Measurement of the differential ZZ+jets production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with CMS full Run 2 data

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Outline

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- Results
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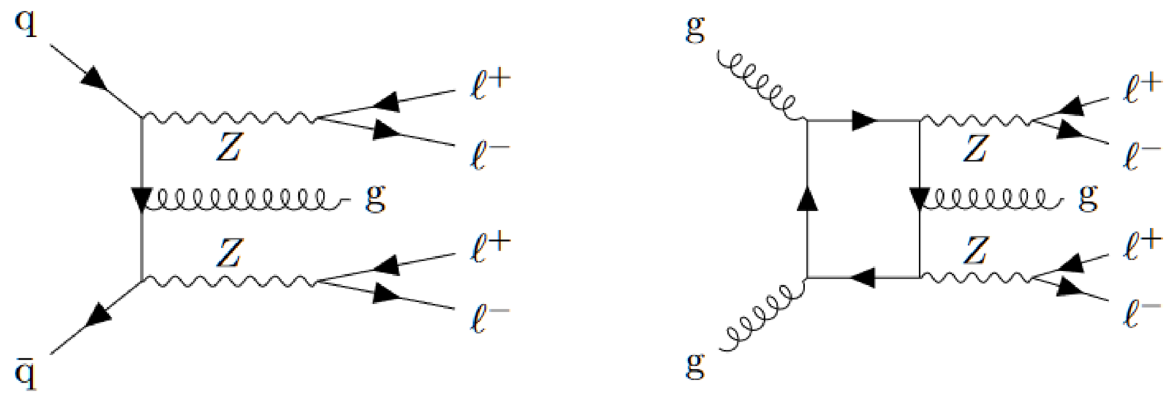
Overview

Introduction

- In the SM, ZZ production proceeds mainly through **quark-antiquark** t- and u-channel scattering diagrams. In calculations at higher order in QCD, **gluon-gluon fusion** also contributes via box diagrams with quark loops. We look at four-lepton production **pp → (Z/γ ∗)(Z/γ ∗) → 2ℓ2ℓ' , (ℓ, ℓ' = e or μ),** mainly in non-resonant m_{4l} region requiring on-shell ZZ, defined as 60 GeV < m_{Z1} ,m_{Z2} < 120 GeV.

- The EW and QCD vertices result in the production of Z pairs and the production of associated jets respectively. Our goal is to measure the **ZZ+jets** processes.

- CMS Full Run 2 data set is used corresponding to an integrated luminosity of 138 fb^{-1} at $\sqrt{s}$ = 13 TeV.

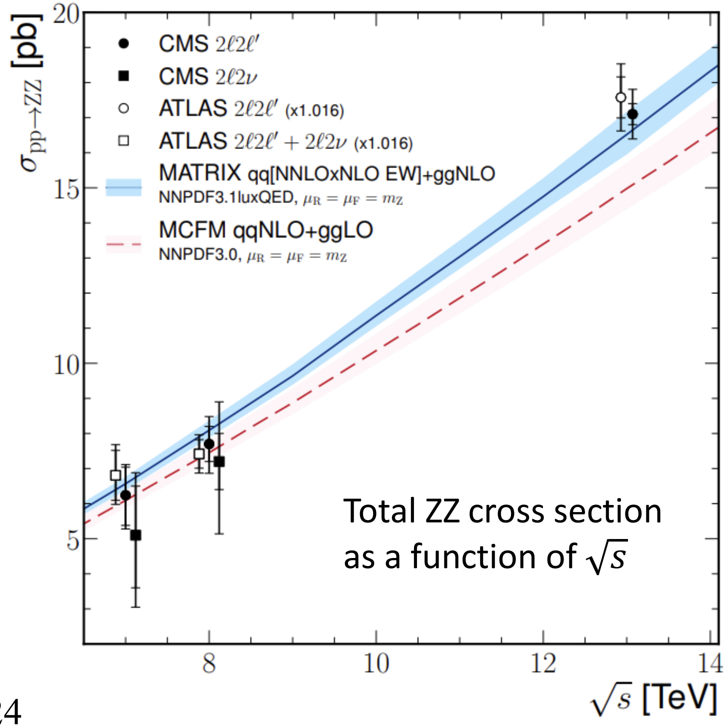


Example Feynman diagrams for the $q\bar{q}$ → ZZ and gg → ZZ processes associated with 1 jet.

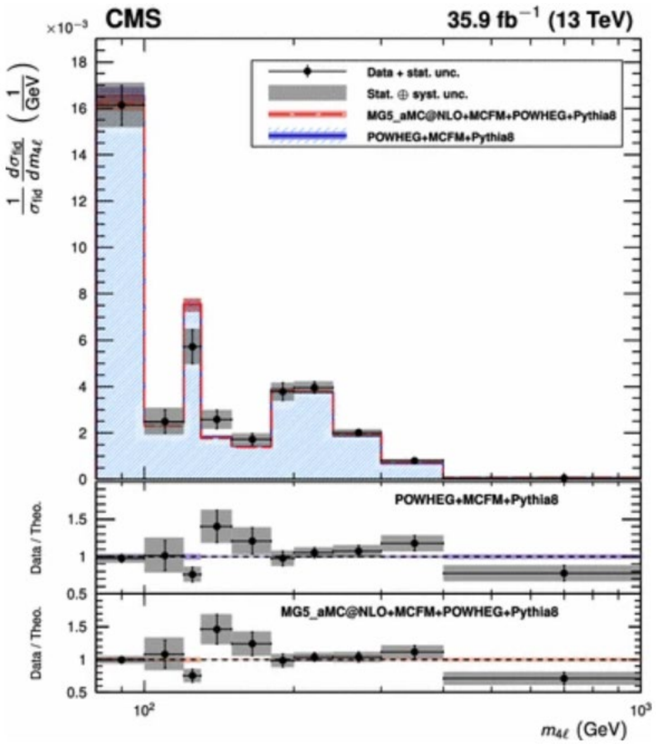
ZZ Measurement Inclusive in Jet Multiplicities

- Previously ZZ production cross section and differential cross sections with inclusive jet multiplicities were measured with full Run 2 data at 13 TeV, with on-shell ZZ requirement in the fiducial region definition.

- Differential cross sections in the full m_{4l} range (without on-shell ZZ requirement) were also measured with an integrated luminosity of 35.9 fb^{-1} at 13 TeV.



Total ZZ cross section as a function of $\sqrt{s}$



Why ZZ+jets with Full Run 2 Data?

- QCD-induced ZZ production is a large background for EWK studies and Higgs production measurement.

- ZZ+jets compared with theoretical predictions provides better understanding and important test of the QCD corrections to ZZ production.

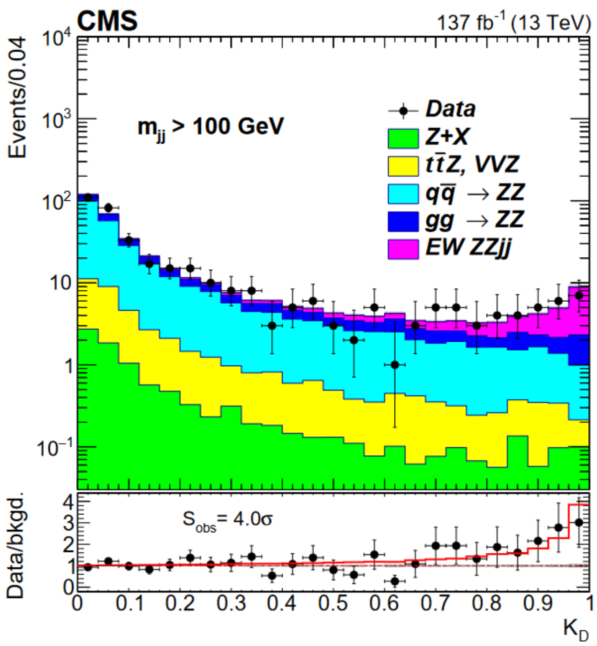
ZZ+jets production was previously studied with integrated luminosity of 19.7 and 35.9 fb^{-1} at 8 and 13 TeV respectively.

In the current analysis:

- ZZ+jets production is studied with higher luminosity (138 fb^{-1}).

- In addition to jet variables, we explore differential distributions and cross sections for m_{4l} both inclusive and as a function of jet multiplicity, with and without the on-shell ZZ requirement.

- We compare to both NLO and nNNLO+PS Monte Carlo predictions.



Distributions of the matrix element discriminant (K_D) for separating EW signal from QCD background in CMS full Run 2 EW ZZ+2jets measurement

Analysis Strategies

Particle-level Event Selections

Fiducial Requirements:

Leptons: - require 4 leptons, $p_T(\ell_1) > 20$ GeV, $p_T(\ell_2) > 10$ GeV, $p_T(\ell) > 5$ GeV, $|\eta_\ell| < 2.5$

- $m_{\ell 1, \ell 2} > 4$ GeV for any OSSF lepton pair

Jets: $p_T > 30$ GeV, $|\eta| < 4.7$, $\Delta R(\ell, \text{jet}) > 0.4$

ZZ: - Designate dilepton pair with invariant mass closest to nominal m_Z as Z_1, the other Z_2

- 40 GeV < m_{Z1} < 120 GeV, 4 GeV < m_{Z2} < 120 GeV
- On-shell requirement: $60 < m_{Z1}, m_{Z2} < 120$ GeV, but we also look at those m_{4l} distributions without this requirement
- $m_{4l} > 80$ GeV

Backgrounds

The requirement of four well-reconstructed and isolated lepton candidates strongly suppresses any background. Therefore, this analysis has very low background contributions, dominated by Z boson and WZ diboson production in association with jets, and $t\bar{t}$ production.

Irreducible Background $(t\bar{t}\mathrm{Z}, \mathrm{VVV})$:
Processes which contain 4 prompt leptons from non-signal processes. Estimated with Monte Carlo (MC) samples.

Reducible Background $(\mathrm{Z}{+}\mathrm{X})$**:**
Processes which contain one or more jets or non-prompt leptons misidentified as signal leptons in the 4-lepton final state.

Not well modeled by MC. Estimated using data-driven tight-to-loose "fake rates" method. The misidentification probability is measured with a sample of $\mathrm{Z} + \ell_{\mathrm{candidate}}$ events, and the number of background events in signal region is estimated with two control samples of $\mathrm{Z} + \ell^{+}\ell^{-}$ events scaled by the misidentification probability for each lepton failing the full selection.

Unfolding

- To correct for detector effects and compare experimental results with theoretical predictions, the data are “unfolded” using the iterative D’Agostini’s method (with the RooUnfold package).

- For each distribution to be unfolded, a response matrix is obtained from simulated signal samples. It represents the correlation map between the distributions obtained after the full detector simulation and the particle-level distribution they originate from.

- Unfolded results are compared with theoretical predictions at particle-level, with the dominant $q\overline{q} \rightarrow \mathrm{ZZ}$ predictions obtained from the MADGRAPH5_aMC@NLO (simulated with up to 1 jet emission at NLO QCD) and POWHEG (inclusive in jets at NLO) MC generators, respectively.

- Results are also compared with the recent nNNLO+PS predictions, which consist of NNLO predictions for quark-initiated channel combined with parton showers using the MiNNLO$_{PS}$ method, and NLO predictions for loop-induced gluon fusion channel matched to parton showers.

- We will be looking at differential cross sections **normalized** to ZZ fiducial cross section.

Systematic Uncertainties

- Uncertainties of this analysis are dominated by statistical uncertainty.

- Most systematic uncertainties are propagated through unfolding by recomputing the response matrix with the sample used to build the matrix shifted or reweighted to reflect a 1σ shift in the quantity in question, then taking the difference in the normalized unfolded results.

$$\text{portion of unc. per unfolded distribution} = \frac{\sum_{i=1}^{N_{\text{bins}}} |h_{\text{central}}(i) - h_{\text{varied}}(i)|}{\sum_{i=1}^{N_{\text{bins}}} h_{\text{central}}(i)}$$

(Table numbers are indicative only)

For jet variables

Systematic source	Uncertainty range
Electron efficiency	0.13–0.30%
Muon efficiency	0.02–0.08%
Jet energy resolution	1.65–3.85%
JES correction	0.93–5.32%
Reducible background	0.05–0.43%
Pileup	0.04–1.08%
Luminosity	$< 0.03\%$
$q\bar{q} \to ZZ$ MC choice	0.52–4.52%
$gg \to ZZ$ cross section	0.01–0.19%
QCD scales	0.16–0.82%
PDF	0.05–0.12%
PDF α_S	0.01–0.10%

For m_{4l} (in on-shell ZZ region)

Systematic source	$m_{4\ell}$ with all jets	0 jet	1 jet	2 jets	3 and more jets
Electron efficiency	0.42%	0.38%	0.66%	0.36%	0.26%
Muon efficiency	0.05%	0.06%	0.07%	0.09%	0.08%
Jet energy resolution	—	0.07%	1.72%	1.65%	0.80%
JES correction	—	0.17%	1.77%	1.95%	0.97%
Reducible background	0.18%	0.18%	0.32%	0.33%	0.96%
Pileup	0.02%	0.05%	0.11%	0.13%	0.35%
Luminosity	0.01%	0.01%	0.02%	0.02%	0.05%
$q\bar{q} \to ZZ$ MC choice	0.35%	0.65%	0.94%	0.48%	0.35%
$gg \to ZZ$ cross section	0.02%	0.03%	0.09%	0.06%	0.09%
QCD scales	0.15%	0.16%	0.58%	0.54%	0.62%
PDF	0.05%	0.05%	0.15%	0.15%	0.21%
PDF α_S	0.02%	0.01%	0.05%	0.03%	0.02%

Results

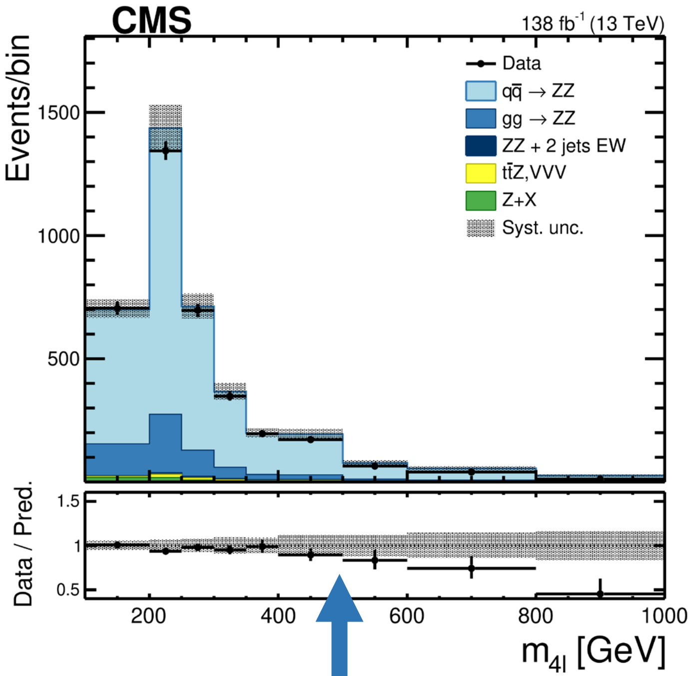
More details and plots available in the paper draft

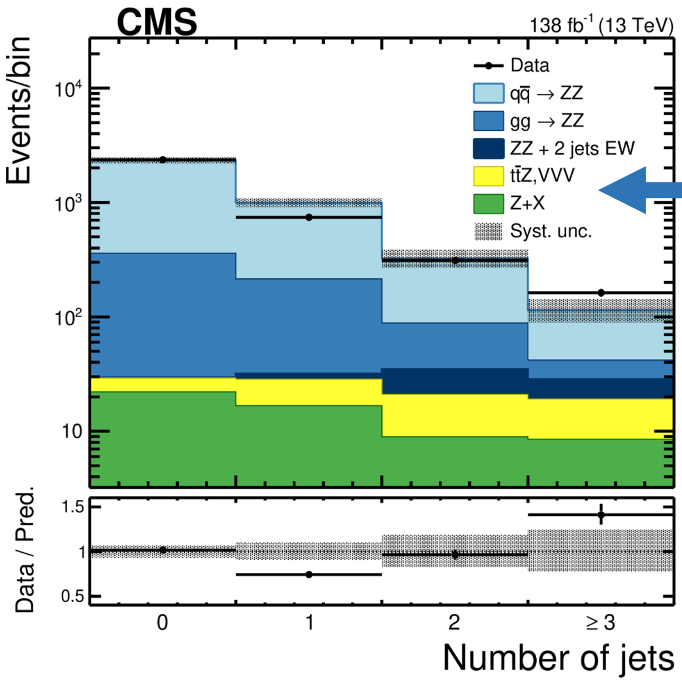
Submitted for publication to JHEP last month

RECO-level Differential Distributions

m_{4l} and Number of Jets Distribution

Require 60 GeV < m_{Z1}, m_{Z2} < 120 GeV. The MG5_aMC@NLO $q\overline{q} \rightarrow ZZ$ sample is used in these plots, along with other contributions. Overflow included in the last bin.





The 0 and 2 jet bins are well described by predictions, but we see significant discrepancy at 1-jet bin and this disagreement is propagated in other distributions.

Description of events with ≥3 jets requires NNLO and even higher corrections, therefore the difference between data and predictions at high jets multiplicity is expected.

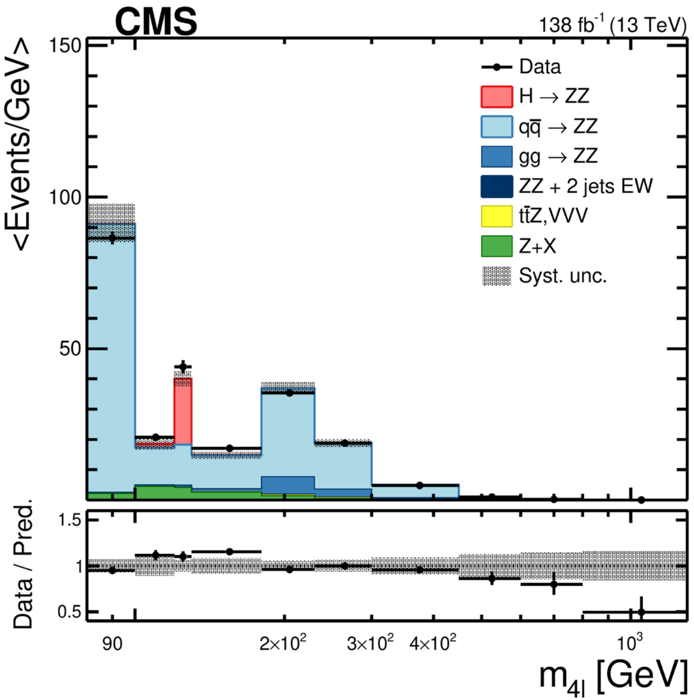
m_{4l} distribution well described by the predictions, except for the increasing data/MC discrepancy towards high masses, which can be mitigated with EW corrections.

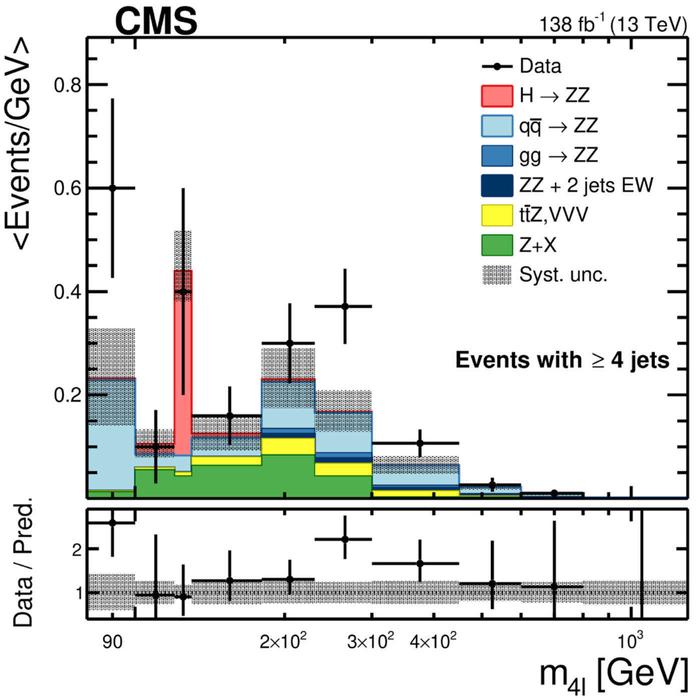
RECO-level Differential Distributions

m_{4l} Distributions for Inclusive and ≥ 4 Jets Region

We also look at full available m_{4l} range featuring 3 mass regions: Z boson, Higgs boson and non-resonant ZZ production region. Requiring only 40 GeV < m_{Z1} < 120 GeV, 4 GeV < m_{Z2} < 120 GeV, without on-shell ZZ requirement. With increased number of jets we see bigger discrepancy with respect to MC predictions.

Inclusive





≥ 4 Jets

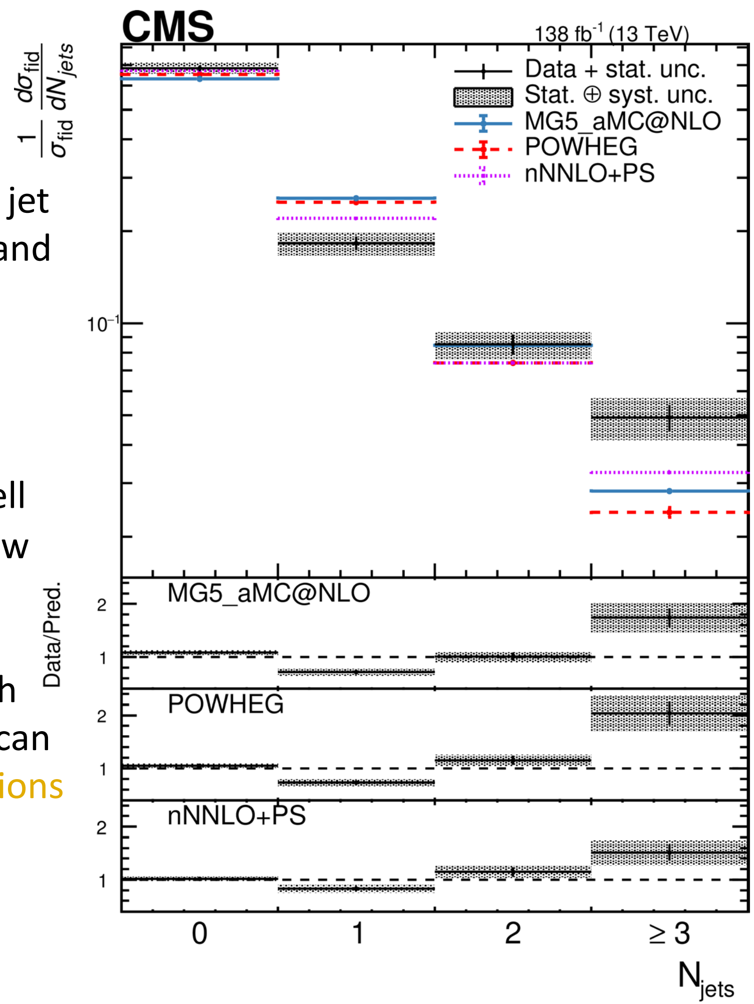
After checking data and MC agreement at reconstruction level, we proceed with unfolding the data.

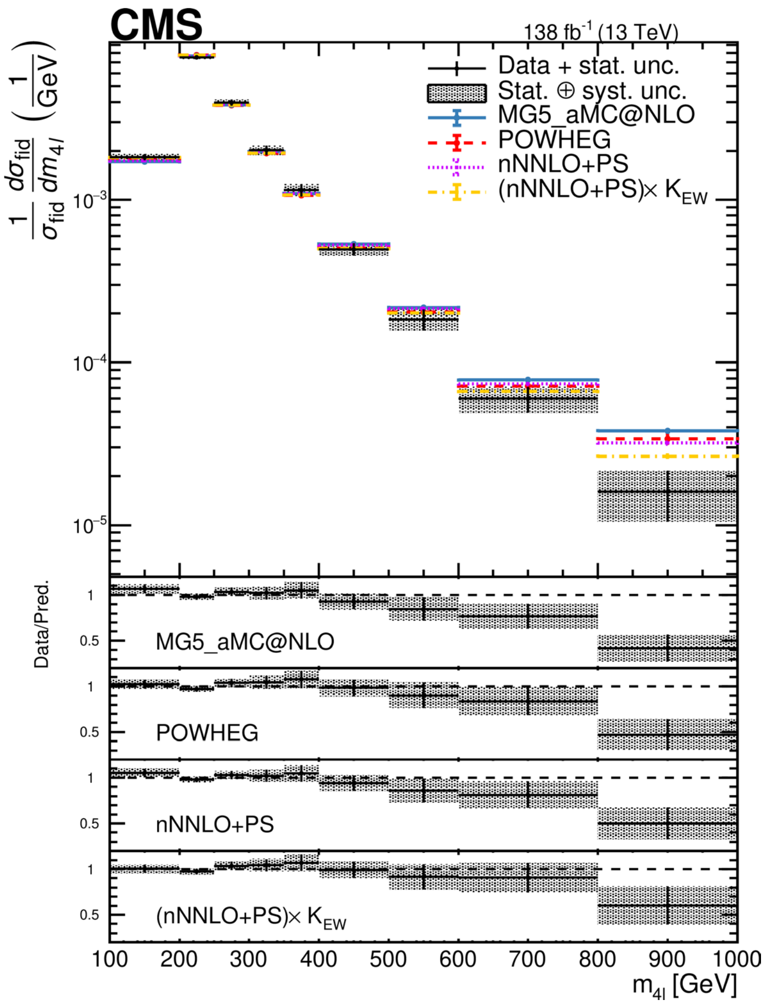
Number of Jets and m_{4l} Differential Cross Sections

Require 60 GeV < m_{Z1} ,m_{Z2} < 120 GeV. Each unfolded distribution normalized by bin width and by the ZZ fiducial cross section. Overflow included in last bin.

N_{jets} distribution has similar behavior in 1-jet bin and high jet multiplicity as at RECO level, and in general, data/prediction agreement is improved with nNNLO+PS predictions.

m_{4l} distribution has shape well described by predictions at low m_{4l}, whereas the predictions overestimate the measured values in the moderate to high m_{4l} regions. This discrepancy can be mitigated with EW corrections (yellow line).





Summary:

- ZZ+jets differential distributions and normalized differential cross sections were measured using full Run 2 data collected in the CMS experiment.

- The theoretical predictions in general agree with the data, but in some regions discrepancies between predicted and measured values were observed.

- The discrepancies in 1-jet bin and high m_{4l} region are mitigated with improved theoretical predictions, demonstrating the necessity for better Monte Carlo modelling in events with complex multi-boson final states and extra jets.

Thank you!

Backup

RECO Event Selections

Leptons:

- Require 4 leptons, $p_T(\ell_1) > 20$ GeV, $p_T(\ell_2) > 10$ GeV
  but in 4e channel the p_T cuts are raised: $p_T(e_1) > 23$ GeV, $p_T(e_2) > 12$ GeV
- $p_T(\ell) > 7(5)$ GeV, $|\eta_\ell| < 2.5(2.4)$ for e(μ)
- $SIP_{3D} = |IP/\sigma_{IP}| < 4$ for each lepton
- Lepton ID, isolation (next slide) and lepton efficiency scale factors in sync with CMS HZZ group
- QCD suppression: $m_{\ell 1, \ell 2} > 4$ GeV for all opposite-sign lepton pairs regardless of flavor

Jets:

- Jets clustered with anti-k_t algorithm R=0.4, $p_T > 30$ GeV, $|\eta| < 4.7$, jet IDs from CMS JetMET POG

Cross cleaning: $\Delta R(\ell_1, \ell_2) > 0.02$, $\Delta R(e,\mu) > 0.05$, $\Delta R(\ell, \text{jet}) > 0.4$

ZZ:

- Basic mass requirement: $40 < m_{Z1} < 120$ GeV, $4 < m_{Z2} < 120$ GeV
- On-shell requirement: $60 < m_{Z1}, m_{Z2} < 120$ GeV,
  but also look at those m_{4l} distributions without this requirement
- $m_{4l} > 80$ GeV

RECO Event Selections (cont.)

Lepton ID and WPs

Lepton	Electron	Muon
Loose ID	p_T > 7 GeV, $\|\eta\|$< 2.5, dxy<0.5cm, dz< 1cm, SIP<4	p_T > 5 GeV, $\|\eta\|$< 2.4, dxy<0.5cm, dz< 1cm, SIP<4, muon track quality requirements
Tight ID	Electron MVA based on XGBOOST	Loose Muons+ (PF* Muon or (p_T > 200 GeV and additional track quality requirements)) (2016,2017) Muon MVA derived by HZZ group including SIP and Isolation (2018)
Isolation	Included in MVA	R_{iso} < 0.35, using PF* combined relative isolation with cone size R=0.3 and Δβ correction

*particle-flow (PF) algorithm: Standard CMS reconstruction and identification algorithms combining the signals from all sub-detectors.

Simulated Samples

Sample Type	Process	DBS Name	$\sigma \cdot BR$
ZZ	$q\bar{q} \to ZZ \to 4\ell$	2 /ZZTo4L_13TeV_powheg_pythia8/[1,2]	1.256pb
	$q\bar{q} \to ZZ \to 4\ell$	1 /ZZTo4L_13TeV_amcatnloFXFX_pythia8/[1,1x]	1.218pb
	$q\bar{q} \to ZZ \to 4\ell$	2 /ZZTo4L_TuneCP5_13TeV_powheg_pythia8/[3]	1.256pb
	$q\bar{q} \to ZZ \to 4\ell$	1 /ZZTo4L_TuneCP5_13TeV_amcatnloFXFX_pythia8/[2,3]	1.218pb
	$gg \to ZZ \to 4e$	/GluGluToContinToZZTo4e_13TeV_MCFM701_pythia8/[1,2,3]	0.00159pb
	$gg \to ZZ \to 4\mu$	/GluGluToContinToZZTo4mu_13TeV_MCFM701_pythia8/[1,2,3]	0.00159pb
	$gg \to ZZ \to 4\tau$	/GluGluToContinToZZTo4tau_13TeV_MCFM701_pythia8/[1,2,3]	0.00159pb
	$gg \to ZZ \to 2e2\mu$	/GluGluToContinToZZTo2e2mu_13TeV_MCFM701_pythia8/[1,2,3]	0.00319pb
	$gg \to ZZ \to 2e2\tau$	/GluGluToContinToZZTo2e2tau_13TeV_MCFM701_pythia8/[1,2,3]	0.00319pb
	$gg \to ZZ \to 2\mu2\tau$	/GluGluToContinToZZTo2mu2tau_13TeV_MCFM701_pythia8/[1,2,3]	0.00319pb
EWK ZZ + jets	ZZ + 2jets	/ZZJJTo4L_EWK_13TeV-madgraph-pythia8/[1,1x]	0.0004404pb
	ZZ + 2jets	/ZZJJTo4L_EWK_TuneCP5_13TeV-madgraph-pythia8/[2,3]	0.0004404pb
VVV	$t\bar{t}Z$	/ttZJets_13TeV_madgraphMLM/[1,1x]	0.2529pb
	WWZ	/WWZ_TuneCUETP8M1_13TeV_amcatnlo_pythia8/[1,1x]	0.1651pb
	WZZ	/WZZ_TuneCUETP8M1_13TeV_amcatnlo_pythia8/[1,1x]	0.05565pb
	ZZZ	/ZZZ_TuneCUETP8M1_13TeV_amcatnlo_pythia8/[1,1x]	0.01398pb
	$t\bar{t}Z$	/ttZJets_TuneCP5_13TeV_madgraphMLM_pythia8/[2,3]	0.2529pb
	WWZ	/WWZ_TuneCP5_13TeV-amcatnlo-pythia8/[2,3]	0.1651pb
	WZZ	/WZZ_TuneCP5_13TeV-amcatnlo-pythia8/[2,3]	0.05565pb
	ZZZ	/ZZZ_TuneCP5_13TeV-amcatnlo-pythia8//[2,3]	0.01398pb
Higgs	$gg \to H \to ZZ \to 4\ell$	/GluGluHToZZTo4L_M125_13TeV_powheg2_JHUgenV6_pythia8/[1]	0.01218pb
	VBF $H \to ZZ$	/VBF_HToZZTo4L_M125_13TeV_powheg2_JHUGenV709_pythia8/[1]	0.001044 pb
	$W^+H, H \to ZZ$	/WplusH_HToZZTo4L_M125_13TeV_powheg2-minlo-HWJ_JHUgenV6_pythia8/[1]	0.000232 pb
	$W^-H, H \to ZZ$	/WminusH_HToZZTo4L_M125_13TeV_powheg2-minlo-HWJ_JHUgenV6_pythia8/[1]	0.000147 pb
	$ZH, H \to ZZ$	/ZH_HToZZ_4LFilter_M125_13TeV_powheg2-minlo-HZJ_JHUgenV6_pythia8/[1]	0.000668 pb
	$t\bar{t}H, H \to ZZ$	/ttH_HToZZ_4LFilter_M125_13TeV_powheg2_JHUGenV709_pythia8/[1]	0.000393 pb
	$gg \to H \to ZZ \to 4\ell$	/GluGluHToZZTo4L_M125_13TeV_powheg2_JHUgenV7011_pythia8/[2,3]	0.01218pb
	VBF $H \to ZZ$	/VBF_HToZZTo4L_M125_13TeV_powheg2_JHUGenV7011_pythia8/[2,3]	0.001044 pb
	$W^+H, H \to ZZ$	/WplusH_HToZZTo4L_M125_13TeV_powheg2-minlo-HWJ_JHUgenV7011_pythia8/[2,3]	0.000232 pb
	$W^-H, H \to ZZ$	/WminusH_HToZZTo4L_M125_13TeV_powheg2-minlo-HWJ_JHUgenV7011_pythia8/[2,3]	0.000147 pb
	$ZH, H \to ZZ$	/ZH_HToZZ_4LFilter_M125_13TeV_powheg2-minlo-HZJ_JHUgenV7011_pythia8/[2,3]	0.000668 pb
	$t\bar{t}H, H \to ZZ$	/ttH_HToZZ_4LFilter_M125_13TeV_powheg2_JHUGenV7011_pythia8/[2,3]	0.000393 pb

} Kfac 1.1 to NNLO (qqZZ samples)

} Kfac 1.7 to NLO (ggZZ samples)

[1] RunIISummer16MiniAODv3-PUMoriond17_94X_mcRun2_asymptotic_v3_*/MINIAODSIM
[1x] RunIISummer16MiniAODv2-PUMoriond17_80X_mcRun2_asymptotic_2016_TrancheIV_v6_v*/MINIAODSIM
[2] RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v*/MINIAODSIM
[3] RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v*/MINIAODSIM

1:Referred to as MadGraph qqZZ sample: QCD NLO 0,1 jets with up to 2 partons emission, nominal qqZZ
2:POWHEG qqZZ sample: QCD NLO with up to 1 parton emission, for comparison

Simulated Samples (cont.)

Results in this analysis are also compared with the recent **nNNLO+PS**[1] predictions, which consist of NNLO predictions for quark-initiated channel combined with parton showers using the MiNNLO$_{PS}$ method, and NLO predictions for loop-induced gluon fusion channel matched to parton showers, with event generators for the two channels implemented in the POWHEG framework.

Spin correlations, interferences and off-shell effects are included by calculating the full process pp → 2ℓ2ℓ' and considering all contributions to the four-lepton final state.

1:https://arxiv.org/abs/2108.05337

Systematic Uncertainties

Most systematic uncertainties are propagated through unfolding by recomputing the response matrix with the sample used to build the matrix shifted or reweighted to reflect a 1σ shift in the quantity in question, then taking the difference in the normalized unfolded results.

Trigger efficiency

Estimated to be 2%, and expected to cancel out in normalized differential cross sections.

Lepton efficiency

The response matrix is remade with the lepton efficiency scale factors shifted up and down by the tag-and-probe fit uncertainties.

JES/JER

The jet p_T is varied by shifting the JES/smearing up and down by their uncertainties obtained from CMS JetMET POG recipes.

Reducible background

The reducible background is shifted up and down by the lepton fake rate uncertainty (40%).

Pileup

The response matrix is remade with the total inelastic cross section — which defines the pileup weights applied to Monte Carlo — shifted up and down by 4.6%.

Systematic Uncertainties (cont.)

Luminosity

The response matrix is remade with the MC normalized to the integrated luminosity shifted up and down by its total uncertainty.

Generator choice

The response matrix is remade with qq → ZZ sample generated by POWHEG.

ggZZ theoretical cross sections

The MCFM samples (gg → ZZ) normalization is changed by the scale and PDF uncertainties of their cross section ($^{+18\%}_{-14\%}$), and the resulting shape difference is taken.

QCD scales

The response matrix is remade with the MadGraph5_aMC@NLO qq → ZZ sample reweighted to reflect the distribution with μ_F and μ_R independently varied up and down by a factor of 2, keeping usual constraint $1/4 < \mu_R / \mu_F < 4$.

PDF + α_s

The PDF + α_s uncertainties are evaluated by reweighting the MadGraph5_aMC@NLO sample to members of PDF and α_s variations, and then redoing the unfolding and combining the results according to the procedure described in PDF4LHC 2015.

Systematic Uncertainties (cont.)

The contributions of each source of systematic uncertainty in the normalized differential cross sections measurements of jet variables.

Systematic source	Uncertainty range
Electron efficiency	0.13–0.30%
Muon efficiency	0.02–0.08%
Jet energy resolution	1.65–3.85%
JES correction	0.93–5.32%
Reducible background	0.05–0.43%
Pileup	0.04–1.08%
Luminosity	$< 0.03\%$
$q\bar{q} \to ZZ$ MC choice	0.52–4.52%
$gg \to ZZ$ cross section	0.01–0.19%
QCD scales	0.16–0.82%
PDF	0.05–0.12%
PDF α_S	0.01–0.10%

Systematic Uncertainties (cont.)

The contributions of each source of systematic uncertainty in the normalized differential cross sections measurements of m_{4l} with jet multiplicity from 0 to ≥3 in the events, with $60<m_{Z1}, m_{Z2}<120$ GeV.

Systematic source	$m_{4\ell}$ with all jets	0 jet	1 jet	2 jets	3 and more jets
Electron efficiency	0.42%	0.38%	0.66%	0.36%	0.26%
Muon efficiency	0.05%	0.06%	0.07%	0.09%	0.08%
Jet energy resolution	—	0.07%	1.72%	1.65%	0.80%
JES correction	—	0.17%	1.77%	1.95%	0.97%
Reducible background	0.18%	0.18%	0.32%	0.33%	0.96%
Pileup	0.02%	0.05%	0.11%	0.13%	0.35%
Luminosity	0.01%	0.01%	0.02%	0.02%	0.05%
$q\overline{q} \rightarrow$ ZZ MC choice	0.35%	0.65%	0.94%	0.48%	0.35%
$gg \rightarrow$ ZZ cross section	0.02%	0.03%	0.09%	0.06%	0.09%
QCD scales	0.15%	0.16%	0.58%	0.54%	0.62%
PDF	0.05%	0.05%	0.15%	0.15%	0.21%
PDF α_S	0.02%	0.01%	0.05%	0.03%	0.02%

Systematic Uncertainties (cont.)

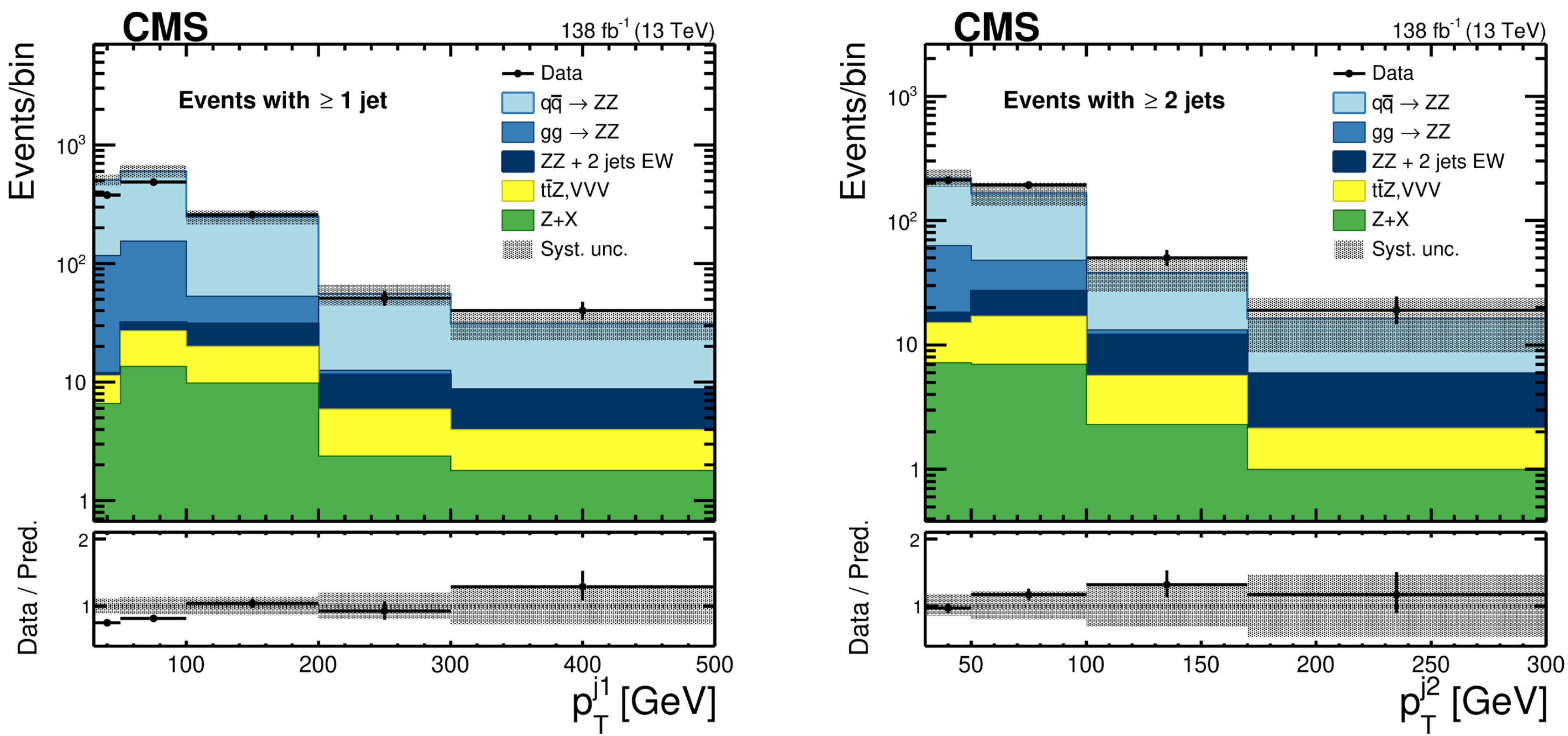
The contributions of each source of systematic uncertainty in the normalized differential cross sections measurements of m_{4l} with jet multiplicity from 0 to ≥3 in the events, without requiring 60<m_{Z1}, m_{Z2}<120 GeV.

Systematic source	$m_{4\ell}$ with all jets	0 jet	1 jet	2 jets	3 and more jets
Electron efficiency	2.12%	2.55%	2.28%	1.77%	1.46%
Muon efficiency	0.71%	0.78%	0.92%	0.79%	0.42%
Jet energy resolution	—	0.11%	1.73%	2.63%	2.32%
JES correction	—	0.33%	1.64%	3.01%	2.02%
Reducible background	2.22%	2.19%	2.88%	3.40%	5.09%
Pileup	0.21%	0.28%	0.19%	0.32%	0.52%
Luminosity	0.12%	0.12%	0.16%	0.17%	0.25%
$q\bar{q} \to$ ZZ MC choice	0.57%	0.48%	1.22%	3.07%	4.21%
gg $\to$ ZZ cross section	0.10%	0.18%	0.61%	0.80%	0.46%
QCD scales	0.27%	0.25%	0.67%	1.25%	1.86%
PDF	0.07%	0.09%	0.20%	0.23%	0.28%
PDF α_S	0.08%	0.08%	0.15%	0.20%	0.28%

Differential Distributions

p_T Distributions for Leading and Subleading-p_T Jets

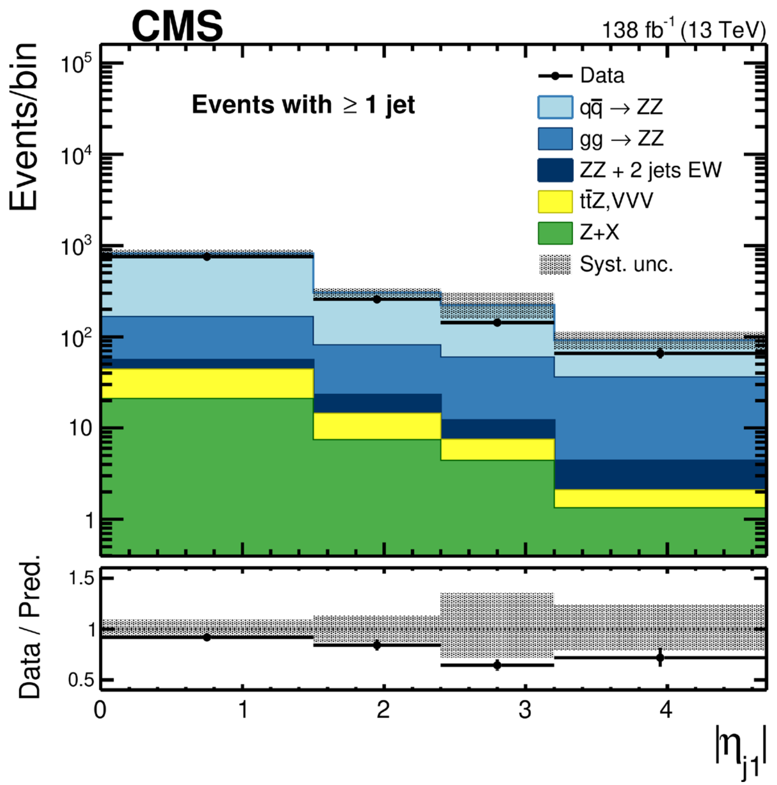
Require 60 GeV < m_{Z1}, m_{Z2} < 120 GeV. The MadGraph qqZZ sample is used in this plot, along with other samples shown in the MC slide. Overflow included.

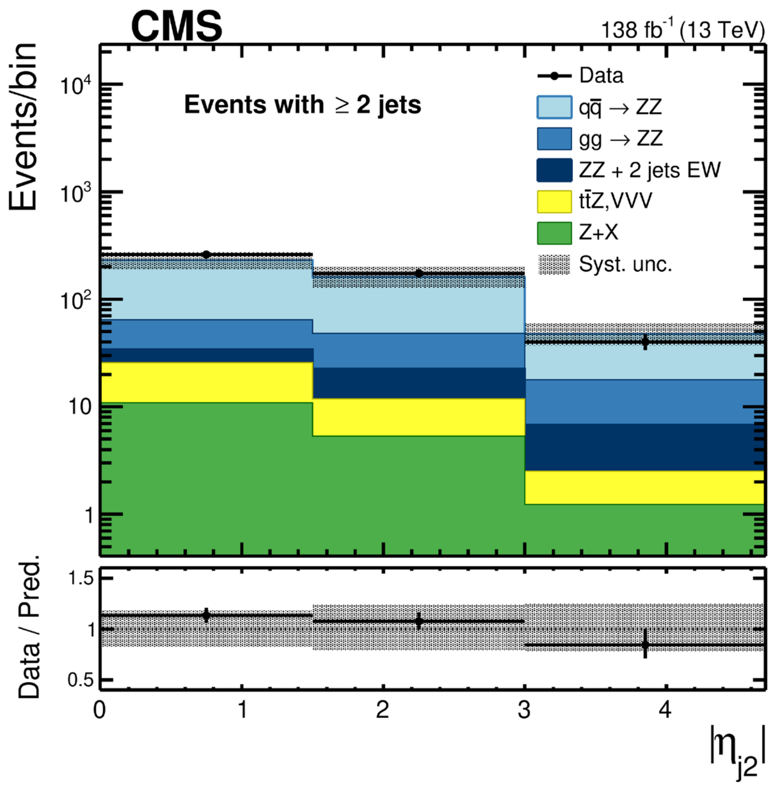


Differential Distributions

|η| Distributions for Leading and Subleading-p_T Jets

Require 60 GeV < m_{Z1}, m_{Z2} < 120 GeV. The MadGraph qqZZ sample is used in this plot, along with other samples shown the MC slide. Overflow included.

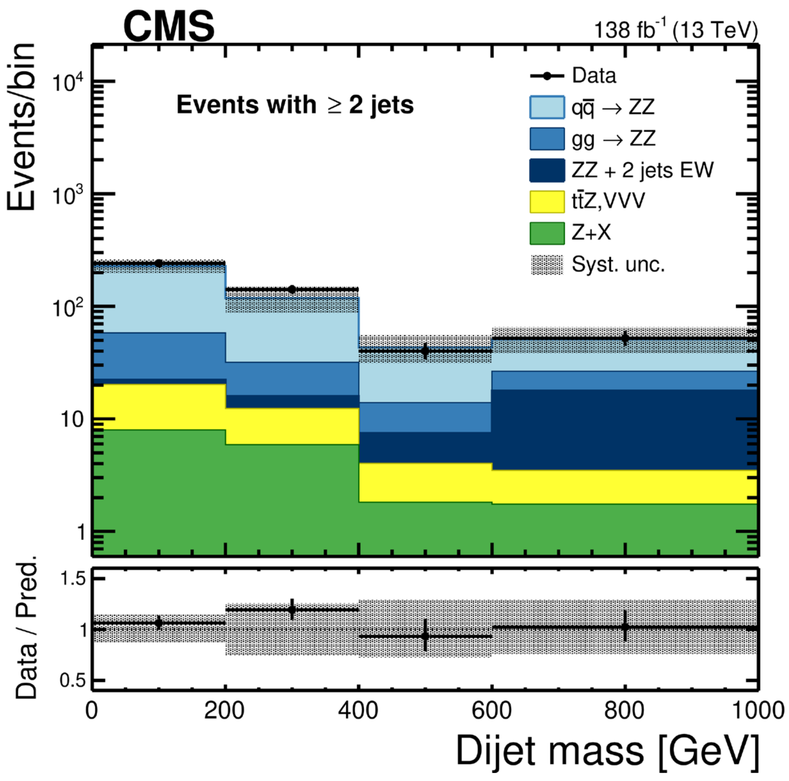


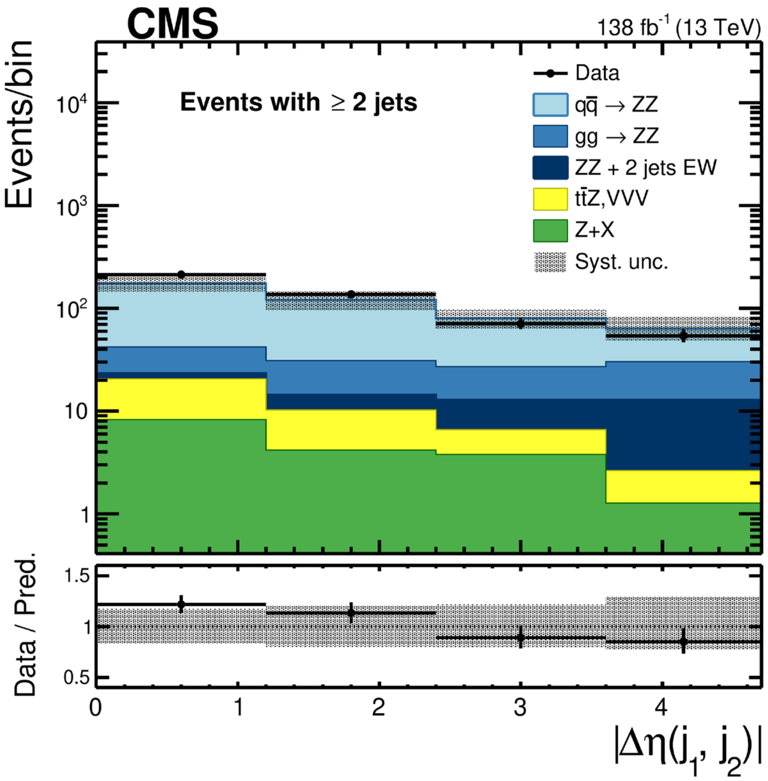


Differential Distributions

m_{jj} and $|\Delta\eta_{jj}|$ Distributions

Require 60 GeV < m_{Z1}, m_{Z2} < 120 GeV. The MadGraph qqZZ sample is used in this plot, along with other samples shown in the MC slide. Overflow included.

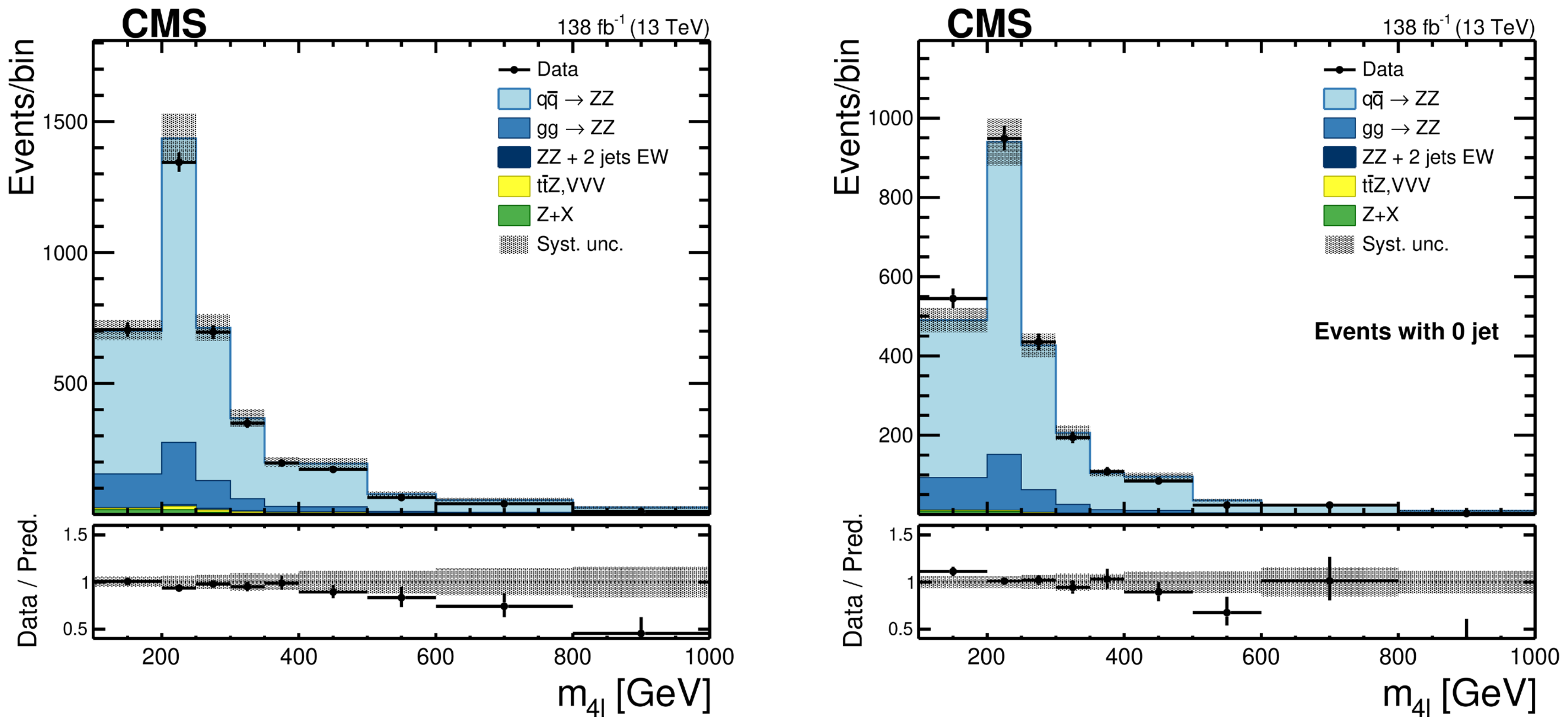




Differential Distributions

m_{4l} Distributions for Inclusive and 0 Jet Region

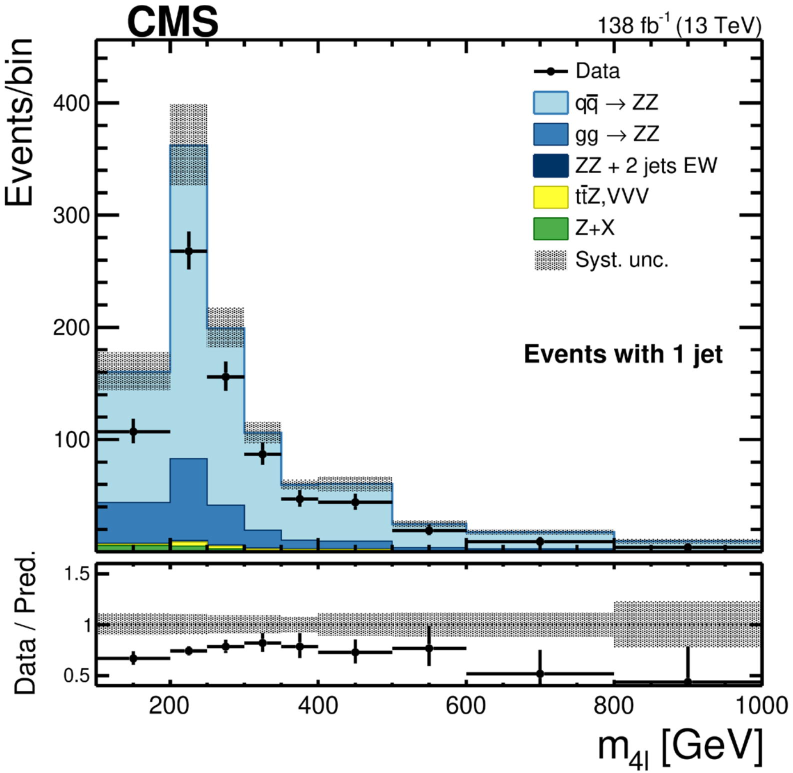
Require 60 GeV < m_{Z1} ,m_{Z2} < 120 GeV. The MadGraph qqZZ sample is used in this plot, along with other samples shown in the MC slide. Overflow included.

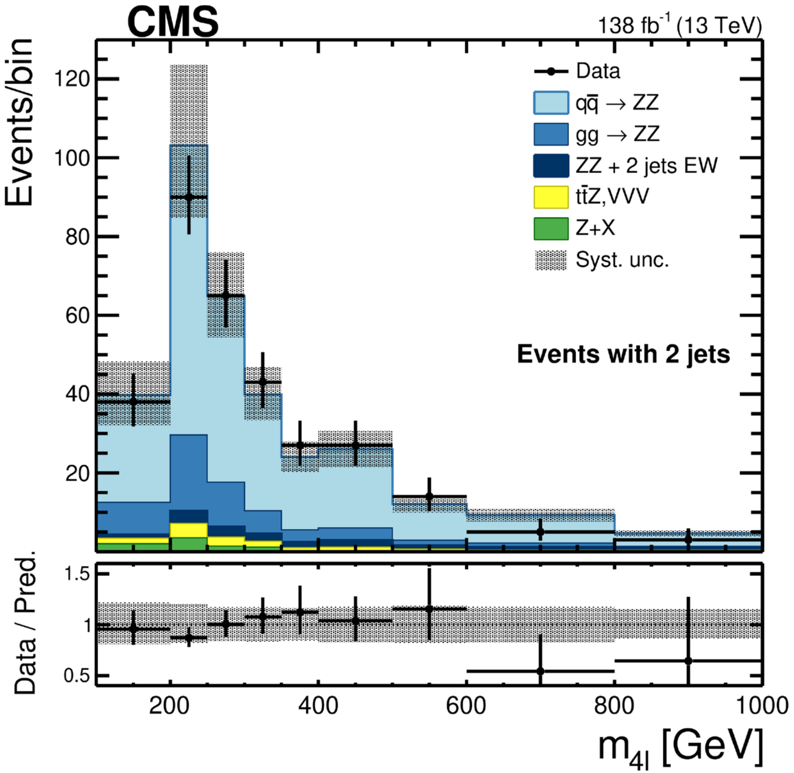


Differential Distributions

m_{4l} Distributions for 1 and 2 Jets Region

Require 60 GeV < m_{Z1}, m_{Z2} < 120 GeV. The MadGraph qqZZ sample is used in this plot, along with other samples shown in the MC slide. Overflow included.

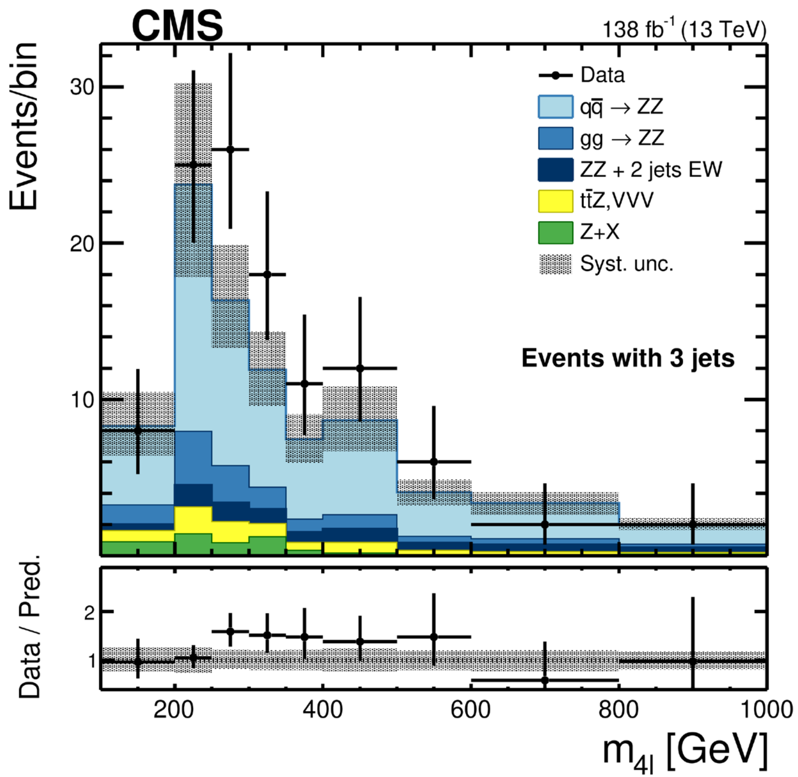


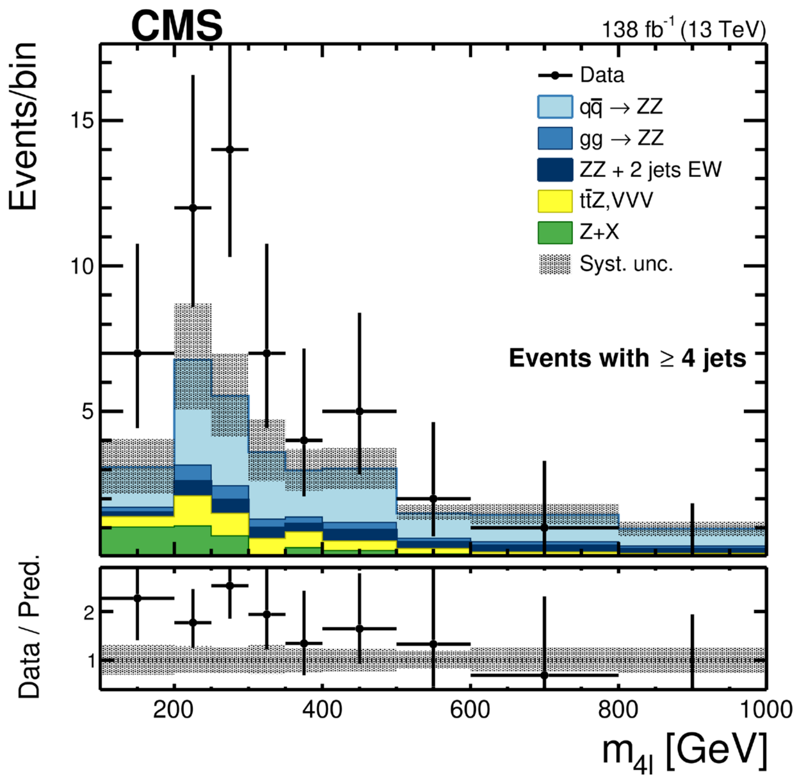


Differential Distributions

m_{4l} Distributions for 3 and ≥4 Jets Region

Require 60 GeV < m_{Z1} ,m_{Z2} < 120 GeV. The MadGraph qqZZ sample is used in this plot, along with other samples shown in the MC slide. Overflow included. Substantial normalizing difference at high jet multiplicity, shapes agree within uncertainties (see later). **We now also look at the full m_{4l} region.**

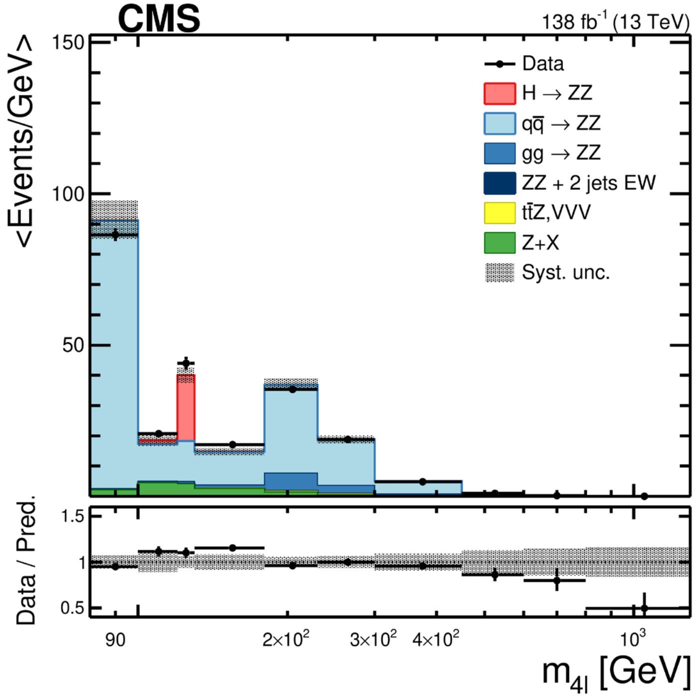


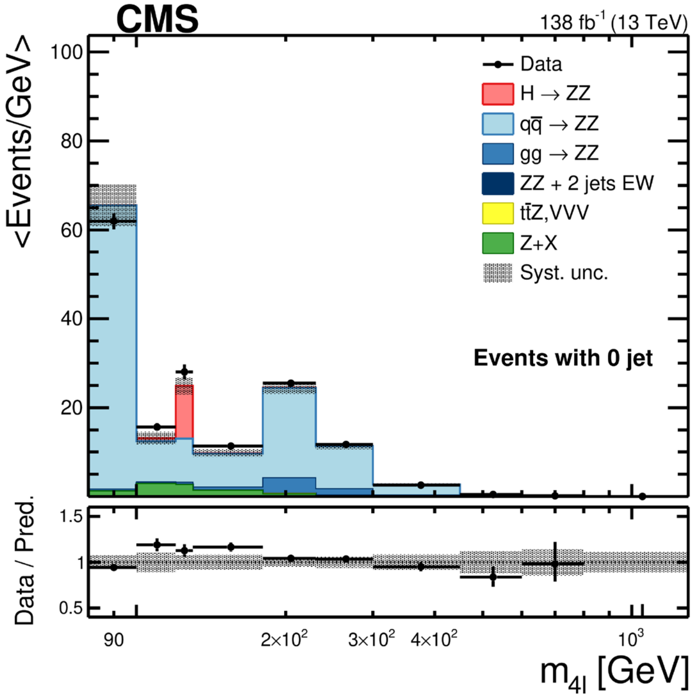


Differential Distributions

m_{4l} Distributions Inclusive and for 0 Jet Region

Require 40 GeV < m_{Z1} < 120 GeV, 4 GeV < m_{Z2} < 120 GeV. Number of events is normalized with bin width to give events/GeV. The MadGraph qqZZ sample is used in these plots, along with other samples shown in the MC slide. Binning: 80-100-120-130-180-230-300-450-600-800-1300 (overflow included).

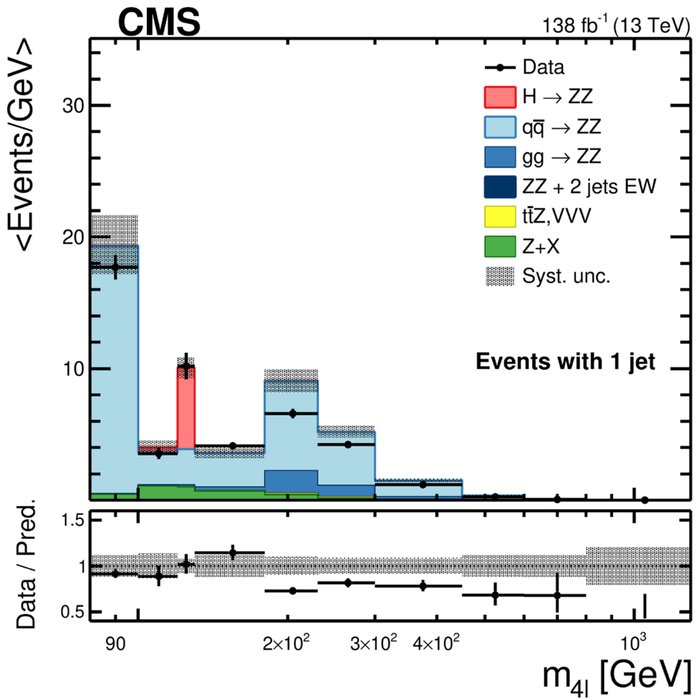


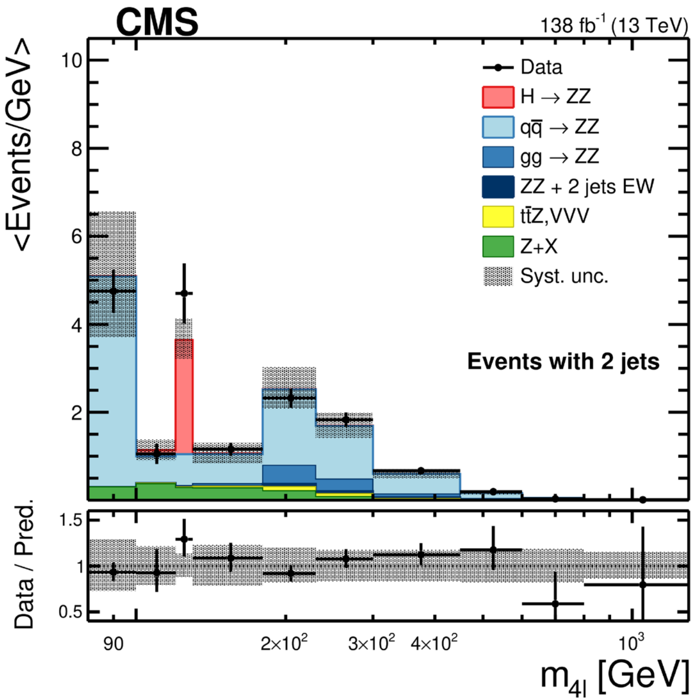


Differential Distributions

m_{4l} Distributions for 1 and 2 Jets Region

Require 40 GeV < m_{Z1} < 120 GeV, 4 GeV < m_{Z2} < 120 GeV. Number of events is normalized with bin width to give events/GeV. The MadGraph qqZZ sample is used in these plots, along with other samples shown in the MC slide. Binning: 80-100-120-130-180-230-300-450-600-800-1300 (overflow included). Same binning for next slide.

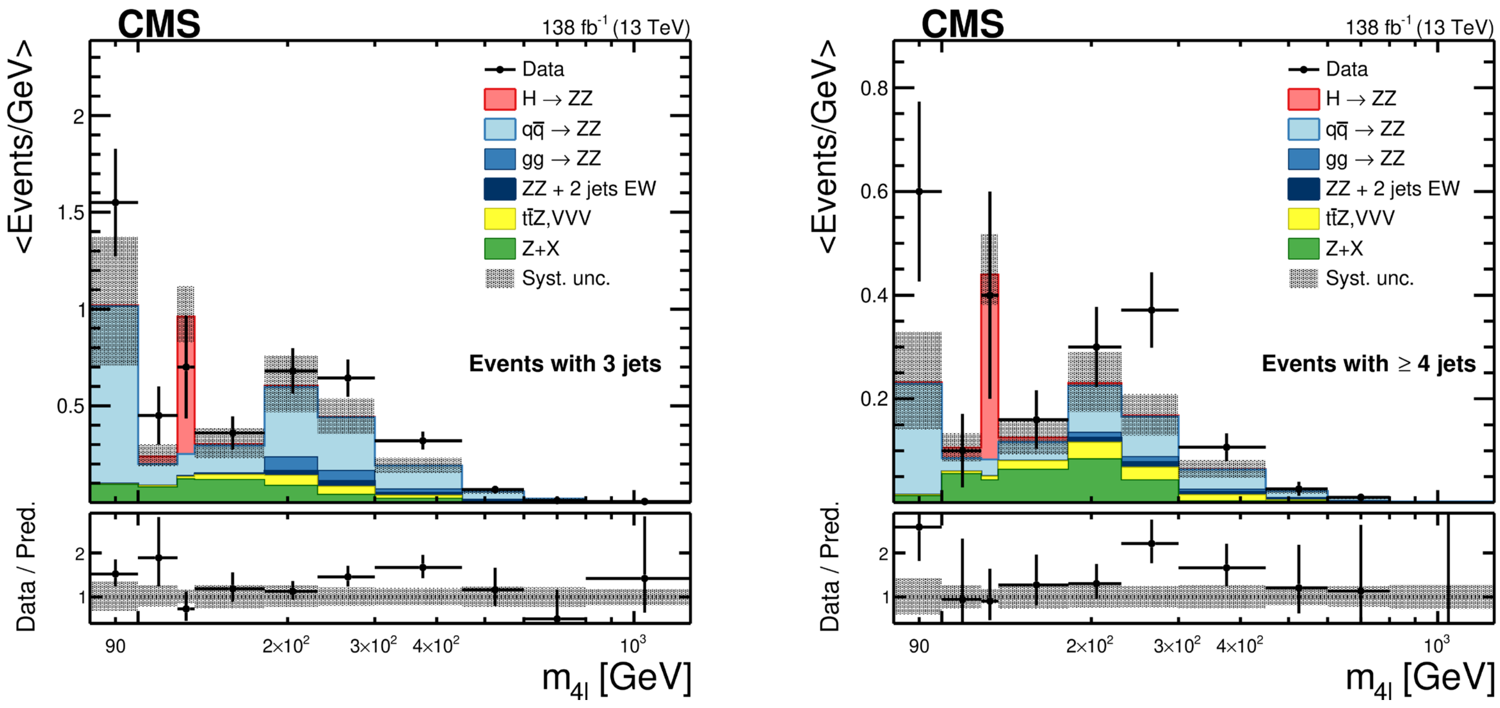




Differential Distributions

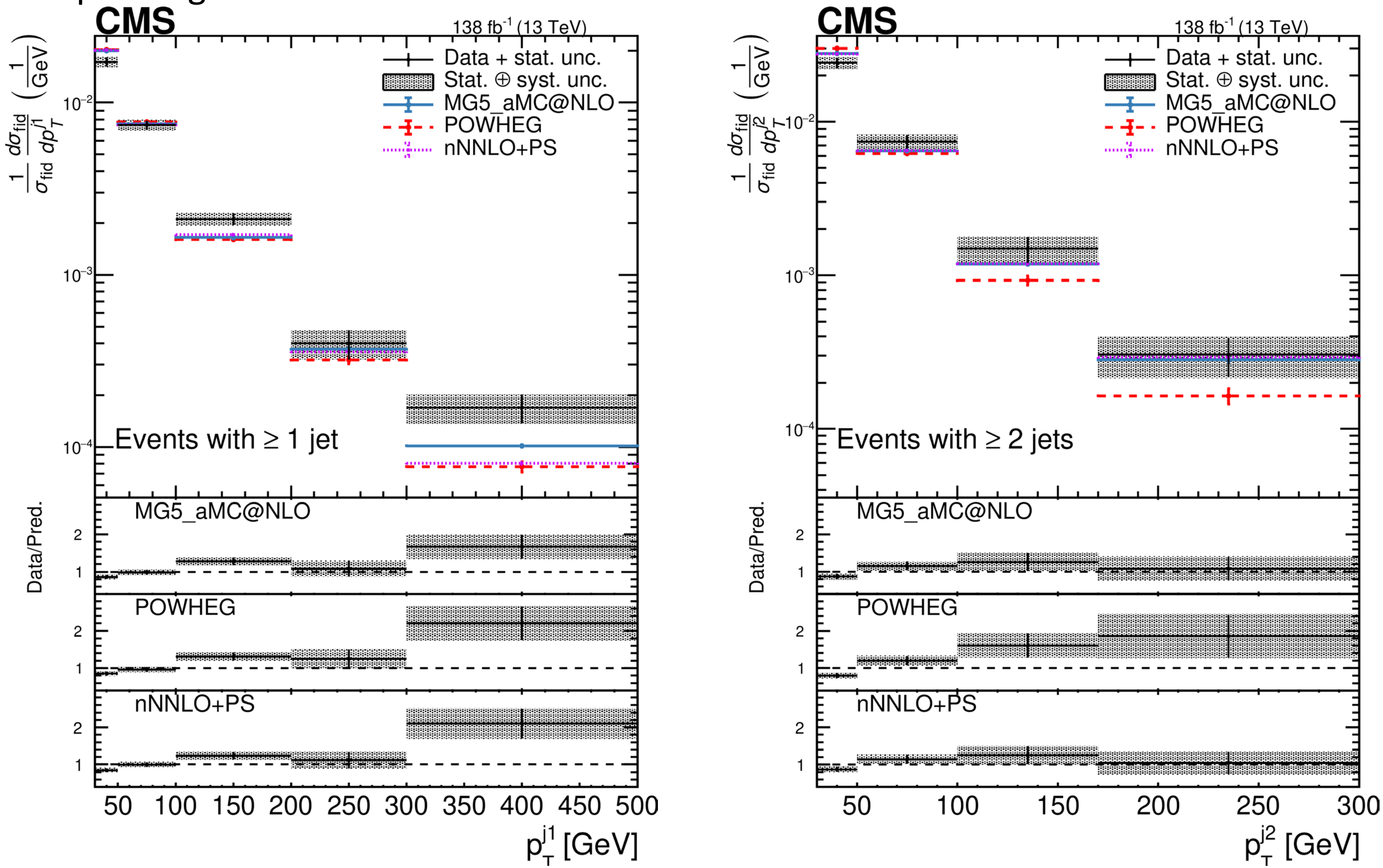
m_{4l} Distributions for 3 and ≥4 Jets Region

Require 40 GeV < m_{Z1} < 120 GeV, 4 GeV < m_{Z2} < 120 GeV. Number of events is normalized with bin width to give events/GeV. The MadGraph qqZZ sample is used in these plots, along with other samples shown in the MC slide. With increased number of jets we see bigger discrepancy with respect to MC predictions.



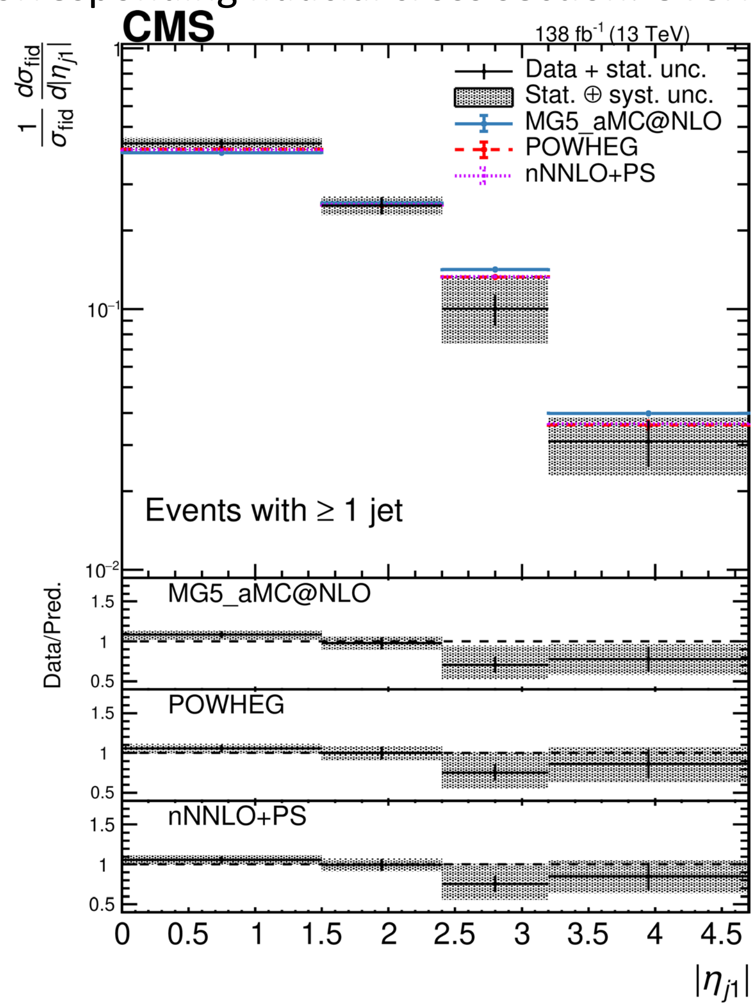
p_T Differential Cross Sections for Leading and Subleading-p_T Jets

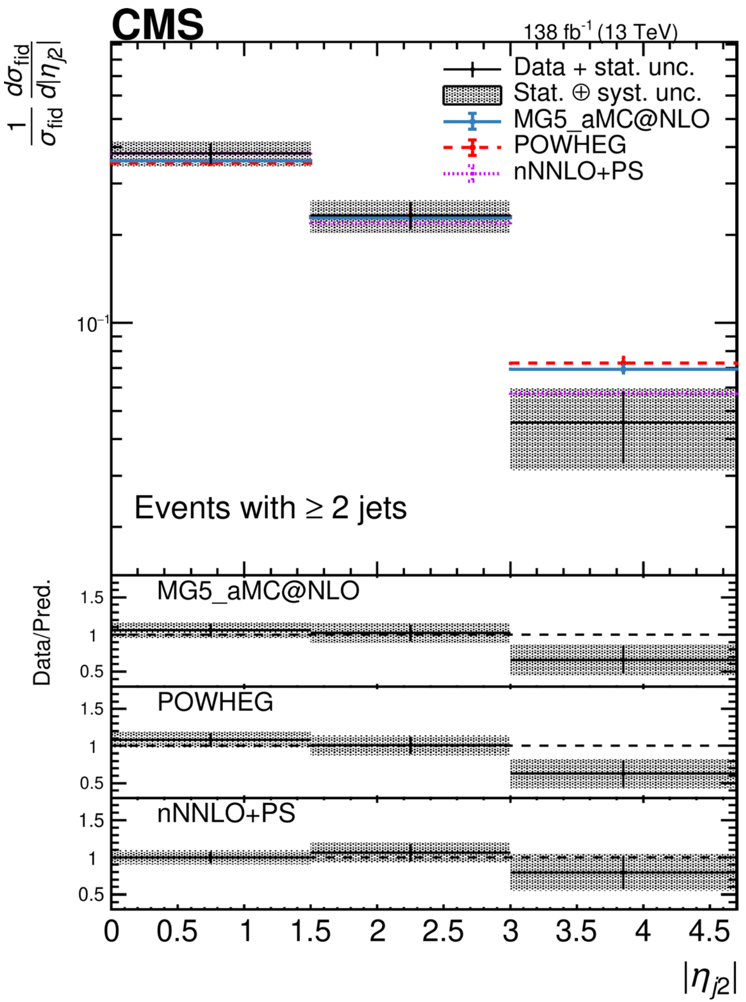
Require 60 GeV < m_{Z1} ,m_{Z2} < 120 GeV. Each plot normalized by bin width and by the corresponding fiducial cross section. Overflow included.



|η| Differential Cross Sections for Leading and Subleading-p_T Jets

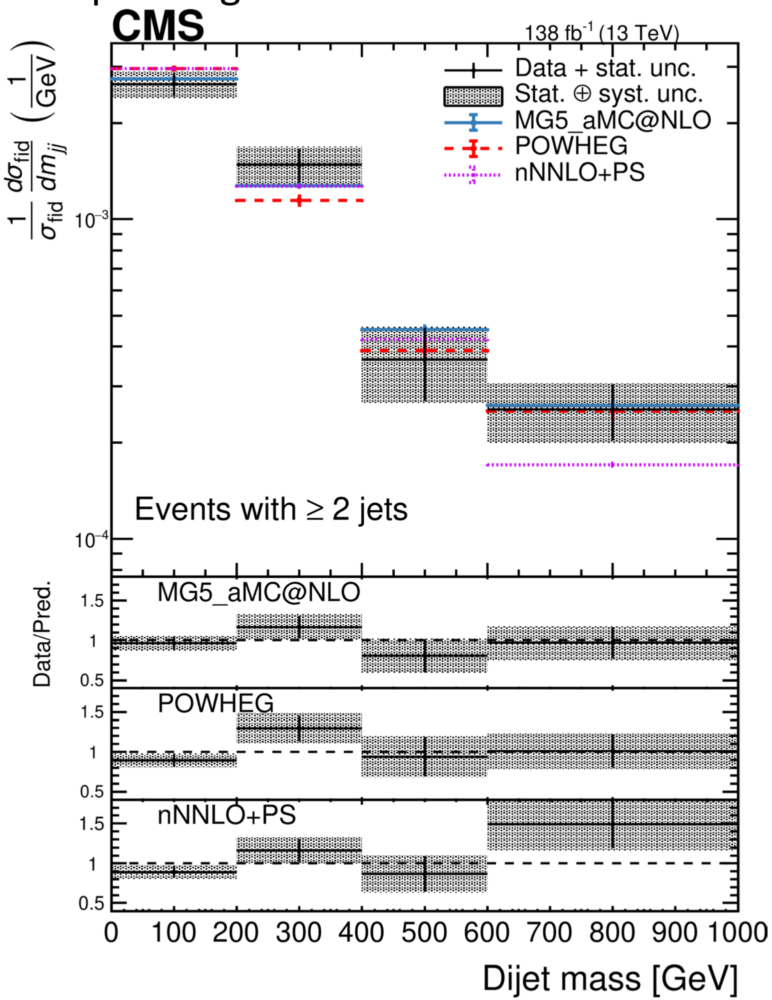
Require 60 GeV < m_{Z1}, m_{Z2} < 120 GeV. Each plot normalized by bin width and by the corresponding fiducial cross section. Overflow included.

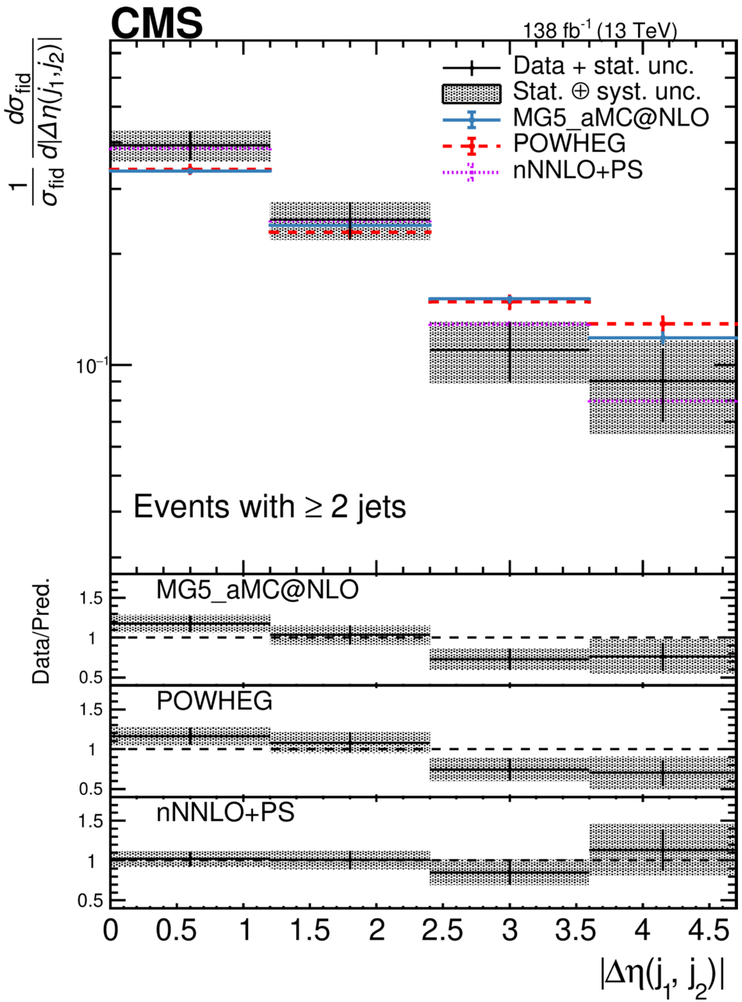




m_{jj} and $|\Delta\eta_{jj}|$ Differential Cross Sections

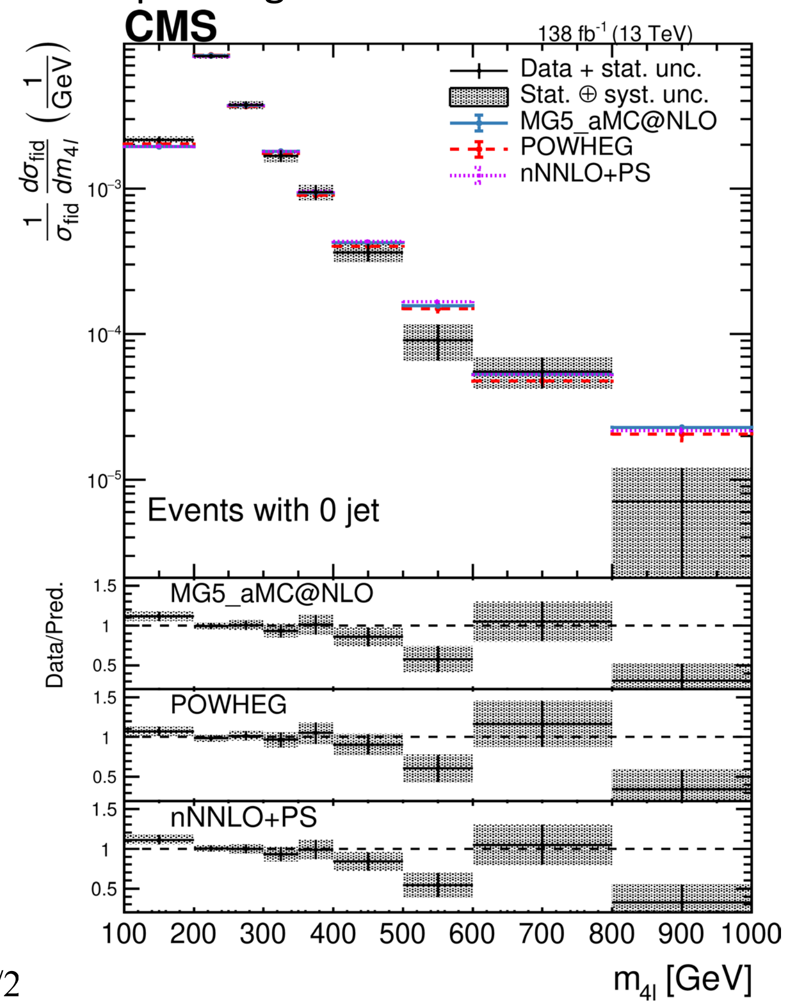
Require 60 GeV < m_{Z1}, m_{Z2} < 120 GeV. Each plot normalized by bin width and by the corresponding fiducial cross section. Overflow included.

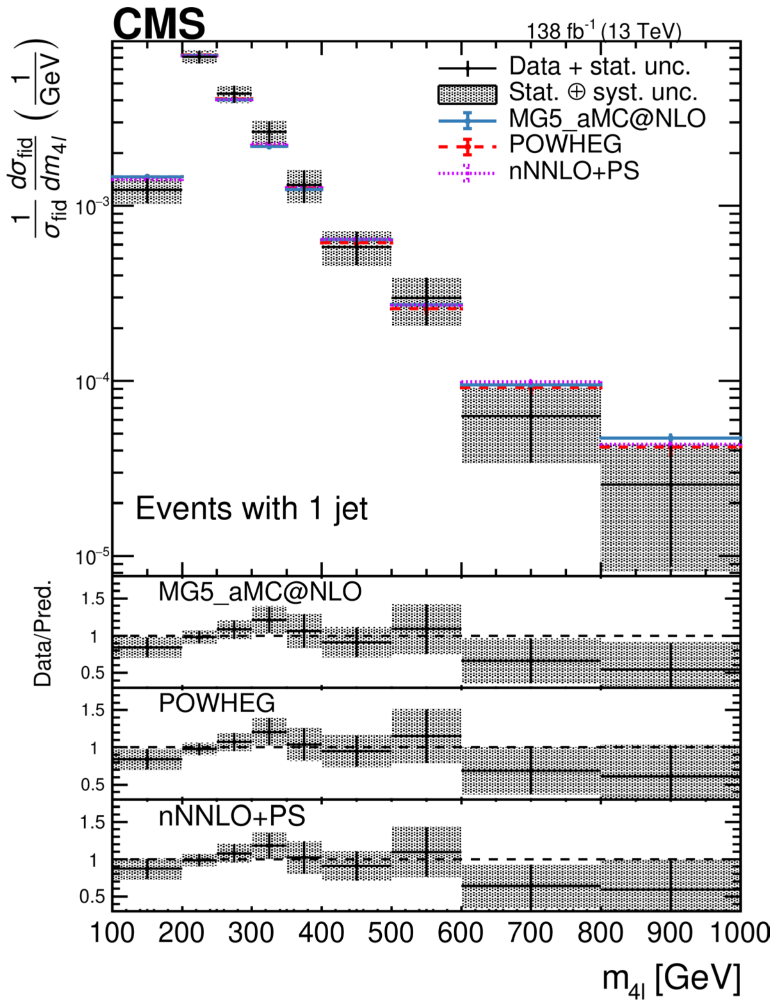




m_{4l} Differential Cross Sections for 0 and 1 Jet Region

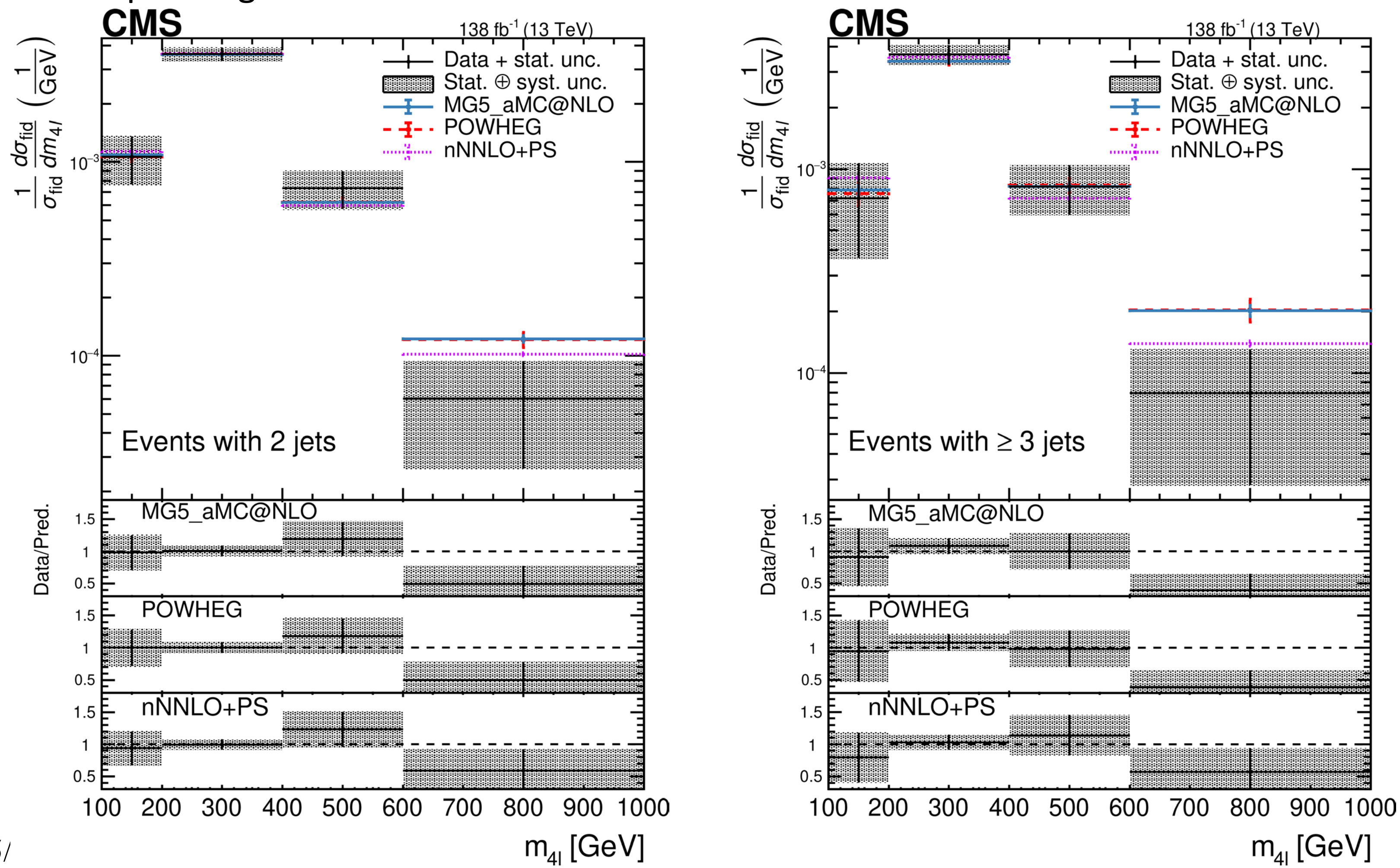
Require 60 GeV < m_{Z1}, m_{Z2} < 120 GeV. Each plot normalized by bin width and by the corresponding fiducial cross section. Overflow included.





m_{4l} Differential Cross Sections for 2 and ≥3 Jets Region

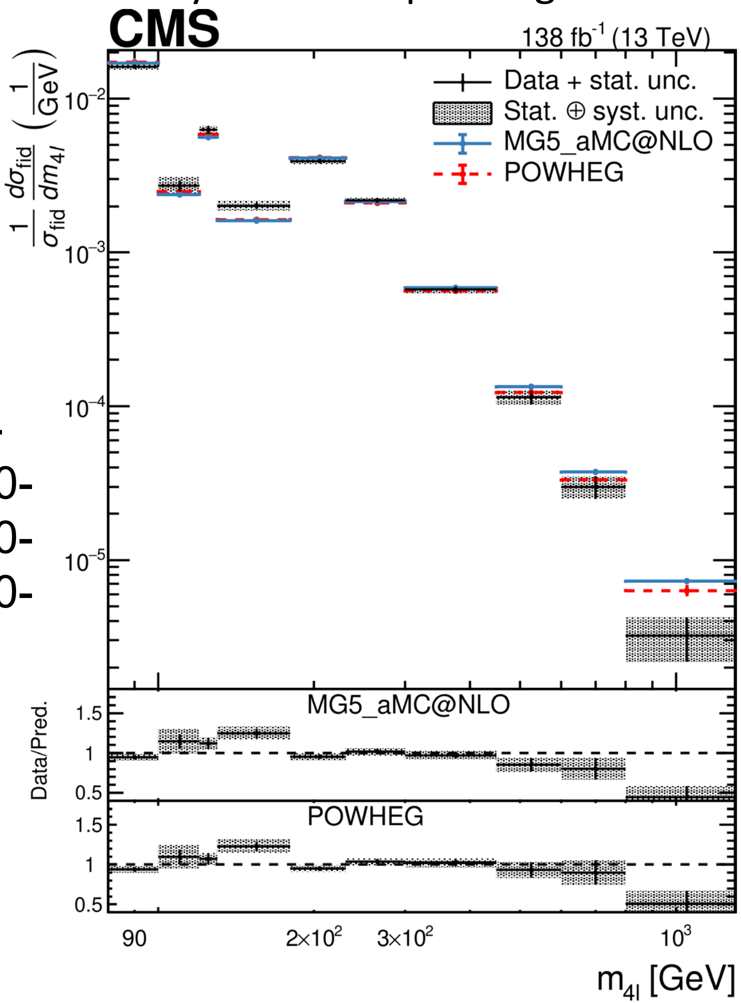
Require 60 GeV < m_{Z1} ,m_{Z2} < 120 GeV. Each plot normalized by bin width and by the corresponding fiducial cross section. Overflow included.

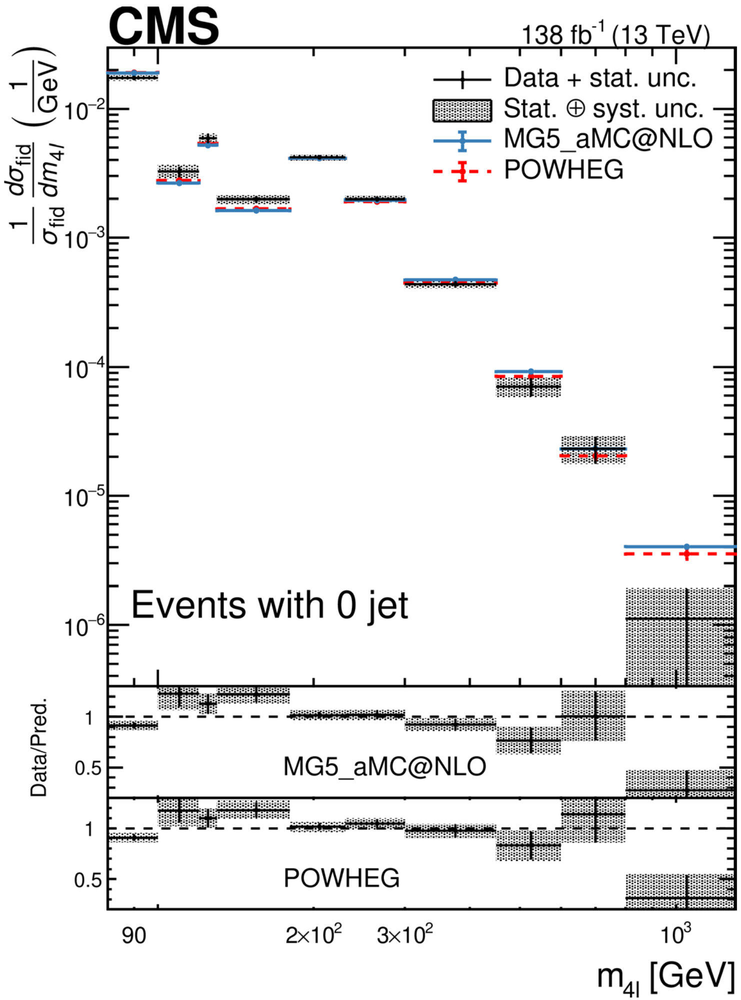


m_{4l} Differential Cross Sections for Inclusive and 0 Jet Region

Require 40 GeV < m_{Z1} < 120 GeV, 4 GeV < m_{Z2} < 120 GeV. Each plot normalized by bin width and by the corresponding fiducial cross section. Overflow included.

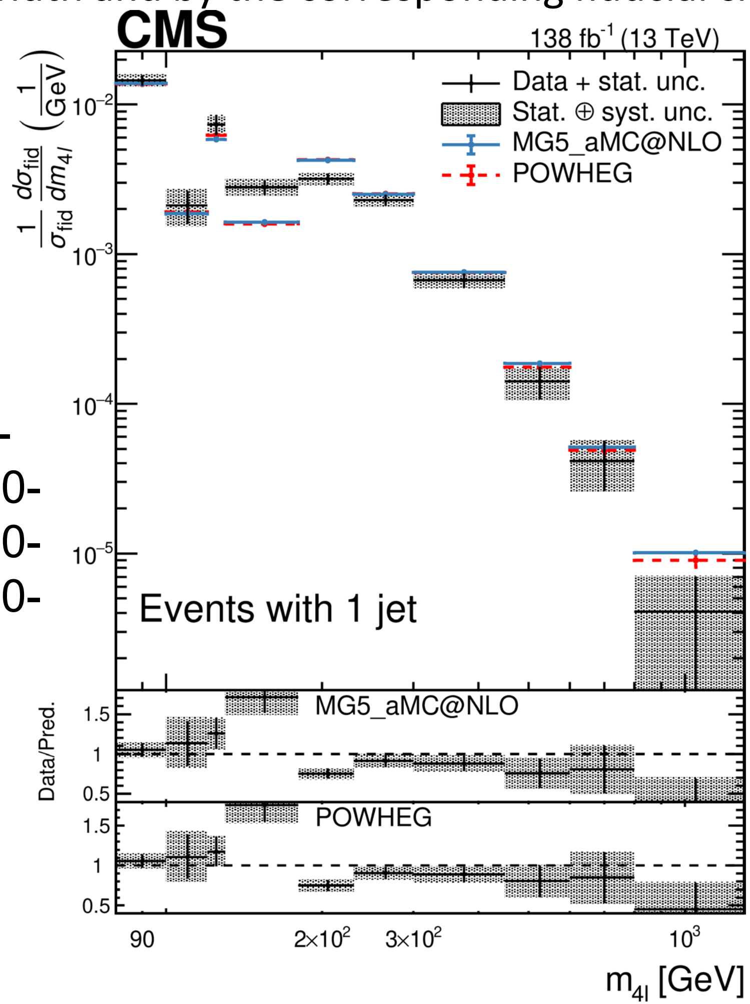
Binning: 80-100-120-130-180-230-300-450-600-800-1300

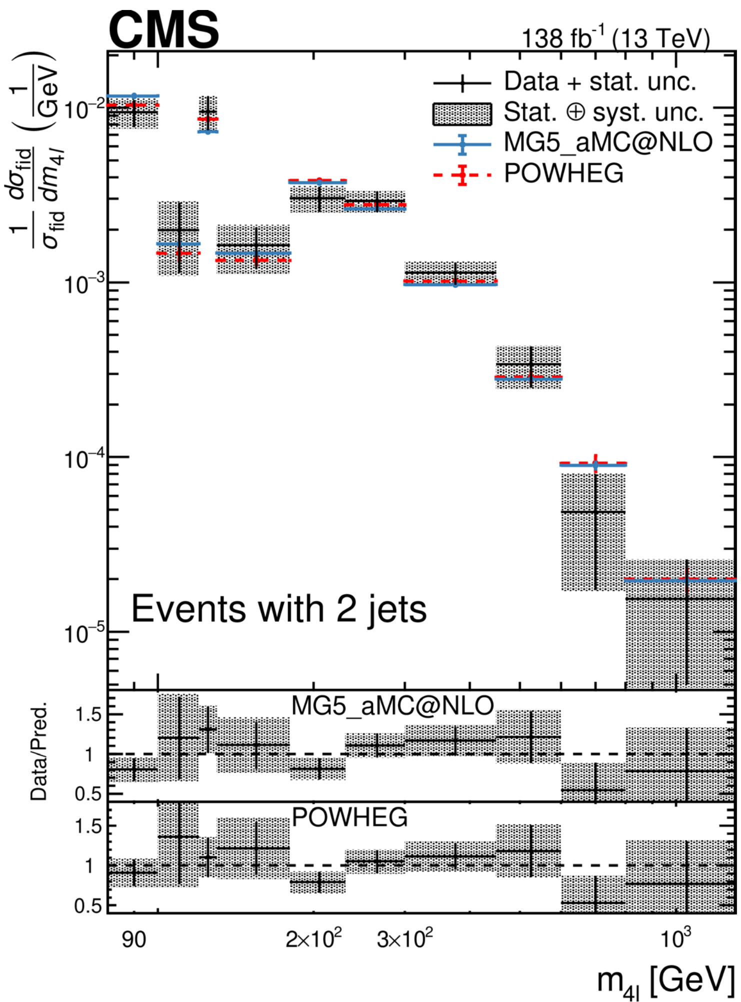




m_{4l} Differential Cross Sections for 1 and 2 Jets Region

Require 40 GeV < m_{Z1} < 120 GeV, 4 GeV < m_{Z2} < 120 GeV. Each plot normalized by bin width and by the corresponding fiducial cross section. Overflow included.



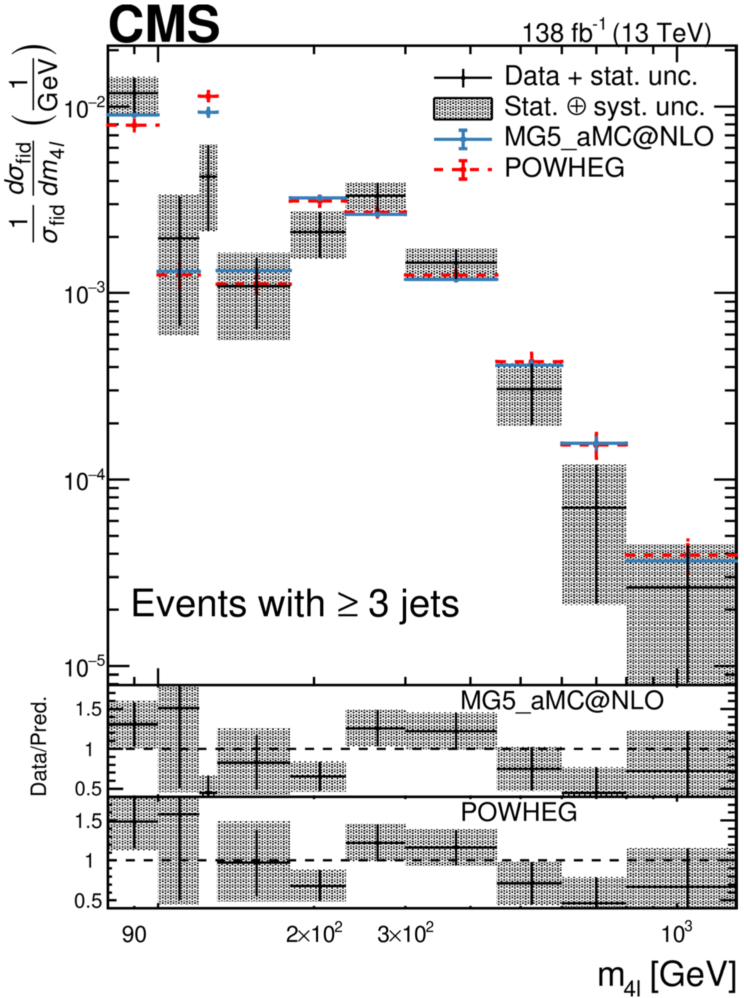


Binning: 80-100-120-130-180-230-300-450-600-800-1300

m_{4l} Differential Cross Sections for ≥3 Jets Region

Require 40 GeV < m_{Z1} < 120 GeV, 4 GeV < m_{Z2} < 120 GeV. Each plot normalized by bin width and by the corresponding fiducial cross section. Overflow included.

Binning: 80-100-120-130-180-230-300-450-600-800-1300



Event Yields

The observed and expected yields of Run 2 ZZ events in different mass ranges, and estimated yields of background events are shown. Statistical (first) and systematic (second) uncertainties are present.

Process	eeee	$ee\mu\mu$	$\mu\mu\mu\mu$	$2\ell 2\ell'$
		$80 < m_{4\ell} < 100\,\mathrm{GeV}$		
Background	$4.6 \pm 0.5 \pm 1.8$	$15.5 \pm 1.6 \pm 6.2$	$22.8 \pm 2.1 \pm 9.1$	$43 \pm 3 \pm 17$
Signal	$216 \pm 1^{+40}_{-36}$	$731 \pm 2^{+66}_{-64}$	$841 \pm 2^{+59}_{-57}$	$1790 \pm 3^{+140}_{-140}$
Total expected	$220 \pm 1^{+40}_{-36}$	$747 \pm 3^{+66}_{-64}$	$864 \pm 3^{+59}_{-58}$	$1830 \pm 4^{+140}_{-140}$
Data	194	698	838	1730
		$60 < m_{Z_1,Z_2} < 120\,\mathrm{GeV}$		
Background	$22.9 \pm 0.9 \pm 5.7$	$46 \pm 2 \pm 10$	$28.9 \pm 1.3 \pm 6.5$	$98 \pm 2 \pm 23$
Signal	$716 \pm 2^{+63}_{-60}$	$1830 \pm 3^{+140}_{-140}$	$1138 \pm 3^{+85}_{-82}$	$3680 \pm 5^{+280}_{-270}$
Total expected	$739 \pm 2^{+63}_{-60}$	$1870 \pm 4^{+140}_{-140}$	$1167 \pm 3^{+85}_{-82}$	$3780 \pm 5^{+280}_{-270}$
Data	671	1805	1106	3582

Shown for each final state and the total

Process	0 jet	1 jet	2 jets	3 jets	≥4 jets
		$80 < m_{4\ell} < 100\,\mathrm{GeV}$			
Background	$25 \pm 2 \pm 10$	$9.1 \pm 1.3 \pm 3.6$	$6.1 \pm 1.0 \pm 2.4$	$1.9 \pm 0.6 \pm 0.8$	$0.4 \pm 0.3 \pm 0.1$
Signal	$1300 \pm 3^{+100}_{-100}$	$371 \pm 2^{+48}_{-45}$	$95 \pm 1^{+29}_{-28}$	$18.7 \pm 0.4^{+7.1}_{-6.2}$	$4.5 \pm 0.2^{+1.9}_{-1.8}$
Total expected	$1320 \pm 3^{+100}_{-100}$	$381 \pm 2^{+48}_{-45}$	$101 \pm 1^{+29}_{-28}$	$20.6 \pm 0.7^{+7.1}_{-6.2}$	$4.9 \pm 0.3^{+2.0}_{-1.8}$
Data	1238	354	95	31	12
		$60 < m_{Z_1,Z_2} < 120\,\mathrm{GeV}$			
Background	$29.3 \pm 1.4 \pm 8.9$	$28.6 \pm 1.2 \pm 6.7$	$21.2 \pm 0.9 \pm 3.7$	$11.6 \pm 0.7 \pm 2.0$	$7.6 \pm 0.5 \pm 1.5$
Signal	$2320 \pm 3^{+160}_{-170}$	$960 \pm 3^{+100}_{-90}$	$303 \pm 1^{+60}_{-56}$	$75 \pm 1^{+20}_{-19}$	$21.9 \pm 0.3^{+7.9}_{-7.2}$
Total expected	$2350 \pm 4^{+160}_{-170}$	$990 \pm 3^{+100}_{-100}$	$324 \pm 2^{+60}_{-56}$	$87 \pm 1^{+21}_{-19}$	$29.5 \pm 0.7^{+8.1}_{-7.4}$
Data	2367	741	312	110	52

Shown for each jet multiplicity