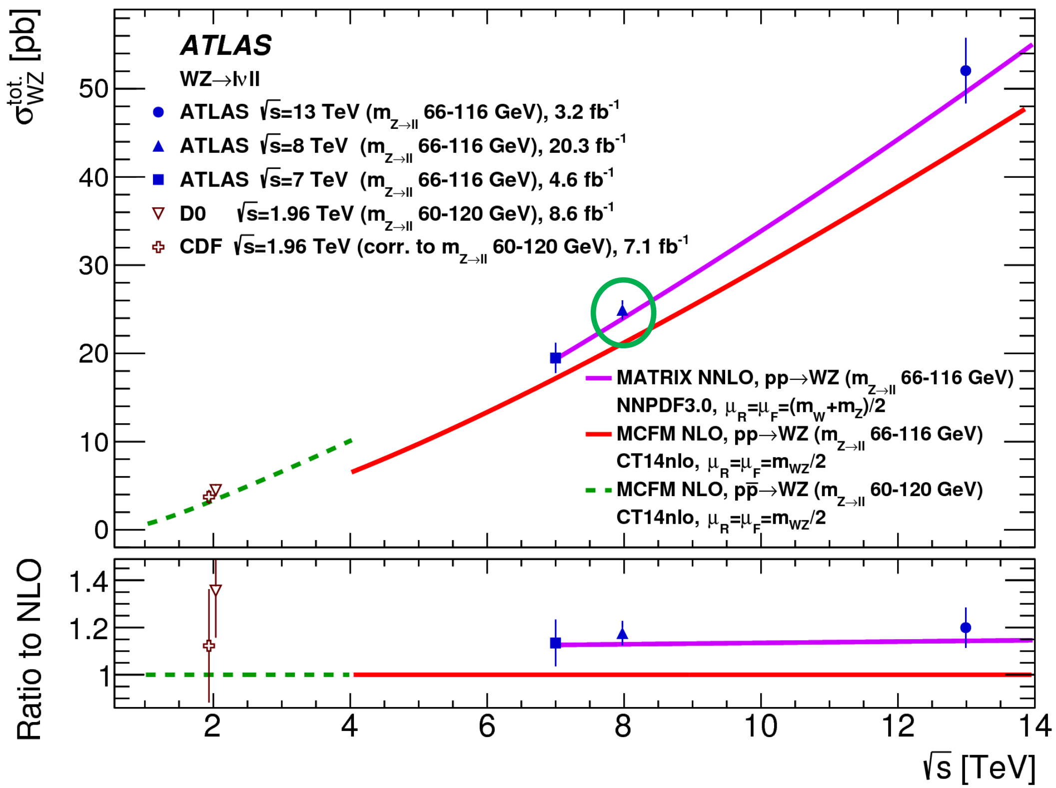
[ATLAS WZ: hep-ex 1603.02151](https://arxiv.org/abs/1603.02151)
Phys. Rev. D 93, 092004 (2016)

Fiducial cross section:
35.1 ± 0.9(stat) ± 0.8(syst) ± 0.8 (lumi) fb
35.1 ± 3%(stat) ± 2%(syst) ± 2%(lumi) fb
35.1 ± 4%(total) fb

Theory: MATRIX
35.6 +1.8%-1.9% (scale) fb
PDF not computed

[MATRIX WZ: hep-ph 1703.09065](https://arxiv.org/abs/1703.09065)
JHEP05(2017)139 Grazzini et. al.

One of the best precision LHC diboson measurements!



4% Uncertainty!

- ATLAS 8 TeV WZ

ATLAS WZ: hep-ex 1603.02151
Phys. Rev. D 93, 092004 (2016)

	eee	μee	$e\mu\mu$	$\mu\mu\mu$	combined
Source	Relative uncertainties [%]				
e energy scale	0.8	0.4	0.4	0.0	0.3
e id. efficiency	2.9	1.8	1.0	0.0	1.0
μ momentum scale	0.0	0.1	0.1	0.1	0.1
μ id. efficiency	0.0	0.7	1.3	2.0	1.4
E_T^{miss} and jets	0.3	0.2	0.2	0.1	0.3
Trigger	0.1	0.1	0.2	0.3	0.2
Pileup	0.3	0.2	0.2	0.1	0.2
Misid. leptons background	2.9	0.9	3.1	0.9	1.3
ZZ background	0.6	0.5	0.6	0.5	0.5
Other backgrounds	0.7	0.7	0.7	0.7	0.7
Uncorrelated	0.7	0.6	0.5	0.5	0.3
Total systematics	4.5	2.6	3.7	2.5	2.4
Luminosity	2.2	2.2	2.2	2.2	2.2
Statistics	6.2	5.4	5.3	4.7	2.7
Total	8.0	6.3	6.8	5.7	4.2

Low lepton identification uncertainty. Orthogonal sources - better in combination

Excellent trigger efficiency uncertainty

Misidentified muon uncertainties are low and muons are the higher statistics channels

Good luminosity uncertainty

Many of these uncertainties should scale with more statistics

Total Cross Section: ZZ

- Example: CMS 13 TeV ZZ analysis
- Fully reconstructed
  - Systematic uncertainty small
  - Statistics no longer dominant with full Run 2 data
  - Background very small
  - Precision cross section measurement feasible!

Total cross section:

17.1 ± 0.3(stat) ± 0.4(syst) ± 0.4 (theo) ± 0.3 (lumi) pb

17.1 ± 2%(stat) ± 2%(syst) ± 2%(theo) ± 2%(lumi) pb

17.1 ± 4%(total) pb

Theory: MATRIX

16.2 +0.6 -0.4 (scale) pb

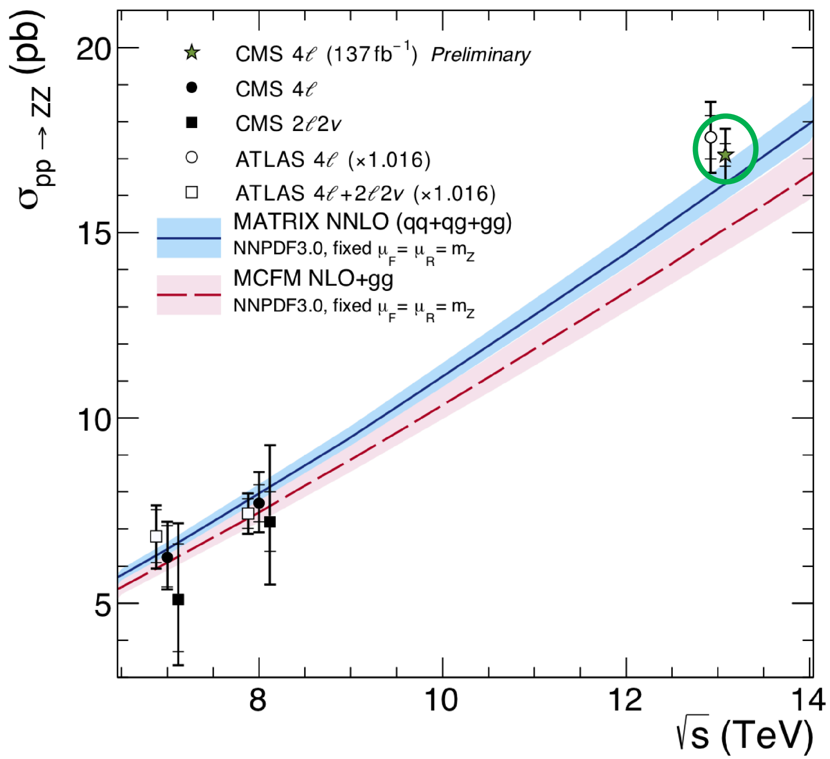
16.2 ± 3% pb

Fiducial cross section:

39.9 ± 0.7(stat) ± 1.2(syst) ± 1.0 (lumi) fb

39.9 ± 2%(stat) ± 3%(syst) ± 2%(lumi) fb

39.9 ± 4%(total) fb



Analysis of Uncertainties

- How low an uncertainty is feasible?

Lepton efficiency and trigger
Lowest values from muons
- Higher statistics
- Weigh measurement toward muon contribution
- Can perform better determination of efficiencies

PDF and scale
- Reduce with careful fiducial definition

Background
- very small

Luminosity
- Order 1.5% achievable

Uncertainty	Range of values
Lepton efficiency	2–8%
Trigger efficiency	1–2%
Background	0.6–1.3%
Pileup	1%
PDF	1%
μ_R, μ_F	1%
Integrated luminosity	2.3% (2017) 2.5% (2018)

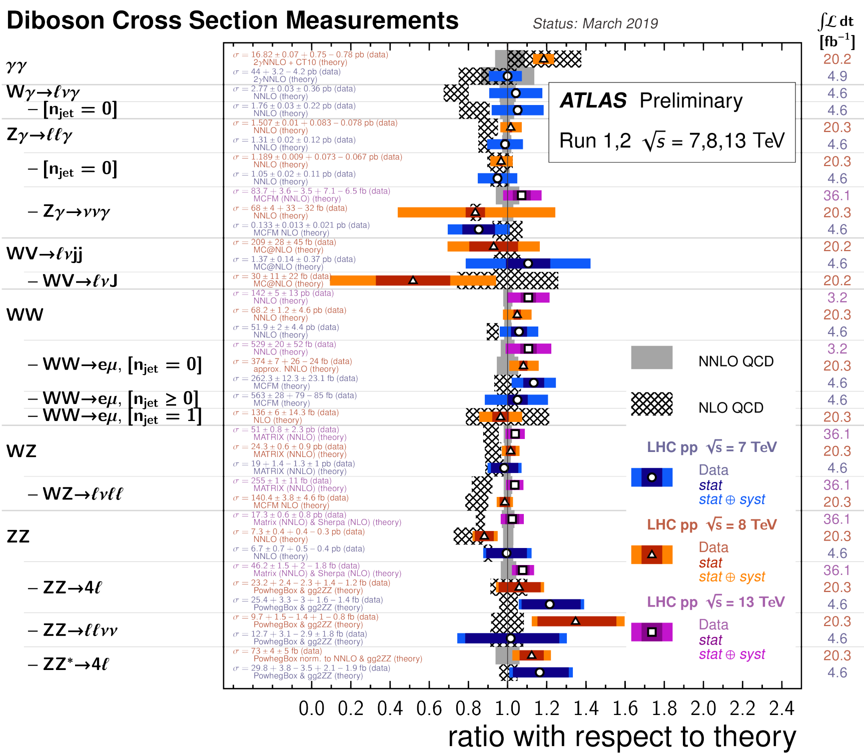
3% Uncertainty is easily in reach!

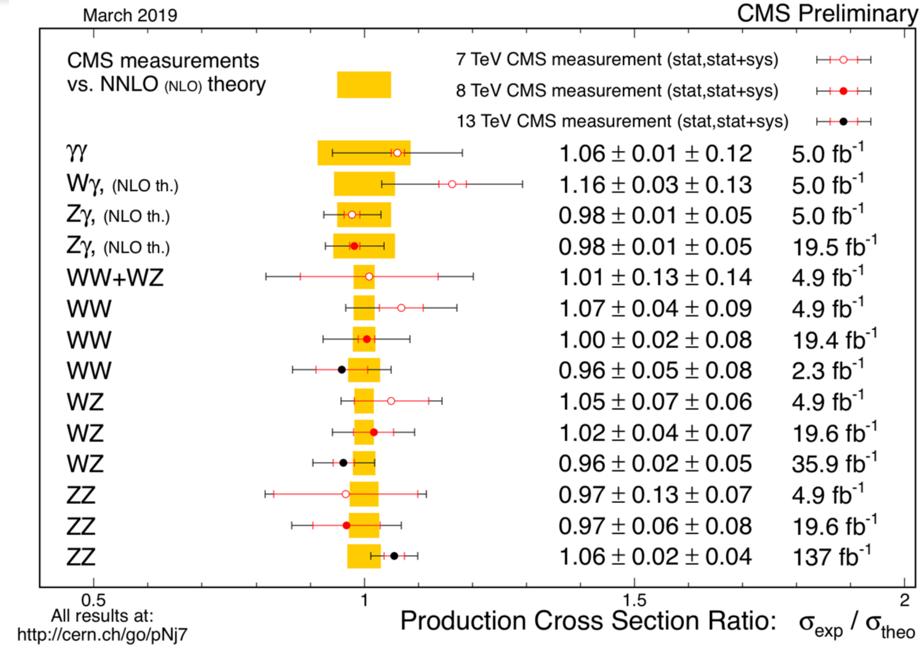
Ratios of production modes will allow us to go lower.

A careful program of addressing systematic uncertainties is necessary to get to 2% or lower

Cross Section measurements

- Summary of all cross section measurements





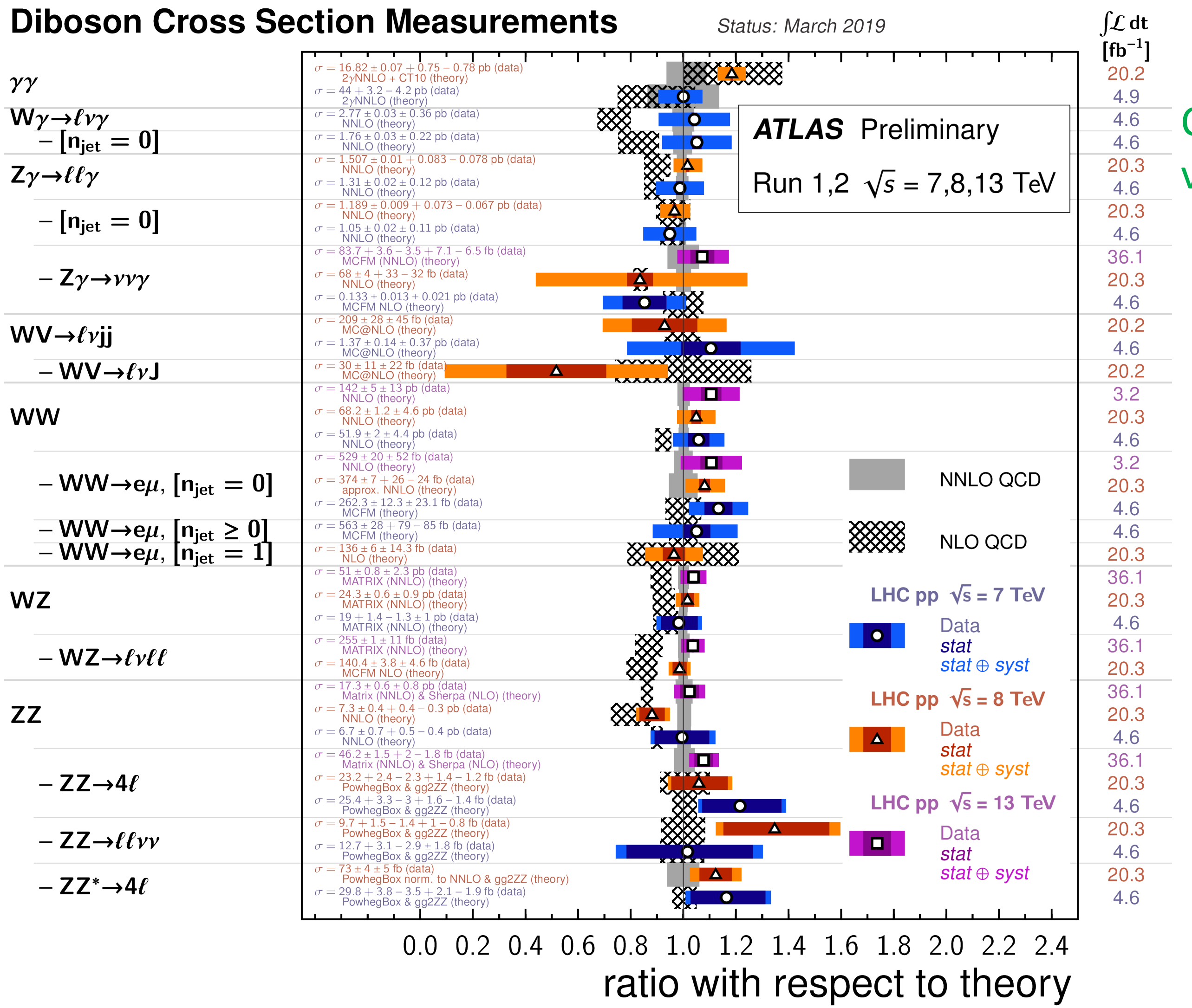
3% Uncertainty achievable for Zγ, WZ, ZZ

WW: top backgrounds, jet vetoes limit precision

Wg: difficult combination misidentified lepton and photon background

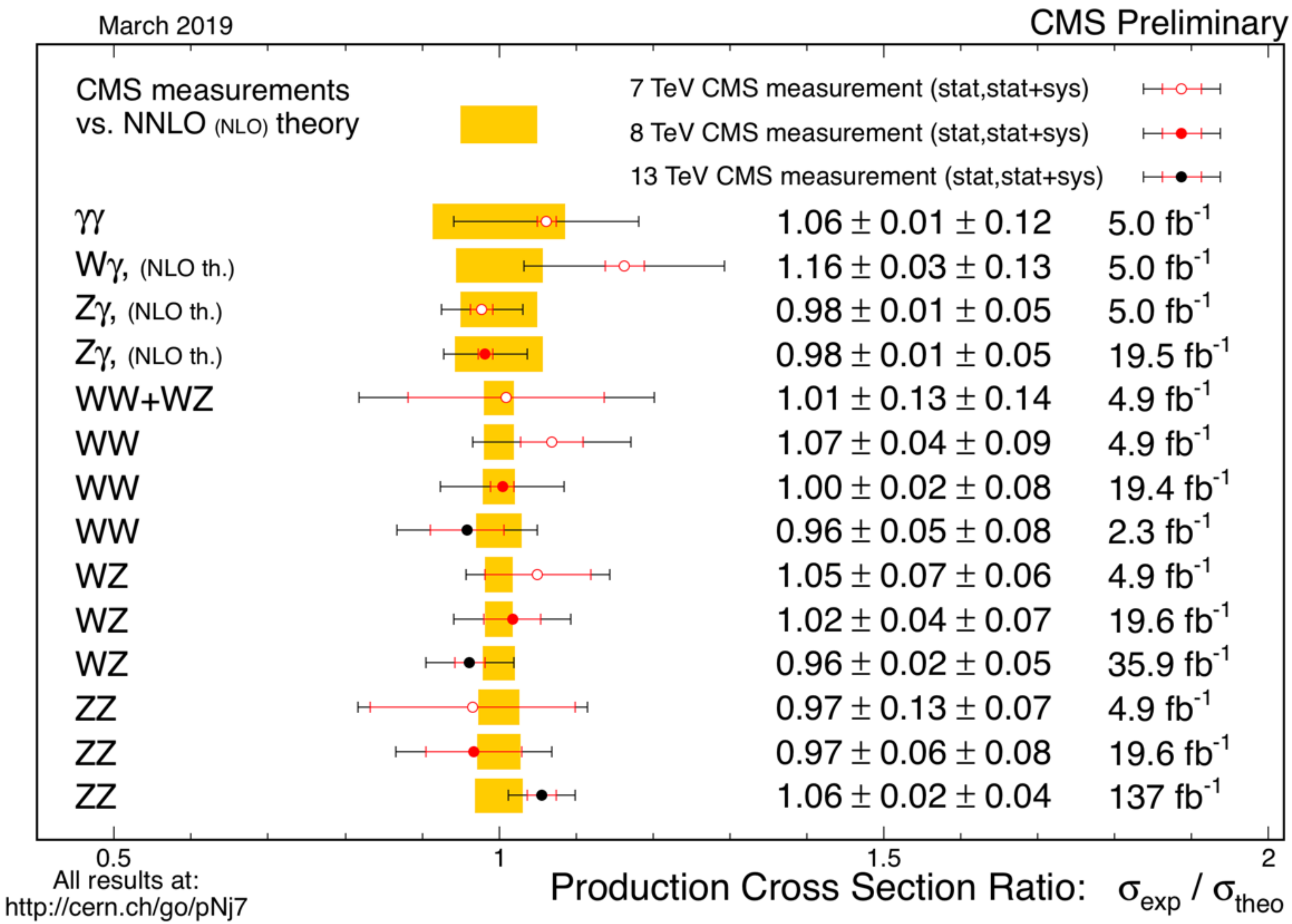
Need updated measurement in many modes

Cross Section measurements



Complete comparison to a variety of predictions

Cross Section measurements



Illustrates the array of precisions.

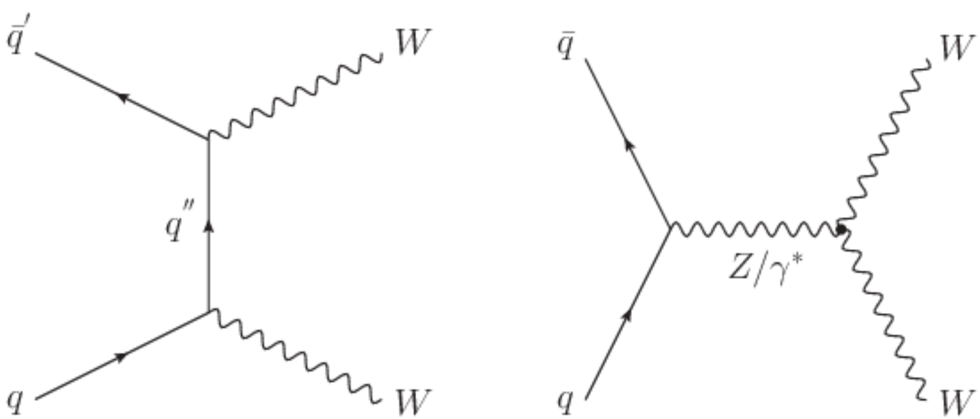
Best precision 4%

Differential Cross Sections: WW

- Example: ATLAS 13 TeV WW analysis

ATLAS WW: hep-ex 1905.04242

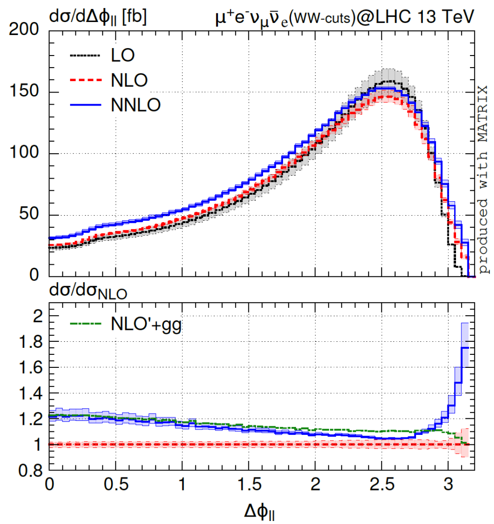
  - Probes quark-boson and multi-gauge boson interactions
  - Production via combination of radiation and TGC diagrams

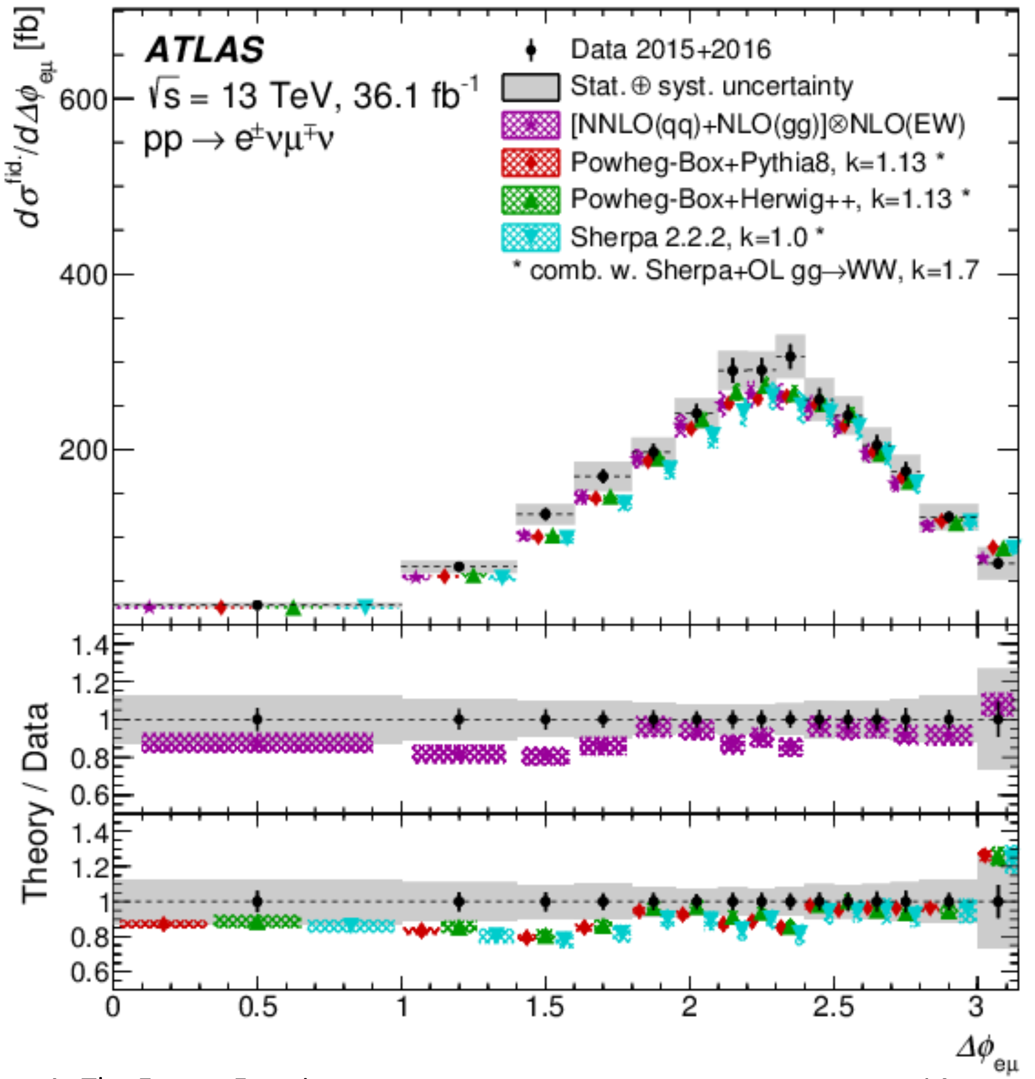


  - NNLO QCD sensitive areas of phase space
  - Difficult issues like jet vetoes
  - New physics sensitivity: aTGC or diboson resonances

WW $\Delta\phi_{ll'}$

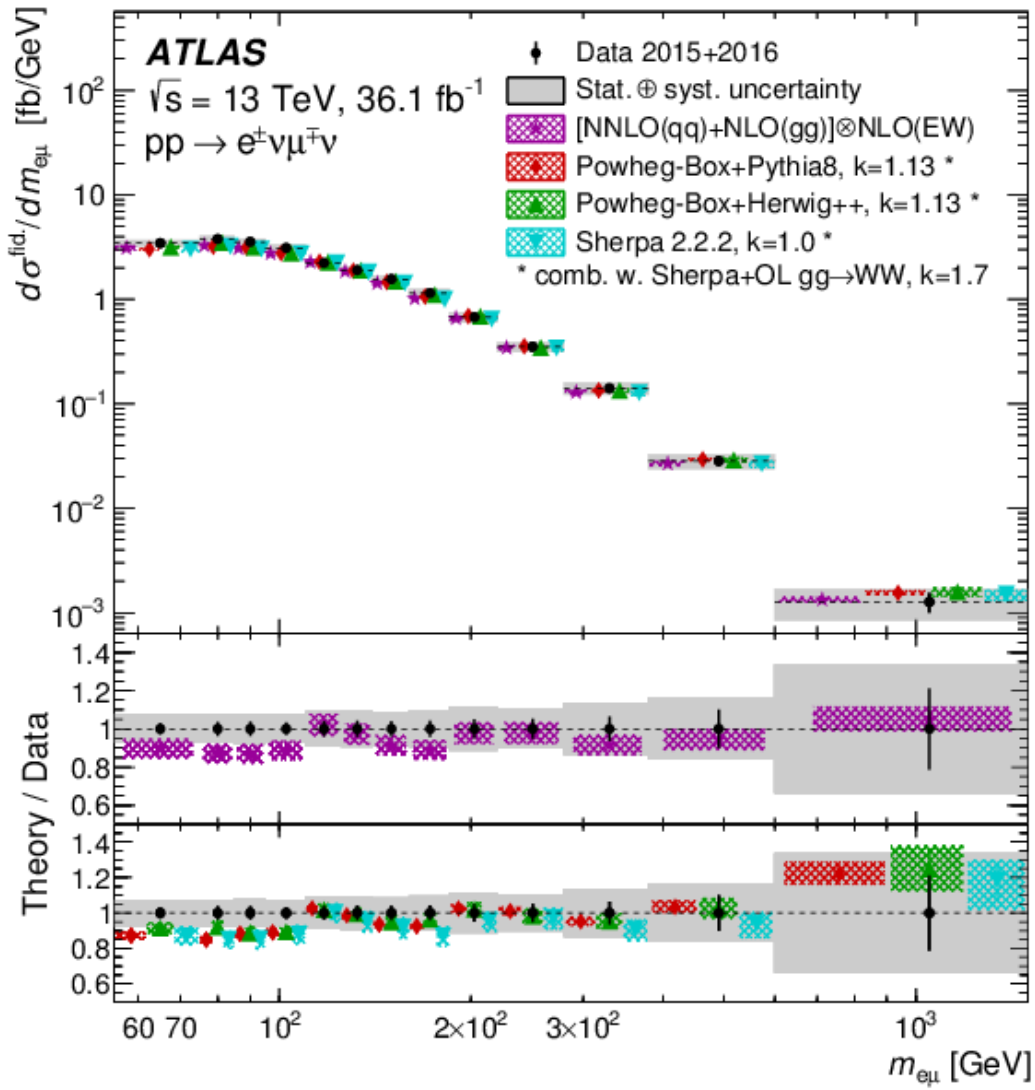
- WW $\Delta\phi_{ll'}$: NNLO QCD Sensitivity
  - Significant NNLO contribution at $\phi = \pi$
    - NNLO x NLO EW prediction more accurate
    - comparison systematics (statistics) limited





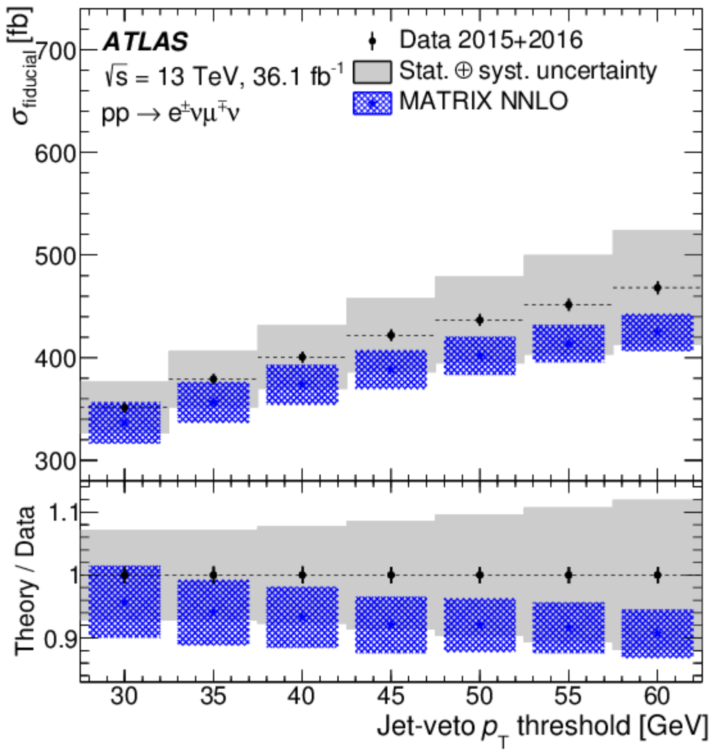
WW $m_{ll'}$

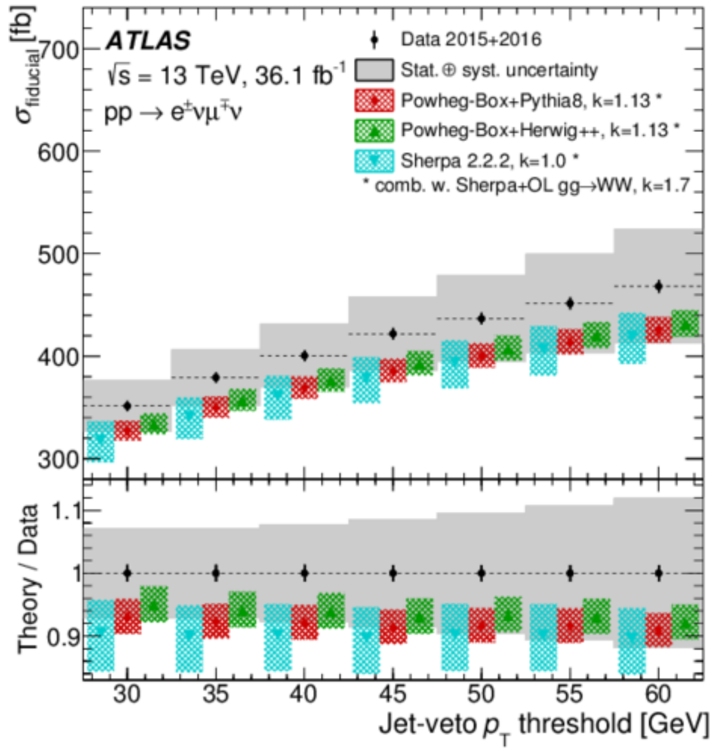
- WW $m_{ll'}$: Sensitivities
  - NNLO QCD, NLO EW
    - NNLO x NLO EW slightly more accurate
    - Comparison statistics limited
  - 4x statistics available
  - Good distribution for new physics



WW Jet Vetoes

- WW Jet Vetoes
  - Test of higher order and PS with matching MCs
  - Critical issue for reducing WW cross section uncertainty



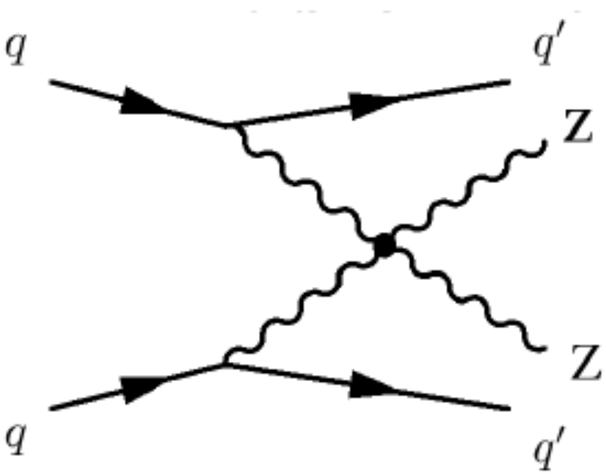


Systematic offset and slope seen. Jet vetoes are still one of our more problematic tools

Differential Cross Sections ZZ + Jets

- Example: CMS 8, 13 TeV ZZ + Jets analysis
  - Comparison to Madgraph, POWHEG and aMC@NLO
    - POWHEG and aMC@NLO NLO QCD
    - aMC@NLO includes up to one jet
    - Madgraph includes up to 2 jet (8 TeV only)
    - Investigate combinations of NLO vs additional hard jets
  - Critical for vector boson scattering
    - Determine level of modeling needed to get correct 2 jet system kinematics

CMS ZZ hep-ex 1806.11073
Phys. Lett. B 789 (2019) 19

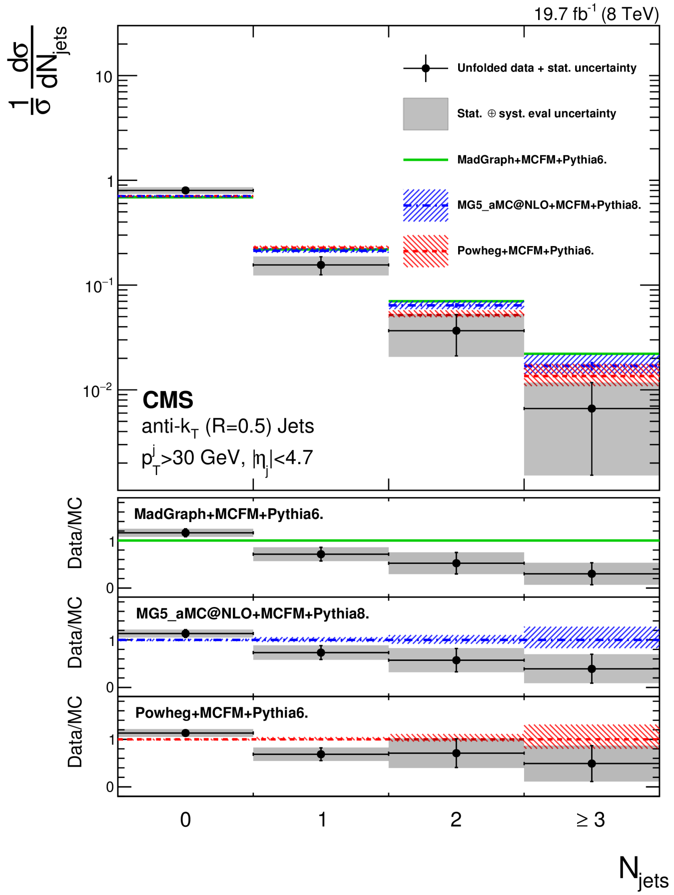


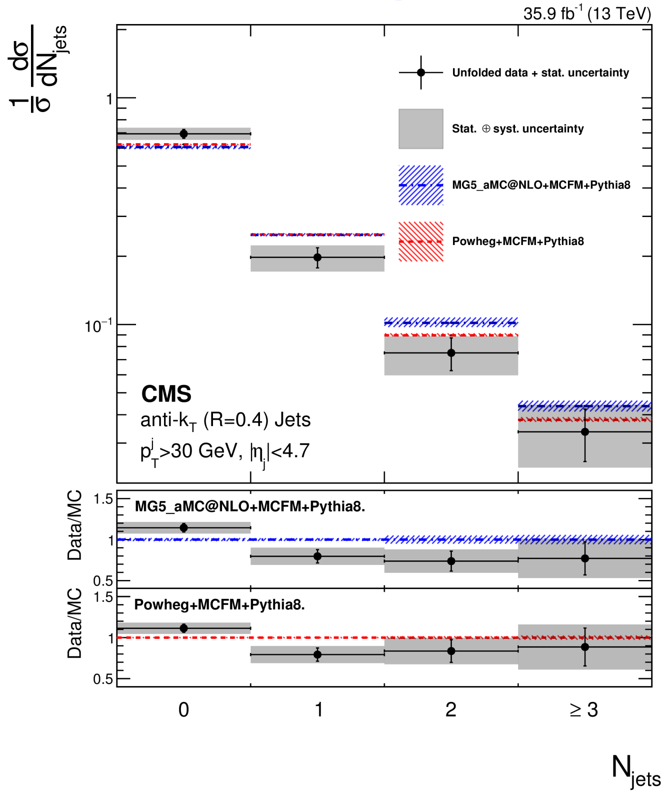
Differential Cross Sections ZZ + Jets

- N Jet distributions

[CMS ZZ hep-ex 1806.11073](https://arxiv.org/abs/1806.11073)
Phys. Lett. B 789 (2019) 19

  – Normalized to accentuate shape differences





LO modeling poor

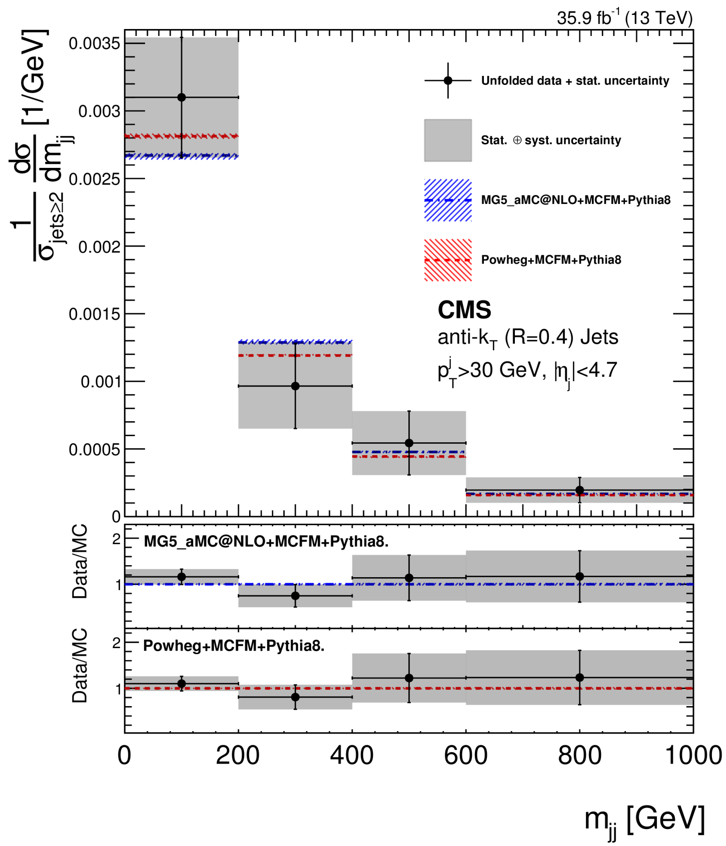
NLO Modeling imperfect but definitely superior

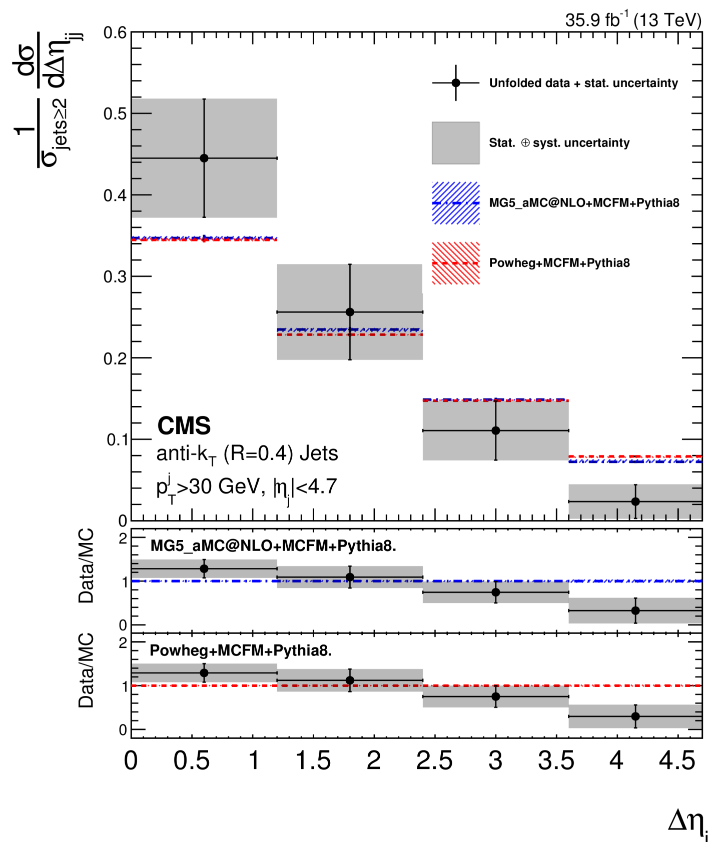
May be systematic issues with modeling seen consistently between NLO MCs

Differential Cross Sections ZZ + Jets

- Two jet kinematics
  - Normalized to accentuate shape differences

[CMS ZZ hep-ex 1806.11073](https://arxiv.org/abs/1806.11073)
Phys. Lett. B 789 (2019) 19





Some key VBS variables ($\Delta\eta_{jj}$) are poorly modeled

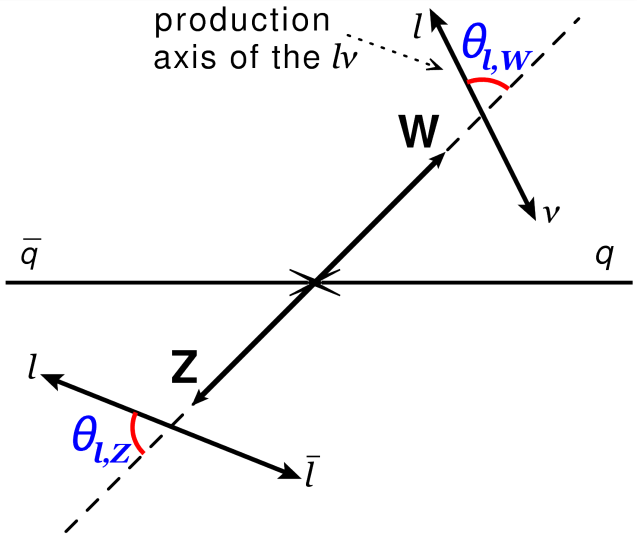
Again may be a systematic issue with modeling - seen consistently between NLO MCs

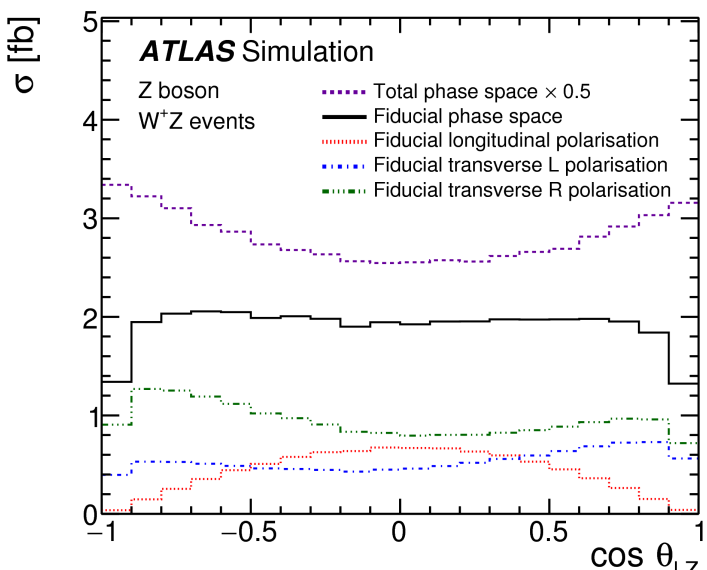
Polarization: WZ

- Example: ATLAS 13 TeV WZ analysis

  ATLAS WZ: hep-ex 1902.05759
  Eur. Phys. J. C 79 (2019) 535

  – Polarization
    - fundamentally intertwined with the production mechanisms
    - Changes as a function of CM energy
  – First di-boson polarization analysis from the LHC
    - Analyzes polarization of the individual vector bosons
  – Will be most interesting in VBS with longitudinal polarization - scattering via the Higgs boson

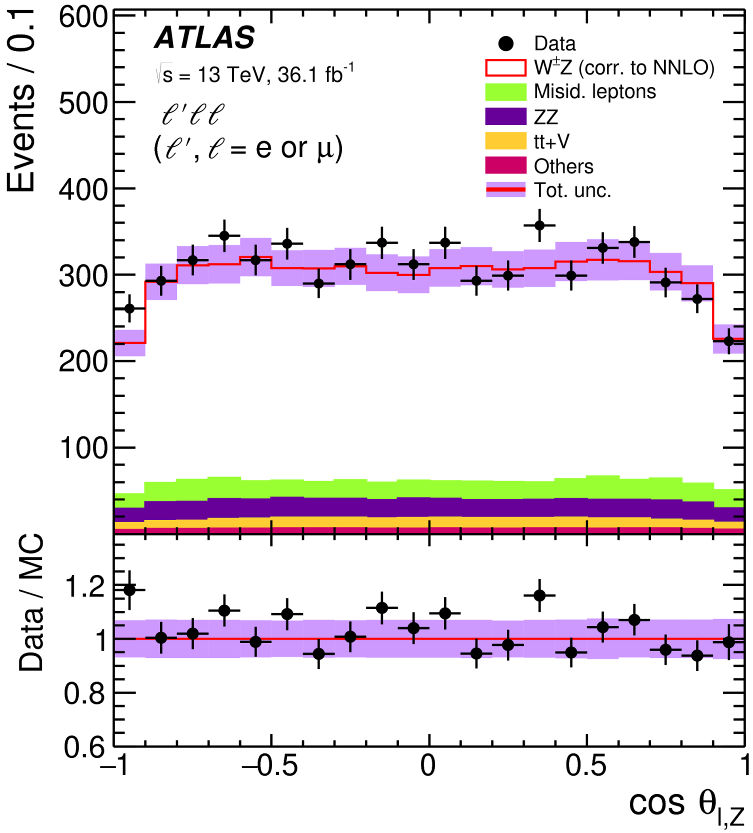


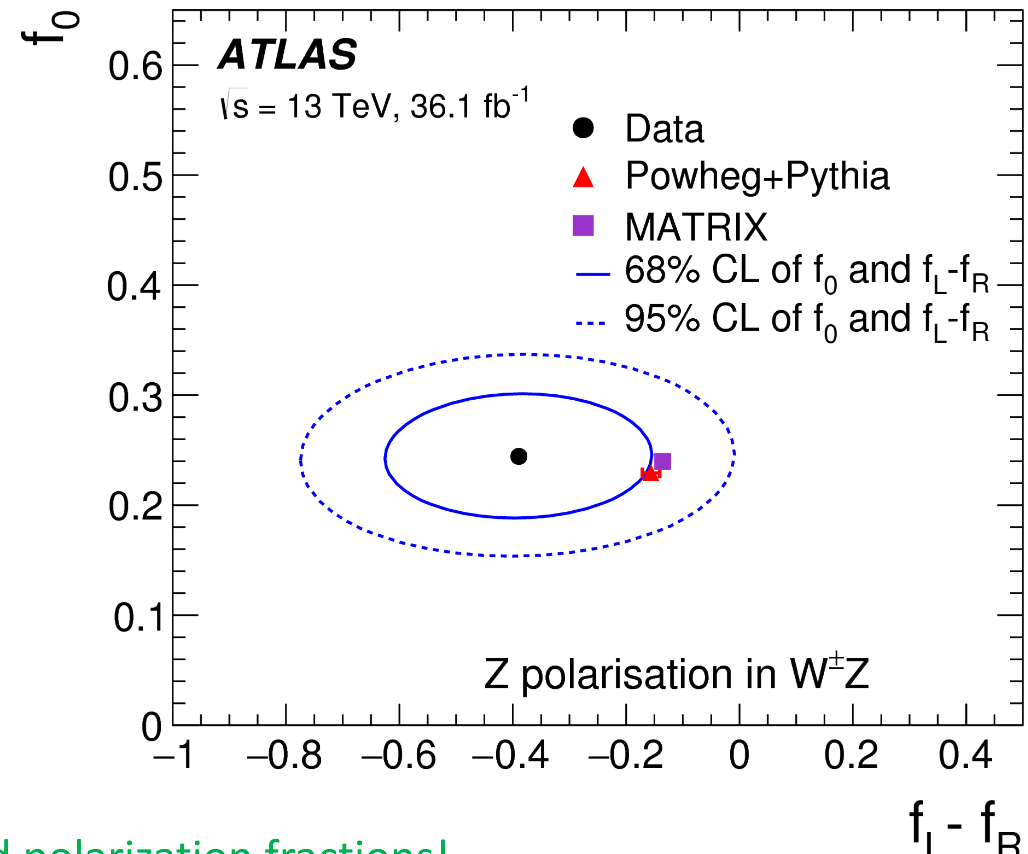


Polarization: WZ

- W and Z polarization

[ATLAS WZ: hep-ex 1902.05759](https://arxiv.org/abs/1902.05759)
Eur. Phys. J. C 79 (2019) 535





Clear evidence for presence of expected polarization fractions!

Summary of Differential Measurements

Exp.	CMS			ATLAS		
Analysis	σ	Diff	Diff Jets	σ	Diff	Diff Jets
γγ	✓	✓		✓ ✓	✓	
Wγ	✓	✓ (γ pT)		✓	✓ (pT W)	✓ (nJ)
Zγ	✓ ✓	✓ (γ pT)		✓ ✓ ✓	✓ ✓ (pT Z) ✓	✓ ✓ (nJ)
WW	✓ ✓	✓		✓ ✓ ✓	✓ (pT l) ✓ ✓	✓ (nJ) ✓ (v)
ssWW	✓ ✓			✓ ✓	✓ (mll)	
WZ	✓ ✓ ✓	✓ ✓ (pT Z) ✓	✓ ✓ (nJ)	✓ ✓ ✓	✓ ✓	✓ ✓
ZZ	✓ ✓ ✓ *	✓ ✓	✓ ✓	✓ ✓ ✓	✓ ✓ ✓	✓ (nJ) ✓

✓ 7 TeV
✓ 8 TeV
✓ 13 TeV
* Full Run 2

Notes
Snapshot as of July 2019
13 TeV ATLAS Zγ(ννγ)
Apologies if any errors

A very incomplete table!
ATLAS effort progressing better

Progress on Differential Measurements

- Need a full set of differential measurements for all di-boson final states
  - Zg and Wg:
    - perform measurements at 13 TeV
  - WW, WZ, ZZ
    - Fill in all missing measurements
    - Include measurements of jets for all modes
    - Compare to all the types of predictions
- Other opportunities
  - Polarization
  - High energy kinematics:
    - Leveraging Z→nunu or V→jj with jet substructure
- "Document" all results using HEPData and Rivet to facilitate comparison with state of the art predictions

Final Thoughts

- Cross section measurements
  - We have entered the era of precision cross section measurements in multiboson physics
    - We should consciously be mapping out a program to even better precision (2% … 1%?)
- Differential measurements
  - We now have sufficient sensitivity to see differences with state of the art MCs
  - Better predictions and MCs are on the way
    - we should move quickly to use them
    - We should actively participate in MC comparison and improvement programs