Vector boson associated with jets in CMS

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On behalf of the CMS Collaboration
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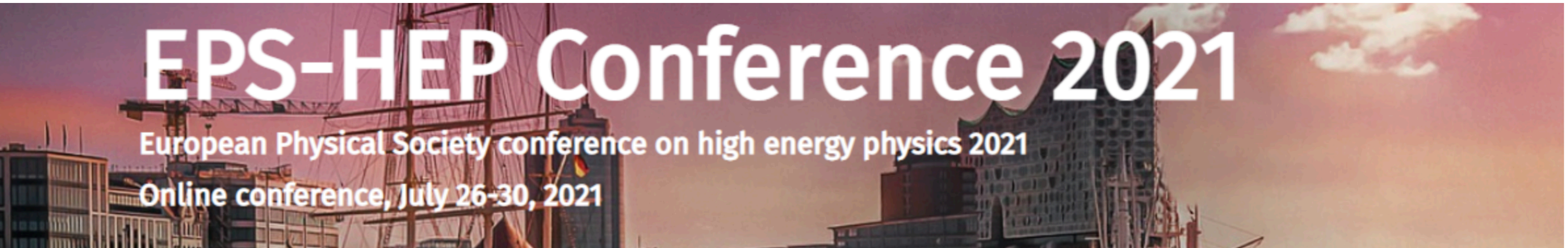


Outline

- Introduction
- V+jets measurements
  - Precision measurement of the Z invisible width at 13 TeV **(SMP-18-014)**
  - Multi-differential Z+jets cross sections at 13 TeV **(SMP-19-009)**
  - Azimuthal correlations in Z+jets at 13 TeV **(SMP-21-003)**
- Summary

Introduction

- Z+jets provides a sensitive evaluation of the accuracy of QCD modeling
  - Important for modeling the production mechanism involved in the Higgs boson and new physics searches.
- This process is a standard candle at LHC:
  - High cross section
  - Almost background free
  - clean signature
- It is a dominant background in many SM processes, such as Higgs production, $t\bar{t}$ production and for searches beyond SM.

Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

- Goal: turns generic jets+MET dark matter search on its head to make precise measurement of Z invisible width.
- Z invisible width extracted from ratio of measured cross sections of Z(vv)+jets to Z($\ell\ell$)+jets.

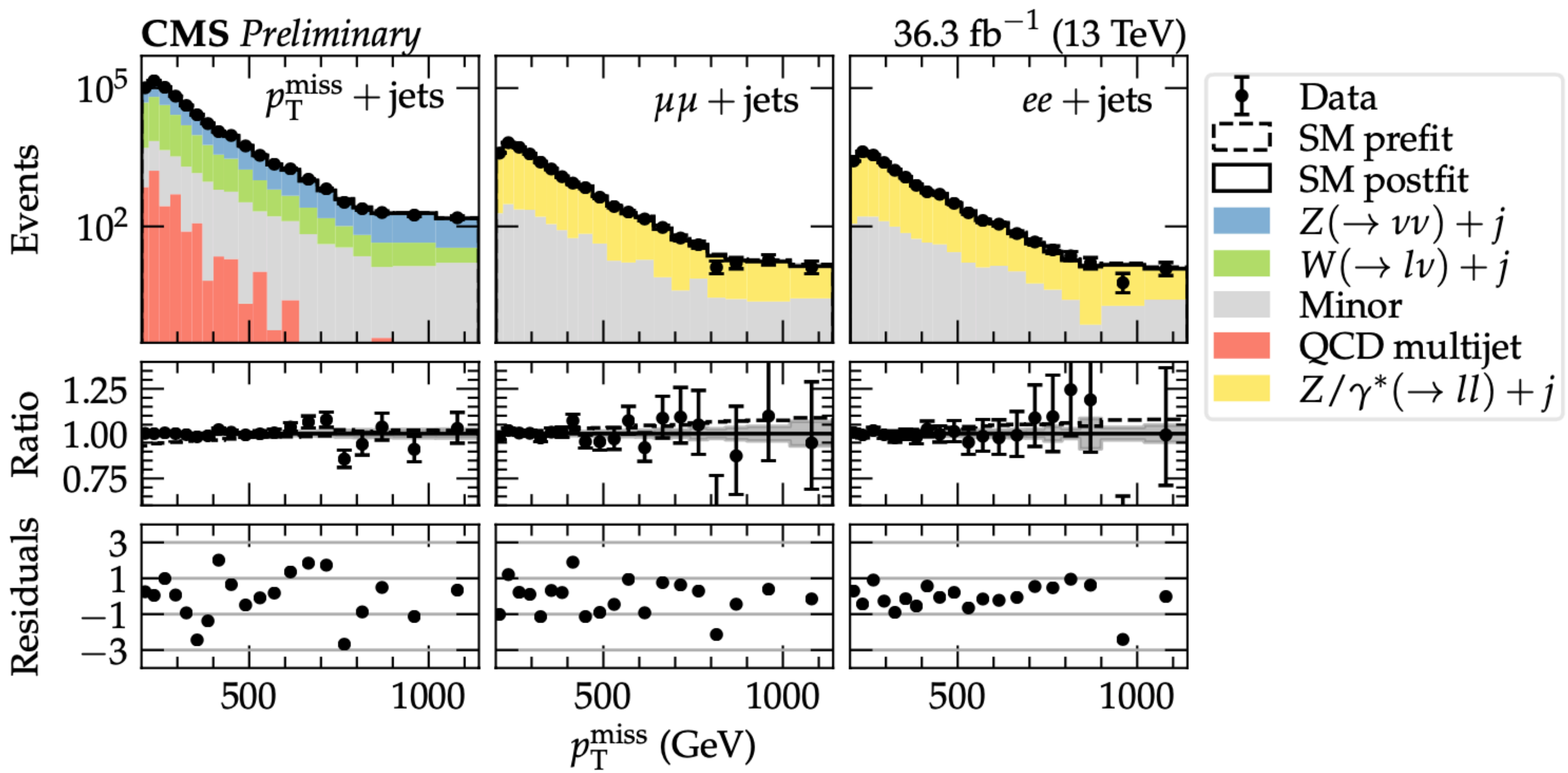
$$\boxed{\Gamma(\mathrm{Z} \to \nu\bar{\nu}) = \frac{\sigma(\mathrm{Z}+\mathrm{jets})\mathcal{B}(\mathrm{Z} \to \nu\bar{\nu})}{\sigma(\mathrm{Z}+\mathrm{jets})\mathcal{B}(\mathrm{Z} \to \ell\ell)}\Gamma(\mathrm{Z} \to \ell\ell)}$$

- Using 36.3 fb-1 of 13 TeV data
  - Jets+MET topology to select Z->vv events
  - μμ+jets and ee+jets to select Z->$\ell\ell$ events
  - μv+jets, ev+jets and τ_h v+jets for W+jets
- Backgrounds:
  - W+jets events, estimated using data driven approach and ℓ+jets control regions.
  - QCD background is estimated using data driven.
  - Contribution from γ*—>$\ell\ell$ and interference between γ*—>$\ell\ell$ and Z->$\ell\ell$ is evaluated.

Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

- Invisible width extracted from simultaneous likelihood fit to the jets+MET, $\ell\ell$+jets, ℓ+jets regions
- The transfer factor estimating the W+jets background is implemented as a global unconstrained parameter scaling the W+jets process in jets+MET and ℓ+jets.
- Systematic uncertainties are treated as nuisance parameters, modeled with Gaussian priors.

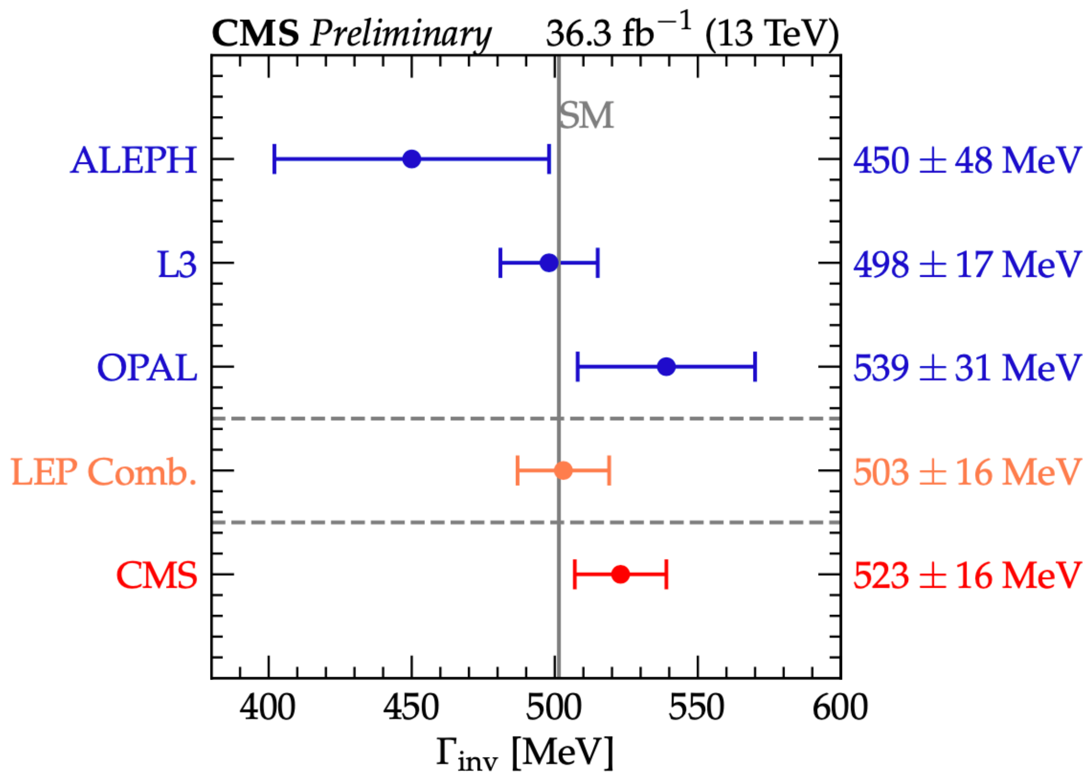


Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

Systematic uncertainties:

Source	Uncertainty (%) up	down
rZJetsToNuNu	3.21	-3.15
muonIdIsoMediumSyst	2.05	-2.03
jesTotal	-1.88	1.93
eleIdIsoMediumSyst	1.53	-1.52
pileup	1.02	-0.93
eleIdIsoMediumStat	0.98	-0.99
eleTrig	0.76	-0.69
tauIdVLoose	0.63	-0.71
metTrigMonojetSyst	-0.70	0.70
metTrigDoubleMuonSyst	0.56	-0.56
metTrigSingleMuonSyst	0.44	-0.46
d2kqcd	0.38	-0.40
jerSF	-0.38	0.37
muonIdIsoMediumStat	0.33	-0.31
eleRecoSyst	0.30	-0.30
d3kewz	-0.30	0.29
lhePdfWeight	0.15	-0.20
lheScaleWeight	0.17	-0.18
eleRecoStat	0.17	-0.17
d1kqcd	0.14	-0.16
dkmix	0.14	-0.15
qcdSystB1	-0.14	-0.14
d2kewe	0.12	-0.13
qcdSystB2	-0.13	-0.13
prefiring	-0.11	0.10
qcdSystB0	0.09	0.09
d2kewz	-0.08	0.06
muonRecoSyst	0.06	-0.07
qcdSystB3	-0.05	-0.05
d3keww	0.05	-0.05



$$\boxed{\Gamma_{inv} = 523 \pm 3\,(\mathrm{stat}) \pm 16\,(\mathrm{syst})\ \mathrm{MeV}}$$

- First direct measurement of invisible Z width at CMS
- Precision competitive with LEP direct measurement
- Most precise single direct measurement

Multi-differential Z+jets cross sections at 13 TeV

SMP-19-009

- Z+jets provides a sensitive evaluation of the accuracy of QCD modeling
- Using 35.9 fb-1 data to measure the differential cross section:
  - Double differential of Z pT and |*y*|
  - Jet multiplicity up to 8 jets
  - Transverse momentum and rapidities of 5 jets
  - Double differential of leading jet pT and |*y*|
  - Angular variables…

Event selections:

Opposite sign leptons with pT > 30/20GeV, |η|< 2.4

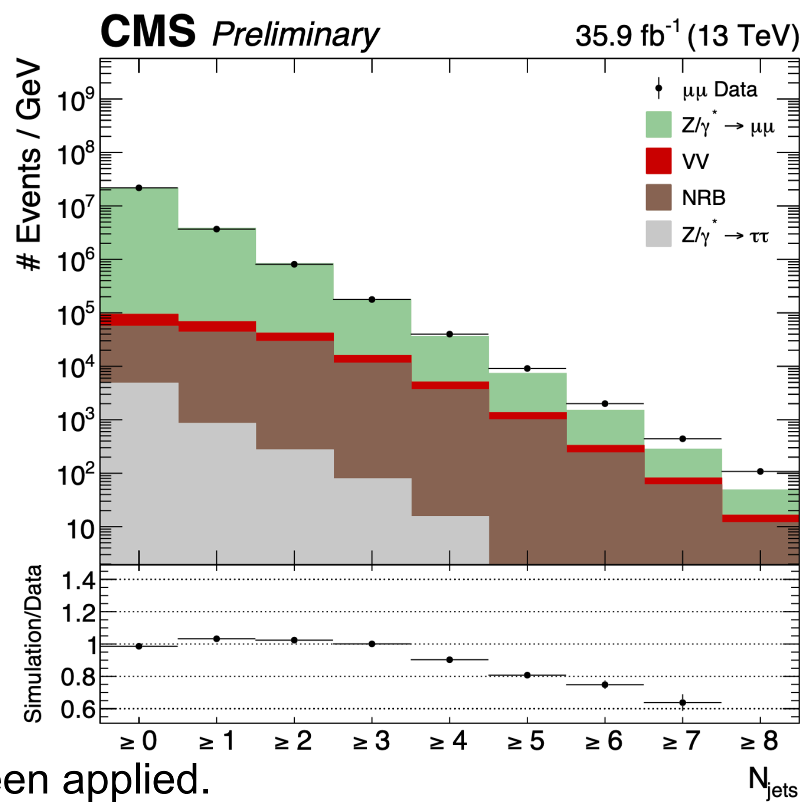
$|m_{\ell\ell} - m_Z| < 20$GeV

Medium ID (+ 0.15 Isolation for muon)

AK4PF chs jets with pT > 30GeV, |η|< 2.4

Jets pass Loose ID and Tight WP for PU MVA

ΔR (ℓ,jets) < 0.4



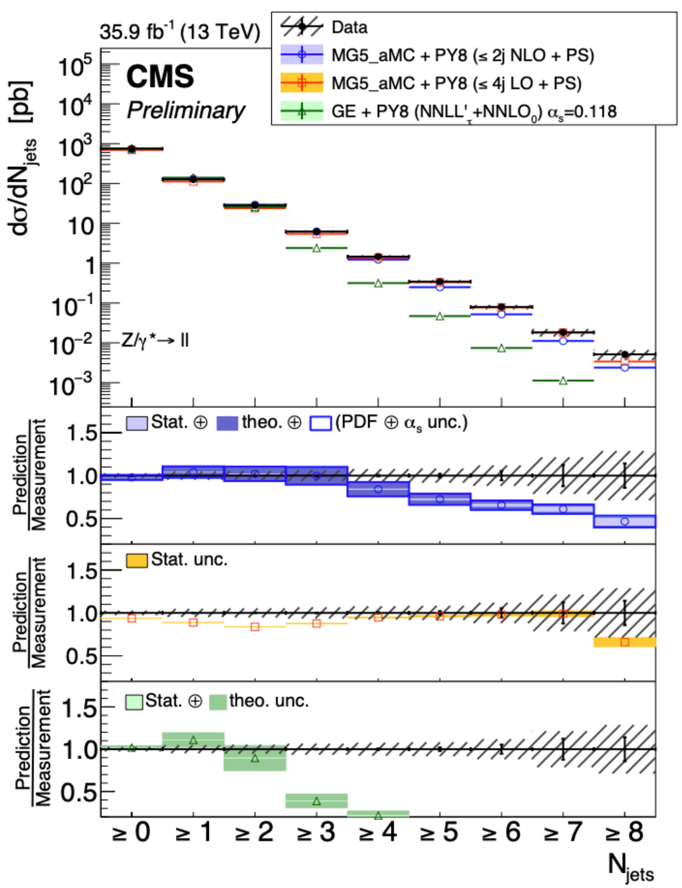
Corresponding corrections and scale factors have been applied.

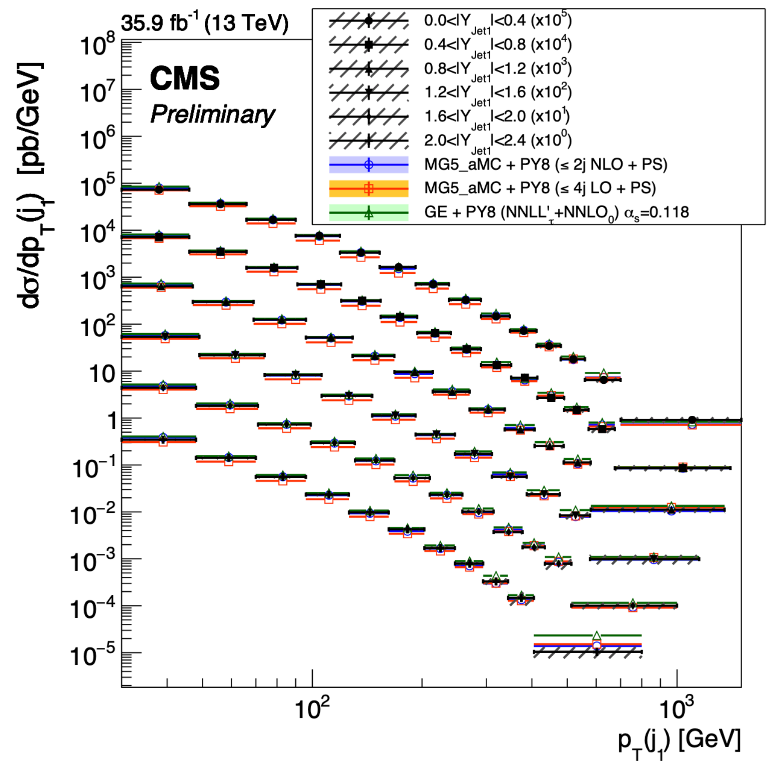
Multi-differential Z+jets cross sections at 13 TeV

SMP-19-009

Predictions:

- Madgraph5 NLO (Labeled NLO MG 5 aMC)
- Madgraph5 LO (Labeled LO MG 5 aMC)
- GENEVA (NNLO + NNLL resummation)





- All the predictions are in agreement with data.
- The NLO prediction provides a better description than LO and GENEVA for double differential cross sections.

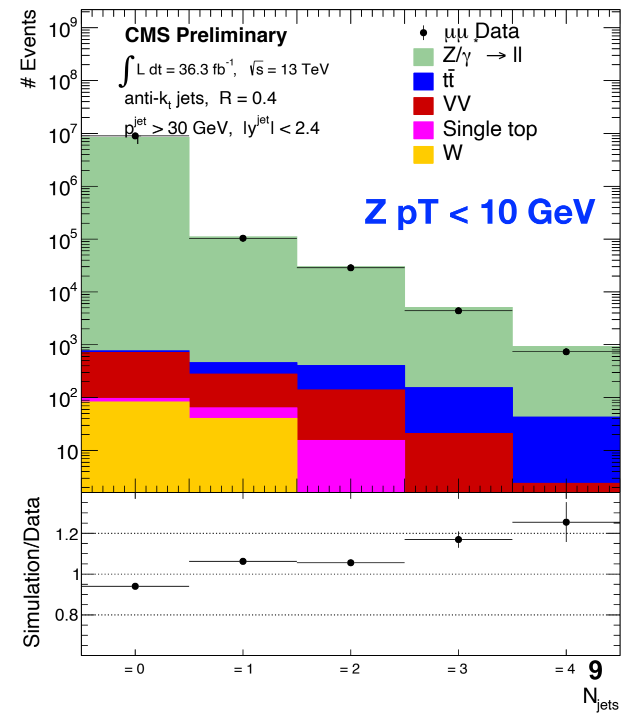
Azimuthal correlations in Z+jets at 13 TeV

SMP-21-003

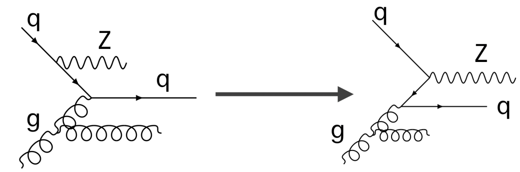
- Sensitive to higher-order corrections and soft gluon resummation.
- At small ZpT, soft-gluon resummations and nonperturbative contributions are essential.
- At high Z pT, Z+jet production is dominant with significant corrections coming from QCD processes.
- Interest in Parton Branching (PB) predictions: (**more in Armando's talk**)
  - PB method was very successful describing inclusive DY pT spectrum
  - Transverse Momentum Dependent parton distribution(TMD) and corresponding TMD parton shower are tied together, no extra free parameters.

Measured observables:

- Jet multiplicity in pT(Z) bins
- Azimuthal correlation between Z and leading jet in pT(Z) bins
- Azimuthal correlation between two leading jet in pT(Z) bins



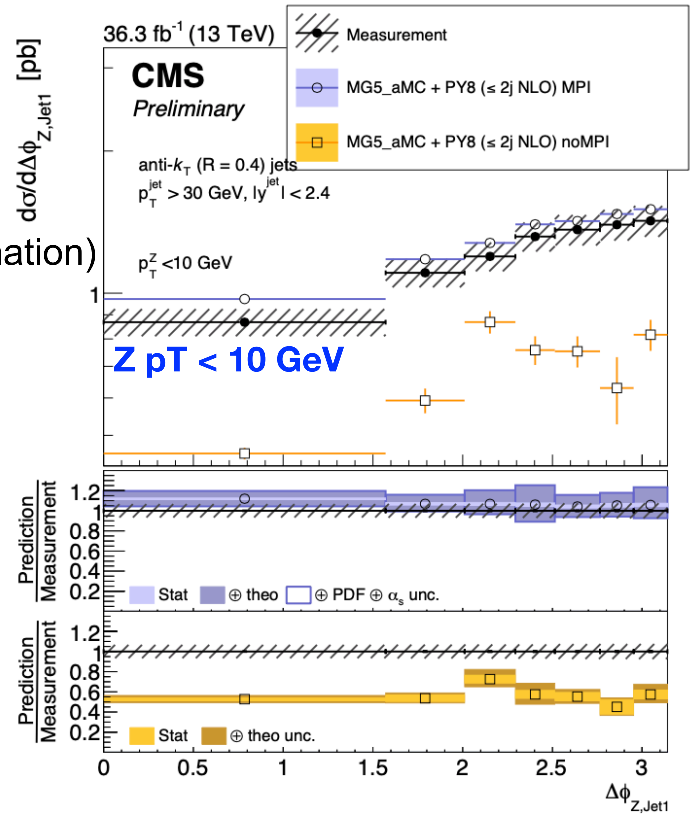
Azimuthal correlations in Z+jets at 13 TeV

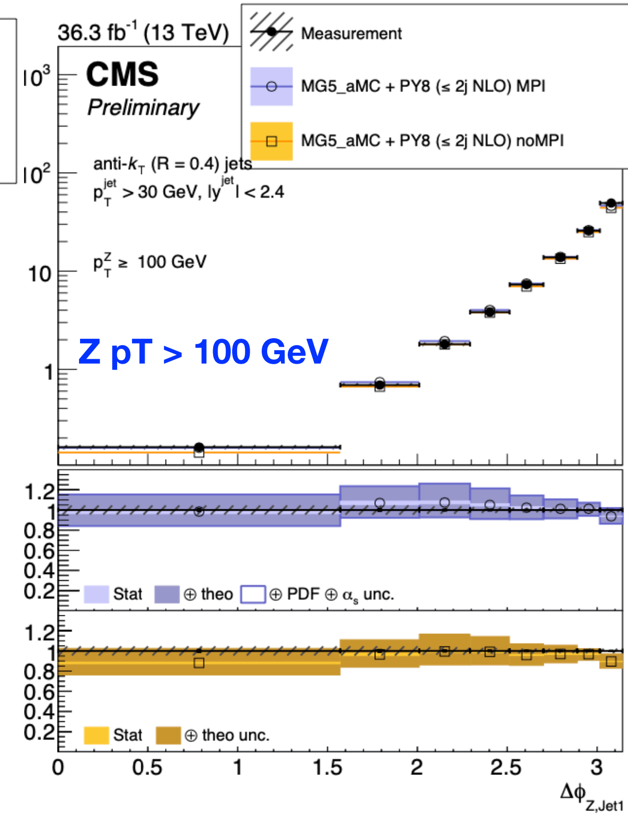


SMP-21-003

Predictions:

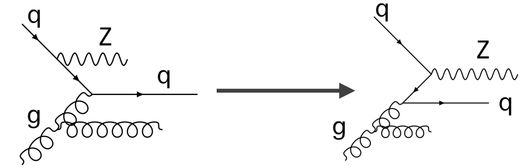
- Madgraph5 NLO MPI
- Madgraph5 NLO noMPI
- GENEVA (NNLO + NNLL resummation)
- MCatNLO-CA3 (Z+1) NLO
- MCatNLO-CA3 (Z+2) NLO





- Good agreement between data and the MG5_aMC NLO PY8 is observed.
- In the low pT(Z) region, the Z boson is only weakly correlated with the leading jet, and the distribution is flat.
- In the large pT(Z) region, Z boson is highly correlated with the leading jet, and peaks in the back-to-back region.
- The contribution from MPI is about 40% for low pT(Z) region, as shown with MG5aMC no MPI

Azimuthal correlations in Z+jets at 13 TeV



SMP-21-003

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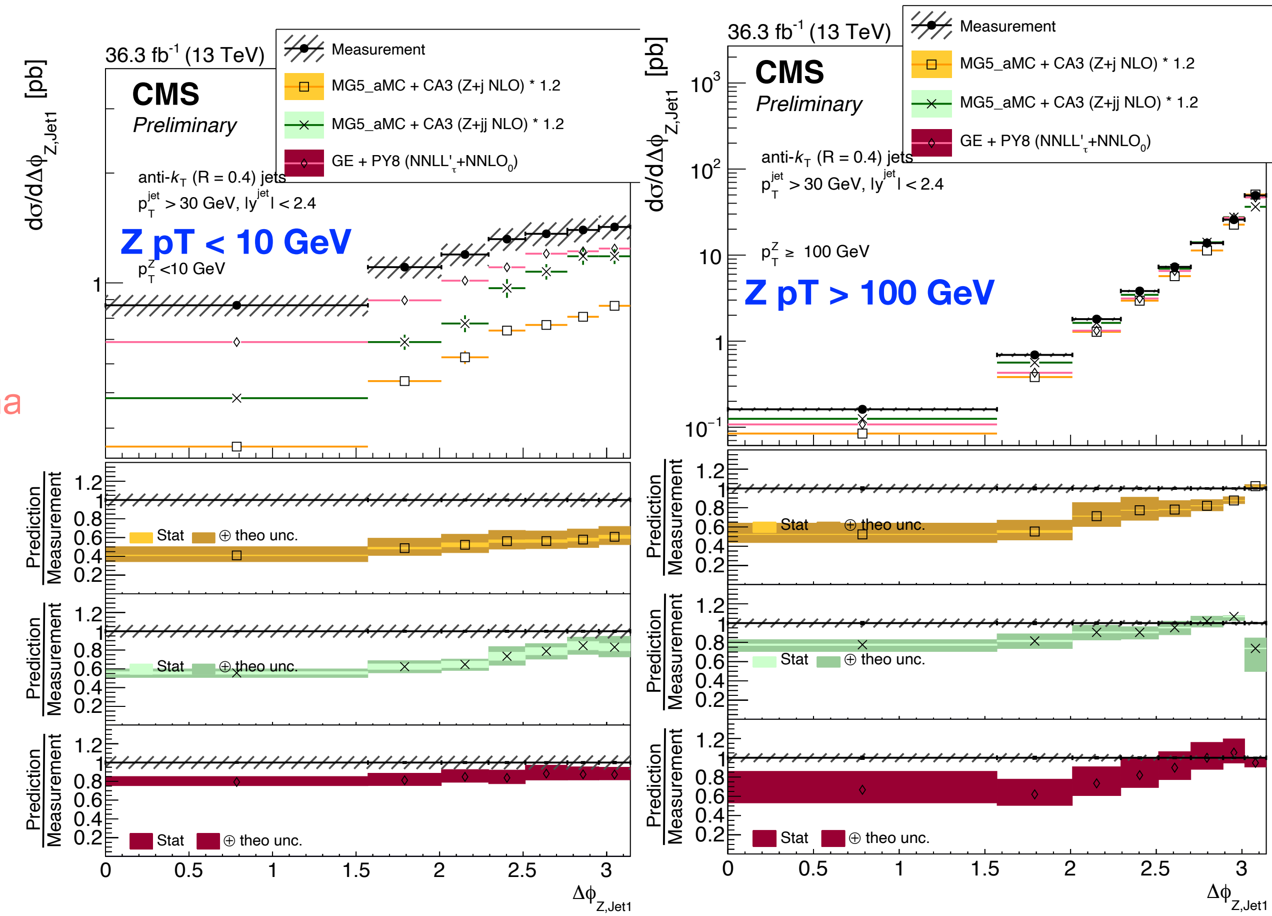


- The contribution from higher order matrix elements become important as seen from the comparison with MG5aMC + CA3 (Z+2) NLO.
- One could see the missing MPI contribution in MG5aMC+CA3 (Z+1) NLO predict, when compared to GENEVA NNLO including MPI at low pT (Z).

Summary

- Wide range V+jets results
  - First direct measurement of invisible Z width at a hadron collider.
  - Multi-differential Drell-Yan production cross section measurements
  - NLO modelling doing well with Z/γ+jets
  - At low Z pT, the jet production is the dominant process for Z+jets process, and the Z boson could be seen as a higher order EW correction.
  - The prediction using PB-TMDs come close to the measuements, with the parameters of the initial state parton shower fixed by TMD.

More results will come in the near future.

Thanks a lot for your attention!

Thank you

Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

- Goal: turns generic jets+MET dark matter search on its head to make precise measurement of Z invisible width.
- Z invisible width extracted from ratio of experimentally measured cross sections of Z(νν)+jets to Z($\ell\ell$)+jets and LEP measured partial width for Z->$\ell\ell$.

$$\boxed{\Gamma(\mathrm{Z} \to \nu\bar{\nu}) = \frac{\sigma(\mathrm{Z}+\mathrm{jets})\mathcal{B}(\mathrm{Z} \to \nu\bar{\nu})}{\sigma(\mathrm{Z}+\mathrm{jets})\mathcal{B}(\mathrm{Z} \to \ell\ell)}\Gamma(\mathrm{Z} \to \ell\ell)}$$

- Using 36.3 fb-1 of 13 TeV data
  - Jets+MET topology to select Z->νν events
  - μμ+jets and ee+jets to select Z->$\ell\ell$ events
  - μν+jets, eν+jets and τ_h ν+jets for W+jets
- Backgrounds:
  - W+jets events, estimated using data driven approach and ℓ+jets control regions.
  - QCD background is estimated using data driven.
  - Contribution from γ*—>$\ell\ell$ and interference between γ*—>$\ell\ell$ and Z->$\ell\ell$ is evaluated.

Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

Baseline

MET filters
$p_T^{miss} > 200$ GeV
$|p_{T,PF}^{miss} - p_{T,Calo.}^{miss}|/p_T^{miss} < 0.5$
Lead jet $p_T > 200$ GeV and $|\eta| < 2.4$ and $0.1 <$ Ch. Had. EF < 0.95
Veto jets $p_T > 40$ GeV and $|\eta| \geq 2.4$
Loose photon veto $p_T > 25$ GeV and $|\eta| < 2.5$
Medium CSVV2 b-jet veto $p_T > 40$ GeV and $|\eta| < 2.4$

Jets+MET

Baseline
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Double Muon

Baseline
2 medium muons $p_T > 25$ GeV and $|\eta| < 2.4$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$71 < M_{\mu\mu} < 111$ GeV
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Double Electron

Baseline
2 medium electrons $p_T > 30$ GeV and $|\eta| < 2.4$
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$71 < M_{ee} < 111$ GeV
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Single Muon

Baseline
1 medium muon $p_T > 25$ GeV and $|\eta| < 2.4$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$30 \leq M_T(\mu, p_{T,PF}^{miss}) < 125$ GeV
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Single Electron

Baseline
1 medium electron $p_T > 30$ GeV and $|\eta| < 2.4$
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$p_{T,PF}^{miss} > 100$ GeV
$30 \leq M_T(e, p_{T,PF}^{miss}) < 125$ GeV
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

Single Tau

Baseline
1 tight tau $p_T > 40$ GeV and $|\eta| < 2.3$
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] > 0.5$

QCD sideband

Baseline
Loose muon veto $p_T > 10$ GeV and $|\eta| < 2.5$
Veto electron veto $p_T > 10$ GeV and $|\eta| < 2.5$
Very loose tau veto $p_T > 20$ GeV and $|\eta| < 2.3$
$\min[\Delta\phi(j_{1,2,3,4}, p_T^{miss})] \leq 0.5$

5

Precision measurement of the Z invisible width at 13 TeV

SMP-18-014

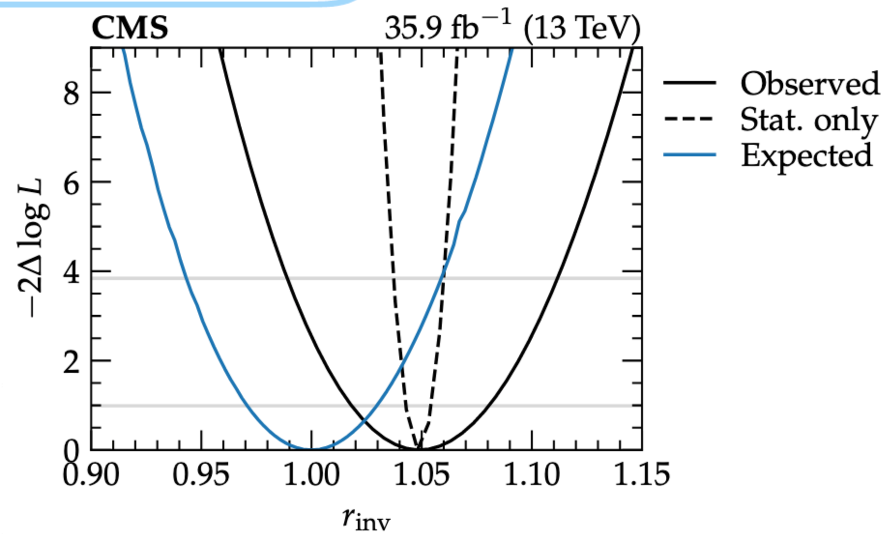
- Invisible width extracted from simultaneous likelihood fit to the jets+MET, $\ell\ell$+jets, ℓ+jets regions

$$\mathcal{L}(n_j, n_\ell, n_{\ell\ell} | r, r_Z, r_W, \boldsymbol{\theta}) =$$
$$\text{Poisson}\left(n_j \,\middle|\, r \cdot r_Z \cdot s_{Z,j}(\boldsymbol{\theta}) + r_W \cdot b_{j,W}(\boldsymbol{\theta}) + b_{\text{bkg.},j}(\boldsymbol{\theta})\right) \quad \text{Jets+MET}$$
$$\text{Poisson}\left(n_\ell \,\middle|\, r_W \cdot b_{\ell,W}(\boldsymbol{\theta}) + b_{\text{bkg.},\ell}(\boldsymbol{\theta})\right) \quad \text{Single lepton}$$
$$\text{Poisson}\left(n_{\ell\ell} \,\middle|\, r_Z \cdot s_{Z,\ell\ell}(\boldsymbol{\theta}) + \sqrt{r_Z} \cdot s_{\text{int.},\ell\ell} + s_{\gamma^*,\ell\ell}(\boldsymbol{\theta}) + b_{\text{bkg.},\ell\ell}(\boldsymbol{\theta})\right) \quad \text{Double lepton}$$
$$\cdot\, p(\tilde{\boldsymbol{\theta}}, \boldsymbol{\theta})$$

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z+\text{jets}) \cdot B(Z \to \nu\bar{\nu})}{\sigma(Z+\text{jets}) \cdot B(Z \to \ell\ell)} \Gamma(Z \to \ell\ell)$$
$$= \frac{\varepsilon_{\ell\ell}\mathcal{A}_{\ell\ell}}{\varepsilon_{\nu\nu}\mathcal{A}_{\nu\nu}} \frac{r \cdot r_Z \cdot s_{Z,j}(\boldsymbol{\theta})}{r_Z \cdot s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma(Z \to \ell\ell)$$
$$= r \frac{\varepsilon_{\ell\ell}\mathcal{A}_{\ell\ell}}{\varepsilon_{\nu\nu}\mathcal{A}_{\nu\nu}} \frac{s_{Z,j}(\boldsymbol{\theta})}{s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma(Z \to \ell\ell).$$

$$\Gamma_{\text{MC}}(Z \to \nu\bar{\nu}) = \frac{\varepsilon_{\ell\ell}\mathcal{A}_{\ell\ell}}{\varepsilon_{\nu\nu}\mathcal{A}_{\nu\nu}} \frac{s_{Z,j}(\boldsymbol{\theta})}{s_{Z,\ell\ell}(\boldsymbol{\theta})} \Gamma_{\text{MC}}(Z \to \ell\ell)$$

$$r_{\text{inv}} \equiv r = \frac{\Gamma(Z \to \text{inv})}{\Gamma_{\text{MC}}(Z \to \text{inv})}$$



$$r_{\text{inv}} = 1.052 \pm 0.006(\text{stat})^{+0.032}_{-0.031}(\text{syst})$$

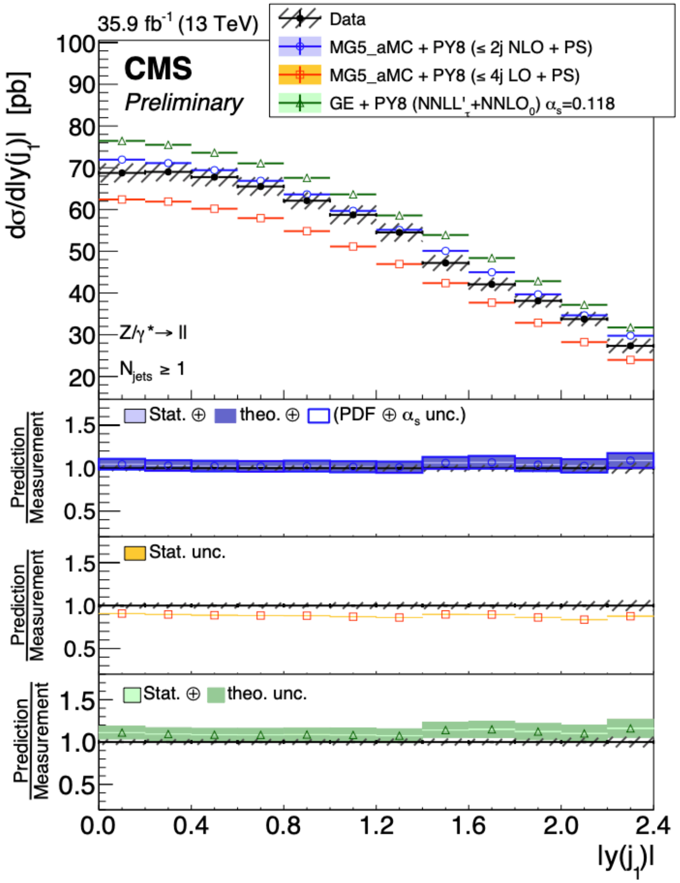
Using input Z width of 510 MeV:

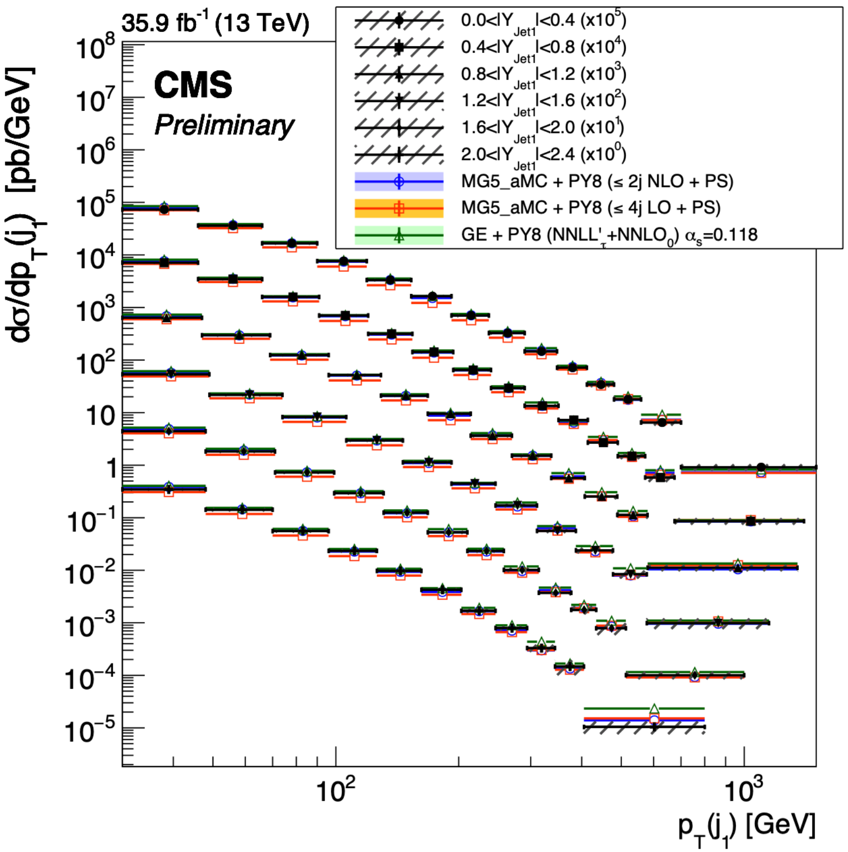
$$\Gamma_{\text{inv}} = 523 \pm 3\,(\text{stat}) \pm 16\,(\text{syst})\,\text{MeV}$$

Multi-differential Z+jets cross sections at 13 TeV

SMP-19-009

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





Multi-differential Z+jets cross sections at 13 TeV

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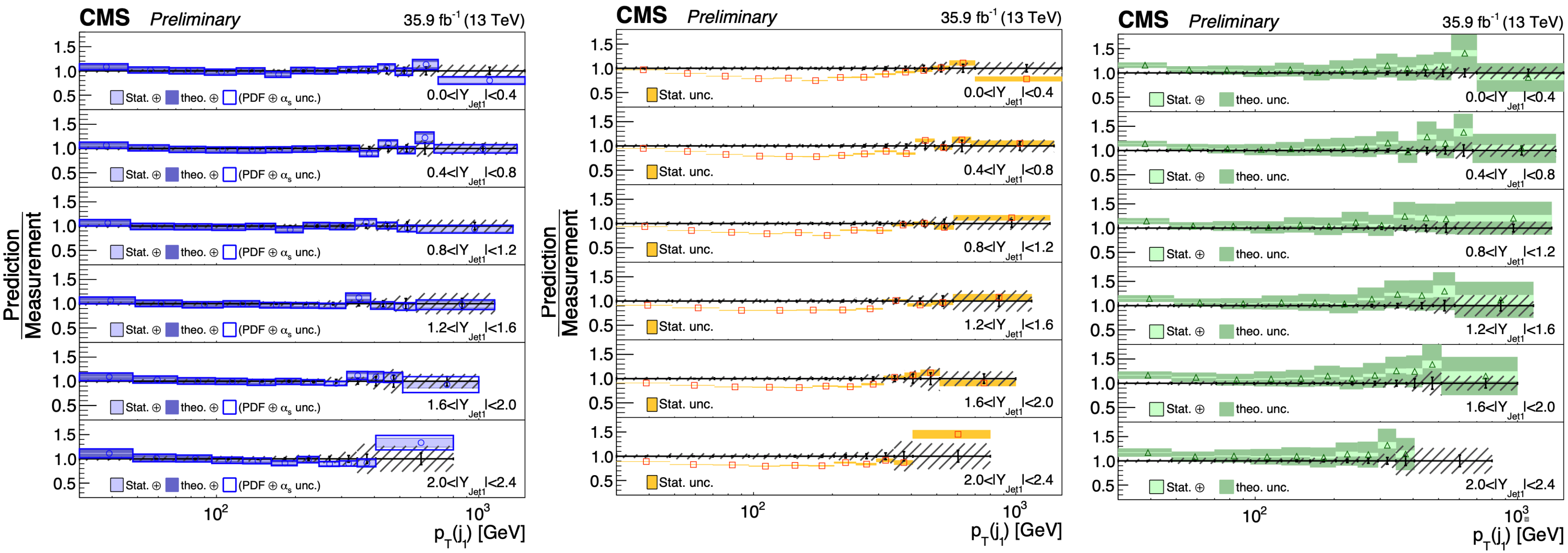
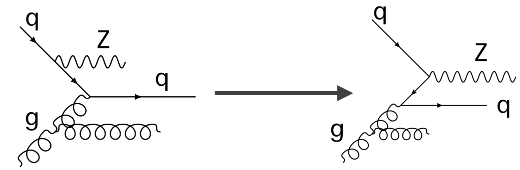
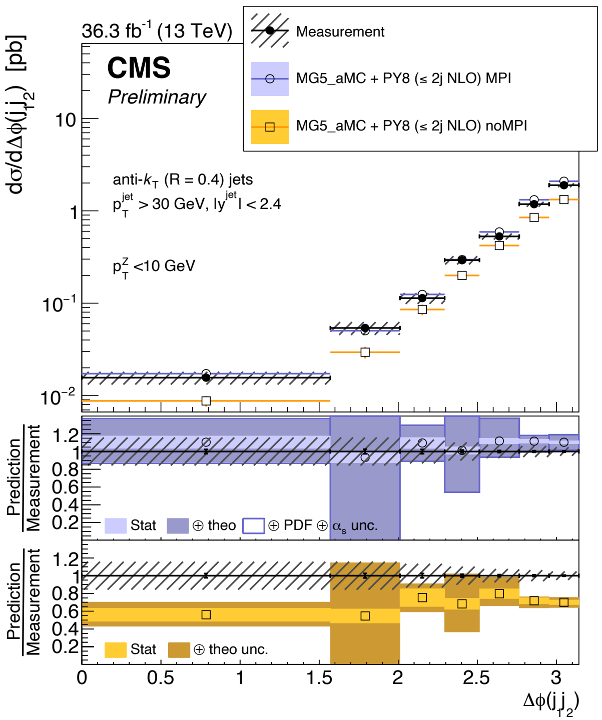


- All the predictions are in agreement with data.
- The NLO prediction provides a better description than LO and GENEVA for double differential cross sections.

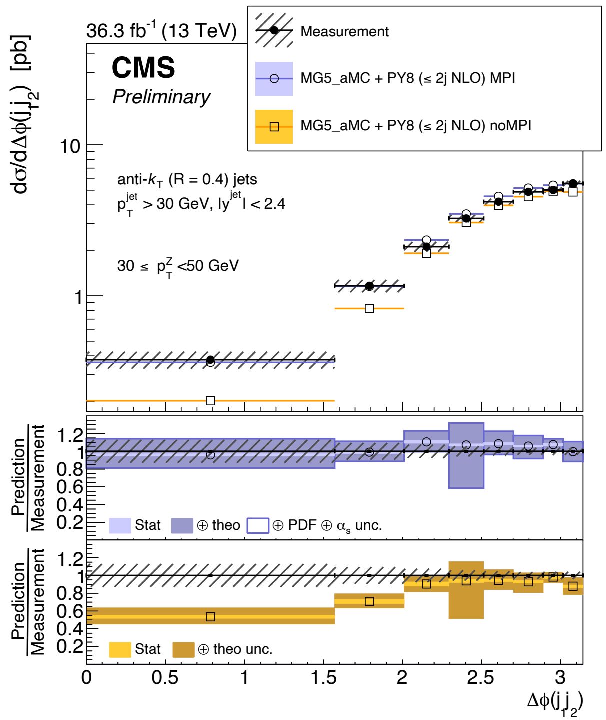
Results-dPhi(jet1, jet2)



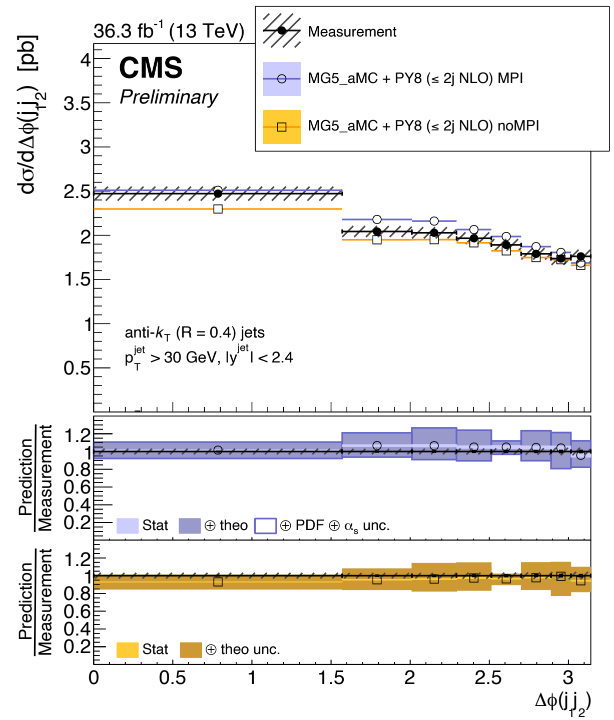
Z pT < 10 GeV



Z pT (30, 50) GeV

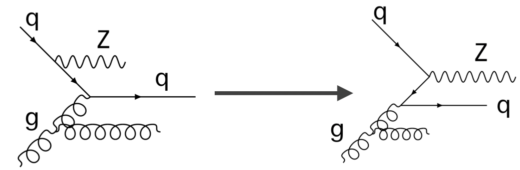


Z pT > 100 GeV

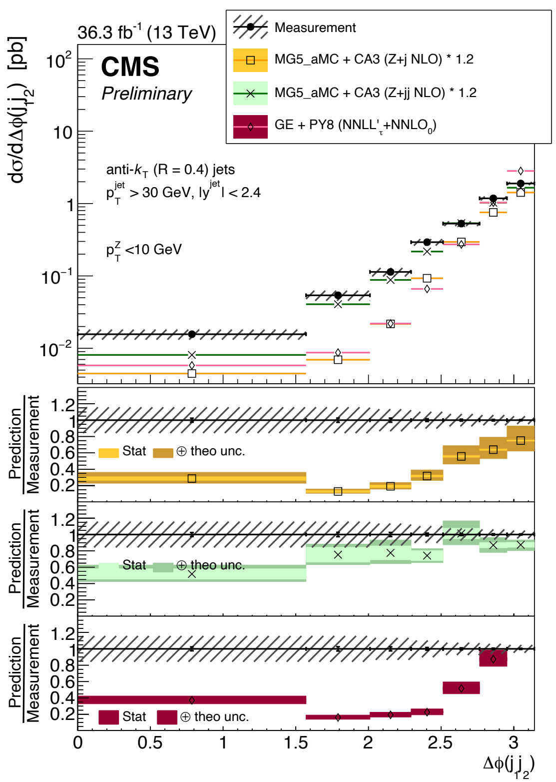


- A strong correlation between the two leading jets is observed at small Z pT, indicating that at low Z pT the process is dominated by jet production and the Z boson is radiated as a higher order EW correction.
- At large Z pT the process is dominated by Z+jet production, with higher order QCD corrections in form of additional jets.
- The contribution from MPI is significant especially at small Z pT, and small dPhi(j1,j2).

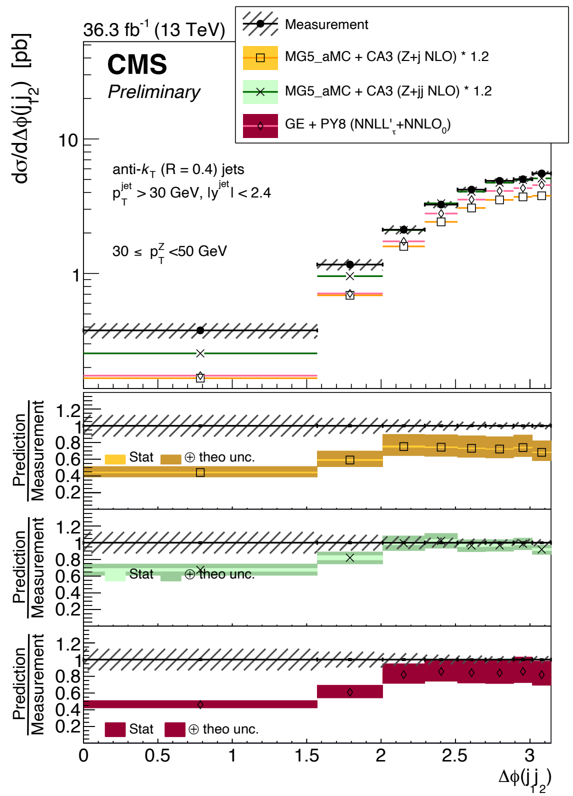
Results-dPhi(jet1, jet2)



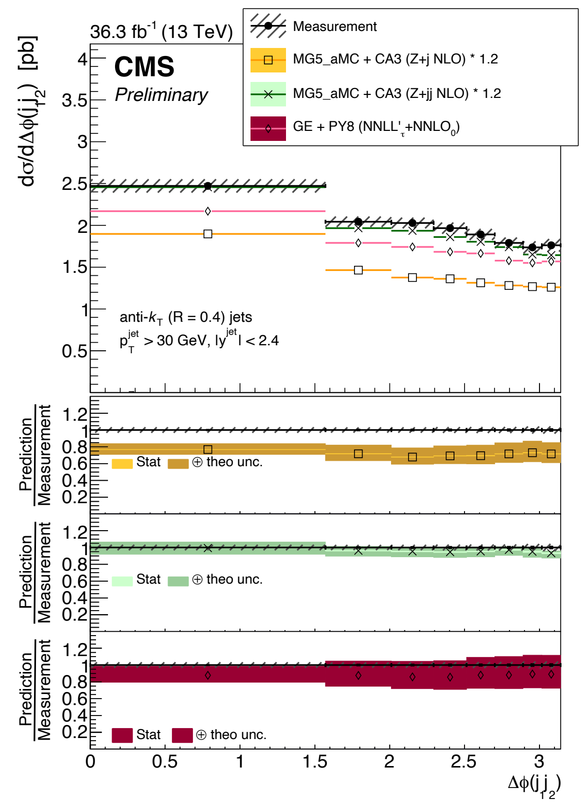
Z pT < 10 GeV



Z pT (30, 50) GeV



Z pT > 100 GeV



- At larger dPhi (j1, j2) region, the measurement is reasonably well described by MG5aMC + CA3 (Z+2) NLO , while it falls at lower dPhi region presumably because of missing MPI contribution.
- The GENEVA NNLO prediction is below the measurement, and it is similar to MG5aMC+CA3 (Z+1) NLO predict prediction.