2016 Z+jets Differential Cross Section Measurement

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October 21, 2019

Motivation and Status

- Z+jets provides a sensitive evaluation of the accuracy of QCD modeling
- Clean event selection with percent level background and well understood recoil object with the Z boson
- Concentrating on the muon channel in this talk

Documentation:

`muon: http://cms.cern.ch/iCMS/user/noteinfo?cmsnoteid=CMS%20AN-2018/005`
`electron: http://cms.cern.ch/iCMS/user/noteinfo?cmsnoteid=CMS%20AN-2018/310`
`CADI: SMP-19-009`
`twiki: https://twiki.cern.ch/twiki/bin/viewauth/CMS/ZJets2016CombinationChannelReview`

Observables

Z kinematics:

- Single and double diff. of Z + 1 jet p_T and $|y|$
- Angular variables between Z and leading jets

Jets:

- Single and double diff. of leading jet p_T and $|y|$
- Single diff. measurements up to 5th jet (p_T ordered)
- Jet multiplicity up to 8 jets
- Angular variables between jets (first, second, and third)
- Di-jet mass

Data and Triggers

Data:

- 2016 legacy re-reco (17Jul2018 94X)
- Single muon

- HLT_IsoMu24 || HLT_IsoTkMu24
- HLT_Ele25_eta2p1_WPTight_Gsf || HLT_Ele27_WPTight_Gsf

MC Samples

Signal MC:

- Madgraph5 NLO (Labeled *NLO MG5_aMC*)
- Madgraph5 LO (Labeled *LO MG5_aMC*)
- GENEVA MC framework (NNLO + NNLL resummation)

Background MC:

- Di-boson - Madgraph5_aMC@NLO and powheg
- Tri-boston - Madgraph5_aMC@NLO

Corrections and scale factors

- Pile-up
- L1 Prefire
- Scale Factors (MuonPOG and EGammaPOG)

Event Selections

Reco Level

- Opposite sign muons with $|m_{ll} - m_Z| < 20 GeV$, $p_T > 30/20 GeV$, $|\eta| < 2.4$
- Muons pass Medium ID + 0.15 Isolation
- AK4PF chs jets with $p_T > 30 GeV$, $|\eta| < 2.4$
- Jets pass Loose ID and Loose WP for PU MVA
- $\Delta R(\mu, jets) < 0.4$

Gen Level

- Opposite sign, same flavor $|m_{ll} - m_Z| < 20 GeV$, $p_T > 30/20 GeV$, $|\eta| < 2.4$
- AK4PF chs jets with $p_T > 30 GeV$, $|\eta| < 2.4$
- Muons dressed with photons (R=0.1)
- $\Delta R(\mu, jets) < 0.4$

Background Estimation

- Resonant background estimated from MC
- Non-resonant background (tt, WW, etc) estimated from opposite sign $e\mu$ data:
    - Comparison with MC samples shown in AN

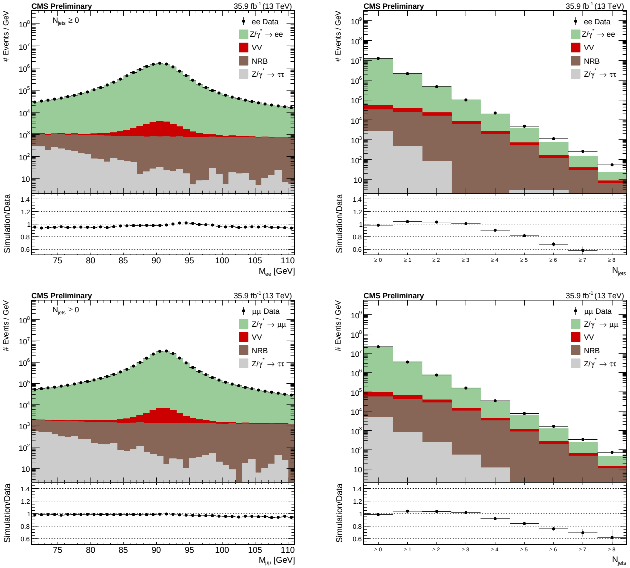
$$N_{\mu\mu} = \frac{1}{2}\, x\; k_{e\mu}\, x\; N_{e\mu}$$

$$with\;\; k_{e\mu} = \frac{\epsilon_{mu}}{\epsilon_e}\; (\sim 1.3)$$

Table : Total Yields

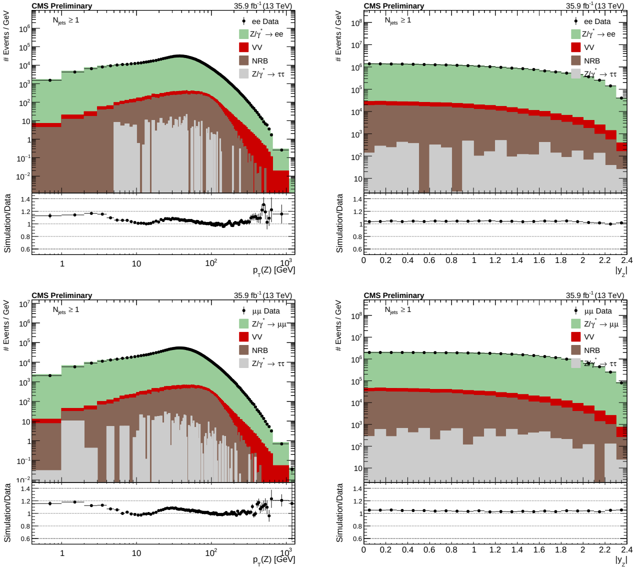
Final State	Data	Signal MC	Non-resonant Bkg	Resonant Bkg
$\mu\mu$	$20.9x10^6$	$20.6x10^6$	$56x10^3$	$34x10^3$
ee	$12.1x10^6$	$11.9x10^6$	$32x10^3$	$21x10^3$

Control Plots



- Very good agreement in inclusive Z mass
- Jet multiplicity is modeled well until parton shower region $>$ 3 jets
- More control plots in backup

Control Plots



- Very good agreement in inclusive Z mass
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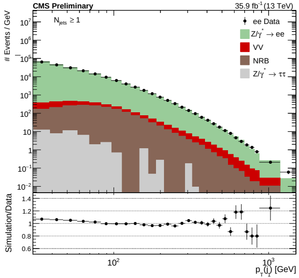
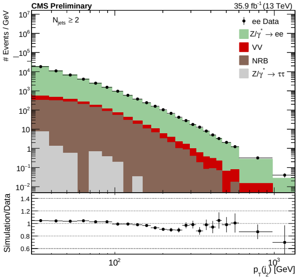
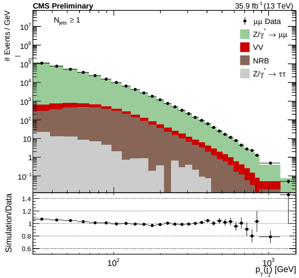
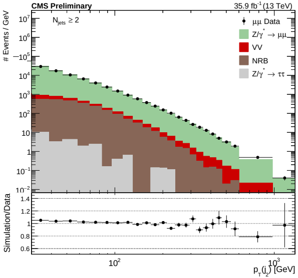
Control Plots









Unfolding Strategy

TUnfold package using Tikhonov regularization

- Response matrix filled by p_T ordered matches - non-reconstructed events entered into Gen underflow bins (efficiency)
- Fakes estimated from response matrix and Reco underflow bins
- Background and fakes subtracted from data bin by bin

Binning:

- 68% on response matrix diagonal - Reco bins then split in half so nReco $>$nGen

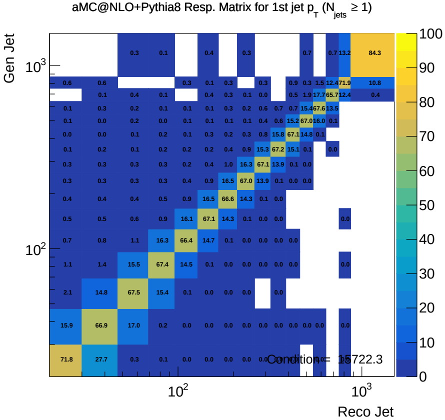
Regularization:

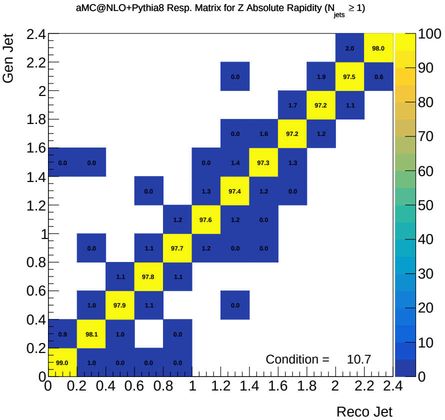
- Curvature mode + area contrained
- τ chosen from L-curve method

Validation:

- Matrix condition and bottom line test
- Closure tests using NLO and LO madgraph response matrix

Unfolding Strategy





- Regularization needed for p_T due to migrations
- Angular + rapidity variables have low migration and do not need regularization

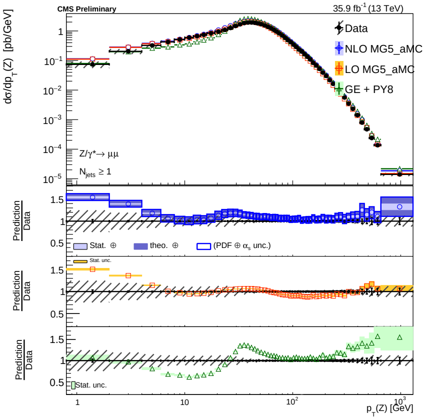
Systematics

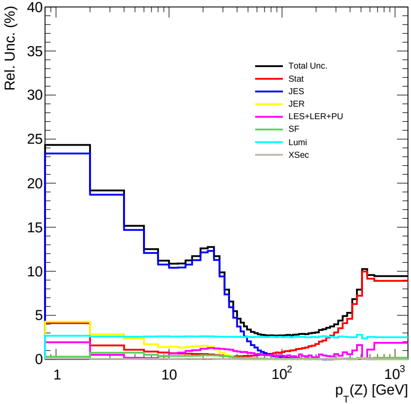
- Sources calculated: JES, JER, PU, Lumi, XSec, LES, LER, Data+MC Stat, SFStat(Eff), SFSyst(Eff), Unf.
- All sources are assumed to be independent

Table : Differential cross section in Inclusive jet multiplicity and break down of the systematic uncertainties for the muon decay channel.

N_{jets}	$\frac{d\sigma}{dN_{\text{jets}}}$ [pb]	Tot. Unc [%]	stat [%]	JES [%]	JER [%]	Eff [%]	Lumi [%]	XSec [%]	PU [%]	LES+LER [%]	Unf [%]
≥ 1	118.	5.8	0.13	4.6	0.37	0.19	2.5	0.038	0.95	1.3	0.062

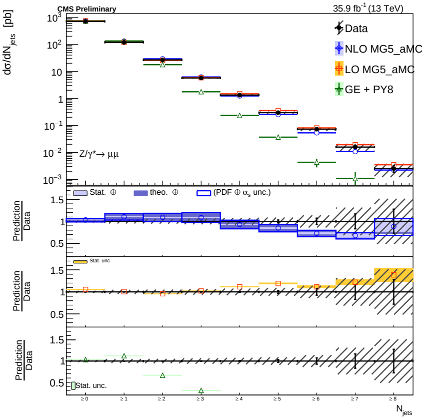
Z p_T 1 jet inclusive

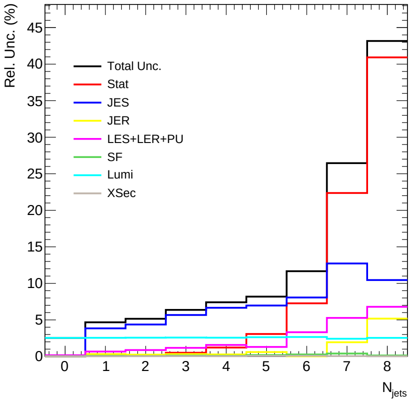




- Z p_T dominated by jet uncertainty below jet p_T cut
- Large discrepencies at low p_T where soft QCD radiation becomes important

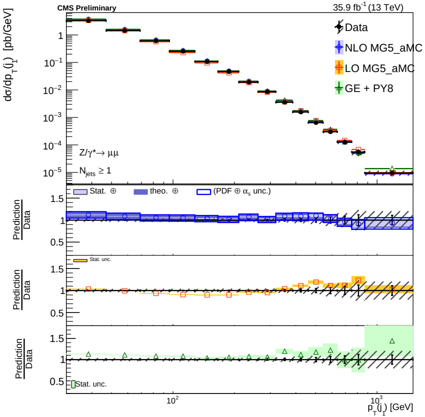
Unfolded Space

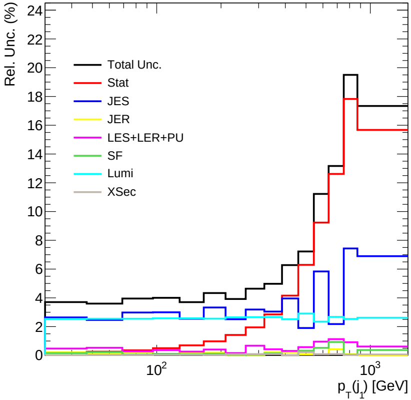




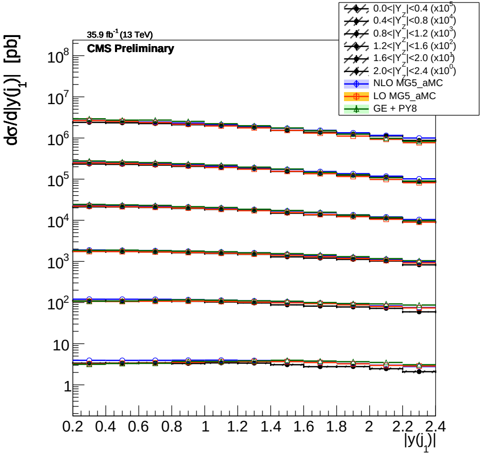
- GENEVA fails to predict multiplicity above the included MEs
- Both madgraph samples predict jet multiplicity within uncertainty even at 8 jets

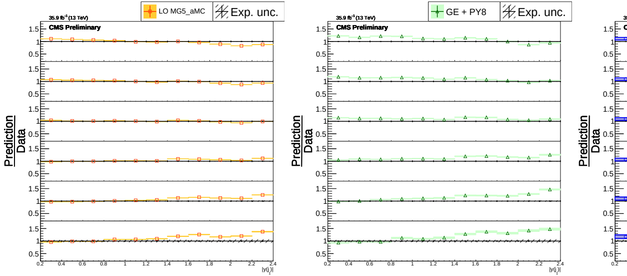
Unfolded Space





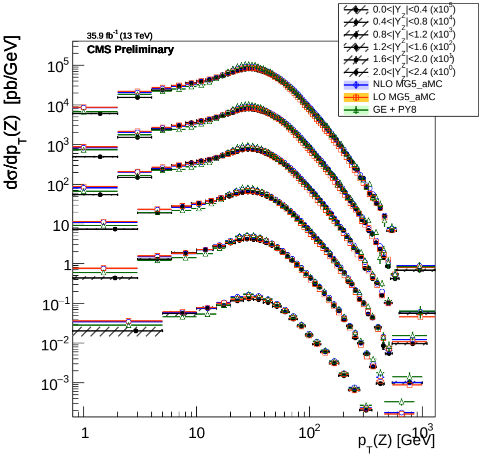
- JES uncertainty on par with lumi at $\sim 3\%$
- Total data uncertainty is lower than NLO uncertainty up to 500GeV

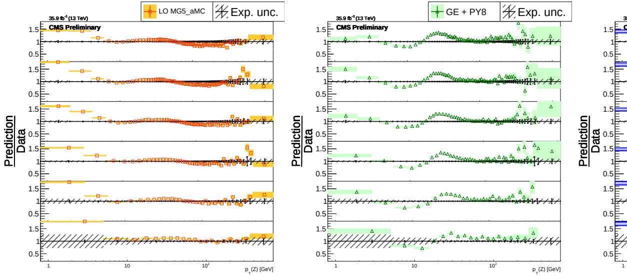




- Double differential in leading jet $|y|$ and Z $|y|$
- Measurements tend to be better predicted when Z has smaller longitudinal boost

Double Differential Results





- Large deviations at very low p_T for both madgraph predictions
- GENEVA has better prediction at low p_T but

Best Linear Unbiased Estimator (BLUE)

- Fully correlated systematics between channels: JES, JER, PU, Lumi, XSec
- Uncorrelated uncertainties: LES, LER, Data+MC Stat, SFStat, SFSyst
- Showing both channels before + combined results in this talk

Conclusions

- We have measured a wide range of Z+jets variables and extented 2015 results well into the TeV range
- Seeking endorsement to include muon channel analysis in dissertation
- Thanks to the many collaborators on this project: ULB, CEA Saclay, SMP+SMP-VJ and BU
- Finalizing last prediction (NNLO fixed order

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muon: http://cms.cern.ch/iCMS/user/noteinfo?cmsnoteid=CMS%20AN-2018/005
electron: http://cms.cern.ch/iCMS/user/noteinfo?cmsnoteid=CMS%20AN-2018/310
CADI: SMP-19-009
twiki: https://twiki.cern.ch/twiki/bin/viewauth/CMS/ZJets2016CombinationChannelReview
```

BACKUP

Sample
/SingleMuon/Run2016B-17Jul2018_ver2-v1/MINIAOD
/SingleMuon/Run2016C-17Jul2018-v1/MINIAOD
/SingleMuon/Run2016D-17Jul2018-v1/MINIAOD
/SingleMuon/Run2016E-17Jul2018-v1/MINIAOD
/SingleMuon/Run2016F-17Jul2018-v1/MINIAOD
/SingleMuon/Run2016G-17Jul2018-v1/MINIAOD
/SingleMuon/Run2016H-17Jul2018-v1/MINIAOD

Datasets

MC	Events	Eff. Events	XSec (pb)
DYJetsToLL_M-50_TuneCUETP8M1_13TeV-amcatnloFXFX-pythia8	122055388	81781064	5931.9
DYToLL_0J_13TeV-amcatnloFXFX-pythia8	93832853	76690000	4620.52
DYToLL_1J_13TeV-amcatnloFXFX-pythia8	91500283	41572416	859.59
DYToLL_2J_13TeV-amcatnloFXFX-pythia8	90299356	26282782	338.26

- Shift in values caused by DY xsec value changing from 5932 to 5818 (sum of npNLO xsec values)
- Improvement is coming from changing weights (applied to inclusive sample as well):
  - npNLO = 0: 1.00 to 1.15
  - npNLO = 1: 0.24 to 0.57
  - npNLO = 2: 0.17 to 0.38

Datasets

MC	Events	XSec (pb)
ZZTo2L2Nu_13TeV_powheg_pythia8		
ZZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8		
ZZTo4L_13TeV_powheg_pythia8		
WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8		
WZTo3LNu_TuneCUETP8M1_13TeV-powheg-pythia8		
WWZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8		
WZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8		
ZZZ_TuneCUETP8M1_13TeV-amcatnlo-pythia8		

Reco Level

- HLT_IsoMu24 and HLT_Ele25_eta2p1_WPTight_Gsf
- Opposite sign, same flavor leptons with $|m_{ll} - m_Z| < 20 GeV$, $p_T > 30/20 GeV$, $|\eta| < 2.4$
- Muons pass Medium ID + 0.15 Isolation
- Electrons pass Medium ID
- AK4PF chs jets with $p_T > 30 GeV$, $|\eta| < 2.4$
- Jets pass Loose ID and Loose WP for PU MVA
- $\Delta R(\mu, jets) < 0.4$

Gen Level

- Opposite sign, same flavor $|m_{ll} - m_Z| < 20 GeV$, $p_T > 30/20 GeV$, $|\eta| < 2.4$
- AK4PF chs jets with $p_T > 30 GeV$, $|\eta| < 2.4$
- Leptons dressed with photons (R=0.1)
- $\Delta R(\mu, jets) < 0.4$

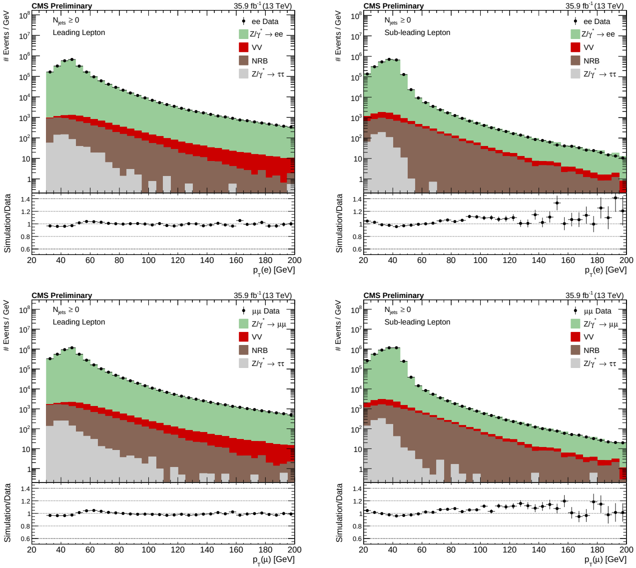
Madgraph5 aMC@NLO

- LO MEs for five processes: pp $\rightarrow Z +$ Njets with $N = 0...4$
- NLO ME calculations for pp $\rightarrow Z +$ Njets with $N = 0...2$

GENEVA MC framework

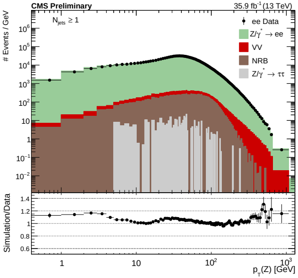
- NNLO DY + NNLL resummation

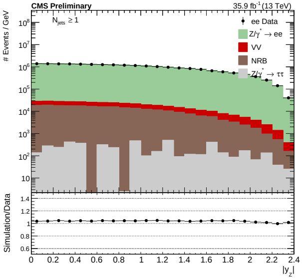
Control Plots

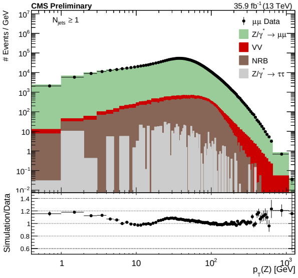


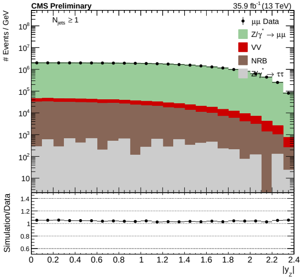
- Electron channel shown in upper plots, muon on lower
- Statistical uncertainty only on control plots

Control Plots



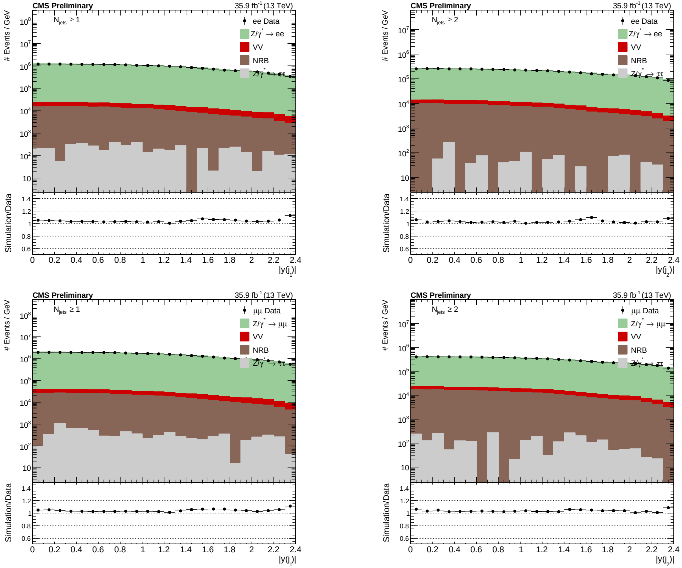




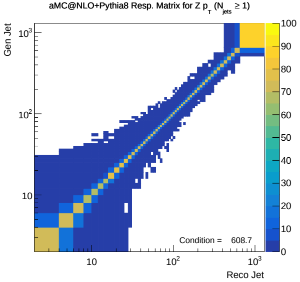


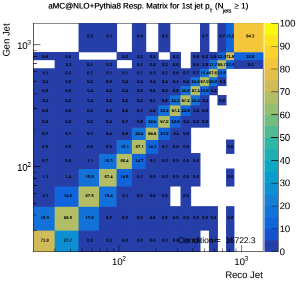
- Very good agreement in inclusive Z mass

Control Plots

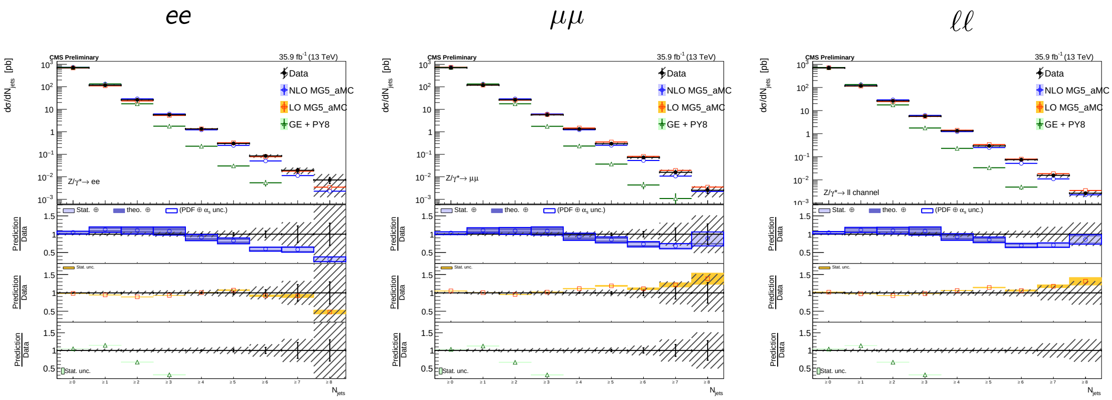


Response Matrices





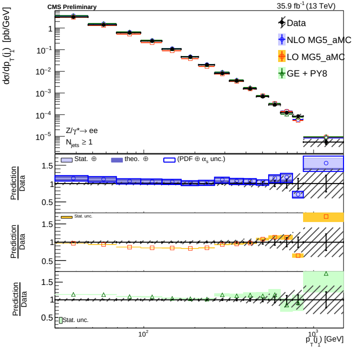
Inclusive Jet Multiplicity



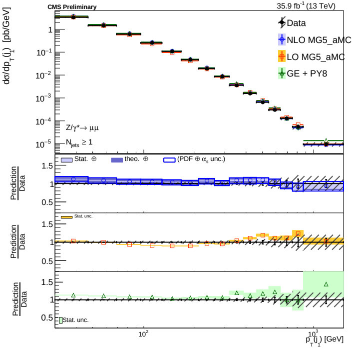
- Only stat uncertainty shown for LO and GENEVA
- GENEVA fails to predict data past 1 jet - PS region

Leading Jet p_T

ee



$\mu\mu$



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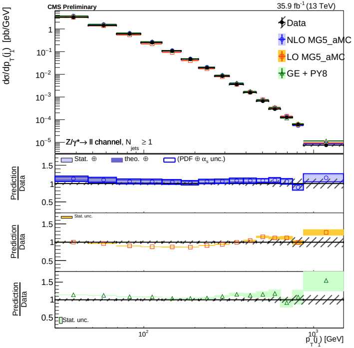
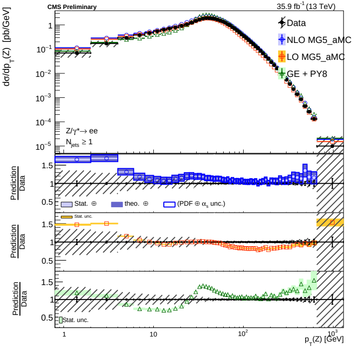


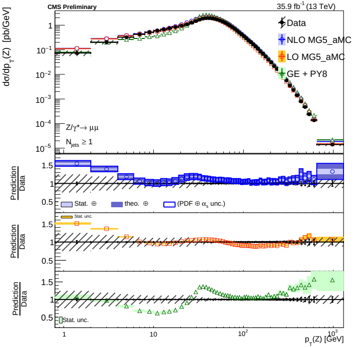
- All models predict jet kinematics within uncertainties
- Jet p_T also broken into 6 rapidity bins (included in paper)

Z p_T 1 Jet Inclusive

ee



$\mu\mu$



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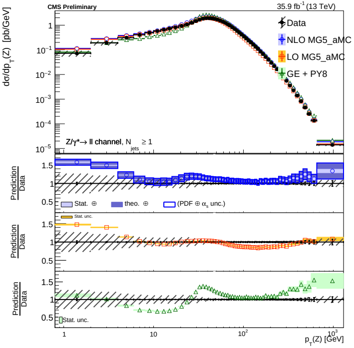
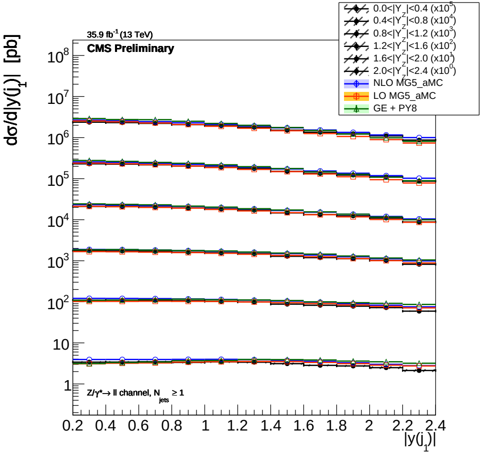
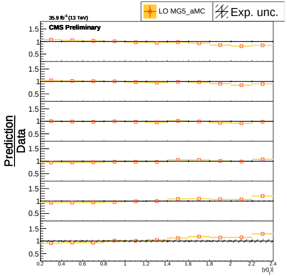
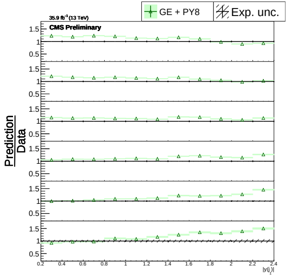


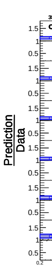
- NLO and LO MG5 predict the data better at and above the jet p_T cut (30GeV)
- Large fluctuations in GENEVA around the jet p_T cut

Double Differential Results



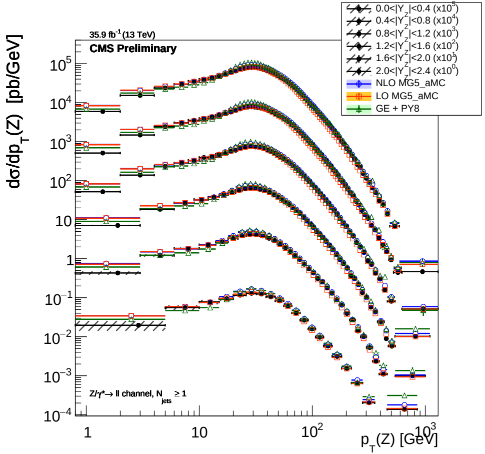


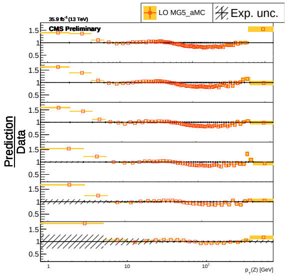


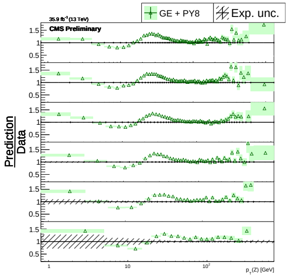


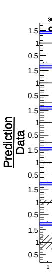
- Double differential in leading jet $|y|$ and Z $|y|$
- Measurements tend to be better predicted in the barrel

Double Differential Results



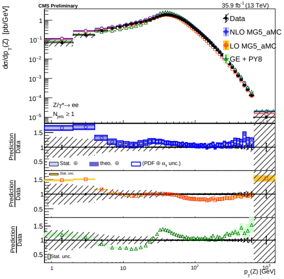


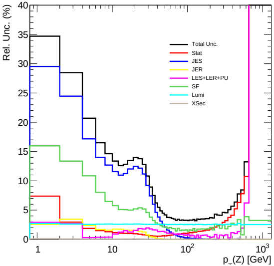


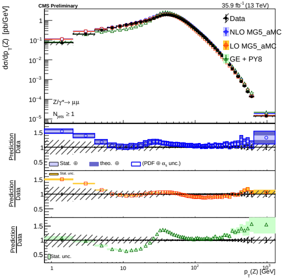


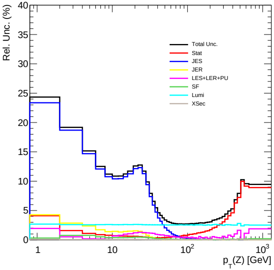
- LO and NLO MG5 predict data in full y range
- Fluctuations in GENEVA do not resolve at higher y

Unfolded Space



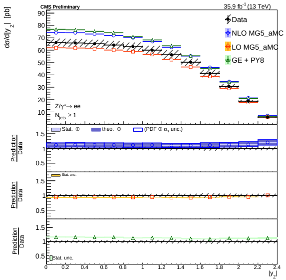


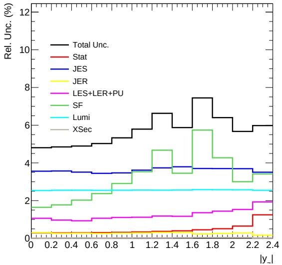


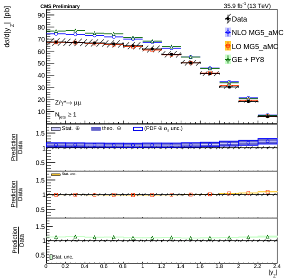


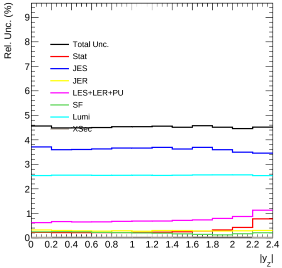
- $Z\ p_T$ dominated by jet uncertainty below jet p_T cut
- 100GeV region is now dominated by lumi instead of SF uncertainty with legacy SFs

Unfolded Space



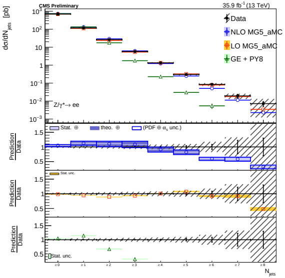


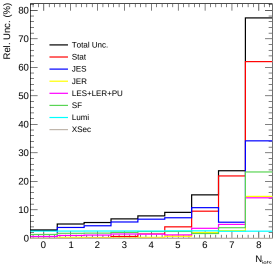


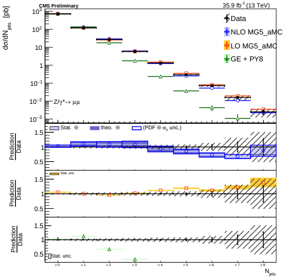


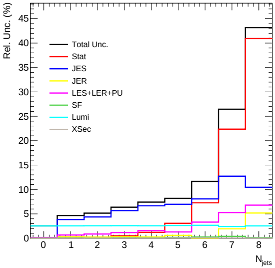
- Good shape agreement in rapidity observables for both jets and Z
- Electron SF uncertainty on average same level as the lumi uncertainty

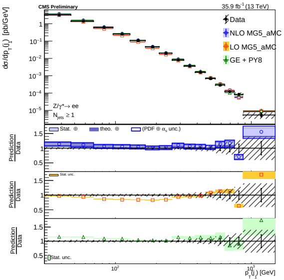
Unfolded Space

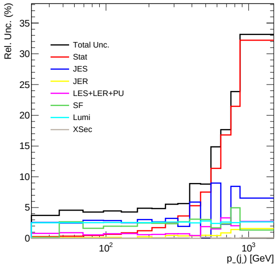


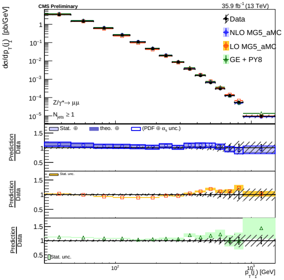


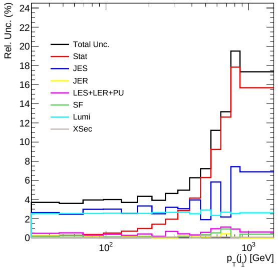






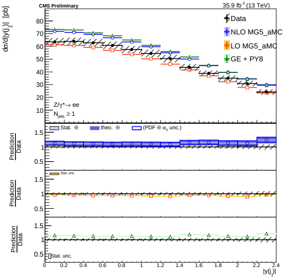


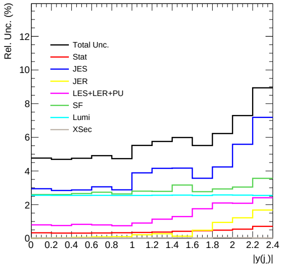


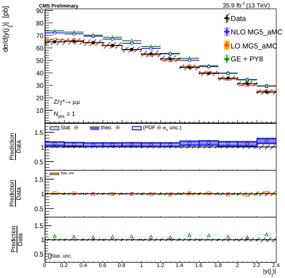


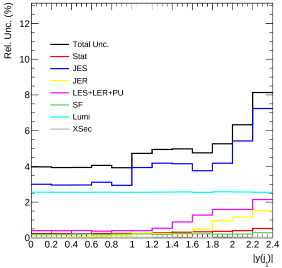
- Jet p_T uncertainty dominated by lumi and jet energy scale

Unfolded Space



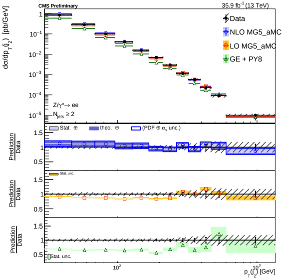


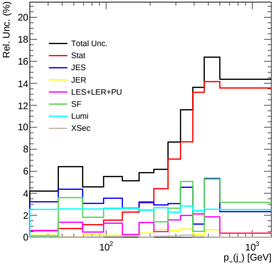


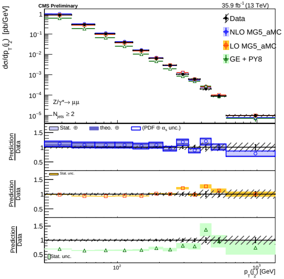


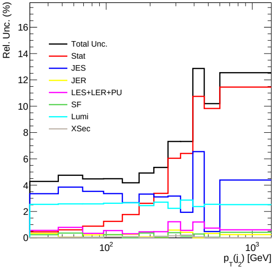
- Good shape agreement in rapidity observables for both jets and Z
- Electron SF uncertainty on average same level as the lumi uncertainty

Unfolded Space



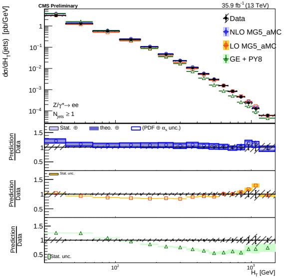


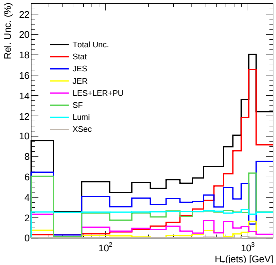


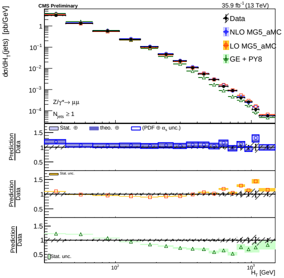


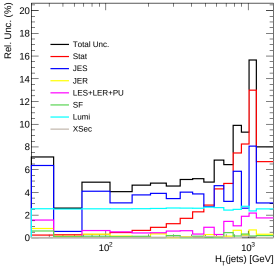
- Results of jet kinematics up to the fourth jet

Unfolded Space









Measurements not shown:

- dPhi with all permutations of Z, 1st, 2nd, and 3rd jet
- Sum and diff of Y between Z and jets
- Dijet mass
- Double Differentials:
  - 1st jet pt, Y
  - 1st jet Y, Z Y
  - 1st jet pt, Z Y