# QCD V and Multi V Production

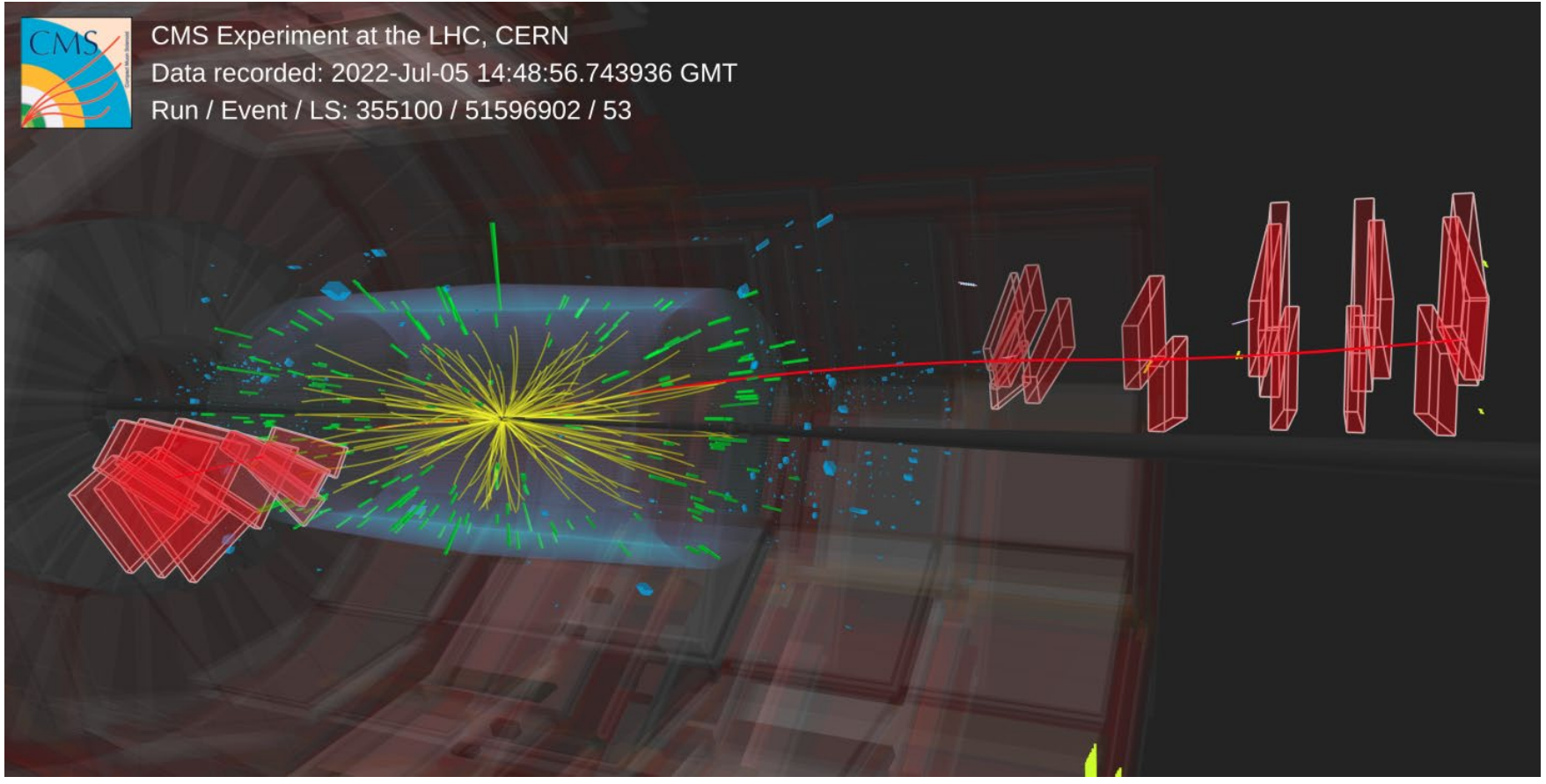
He He
University of Wisconsin-Madison, USA
On behalf of the CMS Collaboration and the ATLAS Collaboration

MBI 2022: Multi-Boson Interaction 2022, 22-25 Aug 2022,
Tsung-Dao Lee Institute and Jiao Tong University Shanghai, Shanghai (China)

Aug 22, 2022

# Introduction

## The LHC Run3 has started!




*Z candidate in CMS recorded first collision events at 13.6 TeV*

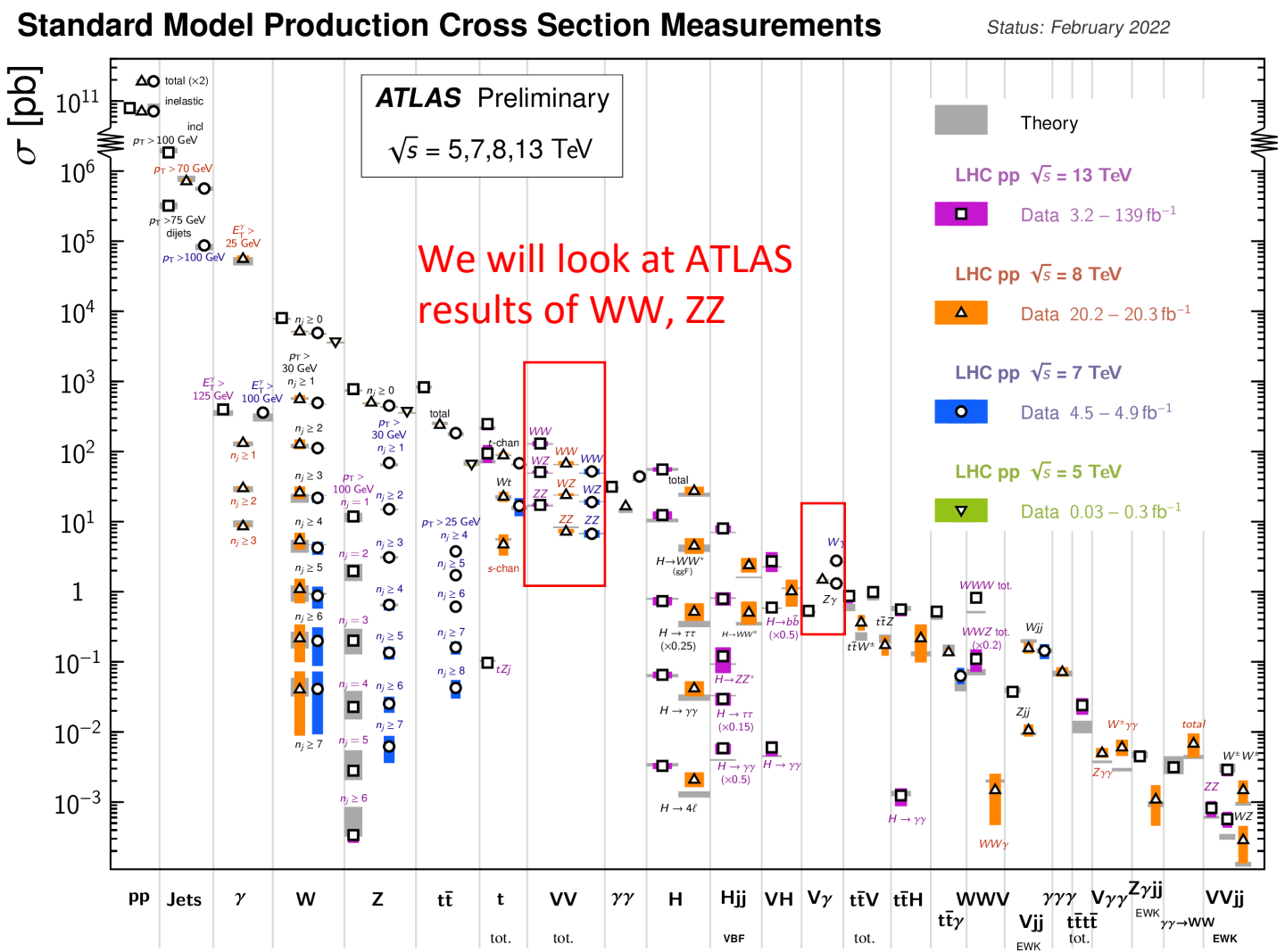
# Introduction

**QCD VV**:

- Clean final states and large cross sections
- Good test for perturbative QCD and EWK theory
- Large background for EWK studies and Higgs production measurement
- Sensitive to variations in SM TGCs

We will present recent ATLAS and CMS results for **QCD VV production**

# Introduction

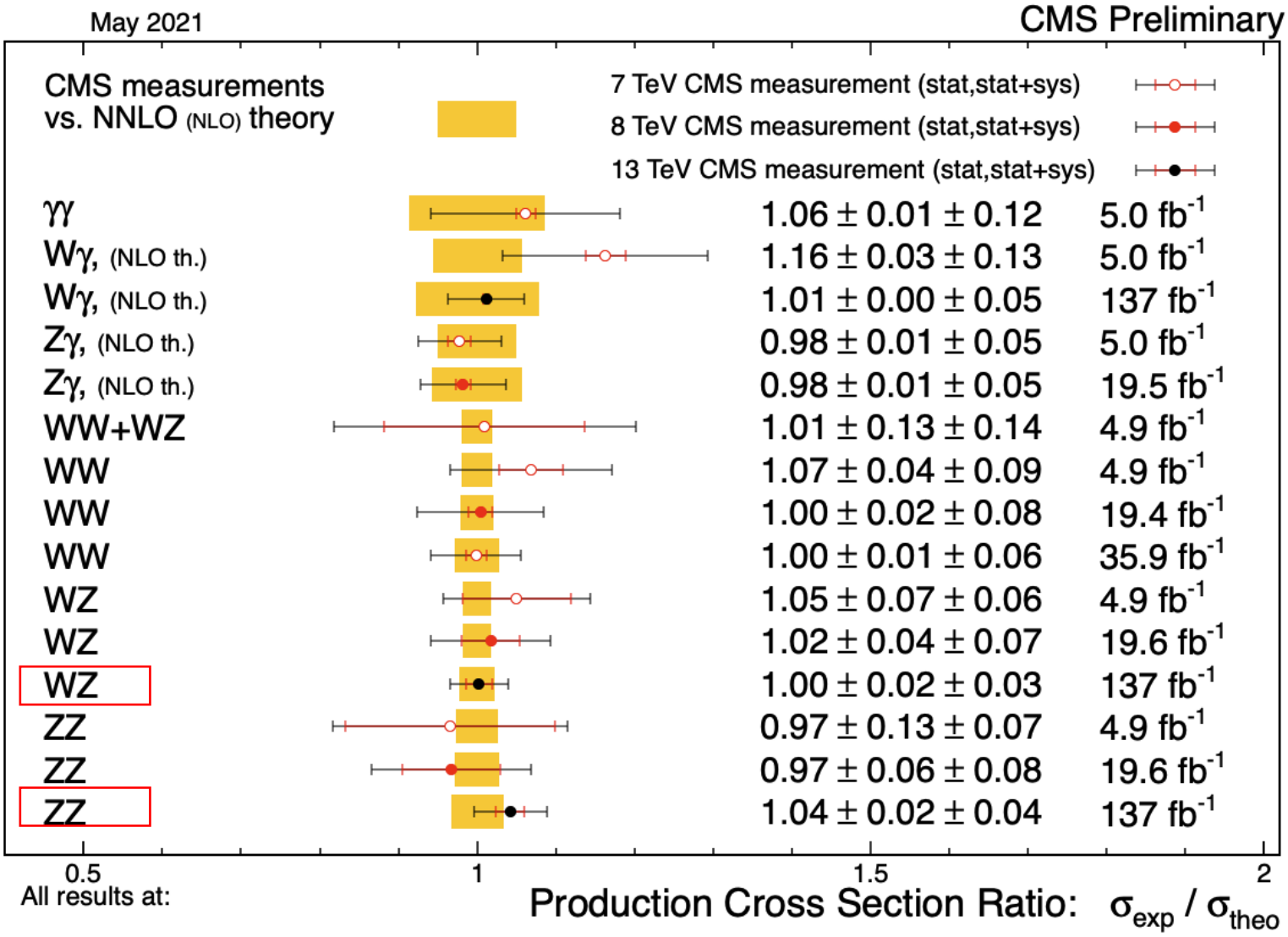



WZ cross section measured with relative unc. less than 5% at 13 TeV and 8 TeV

# Introduction

We will look at CMS results of WZ, ZZ

Relative unc. Less than 5%



# Introduction: QCD VV as Dominant Background for EWK Studies

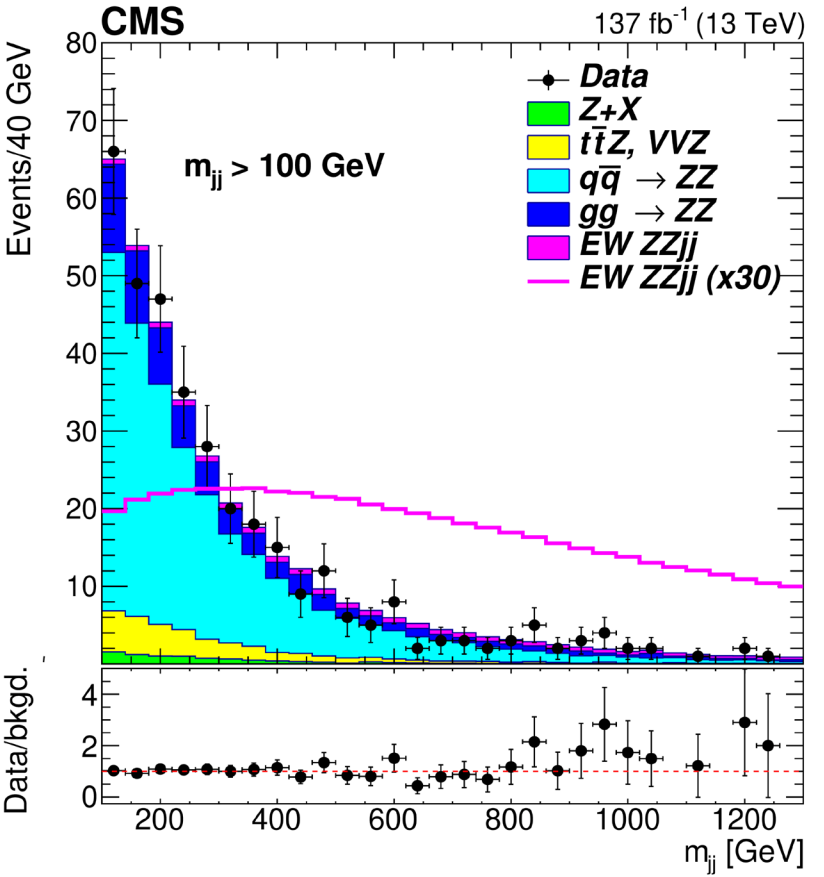
## Evidence for EWK production of ZZjj

137 fb$^{-1}$ at 13 TeV with full Run2 dataset, CMS-SMP-20-001, *Phys. Lett. B 812 (2020) 135992*

- A discriminant based on a matrix element likelihood approach (MELA) is used to extract the signal significance (observed (expected) significance of 4.0 (3.5) standard deviations) and to measure the cross sections for the EWK and the EWK+QCD production of the lll'l'jj final state in a fiducial volume.

- Mingyi Liu: ATLAS ZZ VBS next talk
- Bing Li: EWK production Tue. 19:00

- **Large QCD-induced background. Additional analysis of QCD induced ZZ+jets production underway.**



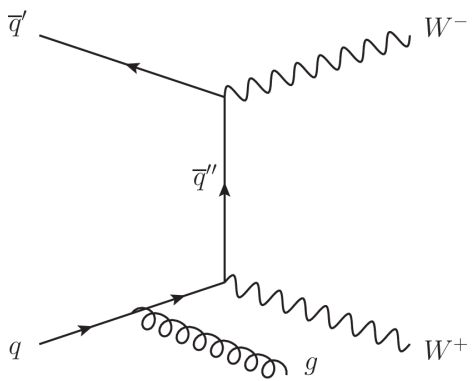
# ATLAS $W^+W^-$ + ≥1 jet

139 $fb^{-1}$ at 13 TeV with full Run2 dataset, ATLAS-STDM-2018-34, ***JHEP 06 (2021) 003***

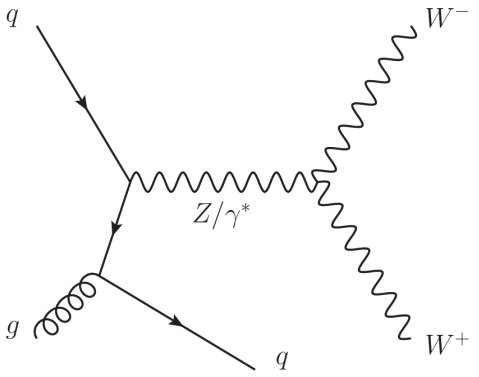
- Measure fiducial and differential cross sections for $WW \rightarrow e^{\pm}\nu\mu^{\mp}\nu$ produced in association with one or more jets

- Limits on aTGC obtained in phase space where interference between SM and anomalous amplitude is enhanced

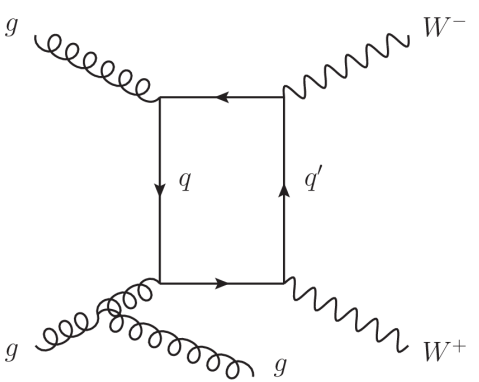
(Andrew Gilbert: Searches for NP and EFT limits in multi-boson final states Tuesday 21:45)




$q\overline{q} \rightarrow W^+W^-$ + jet




$qg \rightarrow W^+W^-$ + jet



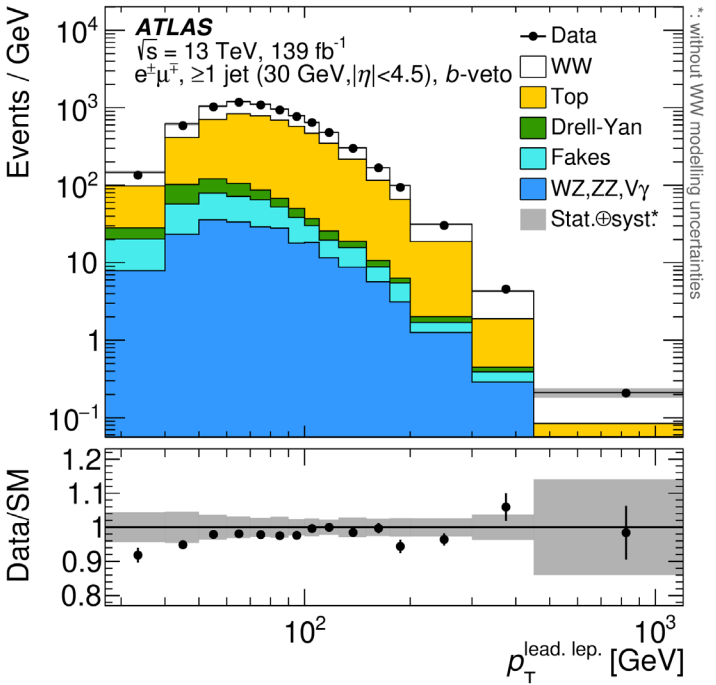

$gg \rightarrow W^+W^-$ + jet

# ATLAS $W^+W^-$ + ≥1 jet: Selection

- Select candidate WW by requiring exactly one isolated e and μ with opposite charge to reduce background from Drell-Yan events. Require at least one jet.
- Reject events containing b-tagged jets to reduce $t\bar{t}$ background
- Reject events with additional leptons with pT > 10GeV and loose requirements to reduce WZ and ZZ background

| Fiducial selection requirements | | |
|---|---|---|
| $p_{\mathrm{T}}^{\ell}$ | > | 27 GeV |
| $\lvert\eta^{\ell}\rvert$ | < | 2.5 |
| $m_{e\mu}$ | > | 85 GeV |
| $p_{\mathrm{T}}^{j}$ | > | 30 GeV |
| $\lvert y^{j}\rvert$ | < | 4.5 |

← Strongly suppress Drell-Yan Z+jets




SR region detector-level distribution

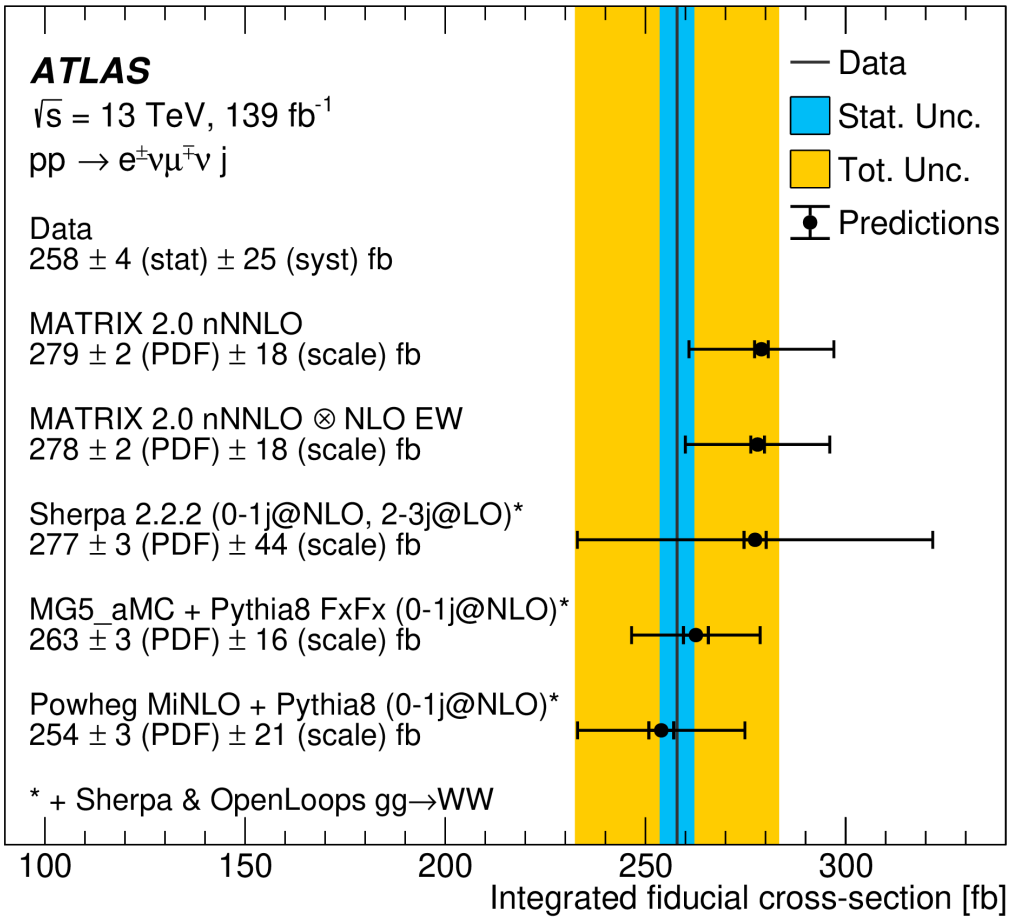
# ATLAS $W^+W^-$ + ≥1 jet: Fiducial Cross Section

$$\sigma^{\text{fid}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times \mathcal{L}}$$

- C: accounts for detector inefficiencies, resolution effects, and $\tau$ decays
- L: integrated luminosity
- $N_{\text{obs}}$: observed events
- $N_{\text{bkg}}$: estimated bkg events

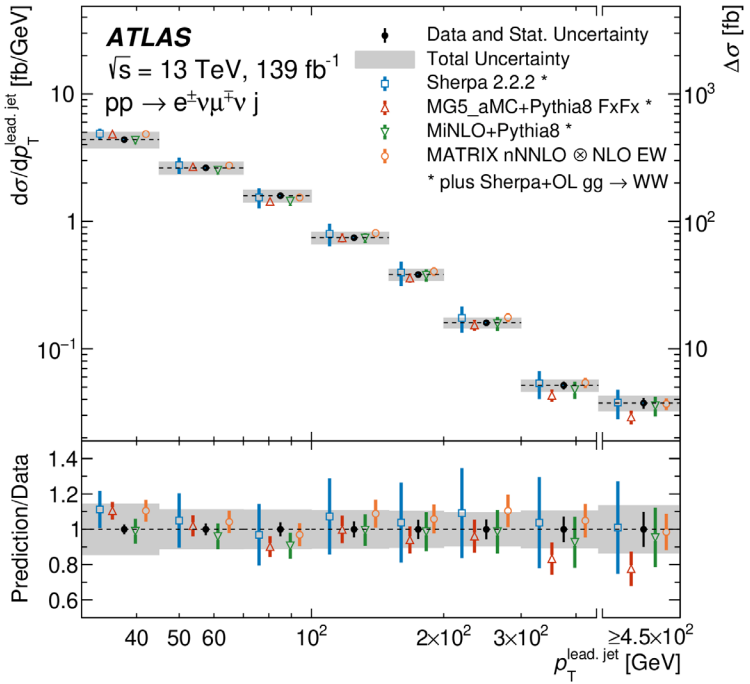
**$\sigma_{\text{fid}}$ = 258 ± 4 (stat.) ± 25 (syst.) fb**

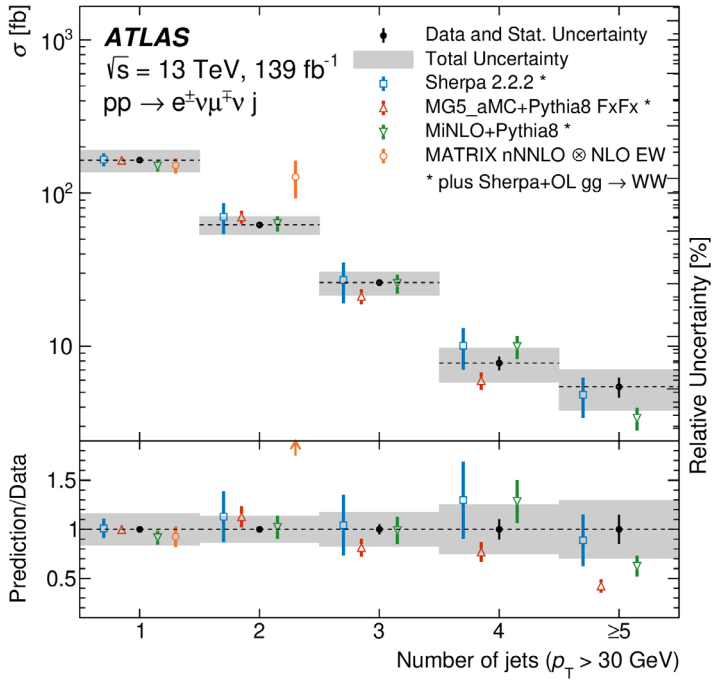
Good agreement with predictions



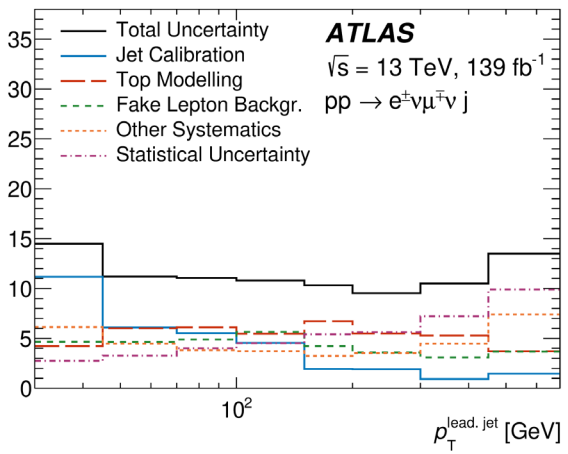
# ATLAS $W^+W^-$ + ≥1 jet: Differential Cross Section

- Measured using iterative Bayesian unfolding method
- As function of lepton-related (e.g. $p_T$, $m_{e\mu}$) and jet-related (e.g. Njets, $p_T^{\text{lead. jet}}$) kinematic variables
- All predictions give good description of the observed data within uncertainties
- >=2 jets region relevant for EWK WW production shows good agreement



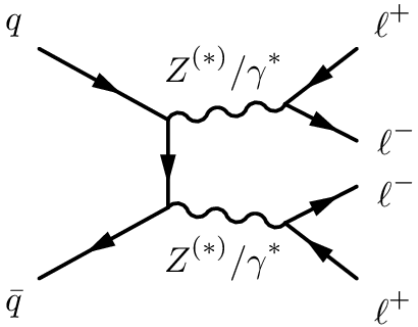

Relative size of unc.



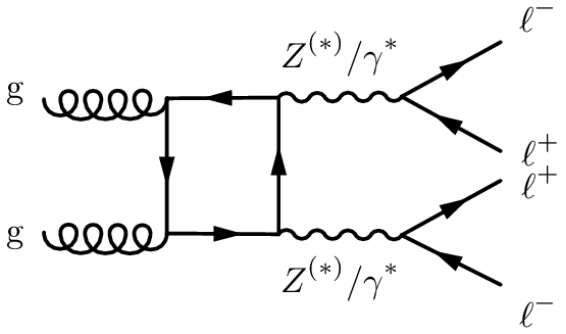
# ATLAS 4l Events

139 fb$^{-1}$ at 13 TeV with full Run2 dataset, ATLAS-STDM-2018-30, ***JHEP 07 (2021) 005***

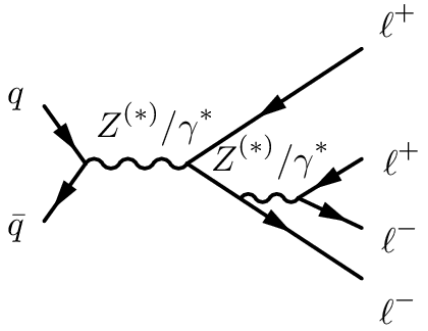
- Measure differential and integrated fiducial cross sections of four-lepton events consisting of OSSF electron and muon pairs
- Involves several interesting SM processes, with possible BSM contributions and can set limits on BSM models
- For more inclusive results, reduce requirement that specifically enhance contributions from SM ZZ. Similar measurement CMS-SMP-19-001 which focuses on on-shell ZZ production.



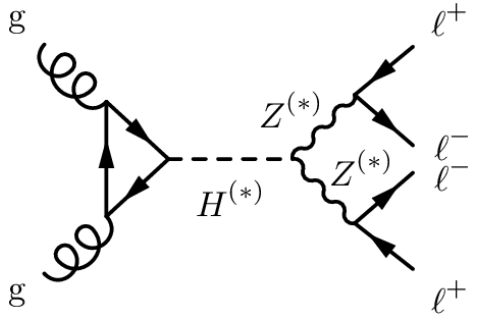

$q\bar{q} \rightarrow 4l$




gluon induced $gg \rightarrow 4l$ via quark loop




$Z \rightarrow 4l$




$(gg \rightarrow)H \rightarrow ZZ \rightarrow 4l$

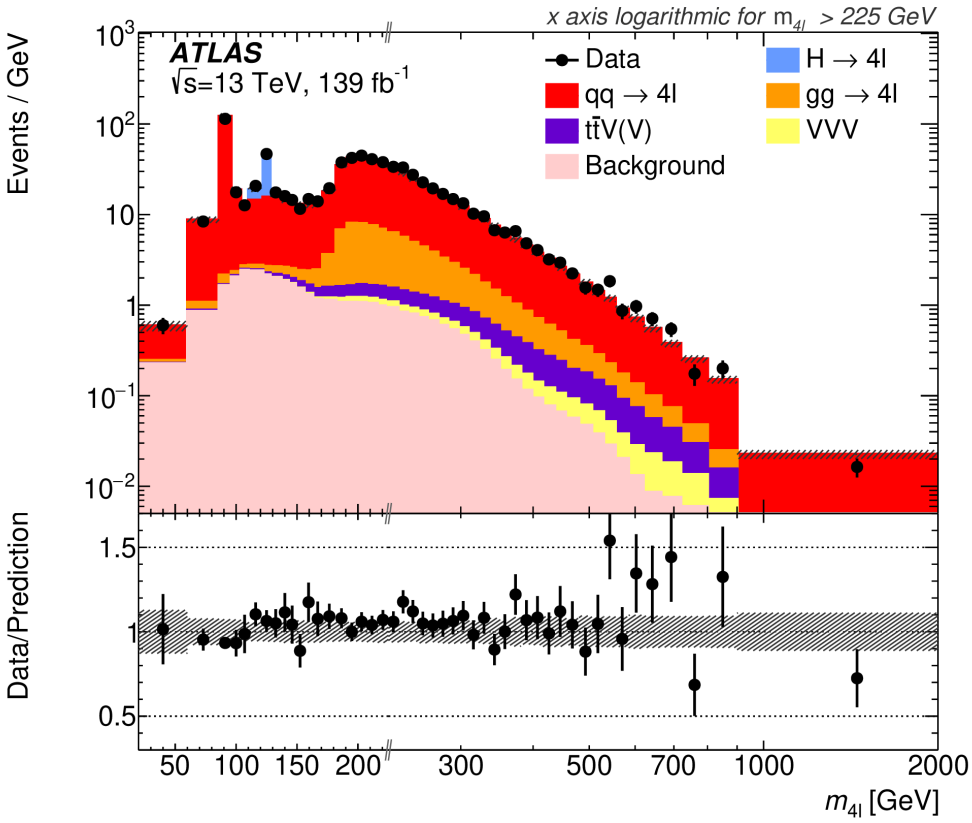
# ATLAS 4l Events: Selection

**Fiducial phase space:**

- At least 4l forming 2 OSSF pairs
- $p_T$ > 7 (5) GeV and |η| < 2.47 (2.7) for e (μ)
- $p_T^{l1}$> 20 GeV, $p_T^{l2}$ > 10 GeV
- $m_{ll}$ > 5GeV OSSF pairs ←Suppress J/ψ decays
- ΔR > 0.05 any l, l'←Suppress conversion e
- Additional particles allowed (leptons, neutrinos, etc. and possible BSM particles)

**Also divided in 4 regions:**

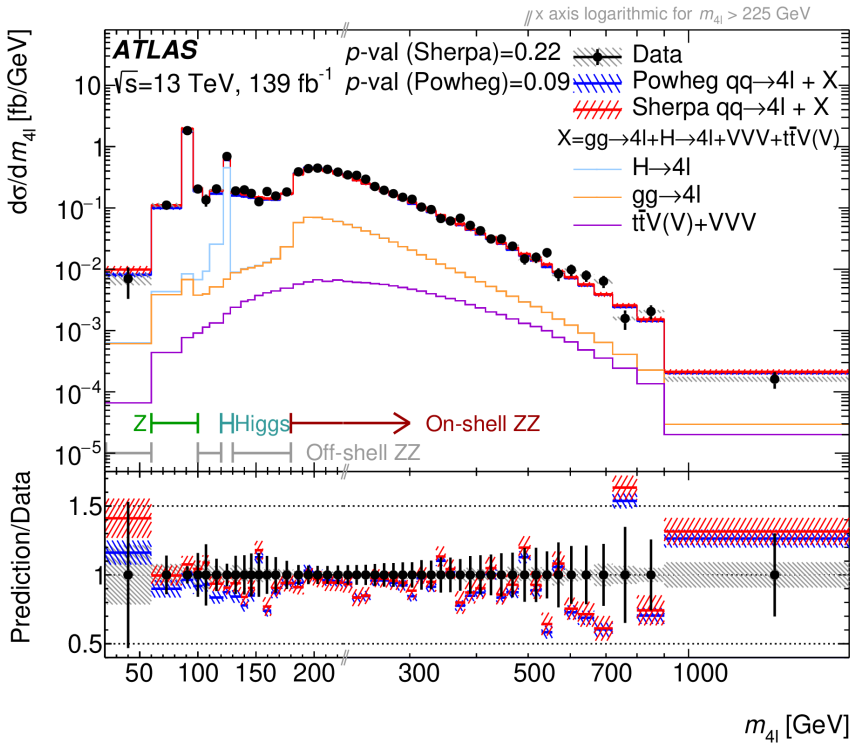
- Z → 4l (60 < $m_{4l}$< 100 GeV)
- H → 4l (120 < $m_{4l}$ < 130 GeV)
- off-shell ZZ (20 < $m_{4l}$ < 60 GeV or 100 < $m_{4l}$ < 120 GeV or 130 < $m_{4l}$ < 180 GeV)
- on-shell ZZ (180 < $m_{4l}$ < 2000 GeV)

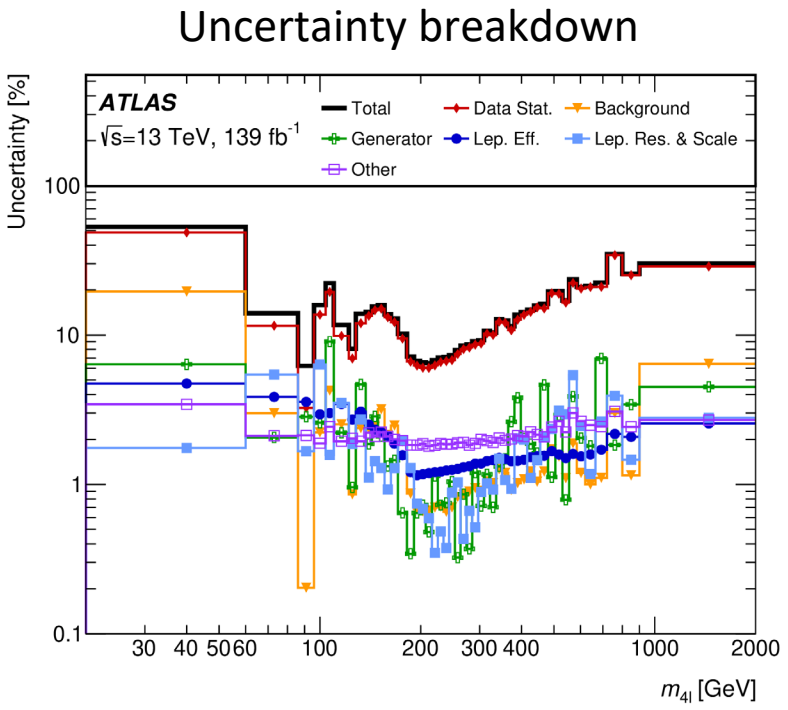


# ATLAS 4l Events: Measured Cross Sections

- Measure differential and integrated fiducial cross sections by correcting for detector effects using iterative Bayesian unfolding technique

- Differential cross sections include $m_{4l}$, dilepton masses, and other kinematic variables of 4l and dilepton pairs, including angular correlations. In general measurements agrees with prediction within uncertainties, including the high $m_{4l}$ region relevant for EFT.

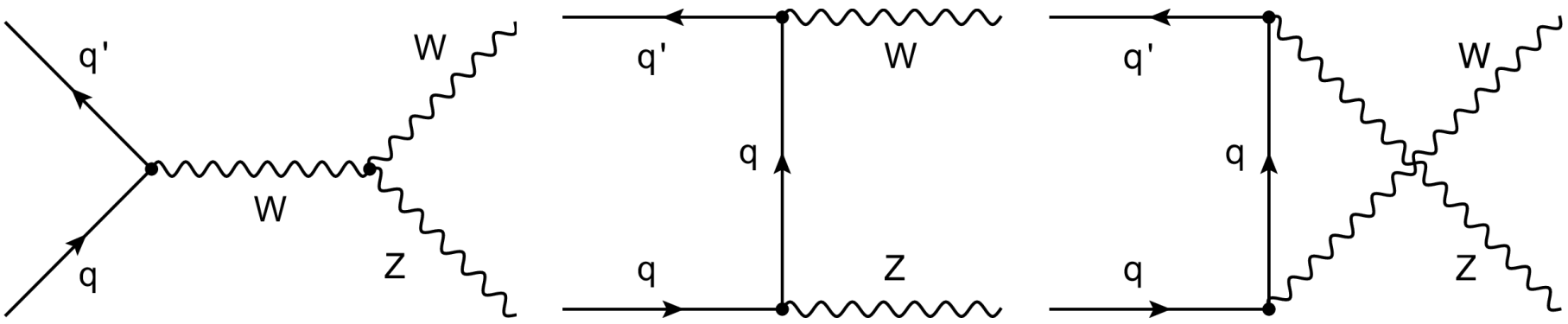


# CMS WZ production

137 fb$^{-1}$ at 13 TeV with full Run2 dataset, CMS-SMP-20-014, *JHEP 07 (2022) 032*

- Measurement of the total inclusive production cross section
- Fiducial and differential cross sections for several key observables
- Direct measurement of charge asymmetry and W and Z vector boson polarization
- New constraints on aTGC




s channel t channel u channel

# CMS WZ production: Selection

**Fiducial region:**

- Require exactly 3 final-state leptons (e/μ not from leptonic τ decays), at least one OSSF pair. Assign OSSF pair with invariant mass closest to $m_Z$ as $l_{Z1}$, $l_{Z2}$, the remaining lepton $l_W$
- $p_T(l_{Z1}) > 25$ GeV, $p_T(l_{Z2}) > 10$ GeV, $p_T(l_W) > 25$ GeV, $|\eta^l| < 2.5$
- $60 < m(l_{Z1}l_{Z2}) < 120$ GeV ← Reduce nonresonant contributions
- $m_{ll} > 4$ GeV OSSF pair ← Avoid low mass resonances, ensure infrared safety in MC
- $m(l_{z1}, l_{z2}, l_W) > 100$ GeV ← Suppress peaking contribution from Zγ

**Total region for measuring total production cross section:**

- Require 3 leptons (including τ) with at least 1 OSSF pair
- $60 < m(l_{Z1}l_{Z2}) < 120$ GeV
- $m_{ll} > 4$ GeV any OSSF pair

# CMS WZ production: Total Inclusive Production Cross Section

$$\sigma_{\text{tot}}(\text{pp} \to \text{WZ}) = \frac{N_{\text{WZ}}^{\text{SR}}}{B(\text{W} \to \ell\nu)B(\text{Z} \to \ell'\ell')\mathcal{A}\epsilon\mathcal{L}} f_\tau$$

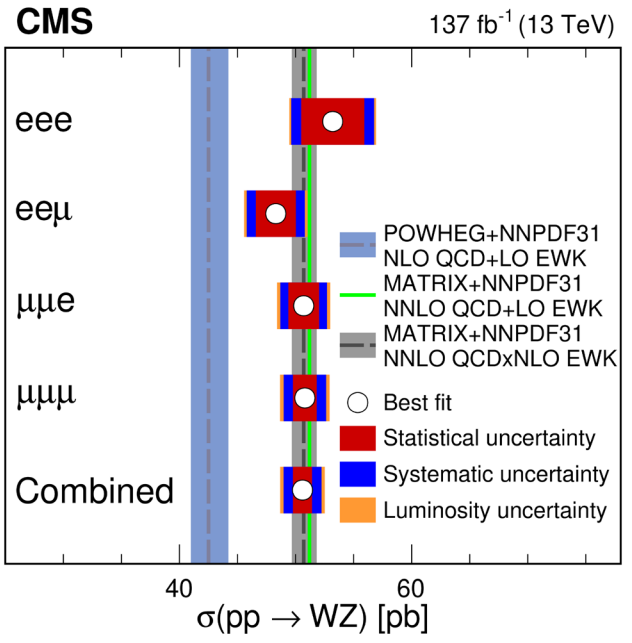
**L**: total collected integrated luminosity
**$N_{WZ}$**: postfit yield for the WZ process
**$f_\tau$**: account for nonfiducial signal events in SR due to leptonic τ decays
**ε**: efficiency of SR selection over FR, computed with nom. and alt. WZ MC
**A**: acceptance factor from TR to FR, computed with both WZ MC
**B**: branching fraction from current world averages

**$\sigma_{\text{tot}}(\text{pp} \to \text{WZ})$ = 50.6 ± 0.8 (stat) ± 1.5 (syst) ± 1.1 (lumi) ± 0.5 (theo) pb**

- Consistent with previous ATLAS and CMS results. With relative uncertainty of 4%.

- NNLO cross section predictions needed to describe the cross section within experimental uncertainty.

ATLAS results: 51.0 pb with relative uncertainty 4.8%



# CMS WZ production: Boson Polarization

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{W^\pm}} = \frac{3}{8}\left\{[1\mp\cos(\theta_{W^\pm})]^2 f_L^W + [1\pm\cos(\theta_{W^\pm})]^2 f_R^W + 2\sin^2(\theta_{W^\pm}) f_0^W\right\}$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_Z} = \frac{3}{8}\left\{[1+\cos^2(\theta_Z) - 2c\cos(\theta_Z)] f_L^Z + [1+\cos^2(\theta_Z) + 2c\cos(\theta_Z)] f_R^Z + 2\sin^2(\theta_Z) f_0^Z\right\}$$

Results in helicity (HE) frame, where the polarization angle is measured between $\mathbf{p}^{l}$ in rest frame of W/Z, and $\mathbf{p}^{W/Z}$ in lab frame.

Split MC into 3 polarization components. Extract expected polarization fractions from MC gen-level fit

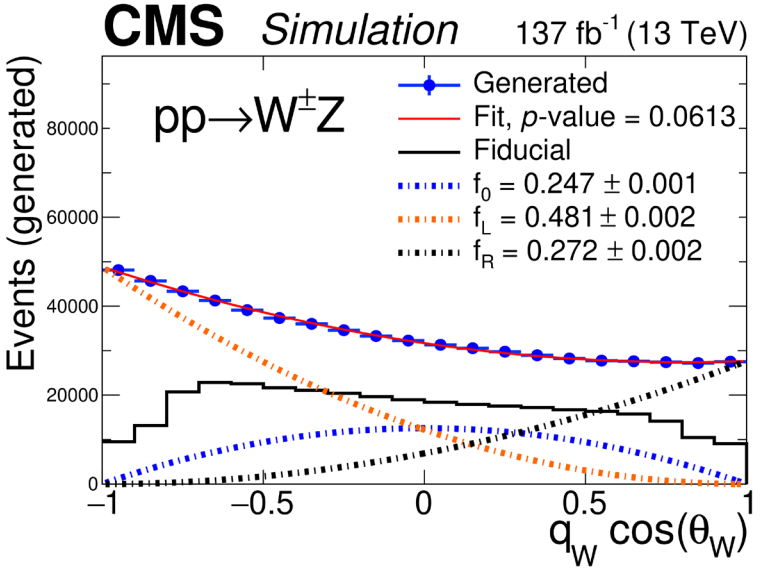
→

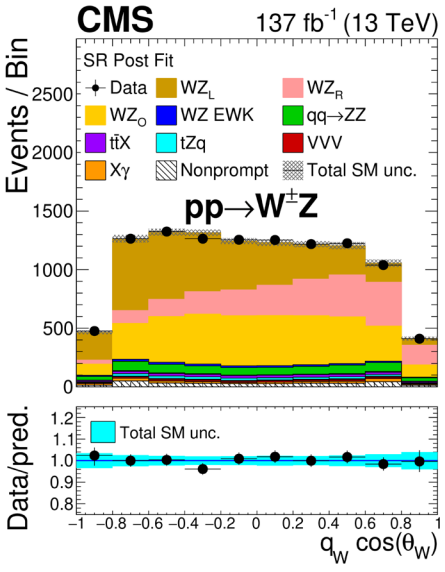
Reweight WZ MC event to match gen-level distr. for each polarization state

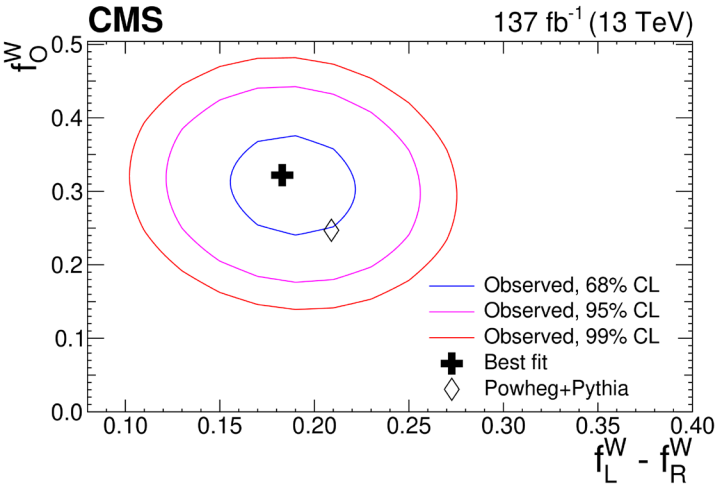
→

Measure polarization fractions by likelihood fitting

(Similar procedure for Z)




Also measure significance for longitudinally polarized bosons. Way above 5σ for Z.

**Observed(expected) 5.6 (4.3) σ for W → first observation in WZ channel**

# CMS ZZ Cross Sections

137 fb$^{-1}$ at 13 TeV, CMS-SMP-19-001, *EPJC 81 (2021) 200*

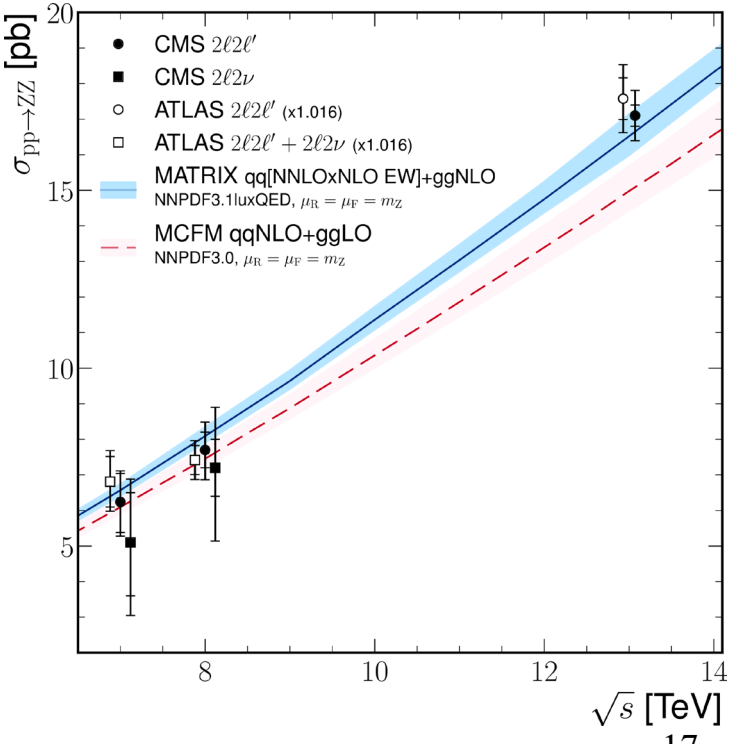
ZZ total production cross section measured with ZZ → 2l2l' events, l,l' = e or μ:

**$\sigma_{tot}$(pp → ZZ) = 17.4 ± 0.3(stat) ± 0.5 (syst) ± 0.4 (theo) ± 0.3 (lumi) pb**

- Consistent with SM prediction. Relative uncertainty less than 5%
- NNLO cross section prediction needed to describe the cross section within experimental uncertainty

**Fiducial Region:**
$p_T^{l1}$ > 20 GeV, $p_T^{l2}$ > 10 GeV, $p_T^{l3,4}$ > 5 GeV
$|\eta^l|$ < 2.5,
$m_{ll}$ > 4 GeV any OSSF pair (remove low mass resonances)
60< $m_{Z1}$, $m_{Z2}$ < 120 GeV (on-shell ZZ)

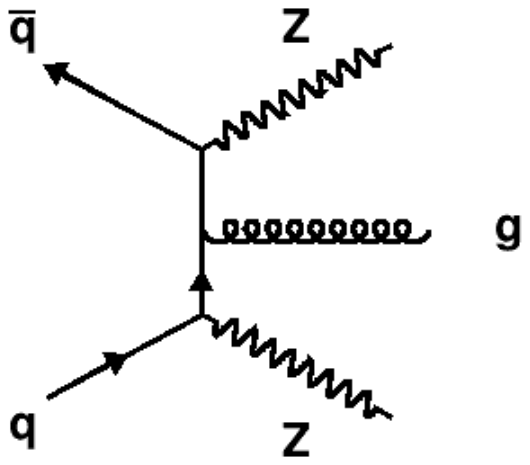
Fiducial and differential cross sections are also measured.



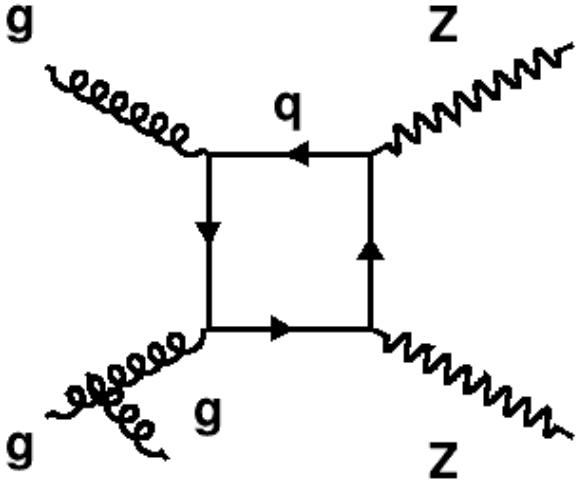
# CMS ZZ+jets (Previous Results)

19.7 and 35.9 $fb^{-1}$ at 8 and 13 TeV respectively, CMS-SMP-17-005, *Phys. Lett. B 789 (2019) 19*

- Measure in leptonic decay modes: ZZ → 2l2l', where l,l' = e or μ, associated with jets
- Measure differential cross sections as function of jet multiplicity and the kinematic properties of the two $p_T$-leading jets, including variables sensitive to VBS, such as $m_{jj}$ and $\Delta\eta_{jj}$




$q\bar{q} \rightarrow ZZ + jet$




$gg \rightarrow ZZ + jet$

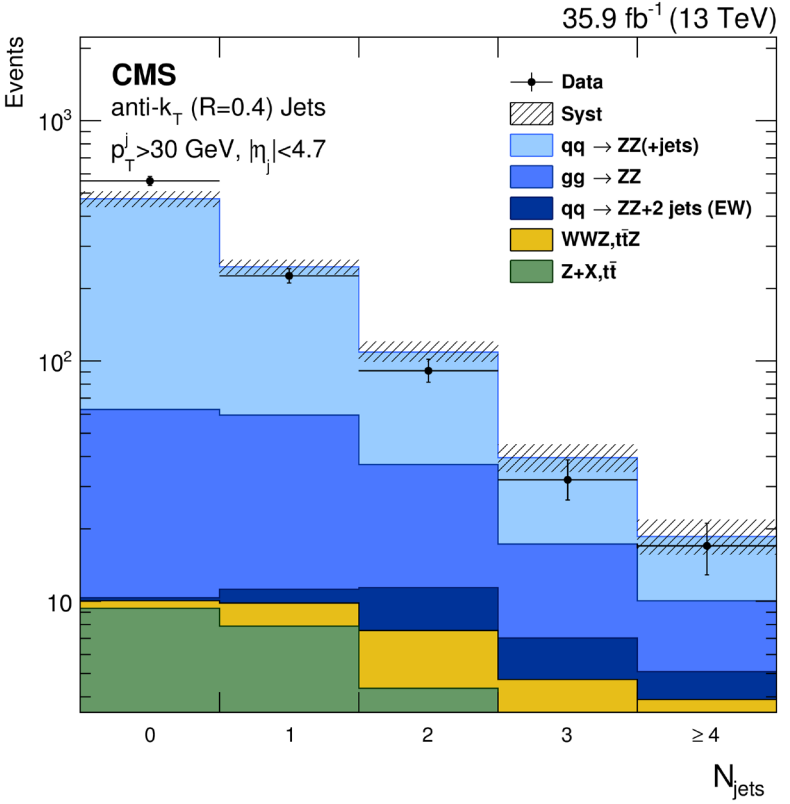
# CMS ZZ+jets (Previous Results): Selection

## Fiducial region definition:

| 8 TeV | 13 TeV |
|---|---|
| $p_T^e > 7\,\text{GeV}, \lvert\eta^e\rvert < 2.5$ | $p_T^e > 5\,\text{GeV}, \lvert\eta^e\rvert < 2.5$ |
| $p_T^\mu > 5\,\text{GeV}, \lvert\eta^\mu\rvert < 2.4$ | $p_T^\mu > 5\,\text{GeV}, \lvert\eta^\mu\rvert < 2.5$ |
| Common definitions | |
| $p_T^{\ell_1} > 20\,\text{GeV}$ , $p_T^{\ell_2} > 10\,\text{GeV}$ | $p_T^j > 30$ GeV, $\lvert\eta_j\rvert<4.7$ |
| $m_{\ell^+\ell^-} > 4\,\text{GeV}$ (any opposite-sign same-flavor pair) | |
| $60 < (m_{Z_1}, m_{Z_2}) < 120\,\text{GeV}$ | |

Remove low mass resonances

on-shell ZZ

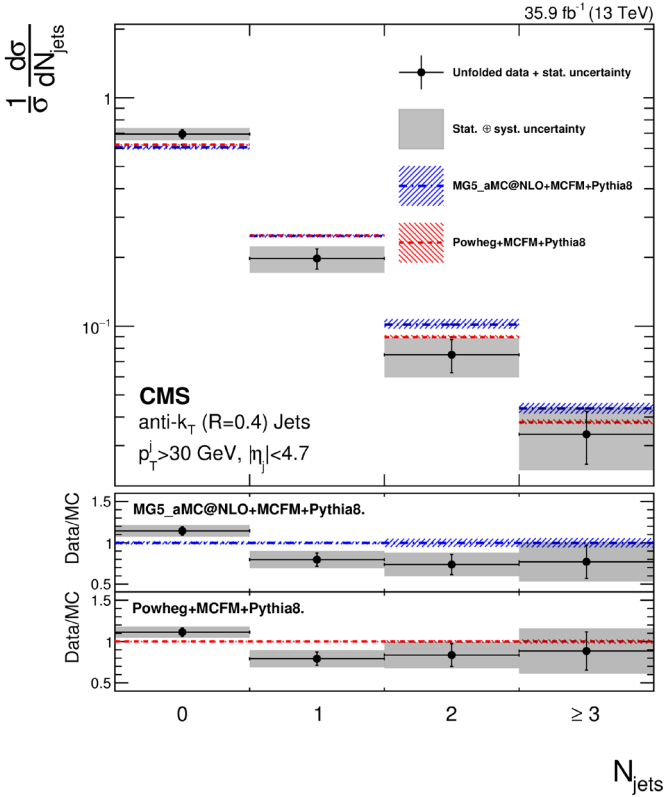


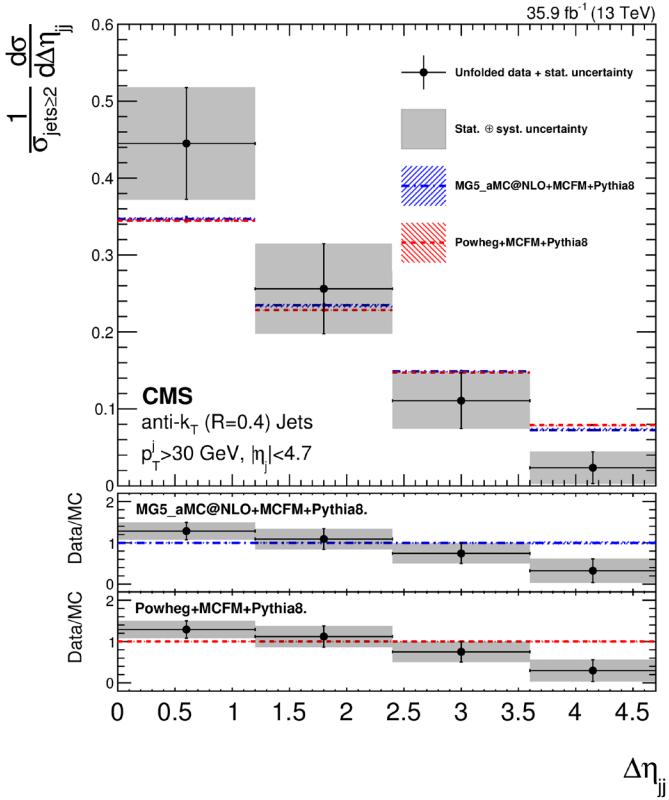

Reconstructed distribution

# CMS ZZ+jets (Previous Results): Differential Cross Sections

- Event selection efficiency and detector resolution effects corrected with iterative D'Agostini unfolding method

- Overall good agreement between data and theoretical predictions

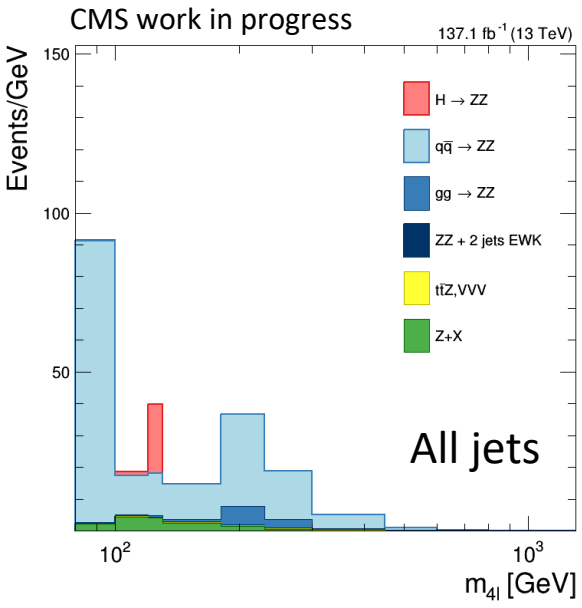


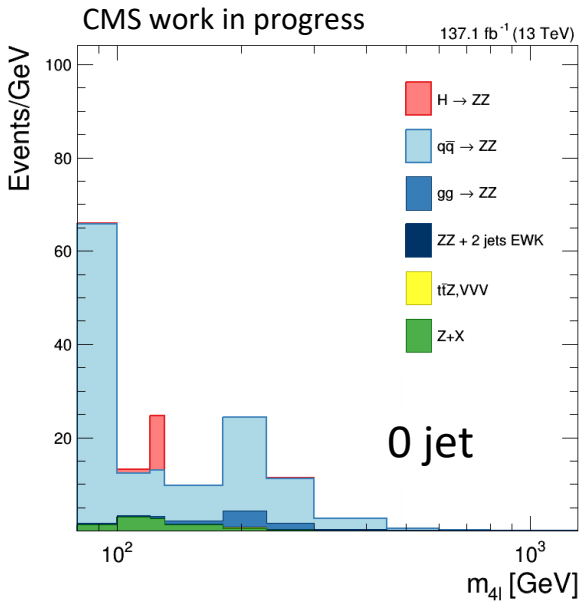



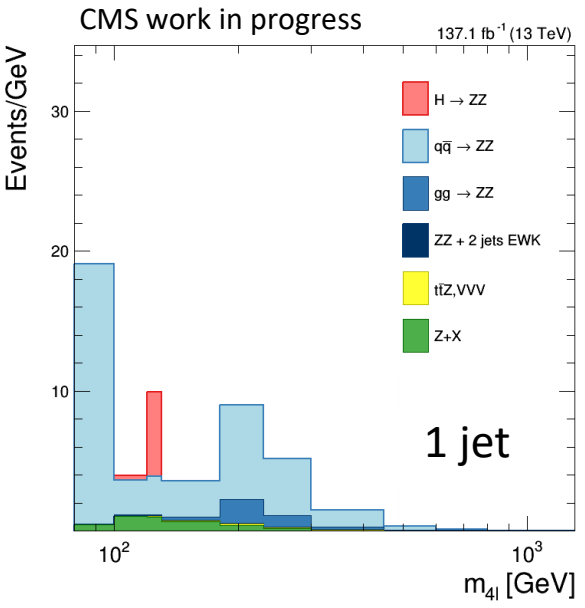

Data/prediction comparison ranging from small $\Delta\eta_{jj}$ (large jet production) to large $\Delta\eta_{jj}$ (important for EWK ZZjj production) and in overall good agreement.

→ Understanding QCD ZZ is important for EWK ZZ discovery

# CMS ZZ+jets: Work in Progress




etc.

- Similar to CMS-SMP-17-005 selections and analysis approach, with full Run2 dataset at 13 TeV
- Also include differential cross sections as function of $m_{4l}$, both with and without on-shell ZZ requirement ($60 < m_{Z1}, m_{Z2} < 120$ GeV), and requiring different numbers of jets
- At the top we show predictions for $m_{4l}$ distributions for different jet multiplicities without on-shell ZZ requirement, where the number of events in each bin is normalized by bin width

# Summary

**Recent ATLAS and CMS QCD VV results presented:**

- ATLAS WW+ ≥1 jet with full Run2 dataset
- ATLAS four-lepton events with full Run2 dataset
- CMS WZ production with full Run2 dataset
- CMS ZZ cross section with full Run2 dataset
- CMS ZZ+jets with full Run2 dataset (work in progress)

- CMS and ATLAS measurements reaching better than 5% uncertainty -- NNLO prediction needed to describe the data

- Agreement at high jet multiplicities and jet rapidity shown in several analyses, demonstrating understanding of background necessary for EWK measurements

# Backup

# ATLAS $W^+W^-$ + ≥1 jet: MC and Background

## Nominal MC

| Process | Generator | Parton shower | Matrix element $O(\alpha_S)$ | Normalization |
|---|---|---|---|---|
| $q\bar{q} \to WW$ | SHERPA 2.2.2 | SHERPA | NLO (0–1 jet), LO (2–3 jets) | Generator† |
| $gg \to WW$ | SHERPA 2.2.2 | SHERPA | LO (0–1 jet) | Generator |
| $t\bar{t}$ | POWHEG-BOX v2 | PYTHIA 8 | NLO | NNLO+NNLL |
| $Wt$ | POWHEG-BOX v2 | PYTHIA 8 | NLO | NLO+NNLL |
| $Z$+jets | SHERPA 2.2.1 | SHERPA | NLO (0–2 jets), LO (3–4 jets) | NNLO |
| $WZ, ZZ$ | SHERPA 2.2.2 | SHERPA | NLO (0–1 jet), LO (2–3 jets) | Generator† |
| $W\gamma, Z\gamma$ | SHERPA 2.2.8 | SHERPA | NLO (0–1 jet), LO (2–3 jets) | Generator† |
| $VVV$ | SHERPA 2.2.2 | SHERPA | NLO (0–1 jet), LO (2–3 jets) | Generator† |

← Includes Higgs contributions

†: The cross-section calculated by SHERPA is found to be in good agreement with the NNLO result [67–70, 73].

## Background Estimate:

- Top-quark background (90% of the total background)
  - $t\bar{t}$ from data-driven technique (correction factor from simulation)
  - Single-top Wt from simulation (16% of the top background)

- Drell-Yan Z+jets from simulation
- Events with nonprompt or misidentified leptons, estimated from data-driven technique
- Diboson (from simulation) and triboson production (negligible in simulation)

# ATLAS $W^+W^-$ + ≥1 jet: EFT interpretation

- $Q_W$ dim-6 aTGC operator of particular interest for VV analysis
- Interference of SM and anomalous amplitudes suppressed with increasing energy due to different helicities of the dominant contributions to the two amplitudes
- This weakens limits on Wilson coefficient $c_W$ in VV measurement and poses problem for validity of interpretation in dim-6 model
- Requiring a hard jet ($p_T$>200 GeV) reduces this interference suppression

CI for $c_W$ from linearized/quadratic EFT fit of $m_{e\mu}$ cross section, Λ = 1 TeV

| Jet $p_T$ | Linear only | 68% CI obs. | 95% CI obs. | 68% CI exp. | 95% CI exp. |
|---|---|---|---|---|---|
| > 30 GeV | yes | [–1.64, 2.86] | [–3.85, 4.97] | [–2.30, 2.27] | [–4.53, 4.41] |
| > 30 GeV | no | [–0.20, 0.20] | [–0.33, 0.33] | [–0.28, 0.27] | [–0.39, 0.38] |
| > 200 GeV | yes | [–0.29, 1.84] | [–1.37, 2.81] | [–1.12, 1.09] | [–2.24, 2.10] |
| > 200 GeV | no | [–0.43, 0.46] | [–0.60, 0.58] | [–0.38, 0.33] | [–0.53, 0.48] |

# ATLAS 4l Events: MC and Background

- **$q\bar{q}$→ 4l** including Z→ 4l: SHERPA at NLO (0-1 jet), LO (up to 3 jets)
  alternatively with: POWHEG at NLO

- **gg→ 4l**: SHERPA at LO (0-1 jet)

- **Dedicated for on-shell Higgs production:**
  - **ggH:** POWHEG NNLOPS at NNLO
  - **VBF, VH, $t\bar{t}$H**: POWHEG

- **VVV** with SHERPA at NLO (inclusive), LO (up to 2 jets)
  **$t\bar{t}$V(V)** with MadGraph5_aMC@NLO at NLO (for particle-level predictions)
  with SHERPA at LO (0-1 jet) (for detector corrections)

**Background**
One or more non-prompt leptons in 4l, estimated using data-driven method (fake factor)

# ATLAS 4l Events: Measured Cross Sections

| | Region | | | | |
|---|---|---|---|---|---|
| | Full | $Z \to 4\ell$ | $H \to 4\ell$ | Off-shell $ZZ$ | On-shell $ZZ$ |
| Measured | 88.9 | 22.1 | 4.76 | 12.4 | 49.3 |
| fiducial | ±1.1 (stat.) | ±0.7 (stat.) | ±0.29 (stat.) | ±0.5 (stat.) | ±0.8 (stat.) |
| cross-section | ±2.3 (syst.) | ±1.1 (syst.) | ±0.18 (syst.) | ±0.6 (syst.) | ±0.8 (syst.) |
| [fb] | ±1.5 (lumi.) | ±0.4 (lumi.) | ±0.08 (lumi.) | ±0.2 (lumi.) | ±0.8 (lumi.) |
| | ±3.0 (total) | ±1.3 (total) | ±0.35 (total) | ±0.8 (total) | ±1.3 (total) |
| SHERPA | 86±5 | 23.6±1.5 | 4.57±0.21 | 11.5±0.7 | 46.0±2.9 |
| POWHEG + PYTHIA8 | 83±5 | 21.2±1.3 | 4.38±0.20 | 10.7±0.7 | 46.4±3.0 |

$Z \to 4l$ branching fraction extracted using the measured cross section in $Z \to 4l$ region:

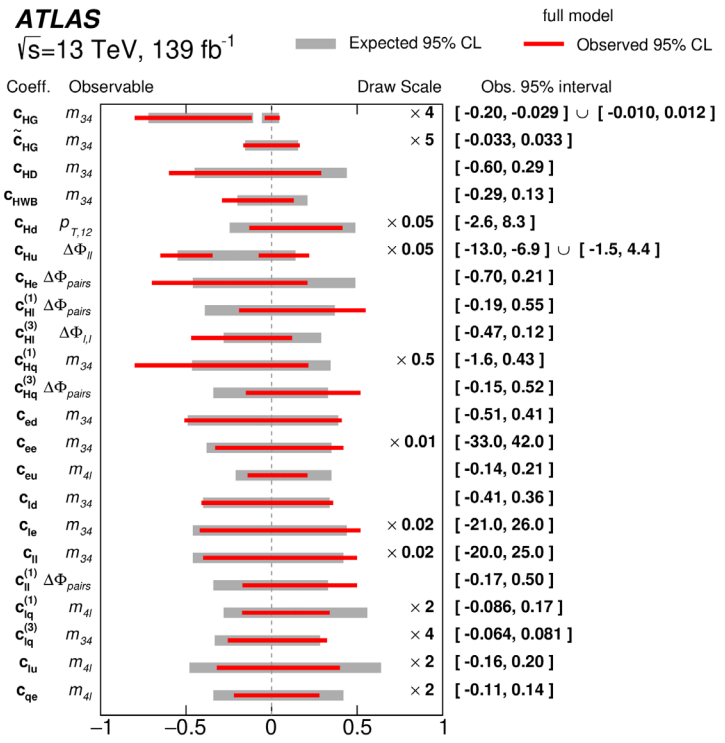
$$\mathbf{B_{Z \to 4l} = (4.41 \pm 0.13\ (stat.) \pm 0.23\ (syst.) \pm 0.09\ (theory) \pm 0.12\ (lumi.)) \times 10^{-6}}$$

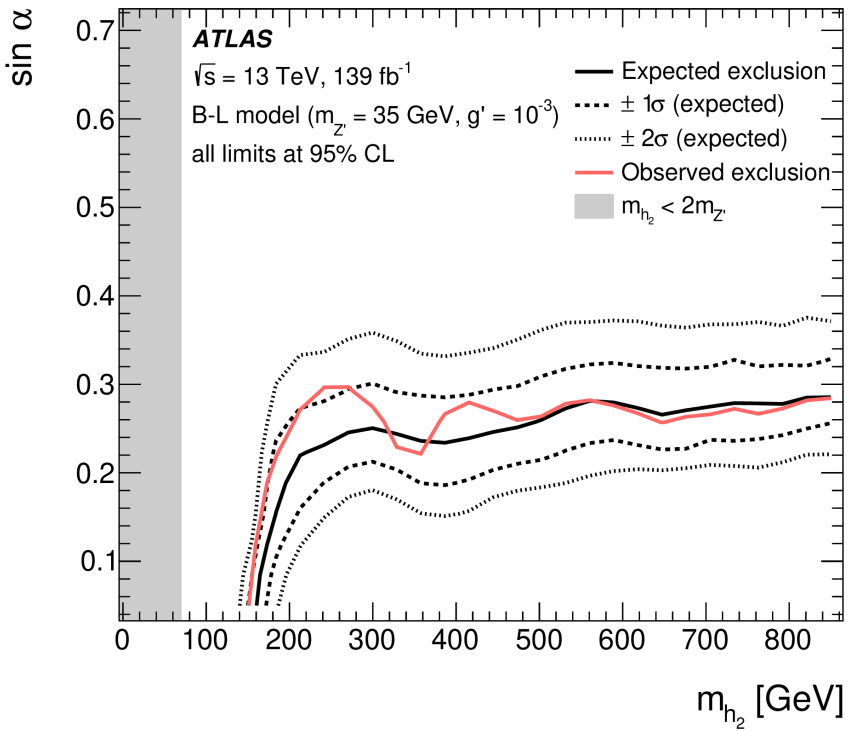
Compatible with previous measurements and SM prediction with POWHEG. Current measurement is the most precise to date.

# ATLAS 4l Events: Constraint on BSM

- Confidence intervals at 95% CL for the SMEFT Wilson coefficients. Most sensitive observable is used for the constraints for each coefficient.

- Exclusion contour at 95% CL for a model based on spontaneously broken B-L gauge symmetry.



# CMS WZ production: MC and Background

- **WZ signal**: POWHEG at NLO

alternatively with: MadGraph5_aMC@NLO at NLO (0-1 jet)

**SM Background MC**

- **qq-initiated WW and ZZ**: POWHEG at NLO
- MadGraph5_aMC@NLO at NLO for:
  - **Other diboson processes** (Zγ, Wγ, ZH, and WH)
  - **Triboson production** (WWW, WWZ, WZZ, ZZZ, and WZγ)
  - **Associated production of top** ($t\bar{t}\,t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, $t\bar{t}\gamma$, and tZq)
- **ggWW, ggZZ**: MCFM at LO
- **EW WZ**: MadGraph5_aMC@NLO at LO

**Irreducible Background (14% SR yield)**

Mainly ZZ production (6% of SR yield), $t\bar{t}Z$ and tZq (together 3.2% SR yield), Xγ (1.5% SR yield)
Each estimated from MC predictions and validated in corresponding CR

**Reducible Background (2.4% SR yield)**

Events with nonprompt or misidentified lepton, mostly due to Z+jets and $t\bar{t}$ production
Estimated with tight-to-loose data-driven method

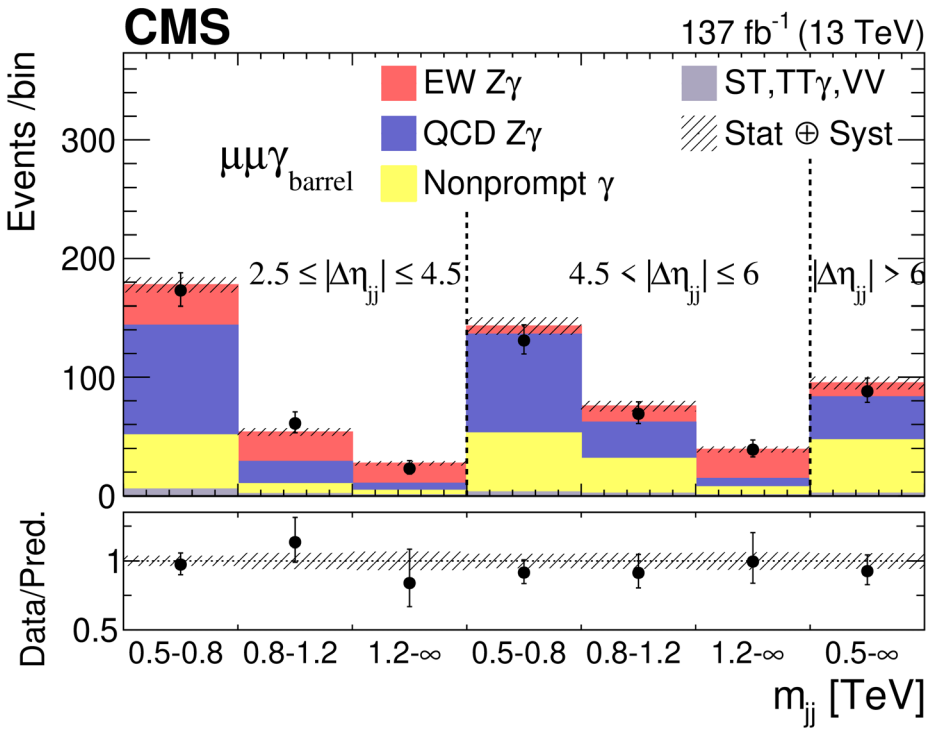
# Introduction: QCD VV as Dominant Background for EW Studies

## EW production of Zγjj

137fb$^{-1}$ at 13 TeV with full Run2 dataset, CMS-SMP-20-016, *Phys. Rev. D 104 (2021) 072001*

- A simultaneous maximum likelihood (ML) fit is used to extract the signal significance, signal strength, fiducial cross sections, and unfolded differential cross sections for both EW and EW+QCD production of Zγjj.
- Constraints on EFT dim-8 operators for aQGC
- **QCD production constitutes major background for EW studies, and this is similar for the case of ZZ**

distributions for dimuon



# Z+jets differential cross sections

CMS-SMP-19-009 *Submitted to Phys. Rev. D*

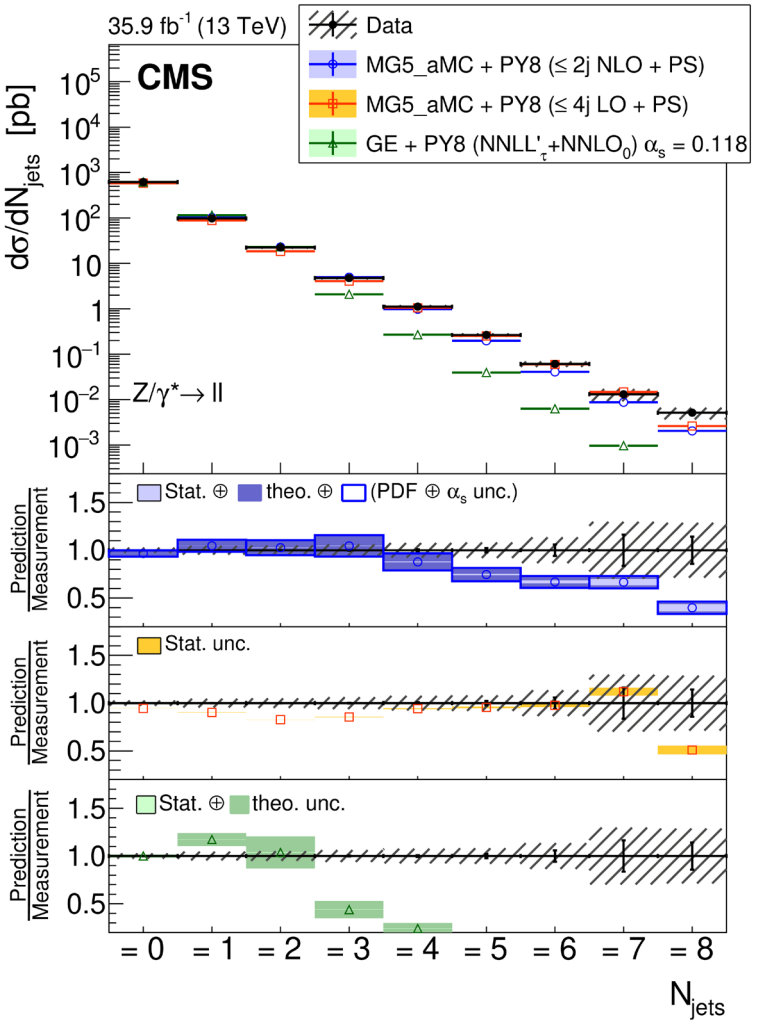
*35.9 fb$^{-1}$ at 13 TeV; jets with $p_T$>30 GeV, $|\eta|$<2.4*

*Differential cross sections measured as function of exclusive/inclusive jet multiplicity, and kinematic variables such as $p_T$, y and HT*

*Compared with 3 predictions:*

- MG5_aMC + PYTHIA 8 at NLO with 0,1,2 jets
- MG5_aMC + PYTHIA 8 at LO with 0,1,2,3,4 jets
- GENEVA (NNLL'$_T$ + NNLO$_0$ ) + PYTHIA 8

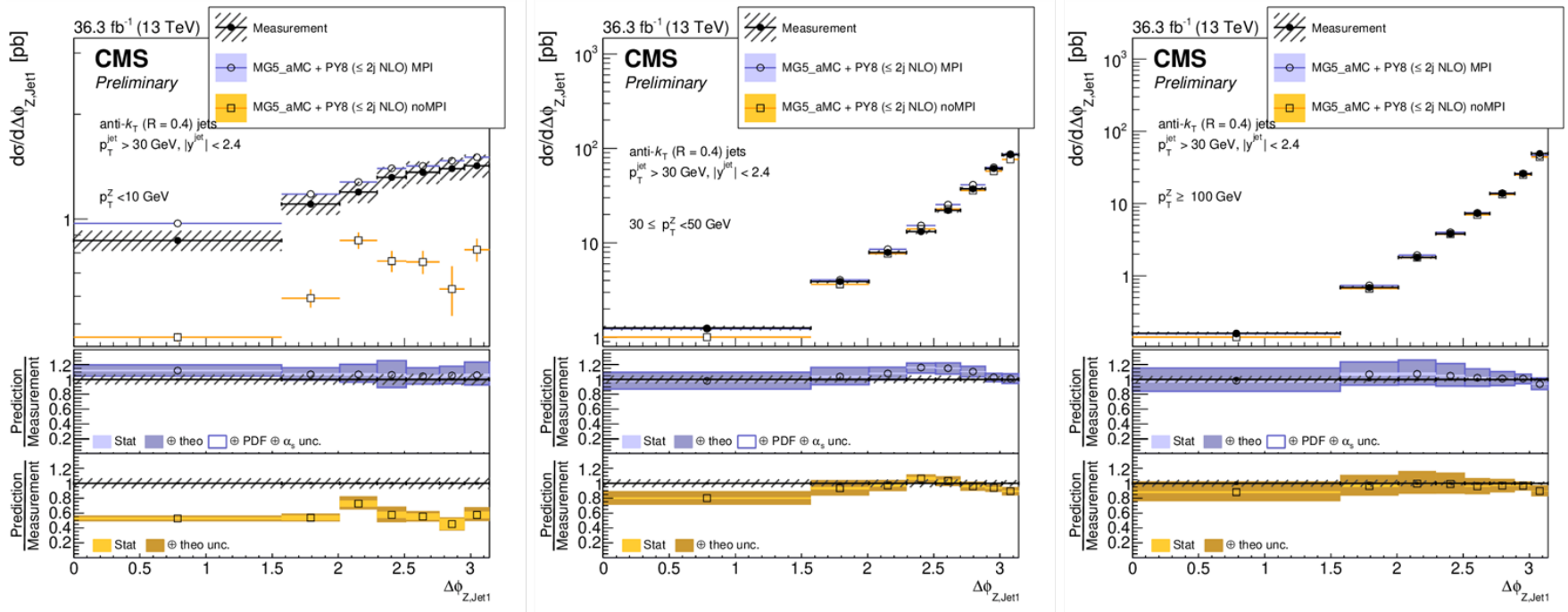
- Good agreement for exclusive distributions for all theoretical predictions, up to maximum number of final-state partons in ME
- GENEVA predicts steeper spectrum than observed, due to lack of hard jets at ME level beyond two



# Z+jets differential cross sections: azimuthal correlations

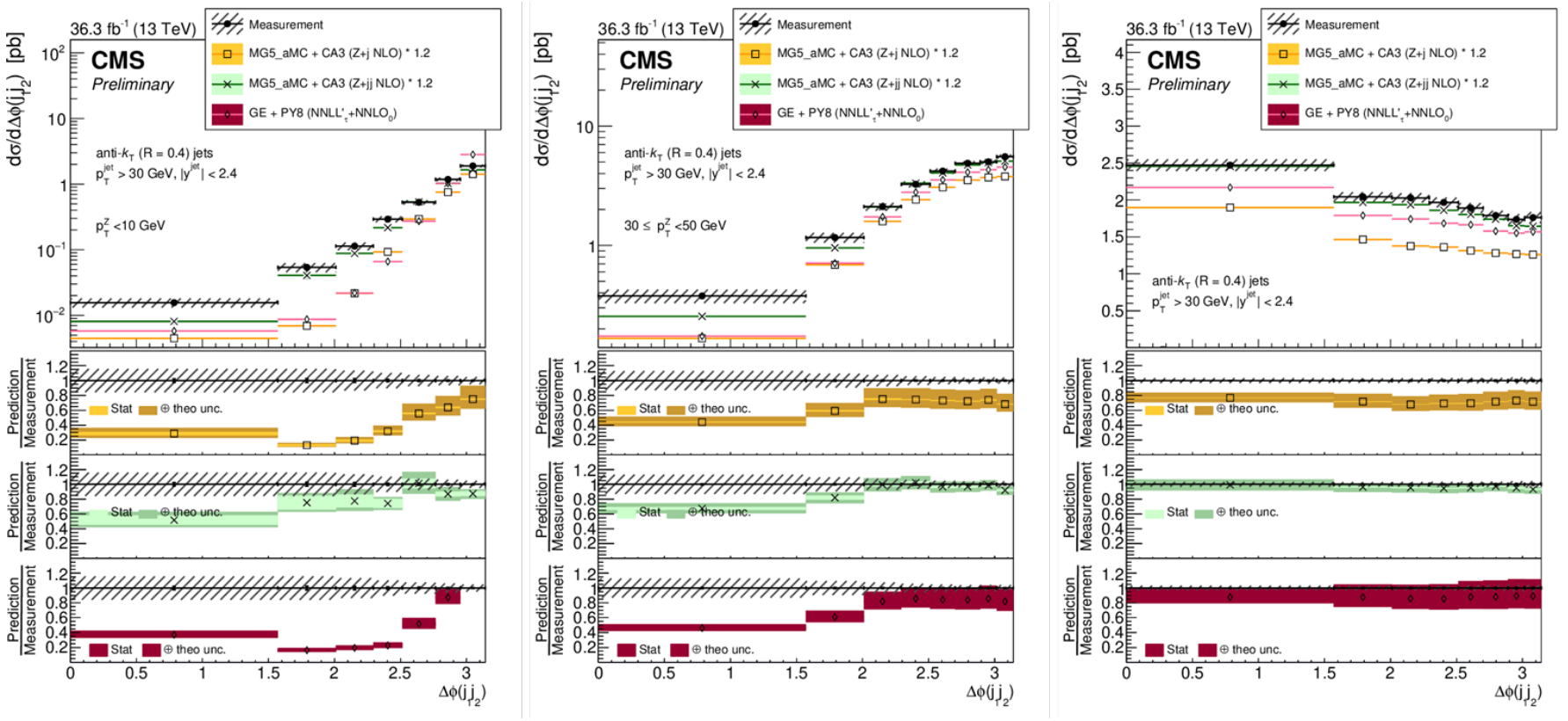
CMS-SMP-21-003, results released July 2021, 36.3 fb$^{-1}$ at 13 TeV

- Azimuthal correlations $\Delta\varphi$ (Z, $j_1$) and $\Delta\varphi$ ($j_1$,$j_2$) for different $p_T$(Z) range are measured
- Measurement compared with MG5_aMC + PYTHIA 8 (≤ 2j) with and without multi-parton interactions. Predictions with MPI in good agreement with measurement.



# Z+jets differential cross sections: azimuthal correlations

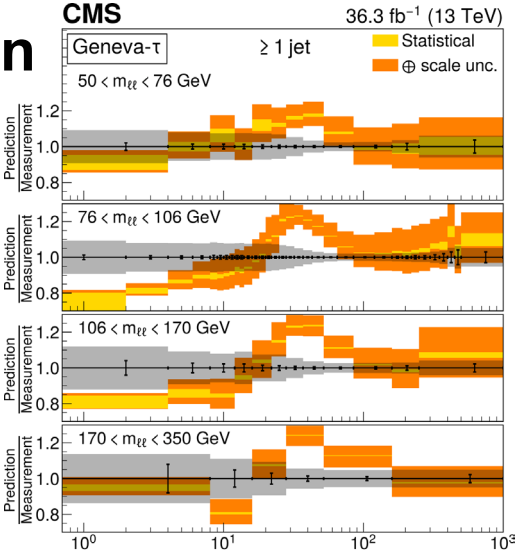
Also compare with predictions (MG5_aMC + CA3, Z+j & Z+jj) based on newly developed Parton Branching (PB) transverse momentum dependent (TMD) parton densities together with TMD based parton shower (CASCADE3), with hadronization using PYTHIA 6. MPI not simulated in this approach.

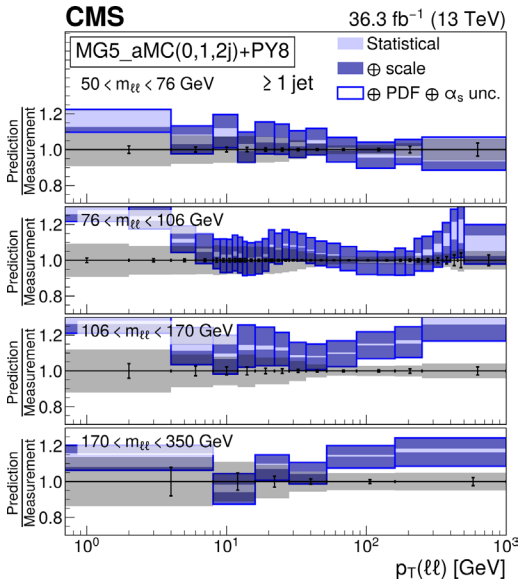


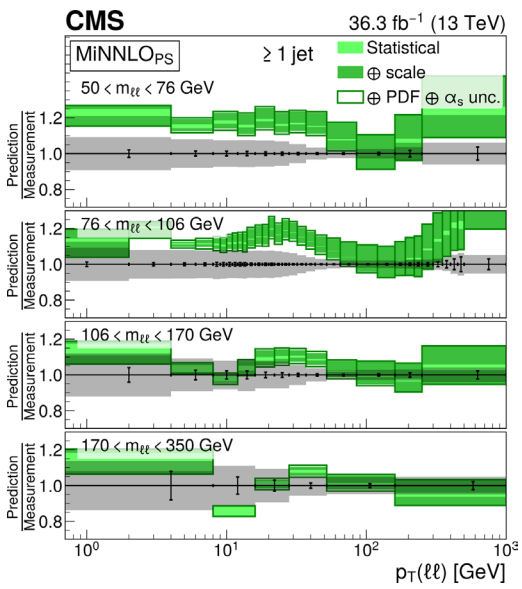
# Mass dependence of di-lepton $p_T$ in Drell-Yan production

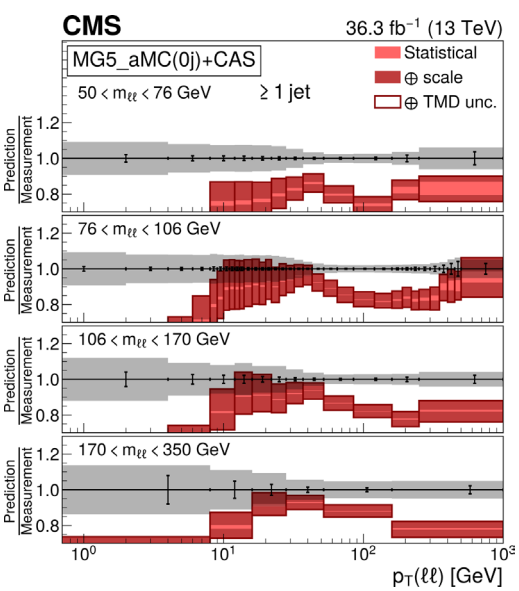
CMS-SMP-20-003, submitted to EPJC, 36.3 fb$^{-1}$ at 13 TeV

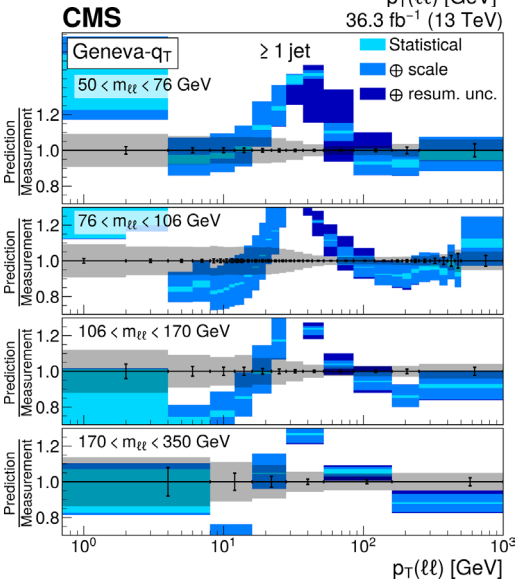
- Differential cross sections measured as function of $m_{ll}$, $p_T(ll)$ and $\varphi_\eta^*$ (derived from angular measurement of leptons)
- Compared with 6 predictions (5 for measurement requiring ≥ 1 jet)
- None of the predictions describe data perfectly in the whole explored phase space



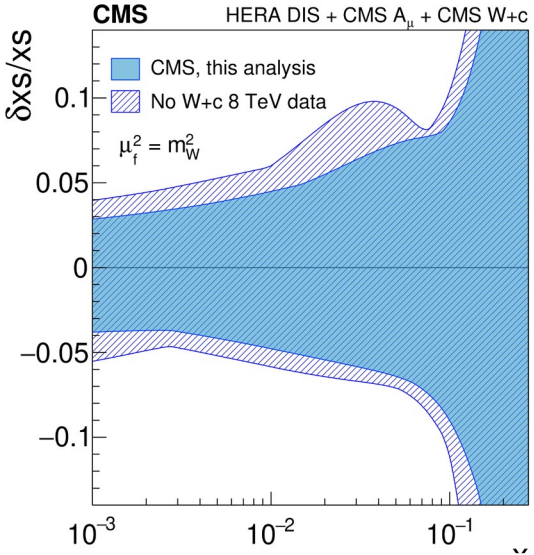



# V + heavy flavor jets: W+c, 8 and 13 TeV

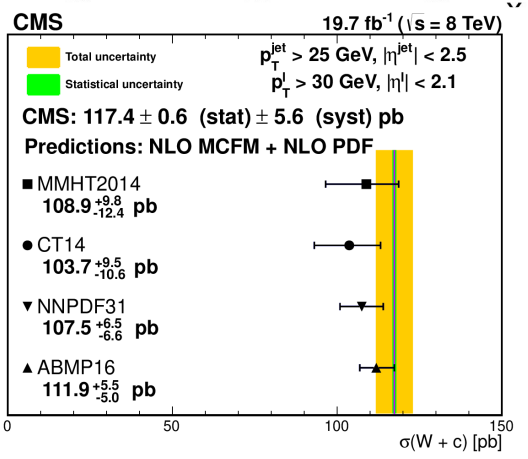
Effect of 8 TeV measurement on relative unc. in strange PDF

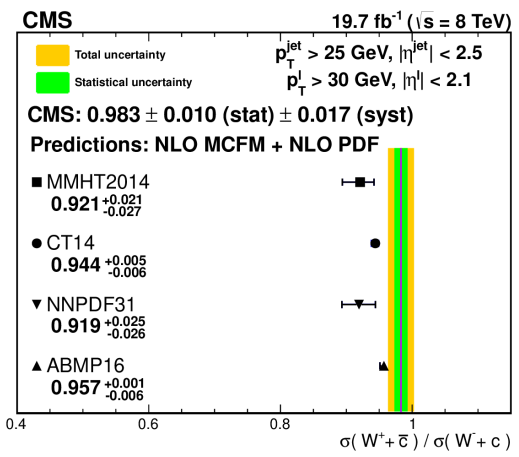


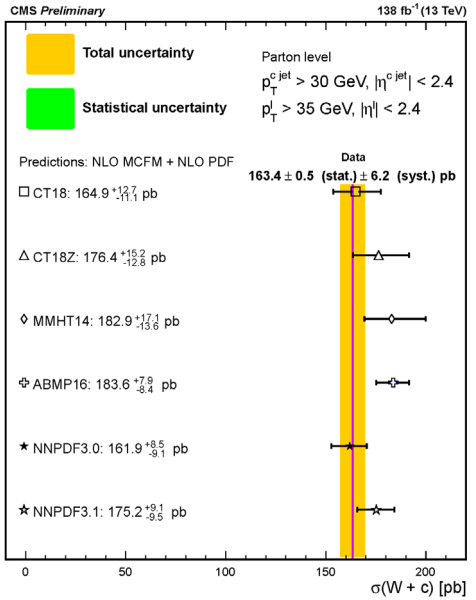

8 TeV: CMS-SMP-18-013 submitted to EPJC

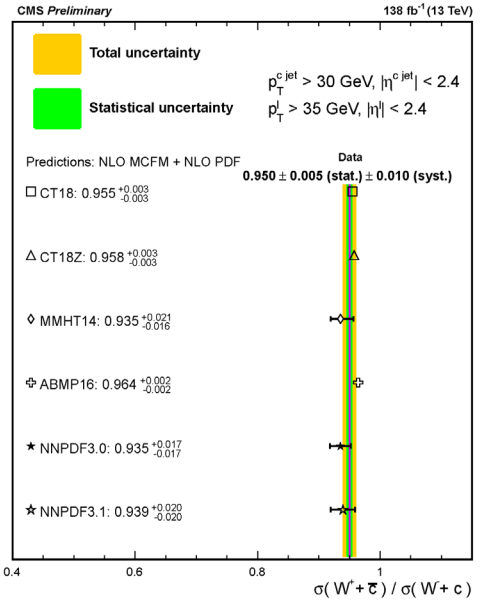
13 TeV full Run2: CMS-PAS-SMP-21-005 new preliminary results

- Sensitive to strange quark content, constitutes major background in e.g. WH production with $H \rightarrow c\bar{c}$
- W+c production cross sections and the cross section ratio $\sigma(W^+ + \bar{c})/\sigma(W^- + c)$ are measured inclusively (shown below) and differentially, and compared with theoretical predictions.



# V + heavy flavor jets: Z+b

13 TeV with full Run2 dataset, CMS-SMP-20-015, *Phys. Rev. D 105 (2022) 092014*

- Can test perturbative QCD, provides information on b quark PDFs, and constitutes major background for ZH, H → $b\bar{b}$
- Measurement includes integrated cross sections and differential distributions of Z (→ ll) + ≥ 1 b jet and Z (→ ll) + ≥ 2 b jet, and ≥ 1 jet, ≥ 2 jet cross section ratios.