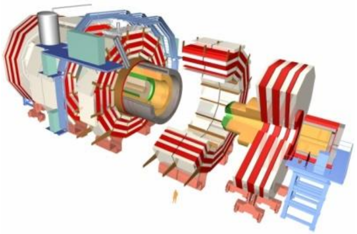


Vector boson production in association with jets from CMS

Fengwangdong Zhang

on behalf of CMS collaboration

Peking University & Université Libre de Bruxelles

2nd CLHCP Workshop

Beijing, China

2016/12/17 – 2016/12/19

Outline

- ➢ Standard Model Public Results from CMS
http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

- Many experimental results on V+jets subjects, here only focus on：

- ➢ 8 TeV (Lumi = 19.6 ~ 19.8 fb^{-1}, BX = 50 ns, average pileup = 20):
  - Z boson + jets
  - W boson + jets
  - Photon (γ) + jets
  - W/Z boson + heavy flavor quark jets
    - W boson + b quark jets
    - Z boson + c/b quark jets

◆Data taken during 2012 (RunI)

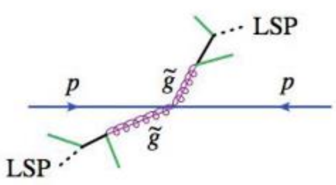
Motivations on V+jets physics

- One can probe different aspects of perturbative QCD with V+jets processes

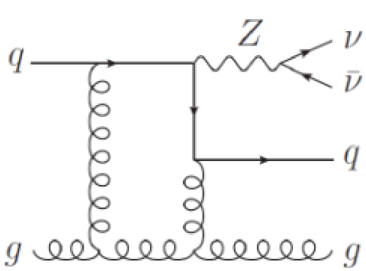
- Precise understanding and modeling of QCD interactions is crucial for LHC discovery potential and precision measurements:
  - W/Z+jets is a dominant background for:
    - Top-quark measurements
    - Precision measurement of Higgs physics in VH(->bb) channel
  - It is important for the modeling of the production mechanism involved in new physics searches (e.g. Supersymmetry)

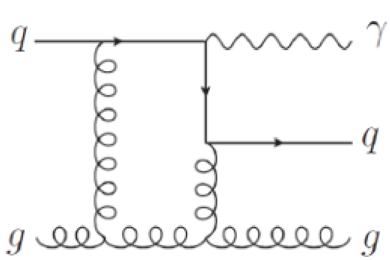
- Z+jets as background to new physics searches:
  - Z(->νν)+jets in SUSY (MET+jets) searches
  - Exploit NLO computations of W+jets/Z(->νν)+jets or γ+jets/Z(->νν)+jets ratios to calculate the transfer functions from W/γ+jets to Z(->νν)+jets
    - ✓ important to constrain theory extrapolation with data

MET+ 4 jets



JHEP 10 (2012) 018
PRD 90, 052008 (2014)
arXiv:1405.7875





$$\sigma(pp \to \underset{\substack{\uparrow \\ \text{irreducible background}}}{Z}(\to \nu\bar{\nu}) + \text{jets}) = \sigma(pp \to \underset{\substack{\uparrow \\ \text{measure this}}}{\gamma} + \text{jets}) \times \underset{\substack{\uparrow \\ \text{theory input}}}{R_{Z/\gamma}}$$

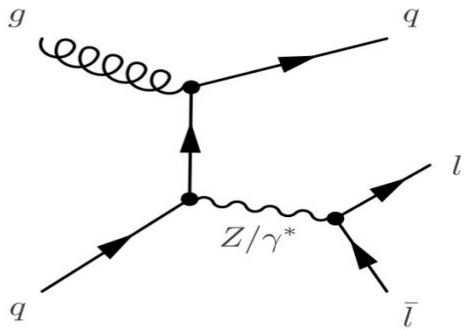
The strategy of V+jets analyses

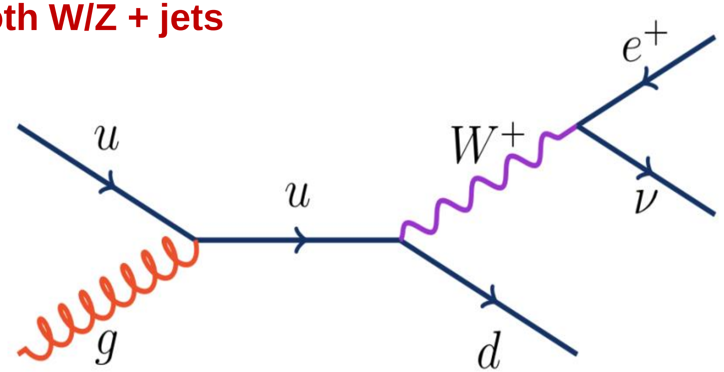
- W/Z bosons are reconstructed through their leptonic decays
  - Muons and electrons are reconstructed using Particle Flow algorithm based on the information from detector subsystems
  - Neutrinos are identified using missing transverse momentum
- Jets are defined with the anti-kt algorithm using size R = 0.5
  - Jets are reconstructed using Particle Flow algorithm
  - Jets are separated from the W/Z boson decay leptons (R > 0.5)
  - Pileup subtraction is implemented in the isolation definition of the jets
  - Heavy flavor (c/b) jets are tagged for the dedicated analyses

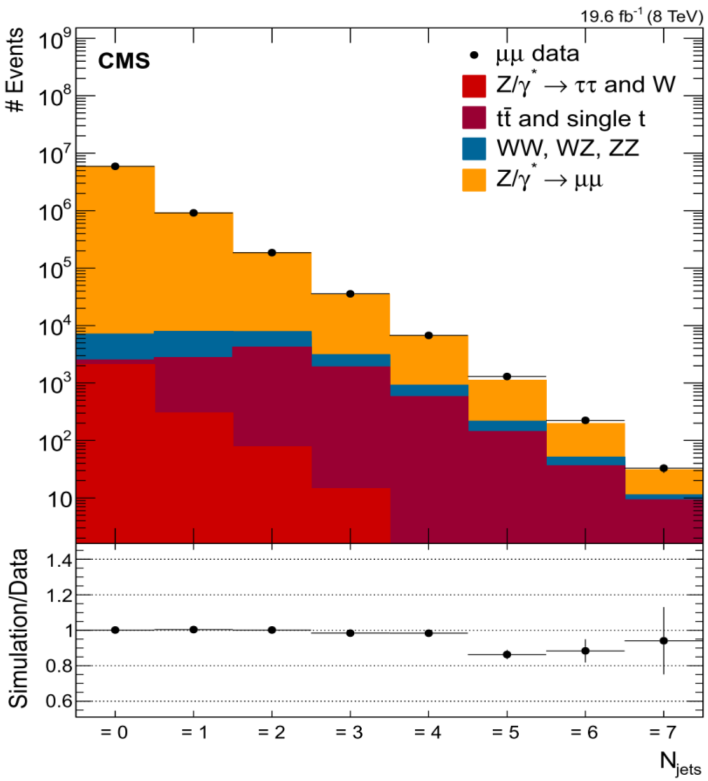
- Restrict the measurement phase space for a good acceptance
- Use Monte Carlo methodology to correct for detector effects on the signal extracted from data
- Compare the unfolded data (measurement) with different theoretical predictions of cross sections at particle level, including the differential cross section as a function of various observables
  - Compared theoretical predictions can be at different accuracy levels

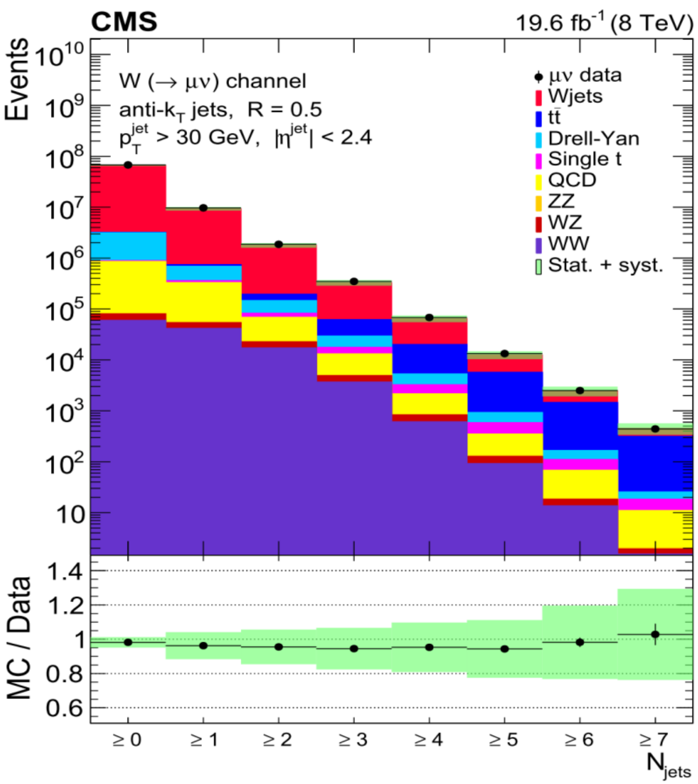
Data statistics for W/Z +jets measurement

- Measured differential cross section as a function of several observables
- Significant statistics up to large jet multiplicity for both W/Z + jets



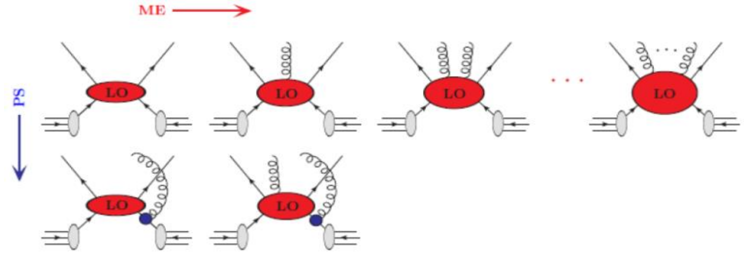




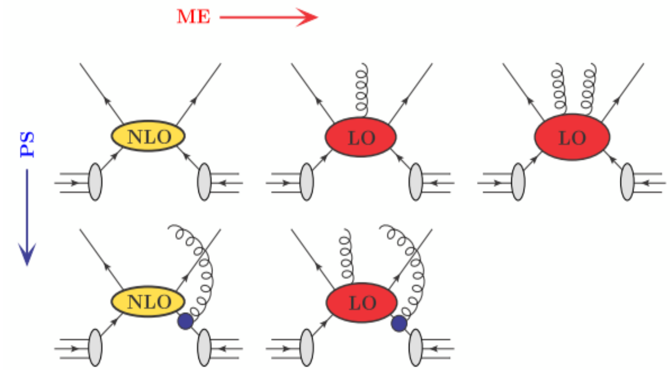


Theoretical predictions for W/Z + jets cross section comparison

- ➢ **MADGRAPH5 + PYTHIA6**
- LO matrix element up to 4 partons in final state
- kt-MLM merging
- CTEQ6L1 PDF

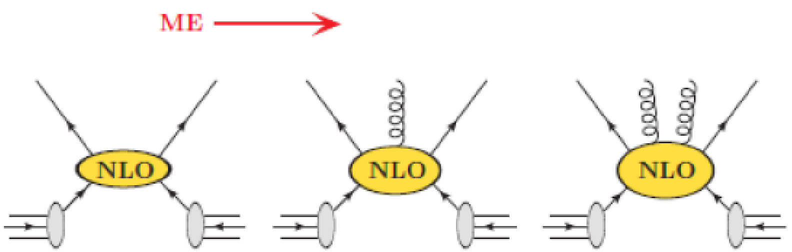


- ➢ **MADGRAPH5_AMC@NLO + PYTHIA8**
- NLO matrix element up to two partons, LO accuracy for 3 partons
- FxFx jet merging, NNPDF3.0 NLO PDF , CUETP8M1 PYTHIA8 tune



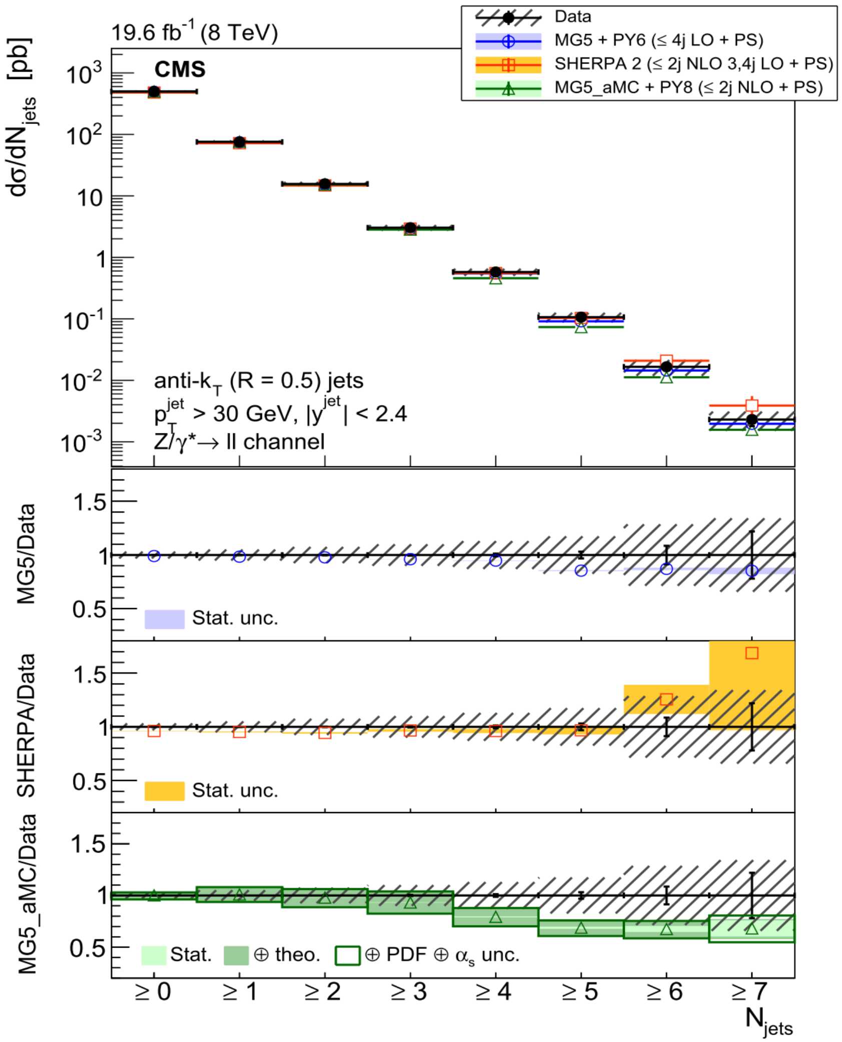
- ➢ **SHERPA + BLACKHAT**
- NLO accuracy up to two partons, LO accuracy for 3~4 partons
- MEPS@NLO merging, CT10 PDF

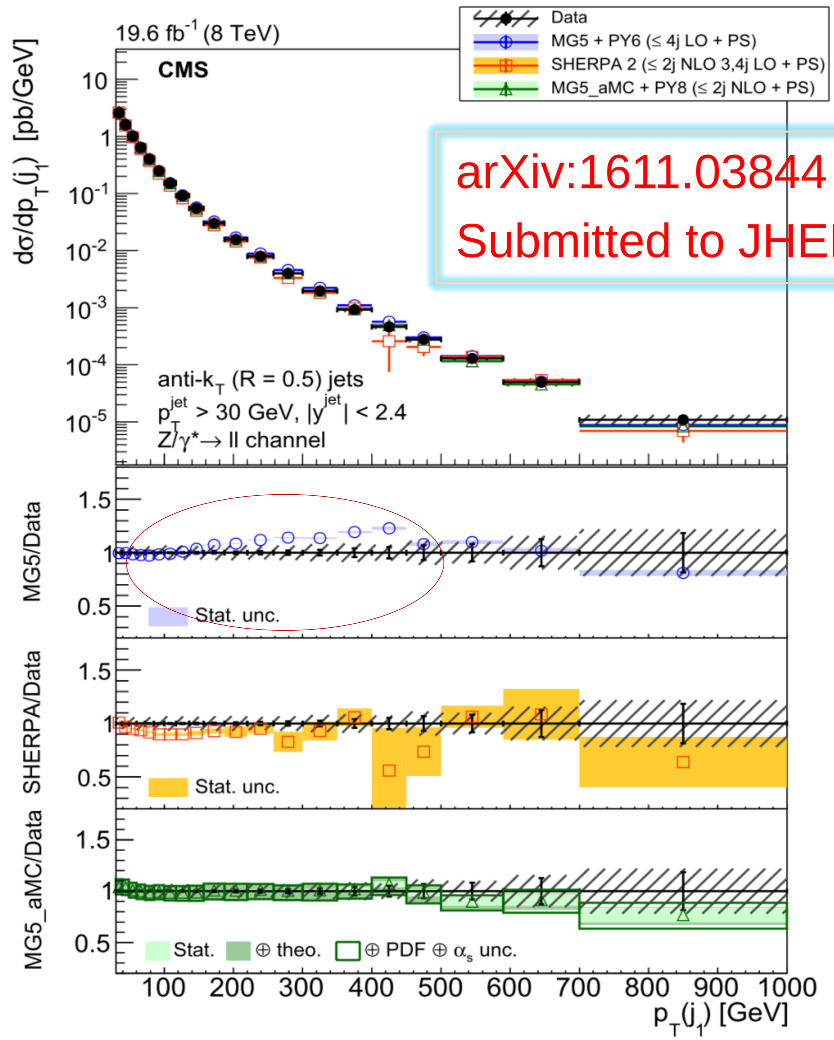
- ➢ **BLACKHAT + SHERPA**
- NLO W + n jet(s) with fixed order (n = 1~4)
- CT10 PDF set
- Correction for hadronization and multiple parton interactions



- ➢ **N-jettiness NNLO (W+1jet fixed order)**
- Correction for hadronization and multiple parton interactions using MG5+PYTHIA6
- CT14 NNLO PDF set
- Reference: PRL.115.062002; arXiv:1602.06965

Z + jets differential cross section results





arXiv:1611.03844

Submitted to JHEP

- Good agreement with SHERPA (NLO)
- MG5_aMC+PY8 differs at large jet multiplicities due to limited number of partons in matrix element calculation (only relying on parton shower)
- Discrepancy with LO computation has disappeared with NLO calculation for leading jet p_T

Rapidity correlation measurement of Z + jets

- The measurement of jet angular correlation of Z+Jets can help understand QCD process much more accurately

$$y_{sum} = \frac{|y_Z + y_{jet}|}{2}$$

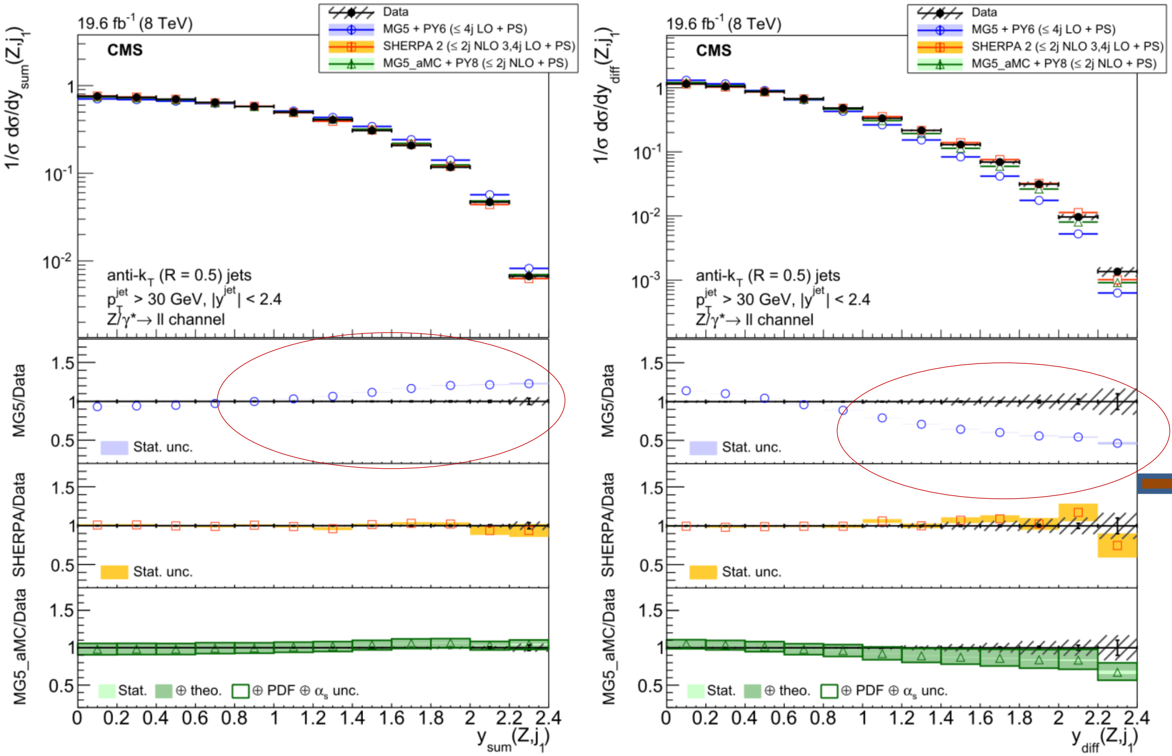
- Depends mainly on parton density functions

$$y_{diff} = \frac{|y_Z - y_{jet}|}{2}$$

- Reflects the leading order partonic differential cross section

arXiv:1611.03844

Submitted to JHEP

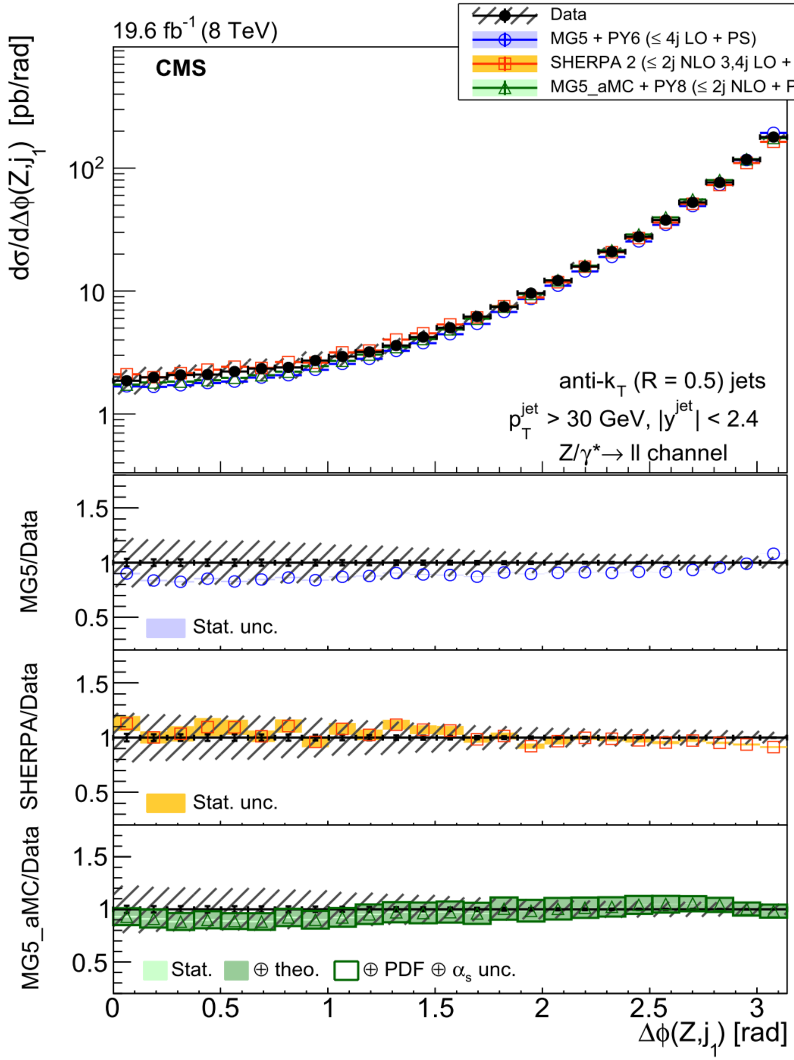


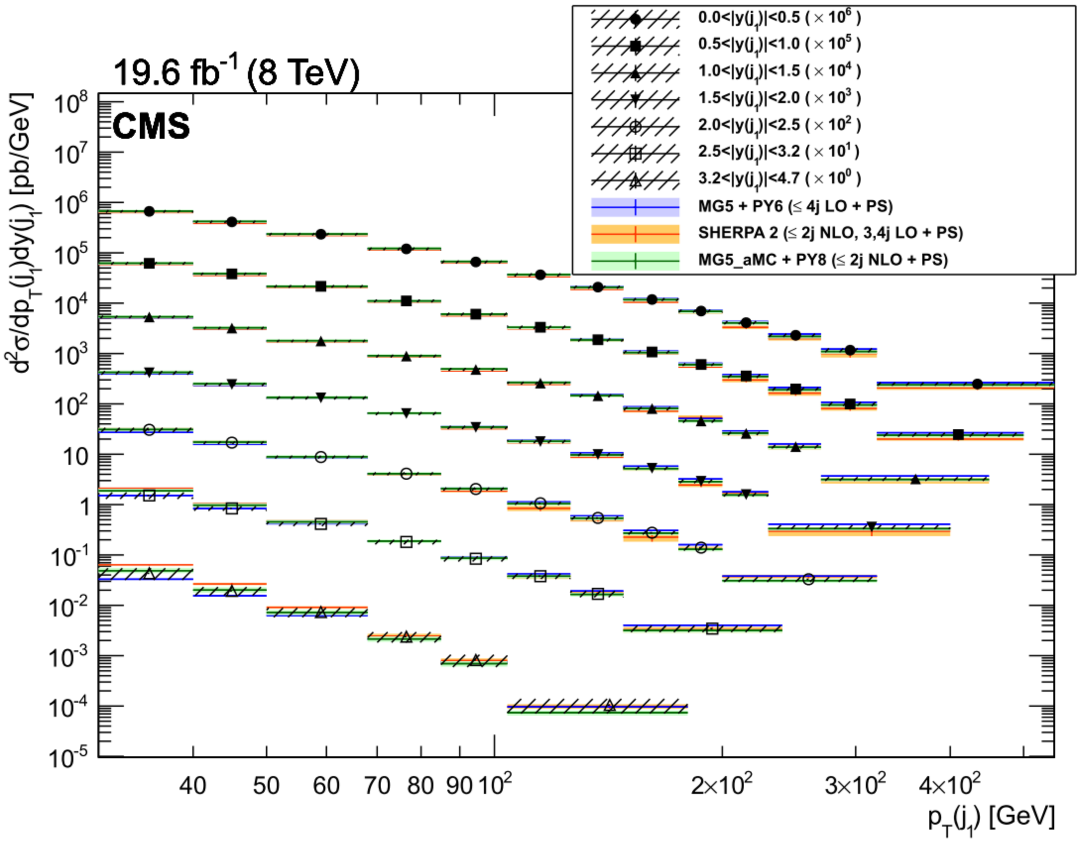
- LO calculation fails to describe the shape, confirms the observation at 7 TeV:
  - *10.1103/PhysRevD.88.112009*
- Discrepancy with LO computation has disappeared with NLO accuracy!

- The observed discrepancy of LO prediction helps us to analyze whether it comes from the matching procedure between matrix element and parton shower

Azimuthal correlation & Multidimensional cross section of Z + jets

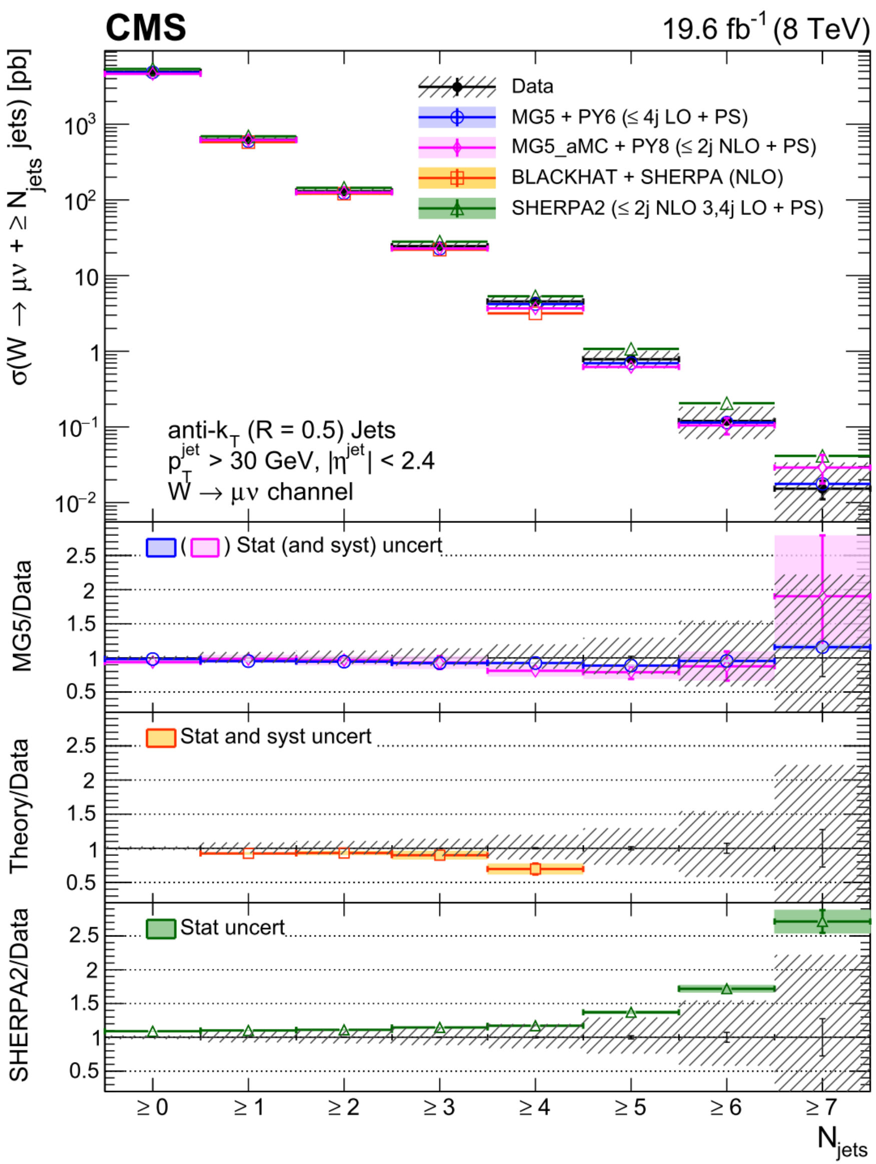
arXiv:1611.03844
Submitted to JHEP

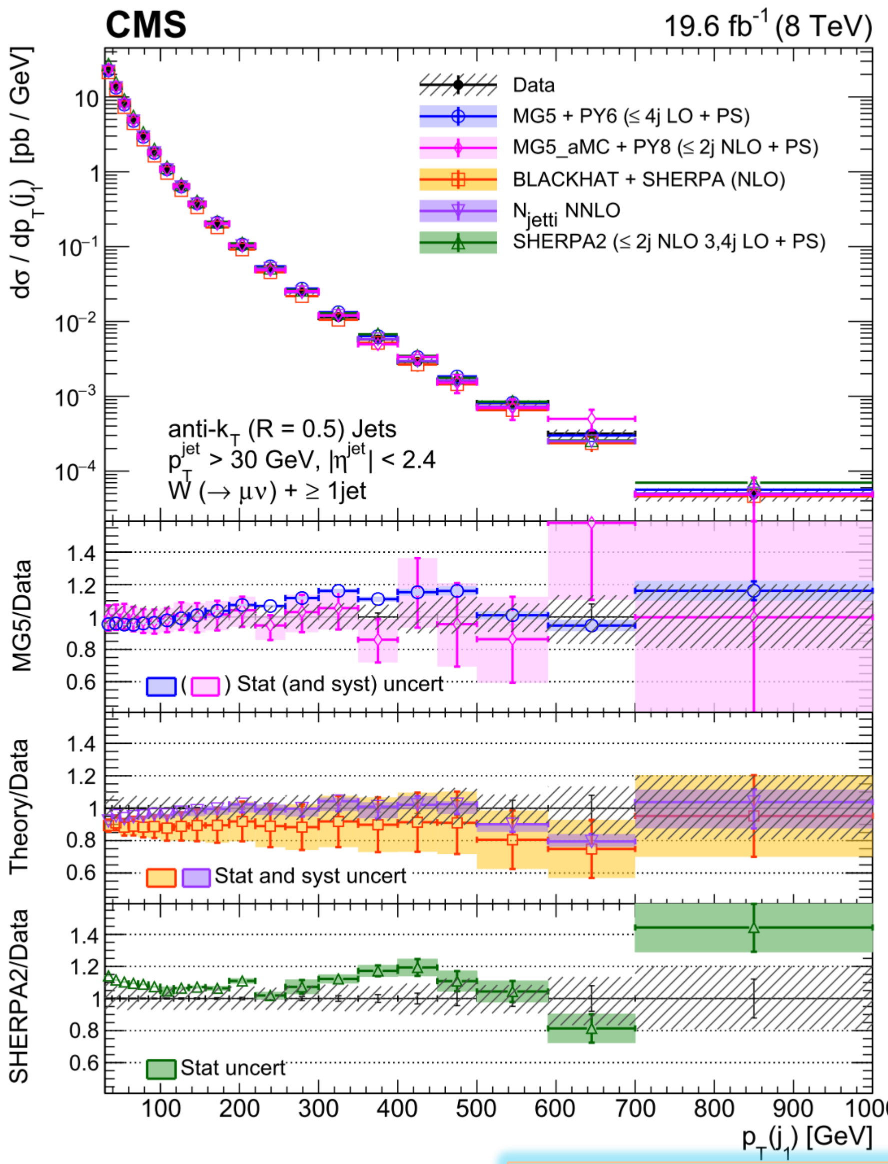




- No apparent discrepancy with LO and NLO predictions for the azimuthal correlation observables
- The multidimensional differential cross section with respect to jet p_T and rapidity is also measured precisely, good agreement with theoretical predictions

W + jets differential cross section results

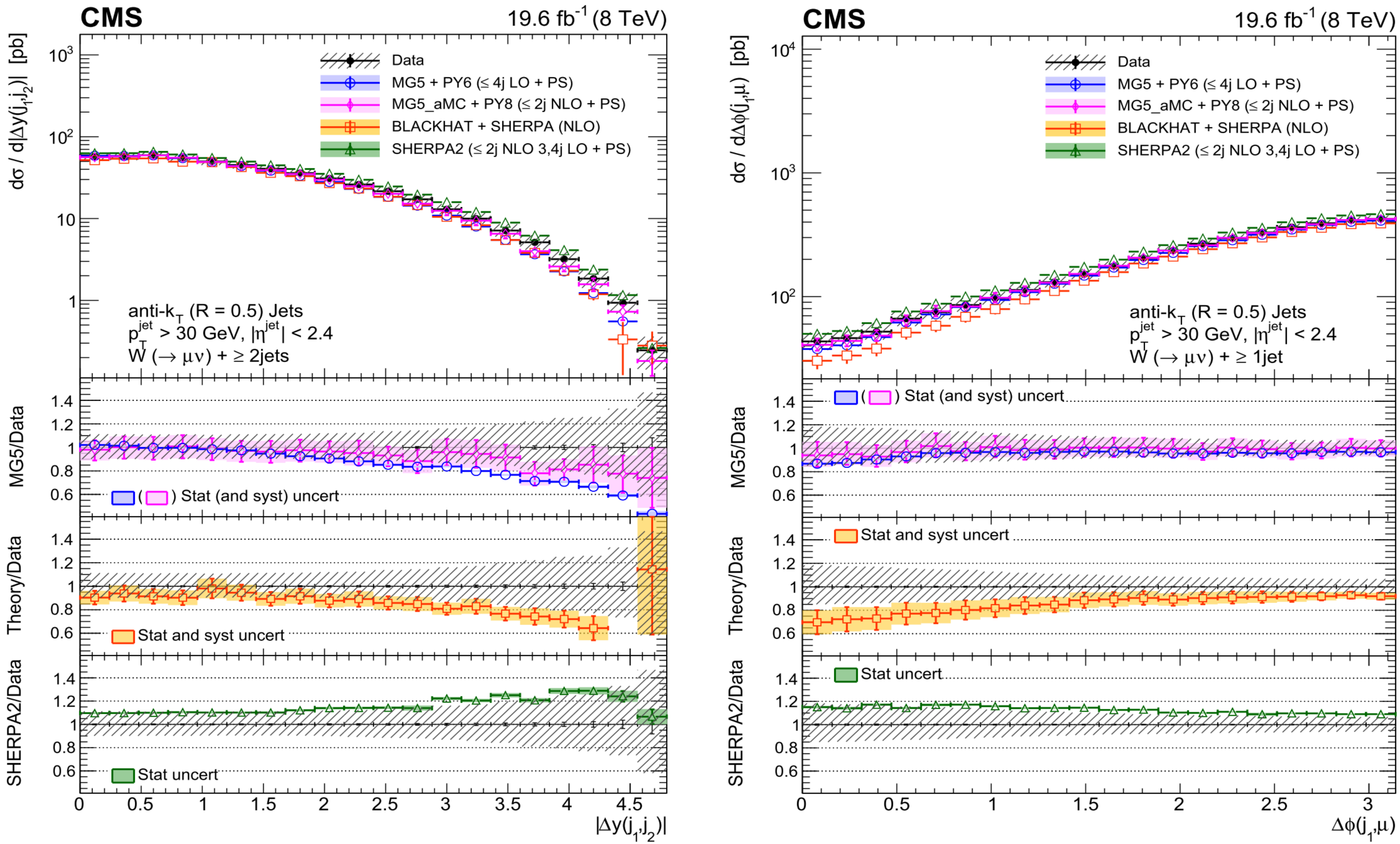




- Only the W(->μν) decay channel is measured
- Excellent agreement with MG5_aMC+PY8 and NNLO W+1J predictions

arXiv:1610.04222
Submitted to PRD

Angular correlation measurement of W+jets

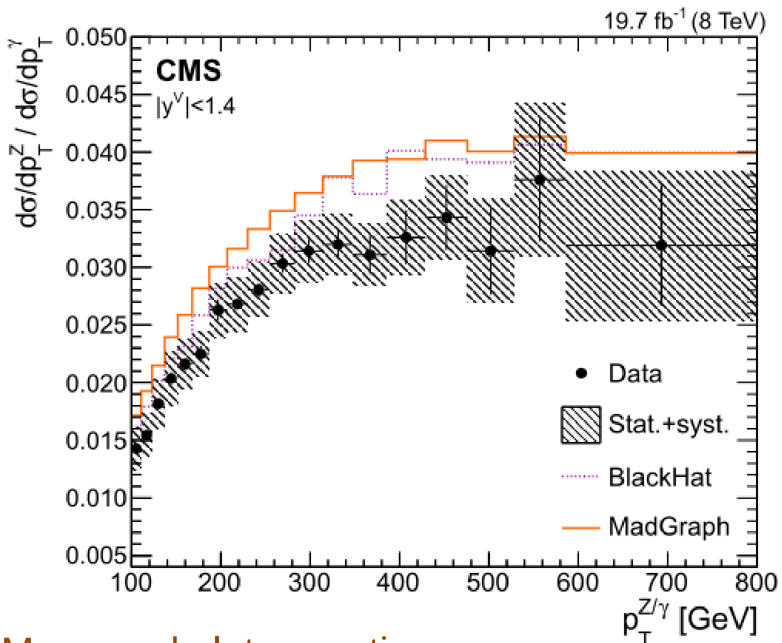


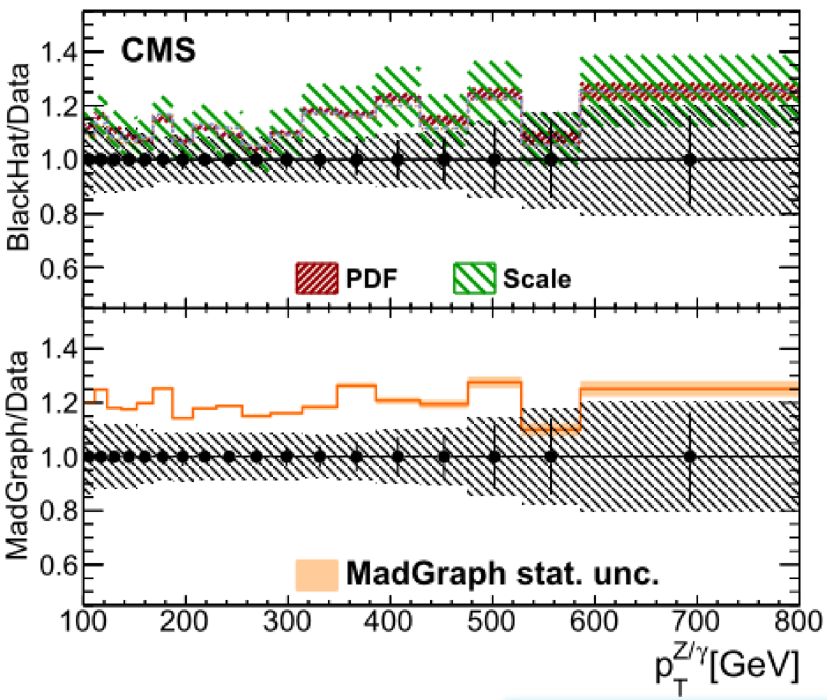
- Discrepancies at large rapidity difference between jets and in small azimuthal angle difference between muon and leading jet
- MG5_aMC+PY8 describes the measured angular correlations best

arXiv:1610.04222
Submitted to PRD

Z + jets & γ +jets cross section ratio

- Precise measurement of this ratio provides important information about the higher order effects of logarithmic corrections at higher transverse momentum
- It helps to reduce the systematical uncertainties corresponding to the Z(->vv)+jets background estimation in SUSY searches





- Measured plateau ratio:

$$R_{\mathrm{dilep}} = \frac{\sigma_{Z\to\ell^+\ell^-}(p_T^Z > 314\,\mathrm{GeV})}{\sigma_\gamma(p_T^\gamma > 314\,\mathrm{GeV})} = 0.0322 \pm 0.0008\,(\mathrm{stat}) \pm 0.0020\,(\mathrm{syst})$$

JHEP10(2015)128

- The observed ratio increases gradually and saturates around 300~350 GeV of p_T:
  - The main distinctions between two processes are mass difference and different coupling
- Both MadGraph (LO) and BlackHat (fixed NLO) reproduce the shape of distribution in general

W/Z + heavy flavor jets ($b/\bar{b}$) measurement

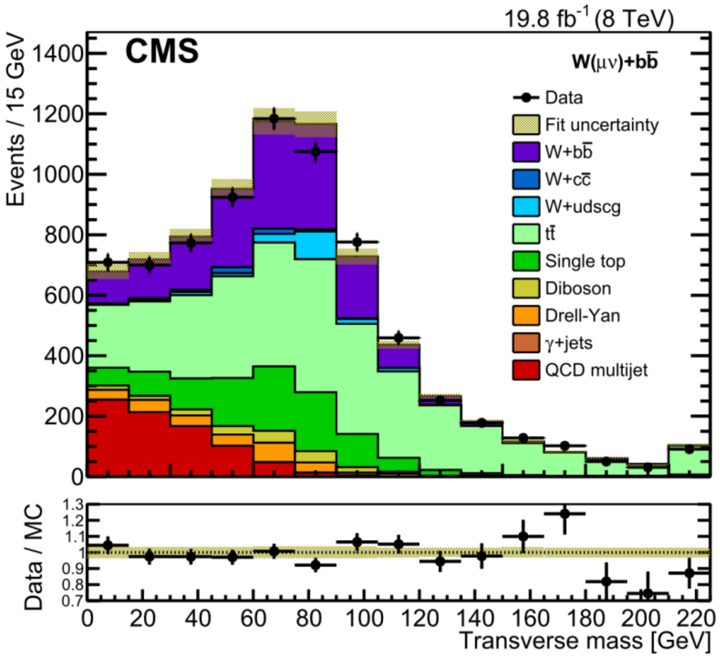
- Theoretical uncertainties on W/Z + heavy flavor jets larger than for light jets case
  - Heavy quark content in the proton
  - Modeling of gluon splitting (initial state or final state)
  - Massive or massless b quark in computations

- Important process for backgrounds of Higgs measurements

- Test of QCD predictions with various implementations (LO + Multipartons + parton shower, NLO, NLO+PS)

- Descriptions of "b-quark initiated processes:"
  - 4 flavors number scheme (4FS): b quark generated with gluon splitting
  - 5 flavors number scheme (5FS): b quark (massless) generated in the initial state

W+$b\bar{b}$ cross section measurement



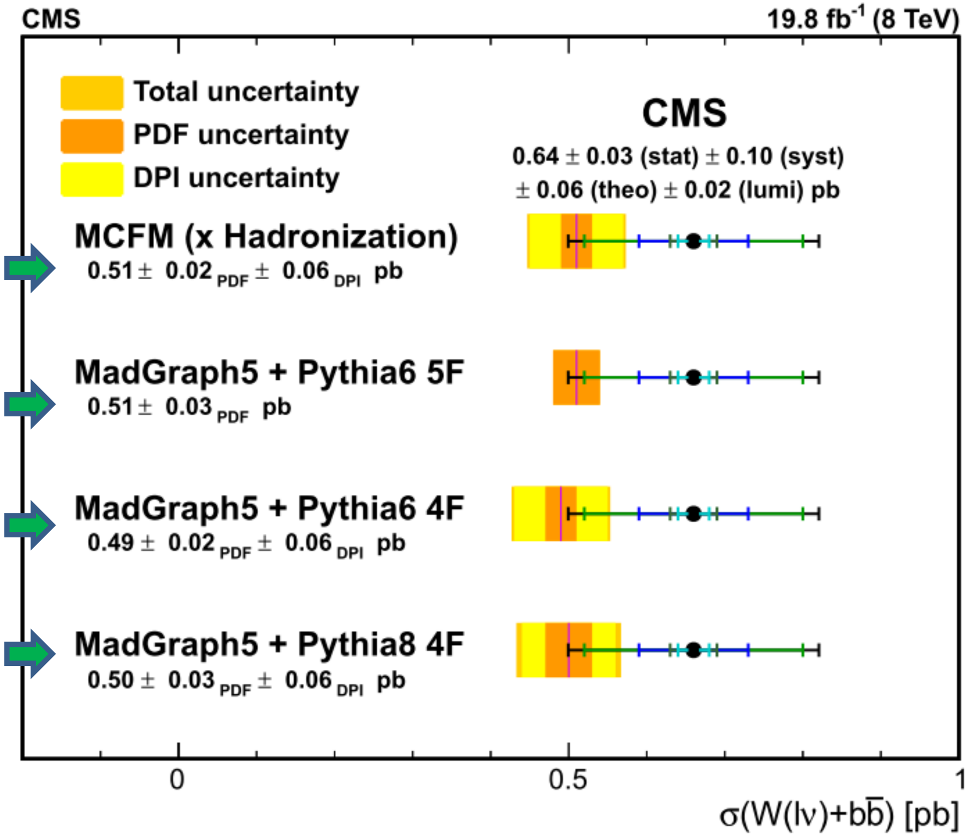
arXiv:1608.07561
Accepted by EPJC

NLO

LO

LO

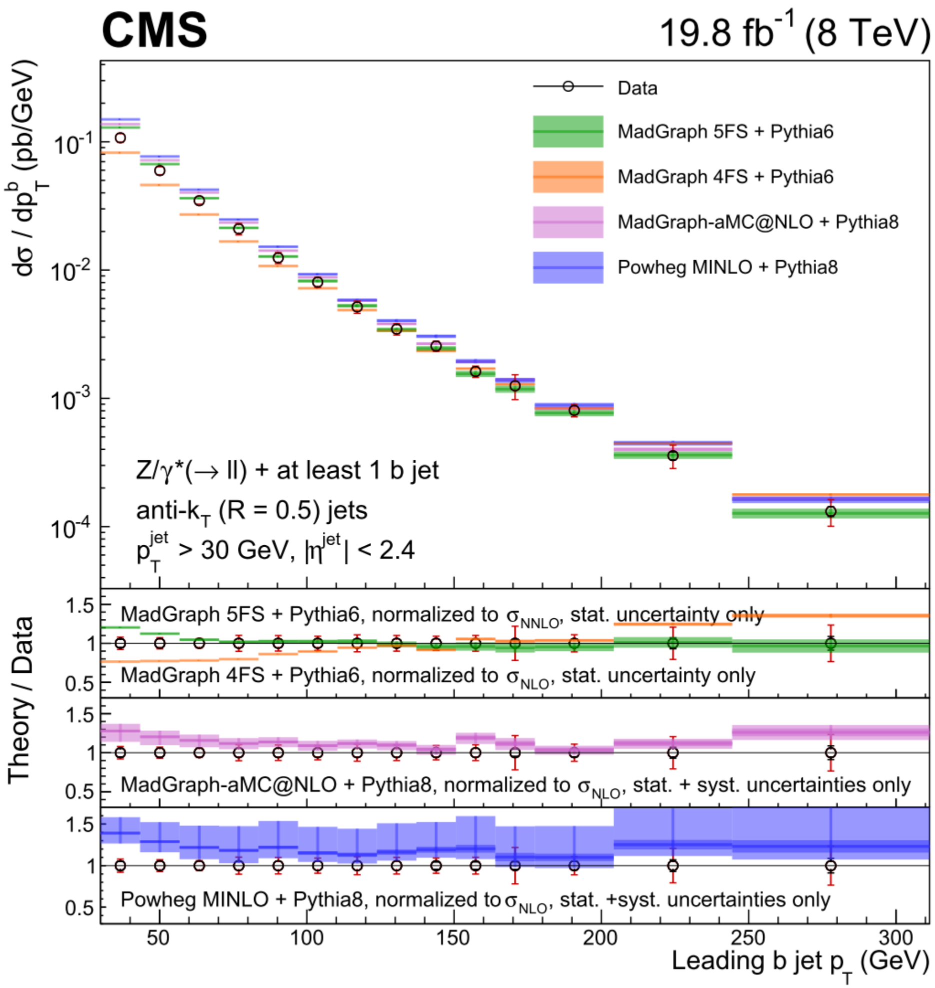
LO

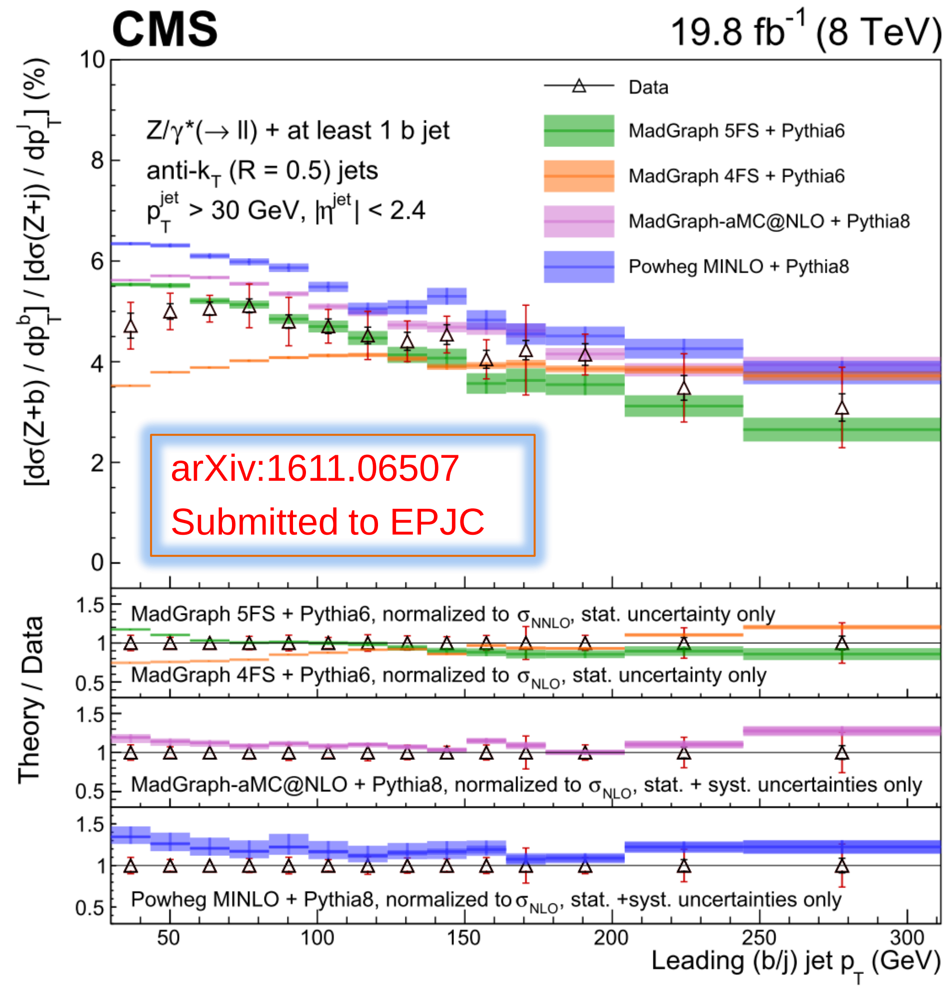


- The MCFM and MG+Py* with 4 flavor scheme do not account for the $b\bar{b}$ coming from multiple parton interaction
- Hadronization correction is added for MCFM prediction which is at parton level

➢ All the predictions agree with measured cross section within one standard deviation

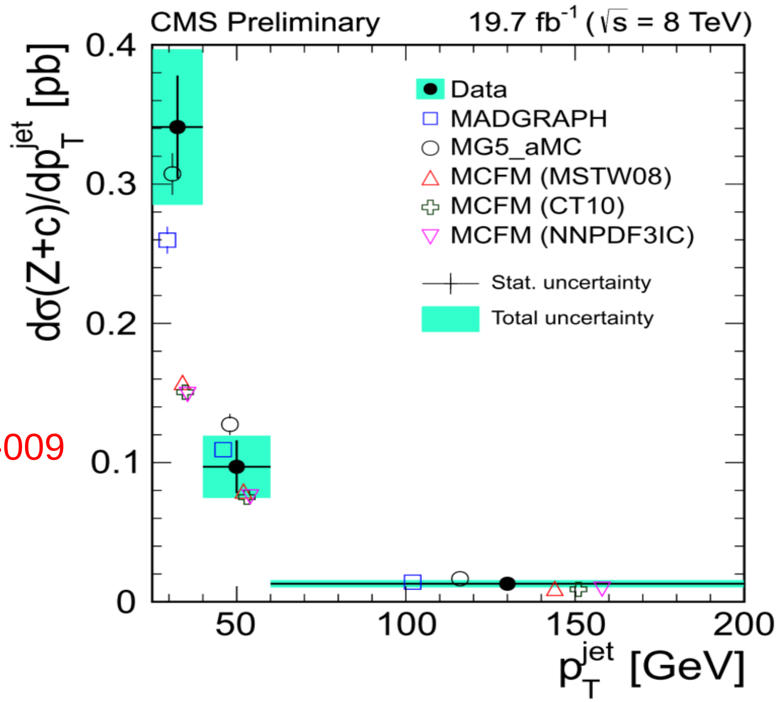
Z+b jets cross section measurement



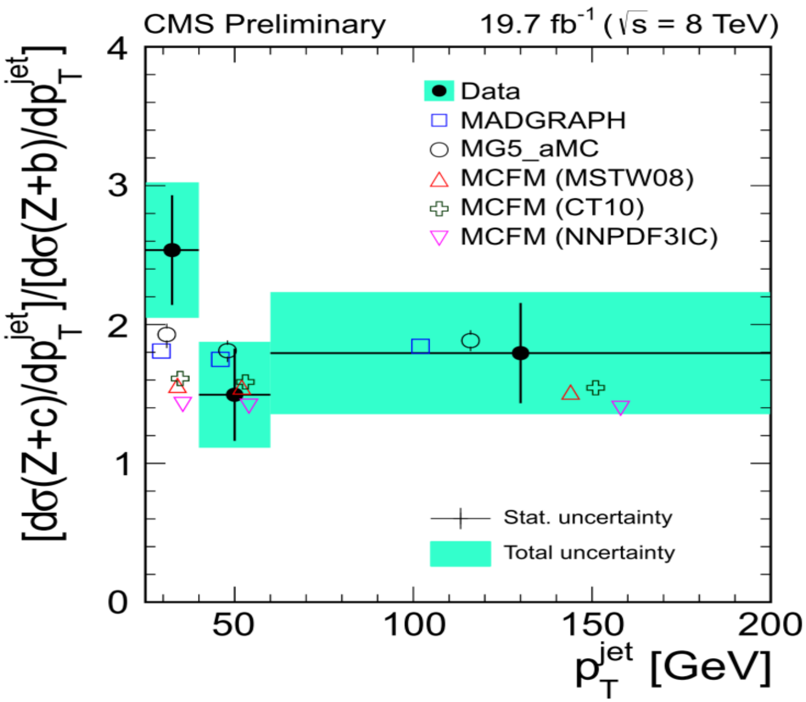


- **Discrepancy of about 20% is observed for 4FNS-based LO prediction**
- **The 5FS-based predictions (LO & NLO) slightly overshoots the data at small transverse momentum of b jet (20%~25%)**
- **Powheg NLO prediction is implemented with "Multi-scale Improved NLO" (MINLO):**
    - **10.1007/JHEP10(2012)155**

Z+c jets cross section measurement



SMP-15-009



- **The predictions with MADGRAPH LO and MG5_aMC predictions successfully reproduce the measurement in general**
- **The MCFM predictions are in good agreement for the p_T region above 40 GeV**

- **The measured Z + c-flavor-jet production cross section:**

  8.6 $\pm$ 0.5 (stat.) $\pm$ 0.7 (syst.) pb

- **The measured cross section ratio of Z+c to Z+b:**

  2.0 $\pm$ 0.2 (stat.) $\pm$ 0.2 (syst.) pb

Outlook

- The measurement on vector boson plus jets processes is quite important:
  - It deepens our understanding on QCD dynamics
  - It improves the modeling of background for Higgs measurement and new physics searches

- There have been significant improvement on theoretical predictions and experimental measurements:
  - Reach high precision of measurement
  - Better agreement with higher order (NLO) calculation than LO in general
  - Remained discrepancy and large uncertainty motivate the ongoing work to improve modeling and precision

- More results at both 8 TeV and 13 TeV will come out soon!

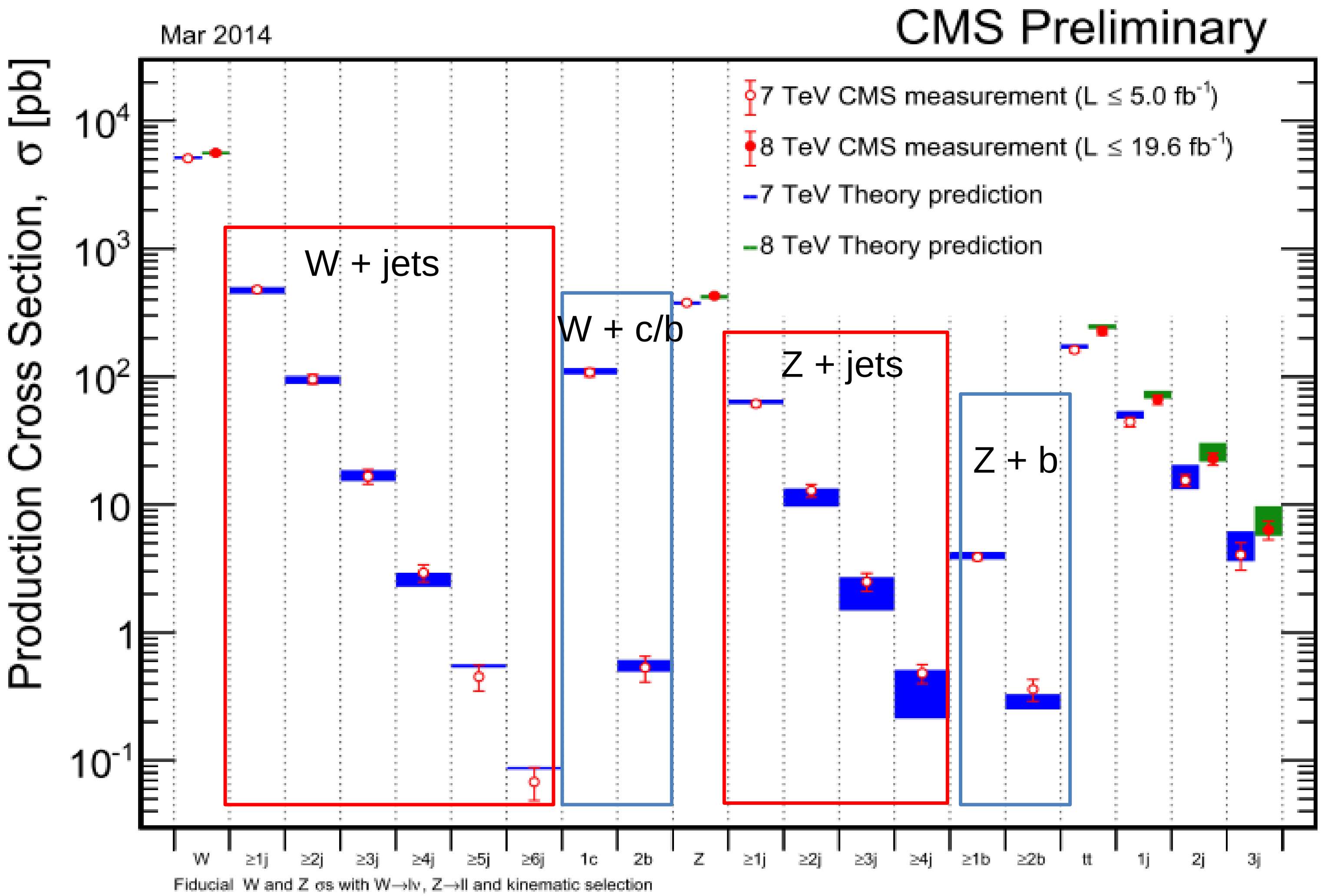
Measurements of W/Z + jets at 13 TeV from CMS will be presented tomorrow by Qun Wang!

Backup

V+jets predictions on Monte Carlo evolution

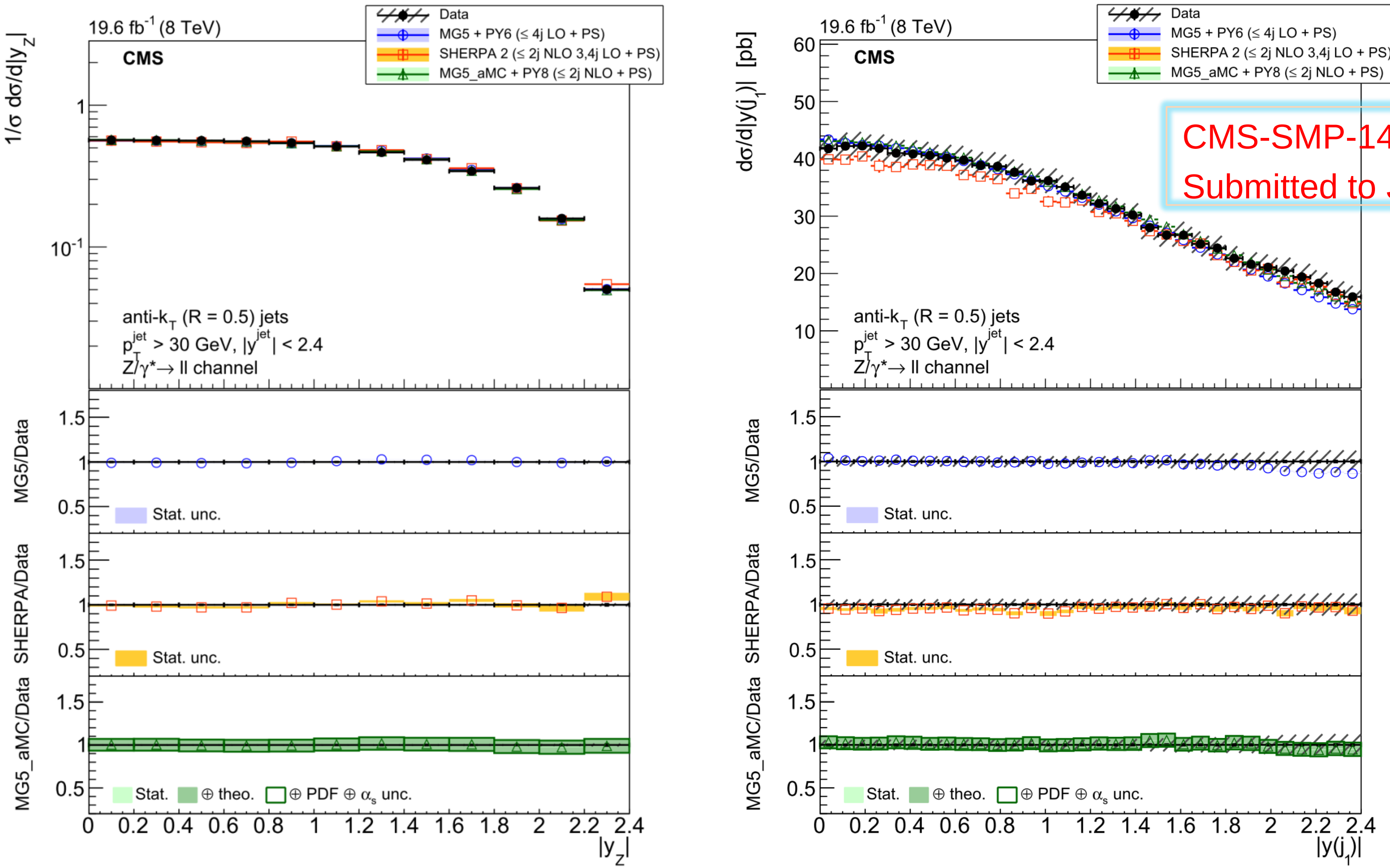
- There are still theoretical uncertainties related to various sources which can be constrained by data:
  - Higher order QCD corrections (NNLO)
  - Electroweak corrections
  - Parton shower and its matched matrix element
  - Parton density functions
  - Underlying event modeling (multiple parton interactions)

Legend of V+jets (Run I)



- Good agreement between experimental measurement and theory for Run I
- High precision up to very low cross section (high jet multiplicity)

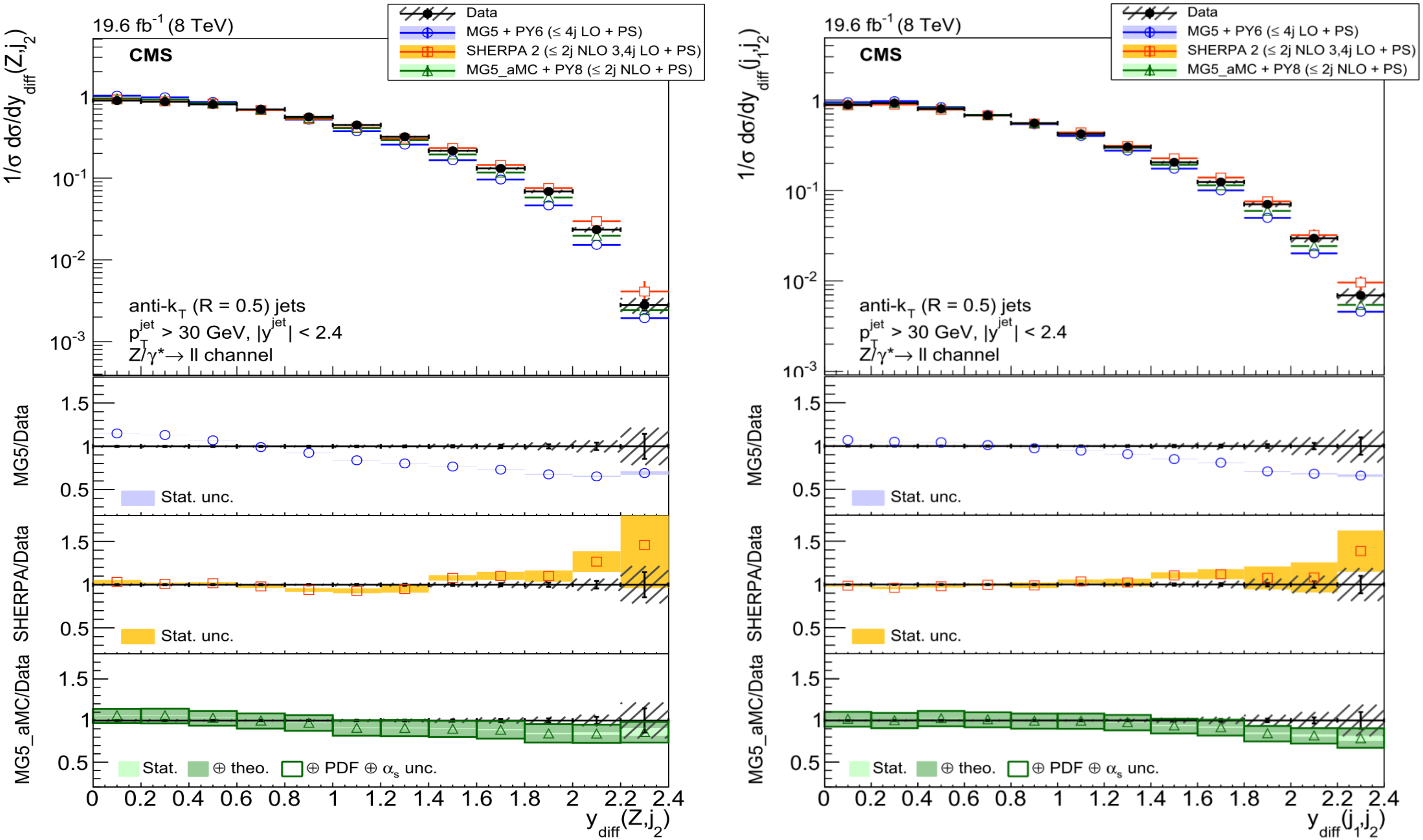
Z + jets differential cross section results



CMS-SMP-14-013
Submitted to JHEP

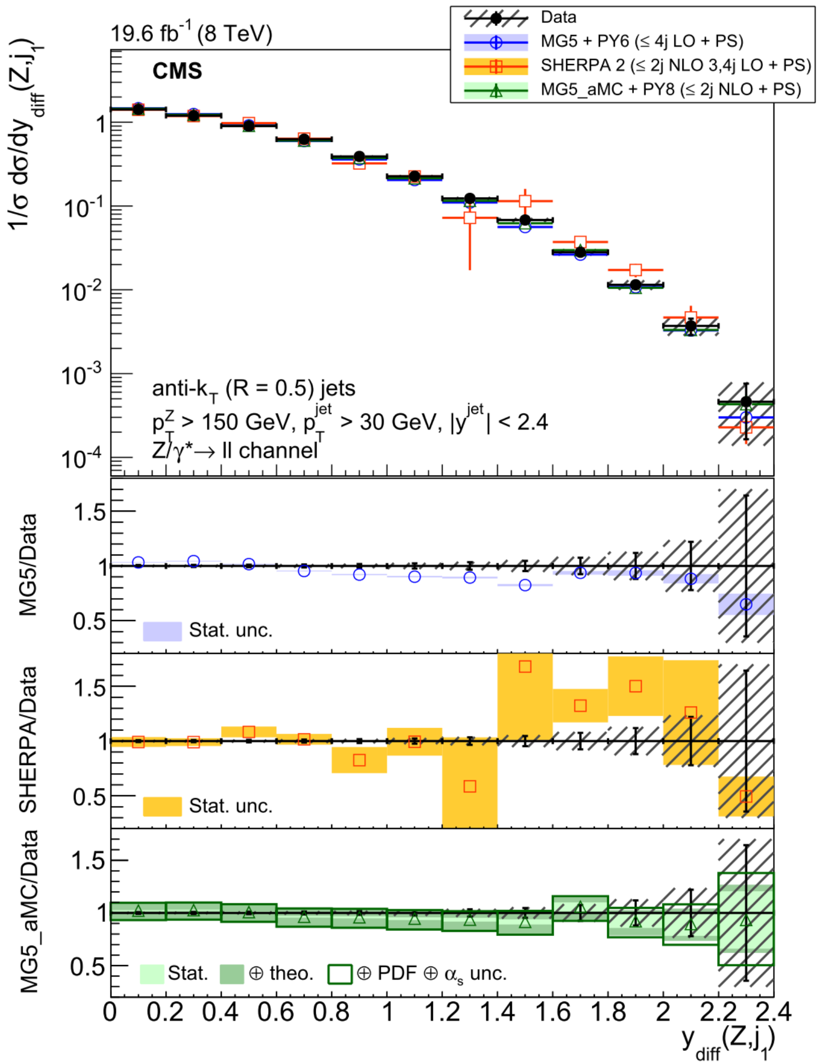
- Good agreement in general for all the predictions
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 5 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

Rapidity correction measurement of Z + jets



- Discrepancy is also seen when taking into account the second jet, while it is less than the case of leading jet with Z boson

Rapidity correction measurement of Z + jets

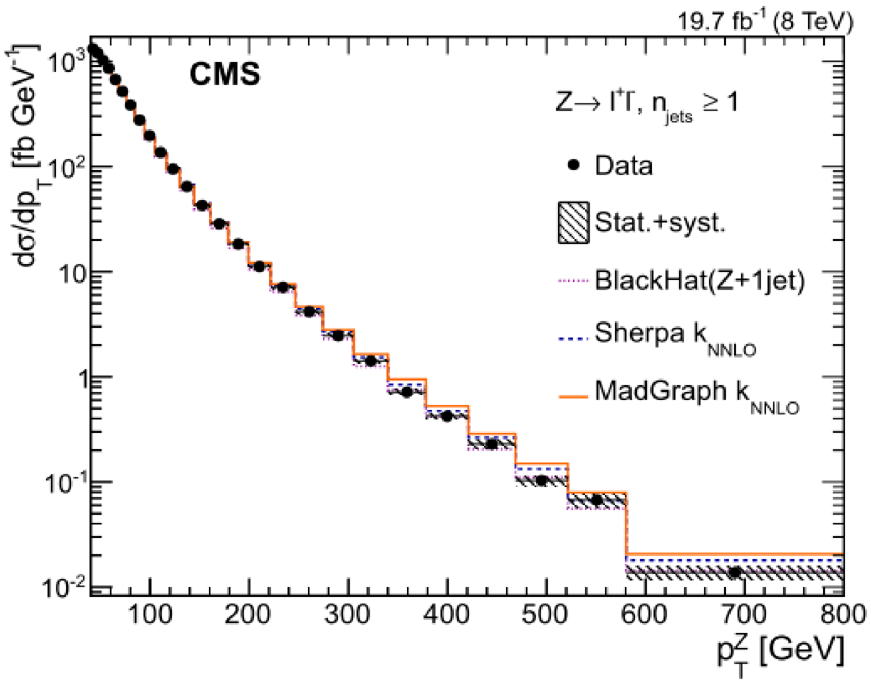


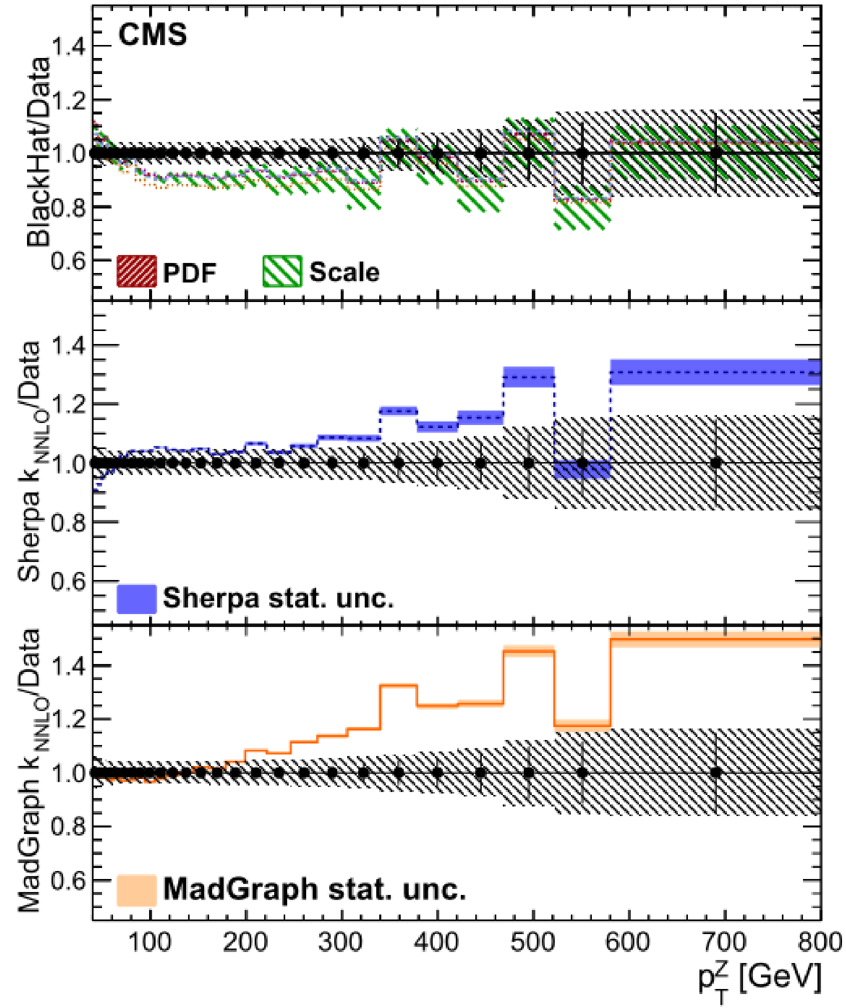
- The discrepancy with LO prediction decreases significantly when requiring the Z boson p_T larger than 150 GeV

Z + ≥ 1 jet cross section as function of Z boson p_T

JHEP10(2015)128

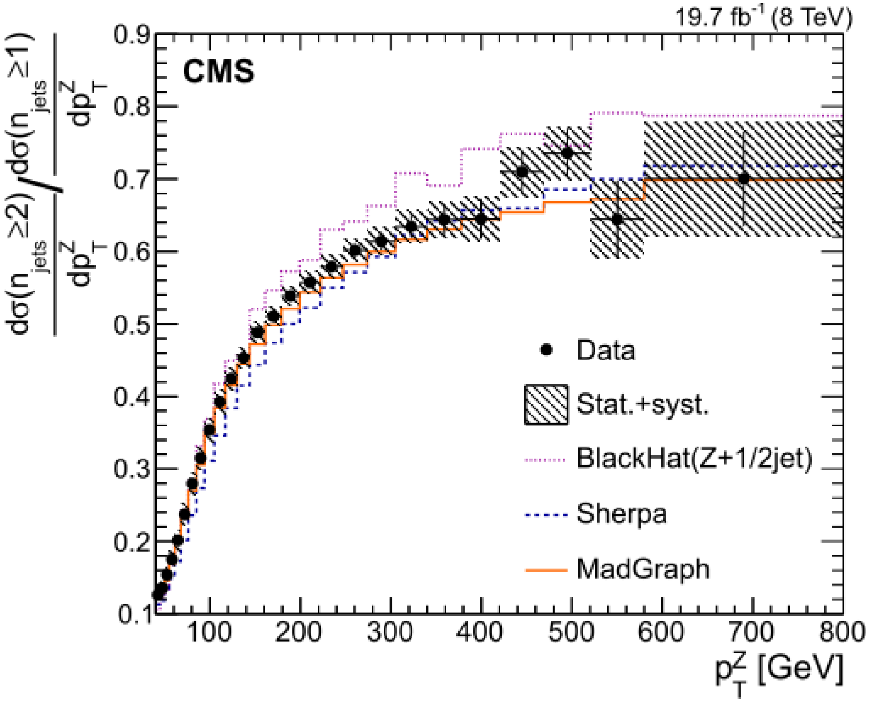
Published





- K_{NNLO}: Z+>=0 jet cross section rescaled to NNLO value from FEWZ
- MG5+Pythia6 comparison is flat until around 200 GeV and up to about 30% discrepancy, which is same for Z+ ≥ 2 jets case
- BLACKHAT reproduces the shape of data in the same region

Z+≥1 jet & Z+≥2 jets cross section ratio as function of Z p_T



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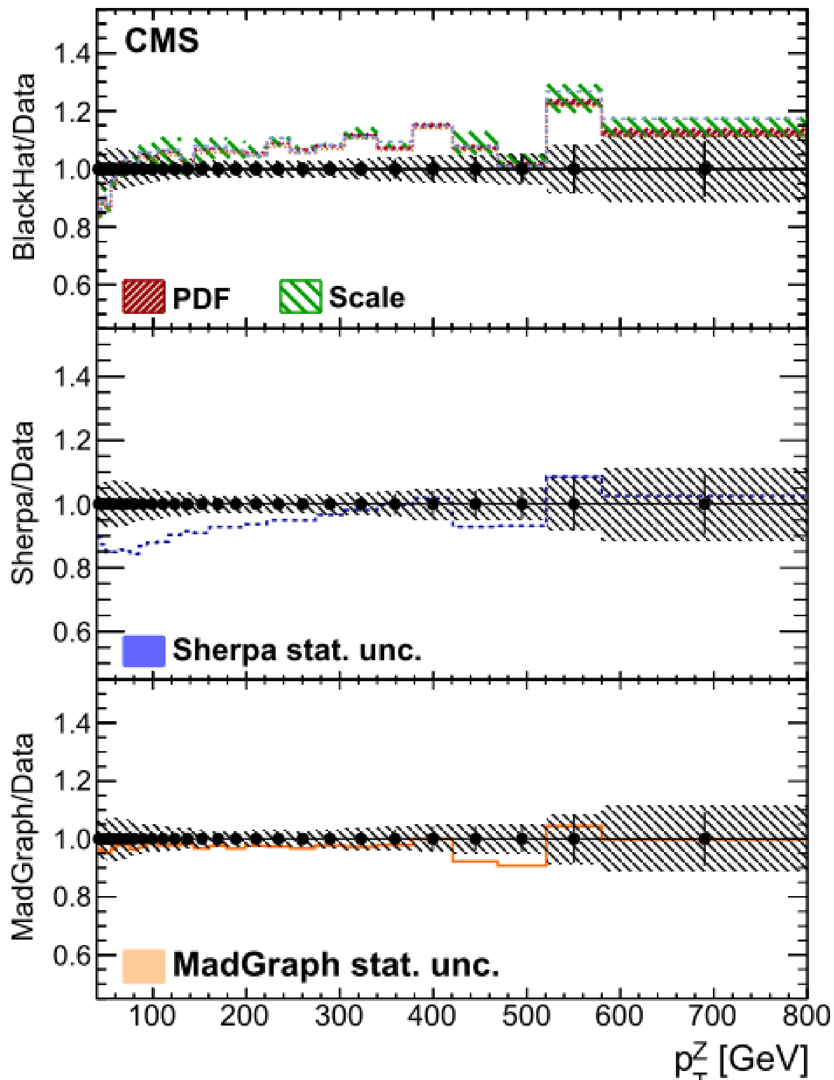

- The ratio increases until reaching around 350 GeV before a plateau
- SHERPA underestimates the relative rate of inclusive 2 jets case
- BLACKHAT overestimates the ratio after around 100 GeV

Z + ≥ 3 jets cross section ratio as function of Z p_T/ HT

- This observable allows to test validity of NLO estimation, which might reach computational limit due to large logarithms or missing higher order effects may play a larger role
- Events in the high-end tail contribute to signatures with a high E_T/HT ratio for hadronic new physics searches

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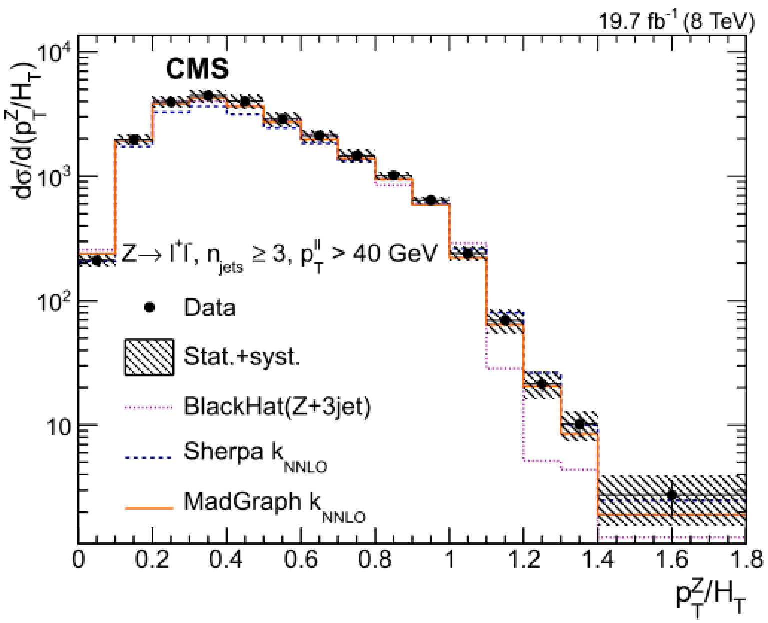
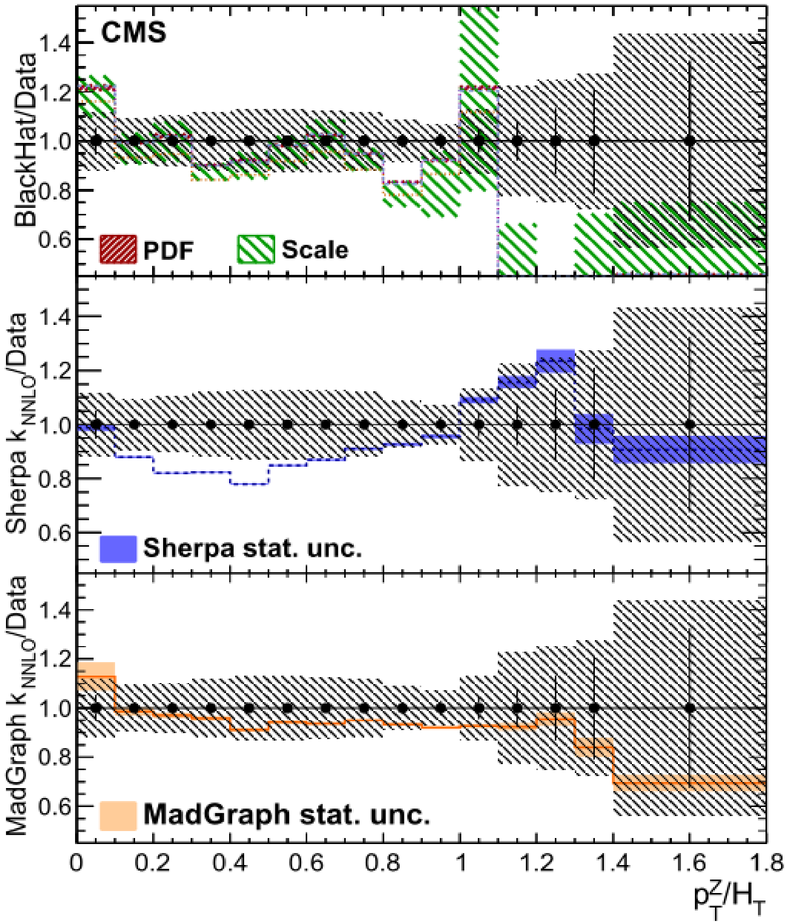
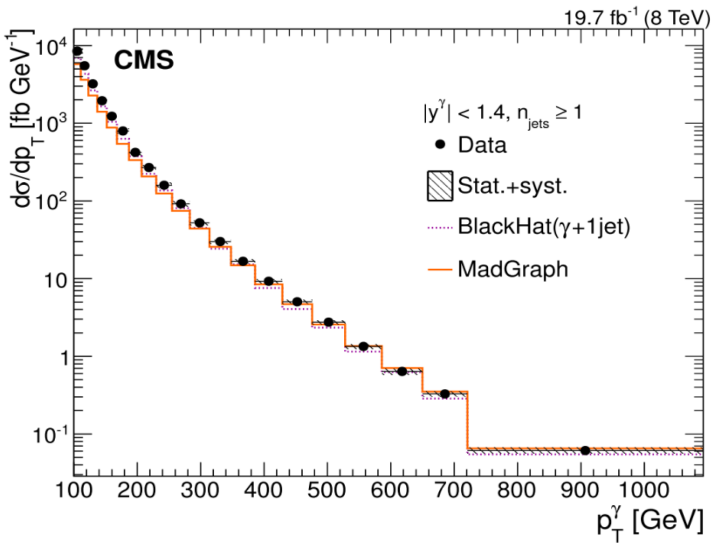
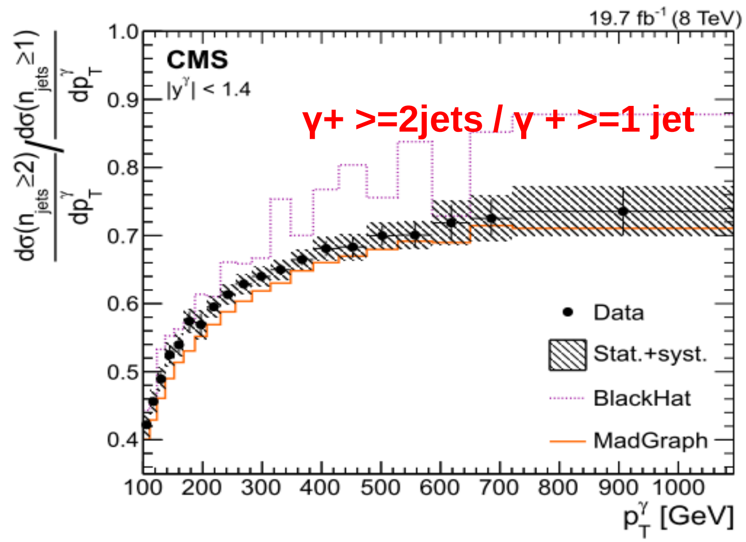




- MG5 generally predicts best on the shape
- SHERPA shows discrepancy on shape and rate
- BLACKHAT performs well on the bulk of distribution while failing to reproduce the tails

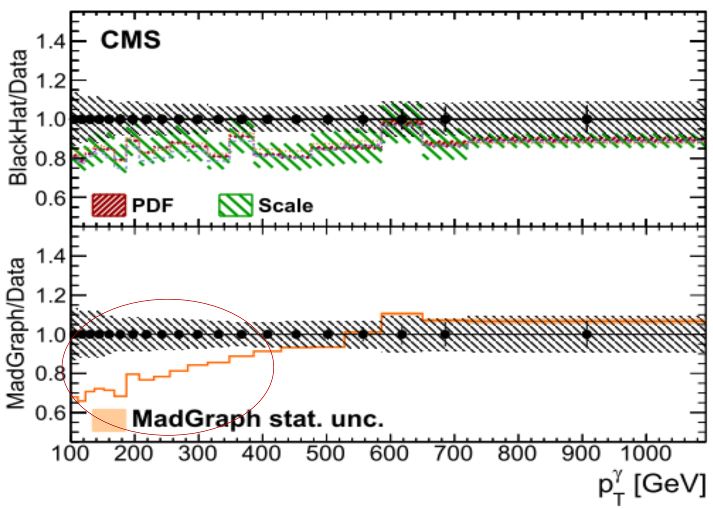
Photon (γ) + jets cross section at 8 TeV

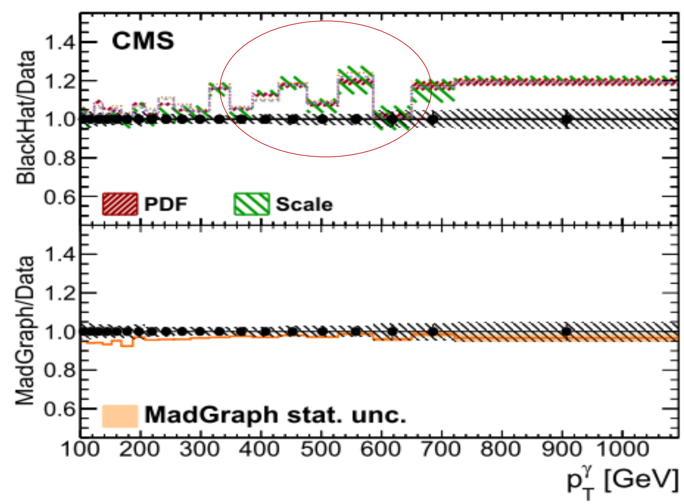




- **Lepton selection:**
  - p_T (l) > 20 GeV
  - |η (l)| < 2.4
- **Photon selection:**
  - p_T (γ) > 20 GeV
- **Jet selection:**
  - p_T (j) > 30 GeV
  - |η (j)| < 2.4

JHEP10(2015)128

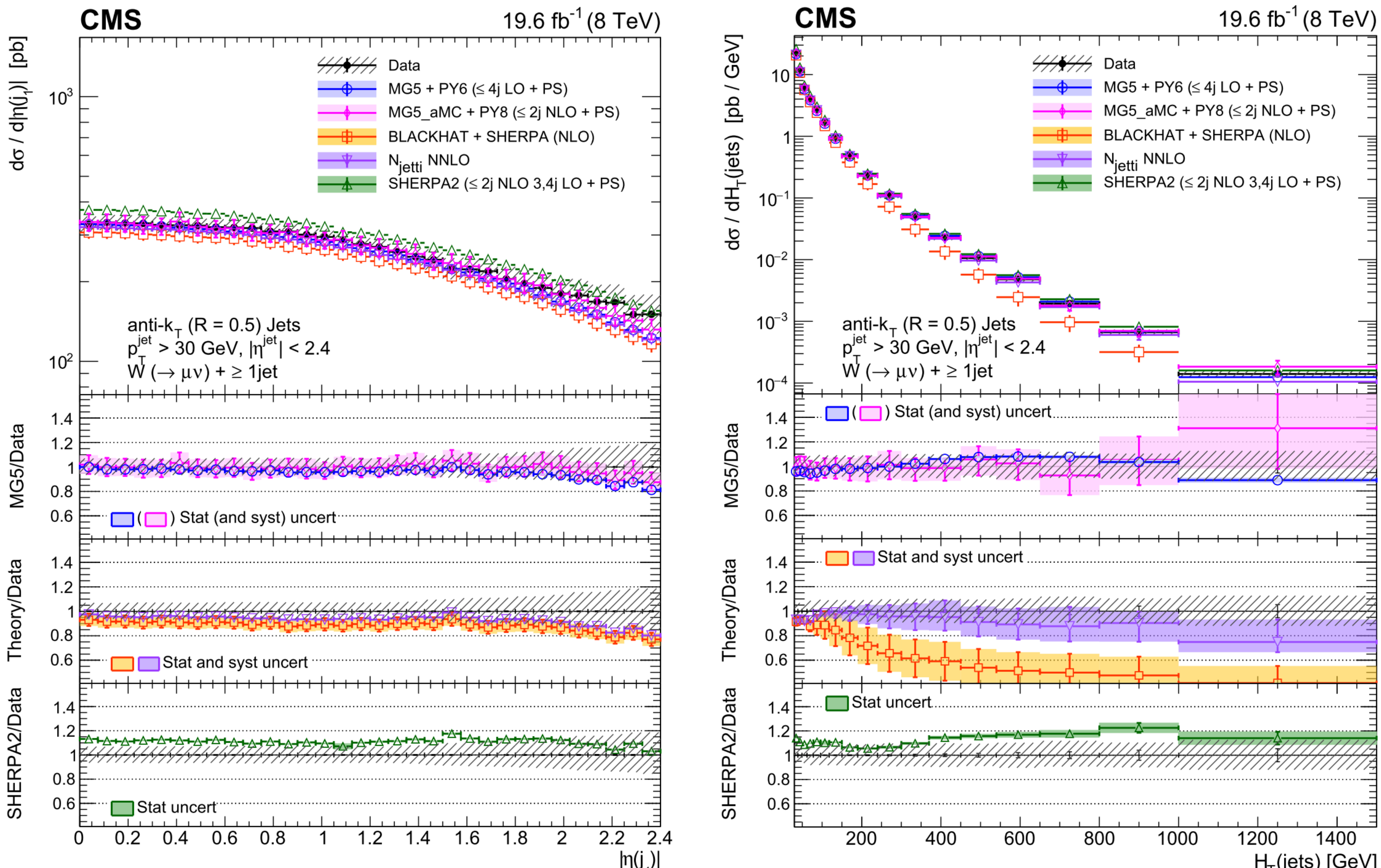




- BLACKHAT reproduces the shape of data better than MADGRAPH

- BLACKHAT overestimates the ratio by 10% for p_T (γ) > 100 GeV
- LO prediction describes the data shape very well

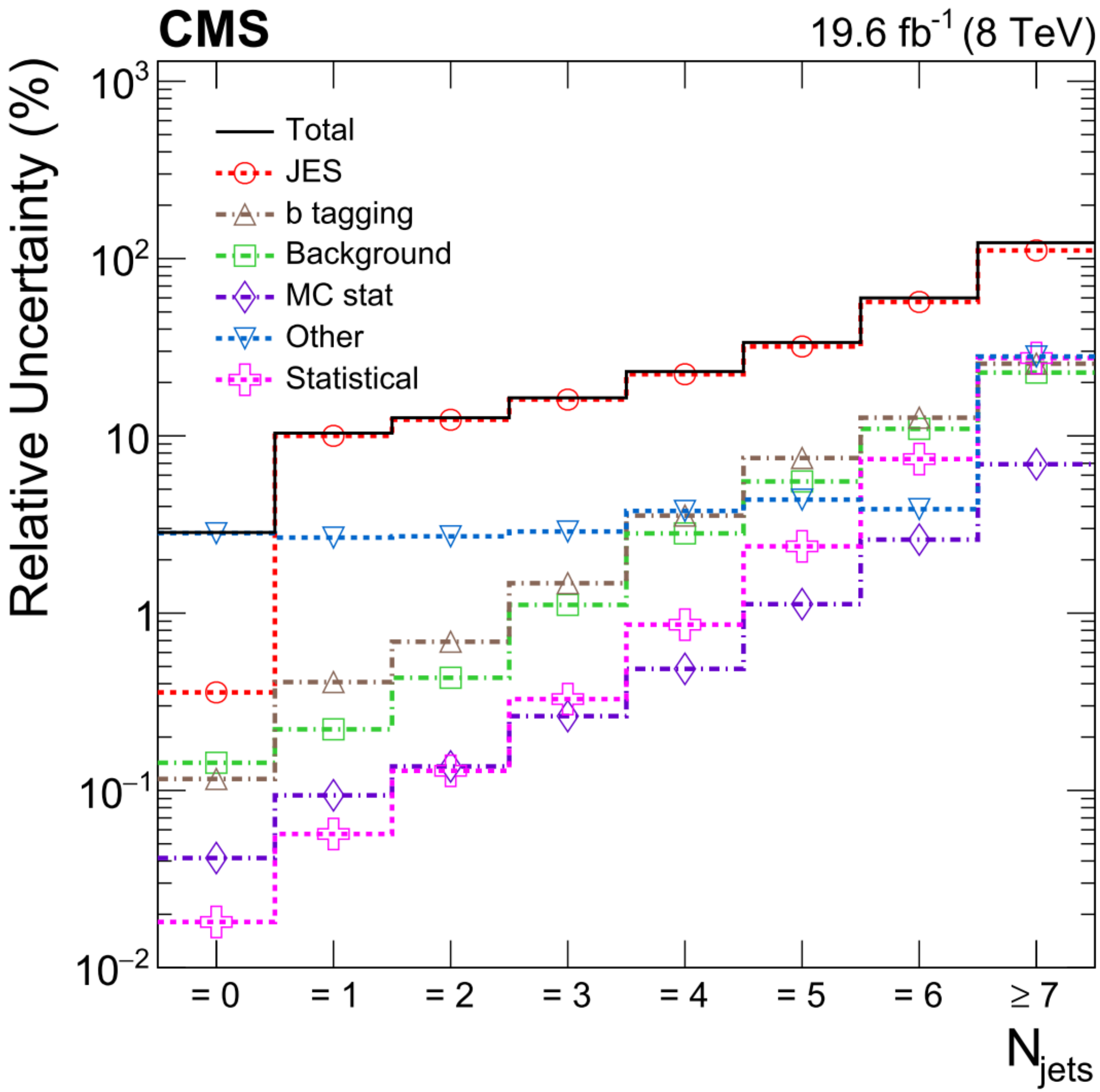
W + jets differential cross section results



- Only the W(->μν) decay channel is measured
- Excellent agreement with AMC@NLO and NNLO W+1J predictions

CMS-SMP-14-023
Submitted to PRD

W + jets differential cross section uncertainties

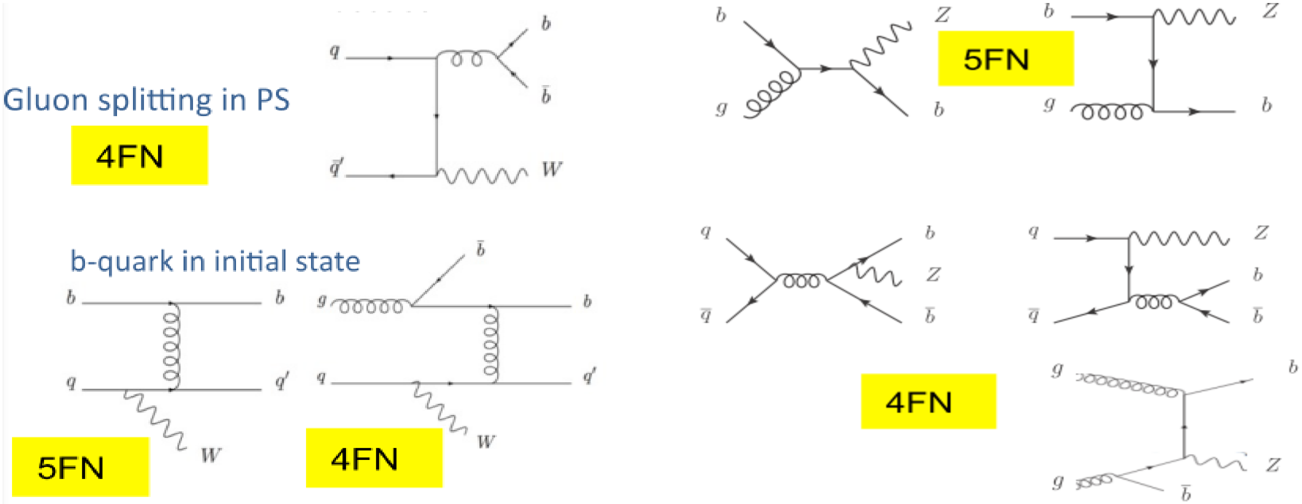


- Only the decay channel of W(->μν) + jets is measured
- The dominant uncertainty comes from the jet energy scale variations

CMS-SMP-14-023
Submitted to PRD

W/Z + heavy flavor jets (b/b̄) measurement at 8 TeV

- Theoretical uncertainties on W/Z + heavy flavor jets larger than for light jets case
  - Heavy quark content in the proton
  - Modeling of gluon splitting (initial state or final state)
  - Massive or massless b quark in computations
- Test of QCD predictions with various implementations (LO+Multipartons + parton shower, NLO, NLO+PS)
- Important process for backgrounds of Higgs searches



- Descriptions of "b-quark initiated processes:"
- 4 flavors number scheme (4FN): b quark generated with gluon splitting
- 5 flavors number scheme (5FN): b quark (massless) generated in the initial state

W+b$\bar{b}$ measurement at 8 TeV

	Muon		Electron	
	Initial	Fitted	Initial	Fitted
Data	7432		7357	
W +b$\bar{\text{b}}$	1323	1712	1121	1456
W+c$\bar{\text{c}}$	60	61	36	37
W+udscg	182	179	220	217
t$\bar{\text{t}}$	3049	3296	2640	2864
Single top	958	1008	820	865
Drell–Yan	261	265	220	224
Diboson	175	181	139	144
γ+jets	—	—	98	105
QCD	1109	803	1654	1373
Total MC	7116	7505	6948	7284
Signal strength	1.21 ± 0.19		1.37 ± 0.23	
Combined	1.26 ± 0.17			

		Uncertainty	Variation	Effect on the measured cross section
Normalization	Uncorrelated	t$\bar{\text{t}}$	3.5%	3.8%
Normalization	Uncorrelated	Single top	5.4%	2.5%
Normalization	Uncorrelated	W+udscg	13.2%	<2%
Normalization	Uncorrelated	W+c$\bar{\text{c}}$	13.2%	<2%
Normalization	Uncorrelated	Diboson	8.1%	<2%
Normalization	Uncorrelated	Drell–Yan	7.9%	<2%
Normalization	Uncorrelated	γ+jets	10.0%	<2%
Normalization	Uncorrelated	QCD	50%	2–3%
Normalization	Correlated	b tag eff rescaling	8.4%	9.2%
Normalization	Correlated	JES rescaling	0–6%	3.8%
Shape	Correlated	UES	0–3%	<2%
Shape	Correlated	MES	0–3%	<2%
Shape	Correlated	EES	0–3%	<2%
Shape	Correlated	Id/Iso/Trg	0–4%	<2%
		Luminosity	2.6%	
		Scales (μ_R,μ_F)	10%	
		PDF choice	1%	

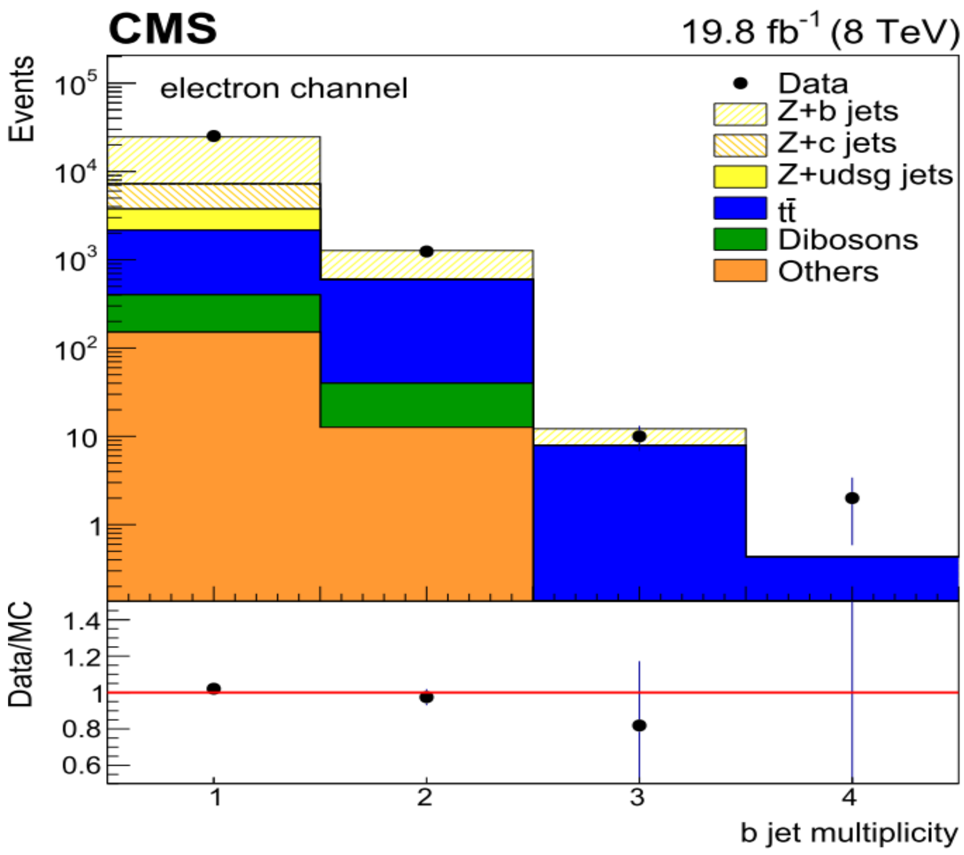
CMS-SMP-14-020

- The signal sample is generated at tree-level by MADGRAPH5 interfaced with PYTHIA6
- The t$\bar{t}$ is the dominant background, which is reweighted by data in the signal free region, in order to predict the transverse mass distribution in the signal region

Z+b jets measurement at 8 TeV

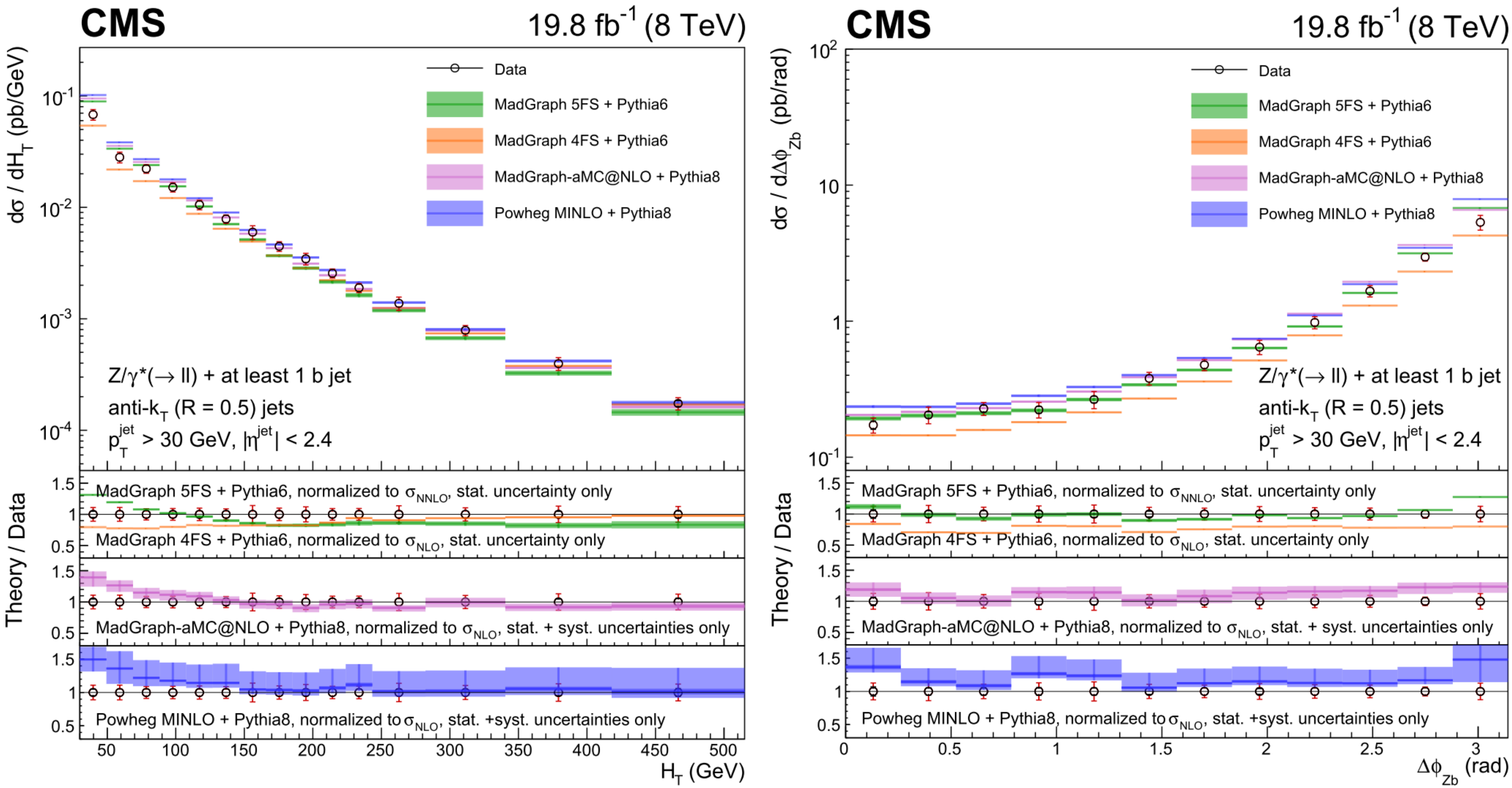
- Lepton selection:
  - P_T > 20 GeV
  - |η| < 2.4
  - 71 < Mll < 111 GeV

- B-tagged jet selection:
  - P_T > 30 GeV
  - |η| < 2.4



- The signal sample is generated with MADGRAPH5 implementing a matrix element up to 4 partons in the final state, interfaced with PYTHIA6
- The $t\bar{t}$ is the dominant background, which is also generated with MG5 implementing a matrix element up to 3 partons in the final state

Z+b jets cross section measurement



- **Discrepancy of about 30% observed for 4FNS-based LO prediction for Z + b jet case**
- **The 5FS-based predictions (LO & NLO) slightly overshoots the data at small scalar sum of transverse momenta of b jets (30%~50%)**
- **Powheg NLO prediction is implemented with "Multi-scale Improved NLO":**
  - **10.1007/JHEP10(2012)155**

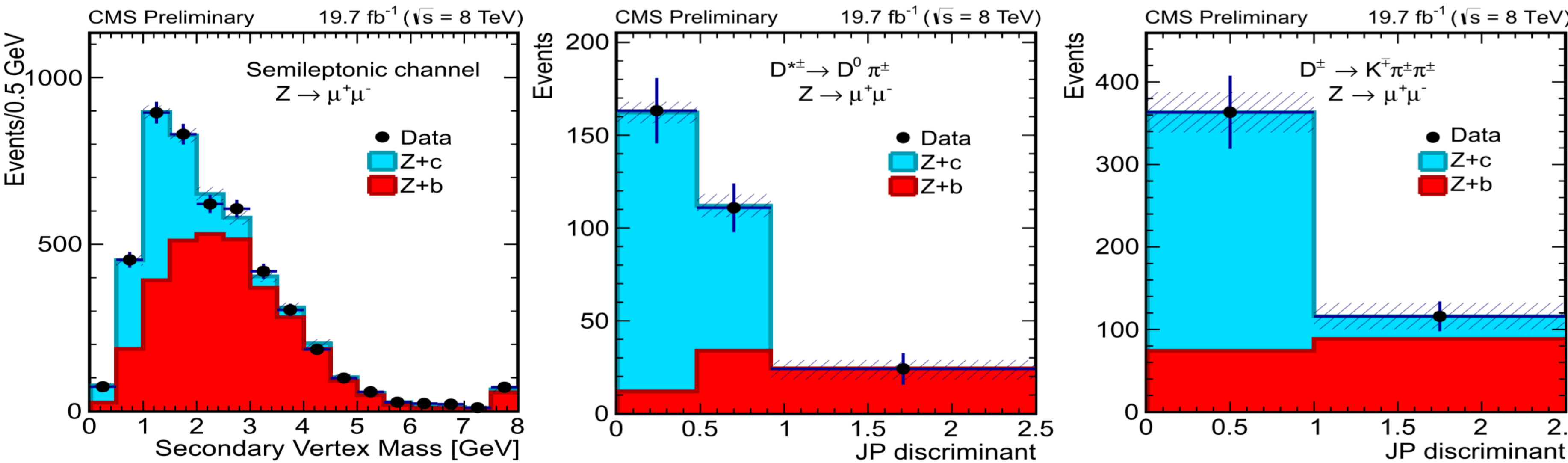
CMS-SMP-14-010
Submitted to EPJC

Z+c jets cross section at 8 TeV

- Three modes for identifying a jet from heavy flavor quarks:
  - Semileptonic decay of a heavy flavor hadron:
    - A muon participating in a secondary vertex
  - $D^{\pm}$ mode: three tracks from a secondary vertex:
    - $D^{\pm}$ -> $K^{\mp}\pi^{\pm}\pi^{\pm}$
  - $D^{*\pm}$ mode: two tracks from a secondary vertex:
    - D^{*+}-> $D^{0}\pi^{+}$ | D^{0}-> $K^{-}\pi^{+}$
    - D^{*-}-> $\overline{D^{0}}\pi^{-}$ | $\overline{D^{0}}$-> $K^{+}\pi^{-}$

SMP-15-009

- Lepton selection:
  - p_T > 20 GeV
  - $|\eta|$ < 2.1
  - 71 < M(ll) < 111 GeV
- High flavor jet selection:
  - p_T > 25 GeV
  - $|\eta|$ < 2.5



- A likelihood estimate of the probability that jet tracks comes from the primary vertex in the pure hadronic decay mode (JP discriminant)
- The invariant mass of all the charged particles (including a muon) constituting the secondary vertex in the semileptonic decay mode

Z+c jets cross section at 8 TeV

SMP-15-009

- Lepton selection:
- p_T > 20 GeV
- |η| < 2.1
- 71 < M(ll) < 111 GeV
- High flavor jet selection:
- P_T > 25 GeV
- |η| < 2.5

Semileptonic mode

Channel	N_{Z+c}^{signal}	$\mathcal{C}_{Z+c}$ (%)	$\sigma(Z+c)$ (pb)
$Z \to e^+e^-$	1066 ± 95	0.63 ± 0.03	$8.5 \pm 0.7 \pm 1.0$
$Z \to \mu^+\mu^-$	1449 ± 143	0.81 ± 0.03	$9.0 \pm 0.7 \pm 1.0$
Channel	N_{Z+b}^{signal}	$\mathcal{C}_{Z+b}$ (%)	$\sigma(Z+c)/\sigma(Z+b)$
$Z \to e^+e^-$	2606 ± 114	2.90 ± 0.08	$1.9 \pm 0.2 \pm 0.2$
$Z \to \mu^+\mu^-$	3241 ± 147	3.93 ± 0.10	$2.2 \pm 0.3 \pm 0.2$

$D^{\pm}$ mode

Channel	N_{Z+c}^{signal}	$\mathcal{C}_{Z+c}$ (%)	$\sigma(Z+c)$ (pb)
$Z \to e^+e^-$	275 ± 55	0.13 ± 0.02	$11.0 \pm 2.1 \pm 0.9$
$Z \to \mu^+\mu^-$	315 ± 75	0.18 ± 0.02	$9.0 \pm 2.1 \pm 0.8$

$D^{*\pm}(2010)$ mode

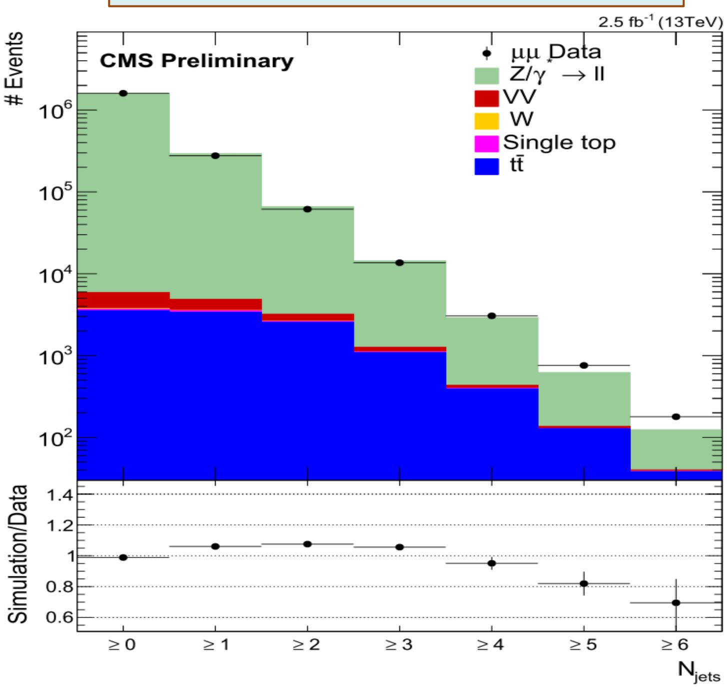
Channel	N_{Z+c}^{signal}	$\mathcal{C}_{Z+c}$ (%)	$\sigma(Z+c)$ (pb)
$Z \to e^+e^-$	151 ± 31	0.11 ± 0.01	$7.3 \pm 1.5 \pm 0.6$
$Z \to \mu^+\mu^-$	228 ± 30	0.14 ± 0.01	$8.6 \pm 1.1 \pm 0.6$

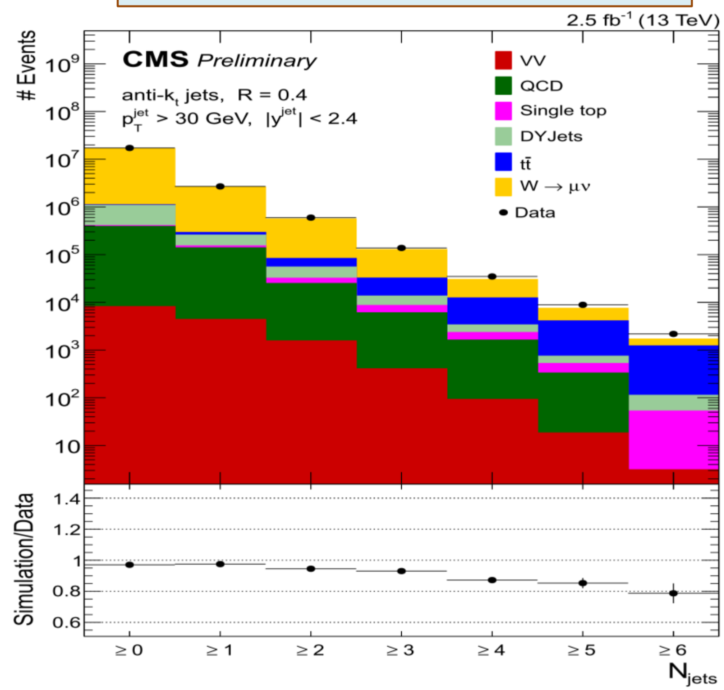
Data statistics for W/Z +jets measurement (13TeV)

- ➢ **Data**
- ◆ **Measured differential cross section as a function of several observables**
- ◆ **The presence of data goes up to large jet multiplicity region for both W/Z + jets**

➢Phase space for Z+jets:
- **Lepton selection:**
  - p_T (l) > 20 GeV
  - |η (l)| < 2.4
  - 71 < M (ll) < 111 GeV
- **Jet selection:**
  - p_T (j) > 30 GeV
  - |y (j)| < 2.4

➢Phase space for W+jets:
- **Lepton selection:**
  - p_T (l) > 25 GeV
  - |η (l)| < 2.1
  - M_T > 50 GeV
- **Jet selection:**
  - p_T (j) > 30 GeV
  - |y (j)| < 2.4





Theoretical predictions for W/Z + jets cross section comparison at 13 TeV

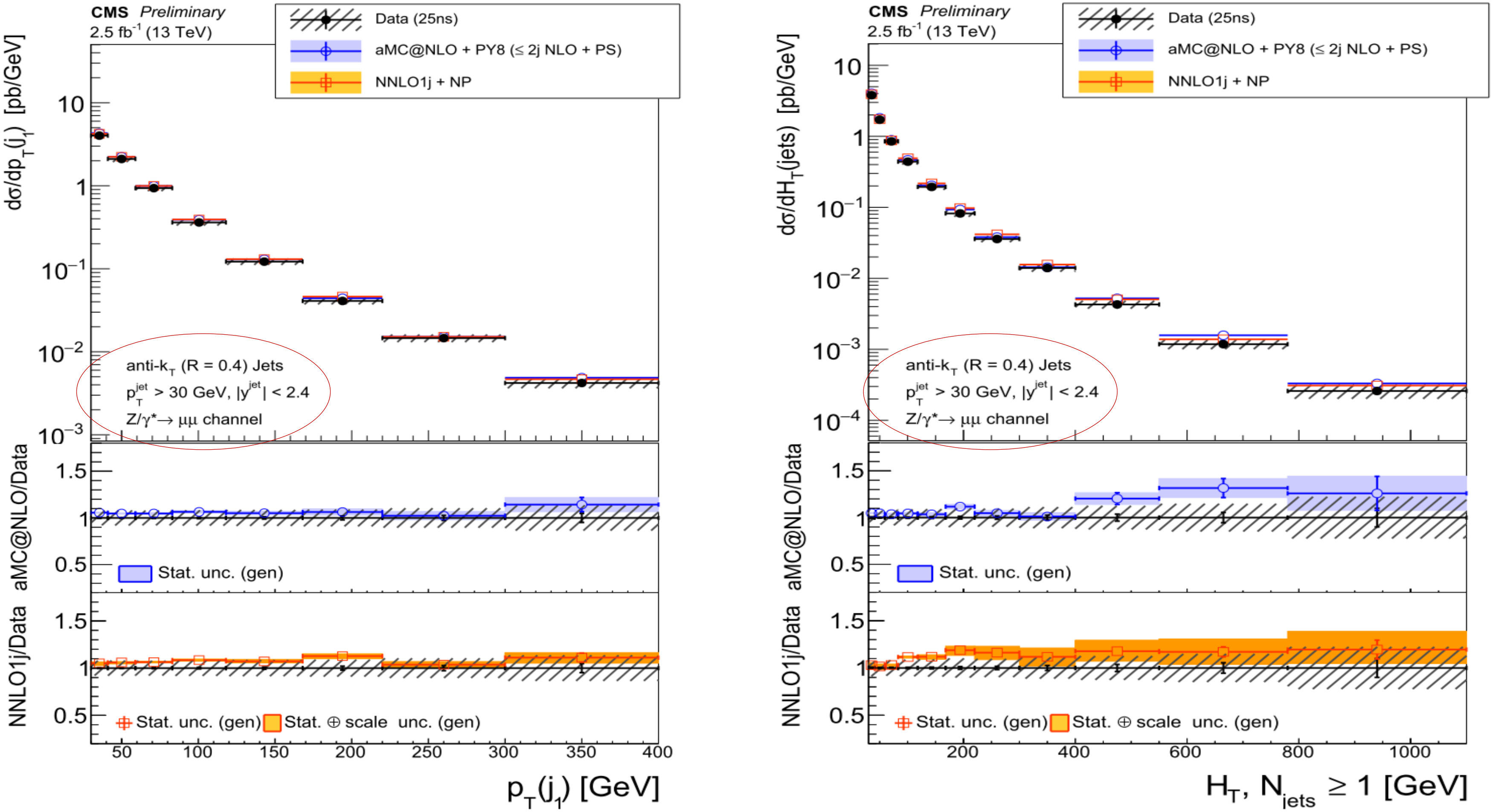
- MADGRAPH5_AMC@NLO + PYTHIA8
- Next leading order multileg matrix element up to two partons in final state, LO accuracy for 3 partons
- FxFx jet merging scheme
- NNPDF3.0 NLO PDF set
- CUETP8M1 PYTHIA8 tune

- NNLO
- NNLO W/Z+1jet with fixed order
- Correction for hadronization and multiple parton interaction computed with MADGRAPH5_AMC@NLO + PYTHIA8
- CT14 PDF set
- References:
  - arXiv:1602.08140
  - arXiv:1512.01291
  - arXiv:1602.06965
  - Phys. Rev. Lett. 115, no.6, 062002 (2015)

- MADGRAPH5 + PYTHIA (only for W+jets)
- Leading order accuracy up to four partons
- KT-MLM merging scheme
- CTEQ6L1 PDF

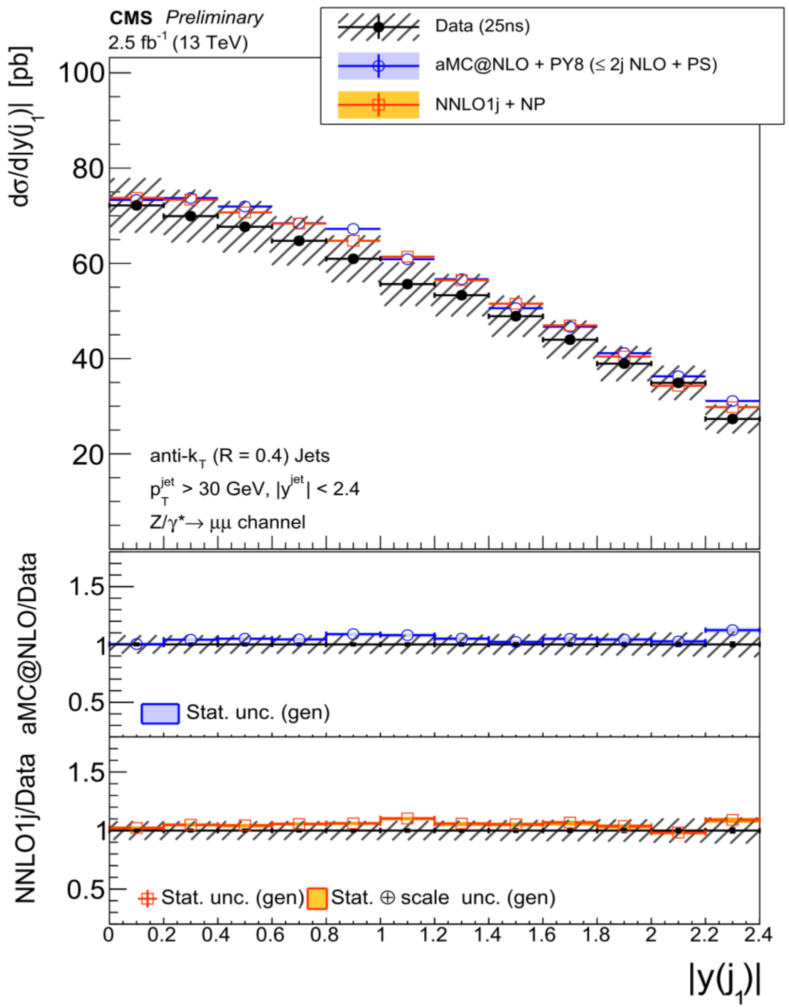
Z + jets differential cross section at 13 TeV

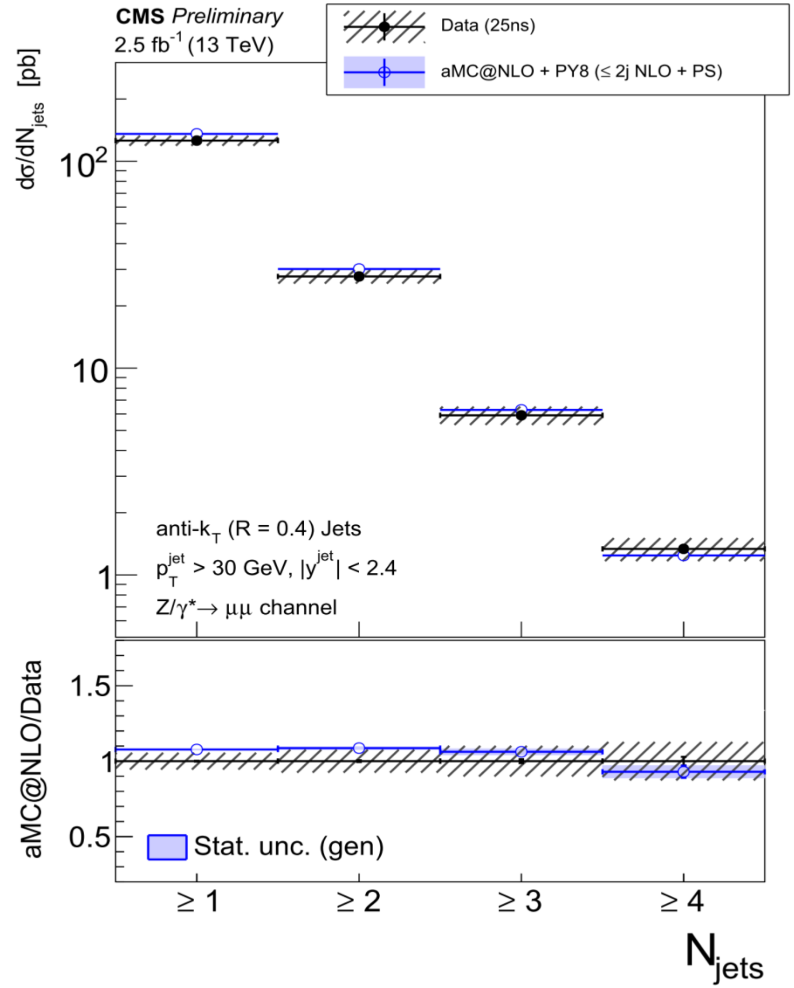
SMP-15-010



- Good agreement with multileg NLO and NNLO calculations
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 3 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

Z + jets differential cross section at 13 TeV

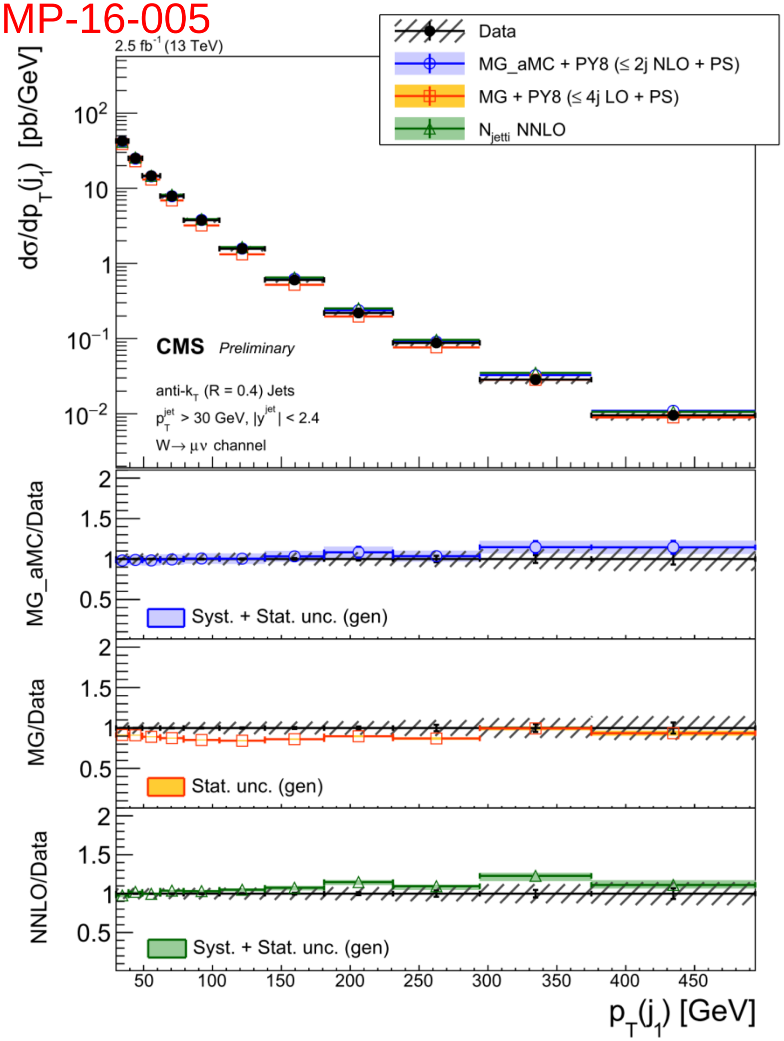


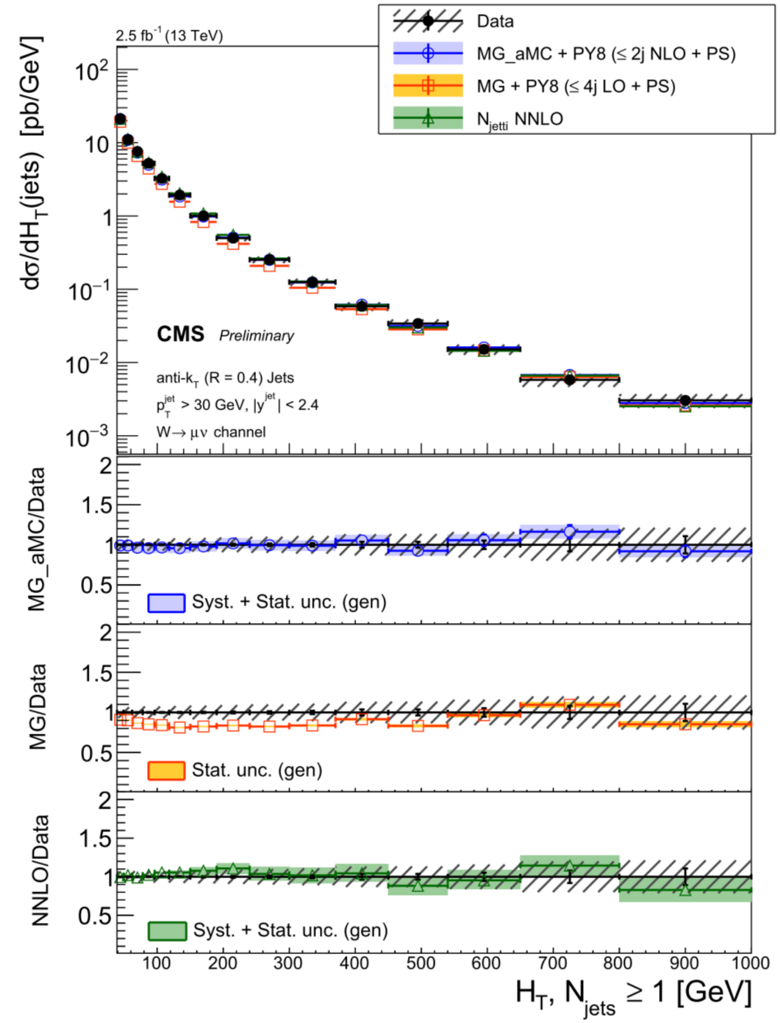


- Good agreement with both multileg NLO and NNLO calculations
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 3 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

W + jets differential cross section at 13 TeV

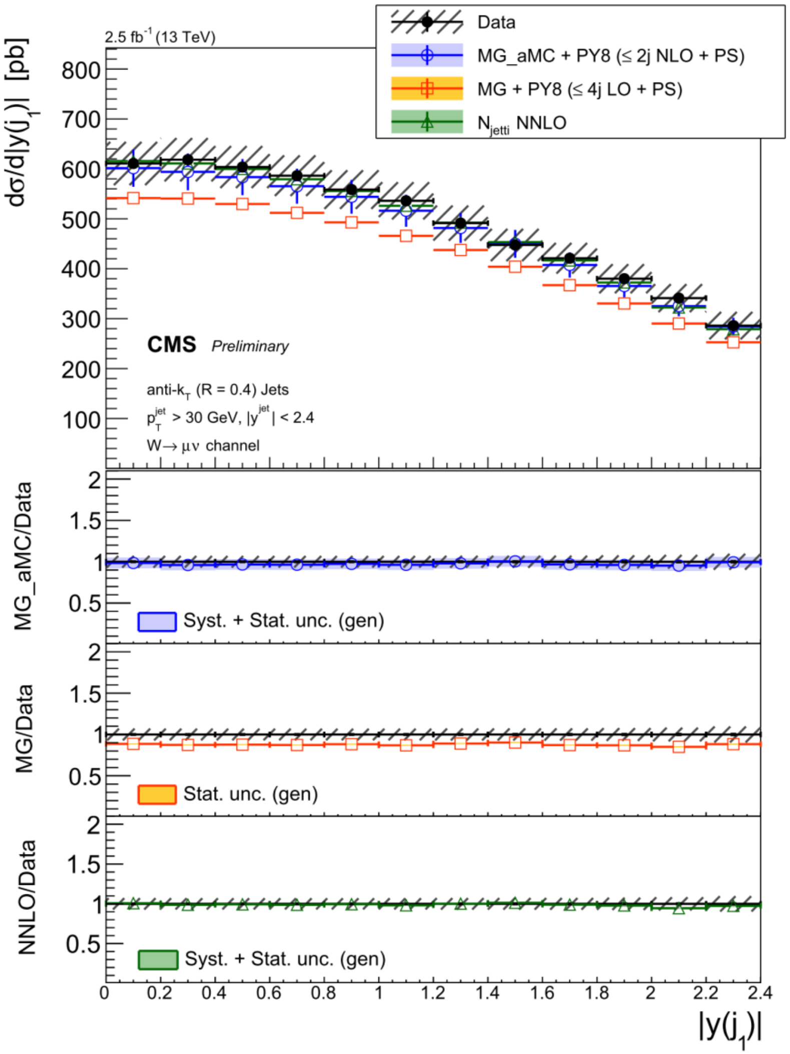
SMP-16-005

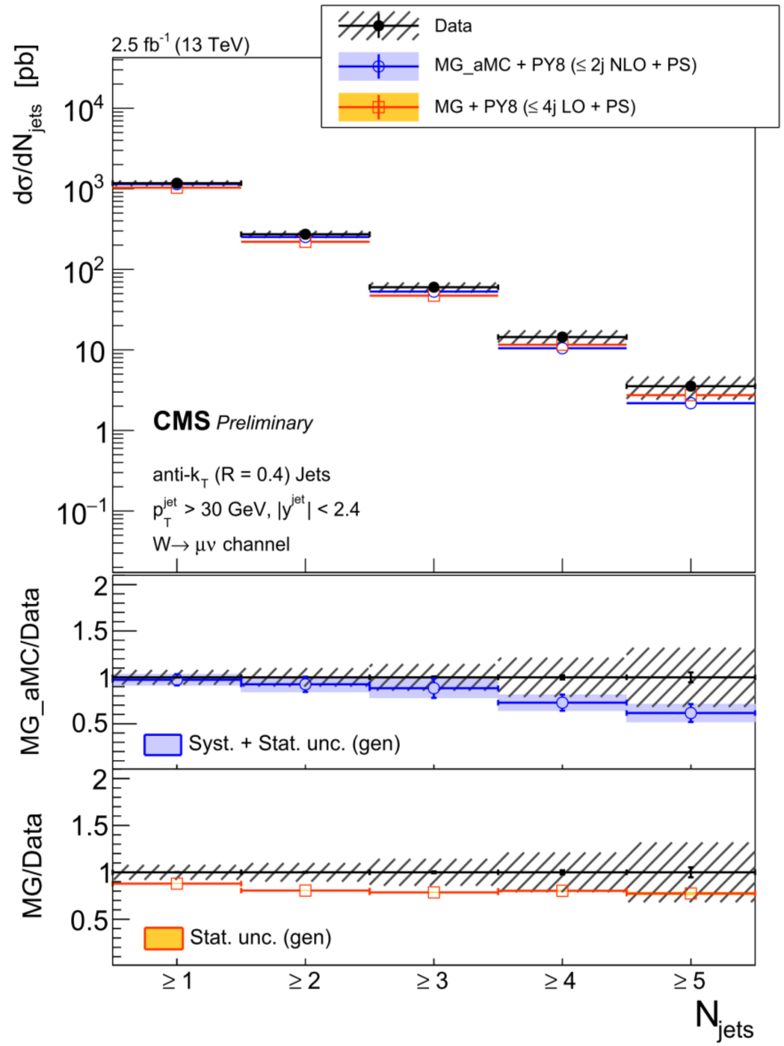




- Agreement is improved significantly with multileg NLO and NNLO calculations
- The p_T , η, H_T of jet for inclusive jet multiplicities up to 3 jets have also been measured
  - H_T is the scalar sum of the p_T of jets

W + jets differential cross section at 13 TeV





- Agreement is improved significantly with multileg NLO and NNLO calculations