# 2016 Z+jets Differential Cross Section Measurement

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November 30, 2019


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# Introduction

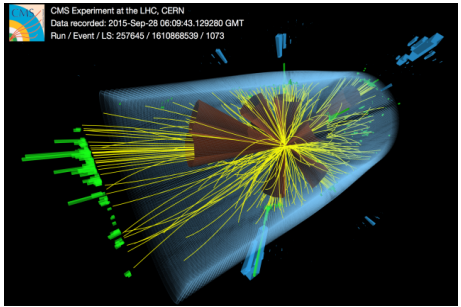
The strong force is a challenge to model accurately due the failure of perturbation theory at low energies

We looked to measure jet dynamics in a wide phase space and compare to latest QCD models

Using the Z as an event tagger and recoil object instead of purely QCD events

Clean event selection with percent level background and well understood recoil object with the Z boson

Previous measurement at $\sqrt{s} = 13 TeV$ using 2015 data set



The strong force is a challenge to model accurately due the failure of perturbation theory at low energies

We looked to measure jet dynamics in a wide phase space and compare to latest QCD models

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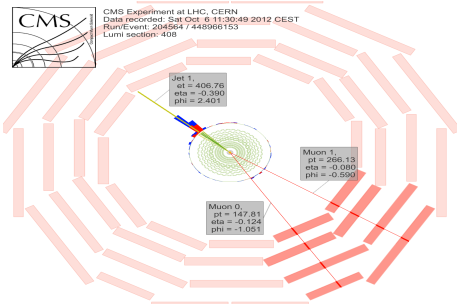
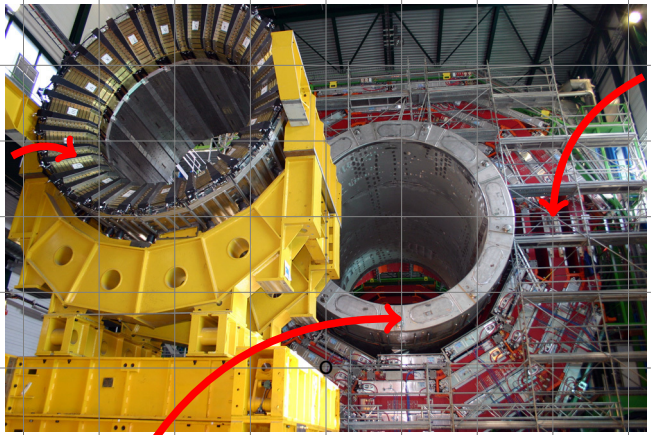


# Large Hadron Collider

# Compact Muon Solenoid



## Hadronic Calorimeter

- Brass absorber and plastic scintillator
- Jet resolution $\sim$ 5%

## Muon Spectrometer

- Resistive plate chambers for fast trigger
- Drift tubes and

## Tracker

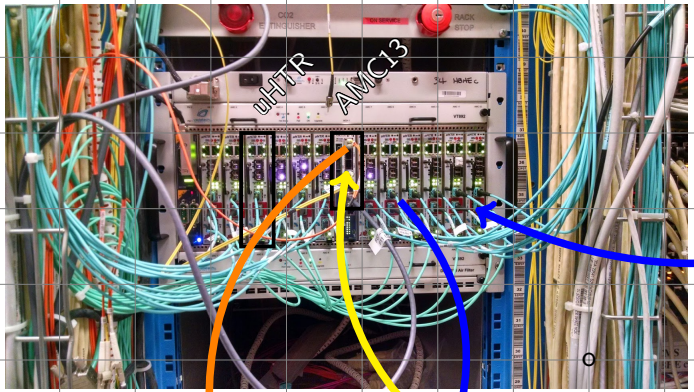
- Silicon pixels and stripts

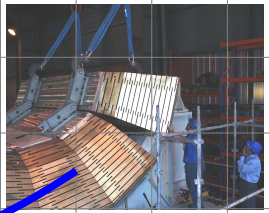
$\rightarrow$ Muon + tracker 2-3% muon momentum resolution

## Superconducting Solenoid

- 3.8T internal field

# Upgrade of HCAL Electronic



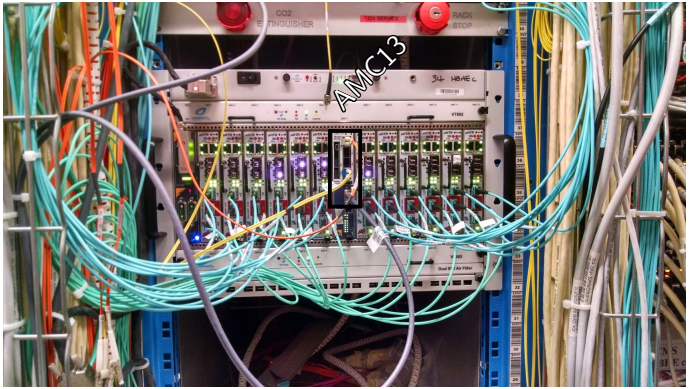



Transducer + Digitizer

## $\mu TCA$ Data Acquisition

- New generation of electronics crate
- Installing to increate data bandwidth
- 2015+2016 commissioned full uTCA system for HCAL

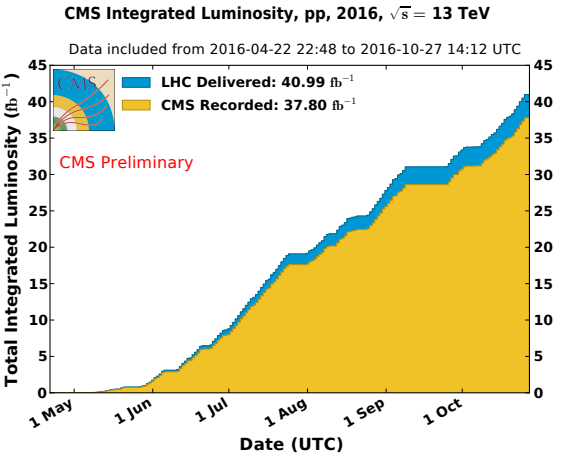
# Upgrade of HCAL Electronic




## BU AMC13

- Manages clock and throttling system for the crate
- Receives triggers and builds event fragments from uHTR
-

# Collection of 2016 Data Set

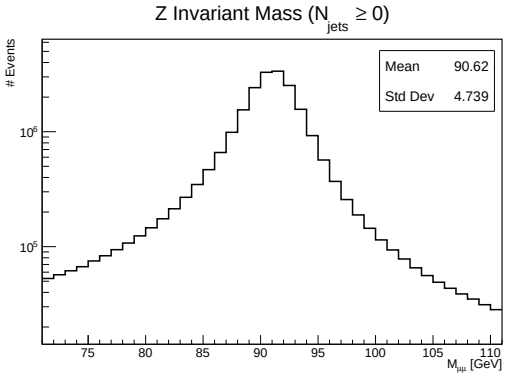



- CMS had a very successful 2016 run with 92% data taking efficiency
- $\mu TCA$ system and AMC13 proved to be solid
- 1.2% of total downtime, 97% good quality data

# Optimized Phase Space

Goal when choosing cuts: most inclusive

- Opposite sign muons with $71 < m_{\mu\mu} < 111$
- Within tracker and muon system coverage: $|\eta| < 2.4$
- Leading leptons limited by triggers: 24 GeV minimum $\rightarrow$ 30 GeV to be safe, Sub-leading lepton 20 GeV
- Jet cut 30 GeV: decent resolution and well above constant PU
- $\Delta R(\ell, jets) < 0.4$



# Models for Comparison

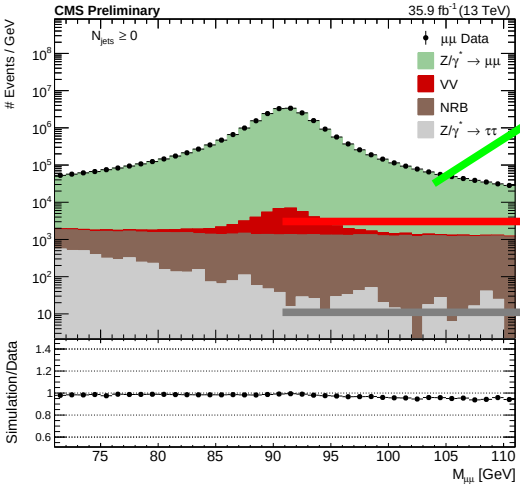
Madgraph5 aMC@NLO

- 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

# Simulated Events

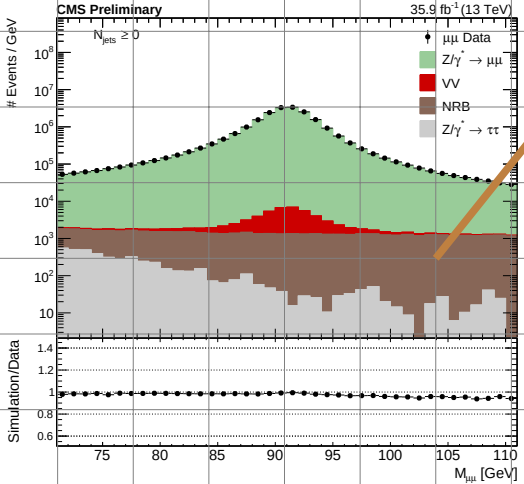



DY Signal - Madgraph5 NLO (Labeled *NLO MG5_aMC*)

Resonant Background - ZZ, ZW: Madgraph5_aMC@NLO and powheg - Tri-boson: Madgraph5_aMC@NLO

$\tau\tau$ - Madgraph5 NLO (Labeled *NLO MG5_aMC*)

# Non-resonant Background




Non-resonant background (tt, WW, etc) estimated from opposite sign $e\mu$ data:

$$N_{\ell\ell} = \frac{1}{2}\left(k_{e\mu} + \frac{1}{k_{e\mu}}\right) N_{e\mu}$$

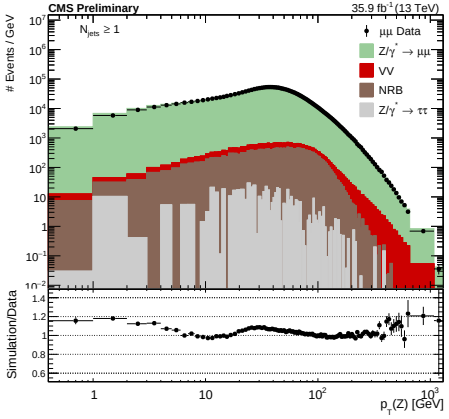
$$with \;\; k_{e\mu} = \frac{\epsilon_{mu}}{\epsilon_e} \approx 1.3$$

Table: Total Yields

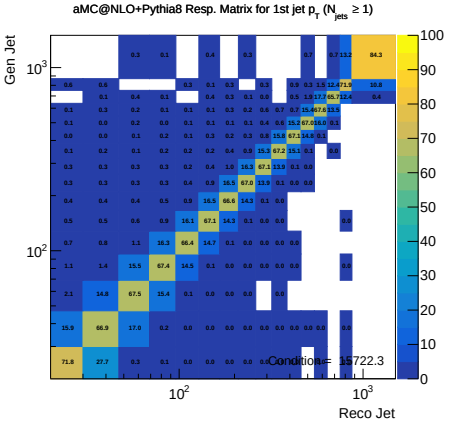
| Data | Signal MC | Non-res. Bkg | Res. Bkg |
|---|---|---|---|
| $20.9x10^6$ | $20.6x10^6$ | $56x10^3$ | $34x10^3$ |

# Unfolding Problem

- Cannot compare easily to model predictions
- Reverse detector effects - called unfolding
- Boils down to a matrix inversion problem



# Unfolding Strategy




- Tikhonov regularization
- Regularization needed for $p_T$ due to migrations
- $\chi^2 = \chi_0^2 + \chi_{reg}^2 = (y - Ax)^T V_{yy}^{-1}(y - Ax) + \tau^2 x^T L^{-1} L x$

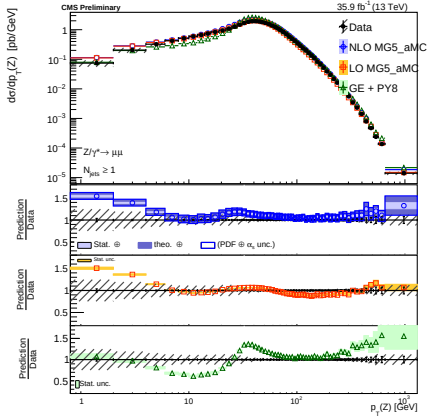
# Uncertainties

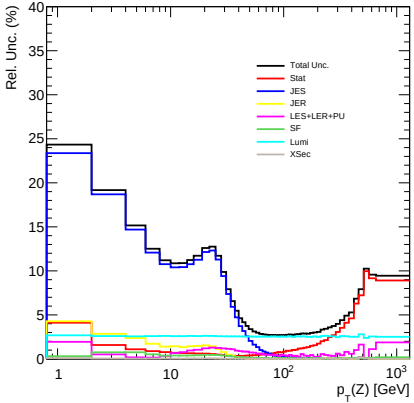
- $\Delta Resp \rightarrow \Delta UnfoldedData$
- Jet energy scale: absolute scale raised and lowered for each jet
- Jet energy resolution: Smear each jet $p_T$ with varying Gaussian widths
- Lumi: overall uncertainty on integrated luminosity
- Many others: Lepton energy scale/resolution (LES/LER), background number (XSec), Pileup (PU), Scale Factor (SF), Unfolding uncertainties (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.

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

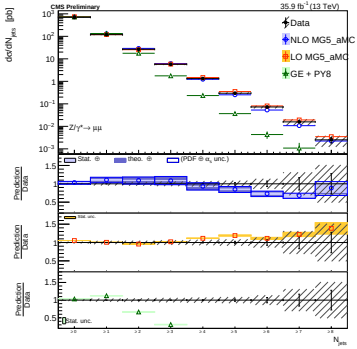
# Z $p_T$ 1 jet inclusive - Diff.

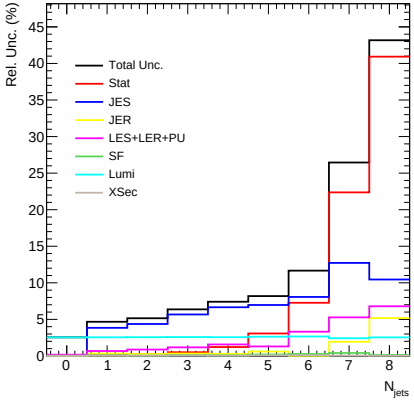



- Large discrepancies at low $p_T$ where soft QCD radiation becomes important
- $Z\,p_T$ dominated by jet uncertainty below jet $p_T$ cut
- SF systematic much larger in electron channel

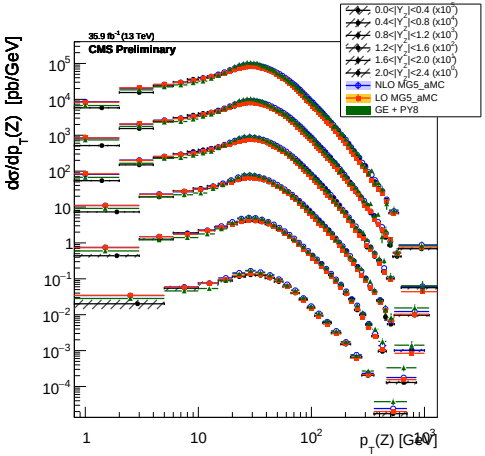
# Inclusive Jet Multiplicity - Diff.

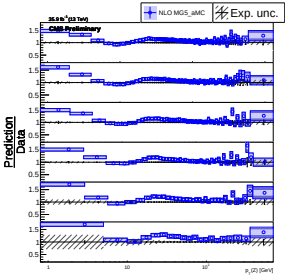


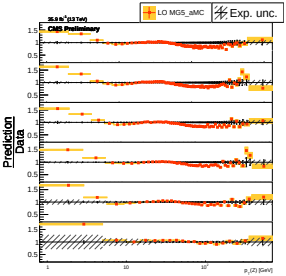



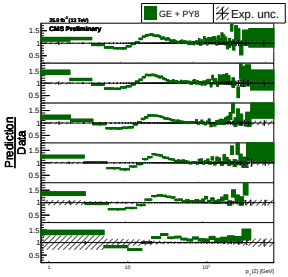

- Only stat uncertainty shown for LO and GENEVA
- GENEVA fails to predict multiplicity above the included MEs and in PS region
- JES dominant until statistically limited at 6 jets
- After lumi, SF is most important for electrons and LES for muons

# Z $p_T$ 1 jet inclusive - Double Diff.



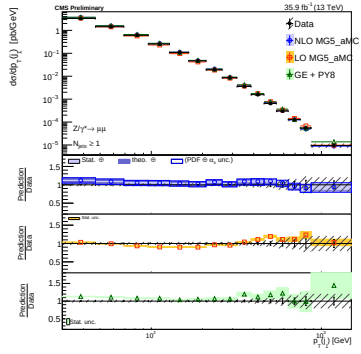



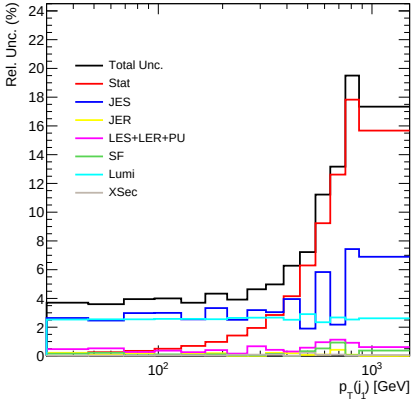




- Large deviations at very low $p_T$ for both madgraph predictions
- GENEVA has better prediction at low $p_T$ but shows larger deviations around the peak

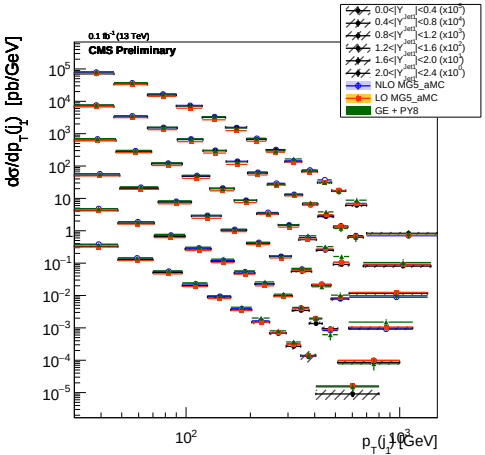
# Leading Jet $p_T$ - Diff.

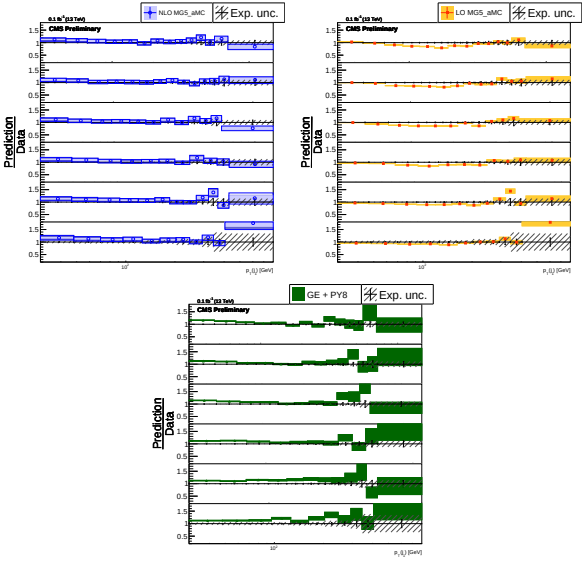



- All models predict jet kinematics within uncertainties
- Total data uncertainty is lower than NLO uncertainty up to 500GeV
- JES uncertainty on par with lumi at $\sim 3\%$

# Double Differential Results




– All models predict jet kinematics within uncertainties

# Conclusions

- We have measured a wide range of Z+jets variables and extended 2015 results well into the TeV range
- Finalizing last prediction (NNLO fixed order)

BACKUP

# Datasets

| 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 | | |

# Event Selections

Reco Level

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

Gen Level

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

# Predictions

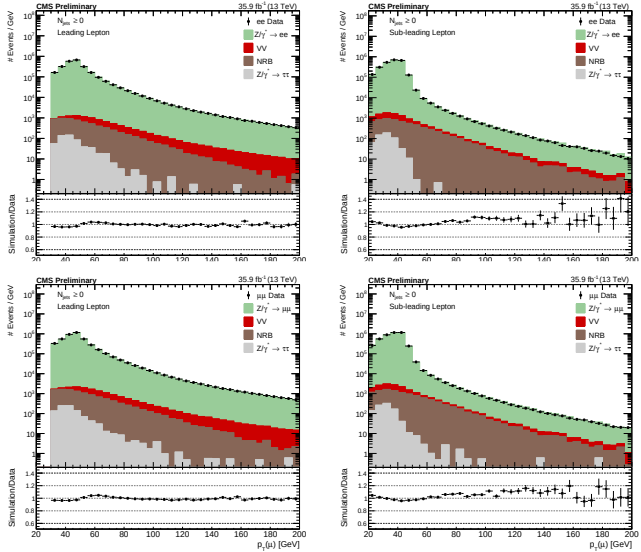
Madgraph5 aMC@NLO

- 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

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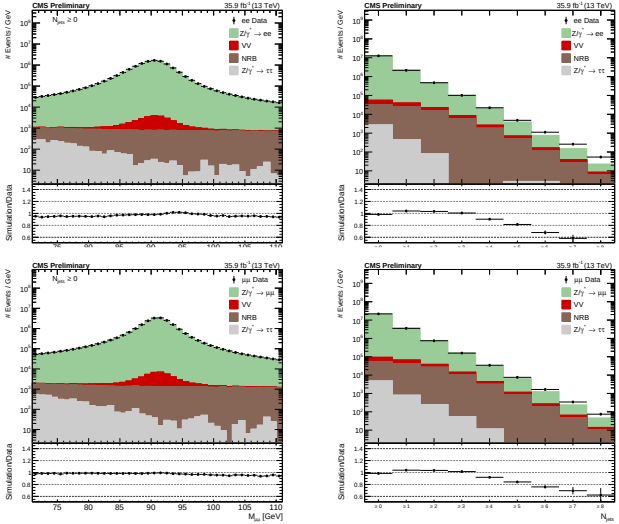


- Very good agreement in inclusive Z mass
- Jet multiplicity is modeled well until parton shower region $>$ 3 jets

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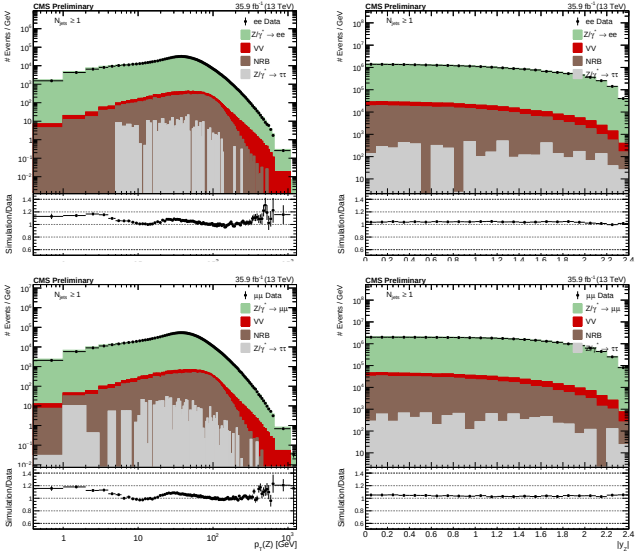


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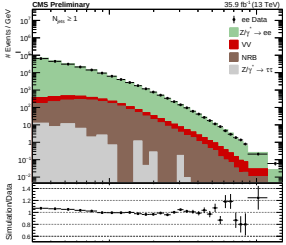


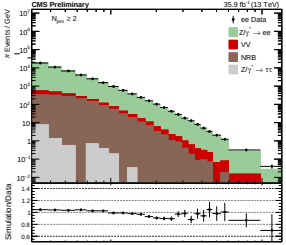


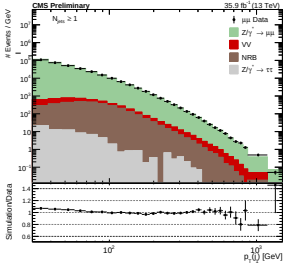


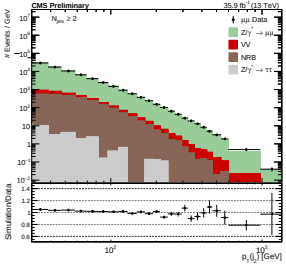

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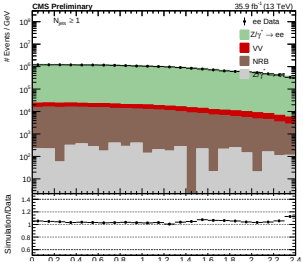
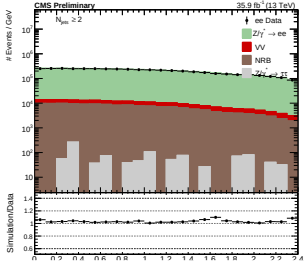
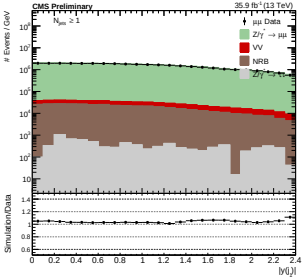
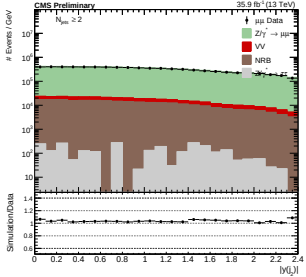


# Unfolding Strategy

TUnfold package using

- 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

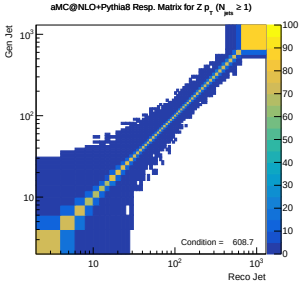
Regularization:

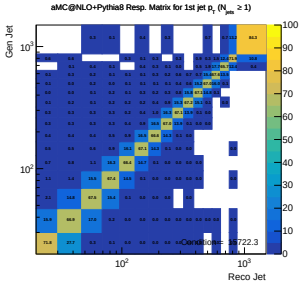
- Curvature mode + area constrained
- $\tau$ chosen from L-curve method

Validation:

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

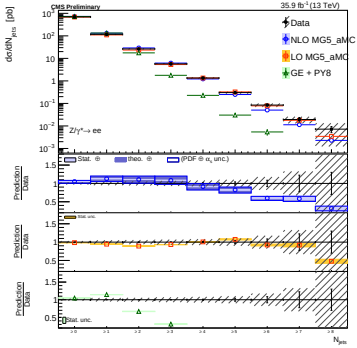
# Response Matrices

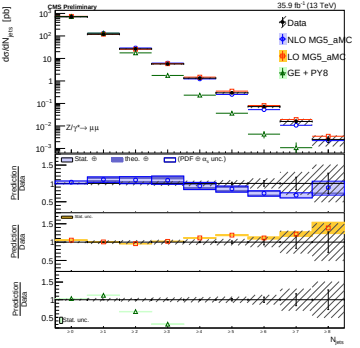


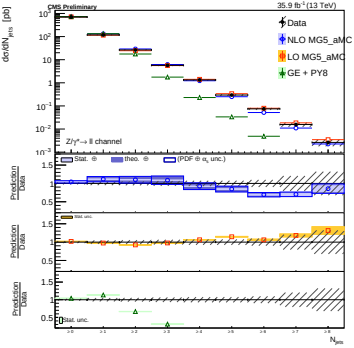



# Inclusive Jet Multiplicity

$ee$ $\mu\mu$ $\ell\ell$



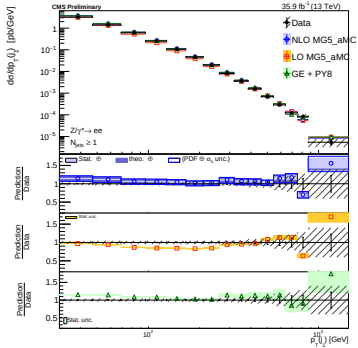



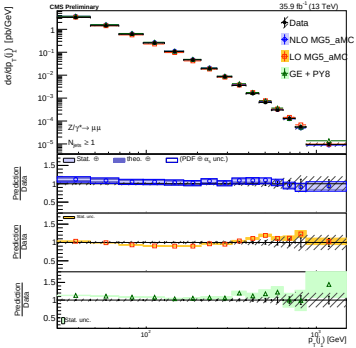



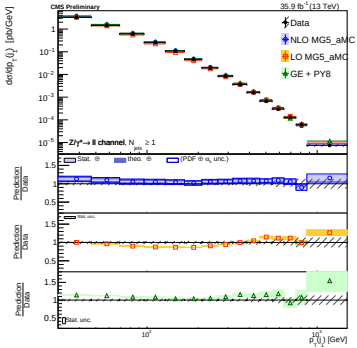

- Only stat uncertainty shown for LO and GENEVA
- GENEVA fails to predict data past 1 jet - PS region

# Leading Jet $p_T$

$ee$ $\mu\mu$ $\ell\ell$



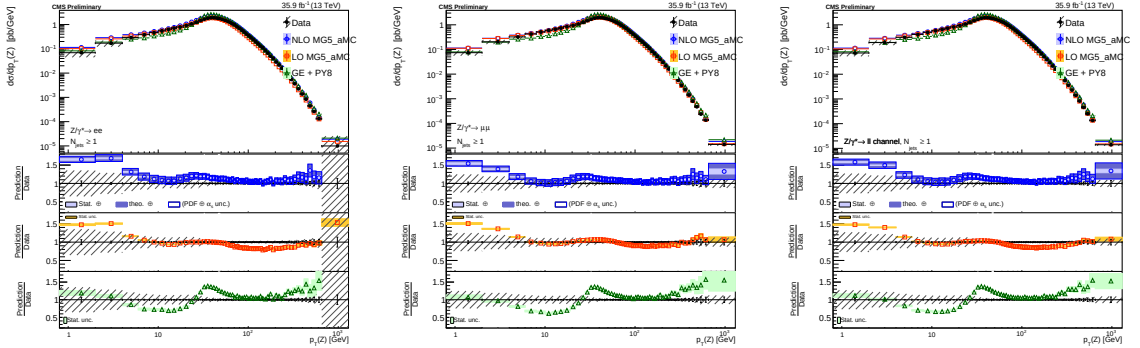




- All models predict jet kinematics within uncertainties
- Jet $p_T$ also broken into 6 rapidity bins (included in paper)

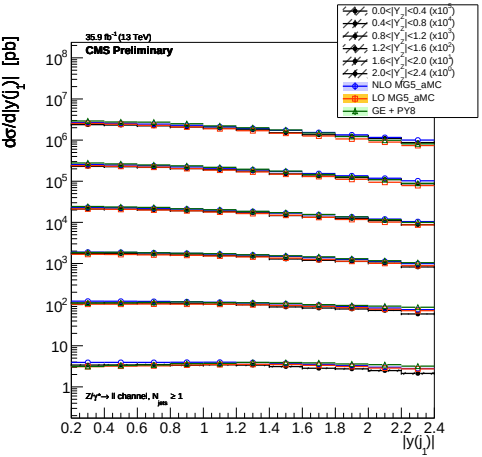
# Z $p_T$ 1 Jet Inclusive

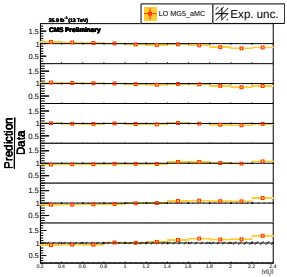
$ee$ $\mu\mu$ $\ell\ell$

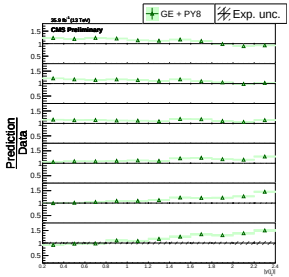


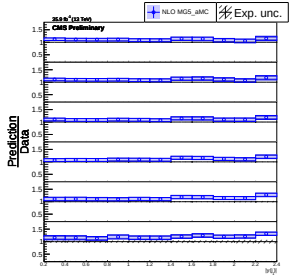

- NLO and LO MG5 predict the data better at and above the jet $p_T$ cut (30GeV)
- Large fluctuations in GENEVA around the jet $p_T$ cut

# Double Differential Results



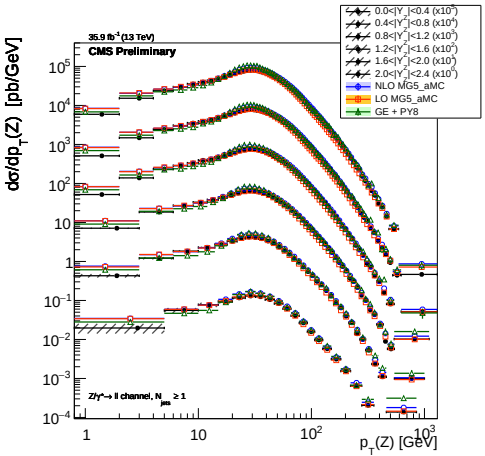



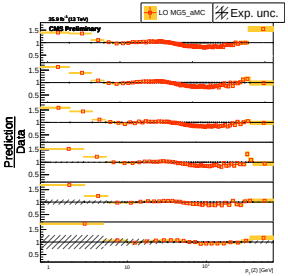



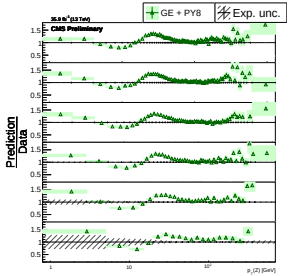



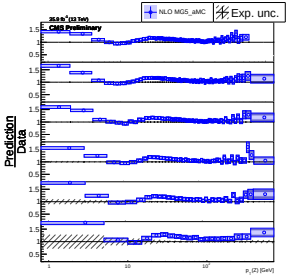

- Double differential in leading jet $|y|$ and Z $|y|$
- Measurements tend to be better predicted in the barrel

# Double Differential Results



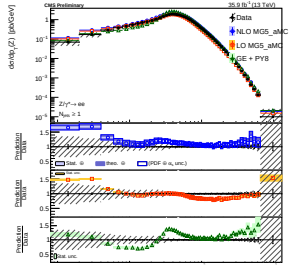



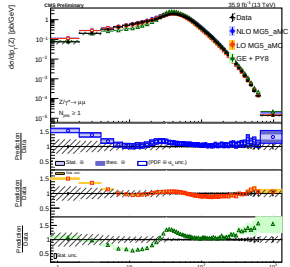



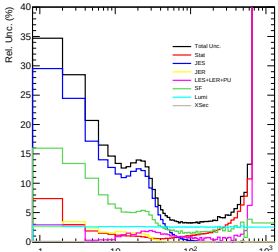



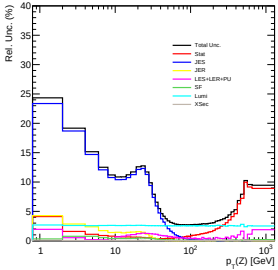

- LO and NLO MG5 predict data in full y range
- Fluctuations in GENEVA do not resolve at higher y

# Unfolded Space



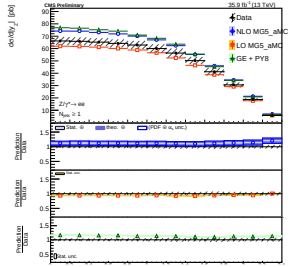



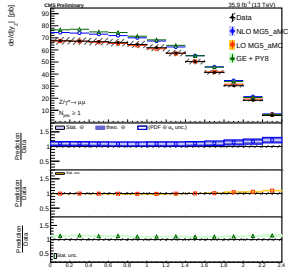



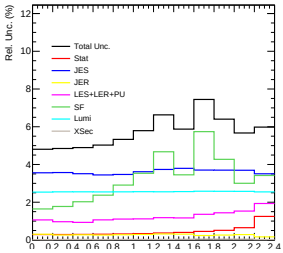



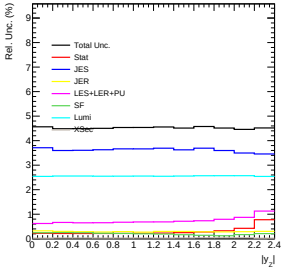

- $Z\,p_T$ dominated by jet uncertainty below jet $p_T$ cut
- 100GeV region is now dominated by lumi instead of SF uncertainty with legacy SFs

# Unfolded Space



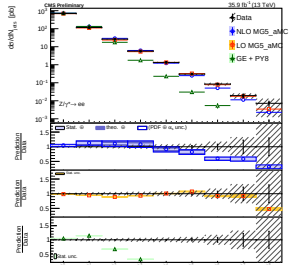



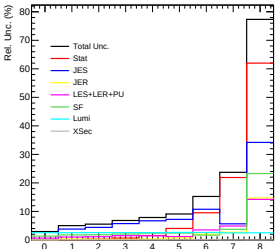



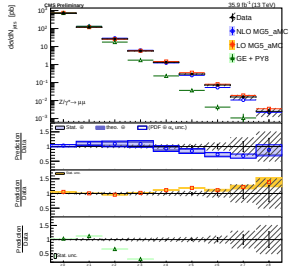



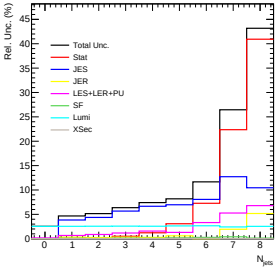

- Good shape agreement in rapidity observables for both jets and Z
- Electron SF uncertainty on average same level as the lumi uncertainty

# Unfolded Space



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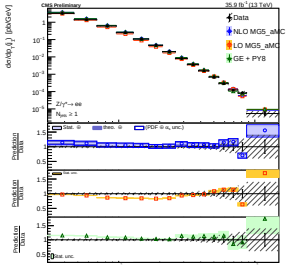
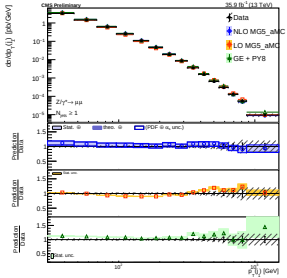
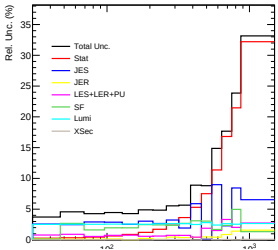
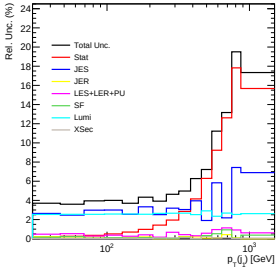


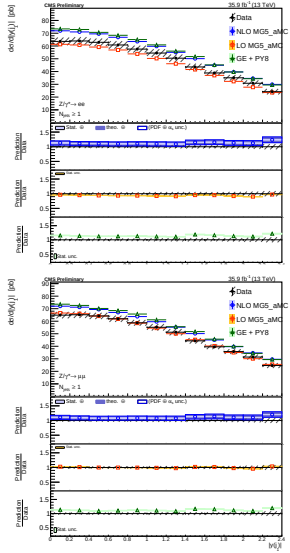



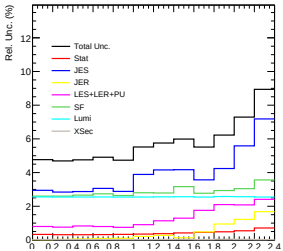



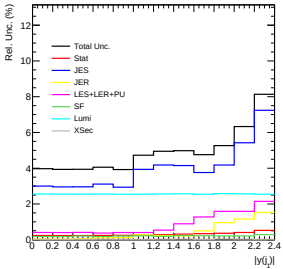




– Jet $p_T$ uncertainty dominated by lumi and jet energy scale

# Unfolded Space

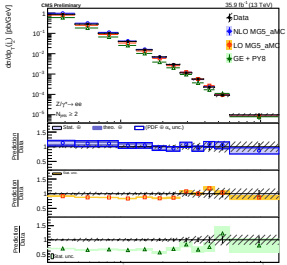


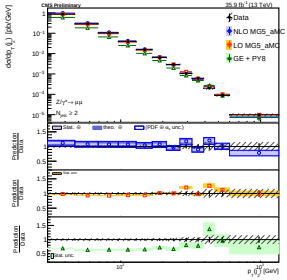



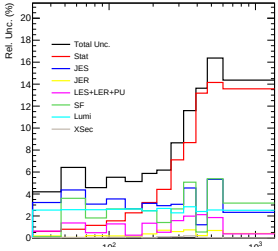



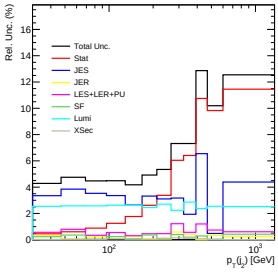

- Good shape agreement in rapidity observables for both jets and Z
- Electron SF uncertainty on average same level as the lumi uncertainty

# Unfolded Space



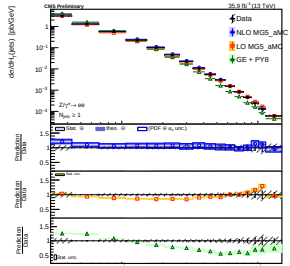



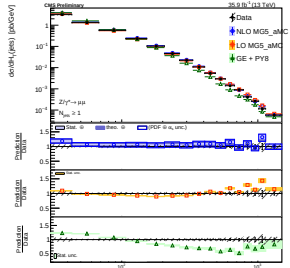



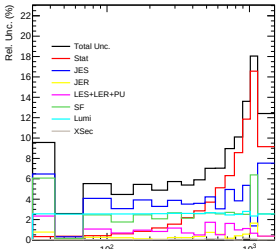



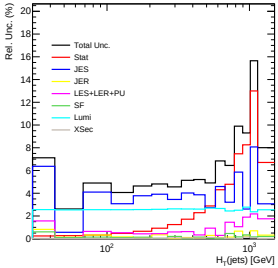

– Results of jet kinematics up to the fourth jet

# 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